CESARE, INC.
Geotechnical Engineers & Construction Materials Consultants

February 13, 2019

Mr. Michael O'Connor
Triumph Development
12 Vail Road, Suite 700
Vail, CO 81657

Subject: Geologic Hazards Analysis Report
East Vail Workforce Housing
Vail, Colorado
Project No. 18.5080

Dear Mr. O'Connor:

A geologic hazards analysis was performed by Skyline Geoscience for the subject project. The purpose of this letter is to transmit the report prepared by Skyline Geoscience.

If you have any questions or comments regarding this information, please contact our office.

Sincerely,
CESARE, INC.

William H. Koechlein

William H. Koechlein, P.E.
Senior Consultant

WHK/ksm

Attachment

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February 12, 2019

Cesare, Inc.
William Koechlein, P.E.
365 Warren Avenue, Suite #201
Silverthorne, Colorado 80497

Geologic Hazard Analysis
East Vail Parcel
Vail, Colorado
Skyline Project No: 18105

Dear Mr. Koechlein:

Skyline Geoscience (Skyline) is pleased to submit to Cesare, Inc. (Cesare) this geologic hazard analysis for the East Vail Parcel located near the I-70 East Vail Exit in the Town of Vail, Colorado. Preliminary development plans for the EVP (not for construction; dated January 30, 2019) have been issued to Triumph Development, Inc. by Alpine Engineering, Inc. (Alpine), and were used in this study. This geologic hazard analysis addresses rockfall, debris flow and the existing landslide, and the potential impacts these hazards may have on the proposed development. Skyline understands that a rockfall impact barrier is planned for the upslope edge of the EVP. This barrier will serve as both a protective barrier for rockfall and debris flows and serve as a wildlife barrier separating human activity from existing wildlife habitats.

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1.0 SCOPE OF WORK

The objectives of this geologic hazard analysis are to characterize the geologic hazard conditions and the potential impact those conditions may have on the intended development of the East Vail Parcel (EVP) located in the Town of Vail, Colorado (Figure 1). This analysis is based on proposed development plans made available at the time of this study (Alpine, January 30, 2019; Figure 2). Geologic hazards addressed in this analysis include rockfall, debris flows, and the existing landslide. Analysis of other geologic hazards including, but not limited to, snow avalanches, expansive soils and bedrock, and seismicity are not included in the scope of this study. Subsurface exploration or slope stability analysis for proposed cuts, fills, structural foundations, retaining wall structures, or other site improvements are not included in the scope of this study.

Based on the documents available to us and our understanding of the project, the scope of work for the geologic hazard analysis included:

1. Review of available literature and published mapping related to geologic conditions in the site area.
2. Review of applicable Town of Vail codes and requirements related to geologically sensitive areas.
3. Analysis of rockfall hazard along three study sections using the Colorado Rockfall Simulation Program (CRSP).
4. Meetings and collaboration with the EVP design team, Town of Vail, Colorado Geological Survey (CGS), and others.
5. Preparation of this report signed by a Colorado Professional Geologist summarizing findings, conclusions, and recommendations.

2.0 SITE DESCRIPTION

The EVP is located on the northeast side of I-70 near the I-70 East Vail exit, in the Town of Vail, Colorado (Figure 1). The site is triangular, about 23.3 acres in size, and is currently undeveloped except for a buried utility easement traversing the west side of the site. The part of the site which will be developed is the western approximate 5.4 acres (Housing Zone District). The remaining 17.9 acres of the site will remain undeveloped and zoned Natural Area Preservation (NAP). Fall Line Drive and the I-70 Frontage Road bound the site along the southwest edge. Pitkin Creek Townhomes is located immediately southeast of the EVP and Booth Falls Mountain Homes (Booth Falls) development is located west/northwest of the site. The land to the north, northeast, northwest, and west is undeveloped, National Forest Service Land. There is a Town of Vail shuttle stop near the intersection of Fall Line Drive and I-70 Frontage Road along the southwest edge of the site. Table 1 summarizes project site characteristics.

Table 1. Project Site Characteristics

Location:	Town of Vail, Eagle County, Colorado
Size:	23.3 acres total; 5.4 acres to be developed
Shape:	Triangular
Existing Condition:	Undeveloped except for a buried utility easement that crosses through the northwest part of the site. Vegetated with aspen trees, shrubs, and grasses. Incised drainages with flowing water on the west side of the site.
Proposed Development:	Multi-level residential buildings and surface parking on 5.4 acres zoned for Housing on the west side of the site. The other 17.9 acres will remain undeveloped and zoned NAP. A rockfall/wildlife barrier will traverse the part of the site to be developed on the upslope side.
Topographic Quadrangle:	Vail East
Township/Range:	SE ¼ of Section 2, Township 4 South, Range 80 West
Latitude/Longitude:	39°38’46”N / -106°18’25”W
Elevation:	8380 to about 8940 from southwest to northeast across entire site. 8380 to about 8530 from southwest to northeast corner of the part of the site to be developed.
Elevation Change Across Site:	About 560 feet across entire site. About 150 feet across part of site to be developed.
Slope of Ground Surface:	About 15 to 20 degrees down toward the south/southwest.
Nearby Drainage Features:	Gore Creek located about 350 to 650 feet to the south. Booth Creek located about 3,200 feet to the northwest. Pitkin Creek located immediately east of the property boundary.
Surficial Geologic Units:	Colluvium, landslide deposits, and glacial till.
Bedrock:	Minturn Formation

The EVP is located in the southeast quarter of Section 2, Township 4 South, Range 80 West, with a latitude and longitude of about 39°38’46”N and -106°18’25”W, respectively. Pitkin Creek is located immediately southeast of the entire site and Booth Creek is about 3,200 feet to the northwest. Both Pitkin and Booth Creek are deeply incised and active drainages that flow to confluence with Gore Creek, located about 350 to 650 feet south/southwest of the site.

The site topography slopes down to the southwest. The slope of the ground surface on the western part of the property (the part to be developed) ranges from about 0 to 20 degrees. The slope of the ground surface on the remainder of the EVP is steeper and exceeds 40 degrees in some places. Elevation ranges from about 8380 feet along the southwest side to about 8940 at the upper northeast corner. Elevation ranges from about 8380 to 8530 on the western part of the site to be developed, about 150 feet of elevation change. Refer to Figures 1 through 3 for site location, proposed development and topographic maps.

3.0 GEOLOGIC SETTING

3.1 REGIONAL GEOLOGY

The EVP is in the Southern Rocky Mountain physiographic province along the western flank of the Gore Range, in a region characterized by montane to subalpine settings. The Gore fault system is the western structural boundary of the Gore Range and was active during the Laramide mountain building event about 70 to 50 million years ago. The Gore Range is comprised of crystalline rock and is separated from the Front Range Mountains to the east by the Blue River Valley and the Williams Range thrust fault zone. Southwest of the Gore fault system are thick sequences of sedimentary units such as the Minturn and Maroon Formations. Sedimentary units underlie the EVP and are comprised of shale, claystone, siltstone, sandstone, conglomerate, and marine limestone. Glacial till is also mapped in the region along Gore Creek Valley and associated tributaries.

3.2 SITE GEOLOGY

Based on published geologic mapping (*Kellogg and others, 2003; Kellogg and others, 2011*), the EVP is underlain by surficial deposits comprised of artificial fill, colluvium, landslide deposits, and glacial till (Figure 4). Bedrock underlying the EVP is Minturn Formation (middle Pennsylvanian in age; about 315 to 307 million years before present) and is generally obscured by surficial deposits except for steep cliff outcrops upslope from the site. Geologic units are described below, from youngest to oldest in age:

Artificial Fill – Artificial fill (af) is present and associated with modifications to the natural condition within and adjacent to the EVP, such as the buried utility easement in the western part and construction associated with Fall Line Drive, the shuttle stop, and the retaining wall in the southeast part of the site.

Colluvium – Colluvial deposits (Qc) of Holocene and upper Pleistocene age (126,000 years ago to present) blanket most of the slope in the site area. Colluvium is described as unconsolidated, non-stratified deposits covering slopes less than 50 degrees. These deposits are typically less than 30 to 45 feet thick and comprised of pebble, cobble, and boulder sized rock and fine-grained material mixed together during movement downslope.

Landslide Deposits – Landslide deposits (Qls) of Holocene and upper Pleistocene age (126,000 years ago to present) are mapped on the eastern part of the EVP, on the approximate 18 acres that will not be developed. These deposits vary from chaotically arranged debris that has mobilized downslope to intact blocks of sedimentary bedrock. The middle and lower members of the Minturn Formation are particularly susceptible to landsliding (*Kellogg and others, 2003*).

Pinedale Till – Glacial till (Qtp) of upper Pleistocene, Pinedale glaciation age (about 30,000 to 12,000 years ago) is mapped in the southeast area of the EVP. Glacial till is also mapped upslope from the site, above the prominent cliff exposures. Glacial till is mapped throughout the Gore Creek Valley and commonly forms well-preserved moraines. The Pinedale Till is unsorted, unstratified, bouldery glacial till, characterized by matrix-supported, subrounded to subangular clasts of igneous, metamorphic, and sedimentary (minor) composition. This unit tends to form hummocky surface topography with common closed depressions and small ponds which have been modified by development in the Gore Creek Valley. The Pinedale Till has been mapped at variable elevations as high as 900 feet above the present elevation of Gore Creek, and may be up to about 90 feet thick in places (*Kellogg and others, 2003; Kellogg and others 2011*).

Minturn Formation, Robinson Limestone Member – The Robinson Limestone Member of the Minturn Formation (Pmr) underlies the northeast part of the EVP. This unit also comprises the steep cliff outcrops upslope from the site. Pmr is thick-bedded, marine and dolomitic limestone, and is gray to yellow-gray, fine- to medium-grained, and locally fossiliferous. This unit can be divided into four distinct depositional sequences which are interbedded with pink-tan and light tan, cross-bedded, micaceous pebbly sandstone, gray-pink sandy siltstone, and shale. The sandstone, siltstone, and shale layers weather to rounded shapes, whereas the limestone and dolomitic layers weather to more angular forms. Based on published mapping (*Kellogg and others, 2003*), Pmr dips about 10 degrees south on the slope above the site. Pmr is about 360 feet thick in the project area, however, is about 660 feet thick at the type section.

> ***Minturn Formation, Individual limestone bed*** – This individual limestone bed of the Minturn Formation (Pmrl) is mapped within Pmr, is cliff-forming and generally greater than 15 feet thick. Pmrl is mapped on the east side of the EVP on the slopes of Pitkin Creek.

Minturn Formation, Lower Member – The Lower Member of the Minturn Formation (Pml) underlies the EVP and is comprised of arkosic conglomerate, sandstone, siltstone, and shale. Pml is pink-gray, gray-brown, gray-green, and mottled maroon and gray-green. This unit is about 1,200 feet thick in the project area.

