ROCKFALL HAZARD ASSESSMENT AT BOOTH FALLS CONDOMINIUMS
AND PROPOSED MITIGATION

prepared for
The Town of Vail, Colorado

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INTRODUCTION

The Colorado Geological Survey has assisted the Town of Vail in assessment of the rockfall hazard at Booth Creek since May 1983, when a severe rockfall event occurred there. Since then the town and property owners in Vail Village Filing 12 formed a Geologic Hazard Abatement District (GHAD). The District has mitigated much of the hazard by the construction of a ditch and berm on the slope above the residential area. As far as the Survey knows, the ditch and berm configuration has been 100% effective for rocks that continually fall from the cliffs of the Minturn Formation. On March 26, 1997, another very serious, potentially lethal, rockfall occurred that incurred substantial damage to the Booth Falls Condominiums that exists to the west of the GHAD and outside the protection envelope provided by the ditch and berm. Under the auspices of the Critical Geologic Hazards Response Program and our concerns expressed in earlier involvement, the CGS can assist the Town of Vail in assessment of the hazard that the condominiums bear, options for mitigation for that portion of slope west of the ditch and berm terminus, and design criteria for said mitigation systems. Included in this report are two appendices. Appendix A, **Booth Creek Rockfall Hazard Area** by Bruce Stover, is a report on the general geology, geomorphology, and the mechanism of rockfall for the Booth Creek site. Appendix B, **Rockfall Mitigation**, is a short paper on types of rockfall mitigation systems that are available.

THE MARCH 26, 1997 ROCKFALL EVENT

At 11:20 p.m., a ledge of Minturn Formation limestone at the highest exposed outcrop of the upper cliff, just below the exposure of glacial till, failed similarly to that shown in Figure 3 of Appendix A. The ledge dimensions that detached and toppled is roughly 20' x 8' x 8'. As it fell, it impacted and broke additional rock blocks from outcrops below. The rock mass broke apart as it tumbled down the cliff. As it fell down the slope, the rock fragments randomly fanned out such that the path of the rockfall formed a swath more than 500 feet across where they came to rest. See Figure #1 of this report. The location of the rockfall source is shown by arrow in Photo # 1 and #2 and the scar easily seen in Photo #3.

Approximately one third of the swath of rolling rocks were retained by the ditch and berm. See Figure #1. The remaining two-thirds of the event came to rest, scattered around the condominiums. The condo structures received three rock impacts and several near misses. Rock sizes ranged from 2 to 5^+ feet in average diameter. Surrounding the condos several items were also damaged or destroyed, (i.e., small haul trailer, trampoline frame, small wooden deck and chairs, wood walkway). Of the three impacts, one was minor and the other two major. The minor impact was from a ~3 foot diameter rock that obviously had slowed almost to a stop upon impacting the westernmost condo structure. The rock came to rest, ominously so, next to a large boulder from an earlier rockfall. A major impact, also about 3-4 feet in diameter at high velocity, had just missed the ditch and berm catchment. The rock impacted and smashed the corner of the easternmost condo, snapped off the side balcony support, and destroyed a trampoline frame along its path before coming to rest in the subdivision below. The third and worst impact was a 5^+ foot block that broadsided the easternmost condo. Sufficient rock velocity enabled the boulder to smash through the outside wall, interior walls, and the floor, finally being caught in the crawlspace below. Luckily the resident, whose bedroom this rock smashed through, was not home at the time of the rockfall.

Booth Creek Rockfall Hazard Area

Vail, Colorado

Areal extent of rockfall impacts from 11:20 pm, 3/26/97 event.

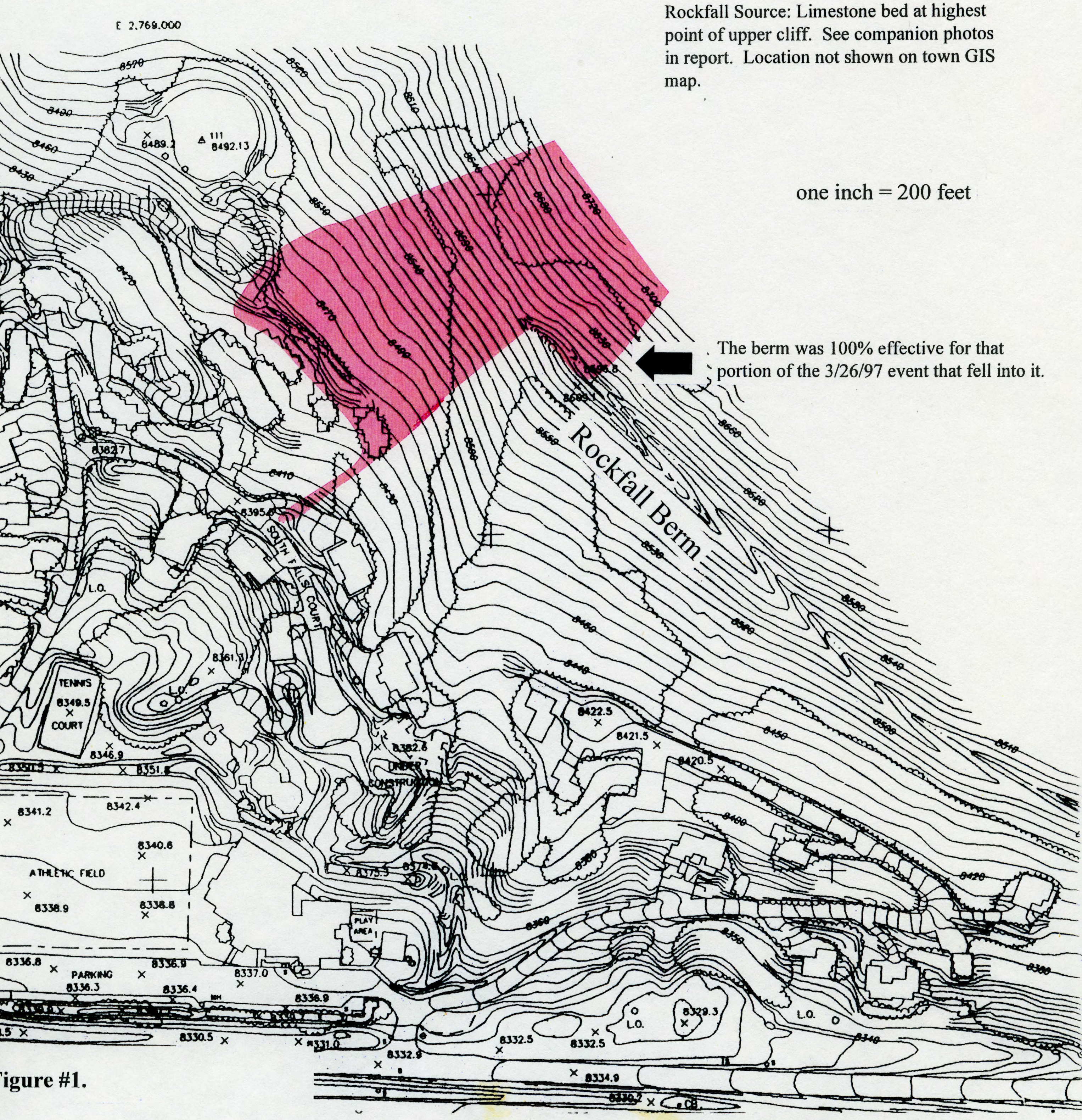

Figure #1.

The CGS made an initial inspection of the site Thursday, March 27, 1997. Our preliminary assessment was that it appeared that the ledge broke away relatively clean and the hazard risk in no greater or less than the day before the rockfall; which is to say that rockfall can occur from this source area anytime. It was on our preliminary inspection of the ditch and berm where we discovered that an earlier rockfall event occurred, either earlier this year or sometime after the town last cleaned the ditch out. Several rocks (≤4 foot diameter) had fallen and, by lithology, could be differentiated from the March 26 event (sandstone vs. limestone). This rockfall occurred without anyone's knowledge because the entire event was contained within the ditch and berm. Friday, March 28, 1997 an aerial reconnaissance was conducted of the source area and while the preliminary assessment has not changed, **we reiterate that rockfall of similar magnitude will continue at this site**. During this inspection we did see several loose rocks on the slopes and rock features with questionable long-term stability.

HAZARD ASSESSMENT

In a ranking of a rockfall hazard the parameters are source area, a steep acceleration zone, proximity of structures to both, and history of rockfall impacts. In two aspects the condominium location is worse than most of the special district to the east because the upper cliff is more fully exposed at this location (it is mostly soil covered to the east) and the slope between and below the cliffs steepen where the slope curves around into Booth Creek Valley. See Photo #1 and Figure #1 map in Appendix A.

Photo #1. Booth Creek rockfall source area. Note enlargement of upper cliff exposure and corresponding rockfall source area, northwest of the ditch and berm terminus.

