1ST NORTH AMERICAN LANDSLIDE CONFERENCE

FIELD TRIPS

VAIL, COLORADO

JUNE 3 – 10, 2007

Sponsored by:

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Aerial oblique photo of Vail, looking to the southeast. Located in the beautiful subalpine valley of Gore Creek, with a base elevation of 8,120 ft (2,475 m), Vail was founded in late 1962 and grew almost overnight to become a world-class resort. It has been ranked as the number one ski resort in North America by *SKI* magazine for 14 of the last 19 years, and is the largest single-mountain ski area in the USA.

The front side of Vail Ski Area is distinctive in that it does not have steep valley walls, as is encountered along most of the glaciated Gore Creek valley. Instead, the mountainside is dominated by landslide and colluvial deposits that overlie and are sourced by sedimentary formations of Pennsylvanian age. Quaternary (post-glacial) movement of the landslide complex resulted in overriding and burial of the valley walls by the landslide toe. This has created a large-scale, “hummocky” terrain that is ideal for skiing.

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PREFACE

These guidebooks were prepared for field trips associated with the 1st North American Landslide Conference from June 3-10, 2007 in Vail, Colorado. The conference, *Landslides and Society: Integrated Science, Engineering, Management, and Mitigation*, was sponsored by the Association of Environmental & Engineering Geologists (AEG), the GEO-Institute of ASCE, the American Rock Mechanics Association, the Canadian Geotechnical Society, the Transportation Research Board, the International Consortium on Landslides, the Federal Highway Administration, and the Geological Society of America Engineering Geology Division.

Field trips were sponsored by the AEG, the Colorado Geological Survey (CGS), the US Geological Survey (USGS), and the Federal Highway Administration (FHWA). The objective of the conference and field trips was to provide a stimulating forum for geoscientists, engineers, planners, economists, program managers, and other decision makers concerned with landslide hazards and their impact on North American society.

All conference participants were given the choice of attending one of nine field trips offered concurrently on Wednesday, June 6. These one-day trips began and ended in Vail. Topics for the trips include: landslide hazards, engineering constraints, and mitigation alternatives along Interstate 70 in Glenwood Canyon; geology of the DeBeque Canyon landslide; a tour of Colorado wineries near Grand Junction; the geology and progression of slump-blocks surrounding Grand Mesa; geologic hazards, related mitigation, and land-use issues between Glenwood Springs and Marble; the geology between Glenwood Springs and Aspen, including the engineering geology of ski areas near Aspen; a tour of landslides, mining, and history in the area between Vail and Leadville; and a guided tour of the geology and geologic hazards of Vail.

Three optional pre-meeting and post meeting trips were also offered. The pre-meeting trips were a half day in length and covered the geology, geologic hazards, and history between the Denver International Airport and Vail. The post-meeting trip was two days in length and ran from Vail to the Slumgullion landslide near Lake City. The Slumgullion trip focused on results from research studies performed at the landslide over the past sixty years.

In closing, we would like to thank all of the field trip leaders for their diligence, enthusiasm, and patience during the process of preparing and editing this compilation. We would especially like to thank Julie Keaton, the Conference Director, and Keith Turner, the Conference General Chair, for their encouragement and assistance with the publication of this volume. Lastly, individual field trip leaders were responsible for the information and opinions presented in the guidebooks, and these opinions do not necessarily reflect the opinions of any of the sponsoring agencies.

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GEOLOGY, GEOLOGIC HAZARDS, AND HISTORY ALONG THE I-70 CORRIDOR FROM DENVER INTERNATIONAL AIRPORT TO VAIL, COLORADO

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Mt. Guyot and Bald Mountain from Dillon Reservoir

1st North American Landslide Conference
Vail, Colorado, June 3, 2007

OVERVIEW

This field trip starts at Denver International Airport and ends in Vail, Colorado. The purpose of the field trip is to acquaint attendees of the conference with some highlights of the area's geology, geologic hazards, history, and scenery. The trip will be run primarily as a bus tour, with a few short stops. Our route takes us along one of the most historic and well traveled transportation corridors in the Rocky Mountains, the Interstate 70 (I-70) corridor. Over 150 years ago, this region was an important mining center renowned for its gold and silver resources. The area is now famous for skiing and outdoor recreation. This guidebook contains narrative descriptions for four stops and several drive-by points of interest (Table 1).

Table 1. Field Trip Stops and Topics.

Location	Topic
Denver International Airport	Brief History of DIA
Denver Metropolitan Area	Geologic setting of the Denver area
US Highway 6, Clear Creek Canyon – **Stop 1**	Rockslide from summer of 2005
Clear Creek Valley	Pleistocene glaciation and geologic hazards
Idaho Springs	Mining history
Georgetown – **Stop 2**	Debris flow and rockfall hazards
Silverplume/Brownville/Bakerville	Rockfall, snow avalanche, and debris-flow hazards
Junction of I-70 and US Highway 6	Eisenhower/Johnson Tunnels
Loveland Pass	The Continental Divide
Arapahoe Basin – **Stop 3**	Alpine debris flows
Keystone Resort	Ski area geomorphology and geologic hazards
Dillon Dam – **Stop 4**	Denver Water interbasin storage and transport system
Tenmile Creek Canyon	Avalanche chutes
Wheeler Junction / Copper Mtn.	Resort planning history and issues
Vail Pass	Landslides and I-70 construction
Gore Creek Valley and Vail	Geologic setting of Vail area; rockfall and avalanche areas

TRIP ROUTE DESCRIPTION

The trip route will take us through the heart of the Front Range of the Rocky Mountains, over the top of the Continental Divide at Loveland Pass, across the Blue River valley, through a canyon that separates the Tenmile and Gore Ranges, and over Vail Pass before descending into the valley of Gore Creek and Vail. We will mostly follow highways I-70 and US-6 (Fig. 1).

The trip route description tables include directions and mileages (stop-to-stop and cumulative). In deference to American odometers, we will use miles instead of kilometers.

Much of the narrative herein has been adapted from recent field trip guidebooks, particularly Noe and others (1999; 2003); Coe and others (2002), and White and Vessely (2006).

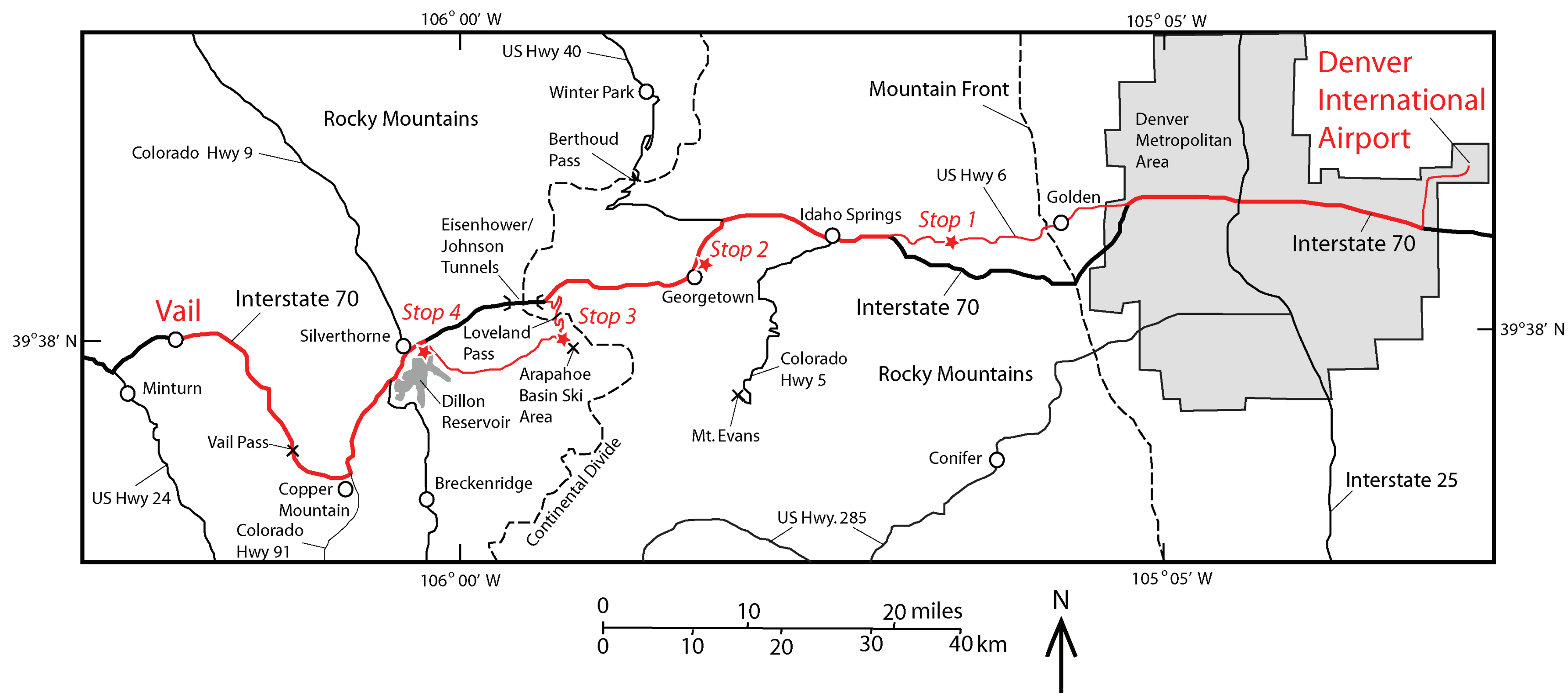


Figure 1. Map showing field trip route (red line) and stops (red stars).

TECTONIC SETTING OF CENTRAL COLORADO

The rocks in Central Colorado have endured multiple periods of deformation. The oldest, Precambrian rocks have incurred at least two periods of ductile deformation associated with deep burial and metamorphism during the Proterozoic. Early Paleozoic tectonism certainly occurred in Central Colorado, but the evidence is incomplete.

During the Pennsylvanian and Permian periods, the Ancestral Rocky Mountains rose as fault blocks out of a shallow sea. Colorado was dominated by the ancestral Uncompahgre and Front Range uplifts with a restricted evaporite basin trapped between the two ranges. Most of the evidence of this uplift is stratigraphic rather than structural. The syntectonic rocks in the Red Rocks area near Denver and in the Vail Valley record the uplift of the ancestral Front Range. It is rare to find a fault that can unequivocally be assigned to this orogeny. The Ancestral Rocky Mountains were mostly worn away by the end of the Triassic.

The next major deformation, the Laramide Orogeny, began with fault blocks rising out of the Late Cretaceous seaway about 80 million years ago. This period of uplift and crustal shortening continued into the early Cenozoic. The structural style is dominated by high-angle reverse faults with a few, low-angle thrust faults (e.g., the Williams Range thrust that we will cross on this trip). Faulting was accompanied by igneous intrusions and mineralization, as well as deposition of syntectonic sedimentary units.

The last major tectonic event, began about 25 million years ago with major east-west extension. This extension broke the crust into large blocks that are subsiding into basins and rising into some of the most impressive mountains in North America. Fifty-eight peaks in Colorado soar above 14,000 ft (4,267 m) in elevation and the entire state averages 6,800 ft (2,073 m) above sea level. The structural style is dominated by normal faults and basaltic volcanism. CGS' current catalogue of Late Cenozoic deformation includes 92 Quaternary faults. The youngest basalt in the state, located 45 mi (73 km) to the west of Vail, is 4,150 years old.

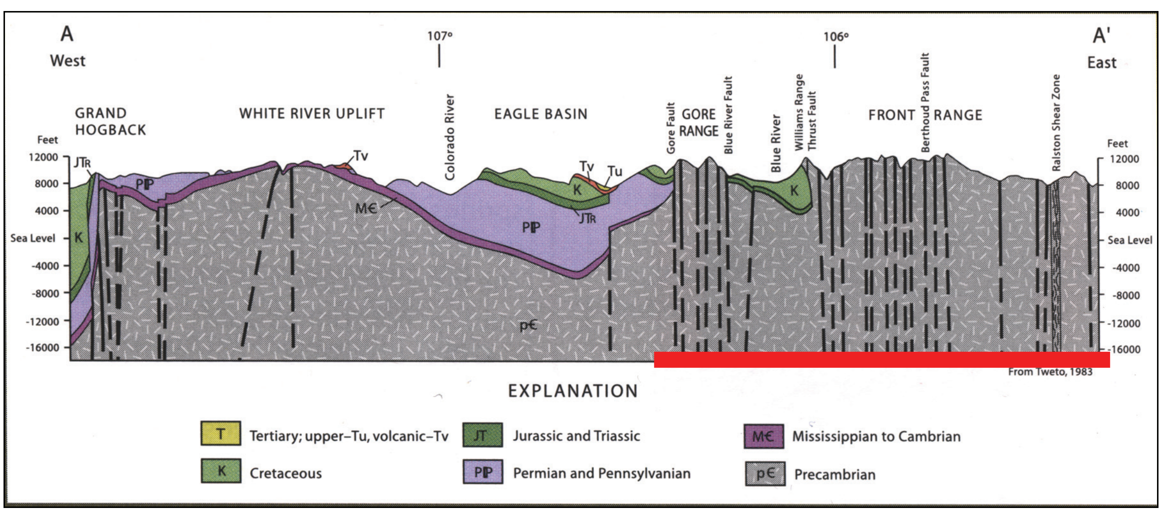


Figure 2. General geologic cross section for the central Colorado mountains along the I-70 corridor, from Glenwood Springs to Golden, a distance of about 150 mi (240 km) (modified from Tweto, 1983). The red bar underlines geology along the trip route.

DENVER INTERNATIONAL AIRPORT – START OF THE TRIP

Denver International Airport (DIA) is located about 25 mi (40 km) northeast of Denver (Fig. 1). The airport opened on February 28, 1995. In terms of geographic area, it is the largest airport in the United States and third largest in the world. As of 2006, DIA was the sixth busiest airport in the United States in terms of air traffic. DIA served about 47 million air passengers in 2006. The airport terminal's unique white fabric roof is designed to be reminiscent of the snow-capped Rocky Mountains, which are visible to the west of the airport.

The airport is located within the Denver Basin, a Rocky Mountain structural basin containing Pennsylvanian to Paleogene rocks. The basin formed during late Cretaceous and early Tertiary time. The deepest part of the basin is located under the western suburbs of Denver where about 13,100 ft (4,000 m) of sedimentary rocks are present. Excavation, grading, and drilling associated with construction of DIA provided numerous sample sites for geologists studying the ages and paleoenvironments of Cretaceous and Paleogene strata in the Denver Basin (Nichols and Fleming, 2002).

The flat terrain surrounding the airport may seem benign, but expansive soil and bedrock have been major issues that figured in the design and safe operation of the airport. In addition, the appearance of the highly expansive mineral, Ettringite, following mixing of lime solutions with the clays, has been a concern. Building foundations and runways have been affected by heaving. Overexcavation and fill replacement was used as a mitigation design for the runways and buildings. Deep reinforcement caissons were also used for the buildings.

Directions to stop 1 are given in Table 2.

Table 2. Mileage and Directions from Denver International Airport to Clear Creek Canyon (Stop 1).

Mileage (miles)	Directions
Not started	Proceed southwest on Pena Boulevard toward I-70 westbound.
0.0 (Intersection of Pena Boulevard and I-70 west bound) 0.0 (cumulative)	Start mileage at "End Pena Boulevard" sign on I-70 westbound merge lane. Proceed westbound on I-70.
18.7 (from Pena/I-70 intersection) 18.7 (cumulative)	Take Colorado Highway 58 westbound (I-70 exit 265) to Golden. Watch for Golden/Colorado School of Mines sign prior to I-70 exit.
24.2 (from Pena/I-70 intersection) 24.2. (cumulative)	Junction of Highways 58, 93, and US 6 at mountain front. Go straight on US 6 westbound and enter Clear Creek Canyon.
34.3. (from Pena/I-70 intersection) 34.3. (cumulative)	Go roughly 0.2 mi past mile post 262.0 and turn left into a large pullout on the south next to Clear Creek. Be careful when crossing in front of eastbound traffic. On the other side of US 6 is a rock slope covered by wire mesh. This is **Stop 1**.

Interstate 70 Corridor

Interstate 70 is the main east-west transportation route serving the Denver metropolitan area, one of the fastest growing regions of the United States. Increasing traffic associated with the growth in population has led to traffic congestion on I-70 east of the Continental Divide, along the mountainous Front Range portion of the highway that parallels Clear Creek (Fig. 1).

Desire to alleviate this congestion has motivated recent investigations into modifications of transportation infrastructure that would increase the capacity along the Front Range portion of the I-70 corridor (Andrew and Lovekin, 2002; Arndt and others, 2002). Modifications that have been proposed include additional highway lanes, a monorail, and an additional highway tunnel under the Continental Divide (there are currently two tunnels, which are referred to as the Eisenhower/ Johnson Tunnels). Two segments of I-70 in Colorado pose an additional difficulty: the Turkey Creek and Georgetown inclines both exceed FHWA standards of a 7 percent grade.

Geologic Setting of Denver

Denver (established 1858) is located on the Great Plains adjacent to the eastern front of the Front Range portion of the southern Rocky Mountains (Costa and Bilodeau, 1982). Uplift near the end of the Cretaceous period built the Front Range as part of the Laramide Orogeny. Uplift tilted sedimentary rocks to the west of Denver, and subsequent erosion resulted in widespread late Cretaceous and early Tertiary piedmont deposits in the Denver area. Uplift and erosion exposed Precambrian units within the Front Range and created hogbacks composed of Pennsylvian to Cretaceous rocks immediately adjacent to the Front Range (Fig. 3).

The Denver metro area is underlain by clay-rich Cretaceous formations. Expansive soil and bedrock is the primary geologic hazard in the area. Farther to the west, in the foothills area along the mountain front, landslides begin to predominate.

Golden and Table Mountain Landslides

Landslides to the west of Denver are most common on dip slopes of the hogbacks, on the flanks of North and South Table Mountains near Golden, and on the flanks of Green Mountain to the south of Golden. The Table Mountains are capped by Tertiary basalt and underlain by the Cretaceous/Tertiary Denver-Arapahoe Formations. Green Mountain is capped by the Tertiary Green Mountain conglomerate, which was deposited as basin-fill material by a stream draining the uplifting Front Range (Costa and Bilodeau, 1982).

Our trip route will take us between the North and South Table Mountains, which are nearly continuously blanketed with landslide deposits beneath the basalt caprock. The landslides are especially prevalent along the north-facing slopes (on our left). An irrigation canal cut into this slope has further destabilized this slope.

Golden (established 1859) was Colorado’s first territorial capital from 1862 to 1867. Today, it is home to two world-famous institutions that are well known to geologists: the Coors Brewery and Colorado School of Mines. At Golden, we will enter the Front Range of the Rocky Mountains via the deep canyon of Clear Creek.

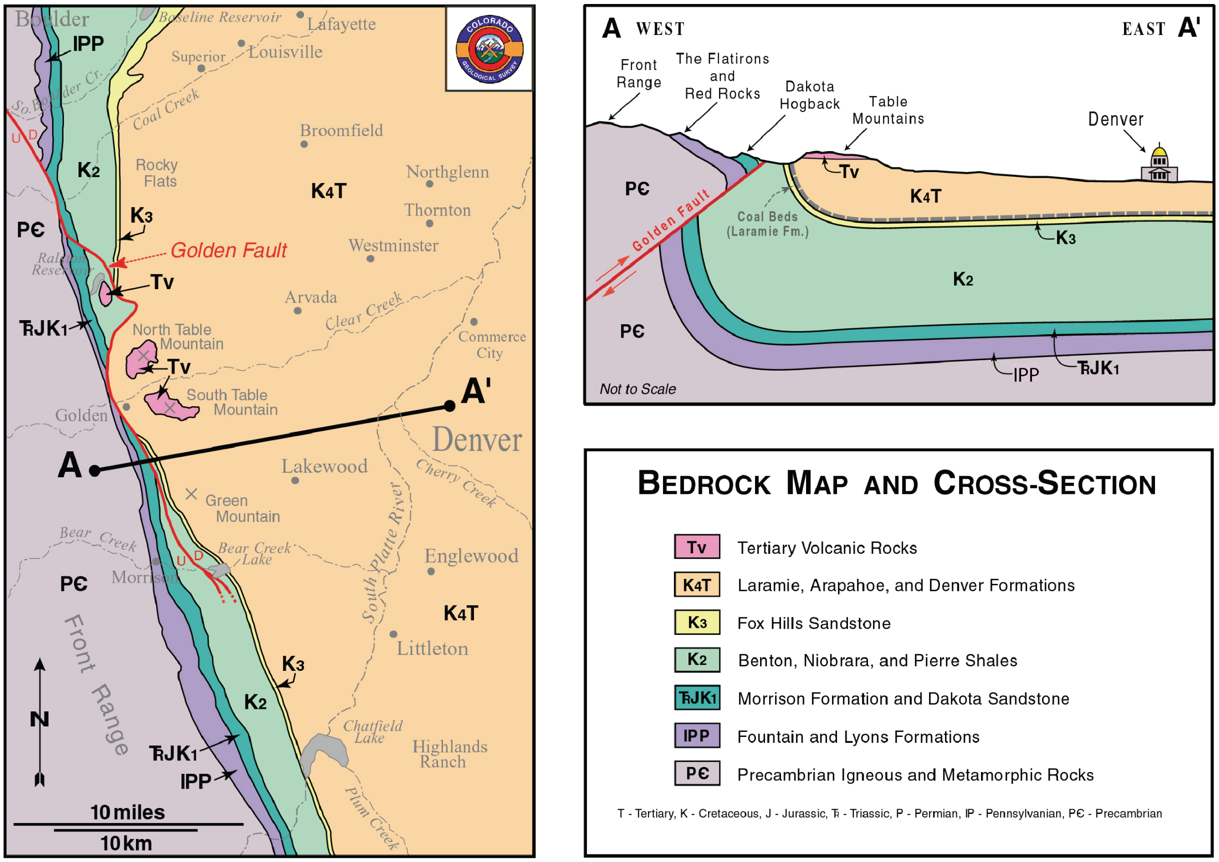


Figure 3. Geologic map and cross section of the western flank of the Denver Basin and the eastern flank of the Front Range. From Noe and others, 1999.

STOP 1. 2005 ROCKSLIDE IN CLEAR CREEK CANYON

Rockfalls and rock slides are common along transportation corridors in the Rocky Mountains. Clear Creek Canyon just west of Golden is one of the most active rockfall areas in Colorado (Rogers, 2003). The Canyon has been cut into Precambrian schists and gneisses by Clear Creek, one of the primary drainages in the Denver area (Fig. 3). Rockfalls occur every year in the Canyon in response to freezing and thawing, snowmelt, and intense or prolonged rainfall. Historical rockfalls have ranged in size from small (less than an inch (several cm) in diameter) individual rocks to large boulders up to 10-13 ft (3-4 m) in diameter (see Fig. 4).

A recent example of a historical rockslide is the subject of Stop 1. This rockslide (Fig. 5) occurred at about 11 am on June 21, 2005 (Ortiz, 2005) after thunderstorms in the area the previous night. The rock slide covered Highway 6 and trapped two semi-trucks that were passing by the area at the time of failure. One of the truck drivers sustained moderate injuries. The amount of material that failed was about 1,960 yards^3 (1,500 m^3) (Ortiz, 2005), but several large overhanging areas of rock remained above the highway after the failure. The slide plane for the rock slide was the surface of a pegmatite intrusion that dipped toward the highway (Fig. 5c).

a

b

Figure 4. July 8, 2006 rockfall in Clear Creek Canyon triggered by prolonged rainfall. Photographs provided by Ty Ortiz of CDOT. a) Source area and rock on edge of road. B) Car destroyed by the rock.

a

b

c

Figure 5. Photographs of the June 21, 2005 rockslide in Clear Creek canyon. a) Trucks trapped by the rockslide. Photograph provided by Ty Ortiz, CDOT. b) View from Highway 6 looking toward the west. c) View of the slip surface looking north (i.e., the surface of a pegmatite intrusion).

The Colorado Department of Transportation (CDOT) looked at two options for mitigating the immediate threat from more rock slides at the site; rock reinforcement or removal of a large portion (about 35,000 yards^3, 2680 m^3) of the rock above the highway. CDOT chose the second option, completed the work, and opened the highway on September 12, 2005, about 3 months after the rock slide. The cost to remove the rock and repair the road was 3.2 million dollars, more than CDOT's typical annual budget for rockfall mitigation for the entire state of Colorado (Leib, 2005).

Directions to Stop 2 are given in Table 3.

Table 3. Mileage and Directions from Rockslide in Clear Creek Canyon (Stop 1) to Georgetown (Stop 2).

Mileage (miles)	Directions
0.0 (from Stop 1) 34.3. (cumulative)	Proceed westbound on US 6 from Stop 1.
1.5 (from Stop 1) 35.8. (cumulative)	Turn left at 3-way junction of Colorado 119 and US 6 and continue westbound on US 6. The Clear Creek Forks rockslide is on the left (south) side of US 6 at the junction.
4.8. (from Stop 1) 39.1. (cumulative)	Merge onto I-70 westbound.
6.8 (from Stop 1) 41.1. (cumulative)	Pass the town of Idaho Springs and the Argo mine and mill on the right (north) side of I-70.
21.0. (from Stop 1) 55.3. (cumulative)	Leave I-70 at Georgetown, Exit 228. Turn left (south) and pass under I-70. Proceed south.
21.2. (from Stop 1) 55.5. (cumulative)	Turn left onto Alvarado Road at the stop sign and proceed east on Alvarado Road.
22.0 (from Stop 1) 56.3. (cumulative)	Turn right into rest area on the shore of Georgetown Lake. This is **Stop 2**.

Clear Creek Valley

After leaving Stop 1, the trip continues up the Clear Creek drainage. Near the intersection of Highway 6 and I-70, the drainage widens into a V-shaped valley. The portion of the valley between the intersection and Downieville (Fig. 1) is non-glaciated and generally characterized by moderately steep hillslopes and large and moderately steep tributary drainage basins. Pleistocene gravels are common along the valley bottom and on hillslopes adjacent to Clear Creek.

The upper part of the Clear Creek valley above Downieville (elevations above about 7,840 ft, 2,400 m) was repeatedly glaciated in Pleistocene time (Madole and others, 1998). The most recent Pleistocene glaciers (Pinedale age) in the Clear Creek valley are estimated to have disappeared between 14,000 and 12,000 ^{14}C yr BP (Caine, 1986, Madole and others, 1998). Above this boundary, the Clear Creek valley typically has steep walls and small and steep tributary-drainage basins. Debris-flow fans are present at the mouths of tributary-drainage basins in both parts of the valley.

Idaho Springs

The City of Idaho Springs lies in the heart of the Colorado Mineral Belt, a zone of mineralization that extends from southwestern Colorado to the Front Range northwest of Denver (Tweto and Sims, 1963). Rocks in the area are predominantly Precambrian biotitic gneisses and quartz monzonites with scattered Tertiary intrusions (Bryant and others, 1981) with associated hydrothermal alteration and silver and gold mineralization (Harrison and Wells, 1956; Sims and Gable, 1967).

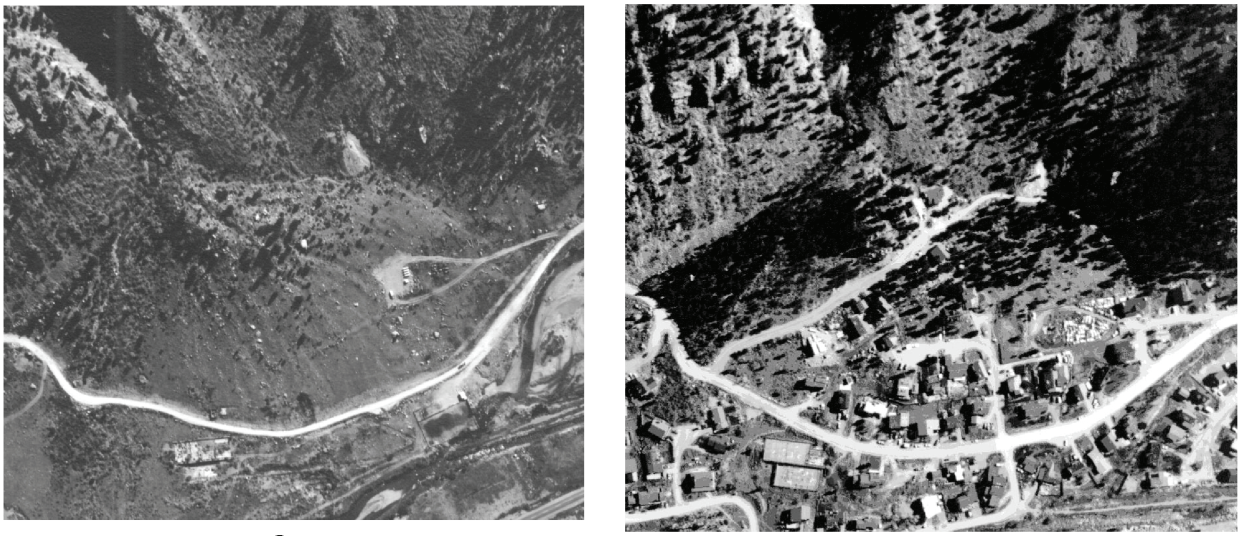
One of the first substantial discoveries of the Colorado Gold Rush occurred in Idaho Springs on January 7, 1859. Gold mining reached a peak in Idaho Springs (and in Central City to the north) in the 1860's when the town's population reached about 12,000 people (Western Mining History, 2006). Today's population is about 1,800. Numerous abandoned mines and mine dumps are still visible on hillslopes in the area.

By the early 1900s there were many deep mines and shafts in Idaho Springs and Central City and the removal of ore and pumping of water was becoming increasingly difficult. Starting in 1893, work on a tunnel from Idaho Springs to the Central City was started to help drain mines and provide for economical transportation of the gold-bearing ore. A processing mill was also constructed at the mouth of the tunnel in Idaho Springs. The tunnel and mill were completed in 1910 and named the Argo Tunnel and Mill (Western Mining History, 2006). At the time of completion, the tunnel was the longest in the world at 4.16 mi (6.7 km). The tunnel and mill were used successfully until January 19, 1943, when a crew of four miners apparently drilled into a flooded mine shaft near Central City. The resulting flood sent water down the tunnel and out the mouth for several hours and killed the four miners. The tunnel and mill were abandoned for many years, but were renovated and opened for tours in the late 1970s. The Argo Tunnel and Mill are the large red buildings that are visible on the north side of I-70 when passing through Idaho Springs.

STOP 2. GEOLOGIC HAZARDS NEAR GEORGETOWN

Georgetown (est. 1859) and the surrounding area are exposed to multiple hazards including rockfalls, debris flows, and snow avalanches. Our stop is at the edge of Georgetown Lake and provides an overview of these hazards. On the southeast side of I-70, houses have been built on fans at the mouths of steep drainages. The channels above these fans contain abundant loose material capable of generating debris flows. For the fan shown in figure 6, radiocarbon dating of charcoal from fan deposits (Coe and others, 2003) suggests that the mean recurrence interval between debris-flow events is about 700 years. The probability of future debris-flow events is about 7 percent in any given 50-year period.

Debris-flow channels on the northwest side of I-70 (Fig. 7) are very active. On average, debris flows in these channels deposit debris on the fans and highway about once every 7 years or less. Spectacular debris-flow levees are present along some of the channels. The debris flows are rather unusual in that they do not originate from landslide source areas, but rather acquire material from hillslope and channel erosion (by fire-hose processes and progressive bulking by sediment entrainment). Progressive bulking can occur when concentrated overland flow mobilizes and entrains loose sediment from hillslopes or channels, and transforms from a water-rich flow into a debris flow (Cannon et al., 2003).



a b

Figure 6. Aerial photographs showing residential development on a fan in Georgetown (fan is visible to the east from Stop 2. From Coe and et al. (2002). a) Photograph from 1961. b) Photograph from 1996. Distance covered by the width of the photos is about 0.3 mi (0.5 km) on the ground.

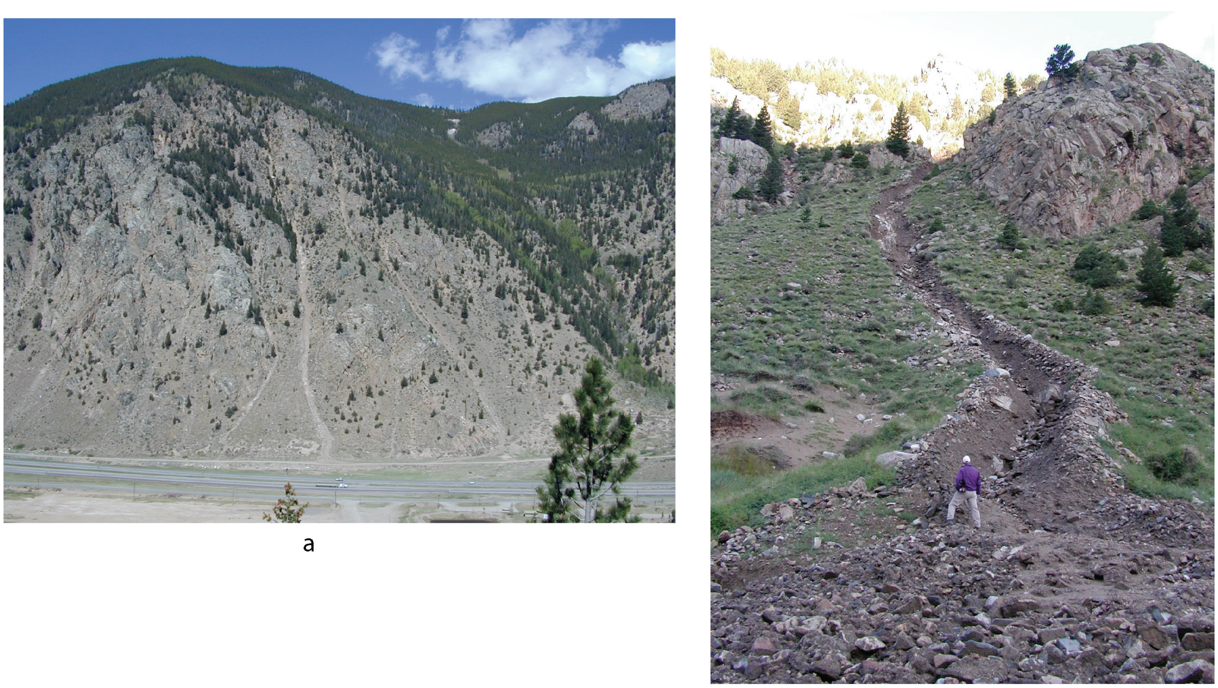


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Figure 7. Active debris flow basins on the northwest side of I-70 near Georgetown. a) Overview of multiple basins. b) Fan and levees deposits from a debris flow on July 14, 2001.

The heads of the fans near this stop are susceptible to rockfall hazards as evidenced by numerous rock-fall deposits. Just to the southeast, and directly upslope from recently built condominiums, a fresh rockfall source area and deposit are visible.

To the southwest, along the Georgetown Incline portion of I-70, lies one of the worst rockfall-hazard sites in Colorado (Fig. 8). Several fatalities from rockfall have occurred along this portion of I-70, with the most recent occurring in September, 2003 when a Silver Plume man was killed when a rock crashed through his car. CDOT is actively involved in mitigation of this hazard area, as we will see on the way to Stop 3.

Georgetown, the "Silver Queen of Colorado," was once Colorado's 3rd largest city with a population of more than 10,000. Founded in 1859, it was not until the silver rush of 1864 that the town boomed. A narrow gauge railroad was built along the torturous route from Golden to Georgetown (along our field trip route) and beyond. The railroad segment between Georgetown and Silver Plume, the next town up the valley, required a series of spiraling loops to ascend the glacial step. This engineering marvel was known as the Georgetown Loop. Today, tourists can ride trains along the Georgetown Loop that are pulled by stout, narrow-gauge steam engines.

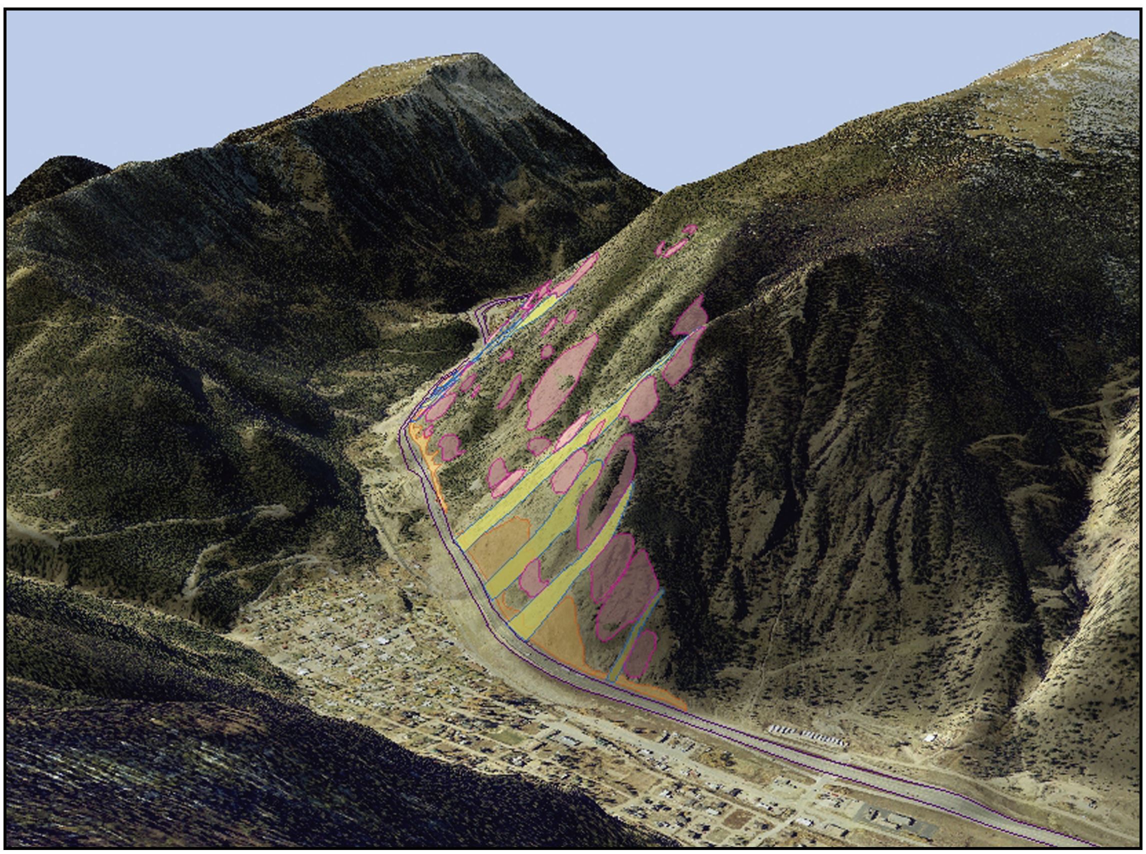

Figure 8. Perspective view to the west showing the segment of I-70 known as the Georgetown Incline between Georgetown and Silver Plume. Georgetown is visible in the foreground. Pink zones are rockfall source areas, yellow zones are rockfall chutes, and orange zones are highway cuts. Draped DEM image provided by CGS.

Directions to Stop 3 are given in Table 4.

Table 4. Mileage and Directions from Georgetown (Stop 2) to Arapahoe Basin Ski Area Overlook (Stop 3).

Mileage	Directions
0.0 (from Stop 2) 56.3 (cumulative)	Leave Stop 2 and return to I-70 westbound.
0.9 (from Stop 2) 57.2 (cumulative)	Enter ramp to I-70 westbound and start up the area known as the Georgetown Incline.
3.1 (from Stop 2) 59.4 (cumulative)	Pass the town of Silver Plume
9.7 (from Stop 2) 66.0. (cumulative)	Pass the mouth of Watrous Gulch on the right (north) side of I-70. Site of a July 1999 debris flow that closed I-70 for 25 hours.
11.1 (from Stop 2) 67.4. (cumulative)	Pass the Mount Bethel snow avalanche chute on the right (north) side of I-70
12.3 (from Stop 2) 68.6. (cumulative)	Leave I-70 at Exit 216, Loveland Pass, and proceed west on US 6 toward Loveland Pass.
13.3 (from Stop 2) 69.6. (cumulative)	Pass the Loveland Ski area on the right side of US 6.
14.2 (from Stop 2) 70.5 (cumulative)	Pass the Seven Sisters snow avalanche chutes on the right side of US 6.
15.8. (from Stop 2) 72.1 (cumulative)	Overlook of Eisenhower/Johnson Tunnels on left side of US 6.
17.2 (from Stop 2) 73.5 (cumulative)	Loveland Pass, Continental Divide at an elevation of 11,990 ft (3,655 m). Proceed down the west side of Loveland Pass toward the A-Basin ski area.
19.9 (from Stop 2) 76.2. (cumulative)	Pull into the large pullout on the left side of US 6. This is **Stop 3**.

Silver Plume and Upper Valley of Clear Creek

The historic mining town of Silver Plume (est. 1870) has rockfall hazards of its own, as well as serious snow avalanche hazards. Deadly avalanches occurred during the 1800s, at the height of the town's population, when the nearby slopes were denuded of timber for the mines. In March 2003, following an unusual 6 ft (1.8 m) snowfall, a huge avalanche flattened a mature forest on the south wall of the valley, as well as the town's water treatment plant on the valley floor.

Just to the west of Silver Plume, a large cone of gravel marks the former location of the mining camp of Brownville. This town was located along the valley floor, immediately downhill from the district's major mine (the Seven-Thirty Mine). Mine waste, which had been end-dumped into the hanging valley of Brown Gulch, about 1,500 ft above the town, collapsed into the creek and became entrained in debris flows on several occasions, driven by snowmelt and rainfall. These debris flows progressively buried the town between the 1880s and 1912.

The upper valley of Clear Creek contains numerous avalanche paths with starting zones above the tree line. Perhaps the largest is located along the north-facing slope of Mt. Bethel.

CDOT attempts to control this avalanche path using a series of snow fences (which reduce snow loading from the west), earthen barriers, and periodic detonation of explosive charges. Another well known path, the Seven Sisters, crosses U.S. Highway 6 where we depart from I-70.

Eisenhower/Johnson Tunnels

Interstate 70 runs through two tunnels under the Continental Divide near the Loveland Basin ski area (Fig. 9). The westbound tunnel is called the Eisenhower Tunnel and was completed first, in March 1973. The eastbound tunnel, called the Johnson Tunnel, was completed in December, 1979. The tunnels are about 50 ft (15.2 m) high and 48 ft (14.6 m) wide. Construction of the eastern approach to the Eisenhower tunnel initiated a large landslide in 1963. Inclinometers suggested that the landslide had multiple slide planes at depths down to about 245 ft (75 m) (White and Vessely, 2006). A large buttress above the east portal was built to stabilize the landslide.

Both tunnels were driven through Precambrian rocks including gneisses and schists of the Idaho Springs Formation and the medium-to-coarse grained Silver Plume Granite. During tunnel construction, movement in numerous shear zones and along clay filled joints caused overbreaks and fallouts, deformed steel sets, and floor heave and side-wall convergence (White and Vessely, 2006). Following these problems, multiple drifts, additional concrete, and stronger steel sets were used to support the tunnel perimeter during construction. In 2006, an average of more than 30,000 vehicles per day passed through the tunnels. A third bore is currently being considered because of traffic backups during winter ski and summer tourist seasons.

Figure 9. Photograph showing the east portals of the Eisenhower and Johnson Tunnels under the Continental Divide.

Loveland Pass

Loveland Pass (11,992 ft, 3,655 m in elevation) is the high point of our tour. It marks the Continental Divide, the major drainage divide in North America. Runoff waters entering Clear Creek drainage, to the east, eventually flow to the Atlantic Ocean (Gulf of Mexico) via the South Platte, Missouri, and Mississippi Rivers. Runoff waters entering the Snake River drainage, to the west, eventually flow to the Pacific Ocean (Gulf of California) via the Blue and Colorado Rivers.

For several miles on either side of the pass, we will be above the treeline. This life zone, the alpine tundra, is dominated by dwarf vegetation such as cushion plants, which resist the ravages of long winters, high winds, and high altitude. This area contains abundant periglacial terrain as well as glacial cirques that date back to the Pleistocene. In northern Colorado, the treeline is at an average altitude of 11,500 ft (3,505 m).

STOP 3. ARAPAHOE BASIN SKI AREA OVERLOOK

Arapahoe Basin is the nation's highest ski area, with a base elevation of 10,783 ft (3,287 m) and a summit elevation of greater than 12,400 ft (3,780 m). It occupies a heavily glaciated headwall composed of Precambrian biotitic gneiss and migmatite and Tertiary felsic intrusive rocks (Tweto, 1979). Lofty A-Basin is usually the last ski area in the contiguous USA to close each year. It is quite possible that we will see skiers in June, many wearing swimwear to celebrate spring skiing, Colorado style!

On July 28, 1999, about 480 alpine debris flows (Figs. 10 and 11) were triggered by an afternoon thunderstorm centered near Arapahoe Basin in Clear Creek and Summit Counties (Godt and Coe, 2003; Godt and Coe, 2007). The thunderstorm dropped about 1.69 in (43 mm) of rain in 4 hours, most of which (1.38 in, 35 mm) fell in the first two hours. Field observations of debris-flow source areas indicate that the debris flows were initiated by three processes (Godt and Coe, 2007). The first process, the fire-hose effect, occurred where overland flow, concentrated in steep bedrock-lined channels, impacted and mobilized debris from talus deposits and the heads of debris fans. The second process was the mobilization of material eroded from steep non-vegetated hillslopes by a system of coalescing rills. The third process was the initiation of debris flows from shallow landslides (commonly called soil slips, Campbell, 1975) on steep tundra-covered slopes.

The debris flows may have long-term implications for snow avalanche and rockfall hazards on and below steep slopes, particularly within the Arapahoe Basin ski area. Many of the debris flows initiated from source areas that are snow avalanche starting zones (Henceroth, 2000). The debris flows altered avalanche paths by eroding new channels and filling wetlands. The effect that the altered avalanche paths will have on avalanche hazards and ski area operations is not yet fully known. Additionally, an abundance of recent rockfall activity in debris-flow source areas (Henceroth, 2000) indicates that some of these areas are now more susceptible to rockfall hazards than they were before July 1999.

Directions to Stop 4 are given in Table 5.

Figure 10. July 28, 1999 debris flows in the Arapahoe Basin Ski Area. Photo by Ed Harp, U.S. Geological Survey.

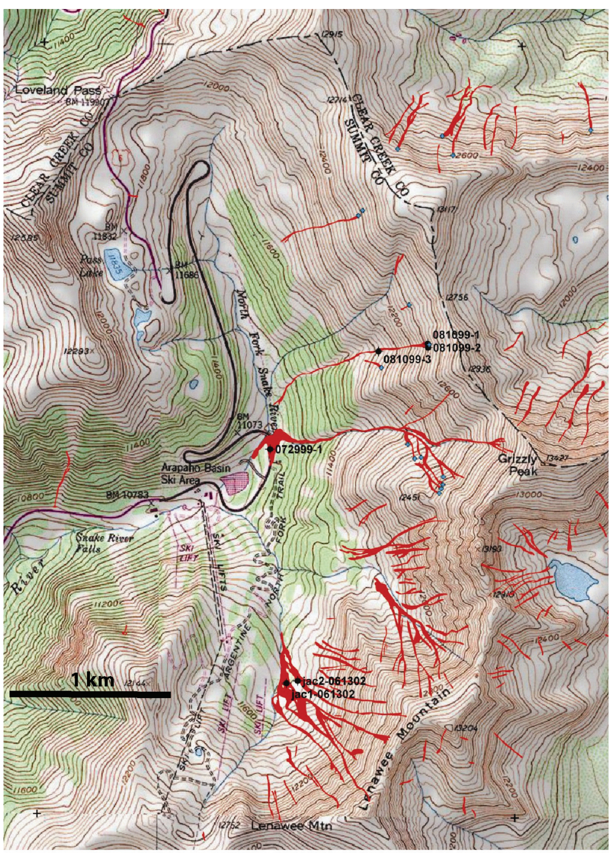

Figure 11. Portion of a map showing debris flows from the July 28, 1999 rainstorm in the vicinity of the Arapahoe Basin ski area (from Godt and Coe, 2003).

Table 5. Mileage and Directions from Arapahoe Basin Overlook (Stop 3) to Dillon Reservoir and Dam (Stop 4)

Mileage	Directions
0.0 (from Stop 3) 76.2. (cumulative)	Leave Stop 3 and continue west on US 6.
1.0 (from Stop 3) 77.2 (cumulative)	Base of Arapahoe Basin Ski Area. Continue driving westbound on US-6.
5.8 (from Stop 3) 82.0. (cumulative)	Keystone resort. Continue driving westbound on US-6.
10.6 (from Stop 3) 86.8 (cumulative)	First view of Dillon Reservoir on left; Dillon Bay Fen is on right. Continue driving westbound on US-6.
13.0 (from Stop 3) 89.2. (cumulative)	Dillon, Colorado. City Market grocery store is visible to the right. Turn left (southwest) at second stop light onto Dillon Dam Road. Follow the road as it curves uphill to the right and drive across the Dillon Reservoir Dam.
14.3 (from Stop 3) 90.5 (cumulative)	After crossing the dam, turn left across road into a dirt parking lot. This is the Dillon Reservoir overlook (**Stop 4**).

Keystone Resort

Keystone Resort lies along the Snake River valley. The original ski area occupies a triangle-shaped, north-facing slope that descends from the northernmost summit of Keystone Mountain (elevation 11,641 ft, 3,548 m) to the floodplain of the Snake River (elevation 9,300 ft, 2,835 m). The lower 600 ft (183 m) of the slope lies below the glacial trimline and is oversteepened.

Keystone Mountain is composed of faulted and overthrusted Precambrian metamorphic and igneous rocks (Fig. 12). Quaternary landslide deposits cover more than 75% of the northern and eastern slopes of Keystone Mountain. Much of this area, however, appears to be composed of large, intact, Toreva (slump) blocks of Precambrian metamorphic rocks. Below the trimline, the landslide area also contains slumped masses of glacial till.

