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Slope Movements in the Cheshire Quartzite, Southwestern Vermont

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ABSTRACT

Slope movements in the Lower Cambrian Cheshire Quartzite of the western Green Mountains in Vermont are characterized by block slides, rock falls, and more rarely by toppling failures. Slides and falls occur on steep hillslopes underlain by massive quartzite, whereas topples are unique to thinly bedded, tectonically deformed quartzite containing interbeds of graphitic schist. Freeze-thaw mechanisms dominate displacements of massive blocks, while rainfall induces toppling displacements. Movement of massive blocks occurs primarily in early spring and late fall.

Bedrock discontinuties, including microfractures, joints, and bedding surfaces, are of primary importance in facilitating initial slope breakup and controlling the subsequent mode of downslope rock-mass movement. The preliminary results of investigations at three sites in the Cheshire Quartzite show that movement rates are controlled by structural conditions and slope-development patterns. A typical freeze cycle during testing of a physical block model in the laboratory produced a displacement of 0.13 mm, which agrees reasonably well with the 0.26 mm annual displacements measured at two cliff-edge blocks at a rockfall site. Gravity-induced toppling movements in much less massive quartzite are more rapid.

INTRODUCTION

In the northern Appalachian Mountains, unforeseen rock slope failures are a continuing hazard that cause damage to roads, houses, and recreational areas. Because causes and rates of mass movements are poorly known, forewarnings of dangerous conditions have been impossible. In Vermont, rockfalls involving single blocks weighing as much as several thousand metric tons have cut swaths down timber-covered mountainsides, whereas others may have triggered debris avalanches. The objective of the current study, begun in October 1984, is the quantification and possible correlation of climatic events and slope deformation rates in foliated and jointed metamorphic rocks. Such information is a first step in assessing slope-movement hazards.

The importance of bedrock discontinuities in mass movement has been amply demonstrated (Terzaghi, 1962; Schuster and others, 1975; Goodman and Bray, 1976; Hoek and Bray, 1977; Piteau and Peckover, 1978). These studies involve slopes that were created or modified by construction or mining operations, however, and the results may not be directly applicable to understanding natural slope processes. Also, a search of the literature revealed that there has been insufficient effort made to investigate the role of frost action in block displacement on rock slopes.

The present report compares and contrasts modes of failure at three locations in the Cheshire Quartzite in western Vermont, and shows how structures in the rock contribute to differences in rock mass behavior. Results of field and laboratory investigations suggest that frost action is an important factor in the incremental downslope displacement of large joint blocks.

PREVIOUS FREEZE-THAW INVESTIGATIONS OF BEDROCK

Several 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), although quantitative studies have been largely limited to soil. 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 to -15 ^{o}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 (145 lbs/in^2), is the chief agent of rock disintegration. Taber also suggested that because freezing and thawing, due to diurnal changes in temperature, are concentrated in the spring and fall, greater opportunity exists at these times for block displacements. Taber observed that repeated freezing and thawing caused significant downhill displacements of various-sized particles.

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 has exerted 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, resulting in the formation of more ice in the crack. A rise in temperature would cause the ice to expand, once again pressuring the rock. Permanent displacements of joint blocks may then occur, most significantly where blocks have little confinement, such as on cliff faces. Early spring is most appropriate for this process to operate when frozen rock, particulary on south-facing slopes, is alternately heated and cooled, sometimes daily, causing incremental strains. Near-surface joint blocks that are sealed at the base and side provide a favorable geometry for a build-up of pressure due to the volume expansion 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, or where drier conditions prevail, by the attempted expulsion of water from saturated zones in the active layer, which become confined by the downward advancing freezing front. In this process, water pressures as great as 400 kPa can be attained within the confined bodies. Dyke also noted that this mechanism does not require a high degree of saturation.

Bjerrum and Jørstad (1968) studied the factors that control the failure of many rock slopes in Norway. Most rock falls and rock slides that they investigated occur in sound, unweathered granites and gneisses. Slopes in altered rocks probably failed and stabilized soon after the last glaciation. Frost shattering is the predominant destabilizing agent and most rockfalls occur below 100 m altitude in the early spring and late fall when the temperature fluctuates around the freezing point. Joint openings widen several years before slope failures. Rockfalls increase immediately before a large slide occurs, and any debris or rock mass resting on a slope steeper than 35-38° will fail. This last finding was discussed in terms of time-dependent destabilizing processes.

Quartzose rocks are ideal candidates for the development of microfractures and subsequent freeze-thaw crack growth. According to Nur and Simmons (1970), the origin of such cracks in igneous rocks can be attributed to the relatively high difference in thermal expansion and compressibility of quartz compared to those of feldspar and sericite such as occur with the quartz grains in the Cheshire Quartzite. The pressure produced by ice-crystal growth perpendicular to the trend of microfractures is an effective agent in rock breakup (Walder and Hallet, 1985). These investigators calculated simulated crack-growth rates under plausible environmental conditions that were within the range of the experimental values of Segall (1984).

GEOLOGIC SETTING

The Cheshire Quartzite is one of many Cambrian and Ordovician quartzites, carbonates, phyllites, minor schists, and local metavolcanic rocks found in the Champlain Valley that are separated by a major unconformity from the gneisses of the Middle Proterozoic Mount Holly Complex (Shumaker and Thompson, 1967). The Cambrian and Ordovician rocks were broken by high-angle faulting, probably in early Middle Ordovician time, and further deformed by folding and faulting by west-directed thrusting during the Devonian Acadian orogeny (Shumaker and Thompson, 1967). This latter deformation produced a regional metamorphic overprint of biotite or upper-greenschist-facies grade.

The Cheshire Quartzite (Brace, 1953; Shumaker and Thompson, 1967) is, in most places, a white to buff, massive, vitreous orthoquartzite occurring in beds as much as 15 m thick, although local structural and compositional conditions alter its characteristic massiveness. The unit extends from Massachusetts northward into Canada (fig. 1) and separates the western front of the Green Mountains from the eastern edge of the Vermont Valley (Doll and others, 1961). In the area of this report, the Cheshire is about 150 m thick although the unit may attain a thickness of over 300 m elsewhere (Brace, 1953). Faulting in the study area makes it difficult to obtain a true maximum thickness.

Although the Cheshire is nearly pure quartzite, thin black graphitic phyllite and sandy dolomite are included at some locations; the latter occurs only near the base of the formation.

