Rockfalls and Debris Avalanches in the Smugglers Notch Area, Vermont

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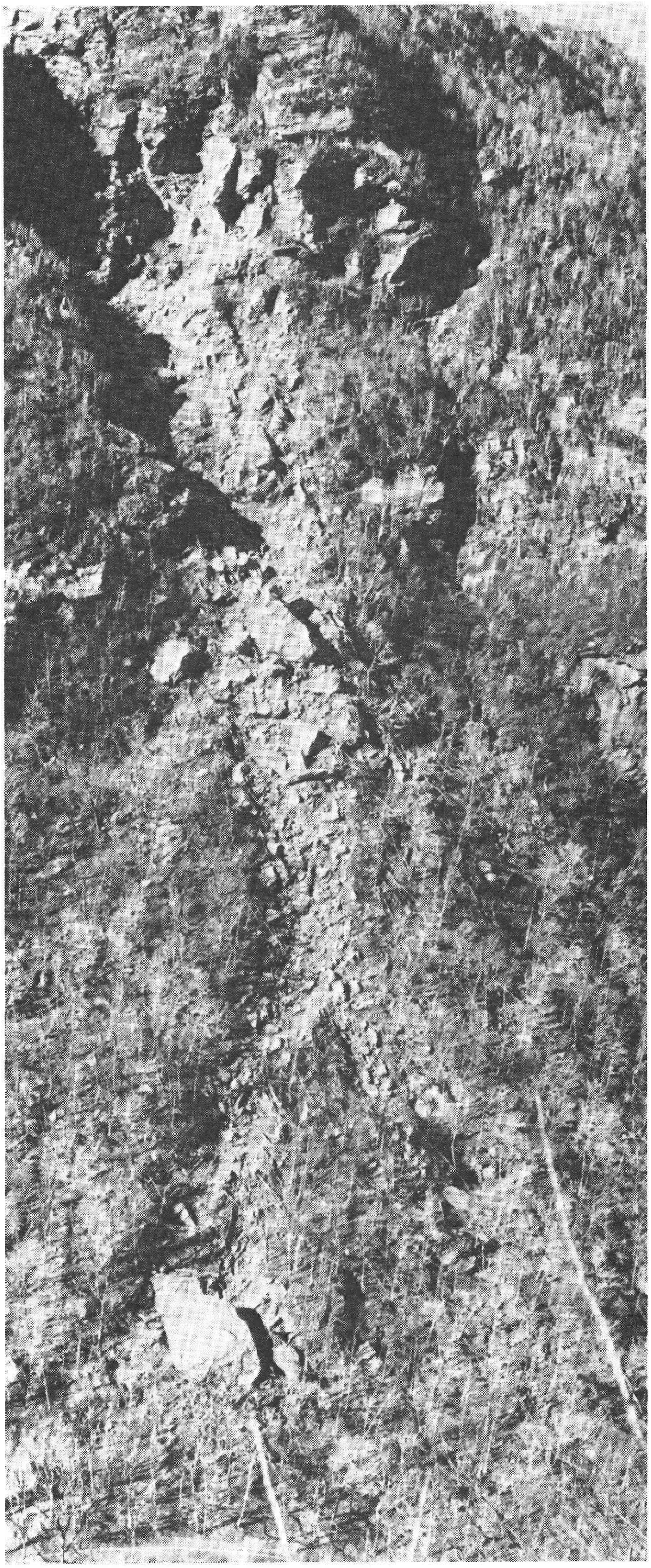
ROCKFALLS AND DEBRIS AVALANCHES IN THE SMUGGLERS NOTCH AREA, VERMONT



Scar and debris from the July 13, 1983, rockfall and debris slide on the west (east-facing) wall of Smugglers Notch. This path (chute) has also been the site of earlier slope failures. Vermont Route 108 is at the bottom of the photograph. Photograph by C.A. Ratté, October 1987.

Rockfalls and Debris Avalanches in the Smugglers Notch Area, Vermont

By Fitzhugh T. Lee, Jack K. Odum, *and* John D. Lee

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A study of block-movement rates and controlling factors

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Rockfalls and Debris Avalanches in the Smugglers Notch Area, Vermont

By Fitzhugh T. Lee, Jack K. Odum, *and* John D. Lee[1]

ABSTRACT

Rockfalls and debris avalanches from steep hillslopes on the southern approach to Smugglers Notch in northern Vermont are a continuing hazard for motorists, tourists, mountain climbers, and hikers. These fast-moving, destructive slope failures frequently block the approach road or nearby streams. Bedrock exposed in the area generally is massive schist and gneiss of the Cambrian Underhill Formation. Some huge blocks can reach the valley floor intact, whereas others may trigger debris avalanches on their downward travel. Block movement is facilitated by major joints both parallel and perpendicular to the glacially oversteepened valley walls. The slope failures occur most frequently in early spring, accompanying freeze-thaw cycles, and in the summer, following heavy rains.

Field mapping identified types and ages of slope movements and aided selection of monitoring stations. Manual and automated, continuous measurements of temperature and displacement were made at two locations on opposing valley walls. Both cyclic-recoverable and permanent displacements occurred during the 13-month monitoring period. The measurements indicate that freeze-thaw mechanisms produce small incremental movements, averaging 0.53 mm/yr, that displace massive blocks and produce rockfalls. The initial freeze-thaw weakening also makes slopes more susceptible to attrition by water, and heavy rains have triggered rockfalls and consequent debris avalanches. Temperature changes on the rock surface produced time-dependent cyclic displacements of rock blocks that were not instantaneous but had lag effects. Statistical analyses of the data show that a model predicting block displacement solely as a function of temperature is poorly constrained. A model using time and temperature predicts block displacement more accurately. Stability analyses show that some slopes would be stable if freeze-thaw forces were not present.

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INTRODUCTION

This report describes the results of an investigation to determine the mechanism and rate of rock-cliff breakup leading to slope failure in the Smugglers Notch area of northwestern Vermont and to forecast where and when slope failures are likely to occur. An additional goal is to assess the feasibility and adequacy of a remote readout system for monitoring the movement of rock blocks near cliffs.

Smugglers Notch, a steep-walled U-shaped valley, forms a north-south-trending mountain pass between Spruce Peak on the southwest and the northernmost ridge of Mount Mansfield on the northwest (fig. 1). The average relief of this valley is approximately 550 m. Christman (1959) attributed the development of Smugglers Notch to headward erosion by an ancient glacial-meltwater river. Slope deformation and attrition are active today, as indicated by open joints and intermittent rockfalls from unstable cliffs (fig. 2). We noted numerous open vertical joints (as wide as 1 m at the surface and more than 7 m deep), parallel with the upper eastern slopes of Mount Mansfield, that have been formed and enlarged by slope movement; even larger joint displacements in this otherwise massive rock have created openings of impressive dimensions, such as "Cave of the Winds" (Christman, 1959).

In view of the general instability of slopes in the area, it is not surprising that rockfalls and debris avalanches in the Smugglers Notch area damage roads and recreational areas and dam and divert streams. For example, in late May of 1986, more than a dozen debris avalanches occurred in the study area following several days of heavy rain. These slides blocked and damaged sections of Vermont Route 108, which climbs through the notch, and temporarily changed the course of the south-flowing West Branch Little River. In the past, single blocks weighing hundreds of tons and measuring as much as 20 m on a side have cut swaths down the timber-covered slopes. In some instances, the impacts of such falling blocks have triggered debris avalanches. These fast-moving masses, which incorporate rock, soil, trees, and water, have heightened the concern of

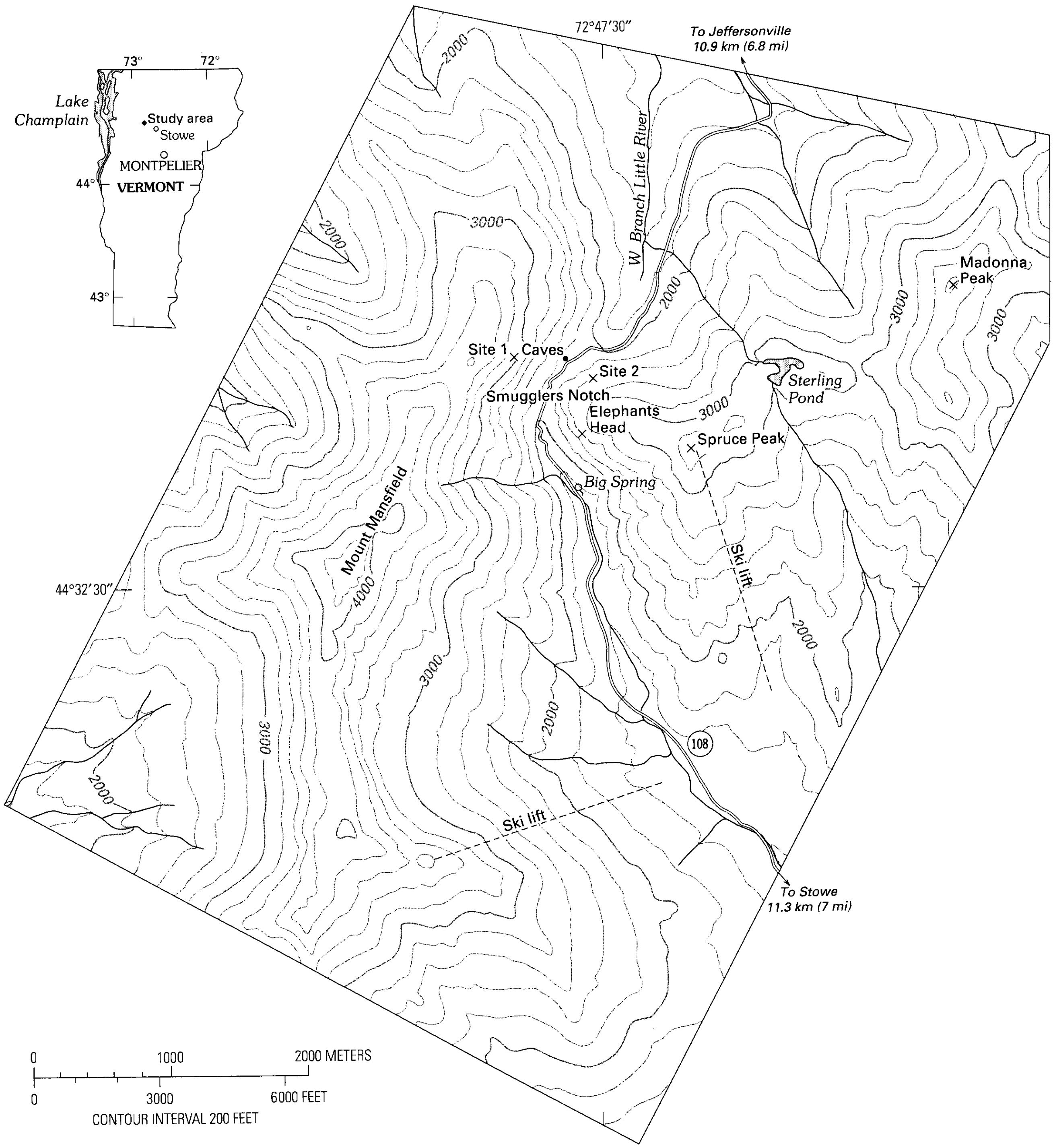


Figure 1. Map showing the location of the Smugglers Notch study area, Vermont.

public officials for users of roads and recreational facilities because of the increasing use of the area.

Near the top of the notch, the valley is particularly narrow and so choked with large blocks that only a sinuous single-lane roadway can be maintained (fig. 3). Nevertheless, this road (which connects the towns of Stowe to the south and Jeffersonville to the north) is heavily traveled, and parts of the road serve three ski areas. In the summer, it is a popular scenic driving and bicycling route and provides access to numerous hiking trails. The study reported here began in August 1986 and ended in June 1989.

Acknowledgments.—We are greatly indebted to Dr. Charles A. Ratté, retired Vermont State Geologist, for his continued encouragement and cooperation. He first suggested the study, and his agency provided partial financial support for the fieldwork. Without his personal assistance,

Figure 2. Unstable, loosened blocks in west-facing cliff at Smugglers Notch. Recent debris-avalanche blocks are in foreground.

both in the office and in the field, our endeavors would have been more difficult and the results of the research less satisfactory. We appreciate the help of Danny R. Miller, especially with the laboratory instrument calibration tests and also for assistance with the field studies. Personnel from Geokon, Inc., of Lebanon, New Hampshire, assisted us in the installation and programming of the data logger, and John McRae of Geokon provided information on the calibration of linear potentiometers and thermistors.

HISTORICAL BACKGROUND

The region has had a colorful past, even discounting undocumented narratives. Smugglers Notch derives its name from the activities of trading agents who operated in this area during the early 1800's. Illicit trade was a way of life for Vermonters during the War of 1812 and for several years preceding it (Hagerman, 1975). The Embargo Acts of 1807 and 1808 forbade export trade with Great Britain. Initially, the embargo applied only to goods moved by ships, but later it was extended to overland movement. Large areas of northern Vermont were then mostly wilderness, and routes that crossed these areas were relatively secure for the commerce of smugglers. Natives are said to have had a trail through the notch that was part of a route between Lake Champlain and the Connecticut River Valley (Hagerman, 1975). Hagerman refers to the notch itself as being an exchange point for illicit goods. Silks and drugs from Montreal were hidden in the caves in the notch (fig. 1), from whence they were taken for sale in the more populated parts of Vermont, New Hampshire, and Connecticut. Cattle were supposedly moved northward through the notch to British forces in Canada. These “caves” are actually the voids in the chaotic piles of large joint blocks of schist that have collected at the base of the western slope (fig. 4). (We measured openings as large as 20 by 10 by 4 m.) One of the largest of these openings is named “Smugglers Cave” and reportedly harbored smugglers being pursued by customs officers from Lake Champlain.

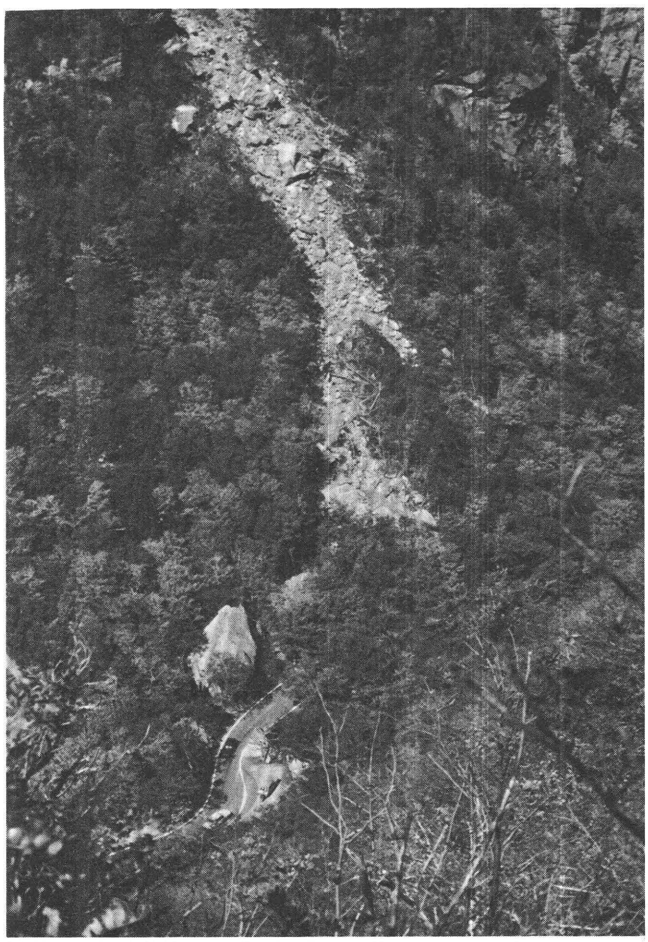


Figure 3. View of part of west wall, Smugglers Notch; single-lane section of Vermont Route 108 is at base of slope. Most of the fresh rock-debris was created by the rockfall and debris avalanche of July 13, 1983.

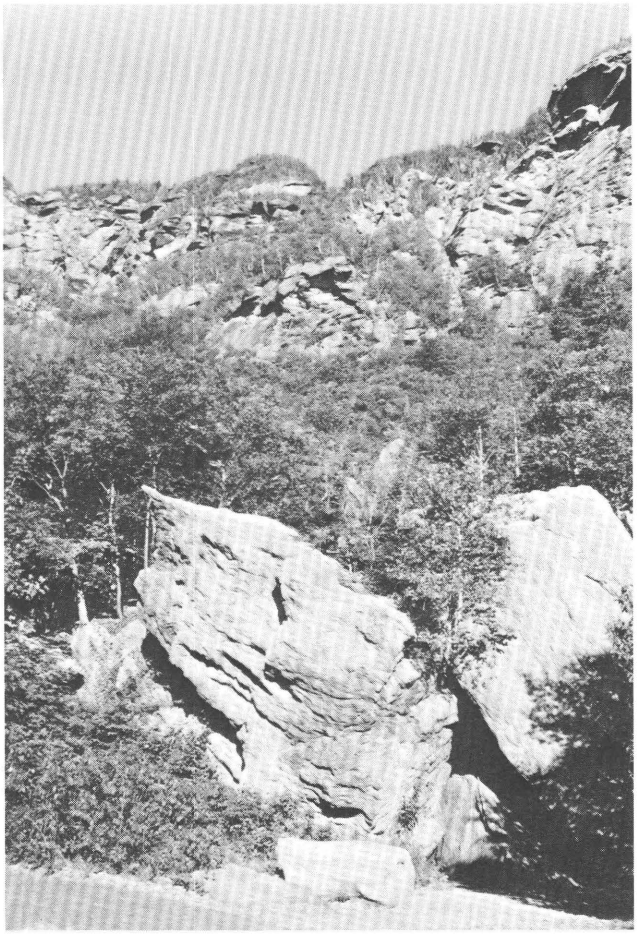


Figure 4. Large joint blocks of quartzitic schist of the type that forms the "caves" at Smugglers Notch.

Adding to the historical mystique of the area are the numerous fanciful images in the cliffs of the notch, an example of which is shown in figure 5.

The steep 15-percent grade approaching Smugglers Notch made travel other than by horseback impractical for many years. Nineteenth-century proposals for a tunnel and for a train route over the notch did not materialize. In 1935, the route through the notch was designated Vermont Route 108, but it was not until 1963 that the steepest section was paved (Hagerman, 1975). Vermont Route 108 through Smugglers Notch has never been open in the winter because plowing the steep, narrow road and disposing of the plowed snow would be difficult and expensive, and the steep grade would be hazardous for cars to negotiate.