4.0 GEOLOGIC HAZARD CONSIDERATIONS

The Town of Vail code 12-21-13 lists the maps that have been adopted as official maps of the town to identify geologically sensitive areas and guide site-specific studies. These maps show debris flow and debris avalanche hazards (*Arthur I. Mears, P.E., Inc., November 1984*), rockfall hazards (*Schmueser and Associates, Inc., November 29, 1984*), and geologic hazard areas (*Lincoln DeVore Engineers, Geologists, August 16, 1982*). Based on these maps, the EVP is within a rockfall hazard area and thus designated as a geologically sensitive area by the Town of Vail. The geologic hazard considerations included in this study include rockfall, debris flows, and an existing landslide (Figure 5).

4.1 ROCKFALL

The EVP has been placed in a rockfall hazard area by the Town of Vail. The EVP is located directly below cliff exposures of the Robinson Limestone Member of the Minturn Formation. Potential rockfall source zones include these cliff exposures, glacial till deposits present further upslope, and other bedrock outcrops and piles of accumulated boulders on the slope above the site. The glacial till produces subrounded, granitic boulders that pose a rockfall hazard as they dislodge from the matrix and cascade downslope. The Minturn Formation tends to break from the source as irregular blocks of various sizes. The primary rockfall trigger for the bedrock is likely alternating freeze-thaw cycles. Additionally, the Minturn Formation has a combination of internal characteristics that contribute to rockfall susceptibility, including:

- thin, interbedded, weak shale layers within the thicker limestone and sandstone beds
- joint patterns
- bedrock dip of 10 to 15 degrees out-of-the slope (toward the valley)

The neighboring development to the northwest (Booth Falls) experienced historic rockfall events in 1983, 1986, 1987, and 1997, when large boulders dislodged from the Robinson Limestone Member of the Minturn Formation and damaged residences (*Kellogg and others, 2003; Colorado Geological Survey, undated*). The 1983 rockfall event prompted a rockfall study for the entire Town of Vail (*Schmueser and Associates, 1984*). The rockfall berm and catchment that was in place at the time of the 1997 rockfall event was 100% effective in containing rocks that intercepted the barrier, however, part of that rockfall mass skirted the edge of the berm and rolled downslope to damage structures in the development below. After the 1997 event, additional barriers (reinforced walls) were constructed to protect residences. Based on the Colorado Geological Survey (CGS) study conducted soon after the 1997 rockfall event, the section of rock that detached from the upper cliff was about 20 x 8 x 8 feet in dimension and broke into smaller pieces as it tumbled down the slope.

Two cliff exposures of the Robinson Limestone Member are present above Booth Falls, and the CGS identified the main rockfall source to be the upper cliff exposure (Figure 5). The upper cliff exposure at Booth Falls can be correlated to the main rockfall source for the EVP. The lower cliff exposure above the EVP is largely obscured by colluvial deposits and not considered a primary rockfall source. The slope below the cliff exposures at Booth Falls constitutes the acceleration and runout zones and is about 40 degrees. The slope below the rockfall source zone for the EVP is less extreme, varying from about 20 to 40 degrees.

Joint spacing in the bedrock source zones may be an indicator for the potential size of rockfalls. Joints observed in the upper cliff exposure above the EVP were spaced about 10 feet apart. Other joint set orientations and spacing may exist but were not observable in the cliffside. Shale layers in the limestone and sandstone, spaced at irregular intervals, are also discontinuities along which blocks can be dislodged. Differential weathering of the shale layers also causing instability. For Booth Falls, the CGS states that:

> *"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."*

The CGS indicates that larger slabs tend to break from the lower source zone above Booth Falls, with diameters of 15 to 20 feet.

4.2 DEBRIS FLOWS

The EVP is not within the limits of the Town of Vail debris flow hazard zone, however, there is the potential for debris flows at the site. Review of a detailed terrain surface derived from the LiDAR (Light Detection and Ranging) and of aerial photographs of the EVP and surrounding area indicates the potential for debris flows. Incised channels with flowing water are present on the west side of the site (the part to be developed) and on the slopes above, evidence for active erosive processes. An intense, prolonged precipitation event or rapid snowmelt has the potential to trigger a fast-moving, hyper-concentrated debris flow. Modifications to the existing, natural condition may increase the debris flow susceptibility.

4.3 EXISTING LANDSLIDE

Landslide deposits are mapped on either side of the Gore Creek Valley and are commonly associated with the middle and lower members of the Minturn Formation (the lower member underlies the EVP). Most of these landslides are considered by investigators to be ancient and inactive. One known exception is a large historic landslide about 1.5 miles to the west of the EVP which was re-activated by undercutting of the toe for construction of I-70. That landslide involved Minturn Formation bedrock units, the same which underlie the EVP. Contributing factors for landslide susceptibility in the project area includes over-steepening or undercutting of slopes by natural processes or human activities, bedding in sedimentary rocks that is oriented out-of-the slope (dip-slope), deforestation and removal of vegetative cover, elevated water content by means of intense, prolonged rainfall or rapid snowmelt, and unit contacts with vastly contrasting material properties (*Kellogg and others, 2003*).

An existing landslide occupies the eastern approximate 18 acres of the EVP, the area to remain undeveloped (NAP). The landslide is visible in the LiDAR collected for the area, shown on Figure 5. Figure 6 shows a slope map derived from the LiDAR, with marked landslide extents. Geomorphic features of landslide movement have been obscured by heavy vegetative cover and smoothed by natural processes over time. The LiDAR imagery assisted in delineating the extents of the landslide (Figure 7), which extend further upslope than previously identified in published geologic maps (*Kellogg and others, 2003*). The landslide extents delineated in this report are approximate.

Historical landslides are complex, and characteristics vary even within a single landslide mass, including type of slope failure (may be a combination of various mobilization mechanisms), timing of slope failure events, causative factors, direction of sliding, and others. The mechanism of sliding for this landslide may be a combination of block sliding and deep rotational processes. The detachment location for the landslide is located further upslope and beyond the boundaries of the EVP. The steep toe of the landslide is abruptly cut off by Fall Line Drive (Figure 7). The western flank of the landslide in the area of the toe is also steep and forms a recognizable break in slope on the topography map. Based on LiDAR imagery, the approximate extent of the landslide is about 1,750 feet wide by about 2,500 feet long from head scarp to Fall Line Drive.

5.0 ROCKFALL ANALYSIS

Skyline modeled rockfall along three representative study sections through the part of the EVP to be developed using the Colorado Rockfall Simulation Program version 4.0 (CRSP). Figure 6 shows the locations of the study sections. CRSP estimates maximum, average, and cumulative probability statistics for rockfall impact kinetic energy, bounce height and velocity at analysis points along each slope profile. The slope geometry for each study section was derived from site-specific survey and from contours developed from LiDAR data. The current condition for each study section was analyzed and the model parameters calibrated to fit site observations of slope characteristics. Analysis points were chosen upslope from the property, at the upslope property line, and at the proposed rockfall barrier locations. Results are reported for the proposed rockfall barrier locations.

Rockfall behavior is generally influenced by slope geometry, material properties of the slope, and the material properties and geometry of the falling rock. Each study section was divided into sections (cells) based on slope characteristics. Cell boundaries were based on slope angle, vegetative cover, and material comprising the slope surface. Parameters that were estimated include density of limestone (source rock composition), surface roughness of the slope (SR), tangential coefficient of frictional resistance (R_t), and the normal coefficient of restitution (R_n).

SR is an estimation of the amount the slope angle varies within the radius of the rock being rolled. SR is a function of the size of the rock and the irregularity of the slope surface and will have greater influence on smaller rock sizes. The SR of the slope along each study section varied based on the size of the rock being modeled. A rock size of 3 to 4 feet is common for the slope and occurs with some frequency. Due to snow cover, it was not possible to directly measure SR along each study section. The SR was estimated based on previous site visits and observations made for the initial Cesare study in May and June 2017, and on aerial photographs and LiDAR data.

R_t is the component of velocity parallel to the slope, which decreases during impact. The R_t was estimated for each cell based on the typical material comprising that section of the slope, and the amount of vegetative cover. Vegetation tends to increase the frictional resistance in the direction parallel to the slope, thus decreasing the tangential coefficient.

R_n accounts for the change in velocity in a direction normal to the slope during an impact – a comparison of the normal velocity of the rock before and after impact of the rock with the ground surface. Skyline referred to the CRSP program manual for reasonable ranges of R_t and R_n for different surface material types along each study section.

Table 2 is a summary of the model parameters used for each study section.

Table 2. Summary of Rockfall Study Section Parameters

Parameter	Study Section A	Study Section B	Study Section C
Length of section analyzed (ft)	1410	1460	1440
Elevation difference across section (ft)	775	770	765
Total number of cells	8	6	7
Analysis Point 1	Property Line	Property Line	Property Line
Analysis Point 2	Rockfall Barrier	Rockfall Barrier	Rockfall Barrier
Top starting zone (y-coordinate)	9080	9080	9080
Bottom starting zone (y-coordinate)	9040	9040	9040
Number of rocks simulated	500	500	500
Starting velocity (x)	1 ft/sec	1 ft/sec	1 ft/sec
Starting velocity (y)	-1 ft/sec	-1 ft/sec	-1 ft/sec
Lithology of modeled rock	Limestone	Limestone	Limestone
Material density of modeled rock	165 lb/ft^3	165 lb/ft^3	165 lb/ft^3
Rock shape	Spherical, Discoidal	Spherical, Discoidal	Spherical, Discoidal
Rock dimension (diameter)	Varied (4, 6, 8, 10)	Varied (4, 6, 8, 10)	Varied (4, 6, 8, 10)

The primary rockfall source zone for the EVP is located at a bedrock outcrop of the Robinson Limestone about 1,240 to 1,280 feet upslope from the property boundary at an elevation of about 9040 to 9080. Rocks deposited on the slope below this source zone are blocky, slab-shaped and primarily comprised of gray limestone interbedded with layers of sandstone, siltstone, and shale. Boulders comprised of sandstone and pebble conglomerate were also observed. A second source for rockfall is the glacial till which caps the slope above the Robinson Limestone cliff outcrop. Subrounded boulders of igneous and metamorphic composition are dislodged from the matrix of this deposit and roll downslope.

The slope directly below the rockfall source zone is vegetated with aspen trees, tall shrubs, and grass. Further downslope from the source zone, the vegetation on the slope thins to aspen trees and grass. The material on the slope is soil, colluvial material that has been transported downslope, and scattered boulders and large slabs of bedrock which are slightly to deeply embedded in the soil. The slope is also incised by active drainages which were flowing water during the Cesare site visits in May 2017.