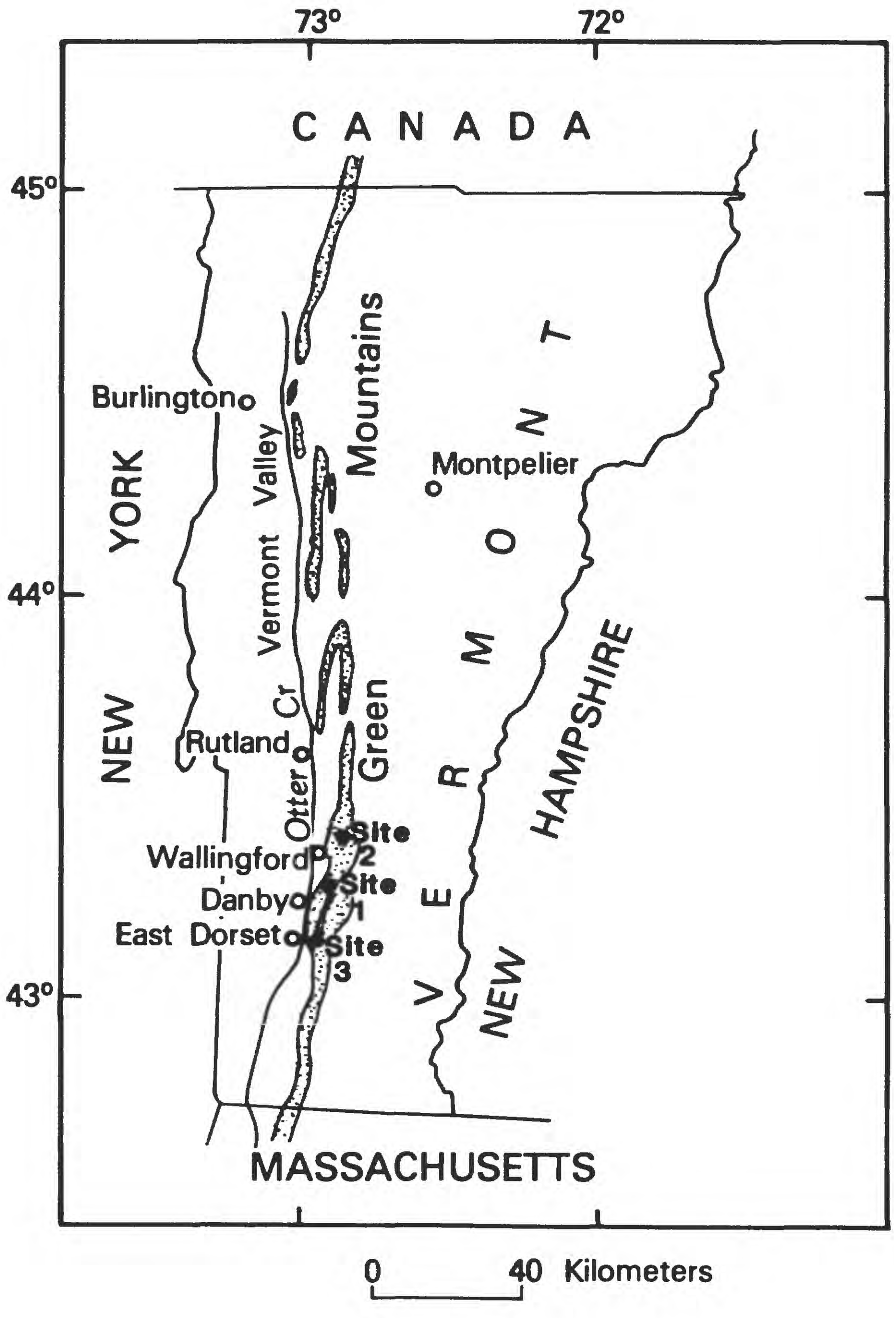

Figure 1.--Location map showing rock-slope study sites in southwestern Vermont. Stippled pattern indicates areas of outcrop of Cheshire Quartzite.

SITE INVESTIGATIONS

The following discussion of slope movements at three sites in western Vermont illustrates the interrelationships of rock structure, slope attitude, and climatic forces.

The three study sites lie east of U.S. Route 7 near west-flowing tributaries to the south-flowing Otter Creek that drains this portion of the Vermont Valley (fig. 1). The relief of the area exceeds 700 m. Topographic changes in the area produced by Pleistocene glaciation probably were modest, and served mainly to modify valleys to U-shapes. The present rock surfaces are relatively new due to the removal of the preglacial weathered rock mantle through the planing off by glaciers of the outer meter or so of bedrock (Stewart, 1961). In massive crystalline rocks such as the Cheshire Quartzite, slope movement was probably slow in early Holocene time (Yardley, 1951); the gradual enlargement of joint openings resulted in a progressively faster rate of attrition. Even so, the presence of striated bedrock surfaces on hillsides and hilltops in the study area (Stewart, 1961) shows that some slopes have experienced little change since glaciation.

SITE 1. WHITE ROCK OVERLOOK ROCKFALLS

This site is 2.8 km northeast of Danby on the southeastern end of Green Mountain (fig. 2) at an elevation of approximately 485 m. The Cheshire Quartzite at this location is extremely massive and joints are widely spaced (table 1). Blocks of the quartzite reach enormous size; some measure as much as 4 m on a side, and the average block is approximately 2 x 1.5 x 1 m. Major structural features at the site are given in table 1. Major joints are approximately parallel with and perpendicular to the trend of the slope. Bedding is difficult to identify with certainty at some locations around this site. Where distinct, it forms widely spaced surfaces of weakness that are vertical and strike north. A steep cliff at this site rises 70 m above the road, and near its base there are large blocks that have fallen from upper ledges. The extension of cracks separates pieces of quartzite joint blocks that then drop into open joints. Ice crystals may grow between these slabby blocks exerting pressure on joint walls and causing displacement parallel and perpendicular to the slope in a similar fashion to ice crystals observed in the block model to be discussed later. As the ice thaws, blocks slip further down the tapered joint opening, "locking in" an increment of displacement. This process is likened to the wedging of crushed rock in joints preventing joints from returning to their former position after they have opened slightly under high-water pressure (Bjerrum and Jørstad, 1968). Such a spreading operation, when repeated for many years, literally drives large blocks over the edges of cliffs (fig. 3). Figures 4 and 5 are photographs of joints and microfractures that illustrate the development of slabby blocks which act as wedges. These joints have an average strike of N. 50° E. and are commonly open 0.03-0.45 m at the surface. Openings over 15 m deep have been measured in these massive rocks from which strikingly cool air emanates in the summer. The cooling may be produced by pockets of perennial ice between joint blocks, such as those which occur nearby at the "Ice Beds" located southeast of Wallingford (fig. 6).