NINETEENTH-CENTURY SLOPE FAILURES

Since the time of early settlers in northern Vermont, the rugged, unstable slopes at Smugglers Notch have held the respect of both natives and tourists. The romantic poem, "A Legend of Smugglers Notch" by Samuel Slaton Luce, first published in 1876, contains a vivid account of a storm and the resulting slope failure:

But never in such fearful storm
Have I been caught. I'd stopped to take
A sketch beside the mountain lake,
When suddenly, and unaware,
A dense black vapor filled the air.
I seemed enveloped in a cloud,
Where lightnings leaped and thunders loud,
Were underneath, above, around,
Filling my ears with stunning sound.
I sought the shelter of a rock,
When instantly I felt a shock.
The earth gave way beneath my feet,
When rocks and trees and shrubs complete,
Went sliding down the mountain side,
Leaving a chasm deep and wide
Behind, while everything before
Was crushed with most terrific roar.
As on I went, with bated breath,
Expecting every instant, death,
A ponderous rock upon one side
Caught on its way the moving slide,
And held it firmly in its course,
While breaking with resistless force
Went crashing o'er a precipice,
Into a seething wild abyss.
I stood upon the arrested part
Quite safe and with most thankful heart.
The storm soon ceased, the stars came out.

Journals and letters of the late 1700's and early 1800's mention roaring sounds and earthquakelike tremors that were later attributed by field observations to debris avalanches (Silliman, 1829). Northern Vermont is almost aseismic (Street and Lacroix, 1979), so these accounts probably did refer to large slope failures. In or near our study area, landslides have been documented in 1833, 1848, 1887, 1892, and on several occasions in the 20th century (Hagerman, 1975). These occurred between late May and early August and typically followed several days of heavy rain.

The 1887 slope failure occurred on June 3 near Underhill on the west side of Mount Mansfield, and, judging from newspaper accounts of the time, it was similar to recent occurrences. As a local farmer, John Flynn, and his family huddled inside their home during a heavy downpour, "the whole mountain reverberated with a terrible crash and roar; the mighty roar of waters increased and giant trees torn from their roots passed by making them believe each moment was their last." Luckily, the house held fast. When the rain subsided and they were able to go outside, they saw trees 15–25 m long and 0.3–1.0 m in diameter protruding from masses of soil and rocks that had been stripped from the mountainside above their home. Large rock blocks weighing from 1 to 500 tons had been hurled about like "baseballs." The family was amazed to discover why their dwelling had been spared: the first rush of debris had created a natural dam just above the house,

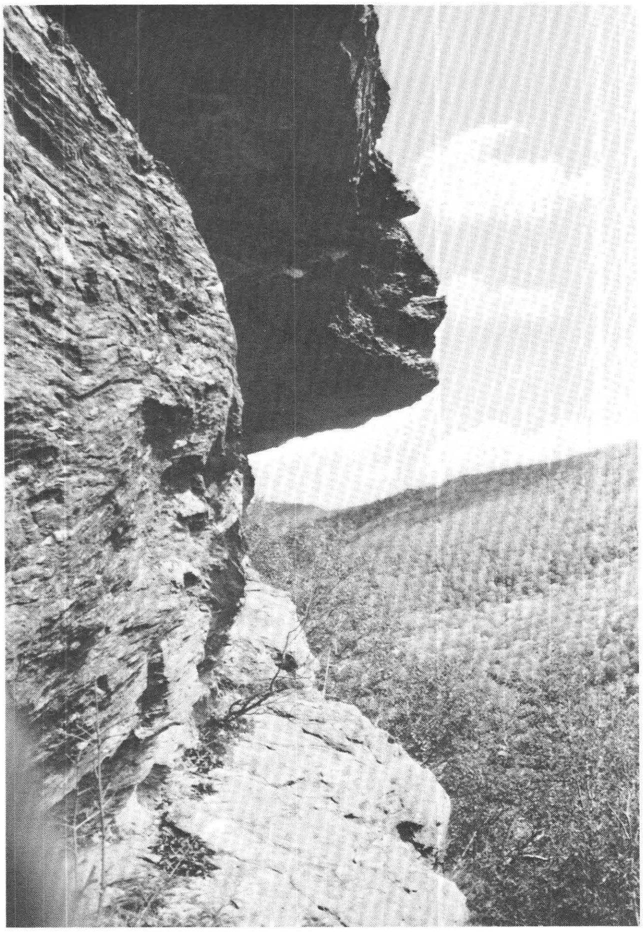


Figure 5. "Old Man of the Mountain," Smugglers Notch, one of the numerous fanciful profiles visible in the notch, produced by physical and chemical weathering of the jointed and unevenly foliated metamorphic rocks.

which caused the water and slide material to pass on either side of the building. Other residents, having lost entire farms, were not as fortunate. The slide was estimated to have been 3.2 km long and 30–185 m wide, and it scoured a gash 6–13 m deep in the mountainside (Hagerman, 1975). In this same area, Christman (1959) identified an elongate scar marking the position of a landslide that occurred in August 1955.

ROCKFALL OF JULY 13, 1983

A large rockfall occurred on July 13, 1983, when an overhanging block of schist, estimated to weigh 11,500 metric tons, broke loose from an east-facing cliff on the west wall near the 915-m altitude at Smugglers Notch (Baskerville and others, 1988). After a vertical fall of several meters, the initial block broke into many smaller blocks when it collided with a tributary valley wall. As some of these large fragments traveled down the 42° slope, they broke into smaller pieces and scoured soil, trees, and other vegetation in their paths. Some large and small blocks crossed the road at an altitude of 665 m (frontispiece). This failure was unusual in that it was not closely preceded by heavy rain; however, the failed block was partly bounded by weathered joint surfaces, and, because of its unstable, overhanging position, a slight disturbance, such as expansion and contraction produced by diurnal temperature changes, might have triggered the failure. An examination of blocks, ranging in length from 1 to 23 m, that came from the original block showed that the foliation surfaces were well bonded and would not have split apart easily. Joint spacings in this part of the valley wall range from 1 to more than 10 m. These factors may explain why such large blocks survive the intense pounding that they receive during their downslope travel.

Fortunately, there was no loss of life or injuries caused by this rockfall-debris avalanche, possibly because the event occurred in the early morning.

SLOPE FAILURES OF MAY 22, 1986

The slope failures that occurred in Smugglers Notch during the night of May 22, 1986, were the most widespread and severe in recent history. We estimate that one of the larger failures on the south side of the notch incorporated 250,000 m^3 of rock blocks, trees, and surficial materials (fig. 6). Fortunately, these debris avalanches and rockfalls occurred at night and before the time of heaviest recreational use. Otherwise, there would almost certainly have been loss of life. In addition to blocking hundreds of meters of Vermont Route 108, guardrails and sections of the roadbed were destroyed, and the course of the West Branch Little River was changed temporarily. More than 5 cm of rain fell on the area the evening of the landslides, adding to the heavy rains of the previous week. These are typical conditions for the generation of this type of slope failure in this area (Baskerville and others., 1993).

The first author interviewed a man who had been caught in one of the debris avalanches that came down the south side of Smugglers Notch on May 22, 1986. The following account is taken from notes made at the time of the interview (September 5, 1986). Brian O'Toole, a resident of Stowe and then in his mid-twenties, was driving home from a fishing trip to Lake Champlain and had passed through Jeffersonville; he then headed south toward the notch (fig. 1). At approximately 11:30 p.m., he reached the top of the notch with his truck and boat and found that the road was almost impassable because of heavy debris. The rain was intense. As he continued over the notch and down Vermont Route 108 to the south, the ferocity of the storm increased. Mud and gravel estimated to be 0.5 m deep were pounding his vehicle and the road was washing away on both sides. He was in fear of being washed into the creek

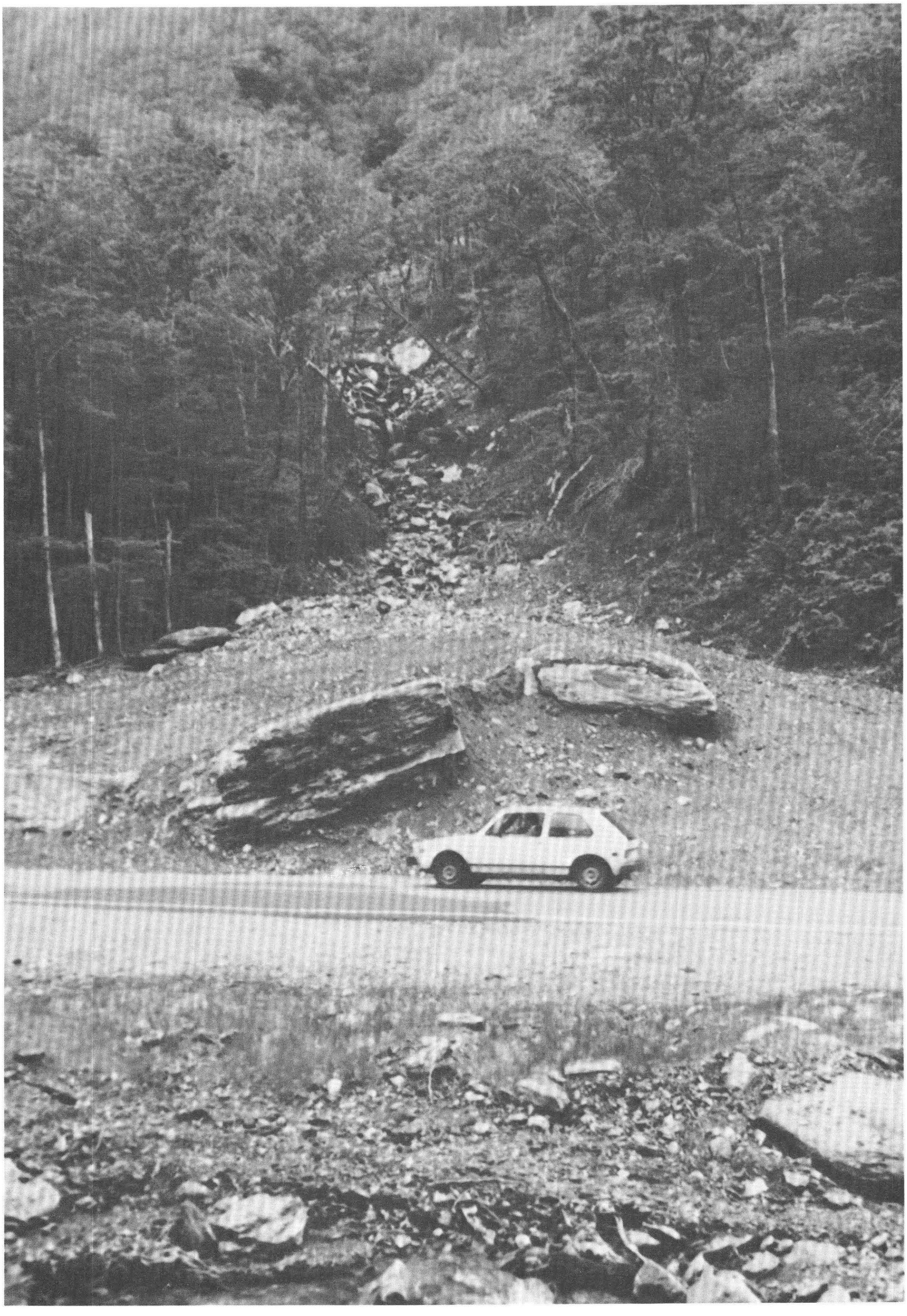


Figure 6. Lower part of rockfall-debris avalanche that occurred on May 22, 1986, Smugglers Notch. This slope failure, which occurred in an old chute, originated as a rockfall in the southeast wall approximately 320 m above road level. The mass incorporated increasing amounts of soil, loose rock, and trees as it moved to flatter slopes, finally crossing Vermont Route 108 and the West Branch Little River in the foreground.

(West Branch Little River); further advance was impossible. Amazingly, O'Toole was able to back his vehicle and boat up the steep, twisting road to a small parking area near the top of the notch. It was pitch black as he started to walk south toward Stowe, and he could not see the road or any guiding markers. The roar of the surging debris-laden water and the crashing of trees was deafening. At places the flow was knee deep, and progress was extremely difficult; the location and even the existence of the road were in doubt. He was fortunate to be able to keep his balance in the rushing mud and gravel and to avoid being hit by the trees and blocks of rock that were being swept across the road. The stream was out of its channel at several places, both above and below Big Spring (fig. 1). O'Toole made his way south to a State Highway Patrol car, probably at the picnic area south of Big Spring, where he collapsed from exhaustion. When he and a friend retrieved his truck and boat the next day, they took a large Lake Champlain trout from their fish storage compartment and posed with it by the still-high water near the notch, presumably impressing curiosity seekers with their tenacity as roughwater anglers!

ROCKFALL OF JULY 4, 1989

In the early morning of July 4, 1989, one or more large blocks separated from an overhang on the east wall of the notch approximately 100 m north of Elephants Head at an altitude of approximately 730 m (figs. 1, 7). An impressive scar was created as the rock tumbled to the valley, and several blocks measuring approximately 2 by 1.5 by 1.25 m reached the highway (fig. 7). The trees slowed the falling blocks and distributed the debris along several paths. Heavy rain had occurred the previous week, but the 2 or 3 days preceding the event were dry (C.A. Ratté, written commun., 1989).

REGIONAL GEOLOGY

The major structural feature in northwestern Vermont is the Green Mountain anticlinorium, which extends for more than 300 km from northern Massachusetts into southern Quebec, where it dies out as a north-plunging anticline (Mock, 1989). The Green Mountains are part of the Taconic allochthon, and these rocks are postulated to have reached their present position by thrusting from the east (Cady, 1945). According to Christman (1959), traces of the thrust surfaces beneath the allochthon have been mapped "several miles" west of the Mount Mansfield quadrangle, but he did not recognize these faults in the quadrangle. Rocks in the anticlinorium have a strike of approximately N. 10°–30° E. In the Mount Mansfield area, the crest of the fold is marked by the ridgelike form of Mount Mansfield. Except where an offset occurs, the anticlinal structure does not have typical complex large-scale drag folds on its limbs, but Christman (1959) prefers to retain the term "anticlinorium." The crest of the fold is rather broad, and the dips of the beds vary considerably due to minor local drag folding and warping. Near Smugglers Notch (fig. 8), dip variation is especially

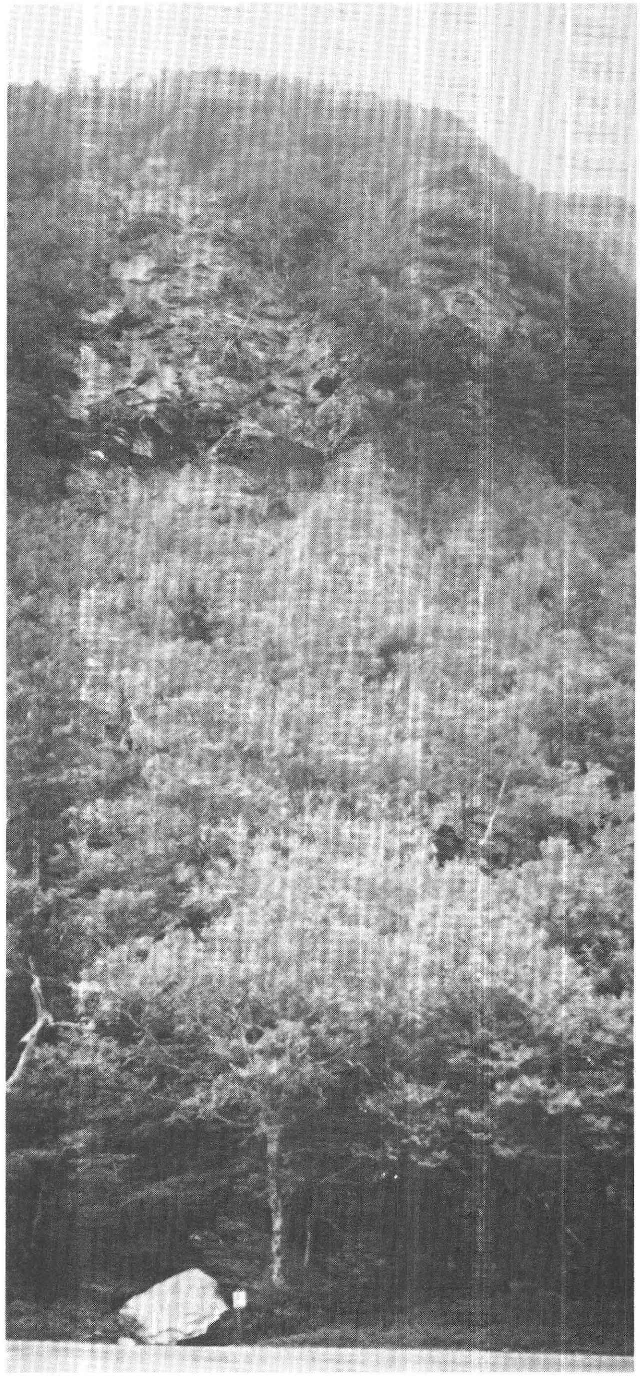


Figure 7. Rockfall that occurred on July 4, 1989, near Elephants Head on the east wall of Smugglers Notch. Trees slowed the velocity of the blocks and distributed them along several paths, although several reached the highway. Photograph by C.A. Ratté.

