EVWHS Development Application - Exhibit 5c

CESARE, INC.
Geotechnical Engineers & Construction Materials Consultants

ROCKFALL HAZARD STUDY

East Vail Parcel
Vail, Colorado

Report Prepared for:

Mr. Kevin Hopkins
Vail Resorts Development Company
PO Box 959
Avon, CO 81620

Project No. 17.5029
June 19, 2017

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1. INTRODUCTION

This report presents the results of a rockfall hazard study for an undeveloped lot located on the east side of Vail, Colorado and owned by the Vail Resorts Development Company (Vail Resorts). It is Cesare, Inc.'s (Cesare's) understanding that a preliminary rockfall hazard analysis is desired prior to potential development of the western portion of this site, along with other geologic hazards which may have a significant impact on the proposed development. The site is located directly north of the I-70 East Vail interchange. Geologic hazards, such as rockfall, debris flow, and avalanche are recognized by the Town of Vail and delineated in the project area. The rockfall hazard has been identified and addressed on the neighboring development to the west (Booth Falls Mountain Homes), with multiple existing catchment structures.

2. SCOPE OF WORK

The scope of services for this rockfall hazard study generally included:

1. Review of available information, including published geologic maps, aerial photography, and readily available studies performed on nearby sites.
2. Site reconnaissance to verify geologic and geologic hazard conditions on and upslope from the subject site, with a focus on rockfall. This involved mapping the geology and geologic hazards by traversing the site on foot, and through photography and video of the site using an unmanned aircraft system (drone).
3. Modeling of the rockfall hazard potential using a critical cross section through the project site and input into the Colorado Rockfall Simulation Program (CRSP).
4. Preparation of this report presenting our findings and preliminary recommendations relative to the rockfall hazards potentially impacting the site, including conceptual techniques that might be used to remediate and reduce the rockfall hazard. Also included in this report are applicable figures, tables, and cross sections.

3. SITE CONDITIONS

The project site is located directly north of the I-70 East Vail interchange on the north side of Fall Line Drive (Figure 1). Pitkin Creek Townhomes (formerly named Falls at Vail) is located immediately adjacent to the site in the southeast corner, and Booth Falls Mountain Homes (Booth Falls) and Vail Mountain School are located on a neighboring property to the west-northwest. The site is rectangular in shape and is located in the southeast 1/4 of Section 2, Township 4 South, Range 80 West of the 6th Principal Meridian in Eagle County, Colorado. The approximate center of the property is situated at latitude 39° 38′ 46″ N and longitude -106° 18′ 25″ W.

Cesare performed site reconnaissance to characterize and map the geologic and geologic hazard conditions during May 2017. The site is currently undeveloped with a variably sloping ground surface ranging from about 7 to over 45 degrees (Figure 2). The elevation ranges from about 8375 feet in the west side of the site to about 8940 feet in the northeast corner, an elevation change of about 565 feet across the site. The site is bound by undeveloped National Forest Service land to the north, northwest, and east. Fall Line Drive and the I-70 Frontage Road bound the site along the southern edge. Pitkin Creek forms a deeply incised drainage immediately to the east of the eastern site boundary. Booth Creek, also deeply incised, is located about 3,200 feet to the northwest of the site. Gore Creek is located on the opposite side of I-70, about 580 feet to the south at closest approach. A retaining wall borders the site along Fall Line Drive near the East Vail I-70 off ramp in the area of the shuttle stop. Design or construction details for this retaining wall were not available at the time of this study. Based on site observations, this retaining wall is constructed of wood cribbage, with gravel placed directly behind the wood facing. The wall appears to generally be in good condition, with one exception near the east end where the wall has bulged out. An unpaved, single track road traverses the site along the edge that borders Fall Line Drive and is barely visible in some historic aerial photographs. Multiple utility service manholes were observed along this single track road and the manhole covers are labeled with "electric utility".

Vegetative cover at the site includes grasses, shrubs, and aspen trees. The western part of the site and the area upslope of the western part of the site are incised with a network of drainages which contained flowing water at the time of our site visits. This western area is generally more densely vegetated with low shrubs and aspen trees than other parts of the site and upslope areas. Refer to Photographs 1 through 8 for views of these onsite features.

Photograph 1. View of the project site. Photograph taken from the eastbound lane of I-70 looking east across the site. The photograph shows the relatively steep slope of the site and the rock outcrops present upslope from the site.

Photograph 2. View of retaining wall located along edge of site that borders Fall Line Drive. Town of Vail shuttle stop is visible in the left side of the photograph.

Photograph 3. View of distressed part of the retaining wall along the edge of the site that borders Fall Line Drive. The slope rises steeply upward to the north at the top of the wall. This photograph was taken near the east end of the wall.

Photograph 4. Aerial view of the west side of the site. The single track road that traverses the site is visible, along with one of the drainages onsite (with flowing water). The white Cesare truck is parked at the beginning of the access road for the rockfall berm, constructed on the neighboring property to the west (Booth Creek). Large, gray limestone boulders which have come to rest on the lower slope are visible in the photograph.

Photograph 5. View of limestone boulders which have come to rest near the base of the slope in the western part of the site. Boulders are about 3 to 4 feet in longest dimension, embedded in the soil, surrounded by mature vegetation, and show lichen on the surface.

Photograph 6. View of large sized limestone boulder located in the southern area of the site. Boulder measures about 21 feet long by 16 feet wide by 6 feet high. A survey marker has been placed on this boulder (Eagle County Survey Control, 1998).

Photograph 7. View of the western part of the site. Note the dense vegetative cover, flowing water, and exposed bedrock outcrops near the top of the slope.

Photograph 8. View of flowing water in the western part of the site.

Rock outcrops are present upslope from the site and are rockfall source zones which have the potential to impact the site and future planned development. Rockfall is a recognized hazard in the site area, as depicted on the "Official Rockfall Hazard Map" for the Town of Vail (Figure 3). A significantly sized rockfall catchment berm and basin, located about 1,300 feet to the northwest at closest approach, has been constructed to reduce the rockfall hazard above the Booth Falls development. It is Cesare's understanding that this consists of an earthen berm ranging in height from about 10 to 15 feet, and an upslope catchment area spanning about 20 feet where the natural slope has been laid back. An access road leading up to the catchment area begins at Fall Line Drive near the western point of the project site. Additional rockfall remediation structures are located upslope from Booth Falls Court and are visible in the aerial imagery. These rockfall remediation features are shown in Photographs 9 through 11.

Debris flows are also a recognized geologic hazard for the area, as shown on the "Official Debris Flow Hazard Map" for the Town of Vail (Figure 4). As shown on Figure 4, the site is not within a debris flow hazard zone, although moderate and high hazard areas are delineated along Pitkin Creek to the east-southeast of the site.

Photograph 9. Google Earth image of Booth Falls Mountain Homes to the west of the project site. Examples of existing rockfall remediation structures are labeled.

Photograph 10. View of rockfall catchment berm and basin, upslope from Booth Falls Mountain Homes. View looking west toward Booth Creek. The berm is between 10 and 15 feet high, and the ditch is about 20 feet from crest of berm to backslope.

Photograph 11. View of rockfall catchment berm and basin upslope from Booth Falls Subdivision. View looking east toward the project site.

4. GEOLOGIC SETTING

4.1 REGIONAL GEOLOGY

The site is included in the Southern Rocky Mountain physiographic province in an alpine setting with elevations ranging from 8000 to 9000 feet. The site is located along the western flank of the Gore Range, a northwest-southeast trending mountain range situated in north-central Colorado. The Gore Range is separated from the Front Range Mountains to the east by the Blue River Valley and Williams Range thrust zone. The core of the Gore Range is comprised of crystalline basement rock uplifted during the Laramide mountain building event (orogeny) about 70 to 50 million years ago (Ma). The Laramide orogeny also uplifted thick sequences of sedimentary units deposited during the occupation of an inland sea in parts of Colorado. The sedimentary units are comprised of shale, claystone, siltstone, sandstone, conglomerate, and limestone.

The Gore fault is located about 500 feet northeast of the site at closest approach and is not considered active (Figures 5 and 6). The Gore fault is characterized as a zone of high angle reverse faults. These faults have had at least five episodes of movement that span from Precambrian (older than 540 Ma) to late Oligocene and younger (about 28 Ma), although most of the displacement likely took place during the Laramide orogeny (Kellogg and others, 2011). A gentle regional tilt of 5 to 15 degrees down to the south-southwest, characterizing the sedimentary bedrock in the site vicinity, is interrupted adjacent to the Gore fault. Beds of the Minturn Formation are steeply dipping and overturned where located close to the Gore fault, as is the case upslope and to the northeast of the site.

4.2 SITE GEOLOGY

The site is underlain by surficial units comprised of artificial fill, colluvium, landslide deposits, and till of the Pinedale glaciation (Figure 5 Geologic Map). The bedrock underlying the site is mapped as Minturn Formation (Kellogg and others, 2003; Kellogg and others 2011). Artificial fill is associated with the construction of Fall Line Road along the southern border of the site and likely with the unpaved, single track road (with buried utilities) in the southwest part of the site. A wedge of colluvium is mapped mid-slope in the western half of the site, however, the colluvium was actually observed to completely cover the site and largely obscure bedrock outcrops. The eastern half of the site is predominantly landslide deposit and Pinedale Till underlies the southeastern corner of the site. Bedrock of the Minturn Formation underlies the surficial deposits at the site. Descriptions of these units are described below, from youngest to oldest. Refer to Diagram 1 for a geologic cross section near the site.

4.2.1 Artificial Fill (af)

Artificial fill is associated with the ground modifications that have occurred within and adjacent to the site boundaries. Based on site observations, artificial fill is likely associated with the single track utility road in the southwestern part of the site, construction of Fall Line Drive, and construction of the shuttle stop and retaining wall in the southeast part of the site.

4.2.2 Colluvium (Qc)

Colluvial deposits (Holocene and upper Pleistocene; 126,000 years ago to present) cover most of the slope in the site area based on site observations. Colluvium is characterized as unconsolidated, generally non-stratified deposits mantling slopes less than 50 degrees. Colluvial deposits are comprised of pebble, cobble, and boulder sized rock and fine grained material mixed together by downslope movement. Colluvium is typically less than about 30 to 45 feet thick.

4.2.3 Landslide Deposits (Qls)

Landslide deposits (Holocene and upper Pleistocene; 126,000 years ago to present) underlie most of the eastern half of the site. Kellogg and others (2003) characterize these mapped deposits as a range of chaotically arranged debris to intact slump blocks of bedrock. The middle member of the Minturn formation (Pmm) is notably susceptible to landsliding, although slope failures can occur in most sedimentary units where over steepening of the ground surface has destabilized slopes. Largescale landslide deposits may be up to about 120 feet thick.

4.2.4 Pinedale Till (Qtp)

Glacial till of Pinedale age (upper Pleistocene; 126,000 to 11,000 years ago) underlies the southeast corner of the site and also a majority of the slopes to the east-southeast, and the area upslope to the north of the site (in part). Pinedale Till is characterized as unsorted, unstratified, and boulder. It tends to form hummocky topography with common depressions and small ponds.

Till deposits were observed upslope from the site and were bouldery (sedimentary and igneous composition) and poorly sorted. This unit has been mapped as high as 900 feet above the present elevation of Gore Creek, with thickness up to about 90 feet.

4.2.5 Minturn Formation

The Minturn Formation (middle Pennsylvanian; 315 to 307 Ma) underlies the entire site and general vicinity. This unit is generally comprised of conglomerate, sandstone, siltstone, claystone, shale, and stratigraphically distinct layers of limestone and dolomite. The Minturn Formation is divided into multiple units, two of which directly underlie the site:

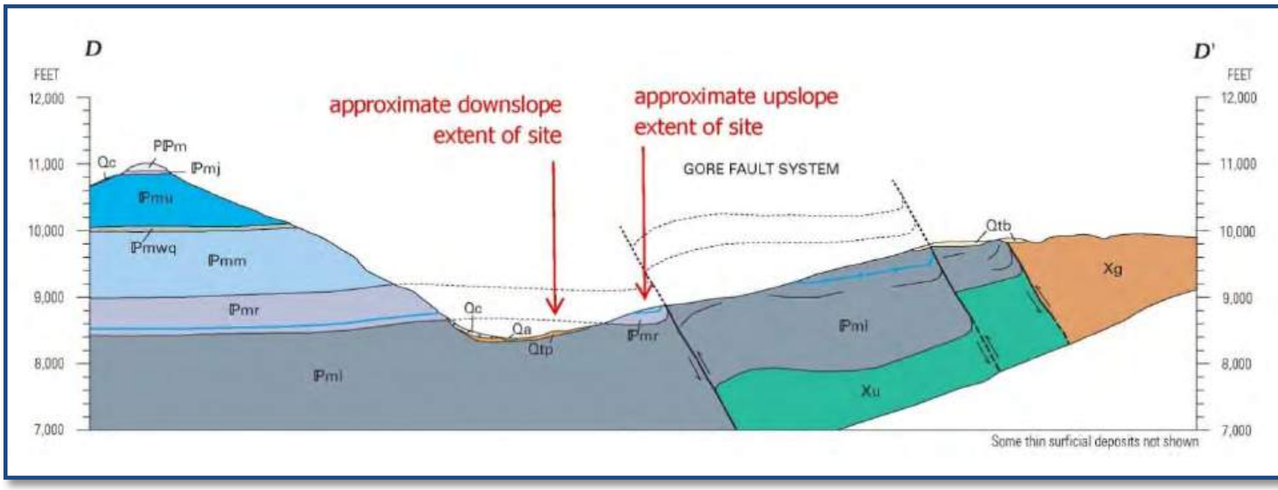
Robinson Limestone Member (Pmr)

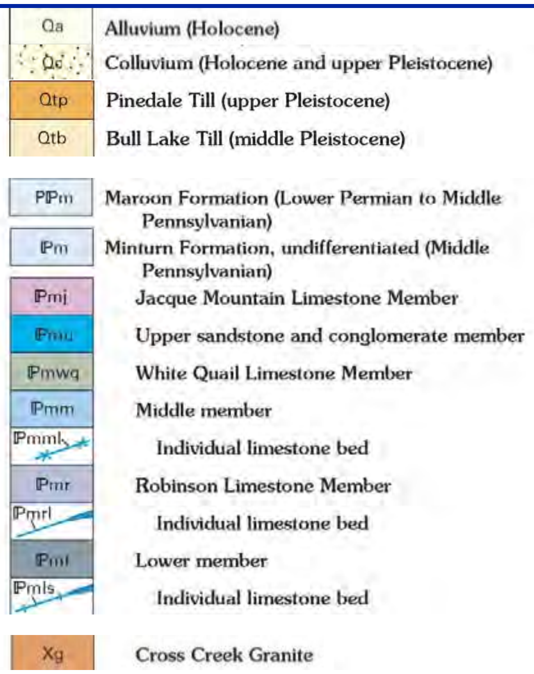
Marine limestone and dolomitic limestone, gray to yellow gray, fine to medium grained, and locally contains fossils. Comprised of four separate sequences (each about 60 feet thick) of limestone interbedded with pinkish tan, light tan, cross bedded, mica rich sandstone and grayish pink sandy siltstone and shale. The sandstone, siltstone, and shale layers weather in rounded forms, and the limestone and dolomite beds weather in relatively angular forms. Outcrops of the Robinson Limestone member are visible in the steep cliffs northwest and are also exposed directly upslope from the site. One large boulder dislocated from upslope and came to rest near the base of the slope along Fall Line Drive is sandstone containing purple gray coral, possibly representative of a reef facies within the Robinson Limestone member. The Robinson Limestone member is about 360 feet thick north of Gore Creek.