The summits southeast of Keystone Mountain contain linear troughs and closed depressions known as "sackungen." These features are most often ascribed to slow, deep-seated gravitational spreading of oversteepened mountain ridges, resulting in splitting of the ridge crests. Sackungen are common in high, glacially carved, alpine areas.

The hummocky landslide topography has created a highly desirable ski terrain with a broad range of expert, intermediate, and beginner slopes. The lower, oversteepened slopes form mostly expert terrain. However, the slumped till landslides have formed localized areas of more gentle terrain that are used by less experienced skiers to bypass these steeper slopes.

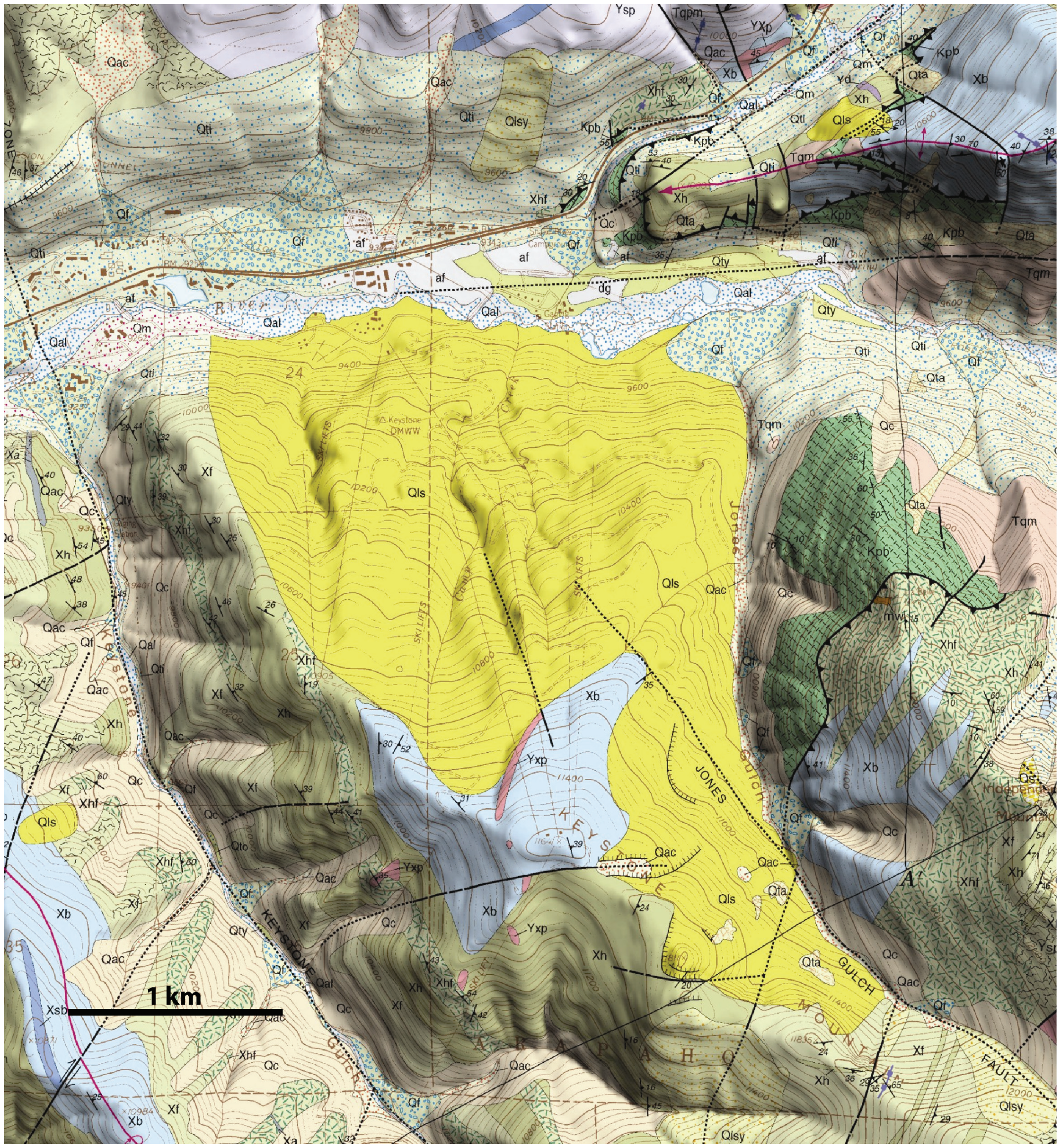

Figure 12. Geologic map of Keystone Ski Area (Widmann and others, 2003a) draped on a shaded relief base. Landslides (Qls) areas are shown as yellow. Sackungen features are shown at hachured lines near summit of Keystone Mountain, in lower right. US-6 and the base resort area lie within the valley of the Snake River in the upper part of the map.

Dillon Bay Fen Wetland

A fen wetland consists of herbaceous vegetation, particularly peat, and has a non-mineral substrate. Fens are widely scattered throughout formerly glaciated areas and periglacial areas in alpine and subalpine zones of the Rocky Mountains. These self-perpetuating plant communities are extremely stable and may exist for centuries. A long-term source of upwardly discharging groundwater must be present, both to maintain the viability of a fen and allow it to accumulate peat and accrete vertically through time.

The Dillon Bay fen (Fig. 13) is rather unusual in that it is at a relatively low elevation (~9,000 ft, 2,740 m) and is not related to glacial geomorphic features. It occupies the lower, distal part of a large alluvial fan that was deposited across the Cretaceous Pierre Shale (Kellogg, 2002). Partway up the slope is the Williams Range thrust fault, a Laramide feature where crystalline Precambrian rocks override the shale.

The fan is coarse grained at its head, where debris flows dominate, and becomes finer grained toward its distal reaches. Surface and ground water entering the upper part of the fan have infiltrated into the coarser sediments, leaving the middle part of the fan surface dry. Bounded below by low-permeability shale, the groundwater is constrained by the thinning fan geometry and the progressively finer-grained sediments, and is forced to the surface as a seep in the toe, forming the fen. Ground water from upland, fractured crystalline aquifers, issuing from the thrust fault, may provide a constant and long-lasting source of water for the fen.

Figure 13. Dillon Bay fen, a sedge and spruce wetland at the distal margin of a large alluvial fan (between the solid lines). The middle, dry part of the fan is dominated by sagebrush and grasses, whereas the upper part contains willow and aspen wetlands. The ground and surface water entering this fan may be significantly augmented by seepage from the Williams Range thrust fault.

Rio Grande Rift and Quaternary Seismicity

The broad valley of the Blue River (Fig. 14), is located in the center of the Rio Grande Rift system. The nearby mountain ranges (Gore, Williams, Front, and Mosquito) all were uplifted during the Late Cenozoic. To the north and east is the Williams Range thrust fault that forms the western margin of the Laramide Front Range structural uplift.

Summit County increased its population 82 percent during the 1990s. Several nearby faults, particularly the Gore Range Frontal fault, Williams Fork Mountains fault, and Mosquito fault, are all listed in the CGS' Quaternary Fault and Fold Database (Widmann and others, 2002).

The Williams Fork Mountains fault displaces Holocene deposits and has a reported slip rate of 0.051 in (1.3 mm) per year. Inclusion of the Williams Fork Mountains fault in the National Earthquake Hazard maps would significantly raise the earthquake hazard for Summit County.

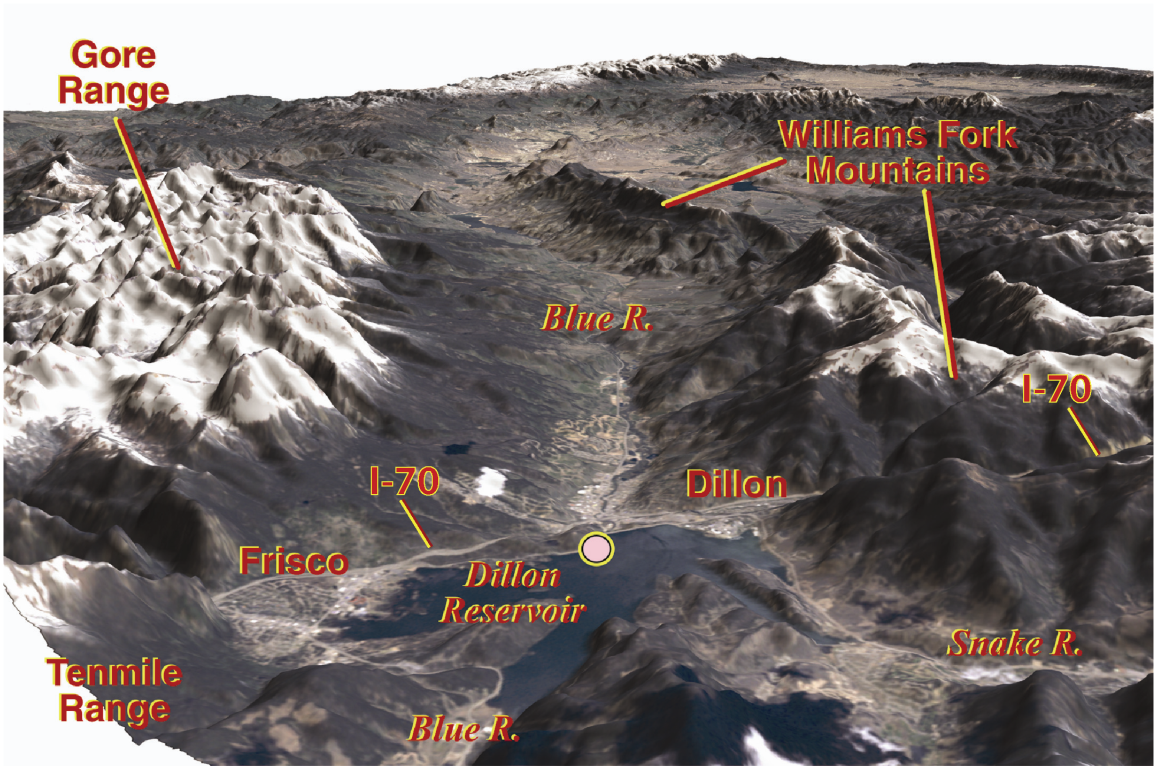

Figure 14. Bird's-eye view of the valley of the Blue River, created from a DEM draped with a satellite image, looking north along the Rio Grande Rift (Noe and others, 2003).

STOP 4. DILLON RESERVOIR AND DAM AND DENVER WATER SYSTEM

After driving through the town of Dillon and over the Dillon Dam, we will stop at a scenic pull-off on the shores of Dillon Reservoir (Fig. 15). The earthen-fill dam and reservoir, completed in 1963, are principle components of the Denver water supply system.

Water from this reservoir is diverted to the eastern side of the Continental Divide through the 23.3 mi (37.6 km) long Harold D. Roberts tunnel, which is the longest major water tunnel in the world (Turner and Rogers, 2003). Both the dam and the tunnel were built into extensively fractured Mesozoic sedimentary rocks. The floor of the dam is covered by up to 80 ft (24 m) of highly permeable Quaternary outwash gravel.

Much of Colorado's municipal water comes from surface water. There are numerous high-country reservoirs that capture snowmelt runoff each spring. The trans-basinal water diversion systems reflect the fact that most of Colorado's snow falls on the west side of the Continental Divide, while most of the state's population resides on the east side.

These water supply systems are susceptible to natural geologic and climatic processes. In particular, large drought-driven wildfires during 2002 choked several reservoirs with ash and sediment and threatened Denver's water supply. Today, an infestation of beetles are killing lodgepole pines in the area surrounding Dillon Reservoir. There is concern about heightened wildfire danger as the trees die, and the related effects on runoff and water quality.

Directions to Vail, the terminus of today's tour, are given in Table 6.

Figure 15. The summit of Peak 1 serves as a backdrop for scenic Dillon Reservoir. The peaks of the northern Tenmile Range are composed of Proterozoic granitic gneiss and migmatite. The lower slopes and the shores of the reservoir are covered with till deposits from the upper Pleistocene Pinedale glaciation.

Table 6. Mileage and Directions from Dillon Reservoir and Dam (Stop 4) to Vail.

Mileage	Directions
0.0 (from Stop 4) 90.5 (cumulative)	Turn left (south) from the parking lot onto Dillon Dam Road and drive westbound along the reservoir to the town of Frisco.
2.4 (from Stop 4) 92.9 (cumulative)	Turn right (north) at stop light onto Summit Boulevard, cross the highway bridge into the traffic circle, and enter I-70 westbound.
4.2 (from Stop 4) 94.7 (cumulative)	Pass Frisco (Exit 201). Continue on I-70 westbound and enter Tenmile Canyon. (Begin “Tenmile Avalanche Chutes” drive-by)
9.6 (from Stop 4) 100.1 (cumulative)	Pass Copper Mountain (Exit 195). Continue on I-70 westbound. (Begin “Wheeler Junction and Copper Mountain” drive-by)
15.0 (from Stop 4) 105.5 (cumulative)	Continue past Vail Pass (Exit 190). Rest area is available at the Pass if needed. Begin descent from Vail Pass along the valley of Black Gore Creek.
21.5 (from Stop 4) 112.0 (cumulative)	I-70 curves to the left (west) and enters the larger valley of Gore Creek. This marks the eastern edge of the town of Vail. (Begin “Gore Creek Valley and Vail” drive-by.)
29.4 (from Stop 4) 119.9. (cumulative)	Town of Vail, main exit (Exit 176). Exit from I-70. Enter the first traffic circle and drive ¾ of the circle. Drive south under the interstate to the second traffic circle.
29.7 (from Stop 4) 120.2. (cumulative)	From the second traffic circle, turn right (west) directly onto the South Frontage Road. Follow this road for about a mile.
30.4 (from Stop 4) 120.9 (cumulative)	Turn left (south) onto West Lions Head Circle immediately after driving under the pedestrian overpass. Keep to the right after one block. The Vail Marriott Hotel is on the left. Welcome to Vail!

Frisco

The town of Frisco (elevation 9,042 ft, 2,756 m) occupies the western edge of the Blue River valley, at the mouth of Tenmile Canyon and the foot of the rugged Tenmile Range. Established in 1873 as a mining camp, Frisco has experienced tremendous booms and busts. From a gold-rush peak population of 250, it became a virtual ghost town by the 1940s. It has since grown to a full-time population of 2,800, aided by its central location along I-70 and proximity to several world-class ski resorts.

Tenmile Canyon Avalanche Chutes

Driving westward from Frisco along I-70, we enter Tenmile Canyon (Fig. 16). The canyon was deeply glaciated, creating oversteepened walls of resistant Proterozoic granitic and amphibolite-hornblende gneiss and migmatite, with about 2,800 ft (850 m) of relief (Tweto and others, 1978; Kellogg and others, 2002; Wallace and others, 2002; and Widmann and others, 2003b).

On the east side of the canyon, along the flank of the Tenmile Range, is a series of spectacular avalanche chutes that head in small bedrock basins above timberline and carve through the forested lower slopes to relatively small, valley-floor fans. These are some of the largest avalanche paths in the state in terms of vertical drop.

Avalanches from these chutes reach I-70 every 15 years on average (Dale Atkins, avalanche consultant, personal communication). In the early 1920s, the “Big Sam” avalanche chute “ran big” and piled snow 50 ft (15 m) deep over what is now the highway alignment. Also at risk was the old grade of the Denver, South Park and Pacific Railroad line (now a paved bike path), across the valley. The railroad line was hit numerous times in this area. Fortunately for today’s I-70 travelers, the accumulation areas face west, into the prevailing wind direction, and there is rarely enough snow in place for big releases. Summit County is number one in terms of avalanche deaths for counties in the U.S. since 1950, according to the Colorado Avalanche Information Center. Over 30 deaths have occurred, mostly among backcountry enthusiasts.

Wheeler Junction and Copper Mountain

During the 1880s, when both the Denver, South Park and Pacific and the Denver and Rio Grande Western railroads laid track through this valley between Frisco and Leadville, this place was called Wheeler Flats or Wheeler Junction (elevation 9,800 ft, 2,987 m). Today, most residents and visitors know it as Copper Mountain, after the ski area and resort that were started here in the 1970s.

Copper Mountain has many of the same geologic constraints and considerations for development as other resort areas in the Rocky Mountains. The valley bottom, consisting of outwash gravel and extensive wetlands (Widmann and others, 2003b), has been developed over a 30-year span. The surrounding land has certain limitations, including federal land holdings, protection of remaining wetlands, and geologic hazards. The base of the ski mountain has landslides, and the flat land on the eastern side of the resort, at the base of the Tenmile Range, has potentially serious avalanche and rockfall hazards.

Figure 16. Avalanche chutes along the steep western flank of the Tenmile Range, above Tenmile Canyon. The snow-covered accumulation areas above timberline are readily apparent in this photo.

Vail Pass Landslides and I-70 Construction

Vail Pass was not the first choice for the interstate highway route between Vail and Frisco, in part because of the numerous landslides that were recognized along the alignment (Barrett, 1968). The favored route, Red Buffalo Pass, was not used because it lies within the Gore Range-Eagle Nest Primitive Area. The subsequent building of the interstate over Vail Pass (Fig. 17) during the 1970s is notable in that it was the first project in Colorado to make use of engineering geology expertise throughout – from planning to design to construction (Turner and Rogers, 2003).

Interstate 70 closely follows the Gore fault on the west side of the pass. Precambrian crystalline rocks are exposed to the east of the fault trace, whereas the Pennsylvanian Minturn and Maroon Formations are exposed to the west. Among the many challenging conditions encountered were a) sheared and structurally deformed bedrock, b) oversteepened bedrock slopes from glaciation, c) colluvium and moraine deposits found at close to their natural angles of repose, d) numerous landslide deposits, e) easily erodible soil deposits, and f) difficult revegetation due to the high altitude (Robinson and Cochran, 1983).

As a result of these conditions and the accompanying environmental constraints, a number of innovative design concepts were used or developed. These included a) widely separated lanes to reduce sizes of cuts and fills, b) avoidance of large rock cuts, c) slope contouring and sculpting, d) use of long, viaduct bridges to span problem areas, e) use of pre-cast, post-tensioned bridge segments, f) use of reinforced earth retaining walls, and g) coordination between geologists and landscape architects to enhance the visual effect of the highway.

Landslides were recognized in metamorphic/igneous rock, sedimentary rock, and surficial deposits. The sedimentary rock landslides are the most significant in terms of number and areal distribution. One landslide complex occupies the highway alignment for nearly 4 miles (6.5 km). Most of the landslides were found to be inactive. Nonetheless, care was taken to minimize cutting and loading, and a variety of drainage and slope sculpting schemes were used. At one location, fill was added to the valley bottom, effectively raising the stream profile of Black Gore Creek. This decreased the erosive power of the stream and allowed two landslides on the opposite sides of the valley to buttress each other.

Figure 17. Looking southeast (eastbound) from 10,666 ft (3,251 m) Vail Pass toward Copper Mountain Ski Area (left) and Jacque Peak. The widely spaced eastbound and westbound lanes of I-70 not only provide a pleasing visual aesthetic for travelers, they are also part of an integrated landslide mitigation design.

Gore Creek Valley and Vail

The Town of Vail occupies the deep, narrow, valley of Gore Creek. To the east, the rugged Gore Range is composed of Proterozoic migmatitic biotite gneiss and the Cross Creek Granite. Closer to town, sandstones, conglomerates, and shales of the Pennsylvanian Minturn Formation form ledgy slopes along the valley. The Pennsylvanian to Permian Maroon Formation forms distinctly red ledges and slopes to the northwest of town.

The valley itself shows a distinctive "U" shape from Pleistocene alpine glaciers that carved its lower walls (Fig. 18). The floor is made up of Pinedale-age (upper Pleistocene) outwash deposits and modern alluvium. On the valley walls to the north, there are scattered deposits of Pinedale and older, Bull Lake-age (middle Plesitocene) glacial till. Vail Ski Area is distinctive in that it does not have steep valley walls. Instead, the mountainside is dominated by landslide and colluvial deposits. Quaternary (post-glacial) movement of the landslide complex has created a large-scale, "hummocky" terrain that is ideal for skiing.

A series of small, first-order drainages along the valley wall serve as avalanche chutes during the winter and debris flow chutes during the summer. At the base of these drainages are well-formed alluvial fan deposits. The cliffs are potential sources of rockfall.

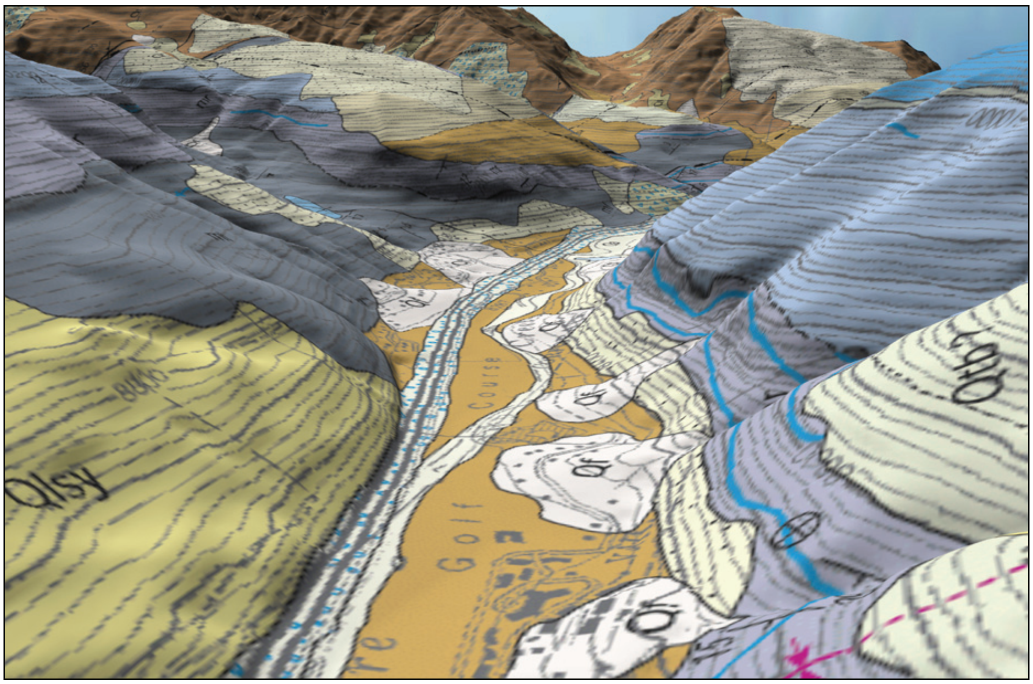

Figure 18. 3-D geologic map looking east from Vail, up the U–shaped glacial valley of Gore Creek. Debris fans spill onto the valley floor from side slopes of Pennsylvanian-age, syntectonic sedimentary rocks (blue and gray). Proterozoic crystalline rocks (dark brown) form the core of the Gore Range in the distance. Geology from Kellogg and others (2003).

The Town of Vail has enacted specific zoning regulations that address geologically sensitive areas, including these potential debris flow and avalanche areas (Fig. 19). The town's master hazard plans delineate areas where development is to be restricted, such as avalanche "red" zones. In hazard fringe areas, such as avalanche "blue" zones, structures may be built providing that proper mitigating measures have been taken. These are among the most stringent avalanche-hazard regulations in the United States.

Figure 19. An alluvial fan in east Vail. Because of the dual threat of debris flows and avalanches, Vail has enacted specific land-use regulations in such areas. On this particular fan, a pair of earthen berms has been built to channel flows away from built-up areas.

Booth Creek Rockfall Area

Notice the large, earthen berm near the base of the slope on the northern side of the valley (Fig. 20), to the right of eastbound I-70. In May 1983, before Vail enacted its geologic-hazard regulations, a major rockfall from the cliffs above caused serious damage to several structures (Stover, 1988). In response, the town and the owners of one subdivision subsequently formed a Geologic Hazard Abatement District (GHAD) and constructed the large ditch and berm, which has performed effectively through subsequent years.

In March, 1997, another major rockfall event deposited a swath of debris more than 500 ft (152 m) wide. All of the rocks that entered the existing ditch and berm were retained. The rest of the rockfall, however, was unchecked in the area of the condominiums. There were two major impacts, and a five-ft-diameter block of rock broadsided one of the buildings (White, 1997). Amazingly, there were no injuries. After this potentially catastrophic incident, two Mechanically Stabilized Earth (MSE) inertial impact barriers have been constructed just uphill from the condominiums.

The Marriot Hotel in Vail marks the end of the field trip. Enjoy your stay. We hope you have a chance to visit some of Colorado's other geological and historical attractions that were not part of this trip.

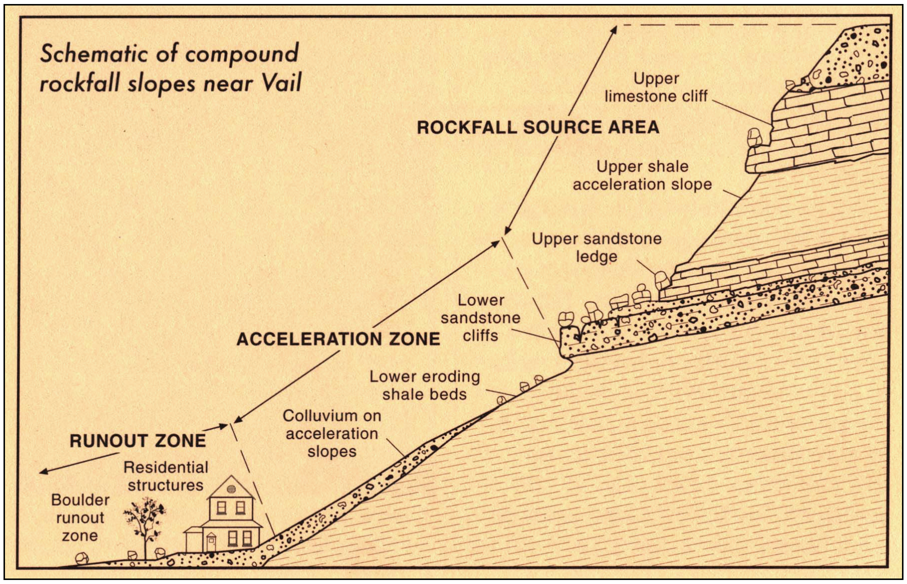

Figure 20. Rockfall hazard setting at Booth Creek, Vail (modified from Stover, 1988).

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REFERENCES

Andrew, R.D. and Lovekin, J.R., 2002, Geologic hazards and geologic constraints, I70 mountain corridor, programmatic environmental impact statement (PEIS): Association of Engineering Geologists Program with Abstracts v. 45, p. 53.

Arndt, B.P., Lovekin, J.R., and Andrew, R.D., 2002, Tunneling through the Continental Divide: Association of Engineering Geologists Program with Abstracts v. 45, p. 53.

Barrett, R.K., 1968, Preliminary geologic report – Gore Creek Campground to Wheeler Junction: Colorado Department of Highways, Report for District 3, 20 p.

Bryant, B., McGrew, L.W., and Wobus, R.A., 1981, Geologic map of the Denver 1 degree x 2 degree Quadrangle, north-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1163.

Caine, N, 1986, Sediment movement and storage on alpine slopes in the Colorado Rocky Mountains, *in* Abrahams, A.D., ed., Hillslope Processes, The Binghamton Symposium on Geomorphology, International Series No. 16: Allen and Unwin, Winchester, Mass., p 115-137.

Campbell, R.H., 1975, Soil slips, debris flows and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.

Cannon, S.H., Gartner, J.E., Parrett, C., and Parise, M., 2003, Wildfire-related debris flow generation through episodic progressive sediment bulking processes, western U.S.A, in: Rickenmann, D., Chen, C.L., (Eds.), Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Millpress, Rotterdam, The Netherlands, pp. 71-82.

Coe, J.A., Godt, J.W., and Henceroth, A.J., 2002, Debris flows along the Interstate 70 corridor, Floyd Hill to the Arapahoe Basin ski area, central Colorado – a field trip guidebook: U.S. Geological Survey Open-File Report 02-398, 38 p.

Coe, J.A., Godt, J.W., Parise, M, and Moscariello, A., 2003. Estimating debris-flow probability using debris-fan stratigraphy, historic records, and drainage-basin morphology, Interstate 70 Highway Corridor, Central Colorado, USA, in: Rickenmann, D., Chen, C. (Eds.), Debris Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Millpress, Rotterdam, The Netherlands, v. 2, p. 1085-1096.

Costa, J.E., and Bilodeau, S.W., 1982, Geology of Denver, Colorado, United States of America: Bulletin of the Association of Engineering Geologists, v. XIX, pp. 261-314.

Godt, J.W. and Coe, J.A., 2003, Map showing alpine debris flows triggered by a July 28, 1999 thunderstorm in the Central Front Range, Colorado: U.S. Geological Survey Open-File Report 03-050.

Godt, J.W. and Coe, J.A., 2007, Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado: Geomorphology, v. 84, p. 80-97.

Harrison, J.E., and Wells, J.D., 1956, Geology and ore deposits of the Freeland-Lamartine district, Clear Creek County, Colorado, U.S. Geological Survey Bulletin, 1032-B, 127 p.

Henceroth, A., 2000, Debris flows and floods at Arapahoe Basin: The Avalanche Review, v. 19, no. 2, p. 5.

Kellogg, K.S., 2002, Geologic map of the Dillon quadrangle, Summit and Grand Counties, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2390, version 1.0, scale 1:24,000.

Kellogg, K.S., Bartos, P.J., and Williams, C.L., 2002, Geologic map of the Frisco quadrangle, Summit County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2340, version 1.0, scale 1:24,000.

Kellogg, K.S., Bryant, B., and 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 1.0, scale 1:24,000.

Leib, J., 2005, U.S. 6 reopens nearly three months after rock slide , Highway cleared for canyon traffic: Denver Post article on Sept. 13, p. B5.

Madole, R.F., VanSistine, D.P., and Michael, J.A., 1998, Pleistocene glaciation in the upper Platte River drainage basin, Colorado: U.S. Geological Survey Geologic Investigation Series Map I-2644.

Nichols, D.J. and Fleming, R.F., 2002, Palynology and palynostratigraphy of the Maastrichtian, Paleocene, and Eocene strata in the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, p. 135-163.

Noe, D.C., Soule, J.M., Hynes, J.L., and Berry, K.A., 1999, Bouncing boulders, rising rivers, and sneaky soils – a primer of geologic hazards and engineering geology along Colorado's Front Range, in Lageson, D.R., Lester, A.P., and Trudgill, B.D., eds., Colorado and adjacent areas: Geological Society of America Field Guide 1, p. 1-20.

Noe, D.C., Matthews, V., Steele Weir, S., and McCalpin, J.P., 2003, Geology, geologic hazards, and water resources in the mountains of central Colorado: Field Trip Guidebook, Association of Engineering Geologists Annual Meeting, Vail, Colorado September 16, 2003, 37 p.

Ortiz, T., 2005, Incident report on US 6 rockslide in Clear Creek canyon, Mile Marker 261.5, Colorado Department of Transportation, 3 p.

Robinson, C.S., and Cochran, D.M., 1983, Engineering geology of Vail Pass I-70, in Hynes, J.L., ed., Proceedings of the 33rd annual highway geology symposium – engineering geology and environmental constraints: Colorado Geological Survey Special Publication 22, p. 116-135.

Rogers, W.P., 2003, Map of critical landslides in Colorado - A year 2002 review. In Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering Geology in Colorado: Contributions, Trends, and Case Histories, Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55, on CD-ROM.

Sims, P.K. and Gable, D.J., 1967, Petrology and structure of Precambrian rocks Central City quadrangle Colorado: U.S. Geological Survey Professional Paper 554-E, 56 p.

Stover, B.K., 1988, Booth Creek Rockfall Hazard Area: Geological Society of America Field Trip Guidebook, Colorado School of Mines Professional Contributions, No. 12, p. 395-401.

Turner, A.K., and Rogers, W.P., 2003, History of engineering geology development in Colorado, in Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering Geology in Colorado – contributions, trends, and case histories: Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55, on CD-ROM, 73 p.

Tweto, O., 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

Tweto, O., 1983, Geologic cross sections across Colorado: U.S. Geological Survey. (Available as Colorado Geological Survey Miscellaneous Investigations MI-63.)

Tweto, O., and Sims, P.K., 1963, Precambrian ancestory of the Colorado Mineral Belt: Geological Society of America Bulletin v. 74, p. 991-1014.

Tweto, O., Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1° by 2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1199, scale 1:250,000.

Wallace, C.A., Keller, J.W., McCalpin, J.P., Bartos, P.J., Route, E.E., Jones, N.N., Gutierrez, F., Williams, C.L., and Morgan, M.L., 2002, Geologic map of the Breckenridge quadrangle, Summit and Park Counties, Colorado: Colorado Geological Survey Open-File Map 02-7, scale 1:24,000.

Western Mining History, 2006, Idaho Springs, Colorado: A web site at http://www.westernmininghistory.com/towns/colorado/idaho-springs/. Accessed 3/20/07.

White, J.L., 1997, Rockfall hazard assessment at Booth Falls Condominiums and proposed mitigation: Colorado Geological Survey, unpublished report for the Town of Vail, 9 p.

White, J.L., and Vessely, M., 2006, Geology, natural hazards, and geotechnical engineering along the Interstate 70 and US 6 corridors in the mountains of Summit and Clear Creek Counties, Colorado: Field Trip Guide for the 57th Highway Geology Symposium and 32nd Northwest Geotechnical Workshop, September 28, 2006, 51 p.

Widmann, B. L., Kirkham, R. M., Morgan, M. L., and Rogers, W. P., with contributions by Crone, A. J., Personius, S. F., and Kelson, K. I., and GIS and Web design by Morgan, K. S., Pattyn, G. R., and Phillips, R. C., 2002, Colorado Late Cenozoic Fault and Fold Database and Internet Map Server: Colorado Geological Survey Information Series 60a, http://geosurvey.state.co.us/pubs/ceno/.

Widmann, B.L., Morgan, M.L., Bartos, P.J., Shaver, K.C., Gutierrez, F. and Lockman, A., 2003a, Geologic map of the Keystone quadrangle, Summit County, Colorado: Colorado Geological Survey Open-File Map 02-3, 20 p., scale 1:24,000.

Widmann, B.L., Bartos, P.J., McCalpin, J.P., and Jackson, J., 2003b, Geologic map of the Copper Mountain quadrangle, Summit, Eagle, Lake, and Park Counties, Colorado: Colorado Geological Survey Open-File Map 03-20, scale 1:24,000.

DRIVE-BY GUIDEBOOK: GEOLOGY AND GEOLOGIC HAZARDS ALONG THE I-70 CORRIDOR, VAIL TO GLENWOOD SPRINGS, COLORADO

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Glenwood Canyon at Cottonwood Falls

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

This “corridor” field trip guidebook is created for drive-through bus tours with no stops. It is intended for tour groups from the First North American Landslide Conference that will pass along this segment of the Interstate Highway 70 (I-70) corridor on the way to other destinations.

There is plenty of great scenery and interesting geology to see along this route, regardless of the fast and continuous pace of the tour. We have included numerous illustrations and short topical descriptions of geologic points of interest along the way. Nearly all of these points may be easily viewed from the bus.

This tour will take us through numerous broad basins, uplifts, and deeply incised canyons. The varied terrain that we will see reflects different sedimentary formations that have been folded or have undergone diapiric movement, and numerous landslides and rockfall areas.

Much of the narrative herein has been adapted from some recent field trip guidebooks, particularly White and others (2003), Noe and others (2003), and Zabel and White (2003).

TRIP ROUTE DESCRIPTION

The trip route begins in Vail and follows I-70 for 60 miles west to Glenwood Springs (Figure 1). Table 1 shows the main segments along the way and lists the pertinent points of geologic interest and topics of discussion.

Table 1. Field Trip Segments and Topics

Segment	Topics
Vail to Wolcott	Gore Creek valley and Vail; Minturn Formation; Dowds Junction landslide complex, evaporite bedrock terrain from Avon to Edwards; Ute Creek syncline
Wolcott to Dotsero	Bellyache Ridge dip-slope landslides; Red Canyon; “double-trouble house;” evaporite bedrock terrain from Eagle to Gypsum; alluvial fans along Eagle River valley; Dotsero volcano and basalt flow
Glenwood Canyon	Lower to Middle Paleozoic section; Bair Ranch rest area; Precambrian-Cambrian nonconformity; early Holocene rock avalanche at Shoshone interchange; Grizzly Creek and No Name faults
Glenwood Springs	Thermal hot springs; geologic setting of Glenwood Springs

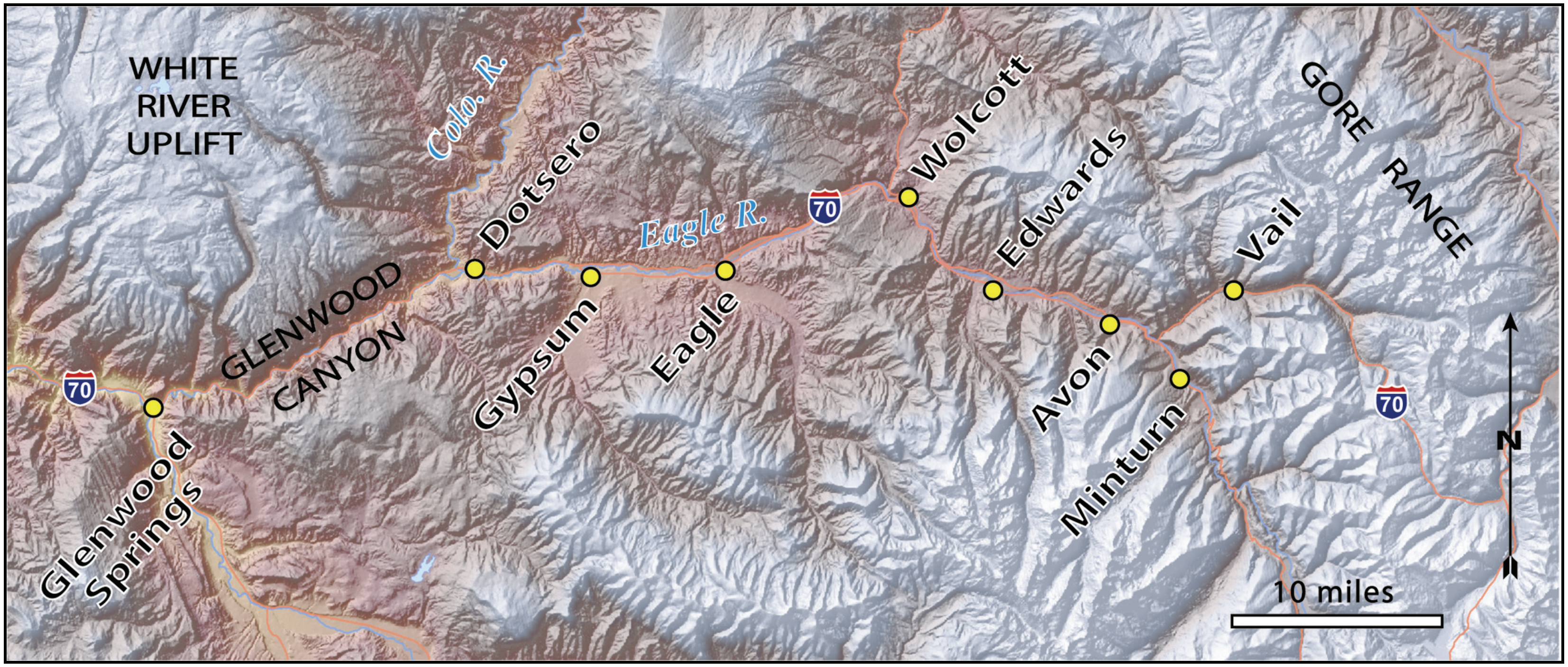

Figure 1. Index map showing field trip route along I-70, from Vail westward to Glenwood Springs.

STRATIGRAPHY

Central Colorado contains abundant sedimentary formations ranging in age from Cambrian to Tertiary (Figure 2). Much of the section consists of marine strata, particularly the Lower Paleozoic (Sawatch Quartzite to Leadville Limestone) and Upper Cretaceous (Mancos and Pierre Shale) formations. The Upper Paleozoic section is more varied and represents restricted marine (Belden Shale and Eagle Valley Evaporite), marginal marine (Minturn Formation), and synorogenic terrestrial paleoenvironments associated with the Ancestral Rocky Mountains (Maroon Formation). The Lower Mesozoic section (State Bridge to Morrison Formations) consists of terrestrial redbed, eolian, and alluvial deposits.

The basement rock in the region is composed of Precambrian (Proterozoic) crystalline rocks. The region also contains basalt flows of Miocene to Holocene age.

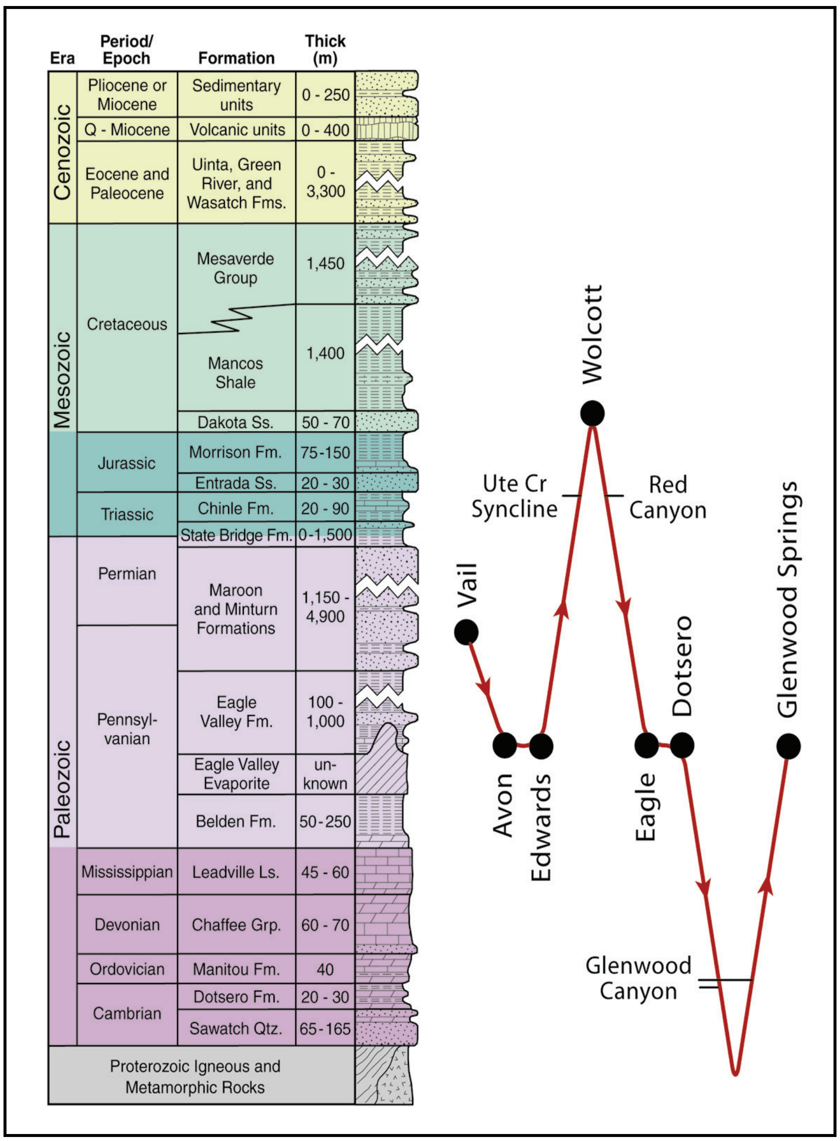

Figure 2. Stratigraphic section of west central Colorado, modified from Kirkham and others (2002). Stratigraphic horizons of various locations along the trip route are shown to the right of the section.

TECTONIC ENVIRONMENT

The rocks in central Colorado have endured multiple periods of deformation. The oldest, Precambrian rocks have incurred at least two periods of ductile deformation associated with deep burial and metamorphism during the Proterozoic. Early Paleozoic tectonism certainly occurred in Central Colorado (probably more than once), but the evidence is incomplete.

During the Pennsylvanian and Permian periods, the Ancestral Rocky Mountains rose as fault blocks out of a shallow sea. Colorado was dominated by the ancestral Uncompahgre and Front Range uplifts with a restricted evaporite basin trapped between the two ranges. Most of the evidence of this uplift is stratigraphic rather than structural. The syntectonic rocks in the Red Rocks area near Denver and in the Vail Valley record the uplift of the ancestral Front Range. It is rare to find a fault that can unequivocally be assigned to this orogeny. The Ancestral Rocky Mountains were mostly worn away by the end of the Triassic.

The next major deformation, the Laramide Orogeny, began with fault blocks rising out of the Late Cretaceous seaway about 80 million years ago. This period of uplift and crustal shortening continued into the early Cenozoic. The structural style is dominated by high-angle reverse faults with a few, low-angle thrust faults. Faulting was accompanied by igneous intrusions and mineralization, as well as deposition of syntectonic sedimentary units. Many of the broad uplifts and intermountain basins along the trip route (Figure 3) are Laramide features.

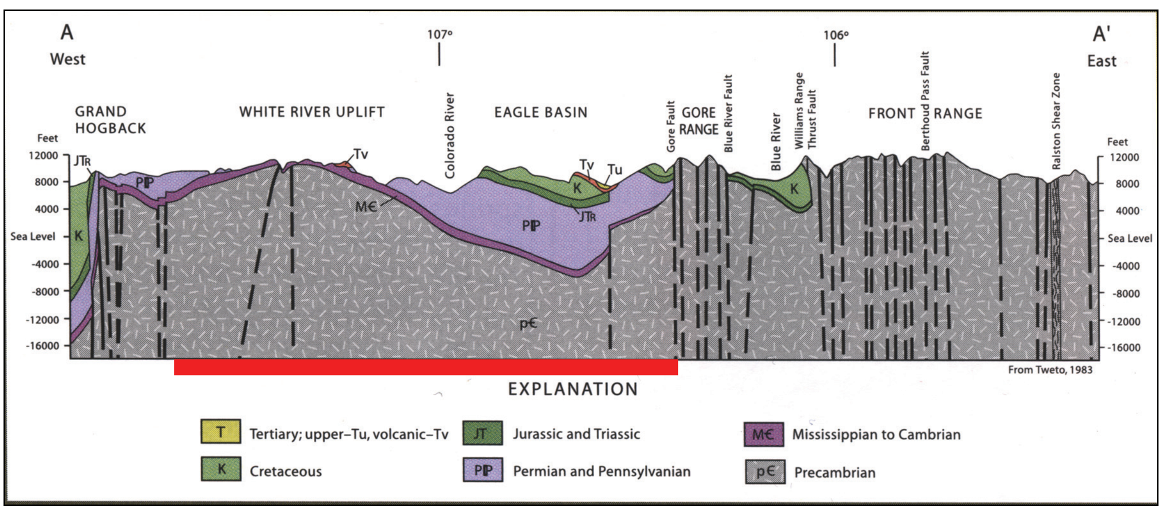

Figure 3. General geologic cross section for the central Colorado mountains along the I-70 corridor, from Glenwood Springs to Golden (modified from Tweto, 1983). The red bar underlines geology along the trip route.

The last major tectonic event, and the one we are in today, began about 25 million years ago with major east-west extension. This extension broke the crust into large blocks that are subsiding into basins and rising into some of the most impressive mountains in North America. Fifty-eight peaks in Colorado soar above 14,000 feet in elevation, and the entire state averages

6,800 feet above sea level. The structural style is dominated by normal faults and basaltic volcanism. Colorado has 92 catalogued Quaternary faults (Widmann and others, 2002).

VAIL TO WOLCOTT

Gore Creek Valley and Vail

The Town of Vail occupies the deep, narrow, valley of Gore Creek. To the east, the rugged Gore Range is composed of Proterozoic migmatitic biotite gneiss and the Cross Creek Granite. Closer to town, sandstones, conglomerates, and shales of the Pennsylvanian Minturn Formation form ledgy slopes along the valley. The Pennsylvanian to Permian Maroon Formation forms distinctly red ledges and slopes to the northwest of town.

The valley itself shows a distinctive "U" shape from Pleistocene alpine glaciers that carved its lower walls. The floor is made up of Pinedale-age (upper Pleistocene) outwash deposits and modern alluvium. On the valley walls to the north, there are scattered deposits of Pinedale and older, Bull Lake-age (middle Pleistocene) glacial till. Vail Ski Area is distinctive in that does not have steep valley walls. Instead, the mountainside is dominated by landslide and colluvial deposits. Quaternary (post-glacial) movement of the landslide complex has created a large-scale, "hummocky" terrain that is ideal for skiing.

Figure 4. Vail ski area and village. The mountain contains a large landslide complex and characteristic hummocky topography. Photo © Airphoto – Jim Wark, used by permission.

Minturn Formation

Just to the west of Vail, the valley of Gore Creek narrows. The interstate is bounded to the north (right) by high, vertical cliffs that expose the Pennsylvanian Minturn Formation, which is jointed and fractured, predominantly gray in color, and contains interbedded sandstone, shale, and conglomerate lenses with minor, persistent limestone beds and localized bioherms. The Minturn Formation is nearly a mile thick in this area. It was deposited as fan deltas and marine deposits along the margins of the Ancestral Rocky Mountains. The strata dip to the north-northeast along the nose of the Sawatch Anticline. A large rockslide in this canyon closed the westbound lanes of I-70 in 1989.

Dowds Junction Landslide Complex

Dowds Junction marks the intersection of I-70 with US-24, where Gore Creek enters the larger valley of the Eagle River. Along the southern side of the valley are four large earthflow landslides: the Meadow Mountain, Dowds number 1 and 2, and Whiskey Creek (Figure 5). These slides have formed within the weak claystone beds of the Minturn Formation. They predate the construction of Interstate 70 and have experienced reactivations and failures when the highway construction altered and cut into the landslide toes.