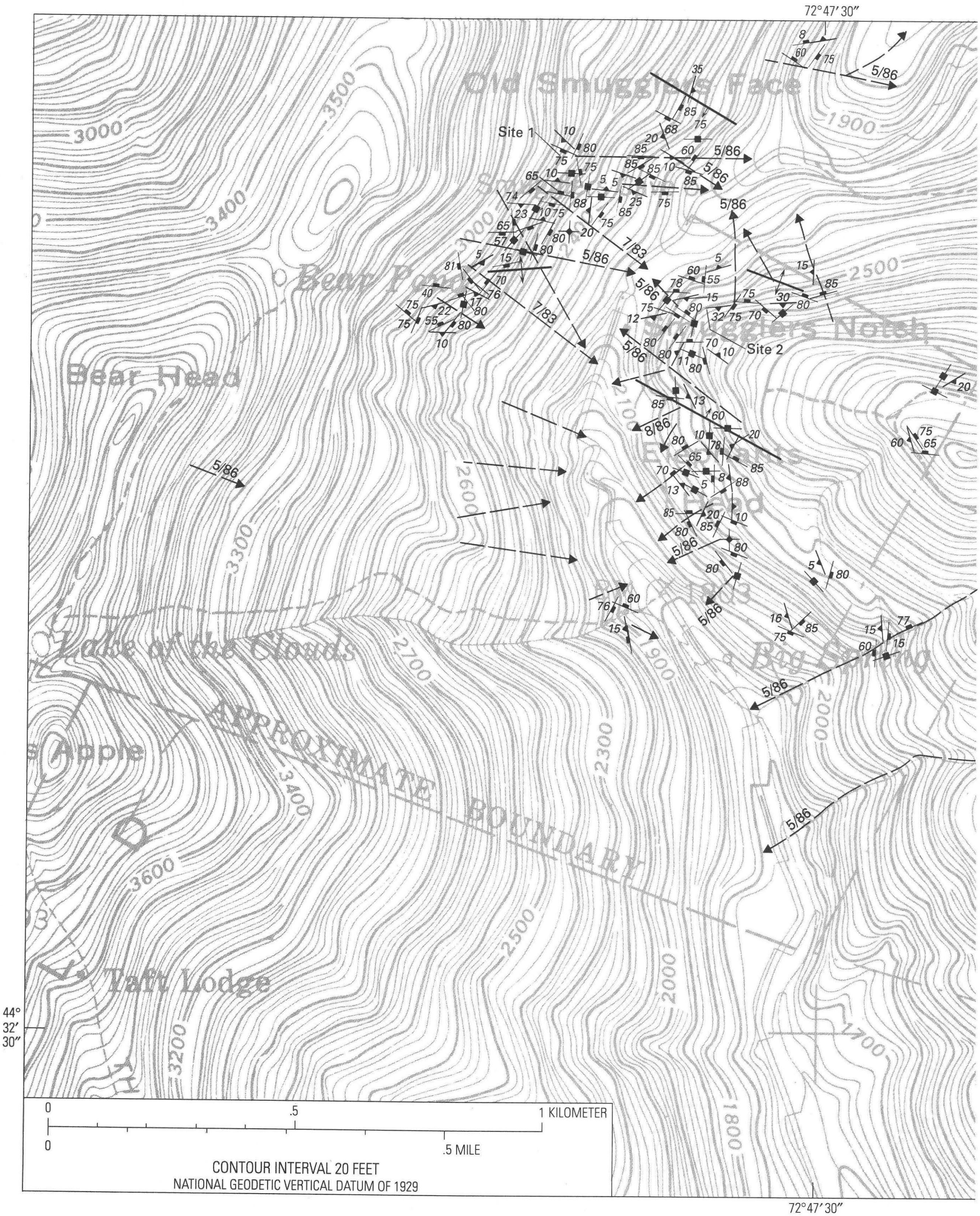
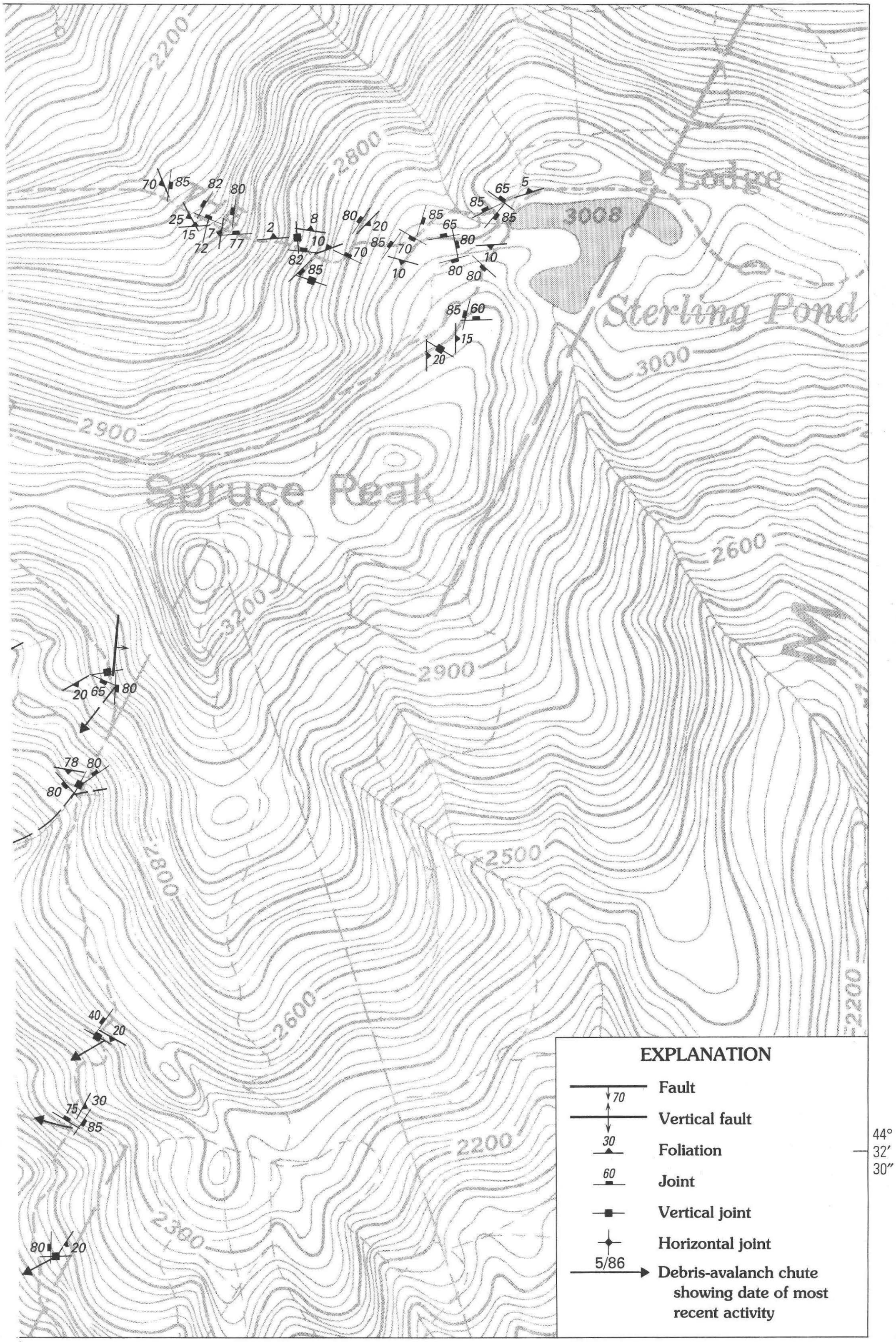


Figure 8 (above and facing page). Map showing major debris-avalalanche chutes, joints, faults, and foliation mapped in the study area, Smugglers Notch, Vermont. Slope failures typically originated as a rockfall of joint blocks at the head of a chute. The mass incorporated smaller and smaller fragments of material as it moved downslope. Base from U.S. Geological Survey, Mount Mansfield, 1:24,000.


Lodge
3008
Sterling Pond
Spruce Peak
2200
2800
2900
3000
2600
3200
2500
2300
EXPLANATION
Fault
Vertical fault
Foliation
Joint
Vertical joint
Horizontal joint
5/86
Debris-avalanch chute showing date of most recent activity
44° 32′ 30″

large because of the plunging and overlapping of the major anticlinorium axis. A poorly developed syncline is present in Smugglers Notch (Christman, 1959). Beds on both sides of the notch dip 10°–15° toward the synclinal axis.

Aerial photographs show three well-developed lineament sets in the area. The most extensive of these sets strikes N. 70° W. and extends across and beyond both valley walls. A second lineament set is best developed on the west wall and strikes N. 30° E. The third set strikes north-south, is visible in the east valley wall, and extends north and south of the study area. Figure 9 is a 1974 aerial photograph of the Smugglers Notch area in which the three sets of lineaments are visible. These features were studied in the field and found to be related to mapped geologic structures. The high-angle faults and joints discussed below are represented by the N. 70° W. lineaments, and foliation and a strong joint set correspond to the N. 30° E. lineaments. Although the third set of lineaments is not as well defined as the other two, it may represent the high-angle north-striking joints mapped near Spruce Peak (fig. 8).

The rocks underlying the study area belong to the Camels Hump Group (Cady, 1956) of Late Proterozoic to Cambrian age (Mock, 1989). They represent the debris shed into a basin formed by rifting of the North American continent during the Late Proterozoic (Rankin, 1976). The Camels Hump Group is a series of clastic rocks that includes quartz-mica-chlorite phyllite, metavolcanic rock, micaceous schist, metagraywacke, and albitic schist and belongs to the biotite zone of the greenschist facies (Mock, 1989). Most rock in the study area is finely laminated to fissile micaceous phyllite and gneiss. Weathered surfaces of these rocks are rusty brown; fresh fracture surfaces are silver gray to greenish gray.

The rocks in this part of the Green Mountain anticlinorium have undergone three episodes of deformation (Mock, 1989). The earliest deformation involved large-scale west-verging nappes and concurrent east-over-west faults on the overturned limbs. The second deformation resulted in development of the dominant schistosity in the area. The last phase of deformation was associated with development of the Green Mountain anticlinorium and was the least intense of the three episodes.

These tectonic events have left their imprint on the bedrock of Smugglers Notch in the form of joints, faults, foliation, and other fabric and mineralogic characteristics. Discontinuities such as these largely determine the susceptibility of rock slopes to movement and the initial size of rockfall blocks (Terzaghi, 1962; Schuster and others, 1975). In the following sections, we describe how rock structures, as well as climatic and glacial processes, formed the slopes and caused subsequent slope failures in the Smugglers Notch area.

GEOLOGICAL CONDITIONS IN THE FAILURE AREAS

Slope failures in the Smugglers Notch area are of two types: rockfalls and debris avalanches. Both types occur frequently, often annually, sometimes in combination, and are capable of considerable destruction, as has been described previously. Rockfalls are more common on the east-facing (western) slopes, whereas debris avalanches are more common on the west-facing (eastern) slopes. In both instances, however, rock discontinuities play a major role in the failure processes. Our field investigations were concentrated on these features.

TYPES OF DISCONTINUITIES

Faults, joints, and foliation are the significant rock discontinuities identified and recorded in the field study. In order to assess the stability of the rock slopes in Smugglers Notch and to explain the failures previously described, we established the structural geometry upon which the slopes had developed. This was done mainly by recording the orientation and spacing of discontinuities, primarily joints.

FAULTS

Only a few faults were identified in the study area (fig. 8), and these are high-angle faults, most of which are exposed in the west-side cliffs and which range in strike from N. 70° W. to N. 85° E. These faults display 4–30 cm of weathered fault gouge and define sections of some channels of debris slides and avalanches, although their overall role in slope behavior is not great. Near Big Spring on the east wall, at an altitude of 896 m, is a 0.3-m-wide fault zone partly filled with milky quartz. This fault zone strikes N. 5° E. and dips 80° SE. The sense of shear movement on these faults could not be determined from the exposures we examined.

JOINTS

Joints are present in all of the rock outcrops that we examined, and they define blocks whose largest dimension ranges from less than 10 cm to greater than 20 m. The average block size in the most active slide areas near the top of Smugglers Notch is approximately 0.75 m on the east side and 1.6 m on the west side. This disparity is due in part to relatively weak tabular or platy graphitic phyllite and schist on parts of the east side of the notch and the more massive schist and metagraywacke that make up cliffs on the west side of the notch. One of these massive blocks (King Rock), weighing an estimated 5,400 metric tons, tumbled at least 590 m down the west slope in the spring of 1910, coming to

Figure 9. Section of aerial photograph, taken in May 1974, enlarged to show several prominent lineaments (arrows) in the Smugglers Notch area.

rest on what is now the east side of Route 108. In addition to joint block size and rock-mass strength, the attitudes of joints and their roughness can influence rock-slope stability (Pariseau and Voight, 1979).

Figures 10 and 11 are azimuthal (strike) and dip-angle diagrams for joints recorded on the opposite walls of Smugglers Notch. They show that the joints exposed in both walls have similar attitudes, with strike maxima of N. 55° W. and N. 5°–25° E. Dip angles are primarily vertical with secondary low or horizontal angles, reflecting the dominant rectangular joint structure. Near ridge tops, open northeasterly trending joints are parallel to and behind the free face. Most of these joints were observed on the west wall; their presence on the east wall was concealed by heavy vegetation.

In numerous instances, the intersection of major joints first forms a rockfall site (head scarp) and then a longlasting debris chute. One such structure is northeast of Big Spring at an altitude of 762 m (fig. 8).

Open, vertical joints parallel to and behind the crests of upper slopes are important indicators of stability and are discussed in a later section.

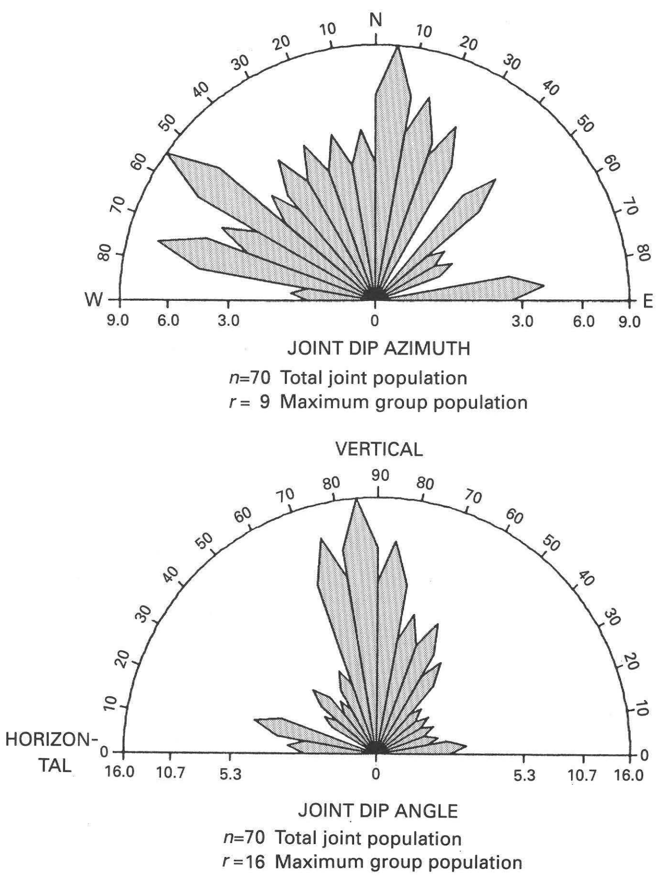


Figure 10. Azimuthal and dip-angle diagrams for joints on the northwest valley wall at Smugglers Notch.

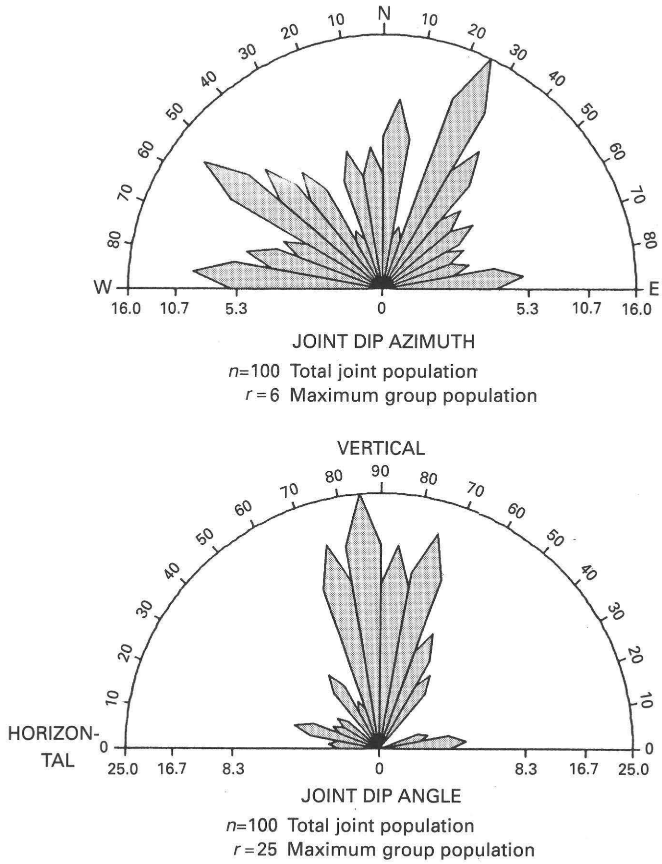


Figure 11. Azimuthal and dip-angle diagrams for joints on the southeast valley wall at Smugglers Notch.

FOLIATION

All rock exposures that we observed were foliated, and, because these surfaces are typically well bonded, the rock is generally massive (fig. 12). Weakly bonded surfaces may separate and form blocks by virtue of their intersection with joints. Figures 13 and 14 are azimuthal and dip-angle diagrams showing the major foliation attitudes in Smugglers Notch. On both walls of the notch, dip angles are low. Foliation strike maxima are N. 15° E. and N. 85° W. on the west wall and N. 15° W. and N. 85° W. on the east wall.

CONDITIONS FAVORING SLOPE FAILURE

Our field investigations and a search of historical records suggest that the following factors are important to recent slope behavior in the Smugglers Notch area and that similar geologic and hydrologic conditions may have been present for many previous rockfalls and debris avalanches in this area.

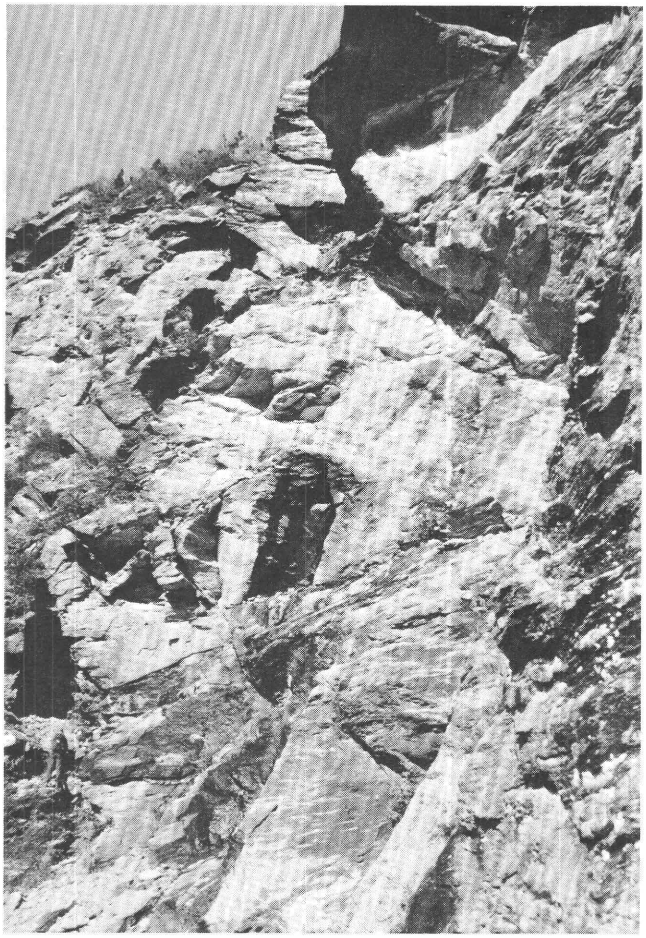


Figure 12. Well-bonded foliation in schist at Smugglers Notch.

1. Several consecutive days of heavy rain may culminate in an intense local downpour producing 6–8 cm of rain in several hours.

2. Vertical to overhanging joint blocks at headscarps, weighing as much as several tons each, tumble downslope, loosen other blocks, uproot trees, and mix with saturated surficial materials. This chaotic and fluid mass rapidly gains momentum and erosive capability and scours impressive channels in soil and bedrock.

3. Debris in the lower reaches of the chutes, 1–6 m thick, may be older deposits that are reactivated and channeled during later events. Some chutes have served several episodes of slope failure.

4. The slope of the valley wall influences the type of failure and the resulting deposits. Narrow, steep-walled valleys are more prone to rockfalls, which choke the valley bottoms with large joint blocks. The deposits associated with more gently sloping valley walls have fewer large blocks and more fine-grained material.

5. Unstable valley walls may be present where intersecting joints and faults are oriented parallel and perpendicular to the strike of the valley wall and foliation surfaces dip gently toward the axis of the valley. These conditions produce a rock mass that is susceptible to mechanical disintegration and downslope movement.