Lower Member (Pml)

Conglomerate, sandstone, siltstone, and shale, pinkish gray, gray brown, gray green, mottled maroon, and gray green. The Lower member may contain clasts of Proterozoic age granite (2,500 to 541 Ma). This unit is generally obscured by vegetation onsite and outcrops were not identified during our site visits. The Lower member of the Minturn Formation can be up to about 1,200 feet.

DIAGRAM 1. Cross Section D-D’

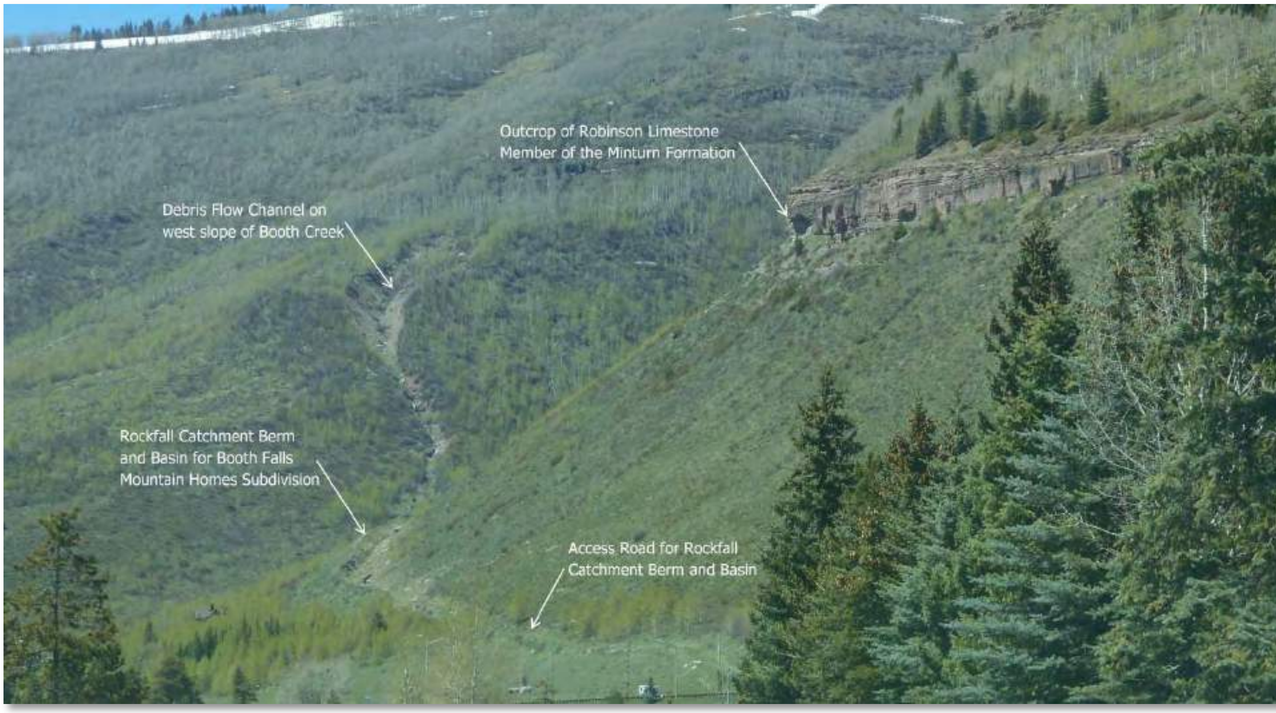




Cross section D-D’ excerpted from the Geologic Map of the Vail East Quadrangle (Kellogg and others, 2003). This cross section is located immediately east of the project site and schematically depicts the surface and subsurface geologic conditions in the site area.

5. GEOLOGIC HAZARDS

The current study focused on the geologic hazard related specifically to slope stability, including rockfall and landslides in particular. Rockfall was analyzed using the Colorado Rockfall Simulation Program (CRSP) for one study section located on the west side of the site where development is most likely (per client communication). The landslide hazard was characterized primarily through review of published maps and site reconnaissance to verify the nature, extents and evidence of recent movement. Debris flows are a significant potential hazard in the site vicinity, although debris flow susceptibility has not been determined for Vail or Summit County to date. The site is not included in the Official Debris Flow Hazard Map for the Town of Vail, although Pitkin Creek located near the southeast corner of the site is considered to have moderate to high hazard potential. One debris flow located on the east-facing slope of Booth Creek (about 3,700 feet from the western site boundary) and visible from the site is shown in Photograph 12.



Photograph 12. View looking west toward Booth Creek. The project site is located beyond the trees in the right side of the photograph. Features are labeled.

Debris flows and rockfalls have damaged buildings in the Gore Creek area since development increased in the 1960's. Debris flows can be triggered by intense summer rainstorms or rapid melting of deep snowpack. Debris flows generally form on fan deposits, such as those composed of glacial till. Freeze-thaw cycles in the spring tend to pry rocks loose, resulting in rockfalls of varying magnitude and runout distance. The rockfall hazard is also related to a combination of weak shale beds between harder sandstone and limestone beds, joints, and a regional bedrock dip toward the valley. Large boulders from cliffs comprised of the Robinson Limestone member of the Minturn Formation fell and damaged several residences in the Booth Falls subdivision in the 1980's. As a result, the homeowners and Town of Vail created a Geologic Hazards Abatement District (GHAD) which aided in construction of a rockfall catchment ditch and berm that has generally proven to be an effective protection measure (shown in Photographs 9 through 12).

The exception would include the event in 1997 when a large scale rockfall skirted around the western end of the catchment structure, rolling downslope, and damaging structures below. This event resulted in the construction of mechanically stabilized earth (MSE) walls to add protection for the downslope condominiums (some of which were not included in the original GHAD). A report issued by the Colorado Geological Survey (CGS; undated) summarizes the 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. […]

Approximately one third of the swath of rolling rocks were retained by the ditch and berm. […] The remaining two-thirds of the event came to rest, scattered around the condominiums."

5.1 ROCKFALL

Rockfall is a potential hazard for the site and poses a risk to the property. Rockfall is the fastest category of slope movement and is common in mountainous terrain near cliffs of broken, jointed, or faulted rock, on steep slopes comprised of rocky material, or where cliff ledges are undercut by erosion or human activity. Stability of a rock mass is generally influenced by the underlying support provided to that rock mass and the structural nature of the rock, including the orientation and spacing of discontinuities. After a rock dislocates from a rock mass, the controlling factors for how far that rock will travel downslope include characteristics of the falling rock (composition, size, and shape), characteristics of the slope (form, length, and angle), the presence or absence of obstructions on the slope, and the height of the initial fall. The rocks exposed upslope from the project site are comprised of the Robinson Limestone member of the Minturn Formation. The rock exposures contain fractures and thin layers of siltstone and shale. As time passes, cracks can be enlarged by weathering of the rock, accumulation of soil or vegetation growth, and the forces associated with freezing-thawing of moisture within the cracks.

5.2 LANDSLIDE

Landslide deposits in the area occur on unstable slopes typically underlain by Minturn Formation shale, siltstone, claystone, or glacial till, and are largely considered inactive. The extents of a large landslide onsite were mapped during field visits, and the published boundaries were verified and refined using available light detection and ranging data (LiDAR). Refer to Figure 7 for the approximate landslide extents mapped for this study. Geomorphic features across the landslide have been masked by heavy vegetative cover, and obscured and smoothed by natural processes. The block sliding mechanism responsible for parts of the landslide mass enable large, relatively intact bedrock masses to slide downslope. These masses may appear to be in-place, when in fact they have moved downslope from their original position. Based on the high level of detail offered by the LiDAR view, Cesare has confidence in the mapped extents of the landslide as depicted in Figure 7.

The toe of the mapped landslide deposit is abruptly cut off by Fall Line Drive. The downslope extents and western flank of the landslide are steep and form a recognizable break in slope shown on the topographic map (Figure 2) and on the LiDAR (Figure 7). Photograph 13 is a view of the landslide toe and western flank, looking eastward. The retaining wall built near the Town of Vail shuttle stop is about 10 feet high and the slope above the top of wall is relatively steep (30 degrees or greater). According to Kellogg and others (2011), a large landslide was activated on the north side of I-70 due to undercutting from highway construction. The landslide is located about 1.5 miles west of the project site on I-70, involves the Minturn Formation (same unit that underlies the subject site), and is failing by combination of shallow earth sliding and deep rotational movement.

Photograph 13. View looking eastward from the western flank of the landslide toe. The ground surface is relatively steep along the toe and flanks of the slide mass, visible in the photograph.

6. ROCKFALL ANALYSIS

6.1 ROCKFALL STUDY SECTION

Cesare analyzed one rockfall study section through the west part of the site (Figure 8). The location of this rockfall study section is representative of the slope on the west side and passes through the area of the project site most likely to be developed in the future. The rockfall study section is considered a reasonable representation of the slope in the western part of the site. The section profile was derived from topographic maps available through the USGS, the Town of Vail, and a topographic map for a portion of the western part of the site provided by the client. The rockfall study section is depicted on Figure 9 and shown in Photographs 14 and 15.

Photograph 14. View looking upslope along the rockfall study section. Notable features include the limestone bedrock exposures visible at the top of the slope and the dense vegetation on the slope. The limestone bedrock forming the cliffs at the top of the slope are considered the primary rockfall source zone.

Photograph 15. View looking downslope along the rockfall study section. Notable features include the rock exposures visible at the top of the slope, the steepness of the slope, and the density of the vegetation. Fall Line Drive, I-70, and East Vail are visible in the background.

The rockfall study section begins upslope above the primary rockfall source area exposed in the cliff comprised of Robinson Limestone and extends southward to Fall Line Drive, with a total elevation change of about 760 feet over a profile length of 1,530 feet. The analysis for the rockfall study section assumes the rockfall source zone is located in the exposed cliff face upslope from the site at an elevation of about 9040 to 9080 feet. Photographs 16 through 18 show the limestone bedrock exposed in the cliff face upslope from the site. Bedrock exposures (potential rockfall source zones) were not observed further upslope from this area, although the glacial till deposits above the primary rockfall source zone may be eroding and contributing to the rockfall hazard. The slope above the western part of the project site is incised with active drainages and covered in aspen trees, tall shrubs, and scattered boulders and outcrops.

Rocks deposited along the rockfall study section slope are primarily blocky to slab shaped, and comprised of gray limestone interbedded with thin layers of sandstone, siltstone, and shale. Boulders comprised of sandstone were also observed. The rockfall study section appears to be an area of more recent rockfall events, compared to other areas of the site. A number of rocks in the rockfall study section area display a comparatively "fresh" appearance, relative lack of lichen or vegetative overgrowth, and some with minimal soil embedment. For other parts of the slope, a majority of the boulders are more deeply embedded in the soil and overgrown with lichen and vegetation (indicating much older rockfall events). Refer to Photographs 19 through 23 for examples of boulders observed on the ground surface in the area of the rockfall study section.

Photograph 16. View of limestone bedrock exposure at the primary rockfall source zone. Note the eroding shale partings and vertical fractures (spaced about 10 to 15 feet apart).

Photograph 17. Close-up view of primary rockfall source zone bedrock. Gray, hard limestone interbedded with thin, weak shale layers.

Photograph 18. Aerial view of the rockfall source zone. This photograph shows the steep cliff forming exposures of Robinson Limestone member of the Minturn Formation, dense vegetation in the form of trees and large shrubs, and flowing water in one of the drainages on the west side of the site. The bedrock exposures are fractured, blocky, and ledge-forming.

Photograph 19. View of limestone boulder, embedded. Blocky, angular, and about 3 feet in diameter. Boulders like this one are common on the property and are either embedded in the soil (older, ancient rockfall events) or are sitting on top of the soil with minimal soil embedment or vegetation overgrowth.

Photograph 20. Limestone boulder, embedded, lichen growth. Blocky, angular, and about 4 foot by 3 foot by 2 foot.

Photograph 21. Limestone boulder, minimal soil embedment. Blocky, angular, and about 3 feet in diameter.

Photograph 22. View of large, angular, slab shaped boulders near the base of the slope within the area most likely to be developed in the future. Boulder sizes were observed to be at least (1) 12 foot by 8 foot by 5 foot, (2) 7 foot by 7 foot by 3 foot, and (3) 21 foot by 12 foot by 9 foot. These boulders are embedded in the soil and have been resting here for some time.

Photograph 23. Aerial view of lower slope in western part of the site. North is toward the top of the photograph. Notice scattered boulders as large as about 7 to 8 feet in longest dimension and slab shaped. Most boulders are 3 feet or less in dimension and are embedded in the soil, representing older, ancient rockfall events.

6.2 ROCKFALL MODELING - CRSP ANALYSIS

Factors which influence the runout distance, mode of travel, speed, and energy of a rock traveling downslope include:

- Type, size, and shape of the rock.
- Type, length, height, and angle(s) of the slope.
- Potential launch points along the slope.
- Presence of obstructions on the slope (including trees, shrubs, and existing boulders).
- Height of the initial fall.

Based on site observations, the types of rocks traveling down the slope are comprised primarily of blocky to slab like limestone. Rocks are also comprised of sandstone to pebble conglomerate and a minor percentage of small, granite boulders (derived from the glacial till capping the slopes above the cliff-face rockfall source zone). Sizes generally range from about 2 to 6 feet in diameter, but can be as large as 20 to 30 feet in longest dimension. The larger dimension rocks are slab shaped, irregular, with angular corners. The falling mechanism for the slab shaped rocks would be primarily sliding after detachment from the source rock, although these rocks may roll downslope end-over-end along the shorter dimension. Based on our experience with similar conditions, site observations, and on opinions presented by the CGS for the rockfall hazard at Booth Falls to the west of the project site, the limestone rocks falling from the cliff source zone tend to break apart during their descent downslope. Cesare opines that some of the larger blocks on the scale of 20 to 30 feet in diameter may have been entrained in block slide movement of the landslide complex onsite.

CRSP requires that the section analyzed be divided into regions (cells) based on areas with uniform slope and characteristics. Cell boundaries are determined based on characteristics, such as slope angle, material comprising the slope, and the presence of obstructions. Surface roughness was estimated with consideration for the size of the rock and the irregularity of the slope surface. The surface roughness (S) is defined as the perpendicular variation of the slope within a slope distance equal to the radius of the rock. This value varied based on rock size analyzed. Based on site observations and available topographic maps, there are no significant launch points below the rockfall source zone along the section.

The tangential coefficient of frictional resistance (R_t) for the rock is the component of velocity parallel to the slope, which is slowed during impact. The tangential coefficient was chosen with consideration for the material which comprised the slope, as well as the amount of vegetation characteristic in each cell. Vegetation would tend to increase the frictional resistance in the direction parallel to the slope, thus decreasing the tangential coefficient. The normal coefficient of restitution (R_n) considers the change in velocity of the falling rock normal to the slope after impact, compared to the normal velocity before impact. For both the R_t and R_n coefficients for each cell, Cesare referred to the CRSP manual which provides ranges of suggested values based on different material types.

Cesare calibrated the model using the current conditions of the slope (no rockfall barrier, native condition) and using rock sizes and shapes based on site observations. Simulation and slope profile parameters are listed in Tables 1 and 2, respectively.