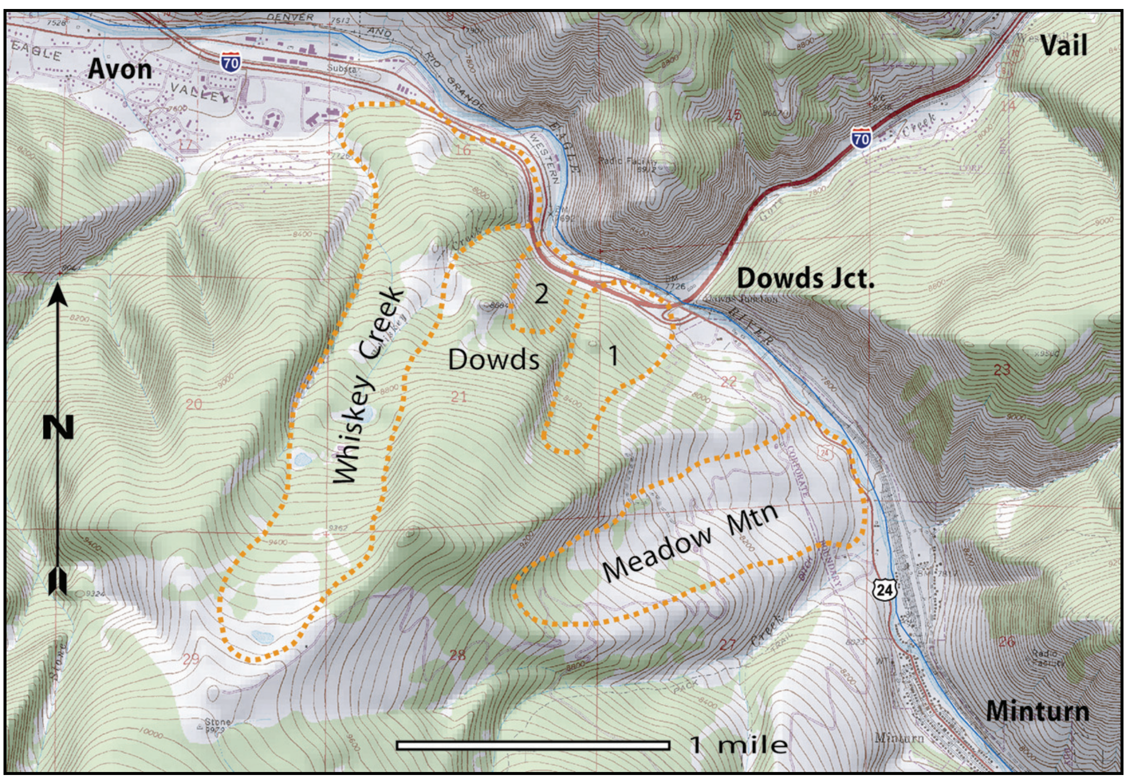

Figure 5. Shaded topographic map of landslides near Dowds Junction. Landslide boundaries (dotted lines) from Minturn Earthflows Task Force (1986).

These landslides have been extensively studied by the Colorado Department of Transportation (CDOT) and the Colorado Geological Survey (CGS) since the interstate was constructed and certain remedial actions have been taken such as rock buttresses and horizontal drains. In the 1980s, a mudslide that initiated from the Dowd number 2 landslide blocked the eastbound lanes of I-70.

A potentially catastrophic hazard scenario, particularly associated with the Meadow Mountain landslide, involves earthflow movements damming the Eagle River (Minturn Earthflows Task Force, 1986). Activation of the toe of the Whiskey Creek landslide could threaten Battle Mountain High School in Avon as well as the interstate highway (Figure 6).

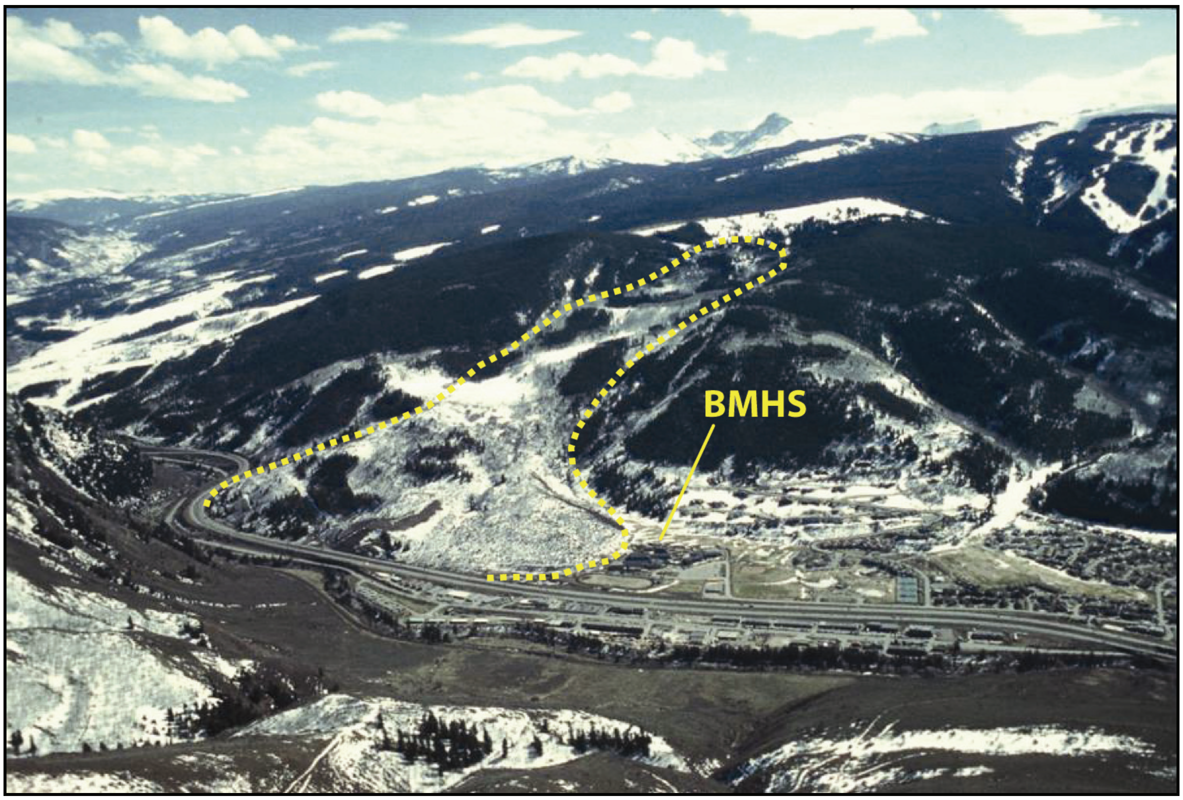

Figure 6. Air photo of the toe of the Whiskey Creek earthflow at Avon, looking to south. I-70 crosses the toe at its eastern end, at left. Battle Mountain High School (BMHS) lies just downhill and to the right of the toe. Photo by Jonathan White, CGS.

The Dowds Junction area is the focus of a recent geotechnical investigation by Yeh and Associates, as part of an assessment of potential traffic improvements along the I-70 Corridor. The abundant and serious geologic hazards here will affect many of the potential alternative designs, which include highway widening and construction of a Fixed Guideway Transit (FGT) line along the highway route. One option is to avoid the rockfall and landslide hazards utilizing a tunnel realignment. The study is in its second phase.

Evaporite Bedrock Terrain from Avon to Edwards

At Avon, the valley broadens as we enter the eastern margin of the Eagle sedimentary basin, a Laramide feature that is also a regional area of Cenozoic evaporate dissolution and subsidence. Lidke and others (2002) have named this area the Eagle Collapse Center. The geology is dominated by the Pennsylvanian Eagle Valley Evaporite and Eagle Valley Formation, which consist of interbedded siltstone, black shale, minor limestone, and thick beds of whitish to gray gypsum. Diapiric halite occurs at depth.

Karst and sinkholes resulting from gypsum dissolution are hazards to development in the valley. An 80-acre sinkhole near Battle Mountain High School is now backfilled and lies directly below I-70. Developments near the Beaver Creek ski resort have encountered several instances of sinkholes and solution voids during foundation investigations, which required mitigation or avoidance. Watch for sinkholes in the gypsum formations along the highway.

Collapsible soils are common here in the unconsolidated surficial deposits that form in hillside colluvial and alluvial fan deposits. These types of soils were deposited in a metastable condition in a semi-arid climatic environment, and are prone to compaction and settlement as a consequence of deep-seated, post-development wetting.

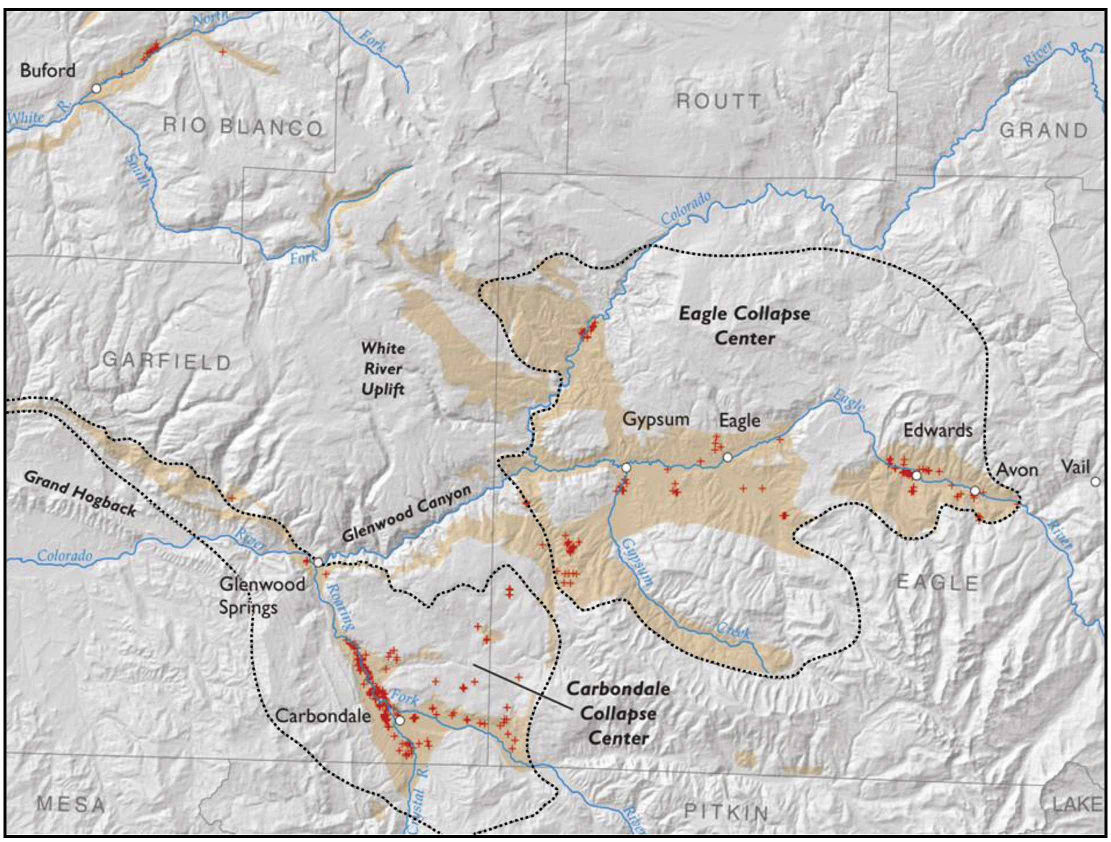

Figure 7. Map showing extent of the Eagle and Carbondale regional evaporite collapse centers (black dotted lines), Pennsylvanian evaporate rocks (tan shading), and karst feature (red crosses). From White (2003).

Ute Creek Syncline

At the Wilmore Lake scenic area, we enter the eastern limb of the asymmetric Ute Creek Syncline. The near-vertical exposed rocks beside the lake are thinly bedded sandstone, siltstone, and shale of the Eagle Valley Formation. Here, I-70 turns to the north and enters a narrow canyon that runs parallel to the axis of the syncline.

Across the valley to the west (left), a shallow landslide occupies the hillside and is exposed in the road cut of the frontage road (US-6) across the Eagle River. Gray soil derived from the Jurassic Morrison Formation high up on the valley wall is exposed in road cut.

The steep limb of the syncline is spectacularly exposed to the east (right) as we reach the end of this short canyon (Figure 8).

Figure 8. Air photo looking to the northeast along the asymmetric eastern limb of the Ute Creek Syncline.

WOLCOTT TO DOTSERO

Bellyache Ridge Dip-Slope Landslides

The valley of the Eagle River opens again near Wolcott and exposes Cretaceous marine strata (the grayish Benton Shale and Niobrara Formation) across the valley. To our left, on the south side of the valley, the broad face of Bellyache Ridge is held up by a hogback of resistant Dakota Sandstone, also of Cretaceous age, at the center of the Wolcott Syncline.

Much of the ridge face is occupied by two large landslides that contain deformed blocks of Dakota and Benton sandstone and shale (Figure 9). The upper slopes and an area between the landslides contain a large rock-block slide of Dakota Sandstone that has failed along bedding planes within the underlying Morrison Formation beneath the dip slope (Lidke, 1998). The landslide complex formed during the late Pleistocene, prior to about 12-35 ka (ibid.).

Localized toe movements of the east Wolcott landslide have caused repeated distress to the eastbound and westbound lanes of I-70. This site was mitigated by CDOT with deep, high-capacity ground anchors, tensioned to large bearing plates that were subsequently covered with fill between I-70 and the US-6 frontage road below in 2000. However, the difficulties of holding a massive landslide in place are evidenced by continued deformation of the roadway.

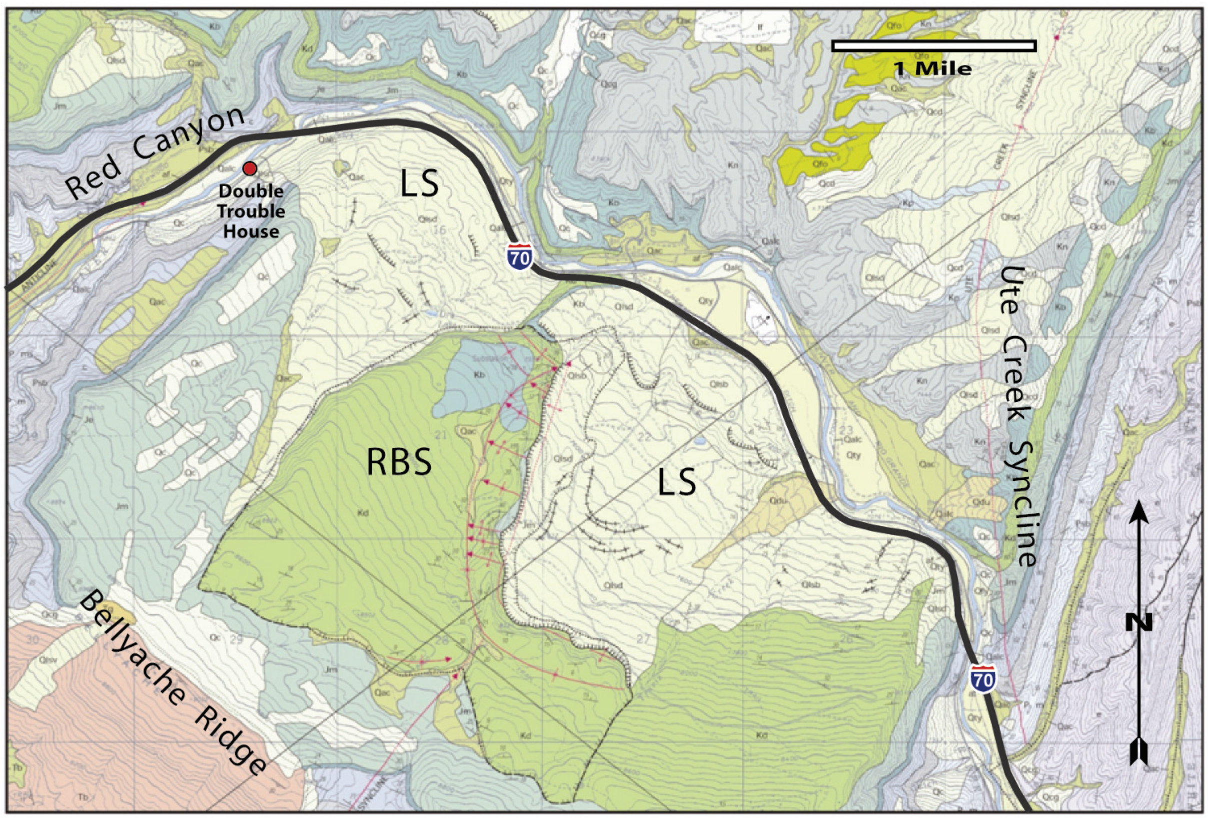

Figure 9. Geologic map of the Wolcott area showing the two large landslides (LS) and rock block slide (RBS) of deformed Dakota Sandstone on the north face of Bellyache Ridge. Modified from Lidke (1998).

Red Canyon

Just past Wolcott, we begin an 8-mile stretch of I-70 through Red Canyon in the west limb of the Wolcott Syncline. Here, we will drop through a superb section of Cretaceous to Pennsylvanian stratigraphy. Watch for the cliffs of tan Dakota Sandstone, the slopes of gray-and-purple shale and sandstone of the Morrison Formation, the distinctively rounded band of salmon-colored eolian Entrada Sandstone, and the redbeds of the Chinle, State Bridge, and Maroon Formation, in succession.

“Double-Trouble House”

Near the mouth of Red Canyon is a well-formed, small, active landslide across the river to the south (left). The landslide is formed in a thick colluvial deposit, and has been activated or reactivated by US-6, which was cut into the lower slope. Directly below the toe of this landslide is a house that is built in a riparian zone along the low banks of the Eagle River (Figure 10). This house is at risk from reactivation and movement of the landslide toe, as well as flooding of the un-dammed and free-flowing river.

Figure 10. Small landslide near the mouth of Red Canyon. Note the proximity of the “double trouble house” to the landslide toe and and the Eagle River.

Evaporite Bedrock Terrain from Eagle to Gypsum

Near Eagle, we have dropped stratigraphically and the Eagle Valley Evaporite once again becomes exposed. The Eagle River valley widens and broad alluvial fans and pediment surfaces form. Gypsum and clastic interbeds are highly deformed, contorted, and tightly folded. Massive gray-white gypsum is commonly exposed. Similar to the Avon-Edwards area, evaporite karst and sinkhole hazards are a significant geologic hazard in this segment from Eagle to Gypsum. The largest sinkhole in the State lies just to the southeast of Gypsum.

Watch for solution slots and sinkholes and contorted strata in the gypsum formations beside the roadway. Many of the roads in this area have a characteristic waviness due to settlement of hydrocompactive soils. In the hills above the highway to the north (right), the American Gypsum Company operates an open-pit mine where massive gypsum is stripped using highway pavement stripping machines (Figure 11). The gypsum is fabricated into wallboard at a factory in Gypsum.

Figure 11. Air photo of American Gypsum Company's open-pit gypsum mine, looking to the north.

Alluvial Fans along Eagle River Valley

To the west of Gypsum, the valley narrows and the surrounding topography becomes steeper and higher. Layered strata of the Eagle Valley and the Maroon Formations are exposed in the valley walls (Figure 12). The alluvial floodplain along this 7-mile stretch is bordered on both sides by numerous alluvial fans at the mouths of ephemeral streams and drainage gullies.

This stretch of the interstate, to the entrance of Glenwood Canyon, is prone to debris and mud flows that commonly flow over the westbound lanes, occasionally the eastbound lanes, and the railroad tracks on the opposite valley side. CDOT Maintenance continually muck out debris and re-excavate detention basins for future flows.

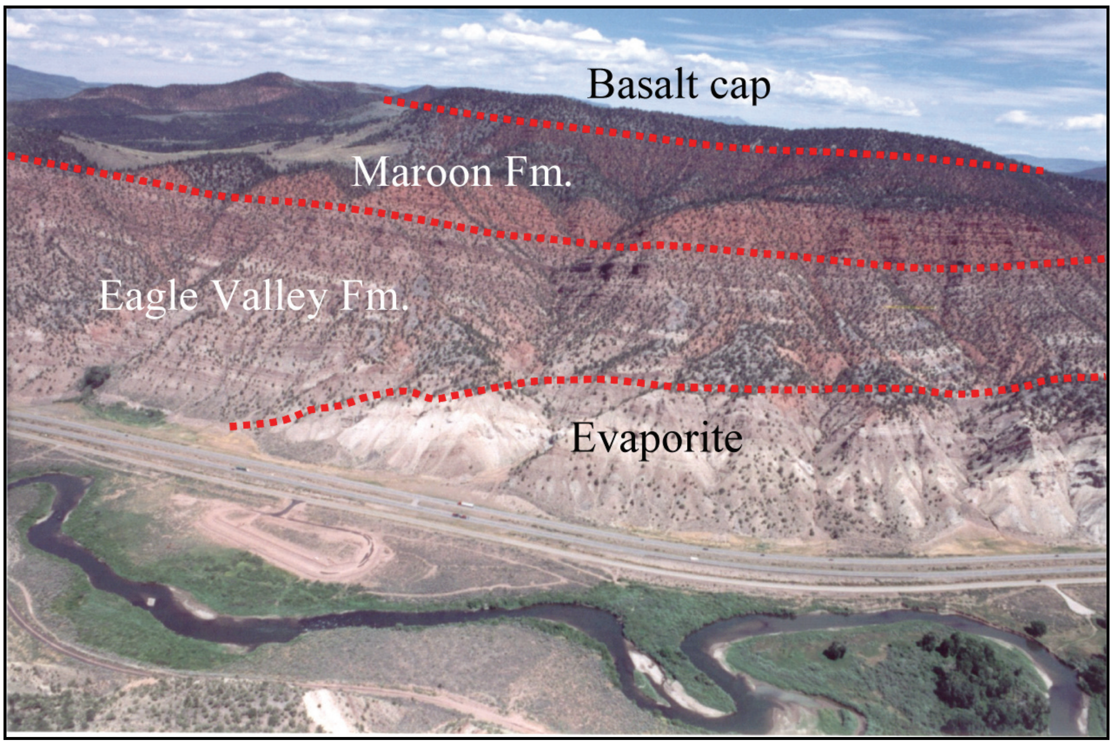

Figure 12. Air photo of north wall of the Eagle River valley between Gypsum and Dotsero.

Dotsero Volcano and Basalt Flow

Approaching Dotsero, we will drive onto a flat expanse of ragged, black, basalt. This lava flow is from the Dotsero volcano, and is the youngest extrusive rock formation in the state at 4,150 ybp (Giegengack, 1962). The volcano, which was located on the hillside to the north (right), has been mostly mined for cinder. The lava flow has been developed and graded as well, destroying the outstanding flow banding (Figure 13).

The Eagle River ends at Dotsero at its confluence with the Colorado River, which enters from the north. From here, we will be following the Colorado River. The Pennsylvanian Belden

Shale, consisting of thin-bedded, marine shale and limestone, is exposed in railroad cuts on the other side of the valley. Look for travertine deposits from warm springs on both sides of the Colorado River just before entering Glenwood Canyon.

Figure 13. Air photo of Dotsero volcano and lava flow, looking north. The flow pushed the Eagle River to the southern side of the valley. Photo by James Soule, CGS.

GLENWOOD CANYON

Glenwood Canyon is a 15-mile long defile that has been carved through the southern flank of the White River Uplift by the Colorado River (Figure 3). The canyon is up to 2,800 feet deep. Based on incision of upland basalt flows, the down-cutting began 3 million years ago (Lidke and others, 2002). The canyon exposes the oldest rocks along the route, including a substantial section of Lower to Middle Paleozoic marine strata and the underlying Proterozoic crystalline rocks (Figure 2).

Because of its narrow, twisting floor and a nearly constant barrage of rockfalls from the high, shattered cliffs, the Glenwood Canyon segment of I-70 was the last segment of the U.S. Interstate system to be completed. Intensive planning and construction took place during the 1970s to early 1990s, and was completed in 1992. A variety of elevated viaducts and tunnels were installed to accommodate the four lanes of highway.

Engineering geologic investigations and mitigation of rockfall and debris flows hazards and soft soils were an integral part of the project. The mitigation included extensive outcrop scaling, removal of unstable formations using explosives, and a variety of rockfall fences, barriers, and attenuators. In 1994, the project won the award for outstanding geologic project from the Association of Engineering Geologists.

Lower to Middle Paleozoic Section

Entering the canyon, we encounter the Mississippian Leadville Limestone, which was deposited in an open-marine shelf setting along the western edge of the North American craton. This extensive formation is also known as the Madison Limestone in the Black Hills and in Montana and Wyoming. The formation has undergone intensive local dissolution and contains many caves and red-claystone-filled paleokarst features (Figure 14). These reddish to vari-colored paleosols are known as the Molas Formation in central and southwestern Colorado.

Beneath the Leadville Limestone, several other sedimentary formations of Devonian to Cambrian age are successively exposed as we go deeper into the White River Uplift (Chaffee Group, Manitou and Dotsero Formations, and Sawatch Quartzite). These formations, which are composed of thin-bedded, marine limestone, dolomite, shale, and quartzite sandstone, are difficult to tell apart (especially from a bus going 50 mph). To orient yourself to the formations, watch for the double white bands that mark the top of the Sawatch Quartzite.

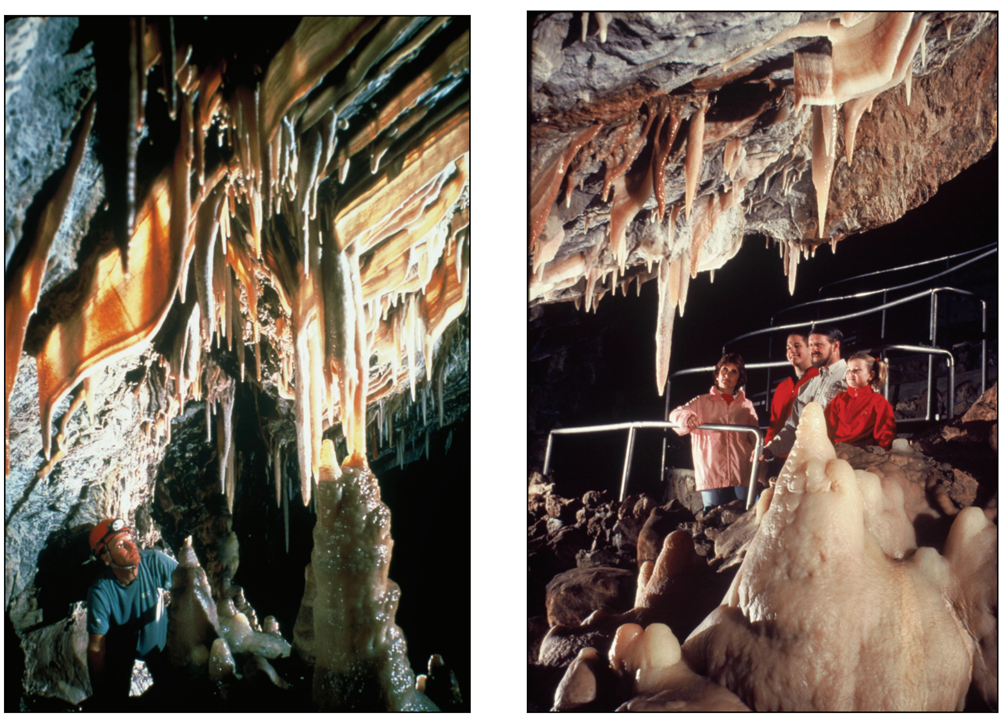

Figure 14. The Leadville Limestone contains numerous caves. Photos by David Harris and Norman Thompson, courtesy of Glenwood Caverns.

Bair Ranch Rest Area

This small structural graben exposes the Belden Formation in the surrounding hills. This area has been prone to debris flows from the small ephemeral drainages to the north. I-70 is located on alluvial fans that contain hydrocompactive soils. The east overpass abutment settled shortly after construction and required compaction grouting remedial repair during the Glenwood Canyon construction project.

During preliminary investigations for the interstate construction, it was found that the entire eastern half of the canyon contained a 30- to 60-foot thick deposit of compressible clay, sand, and silt. This "gray layer" is bounded below, above, and sometimes laterally by fine- to coarse-grained river alluvium and colluvial deposits of Holocene age. Its presence necessitated costly and innovative deep-foundation designs for bridge piers, abutments, and retaining walls, and staged construction to allow for consolidation of the compressible sediments.

Precambrian-Cambrian Nonconformity

About 3 miles to the west of Bair Ranch, look for the distinctive, nonconformable boundary between the Cambrian Sawatch Quartzite and the underlying Precambrian basement rocks, which consist of gray granite, pegmatite, and metamorphic rocks (Figure 15).

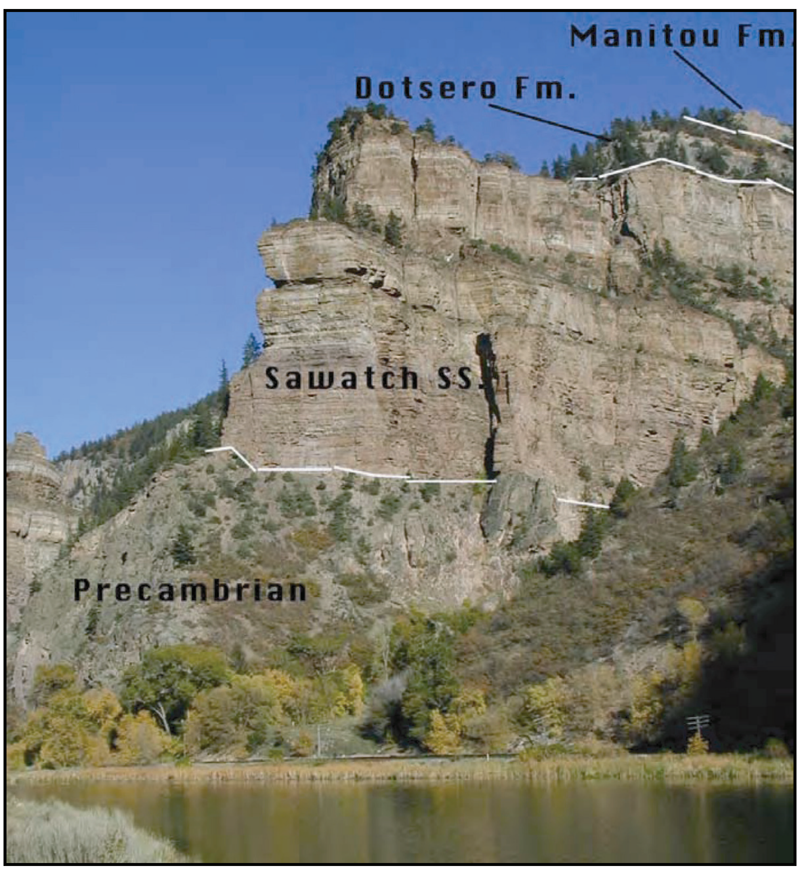

Figure 15. Thin-bedded Sawatch Quartzite overlying Precambrian crystalline rocks along a nonconformity in Glenwood Canyon. From Zabel and White (2003).

Watch for rockfall fences on certain cut slopes and ledges above the highway. At the entrance to the Reverse Curves tunnel, cut through Sawatch Quartzite, notice the masterful use of paint on the exposed cut wall, giving the wall a faux "weathered" look.

Hanging Lake Tunnel and Shoshone Interchange

We will pass through the Hanging Lake Tunnel, which is cut through Precambrian rock. A CDOT traffic-management facility, built in a narrow valley over the center of the tunnel, has been impacted by rockfall, including a minivan-sized boulder that fell from the cliffs. In July 2006, a large crack was found in the facility's concrete roof, which is overlain by up to 30 feet of fill plus fallen boulders. The eastbound tunnel bore was closed in April 2007 after inspections revealed that the crack was growing rapidly and threatening both the facility and the tunnel. At present, the crack is 70 feet long, 4.5 feet deep, and 1.5 inches wide. Remediation activities and lane closures are expected to be ongoing during our field trip.

After passing through the tunnel, we emerge at the Shoshone interchange and cross the elevated Hanging Lake Viaduct. Look to the south (left) over the river where we can see the scar of a large, early Holocene rock avalanche that dammed the Colorado River (Figure 16). The troublesome "gray layer" sediments formed upstream from this point in a lake that was created by the dam, and were dated at 9,820 +/- 130 C14 ybp (Kirkham and Matthews, 2000). Today, this stretch of the river is known as Cottonwood Falls.

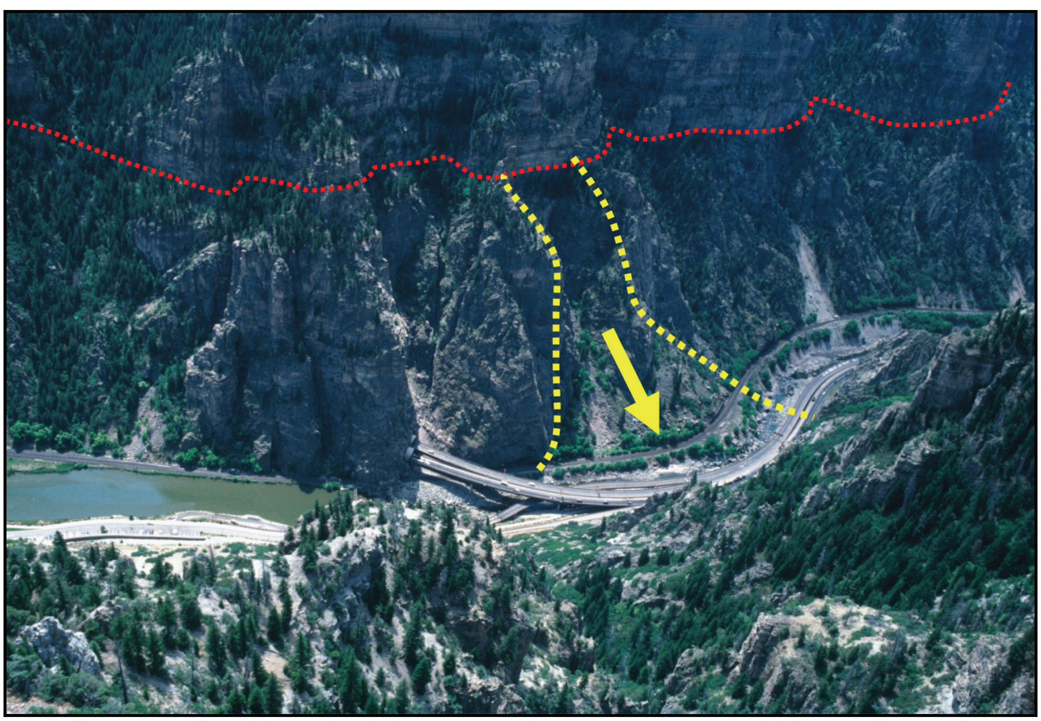

Figure 16. West portal of the Hanging Lakes Tunnel, showing the Precambrian-Cambrian nonconformity (red dots) and the outline of an early Holocene rock avalanche (yellow dots) that dammed the Colorado River.

On Thanksgiving 2004, a small rock avalanche from the opposite north wall occurred, pummeling the viaduct with boulders ranging up to bus size. Several of the boulders pierced through the concrete viaduct decking, rendering the lanes impassable. Fortunately, traffic in the canyon had been stopped a few minutes before because of an overturned beer truck, and no vehicles were in the area when the rocks fell.

Grizzly Creek and No Name Faults

Up to 1,600 vertical feet of Precambrian rock is exposed on the north side of Glenwood Canyon between the Shoshone interchange to the Grizzly Creek Rest Area. At that point, the Grizzly Creek Fault has downdropped the entire Paleozoic section to near the canyon floor. The strata seen to the south (left) of the viaduct dip steeply to the southwest, and we will quickly climb the stratigraphic section.

A few miles further down the canyon, near the No Name interchange, the No Name Fault displaces Leadville Limestone against porphyritic Proterozoic rocks. This fault, along with a nearby fault to the north, forms a graben. A large alluvial fan has been deposited within the gragben at the confluence of the Colorado River and No Name Creek, which drains the White River Uplift.

After passing through a tunnel through the porphyry, we will rise through the entire Lower to Middle Paleozoic section once more as we approach the end of Glenwood Canyon and the White River Uplift. The Leadville Limestone across the river is pockmarked with numerous caves. Above the highway along a steep colluvial slope, a number of gabion mattresses dating back to the late 1960s are undergoing various degrees of failure.

GLENWOOD SPRINGS

Our arrival at Glenwood Springs coincides with the end of the canyon. The best exposure of the Molas Formation in this region is just north of the Vapor Caves bath house on the north (right) side of the highway. A good exposure of the Belden Shale is present across the river to the south (left), above the houses.

Thermal Hot Springs

As we enter Glenwood Springs, look for the Vapor Caves and the Glenwood Hot Spring Pool on the north (right) side of the highway (Figure 17). Thermal springs in the area discharge large volumes of dissolved halite and gypsum directly to the Colorado River.

Yampah hot spring (encircled by a small white fence), which supplies water for the Glenwood Hot Springs Pool flows at a flow rate of about 2,000 gpm and a temperature of 130º F, is rich in chloride, sodium, sulfate, and calcium. This one single source adds about 240 metric tons of dissolved halite and gypsum each day to the Colorado River. This is roughly equivalent to the creation of one new sinkhole with a volume of about 108 m^3 per day, assuming a specific gravity of 2.23 g/cm^3.

Figure 17. Glenwood Hot Springs resort, looking to the southeast. Photo by Vince Matthews, CGS.

Geologic Setting of Glenwood Springs

Glenwood Springs is located at the confluence of the Roaring Fork River with the Colorado River (Figure 18). The valley walls are cut into Maroon Formation, Eagle Valley Formation, and Eagle Valley Evaporite. Tilted Paleozoic formations capped by the Leadville Limestone can be seen to the north (right) and west of town as they rise onto the White River Uplift. There are appreciable unconsolidated Quaternary deposits in the valley including alluvial floodplain and terrace-capping deposits, large alluvial fans, and hillside colluvium. Mt. Sopris, a distinctively pyramidal mountain that forms the backdrop to the south of Glenwood Springs, is the remnant of an Oligocene pluton.

Major geologic hazards in the area include rockfall from the valley walls, debris flow from hillside ephemeral streams, evaporite-karst sinkholes, and hydrocompactive or collapsible soils in the silt-rich surficial deposits. The large, Wulfsohn Ranch alluvial fan blankets the base of the red cliffs to the west of the city. New commercial and local-government facilities have been built upon the distal parts of the fan, and are protected by large berms and detention basins (Figure 19). Forest fires in 1994 and 2002 have elevated the debris flow hazard in the area in recent years.

This is the northern edge of another regional evaporite collapse area, the Carbondale Collapse Center, along the southern edge of the White River Uplift (Figure 7). Quadrangle-scale geologic mapping by CGS reveals that there is a diapiric salt anticline centered beneath the Roaring Fork River valley (see Lidke and others, 2002). The highest density of sinkholes in Colorado occurs in the Roaring Fork River Valley from Glenwood Springs to Carbondale.

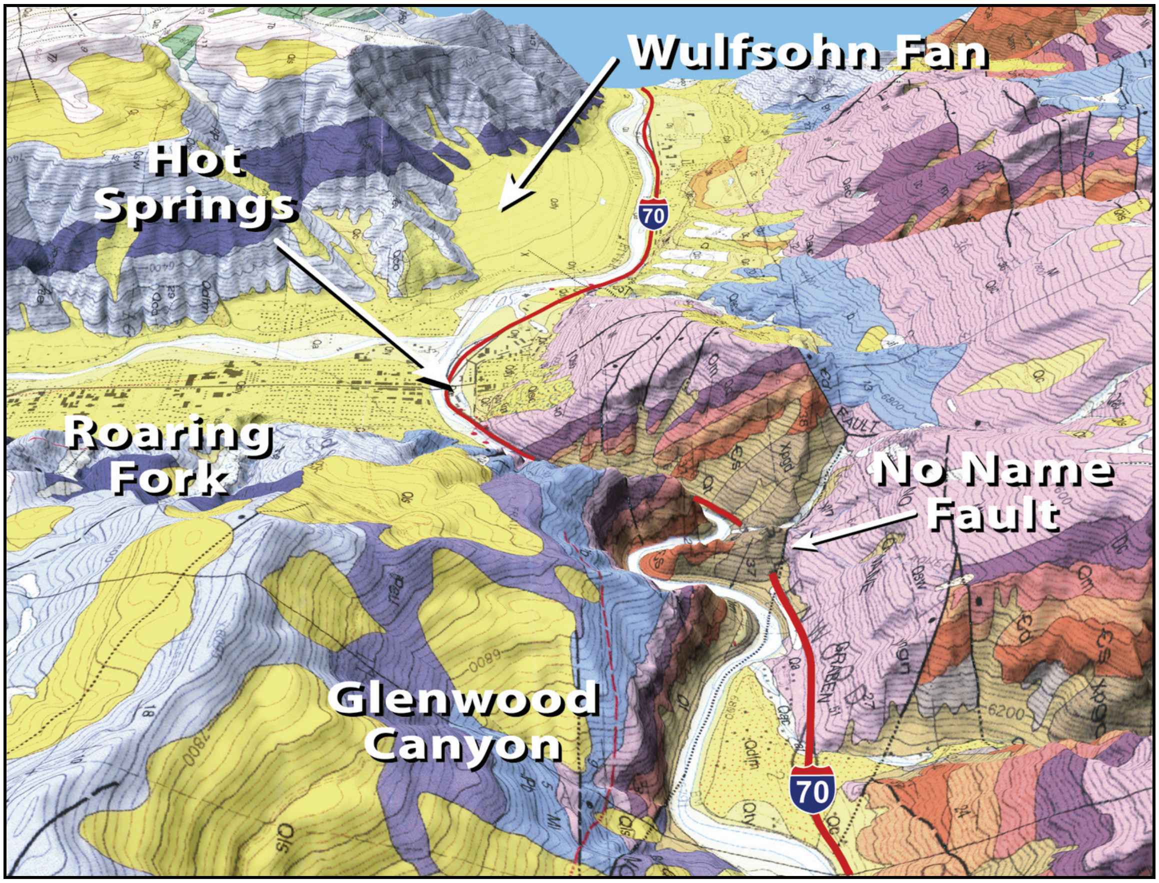

Figure 18. Draped DEM of the Glenwood Springs area, looking west. This resort town is located at the mouth of Glenwood Canyon where the Roaring Fork enters the valley of the Colorado River. The map shows some prominent local features. The local geology includes Precambrian (brown), Lower Paleozoic (red to purple), Upper Paleozoic (blue), and Quaternary (yellow) units. Image generated by Jonathan White, CGS; geology from Kirkham and others (1997).

This marks the end of this "corridor" field trip guidebook. At Glenwood Springs, the different field trips associated with the First North American Landslide Conference will branch out and proceed along different routes to their destinations.

ACKNOWLEDGEMENTS

The trip leaders would like to recognize the following people who provided information as co-authors for previous field trip guidebooks that we have shortened for this narrative: David Lidke, Bob Kirkham, Vince Matthews, and Sylvia White. All oblique air photos were taken in 2002 by Jonathan L. White and David C. Noe, CGS, except where noted.

Figure 19. Air photo of Glenwood Springs and the Wulfsohn Ranch alluvial fan, looking toward the south with Mt. Sopris on the skyline at left. Since this photo was taken in 2001, extensive development has taken place across the lower apron of the fan, a large detention berm has been built across the mid fan, and a major wildfire has burned nearly all of the gambrel oak trees on the upper fan.

REFERENCES

Giegengack, R.F., Jr., 1962, Recent volcanism near Dotsero, Colorado: M.S. Thesis, University of Colorado, Boulder, 43 p.

Kirkham, R.M., Streufert, R.K., and Cappa, J.A., 1997, Geologic map of the Glenwood Springs 7.5 minute quadrangle, Garfield County, Colorado: Colorado Geological Survey Map Series MS-31, scale 1:24,000.

Kirkham, R.M., and Matthews, V., 2000, Guide to the geology of the Glenwood Springs area, Garfield County, Colorado: Colorado Geological Survey Earth Science Week Field Trip, October 13, 2000, 41 p. (http://geosurvey.state.co.us/Portals/0/GlenFieldTripGuidebook_web.pdf)

Lidke, D.J., 1998, Geologic map of the Wolcott quadrangle, Eagle County, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-2656, scale 1:24,000.

Lidke, D.J., Hudson, M.R., Scott, R.B., Shroba, R.R., Kunk, M.J., Perry, W.J., Jr., Kirkham, R.M., Budahn, J.R., Streufert, R.K., Stanley, J.O., and Widmann, B.L., 2002, Eagle collapse center: Interpretation of evidence for late Cenozoic evaporite-related deformation in the Eagle River basin, Colorado, *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America Special Paper 366, p. 101-120.

Minturn Earthflows Task Force, 1986, Options to mitigate potential damages from earthflows near Dowds Junction, Colorado: 50 p. (Interagency report archived in Colorado Geological Survey Landslide Library)

Noe, D.C., Matthews, V., Steele Weir, S., and McCalpin, J.P., 2003, Geology, geologic hazards, and water resources in the mountains of central Colorado: Field Trip Guidebook, Association of Engineering Geologists 46th Annual Meeting, Vail, Colorado, September 16, 2003, 37 p.

Tweto, O., 1983, Geologic cross sections across Colorado: U.S. Geological Survey. (Available as Colorado Geological Survey Miscellaneous Investigations MI-63.)

White, J.L., Cannon, S.H., Kirkham, R.M., Lidke, D.J., White, S., and Gartner, J.E., 2003, Geologic hazards of west-central Colorado: Field Trip Guidebook, Association of Engineering Geologists 46th Annual Meeting, Vail, Colorado, September 30, 2003, 43 p.

Widmann, B.L., Kirkham, R.M., Morgan, M.L., and Rogers, W.P., with contributions by Crone, A.J., Personius, S.F., and Kelson, K.I., and GIS and Web design by Morgan, K.S., Pattyn, G.R., and Phillips, R.C., 2002, Colorado Late Cenozoic Fault and Fold Database and Internet Map Server: Colorado Geological Survey Information Series 60a, http://geosurvey.state.co.us/pubs/ceno/.

Zabel, G., and White, S., 2003, Stratigraphy and engineering geology of the Glenwood Springs I-70 Corridor: Field Trip Guidebook, 40th Annual Meeting of American Institute of Professional Geologists, Glenwood Springs, Colorado, October 9, 2003, p. 55-63.

DRIVE-BY GUIDEBOOK: GEOLOGY AND GEOLOGIC HAZARDS ALONG THE I-70 CORRIDOR, GLENWOOD SPRINGS TO GRAND JUNCTION, COLORADO

Trip Leaders:

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Mt. Garfield, Book Cliffs, near Palisade (photo by Vince Matthews, CGS)

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

This “corridor” field trip guidebook is created for drive-through bus tours with no stops. It is intended for tour groups from the First North American Landslide Conference that will pass along this segment of the Interstate Highway 70 (I-70) corridor on the way to other destinations.

There is plenty of great scenery and interesting geology to see along this route, regardless of the fast and continuous pace of the tour. We have included numerous illustrations and short topical descriptions of geologic points of interest along the way. Nearly all of these points may be easily viewed from the bus.

This tour will take us through broad basins, uplifts, and incised canyons across the boundary between the Southern Rocky Mountains and the Colorado Plateau physiographic provinces. The terrain that we will see reflects different sedimentary formations of upper Paleozoic to Cenozoic age, and numerous landslides and rockfall areas. We will also view and discuss the abundant mineral fuel resources of the Piceance Basin.

Parts of the narrative herein has been adapted from some recent field trip guidebooks, particularly Chronic and Williams (2002) and White and others (2003), and an unpublished road log created by Garry Zabel.

TRIP ROUTE DESCRIPTION

The trip route begins in Glenwood Springs and follows I-70 for 60 miles west to Palisade, at the gateway to the Grand Valley near Grand Junction (Figure 1). Table 1 shows the main segments along the way and lists the pertinent points of geologic interest and discussion topics.