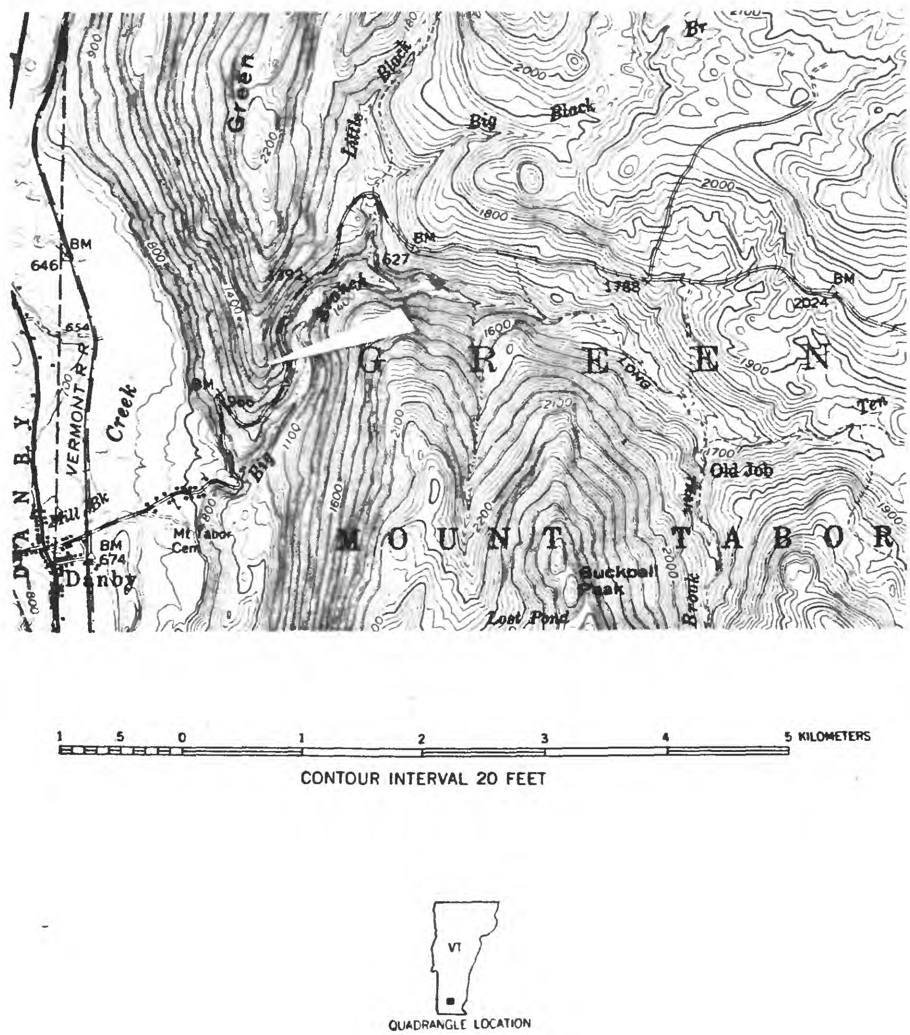

Figure 2.--Location map of Mount Tabor Road rockfalls (site 1). Base from 1:62,500 scale, U.S. Geological Survey Wallingford quadrangle map.

TABLE 1. MAJOR JOINTS IN THE CHESHIRE QUARTZITE AT STUDY SITES, SOUTHWESTERN VERMONT

	JOINTS				
	Attitude		Spacing(m)	Surface condition	Remarks
Site 1* (Mt. Tabor Road)	N. 50° E.	80° SE.	0.5 to 1.5	Smooth, planar	Strikes approx. parallel to slope.
	N. 75° W.	90°	1 to 3	Smooth, planar	Strikes approx. perpendicular to slope.
	N. 65° W.	50° NE.	1 to 4	Rough, planar	
	N. 40° E.	25° SE.	0.5 to 1.2	Smooth, planar	Surface of block movement.
Site 2 (White Rocks)	N. 2° W.	65° NE.	0.02 to 3	Smooth, planar	Strikes approx. parallel to slope.
	N. 75° W.	90°	0.2 to 3	Rough, planar	Strikes approx. perpendicular to slope.
	N. 6° E.	55° NW.	0.2 to 2	Smooth, planar	Also bedding/foliation attitude.
Site 3 (Mad Tom Brook)	N. 15° E.	80° SE.	0.01 to 0.7	Rough, altered	Also bedding/foliation attitude.
	N. 70° E.	75° NW.	0.02 to 0.5	Smooth, altered	
	N. 65° E.	25° NW.	0.02 to 0.5	Rough, planar	Bedding planes in slide have variable surface condition and orientation.
	N. 80° W.	90°	0.4 average	Smooth, altered	Bordering the slide, bedding is N. 15° E., beds are 1-70 cm thick.
	N. 60° W.	18° SW.	0.1 to 0.3		

* Location of sites are shown on figure 1.