TABLE 1. CRSP Simulation Parameters

Parameter	Study Section A
Length of section analyzed (ft)	1,530
Elevation difference across section (ft)	760
Total number of cells	6
Analysis Point 1 (x-coordinate)	1,000
Analysis Point 2 (x-coordinate)	1,200
Top starting zone (y-coordinate)	9,080
Base starting Zone (y-coordinate)	9,040
Number of rocks simulated	500
Starting velocity (x)	1 ft/sec
Starting velocity (y)	-1 ft/sec
Material density of modeled rock	160 lb/ft^3
Rock shape	Spherical
Rock dimension (diameter)	10
Starting cell number	2
Ending cell number	6

TABLE 2. Slope Profile Parameters

Cell	Begin (x,y)	R_t	R_n	Approx Slope Angle (°)	Description of Slope	Geologic Unit
1	0,9140	0.65	0.15	35	Vegetated slope above rockfall source zone.	Glacial till (Pinedale).
2	100,9080	0.85	0.20	Near vertical	Cliff face, rockfall source zone, approximately 30 to 40 feet high.	Robinson Limestone member of the Minturn Fm.
3	110,9040	0.70	0.15	30	Vegetated slope below rockfall source zone, runout accumulation zone.	Colluvium overlying Robinson Limestone/Lower members of the Minturn Fm.
4	930,8540	0.60	0.15	20	Vegetated slope, accumulation zone.	Colluvium overlying Lower member of Minturn Fm.
5	1180,8438	0.60	0.15	8 to 16	Vegetated slope, accumulation zone.	Colluvium overlying Lower member of Minturn Fm.
6	1411,8382	0.90	0.60	Paved roadway (flat)	Fall Line Drive, asphalt paved roadway.	Not applicable.

Rt: Tangential coefficient
Rn: Normal coefficient
Surface roughness varied based on rock size analyzed.

6.3 ROCKFALL ANALYSIS RESULTS

The results of the analysis using the current condition of the slope are summarized in Table 3. Reported are results for common rock sizes observed at the site (3 feet diameter) and an estimated maximum case (10 feet diameter). Although boulders as long as 30 feet in longest dimension were observed embedded near the base area of the slope, these are considered more likely to have been placed during block sliding of the landslide mass.

The rocks were modeled as spherical in order to represent the worst case scenario. Rocks which are spherical will tend to have longer runout distances and higher velocities and kinetic energies associated with them. Elongate, angular rocks will tend to lose momentum sooner than a rounded rock as they travel downslope. Analysis Point 1 was placed about 200 feet upslope from the property boundary and Analysis Point 2 was placed right at the upslope property boundary. Based on observed runout and accumulation zones and calibration analysis results, it is Cesare's opinion that the input values listed in Tables 1 and 2 adequately model the slope in question. Rockfall analysis results are listed in Table 3.

TABLE 3. Summary of Rockfall Analysis Results

	Number of Rocks Passing AP	Velocity (ft/sec)		Bounce Height (ft)		Kinetic Energy (ft-lb)		Kinetic Energy (kilojoules)	
		Max	Avg	Max	Avg	Max	Avg	Max	Avg
Rock Shape = spherical; Rock Size = 3 ft (2,262 pounds),									
AP1	492	37.6	19.2	4.3	0.7	65,545	18,906	90	26
AP2	21	16.9	8.0	0.3	0.1	13,957	3,649	19	5
Rock Shape = spherical; Rock Size = 10 ft (86,394 pounds)									
AP1	499	52.9	35.7	3.9	1.1	4,570,623	2,240,805	6,197	3,038
AP2	497	33.2	20.8	2.7	0.7	1,846,786	800,467	2,504	1,085
Rock Shape = discoidal; Rock Size = 12 ft diameter by 5 ft thick (90,478 pounds)									
AP1	499	46.7	37.6	3.4	1.0	4,112,846	2,861,685	5,588	3,880
AP2	499	33.8	24.7	2.6	0.8	2,243,475	1,270,950	3,042	1,723

AP = analysis point
ft/sec = feet per second
ft-lb = foot-pounds

6.4 DISCUSSION OF ROCKFALL ANALYSIS RESULTS

The CRSP analysis results show that a 10 foot diameter, spherical limestone boulder rolling downslope along the rockfall study section from a source zone between 9040 and 9080 feet elevation will have an estimated maximum kinetic energy of 1,846,786 foot-pounds (ft-lb), an equivalent of about **2,500 kilojoules**, at the upslope property boundary. The slope gradually decreases between Analysis Point 1 and 2, resulting in a decrease in kinetic energy of a rolling rock between these points. The area of Cell Number 4 along the profile is a zonal transition from rockfall runout in Cell 3 to rockfall accumulation in Cell 5.

For comparison, the worst case scenario considered in the CRSP analysis performed by the CGS for Booth Falls was a spherical boulder 7 feet in diameter with an impact force of 5,000,000 ft-lb (**about 6,800 kilojoules**). This estimated energy is extreme when considering rockfall fences (flexible mesh barriers) currently on the market are rated for impacts up to a maximum of 8,000 kilojoules. The ground surface in the area of the slope analyzed at Booth Falls is generally steeper and vegetatively bare compared to the section analyzed for this study. CGS recommended the design height for the proposed rockfall mitigation structure be at least 12 feet, if placed at the analysis point located 30 feet upslope from the existing condominiums. An added option to mitigate for smaller rock fragments which tend to break from larger rockfalls, included adding a fence to the top of the berm or wall to be constructed. Cesare understands that for Booth Falls, a pair of soil walls reinforced with geotextiles and sized 8 feet high by 10 feet thick and 12 feet high and 12 feet thick were constructed after the 1997 rockfall event.

The nature of the ground surface at the project site acts to dissipate rockfall energies compared to the slope above Booth Falls. The ground surface on the west side of the site is comparatively less steep, heavily vegetated with aspen trees and large shrubs, dotted with scattered, embedded boulders, with incised drainages that act to channel and slow rockfalls. Vegetation, incised drainages, and embedded boulders act to increase surface roughness of the slope, creating obstacles which decrease rockfall energies. Comparison of the ground surface characteristics and the CRSP results for both the project site and the neighboring Booth Falls indicates the rockfall hazard is higher for the Booth Falls area than for the project site.

7. LANDSLIDE HAZARD MAPPING

The extents of a large landslide complex were mapped on the east side of the site (Figure 7). A landslide study section passes through the middle of the landslide, location shown on Figure 8 and profile shown on Figure 10. The landslide study section begins upslope above an exposed outcrop comprised of Robinson Limestone at about 8900 to 8920 feet elevation and extends southward to Fall Line Drive, with a total elevation change of about 588 over a profile length of 1,220 feet. The elevation of the Robinson Limestone bedrock exposure can be correlated to the rock exposures to the west which are the primary rockfall source zone for the Booth Falls subdivision, although the outcrop on the subject site is not as pronounced or as exposed as areas to the west. Based on the landslide morphology visible in the LiDAR image, this bedrock exposure at about elevation 8900 likely slid down from a higher elevation upslope.

The LiDAR bare earth surface and the landslide study section both display a benched and hummocky pattern characteristic of landslide terrain. The flatter parts of the benched areas range from about 15 to 20 degrees, while the toe areas of the benches range from about 30 to 40 degrees. A slope map is shown on Figure 11 and depicts the range of slope angles across the site and surrounding area.

Cesare understands that the Pitkin Creek townhome development located southeast of the site and also at the toe of the mapped landslide extents has not reinforced the slope above the residences. It was beyond the scope of this study to research potential landslide movement causing distress to the Pitkin Creek development townhomes, and at this time Cesare is not aware of landslide movement or related structural distress in the southeast area of the site. Chen and Associates, Inc. (Chen) issued a soil and foundation investigation report for the proposed Pitkin Creek Townhomes (dated September 20, 1978) which included subsurface exploration using test pits to a maximum depth of 10 feet. The soils encountered were described as 1 to 3 feet of topsoil over dense, sandy gravel, with cobbles and boulders to the maximum depth explored. Groundwater was not encountered in the test pits. The Chen report mentions how the slope of the site rises steeply to the north and that several large boulders were observed on the ground surface, but does not discuss landslide or rockfall hazard or potential.

8. CONCLUSIONS AND RECOMMENDATIONS

This report presents findings of a geologic hazard study specifically focused on rockfall. During the course of the study, a significant landslide hazard was identified and is discussed in this report.

8.1 ROCKFALL CONSIDERATIONS

Based on the CRSP analysis results and existing rockfall mitigation structures on the neighboring site to the west, a rockfall barrier or wall at least 12 feet in height is recommended. Based on site conditions, including such aspects as slope angle and property boundaries, a rigid wall would be more ideal than a flexible fence or berm/basin. The flexible fence system would require a downslope buffer zone for flexure during rockfall events. A berm and basin system would require a significantly sized footprint on the slope, something this project site does not necessarily have flexibility towards. Cesare's CRSP model represents an estimate of rockfall energies at the analysis point placed at the upslope property boundary along the section line and is not representative of other locations on the slope. Changing the placement of the rockfall barrier will require changing the location of the analysis point. Rockfall energies were modeled to be significantly higher at Analysis Point 1 located 200 feet upslope from the property.

A catchment zone large enough for accumulation of boulders and for equipment to access the area behind the barrier will be necessary, a width of at least 10 or more feet. It is the responsibility of the wall designer to provide criteria for a wall that will withstand impacts with the sizes and energies predicted by the CRSP analysis, and one which will allow for successful implementation of recommended maintenance requirements. For rigid rockfall walls similar to those constructed at the Booth Falls site, the height to width ratio is typically a 1:1 relationship. The rockfall catchment will be reducing the rockfall hazard for a potential residential development and should be designed with consideration for the nature of the structures (full-time occupancy).

8.1.1 Placement of the Rockfall Catchment Structure

Factors which influence the placement of the catchment structure include the rockfall energies, sizes, shapes, and bounce heights estimated in the CRSP model for that analysis point on the slope. Other considerations include site topography, site boundaries, and the spatial footprint of the proposed rockfall catchment structure. The mitigation structure must provide an adequately sized catchment zone behind the wall and a buffer zone in front of the wall. The catchment zone behind the wall must be sized to allow for accumulation of large boulders on the scale of 10 feet in diameter, as well as access for equipment to remove accumulated debris from behind the wall. Design considerations should include access for excavation equipment and adequate surface drainage. Based on topography, the west side of the property provides adequate access for a track mounted vehicle from Fall Line Drive and possibly a rubber tire vehicle (although access depends on actual site development/grading plans, not available at the time of this study).

An adequately sized buffer zone in front of the wall is necessary in order to allow for a certain amount of potential outward deflection in the event of an impact. The amount of deflection depends on the type of wall to be constructed. The downslope buffer zone must be designed and maintained as an open, empty space. The type of catchment structure has not been decided, and may vary from a flexible barrier to a more rigid design, so it is important that this buffer zone is a consideration during design stages. A flexible catchment fence will require more consideration of outward deformation than a rigid wall, and will require a conservatively sized buffer zone. The intent of flexible barriers is to slow the velocity and decrease the energy of the falling rock, not necessarily to stop it completely. Rigid barriers have the limitation of being prone to damage during high energy events, but this is generally the case with most constructed rockfall barriers. The barrier should be designed to withstand the types of energies predicted by CRSP analysis results described in this report. The catchment structure will require periodic and routine cleaning of the accumulation areas to remove debris.

The rockfall remediation should be designed, constructed, and maintained to ensure hazards impacting adjacent or downslope properties are not aggravated. In its current condition, the western half of the site is impacted by rockfall consisting of boulders the size of 10 feet or more. These boulders have historically rolled and slid down the slope from the steep cliff faces exposed upslope from the site. The vegetative cover on the slope above the project site acts to slow rockfall events in its current condition. If this vegetative cover were to be removed for some reason (e.g. clear cutting, wildfire), these obstacles would be removed and the rockfall hazard would increase.

8.2 LANDSLIDE CONSIDERATIONS

Cesare did not observe evidence of recent landslide movement at the project site. The retaining wall for the Town of Vail shuttle stop which is located at the toe of the landslide, appears to be performing adequately. The landslide area displays benched and hummocky topography with over-steepened toe and flank areas, however, fresh landslide features, such as tension cracks, scarps, slumps, and other features, were not observed. Figure 7 shows the bare earth land surface and provides a convincing depiction of the landslide extents. Cesare is not aware of landslide movement causing distress to the townhomes in the Pitkin Creek subdivision notched into the toe near the southeast corner of the site.

Based on the lack of evidence of recent landslide movement as observed onsite and through aerial photographs and LiDAR imagery, Cesare does not recommend monitoring of the landslide at this time. Slope stability should be a primary consideration if ground modifications and development are planned in or near the landslide mass. The landslide has the potential to destabilize if the ground is disturbed or modified in adverse ways. Slope stability of the over-steepened toe and flank areas, as well as large-scale global stability should be considered. In addition, the bedrock is dipping gently out-of-slope, exacerbating the slope instability issue.

8.3 DEBRIS FLOW CONSIDERATIONS

Although the site is not within the limits of the Town of Vail Debris Flow Hazard zone, there exists the potential for debris flows at the site. Material and debris which could mobilized in a debris flow event cover the slopes at and above the site, including glacial till capping the ridge above, and rock talus and colluvium on the slope above the site. Incised drainages actively flowing with water are present on the west side of the site, and ground surface patterns visible in the LiDAR imagery suggest erosive processes are underway in this area. A significant precipitation event has the potential to trigger or increase the probability of a debris flow event, additionally, ground modifications may alter or increase this debris flow hazard in some areas. Cesare recommends the debris flow hazard potential be considered in future development stages.

9. LIMITATIONS

This report has been prepared for the exclusive use of our client for specific application to the project discussed and has been prepared in accordance with generally accepted geologic and geotechnical engineering practices. No warranties, either expressed or implied, are intended or made. In the event that changes in the nature, design, or location of the project as outlined in this report are planned, the conclusions and recommendations contained in this report shall not be considered valid unless Cesare reviews the changes and either verifies or modifies the conclusions of this report in writing.