The main source area for Booth Falls Condominiums is the upper cliff. The exposed, lower cliff of sandstone reduces in height as it trends to the northwest. Photo #1 and a close-up photo #2 show the extent of the upper cliff where it is not soil covered. They reveal a benchy cliff of beds of limestone, thin shales, and minor sandstone. It is the dense, hard, gray limestone that creates the largest rockfall boulders in the Booth Creek area. The report by B. Stover in Appendix A provides further in-depth discussion on the source areas. Photos #1 and #2 also show the exposed shale slope, between the cliffs, steepening to the left. The general lack of soil and vegetation suggests that this slope is harder and smoother, compared with the right. A further close-up, Photo #3, reveals limestone blocks, pedestals, and ledges, defined by the crisscrossing joint pattern, being undermined by the quickereroding interbedded shale partings. Also in Photo #3 are several slumped and isolated limestone blocks on the rock slope that have not yet fallen. The history of reported rockfall events at Booth Creek and the physical nature of the slope merits our assessment that, **Booth Falls Condominiums is in a severe rockfall hazardous area.**

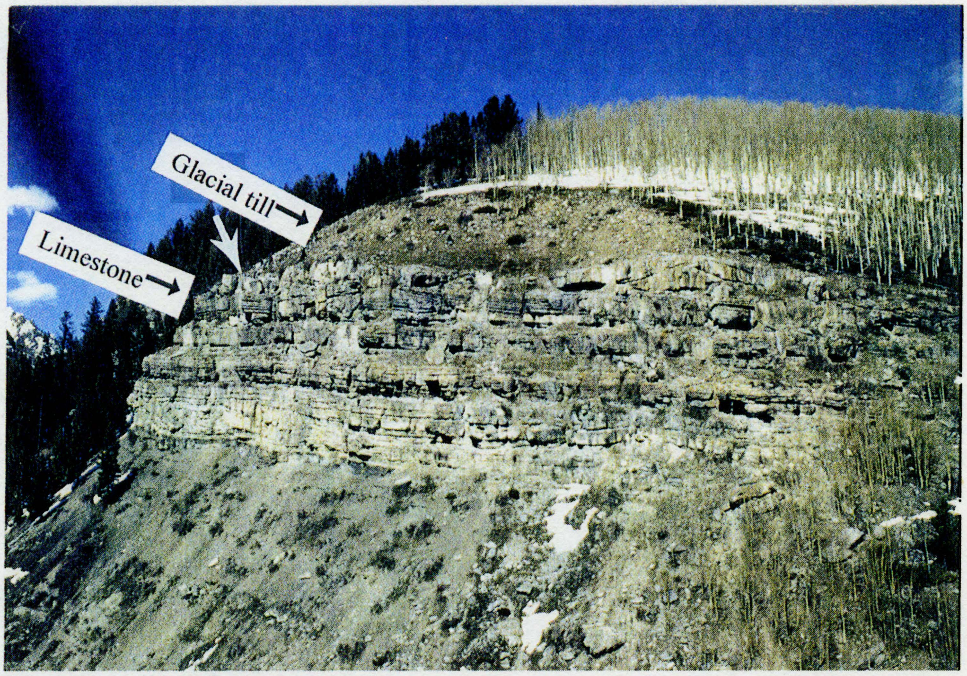

Photo #2. Top cliff rockfall source area. White arrow marks location of March 26, 1997 rockfall.

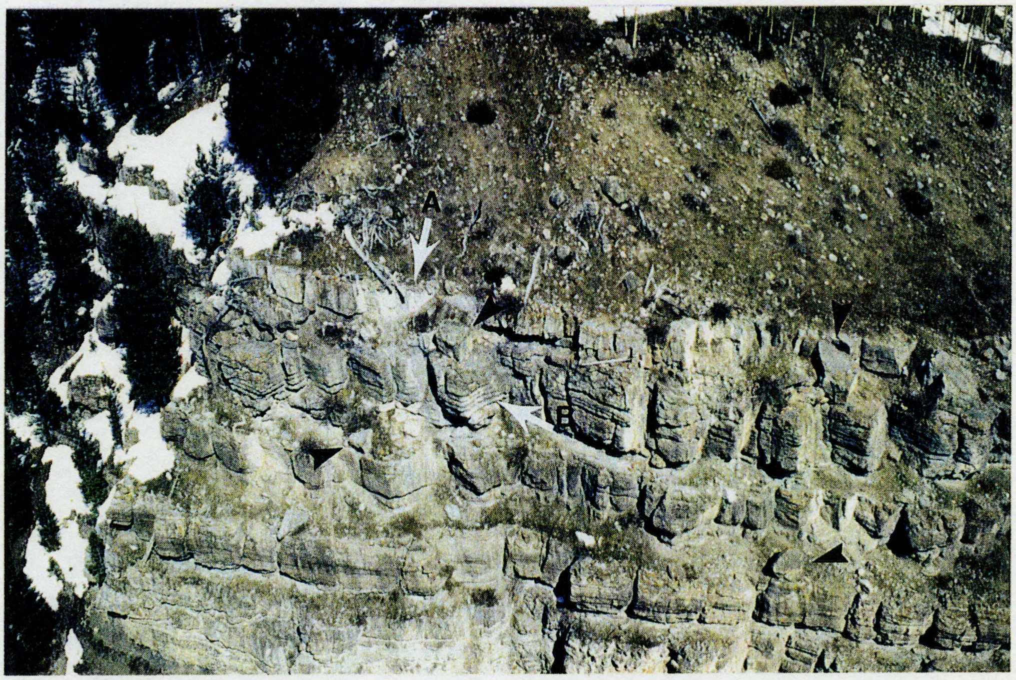

Photo #3. Close-up aerial view of source area. Note ledgy appearance with joint defined blocks undermined by eroding shale partings. White arrow A marks scar from March 26, 1997 rockfall. White arrow B marks rock pedestal that was hit by rockfall and may be destablized. Note loose blocks, marked by black arrows.

ROCKFALL MITIGATION OPTIONS

Appendix B contains most of the recognized forms of rockfall mitigation and protection devices commonly used. Rockfall mitigation is divided into two types: stabilization of the rock mass at the source area to prevent rocks from falling; and rockfall protection systems that acknowledge that rocks will fall but structures or public areas are protected from the impacts. At the Booth Creek site stabilization of the rock mass at the source area is not being contemplated for several reasons. They include:

1. The source area is in the USFS Eagles Nest Wilderness Area;
2. Source area stabilization at this site would need to cover a large area, be labor intensive, require technical rock climbing skills, and helicopters for mobilization that would make the project cost prohibitively high;
3. Source area stabilization construction activity would present unacceptable risks that rock could be inadvertently knocked down, by workers or equipment, onto the residential areas.

Rockfall protection systems that will be considered at this site are ditch and berm configurations and impact barrier wall systems. Fences will not be considered because they can have high maintenance cost and generally cannot withstand high impact forces without being destroyed.

ROCKFALL ANALYSIS and DESIGN CRITERIA

Proper analysis of the hazard for design purposes requires accurate slope geometry and a determination of appropriate rockfall sizes. For the slope geometry we used information gained from our earlier investigation for the special district mitigation, the Town of Vail GIS 1:2400 scale maps, photos, and the USGS 1:24,000 scale map. For the rockfall size using the maximum size boulder that is found on site would be prudent. We used the Colorado Rockfall Simulation Program (CRSP) ver. 3.0a for our analysis. Four to seven foot diameter boulders were modeled, and weight was calculated using the unit weight of limestone. The analysis seemed to bear out observable results of rockfall in the area. Bounce heights were highest on the cliffs and at the transition to the lower, softer slopes the rocks begin just to roll. The critical design factor is the high impact energies developed by these larger rocks. A screen dump is shown on Figure #2 of the CRSP program slope profile. An analysis point was chosen 30 feet upslope from the condominiums where the slope breaks to a grade of 40% to 50%. In modeling rockfall with CRSP we arrived at the following bounce heights, impact kinetic energies (K.E), and velocities at this analysis point.

Rock Size	Rock Weight	Bounce ft.	K.E.(max.) ft-lbs.	K.E.(avg.) ft-lbs	Vel.(max.) ft/sec	Vel.(avg.) ft/sec
4' sphere	5058	3.0	1,000,000	800,000	98	83
5' sphere	9878	2.1	1,900,000	1,400,000	95	81
6' sphere	17069	2.0	3,000,000	2,300,000	96	78
7' sphere	27106	1.7	4,600,000	3,300,000	89	74
4'x7' cyl.	13272	1.7	2,500,000	1,700,000	93	74
5'x6' cyl.	17775	1.9	3,600,000	2,400,000	94	76
6'x6' cyl.	25600	1.9	4,900,000	3,500,000	89	74
6'x7' cyl.	30000	1.8	5,700,000	3,700,000	90	72

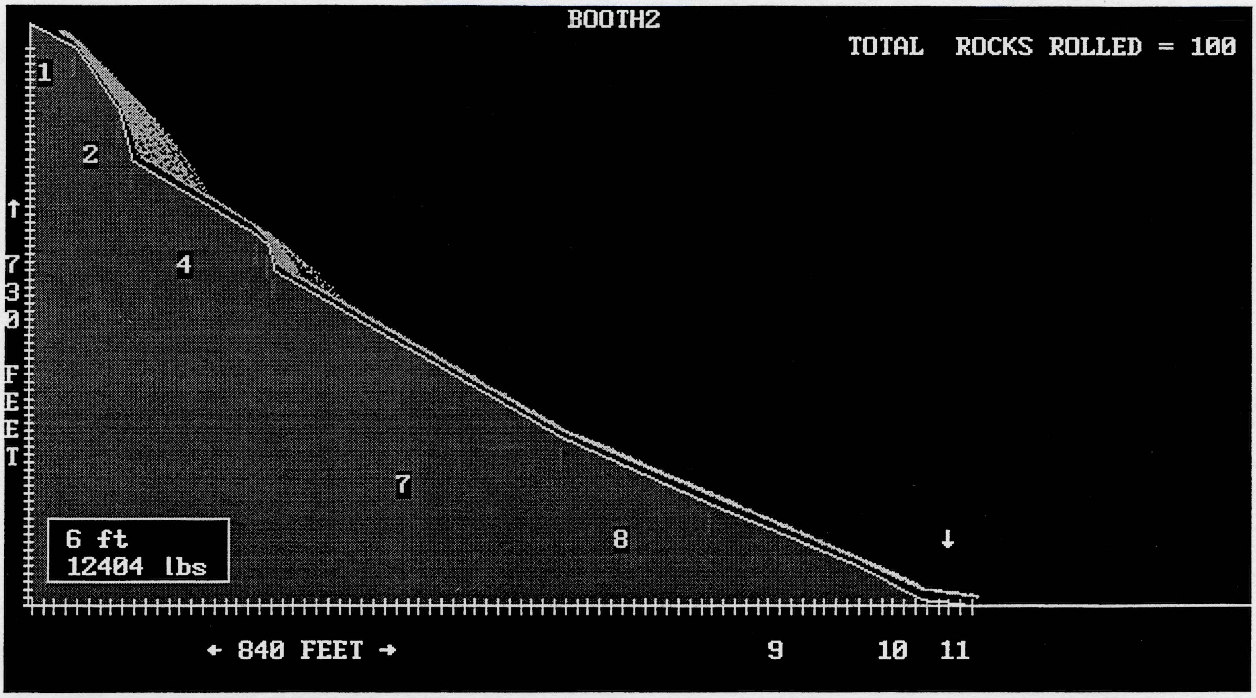

Figure 2. Screen dump of CRSP program of Booth Creek-west side. Analysis point arrow is 30 feet above condominiums. Horizontal and vertical are not at the same scale.