6. The east-southeast exposure and higher altitude of the west side of the notch may promote greater block movement, as compared to the east side of the notch, by increased precipitation and cyclic frost wedging.

7. Most of the recorded rockfalls and debris avalanches occurred between late May and early August. For example, the first author observed a 3-m block fall from an overhanging cliff on the west face of the notch at an altitude of 1,006 m on September 13, 1986, following 2 days of heavy rain. The block came from the headwall of a small V-shaped gorge and fell approximately 100 m, breaking up as it bounced downward.

Although we have not found accounts of mechanisms of these specific failures, in other areas such failures typically are associated with steep, forested slopes and conditions of either prolonged or intense precipitation (Pariseau and Voight, 1979). Pariseau and Voight (1979, p. 66–67) summarized investigations showing that Appalachian slides originate on slopes of 17°–44° with rainfall intensity as much as 10 cm/hr or 56 cm in a 2-day period. We found that, in the Smugglers Notch area, rockfalls occur on

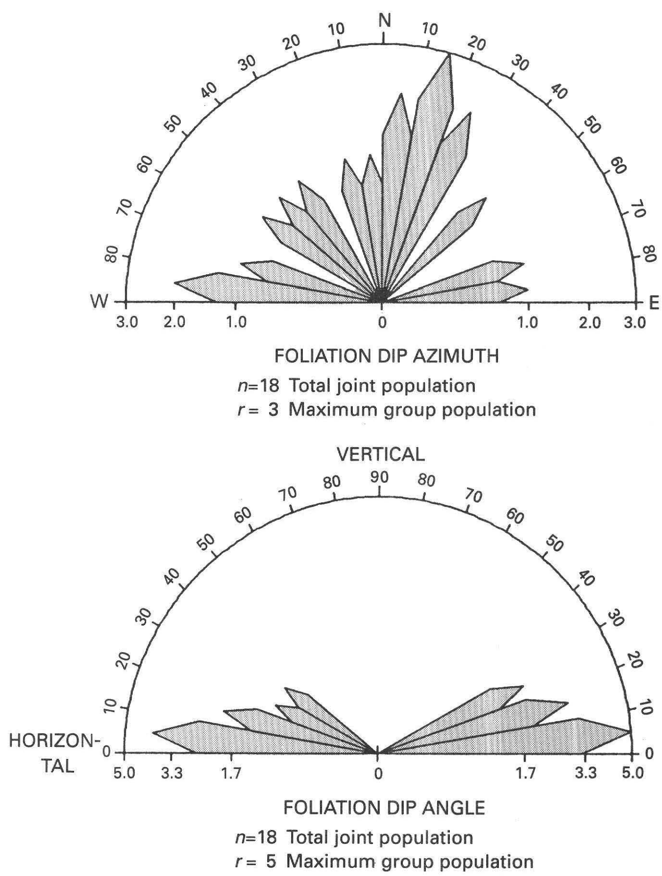


Figure 13. Azimuthal and dip-angle diagrams for foliation on the northwest valley wall at Smugglers Notch.

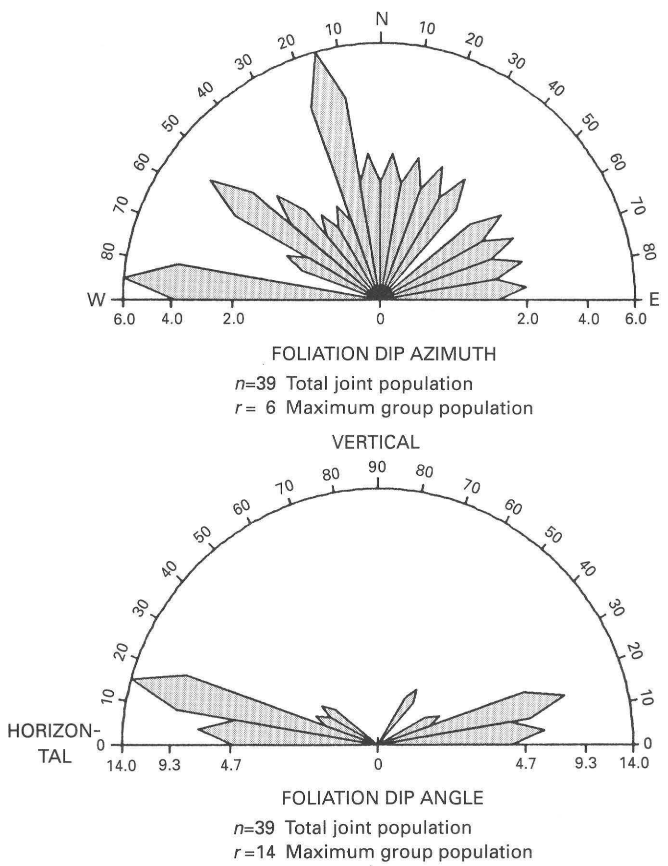


Figure 14. Azimuthal and dip-angle diagrams for foliation on the southeast valley wall at Smugglers Notch.

vertical to overhanging slopes and frequently either trigger or accompany debris avalanches. The upper boundary of the above slope range is appropriate for zones in which falling blocks land on saturated soil and loose rock and from where the mass continues down a gentler slope as a debris avalanche.

FREEZE-THAW EFFECTS ON ROCK SLOPES

The annual freezing and thawing of massive near-surface rocks in northern New England may be the dominant process causing cliff breakup and retreat (Lee, 1989). Several previous field, laboratory, and theoretical studies have examined frost cracking and freeze-thaw cycling of soil and rock (Taber, 1929, 1930, 1943; Yardley, 1951; Dyke, 1984; Walder and Hallet, 1985; Lee, 1989). These authors concluded that conditions favoring joint-block displacement by freezing are (1) slow freezing, which promotes growth of ice crystals in a hydraulically open system where pore-water pressures are atmospheric, (2) movement of a moisture film from unfrozen rock laterally or upward toward frozen rock, and (3) progressive cooling from a surface or surfaces. In a hydraulically open system, such as near-surface jointed rock, sustained freezing is most effective in producing microfracture growth when the cooling rate is low and when temperatures range from approximately –4°C to –15°C (Walder and Hallet, 1985); lower temperatures inhibit moisture movement. Taber (1943) determined that the growth pressure of ice crystals, which in his experiments exceeded 1 MPa (megapascal), is the chief agent of rock disintegration. Taber (1943, p. 1449) also suggested that, because freezing and thawing due to diurnal changes in temperature occur primarily in the spring and fall, greater opportunity exists at these times for block displacements. Taber (1943, p. 1453) also observed that repeated freezing and thawing caused significant downhill displacements of particles of various sizes.

Ice has a coefficient of expansion that is about ten times that of rock. Because of this disparity, a drop in temperature may sharply reduce the pressure that the ice exerts on the rock. The resulting contraction acts to pull the ice away from the rock surface and may open a crack into which water or water vapor can enter, which could cause the formation of more ice in the crack. A rise in temperature would cause the ice to expand and once again pressure the rock. Permanent displacements of joint blocks may then occur, most significantly where blocks have little confinement, such as on cliff faces. In northern Vermont, early spring is the most likely time for this process to operate; frozen rock, particularly on south-facing slopes, is alternately heated and cooled, sometimes daily, causing incremental displacements. Near-surface joint blocks that are sealed at their bases provide favorable geometries for buildup of pressure due to ice-crystal growth associated with freezing.

From studies in the Canadian Arctic, Dyke (1984) observed that horizontal movements of joint blocks could be produced by the growth of segregated ice in soil-filled cracks. Where drier conditions prevail, block movement occurs due to the confinement of saturated zones in the active layer by the attempted expulsion of water from this layer by the downward-advancing freezing front. In this process, water pressures as great as 400 kPa (kilopascal) can be attained within the confined bodies. Dyke (1984) also noted that this mechanism does not require a high degree of saturation.

In Norway, Bjerrum and Jorstad (1968) studied factors that control the failure of many rock slopes. They found that most rockfalls and rock slides were in sound, unweathered granite and gneiss. Slopes in altered rocks probably failed and stabilized soon after the last glaciation. Frost shattering was the predominant destabilizing agent, and most rockfalls occurred below 100-m altitude in the early spring and late fall, when the temperature fluctuated around the freezing point. Joint openings widened for several years before slopes failed. Rockfalls increased immediately before a large slide occurred, and any debris or rock mass resting on a slope steeper than 35°–38° failed by time-dependent destabilizing processes.

Rapp (1974) found that mass movements in Scandinavia have two peak seasons annually. One is in May and June, the period of rapid snowmelt. Rockfalls, snow avalanches, and solifluction have their seasonal peaks at this time. The other peak time is in summer and autumn, when debris slides and flows are triggered by heavy rains over intervals of several days.

There is no agreement on the mechanism of rock-slope deformation in cold regions. For example, Wyrwoll (1977) observed that the role of frost action did not seem to be supported by actual field measurements. He argued that the large volumes of Holocene talus accumulations in cold regions were unlikely to be generated by the slow fixed accumulation indicated by reported rates of free-face retreat. These rates of free-face retreat varied from 0.007 to 0.2 mm/yr (Wyrwoll, 1977). Wyrwoll conceded that rates of retreat might have been different in the past, but he evoked residual stress release, joint-water pressure, and weathering as the principal agents of slope degradation. Luckman (1976) cautioned against an overly simplistic explanation of the interaction between climate and rockfall. He found in the Canadian Rockies that, although freeze-thaw is a major destabilizing factor, snowstorms, heavy rains, and even short showers may trigger rockfalls. Luckman also determined that slopes of different aspect, geology, and morphology respond differently to climatic events and that some generalizations can be masked by characteristics peculiar to individual rock faces.

SLOPE-MOVEMENT MONITORING PROGRAM

The slope-movement monitoring program had two main purposes: first, to establish the mechanism of rock-cliff breakup and, second, to estimate the rate of block displacement. In addition, we evaluated the performance of the monitoring system. To support our study, we collected geologic, climatic, and geomechanical data. Specifically, we recorded the attitude, spacing, and condition of joint surfaces; the attitude, width, and amount of gouge on fault surfaces; the attitude and ease of cleavage of foliation surfaces; the location, relative age, and size of previous slope failures; and location of water-producing zones. It became obvious from observing the slopes at Smugglers Notch that block assemblages at certain locations display greater signs of instability than at others, indicated by the debris trails and overhanging cliffs, particularly on east-facing cliffs. Our monitoring focused on the behavior of large intact blocks. Although evidence of microfracturing exists, as shown by spalling and discontinuous fresh fractures, our investigation was concerned only with displacement of existing joint blocks rather than with initiation of new fractures.

DESCRIPTION AND CALIBRATION OF JOINTMETERS AND THERMISTORS

Before instruments were installed at field locations, they were tested in the laboratory for reliability and accuracy under controlled temperature conditions. Because seasonal block displacements were anticipated to be on the order of 1 mm or less with smaller incremental diurnal movements (Lee, 1989), displacement measurements required a resolution of at least 0.1 mm and preferably 0.05 mm. Both remotely read and manually read instruments were employed in the study, affording desirable redundancy.

REMOTELY READ INSTRUMENTS

A model 1550 jointmeter, manufactured by Geokon, Inc., was selected for cliff-block displacement measurements. This instrument has an internally mounted thermistor. The gage uses a linear potentiometer as the sensing element, has a measurement range of 5 cm, and has a resolution of 0.025 mm with linearity and accuracy of 0.1 percent of the full-scale measurement range. The jointmeter was attached to the rock block(s) to be monitored by cementing the notched cylinders of brass measuring 1.27 by 6.35 cm with "Sulfaset" into 2.3-cm-diameter drilled holes. The cylinders had holes tapped to receive the threaded socket screws at both ends, and the assembly was mounted on the rock as shown in figure 15. The durability of this anchor system is considered excellent under severe field conditions (Lee, 1989). For example, strength tests on cylinders of the cement that had been subjected to freeze-thaw cycling showed that that cement was slightly stronger than cylinders of cement that were not freeze-thaw cycled. When the gage is installed in the field, it is coated with silicone lubricant and encapsulated in a section of bicycle inner tube to prevent ice from interfering with movement of the jointmeter shaft.

Figure 16 shows a typical calibration curve that compares jointmeter measurement precision with a digital caliper (resolution 0.013 mm) at a constant temperature of 25°C. The excellent agreement is expressed by the correlation coefficient of 0.9999, which indicates a precision of approximately twice that claimed by the manufacturer (Geokon, written commun., 1988). Temperature changes have no measurable effect on the indicated displacement of an unattached jointmeter, as shown in the graph in figure 17. Our concern here was that, if gage materials were dissimilar, there could have been differential and unequal expansion of components.

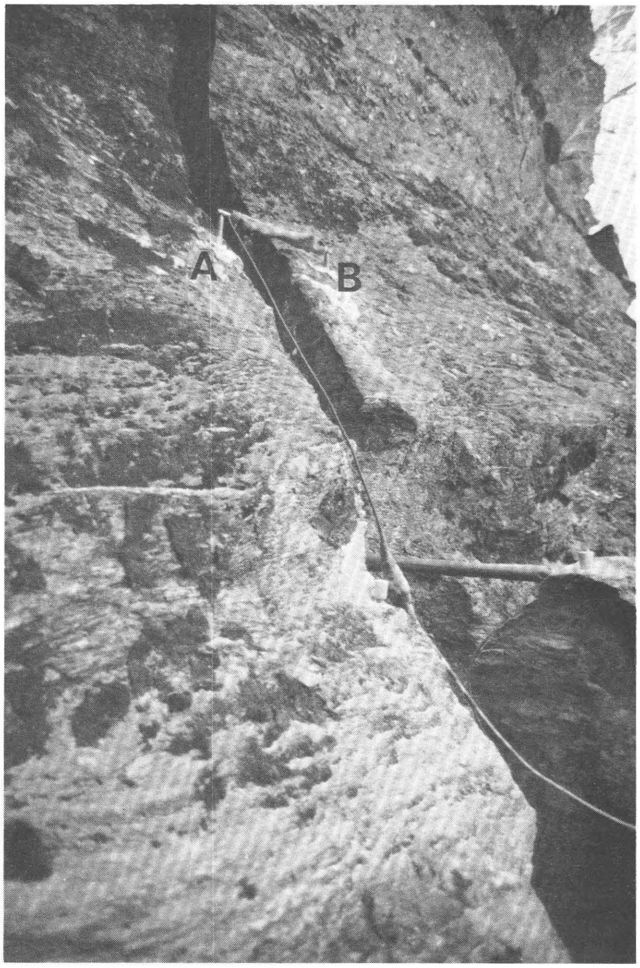


Figure 15. Photograph showing jointmeter installation. Anchors are shown at A and B.

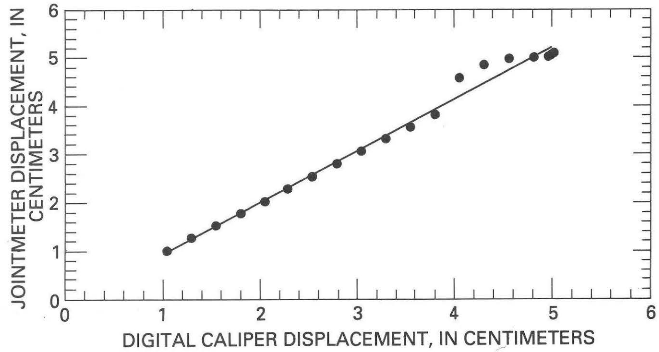


Figure 16. Typical calibration curve comparing jointmeter and digital caliper precision; this curve yields a correlation coefficient of 0.9999.

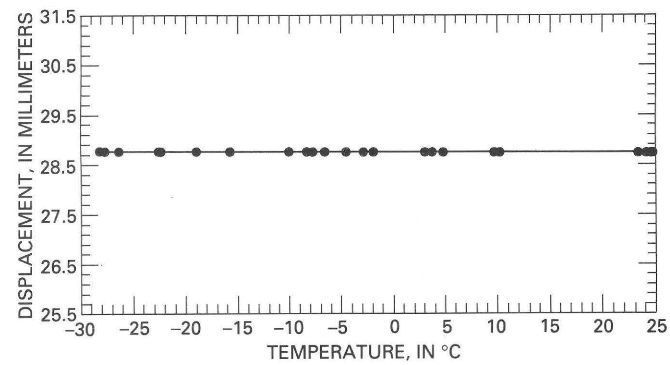


Figure 17. Graph showing results of temperature-change test of jointmeter. The instrument was placed unattached on block of styrofoam in freezer. As is indicated, temperature had no effect on displacement measured by the jointmeter.

Each of the thermistors (bonded internally to the jointmeters) was calibrated in the laboratory through several cycles of the approximate range of temperatures expected at the Smugglers Notch sites (figs. 1, 8). Calibrations were repeated after recovery of the gages from the field, with similar results. Figure 18 is a typical thermistor temperature-response curve for a range of −38°C to 19°C. The histogram indicates that the thermistor tracks closely the values of the digital thermometer utilizing a thermocouple (which was itself compared to the laboratory standard mercury thermometer) for the higher temperatures but reads 1°–3° too low at temperatures near and below zero because of the nonlinear response of this type of sensor. When read by the programmed data logger, a polynomial equation linearizes the thermistor output and overcomes this deficiency.

In the field installation, the thermistor was not in direct contact with the rock surface; therefore, it registered the instrument temperature. Because their separation was usually less than 10 cm, the difference between the instrument temperature and the rock-surface temperature was small (Hooker and Duvall, 1971), but the temperature, and thus the displacement of each gage, was influenced by changing weather conditions due to site exposure and the season of the year. These concerns are important because of the different exposures of sites 1 and 2.

In addition to calibrating jointmeters and thermistors, we monitored in the laboratory the freeze-thaw behavior of a block of schist from the field site. Because the jointmeters span joint openings in the field, we tested an instrumented solid rock block parallel to foliation in the laboratory to differentiate the expansion and contraction of the solid rock from changes in joint openings. The test block is shown in figure 19. The jointmeter was set at midrange and mounted so that it moved freely with thermal expansion and contraction of the block. A thermocouple was cemented in a shallow drilled hole in the top surface. The block was placed in a freezer and subjected to temperatures ranging from −27.6°C to 24.0°C in slowly changing increments so that the entire block equilibrated to each increment of temperature change. The test duration was 13 hrs.