W:\2017\Summit\17.5000\17.5029.A Vail Valley Rockfall Analysis\ACAD\Figure 1 Site Location Map.dwg 6/15/2017 4:48 PM

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FIGURE 1
Site Location Map

PROJECT NO:	17.5029
PROJECT NAME:	Rockfall Hazard Study, East Vail Parcel
DRAWN BY:	RAB
CHECKED BY:	JMF
DWG DATE:	06.16.17
REV. DATE:	--

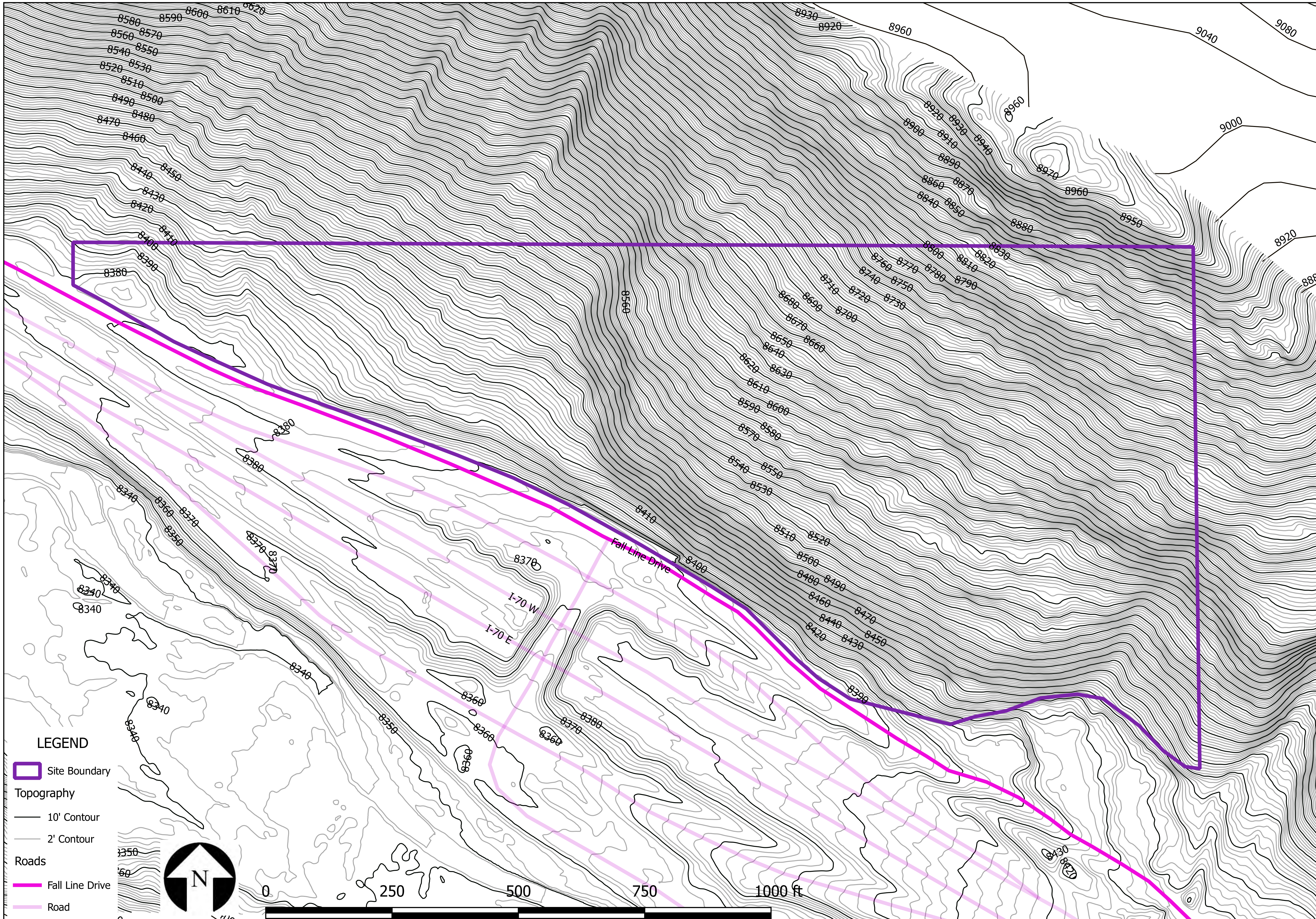

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FIGURE 2
Topographic Map

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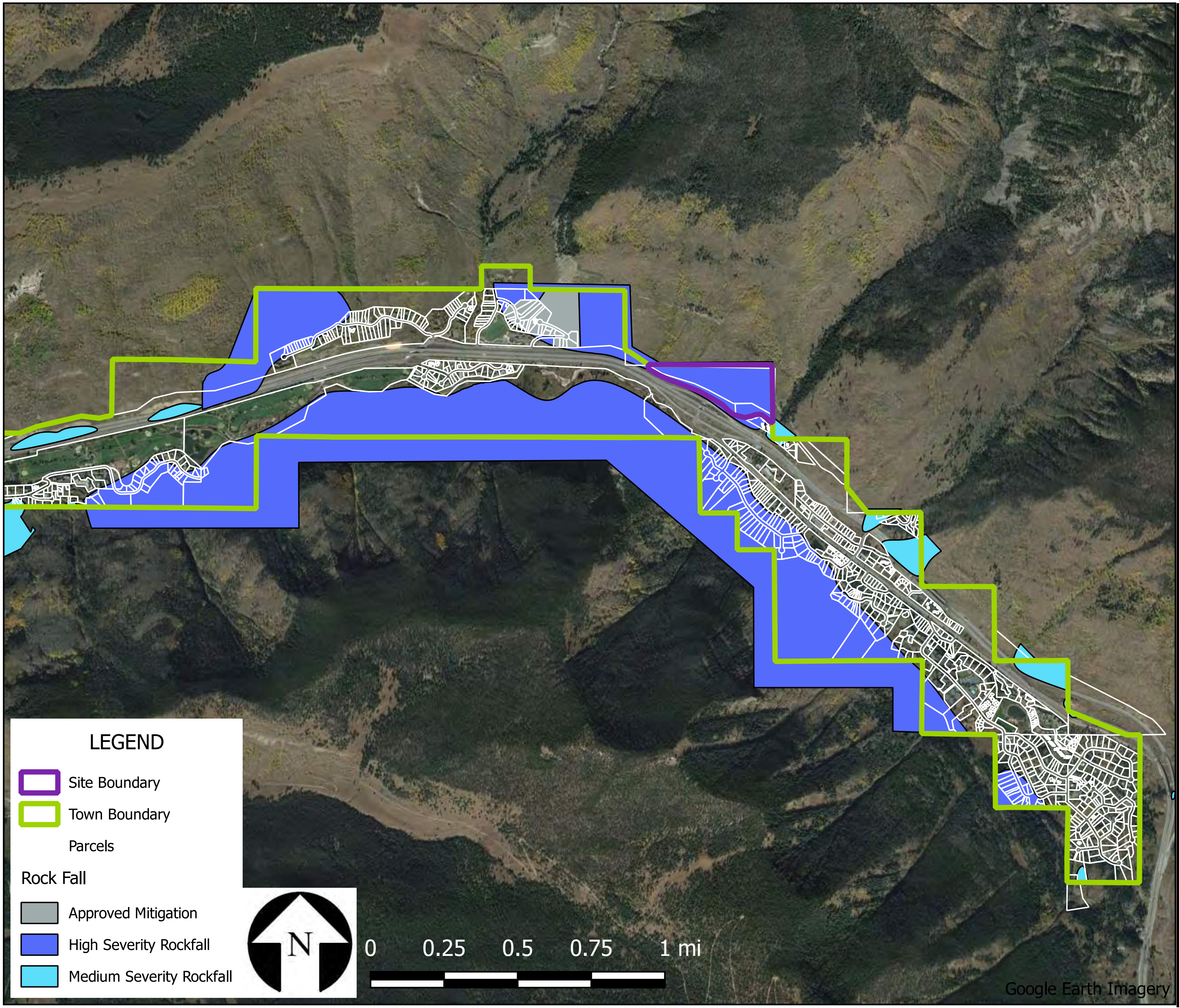

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FIGURE 3
Official Rockfall Hazard Map
Town of Vail, Colorado

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PROJECT NAME:	Rockfall Hazard Study, East Vail Parcel
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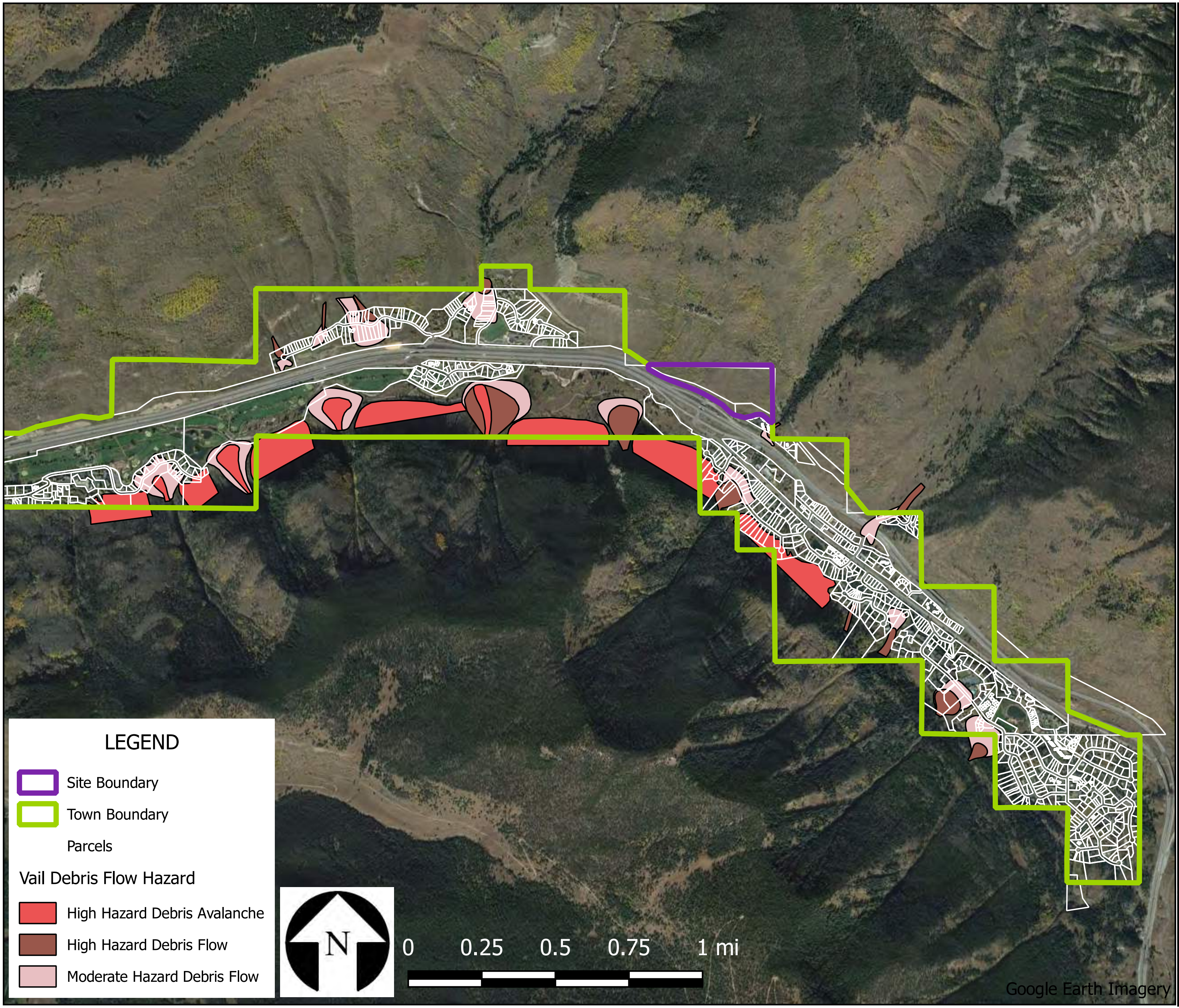

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FIGURE 4
Official Debris Flow Hazard Map
Town of Vail, Colorado

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PROJECT NAME:	Rockfall Hazard Study, East Vail Parcel
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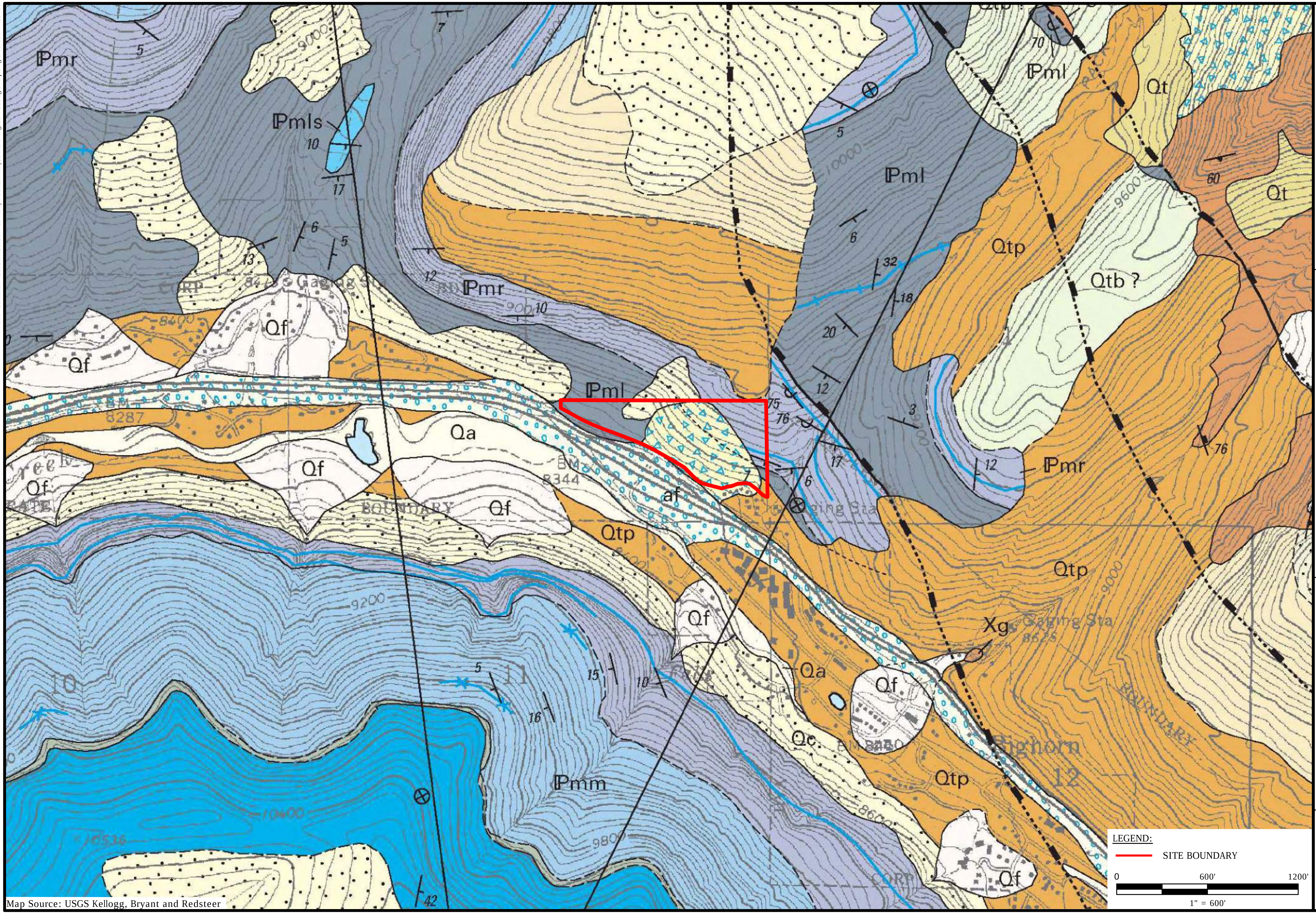

Map Source: USGS Kellogg, Bryant and Redsteer

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FIGURE 5
Geologic Map

PROJECT NO:	17.5029
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W:\2017\Summit\17.5000\17.5029.A Vail Valley Rockfall Analysis\ACAD\Figure 5 Legend for Figure 4 Geologic Map.dwg 6/15/2017 4:57 PM

Map Source: USGS Kellogg, Bryant and Redsteer

LIST OF MAP UNITS

s	**Snowfield (latest Holocene)**
af	**Artificial fill (latest Holocene)**
Qa	**Alluvium (Holocene)**
Qlsy	**Recent landslide deposits (Holocene)**
Qf	**Fan deposits (Holocene and upper Pleistocene)**
Qt	**Talus (Holocene and upper Pleistocene)**
Qdf	**Debris-flow deposits (Holocene and upper Pleistocene)**
Qr	**Rock-glacier deposits (Holocene and upper Pleistocene)**
Qw	**Wetland deposits (Holocene and upper Pleistocene)**
Qac	**Alluvium and colluvium, undivided (Holocene and upper Pleistocene)**
Qc	**Colluvium (Holocene and upper Pleistocene)**
Qls	**Landslide deposits (Holocene and upper Pleistocene)**
Qfm	**Felsenmeer (Holocene and Pleistocene)**
Qbf	**Boulder field (upper? Pleistocene)**
Qtp	**Pinedale Till (upper Pleistocene)**
Qtb	**Bull Lake Till (middle Pleistocene)**
Qd	**Diamicton (middle to lower Pleistocene)**
Ti	**Dike rocks of intermediate to felsic composition (Tertiary)**
PIPm	**Maroon Formation (Lower Permian to Middle Pennsylvanian)**
IPm	**Minturn Formation, undifferentiated (Middle Pennsylvanian)**
IPmj	**Jacque Mountain Limestone Member**
IPmu	**Upper sandstone and conglomerate member**
IPmwq	**White Quail Limestone Member**
IPmm	**Middle member**
IPmml	**Individual limestone bed**
IPmr	**Robinson Limestone Member**
IPmrl	**Individual limestone bed**
IPml	**Lower member**
IPmls	**Individual limestone bed**
IP€u	**Pennsylvanian to Cambrian units, undifferentiated**—Shown on cross section B-B' only
Pzcd	**Clastic dike (lower Paleozoic?)**
Dp	**Parting Formation (Upper Devonian)**
€p	**Peerless Formation (Upper Cambrian)**
€s	**Sawatch Quartzite (Upper Cambrian)**