Table 1. Field Trip Segments and Topics

Segment	Topics
Glenwood Springs to New Castle	Geologic setting of Glenwood Springs; recent forest fires and debris flows; Red Canyon and Maroon Formation; Dakota Sandstone and Morrison Formation outcrop; Grand Hogback and coal mines on Coal Ridge
Silt to DeBeque	Piceance Basin; Silt; radioactive tailings cleanup and geo-artwork at Rifle; Battlement Mesa and Pleistocene mesas; asymmetry of Colorado River valley; Roan Cliffs and Wasatch and Green River formations; natural gas fields and oil shale deposits; Rulison nuclear blast site
DeBeque Canyon	Purple earthflow landslide; Mesaverde Group lithofacies and rockfall hazards; DeBeque Canyon landslide; Cameo landslide
Palisade and Grand Junction Area	Geologic setting of the Grand Valley; the Book Cliffs; Grand Mesa; the Uncompahgre Plateau and Colorado National Monument

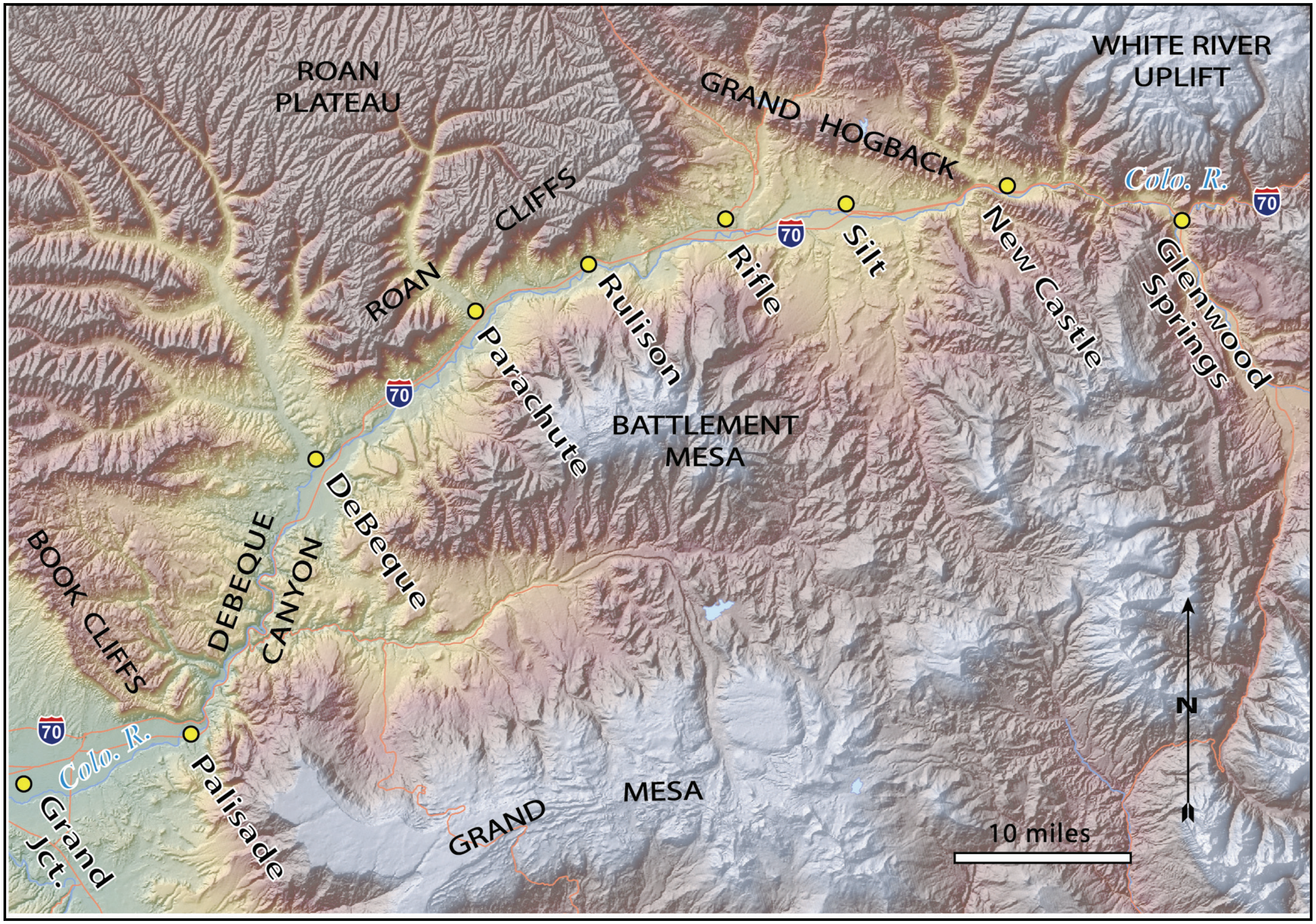

Figure 1. Index map showing field trip route along I-70, from Glenwood Springs westward to Palisade and the Grand Valley near Grand Junction.

STRATIGRAPHY

West central Colorado contains abundant sedimentary formations ranging in age from Mississippian to Cenozoic (Figure 2). The section varies between marine (Leadville Limestone, Belden Formation and Mancos Shale), restricted marine (Eagle Valley Formation / Evaporite), marginal marine (Minturn Formation, Dakota Sandstone, and Mesaverde Group), continental (Maroon Formation, Mesaverde Group, and Wasatch Formations), and lacustrine deposits (Green River shale). The Lower Mesozoic section (State Bridge to Morrison Formations) consists of terrestrial redbed, eolian, and alluvial deposits.

The basement rock in the region is composed of Precambrian (Proterozoic) crystalline rocks, which are exposed in Glenwood Canyon near Glenwood Springs and in the Uncompahgre Plateau near Grand Junction. The region also contains basalt flows of Miocene to Holocene age.

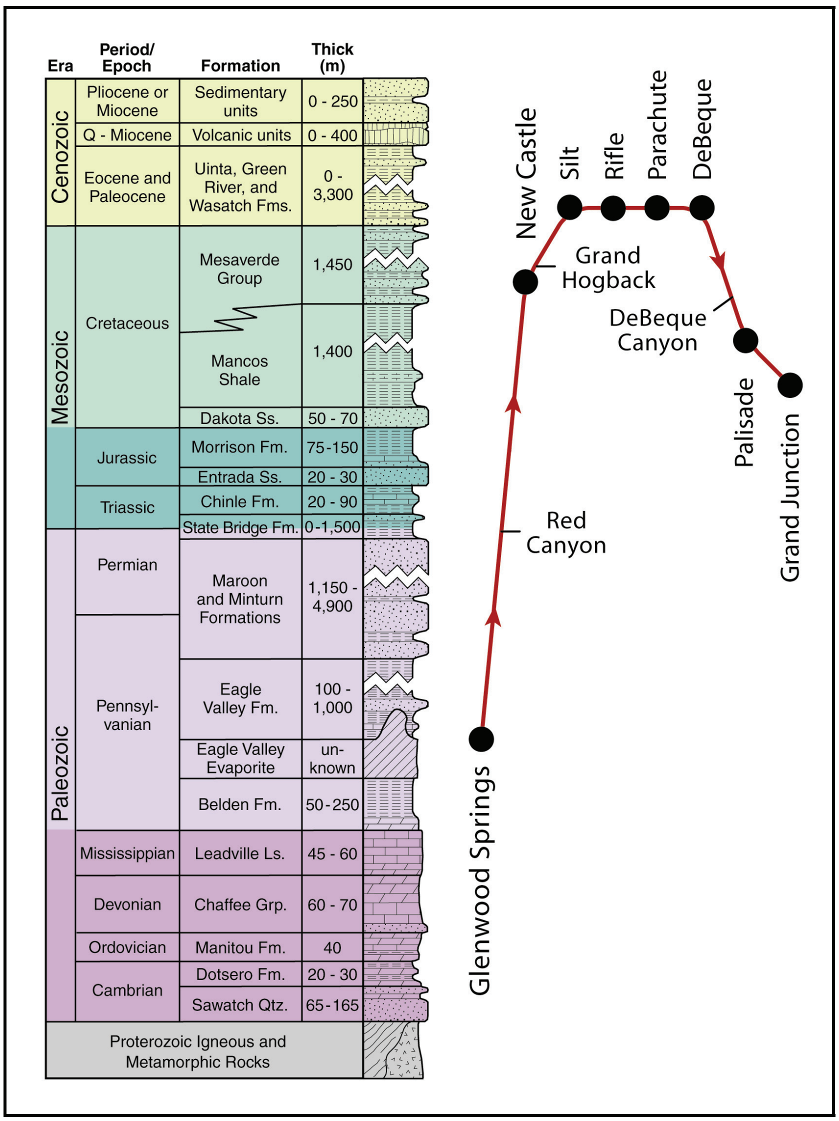

Figure 2. Stratigraphic section of west central Colorado, modified from Kirkham and others (2002). Stratigraphic horizons of various locations along the trip route are shown to the right of the section.

TECTONIC ENVIRONMENT

The rocks in west central Colorado have endured multiple periods of deformation. The oldest, Precambrian rocks have incurred at least two periods of ductile deformation associated with deep burial and metamorphism during the Proterozoic. Early Paleozoic tectonism certainly occurred in Central Colorado (probably more than once), but the evidence is incomplete.

During the Pennsylvanian and Permian periods, the Ancestral Rocky Mountains rose as fault blocks out of a shallow sea. Colorado was dominated by the ancestral Uncompahgre and Front Range uplifts with a restricted evaporite basin trapped between the two ranges. Most of the evidence of this uplift is stratigraphic rather than structural. Syntectonic rocks in the Maroon Formation near Glenwood Springs record the uplift and erosion of the ancestral Front Range.

The next major deformation, the Laramide Orogeny, began with fault blocks rising out of the Cretaceous Western Interior seaway about 80 million years ago. This period of uplift and crustal shortening continued into the early Cenozoic. The structural style is dominated by high-angle reverse faults with a few, low-angle thrust faults. Faulting was accompanied by igneous intrusions and mineralization, as well as deposition of syntectonic sedimentary units. Many of the broad uplifts and intermountain basins along the trip route (Figure 3) are Laramide features.

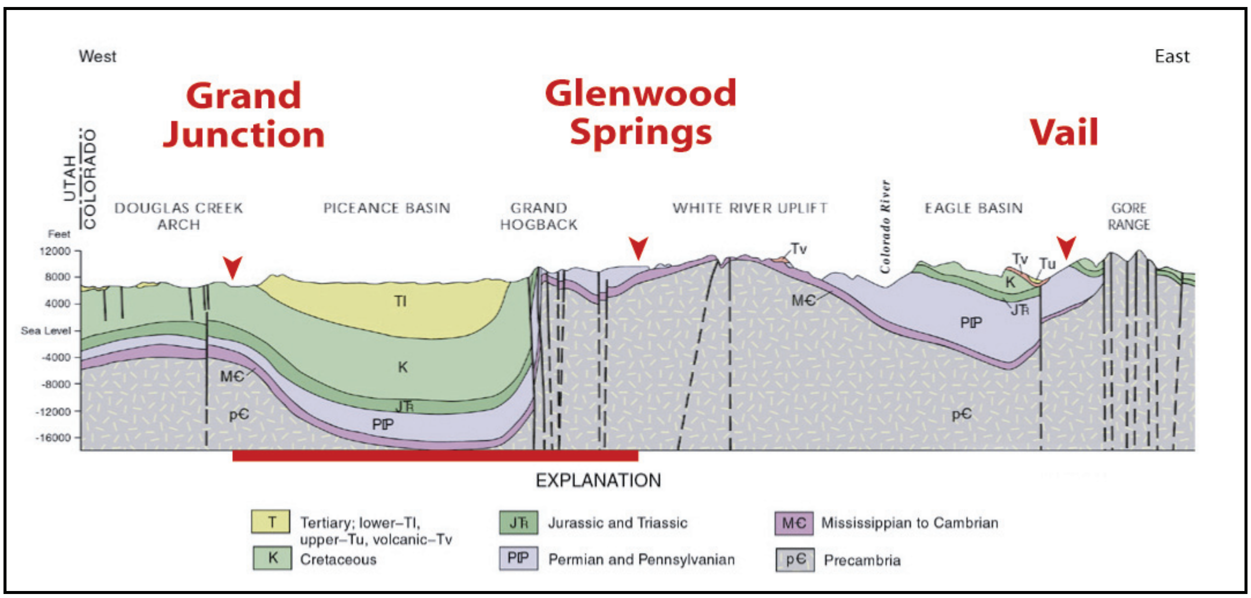

Figure 3. General geologic cross section for the central Colorado mountains along the I-70 corridor, from Vail to Grand Junction (modified from Tweto, 1983). The red bar underlines geology along the trip route.

The last major tectonic event, and the one we are in today, began about 25 million years ago with major east-west extension. This extension broke the crust into large blocks that are subsiding into basins and rising into some of the most impressive mountains in North America. Fifty-eight peaks in Colorado soar above 14,000 feet in elevation, and the entire state averages 6,800 feet above sea level. The structural style is dominated by normal faults and basaltic volcanism. Colorado has 92 catalogued Quaternary faults (Widmann and others, 2002).

GLENWOOD SPRINGS TO NEW CASTLE

Geologic Setting of Glenwood Springs

Glenwood Springs is located at the confluence of the Roaring Fork River with the Colorado River (Figure 4). The valley walls are cut into Maroon Formation, Eagle Valley Formation, and Eagle Valley Evaporite. Tilted Paleozoic formations capped by the Leadville Limestone can be seen to the north (right) and west of town as they rise onto the White River Uplift. There are appreciable unconsolidated Quaternary deposits in the valley including alluvial floodplain and terrace-capping deposits, large alluvial fans, and hillside colluvium. Mt. Sopris, a distinctively pyramidal mountain that forms the backdrop to the south of Glenwood Springs, is the remnant of an Oligocene pluton.

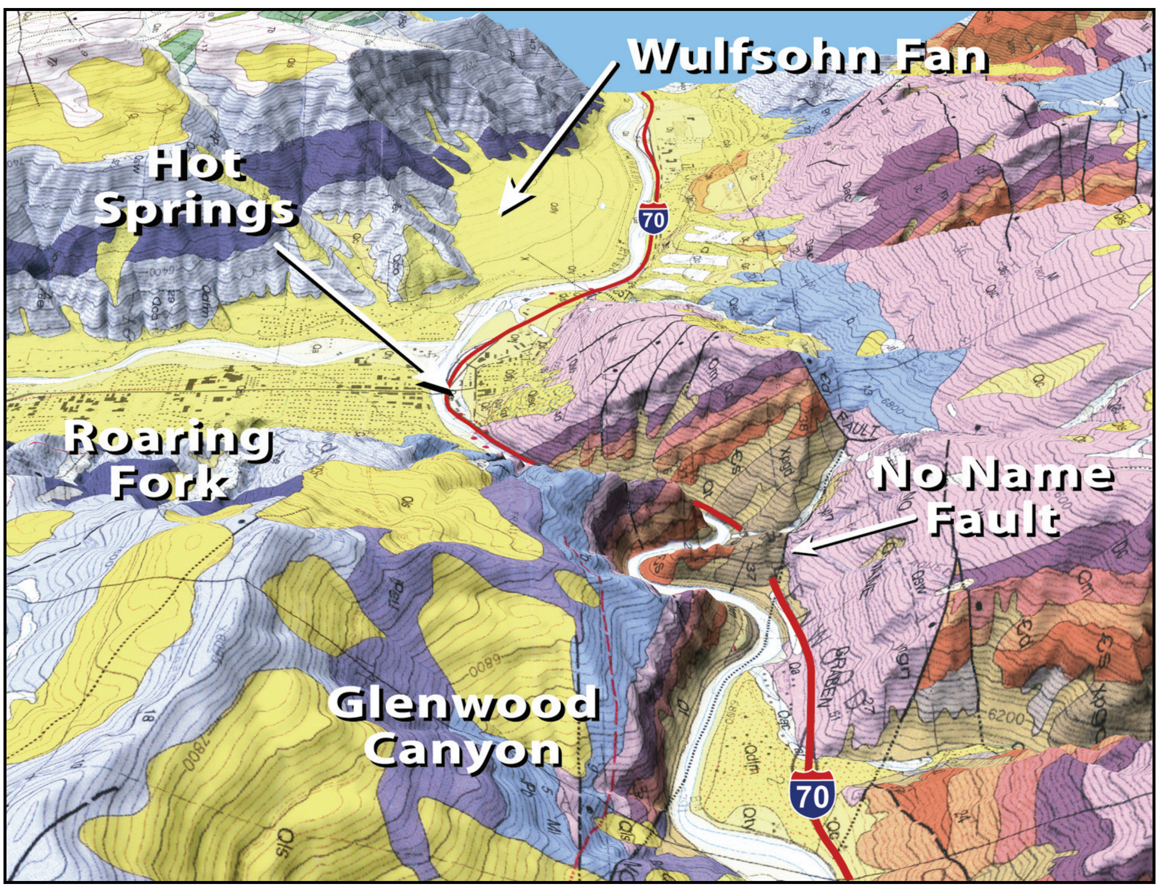

Figure 4. Draped DEM of the Glenwood Springs area, looking west. This resort town is located at the mouth of Glenwood Canyon where the Roaring Fork enters the valley of the Colorado River. The map shows some prominent local features. The local geology includes Precambrian (brown), Lower Paleozoic (red to purple), Upper Paleozoic (blue), and Quaternary (yellow) units. Image generated by Jonathan White, CGS; geology from Kirkham and others (1997).

Major geologic hazards in the area include rockfall from the valley walls, debris flow from hillside ephemeral streams, evaporite-karst sinkholes, and hydrocompactive or collapsible soils in the silt-rich surficial deposits. The large, Wulfsohn Ranch alluvial fan blankets the base of the red cliffs to the west of the city. New commercial and local-government facilities have been built upon the distal parts of the fan, and are protected from debris flows by large berms and detention basins.

This is the northern edge of a regional evaporite collapse area, the Carbondale Collapse Center, along the southern edge of the White River Uplift. Quadrangle-scale geologic mapping by CGS reveals that there is a diapiric salt anticline centered beneath the Roaring Fork River valley (see Lidke and others, 2002). The highest density of sinkholes in Colorado occurs in the Roaring Fork River Valley from Glenwood Springs to Carbondale.

Yampah hot spring, which supplies water for the Glenwood Hot Springs Pool flows at a flow rate of about 2,000 gpm and a temperature of 130º F, is rich in chloride, sodium, sulfate, and calcium. This one single source adds about 240 metric tons of dissolved halite and gypsum each day to the Colorado River. This is roughly equivalent to the creation of one new sinkhole with a volume of about 108 m^3 per day, assuming a specific gravity of 2.23 g/cm^3.

Recent Forest Fires and Debris Flows

Recent forest fires have elevated the debris flow hazard in the Glenwood Springs area in recent years. The South Canyon fire burned 1,800 acres to the west of town in 1994. Fourteen firefighters were trapped and perished in that fire on the flank of Storm King Mountain. We will see debris flow paths from this burned area a few miles to the west, in Red Canyon.

In 2002, the 12,209-acre Coal Seam fire burned extensive tracts to the north and south of I-70, including the surface of the Wulfsohn alluvial fan (Figure 5). Properties along Mitchell Creek, to the north (right) of the highway, have experienced numerous debris flows following the wildfire. The debris flow hazard is diminishing several years later as vegetative cover is re-established on the hillsides

Red Canyon and Grand Hogback

Immediately to the west of Glenwood Springs, the Colorado River valley narrows and steepens, and we enter Red Canyon (Figure 6). The red sandstone beds here are the Maroon Formation (which we encountered earlier in the day in another Red Canyon, between Wolcott and Eagle). Here, on the southern flank of the White River Uplift, the bedding tilts up steeply to the northeast (right). This canyon is a rockfall hazard area, and detached slabs sliding onto the highway have caused fatalities in the past.

Red Canyon lies within a strike valley. To the south (left) and up the hillsides, one can see progressively younger strata including the Triassic State Bridge and Chinle formations (red sandstone and shale), Jurassic Entrada Sandstone (a thick, pinkish, somewhat rounded unit) and Morrison Formation (varicolored shale and sandstone), and Cretaceous Dakota Sandstone (tan to gray sandstone and shale). Scrubby Gambrel oak vegetation covers many of the shaley intervals along this north-facing slope.

Figure 5. Photo of the Wulfsohn Ranch alluvial fan, looking to the north, following the 2002 Coal Seam wildfire. Photo by Sue Cannon, US Geological Survey.

Figure 6. View of Red Canyon to the west of Glenwood Springs. The Roan Plateau forms the skyline, and the dark ridge in the middle background is the Grand Hogback. Storm King Mountain, comprised of reddish Upper Paleozoic sedimentary formations, is at the center right. Photo by Jason Wilson.

Both of the aforementioned wildfires burned along the sides of this canyon. Ash-laden debris flows emanating from Storm King Mountain in 1994 closed I-70 and built a fan delta that extended halfway across the Colorado River (Figure 7). Many of these debris flows were initiated during a rainstorm due to progressive sediment entrainment along upland arroyos, rather than from soil slips (Kirkham and others, 2000). The 2002 Coal Seam fire started to the south of the South Canyon exit when a near-surface coal mine fire ignited drought-parched vegetation.

Studies of wildfires and subsequent debris flow and flooding incidents by the US Geological Survey, Colorado Geological Survey, and Colorado Water Conservation Board during the mid to late 1990s helped to establish and publicize the close relationship between these phenomena. By 2002, a year of extreme drought and wildfire throughout Colorado, the phrase, "After the fire, comes the flood," had been effectively disseminated to emergency management personnel and the Media, and temporary emergency protective installations (such as Jersey-barrier walls to re-route mudflows) were utilized in Glenwood Springs immediately after the wildfire was extinguished.

Figure 7. Cleanup of I-70 following the 1994 post-wildfire debris flows. Photo by Jim Scheidt, US Bureau of Land Management.

Exiting Red Canyon, a small but distinctive hogback of dipping bedrock is seen across the river to the south (left). This exposure contains two formations that are widespread across the west central United States: the varicolored Jurassic Morrison Formation, which is famous for its fossil dinosaur assemblage, and the overlying Cretaceous Dakota Sandstone.

The long, 1,800-foot-high ridge that dominates the skyline on the south side of the river is the Grand Hogback (locally called Coal Ridge). This heavily vegetated feature is underlain by steeply dipping sandstone, shale, and coal strata of the Upper Cretaceous Mesaverde Group. The bare strip halfway up the hill marks the location of coal seams that have been burning for several decades (Rushworth and others, 1989). The reddish rock in the water gap above the town of New Castle is clinker, an aftereffect of burning coal in outcrop fires.

SILT TO DEBEQUE

Piceance Basin

After passing through the Grand Hogback, we enter the main part of the Piceance Basin (Figure 3), a broad Laramide feature that formed during Late Cretaceous and Early Cenozoic time. This is also the boundary between two major physiographic regions of North America, the Southern Rocky Mountains to the east and the Colorado Plateau to the west.

For several miles we will follow the Colorado River as it angles obliquely away from the Grand Hogback. Note the magnificent rock flatirons along the hogback. These chevrons are formed by steeply dipping fluvial-sandstone channels within the Mesaverde Group (Figure 8).

The Colorado River valley widens considerably as the terrain opens into a relatively low topographic area. This lowland was formed by differential weathering of the Tertiary Wasatch Formation, a terrestrial formation composed of soft and easily eroded shale and sandstone.

To the south (west), across the river, is a mesa that shows a mosaic of vegetation upon its slopes (mostly pinon pine, juniper, and sage brush) as a result of numerous wildfires. The most recent burn occurred in 2006 and this particular area is devoid of vegetation. This burned-out slope is now highly susceptible to debris flows onto the alluvial fans at the base of this area.

The first town west of the hogback water gap is Silt. This name reflects the abundance of thick deposits of fine-grained, surficial sediments in the area, including windblown loess, slope wash, and alluvial fan deposits. Because this area of Colorado is semi-arid, many of these fine-grained soil deposits that mantle the Colorado River valley are dry and thus are prone to hydrocompaction, where the soil structure collapses if it becomes wetted under load. This phenomenon causes ground settlement and damage to structures and roadways.

Uranium Tailings and Geo-Artwork at Rifle

Rifle is the largest town in the Piceance Basin. It formerly contained two mills that processed uranium and vanadium ore from 1924 to 1973. Radioactive tailings were stockpiled within the modern floodplain of the Colorado River, which experiences a seasonally high water table. The alluvial aquifer is contaminated from seepage from the mill tailing; however, alluvial ground water discharging to the river is quickly diluted. Following a 1991 federal land transfer, the US Department of Energy moved the tailings to a 95-acre disposal cell located 6 miles to the north of Rifle. The site is underlain by the Wasatch Formation, which is considered to be an aquitard. The clean-up strategy for the old mill sites involves natural flushing by ground water (US DOE Legacy Management, 2006).

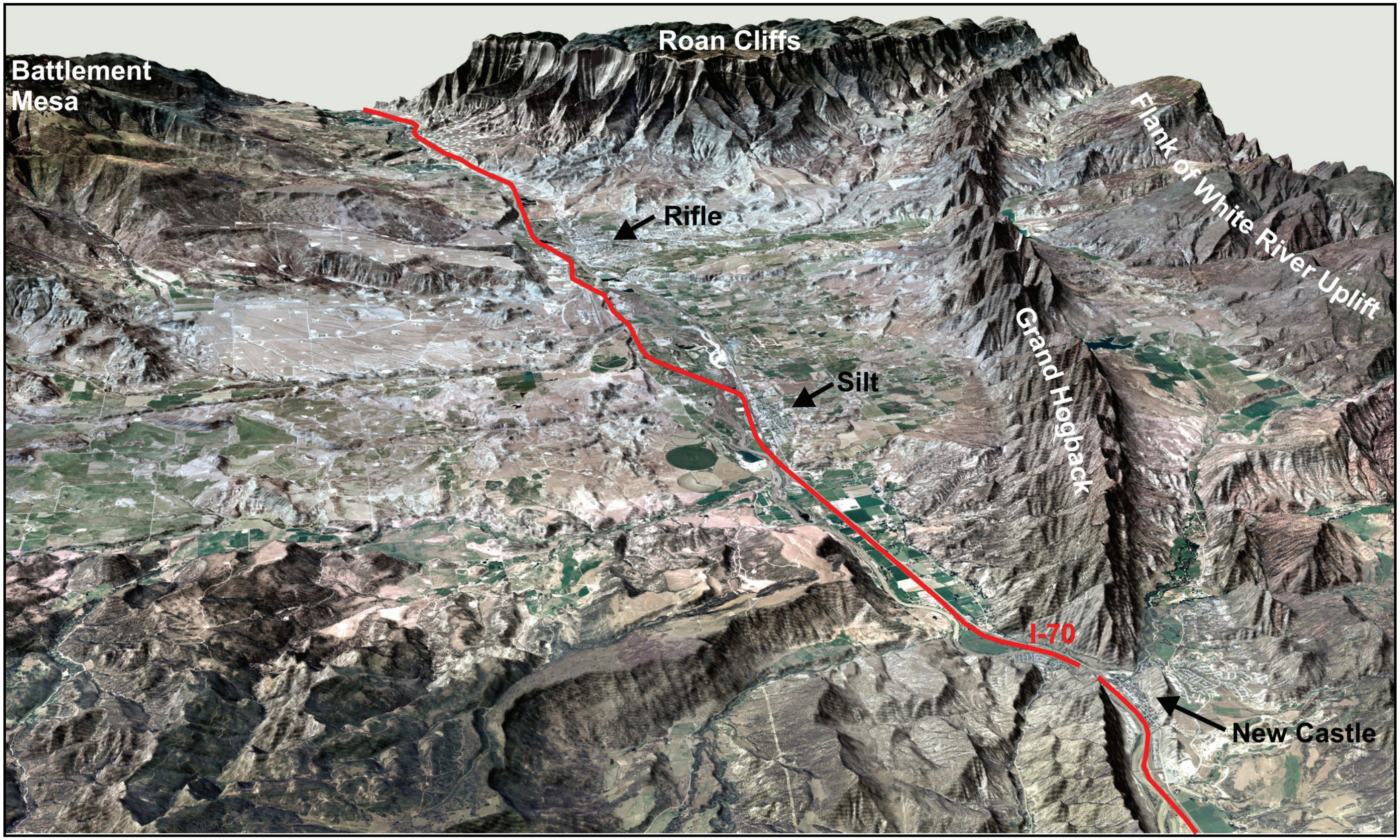

Figure 8. Draped DEM image showing the landscape along the Colorado River Valley below the Grand Hogback water gap, in the western part of the Piceance Basin. View is to the northwest. Terrain model created by Jonathan White, CGS, using USGS 10-m DEM data and USDA NAIP aerial photography.

Look for the water gap in the Grand Hogback about 7 miles to the north of town. In August 1972, the eyes of the art world were on Rifle Gap as *Valley Curtain*, a creation of the artists Christo and Jeanne Claude, was unveiled (Figure 9). The orange, woven-nylon curtain was 1,250 ft long. The anchoring cables weighted 110,000 lbs and were attached to 792 short tons of concrete foundations along the rock walls. The project took 28 months to complete, but the project was removed only 28 hours after completion because of 60-mph winds.

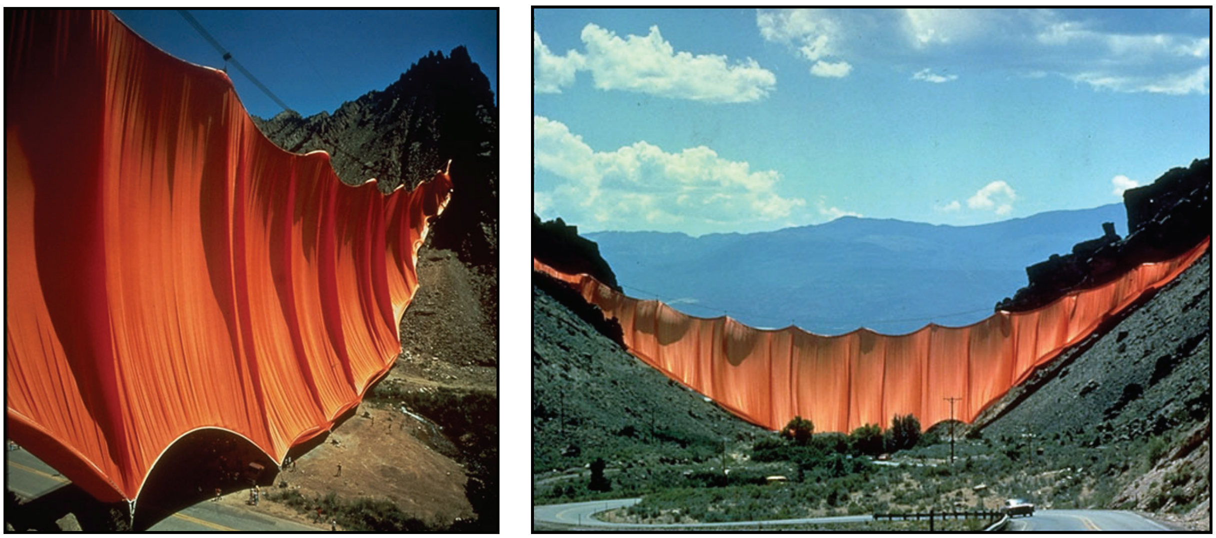

Figure 9. *Valley Curtain* across Rifle Gap in the Grand Hogback in August 1972, before the winds came (from www.christojeanneclaude.net/vc.html).

Battlement Mesa, Roan Cliffs, and Valley Asymmetry

Battlement Mesa, to the south (left) of I-70, is a remnant ridge of Tertiary basaltic flows that lies at an elevation over 10,000 ft. Topographic reversal from erosion of the surrounding, weaker strata has left these resistant flows perched almost 6,000 feet above the current valley floor. The north-slope aspect of the mesa, along with relatively high altitude and wet conditions, has generated appreciable debris flooding since the early Pleistocene. As a result, extensive debris-flow fans occur on this side of the Colorado River valley (Figure 10). These deposits contain abundant basaltic gravel, and boulders up to 5 ft in diameter (Shroba and Scott, 1997).

The successive ages of the debris-flow mesas can be seen by their staggered elevation differences from the current stage of the Colorado River, with the highest (Flatiron Mesa) being the oldest. The general stratigraphy consists of Wasatch Formation that is capped with debris gravel of variable thickness, commonly covered with a thin mantle of late Pleistocene loess. The older mesa tops are generally covered with multiple loess sheets.

By comparison, the north (right) side of the Colorado River valley is dominated by the strikingly steep Roan Cliffs, comprised of the cliffy Green River Formation (Eocene) and the underlying Wasatch Formation (Paleocene), which is exposed as lower ridges near the valley floor. The Roan cliffs are about 8,800 ft in elevation and, with a strong southern aspect facing the sun, are considerably drier than Battlement Mesa. Relatively low and broad alluvial fans occur on the north side of the valley. These sediments were sourced from smaller basins within the ridges of exposed Wasatch bedrock. The slope grade of these fans is much flatter and the sediments much finer than those from the basaltic fans across the river.

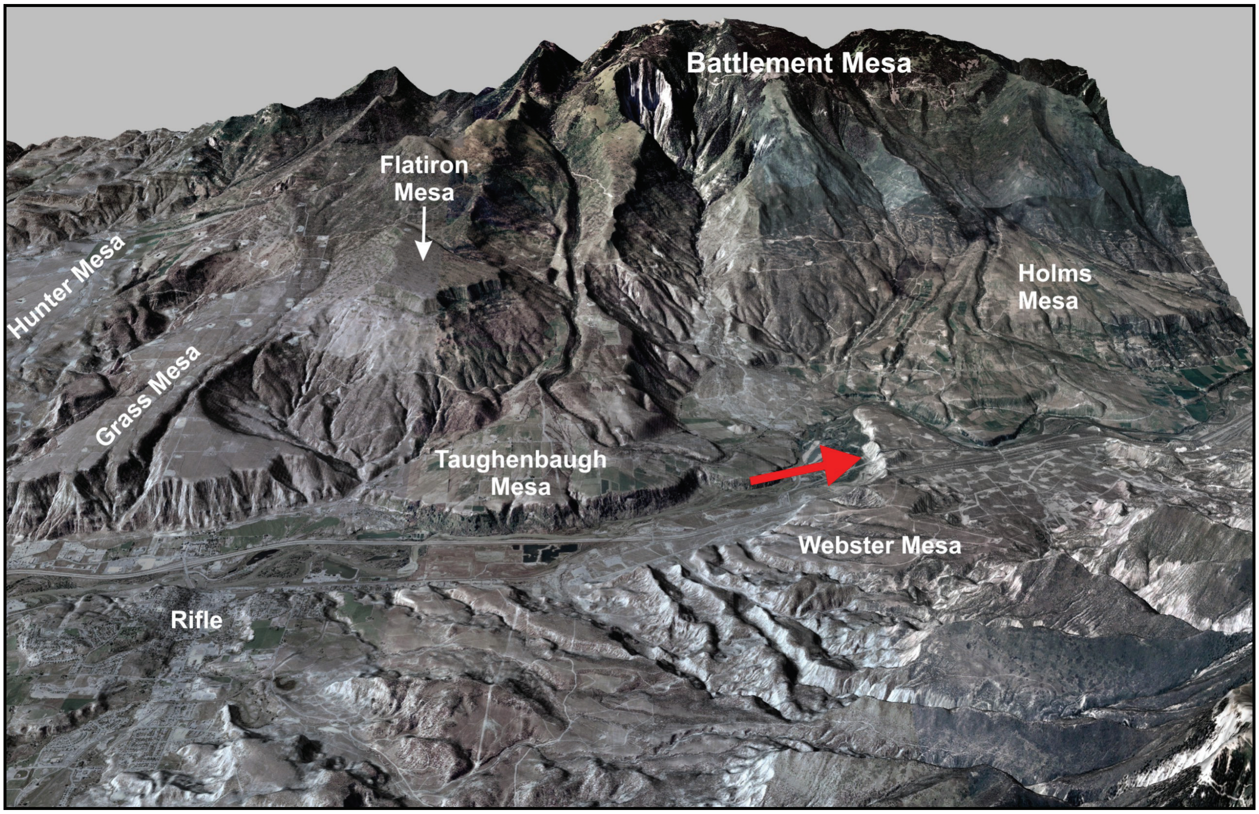

Figure 10. Terrain model of Rifle area, looking SSW toward Battlement Mesa. Well-defined debris-flow fans and paths emanate from highlands of the mesa. Image created by Jonathan White, CGS, using USGS 10-m DEM data and USDA NAIP aerial photography of Garfield County. View direction of Figure 11 is shown by red arrow.

The differing modes of geology, slope aspect, microclimates, and Pleistocene deposition have created an asymmetric valley profile between the towns of Rifle and DeBeque. The varied deposits and landforms have created different types of ground instability. Debris-flow hazards exist within the drainages that extend from Battlement Mesa. Slope instability and landslides are a threat along the steep slopes and edges of the older alluvial-fan mesas where seepage from the overlying gravels is introduced into weak Wasatch claystones. The mesa edges and extensive landslide complexes are all we can see of most of these large fan landforms from the valley floor. On the north valley side, the broad, more geologically recent alluvial fans contain fine-grained soils that are especially prone to hydrocompaction. Settlement of I-70 where it runs over these fans has been a problem since the highway was completed in the late 1970s.

At Webster Hill, I-70 passes through an eroded road cut in the Wasatch Formation. Just past the road cut, the asymmetry of the valley becomes quite apparent. High mesas on the south (left) side slope gradually up to the highlands of Battlement Mesa, whereas low broad alluvial fans on the north (right) side exit small basins within the Wasatch Formation at the base of the Roan Cliffs (Figure 11). Along the valley floor there is evidence that early debris flows from Battlement Mesa temporarily blocked and diverted the Colorado River (Stover and Soule, 1985). There are remnants of these flows with basaltic clasts on the north side of the river, across from obviously more geologically recent debris flow paths that have bypassed Holms Mesa.

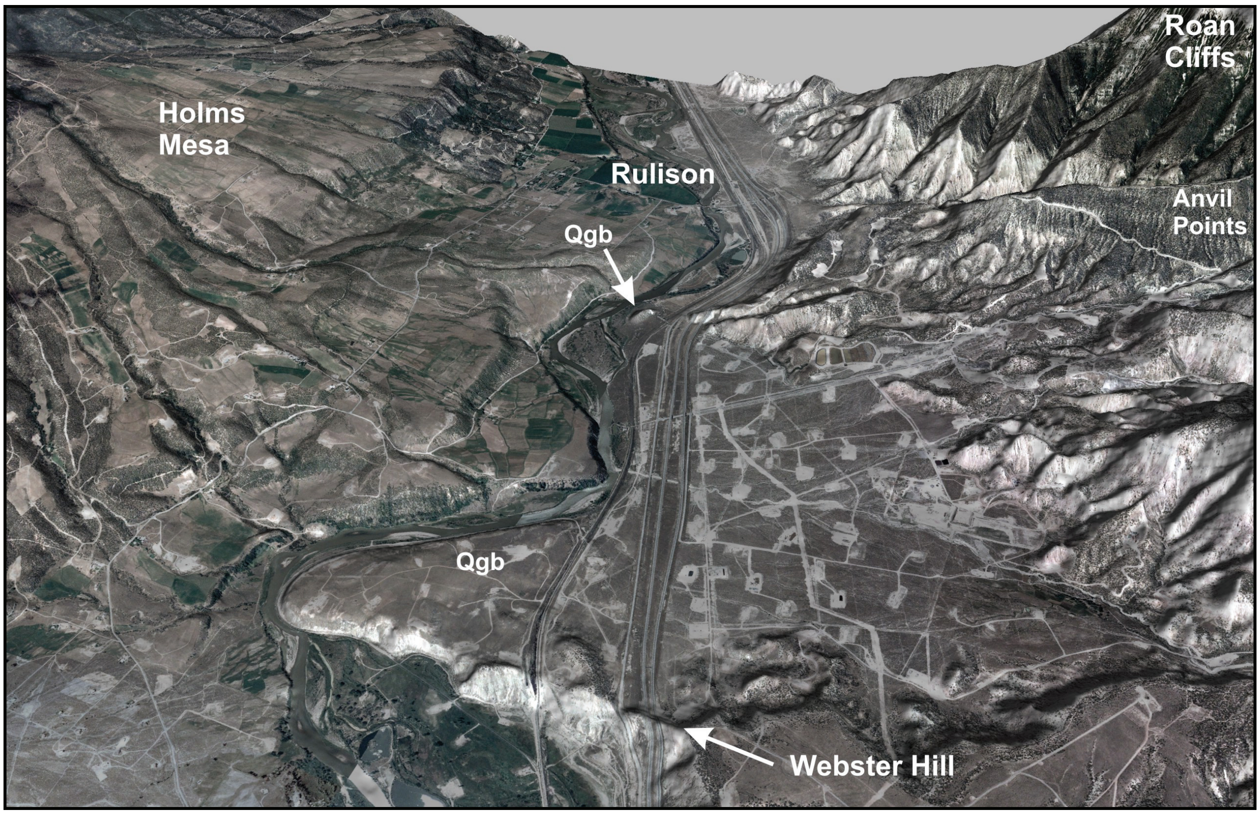

Figure 11. Terrain model of Colorado River Valley, looking downriver to the west. Note geologically recent debris flow morphology on near side of Holms Mesa. Basaltic debris deposits locations across river are shown by Qgb. The grid-like patterns on the broad Webster Hill alluvial fan are from drilling and production pads associated with Piceance Basin natural gas fields. Image created by Jonathan White, CGS, using USGS 10-m DEM data and USDA NAIP aerial photography of Garfield County

Natural Gas Fields and Oil Shale Deposits

The Piceance Basin is an energy powerhouse. Note all of the drilling activity along the highway after we crest Webster Hill (Figures 11 and 12). This area of Colorado has been an important “tight gas” play since the 1970s. The reservoirs are fluvial sandstone bodies in the

Mesaverde Group. Recently, high natural-gas prices and new production technologies have led to a resurgence in drilling in the valley. A surge in population in this formerly rural valley has increased the level of conflict between land owners and energy companies.

Figure 12. Natural gas drilling in the Piceance Basin at the base and the top of the Roan Cliffs. Note the prominent cliff of oil shale (Parachute Creek Member of the Green River Formation) in the background and the reddish-pink slopes (Wasatch Formation) in the middleground. Photo by Chris Carroll, CGS.

The future of energy production in the basin is represented by the oil shale deposits of the Green River Formation. Approximately 300 million barrels of recoverable petroleum is contained in the Roan Pleateau in Colorado, equal to 48% of Middle Eastern reserves. However, the petroleum occurs as kerogen, a waxy substance that is difficult to extract and process. Previous efforts entailed a retorting process (i.e., large ovens) that required large amounts of energy and water and resulted in vast piles of waste rock.

A current effort, led by Royal Dutch/ Shell, involves heating the shale in situ with underground electric heaters and then extracting the liquefied kerogen using traditional oil-drilling and recovery techniques (Figure 13). It remains to be seen whether this method will prove to be economically viable.

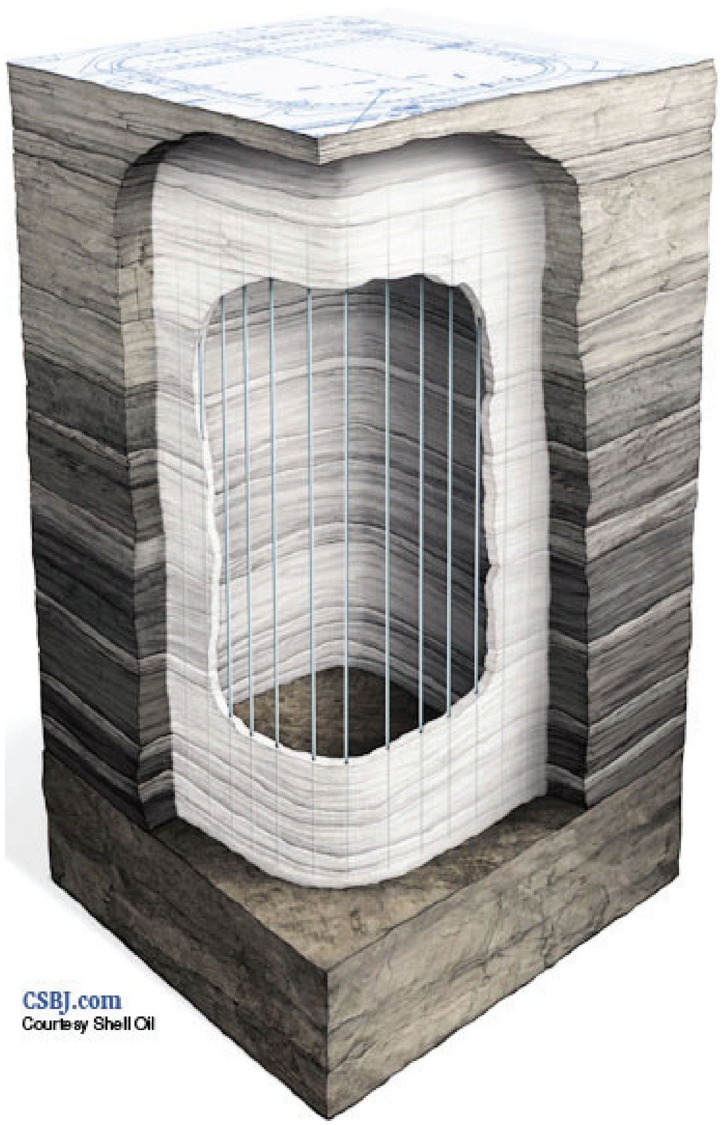

Figure 13. Oil shale production model proposed by Shell Exploration and Production Company. The method involved drilling a ring of boreholes that house heating elements, heating the shale, and extracting the liquid kerogen from a central production well.

Rulison Nuclear Blast Site

A high valley on the flanks of Battlement Mesa to the south (left) of the sleepy crossroad of Rulison was the site of an unusual experiment as part of the federal Plowshare Program, which was designed to develop peaceful uses for nuclear energy. On September 10, 1969, the U.S. Atomic Energy Commission detonated a 43-kiloton nuclear device, at a depth of 8,400 feet within the Williams Fork Formation of the Mesaverde Group. The objective was to release commercially marketable natural gas from tight (low permeability) fluvial sandstone strata.

By design, the underground blast would create a 160-ft-diameter cavity of melted and vaporized rock, the roof of which would collapse to form a 370-ft-high chimney. Nearby rock, to a horizontal distance of 740 ft, would be crushed and fractured, freeing and creating passageways for natural gas migration (Figure 14).

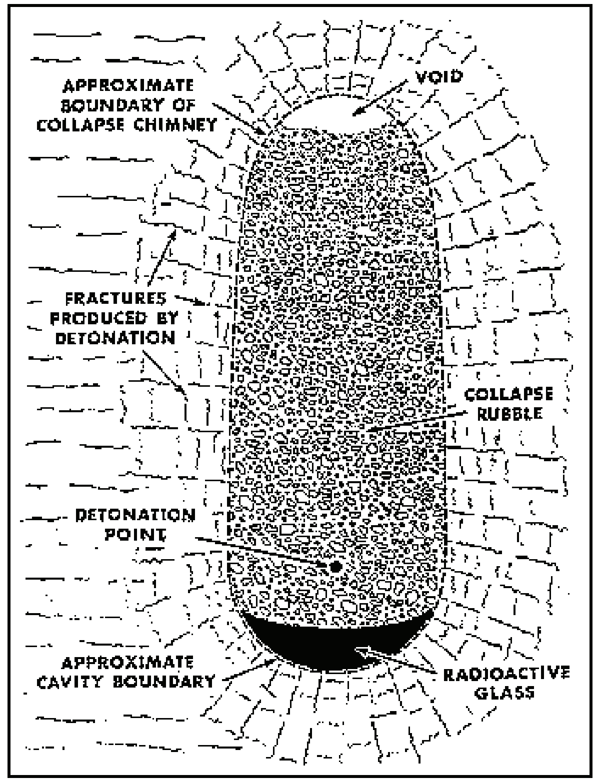

Figure 14. Nuclear device used for the Rulison experiment (USDOE), and model of the blast cavity (www.elmada.com).

The blast produced an earthquake of magnitude 5.3 (Kirkham and Rogers, 2000). No radiation was released at the ground surface at the time. Four natural-gas flaring events were conducted in 1970 and 1971. Approximately 455 mcf of natural gas was produced; however, the gas contained elevated levels of radioactivity and was not acceptable for commercial use. Today, two protection areas that limit the drilling of conventional gas wells at 3.0 and 0.5 miles around surface ground zero are maintained by the Colorado Oil and Gas Conservation Commission (USDOE Legacy Management, 2007).

DEBEQUE CANYON

At the town of DeBeque, we will begin passing out of the Piceance Basin and through progressively older strata along its gently dipping western limb. We will encounter once again the Upper Cretaceous sedimentary section seen earlier in the Grand Hogback. For the next 22 miles we will follow the Colorado River as it flows through DeBeque Canyon, which has been incised into resistant sandstones of the Upper Cretaceous Mesaverde Group. Watch for seams of coal between the sandstone bodies. The Piceance Basin is an important source of bituminous, low-sulphur coal.

Purple Earthflow Landslide

Near the mouth of the canyon, to the south (left) on the cliffs above I-70, notice a tongue of purplish clay that appears to be cascading down the hillslope (Figure 15). This is a small earthflow that formed within the lowermost interval of the Wasatch Formation, atop a resistant Mesaverde sandstone ledge. The strata dip very gently toward the highway. Ground water from the extensive uplands to the south has migrated to the canyon's edge to form seeps. At this spot, the clay layer has become charged with water and has flowed plastically down the hill.

Figure 15. Oblique air photo, looking to the south, of a distinctive, purplish earthflow (in gulley at center of photo) near the mouth of DeBeque Canyon. I-70 is just out of view at bottom of photo.

Mesaverde Group Lithofacies and Rockfall Hazards

The Mesaverde Group consists of shoreface, tidal, and fluvial floodplain deposits. It forms an eastward-thinning wedge that extends from central Utah to Central Colorado and intertongues with the marine Mancos and Lewis Shales, and is much thicker here than at the Grand Hogback we passed through earlier. In DeBeque Canyon, the canyon walls display amalgamated, laterally extensive sandstone-channel facies with minor coal and shale interbeds. This same interval serves as tight-sand reservoir rock in the Piceance Basin.

The combination of steep canyon walls, large sandstone blocks, and soft fine-grained interbeds has resulted in dangerous rockfall conditions that have affected the highway for many decades (Figure 16). Several large rockfalls have occurred near the canyon mouth. Elsewhere along the cliffs, look for detached, bus-sized pillars of sandstone balanced precariously on wedges of failed shale and thin-bedded sandstone.