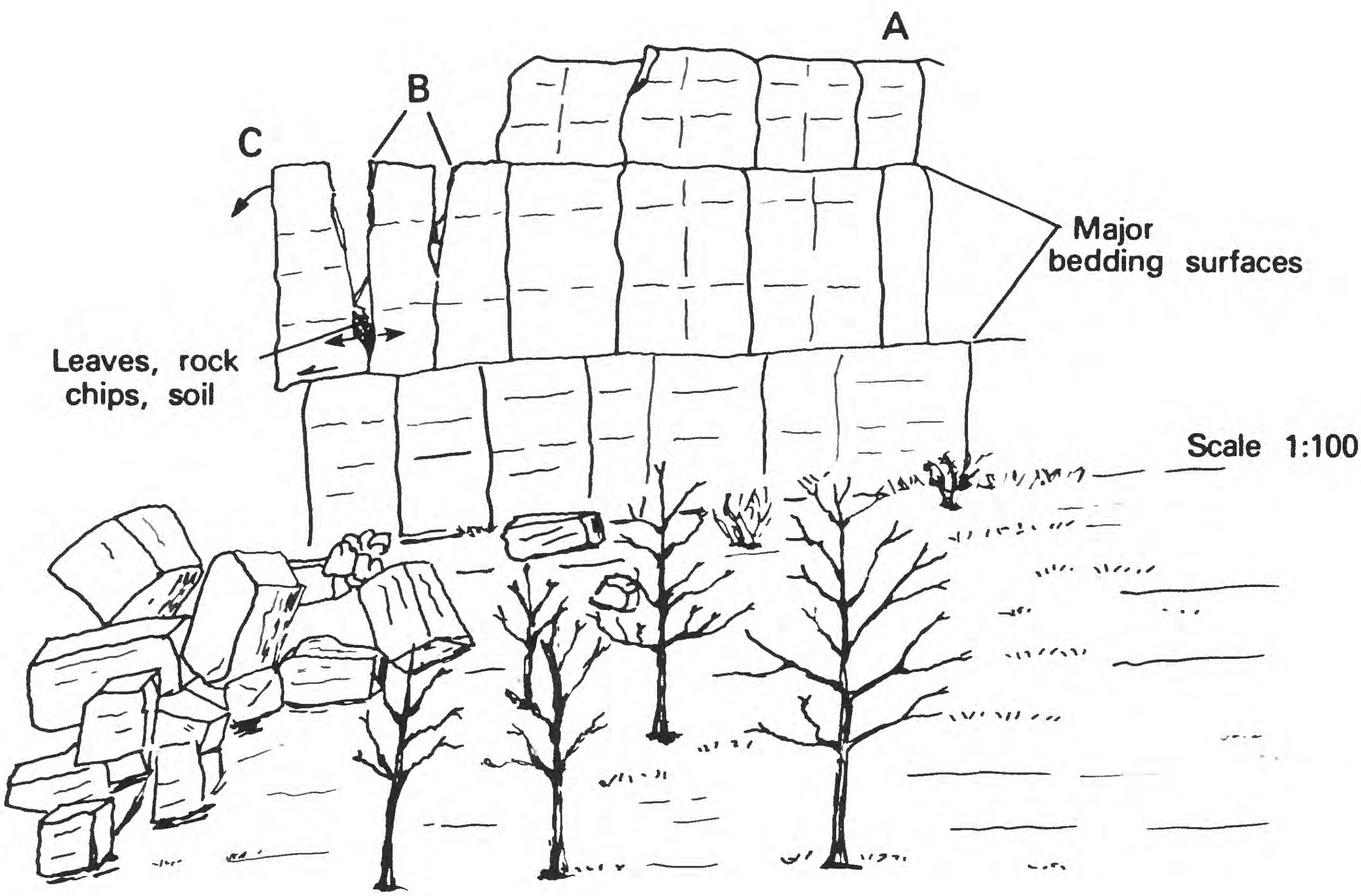

Figure 3.--Process of freeze-thaw spalling, wedging, and block displacement at site 1.

A. Initial condition with pre-existing tight tectonic joints and parallel microfractures.

B. Condition produced by freezing and thawing. Microfractures have enlarged downward forming slabby, often wedge-shaped blocks. Tectonic joints open and close with freeze and thaw episodes, probably without producing appreciable basal displacement.

C. Basal displacement downslope occurs as spalled tabular blocks move toward the left in response to freezing. Blocks ultimately slide or topple off the cliff forming talus below.

Figure 4.--Dial-gage extensometer bridging open tectonic joint parallel to cliff face in Cheshire Quartzite at site 1. Numerous and partly developed, but still intact, slabs and spalls can be seen on the face of the left (south-facing) joint block. Invar calibration bar lies next to extensometer.

Figure 5.--Photograph of open joint shown in figure 4, looking downward, and showing several slabby wedges of quartzite that have dropped into opening. The distance across photograph is 0.85 m.

The proposed mechanism of downslope transport of blocks under the combined influence of gravity and frost action is in agreement with observed slope conditions. Angles of repose ("friction angles") were measured in the field by inclining pairs of joint blocks (or parts of joint blocks) until sliding of the top block took place. The angles of repose of several quartzite blocks tested in this manner were found to be approximately 35°. The surface on which the blocks would slide is presently inclined less than 30°, so these blocks should be stable unless there is an additional driving force.

Field displacement measurements were made over a period of 19 months (two freeze-thaw seasons) at four cliff locations using a dial-gage extensometer (fig. 4) with a resolution of 0.01 mm. Measurement points were established in joint blocks by cementing notched brass cylinders (1.27 x 6.35 cm) in drilled holes. The cylinders were tapped to receive 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. Numerous wet and dry freezing tests of the system were made in the laboratory and they showed no breakup of the cement or weakening of the bond, and no anelastic (creep) deformation was measured between anchor points. The extensometer was calibrated for temperature-induced strains with an Invar steel bar. Displacements are positive, indicating crack widening and ranged from 0.03 to 0.75 mm. The largest value was from a cliff-edge block and the lowest value is from a neighboring upslope block. The average displacement of two cliff-edge blocks was 0.30 mm (0.15 mm annually), a small value but in agreement with a typical laboratory freeze-cycle displacement of 0.13 mm (see Appendix). These data suggest that cliff retreat by rockfall in the Cheshire Quartzite is a very slow process compared to other modes of slope failure. Although they are not a widespread occurrence at this site, rockfalls are annual phenomena where marginally stable blocks are driven over cliff edges. The modest postglacial accumulation of rockfall blocks below cliffs in the site 1 area (a volume of approximately 100 m^3) also attests to the slowness of block movement. A minimum rate of 15-20 cm per 1,000 yrs is suggested by the data.

SITE 2. WHITE ROCKS BLOCK SLIDE

The White Rocks slide is located 4 km southeast of Wallingford, Vt., on a steep, west-facing hillslope at an elevation of 670 m (fig. 6). An area of approximately 3 km^2 was studied. The Cheshire Quartzite at this site is somewhat less massive than at site 1 to the north. Joint spacing ranges from 0.02 to 3 m (table 1); an average in-place joint block is 0.4 x 1 x 1.5 m. Two joint sets dominate the rock mass in this area: N. 2° W., 65° NE., and N. 70°-75° W., vertical. Relict bedding at this site can be easily identified; the beds are 0.2-2 m thick, strike N. 6° E., and dip 40-60° NW., averaging 55° NW. The N. 75° W. joint surfaces are rough but the N. 2° W. joints and the bedding surfaces are smooth; all three sets of surfaces are planar.