EARLY PROTEROZOIC ROCKS

Xu	**Early Proterozoic rocks, undifferentiated**—Shown only in cross sections
	Rocks of the Cross Creek batholith (Early Proterozoic)
Xap	**Aplitic granite**
Xg	**Cross Creek Granite**
Xdi	**Diorite**
Xgb	**Gabbro**
Xm	**Migmatitic biotite gneiss (Early Proterozoic)**
Xbg	**Biotite gneiss (Early Proterozoic)**

Contact—Dashed where approximately located; dotted where concealed; showing dip where known

Fault or prominent fracture—Dashed where approximately located; dotted where concealed. Showing dip where known. For some faults, no apparent offset interpreted from air photographs

Normal fault—Dashed where approximately located; dotted where concealed. Ball and bar on downthrown side. Dip of fault plane shown where known

Reverse fault—Dashed where approximately located; dotted where concealed; rectangles on upper plate

Thrust fault—Dotted where concealed. Teeth on upper plate. Dip of fault plane shown where known

Strike-slip fault—Dashed where approximately located; dotted where concealed; arrows show relative slip direction

Mylonitic shear—Generally parallel to Proterozoic Homestake shear zone (Tweto and Sims, 1963)

Anticline—Showing trace of axial plane. Dotted where concealed

Syncline—Showing trace of axial plane. Dotted where concealed

Strike and dip of beds
- Inclined
- Vertical
- Overturned
- Horizontal

Approximate strike and dip of beds
- Inclined

Strike and dip of foliation
- Inclined
- Vertical

Bearing and plunge of lineation

Strike and dip of foliation and bearing and plunge of associated lineation

Strike and dip of small fault or fracture
- Inclined
- Vertical

A **Letter indicates locality referred to in text**

CONVERSION FACTORS

Multiply	By	To obtain
centimeters (cm)	0.3937	inches (in.)
meters (m)	3.281	feet (ft)
kilometers (km)	0.6214	miles (mi)

Multiply	By	To obtain
inches (in.)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)

INDEX MAP SHOWING SURROUNDING QUADRANGLES

PROJECT NO:	17.5029		
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FIGURE 6
Legend for Geologic Map Figure 5

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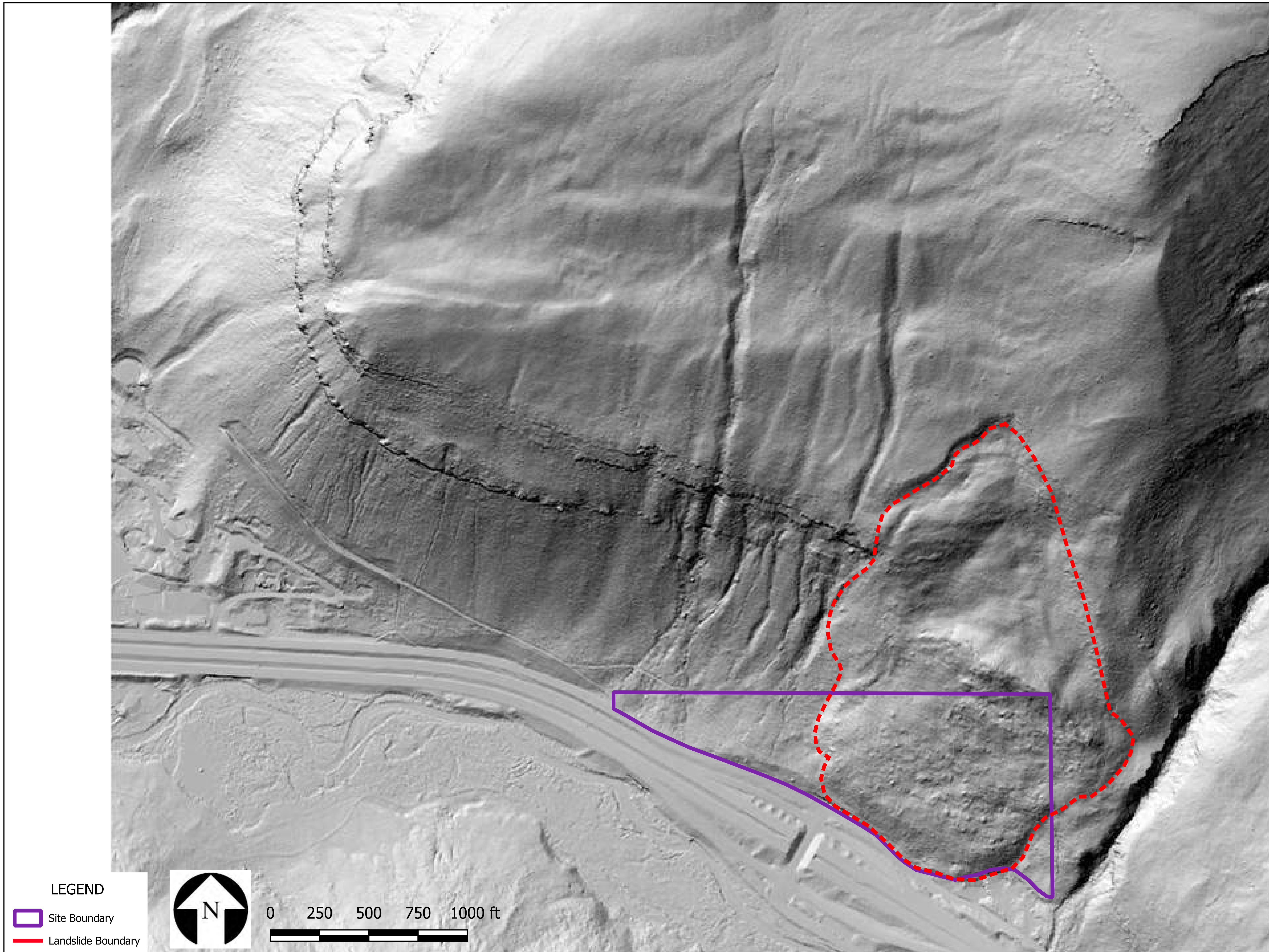

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FIGURE 7
Landslide Extents Map

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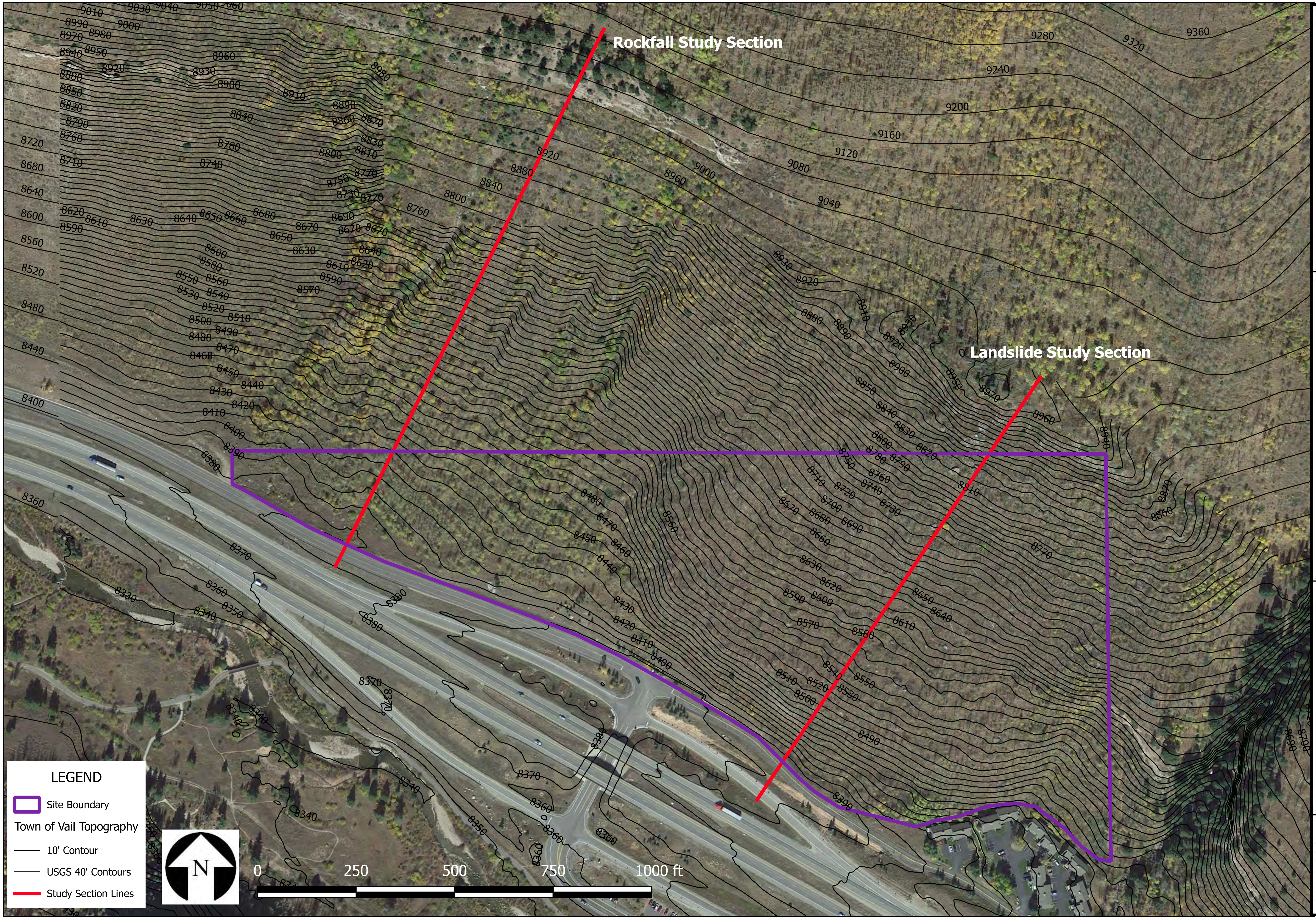

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FIGURE 8
Study Sections Map

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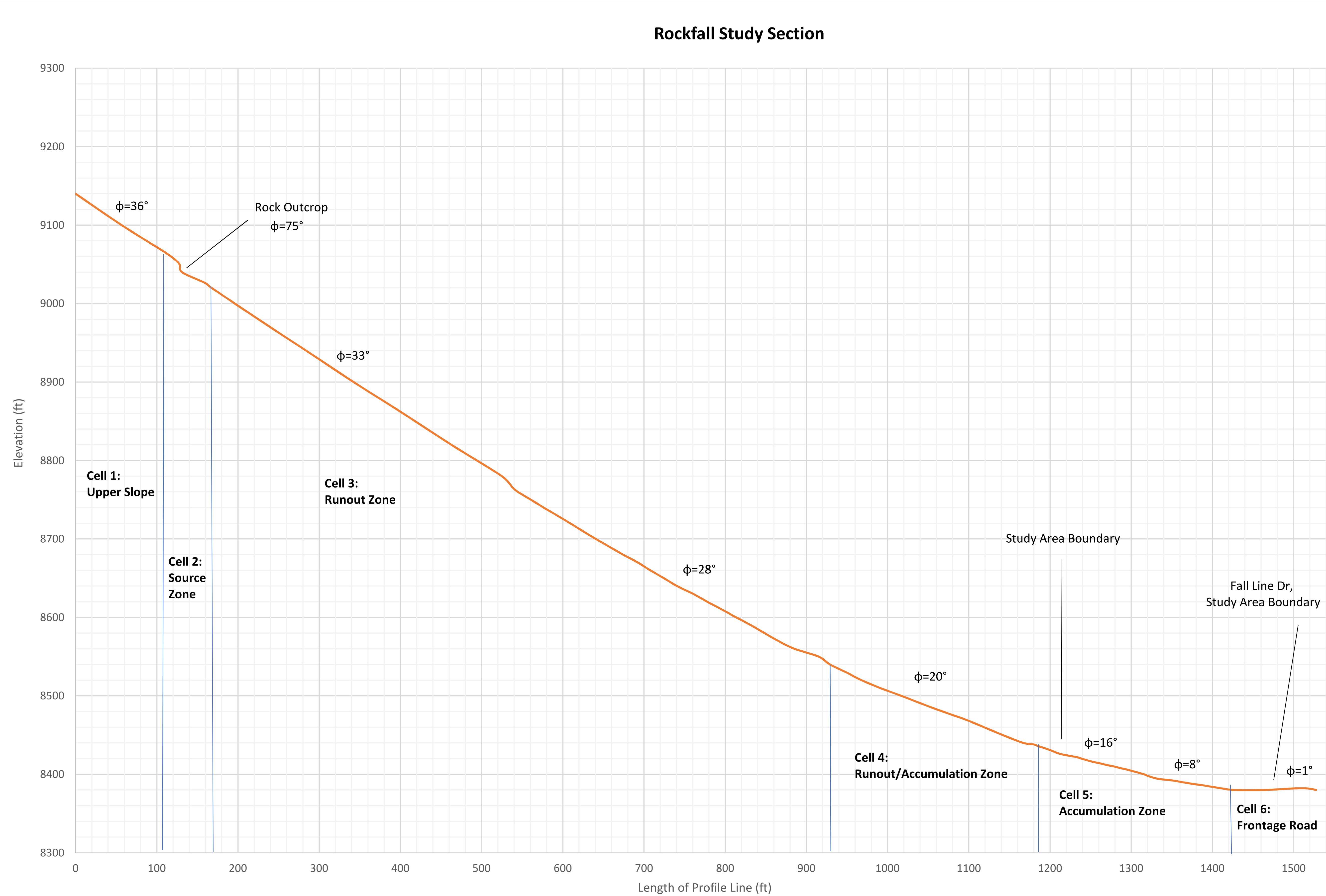

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FIGURE 9
Rockfall Study Section