RECOMMENDATIONS

The following recommendations and design criteria are based on modeled rolling rocks analyzed at 30 feet upslope from the condominiums, so are only valid at that point on the slope. Mitigation design should not only insure that rockfall is contained but also the impact structure remains sound and does not require costly reconstruction afterwards. The CGS recommends that design criteria for mitigation at the condominiums should be capable to withstand and retain a worst case scenario, which is believed to be a boulder in the 6 to 7 foot diameter range. An examination of the source area, the most recent rockfall, and earlier research done by Stover and Cannon for work the CGS did in 1988 seems to confirm this scenario. That translates to a rolling rock with an **impact force of 5,000,000 ft-lbs** at the analysis point. Besides withstanding the impact force the mitigation system would need to prevent any rock that encounters it from climbing and overtopping, or bouncing over. The impact face should be vertical and have an effective height that prevents overtopping. Design height will be specific to siting of the structure. At the analysis point it should be no less than 12. These design parameters do not take into account smaller rock fragments that separate from larger boulders. During inspection of the site following the March 26, 1997 event there was evidence of smaller rocks snapping off the tops of Aspen trees, 25 feet high, near the condos. These rock fragments do not reflect actual bounce heights but display the high rotational velocity of the rock and the centrifugal force acting on fragments as they detach. Options to mitigate these highly random rock fragments are limited to moving the protection system farther up the slope (which will change design criteria) or constructing a low capacity rockfall fence at the top of the berm or wall.

Photo #4. Location of proposed impact barrier or berm site. Note accumulation of rocks in existing ditch. The largest are 5 feet in diameter.

Only a stout protection system can be designed at the criteria stated above. Both ditch and berm systems and inertial impact barriers, or a combination of both, can be designed for the site and be cost effective. No rockfall fence on the market can probably withstand the impact forces that are being contemplated. The rockfall protection must be designed to begin at the road and extend to the southeast to a point where sufficient overlap exists with the existing berm above, a length no less than 350 feet. Rocks that skirt the edge of the top berm must be caught by the lower. See Photo #4. At the high impact velocities and corresponding impact forces both ditch and berm and reinforced impact walls will need to be carefully designed. In a ditch and berm option a careful look will be needed to determine whether the berm of only compacted soil will have the strength to withstand these forces. The earthen berm may need to be reinforced with geotextiles. A rockfall impact barrier or earth wall will need to be reinforced with geotextiles in lifts of 8-12 inches and have a width no less than 10 feet. **We recommend that the Town of Vail retain the CGS for review of the mitigation design and our approval be a condition for design acceptance by the town.**

CURRENT AND FUTURE ACTIONS

Adverse or highly variable weather prevented the CGS from doing a site inspection of the source area immediately after the March 26 event. Later this spring we plan to conduct this site inspection where the failure occurred and examine those impacted rock features below that may be of questionable stability. During our aerial inspection we also found a rock feature above the special district ditch and berm that may require long term monitoring. See Photo #5. While we believe this feature will not be a threat for many years it bears watching because of its size. If this feature were to fail the volume of the fall would quickly overwhelm the capacity of the ditch and overtop it. We will provide the Town of Vail a supplemental report based on our field studies later this summer.

For the interim, residents of Booth Falls Condominiums who are concerned about their safety can take precautions to lessen their exposure to rockfall hazards. As stated the larger rocks are basically rolling when they reach the condos. The safest area in these condos presently is the top floor on the side facing downhill. The worst case rockfall impact can put a big hole through a

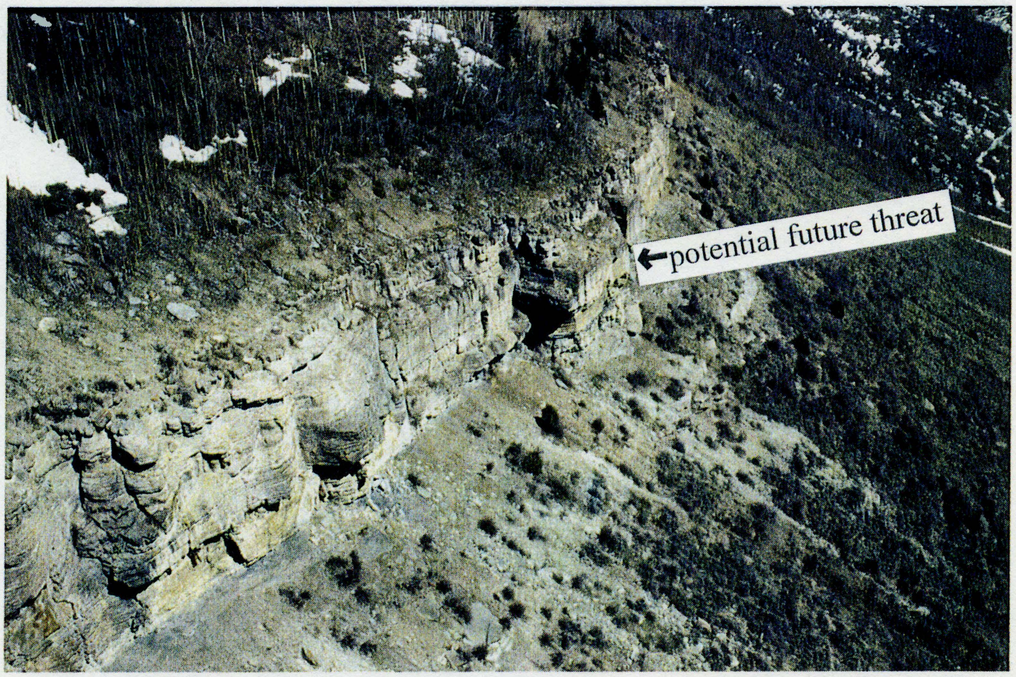

Photo #5. Lower sandstone cliff above district ditch and berm. The CGS will visit this feature this spring and install movement gauges for future monitoring.

structure and possibly condemn it, but probably will not tear it down. Our advice to residents is that they not establish living areas where they spend the bulk of their time, such as bedrooms and the sitting areas of living rooms, against the exterior wall that faces upslope. Bedrooms should be moved upstairs and/or beds placed against the wall facing downhill. Do not place beds directly in front of, or below, windows that face uphill. The Home Owners Association and Town of Vail should act quickly so that these structures are protected from the next rockfall of similar magnitude.

APPENDIX A

Booth Creek Rockfall Hazard Area

Bruce K. Stover
Colorado Geological Survey, 1313 Sherman Street, Room 715, Denver, CO 80203

Residences situated at the base of the valley wall at the mouth of Booth Creek in Vail Valley are exposed to varying degrees of rockfall hazard (Figure 1). The hazard ranges from low to moderate for structures near the limits of the runout zone on the valley floor, to very high for some residences constructed in the lower part of the acceleration zone at the base of the cliffs. The area was developed prior to the time when Vail had adequate geologic hazard mapping or zoning completed. The rockfall hazard was thus not identified prior to development.

The problem was investigated in detail after a major rockfall event in May 1983, caused serious damage to several structures. In the years since the original hazard investigation was conducted, several more significant rockfall events have occurred; boulders have destroyed timber patios and log retaining walls, damaged exterior walls, and smashed completely through structures causing considerable damage to interiors and furnishings.

The town of Vail and affected property owners are currently pursuing a means and framework for administering design and construction of protective rockfall structures and barriers in an attempt to safeguard the residential area.

Geology of Rockfall Source Areas

The geologic make-up of the cliffs above Vail Village Filing 12 is shown diagrammatically in Figure 2. Sedimentary strata exposed in the cliffs are part of the Minturn Formation of Middle Pennsylvanian age, and include beds of sandstone, shale, grit, conglomerate, and limestone. The beds strike N85°W and dip 15° to 18° into the valley axis. The lower cliff consists of shaley sandstone beds about 12 m thick resting on a weak, fissile, rapidly eroding black to gray shale. The sandstone unit has two prominent joint sets striking N85°W and N55°W. These joints combine to separate large slabs and define the cliff face angle visible from the valley below. Above the sandstone is a soft, friable coarse sandy conglomeratic bed 1 m thick which weathers to a smooth rounded ledge and continually undercuts a 0.6 to 1 m thick dense, hard gray limestone unit resting above it. The limestone is jointed so that subangular blocks (.5 x .6 x 1 m) continuously detach from the bed and fall off the sloping cliff edge. These limestone blocks are commonly involved in the more frequently recurring events that can often cause damage to structures in the runout zone.

A thick shale unit between the upper and lower cliffs has weathered back to a 68 percent slope. The shale is soft, clayey, and shows evidence of localized slippage and small slope failures which probably occur during intense rainstorms or heavy snowmelt. Very small mudflows appear to start on this steep slope and spill over the lower cliff edge. They are capable of disturbing or initiating rockfalls if boulders happen to be in their paths, or are resting near points of initial failure.

Above this soft eroding shale is a thicker cliff-forming unit of the Robinson Limestone. This bed of dense, hard, gray limestone varies from 1.5 to 10 m thick in the study area and is the source for the largest rockfall boulders encountered in the runout zone. The limestone boulders that detach from the cliff are quite resistant and tend not to break up or shatter on their way downslope. The largest boulders found in the runout zone appear to be derived from this upper cliff-forming limestone.

The shale zone upon which the upper limestone cliffs rest is weak and by erosion undercuts the massive limestone ledges, creating pedestal-like blocks which eventually topple off their perches. The limestone is jointed such that blocks approximately 3 m x 1.2 m x 1.2 m are separated from the cliff and tilt outward toward the cliff edge. Thinner beds within the limestone cliff produce more slabby blocks that, if not turned onto their edges by chance during the initial fall, remain flat-side down on the steep slopes.