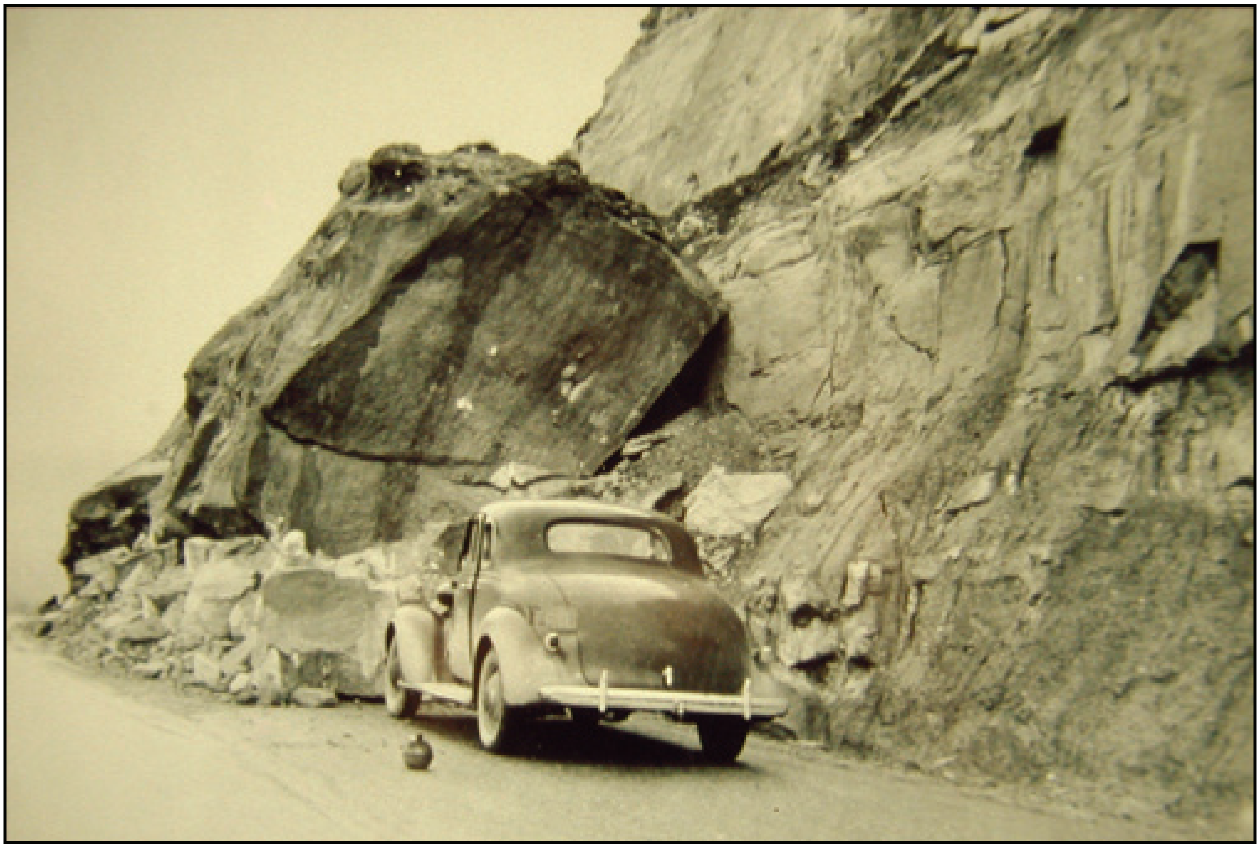

Figure 16. Large rockfalls have been a long-term hazard in DeBeque Canyon. Photo courtesy of Colorado Department of Transportation.

DeBeque Canyon Landslide

At milepost 51 of I-70 the south wall of the canyon has failed and a complex rockslide/ landslide has formed (Figure 17). This is the final destination for the DeBeque landslide field trip, and more detailed information about the slide is in that trip-specific guidebook

The DeBeque landslide failed as a massive rockslide at the turn of the last century. The precise date is unknown, but a historic photograph taken in 1910 from the canyon rim showed relatively fresh slide material in the river. This particular rockslide pushed enough material into the river to partially block and divert its course. On the opposite bank was a railroad siding and the old work camp of Tunnel. Reportedly the diverted river washed out a portion of the railroad tracks, as well as a peach orchard and some near-river structures.

Figure 17. Air photo of the DeBeque Canyon landslide, looking to the west. Note rubble zone and headwall fissure that has detached a large block from the canyon rim. This block continues to creep towards the highway and river. Photo by Jonathan White, CGS.

In 1927 the first road was constructed over the toe of the landslide along the south side of the river. This road, Highway 6, was widened in 1958 and significant cuts were excavated into the landslide toe. The landslide reactivated as a rotational failure and heaved the road 24 vertical feet. In 1984, I-70 replaced old Highway 6 and nuisance-type movements were continuously noted by highway department maintenance workers.

In April 1998, another significant rotational reactivation of the landslide occurred that pushed the interstate laterally about 10 ft and heaved it about 14 ft. The landslide continues to move today. Of most concern is the large fissured upper block that is creeping away from the headwall at the canyon rim, and the associated potential for another catastrophic rockslide.

Rockfall and landslide movements have exposed numerous sandstone blocks within the rubble zone of the DeBeque Canyon landslide. Occasionally, these blocks contain several different types of leaf and wood imprints upon their former bottom surfaces, such as palmetto fronds, and dinosaur and reptile tracks including those of hadrosaurs (duck-billed dinosaurs), ceratopsians (horned dinosaurs), iguanodons, and crocodiles. In this manner, landslides may serve as rich hunting grounds for paleontologists (Figure 18), especially in areas where basal bedding exposures are otherwise limited in cliffy terrain.

Figure 18. Dinosaur track imprints exposed in sandstone blocks within the rubble zone of the DeBeque Canyon landslide. Photos by David Noe, CGS.

Cameo Landslide

At Cameo we continue to descend stratigraphically and enter the tidally influenced facies of the Mesaverde Group. This interval contains larger proportions of shale and coal, and the terrain becomes less cliffy. In the valley to the north (right) of the Public Service Company power plant is the Cameo Coal Mine. Notice the large area of hummocky terrain below the high cliffs on Mt. Lincoln, immediately to the left of the mine (Figure 19).

This is the Cameo landslide, a large feature that covers over 1,000 acres. The steep headwall exposes thick fluvial sandstones, whereas the slip plane occurs within the shale-rich, thin-bedded section below. The toe of the landslide spills over another cliff (the Cameo shoreface sandstone) and onto the valley floor. In the spring of 1950, a landsliding event catastrophically blocked a tunnel that carried the Highline Canal, threatening the valuable peach crop in the Grand Valley, and interrupted railroad service. In an extraordinary effort, 2 miles of new tunnel were dug in 19 days, and the peach crop was saved (Lohman and Donnell, 1959).

Figure 19. Air photo of the Cameo landslide, looking to the southwest. Landslide movement is to the left, away from the Mt. Lincoln headwall and toward I-70 and the Colorado River. Note the water canal winding through tunnels at the landslide toe.

PALISADE AND GRAND JUNCTION AREA

Geologic Setting of the Grand Valley

After passing through a narrow water gap formed by resistant Mesaverde shoreface sandstones, the topography opens up significantly and we enter the Grand Valley. (The name stems from the former name of the Colorado River: Grand River.) Several agricultural towns occupy the valley floor. Palisade lies directly beneath the Book Cliffs, an impressive wall of rock that stretches across the northern skyline and into Utah. Beyond, Grand Junction is located at the confluence of two major rivers, the Colorado and the Gunnison (Figure 20).

The main valley, as well as the lower cliffs of the Book Cliffs is comprised of the Late Cretaceous Mancos Shale, a marine shale that formed in the epicontinental Western Interior Seaway. At the top of these cliffs we can see individual shoreface sandstone beds that form the basal deposits of the Meseverde Group. A striking example of this shale-to-sandstone succession is seen at Mt. Garfield (title page photo).

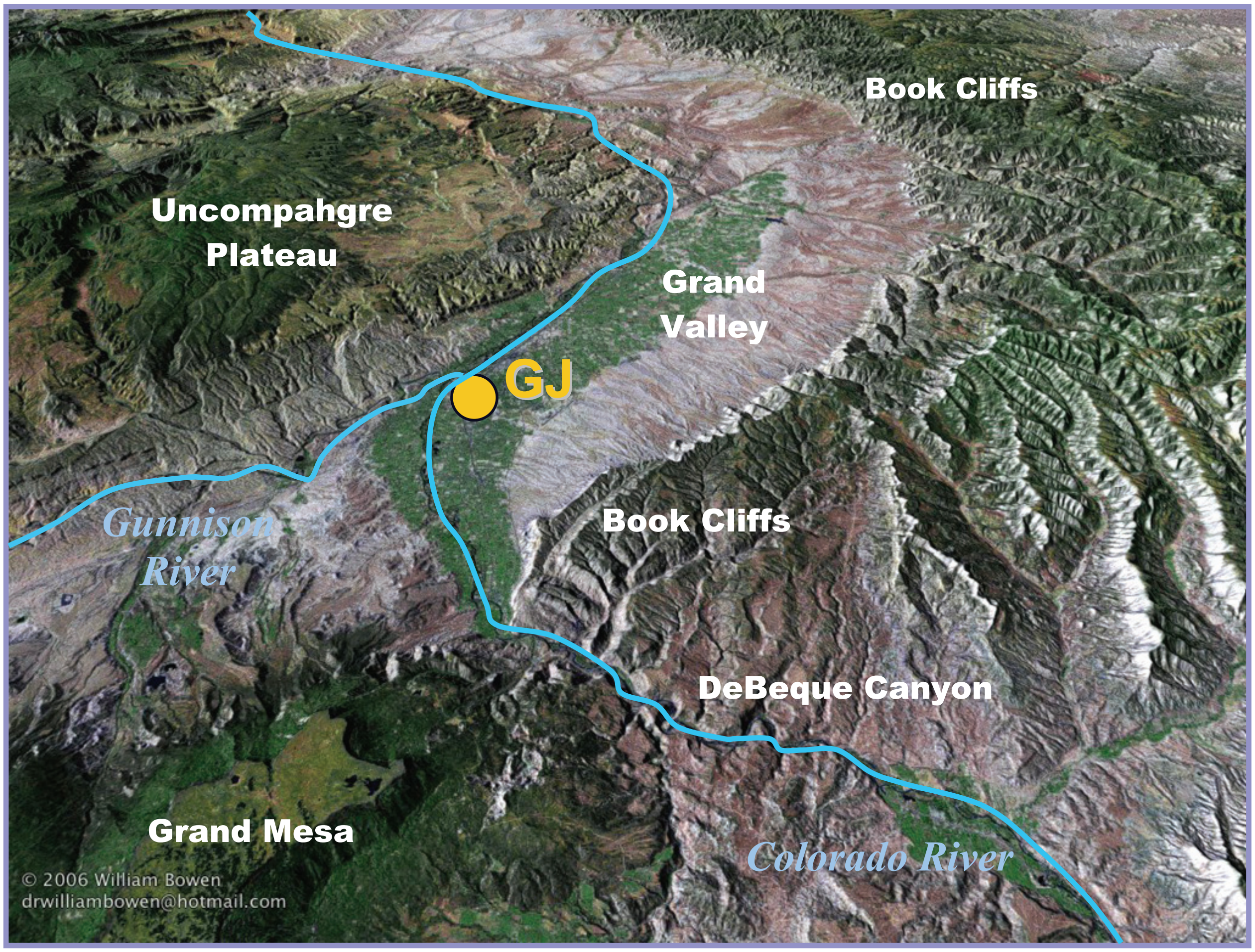

Figure 20. Draped DEM image showing the main topographic features surrounding the Grand Valley and Grand Junction (GJ), looking toward the northwest. Image from California Geographical Survey, created and copyrighted by William Bowen and used by permission.

To the southeast (left) of the valley is the mighty rampart of Grand Mesa, which is purportedly the world's largest (380,000 acres) and highest (10,500 ft) flat-topped mountain. This was once a river valley that filled with basaltic lava during the Miocene period, about 10 mya. The topography has since become inverted due to the erosional resistance of the lava flows. Glaciation and massive landsliding have whittled away at the sides of this high mesa since Pleistocene time.

The southwestern skyline beyond Grand Junction is formed by the Uncompahgre Plateau, an elongate block of tilted Precambrian basement rock that is veneered by Mesozoic sedimentary formations. This basement block was a prominent mountain range during the Pennsylvanian orogeny that formed the Ancestral Rocky Mountains. Called Uncompahgria, it was the source of coarse synorogenic sediments of the Maroon and Cutler formations. The block was worn away and buried by the close of the Permian, and was uplifted anew during the Laramide orgeny.

At the north (right) end of the Uncompahgre Plateau, a steep monocline exposes pink and white cliffs of Triassic-Jurassic Wingate Sandstone and red shale of the Triassic Chinle Formation that are draped and folded across a basement fault. Dark-reddish-gray Precambrian gneiss and granite from the plateau's core are exposed at the base of deeply scalloped canyons in the monocline face. This area, Colorado National Monument, is a scenic tourist destination.

The Colorado and Gunnison River valleys contain numerous terrace-capping deposits of gravels derived from Pleistocene glacial outwash. These terraces (e.g., Orchard Mesa) provided fertile soil for agriculture, particularly orchards. Today, vineyards and wineries are becoming more common in the valley. The source of water includes surface water from the rivers, diverted and carried by extensive irrigation canals, and deep water wells that penetrate the thick Mancos Shale aquitard. These wells were originally artesian, but most of them now require pumping.

* * * * *

This marks the end of this "corridor" field trip guidebook. At points between DeBeque and Palisade, several field trips associated with the First North American Landslide Conference will branch out and proceed along different routes to their destinations.

ACKNOWLEDGEMENTS

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REFERENCES

Chronic, H., and Williams, F., 2002, Roadside geology of Colorado, second edition: Missoula, MT, Mountain Press Publishing Co., 399 p.

Kirkham, R.M., Streufert, R.K., and Cappa, J.A., 1997, Geologic map of the Glenwood Springs 7.5 minute quadrangle, Garfield County, Colorado: Colorado Geological Survey Map Series MS-31, scale 1:24,000.

Kirkham, R.M., Parise, M., and Cannon, S.H.., 2000, Geology of the 1994 South Canyon fire area, and a geomorphic analysis of the September 1, 1994 debris flows, south flank of Storm King Mountain, Glenwood Springs, Colorado: Colorado Geological Survey Special Publication 46, 39 p.

Kirkham, R.M. and Rogers, W.P., 2000, Colorado Earthquake Information 1867-1996: Colorado Geological Survey Bulletin 52, CD-ROM

Kirkham, R.M., and Matthews, V., 2000, Guide to the geology of the Glenwood Springs area, Garfield County, Colorado: Colorado Geological Survey Earth Science Week Field Trip, October 13, 2000, 41 p. (http://geosurvey.state.co.us/Portals/0/GlenFieldTripGuidebook_web.pdf)

Lidke, D.J., Hudson, M.R., Scott, R.B., Shroba, R.R., Kunk, M.J., Perry, W.J., Jr., Kirkham, R.M., Budahn, J.R., Streufert, R.K., Stanley, J.O., and Widmann, B.L., 2002, Eagle collapse center: Interpretation of evidence for late Cenozoic evaporite-related deformation in the Eagle River basin, Colorado, in Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America Special Paper 366, p. 101-120.

Lohman, S.W., and Donnell, J.R., 1959, Road log, U.S. Highways 6 and 24, Rifle to Grand Junction, Colorado, in Haun, J.D., and Weimer, R.J., eds., Symposium on Cretaceous Rocks of Colorado and adjacent areas: Denver, Rocky Mountain Association of Geologists Eleventh Field Conference, p. 180-182.

Noe, D.C., White, J.L., and Zabel, G., 2007, Drive-by guidebook – Geology and geologic hazards along the I-70 corridor, Vail to Glenwood Springs, Colorado, in Noe, D.C., and Coe, J.A., eds., Field trip guidebooks, 1st North American Landslide Conference, Vail, CO, June 3-10, 2007: Association of Environmental and Engineering Geologists Special Publication 21 and Colorado Geological Survey Special Publication 56, CD-ROM.

Rushworth, P., Haefner, B.D., Hynes, J.L., and Streufert, R.K., 1989, Reconaissance study of coal fires in inactive Colorado Coal Mines: Colorado Geological Survey Information series 26, 60 p.

Shroba, R.R., and Scott, R.B., 1997, Revised preliminary geologic map of the Rifle quadrangle, Garfield County, Colorado: US Geological Survey Open-File Report 97-852, scale 1:24,000.

Tweto, O., 1983, Geologic cross sections across Colorado: U.S. Geological Survey. (Available as Colorado Geological Survey Miscellaneous Investigations MI-63.)

USDOE Office of Legacy Management, 2006, Rifle, Colorado, processing sites and disposal site: Fact Sheet, U.S. Department of Energy Office of Legacy Management, 4 p.

USDOE Office of Legacy Management, 2007, Rulison, Colorado site: Fact Sheet, U.S. Department of Energy Office of Legacy Management, 4 p.

White, J.L., Cannon, S.H., Kirkham, R.M., Lidke, D.J., White, S., and Gartner, J.E., 2003, Geologic hazards of west-central Colorado: Field Trip Guidebook, Association of Engineering Geologists 46th Annual Meeting, Vail, Colorado, September 30, 2003, 43 p.

Widmann, B.L., Kirkham, R.M., Morgan, M.L., and Rogers, W.P., with contributions by Crone, A.J., Personius, S.F., and Kelson, K.I., and GIS and Web design by Morgan, K.S., Pattyn, G.R., and Phillips, R.C., 2002, Colorado Late Cenozoic Fault and Fold Database and Internet Map Server: Colorado Geological Survey Information Series 60a. (http://geosurvey.state.co.us/pubs/ceno/)

GLENWOOD CANYON CORRIDOR

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OVERVIEW

This guidebook summarizes the landslide hazards, engineering constraints and mitigation alternatives evaluated within the reach of the I-70 Corridor from Vail to Glenwood Springs, Colorado. The emphasis of the field trip will be on two areas that have presented significant challenges to transportation improvements. These areas are Dowd Canyon located near Vail and Glenwood Canyon located near Glenwood Springs. The corridor represents highly complex and varied ground conditions with the potential to pose hazards during construction and operation of the transportation system. The facility is influenced by numerous faults, collapsible soil, landslides, rockfalls, debris flows and avalanches. Many of these naturally occurring hazards have affected previous corridor improvement projects and continue to affect the mobility of the existing transportation system.

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Vail Valley to Dowd Canyon (drive by)	Geologic setting; avalanche chutes, rock fall	Rick Andrew
Whiskey Creek Landslide – Stop 1	Landslide complex, mitigation alternatives	Rick Andrew and Ben Arndt
Dowd Canyon to Glenwood Canyon (drive by)	Geologic setting; Landslide mitigation, debris flows	Rick Andrew
Glenwood Canyon – Bair Ranch (Stop 2)	Debris flow; rock fall and the "gray layer"	Rick Andrew
Glenwood Canyon – Hanging Lake (Stop 3)	Rock fall mitigation, rockslide dam, tunnel construction	Rick Andrew, Ralph Trapani and Ben Arndt
Glenwood Canyon – Grizzly Creek (Stop 4)	Geologic setting; rock fall	Rick Andrew

TRIP ROUTE DESCRIPTION AND MAPS

The trip route will take us from the Vail Valley following Gore Creek in Dowd Canyon, pause at the Whiskey Creek Landslide Complex, continue through the Eagle Valley and descend through the White River Uplift in Glenwood Canyon. While in Glenwood Canyon, we will stop in several locations to review the improvements to Interstate 70 and the challenges of constructing in a difficult geologic setting. We will mostly follow highways I-70 and US-6 (Fig. 1).

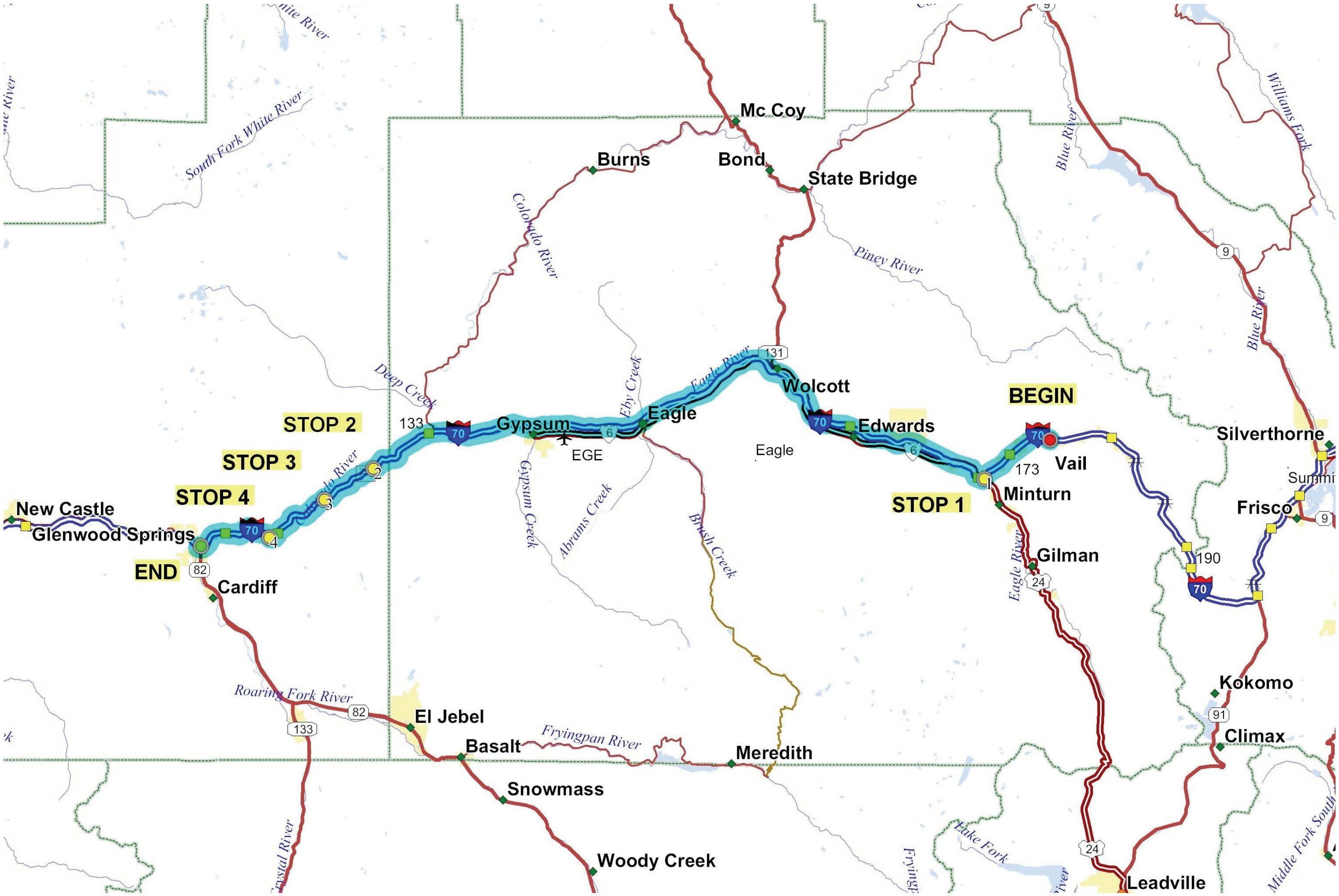

Figure 1. Index map showing field trip route.

Geologic Setting

A wide range of geologic conditions are represented and exposed along the corridor due to the vast amount of time represented in the multiple rock formations. The geologic time reflected along the Corridor ranges from recent river, debris and mudflow deposits to Precambrian rocks between 1 and 2 billion years old. But much of the mountain and rugged terrain associated with the Rocky Mountains began during a mountain formation ~72 million years ago and lasted ~7 million years. Numerous faults and folds are present along the Corridor depicting the extensive tectonic episodes.

The multiple sedimentary units represented along the corridor derive from the erosion of a mountain range that pre-dates the present Rocky Mountains, and numerous inland sea advances and retreats. The formations that remain from the inland sea sequences include; shale deposits representing shallow sea environments, sandstone and quartzite deposits representing beach environments, and limestone deposits representing offshore coral reefs.

The present topography represents 20,000 years of erosion. With the notable exception of widespread glaciers, the processes that impose hazards to our activities today have been active during this 20,000-year span.

Most of the present configuration of valleys, mountains and canyons seen along the Corridor were shaped either directly or indirectly through alpine glaciation. Periods of glaciation are difficult to identify prior to 100,000 years age (pre-Bull Lake) due to the continual erosion of the loose sediments. Glacial deposits ranging from Bull Lake to more recent Pinedale (10,000 years) have been mapped and dated. Cirques and the U-shaped valleys are some of the remaining features associated with the episodes of glaciation.

Geologic Hazards

The varied and complex geology and geomorphic processes present along the Corridor have led to the development of several zones of instability and marginal subsurface material. Although a natural process, these features can pose a risk to humans either directly by an encounter with the hazard or indirectly through effect of the hazard on roadways, railways or buildings. Conditions that may adversely affect the humans and/or the proposed improvements in the corridor include: faults, adverse rock structure, poor rock quality, and existing geologic hazards (debris/mudflows, rock fall, landslides, avalanche, collapsible soils and rapid subsidence).

Mitigation on Previous Projects

The transportation facility along the I-70 Mountain Corridor has undergone numerous modifications through the years. Many of the early projects did little or nothing to mitigate existing geologic hazards. In fact, through the design of many of these early projects, some naturally occurring hazards were exposed. More recent projects have incorporated design features that have mitigated the geologic hazards. Projects such as the I-70 Glenwood Canyon Project, the I-70 Vail Pass projects and the US 40 Berthoud Pass projects have utilized excavation and landscaping techniques to minimize soil loss and reclaim existing erosion problems. In addition, the roadway geometry on these projects was designed to minimize slope excavation and follow much of the natural topography.

During construction of the Glenwood Canyon Project excavations utilized rock-sculpting techniques. Rock Sculpting is the blasting of rock by using the existing rock structure to control over-break and blast damage, while creating a more natural appearing rock cut. This technique, originally developed in the canyon, has been used in other projects in Colorado and throughout the western United States.

Other projects have been constructed to remediate erosion problems and geologic hazards that were inherent in the original design of I-70. The Straight Creek erosion control projects along the west approach to the Eisenhower-Johnson Memorial Tunnel have been constructed to mitigate the soil loss originating from the over-steepened cuts slope. Rockfall mitigation projects and scaling programs have been implemented at several locations including Dowd Canyon and the Georgetown Incline. These mitigation measures installed along the Georgetown Incline specifically address rockfall originating from the cut slope and area of disturbance from the Interstate construction.

Table 2. Mileage from Start of Field Trip at Vail Marriott Mountain Resort to the Whiskey Creek Landslide Complex (Stop 1).

Mileage	Description
0.0 (from start) 0.0 (cumulative)	Leave Vail Marriot Resort. From West Lions Head Circle, turn right (east) onto the South Frontage Road and drive to the main Vail traffic circle. From traffic circle enter I-70. Begin Vail Valley/Dowd Canyon (drive by).
5.8 (from start) 5.8 (from start)	Whiskey Creek Landslide. This is Stop 1. There will be a short but relatively steep hike to the landslide area and a scenic bench above the valley.

VAIL VALLEY/DOWD CANYON (DRIVE BY)

The Gore fault bounds the west side of the Gore Range and sets older metamorphic and granite against the younger Permian-Pennsylvanian sedimentary red beds. The Vail Valley and the east side of Vail Pass display U-shape slope walls characteristic of alpine glaciation.

Geologic Hazards

Several large, steep cuts were made in the Minturn Formation between the West Vail interchange and Dowd's Junction during construction of Interstate 70. The Minturn contains numerous joints and fractures and these have contributed to major rockfalls onto the highway. Fortunately, no fatalities or injuries have resulted, but the westbound lanes have been closed for hours on several occasions. Falls of individual rocks are a frequent occurrence, and the roadside ditch is too narrow to provide an adequate catchment area.

The rockfall that originates from the Minturn Formation is caused by the difference in erosion rates of the interbedded sandstone and shale layers. The less resistive shale layers erode, undermining the more resistive sandstone units. In addition, near vertical fractures in the sandstone allow the rock to release in small individual events and larger rockslides.

Some attempts have been made along the existing rock cuts to mitigate the hazard including constructing mid-slope benches, placing Type IV (Jersey) barrier and scaling. These methods have been partially successful, but rocks continue to reach the Interstate. All of the proposed alternatives will be affected by the existing rockfall hazards and will require mitigation measures.

STOP 1. WHISKEY CREEK LANDSLIDE

Three bedrock units are present in the study area: the Minturn Formation, the Maroon Formation and the Eagle Valley Formation. Of these, only the Minturn and Eagle Valley have the potential to cause problems for the proposed alignment changes. Construction of Interstate 70 required substantial cuts in the Minturn just west of the West Vail interchange and rockfalls have occurred from these. A few small cuts were made in the Eagle Valley Formation near Avon but have not caused any problems. The Maroon caps the hills on the north side of the Eagle River valley but is not exposed at low enough elevations to be encountered by any of the construction alternates presently proposed.

Younger, unconsolidated deposits present along the project corridor consist of terraces along the stream valleys, colluvial deposits, alluvial fans and landslide deposits along the base of the bluffs lining the valleys, and glacial moraine and drift deposits at either end of the canyon. Most of these are encountered along the existing highway, but with the exception of the landslides and possible exception of the alluvial fans, none constitute geologic hazards.

Minturn Formation

The Minturn Formation is over a mile thick in this area and consists of a sequence of rocks described as clastic, or made up of fragments of pre-existing rock. These consist of grit, sandstone, conglomerate, shale and siltstone, interbedded with occasional layers of limestone and dolomite. Grit is defined in United States Geological Survey (USGS) Professional Paper P-0956 as a coarse grained rock, friable to firmly cemented and frequently containing pebbles or cobbles, and it is the predominant rock type of the formation. The clastic beds are lenticular and change rapidly in character over short distances, in contrast to the limestone and dolomite beds, which are relatively persistent. Color is primarily gray with occasional tints of green, yellow and pink.

Eagle Valley Formation

The Eagle Valley Formation consists of interbedded light to dark gray or black shale and tan to greenish gray siltstone with occasional thick beds of whitish pure gypsum. The formation crops out in the bluffs on both sides of the Eagle River valley and is over 1000 feet thick.

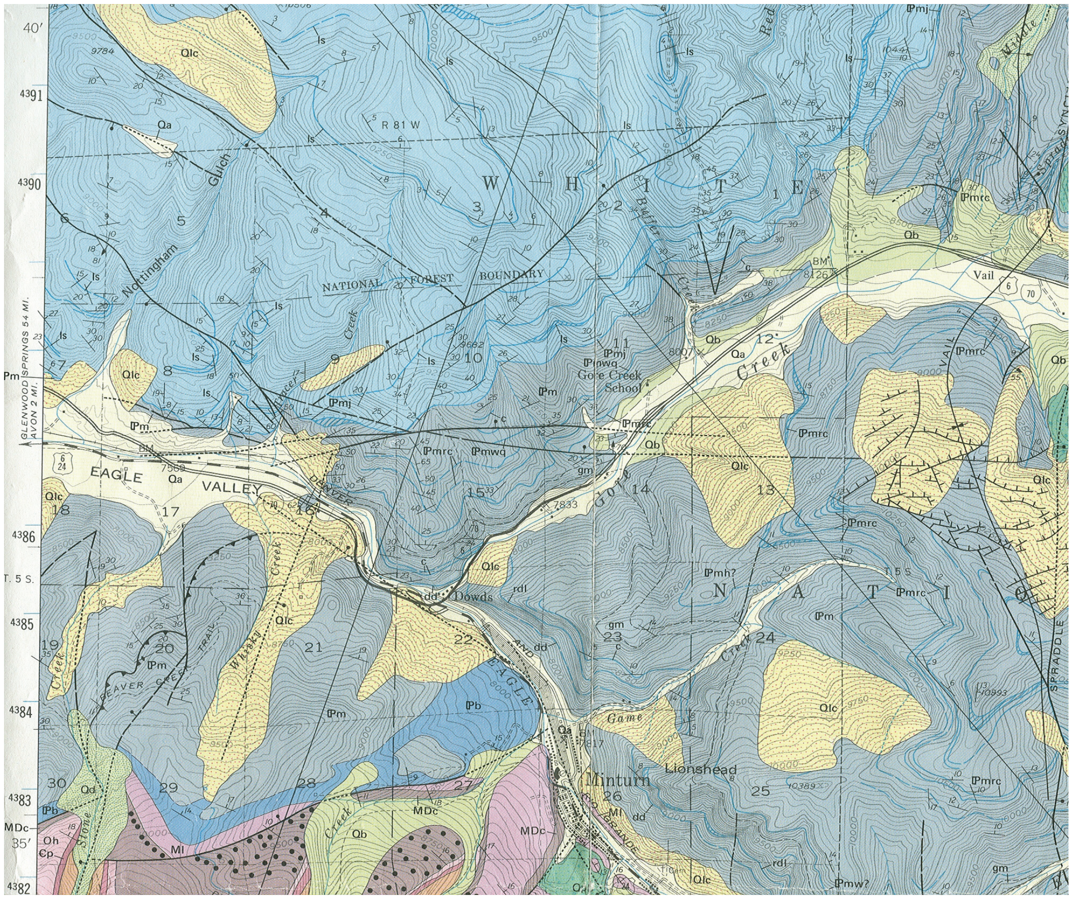

Figure 2. Geologic map of the Dowd Canyon Region.

Geologic Hazards

The overall slide complex, which includes Whiskey Creek, Dowd 1 and Dowd 2 as well as the Meadow Mountain slide, is geographically large and geologically very complex. The Meadow Mountain slide is located just southeast of the study area and several episodes of large-scale movements have been documented at this slide over the past 30 years. A relationship between Meadow Mountain and Dowd 1 & 2 slides was considered and dismissed based on numerous factors. The slope steepness and aspect, geology and hydro-geological environment of Meadow Mountain seem to be considerably different. While better documented, the episodes of movement concurrent with episodes of movement at the subject slides, is likely coincidental and related to high groundwater events, which have a profound impact on both of these areas.

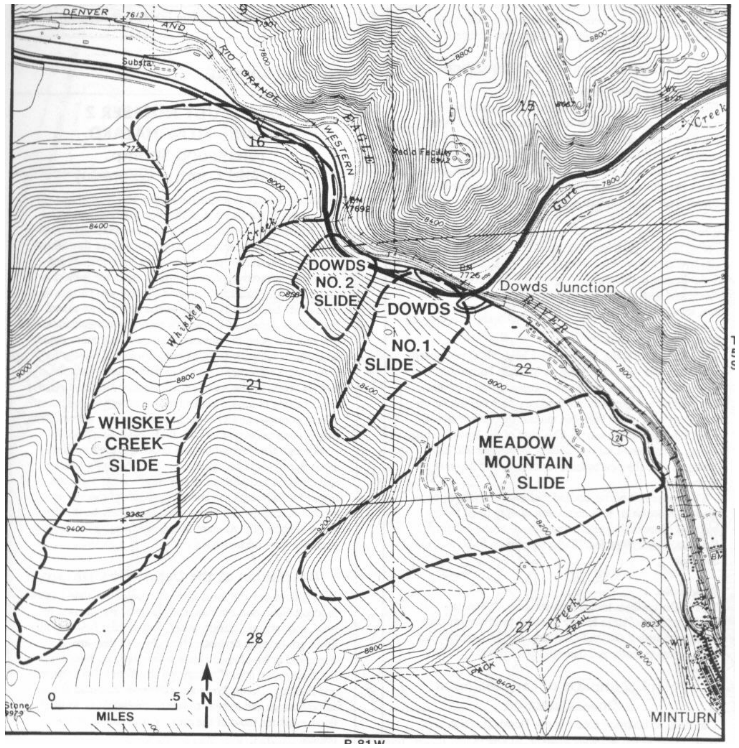

Figure 3. Locations of major landslide features near Dowd Junction

There are a total of three historic landslides within view of Stop 1: Dowd 1, Dowd 2 and Whiskey Creek. The Dowd slide area has been mapped as both a single slide and as two adjacent slides. There are numerous documented landslide features within ten miles of the confluence of Gore Creek and the Eagle River, where the Whiskey Creek slide complex is located. North of the confluence in the Gore Creek Valley toward the Town of Vail, there are several active slides on both the north and south sides of this glacial valley. To the east, US 24 traverses the toe of the Meadow Mountain slide. This slide has impacted the highway several times over the past 30 years. Farther up the Eagle River valley, the lateral traverse made by the highway up the side of Battle Mountain crosses three slide areas, which are active and have required mitigation by the Colorado Department of Transportation (CDOT).

Dowd 1 and 2

In short, there have been at least three events in the past 40 years that have severely impacted transportation through the corridor. A significant effort has been expended on studies and speculation of the probability and potential impacts of a large landslide event occurring at either the Dowd site or the adjacent Meadow Mountain site.

Figure 4. Looking south at Dowd 1 landslide.

Several events occurred in 1983, which lead to the identification of two slides in the area described in this report as the Dowd slide complex. Sequential years of above average precipitation in the early 1980's resulted in several slope failures which impacted the road in the cut slope above the interstate and in the fill slope between the interstate and US 6. In addition several issues related to the interstate bridge and adjacent slopes were possibly attributed to the slide in the late 1960's and early 1970's.

Numerous reports by CDOT document the history of problems at the south abutment of the bridge over the Eagle River at the junction of I-70 and US 24. Movement of the pile-founded abutment was documented over several years in the late 1960's and early 1970's. Aerial photography was found that was acquired during the construction of the fill that supports the approach roadway and abutment backfill. The photos show cut material being end dumped and dozed over the slope to form the fill. The sloping subgrade did not appear to be grubbed or benched. The backfill soil properties from the sample indicate low quality fill material.

Figure 5. Current I-70 interchange at Dowd Junction.

Later photos also showed several areas of patched pavement in the approach fill, which were identified as being caused by artesian groundwater flow through the pavement. There is currently an intermittent spring exiting the embankment between the westbound off-ramp and the interstate. The horizontal drains above the interstate at this location are frequently flowing. The reported movement can be explained by these geological factors or by a structural explanation offered by a group of Bureau of Public Roads engineers in the early 1970's. The bridge problems do not appear to be caused by movement of the mega-slide.

A slope failure occurred during, or shortly after, construction of the interstate just west of the gore area of the eastbound off-ramp at milepost 170.8. The failure occurred in a cut slope above the interstate. The failed area measured approximately 70 feet uphill and 300 feet parallel to the road in plan view. A partially backfilled rock buttress was installed at the toe of the slope as a solution. The failure appears to have been shallow and was probably water-related to some extent.

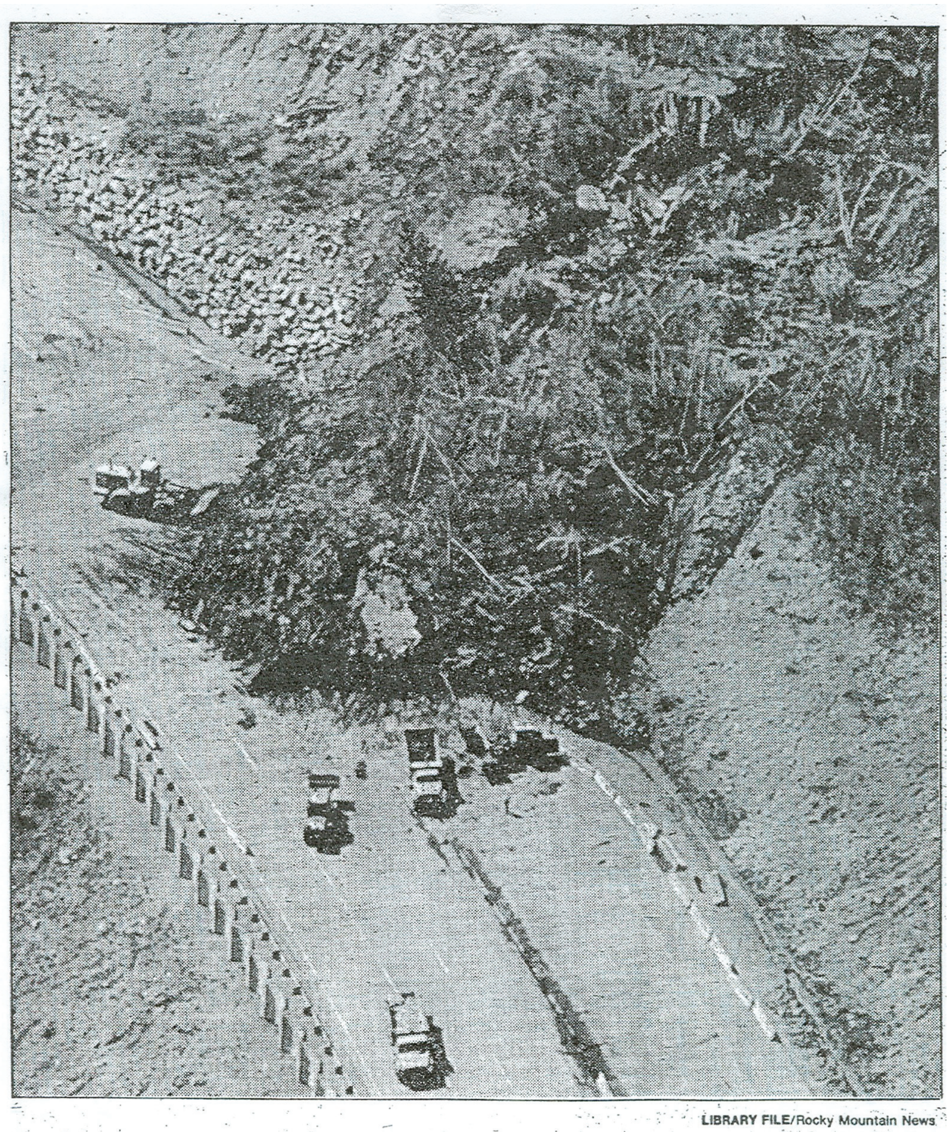

Figure 6. Debris flow on I-70 near eastbound exit 171 at Minturn (from library file, Rocky Mountain News, Denver, 1983).

A second failure occurred in May of 1983 just west of the rock-buttressed area at milepost 170.6. This cut slope failure is shown in Figure 6, which is a Rocky Mountain News photo showing what appears to be fairly wet conditions. The failed area was 100 feet along the highway by 200 feet above the highway in plan view. The solution was to excavate the unstable material. In-place sandstone and shale bedrock ridges are visible in the bottom of the excavation indicating that the failure was shallow and slid on the bedrock.

Figure 7. Clean up along US 6 after 1983 slope failure.

A fill slope failure occurred in late June of 1983 at milepost 170.7, just west of the westbound on-ramp. The failed area was approximately 300 feet laterally and extended from the center of the westbound lanes of I-70 to the toe of the fill slope just above US 6. Drilling revealed high water pressure within the slope adjacent to the failed area. It is possible that the placement of fill against the natural, wet slope without adequate drainage provisions caused this failure to occur during high precipitation years. Horizontal drains were installed at the base of the slope and are still functioning as of this writing.

Figure 8. Installation of horizontal drains near Minturn exit 171 eastbound above I-70

It is significant that combinations of slope design and construction, and adverse ground water conditions can explain all of the documented problems over the years. No evidence was found of recent slope movements in the areas above what is influenced by the cut slopes. The short steep slopes in this area could be evidence of shallow surface failures but are more likely caused by very large 30 and 40-foot diameter boulders supporting locally steep slopes.

Some of the largest coniferous trees appear to be 50 to 150 years old and with few exceptions are not preferentially oriented in such a way that would indicate recent ground movements. Trunk bending and other abnormalities in the tree growth are more likely attributable to the high snow load seen in this area of the mountains at the 9,000 foot elevation as well as some soil creep and near surface soil slumps.

In addition to the localized slope failures, a much larger slope failure exists, which has occurred at some time in the Quaternary Period of the geological time scale. The field reconnaissance and aerial photography study suggested a possible mega-slide event at the Dowd 1 location, which involved displacement of a thick section of Minturn Formation bedrock to a new location to the north, which is down dip and toward the river channel. The upper part of the study area is a bowl-like feature bounded on the east, west and south by steep slopes and sandstone cliffs. It is possible that the displaced bedrock slab was detached from the steep sandstone cliffs when the mega-slide occurred. The northerly, lowest end of the displaced bedrock slab is near the present interstate location.

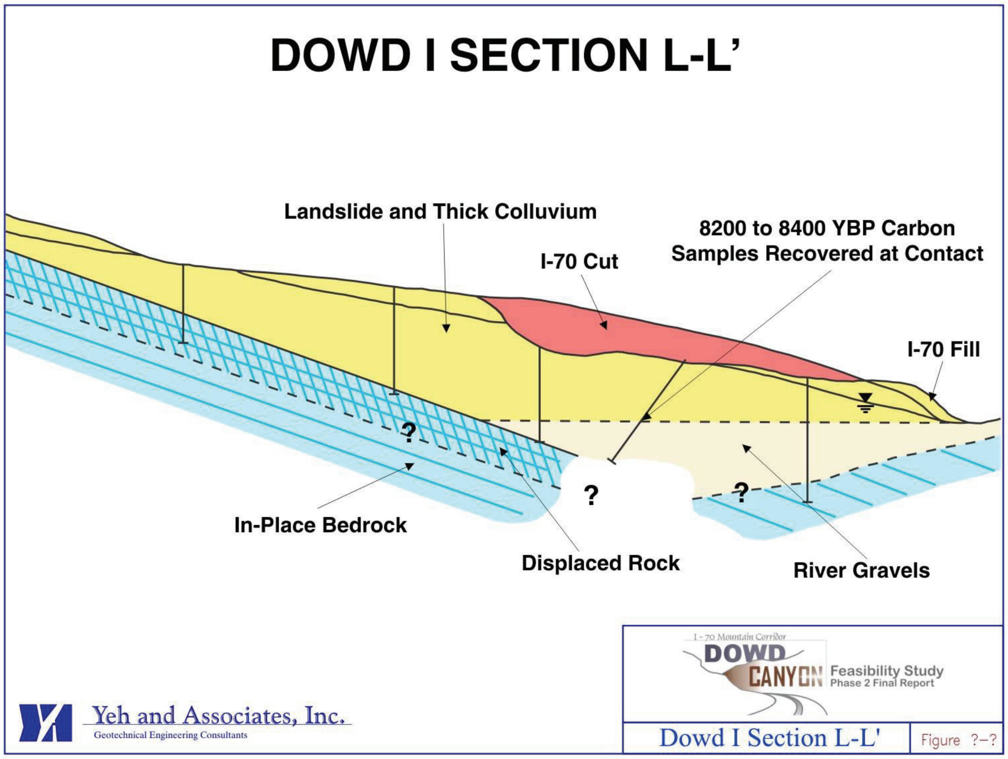

Figure 9. Cross section of Dowd 1 slide.

Test borings have revealed that river gravels are buttressed against the toe of the displaced slab or above the slab. Core samples from the displaced slab showed significant alteration of the rock and evidence of groundwater transport through the rock. The top of the displaced slab is overlain by approximately 40 feet of unconsolidated slide debris. Yeh was unable to penetrate below the displaced slab by drilling. This would take a deep, well-placed hole to accomplish. Other test holes also provided recovery of a clay sample from a slide plane, which was deposited on top of alluvial river gravels. The age of this event was radiocarbon dated at 8270 Years Before Present (YBP), during neoglaciation (10,000 to 7,500 YBP) when the climate cooled and warmed several times and the post-glacial landscape was being formed by extremely high volumes of runoff.

One possible explanation of these ancient events is that at some time before 8300 YBP the river or glacial retreat cut into the toe of the bedrock slope enough to trigger a bedrock landslide, which moved the displaced slab into the bottom of the river channel, which existed at that time. The slide's location at the confluence of the Eagle River and Gore Creek would make this a likely location for debris deposited during flood events in the Gore Creek Valley to push the Eagle River to the south and allow erosion at the toe of the slide area. The slide then released and pushed the river back to the north. Some time after this single event, or series of events, postglacial river gravels were deposited at the toe of the displaced bedrock slab. Around 8300 YBP some factor caused the overburden soils and surface vegetation to move downhill and be deposited onto the gravel terrace. This provided the clay sample from which the carbon was extracted for dating. This was most likely a major event and since no other evidence was found of any other higher slide planes in the drilling, it is presumed that this was the last major event at this location.

Whiskey Creek

The Whiskey Creek Slide, as shown in Figure 10, consists of an earth flow originating from the Minturn Formation and is by far the largest of the slides in the subject area, ranging up to two miles in length and about three-quarters of a mile across at the toe. It is several thousand years old and appears to be relatively stable with the exception of several minor cut slope failures, which have occurred since the interstate was built.

Figure 10. Looking southwest at Whiskey Creek Landslide.

A preliminary site investigation of the area included one boring into this slide and subsequent installation of an inclinometer casing. The boring and inclinometer extend through the slide material and into the river gravels below, at a depth of 158 feet, which is approximately 70 feet below the current interstate elevation. The top of a gravel terrace was reportedly encountered in past CDOT drilling near the parking lot for the condominiums.

The intent of the site investigation of the Whiskey Creek slide was to make general observation of the ground conditions and to evaluate any signs of movement in the geologically recent past based on the scarps, vegetation or other relevant signs. Several other studies have identified scarps and have shown strike and dip measurements on outcroppings or on remnant pieces of bedrock which may have been transported from their original positions. We were unable to confirm the existence of recent, deep seated scarps but noted the general ground conditions as hummocky with evidence of shallow, water related failures in the weak surface soils throughout the identified slide mass. Most likely, the outcroppings upon which the strikes and dips were taken are displaced bedrock pieces, which were moved by one of the latest events or exposed by subsequent erosion. The vegetation on the slope consists of conifer and deciduous trees, sage, willow, and grasses.

Intact bedrock is exposed in the US 6 road cut at approximate I-70 milepost 170.5. We also located near vertical beds on both sides of the current Eagle River channel directly to the north of the Whiskey Creek slide. We believe that these are in place and provide a lower reasonable boundary for the mega-slide event. The vertical bedding is likely related to a large structural discontinuity trending roughly due south, coincident with the primary axis of the Whiskey Creek Slide. This discontinuity may have influenced the location of the mega-slide event.

It may be logical to assume that the recurrence interval at the Whiskey Creek slide is similar to that of the Dowd slide area based on the likelihood that environmental conditions were conducive to slope failures during that period of history. Smaller failures in the cut and fill slopes can be expected to continue, unless mitigation measures are implemented.

Table 3. Mileage from Whiskey Creek (Stop 1) to Glenwood Canyon – Bair Ranch (Stop 2).

Mileage	Description
0.0 (from Stop 1) 5.8 (cumulative)	Leave the Whiskey Creek Landslide area. From Whiskey Creek follow Interstate 70 though the Eagle Valley.
12.2 (from Stop 1) 18.0 (cumulative)	Continue along I-70 passing the Wolcott Landslide.
36.2 (from Stop 1) 42.0 (cumulative)	Continue along I-70 passing the Dotsero volcano.
41.2 (from Stop 1) 47.0 (cumulative)	Glenwood Canyon – Bair Ranch. This is Stop 2.