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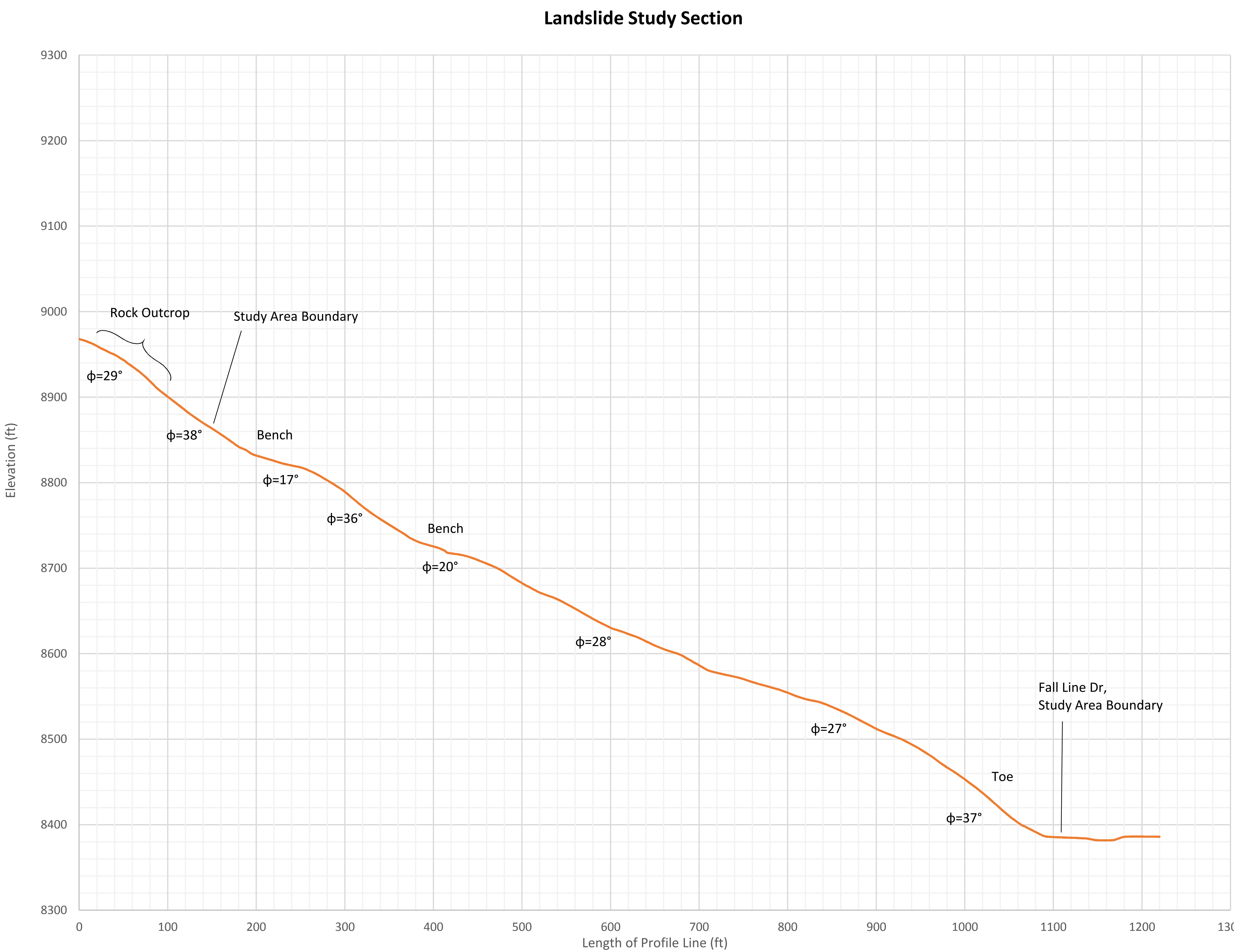

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FIGURE 10
Landslide Study Section

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REV. DATE:	

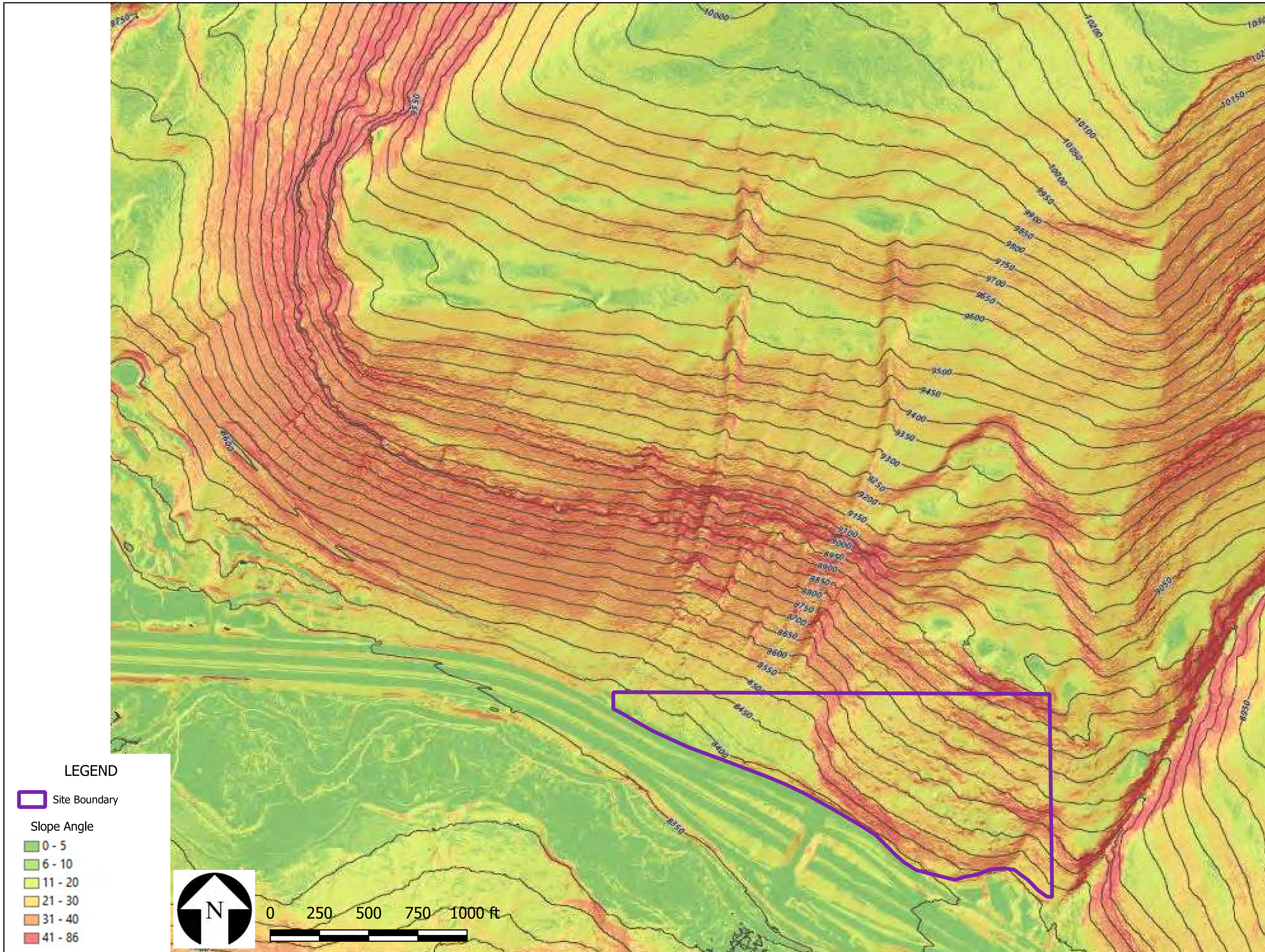

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FIGURE 11

Slope Map

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APPENDIX A

Documents and Drawings Reviewed
References

DOCUMENTS REVIEWED

DOC1. Chen and Associates, Inc., Soil and Foundation Investigation for Proposed Pitkin Creek Townhouses Near Interstate Highway 70, East Vail, Eagle County, Colorado, Project No. 17,046, dated September 20, 1978.

DOC2. Chen and Associates, Inc., Geologic Hazards Reconnaissance, Lot 11, Block 1, Vail Village 12th Filing, Vail, Colorado, Project No. 25,474, dated January 26, 1983.

DOC3. Colorado Geological Survey, Rockfall Hazard Assessment at Booth Falls Condominiums, and Proposed Mitigation, prepared for the Town of Vail, Colorado, undated.

DOC4. Nicolas Lampiris, letter re: Unit #13, Pitkin Creek Townhomes, prepared for Nedbo Construction Company, dated September 12, 1987.

DRAWINGS REVIEWED

DWG1. Topographic Map of a Portion of the South 1/2 of the Southeast 1/4 of Section 2, Township 5 South, Range 80 West, Town of Vail, Eagle County, Colorado, prepared by Peak Land Consultants, Inc., dated January 10, 2017.

REFERENCES

REF1. Kellogg, K.S., Bryant, B., Redsteer, M.H., 2003, Geologic Map of the Vail East Quadrangle, Eagle County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2375, Version 1.1.

REF2. Kellogg, K.S., Shroba, R.R., Premo, W.R., Bryant, B., 2011, Geologic Map of the Eastern Half of Vail 30′ x 60′ Quadrangle, Eagle, Summit, and Grand Counties, Colorado: U.S. Geological Survey Scientific Investigations Map 3170.

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APPENDIX B

Rockfall Hazard Assessment at Booth Falls Condominiums and Proposed Mitigation
(Colorado Geological Survey)

ROCKFALL HAZARD ASSESSMENT AT BOOTH FALLS CONDOMINIUMS
AND PROPOSED MITIGATION

prepared for
The Town of Vail, Colorado

by
Jonathan L. White

Colorado Geological Survey
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fax (303) 894-2174

CONTENTS

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.

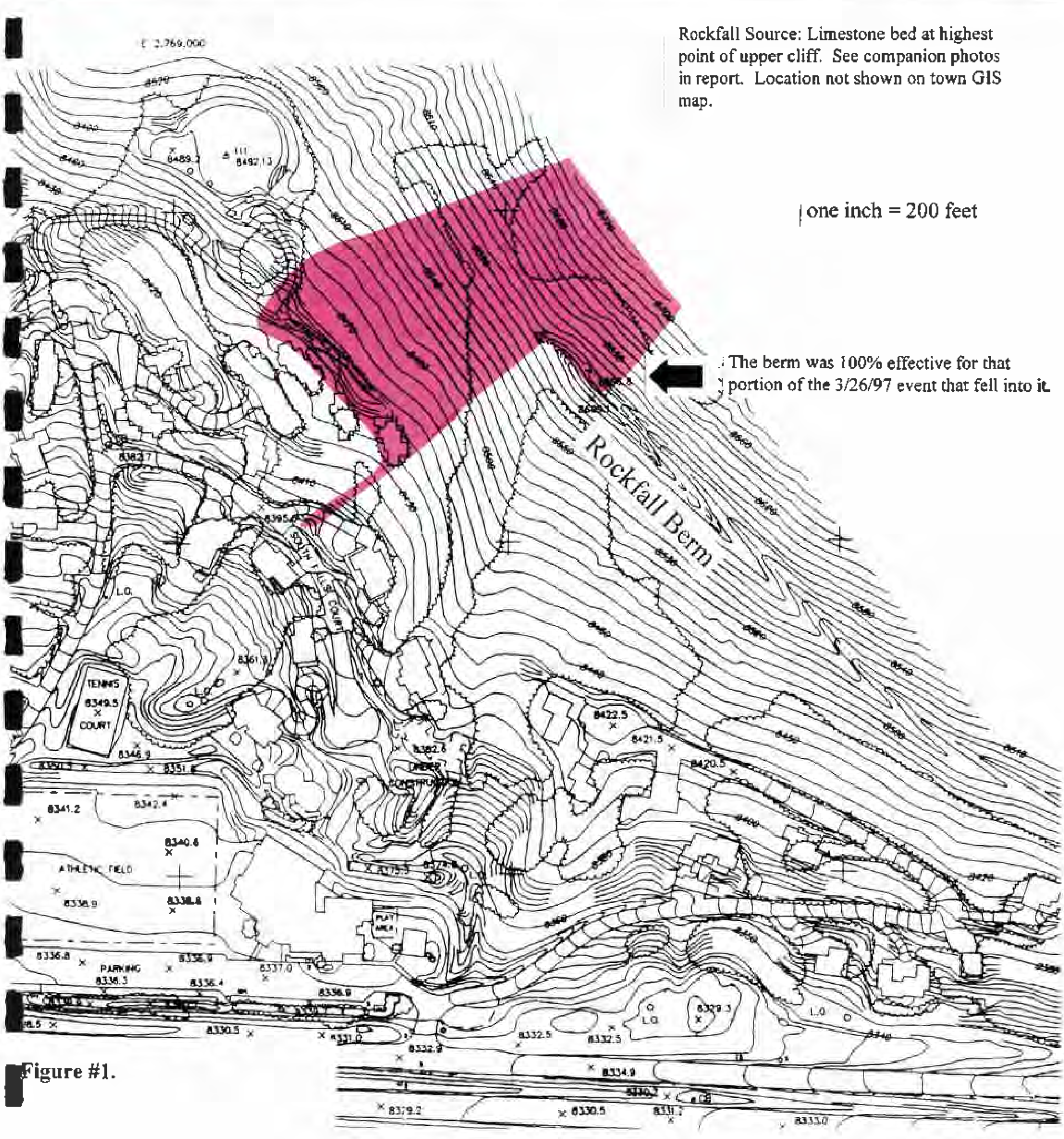

Figure #1.

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 <u>entire</u> 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 <u>will</u> 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

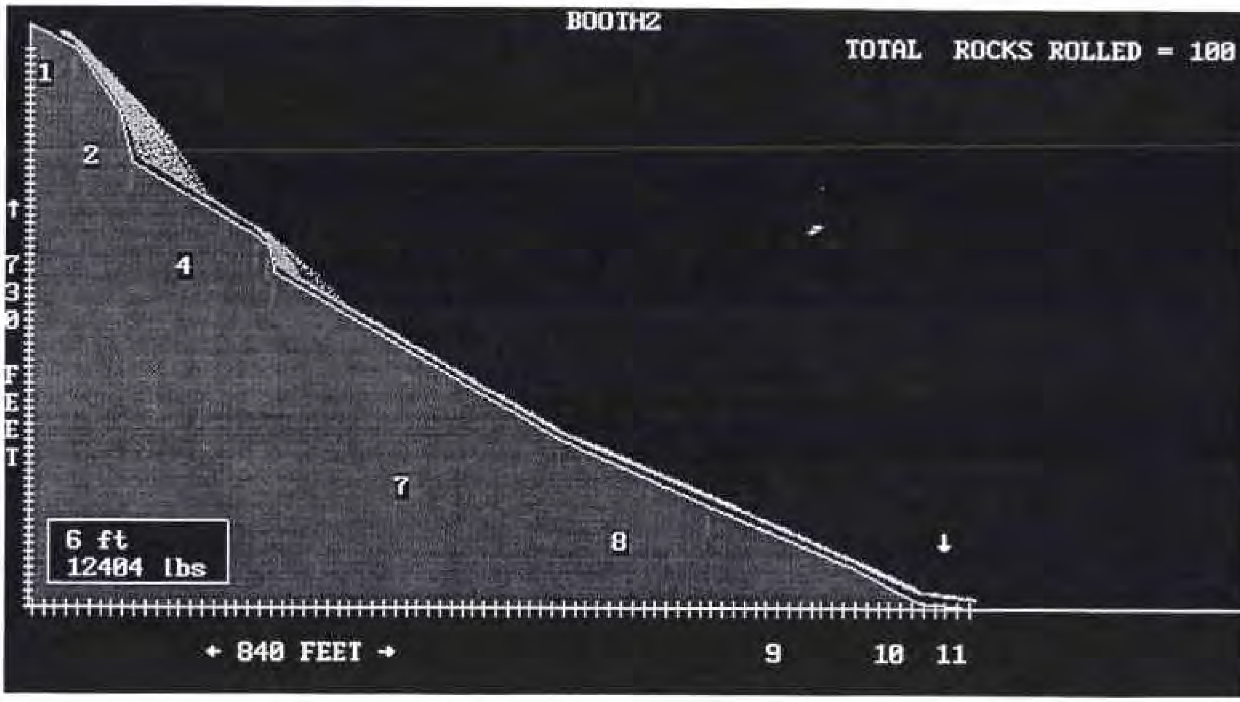

Figure 2. Screen dump of CRSP program of Booth Creek-west side. Analysis point arrow is 30 feet above condominiums. Horizontal and vertical are not at the same scale.

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.