An eroding slope in glacial till rests directly above the cliff-forming upper limestone in the northern part of the study area. The eroding slope periodically sheds smooth, rounded granitic boulders which tumble down the cliff into the runout zone. Other areas of this till farther east along the cliff appear relative-

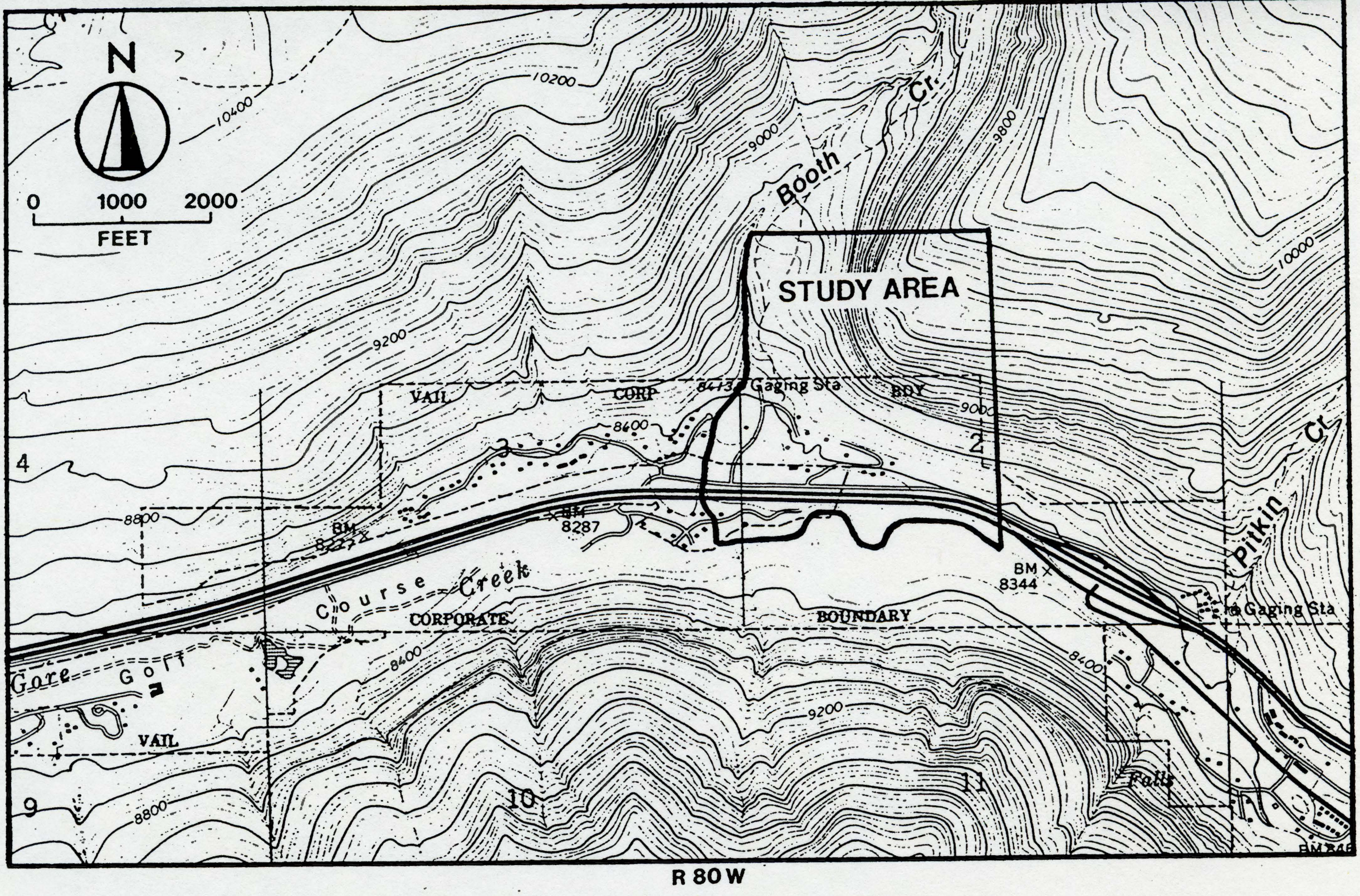

Figure 1. Location map of study area, scale, 1:24,000

ly stable, and are not actively shedding large rocks to the slopes below.

Above this till, slopes flatten dramatically to grades of 0 to 35 percent. Large stands of mature aspen indicate that these gentle upper till slopes are relatively stable. No other rockfall sources exist above these gentle slopes, which start at an elevation of approximately 9,450 ft.

Physical Configuration

The steep southwest-facing slope and rocky cliff tower 1,000 ft (305 m) above Vail Village Filing 12 on its northern boundary. These heights are attained within a horizontal distance of 1,700 ft (520 m) resulting in an average slope of 58 percent. The slope can be divided into several zones. (Figure 2)

A) Runout zone - slopes of 28 to 45 percent along the foot of the valley wall. This area is moderately wooded with fairly young aspen and has been developed as a residential subdivision. The majority of rocks falling from the cliffs come to rest in this zone.

B) Acceleration zone - slopes of 55 percent to 65 percent and steeper immediately below source area. No boulders of significant size can remain at rest on these slopes due to the steepness. Sparse, stunted aspen occur in small stands, but generally the slopes do not support much vegetation. Rocks traversing this portion of the slope will continue to gain momentum as they roll and skitter downslope.

C) Lower vertical cliff source area - A 50 ft high (16 m) cliff of jointed sandstone and limestone crop outs 560 vertical ft (175 m) above the runout zone. Large slabs 15 to 20 ft (4.5 to 6 m) in diameter, periodically detach from the cliff face and tilt outwards until they topple over and shatter, showering boulders onto the acceleration-zone slopes below. (Figure 3)

D) Upper shale-slope acceleration zone - A steep (68 percent) shale slope above the lower vertical cliff allows boulders from a higher cliff to gain momentum before becoming airborne at the cliff edge.

E) Upper vertical cliff source area - Jointed slabs and boulders 1,000 vertical ft (305 m) above the runout zone periodically detach from the cliff and free fall and bound downslope and off the lower cliff. Most rocks do not shatter, but remain as intact approximately 8 by 5 ft (2.5 by 1.5 m) limestone boulders which are capable of reaching the farthest limits of the runout zone. (Figure 4)

F) Eroding upper till slope - Glacial till resting on top of the upper cliff sheds rounded granitic boulders

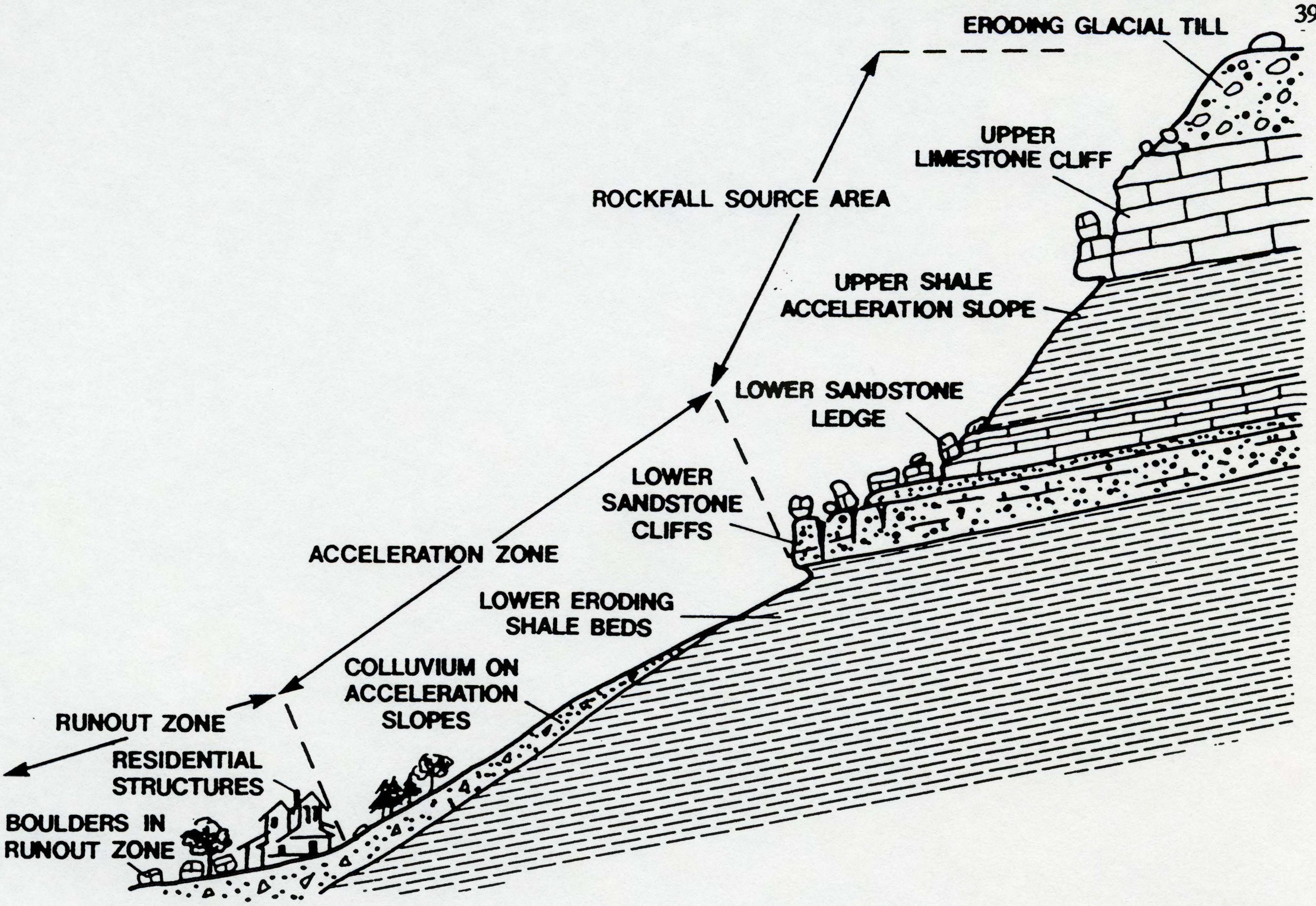

Figure 2. Geologic diagram of compound rock-fall slopes in study area. Drawn to scale with no vertical exaggeration. Note dip of strata toward valley.

downslope which roll and fall off the cliffs. This till slope is considered to be a part of the upper source area.

Rockfall Mechanisms

Several natural geologic and topographic factors combine to cause rockfalls from the cliffs exposed on the north valley wall of Gore Creek in the study area. These factors include joint patterns, differential weathering of various rock types, dip of strata, and the slope of cliffs and acceleration zones.