EAGLE VALLEY (DRIVE BY)

Red sandstones of the Pennsylvanian-Permian period(s) characterize much of this domain. The rock is fractured with interbedded shale and sandstone layers. The more massive sandstone layers create many of the cliff forming slopes (Lidke, 1998). Due to the complex folding that occurred in the region, the bedding dips into the highway at some locations creating areas of potentially unstable slopes, while other areas are more stable due to favorable trends in the structure of the rock.

The Eagle Valley cuts through bedrock that consists of highly erodible, sparsely vegetated sedimentary rocks bounded by Eagle Valley Evaporites on either side. The Eagle

Valley Evaporites are composed primarily of halite, gypsum and anhydrite, and some potassium salt deposits. The town of Gypsum is so named for the rich deposits of gypsum located north of I-70. An active mine is located in this area and the rock is processed in town. Most of the gypsum mined from this site is used in the manufacturing of wallboard or sheet rock.

I-70 passes through a basalt lava flow (a remnant of Colorado's youngest volcano) near the Dotsero Interchange at milepost 136. As recently as 4200 years ago, this volcano was active, emitting mostly cinder, ash, and the small lobe of lava. The cinder cone is located a couple miles north of I-70 in the adjacent foothills. The volcano is currently being mined for its lightweight cinder for use in concrete blocks.

Geologic Hazards

The evaporative rock is prone to collapsible soils and debris flows hazards. Collapsible soils are present around Eagle (MP 147) and Gypsum (MP 140) (Robinson, 1975). Subsidence is very generalized and is not usually accompanied by differential movement that would affect structures. I-70 was constructed in the deposit zone of a series of debris flows located in this region, but construction did not affect the source areas. The Wolcott landslide complex is located on the south side of the highway at the east of this domain (MP 154-160) (Colton, 1975). Both overburden and blocks of sedimentary rock moving in a metastable state characterize this complex landslide.

Figure 11. Typical debris flow along I-70 in the Eagle Valley.

During the construction of I-70, large blocks of bedrock slid and arrested in a metastable state on the west side of the exit. The road was realigned because no reasonable mitigation could be constructed. More recently, a lobe east of the Wolcott exit was mitigated with tieback anchors. In this area the overburden was sliding on the bedrock surface that was dipping into the roadway, resulting in costly pavement repair to I-70 and Highway 6.

STOP 2. GLENWOOD CANYON – BAIR RANCH

This rest area is located in a wide portion of the canyon formed by a graben, which has brought less resistant shales of the Belden Formation (Pennsylvanian) down near the river level on the south side of the river. The Belden Formation is also exposed in hills to the north of the highway here. This area is susceptible to debris flows from the small intermittent drainages to the north of the highway.

A cliff formed by Leadville Limestone, underlain by Chaffee Group rocks consisting of Dyer Formation (dolomite) and Parting Formation (orthoquartzite) is visible from our stop. To the north of the Bair Ranch rest area, brown cliffs are visible approx. 65 feet above the road. These are formed by the Tie Gulch Member of the Lower Ordovician Manitou Formation. The Tie Gulch Member consists of a crystalline, somewhat siliceous, dolomite with minor limestone. Underlying beds consist of the Dead Horse Conglomerate Member of the Manitou Fm. In this area the Tie Gulch Member is about 65 ft. thick and the Dead Horse Member is about 100 ft. thick. Slopes below these cliffs are good collecting spots for Ordovician trilobites, brachiopods, and gastropods. The Dead Horse Conglomerate may also be a source of rockfall debris.

During construction of I-70 in the Bair Ranch area, bridge piers and abutments were driven to bedrock, or at least beyond the "gray layer" to refusal. The gray layer will be discussed further at the next stop. To the east of the rest area are several MSE walls which experienced significant settlement during construction. Construction activities had to be postponed for several months to allow this settlement to take place before the pre-cast panels were installed. Glenwood Canyon begins to get much more narrow from this point westward.

Table 4. Mileage from Glenwood Canyon – Bair Ranch (Stop 2) to Glenwood Canyon – Hanging Lake (Stop 3).

Mileage	Description
0.0 (from Stop 2) 47.0 (cumulative)	Leave the Bair Ranch Rest Area. Follow Interstate 70 through Glenwood Canyon.
3.8 (from Stop 2) 50.8 (cumulative)	Glenwood Canyon – Hanging Lake. This is Stop 3.

STOP 3. GLENWOOD CANYON – HANGING LAKE

There is evidence of a huge rockslide, which filled the canyon floor and dammed the Colorado River, just to the west of the Shoshone dam. Figure 12 shows the approximate location of this rockslide. The dam created by this failure caused a natural reservoir, resulting in lacustrine deposits of clay and silt, today referred to as the "Gray Layer." This layer extends upstream to the Dotsero area; the precise up valley extent is unknown. The Gray Layer is predominately dark gray to gray-black in color, and is 30 to 60 feet thick (Kirkham and Matthews, 2000). It is a compressible clay deposit that was often problematic during construction of I-70. Commonly within the deposits are reddish-brown laminations. Presumably, these red bands were the result of fine-grained sediment settling from single storm events.

Several steep, rugged tributaries upstream are located within the Maroon Formation red beds; after local rain events in the McCoy, Bond, State Bridge area, this sediment has been observed to turn the Colorado River a chocolate-red color through Glenwood Canyon in modern times. On several occasions during the construction of I-70 through Glenwood Canyon, the river was observed turning a chocolate-red color as it become hyperconcentrated with clay and silt. The river sediment load at these times gives it the appearance of chocolate milk. (Kirkham and Matthews, 2000.)

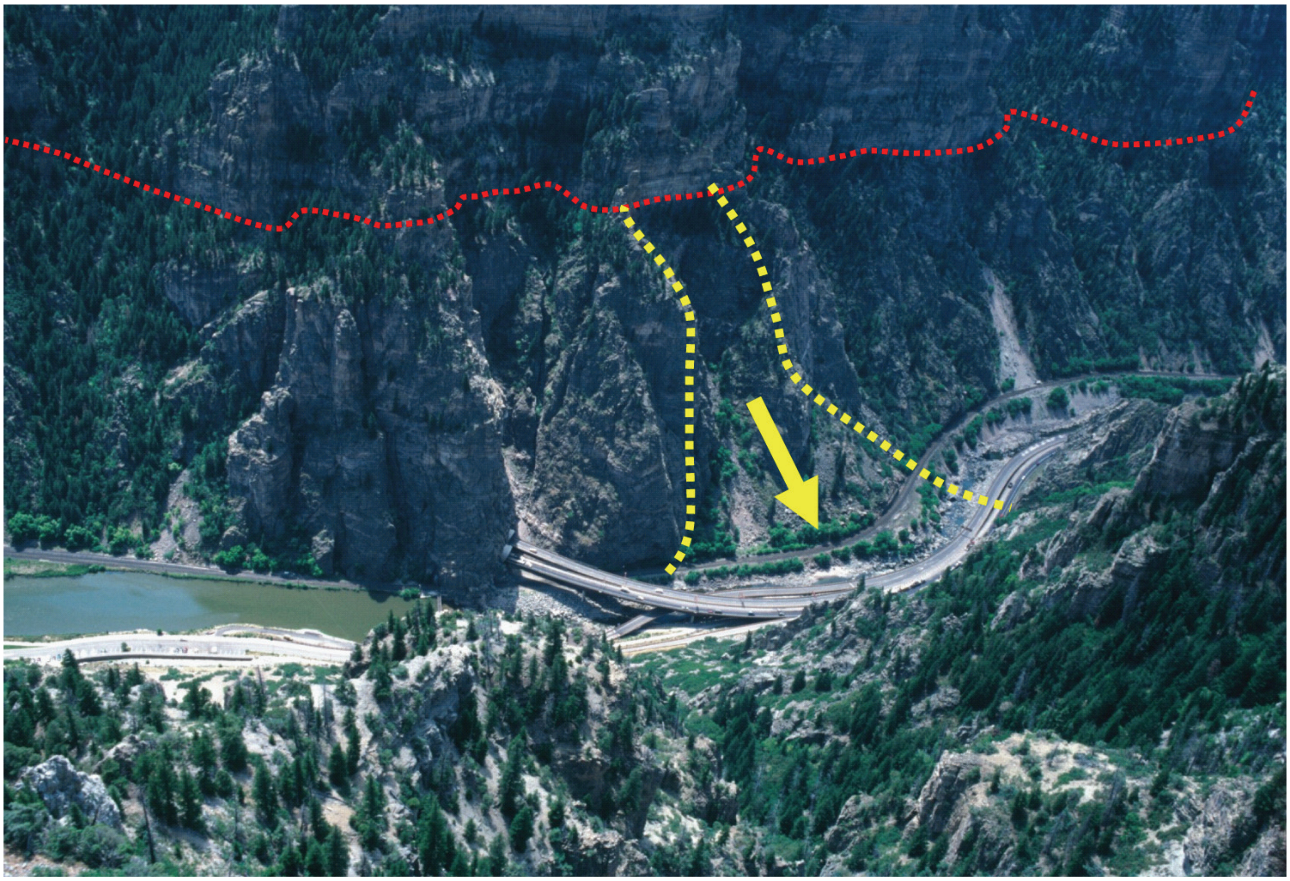

Figure 12. Cottonwood Falls. Location of Late Pleistocene rockslide that dammed the Colorado River in Glenwood Canyon.

Organic material from the base of the Gray Layer was retrieved by exploratory drilling and dated in December 1981. This dating gives the rockslide a date of 9,820 ± 130 years before present using Carbon-14 dating (Kirkham and Matthews, 2000). This confirms that during Holocene time a lake existed within this part of Glenwood Canyon. Eventually the lake was filled in with sediment, and the natural dam was overtopped, leaving the Gray Layer intact, and forming a knick point in the river. Today this is visible as the Cottonwood Falls rapids. The Gray layer is overlain by a 20 to 40 foot thick layer of rockfall debris that accumulated on the canyon floor afterwards.

In October 1992, the grand opening of the Glenwood Canyon Interstate 70 Project was celebrated when both eastbound and westbound lanes were opened to traffic. Construction of I-

70 through Glenwood Springs was a major engineering feat that took 13 years to complete at a total cost of $490,000,000. The opening was a culmination of efforts begun with a draft Environmental Impact Statement and conceptual designs of the early 1970's, more than 20 years prior. Preliminary design work took place in the late 1970's, and final design and actual construction began in 1980. Final completion of rest areas and miscellaneous work was completed in 1994. The project was completed a year ahead of schedule. Most people consider the Glenwood Canyon section to be the last piece of the Interstate Highway System, as originally planned, to be opened. (Kirkham and Matthews, 2000.)

Figure 13. Section of I-70 through Glenwood Canyon.

The complexity of the geology, geomorphology, and surficial deposits required extensive preliminary geological and geotechnical investigations, continual geotechnical inspection during construction, and ongoing frequent inspections during operation. In addition to geologically complex highway construction, serious geologic hazards exist within the canyon. These hazards include rockfall, and to a lesser extent, debris flows, ice falls, and avalanches. Prior to construction of I-70, the highest rates of rockfall incidents and injury accidents related to rockfall on Colorado highways occurred on US Highway 6, the old two-lane road that originally existed within the canyon. (Kirkham and Matthews, 2000.)

Figure 14. Road damage caused by the Thanksgiving Day 2004 rockfall event, just west of the Hanging Lake rest area, which released an estimated 1300 to 1500 cubic yards of rock.

Rockfall is the most critical geologic hazard in Glenwood Canyon, and the cost of rockfall mitigation was $10,000,000 during the I-70 Glenwood Canyon Project. Rockfall can initiate from as high as 2,500 feet above the roadway at the rim of the canyon. Even with the rockfall hazard studies and mitigation features, accidents can and do still occur. In recent years, fatalities have occurred within the canyon from falling rocks striking vehicles. (Kirkham and Matthews, 2000.)

Rock stabilization methods are required to ensure safety in Glenwood Canyon and at the Hanging Lake Rest Area. Some of the various techniques employed within the canyon include:

- Rock scaling and trim blasting: removal of loose and unstable rock from a cliff or steep rocky slope by technical rock climbers using steel bars as levers, jacks, or blasting.
- Earthen walls reinforced by geotextiles (visible at the Hanging Lake rest area): These are capable of stopping large rocks moving at high velocities with large impact energies.

- “Elephant traps”: Large basins are excavated into rock slopes above the roadway, and catch falling rocks from above.
- Hanging tire attenuators: closely-spaced columns of stacked tires on steel posts, hung vertically from a horizontal cable that spans an active rock chute. Rocks falling down the chute hit these columns, and either stop or slow down considerably on the slope above the roadway.

A single innovative rubber tire wall was installed near the west portal of Hanging Lake Tunnel to prevent further erosion of a cut slope. Approximately 400,000 tires were used to make the fill and fabricated rubber blocks that face the wall. Unfortunately, the wall spontaneously caught fire in 1995. The upper portion of this tiered wall has been removed, and the exposed eroded cut slope is currently draped with wire mesh. (Kirkham and Matthews, 2000.)

Two methods used to control falling ice include hanging heavy chains and ice attenuation posts. The chains prevent large ice chunks from falling en masse. The array of grouted posts in the ice fall runout path are positioned to break up falling ice into smaller pieces before they are stopped by a fence.

The rockfall mitigation techniques that are observable from the vicinity of the Hanging Lake rest area include rock bolts, cable lashings, concrete buttresses, mechanically stabilized earth (MSE) rockfall impact walls, rockfall and icefall fences, ice fall attenuation posts, and draped wire mesh. Two significant hazard locations exist at the Hanging Lake rest area. One is the location of a large seep near the nonconformity of the Sawatch Quartzite and underlying Precambrian basement rock. This site, known by local ice climbers as Glenwood Falls, freezes every winter to form large slabs of ice on the rock face. Every spring these large slabs fall (they used to impact the old US 6 roadway). Attenuation posts now break the large ice slabs into manageable chucks no more than 3 feet in diameter, and an icefall fence is located lower on the slope. The second significant hazard visible from the Hanging Lake rest area is an active rockfall chute mitigated using an MSE impact wall. (Kirkham and Matthews, 2000.)

Mileage	Description
0.0 (from Stop 3) 50.8 (cumulative)	Leave the Hanging Lake Rest Area. Follow Interstate 70 through Glenwood Canyon.
4.0 (from Stop 3) 54.8 (cumulative)	Glenwood Canyon – Grizzly Creek. This is Stop 4.

STOP 4. GLENWOOD CANYON – GRIZZLY CREEK

From this stop, the Precambrian-Paloezoic contact is visible on the south wall of the canyon. Precambrian rocks in the vicinity of the rest area include granites, pegmatites and gneisses. To the southeast of the rest area across the river, there are exposures of green epidote and pegmatites. The cliff-forming Paleozoic rocks above this are the Sawatch Quartzite. Above this lies the Leadville Limestone, in which the commercial Glenwood Caverns and “wild” Hubbard’s Cave were both formed.

Figure 15. Cliffs within the canyon, capped by Sawatch quartzite, with the Precambrian contact visible at the base of the sedimentary section.

Differential settlement and slope stability have been the main engineering geology constraints to construction in this section of the highway. Both the westbound and eastbound lanes are supported by bridges and cantilevered wall designs in this section. These structures are in turn founded on colluvial and alluvial materials from Grizzly Creek and the Colorado River, as well as stable bedrock beneath the alluvium. These material boundaries run parallel to the roadway, creating the potential for differential settlement.

REFERENCES

Colton, R.B.; Holligan, J.A.; Anderson, L.W.; Patterson, P.E., 1975, Preliminary map of landslide deposits, Leadville 1ox2o quadrangle, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-701.

Lidke, D.J., 1998, Geologic map of the Wolcott quadrangle, Eagle County, Colorado: U.S. Geological Survey Geologic Investigations Series Map I-2656.

Kirkham, R.M., and Matthews, V, 2000, Guide to the Geology of the Glenwood Springs Area, Garfield County, Colorado: Colorado Geological Survey for Earth Science Week Field Trip 2000.

Robinson, C.S., 1975, Folio of land use maps, Eagle County, Colorado: Charles S. Robinson & Associates, 7 sheets, scale 1:24000.

White, J.L., 1997, Field trip of engineering geology and geotechnical engineering of the Interstate 70 Glenwood Canyon project *prepared for* AASG 1997 Annual Meeting, June 21-27, 1997, Breckenridge, Colorado, 9 p.

THE DEBEQUE CANYON LANDSLIDE AT INTERSTATE 70, MESA COUNTY, WEST-CENTRAL COLORADO

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The Debeque Canyon landslide

1st North American Landslide Conference

Vail, Colorado, June 6, 2007

Warning: This field trip will visit an active landslide where hazardous conditions exist. There are steep slopes, dangerously high cliffs, unstable ground, and open ground fissures. Where furrows or ground offsets exists, unstable soil bridges may be spanning open subsurface fissures. Cliff edges mantled with loess may also be unstable. Always buddy up with another field trip participant as you explore the landslide.

About lunch: If all goes well, the field trip leaders will have lunches and cold soft drinks waiting at the landslide headwall at stop #3. If adverse weather makes 4WD vehicular access unavailable or too dangerous, field trip attendees will be required to pack their lunches and drinks for the hike.

OVERVIEW

This one-day field trip offers the opportunity to visit an important active landslide that is impacting Interstate Highway 70 in DeBeque Canyon. The landslide is located in Mesa County of west-central Colorado, 20 miles (32 km) east of Grand Junction and 125 miles (200 km) west of Vail. The south wall of a 500-foot (152-m) deep canyon that was incised by the Colorado River into Cretaceous Mesa Verde Group sedimentary strata has been displaced by the landslide complex.

Note: This field trip will be visiting only one site. The field trip attendees will have the freedom to examine the landslide terrain in small groups hosted by a field trip leader. This guidebook has been written more as a general paper that the attendee can refer to. Points of interest along the Interstate-70 corridor from Vail to the DeBeque landslide are covered in the I-70 corridor field trip guidebooks that will also be given to the field trip registrants.

The historical record of the DeBeque Canyon landslide, also referred to as the "Tunnel Landslide," dates to the late 1800s. The slide has periodically impacted the transportation corridors on the valley floor since the early 1900s. The last major reactivation in April 1998 caused Interstate 70, which passes over the toe of the landslide, to heave 14 feet (4.3 m) and shift 10 feet (3 m) laterally toward the river. Two other large historic landslide movements prior to 1998 have been documented. Catastrophic movements occurred at the turn of the last century (precise date is unknown) when the landslide toe entered the Colorado River and caused flooding that damaged the railroad and structures at the Tunnel work camp on the opposite riverbank. In 1958, during a road-widening project, the landslide toe heaved the highway 24 feet (7.3 m). In subsequent years and following construction of Interstate 70, periodic nuisance-type slide activity was reported by Colorado Department of Transportation (CDOT) leading up to the 1998 event. Today, the landslide is still moving, which forewarns of possible future rockslides from above and heaving rotation failures at the roadway.

This will be a three-stop field trip (Figure 1). Stop #1 will be at a roadside pullout along the westbound I-70 shoulder that provides an overview of the landslide from the canyon floor. The trip will proceed to I-70 Exit 47 where we will exit and return eastbound to pull off at the eastbound-only old Highway 6 exit that follows the river meander around Beaver Tail Tunnel to stop #2. There we will debus and have a safety meeting. The rest of this field trip will be a 1-mile (1.6 km) hike on a 4WD track from old Highway 6 that will become more strenuous as we climb the canyon wall along game trails to stop #3 at the landslide headwall. At the landslide, the field trip leaders will discuss the geologic setting of the canyon, the major landforms and age of the landslide, the emergency response, instrumentation and current movement trends, landslide analyses, and the decision analysis workshop. The recommendation at the conclusion of the decision analysis workshop was a landslide water diversion project.

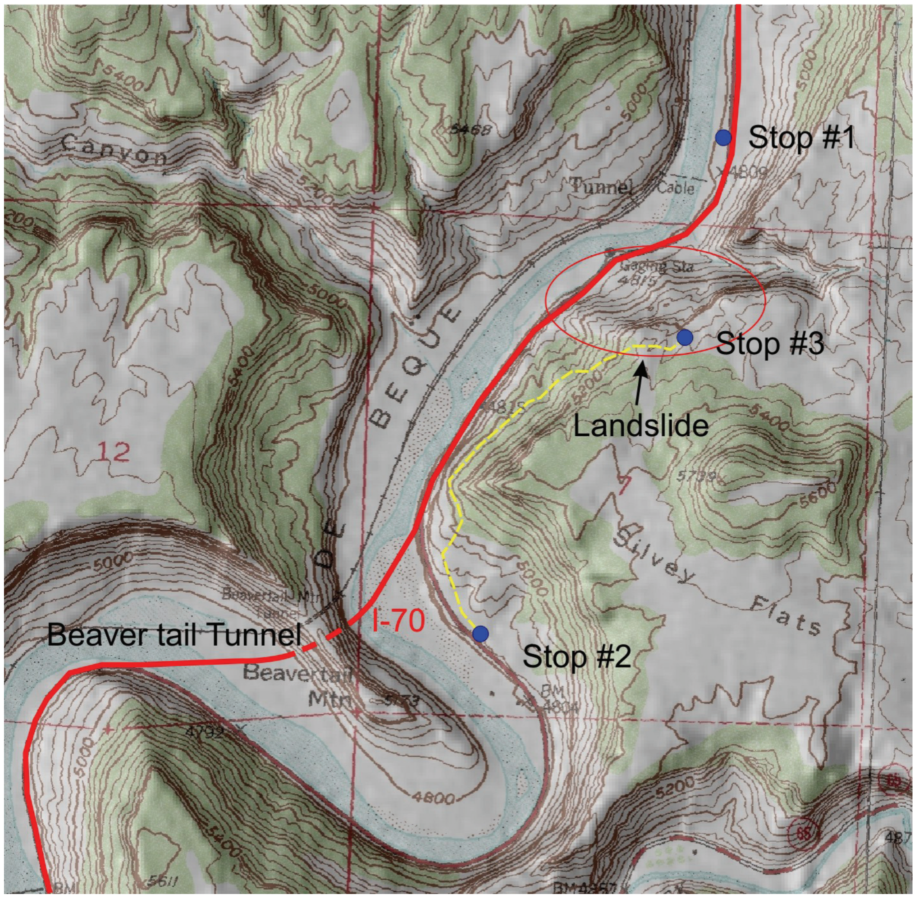

Figure 1. Site map showing landslide and location of access trail (in yellow) to the canyon rim. Basemap from USGS 1:24,000 topo and 10-m DEM series.

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Stop #1. I-70 westbound shoulder at Milepost 51	Overview of the landslide from the canyon floor.	White, Dessenberger, Higgins
Stop #2. Beaver Tail Rest Area	Trailhead to landslide, safety discussion	White
Stop #3. Top of landslide	Visit and discussion of landslide	All field trip leaders

LANDSLIDE OVERVIEW AND REGIONAL SETTING

The landslide is located on the southeast side of DeBeque Canyon near milepost 51 of Interstate 70. The landslide is shown on the USGS Cameo 7.5-minute Quadrangle topographic map, centered on the NW ¼ of the NE ¼ in Section 7, Township 10S, Range 97W of the 6th Principle Meridian in west-central Colorado. The climate is semi-arid to arid, with the area receiving about 12 inches (30.5 cm) of annual rainfall. Patchy sage and juniper flora are characteristic of the area.

DeBeque Canyon is located within the Colorado Plateau physiographic province on the western flank of the Piceance Basin, a Late Cretaceous to early Tertiary structural and depositional basin. The extent of the basin is defined primarily by the regional Laramide uplifts of the Uncompahgre Plateau along its western flank and the Grand Hogback monocline (White River uplift) along the eastern flank (Figure 2). The landslide is located in the upper Mesa Verde Group, a thick sequence of interbedded sandstone, siltstone, shale, and coal units deposited in non-marine, deltaic/fluvial/coastal plain environments during transgressive and regressive cycles of the Cretaceous intercontinental seaway (Tyler and McMurray, 1995). The Mesa Verde Group strata are nearly horizontal in the canyon with only a gentle regional rise, of about 4 degrees, to the southwest towards the Uncompahgre Uplift. The bedrock stratigraphy at the landslide includes thick sandstone beds at the canyon rim, sequences of thinly interbedded shale, siltstone, and sandstone, as well as a thick problematic shale unit that overlies the lower cliff-forming sandstone that is exposed at road level.

Figure 2. Map of the Piceance Basin showing surface exposure of the Mesa Verde Group and location of landslide. East limb of Mesa Verde is sharply tilted, forming the Grand Hogback. The west limb rises more gently towards the Uncompahgre Uplift, west of Grand Junction (from Tweto, 1979).

The surficial geology in the immediate vicinity of the landslide is predominantly exposed Mesa Verde bedrock along the canyon walls, thin colluvial soils along benches of the valley walls, recent river alluvium on the canyon floor, and a remnant of a mid-Pleistocene terrace on the canyon wall. The plateau at the top of the canyon, called Silvey Flats, is mantled with late-Pleistocene loess, as are some of the flatter mid-slope benches of the canyon wall. The loess and terrace gravels are fissured within the landslide so their deposition predates ground movements.

LANDSLIDE MORPHOLOGY

The landslide complex exhibits several mechanisms of both rock and soil slope failures, including rockmass shearing, block gliding and toppling, and translational and rotational soil-type movements. It covers 36 acres (14.6 ha) and extends from an elevation of 4,800 feet (1,463 m) at the river level to 5,300 feet (1,615 m) at the top of the canyon wall. The landslide can be sub-divided into three main divisions based on sliding mechanisms and morphology: the Upper Block, the Rubble Zone, and the West Disturbed Block. Figure 3 shows these zones of the landslide complex in oblique view from across the river.

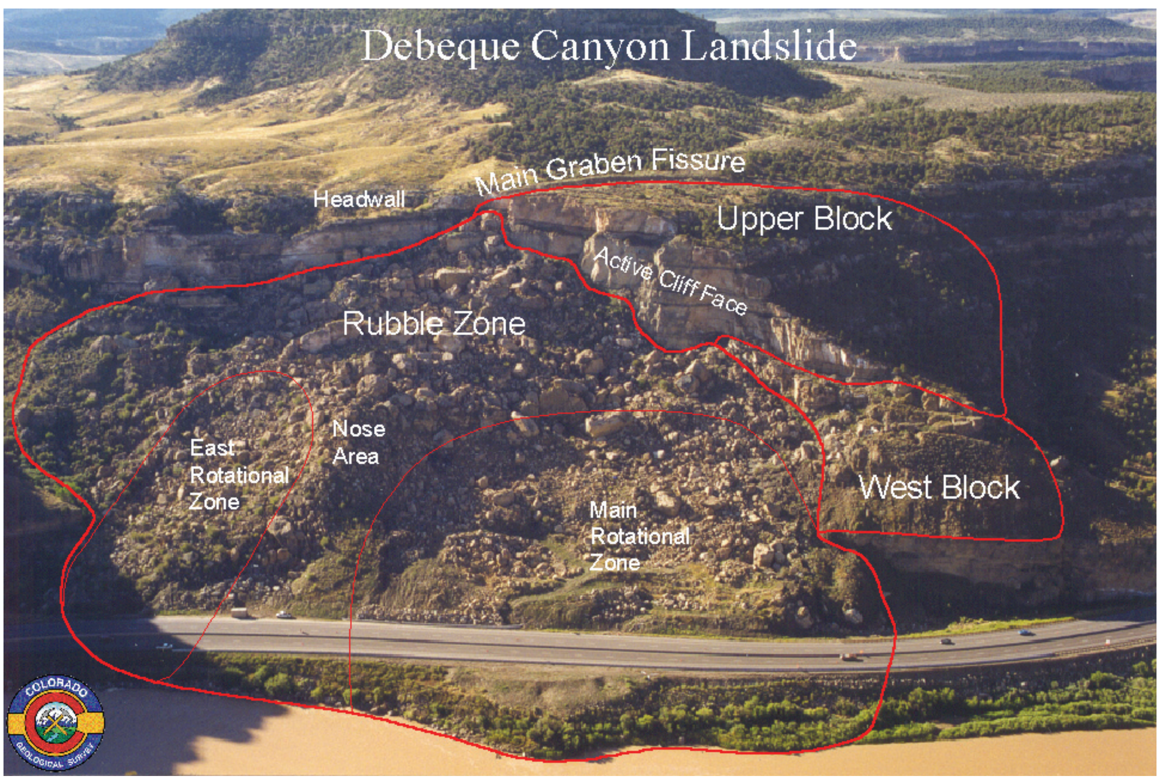

Figure 3. Oblique aerial photo showing general landslide morphologic units used in this guide. View is to the south. In the text the West Block shown in the photo is referred to as the West Disturbed Block.

The headscarp of the landslide consists of a main fissure that developed along a pre-existing, vertical, northeast-trending, 4 to 5-foot (1.2 to 1.5-m) wide shear zone. This calcium carbondate-encrusted shear is more properly a fault zone since 6 feet (1.8 m) of vertical offset was measured at the shear in the box canyon east of the landslide. Interestingly, what was the original down-dropped side of this fault zone is now the headwall. Landslide extensional and slumping movements have reversed the original throw of the fault. This feature separates the landslide from the intact Mesa Verde Group bedrock that forms the canyon walls. The major regional joint set roughly parallels this shear. Upon separation and extension of the main fissure, sympathetic joint-defined linear blocks have slumped into the fissure, forming a graben-like morphology. The fissures are open to over 50 feet (15 m) in depth so care is needed when walking near them.

At the east side of the landslide, the material in front of the graben has slid down the slope and completely broken apart to become the Rubble Zone. Farther west, the graben traverses through the still-intact Upper Block. Continuing westward the fissure gap closes and, as it curves downslope, narrows and becomes hidden by the colluvial soil cover at the west boundary of the landslide. Several small drainage basins in the plateau above the slide (Silvey Flats) flow into the main landslide fissure.

Upper Block

The Upper Block presents the greatest hazard because of its potential for catastrophic failure. This fissured, triangular-shaped block is composed of thick sandstone beds and minor thin interbedded shale. The Upper Block has an areal dimension of 1000 x 950 x 680 feet (305 x 290 x 210 m) and is almost 300 feet (90 m) thick. This rock mass is sliding to the north towards the river (Figure 4) and the displacement has created extensional deformation features such as open fissures, depressions, structural offsets (faults), and localized tilting or slumping of the disturbed strata. The Upper Block is the remnant of a much larger mass that previously failed and disintegrated, creating the Rubble Zone shown in the historic photo in Figure 5. An active cliff face, up to 200 feet (61 m) high, marks the separation between the Upper Block and the Rubble Zone. This cliff line is oriented parallel to another major east-west trending joint set. The Upper Block is a major concern because if it were to fail catastrophically, the highway corridor would likely be blocked and the Colorado River could possibly be partially dammed, or diverted. Such a failure could also possibly threaten the railroad on the opposite bank, as previously occurred in the early 1900s.

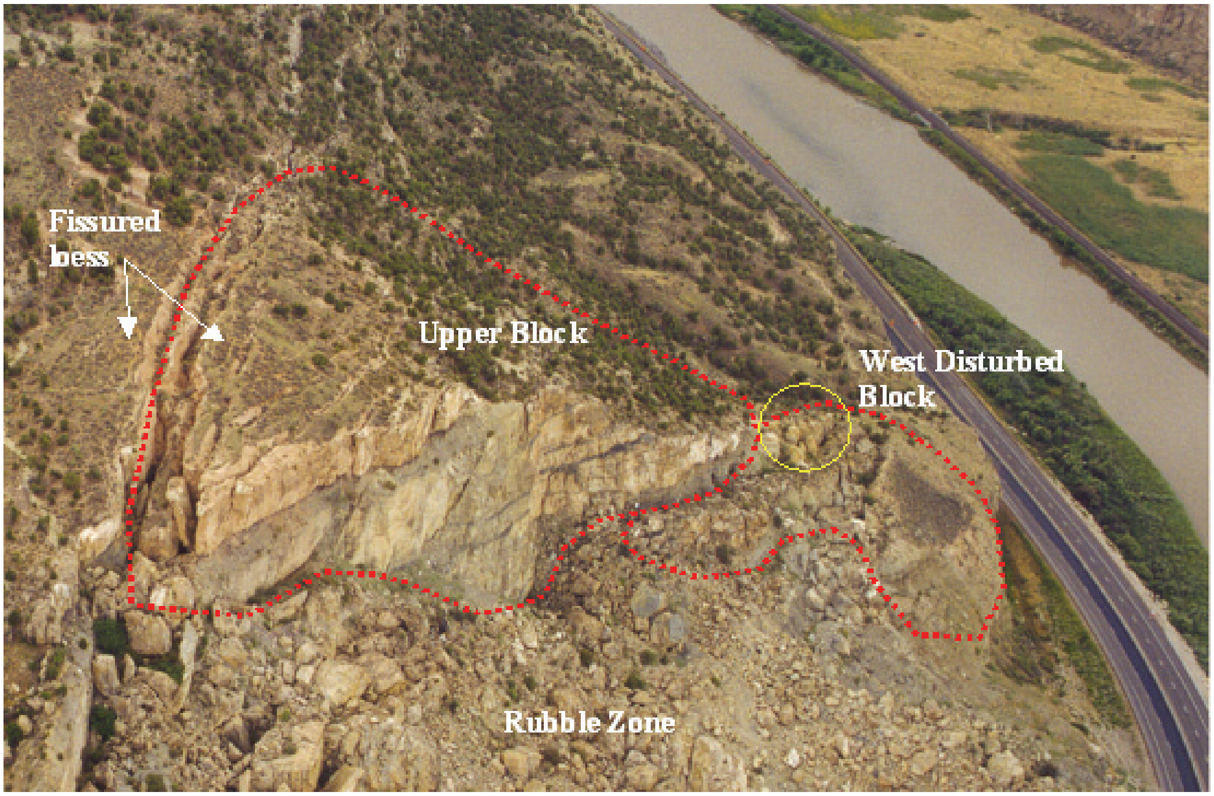

Figure 4. Oblique aerial photo of the Upper Block and West Disturbed Block. Note main graben and the fissures in loess that mantle top of Upper Block. Note also the proximity to Interstate 70, the Colorado River, and the railroad tracks below. Yellow circle is location of mid-Pleistocene (Bull Lake) gravel terrace remnant. View is to the west.

The Rubble Zone

The Rubble Zone is the main body of the landslide. The large failure of the landslide at the turn of the last century created most of the rubble seen today and partially diverted the river course (Figure 5), affecting the railroad and work camp on the opposite bank of the river. In the 1920s, the toe of the Rubble Zone was cut to align a roadway on the south side of the river, and subsequent lateral and vertical movements at the toe of the rubble have repeatedly damaged roadways since their construction. The Rubble Zone is derived from major block-glide failures, shearing and breaking up of the valley wall, rockslides, and translational movements of the rubble material down from the headwall fissure and active cliff face of the Upper Block. Chaotic mixing of Mesa Verde sandstone, siltstone, and shale during down-slope movements has created a rubbly area of random angular blocks and boulders with a basal clayey matrix layer that is shearing along its contact with underlying weathered shale. The Rubble Zone can be further subdivided based on landslide mechanisms: an upper translational area, and two lower rotational areas (Figure 3).

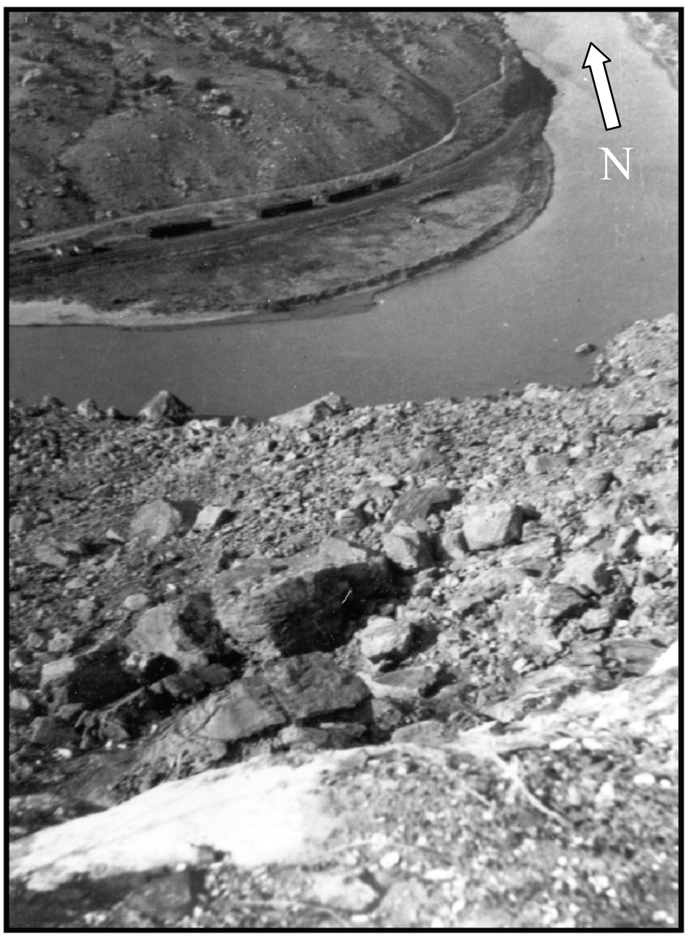

Figure 5. This historic 1910 photo was taken previous to any roadway construction on the south canyon side through the landslide toe. View is looking up the Colorado River with the flow direction from right to left. Note the very recent, fresh, landslide toe in the outside curve of the Colorado River and lack of any reworking of the debris by the river. Also note the light-colored flooding scar on the opposite riverbank. Copyrighted photo is courtesy of the Julia Harris Collection at the Museum of Western Colorado, Grand Junction.

The upper translational area is characterized by very large blocks, some the size of small houses. This area contains the rubble remains of the much larger rockslide. Relicts of the main fissure and graben can still be seen at the top along the headwall. The active cliff face of the Upper Block feeds additional rubble into this area. The change from translational to rotational slide movements occurs at a buried formational knickpoint, a sandstone bench that becomes visible as a roadside cliff west of the landslide. Below this buried cliff, which was verified by drill holes, the landslide deposit thickens where it has buried the modern Colorado River alluvium.

The lower rotational area of the Rubble Zone includes the more recent slide movements. Large rotational failures have occurred in two directions into the river and caused major deflation of the original landslide topography that is shown in Figure 5. Major reactivation occurred in 1958 after construction of a modern two-lane highway removed a portion of the landslide toe. In the center of the Rubble Zone, a large hump of material, also referred to as the Nose Area (see Figure 3), topographically separates a smaller eastern rotational slide from the main rotational slide to the west. The crest of the Nose Area probably represents the original elevation of the Rubble Zone reflected in the 1910 photo.

The main rotational slide area of the Rubble Zone was the site of the major ground movements in 1998. As rotational landslide movement deflated the area below the buried cliff knickpoint, upper concentric scarps formed in the translational zone as secondary, retrogressing slumps moved landslide debris into the depleted zone. These retrogressing slumps extended to the base of the Upper Block. Immediately after the 1998 reactivation, fresh soil remnants and smears were seen on the base of the Upper Block cliff where the rubble had slid down.

The West Disturbed Block

The West Disturbed Block is located west of the Rubble Zone and directly below (north of) the Upper Block (Figure 4). The West Disturbed Block is a transitional feature in the landslide that has differentially sheared and separated from the Upper Block in a hinge-like fashion, pivoting down from the western edge of the landslide boundary. Even though slumping, shearing, tilting, and fissuring have disturbed the rock strata, it has not been completely reduced to rubble so the stratigraphic relationship is still discernible.

The disturbance of rock strata in the West Disturbed Block appears to be from gliding and shearing within the same thick underlying claystone that is responsible for the block sliding of the Upper Block and the translational movements of the Rubble Zone. Prominent pressure ridges run parallel to the major shears and scarps in the disturbed block. The original vegetated shale slope in the disturbed block has been oversteepened, fissured, and disturbed by lateral movements, and small, soil-slip sloughing failures have occurred over the lower sandstone cliff to the roadway level below. Deflation of the Rubble Zone has left the adjacent West Disturbed Block at an elevation some 40 feet (12 m) higher than the adjacent Rubble Zone surface.

The top of the West Disturbed Block includes remnants of an alluvial gravel terrace. The gravel, also fissured, predates landslide movement and lies 240 feet (73 m) above the present Colorado River elevation. This terrace is likely Bull Lake age (approximately 160 ka) based on its elevation above the current river level and its reddish-brown hue (Yeend, 1969).

LANDSLIDE ANALYSES

Landslide Movements

This landslide has experienced nearly continual ground movements since the roadways were excavated into the landslide toe that was formed by the major rockslide in the early 1900s (Figure 4). Major episodic ground movements that damaged the roadways occurred in 1958 and 1998. One of the reasons for long-term monitoring of the landslide is to determine whether current movement rates are wholly in response to short-term re-adjustment of the landslide mass following the major movements that occurred in April 1998, or whether they indicate some form of steady-state movement that results in periodic failure that could be anticipated.

Photogrammetric digital analysis of early stereographic aerial photography has verified continual movements; including widening of the major graben fissure, rockfall from the active cliff face, both deflation and heave of the Rubble Zone ground surface, and continual downward movement of identifiable rock blocks since 1950 (White and others, 2003). Project monitoring surveys for CDOT over the last six years by CGS and USGS has shown continued movements of the Upper Block, the upper reaches of the Rubble Zone, and the West Disturbed Block**.** Figure 6 presents a vector graph of the prism survey that has been completed from 1999 to 2006. The graphical data presented indicate that the movement of the landslide is a continuous and dynamic process with movement rates of the Upper Block averaging about 1 inch (2.54 cm) per year, trends that do not appear to be diminishing over time. GPS surveys by USGS (Figure 7) also show very close correlation with the prism surveys and, most importantly, reveal that the Upper Block is still moving en masse, instead of displacements only along the active cliff face.

Inclinometers casings located in the upper reaches of the Rubble Zone sheared early after installation, within a few months. Those nearer the roadway were quiet, until 2005, when appreciably wetter conditions occurred in the region. Following the increased precipitation, movements were seen in the inclinometer casings at DLS-3, DLS-4, and GAI -1 (see locations in Figure 6) for the first time since the 1998 reactivation.

Subsurface Conditions

For the landslide investigation that CDOT commissioned in 1999, several geologic cross sections were developed (Golder Associates, 2000). The locations of two section lines that revealed the most information on the subsurface conditions of the landslides are shown in Figure 6. Cross section A passes through the Upper Block, the main rotational center of the Rubble Zone, and the landslide toe below the highway. Cross section B also passes through the Upper Block, but crosses the upper cliff face obliquely to pass through the West Disturbed Block and extend over the lower cliff face that is adjacent to the roadway. This lower cliff face has not shown any movement to date. The geologic investigation revealed that a thick shale bed in the stratigraphy of the canyon wall was a major causal agent for the triggering of the landslide. This approximately 100-foot (30-m) thick shale is labeled as the “weak shale” in cross sections A and B shown in Figures 8 and 9.

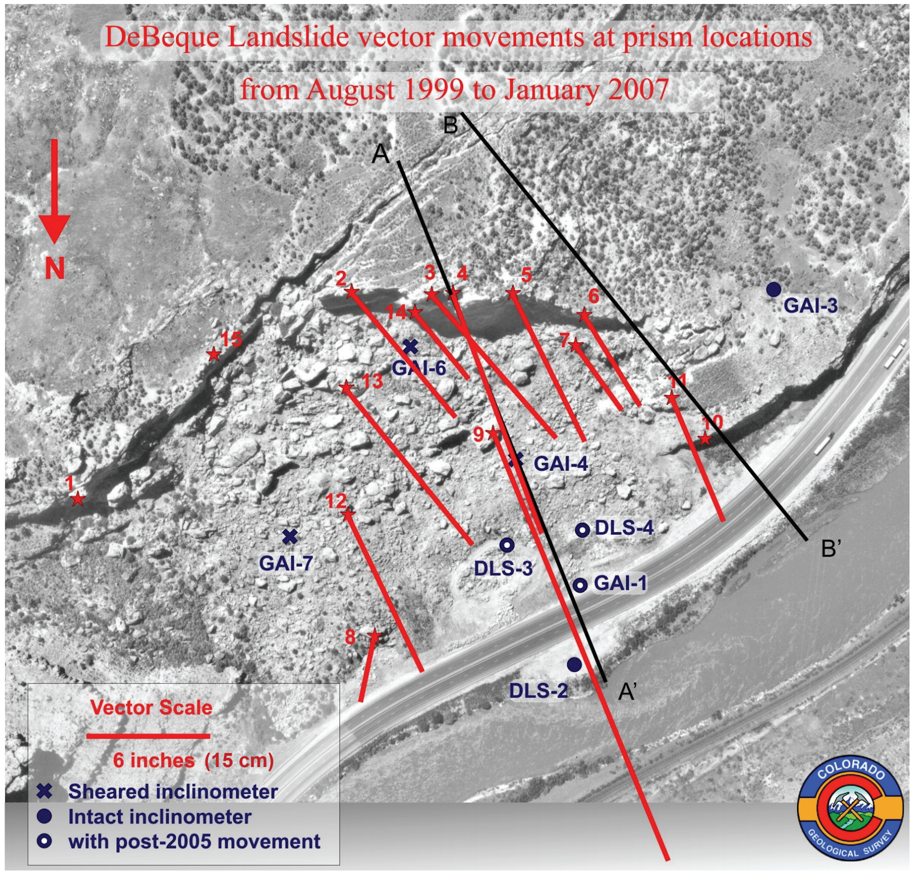

Figure 6. Aerial photograph of the landslide showing horizontal displacement vectors of prisms (red arrows) and inclinometer locations. No movements have been discerned at prisms #1 and #15 on the headwall, and #10 at the lower cliff face near the roadway.

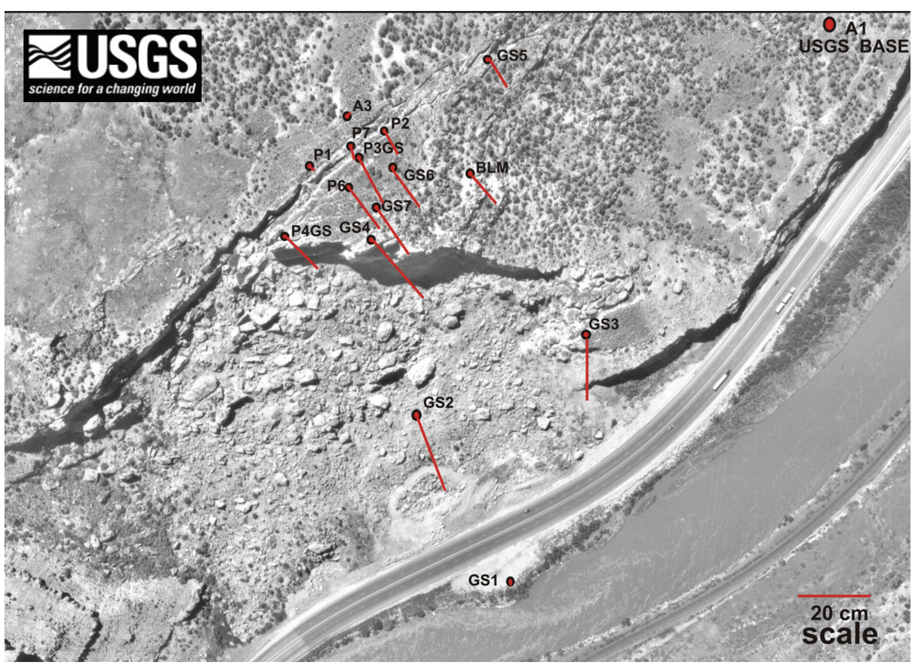

Figure 7. Horizontal displacement vectors of USGS GPS surveys from 9/9/99 through 7/14/05. Note that the vector scale is different from that used in Figure 6.

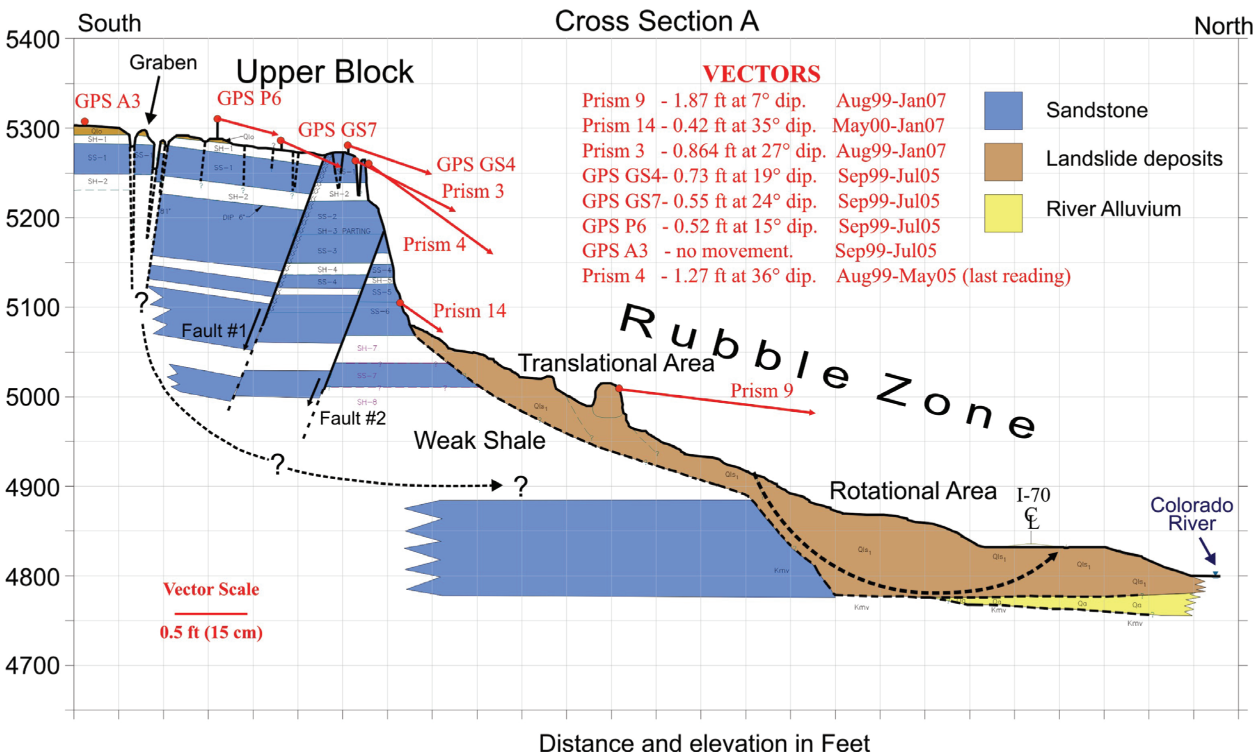

Figure 8. Cross section A. Section location is shown in Figure 6. Plunge vectors were calculated from survey data. Failure surface in the Weak Shale is an approximation shown for illustrative purposes. Actual failure surface is likely a continuum of sheared and disturbed shale.