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.**

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

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-

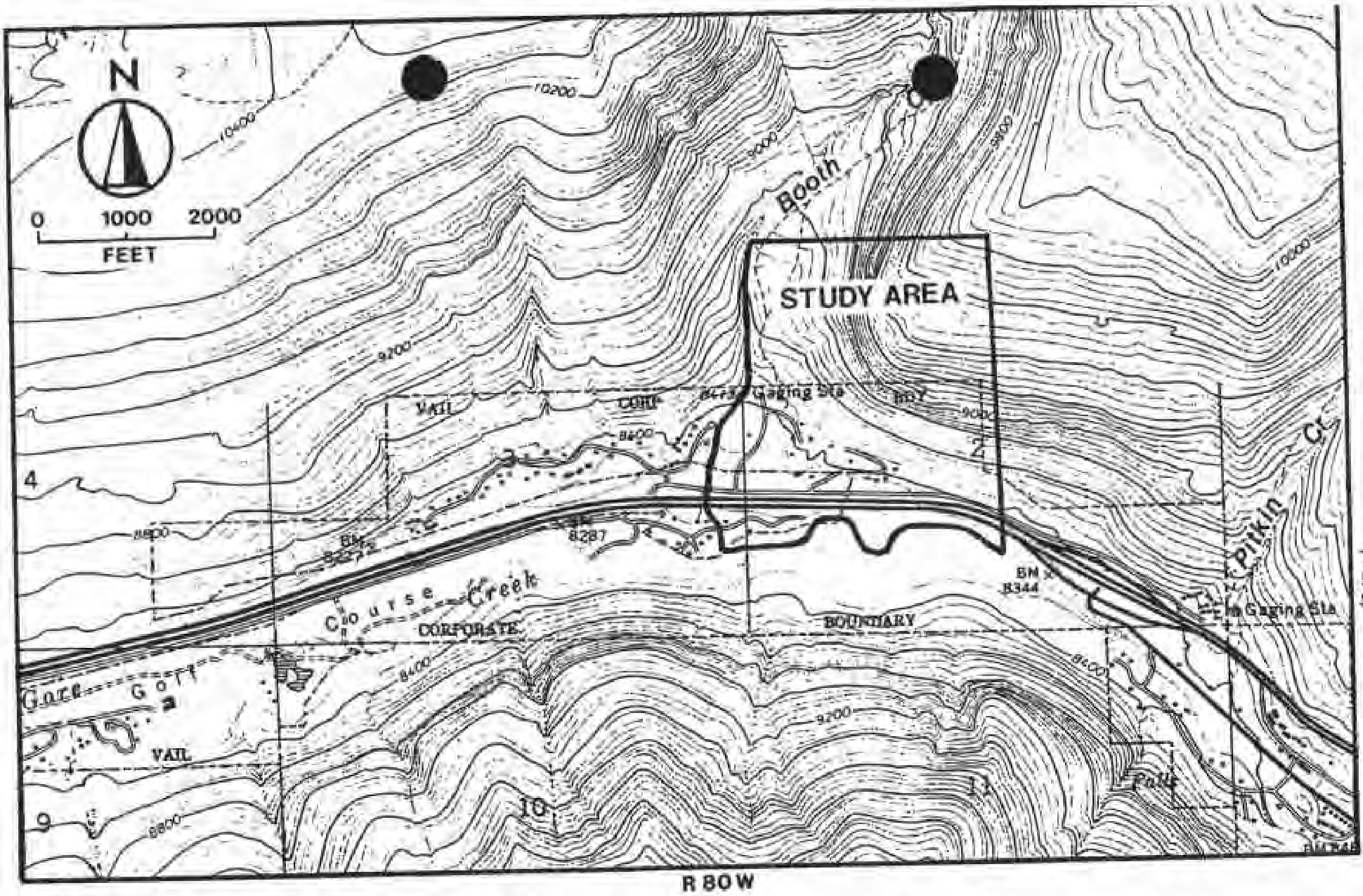

Figure 1. Location map of study area, scale, 1:24,000

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

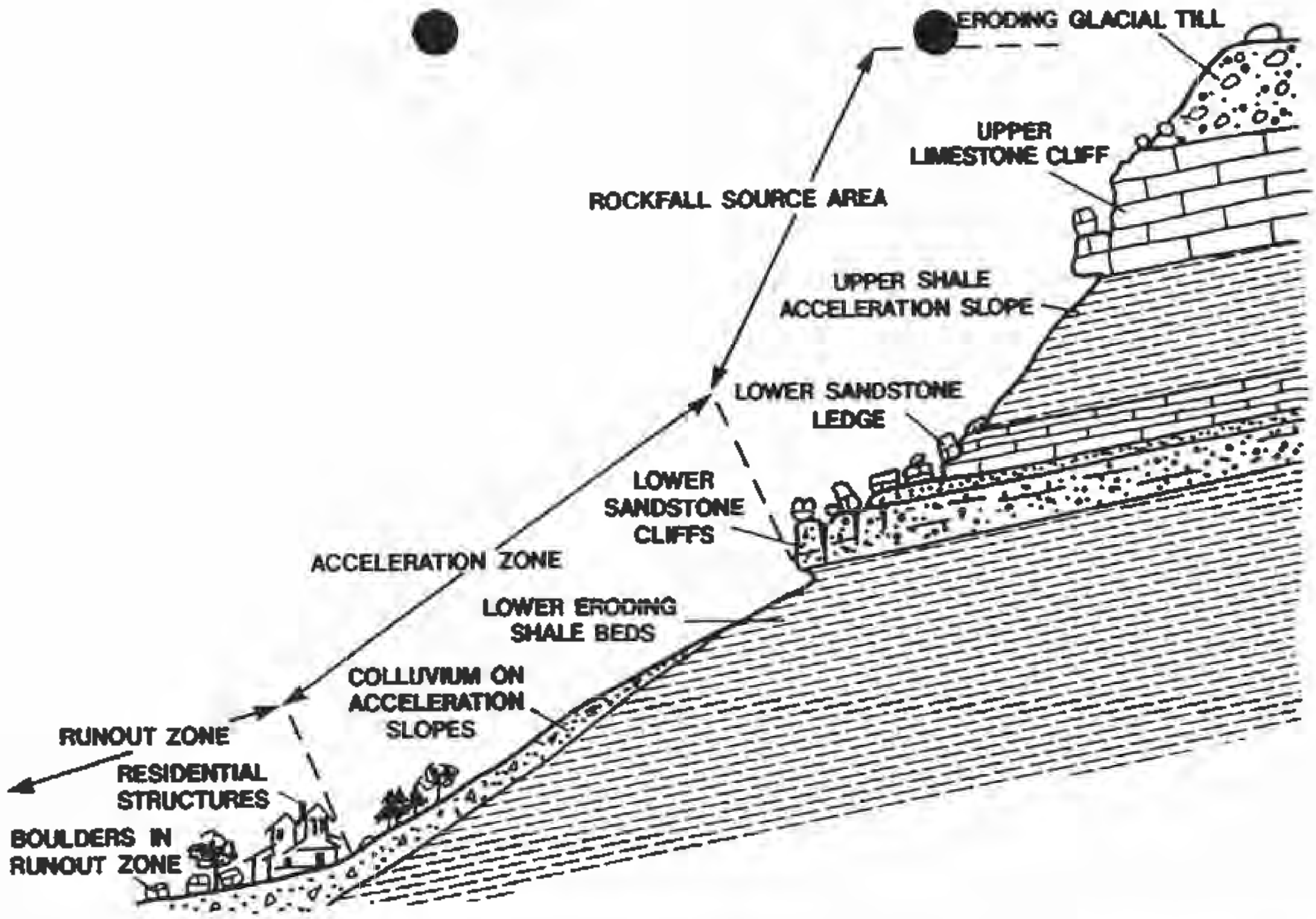

Figure 2. Geologic diagram of compound rock-fall slopes in study area. Drawn to scale with no vertical exaggeration. Note dip of strata toward valley.

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

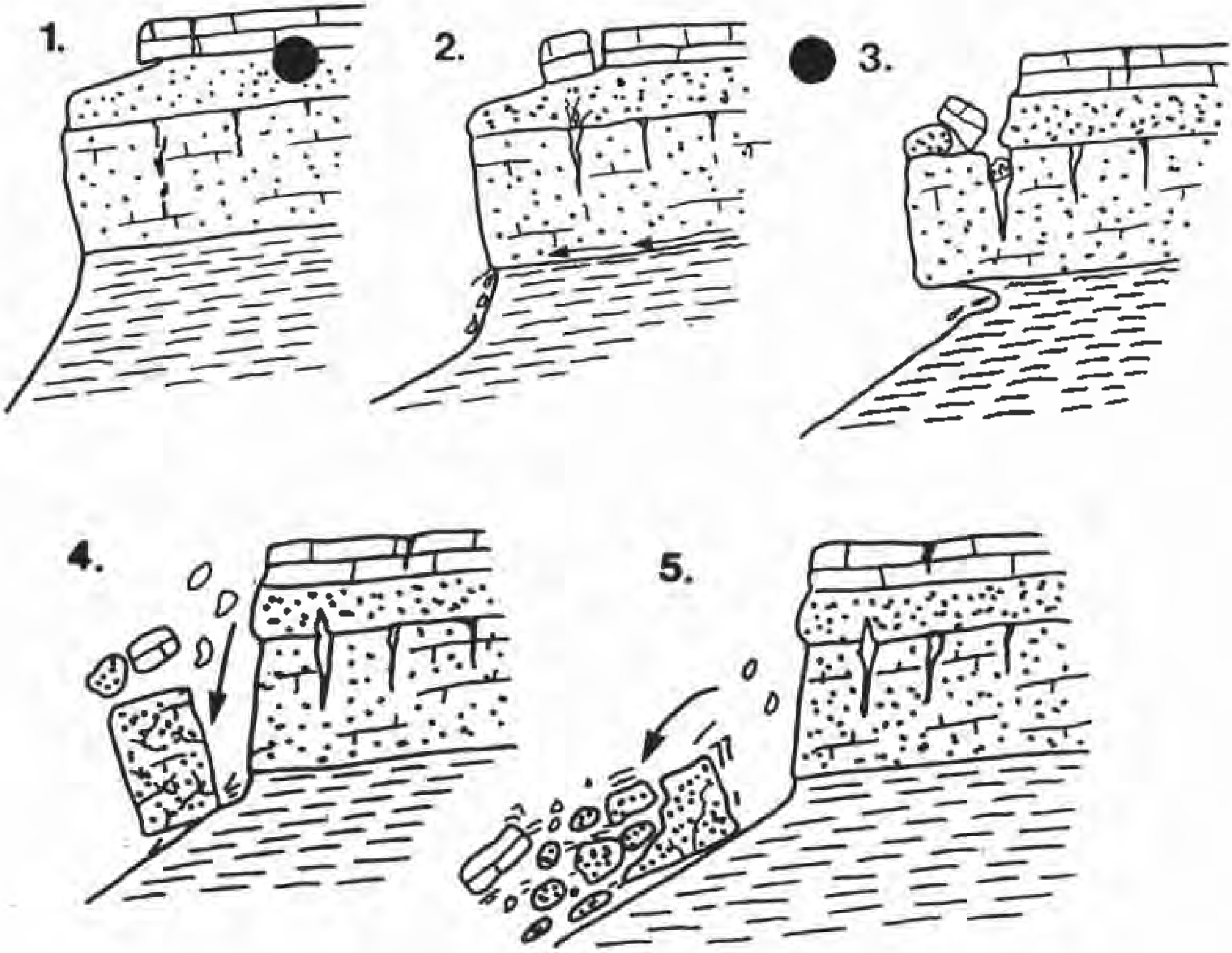

Figure 3. Toppling Slab-failure Sequence. 1. Initial cliff configuration. 2. Differential weathering of soft shale begins to undercut massive cliff forming slabs. Joints open and widen due to slope creep and frost wedging. Springs issue from contact beneath cliff. 3. Undercutting continues. Joints widen 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.

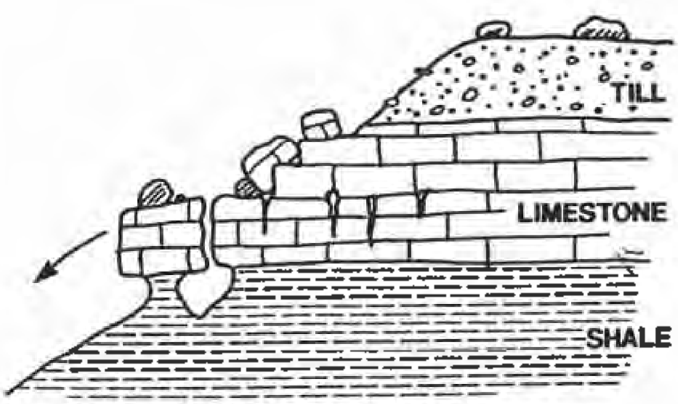

Figure 4. Limestone slabs resting on weak shale pedestals, upper cliff source area.

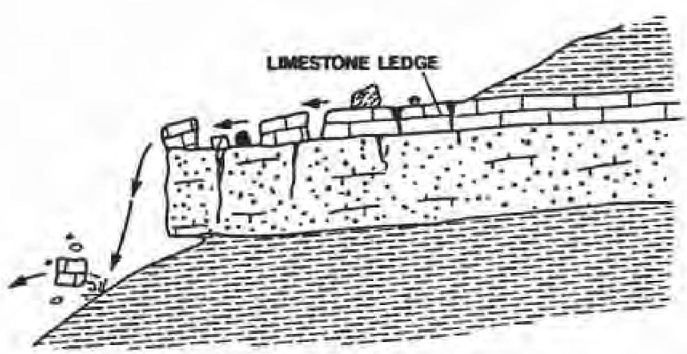

Figure 5. Slope creep causing limestone blocks to move down bedding planes and off lower cliff edge. Blocks are generally 2 ft x 3 ft. This mechanism is responsible for frequent rock falls in the study area.

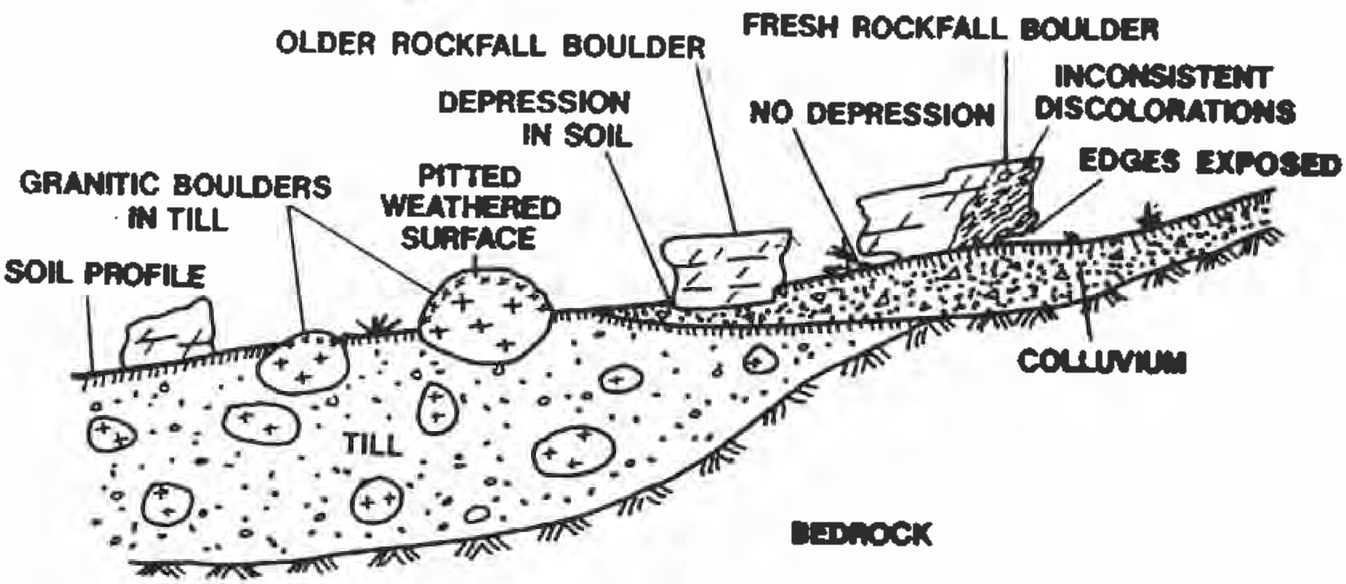

Figure 6. Physical differences between rockfall and glacially deposited boulders in runout zone. Rockfall boulders are all limestone or sandstone, while glacial boulders are mostly rounded granite or metamorphic lithologies. Note that soil exists below rockfall boulders, while it is absent beneath glacial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

Jonathan L. White
Colorado Geological Survey

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 . 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.)