Jointing and Differential Weathering of Cliff Faces

Joint patterns in the cliff forming rocks are caused by stress relief and physical properties of the rock. The joints so formed define planar, vertical cliff faces and act to separate large sections of the cliff into slabs along joints subparallel to the cliff face. Once a slab has detached from the sedimentary bed, it begins to creep outwards owing to gravity and frost wedging in the joints. The joints widen with time, and are often wedged farther apart by tree roots, and smaller rocks that fall into the cracks formed by the joints. (Figure 3)

Differential weathering of shales has undercut the more resistant overlying sandstones or limestones creating a horizontal groove or overhang at the base of the cliff which removes support for the rocks above. Eventually, the overhanging ledge becomes incapable of supporting its own weight, and falls or topples from the cliff. If the overhanging slab has already detached form the cliff along joints and is resting precariously on the shale, undercutting and differential weathering accelerate the process which finally results in inevitable toppling of the slab. As the large slabs topple onto the acceleration slopes below, they usually shatter into many smaller boulder sized chunks which accelerate downslope to the runout zone. The toppling may trigger adjacent unstable parts of the cliff to fall as well.

Dip of Strata and Topography

The dip of the rock ledges making up the source area also contributes to rockfall along cliffs in the study area. The strata in the two cliffs dip approximately 15 degrees into the valley, causing any loose stones, cobbles, or boulders on the ledges to inevitably move down to the edge of the 16 m vertical cliff. Limestone blocks separated from their beds by jointing and weathering creep down toward the valley along these dipping bedrock surfaces (Figure 5). Rounded glacial cobbles and gravel

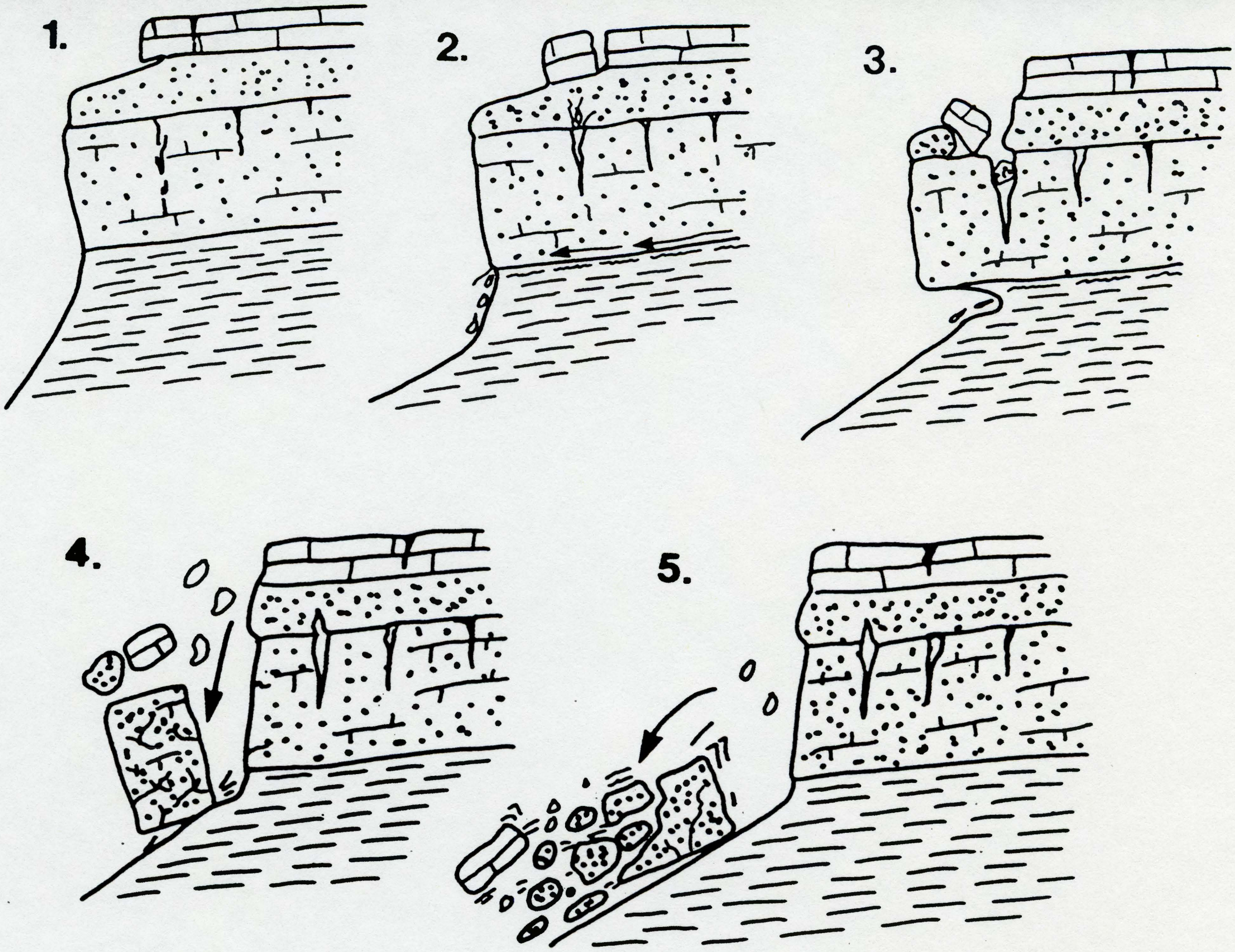

Figure 3. Toppling Slab-failure Sequence. 1. Initial cliff configuration. 2. Differential weathering of soft shale begins to undercut massive cliff forming slabs. Joints open and widen due to slope creep and frost wedging. Springs issue from contact beneath cliff. 3. Undercutting continues. Joints widen and are wedged open by smaller rocks, causing slab to tilt outwards. 4. Slab falls from cliff face onto acceleration slopes, bringing down overlying rocks. 5. Slab topples and shatters, showering runout zone below with boulders, and exposing new cliff face to erosion.

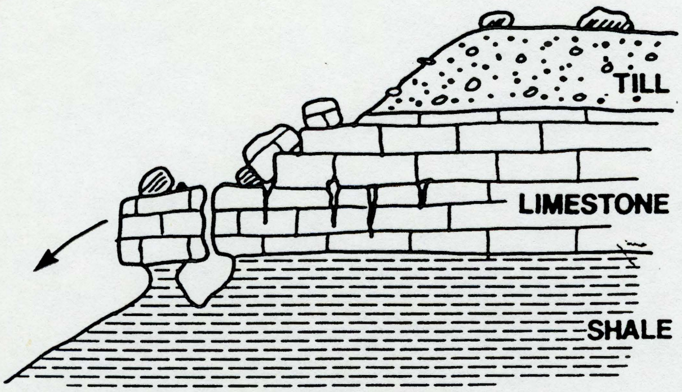

Figure 4. Limestone slabs resting on weak shale pedestals, upper cliff source area.

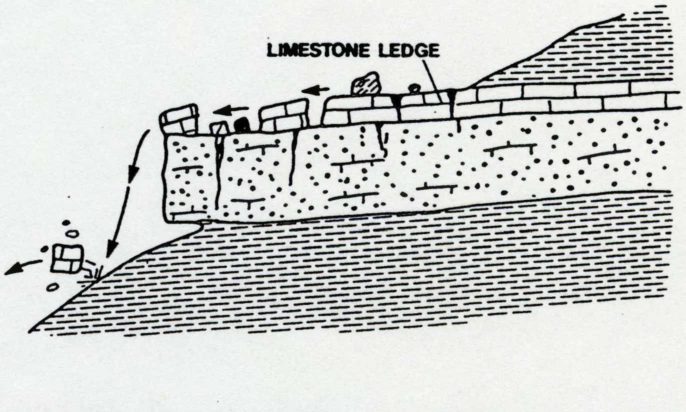

Figure 5. Slope creep causing limestone blocks to move down bedding planes and off lower cliff edge. Blocks are generally 2 ft x 3 ft. This mechanism is responsible for frequent rock falls in the study area.

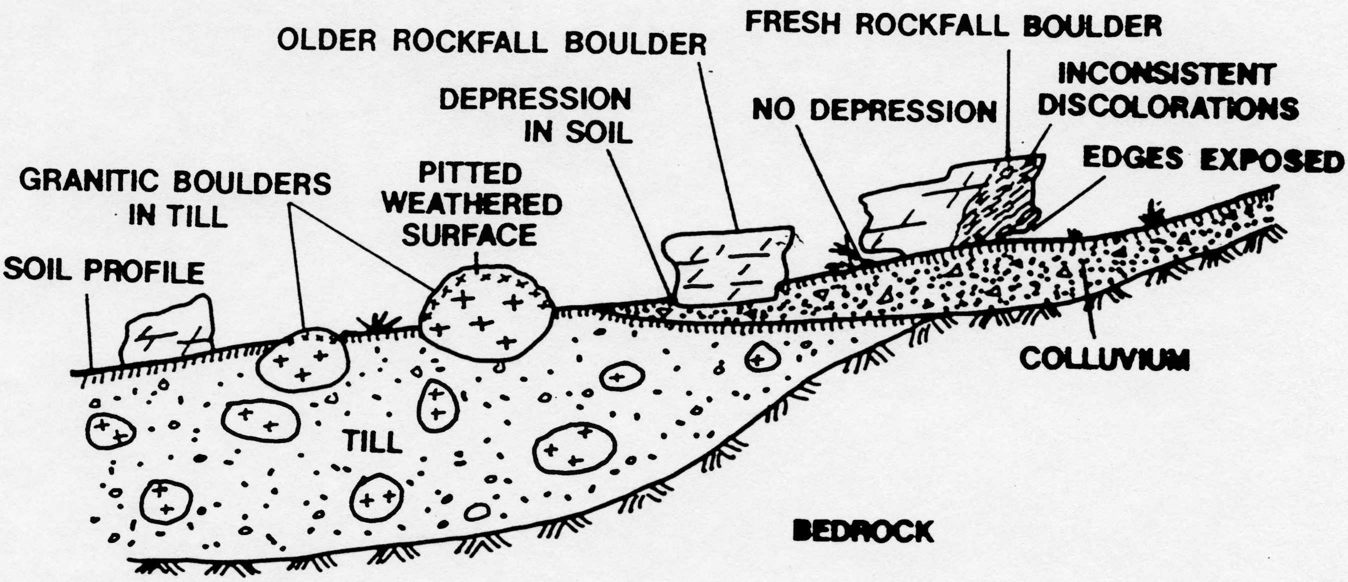

Figure 6. Physical differences between rockfall and glacially deposited boulders in runout zone. Rockfall boulders are all limestone or sandstone, while glacial boulders are mostly rounded granite or metamorphic lithologies. Note that soil exists below rockfall boulders, while it is absent beneath glacial boulders.

slough down along the dip slopes and eventually fall into open cracks formed by joints, wedging slabs farther apart.