Section A reveals a highly fissured, offset Upper Block of thick sandstone and thin interbedded shale strata that separated from the headwall along the major fissure. Plunge vectors also reveal that the fissured sandstone blocks are now "grinding" into the underlying weak shale. Weak, weathered, ductile portions of this lower shale have been deformed by the tilting and high angle (72 degrees) extensional faulting of overlying, brittle sandstone blocks that fissured along the preexisting, east to west, shear zones. Ductile shearing, bearing failure, and lateral deformation of this shale has not only caused the extensional-deformation features of the Upper Block, but also provided the clay content for the soil-type translational and rotational portions of the Rubble Zone. The buried lower sandstone strata, exposed at road level to the west and verified in the subsurface by drill borings, acts as a knickpoint where the soil-type landslide behavior changes from translational to rotational failure mechanisms

Section B is similar to section A with respect to the Upper Block, but still contains a lower sandstone unit above the thick weak shale that, while highly fissured, tilted, and disturbed, has not completely rubblized so the coherent strata can still be recognized. Northward lateral displacement of the disturbed shale over the unmoving lower sandstone unit (roadside cliff) has oversteepened the shale slope.

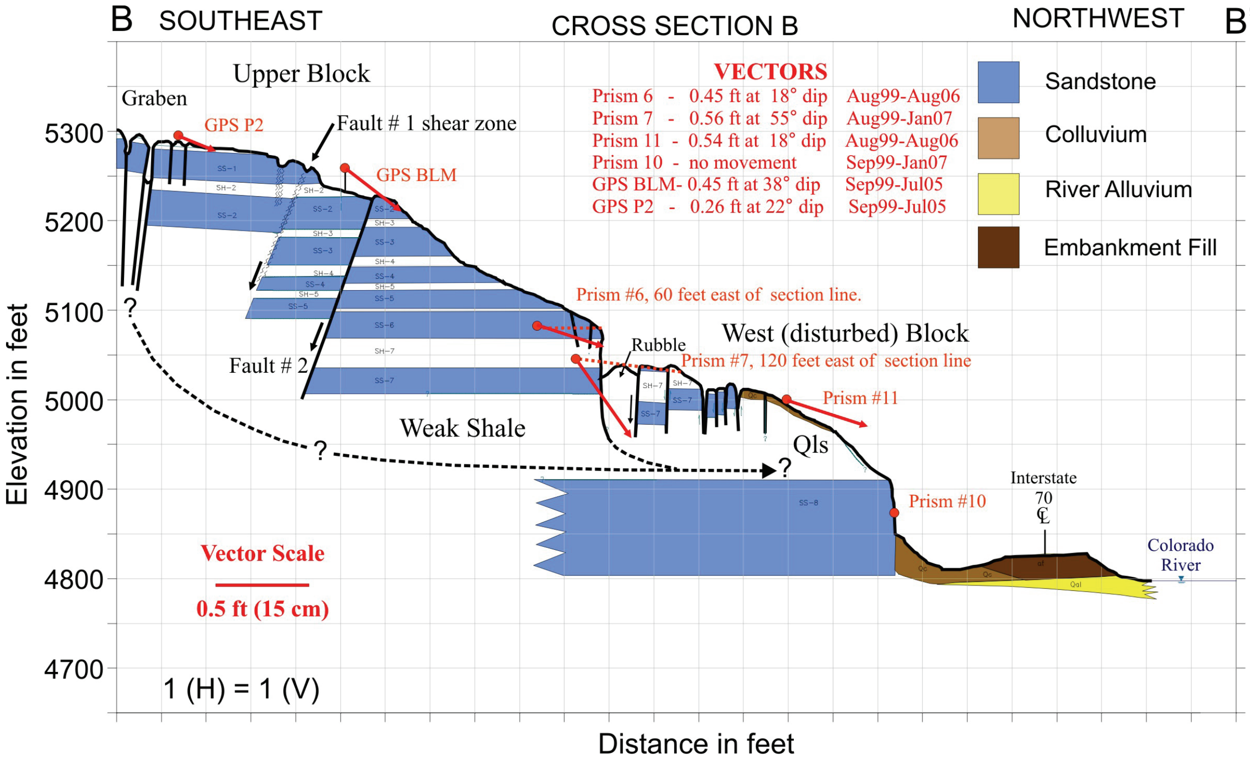

Figure 9. Cross section B. Section location is shown in Figure 6. Plunge vectors were calculated from survey data. Failure surfaces in Weak Shale are an approximation shown for illustrative purposes. Actual failure surface is likely a continuum of sheared and disturbed shale.

Engineering Analyses

Analyses were carried out to examine both the mechanism of instability, and the potential for failure in the Rubble Zone and Block areas of the landslide. Because the mechanisms of instability are different in these two areas, it was necessary to use different methods of analysis. The following is a brief summary of the analysis methods and reasons that they were used.

The type of failure in the broken and weathered rock of the Rubble Zone that heaved the highway in 1958 and 1998 was a rotational, soil-type slide. For these conditions it is appropriate to use limit equilibrium methods to determine the factor of safety of the slope, and the influence on stability of conditions such as ground water levels and slope geometry. The program used for this analysis was XSTABL. The results of the XSTABL modeling were used to develop conceptual alternatives for stabilizing the lower, rotational portion of the slide complex.

Along the cliff faces and at the toe of the slide debris there is a potential for rockfall. An analysis of rockfall trajectories to determine if they could reach the highway was carried out using the program CRSP (Colorado Rockfall Simulation Program). The CRSP modeling indicated that the likelihood of rockfall entering the highway is generally quite small for most areas of the slide complex. The extreme roughness of the slope, its length and relatively low slope angle from the base of the cliff to the highway in most areas likely contribute to this effect. This assessment was seemingly verified by a large rockfall that occurred from the active cliff face in June 2005 at the location of prism #4. A 250 cy (190 m^3) slab of sandstone dropped over 200 feet (61 m) to the Rubble Zone below but no rocks were reported by CDOT to have entered the roadway. The Nose, where a steep slope is closely adjacent to the highway, provides a notable exception of the potential for rockfall to reach the travel lanes. The CRSP model indicated that rocks rolling from the crest of the Nose have a high likelihood of reaching the travel lanes.

In the block areas (Upper Block and West Disturbed Block) the purpose of the analyses was to simulate the displacement of the slope, the opening of tension cracks and the development of grabens. Three independent methods of analysis used for this included:

- Limit Equilibrium Analysis of the stability of a simple, single block;
- Continuum modeling using the FLAC program; and
- Analysis using the UDEC program, which models the slope as an assembly of discrete blocks with movement along the discontinuities.

UDEC and FLAC analyses of the Upper and West Blocks were undertaken as parallel studies to provide corroboration of results. This corroboration was judged to be desirable because analyses were initiated without benefit of significant monitoring results. The two models resulted in similar findings. In particular, the faults seen in the east face of the Upper Block (see Figures 8 and 9) were mimicked by deformations expressed in the model results.

Also, failure of the Upper Block could result in catastrophic consequences for the highway and its users. Consequently, the modeling was also considered to be an important component of the study to provide an understanding of the movement of the Upper Block. The computer modeling studies indicated a low probability of sudden failure under current site conditions, but also indicated that ongoing creep would be expected to continue. Changing site conditions, such as moisture conditions in critical layers, could act to change the rate of movement.

INTERPRETED AND RECENT LANDSLIDE HISTORY

The landslide exists at this site because of an interesting set of geologic and geomorphic circumstances. The following is an interpretation of the landslide activity based on the landslide investigation, the subsequent monitoring program, and the historical record.

1. The natural bend in the Colorado River accelerated the rate of southward river-bank erosion, which steepened the canyon wall below the outlet of the box canyon and over-steepened the 100-foot thick “weak shale” slope above. This shale was likely in a weakened state from the near-subaerial exposure to weathering during the aggrading of the Pleistocene terrace when the river floor was 240 feet (73 m) above present level.
2. Concurrently, several drainage channels from a small network of drainage basins on Silvey Flat started to erode into the rim of the canyon where they drained over the top sandstone bed.
3. The oversteepened thick shale began to fail, and the upper sandstone strata began to creep northward.
4. Preexisting faulted shear zones, trending northeast to southwest, began to open and intercepted the seasonal storm waters from the drainage channels above, causing it to infiltrate and flood the shale strata, further weaken it.

5. The main fissure opened further, east to west much like a zipper, as the strength of the underlying shale deteriorated. Several factors indicate this opening of the fissure occurred over a long period of time – hundreds if not thousands of years into the early Holocene and possibly the late Pleistocene. The relative age indicators include advanced weathering of the rock surfaces in the fissure interior, varnish coatings where drainage channels flowed into the fissure, remnant columns of rocky soil in the graben that formed from fissure in-fill, and lichen growth on the fissured rock surfaces.
6. A critical threshold was met where the paleo Upper Block, probably looking very similar to the fissured remnant remaining today, failed catastrophically and slid onto the canyon floor, burying the lower sandstone cliff. This was likely the rockslide that was first mentioned in the historical record (see Figure 4). The toe of the rockslide buried recent river alluvium and changed the river course, creating the kink that is seen in current aerial photography. The only portion of the paleo Upper Block that remained was where the main graben did not intercept any drainage channels.
7. The landslide was destabilized by excavation of cut slopes through the toe during road construction in the 1920s.
8. During widening of Highway 6 in 1958, a year when climate conditions were wetter than average, two rotational landslides initiated within the Rubble Zone that heaved the roadway. The arcuate scarps and depletion zones created have been called the East and Main Rotational zones, separated by a higher ridge in the Rubble Zone called The Nose.
9. Interstate 70 was constructed in 1988 and obscured and slightly buttressed the landslide toe with the road embankment.
10. From 1994 to 1998, the slide experienced minor movements at the toe, and the interstate roadway required routine repairs such as minor pavement overlays and ditch cleaning.
11. Wetter than normal conditions triggered significant movements of the East and Main rotational zone in April 1998. A small slip occurred in the East Rotational Area during the roadway repair that was stabilized by a rock buttress. The East Rotational zone continued to creep and sheared an inclinometer casing but didn’t affect the roadway. The Main Rotational Zone heaved and shifted the interstate roadway.
12. The depletion of the Main Rotational Zone has caused sympathetic, downward movements of the translational zone, which has extended to the base of the Active Cliff Face of the Upper Block (Figure 10). Smeared soil remnants where observed on the cliff face that indicated rubble material had slid away and down from the cliff face.

Landslide monitoring continues in order to determine whether removal of this lateral support by the rubble will further destabilized the Upper Block and cause long-term movement rates to increase.

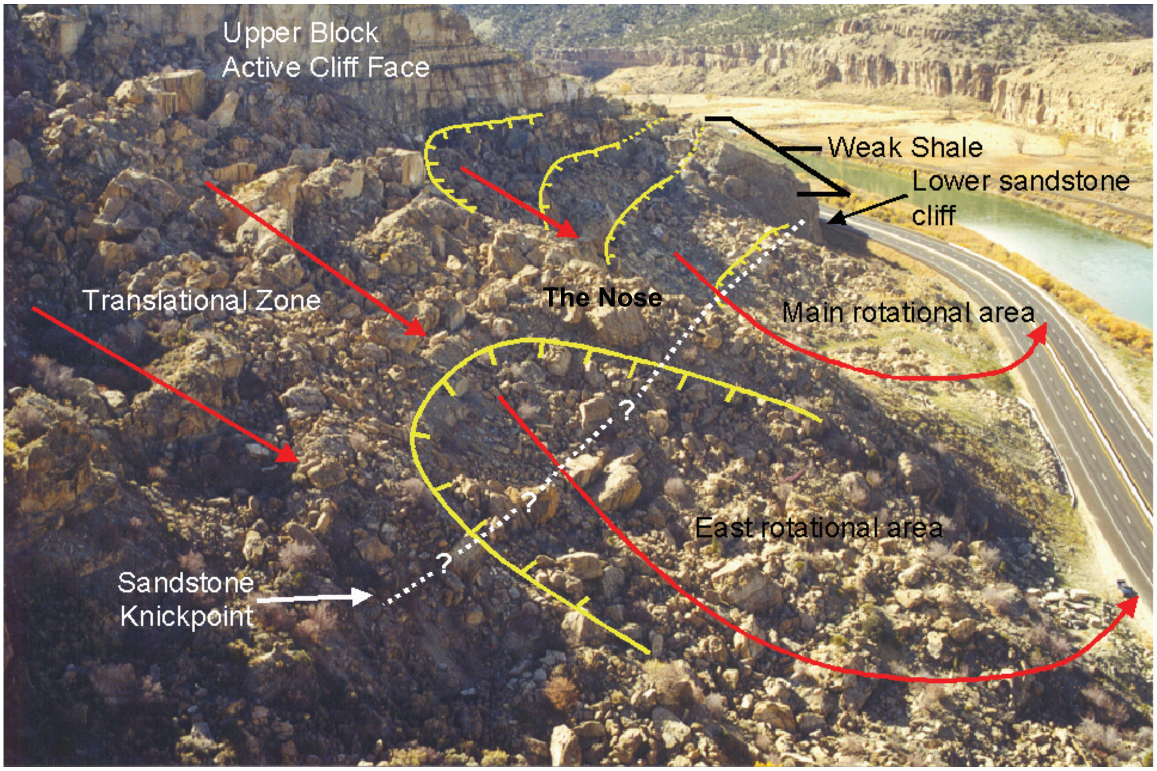

Figure 10. Theorized failure mechanisms and transition of translational movements to rotational movements. Higher ridge called "The Nose" reflects original ground surface of rubble after the pre-1910 rockslide. Deflation and evacuation of slide material at both rotational zones has removed lateral support and caused accelerated movements in the translational zone, which has undermined the base of the Upper Block. Monitoring continues in order to understand whether the accelerated movements of the upper rubble zone will destabilize and accelerate movements of the Upper Block and threaten another catastrophic rockslide.

DECISION ANALYSIS WORKSHOP AND MITIGATION

The analyses for the DeBeque Canyon Landslide Project included development of a Decision Tool to assist CDOT in selecting the most appropriate course of action. The Decision Analysis incorporates the quantitative results of analyses used in examining the potential failure scenarios. The Decision Analysis procedure consists of several steps, as depicted in Figure 11.

The first step consists of a Failure Modes and Effects Analysis (FMEA), used to examine the various potential failure modes identified during the study. The FMEA examined each failure mode (rotational, block creep, etc.) and assessed its expected effects on public safety, transportation, maintenance, and qualified the expected consequences and their likelihood. A similar type of comparative evaluation was then used in a second step (Mitigation Options Analysis) to examine various mitigation options and their likely effectiveness in addressing the various failure modes. In each of these two steps, non-critical and non-effective items were rejected from further examination.

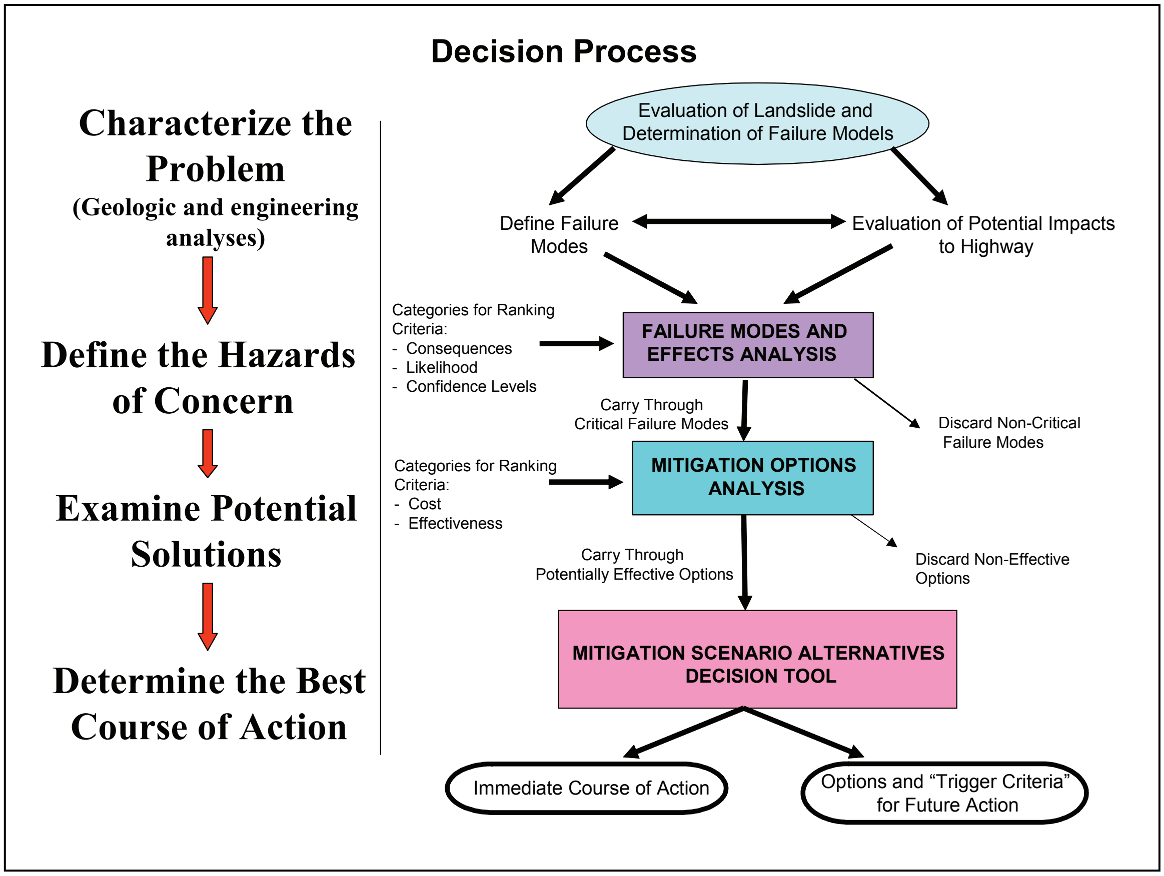

Figure 11. The decision tool process used in the landslide analysis workshop.

The third major step, the Mitigation Decision Tool, included defining and prioritizing the needs for mitigation, and the effectiveness of potential mitigation options. At this stage of the process, input was needed beyond the technical information presented in this study, including legal issues, maintenance concerns, highway safety concerns, and financial trade-offs. The decision process was implemented in a workshop format, where key stakeholders and selected experts were brought together to execute the main process of the Decision Analysis. The indications of the decision process were used by CDOT in determining both a course of immediate action (the water diversion described below and the long-term monitoring program) and can also be used in the future to weigh options for future measures.

CDOT water diversion ditch

In 2001, following the conclusion of the decision analysis workshop, CDOT developed a project design of rock-excavated trenches and embankment dams to intercept small drainage basins that flow into the landslide, and divert those flows away from the landslide mass to the unnamed box canyon to the east (Figure 12). While difficult to quantify the effectiveness of intercepting storm flows from ephemeral streams that drain into the landslide, common sense dictates that removing moisture from landslides is beneficial. From a cost basis, diversion of water was by far the least expensive technique available for mitigation of this landslide. Groundwater and overland flows of water are typical triggers for landslide movement. Natural drainage channels above the landslide complex flowed into the main graben fissure within the

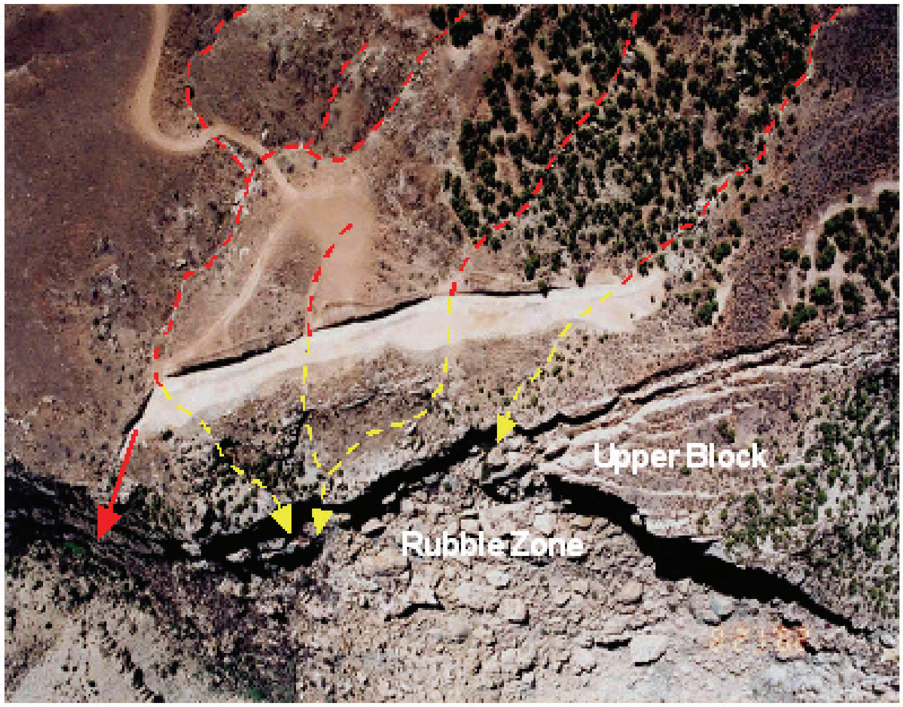

Figure 12. Water diversion structure completed in 2003 to intercept drainage basins above landslide. Dashed red line of existing channel locations become dashed yellow where intercepted. Red arrow shows out-fall of diversion ditch over canyon rim to unnamed box canyon east of the landslide complex. Note that the original drainage channels flowed into the slide only above the Rubble Zone. Aerial photo courtesy of the CDOT aerial reconnaissance unit.

Rubble Zone below, where more and increasingly chaotic landslide movement has obviously occurred. It is probably no coincidence that the Upper Block remained intact at the point where the last drainage channel flowed into the main landslide fissure. The CDOT construction project was completed in the summer of 2002.

Long-term monitoring program

The CGS is assisting CDOT in monitoring the movements of the DeBeque landslide. The USGS is also providing support by the periodic GPS surveys of monuments that were set as part of their emergency response. CGS is hosting a website that is updated as surveys periodically occur. The web site address is: http://geosurvey.state.co.us/Default.aspx?tabid=311

ACKNOWLEDGEMENTS

Portions of this field trip guide were excerpted and revised from White (2005), White and others (2003), and the content of the Technical Report (Golder Associates, 2000) of the DeBeque Canyon Landslide that was submitted to CDOT on December 11, 2000.

REFERENCES

Golder Associates, Inc., in association with Colorado Geological Survey and Colorado School of Mines, 2000, DeBeque Canyon Landslide Project, Technical Report prepared for Colorado Department of Transportation, March 2, 2002, revised December 8, 2000, 3 volumes.

Tyler, R. and McMurray, R.G., 1995, Genetic stratigraphy, coal occurrences, and regional cross section of the Williams Fork Formation, Mesaverde Group, Piceance Basin, Northwestern Colorado: Colorado Geological Survey Open File Report 95-2, 42 p.

Tweto, O., 1979, Geologic Map of Colorado: U.S. Geological Survey, scale 1:500,000.

White, J.L.; Ellis, W.L.; Higgins, J.D.; Dessenberger, N.C.; Gaffney, S.; and Coe, J.A., 2003, Geology, instrumentation, and movement history of the DeBeque Canyon Landslide, Mesa County, West-central Colorado*, In* Boyer, D.D., Santi, P.M., and Rogers, W.P., editors, Engineering geology in Colorado: contributions, trends, and case histories: Association of Engineering Geologists Special Publication 14 and Colorado Geological Survey Special Publication 55 on CD-ROM, 31 p.

White, J.L., 2005, The DeBeque Canyon landslide at Interstate 70, Mesa County, West-central Colorado, field trip guidebook, Geological Society of American, Rocky Mountain Section Meeting, Grand Junction, CO, Field Trip No. 407, May 25, 2005, 7 p.

Yeend, W.E., 1969, Quaternary Geology of the Grand and Battlement Mesas Areas, Colorado: U.S. Geological Survey Professional Paper 617, 50 p.

TERROIR OF THE GRAND VALLEY, COLORADO: A STUDY OF THE GEOLOGY, SOILS, CLIMATE AND RESULTING WINES – OR WINES WITH AN ALTITUDE!

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Colorado's Western Slope

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

This one day field trip will allow us to visit the Grand Valley region of eastern Colorado to study the terroir of the wine industry in Colorado (Figure 1). After a two hour bus ride from Vail, we will get a chance to visit three (maybe four) wineries to try their different wines. At each site we will discuss how the geology, soils and climate affect the different wines of the local vineyards. We will also point out much of the geology along the way and the geological hazards found in the region. This field guide contains a background description of the Colorado wine industry, the geology, climate and soils of the region, and the four wineries we will be visiting. Table 1 summarizes the timetable of stops for the day.

Our aims on the field trip are first to show everyone the geology between Vail and the Grand Valley (which is the covered in two additional field trip guides) and second to visit three to four wineries in the Grand Valley to taste their wines and study the terroir of their wines.

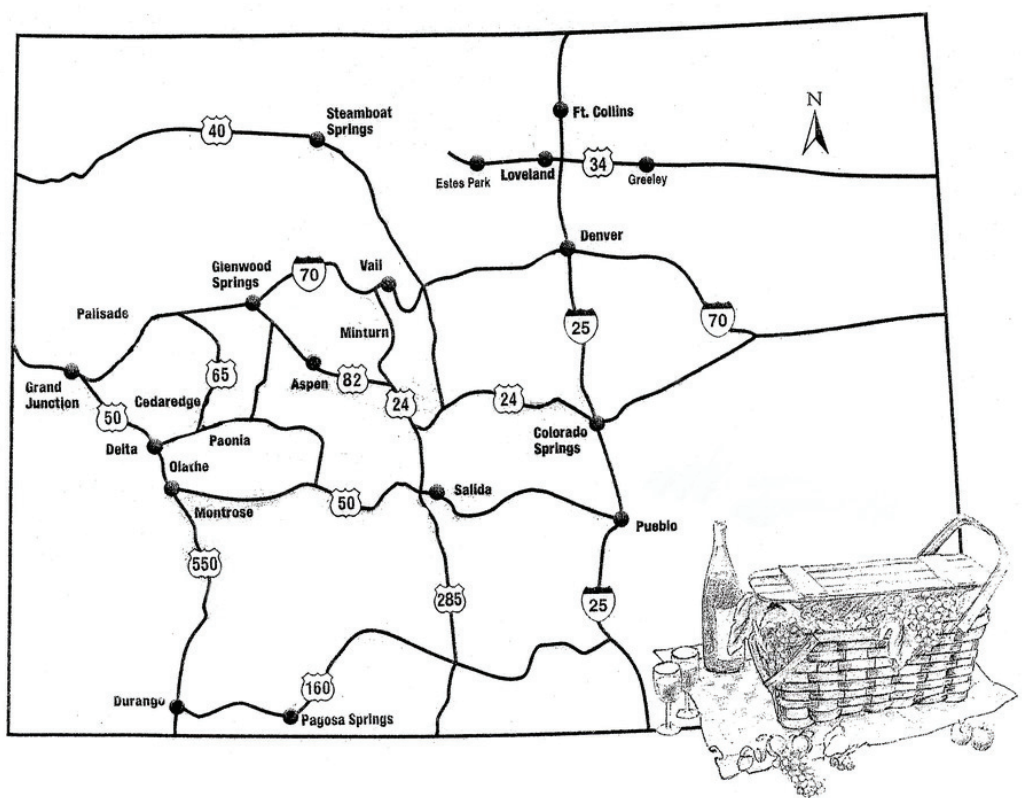

Figure 1. Map of Colorado.

Table 1. Field Trip Stops and Topics

Time	Activity
8:00 AM	Depart Vail
10:00 AM	Arrive Plum Creek Winery, **Stop 1**
11:15 AM	Depart Plum Creek Winery
12:00 Noon	Arrive Varaison Winery, **Stop 2**, eat lunch
2:00 PM	Depart Varaison Winery
2:30 PM	Arrive Carlson Vineyards, **Stop 3**
3:45 PM	Depart Carlson Vineyards, leave for Vail
5:30 PM	Arrive at Vail

WHAT IS TERROIR?

There are five factors that affect every bottle of wine produced. These factors together make each wine unique. First, one has the grape variety. Is it red or white? Is it a cold climate, Pinot Noir, or is it a warm weather Cabernet Sauvignon? Second, what techniques have been used by the winemaker in the making of the wine? Thirdly, one has different vineyard management techniques. How have the vines been trellised? What is the plant density? Fourthly, what is the climate? What is the annual rainfall, and what are the yearly temperatures. Lastly, one has the geology and the resulting soils. Changes in each of these factors will change the characteristics of a wine.

Terroir is a French term for "of a place". It is the summary of the geology, soils and climate of a vineyard (Wilson, 1998; Haynes, 1999). Each vineyard will produce a unique flavor. It is the taste of place! In the Grand Valley we will be studying how the terroir of the wines of the area are affected by the soils, geology and the climate.

COLORADO WINE INDUSTRY

In the United States there are wineries in each of the states except Alaska. Colorado ranks 37th in total acreage of wine grapes (about 500 acres) in the United States (Caskey, 2007). Colorado is essentially a state of many small, boutique wineries. We will be visiting the largest wine grape growing region in Colorado, the Grand Valley Appellation.

Winemaking really started in Colorado in 1883 when the first grape plants were planted near Fruita. In 1890 sixty acres were planted above Palisade. By 1909 there were 1034 farms in Colorado involved in grape production (EPICS, 2001). The US Census in 1899 listed Colorado as having produced 1744 gallons of wine. Prohibition in 1916 put an end to winemaking in Colorado until the first modern grapes were planted in 1968. In 1978, Colorado Cellars Winery opened up as the first modern winery in Colorado. In the western Grand Valley, agriculture was shifting from apples to peaches and grapes. In 1983, there were only 20 acres of wine grapes in Colorado. In 1990, Colorado got its first American Viticultural Area (AVA), Grand Valley, even though it only had four wineries!

Today, there are 70 wineries in Colorado with two AVA's producing 91,000 cases of wine each year (819,517 liters/year). Retail value of the wines is $14 million with an economic impact of $21 million. In those vineyards there are 700 producing acres of grapes with a total of 850 acres of planted grapes. Average yield per acre is 1.9 tons. Average vineyard size is 7 acres. In total there are over 120 grape growers with about 45% of the grapes coming from winery vineyards and the other 55% of the grapes from independent growers (Caskey, 2007).

It seems that Merlot is destined to become the signature grape in Colorado. The Grand Valley AVA produces mainly the warm-weather, heavy red Bordeaux style grapes, whereas the West Elks AVA produces mainly central European "cool climate" grapes like Pinot Noir, Chardonnay, Riesling, and Gewurtztraminer. There are 35 grape varieties of Vitis vinifera grown in Colorado. The percentage breakdown of the main grape varieties in Colorado are: Merlot, 22%; Cabernet Sauvignon 19%; Syrah, 15%; Chardonnay; 11%, Riesling, 9%; and Cabernet Franc, 7% (Caskey, 2007). Rieslings here are very smooth, and they average about 3% residual sugar. Even though the state has more degree days than Napa Valley, it has fewer frost-free days than Oregon so no Zinfandels can be grown here.

During the past two years Colorado wines have won nearly 150 awards for outstanding quality in regional, national and international competitions. These awards include 23 gold medals (Colorado State, 2007)! Today, most of these wines are soil within the state. Costs of the white wines are generally $10-12, and for the reds from $15-20.

TERROIR OF THE GRAND VALLEY

Geology of the Grand Valley

Most of the vineyards (Figure 2) are underlain by the Mancos Shale, but most rest directly on alluvium of terraces from the Colorado River which is a combination of sediments from the surrounding sedimentary rocks. There is also an input of basalt into the sediments from flows found on the top of Grand Mesa nearby. The Mancos Shale is mainly a lithified marine sediment of silts and clays. The soils from this shale tend to have excellent water and plant nutrient holding capacity.

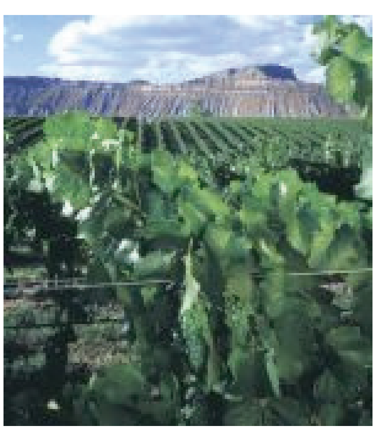

Figure 2. Grand Valley Vineyards.

Climate of the Grand Valley

The extremely dry climate (8 inches/year) with low relative humidity keeps pest and disease pressures low so applications of chemicals and pesticides are almost unnecessary compared with more humid climates. Because most grape vines need at least 20 inches of rainfall each year to survive, most of the vineyards are irrigated. With the elevations of the vineyards in the valley being between 4500 ft. and 4800 ft., these are some of the highest vineyards in the world, and the plants receive intense sunlight.

The high temperature fluctuations between day and night lead to rich colors and high acidity in the wines. The day to night temperatures can range from 25 to 30 degrees F. during the grape maturation period. The long warm daylight hours of intense sunlight mature the fruit completely and build natural sugars. The cool nights allow the grapes to retain the acids vital to premium winemaking. Average temperatures for the Grand Valley from April 1 to October 1 are 79.5 degrees F (average maximum temperature) and 52.2 degrees F (average minimum temperature) (EPICS, 2001). For growing grapes one needs at least 180 days in the growing season (from the last spring frost to the first fall frost). Grand Valley has 207 days (EPICS, 2001).

Bud break generally comes in May. This region experiences mild winters and a short growing season needed for the Bordeaux style grapes. Intense summer temperatures make up the long growing season, but some feel that it leaves some of the wines a little short on flavor then too. Winter hardiness is a major challenge facing the Colorado wine grape growers. Another challenge for grape growers is the chance of extreme weather like baseball-sized hail, high winds, and heat spikes in August and September

Soils of the Grand Valley

The soils of Colorado are generally very alkaline (pH between 7.2-8.5) which makes them similar to soils of the wine regions of France. As a result, Colorado Merlots many times taste more like Bordeaux Merlots than California Merlots. Syrahs are more like Rhone wines than Australian Shiraz. The soils are moderately high in salts, and the vineyards frequently have high potassium and magnesium problems in the grapes. The caliche found in many of the soils is important for it allows for Chardonnay grapes to be grown like in Burgundy where they are on the limestone soils. The soils of the Grand Valley are influenced heavily by eolian inputs creating calcium and gypsum rich soils (Aslan et al., 2003).

GRAND VALLEY WINERIES

The stark, sweeping landscape of the Grand Valley gives dramatic vistas punctuated by towering flat-topped mesas. It is located 250 miles west of Denver. This was Colorado's first AVA. There are 16 wineries in the Grand Valley, and they together produce 90% of the grapes from Colorado (Figure 3). The largest vineyard in the state (Grand River Vineyards) is here, and it is 60 acres. The main grapes grown here are the Bordeaux and Rhone varieties. The Grand Valley is surrounded by three major geological features: The Bookcliffs (northwest), Grand Mesa (east), and the Colorado National Monument (southwest).

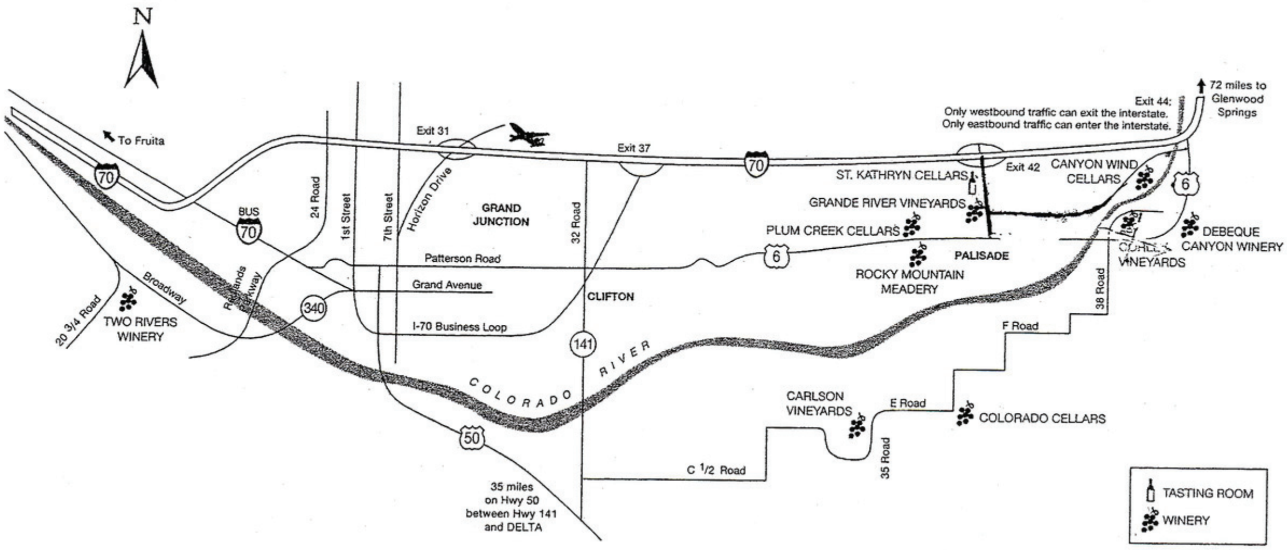

Figure 3. Map of Grand Valley Vineyards.

The second Colorado AVA is the West Elks which is to the east of the Grand Valley along the North Fork Valley of the Gunnison River. The eight wineries there focus on "cool climate" varieties of grapes from central Europe (German wines, Pinot Noir, Chardonnay). The highest winery in the United States is Terror Creek Winery at 6400 ft. elevation in this AVA near Paonia. They receive a little more rainfall (10-12"/year) than the Grand Valley.

<u>STOP 1.</u> PLUM CREEK WINERY

Plum Creek Winery is one of Colorado's oldest wineries and most award-winning wineries (Figure 4). Owners Doug and Sue Phillips and winemaker Jenne Baldwin produce over 13,000 cases annually. They have capacity for over 75,000 gallons of wine in the winery. Grapes from 75 acres of vineyards go into their wines. They have two main vineyards plus buy from other vineyards. They have been growing grapes since 1980, and they use only grapes from Colorado in their wines. They grow the following grapes: Cabernet Sauvignon, Riesling, Cabernet Franc, Chardonnay, Sauvignon Blanc, Sangiovese, Merlot, and Syrah. They have won gold medals with the following wines: Cabernet Sauvignon, Riesling, Cabernet Franc, Redstone Chardonnay, Sauvignon Blanc, Riesling Ice Wine, Syrah, and Sangiovese. (Plum Creek, 2007)

Figure 4. Plum Creek Winery. Photos are of the winery, the owners in the tasting room, and awards (Plum Creek, 2007).

Grand Mesa Vineyard of Plum Creek (Grand Valley AVA), Palisade, Colorado

This 12 acre vineyard is more than 100 feet above the Colorado River on an old stream terrace at the mouth of DeBeque Canyon. The eastern half is planted in Cabernet Sauvignon, and the western part has mainly Cabernet Franc. The vineyard is irrigated, and a cover crop of clover is between the rows. Elevation is 4700 ft. (Plum Creek, 2007).

Redstone Vineyard of Plum Creek (West Elks AVA), near Paonia, Delta County

This 27 acre vineyard was planted in 1987 at an elevation of 6000 ft. Sun shines here with greater intensity, and the vineyard yields less fruit. Spring comes later, and late spring frosts can be a threat into June. The vineyard is almost flat. Today, there are 24 acres of Chardonnay and 3 acres of Riesling. The bedrock of the area is Mancos Shale, but the vineyard is really developed on 15-20 ft. of gravels on an alluvial terrace. Soils have a stony loam texture at the surface and a heavy clay loam texture at depth with a caliche layer at 6-24 inches depth. Much of the alluvium has developed from basalt flows that cap nearby Grand Mesa. High iron content of the soils comes from the weathering of the basalts, giving the soils a red color, hence the name of the vineyard. Chardonnays from this vineyard are more complex and less fruity than those from the Grand Valley AVA vineyards. The vineyard is irrigated. Fruit is limited to 2-3 tons per acre (Plum Creek, 2007).

<u>STOP 2.</u> VARAISON WINERY

This winery is just across the street from Plum Creek Winery and is very new. It does not have a website at the time of writing this guide so we have no information on the site.

<u>STOP 3.</u> CARLSON WINERY

Parker and Mary Carlson started Colorado's fourth winery by planting grapes in 1981 and marketing their first wines in 1988 (Figure 5). Many of their wines are marketed under the name of Cougar Run. In 2003, their Riesling won the World Riesling Cup at the 28th International Wine Competition in Corning, New York. One hundred fifty six wines from over 9 countries were entered in the competition, and Carlson won the Best of Class in the semi-sweet category. They produce about 20,000 gallons of wine per year. They produce mainly Merlot, Shiraz, Chardonnay, Riesling, Gewurtztraminer, Muscat, and Lemberger. They use some unique names for their wines like Tyranosaurus red which is their largest volume wine that is mainly Lemberger. This red wine is more tannic and acidic and is best drunk with food. It comes from a high yield, too, of four tons/acre. They also have a Pinotsaurus red, a Pearadactyl (pear fruit wine), Prairie Dog Blush and Fat Cat Muscat. They have many blends of the heavy red wines. This winery has been named several times in years past at Colorado's Favorite Winery".

Figure 5. Carlson Winery owners in the tasting room.

<u>STOP 4.</u> DEBEQUE WINERY (if there is time)

Bennett Price and his wife, Davy, opened this winery in 1998 and have been successful since then (Figure 6)! He produces about 3000 gallons of wine each year. He is a retired geologist! The vineyards are located 1.5 miles from the town of Palisade at the entrance to Debeque Canyon. He produces wines from the following grapes: Chardonnay, Gewurtztraminer, Viognier, Syrah, Merlot, Tempranillo, Malbec, and Cabernet Sauvignon. His signature and award winning wine is Claret, which is a Bordeaux-style blend of Cabernet Sauvignon, Cabernet Franc, Merlot, Malbec, and Petite Verdot. He has also been experimenting with two different ports.

Figure 6. Debeque Canyon Winery and Bennett Price, owner (Debeque, 2007).

REFERENCES

Aslan, A., Wilson, R., Riddle, P, and Quist, E., 2003, Eolian influences on soils of the Grand Valley, Western Colorado. Abstracts with Programs, Geological Society of America, Vol. 35, No. 6, p. 170.

Carlson, 2007, www.carlsonvineyards.com.

Caskey, D., 2007, www.coloradowine.com.

Colorado State, 2007, www.colostate.edu/Depts/Coop/Ext/TRA/PLANTS/wine.html

Debeque, 2007, www.debequecanyonwinery.com.

EPICS, 2001, The soul of wine, term paper written for the engineering practices introductory course sequence at Colorado School of Mines, 8 pages.

Haynes. S.J., 1999, Geology and Wine 1: Concept of terroir and the role of geology. Geoscience Canada. Vol. 26., pp. 190-194.

Plum Creek, 2007, Plum Creek Winery, www.plumcreek.com.

Wilson, J., 1998, Terroir. University of California Press, Berkeley, CA., 336 pages.

GRAND MESA LANDSLIDE COMPLEX

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OVERVIEW

This one-day field trip involves visits to sites on Grand Mesa, a 3400-m-high, flat-topped mountain in western Colorado (Fig. 1). All stops are along Colorado Highway 65 to ensure their accessibility in early June. The trip highlights ancient slump blocks that surround much of Grand Mesa and formed during the break-up of its basalt cap rock (Table 1). The trip will also briefly cover the bedrock and surficial geology of the area. Planned stops show stages in slump-block progression from incipient blocks formed in the basalt cap rock to their final destruction by modern earth flows, slump-block morphology and anatomy, landslide mechanisms, and overviews of enormous slump-block complexes.

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Plateau Creek (Drive By)	Geologic setting, bedrock Geology	Rex Baum
Town of Mesa (Drive By)	Geologic setting, glacial geology	Rex Baum
Entrance to Grand Mesa National Forest (Drive By)	Geologic setting, bedrock and earth slides	Rex Baum
Skyway Point (Stop 1)	Overview and age of huge basalt slump blocks	Rex Baum
Island Lake (Drive By)	Incipient slump blocks, Lakes on the landslide bench	Rex Baum
Abandoned quarry (Stop 2)	Anatomy of a slump block	Rex Baum
Ward Reservoir (Stop 3)	Claystone outcropping, slump block mechanics	Rex Baum
Grand Mesa Visitor's Center (Stop 4)	Lunch	--
Mesa Lakes (Stop 5)	Slump block cross section & panorama, stages of formation and degradation.	Rex Baum
Active earth slide (Stop 6)	Final destruction of slump blocks, modern landslide problems	Rex Baum

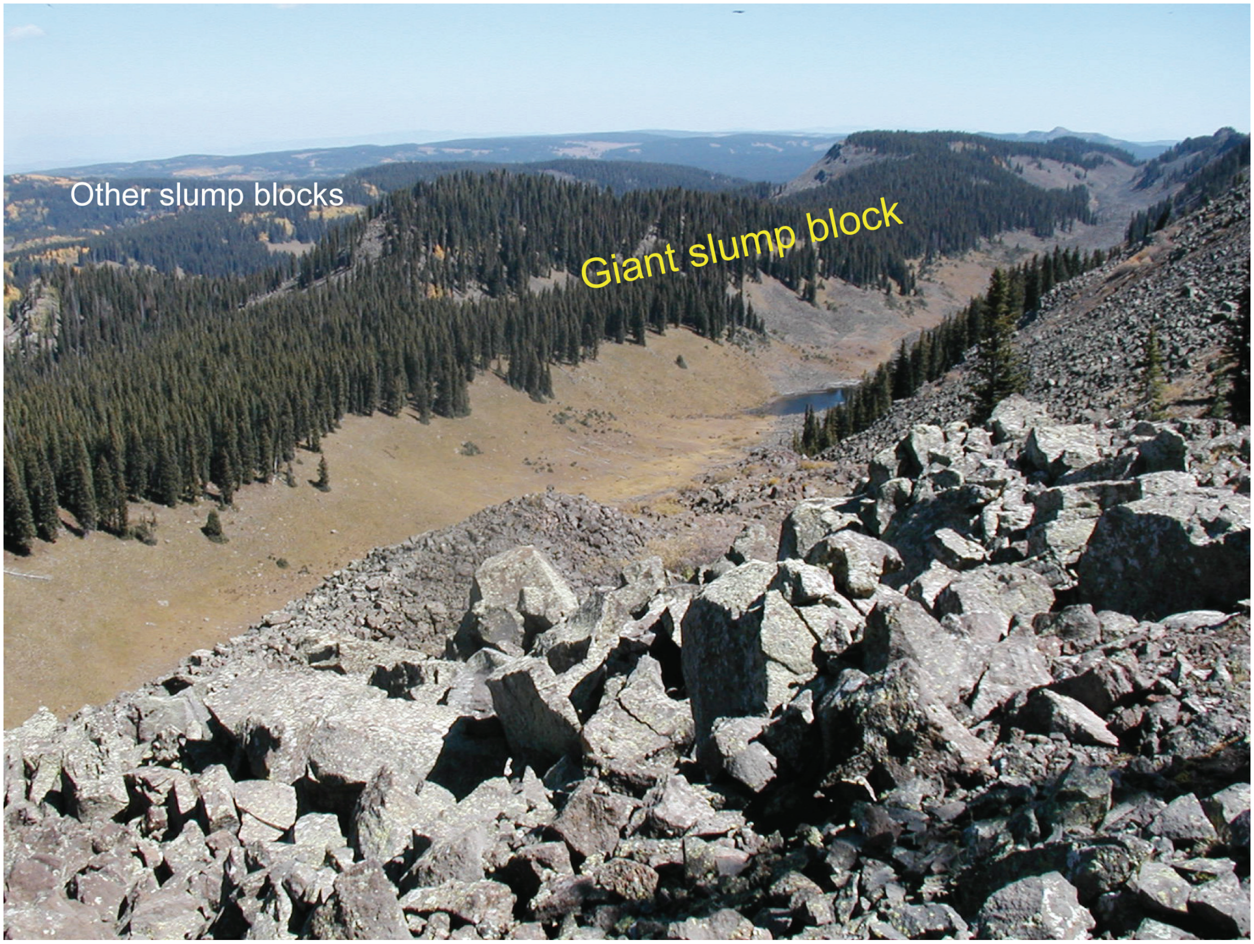

Figure 1. View to northeast from Crag Crest, a narrow basalt remnant at the east end of Grand Mesa. Small lake near center of photograph occupies a trough between talus-covered in-place basalt cap rock (right edge) and a giant basalt slump block (center, left). The crests of other slump blocks are visible in the upper left part of the photograph.

TRIP ROUTE DESCRIPTION AND MAPS

Although this field trip begins and ends in Vail Colorado, other field trip guides prepared for the North America Landslide Conference (June 3-8, 2007) cover the route from Vail along Interstate Highway 70 to the starting point of this trip. The field trip covered by this guide begins and ends at the point of departure from the Interstate Highway 70 field trip route, 130 miles west of Vail.