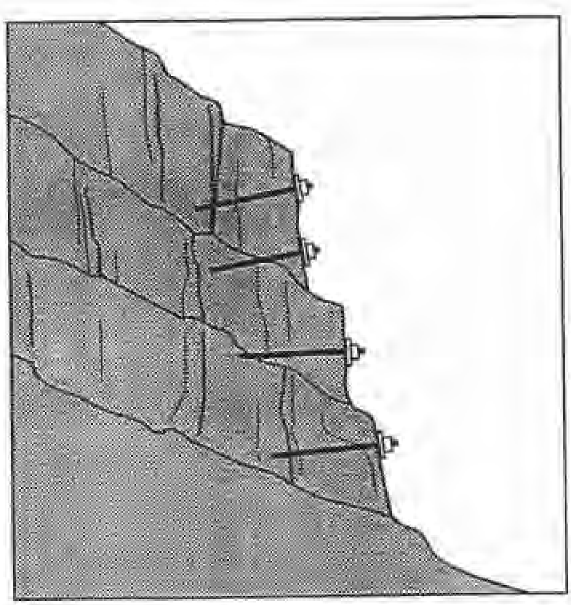

Figure 1. Rockbolts and dowels.

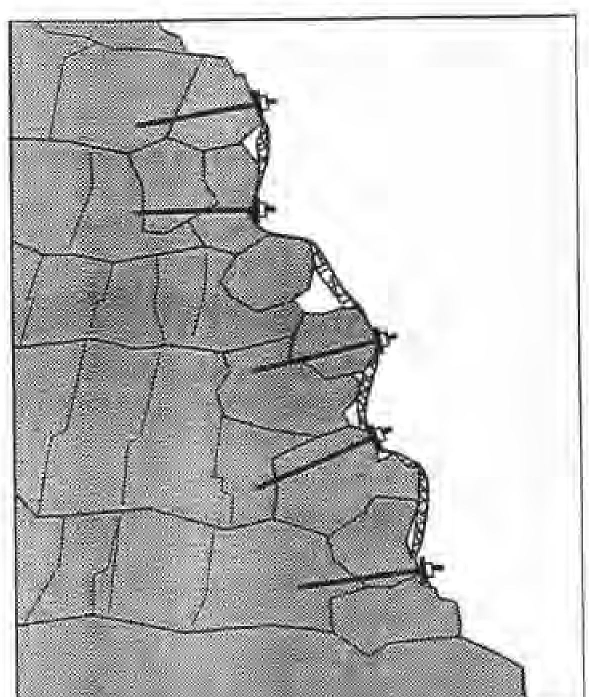

Figure 2. Anchored mesh or nets.

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.)

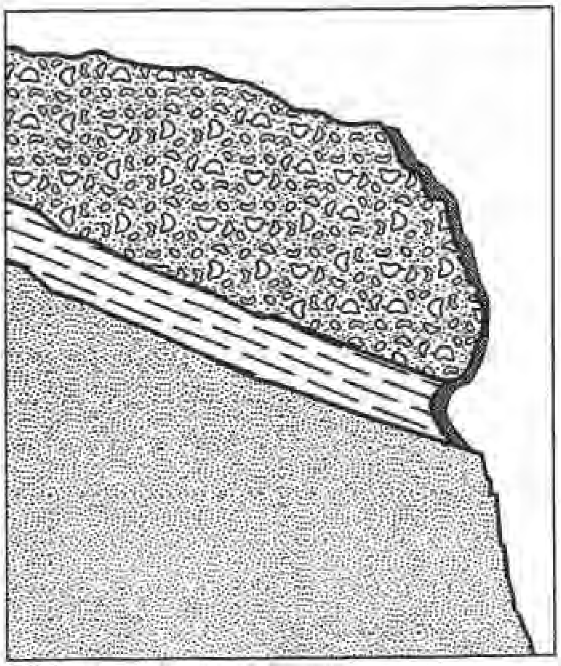

Figure 3. Shotcrete.

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.

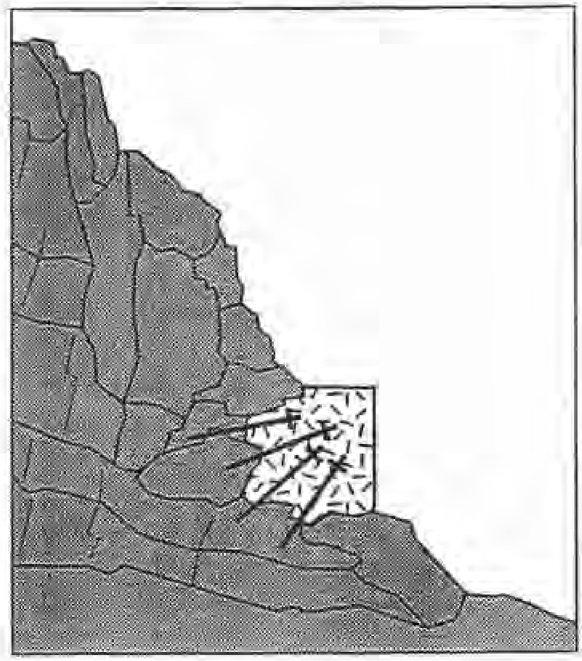

Figure 4. Anchored concrete buttress.

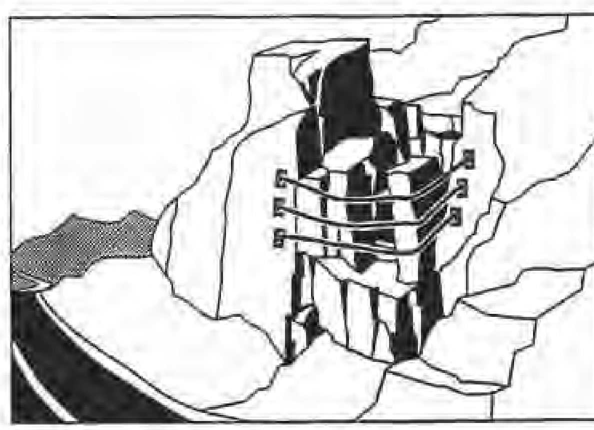

Figure 5. Cable lashing.

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.)

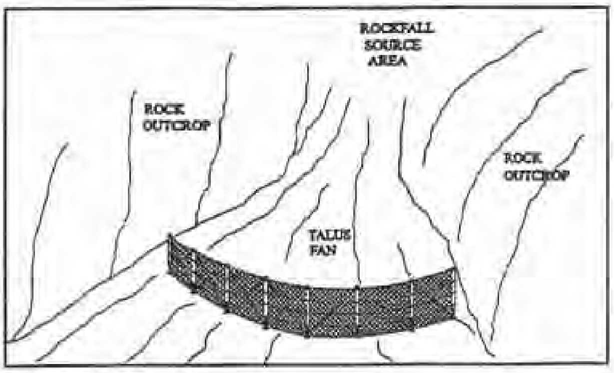

Figure 6. Rockfall fence.

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.)

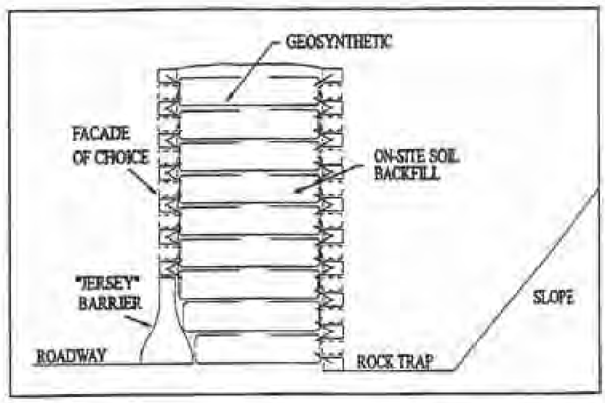

Figure 8. Mechanically stabilized backfill barrier.

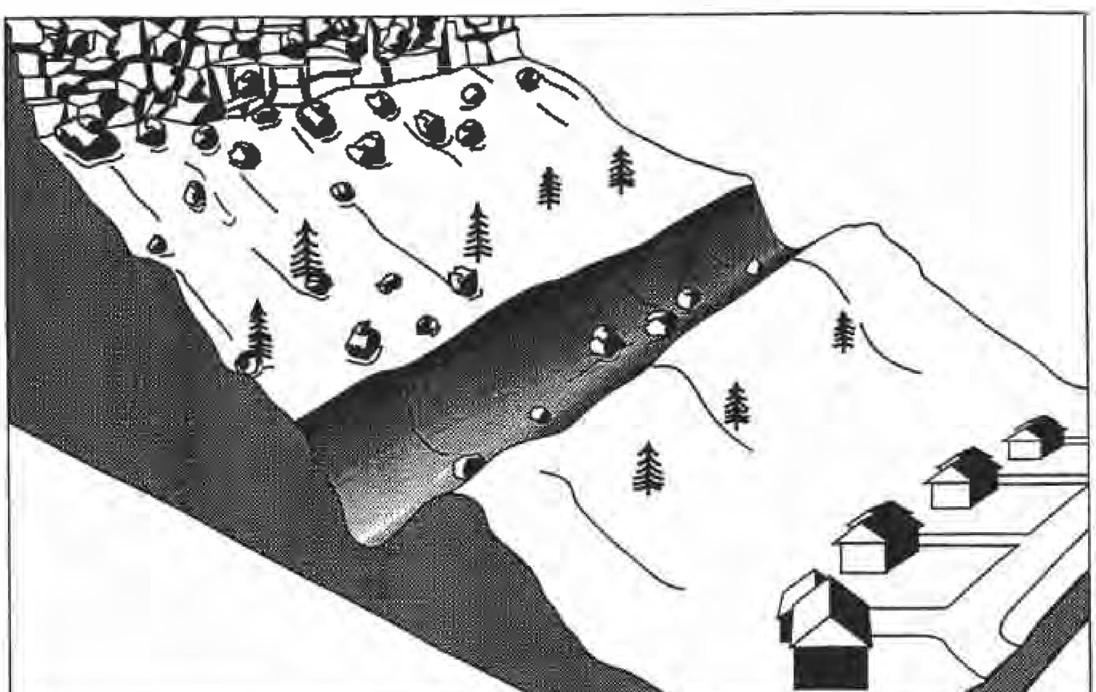

Figure 7. Rockfall ditch and berm.

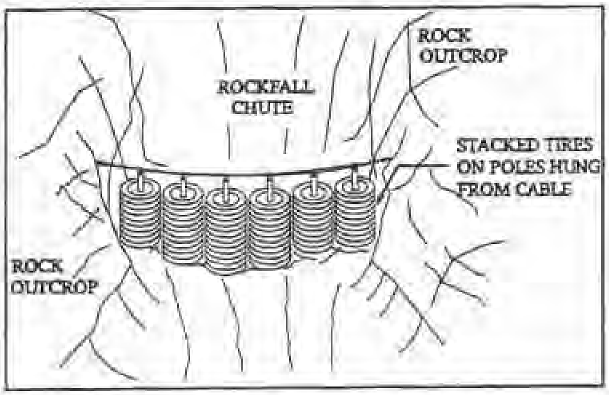

Figure 9. Tire impact attenuator.

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.)

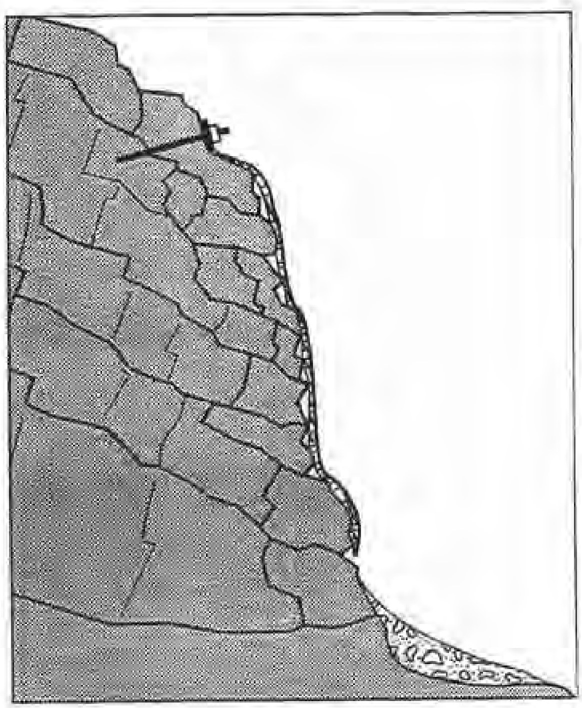

Figure 10. Draped mesh.

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.

SUGGESTED READING

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DEPARTMENT OF NATURAL RESOURCES

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Division Director

Vicki Cowart
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March 12, 2002

Mr. Russell Forrest
Senior Environmental Planner
Town of Vail
75 South Frontage Road
Vail, CO 81657

RE: **Review of Rockfall Mitigation for Booth Falls Condominiums.**

Dear Russ:

The CGS was requested by you to provide some additional comments on the completed rockfall mitigation at the Booth Creek Condominiums in the Town of Vail. At your earlier request, I inspected the rockfall mitigation structures on October 22, 2001after construction was completed last fall and sent comments to you in a letter dated November 9, 2001.

A question arose concerning any potential impacts to adjacent owners from the construction of the inertial barrier walls designed for rockfall impact. During my site inspection last fall I did not note any way in which these structures would adversely impact adjacent owners, except for a remote possibility to the access road to the Town water tank. There should be sufficient room to stockpile the snow against the foot of the western wall if the water tank road needs plowing for access during the winter.

Also the issue of maintenance and inspection of the structures was raised. The mechanically stabilized earth impact walls are basically maintenance-free. One concern I raised last fall was potential for sloughing or slumping of soil into the catchment zone from the bare cut slopes. If not cleaned out, the soil accumulation could effectively reduce the wall height. The cut slopes behind the walls (re-vegetated and stabilized as recommended) should be inspected every spring or after an unusually heavy precipitation event. The barrier walls should also be inspected after any rockfall impacts. Crushed portions of the wall facing after impact should be quickly repaired. Yenter Companies can provide guidance on recommended repair techniques for the wall facing.

The only other type of failure of the system that could arise is a bearing failure of the native soils that the impact barrier wall is founded on. If tilting or sagging of portions of the walls is observed, the homeowner's association should inform Yenter Companies and require their staff to inspect the structure. Slight undulations along the length of the walls by differential settlement will not effect the performance of the structures. While an unlikely scenario, adverse tilting of the structures could be more problematic.

Inspection of the walls and catchment zone behind should be part of a normal maintenance item of the condominium grounds by the homeowners association. I do not believe this action needs to be conducted by city staff unless distress of the wall parallel to the water tank access road is observed, which could possibly affect the roadway. Again, I believe it is very unlikely that this would occur.

Enclosed with this letter is a copy of the original rockfall assessment report the CGS prepared after the March 26, 1997 rockfall event. If you have any questions, please contact this office at (303) 866-3551 or e-mail: jonathan.white@state.co.us

Sincerely,

Jonathan L. White

Jonathan L. White
Engineering Geologist