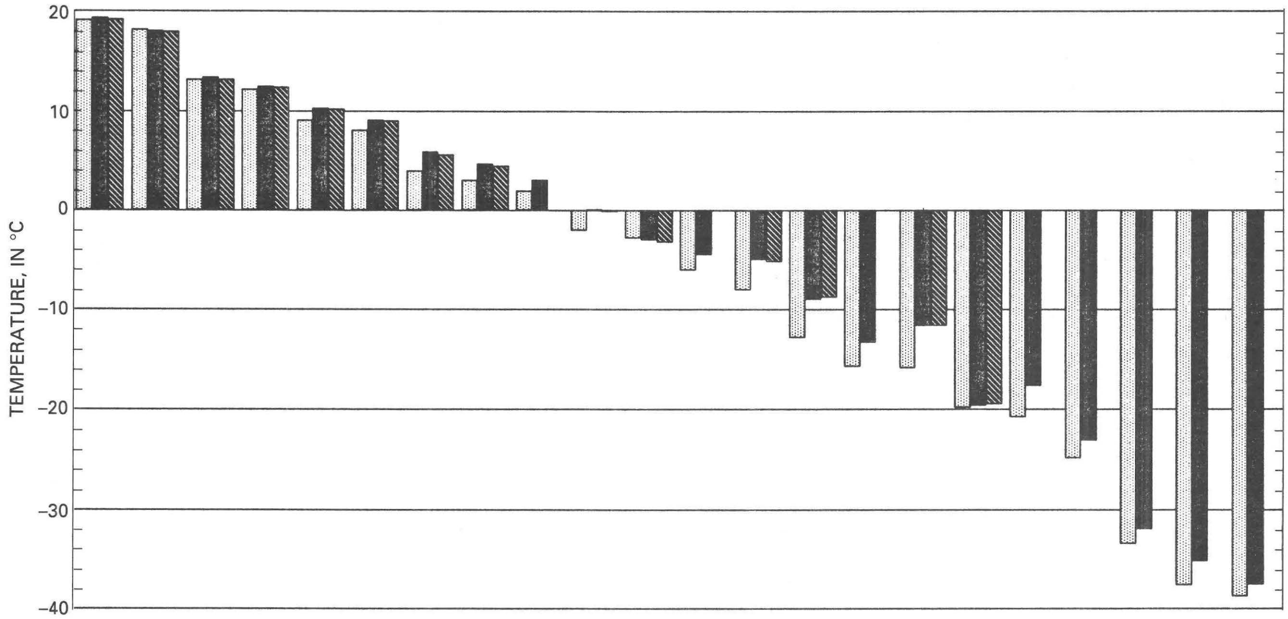


Figure 18. Temperature-response curve of jointmeter thermistor over range of –38°C to 19°C.

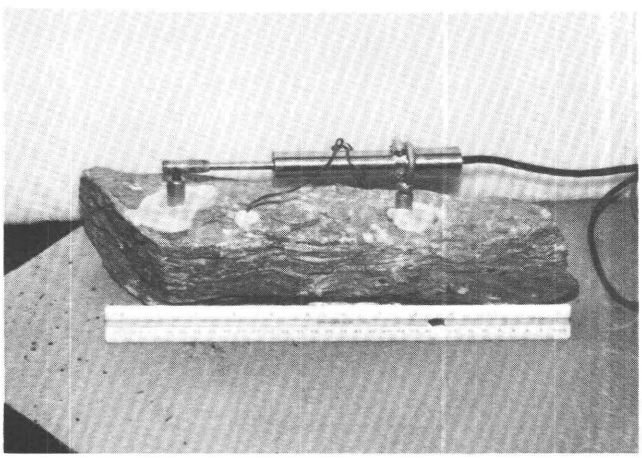


Figure 19. Block of schist from Smugglers Notch used for testing reaction of jointmeter to temperature-induced expansion.

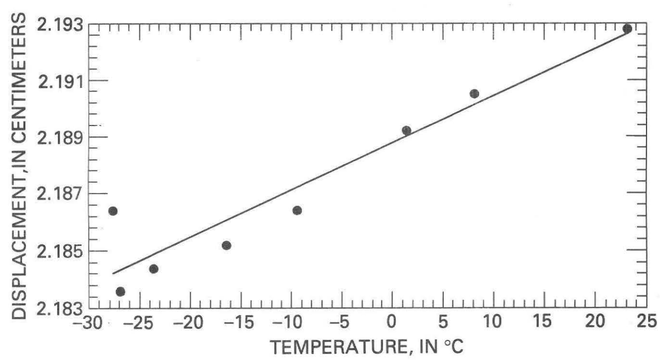


Figure 20. Temperature-change test of block of schist from Smugglers Notch.

The results are shown in figure 20. There is an approximately linear expansion and contraction over the test range as the gage tracks the rock behavior. The average linear thermal-expansion coefficient is 2×10^{-5}. This compares with a value for slates of 9×10^{-6} given by Skinner (1966). Large variations in the thermal coefficient of similar rock were anticipated by Skinner, who quoted Dane (1942) as follows:

> When a rock specimen is measured in the laboratory, it is found that the coefficients of expansion are very different on heating and cooling, with a still different result on each subsequent run. This is due to the unlike expansions of adjacent grains because of differences both of composition and orientation. As a result, when a rock is heated the grains with the largest thermal dilation tend to determine the apparent change of length of the whole specimen, creating internal fractures and 'pores.' Thus what is actually measured is rather the increase in porosity than the true thermal expansion. In the earth, several factors tend to minimize these effects. The directions of maximum compressibility usually lie close to those of maximum thermal expansion, so that, when temperature and pressure tend to vary in the same direction at the same time, the effects partly cancel each other.

We believe that effects such as these could account for our results, especially considering the possible influence of void spaces in the medium- to coarse-grained schist that we tested.

The field displacement measurements probably represent a very different and more complex behavior than the laboratory results because the gages span fractures. The fractures are of different widths, orientations, and depths. The fabric properties can be expected to vary with direction, and our gages were not purposely oriented with respect to these properties or to the direction of maximum thermal expansion, which is most probably perpendicular to major fractures. This is borne out by the daily temperature changes that produced expansions and contractions that were several orders of magnitude greater than the referenced values (Skinner, 1966). A statistical analysis, presented below, of the temperature-displacement data is a helpful tool for drawing meaningful conclusions.

MANUALLY READ INSTRUMENTS

Field displacement measurements also were made manually at the two cliff sites using a dial-gage extensometer having a resolution of 0.01 mm (fig. 21). The measurement anchors were installed in the same way as the jointmeter anchors that were described above. A threaded stainless-steel anchor point, having a drilled hole in the top to accommodate the conical hardened-steel measurement points on the dial-gage extensometer, was screwed into the brass anchor. The extensometer was calibrated for temperature-induced strains using an Invar rod. Measurements made at other sites using this gage have been reported previously (Lee, 1989).

The results of the manual measurements are compared in table 1 with those obtained from the remotely read instrument. The values for total displacement differ from the jointmeter results, possibly because of differences in gage location and orientation. Because we made only a few readings, their main value is an additional recording of permanent block movement rather than a source of detailed cyclic rock-block displacement.

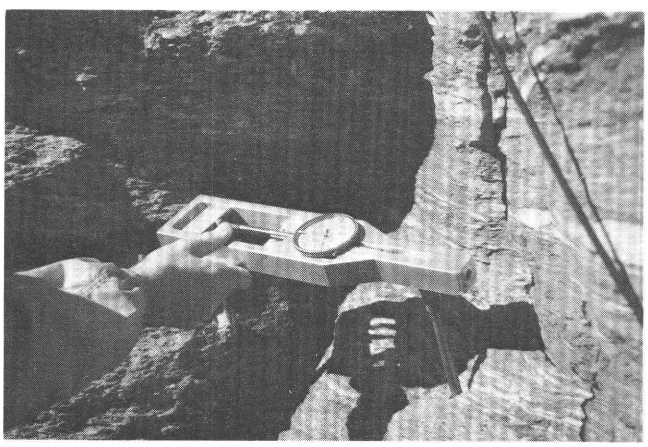


Figure 21. Dial-gage extensometer used for manually recording rock displacement caused by temperature-induced expansion. This instrument was calibrated between measurements with an Invar rod.

Table 1. Permanent displacements at sites 1 and 2 for the period May 16, 1988, to June 11, 1989.
[Displacements in millimeters]

Gage	Site 1	Site 2
	Remote	
1	1.605	0.508
2	0.112	0.203
3	0.427	0.152
4	[1]	0.203
5	0.102	1.468
Average	0.562	0.507
	Manual	
1	1.02	0.75
2	No reading	0.70
3	1.73	2.1
4	1.80	1.2
5	0.51	2.15
Average	1.27	1.38

[1]Gage was struck by falling rock.

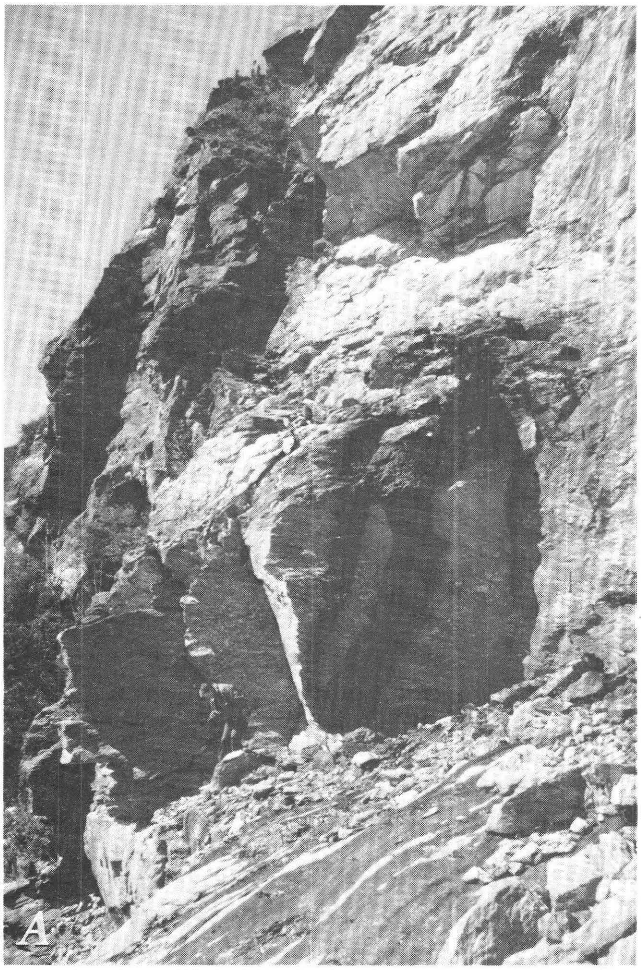
FIELD MONITORING SITES

In order to investigate the role of freeze-thaw processes in slope attrition, two sites were selected that are representative of rock and slope conditions on opposite valley walls for monitoring block displacements and temperatures (figs. 8, 22, 23). We collected data from fall 1988 through spring 1989; readings were discontinued in early June 1989.

The manual and remote measurement points for site 1 were installed in May 1988 and for site 2 in September 1988. A total of approximately 4,200 m of cable was laid from the instruments downhill to the data-acquisition system in June and September 1988. The datalogger began continuous operation in November 1988. A Campbell 21x datalogger with a multiplexer provided the necessary 24 channels for linear potentiometers, thermistors, and a system voltage check. A 12-volt automobile battery supplied adequate power and was charged by a 34-watt solar panel fitted with a voltage regulator. The system was housed in the secured building shown in figures 24 and 25; it functioned satisfactorily through a cold Vermont winter. Some condensation occurred in the data-logger case (fig. 26) in May 1989 because the cable entries were not adequately sealed. Only intermittent data were recorded after mid-May, and the system was dismantled in June 1989. All data channels were sampled four times daily—at midnight, 6:00 a.m., noon, and 6:00 p.m. A digital voltmeter was also used to obtain jointmeter readings as a check on the datalogger and to extend the monitoring period.

DESCRIPTION OF SITE 1

Site 1 is on the northwest (east-facing) slope of Smugglers Notch at an altitude of approximately 900 m in a zone



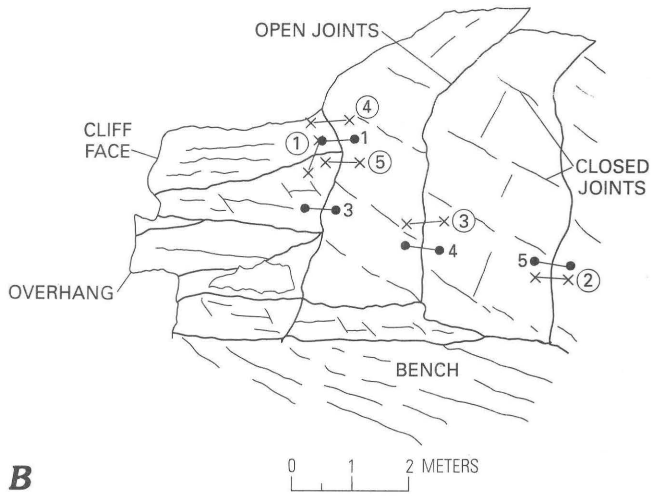


Figure 22 (above and facing column). Site 1, Smugglers Notch. Location of site 1 is shown in figure 8. *A*, Photograph of site after a summer rain. View is to southwest. Water is draining from the vertical fractures to subhorizontal fracture surfaces at base of cliff. *B*, Sketch of vertical section of cliff (in center of photograph shown in *A*) showing major blocks and gage locations. Numbers correspond to gage numbers in table 1. Manual gage 2 is not shown because no readings were obtained.

of active slope breakup (figs. 8, 22, 27). The rock is a finely laminated micaceous phyllite that contains gneissic layers. In places, the foliation is contorted and has no consistent orientation, but it strikes generally approximately N. 75° E. and dips 5°–20° SE., the downslope direction. The major joints are N. 50° W., vertical; N. 75° E., 45°–55° NW. (striking parallel to and dipping into the valley wall); and N. 20° E., vertical. Most surfaces are typically fresh and are open from a few millimeters to several centimeters near the cliff face. The blocks at this site are detached from the main wall. Water issues from the joints in and adjacent to the site in the spring and early fall. Recently fallen blocks litter the rock bench forming part of the base of the cliff (fig. 28). Not surprisingly, a jointmeter was damaged when struck by a block during the monitoring period. Figure 22*A* is a photograph of the assemblage of blocks and the relation of the blocks to the main wall, and figure 22*B* shows the gage locations at site 1. Because of the easterly exposure of this site, it receives considerable year-round direct solar radiation. As a result, there is more freeze-thaw activity here, and the permanent displacements of blocks were, on average, somewhat greater than at site 2, namely, 0.565 mm versus 0.507 mm (table 1). Monitoring of additional annual cycles is necessary to more adequately support this conclusion.

DESCRIPTION OF SITE 2

Site 2 is on the east (west-facing) slope of Smugglers Notch at an altitude of approximately 740 m (fig. 8). The cliff is vertical to overhanging and is somewhat steeper than at site 1. Block movement and cliff breakup are less rapid, based on the more weathered condition of rock surfaces and the absence of recently fallen rock blocks. The rock is a greenish-gray, medium- to fine-grained schist containing numerous 0.1- to 5-cm-thick quartz lenses parallel to the schistosity. The schistosity surfaces are strongly bonded, similar to those at site 1, and form widely spaced benches on the cliff front. Joints are spaced from 1 to 6 m and average approximately 2 m. Principal joints are oriented N. 47° E., vertical (parallel to the valley wall); N. 45° W., vertical; and N. 70° W., horizontal to 20° SW. (parallel to foliation). At this site, we did not observe deep, open joints striking parallel to the ridge, and benches were somewhat flatter than at site 1. Joint opening due to toppling may not be a factor here; rather, our observations suggest that basal sliding is more likely. Figure 23*A* is a photograph of the cliff at site 2 showing the joint blocks that were

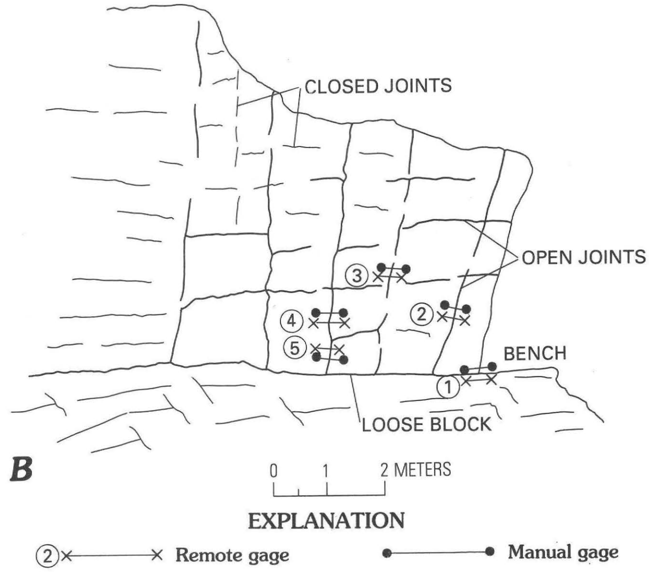


Figure 23 (above and facing column). Site 2, Smugglers Notch. Location of site 2 is shown in figure 8. *A*, Photograph of site. The cliff faces north-northwest and receives no direct sunlight for most of the year. *B*, Sketch of vertical section of cliff showing major blocks and gage locations. Numbers correspond to gage numbers in table 1. Gage 1 is mounted on horizontal bench. Manual and remote numbers are same. View is to southwest.

monitored, and figure 23*B* shows the gage locations at this site. Because of the westerly exposure of this site, it receives little direct solar radiation much of the year, which causes fewer freeze-thaw cycles and somewhat smaller permanent displacements than at site 1. Gage 5 has a significantly greater displacement than the other gages at site 2, probably because it is connected to an unconfined, loose block that can move more freely than the other monitored blocks.

WEATHER CONDITIONS DURING THE MONITORING PERIOD

The winter of 1988–89 brought precipitation to northwestern Vermont that was approximately 50 percent below normal, although by March moisture was near normal and remained so through June 1989 (National Oceanic and Atmospheric Administration, 1988, 1989). Average monthly temperatures during the monitoring period were within 2°C of normal except for January 1989, when the average temperature was approximately 3°C above normal (National Oceanic and Atmospheric Administration, 1988, 1989).

TEMPERATURE MEASUREMENTS

The nearest weather station to the monitoring sites is at Mount Mansfield, 4 km southwest of Smugglers Notch, at an altitude of 1,204 m. Precipitation and temperature data from this station are more site specific than the general conditions mentioned above. This station reported a total

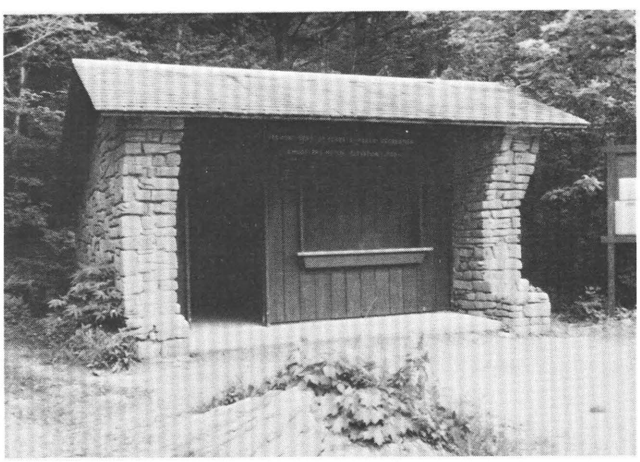


Figure 24. Vermont State Park information building, Smugglers Notch, a secure facility where monitoring equipment was located.

Figure 25. Solar panel and cable entry at monitoring site, Smugglers Notch. The panel faces south and receives sufficient sunlight to recharge recorder battery, even with leaves on trees.