5.1 STUDY SECTION A

Study Section A is located on the west side of the EVP (Figure 6). Study Section A spans a length of about 1,600 feet along the slope and an elevation range from 8380 to 9150 (Figure 8). The slope is vegetated with aspen trees, shrubs, and grass, and covered in colluvium and limestone boulders that have broken from the steep cliff rockfall source zone at about elevation 8040 to 9080. Skyline understands that the intended barrier system at this location is a reinforced, rigid wall with catchment area. The distance along the slope from the rockfall source zone to the property boundary is about 1,300 feet. Table 3 lists slope profile parameters used for Study Section A.

Table 3. Study Section A – Slope Profile Parameters

Cell	Begin (x,y)	R_t	R_n	Approx. Slope Angle (°)	Slope Surface Characteristics	Slope Material Designation
1	0, 9150	0.70	0.15	35	Vegetated slope above rockfall source zone (Glacial Till)	Talus/Firm Soil
2	100, 9080	0.90	0.25	80-90	Steep cliff face, rockfall source zone (Limestone, jointed)	Bedrock
3	110, 9040	0.65	0.18	30-35	Vegetated slope below rockfall source zone (Colluvium)	Talus/Firm Soil
4	209, 9000	0.65	0.18	40-45	Vegetated slope (Colluvium)	Talus/Firm Soil
5	500, 8750	0.65	0.18	30-35	Vegetated slope (Colluvium)	Talus/Firm Soil
6	645, 8650	0.65	0.16	20-30	Vegetated slope (Colluvium)	Talus/Firm Soil
7	1078, 8450	0.70	0.16	15-20	Vegetated slope (Colluvium)	Talus/Firm Soil
8	1310, 8376	0.90	0.60	FLAT	Paved roadway (Fall Line Drive)	Paving

Rt: tangential coefficient; Rn: normal coefficient

5.2 STUDY SECTION B

Study section B is located near the middle of the proposed development (Figure 6). Study Section B spans a length of about 1,650 feet along the slope and an elevation range from 8380 to 9150 (Figure 9). The slope is vegetated with aspen trees, shrubs, and grass, and covered in colluvium and limestone boulders that have broken from the steep cliff rockfall source zone at about elevation 8040 to 9080. Skyline understands that the intended type of barrier system at this location is an earthen berm with catchment area located upslope from the proposed buildings. The distance along the slope from the rockfall source zone to the property boundary is about 1,260 feet. Table 4 lists slope profile parameters used for Study Section B.

Table 4. Study Section B – Slope Profile Parameters

Cell	Begin (x,y)	R_t	R_n	Approx. Slope Angle (°)	Slope Surface Characteristics	Slope Material Designation
1	0, 9150	0.70	0.15	35	Vegetated slope above rockfall source zone (Glacial Till)	Talus/Firm Soil
2	92, 9080	0.90	0.25	80-90	Steep cliff face, rockfall source zone (Limestone, jointed)	Bedrock
3	100, 9040	0.65	0.18	30-35	Vegetated slope below rockfall source zone (Colluvium)	Talus/Firm Soil
4	868, 8550	0.65	0.16	20-25	Vegetated slope (Colluvium)	Talus/Firm Soil
5	1150, 8430	0.65	0.15	10-15	Vegetated slope (Colluvium)	Talus/Firm Soil
6	1356, 8382	0.90	0.60	FLAT	Paved roadway (Fall Line Drive)	Paving

Rt: tangential coefficient; Rn: normal coefficient

5.3 STUDY SECTION C

Study section C is located near the east side of the proposed development (Figure 6). Study Section C spans a length of about 1,630 feet along the slope and an elevation range from 8384 to 9150 (Figure 10). The slope is vegetated with aspen trees, shrubs, and grass, and covered in colluvium and limestone boulders that have broken from the steep cliff rockfall source zone at about elevation 8040 to 9080. Skyline understands that the intended type of barrier system at this location is an earthen berm with catchment area located upslope from the proposed buildings. The distance along the slope from the rockfall source zone to the property boundary is about 1,100 feet. Table 5 lists slope profile parameters used for Study Section C.

Table 5. Study Section C – Slope Profile Parameters

Cell	Begin (x,y)	R_t	R_n	Approx. Slope Angle (°)	Slope Surface Characteristics	Slope Material Designation
1	0, 9150	0.70	0.15	35	Vegetated slope above rockfall source zone (Glacial Till)	Talus/Firm Soil
2	89, 9080	0.90	0.25	80-90	Steep cliff face, rockfall source zone (Limestone, jointed)	Bedrock
3	96, 9040	0.75	0.18	30-40	Vegetated slope below rockfall source zone (Colluvium)	Talus/Firm Soil
4	600, 8700	0.75	0.18	20-30	Vegetated slope (Colluvium)	Talus/Firm Soil
5	873, 8550	0.65	0.17	15-20	Vegetated slope (Colluvium)	Talus/Firm Soil
6	1140, 8450	0.65	0.15	10-15	Vegetated slope (Colluvium)	Talus/Firm Soil
7	1386, 8384	0.90	0.60	FLAT	Paved roadway (Fall Line Drive)	Paving

Rt: tangential coefficient; Rn: normal coefficient

5.4 ROCKFALL ANALYSIS RESULTS

Based on observations of the rockfall source zone and evidence on the ground surface along the slope, Skyline considers the design rock size for this site to be 8 to 10 feet in diameter. Two analysis points were analyzed for each study section: (AP1) located at the upslope property boundary and (AP2) located at the proposed barrier. For Study Sections A and B, the barrier is located at the upslope boundary. For Study Section C, the barrier is placed about 115 feet downslope from the property boundary (Figure 2). Estimates for the maximum, 98% and 95% cumulative probability statistical results are reported for velocity, kinetic energy (KE), and bounce height.

Based on the CRSP results from the three study sections (summarized in Table 6), the maximum KE at the barrier locations should be considered 2,300 kJ (1,700,000 ft-lb). The maximum bounce height should be considered 3.0 feet. A higher KE of about 3,160 kJ was estimated at AP1 for Study Section C, located at the property boundary about 115 feet upslope from where the barrier system is placed (AP2). This part of the slope along Study Section C ranges from 15 to 20 degrees and is a soil covered, vegetated slope with scattered boulders. The difference in estimated impact energies between AP1 and AP2 shows how the rockfall energy dissipates along this portion of the slope.

Table 6. Rockfall Analysis Results

SS	AP	Rock Size/Shape	Rock Weight (lbs)	Velocity (ft/sec)			Kinetic Energy (kJ)			Bounce Height (ft)
				max	98%	95%	max	98%	95%	max
A	2	8' spherical	44,234	-no rocks past AP						
	2	10' spherical	86,394	24.8	22.3	20.9	1,550	1,120	1,010	1.3
	2	10'x4' discoidal	51,836	24.5	20.5	19.0	920	590	530	1.2
B	2	8' spherical	44,234	14.2	16.2	14.7	260	290	260	0.7
	2	10' spherical	86,394	29.8	22.5	20.4	2,200	1,130	990	2.6
	2	10'x4' discoidal	51,836	24.4	19.0	17.1	930	520	450	1.8
C	2	8' spherical	44,234	-no rocks past AP						
	1	10' spherical	86,394	37.0	30.2	27.8	3,160	1,980	1,750	3.3
	2	10' spherical	86,394	31.8	23.6	21.3	2,300	1,230	1,070	2.4
	2	10'x4' discoidal	51,836	32.7	27.1	24.8	1,690	1,000	890	3.0

SS – study section; kJ – kilojoules; AP – analysis point; lbs – pounds; ft/sec – feet per second

A 10-foot high barrier placed at AP2 for each study section successfully stopped all 10-foot spherical rocks in the CRSP model. A 10-foot spherical rock will have higher estimated impact energies than a discoidal rock of similar dimension. Due to overtopping conditions that may occur and due to the size of boulders visible on the ground surface within the property limits (exceeding 10 feet in longest dimension), the recommended height of the barrier is 12 feet.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This report addresses rockfall, debris flow, and existing landslide hazards for the EVP, and the potential impacts those geologic hazards have on the proposed development of the western 5.4 acres of the site.

6.1 ROCKFALL AND DEBRIS FLOW MITIGATION

Rockfall and debris flow hazards can be mitigated at the site with a single barrier system. The mitigation system will reduce but not eliminate rockfall and debris flow hazards in the area of the proposed development. Considerations for each hazard will have to be incorporated into structural and civil design of the system. The system will also act as a wildlife barrier, limiting pedestrian access to the open space beyond and separating human activity from existing wildlife habitats. Skyline understands the barrier system under consideration is an earthen berm and catchment ditch. An impact barrier wall with a smaller spatial footprint is also being considered for the western part of the site where there is limited space between the property boundary and edge of development. Refer to Figure 11 for typical sections of each barrier type.

Recommendations for the barrier system include:

a) Height = 12 feet.

b) Designed to withstand the maximum impact energy estimated = 2,300 kJ.

c) The impact face of the barrier should be as vertical as possible. A 1:1 slope is assumed for the earthen berm option, although a steeper grade is preferred. A vertical face with minimal to positive batter on the upslope side is recommended for the impact barrier wall option.

d) Ideal orientation of the barrier is perpendicular to the fall line of the slope. If a perpendicular orientation is not possible, a staggered wall geometry may be considered. There shall be no gaps in the barrier system and staggered sections should have appropriate angles and lengths to accommodate coverage of site development. If the angle of the barrier diverges significantly from perpendicular to the fall line of the slope, the system must be designed to accommodate for containment of rocks within the property boundaries. The orientation of the proposed barrier system is perpendicular to the fall line of the slope, except at the western end where the wall deviates about 10 to 15 degrees from the preferred orientation. It is not recommended for the barrier system to deviate more than 20 degrees from perpendicular to the fall line of the slope.

e) Adequate space uphill of the barrier for catchment and accumulation of rockfall, and for routine access of equipment for removal of accumulated debris. This area should be graded flat. The actual width of the catchment depends on the size of the equipment to be used to remove accumulated debris and the angle of the slope above. The use of explosives or expansion grout can be used to break up large boulders that accumulate in the catchment, creating smaller fragments that can be removed.

f) The catchment area must be routinely maintained, and accumulated debris removed. Debris should not be allowed to pile up and thus diminishing the effectiveness of the catchment.

g) Surface drainage within the catchment should be controlled with adequate slope of the ground surface. Based on proposed development plans available at the time of this study, the ground surface of the catchment slopes down from east to west with a grade of 2%. Water should not be allowed to accumulate or pond in the catchment. Surface drainage and erosion management related to the deeply incised drainages which were flowing water during the Cesare site visits in May and June 2017 must be considered.

h) An access road to the catchment area must be designed and maintained.

i) Routine inspection of the barrier system must be enforced and will assist in determining the maintenance and repair needs of the system. Inspections should be conducted on a regular basis and immediately following a rockfall or debris flow event. Other construction, maintenance and inspection recommendations may be provided by the wall manufacturer.

j) Observation and inspection by a qualified engineering geologist or geotechnical engineer during construction and upon completion of the rockfall barrier system is recommended.

