ATTACHMENT G - ROCKFALL HAZARD STUDY, PART 1 OF 3

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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**Report Prepared by:**

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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:

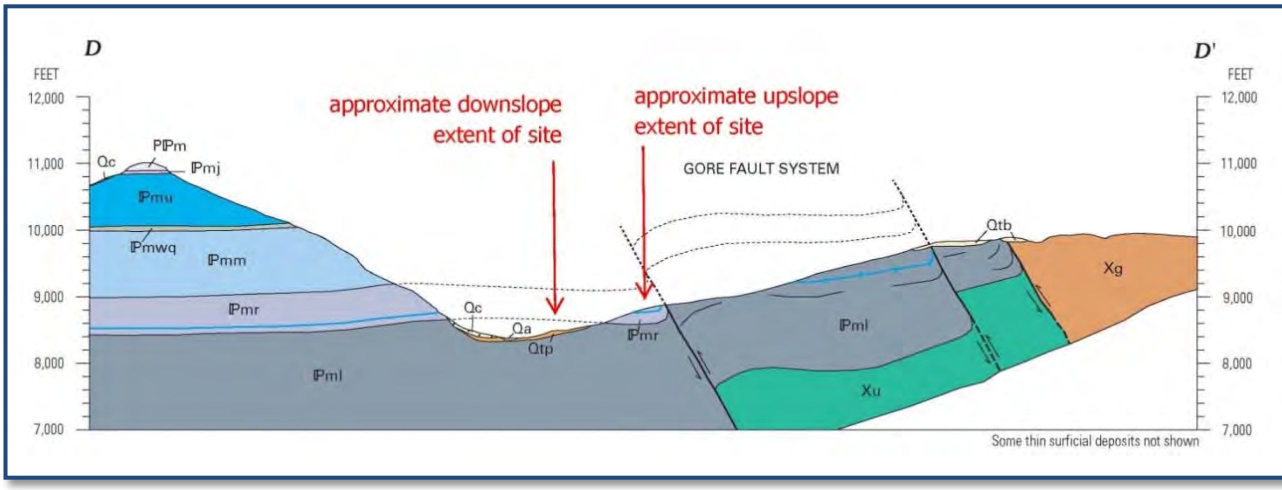
**Robinson Limestone Member (Pmr)**

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'**

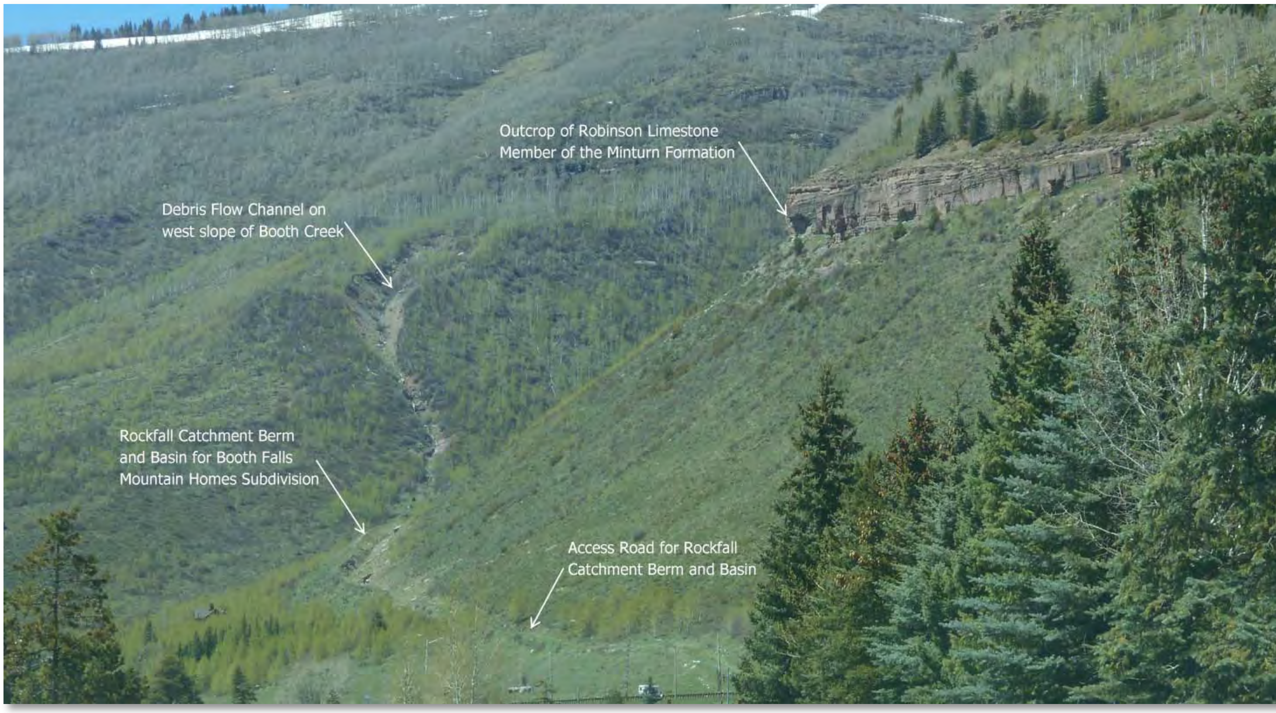




Cross section D-D' excerpted from the Geologic Map of the Vail East Quadrangle (Kellogg and others, 2003). This cross section is located immediately east of the project site and schematically depicts the surface and subsurface geologic conditions in the site area.

## 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.