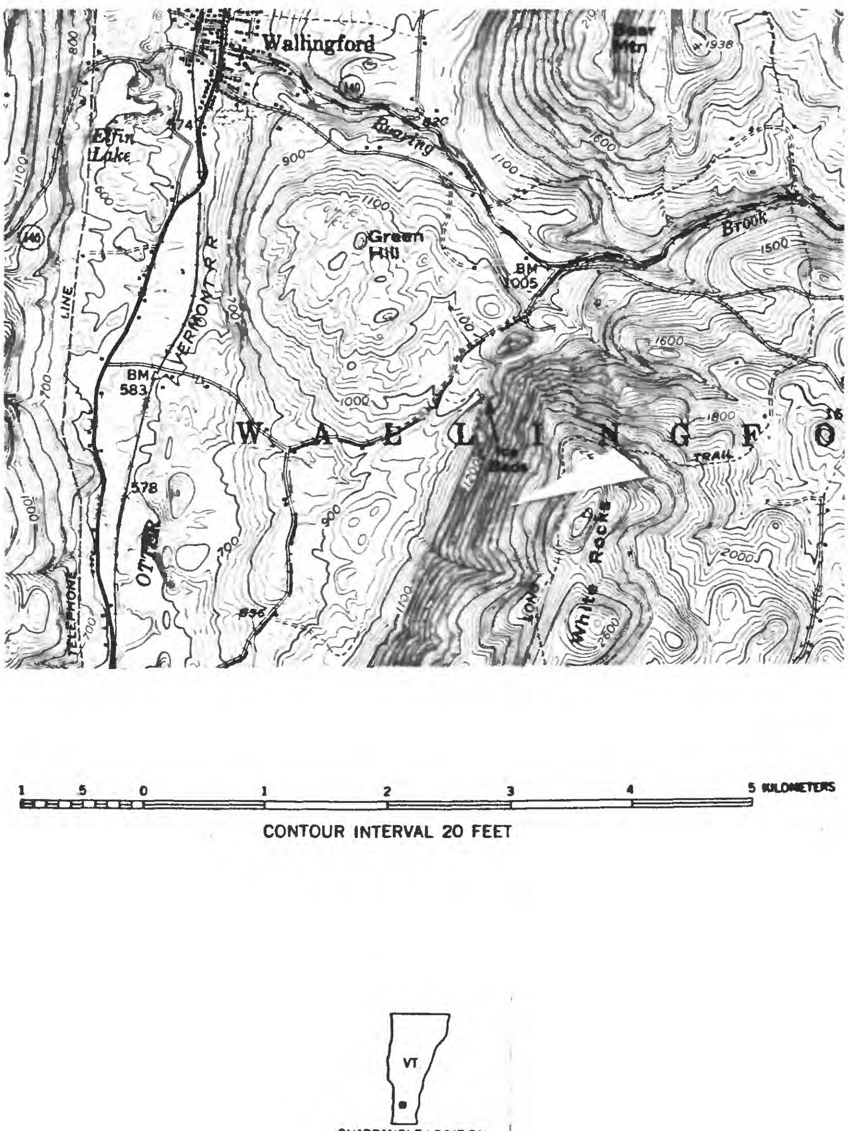

Figure 6.--Location map of White Rocks block slide (site 2). Base from 1:62,500 scale, U.S. Geological Survey Wallingford quadrangle map.

Figure 7 is a view of the White Rocks showing the accumulation of joint blocks at the base of the slope. Bedding dips parallel to the hillslope ("dip slope") in the direction N. 70^{o} W. The most active parts of the mountainside have dip slopes greater than 45^{o}. Vertical travel distances of blocks are as much as 400 m from the upper cliffs to the talus pile. Angles of repose range from approximately 30^{o} to 50^{o}. The higher values represent the influence of asperities on the sliding surfaces. High-angle joints strike approximately parallel with and perpendicular to the dip-slope trend.

Slow downslope translation of joint blocks is characteristic of slabby, thin-bedded quartzite (figs. 8 and 9), whereas more equant blocks from thick-bedded zones commonly rotate and tumble downslope with much greater velocity. In both cases, major movement was observed to be one block deep. The rock surface on the slope studied displays a complete sequence of block loosening and downslope gravitational movement: there are both large, smooth surfaces that show no loosening and isolated, cliff-like remnants that show the results of extensive slope movement (fig. 10). The equant blocks travel farther than the slabby blocks as shown by the geometric distribution of variously shaped blocks in the talus piles at the base of the slope; the slabs lie nearer to the base than do the equant blocks.

Because of the presence of throughgoing open joints that separate the blocks being studied at this site, rainfall is dissipated rapidly and pore (cleft water) pressures should be minimal. However, short-term pore-pressure increases may occur as a result of ice-damming of snowmelt and rainstorms. This agrees with the findings of Morgenstern and Sangrey (1978), who state that high rock-mass permeability precludes significant undrained loading, permitting stability analysis in terms of total stress.

SITE 3. MAD TOM BROOK SLIDE-HEAD TOPPLE

This slope failure is located 2 km east of East Dorset on the east bank of Mad Tom Brook at an elevation of 457 m (fig. 11). The Cheshire Quartzite at this site is characterized not by its massiveness but by its fractured and altered condition. In addition, the beds are much thinner than at the other sites and separate easily. The slope displacements occur in a narrow zone of closely fractured rock, approximately 45 m wide, in which there are thin graphitic schist interbeds and iron-oxide coatings on most blocks. The presence of alteration products suggests that fracturing is an old pre-landslide phenomenom. The width of the slope failure is approximately the same as the width of the broken zone.

Figure 7.--View of Cheshire Quartzite at site 2 ("White Rocks") showing talus accumulation at base of slopes. View to the south.

Figure 8. Dip slope of Cheshire Quartzite at site 2 ("White Rocks") showing loose, slabby blocks. View to the north.

Figure 9.--Downslope creep of blocks at site 2. Bedding is parallel to slope and dips at a 50° angle.

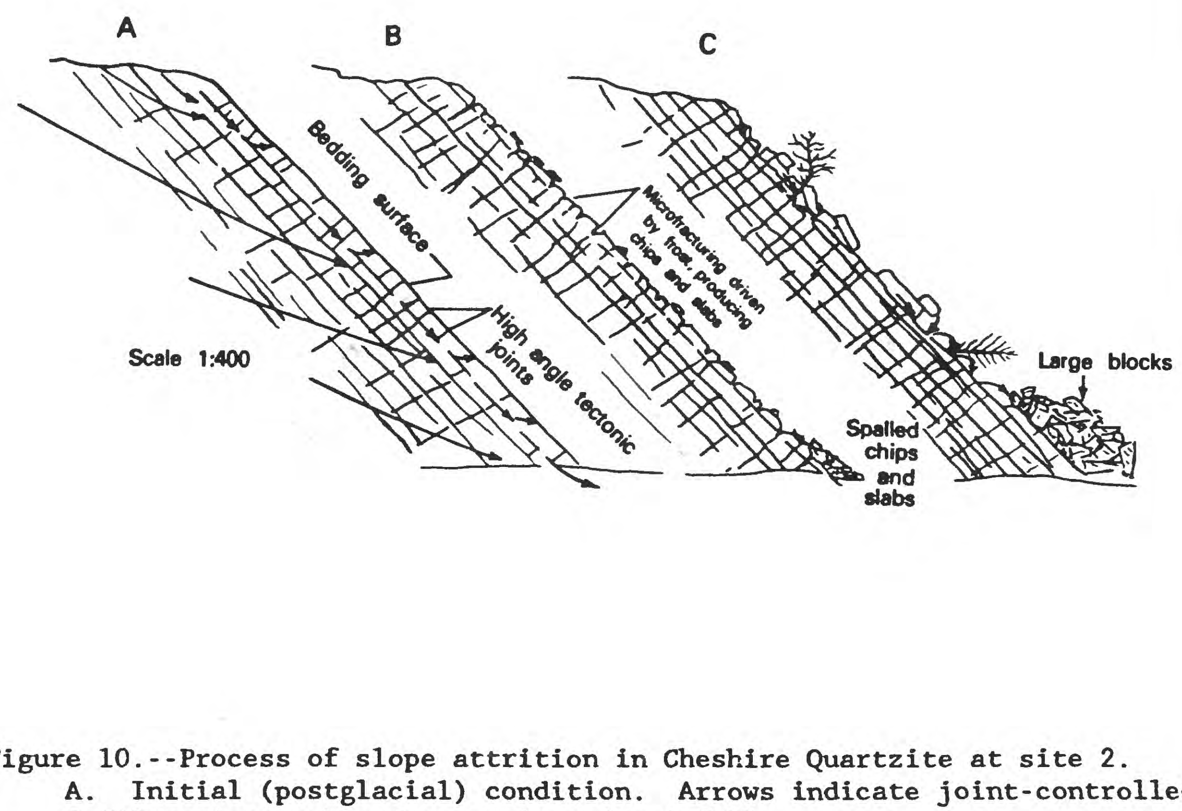

Figure 10.--Process of slope attrition in Cheshire Quartzite at site 2.
A. Initial (postglacial) condition. Arrows indicate joint-controlled infiltration paths of snowmelt and rainfall.
B. Frost-induced microfracturing produces spalling of block edges opening up top layer of joint blocks to frost heaving.
C. Blocks heave, slide, and ultimately tumble downslope as a result of continued freeze-thaw cycling, loosening by tree roots, and periodic short-term pore-pressure increases caused by rainstorms and ice-damming of spring runoff.