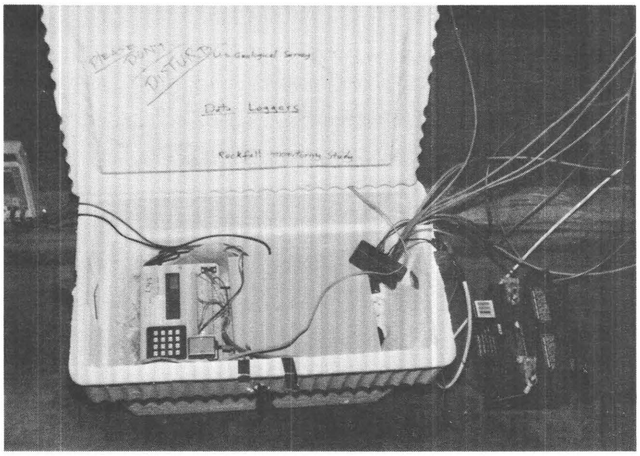


Figure 26. Data logger and batteries in building at Smugglers Notch.

snowfall of 4.14 m during the monitoring period. Rainfall during May and June 1989 totaled 20.5 and 24.4 cm, respectively, which was 10 percent above normal. The temperature extremes ranged from –31°C on January 4 and 5 to 24.5°C on May 19. This compares with average low temperatures recorded at sites 1 and 2 of –35.8°C and –37.6°C, respectively, on the same days (figs. 29, 30). The average high temperatures on May 19 at sites 1 and 2 were 18.5°C and 18.9°C, respectively. The last day having a below-freezing average temperature at the monitoring sites was on April 24 (Julian date 114). The somewhat more extreme low spikes for site 2 (fig. 30) for January 4 (Julian date 4) and March 7 (Julian date 66) may have been caused by differences in exposure of the sites. The response to temperature changes of the thermistors that are bonded to the jointmeters is acceptable (fig. 18). As shown in figure 15, the thermistors are located 5–10 cm above rock surfaces.

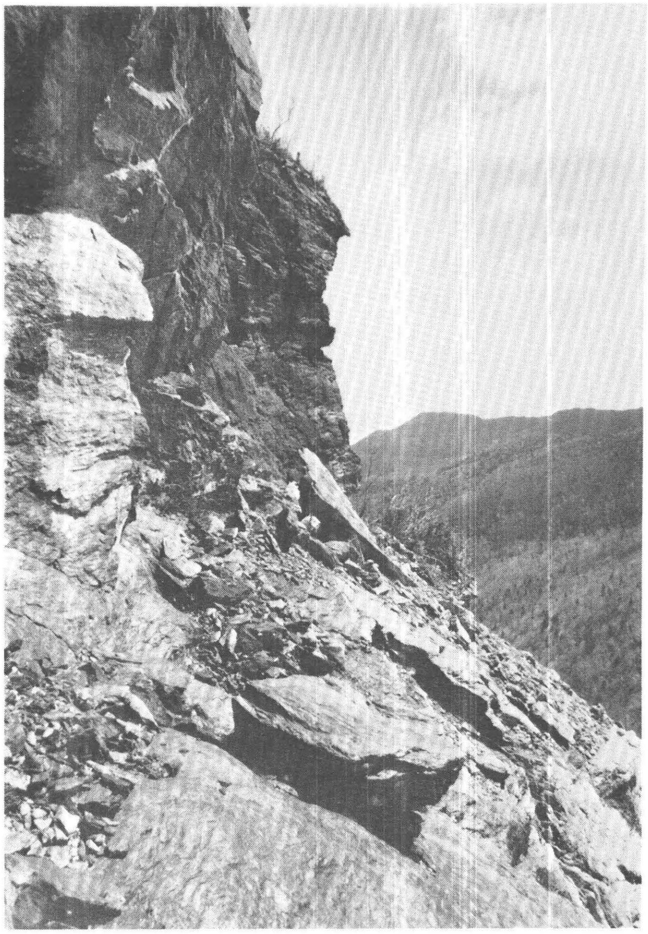


Figure 27. View to northeast of cliff at site 1, Smugglers Notch. The slabby blocks at this location are more stable than equidimensional blocks would be on such a steep slope.

DISPLACEMENT MEASUREMENTS

Instruments for monitoring temperature and displacement were installed on May 16, 1988 (site 1), and September 21, 1988 (site 2). Measurements were recorded at both sites until June 11, 1989, when the sites were dismantled.

Figures 31 and 32 show typical examples of temperature-induced displacements of jointmeters at the two sites. Displacements are greatest in the late fall and early spring, as shown on later records. Displacements in the winter are smaller, probably impeded by ice buildup and almost constantly freezing temperatures. Most gages recorded a small net positive displacement over the monitored period (table 1). They have both daily and seasonal cyclicity and both elastic and permanent components. The permanent displacements were smaller than the elastic cyclic displacements. For example, gage 3 at site 1 had cyclic displacements of more than 2.5 mm but a net positive displacement of only 0.427 mm. Other gages had a net permanent displacement of from 0.102 to 1.605 mm. This compares with

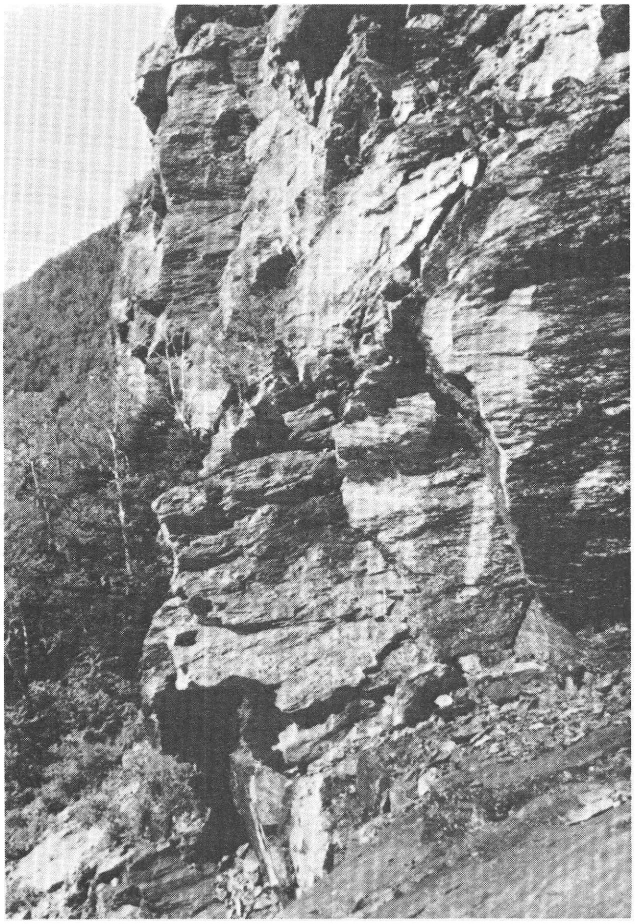


Figure 28. Rock blocks on bench at base of cliff at site 1, Smugglers Notch. The east-southeast-facing exposure produces greater temperature extremes than the northwest-facing exposure at site 2.

an average permanent displacement of 0.013 mm measured in one cycle in laboratory freeze-thaw tests of rock blocks (Lee, 1989). The variation of displacements may have been caused by differences in gage orientation and exposure so that the numerous freeze-thaw cycles in the late fall and early spring would not have affected all gages uniformly.

The temperature displacement records suggest that block behavior is complex; displacements vary both directly and inversely with temperature. All gages showed this pattern, although inspection indicated that there was more inverse response than direct response at both sites. All gages were installed across joints that were open at the surface (fig. 15). The measurements could be interpreted as the expansion of the two adjacent blocks during heating, which closed the joint opening and decreased gage displacements; however, this explanation is too simplistic because, in some instances, blocks appear to move apart with heating, and there is a lag between temperature change and displacement. In addition, we could not be certain of the actual confinement of the sides and bases of the blocks; vertical joint openings typically close with depth. As we discuss in the following section, there is probably a complex interaction between changing temperatures within blocks and displacements. Such trends would not represent a simple and immediate rock surface reaction to temperature change. In order to study the linkage of temperature changes and displacements, we made several statistical analyses of the data, presented in the next section. As noted above, the effects of mineral orientation and microfractures, as well as many other factors, can influence rock behavior.

STATISTICAL ANALYSIS OF FIELD MEASUREMENTS

In this section we present the results of statistical tests used to examine how temperature fluctuations induced thermal expansion and contraction in massive rock at Smugglers Notch during the period November 8, 1988, to May 3, 1989. Another aim of the tests was to determine the reproducibility of the gage data. We used linear-regression and time-series analysis of the residuals (the difference between values predicted by the regression analyses and the observed displacements). These statistical techniques quantify the effects of thermal-mechanical behavior on rock displacement using probabilistic data. The results of these analyses were used to predict rock displacement as a function of temperature and time. Our models are general; that is, they analyze both rock-mass expansion and contraction upon heating and cooling.

As far as we know, this approach has not been used to analyze rock behavior; however, it has been used in a wide variety of other applications (Pandit and Wu, 1983). It has been used to analyze heat transfer (Pandit and Rajurkar, 1983), to examine pulp and paper-making processes (Tee and Wu, 1972), and to model chemical reactions (Adeyemi and others, 1979).

The first linear regression equation that we used simply predicts displacement as a function of temperature; that is, thermal expansion and contraction.

$$\text{Displacement}=f(\text{temp}) \qquad (1)$$

The second equation predicts displacement as a function of temperature and time.

$$\text{Displacement}=f(\text{temp, time}) \qquad (2)$$

The third equation predicts displacement as a function of temperature, time, and previous values of displacement.

$$\text{Displacement}=f(\text{temp, time, displ}(t-1)) \qquad (3)$$

The predictions shown in figures 33, 34, and 35 were generated using a least-squares estimate of the parameters in equations 1, 2, and 3. These parameters were then

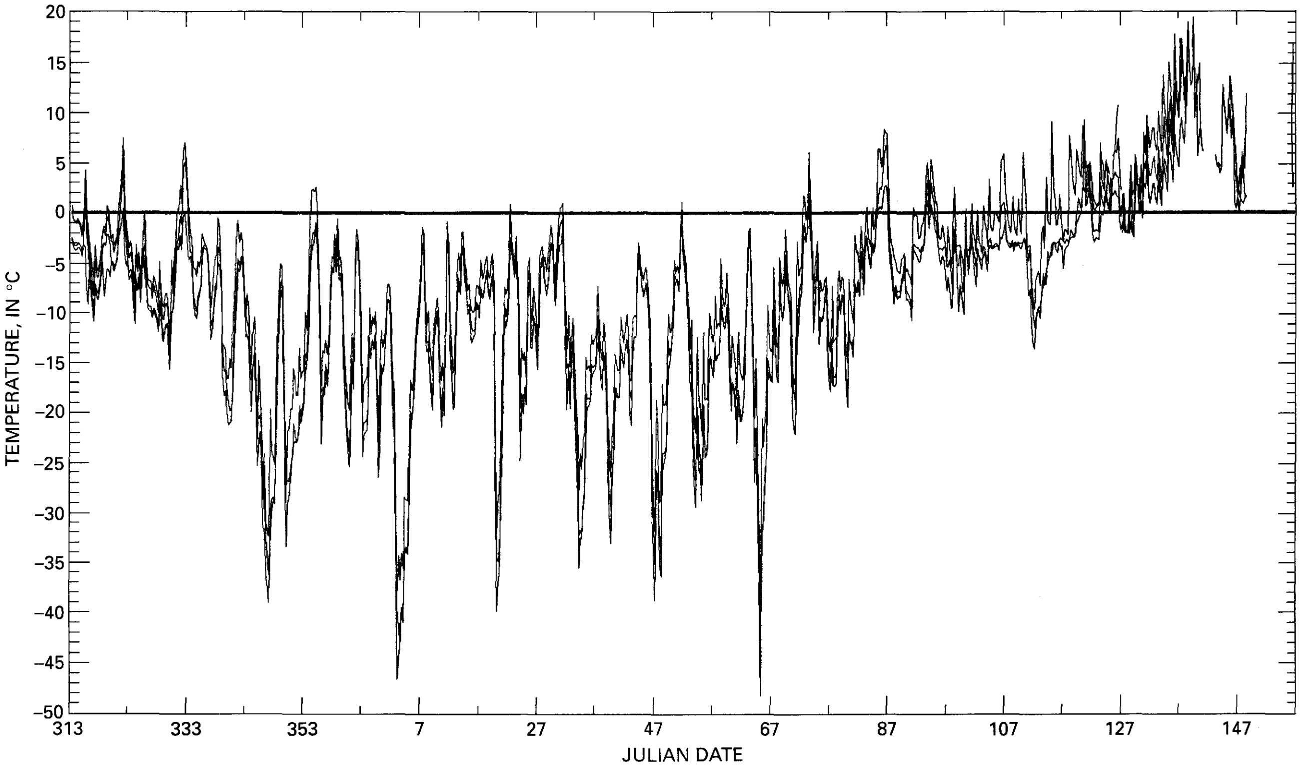


Figure 29. Temperature records for three monitoring points at site 1, Smugglers Notch.

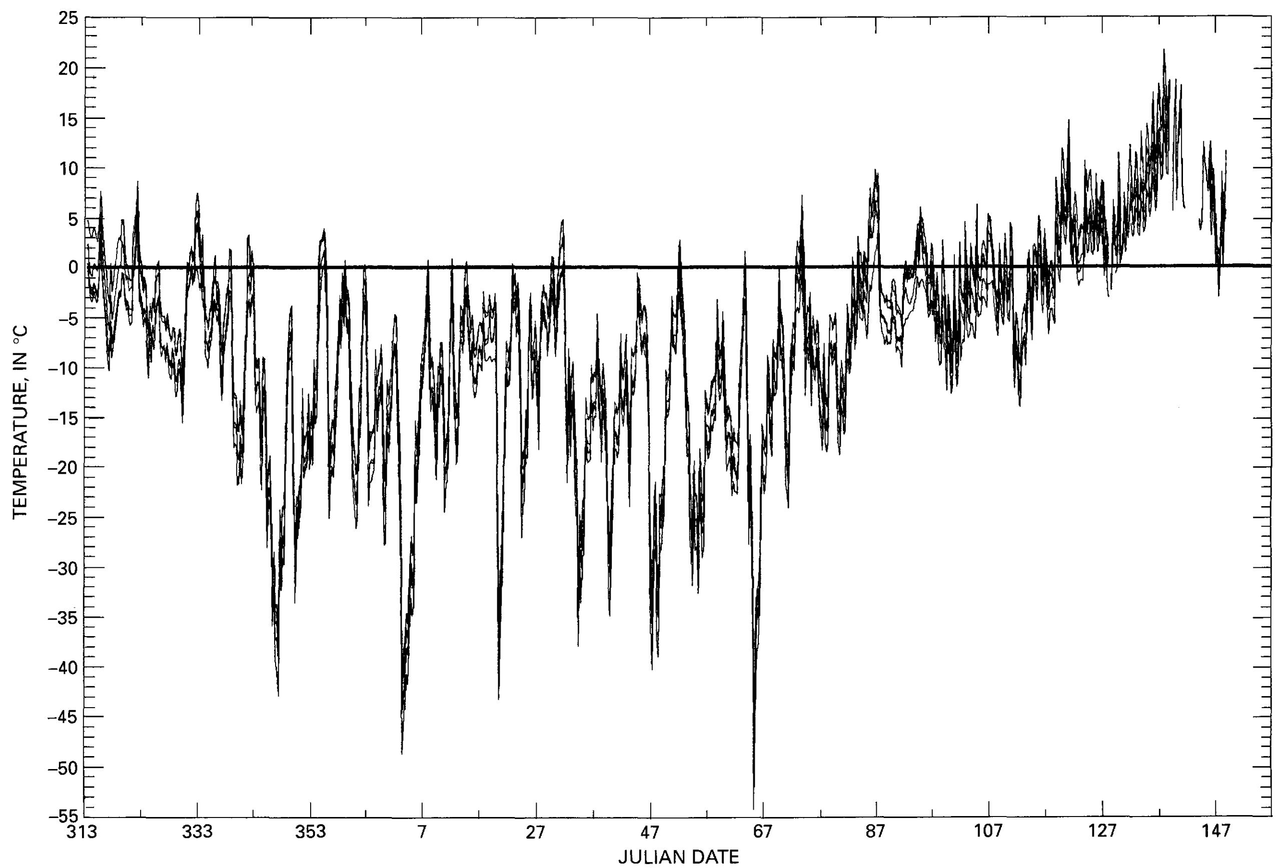


Figure 30. Temperature records for five monitoring points at site 2, Smugglers Notch.

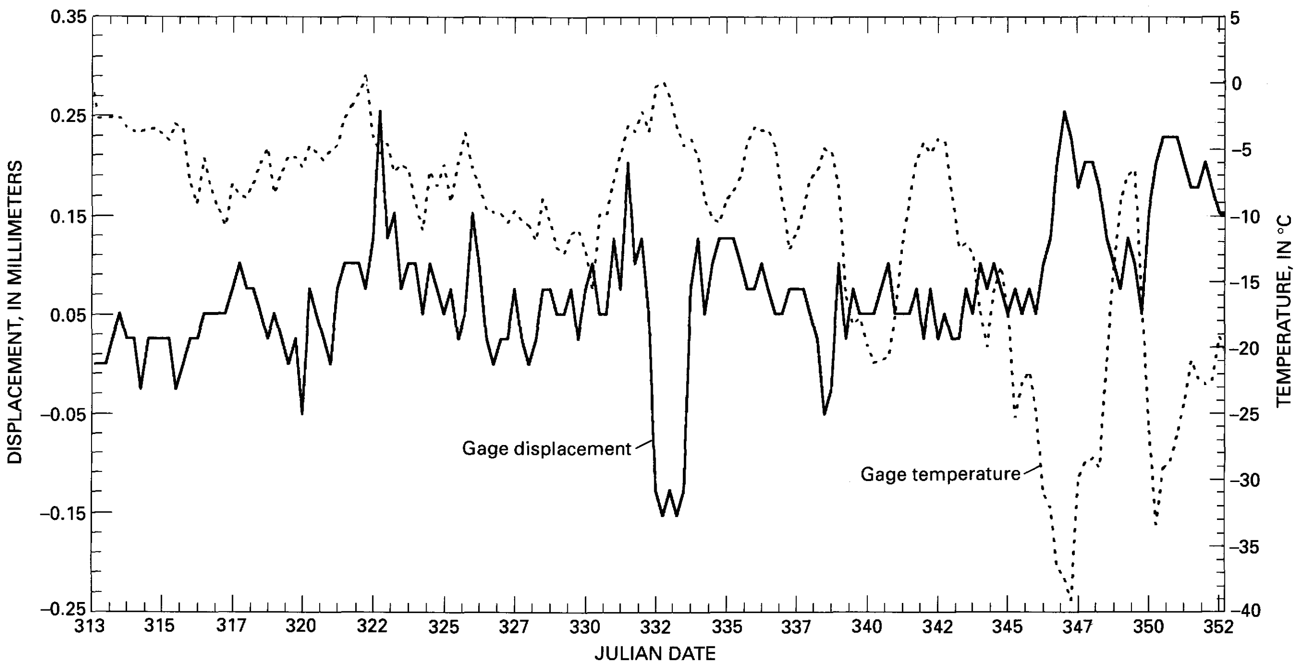


Figure 31. Plot of displacement and temperature versus time for gage 5 at site 1, Smugglers Notch, during the period November 8–December 16, 1988.