For comparison, the CGS study completed after the 1997 rockfall event at Booth Falls and in support of the design of the additional MSE wall barriers constructed downslope from the initial rockfall earthen berm recommended a design impact energy of about 6,800 kJ (5,000,000 ft-lbs) at an AP about 30 feet upslope from existing structures. The design rock size used by the CGS was about 6 to 7 feet in diameter. CGS recommended a design height of no less than 12 feet, with a low capacity rockfall fence at the top of the wall. Photographs 1 and 2 show one part of this wall system, taken during the winter months of 2017. Although the height of the wall was not measured, it is apparent from the photographs that the wall is about 10 feet high (assuming each block is 6 inches high) with a chain link fence on top to stop smaller rocks. Photographs 3 and 4 show the earthen berm upslope from Booth Falls. The slopes of this berm are steep and between 10 to 15 feet high. The crest is narrow and about 1 foot wide.

***Photograph 1**. Existing rockfall impact barrier wall located about 50 feet upslope from existing Booth Falls residences. This system is about 10 feet high, with an additional low capacity, chain link fence at the top. (photo courtesy of Nathan Thompson, GSI)*

***Photograph 2**. Sideview of the existing rockfall impact barrier wall located upslope from Booth Falls. (Photo courtesy of Nathan Thompson, GSI)*

***Photograph 3**. Existing rockfall berm upslope from Booth Falls. Photograph was taken while standing on the crest of the berm, looking east. Interstate 70 is visible in the background.*

***Photograph 4**. Existing rockfall berm and catchment system upslope from Booth Falls, looking west. Photograph was taken while standing in the catchment area near the east end.*

6.2 EXISTING LANDSLIDE

The existing landslide exhibits geomorphic evidence of past movement. Features such as a detachment zone upslope, over-steepened toe and flank areas, and hummocky topography are visible on the ground surface and in the LiDAR imagery (Figures 5 through 7). Evidence of recent movement such as tension cracks, fresh scarp exposures, and other features were not observed. As noted by previous authors (*Kellogg and others, 2003; 2011*), large landslides in the Gore Creek Valley are generally ancient and inactive. Ground modifications and development around these ancient landslides will increase the potential for re-activation and re-mobilization of the landslide mass, as is the case on I-70 about 1.5 miles west of the EVP.

Based on the proposed development plan made available to Skyline at the time of this report, development and planned structures are limited to 5.4 acres on the west side of the EVP. Planned development extends up to the limits of the steep western flank of the landslide extents as delineated from LiDAR imagery and surface topography. Skyline recommends avoiding development within or near the mapped extents of the landslide. Site improvements and regrading near the toe of the landslide may re-activate slope movement and should be avoided. Landslide extents have not been verified with subsurface exploration and the geomorphic expression of the landslide has been smoothed with time and erosive processes. Thus, the landslide extents presented in this report are approximate.

Skyline recommends implementing a slope monitoring program during construction or grading activities near the landslide. If development within the extents of the landslide is planned, additional geological and geotechnical analysis should be performed to further characterize the landslide and the potential impact the proposed development would have on slope stability.

7.0 LIMITATIONS

The purpose of this report is to provide a geologic hazard analysis as it relates to rockfall, debris flows, and the existing landslide for the development of the western 5.4 acres of the East Vail Parcel located in Vail, Colorado. The professional judgments and conclusions presented in this report meet the standard of care for our profession. This geologic hazard analysis is based on review of available literature and published geologic and topographic maps, an understanding of geologic conditions and processes in the project area, and experience with similar conditions. Variations in geologic conditions can and do occur. Subsurface exploration was not included in the scope of this study and snow cover prevented field verification of ground surface conditions along study sections. There is a potential for variations in the geologic conditions presented in this report. These variations, if present, may be enough to necessitate modifications to this report. If unexpected, adverse, or differing conditions are encountered during geotechnical investigations or construction, Skyline should be notified for additional review and potential modification to the conclusions and recommendations herein.

8.0 REFERENCES

Arthur I. Mears, P.E., Inc., 1984, Debris Flow and Debris Avalanche Hazard Analysis, prepared for the Town of Vail.

Cesare, Inc., June 2017, Rockfall Hazard Study, East Vail Parcel, Vail, Colorado, prepared for Vail Resorts Development Company.

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

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.

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.

Schmueser and Associates, Inc., 1984, Rockfall Study – Town of Vail, prepared for Stan Berryman, Public Works Director, Town of Vail.

Lincoln DeVore Engineers, Geologists, August 16, 1982, Geologic Hazards Investigation and Subdivision Evaluation, Highland Park Subdivision, Highland Meadows Subdivisions, and Vail Village West, Filings 1 and 2, West Vail, Colorado.

Thank you for the opportunity to provide this geologic hazard analysis for the East Vail Parcel, Town of Vail, Colorado. Please contact Skyline if you have any questions or comments regarding the information provided in this report.

Sincerely,

SKYLINE GEOSCIENCE
Golden, Colorado
www.skylinegeoscience.com

Report Prepared By:

Julia M. Frazier, P.G. | Owner

Basemap: Google Earth

East Vail Workforce Housing Parcel (+/- 23.3 acres)

Area to be developed (+/- 5.4 acres)

0 500 1000

APPROXIMATE SCALE IN FEET

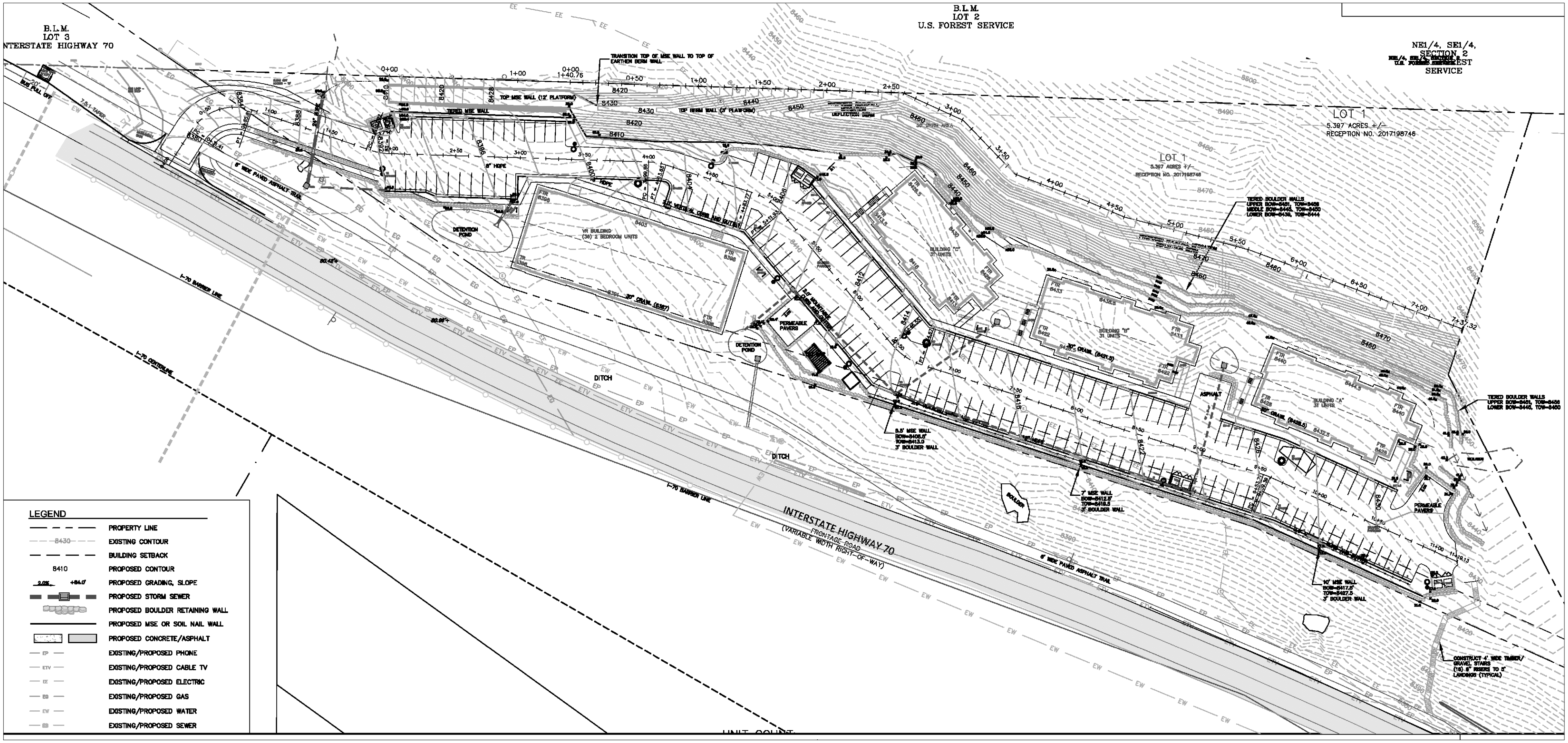
N

Project No: 18105
Project Name: East Vail Parcel

Date: 01.25.2019

FIGURE 1
Site Location

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



Map Source: Alpine Engineering (January 30, 2019)