The glaciated valleys of Gore and Booth Creeks both possess relatively flat bottoms and steep nearly vertical sides. The slopes are so steep that once a boulder or slab topples from the cliffs, it usually cannot come to rest until it reaches the lower footslopes of the valley wall. An examination of the runout zone shows that large boulders and slabs have travelled onto and across parts of the valley floor due to the tremendous momentum they acquire in the acceleration zone.

Factors Triggering Rockfalls

Most of the rockfalls reported in this area appear to be related to alternating freeze-thaw conditions. Events have occurred at night in winter, spring, and fall, after warm days of melting have introduced runoff into joints and fractures. Upon freezing, the ice expands in the cracks sufficiently to topple an unstable block. Some events have also occurred on the other side of the cycle, as sunshine thaws the frozen cliffs, releasing a precariously perched block or boulder.

Hazard Classification and Zonation

The rockfall hazard associated with geologic and topographic conditions and the proximity of dwellings as described above is considered to be severe. The majority of large boulders found among structures in the runout zone have fallen from the cliffs. Field study indicates that the question is not, "Will significant rockfall occur?", but rather, "What is the recurrence interval between significant rockfall events?".

Acceleration slopes are so steep and smooth that rocks traversing them are free to deflect and skitter laterally in any direction radiating from he point of initial fall. The pattern or trajectory a given boulder could follow is so unpredictable that it is impractical to delineate individual hazard zones based on the physical conditions of various segments of the cliff faces. In the present situation, hazard zones are more practically related to horizontal distance from the source areas, zones farther away experiencing a smaller probability of being encompassed by a given event. This approach yields an approximately radial series of zones radiating out from the source area; the more severe hazards are obviously closest to the cliffs. It should be pointed out, however, that any area within the extent of the runout zone is subject to some degree of rockfall hazard.

Hazard Zone Delineation

Varying degrees of rockfall hazard severity can be approximated by examination of the nature and positions of boulders and slabs in the runout zone. Each large boulder was examined to determine several factors which were used to approximate the extent of the runout zone, and estimate the time spans since each rockfall boulder came to rest. These factors are:

1) Whether or not a boulder was of rockfall origin or glacially deposited.
2) Whether or not a rockfall boulder was resting undisturbed in its original position or had been moved by human activities.
3) The physical nature of undisturbed rockfall boulders with respect to basal contact, (resting on surface, embedded, partially covered, etc.) and lichen, moss, and weathering patterns on exposed surfaces.
4) The comparative size distributions of boulders within the runout zone.

Rockfall Versus Glacial Origin of Boulders

In order to determine the extent of the rockfall runout zone, it is necessary to determine whether boulders encountered below the cliffs in Vail Village have fallen from one of the source areas and come to rest on the surface, or if they were transported in and deposited by ice or outwash during Pleistocene glaciations. This distinction can be made by comparing the character of boulders found embedded in undisturbed glacial deposits with the limestone and sandstone boulders derived from the cliffs (Figure 6). Glacially deposited boulders are mostly rounded to subrounded smooth granite or metamorphic rocks which are imbedded in the surrounding glacial deposits. The exposed surfaces of these boulders are almost totally covered with lichens and moss. The heavy lichen cover and other well developed surface rock weathering features such as pits and etched relief of individual mineral grains, suggest that these boulders have been in place for 20 to 40 thousand years. The glacially deposited cobbles and boulders are 85 to 90 percent granitic and metamorphic rock types, and very few limestone or sandstone cobbles or boulders can be found in the till. This is due to the fact that the only source area where valley glaciers could scour and incorporate limestone blocks is a narrow band of rock one mile upstream from the runout zone. The extensive upper basin which spawned the glaciers is composed of Precambrian igneous and metamorphic lithologies, which make-up the vast majority of the rock types encountered in till deposits found in the rockfall runout zone. In contrast, large boulders and slabs of rockfall origin are angular or poorly rounded, rest directly on the ground surface, do not show an equal amount of weathering on all exposed surfaces, and are almost exclusively limestone or sandstone. A few granitic rockfall boulders are also present, and are derived from till in the upper source area. These differences were used to map the locations of large boulders of rockfall origin and determine the approximate limits of the runout zone.

Disturbed Versus Undisturbed Rockfall Boulders

Once a specific boulder was identified as being of probable rockfall origin, its position on the foot slopes could be used to predict the nature and extent of the runout zone. A problem with using the positions of rockfall boulders in the subdivision and adjacent areas to delineate the runout zone is that many have been disturbed and moved from their original positions during development and construction activities. Many of the boulders are too large (some weighing up to 15 tons) to be moved easily, even by heavy equipment, and it is assumed that they were moved only a few feet to several tens of feet from their original position in order to carry out construction of roads and building foundations. The accuracy of this assumption is not easily determined, and the present positions of the disturbed boulders as indicators of runout zone and hazard zone characteristics are not entirely reliable.

Disturbed or transported rockfall boulders always show fresh gouges and abrasions caused by heavy earth moving equipment. Additionally, the moss and lichen growth patterns, if any, are inconsistent with the present orientations of the boulders, indicating that they have been moved after the patterns were established. Discolorations of the disturbed boulders caused by soil contact can be observed on the sides or top of those which have been pushed over and moved. The boulders often leave trails or marks where they have been pushed along the ground, creating a small berm of scraped up soil along one of their basal edges. Undisturbed rockfall boulders do not show fresh gouges or scrapes, have consistent lichen and moss growth patterns, do not show soil discolorations on their sides or tops, and are often surrounded by young bushes, aspen trees, or natural vegetation, which has obviously not been disturbed. The positions of these boulders can be used to more accurately project the minimum limits of the runout zone, since they can be inferred to have come to rest in their present positions after falling from the cliffs.

Factors Used to Approximate Ages and Recurrence Intervals of Major Rockfall Events

Certain characteristics exhibited by undisturbed rockfall boulders and slabs in the runout zone, suggest approximate or relative time spans since they came to rest after falling, and give a rough estimate of the recurrence intervals between large slab-failure events. The contact made by a boulder with the surface suggests how long the rock has been resting in its present position. As the length of time increases, the rock will tend to press into the ground, and slope wash, soil creep, and frost wedging will act to fill in around the base of the rock with soil materials. Rocks which have been sitting for long periods tend to be somewhat embedded in the soil, and if moved, would reveal an indentation in the ground. Rocks which have recently fallen rest directly on the ground surface, and may lie on brush or small trees they have crushed beneath them. One can push a stick beneath the edges of such a rock in some places.

Older rocks also have more consistent lichen growth patterns than recently moved rocks which have detached from the cliff. Recently moved rocks may possess differentially weathered surfaces, as a result of their former positions on the cliff. If the boulder acquired a surface weathering and color pattern while on the cliffs, it is unlikely to roll to a stop in the same position, and the surfaces which were previously against the ground or facing joints may still possess a characteristic coloration contrasting with older, exposed weathered surfaces. Considerable time is necessary for natural weathering processes to remove this discoloration and create a new uniform surface color on the rock.

Distribution of Rockfall Events

Examination of the source area and runout zone reveals that two basic types of rockfall events take place in the study area. The first and most common involves smaller individual boulders generally in the (0.5 x 1 m) size range, which detach from sedimentary beds and eventually fall from the cliffs. These falls commonly involve several boulders, many of which are set in motion after being struck by the initial falling rock. This type of minor rockfall is common, and based on examination of the runout zone and cliffs above, can be expected to occur every one to three years. This is the type of rockfall which occurred in the reported events of May 1983, January 1986, and September 1987, damaging several structures. Many rockfall events go unreported unless significant damage to structures occurs.

The second type of rockfall is much less frequent, but of far greater danger and destructive potential. It involves massive slab failures of the cliff faces, along joints which liberate large (4.5 x 6 m) slabs and (2.5 x 1.5 m) limestone boulders, showering them onto the acceleration slopes below. The next rockfall of this magnitude will almost certainly result in extensive damage or destruction to structures in the runout zone below.

An imprecise preliminary estimate of recurrence intervals for these large slab-failure events, based on examination of the source area and undisturbed rockfall boulders in the runout zone, is on the order of 40 to 100 years. Large boulders set in motion during these events can travel through the runout zone as far as the maximum probable limit. An estimate of the last occurrence of this type of event, based on the freshest, undisturbed rockfall boulder in the runout zone, and weathering patterns on the cliffs, is on the order of 40 to 60 years ago.

Potential Solutions to Rockfall Hazards

The feasibility of protective structures and other preventive measures were evaluated during the study.

Smaller boulders commonly falling off the lower cliff could probably be arrested by protective structures built near the lower acceleration zone on property within the platted subdivision. The structures must be capable of absorbing the energies of one ton boulders traveling at 50 mph, and would probably involve energy absorbing materials held within timber or rock cribbing. Maintenance of the structures would be necessary each time a boulder is stopped, since the energy dissipation will damage or deform that part of the structure involved. It is probably not feasible to build an armoring wall or other type of structure which attempts to arrest the boulders through rigid strength, due to the extremely high momentum rocks gain through the acceleration zone. The unpredictable paths and patterns followed by rocks skittering down slope makes it difficult to determine the best places to site the protective structures. One approach would be to construct individual protective structures for each building within the runout zone. Alternatively, a single large structure above the subdivision might provide as much protection and create less overall disturbance to the area. The structure would have to be carefully designed and constructed to be free draining and to prevent adverse snow or ice accumulations from forming above the protective barrier. Siting a community type protective structure appears to be feasible if based on the detailed siting studies which would be necessary to determine the most suitable location. In either case, costs for these structures are estimated to be on the order of 0.75 to one million dollars, and could be higher. Unfortunately, these structures would do little to prevent larger boulders or slabs derived through toppling failures from destroying structures in the runout zone. The energies possessed by such slabs or boulders are simply too great to contain within the restricted space available between the source areas and existing residences.

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APPENDIX B

ROCKFALL MITIGATION

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INTRODUCTION

Rockfall is a geologic hazard that is catastrophic in nature. For the most part it is viewed as a nuisance by highway maintenance personnel who are required to clean the debris off the roadway and periodically clean out the fallen rocks within the roadside ditches. When rockfall occurs in populated areas or areas frequented by people, lethal accidents can occur.