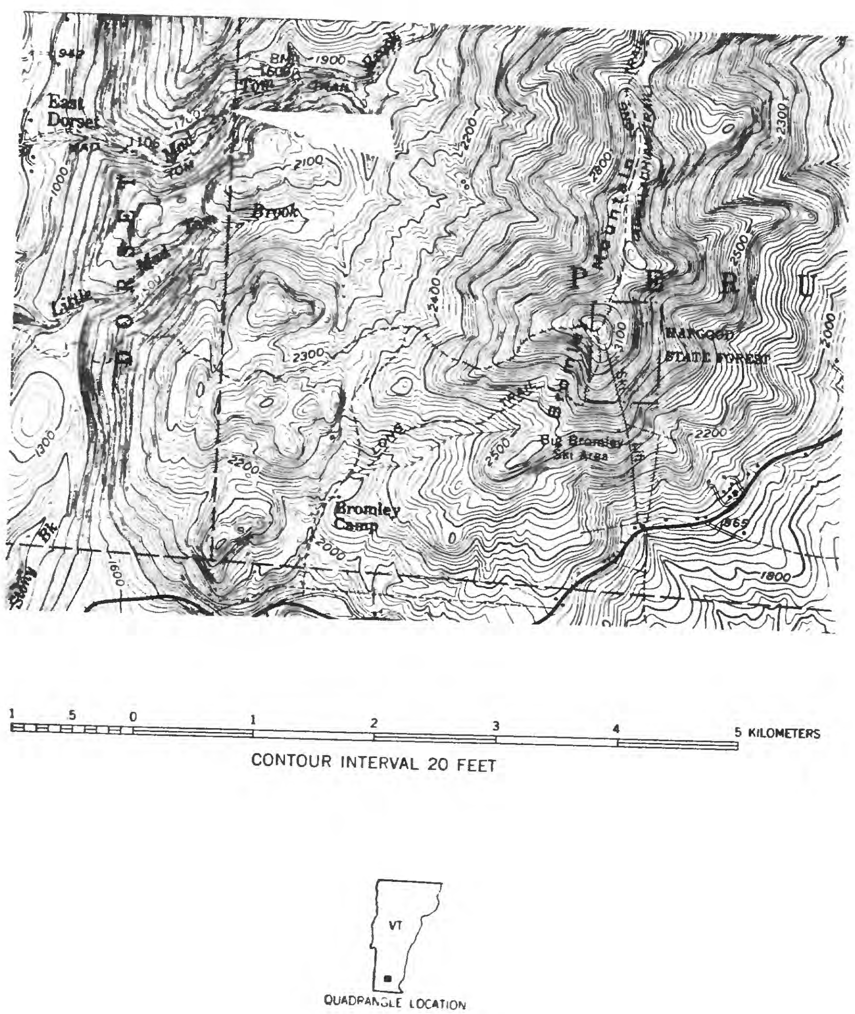

Figure 11.--Location map of Mad Tom Brook slide-head topple (site 3). Base from 1:62,500 scale, U.S. Geological Survey Londonderry quadrangle map.

Major structural discontinuities at site 3 are given in table 1. Where undisturbed by slope movements, bedding surfaces are oriented N. 15° E. and dip steeply to the southeast (that is, into the slope). Within the slide, slope movements have rotated the beds so that the strike of the quartzite beds is approximately parallel to the brook and valley at this location. The slide axis is oriented N. 50° W. and has an average slope of 60°, although at the headwall and near the base it is vertical to overhanging. The slope distance is 37 m, and the unstable slope rises abruptly from the edge of the brook (fig. 12). The stream flow is rapid and water levels change dramatically in response to precipitation, causing some undercutting of the toe. Displacements are occurring primarily at the headwall scarp and midway down the slide axis where a prominent bulge has developed. Secondary activity is apparent on the flanks of the slide, mainly in the form of isolated block topples and shear displacements along N. 70° E.- and N. 80° W.- striking joints.

It is informative to examine structural features of the quartzite in a stable slope adjacent to the active slope (fig. 13). This section is drawn perpendicular to bedding, which is N. 5° E., and displays the bedrock condition that would have existed on the active slope before slope movement began. Figure 13B shows the present appearance of the failed, active slope.

The most dramatic deformation at this site has been block toppling similar to the type that Teme and West (1983) have designated slide-head toppling. In this failure mode, major movement occurs in areas of relatively high bedding dip angles and low joint-friction angles, conditions that are present at the Mad Tom Brook slide but not at the other two sites. While friction angles of blocks are as high as 55° on slopes underlain by massive, unaltered quartzite, the sliding friction angles determined at the Mad Tom site are in the range of 30°-40°. The overall slope angle is greater than this range because, at many locations on this slope, there are (1) no well-developed, throughgoing, weakness surfaces parallel to the strike of bedding, (2) individual blocks commonly "keyed" or interlocked with adjacent blocks, and (3) beds dipping into the slope. These structural conditions make overturning and toppling mechanically more likely than sliding (fig. 14). The overturning and toppling beds shown in figure 14 are presently moving at an average annual rate of 44 mm based on tape-extensometer measurements. Overturning produces unstable overhangs, and individual blocks tumble downslope, many reaching the brook below.

At the present time, much of the smaller debris falling from the slope is carried away by spring floods of Mad Tom Brook. The stream bed contains large, well-rounded glacial boulders and large pieces of slide debris which the stream has been unable to transport. A sudden failure of a large part of the slope would likely dam the stream.

Figure 12.--View (looking east) of slide at site 3 from the base near the level of Mad Tom Brook. The Cheshire Quartzite here is much less competent than at the other sites owing to closer jointing and the presence of thin beds of graphitic schist.