0 120 240

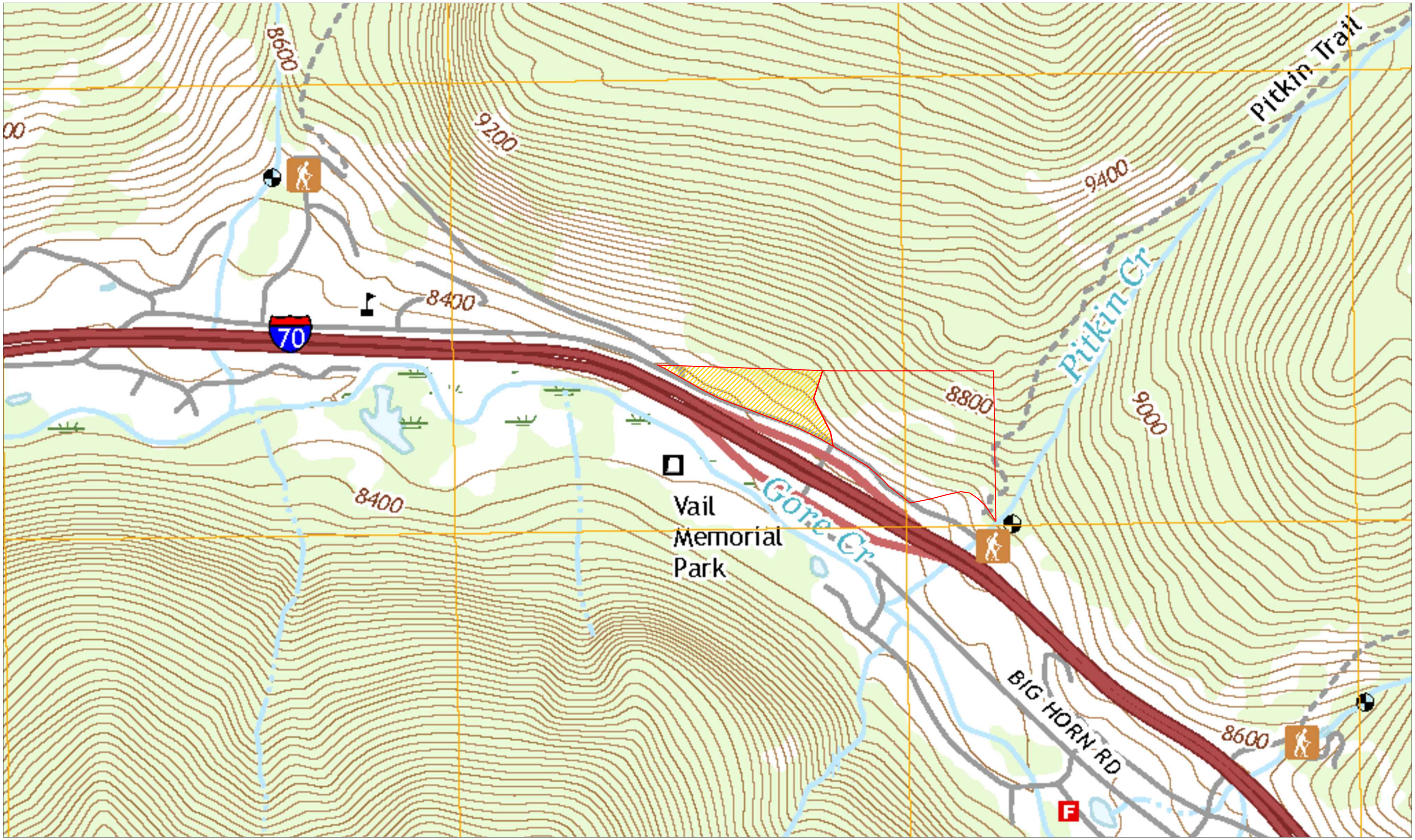
APPROXIMATE SCALE IN FEET

N

Project No: 18105
Project Name: East Vail Parcel
Date: 01.30.2019

FIGURE 2
Proposed Development

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



Basemap: Vail East Topographic Quadrangle (USGS)

East Vail Workforce Housing Parcel (+/- 23.3 acres)

Area to be developed (+/- 5.4 acres)

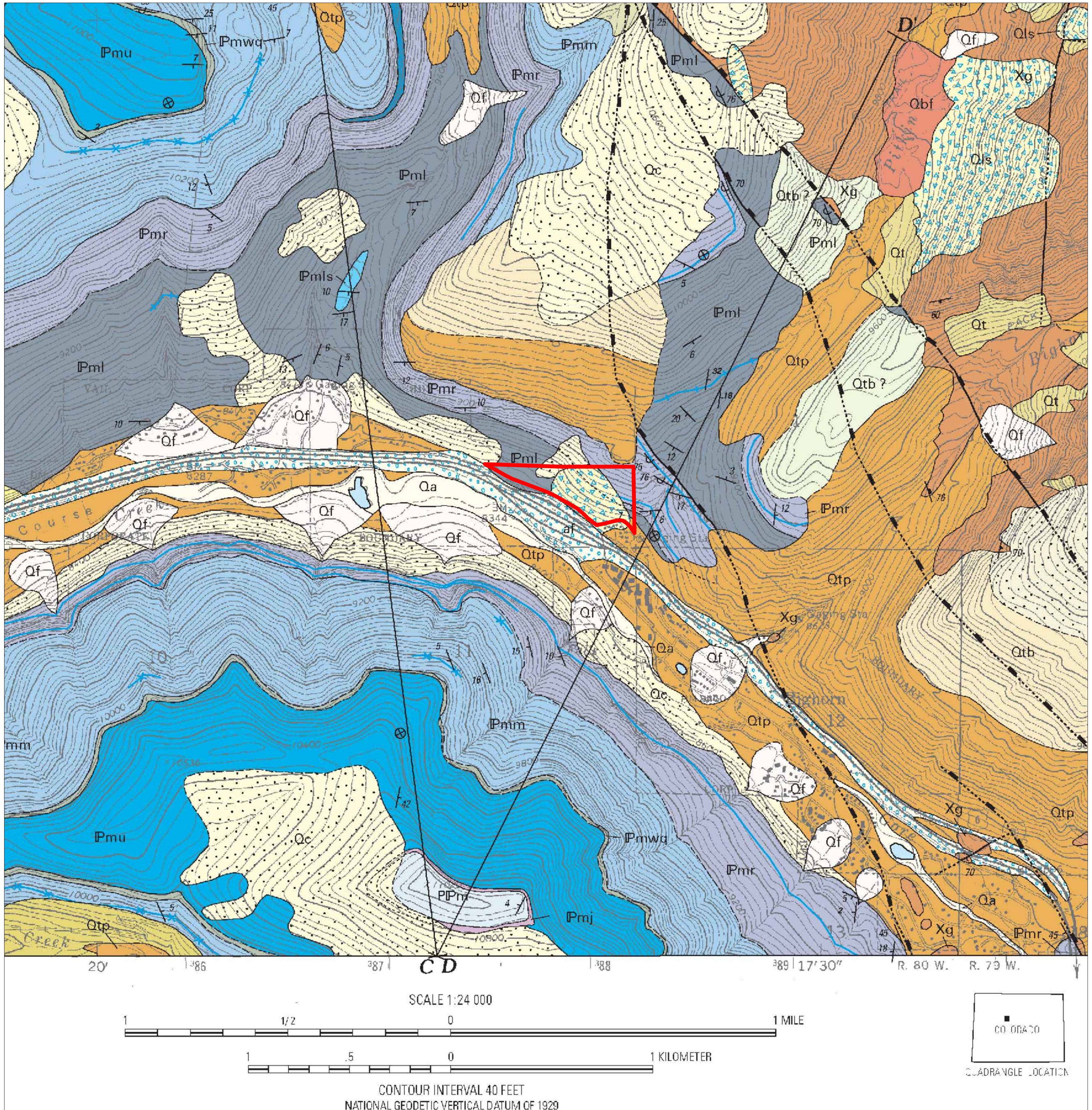
N

0 1000 2000
APPROXIMATE SCALE IN FEET

Project No: 18105
Project Name: East Vail Parcel
Date: 01.25.2019

FIGURE 3
Topographic Map

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



Map Source: Kellogg and others, 2003

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)
- PℙM — Maroon Formation (Lower Permian to Middle Pennsylvanian)
- ℙm — Minturn Formation, undifferentiated (Middle Pennsylvanian)
  - ℙmj — Jacque Mountain Limestone Member
  - ℙmu — Upper sandstone and conglomerate member
  - ℙmwq — White Quail Limestone Member
  - ℙmm — Middle member
  - ℙmml — Individual limestone bed
  - ℙmr — Robinson Limestone Member
  - ℙmrl — Individual limestone bed
  - ℙml — Lower member
  - ℙmls — Individual limestone bed
- ℙ-Cu — Pennsylvanian to Cambrian units, undifferentiated—Shown on cross section B-B' only
- Pzcd — Clastic dike (lower Paleozoic?)
- Dp — Parting Formation (Upper Devonian)
- Cp — Peerless Formation (Upper Cambrian)
- Cs — 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

East Vail Workforce Housing Parcel (+/- 23.3 acres)

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)

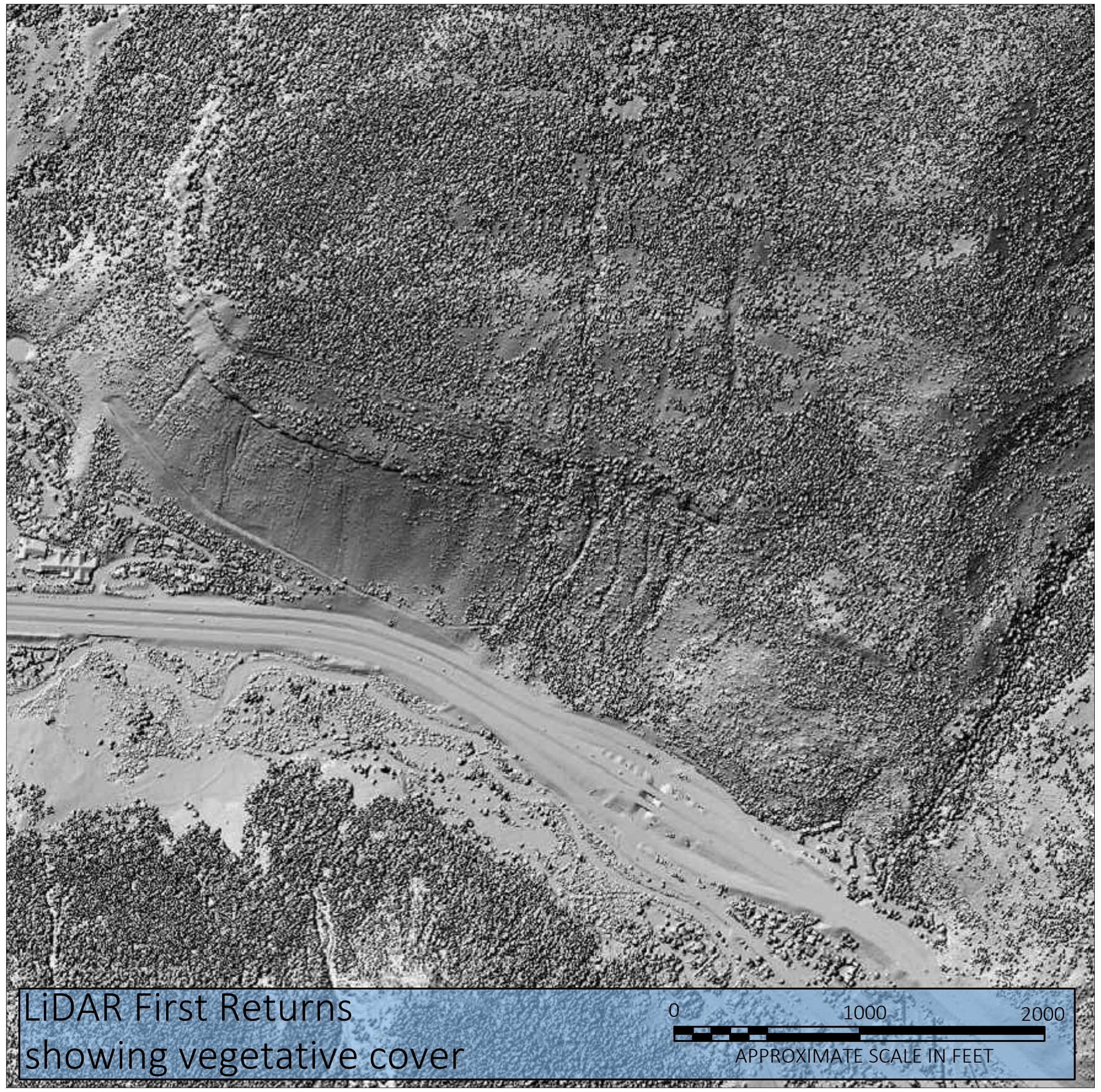
Multiply	By	To obtain
inches (in.)	2.54	centimeters (cm)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)