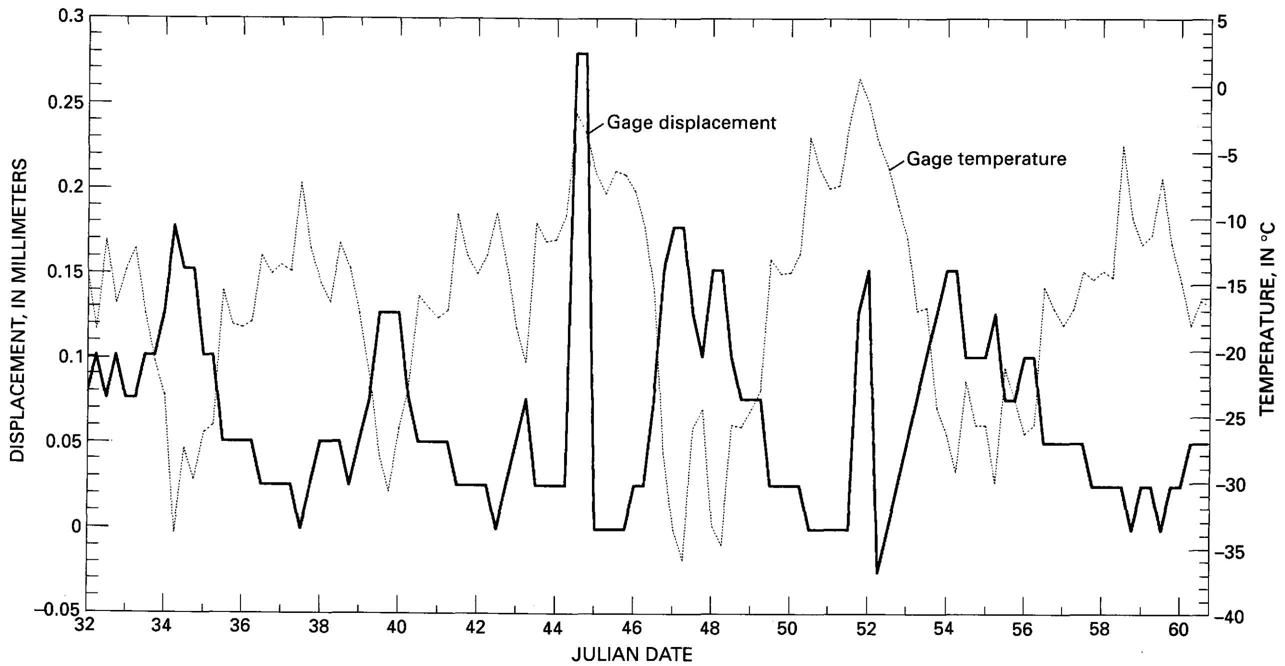


Figure 32. Plot of displacement and temperature versus time for gage 3 at site 2, Smugglers Notch, during the period February 1–28, 1989.

multiplied by the independent variables (temperature or elapsed time) to generate predictions of the dependent variable, rock displacement. In figure 33, the predicted displacement is solely a function of temperature fluctuations during the measurement period. The predictions vary erratically, mimicking the temperature fluctuations, because the predictions are based on a discrete, point-by-point linear relationship between temperature and rock displacement. The predicted displacements shown in figure 34 are based on a slightly more complex calculation. In addition to the effects of temperature (fig. 33), the predicted displacements shown in figure 34 include an estimate of rock

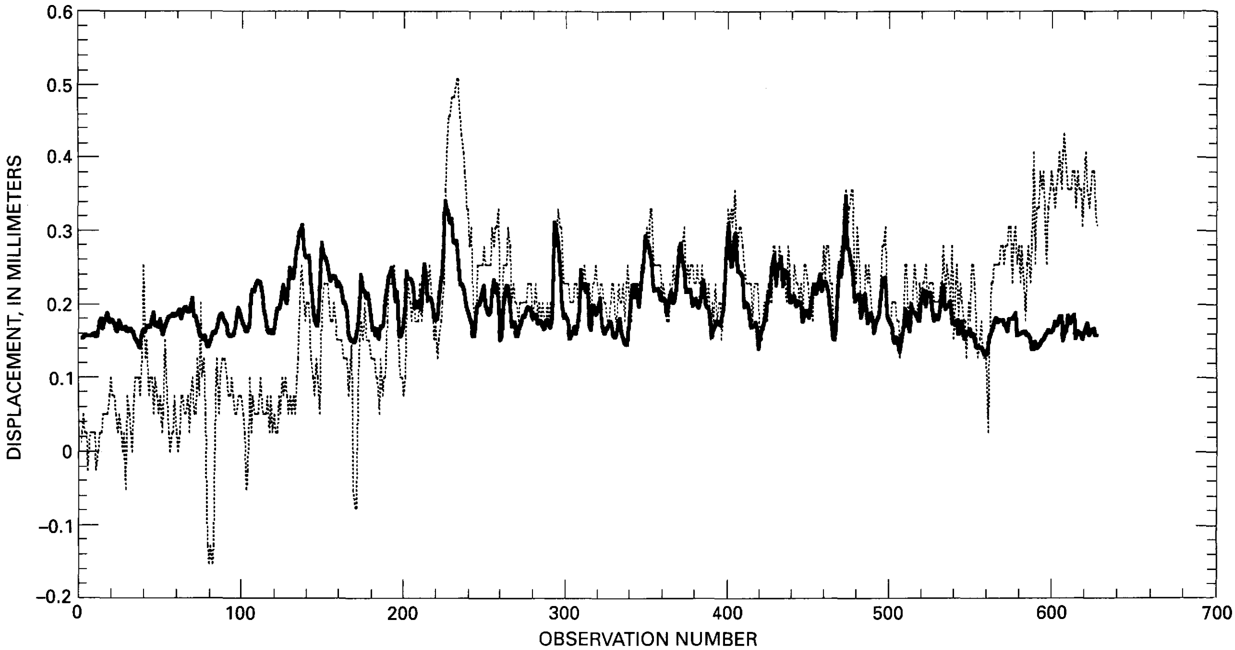


Figure 33. Graph showing observed displacement (dashed line) and predicted displacement as a function of temperature (solid line). Displacement=*f*(temp) (text equation 1). The gages listed in table 2 were used in this analysis. Observations cover the period November 8, 1988, through May 3, 1989. One observation interval is 6 hr.

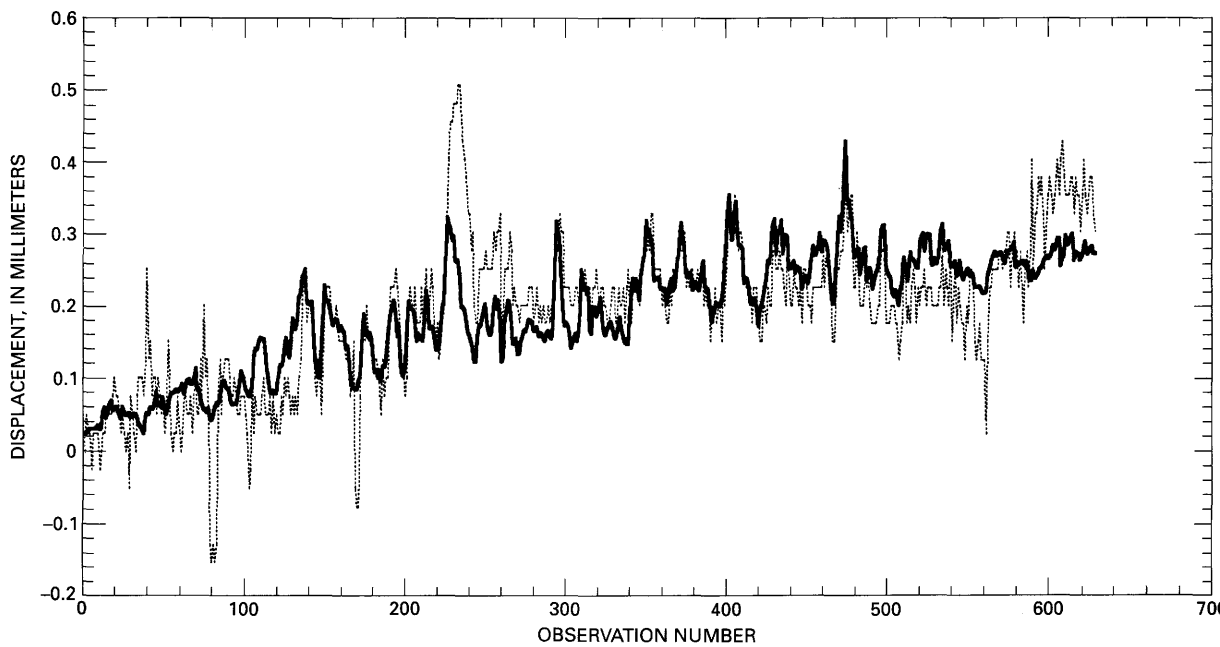


Figure 34. Graph showing observed displacement (dashed line) and predicted displacement as a function of temperature and time (solid line). Displacement=*f*(temp, time) (text equation 2). The gages listed in table 2 were used in this analysis. Observations cover the period November 8, 1988, through May 3, 1989. One observation interval is 6 hr.

displacement over time (the superimposed linear increase or drift), which is independent of temperature changes. In other words, figure 34 shows a continuously increasing displacement upon which the temperature-induced fluctuations are superimposed.

Figure 35 is the most complex and also the most accurate depiction of rock displacement. Not only do the predictions on this graph reflect the temperature changes and time-dependent displacement, they also include a factor that accounts for the thermal-mechanical dynamics affecting

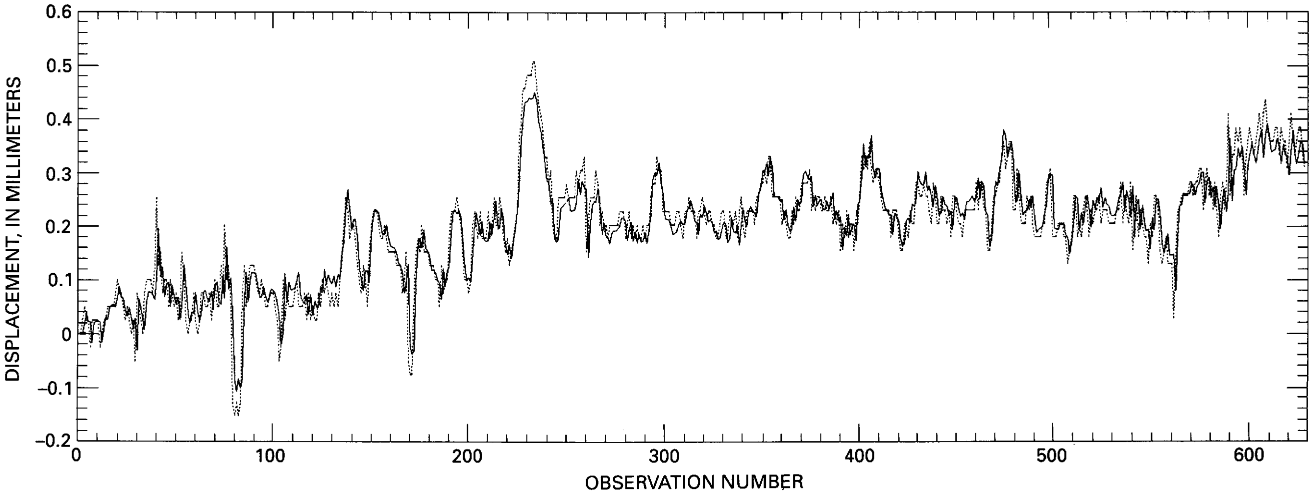


Figure 35. Graph showing observed displacement (dashed line) and predicted displacement as a function of temperature, time, and the previous value of displacement between time and temperature (solid line). Displacement=*f*(temp, time, displ(t−1)) (text equation 3). The gages listed in table 2 were used in this analysis. Observations cover the period November 8, 1988, through May 3, 1989. One observation interval is 6 hr.

rock displacement. These dynamics may reflect such phenomena as the thermal inertia of the rock that introduces a lag of the temperature at the rock surface and the temperature in the interior of the block. These dynamics can be represented as a linear dependency between the current displacement and the previous displacements. This dependency is a first-order exponential lag and is common to many heat-transfer models. Thus, the predictions in figure 35 include the temperature-induced fluctuations and the continuously increasing displacement, both of which are tempered by the dynamics of the process that make each displacement dependent on the previous displacements.

Table 2 shows that temperature has a strong influence on rock movement and that most gages show a displacement that increases with time, as noted in table 1. Gage 2, site 1, had a defective thermistor for part of the monitoring period, and gage 4, site 1, was damaged by a falling rock; these records were not used in the analysis. Only gage 3, site 1, and gage 2, site 2, fail to show a strong time-dependent displacement. A time-series analysis of the residuals indicates that they are highly correlated.

Figure 36 illustrates this strong correlation between residuals. This graph shows the 1st through 40th autocorrelations for the residuals of equation 2 for gage 5, site 1. A quantitative measure of the correlations shown in this graph is the Durbin-Watson statistic. The value for this statistic for the residuals of equations 1 and 2 for all of the gages in table 2 is significantly less than 2, averaging 0.51. This confirms the strong autocorrelations shown in figure 36. The high correlation of residuals that persists over several measurement intervals indicates a dynamic process. In other words, the effects of temperature fluctuations are not immediately translated into rock displacements but, instead, are translated into rock displacements through a process that depends on the past state of the system, including past temperatures and displacements and frictional effects. Thus, the thermal inertia of the rock acts as a shock absorber by diffusing abrupt temperature changes over time. A rapid increase in surface temperature will only gradually translate into an increase in block core temperature, as reflected in block movement.

The bottom row of values (equation 3) in table 2 illustrates how a simple autoregressive time-series model accounts for much of the dynamic interaction of surface temperature, time-dependent movement, and rock displacement. Just as the Durbin-Watson statistic indicates a strong

Table 2. Percentage of variation in gage displacements predicted by linear regression equations 1, 2, and 3, which use different combinations of temperature, elapsed time, and previous rock position.

	Site 1			Site 2				
	Gage 1	Gage 2	Gage 3	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5
f(temp)	28.6	4.0	13.4	28.2	4.1	77.6	45.3	10.1
f(temp, time)	29.3	16.8	61.3	62.0	8.4	78.3	53.8	25.4
f(temp, time, displ(t-1))	65.0	49.2	85.5	98.5	42.9	98.1	92.3	91.2

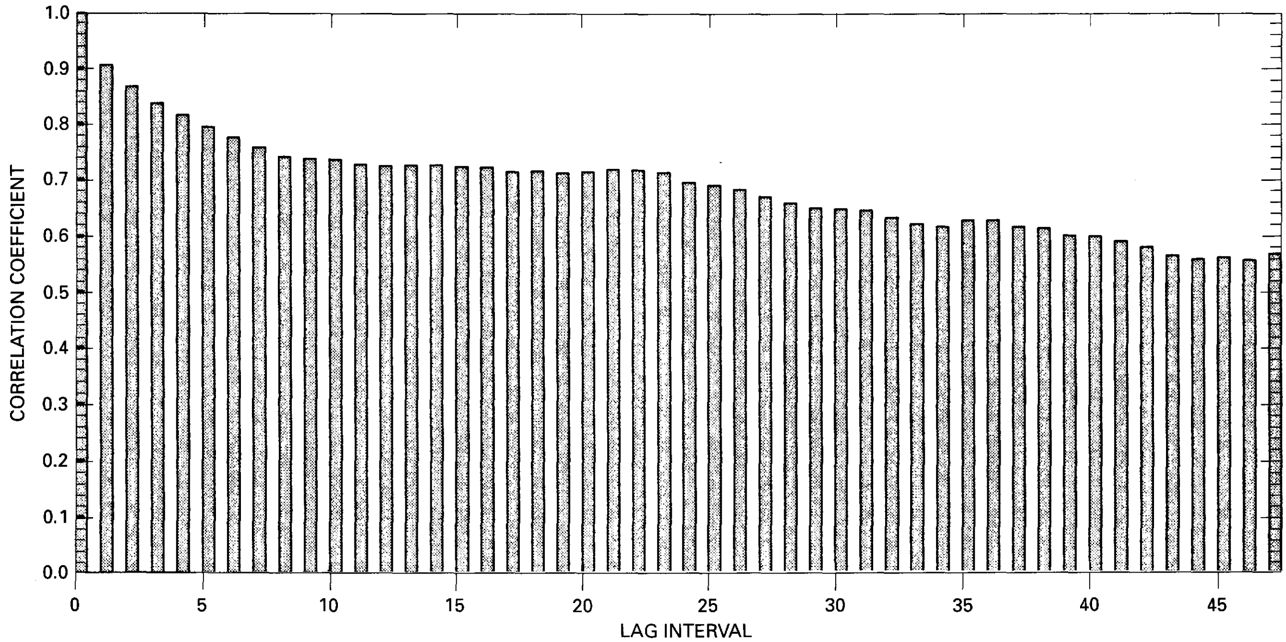


Figure 36. Graph of the 1st through 40th autocorrelations for the residuals of equation 2 for gage 5, site 1, Smugglers Notch. One lag interval (t)=6 hr.

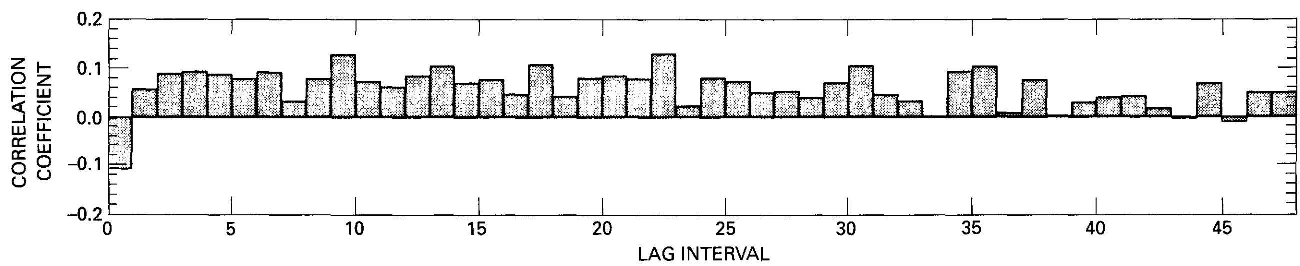


Figure 37. Graph of the 1st through 40th autocorrelations for the residuals of equation 3 for gage 5, site 1, Smugglers Notch. One lag interval (t)=6 hr.

correlation between residuals, the bottom row in table 2 shows that all gages at both sites have a strong dynamic aspect that is reflected in the large amount of variance that the autoregressive time-series model accommodates. The appropriateness of this model is further illustrated by the small residual autocorrelation indicated in figure 37. The Durbin-Watson statistic for all gages is approximately 2.0, which indicates that the residuals are independent (no correlation) and that the time-series model accurately represents the dynamics associated with joint-block behavior.