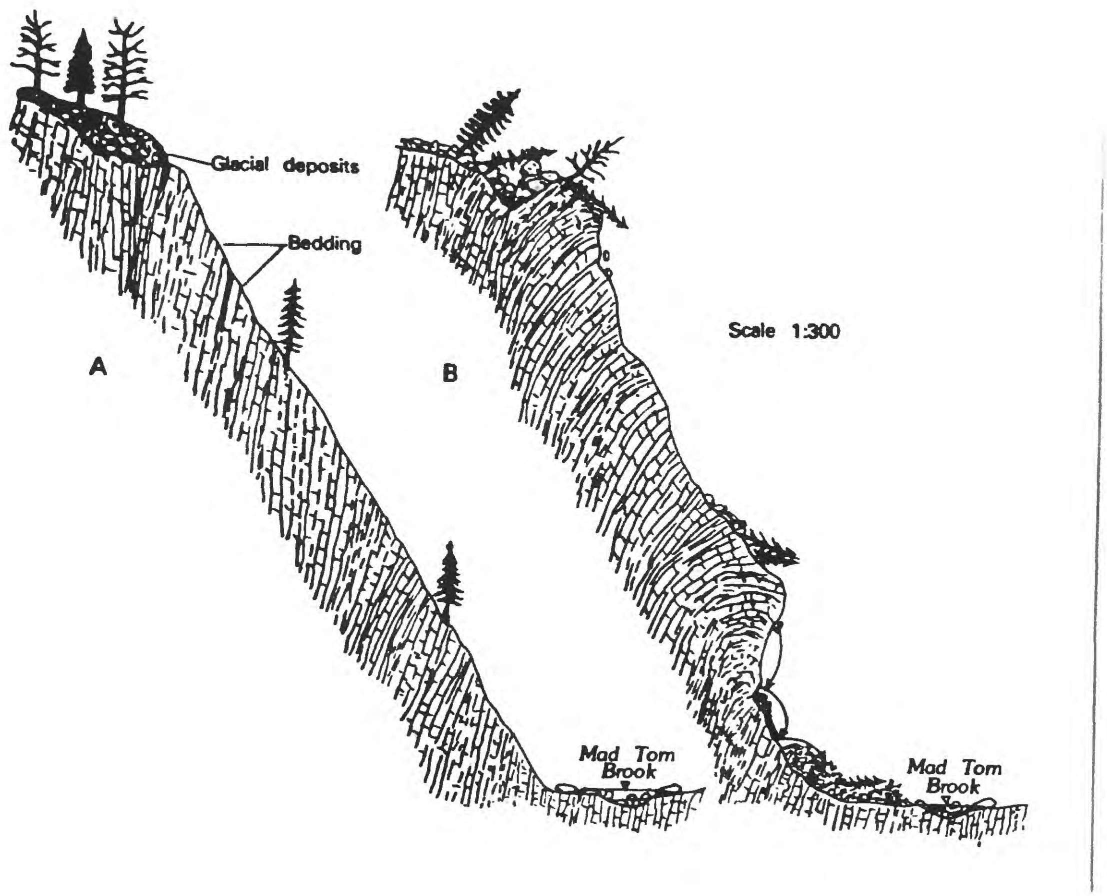

Figure 13.--Slope deformation in the Cheshire Quartzite at site 3, (looking west).

A. Initial (postglacial) condition showing steeply dipping beds of quartzite and graphitic schist. Although fracturing is severe, infiltration is impeded by schistose layers and steepness of slope. The stream is not actively downcutting its bedrock channel.

B. Present condition of slope showing creep-produced structural changes. A topple has formed due to over-turning of beds, particularly at top and near base of slope. Stresses are increased near base due to severe notches. Bending has opened joints at several locations (fig. 14) and most deformation is by discrete displacements of blocks rather than by changes in block geometry. Access of rainfall and snowmelt to the rock mass has now been greatly increased.

Figure 14. Overturning and toppling beds of Cheshire Quartzite at a slide-head topple location near the top of site 3.

SLOPE-MOVEMENT PREDICTIONS

Several findings in this study that should be helpful in anticipating slope failures in the Cheshire Quartzite are:

1. Massive blocks movements occur primarily in the late fall and early spring due to freeze-thaw action; whereas, movements of fractured and altered rock slopes occur mostly in late spring and summer following heavy rainfall.

2. Block displacements are facilitated by orthogonal joint systems that dip steeply and strike parallel and perpendicular to the slope trends where bedding is parallel to the slope contours.

3. Many blocks separated by open joints near cliff edges are not stable and are being steadily displaced toward free faces.

4. Translational block-movement rates range from 0.1 mm to over 10 cm per year. Rotational movements occur on slopes steeper than approximately 50°, and these displacements are of much greater magnitude than translational movements. Equant blocks may travel tens of meters in a single-movement episode.

CONCLUSIONS

Block slides, rockfalls, and topples are the dominant slope-failure modes of the Cheshire Quartzite in the western Green Mountains of Vermont. Slope movement is facilitated by frost heave, rock wedging, precipitation, and gravitational forces. These agents exploit preexisting discontinuities in the quartzite, particularly joint and bedding surfaces, in a preferential manner that is most effective where bedding is parallel to the slope contours, and steeply dipping joints strike perpendicular and parallel to the trend of the slope bedding. In such a case, joint blocks are orthogonal and seldom form interlocking assemblages that might impede displacements of individual blocks.

Seepage forces of percolating water are of little consequence in steep slopes underlain by massive quartzite because open joints rapidly drain rainfall to the base of slopes where the underflow passes into streams. In the more closely jointed quartzite at site 3, which contains alteration products along fracture surfaces and has weak schistose interbeds, heavy rainfall erodes the weaker materials, thereby loosening and destabilizing the blocks. At this site the development of a throughgoing failure surface may be restricted by the interlocking of joint blocks so that overturning and toppling are more likely.

The formation of ice crystals in preexisting fracture openings may contribute substantially to slope failures in the Cheshire Quartzite and is the primary contributor to rockfalls in the most massive bedrock such as that at site 1. Frost penetration acting between open joints may explain how and why frost wedging of large blocks occurs. The key element in this interpretation is a wet surface exposed to air rather than the vertical penetration of frost through 1-3 m of solid bedrock. Based on block movements that can be approximately dated from physical measurements and evidence of freshly downed trees, major block activity occurs in early spring and late fall when thawing unlocks and releases blocks that may then become unstable. Displacements of rock blocks by freezing in the laboratory (see Appendix) were in agreement with displacements measured between cliff-edge blocks. Repeated frost cycles combined with block wedging by debris explain several types of slope movement observed at the field sites.

Rock structure determines a potential for slope instability; temperature change and precipitation provide the forces that reduce the stabilizing frictional forces and cause block movement. Frost action may be the primary cause of movement on slopes underlain by massive quartzite, whereas rainfall is more destabilizing on slopes having closely spaced, clay-filled fractures. Although ice damming, as a cause of high pore pressures, cannot be dismissed, such effects are believed to be local and infrequent.

Inexpensive monitoring systems utilizing durable measurement points can be easily established on those slopes that pose a risk to life or property. If annual displacements are expected to be small (<1 cm) and stations are closely spaced (<10 cm), a dial-gage extensometer provides adequate precision (fig. 4). For larger annual displacements (>1 cm) and more widely spaced stations (>1 m), a tape extensometer is appropriate (fig. 15). This system provides quantitative rate determinations of movement, upon which failure predictions can be based.

Figure 15. Photograph of tape extensometer used to measure displacements of joint blocks at widely spaced stations.