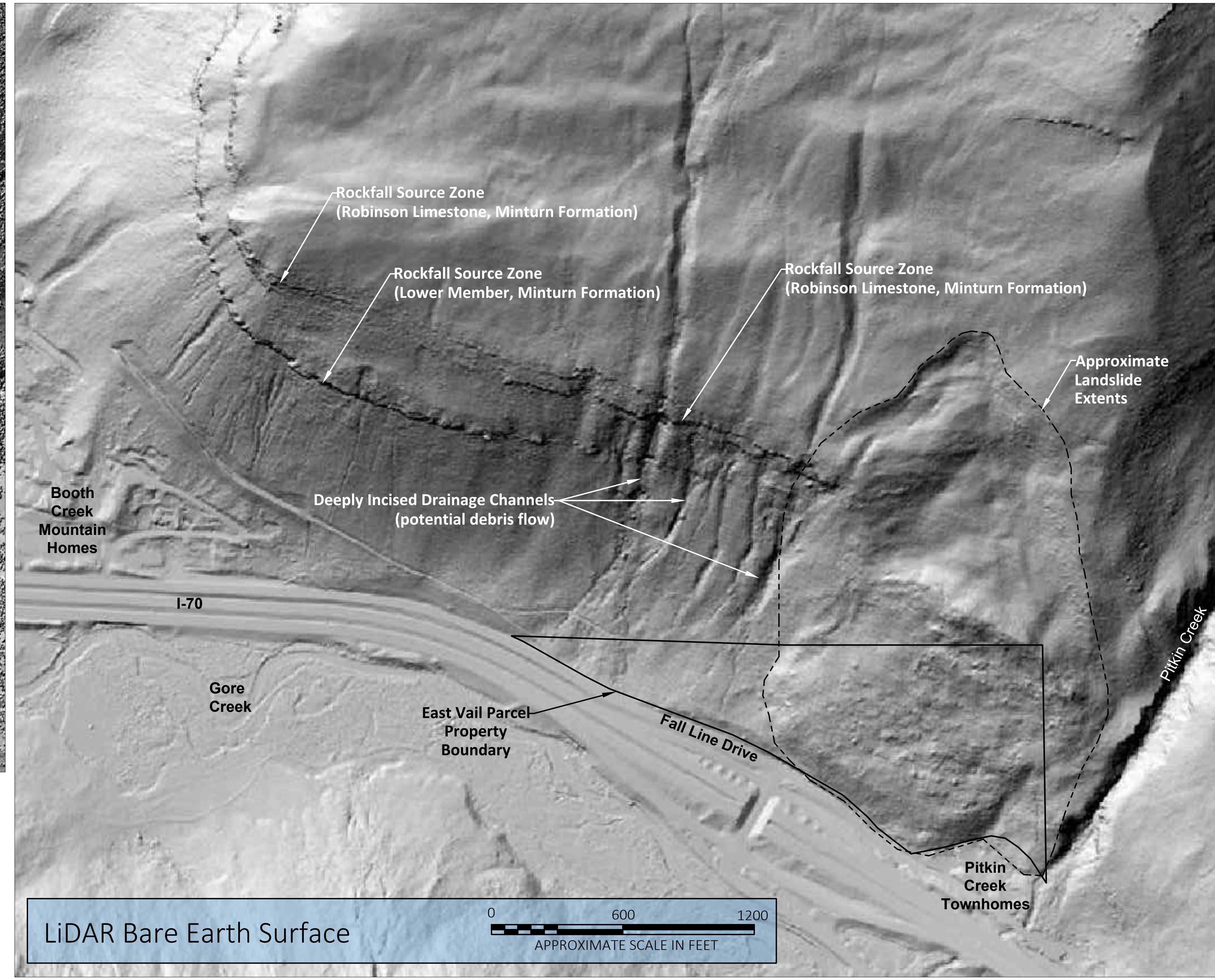
INDEX MAP SHOWING SURROUNDING QUADRANGLES

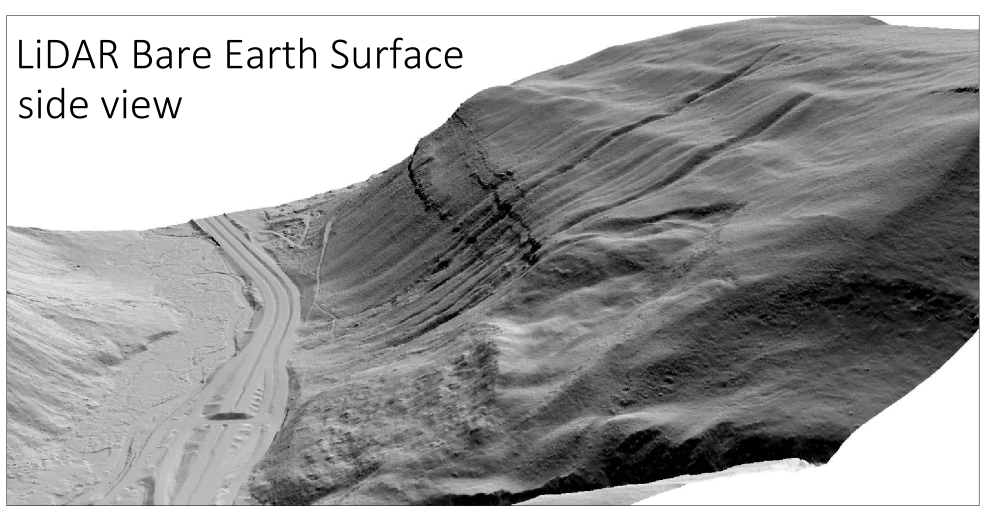
Project No: 18105
Project Name: East Vail Parcel
Date: 01.25.2019

FIGURE 4
Geologic Map

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING





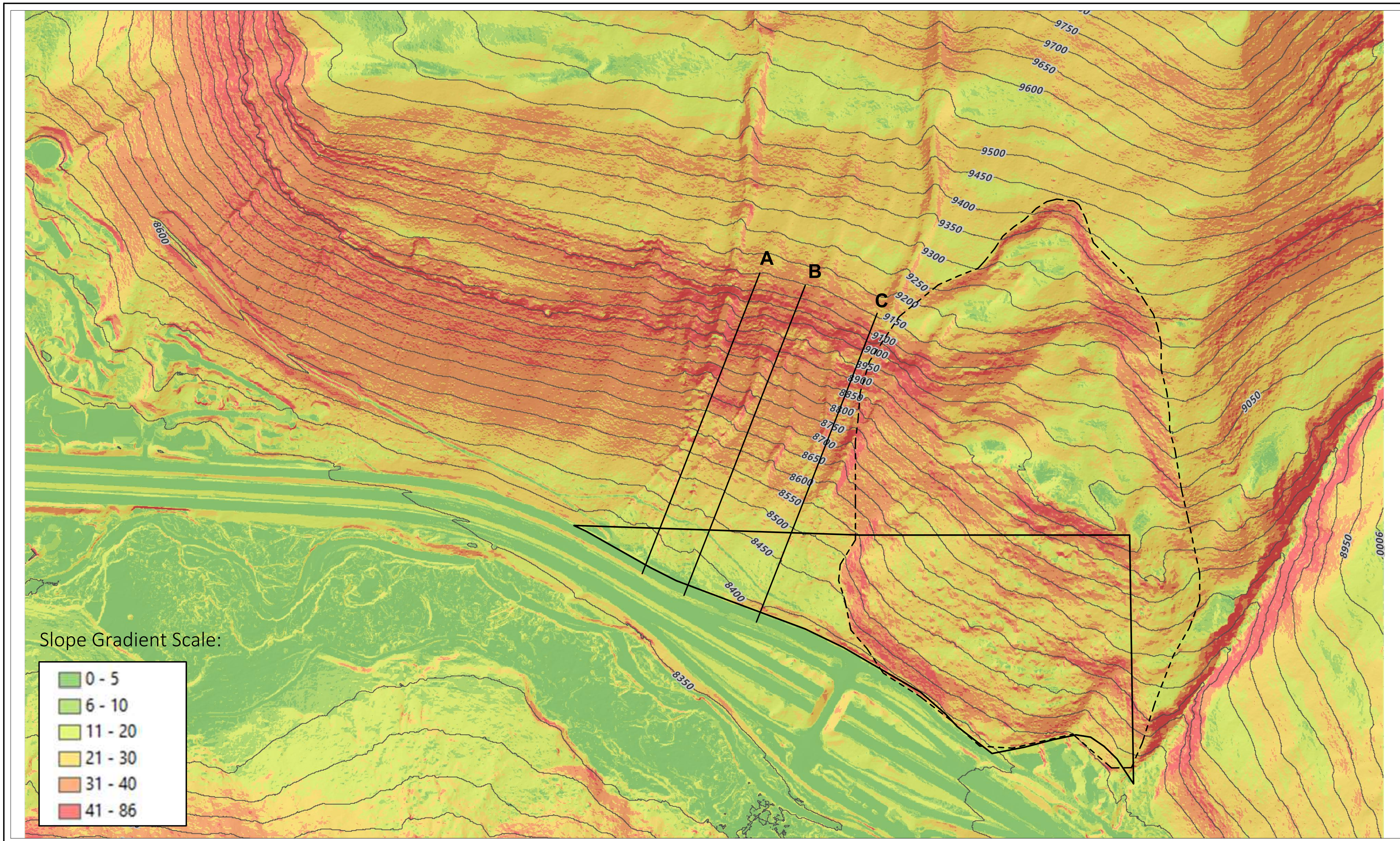


Project No: 18105
Project Name: East Vail Parcel

Date: 01.25.2019

FIGURE 5
LiDAR Imagery

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



Basemap: Topography and slope gradient derived from LiDAR.