In general, rockfall occurs where there is a source of rock and a slope. Within the rock mass, discontinuities (bedding planes, joints, fractures, etc.) are locations where rock is prone to move, and ultimately, fail. Depending on the spatial orientation of these planes of weakness, failures occur when the driving forces, those forces that cause movement, exceed the resisting forces. The slope must have a gradient steep enough that rocks, once detached from bedrock, can move and accelerate down the slope by sliding, falling, rolling, and/or bouncing. Where the frequency of natural rockfall events are considered unacceptable for an area of proposed or current use, and avoidance is not an option, there are techniques of mitigation that are available to either reduce rockfall rates and prevent rocks from falling, or to protect structures or areas of use from the threat.

There have been important technological advancements in rockfall analysis and mitigation techniques in the last several years. They include rockfall simulation software, rock mechanics software, and research and development in new, innovative mitigation techniques. This paper emphasizes mitigation techniques.

There are many factors that influence a selection and design of a mitigation system to reduce or eliminate a rockfall hazard. They include:

1. The rock source (lithology, strength, structure, and weatherability) and expected resultant fallen rock geometry (size and shape);
2. Slope geometry (topography);
3. Slope material characteristics (slope surface roughness, softness, whether vegetated or barren);
4. Proximity of the structure requiring protection to source area and rockfall run-out zone;
5. Level of required rockfall protection (the acceptable degree of risk);
6. Cost of the various mitigation options (construction, project management, and design);
7. Constructability (mobilization difficulties, equipment access, and other constraints);
8. Future maintenance costs.

For any public or private land use proposal, in steep sloping areas, the geologic hazard investigation should initially recognize those physical factors listed above. If rockfall has been identified as a hazard then a detailed rockfall hazard analysis is warranted. The conclusion of such analyses, in addition to the determination of the factors above, must include:

1. An accurate determination of anticipated risk and frequency of rockfall at the location of the proposed land use, and;
2. Site specific calculations of the velocities, bounding heights, and impact forces for the range of anticipated rockfall events.

Once all physical characteristics and calculated falling rock dynamics are determined then the appropriate engineering and design can be completed for mitigation of the rockfall threat.

ROCKFALL MITIGATION TECHNIQUES

The available techniques in effective prevention and mitigation of rockfall, fall into two categories. One is stabilization of the rock mass at the source to prevent or reduce rockfall occurrences. The other is the acceptance that hazardous rockfall will occur, but with the placement of protective devices to shield structures, or public areas, from the threat of impact. There is a third category that, while not a form of mitigation, is a method that can diminish the catastrophic nature of rockfall. It is rockfall warning and instrumentation systems. Systems, electrical and mechanical, that either will indicate that a rockfall event is imminent, or has just occurred.

Stabilization and Reinforcement

Techniques that require in-situ or surficial treatments of the slope to induce additional stability to the exposed rock mass are termed rock and/or slope stabilization and reinforcement. Stabilization can be accomplished by any combination of the following: removing unstable rock features, reducing the driving forces that contribute to instability and ultimate failure, and/or increasing the resisting forces (friction or shear strength).

1. **Scaling (hand scaling, mechanical scaling, and trim blasting).** Scaling is the removal of loose and potentially unstable rock from a slope. On slopes of poor rock conditions scaling is generally viewed as a continual maintenance procedure because the loose rock removed exposes the rock underneath to further weathering.
2. **Reduce slope grade.** Laying a slope back can prevent rocks from falling from a source area.
3. **Dewater or drain rock slope to reduce water pore pressures.** The installation of drainage holes in rock can reduce the pore pressure in rock fractures—one of the driving forces mentioned above.
4. **Rock dowels.** Rock dowels are steel rods that are grouted in holes drilled in rock, generally across a joint or fracture in the rock of unfavorable orientation. It is a passive system in which loading or stressing of the dowel occurs only if the rock moves (slides) along the joint plane. (See Figure 1.)
5. **Rockbolts.** Rockbolts are installed much like dowels but are usually loaded or stressed, which imparts a compressive force on the rock. The loading of the steel rod during the installation increases the shear strength of the joint or fracture and prevents movement, reinforcing the exposed rock mass. There are wide varieties of rockbolts, including mechanical, grouted, and binary epoxy resin systems.
6. **Steel strapping.** Steel strapping, also called mine strapping, is a strip of steel that bridges between offset rockbolts or dowels to support the rock mass between them.
7. **Anchored wire mesh or cable nets.** Fence wire or, depending on loading criteria, cable nets are draped on a rock slope and anchored to the rock mass by the bearing plates of rock dowels or rock bolts. The anchor pattern is set so that the wire mesh or cable nets are in continuous contact with the rock face so that there is complete confinement of the loose rock material. (See Figure 2.)

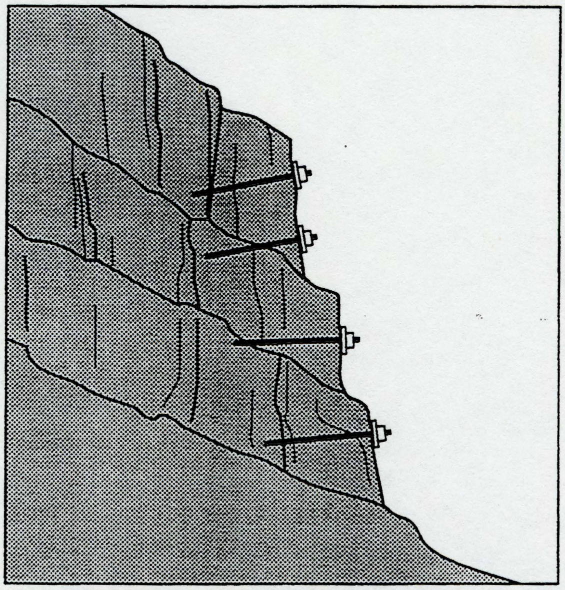

Figure 1. Rockbolts and dowels.

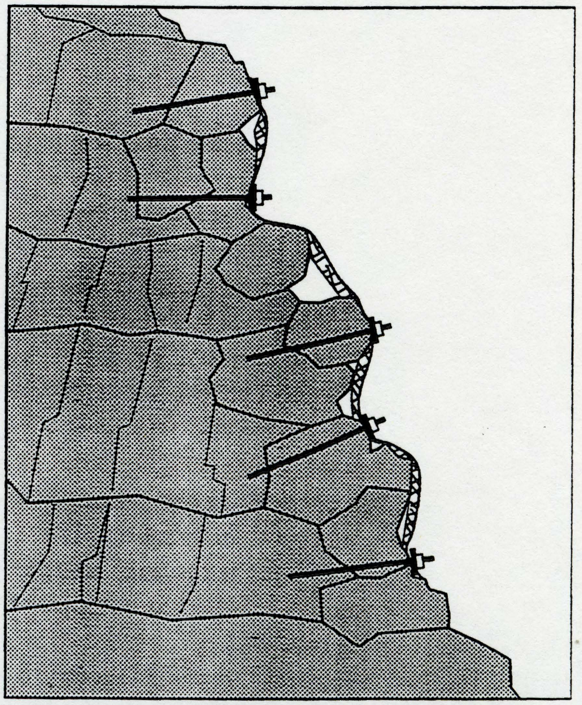

Figure 2. Anchored mesh or nets.

8. **Shotcrete.** Shotcrete is the sprayed application by compressed air of concrete on rock or rocky soil slopes for reinforcement and containment. Shotcrete applications can be strengthened by the addition of nylon or steel fibers to the concrete mixture, or the placement of a wire grid on the rock slope prior to application. Weep holes are usually drilled into the shotcrete to ensure that the contained material is free draining. (See Figure 3.)

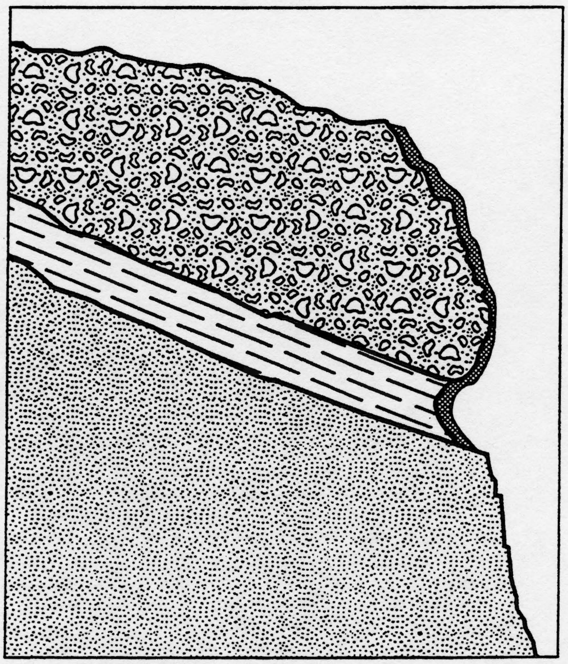

Figure 3. Shotcrete.

9. **Buttresses.** Buttresses are used where overhanging or undermined rock features become potentially unstable and require passive restraint. Buttresses can be constructed from many types of material. For concrete buttresses, rock dowels are generally installed into surrounding competent rock to anchor the buttress in place. (See Figure 4.)
10. **Cable lashings.** Cable lashing is the wrapping of high capacity cables around a potentially unstable rock feature. The cables are then attached to anchors (rock dowels) installed in adjacent competent rock. (See Figure 5.)
11. **Ground Anchors.** Ground anchors are generally used to prevent large, potential landslide-type failures in heavily weathered, fractured rock and rocky soils. Their installation requires the drilling of deep holes and the grouting of thick bundles of high-strength wire strand, which are attached to large load-bearing panels and then stressed (pulled) to a desired tensional load and locked off.

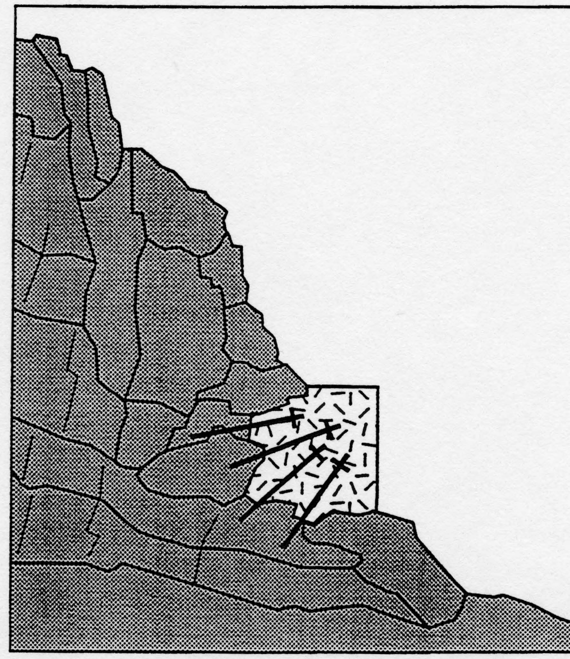

Figure 4. Anchored concrete buttress.