APPENDIX

In order to test the potential of freezing forces to cause block displacements in an open system, a simple physical model was assembled (fig. 16). Temperature ranges and cycle durations are not intended to represent specific field conditions. Low-porosity rock (granite) blocks were placed in a rigid frame so that the bases of the blocks were in contact with the frame. The blocks are in contact with one another although the contact area decreased toward the "free" face in accord with field observations. Block surfaces were smooth (sawed) and no attempt was made to duplicate the roughness of natural rock surfaces. The sides of the blocks are not in contact with the loading frame, a condition that has been observed near cliffs where the principal joints strike approximately parallel and perpendicular to the slope. Rock debris and organic material were placed in the lower 1/3 of the opening(s) simulating the accumulation of rock slabs, leaves, and branches observed in many open joints. A dial gage having resolution of ±0.002 mm was mounted as shown. After wetting this material, the model was placed in a freezer and the temperature lowered to -5 ^{o}C and held below freezing until displacement ceased; then the model was thawed. The experiment was repeated several times with consistent results. A typical freeze-thaw cycle produced 0.13 mm of nonrecoverable (permanent) displacement (fig. 17).

Under some conditions, several freeze-thaw cycles that disrupt rock may occur annually. For example, in the early spring on south-facing slopes, the sun melts ice in near-surface fractures during the day, which refreezes at night, giving rise to rock stress concentrations that could be sufficient to extend microfractures. This process could create new blocks and slabs (figs. 4 and 5). Walder and Hallet (1985), however, in explaining the conditions that are necessary for sustaining crack growth, stated that large diurnal temperature changes of sufficient magnitude to cause freeze/thaw would not be expected in deep joints where an insulated environment would inhibit short-cycle freeze-thaw and displacement. However, deep joints at sub-zero temperatures may offer appropriate sites for sustained ice growth due to frequent inputs of meltwater from the surface.

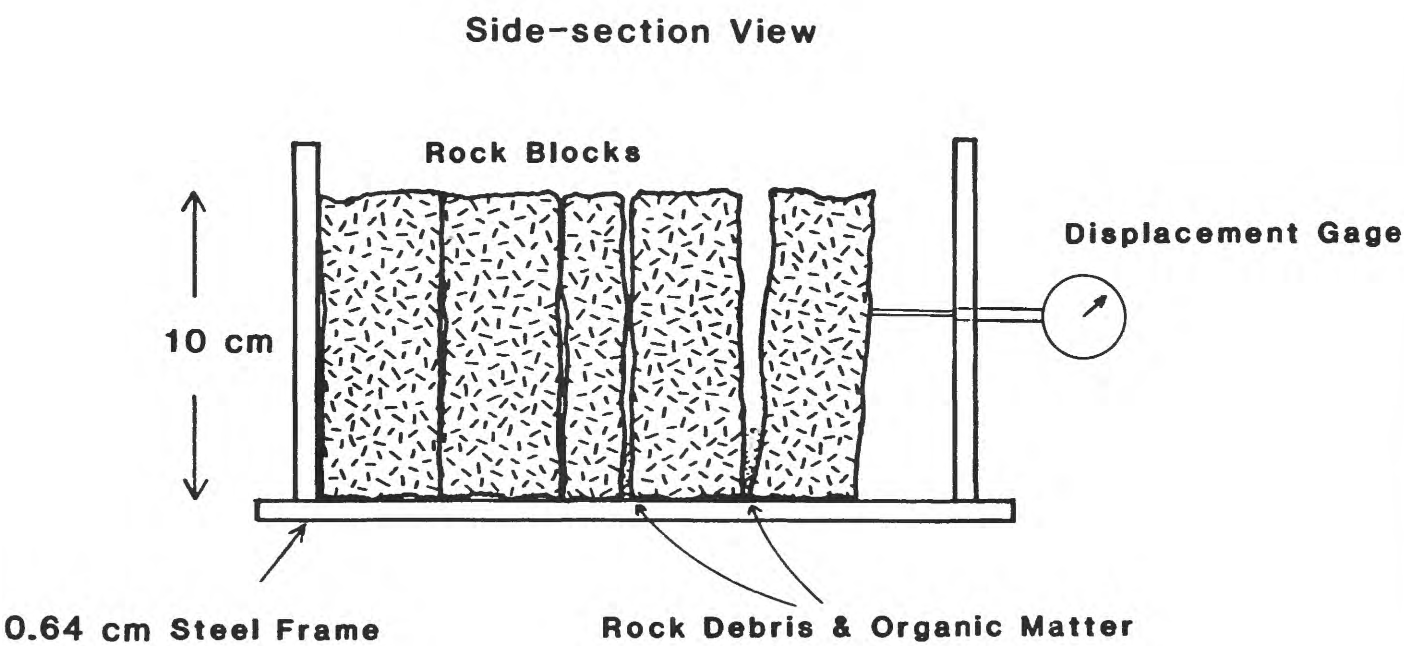

Figure 16. Loading frame and arrangement of blocks for freeze-displacement experiment. The scale of the model is approximately 1:25.

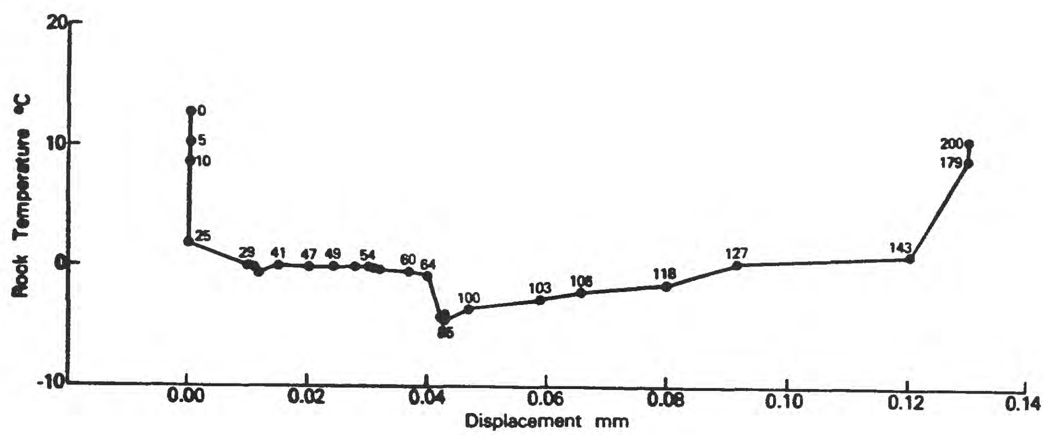

Figure 17. Graph of a typical freeze-thaw cycle of rock model shown in figure 16. Temperature is measured by a thermocouple placed in debris between the two right-hand blocks. Numbers on curve indicate elapsed time in minutes. In order to obtain slow cooling, particularly at the temperature of maximum ice volume (0 ^{o}C), the freezer control was operated manually. A cycle required 3-4 hours. A lag time occurs in the freezing and thawing of various parts of the model. Near the base, closer to the metal "heat sink", freezing and block displacement probably occur later than higher in the open joint where the temperature sensor is located.

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