East Vail Workforce Housing Parcel

Approximate Landslide Extents

A Study Sections

N

0 600 1200

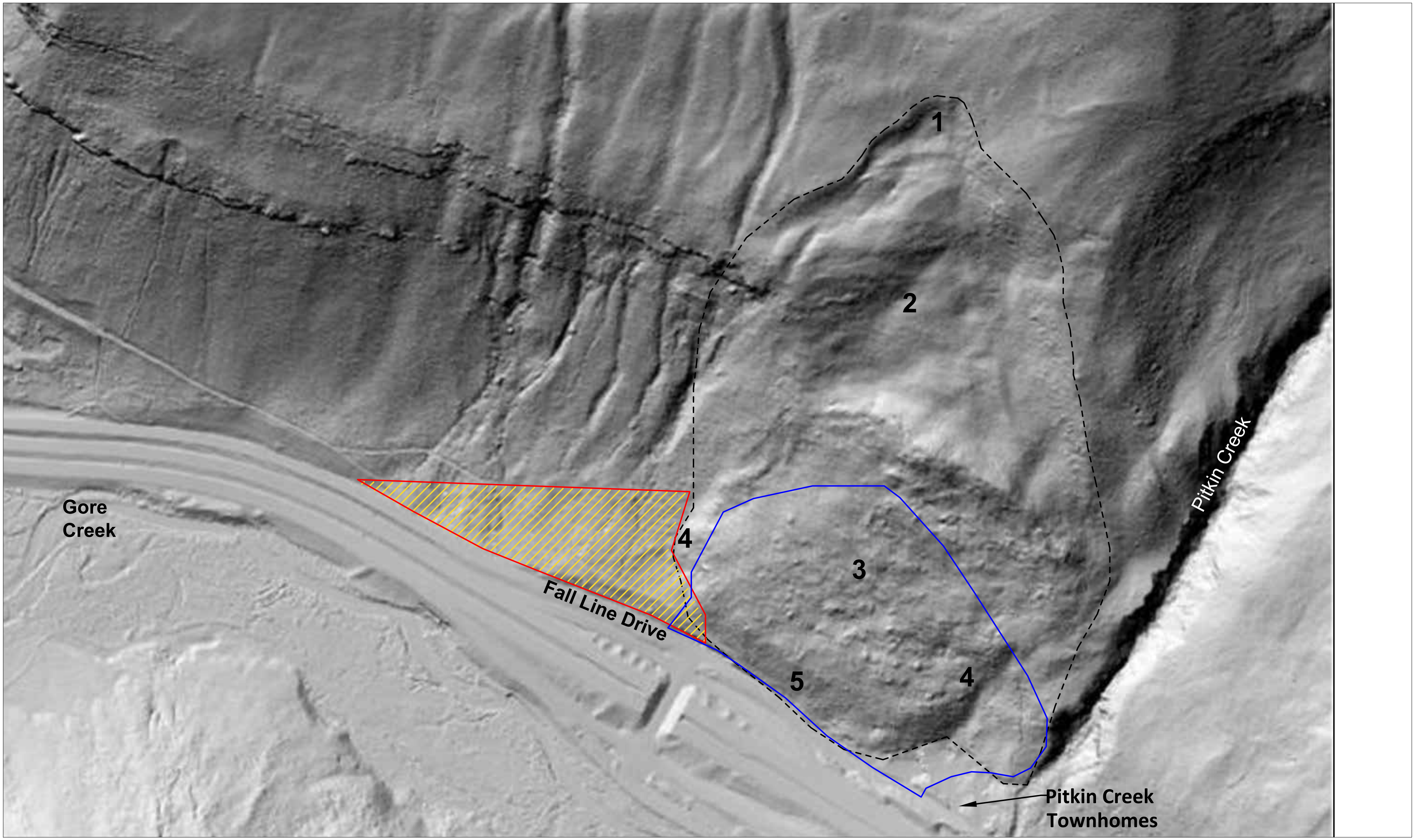
APPROXIMATE SCALE IN FEET

Project No: 18105
Project Name: East Vail Parcel

Date: 01.25.2019

FIGURE 6
Slope Map and Landslide Extents

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



Basemap: LiDAR ground surface.

East Vail Workforce Housing Parcel - part to be developed (+/- 5.4 acres)
Approximate Landslide Extents
Approximate Extents, published landslide deposit (Kellogg and others, 2003)

Area 1 - landslide headscarp, down-dropped, detachment area.
Area 2 - down-dropped area with irregular topography.
Area 3 - dislocated, semi-intact block that has moved downslope from the point of origin, hummocky and uneven topography.
Area 4 - landslide flank, over-steepened slope.
Area 5 - landslide toe, over-steepened slope.