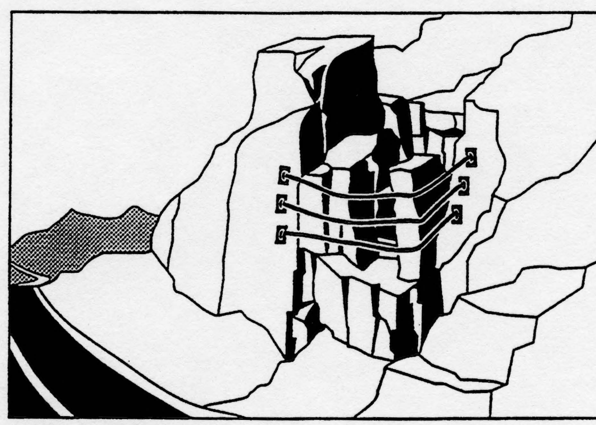

Figure 5. Cable lashing.

Rockfall Protection Devices

When stabilization of rock slopes is not practical and sufficient room exists, protective devices or structures can be constructed to shield areas from rockfall impact.

1. **Fences.** Rockfall fences come in a variety of styles and capacities. They tend to become less effective and are damaged if not destroyed by larger rockfall events. (See Figure 6.)

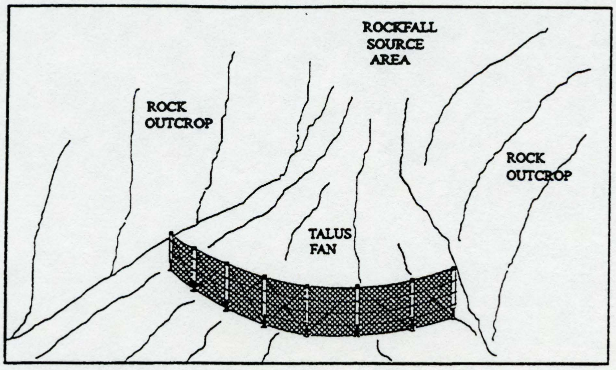

Figure 6. Rockfall fence.

2. **Ditches.** Ditches excavated into slopes can provide excellent rockfall protection. Care is needed in analysis and design to insure that bounding rocks cannot span the ditch width. (See Figure 7.)
3. **Impact barriers and walls.** Impact barrier and walls can be made from many types of material, from fill mechanically stabilized by geotextiles, rock gabion baskets, timber, steel, concrete, or even haybales. Highway departments commonly use Jersey barriers on roadsides to contain smaller falling rock in the ditch. The inertial systems, able to absorb the forces of momentum of the moving rock, have higher capacities, without costly impact damage, compared to more rigid systems. (See Figure 8.)
4. **Earthen berms.** Berms are elongated mounds of fill, commonly used in association with ditches to increase the effective height and catchment of the protection device. (See Figure 7.)
5. **Hanging fences, nets, and other attenuation devices.** In well-defined rockfall chutes in steeper rock slope areas it is possible to anchor cables to span the chute and hang fence mesh, cable netting, or rock attenuation elements. Rocks that roll and bounce down the chute impact these devices, which attenuates (reduces) the rock velocity. (See Figure 9.)

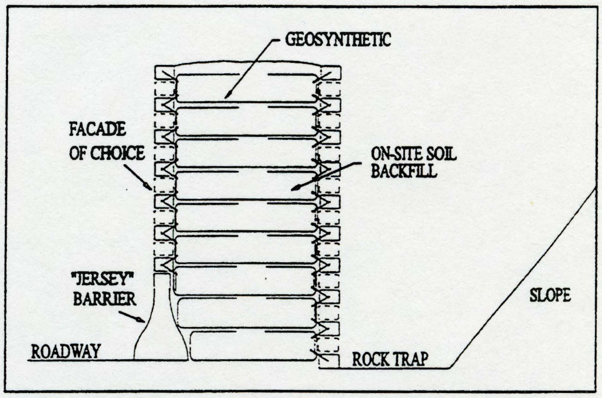

Figure 8. Mechanically stabilized backfill barrier.

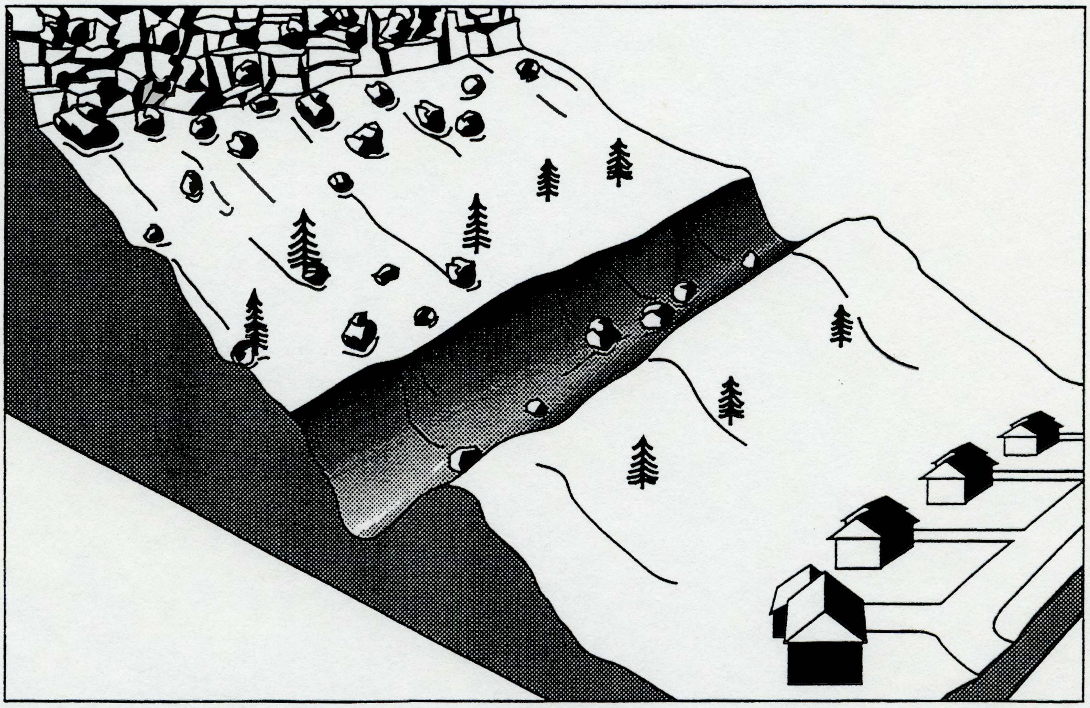

Figure 7. Rockfall ditch and berm.

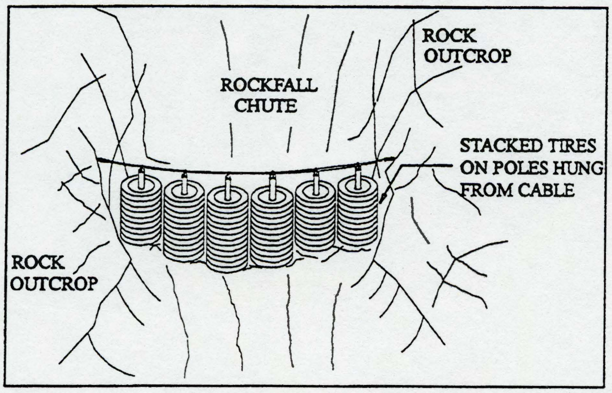

Figure 9. Tire impact attenuator.

6. **Draped mesh or netting.** Draped mesh is similar to the stabilization technique **anchored mesh** but is only attached to the rock slope at the top. Rocks from the slope are still able to fail but the mesh drape keeps the rock fragment next to the slope where they safely "dribble" out below to a catchment ditch or accumulate as small detrital fans. (See Figure 10.)

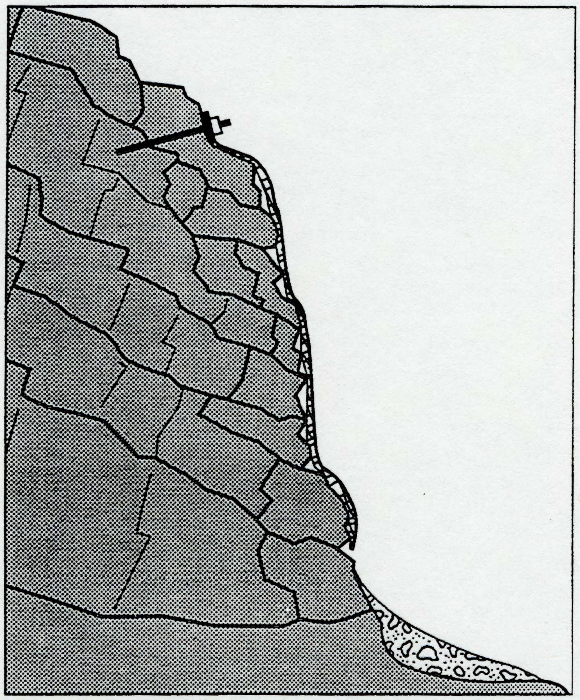

Figure 10. Draped mesh.

7. **Rock sheds and tunnels.** Rock sheds and tunnels are mentioned here only because they are used mostly for transportation corridors. They have little or no application in most types of land use.

AVOIDANCE—THE 100 PERCENT SOLUTION

There is one more mitigation method that is neither a stabilization/reinforcement system nor protection system. It is strongly recommended at locations where rockfall hazards are very severe, and/or risks very high. Mitigation designs proposed in such areas may not afford the necessary level of protection. Bear in mind that no rockfall mitigation is 100 percent guaranteed, even in mild rockfall hazard zones. **Avoidance** is excellent mitigation and must be considered where circumstances warrant. Any professional in rockfall analysis and mitigation (as with any geologic hazard) must, at times, inform developers, planners, and the public that a proposed land use is incompatible with the site conditions.

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