In summary, the highly correlated residuals suggest that temperature fluctuations are not immediately translated into rock displacement. Instead, the thermal inertia of the rock causes the internal temperature of the rock to lag behind its surface temperature, making the time-dependent displacements highly dependent on past displacements. More support for our conclusions of thermal behavior within massive rock blocks is available from other investigations. For example, the thermal lag effect has been identified by Hooker and Duvall (1971) and Swolfs and Savage (1984). The general agreement of the statistical tests across gages and sites shows the robustness and validity of the method.

Other writers have monitored block displacements with varying results. On the Frank Slide in Alberta, Canada, Kostak and Cruden (1990) recorded permanent movements of less than 1 mm/yr during a period of several years across an open crack at the crown of the slide. These authors ascribed the movements to a continuing dilational instability of the top of the slide. Kostak (1991) investigated slope movement in block fields in Czechoslovakia and found shear displacement of 0.1 mm/yr between blocks. In other cases, he determined that seasonal movement variations were reversible. In the case of a 30-m-high sandstone block, Kostak (1991, p. 58) stated "only the rotation can be readily interpreted as a proof of instability." Blocks at some locations moved by basal slip.

Our gage data do not validate either basal slip or block overturning; however, our field observations suggest that a combination of these mechanisms has occurred in the cliffs at Smugglers Notch. In general, the writers quoted above found that most permanent displacement results from seasonal, rather than diurnal, temperature variations, a conclusion with which we agree because time is a major factor in driving the thermal "front" into the blocks. Our results simply show small seasonal increases of displacement at each gage location.

SLOPE FORMATION AT SMUGGLERS NOTCH

Rock surfaces at Smugglers Notch are relatively new because of the removal of preglacial weathered rock mantle by glacial scouring. Rather than excavating intact rock, Pleistocene glaciers in the Green Mountains reworked and removed already loose or eroded rock material and modified the valley walls to broader U-shapes (Stewart, 1961). Christman (1959) concluded that the initial valley formation was accomplished by ancient stream erosion and modified by glaciation, although some sections of the notch lack a U-shape. The divide generally is narrow, with high cliffs on either side, and is partly filled with large talus blocks derived from these cliffs. Although slope changes in massive crystalline rock may have been slow in early Holocene time (Yardley, 1951), a gradual enlargement of joint openings resulted in slope attrition. Stewart (1961) stated that the striated rock surfaces in the Green Mountains indicate that some slopes had experienced little change since glaciation. We saw numerous southeast-trending striations on the tops of the higher slopes of Mount Mansfield; however, we did not observe striations on the valley walls or on the tops of lower slopes.

Several writers have investigated the formation and opening of steeply dipping joints parallel to valley walls (Feld, 1966; Ferguson, 1967; Matheson and Thompson, 1973; Nichols, 1980; Ferguson and Hamel, 1981). These references describe a process of rebound that is defined as the expansive recovery of surficial crustal material either instantaneously, time dependently, or both and is initiated by the removal or relaxation of superincumbent loads (Nichols, 1980). The applied loads resulting from past or present geologic processes are removed or relaxed, typically by valley erosion or deglaciation. These ancient "geological loads" caused strains to be stored in the rock that were relieved when the confining rock or ice was removed. River erosion and deglaciation remove horizontal support from valley walls and vertical support from the valley floor, causing valley walls to deform outward and valley floors to deform upward (Ferguson and Hamel, 1981). This unloading causes new fracturing or the opening of old fractures that develop parallel or subparallel to the unloaded valley walls (Ferguson, 1967). The opening of fractures may have been an early manifestation of Holocene slope deformation in the steeper, glaciated slopes. It is also an early indicator of slope instability (Hoek and Bray, 1981, p. 164).

We noted the presence of open vertical joints behind crests of the upper slopes of Smugglers Notch. Some of these features are quite old, as evidenced by lichens and other vegetation on inner surfaces. It is useful to consider the history of these joints and the clues they offer on the development and behavior of the slopes. Barton (1971) studied numerous detailed physical models of the initial breakup and failure of slopes in jointed rocks. He found that steeply dipping tension fractures propagated as a result of small shear displacements in the rock mass. The cumulative effect of these small movements was a significant displacement of the slope surfaces that caused the opening of existing vertical joints behind the crest of the slope. The fact that shear movements caused tensile deformations indicates that when open vertical fractures form shear failure has started within the rock mass. This complex and progressive failure process is difficult to quantify on natural slopes, but it affords a framework for the analyses of Hoek and Bray (1981).

Hoek and Bray (1981) suggested that, in some cases, the improved drainage resulting from the initial opening of rock structures and interlocking of blocks within the rock mass can increase the stability of a slope. Conversely, in cases where the strengthening effect of block interlocking is absent, there can be a very rapid decrease in stability and a consequent failure of the slope.

STABILITY OF BLOCKS AT SMUGGLERS NOTCH

Because of the conditions we observed at Smugglers Notch, there appears to be a considerable range of stability, as shown by the presence of trees and bushes, recently toppled blocks, and fresh debris-avalanche deposits. Overhanging blocks are obvious warnings of future failures. Some exposed joints issue water as soon as rain begins; others remain dry. We observed that, during a brief rain, water drained unimpeded through some slope faces that contained massive blocks, raising cleft water pressures only slightly and decreasing stability very little. Very heavy rains may build up cleft water pressures, causing blocks of marginal stability to fail, although Terzaghi (1962) showed that destructive pressures are most likely to develop in late winter or early spring when joints are plugged with ice and snowmelt is feeding large quantities of water into the rock mass. Slope stability conditions can change dramatically when blocks move or fall.

Figure 22*A* is a view of the cliff nose at site 1 on the west wall; it shows the gradual breakup of the slope. Blocks formed by the intersection of the vertical, open joints and the subhorizontal joints are failing by sliding, toppling, or falling, exposing fresh joint surfaces. This is probably the primary process of slope retreat in the higher valley walls at Smugglers Notch.

The postglacial slopes generally are steeper and less stable than the former V-shaped valley walls. The stress-relief rebound process that accompanied stream erosion and deglaciation weakened the rock mass, as shown by the opening of northeast-striking joints. The resulting rock movement is part of the longterm equilibrium process, which is complex and nonuniform, as demonstrated by irregular slope angles and episodic movement of blocks. Movements are controlled by block size, geometry and orientation of blocks, rock-joint strength, freeze-thaw activity, and precipitation. Because any of these factors could control the stability of a specific section of slope, the steepest, even overhanging, slope *may* not be the one most likely to fail. For this reason, it is not possible to calculate a uniform, stable slope angle for the entire area. In addition, the failure of a slope may have further destabilized, rather than stabilized, that part of the valley wall.

Any model of rockfall must explain the observations of debris accumulation, structural control, and climatic affects. Hoek and Bray (1981) recognized the significance of the opening of vertical joints as a precursor of slope breakup, a phenomenon that is evident at Smugglers Notch. We believe that their analysis of rock-slope behavior and cliff retreat is a useful model for Smugglers Notch. The following plane-failure analysis provides a simple method of assessing cliff stability that can be used at other cliff sites to make rapid estimates of stability.

PLANE-FAILURE ANALYSIS

Plane-failure analysis is a useful way to demonstrate the sensitivity of a rock slope to changes in shear strength and ground-water conditions. The initial slippage on an inclined surface is a key factor in triggering a rockfall, which typically occurs when a block slides or topples over a cliff. We have noted that the presence of vertical tension fractures indicates that the slope has started to deform and additional activity may be expected.

The prominent vertical fractures parallel and perpendicular to the valley wall (figs. 3, 4, 27, 28), together with low-dipping, bench-forming joints (typically foliation surfaces), define throughgoing release surfaces (surfaces that bound a block or group of blocks and provide negligible resistance (Hoek and Bray, 1981)). They facilitate the displacement and fall of face blocks. Our observations suggest that these face blocks and their neighbors are incrementally moving both laterally and downslope, as is also shown by the increasing openness of fractures near the free face. The front blocks slide on their bases until they fall or topple over a ledge. In some cases, an overhanging block will fail when its basal support is further undercut, although there has usually been pre-failure sliding.

In the following analysis of sliding, specific conditions need to be satisfied (Hoek and Bray, 1981, p. 150).

1. The surface on which sliding occurs must strike approximately parallel to the slope face.

2. The dip of the failure surface must be less than the dip of the slope face.

3. The dip of the failure surface must be greater than the angle of friction on this surface.

4. Release surfaces that provide negligible resistance to sliding must be present in the rock mass to define the lateral boundaries of the slide, or, alternatively, failure can occur on a failure surface passing through the convex nose of the slope.

In the analysis of Hoek and Bray (1981), a slice of unit thickness must be taken at right angles to the slope face so that the volume of the sliding block is represented by the area of the figure representing this block on the vertical section.

Figure 38 is a sketch of the cliff at site 1 (see fig. 22*A*, viewing west) that includes the blocks that were monitored. The blocks in the sketch have an open, vertical fracture system that is most likely to be water-filled at times in the early spring when water from rapid snow melt fills fractures or in the summer following heavy rain. After considering this saturated example, we will consider the stability of the same slope when it is dry, a condition that occurs in late spring or summer, providing there has been no recent heavy rain. There may be moisture in the slope, but, as long as it does not generate pressure, it will not influence the stability of the blocks. The safety factor (F) of the slope is defined by Hoek and Bray (1981, p. 154) as

$$F = \frac{(2c/\delta H)\,P + \left[Q\cot\psi_p - R\,(P+S)\right]\tan\phi}{Q + R\,(S\cot\psi_p)} \qquad (4)$$

where

$P = (1-Z/H)\,(\operatorname{cosec}\psi_p)$

$Q = [(1-Z/H)^2 \cos\psi_p\,(\cot\psi_p \times \tan\psi_f - 1)]$

$R = (\frac{Zw}{Z})\,(\frac{Zw}{Z})\,(\frac{Z}{H})$

$S = (\frac{Zw}{Z})\,(\frac{Z}{H})\sin\psi_p$

P, Q, R, and S are dimensionless ratios that depend on the geometry, but not the size, of a slope and are taken from

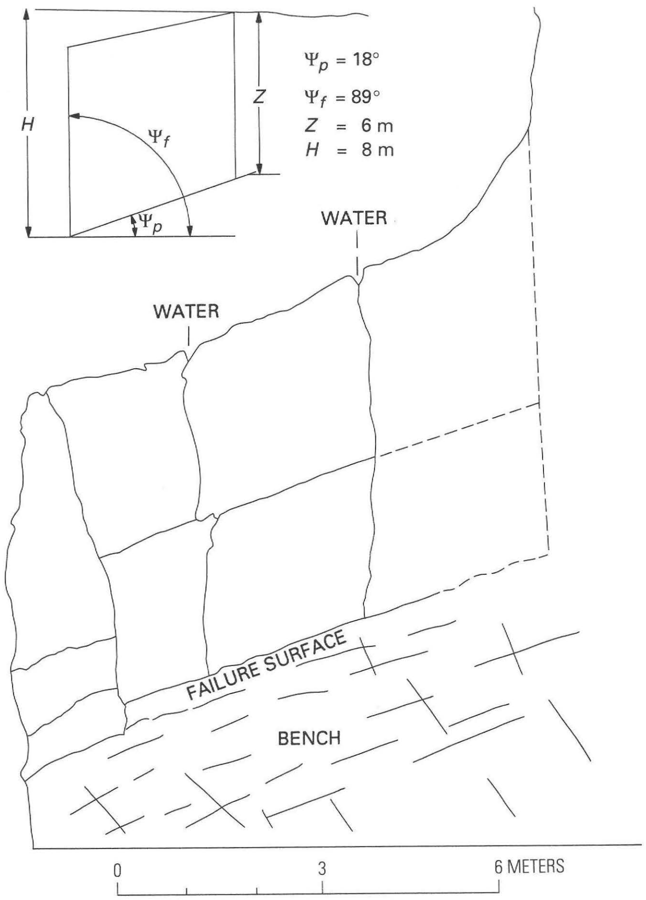


Figure 38. Sketch of cliff at site 1, Smugglers Notch, showing open vertical fractures and the parameters used for the stability analysis. This is a simplified representation of the blocks shown in figure 22. View is to the southwest.

graphs of Hoek and Bray (1981, p. 155–156); tan ϕ is taken from Hoek and Bray (1981, p. 23).

P=0.8
Q=0.4
R=0.2725 and 0.1363
S=0.23 and 0.12
δH=2,052 kg (4,515 lb)
ψ_p (failure plane dip)=18°, cot 19°=3.077
Tan ϕ (angle of friction on failure plane)=0.577
ψ_f (cliff-face dip)=89°
Z (depth of tension fracture)=6 m (19.69 ft)
H (height of slope)=8 m (26.25 ft)
Z/H=0.75
δ (unit weight of rock)=276 kg/m^3 (172 lb/ft^3)
Zw=Depth of water in tension fracture

Table 3 shows the factors of safety for this slope, both for appreciable cohesion on the sliding surface and for a more conservative calculation using no cohesion. Factors of safety above 1 indicate stability, whereas values less than 1 indicate instability or failure. These values should not, however, be used as absolute pronouncements of the safety of a slope but rather should be tempered by careful field investigations. Also, we examined stability with the fractures completely water-filled, half-filled, and with no water. If the cohesion is indeed low or nonexistent, the conservative case, movement could be expected at times of heavy rain or in the early spring when meltwater is stored

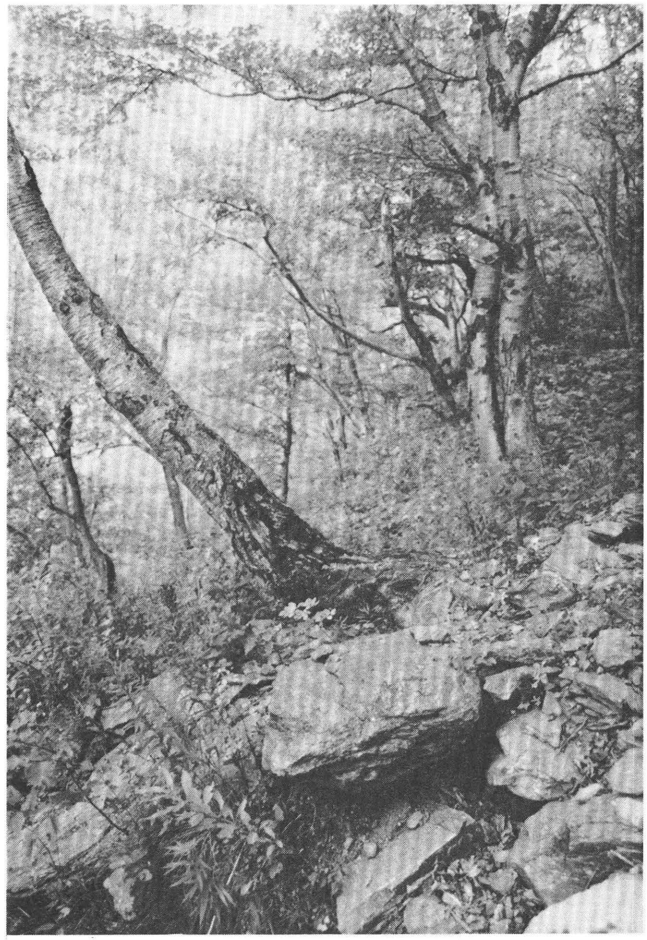


Figure 39. A chute that has been the site of many debris avalanches, Smugglers Notch. Rings in cores from these birch trees show several episodes of scarring and healing.

Table 3. Factors of safety (F) for cliff at site 1.
[Sketch of site 1 is shown in figure 38. See text for equations defining R, S, and F. Zw is depth of water in tension fracture, and Z is depth of tension fracture]

		Water level (Zw/Z)		
Assumed cohesion		1.0 (full)	0.5 (half)	0 (dry)
4,882 kg/m^2(1,000 lb/ft^2)	R	0.2725	0.1363	0
	S	0.2318	0.1159	0
	F	1.52	2.347	2.66
0	R	0.2725	0.1363	0
	S	0.2318	0.1159	0
	F	0.92	1.42	1.78

Figure 40. Overhanging blocks on the northwest wall at the top of Smugglers Notch.

by a frozen face. The most dangerous slope condition occurs when a fractured rock mass, which is relatively permeable, develops a flow system similar to a porous system. This situation develops after a prolonged heavy rain and leads to the rockfall-debris avalanches that are common in Smugglers Notch.

Because of the uncertainties attached to the definition of actual block geometries and water-pressure conditions, this analysis is not meant to apply to a specific location or event. When the position and depth of the tension fracture is unknown, its most likely position must be estimated. For dry slopes, the factor of safety reaches a minimum value of $0.42H$ (Hoek and Bray, 1981).

CONCLUSIONS

The data that we collected at Smugglers Notch, Vermont, show that individual cliff behavior is a complex time-dependent response of rock-block systems to temperature changes and to freeze-thaw cycles, on both short-term (daily) and long-term (annual) bases. Several other factors are obvious potential contributors to the pattern of cliff behavior but are difficult to quantify. These factors include the geometry of the blocks and their interaction, as well as frictional constraints, precipitation, root wedging, and exposure. For example, there are more platy blocks on the east side of the notch and more equidimensional blocks on the west side, a relationship that may explain why blocks from the west side have traveled farther. The simplified block analysis presented can be used to estimate the stability of blocks at specific slope locations, but it cannot be used to predict the stability of a larger slope section having variations in slope angle, height, and geologic discontinuities. This would require three-dimensional finite-element modeling using accurate block sizes and geometries, a task that is beyond the scope of this study.

The numerous scars, channels (chutes), and accumulations of large rock blocks in the upper reaches of the notch attest to the continuing occurrence of rockfalls and debris avalanches (fig. 39). At some locations there are significant hazards to the public. A dramatic example is in the narrow stretch of roadway near the top of the south approach to the notch. Here, large blocks, fallen from both slopes, crowd the narrow passage, as shown in figures 3 and 4. Overhanging blocks are an ever-present hazard in the upper reaches of the notch cliffs and one that is easily recognized.

Figure 40 is an example of such a concern near the top of the notch on the west side. It is clearly imprudent for individuals to pass directly below or to attempt to climb these overhangs. Debris avalanches are most likely along Vermont Route 108, from approximately 1.5 km south of Big Spring northward to the top of the pass. Rockfalls and debris avalanches are typically associated with periods of intense rainfall and occur from late May to early August, the time of heaviest recreational activity in the Smugglers Notch area. The fact that this area experiences slope failures annually suggests that warning of these events should be posted at strategic locations. As a means of educating the public, typical debris avalanches and rockfalls should be identified and descriptions placed at safe and accessible locations. Future work should maintain a record of the timing and location of failures, as well as of the weather conditions associated with the event.

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