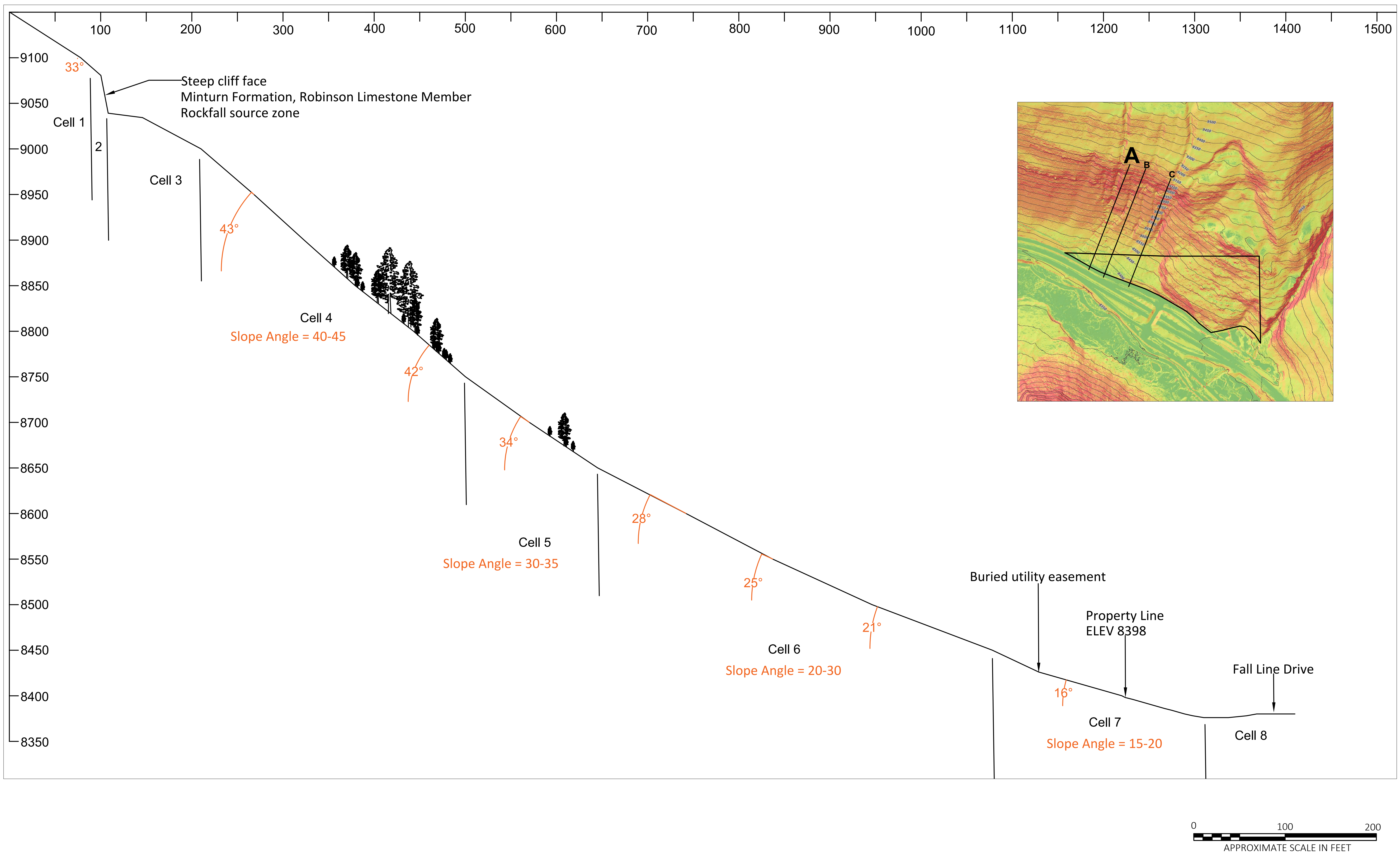
N

0 500 1000
APPROXIMATE SCALE IN FEET

Project No: 18105
Project Name: East Vail Parcel
Date: 01.31.2019

FIGURE 7
Landslide Map

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



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Date: 01.25.2019

FIGURE 8
Study Section A

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING

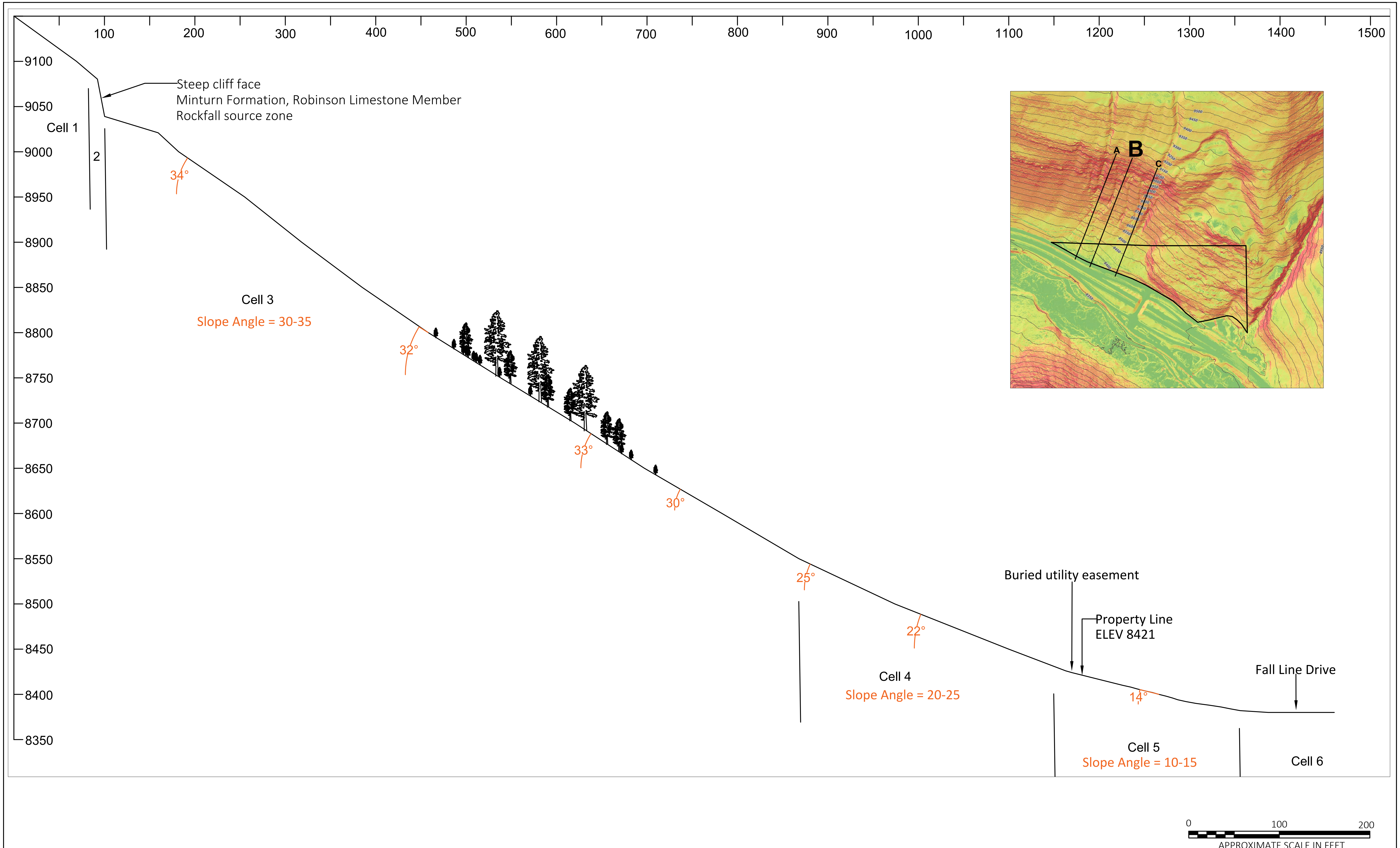

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FIGURE 9
Study Section B

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING

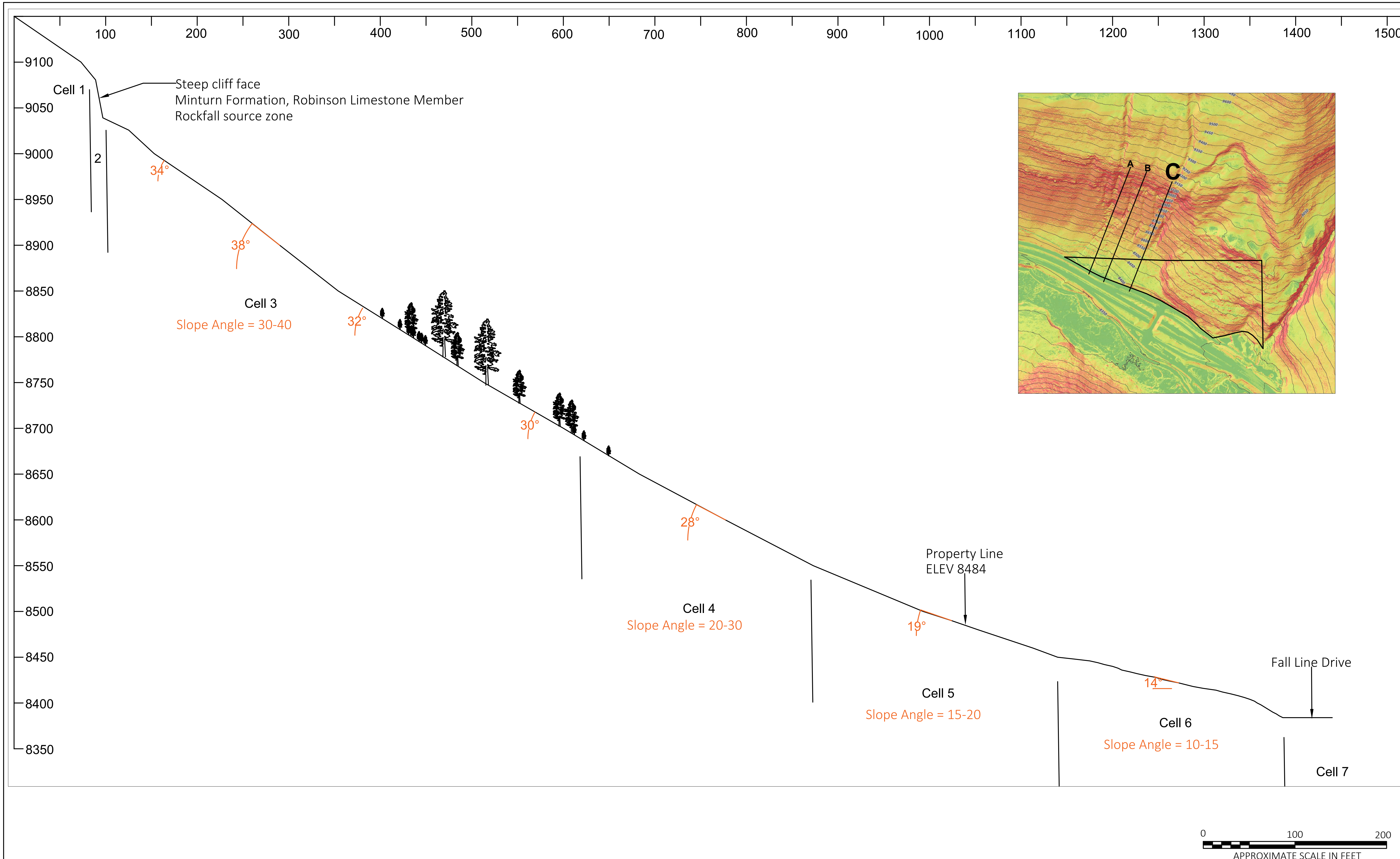

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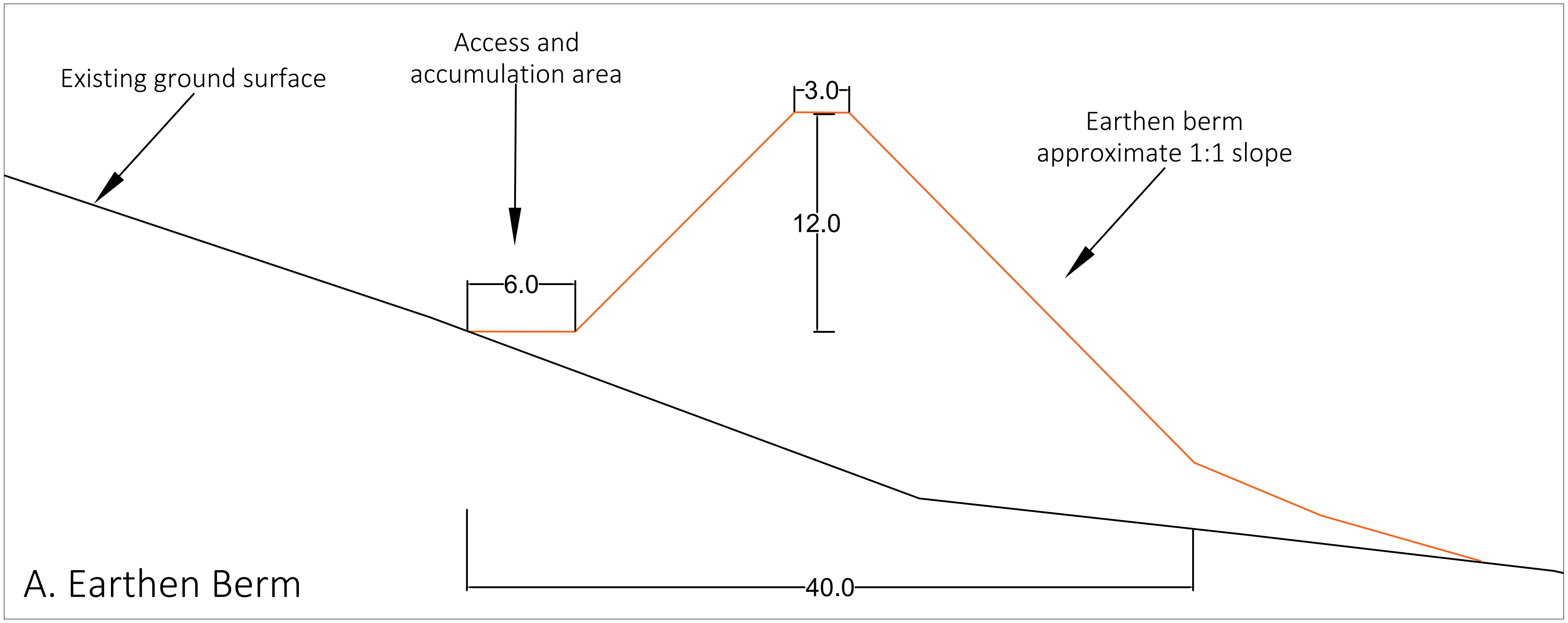
FIGURE 10
Study Section C

SKYLINE GEOSCIENCE
GEOLOGICAL CONSULTING



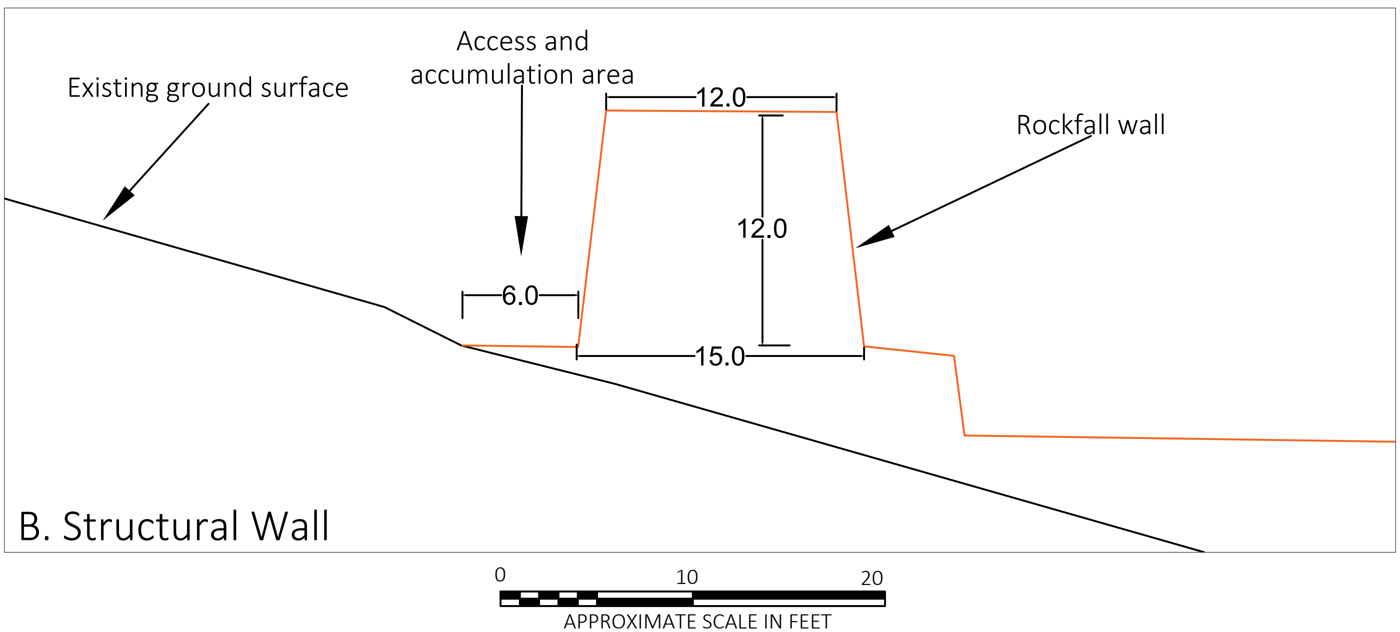


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FIGURE 11
Typical Sections - Rockfall Barriers

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