This field trip begins at the junction of Interstate Highway 70 (I-70) and Colorado Highway 65 (CO 65), near the mouth of Plateau Creek, in DeBeque Canyon (Fig. 2 and Table 2). From I-70, the route follows CO 65 east along Plateau Creek and then south through the town of Mesa and up the north face of Grand Mesa, to Stop 1 at Skyway Point (Table 1 and Fig. 2). The trip continues across the top of Grand Mesa as far south as Ward Reservoir (Stop 3). After the stop at Ward Reservoir, the trip returns northward along CO 65 to the Grand Mesa Visitor's

Center (Stop 4, lunch stop), Mesa Lake overlook (Stop 5) and finally Stop 6 on the north edge of the landslide bench. The trip returns to its starting point at I-70 by way of CO 65.

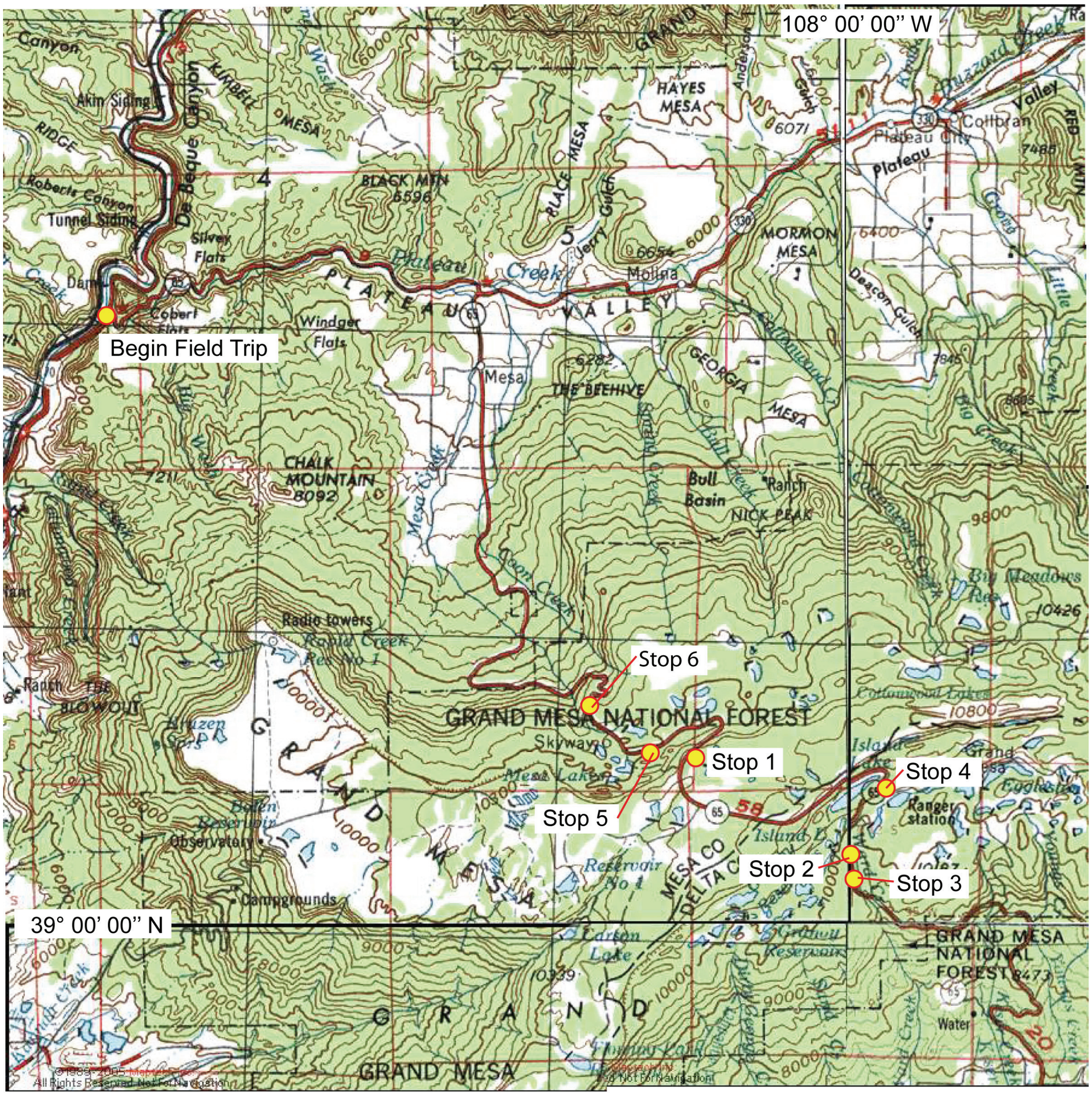

Figure 2. Field trip route along Colorado Highway 65 from Interstate 70 across Grand Mesa. (Base by USGS, Grand Junction, Leadville, Montrose and Moab, 1 x 2 degree sheets)

Table 2. Mileage from Start of field trip at Colorado Highway 65 Interchange with Interstate 70 (130 miles west of Vail, Colorado) to Skyway Point (Stop 1).

Mileage	Description
0.0 (from start) 0.0 (cumulative)	Exit westbound I-70. From right lane, take exit ramp (Exit 49) to CO 65. At top of ramp, turn left and cross over I-70 and follow CO 65 up Plateau Creek. Begin Plateau Creek (Drive By)
10.4 (from start) 10.4 (cumulative)	At junction with Colorado Highway 330 (to Molina and Colbran) turn right to stay on CO 65.
11.9 (from start) 11.9 (cumulative)	Enter town of Mesa, continue south on CO 65 (Drive By) past the turnoff for Powderhorn Ski Area and the entrance to Grand Mesa National Forest.
21.3(from start) 21.3 (cumulative)	Enter Grand Mesa National Forest, continue on CO 65 (Drive By)
29.2 (from start) 29.2 (cumulative)	Skyway Point Overlook. This is Stop 1. In case there is not sufficient space to park a tour bus, drive on to the alternate parking area.
29.5 (from start) 29.5 (cumulative)	Skyway Point parking area. This is an alternate Stop 1. There will be a short hike to the Skyway Point Overlook.

PLATEAU CREEK (DRIVE BY)

The field trip area is in the southern part of the Piceance basin and within the northeast part of the Colorado Plateau physiographic province. From Interstate 70, Highway 65 follows the gorge of Plateau Creek eastward for several miles. As we drive eastward through the meandering gorge, we see brown sandstone with a few thin shale and coal interbeds. These rocks belong to the lower part of the Upper Cretaceous Mesaverde Formation.

General Geology

After driving a few miles we begin to emerge from the gorge and can see the rim of Grand Mesa to the south. The mesa is capped by a thick sequence of basalt flows of Miocene age (Marvin et al., 1966; Yeend, 1969). Slumping at the edge of the mesa has created a broad, gently sloping landslide bench that surrounds the basalt cap (Figs. 1 and 2). Toward the east, slumping has almost completely destroyed the basalt cap leaving small remnants surrounded by numerous slump blocks (Fig. 3, also Yeend, 1969). Upper Cretaceous and lower Tertiary (Paleocene through upper Eocene) sedimentary rocks underlie the lower slopes surrounding Grand Mesa. These rocks dip gently to the northeast beneath the western half of the mesa and gently to the northwest beneath the eastern half of the mesa, defining the north-trending axis of the Montrose syncline, which passes approximately through the east end of Grand Mesa (Ellis & Gabaldo, 1989).

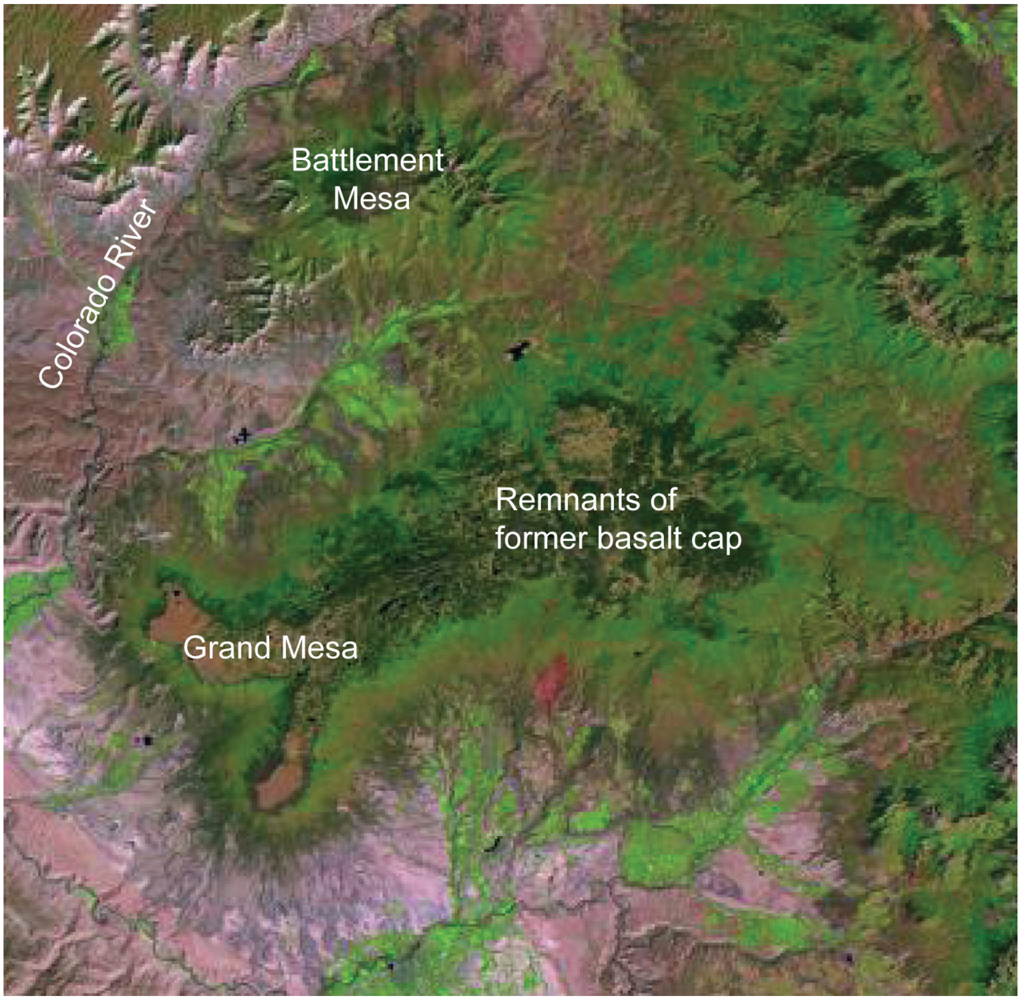

Figure 3. Landsat 5 Thematic Mapper Image (part of Scene 5035033000425910, 2004/09/15) of Grand Mesa and surrounding area. The former extent of the mesa included a large area to the northeast of present day Grand Mesa (Remnants of former basalt cap) and Battlement Mesa to the north (Yeend, 1969; Cole and Sexton, 1981).

TOWN OF MESA (DRIVE BY)

The town of Mesa is built on terrace gravels deposited during the last glaciation of Grand Mesa (Yeend, 1969). Underlying bedrock is the Mesaverde Formation and the Wasatch Formation. Variegated shale and claystone with lenticular sandstone, conglomerate, and limestone occur in the lower part of the Wasatch; thick, brown, massive, ledge-forming arkosic sandstone, locally conglomeratic comprises the middle part; and purple to red claystone the upper part (Donnell, 1969; Yeend 1969).

Glacial & Surficial Geology

Yeend (1969) recognized at least three ages of glacial deposits in the vicinity of Grand Mesa. All the stops on the field trip are in areas where Yeend (1969) mapped deposits of the last, Pinedale(?) glaciation. Shortly after we drive south out of Mesa, the highway will cross the terminal moraine of a valley glacier that flowed down Mesa Creek drainage from the top of Grand Mesa. Watch for the hummocky surface of the till, which is strewn with rounded but relatively unweathered basalt boulders.

Geologists differ on the nature of deposits on either side of the lobe of till in Mesa Creek. Yeend (1969) mapped these as earth flow and soil creep deposits; Cole and Sexton (1981) similarly mapped them as Pinedale colluvial deposits. However, Ellis and Gabaldo (1989) identified deposits to the west of Mesa Creek as Bull Lake or pre-Bull Lake glacial till.

ENTRANCE TO GRAND MESA NATIONAL FOREST (DRIVE BY)

Slopes steepen after we pass the entrance to Powderhorn Ski area; begin noticing evidence of recent/active landslides, including road damage and lines of large boulders along the edge of the highway used as barriers to shallow earth flow movement. Once we enter Grand Mesa National Forest, bedrock belonging to the Wasatch, Green River, and Uinta Formations is locally exposed in road cuts (Ellis and Gabaldo, 1989).

After passing through a series of switchbacks, CO 65 levels out on the gently sloping landslide bench (Figs. 2 and 5). Strongly weathered and degraded slump blocks are interspersed with talus, glacial deposits and lakes. As the highway approaches the turnoff to Mesa Lake, slump blocks increase in height and their forms become sharper.

<u>STOP 1.</u> SKYWAY POINT

As we make the final climb to the north edge of Grand Mesa, a panorama of slump blocks and lakes covering the landslide bench opens to view toward the west and northwest. Rather than try to park a 50-passenger bus at the one of the overlooks along Highway 65, we will drive to a nearby parking area on top of Grand Mesa and hike back to the overlook. Standing at the overlook, we can see large numbers of tree-covered ridges. Many have an armor of basalt blocks along their crests. Viewed from the air, it is apparent that these ridges are slump blocks arranged in either linear or concentric patterns (Figs. 4, 5, and 6). Glacial deposits, talus, and lakes occupy the intervening troughs. A large incipient slump block occupies the area directly west of CO 65 (Fig. 5). Figure 7 is a geologic cross section that shows the relationship between the slump blocks and the other geologic units in this area.

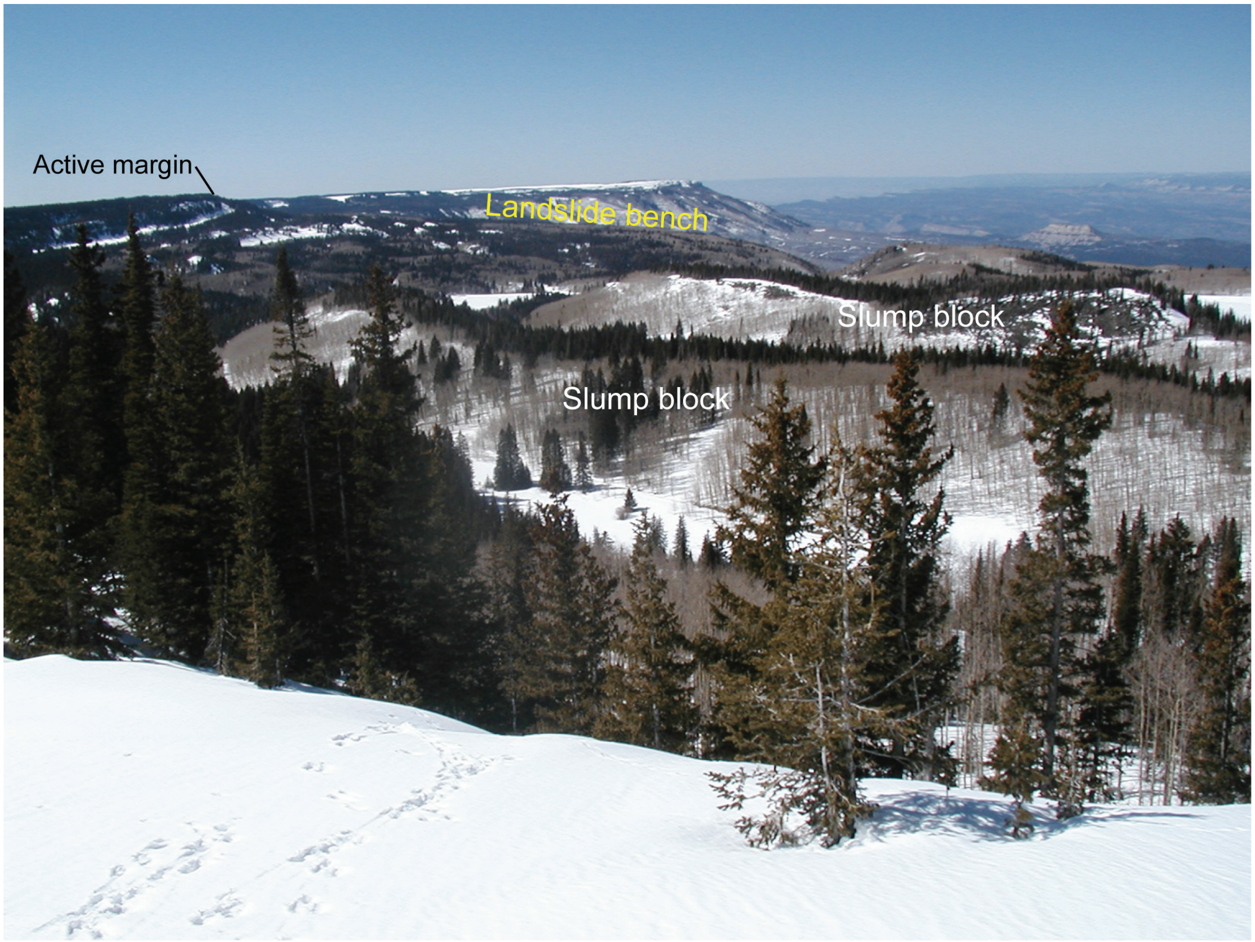

Figure 4. View toward northwest from Skyway Point (Stop 1). The slump blocks near the center of the photograph were formerly part of Grand Mesa's basalt cap rock and their backslopes (facing the viewer) were formerly horizontal. A profile of the landslide bench is visible in the middle distance. The active margin is the present edge of the basalt cap.

Age of Slump Blocks

Most slump blocks probably moved during the Pleistocene and are presently inactive; however, a few incipient blocks (blocks that have been displaced less than a few meters) may have first moved during the late Holocene. Most blocks probably slumped to their present positions before the last glaciation of Grand Mesa (Pinedale(?)); fresh glacial striations are present on both sides (scarp slope and back slope) of several slump blocks, and undisturbed till of Pinedale(?) age is present in valleys between slump blocks. Had striations occurred only on the back slopes of the blocks (former mesa surface) and the till been absent or disturbed between blocks, the blocks would clearly be postglacial features (Yeend, 1969). A few incipient blocks were active in the 1960's and moved 0.17-0.60 in/yr (0.43-1.5 cm/yr); however, monitoring over a period of eight years (1963-1971) detected no movement in others (Yeend, 1969; 1973). Assuming continuous movement at these rates since their inception, and dividing the total displacement of the active blocks by their rate of movement, we estimate that some of the active blocks (Yeend, 1973) could have started moving as little as 130-1500 years ago. Thus even though movement rates have undoubtedly varied through time, it seems probable that the actively moving incipient blocks first moved during the Holocene. Inactive incipient blocks may have moved during either Pleistocene or Holocene time.

After enjoying the vistas at Stop 1, head south across Grand Mesa to stop 2 (Table 3).

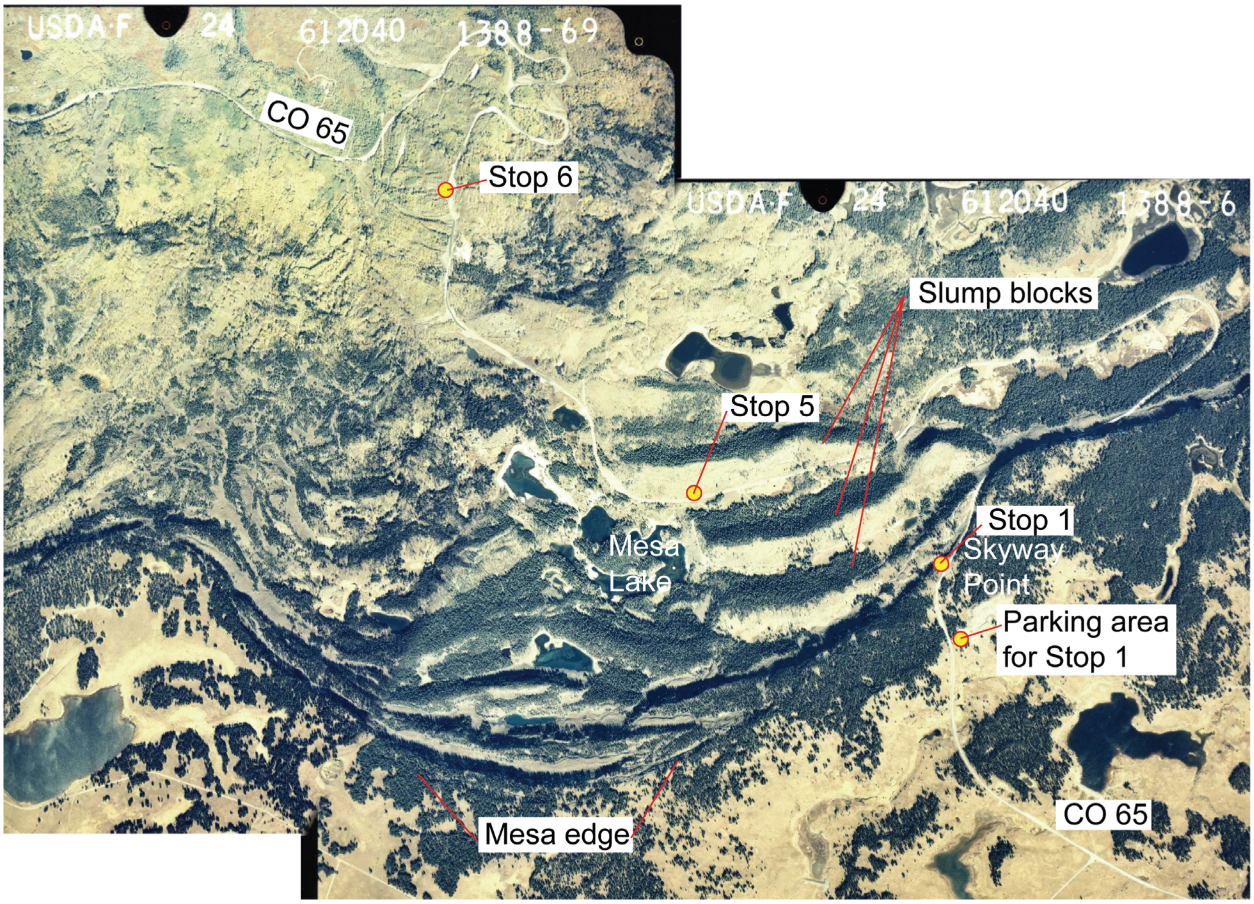

Figure 5. Vertical aerial photographs (USDA Forest Service, Roll 1388, frames 6 and 69, 9/20/1988) showing locations of stops 1, 5, & 6. Slump blocks of various sizes and relative ages are visible in the area to the left of stop 1. Three of the largest ones along this segment of the field trip route are labeled.

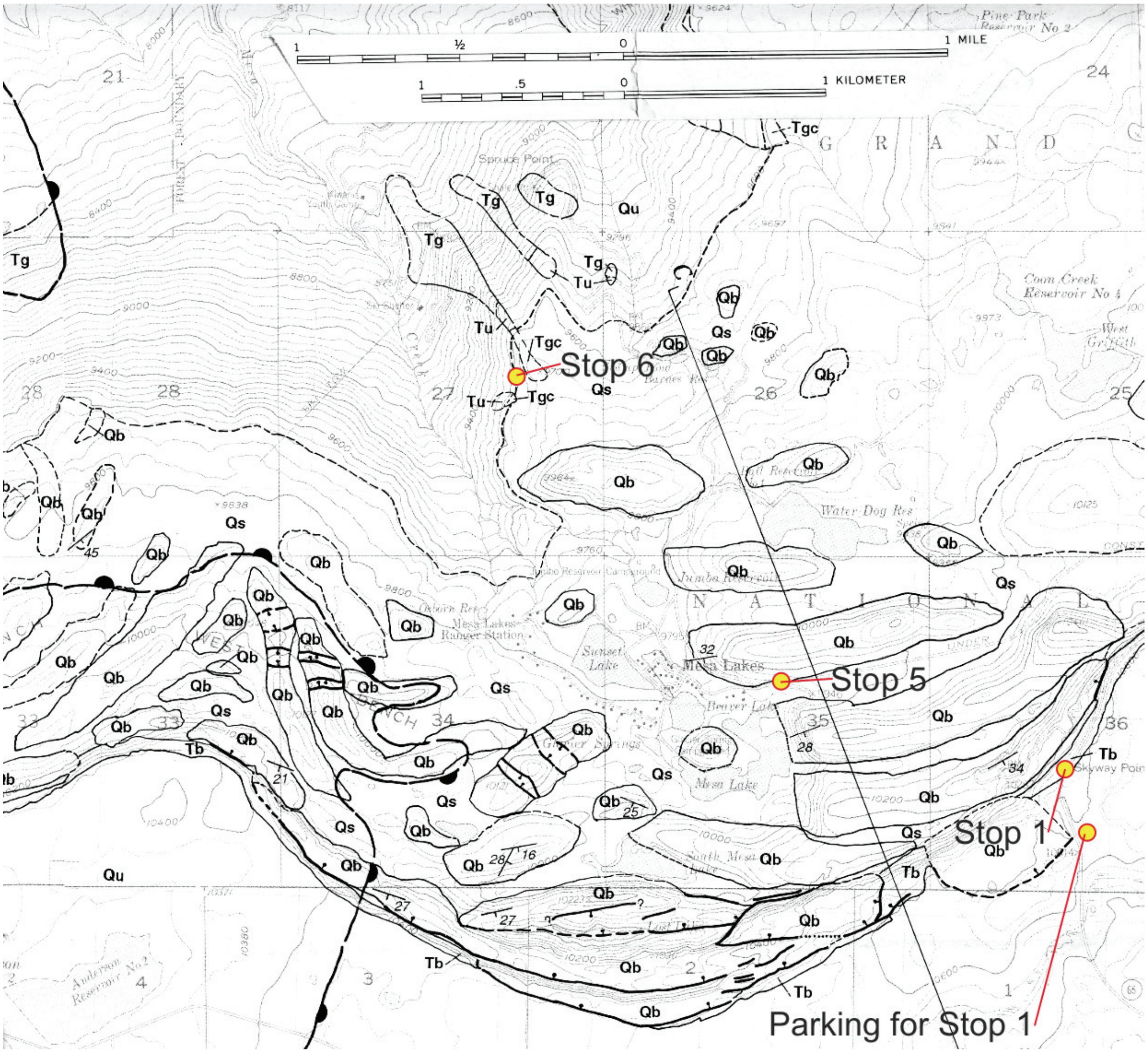

Figure 6. Portion of Baum and Odum's (1996) geologic map of area included in Stops 1, 5 and 6. Map units, Qb, coherent basalt slump blocks; Qs; noncoherent slump deposits (deformed claystone, locally covered by other surficial deposits); Qu, surficial deposits, undivided (includes talus, till, outwash, colluvium alluvium, rock glacier, and landslide deposits; Tb, basalt; Tgc, gravel and claystone beds; Tg, Green River Formation (oil shale, sandstone, and siltstone) Tu, Uinta Formation (fossil-bearing sandstone, marlstone and siltstone). Line work, unornamented, formation contact; small ball, shallow fault, ball on downthrown side; filled half circles, western limit of Pinedale(?) glacial deposits.

Table 3. Mileage from Skyway Point (Stop 1) to Abandoned Quarry (Stop 2).

Mileage	Description
0.0 (from Stop 1) 29.5(cumulative)	Leave Skyway Point parking lot. From parking lot, turn left and head south on CO 65.
4.2 (from Stop 1) 33.7 (cumulative)	Island Lake on right (Drive By)
6.3 (from Stop 1) 35.8 (cumulative)	Abandoned basalt quarry. Park a short distance north of the quarry at road cut exposing northward dipping basalt beds. Parking area is on east shoulder of road. After looking at road cut, walk south along shoulder of road 0.5 mi. to quarry. This is Stop 2.

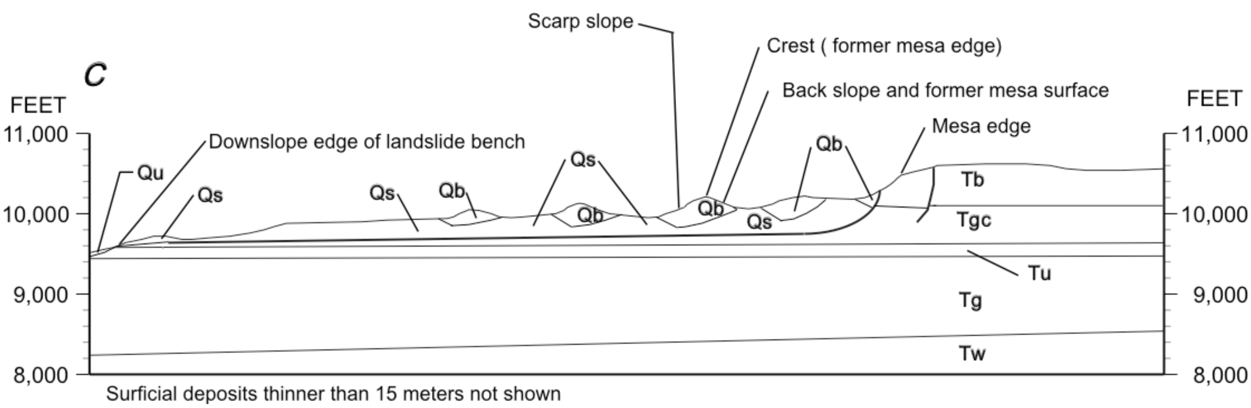

Figure 7. Northern part of Baum and Odum's (1996) cross section C-C' indicated in Figure 6 (looking east). Map units, Qb, coherent basalt slump blocks; Qs; noncoherent slump deposits (deformed claystone, locally covered by other surficial deposits); Qu, surficial deposits, undivided (includes talus, till, outwash, colluvium alluvium, rock glacier, and landslide deposits; Tb, basalt; Tgc, gravel and claystone beds; Tg, Green River Formation (oil shale, sandstone, and siltstone), Tu, Uinta Formation (fossil-bearing sandstone, marlstone and siltstone), Tw, Wasatch Formation. Line work, unornamented, formation contact; heavy line, shallow fault or landslide basal shear surface.

ISLAND LAKE (DRIVE BY)

As we depart the Skyway Point parking lot and head south across the gently undulating surface of Grand Mesa we see relict glacial features and thin deposits of Pinedale(?) till. Near the south rim of Grand Mesa, the highway turns east and begins to descend toward Island Lake. The initial descent is across the head scarp of a large slump and then down onto an eastward sloping, inactive slump block that is "frozen" in an early stage of its downward movement (Figs. 8 and 9). Downward displacement of this block is greater on its east end than the west, resulting in an eastward tilt in addition to backward tilting (toward the northwest) as the block slid away from the mesa rim. Similar lateral tilting has been observed in a number of other slump blocks along the edge of the mesa.

Figure 8. Vertical aerial photographs (USDA Forest Service, Roll 1288, frames 201 and 210, 9/29/1988) showing locations of stops 2, 3, and 4.

Figure 9. Part of Baum & Odum's (1996) map for area included in Stops 2, 3, and 4. Map units, Qb, coherent basalt slump blocks; Qs; noncoherent slump deposits (deformed claystone, locally covered by other surficial deposits); Qu, surficial deposits, undivided (includes talus, till, outwash, colluvium alluvium, rock glacier, and landslide deposits; Tb, basalt; Line work, unornamented, formation contact; small ball, shallow fault, ball on downthrown side; filled circle with number, sample location.

STOP 2. ABANDONED QUARRY

Stop 2 is in an abandoned basalt quarry on the west side of CO 65. This stop is an opportunity to see internal structure of one of the many large slump blocks on the landslide bench that partially surrounds Grand Mesa. A road cut just before Stop 2 exposes backward tilted basalt layers in the same slump block exposed at the quarry. The beds dip steeply toward the northwest, which is also toward the in-place basalt cap of Grand Mesa. The quarry exposes dipping basalt beds underlain by gray sandstone and red claystone of the unnamed (Miocene or Oligocene) gravel and claystone unit found throughout the area (Fig. 10). The unit directly underlies the basalt and ranges in thickness from 15 m near the west edge of Grand Mesa to about 240 m near Crag Crest, about 3 km east of Stop 2 (Yeend, 1969). Stop 3 provides a better look at the claystone (Table 4).

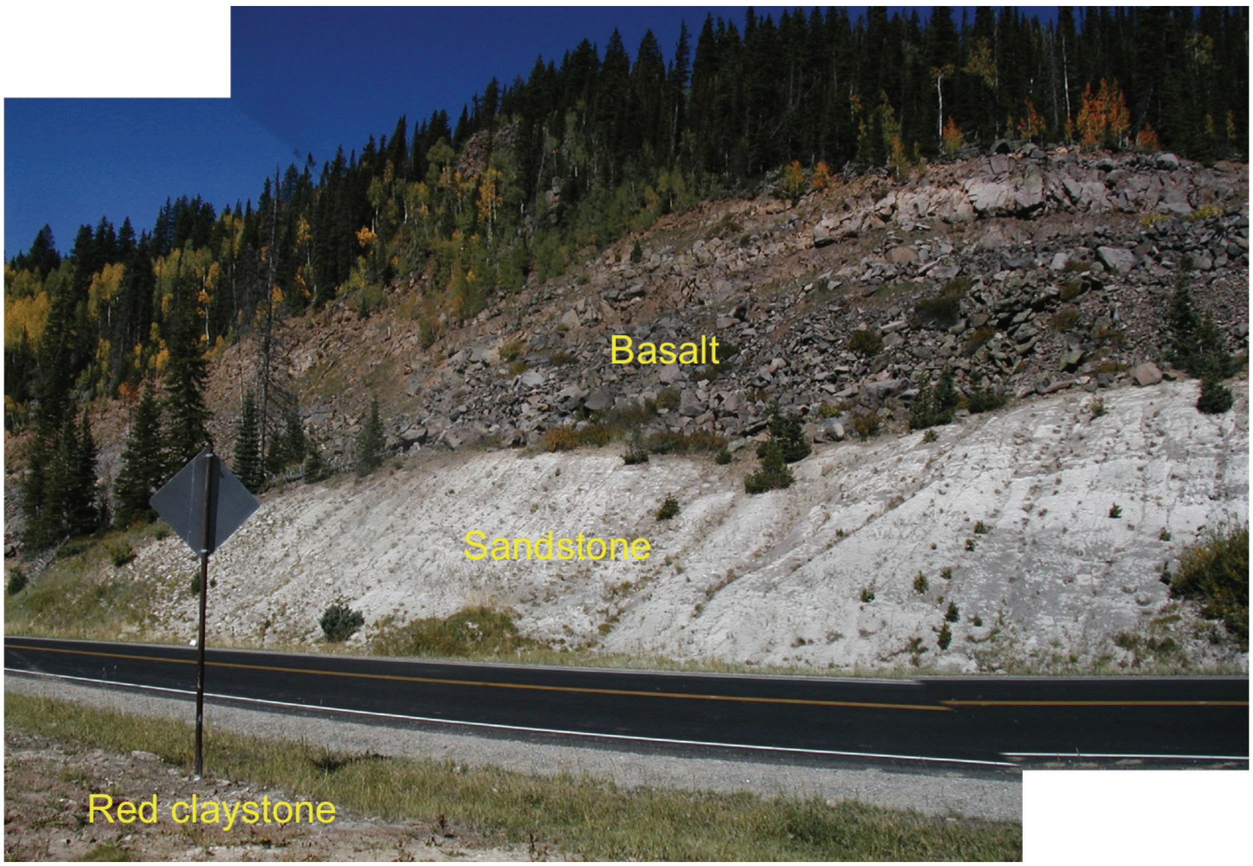

Figure 10. View to southwest at abandoned quarry (Stop 2). Red claystone is the lowest unit here (lower left corner of photograph). Gray, poorly cemented sandstone overlies the claystone and crops out along the opposite side of the highway. Layered basalt overlies the sandstone to the top of the ridge. The basalt dips away from the viewer.

Table 4. Mileage from Abandoned Quarry (Stop 2) to Ward Reservoir (Stop 3).

Mileage	Description
0.0 (from Stop 2) 35.8 (cumulative)	Leave abandoned quarry. From quarry, drive south on CO 65.
1.2 (from Stop 2) 37.0 (cumulative)	Turn left into parking area adjacent to Ward Reservoir. This is Stop 3.

STOP 3. WARD RESERVOIR

Stop 3 is a chance to get a closer look at the variegated claystone of the gravel and claystone unit that underlies Grand Mesa's basalt cap and is largely responsible for the early destruction of the east half of the cap by retrogressive slumping. Although claystone deposits found throughout the Grand Mesa area range in color from red and white through green and gray; red is the dominant color at this location. Figure 11 shows complex folding of claystone layers exposed after failure of the road cut at Stop 3.

The abundance of claystone beneath the basalt flows is probably a key factor in the widespread slumping of Grand Mesa (Yeend, 1969). Baum and Odum (1996, 2003) examined deformed beds of claystone and clayey sand exposed in road cuts near this stop and elsewhere around Grand Mesa and tested representative samples in the laboratory. The claystone and clayey sand are uncemented or weakly cemented, contain little or no material coarser than 0.425 mm, and behave plastically when remolded. The claystone has high plasticity and the clayey sand has low plasticity. High plasticity of the claystone is consistent with the deformation and folding observed in claystone exposures (Yeend, 1969) and with the low shear strength (coeffcient of residual friction of 0.096–0.13, residual cohesion of 0–60 kPa, under normal stresses up to 2.75 MPa) determined by laboratory tests (Baum and Odum 2003). Vertical loading of the weak claystone beds by the overlying basalt cap rock causes it to deform laterally, which in turn puts the cap rock in tension, thus contributing to break-up of the cap rock. Low shear strength of the claystone is also necessary to explain the transport of slump blocks across the gently sloping landslide bench (Baum et al. 1996, Baum 1997).

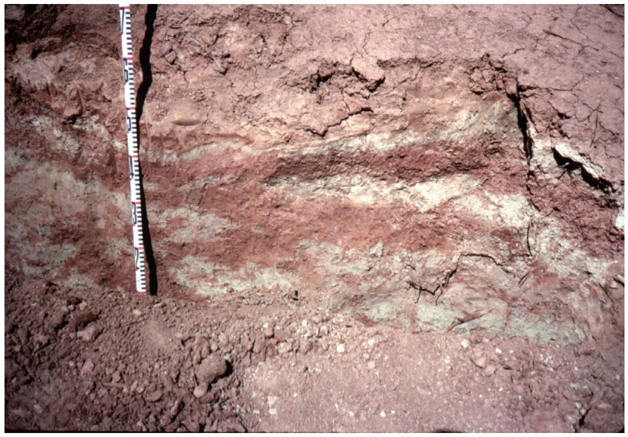

Figure 11. Claystone exposed in road cut at Stop 3. Left, road cut with shallow slope failure illustrating the low shear strength of the variegated claystone, Right, view of folded strata within the claystone.

See Table 5 for directions from Stop 3 to Stop 4.

Table 5. Mileage from Ward Reservoir (Stop 3) to Grand Mesa National Forest Visitors Center (Stop 4).

Mileage	Description
0.0 (from Stop 3) 37.0 (cumulative)	Leave Parking area at Ward Reservoir. From parking area, drive north on CO 65.
1.7 (from Stop 3) 38.7 (cumulative)	Turn right into parking area adjacent to Cobbett Lake (Carp Lake on map) and Grand Mesa National Forest Visitors Center. This is Stop 4.

STOP 4. GRAND MESA VISITOR CENTER

Stop 4 is the lunch stop. Picnic tables are south of the parking lot. While you eat lunch enjoy the scenery of this glacially modified slump-block terrain (Fig. 12). Most of the lakes are in natural depressions formed between slump blocks and enhanced by glacial processes. In the early 1900s most of these lakes were enlarged by construction of earthen dams (Schuster, 2006). Grand Mesa has the largest concentration of lakes in the western U.S. In addition to recreation, the lakes supply irrigation water to many orchards south of Grand Mesa. Table 6 gives directions to Stop 5.

Figure 12. Aerial view, looking west, of Crag Crest (right-center of photograph) and many lakes and glacially modified slump blocks on the south side of Grand Mesa (left half of photograph).

Table 6. Mileage from Grand Mesa Visitor Center (Stop 4) to Mesa Lake Overlook (Stop 5).

Mileage	Description
0.0 (from Stop 4) 38.7 (cumulative)	Leave parking area at Ward Reservoir. From parking area, drive north on CO 65.
9.7 (from Stop 4) 48.4 (cumulative)	Drive across Grand Mesa and down the north edge of the mesa After CO 65 turns back toward the west, watch for Forest Road 253 (near Spruce Grove campground) and park along the right shoulder of the highway. This is Stop 5.

STOP 5. MESA LAKE OVERLOOK

Leave the bus and cross CO highway 65 to the entrance of Forest Road 253. Hike a short distance up the road to see a cutaway view of a basalt slump block on your left. Look to the right (west) to see a panorama across the landslide bench (Fig. 13).

Figure 13. Photograph of landslide bench from Mesa Lake overlook. Mesa Lake in foreground. The western part of Grand Mesa is on the horizon, Tree-covered slump blocks in foreground.

Shape of the failure surface

Several observations constrain the general shape of the basal failure zone beneath slump block complexes at Grand Mesa (Fig. 7). Steeply inclined fractures occur at the heads of the complexes, where slump blocks separate from the edge of the mesa. After the head fracture opens, the blocks move downward and outward and become strongly back-tilted. Block crests on the landslide bench have relatively wide spacing and the landslide bench slopes gently away from the mesa. These combined observations indicate that the block complexes have moved on listric failure zones that are steeply inclined at the head, bend sharply beneath the slump block, and gradually flatten toward the toe of the landslide complex at the downslope edge of the landslide bench. Analyses of strike and dip measurements and ground-surface profiles for several slump complexes at Grand Mesa indicate that the profile of the curving part of the failure surface is more like a cycloid or hyperbola than a circle (Baum and Odum, 2003). Both cycloidal and hyperbolic slip-surface profiles allow backward rotation of a slump consistent with the amount observed in the field; whereas a circular slip-surface profile allows less than the observed amount of backward rotation.

Slump Block development and degradation

Slump-block profiles change gradually as movement and degradation progress (Baum and Odum, 1996, 2003). The western part of Grand Mesa has been free of glacial ice since the end of Bull-Lake(?) time and glacial processes have done little to alter or obscure profiles of the slump blocks. Study of Baum and Odum's (1996) map and cross sections, supplemented by field observation, shows that blocks have similar, though less distinct, profiles in areas glaciated during Pinedale(?) time. Figure 14 shows profiles of blocks after various amounts of movement and weathering, based mainly on observations to the southwest of here (Figs. 4, 5, 6, 7, and 13).

The initial profile of a slump block depends on the topography of the mesa top and the underlying basalt. The mesa top undulates gently and slopes toward the southwest. Some flow units in the basalt are thick and massive and form near-vertical cliffs 20-60 m high at the mesa edge, whereas others ravel as an adjacent slump block subsides leaving the mesa edge rounded at the top and the scarp covered with talus (Figs. 1 and 5). Raveling and talus accumulation has occurred on scarps as small as 3-12 m high. Thus, some slump blocks start out with a nearly flat top, sharp or slightly rounded edge, and a steep, nearly vertical, face, while others start with a nearly flat or undulatory top, a rounded edge, and a sloping, talus-covered face (Fig. 14A).

As a block rotates, dropping away from the mesa and tilting towards it, the relict mesa surface forms a back slope and the former mesa edge becomes the crest of the slump-block ridge (Fig. 14B). The back slope gradually becomes steeper as downward displacement (and backward rotation) increase (Fig. 14C). This relation between increasing downward displacement and tilt is apparent in slump blocks south of Mesa Lake, and northwest of Island Lake (Stop 4). Meanwhile, a linear or crescent-shaped depression forms at the base of the back slope, between the block and the new mesa edge (Figs. 7 and 14C). Ponds or lakes, such as Mesa Lake (Fig. 13), may occupy the depression; most lakes in the area, although retained by artificial dams, occupy such depressions (Schuster, 2006). A low bulge or ridge commonly forms downhill from the coherent slump block (Figs. 14C and 14D) probably as a result of compression of claystone and surficial deposits below and ahead of the slump block. Such bulges are apparent downslope from several coherent slump blocks on color aerial photographs of the Mesa Lakes and West Bench area (Fig. 5). Finally, after much downward movement and backward rotation, the block reaches the landslide bench (Figs. 7 and 14D).

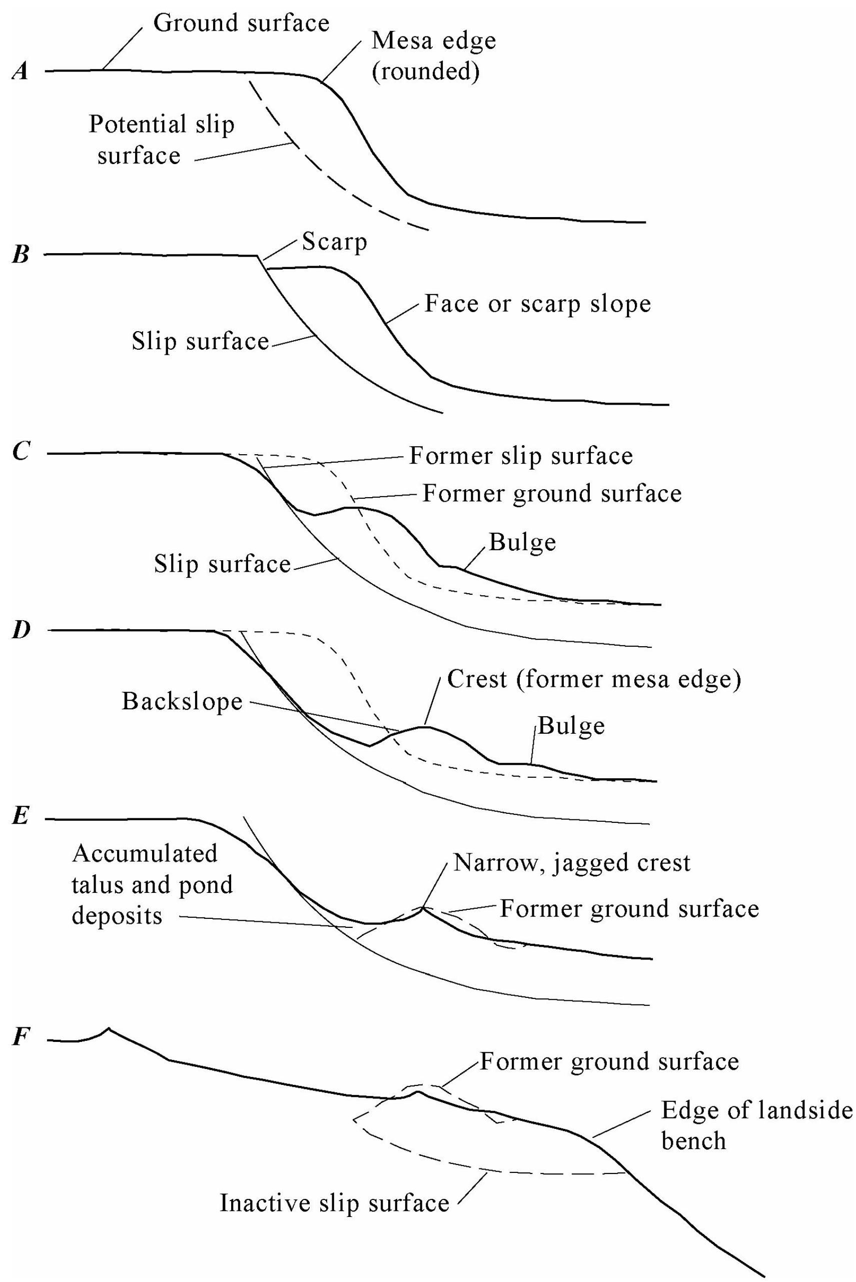

Figure 14. Stages in slump block formation and degradation (after Baum & Odum, 1996) The same slump block is depicted in all six profiles, *A*, …, *F*, but the active margin of the mesa is far to the left of profile *F*.

By the time a block reaches the landslide bench, its slopes begin to flatten; the depression gradually fills with talus deposits and pond sediment until most of the former mesa top is buried (Fig. 14E). Meanwhile the crest of the ridge (former edge of the mesa) erodes and ravels to form a narrow, jagged crest ridge and most of the scarp slope below becomes covered with talus deposits (Figs. 5 and 13). Many blocks near the edge of the landslide bench are soil covered and forested, and have low, rounded, asymmetrical profiles. Such blocks probably represent a late stage of slump-block evolution (Figs. 7 and 14F). Retreat of steep slopes below the landslide bench undermines blocks near the edge of the bench, resulting in their incremental collapse over the edge of the landslide bench, as we will see at stop 6. Directions to Stop 6 are in Table 7.

Table 7. Mileage from Mesa Lakes (Stop 5) to Active Earth Flow (Stop 6).

Mileage	Description
0.0 (from Stop 5) 48.5 (cumulative)	Leave Mesa Lake overlook area; drive north on CO 65.
1.1 (from Stop 5) 49.5 (cumulative)	Turn left into parking area adjacent to CO 65. This is Stop 6.

<u>STOP 6.</u> ACTIVE EARTH SLIDE

At stop 6, exit the bus and walk south toward the head of the active earth slide depicted in Figure 15. Earth slides (also known as earth flows) like this one surround the edges of the landslide bench as well as the west end of the mesa where no landslide bench exists (Fig. 16). As we discussed at Stop 5, this is the end of the line for slump blocks. After a long period of slow downward transport across the gently sloping (2-5° away from the edge of the mesa) landslide bench and gradual retreat of the bench, slump blocks reach the downhill edge of the landslide bench where they begin their descent down steeper slopes (Figs. 5, 6, and 14F). What remains of the slump blocks after ages of weathering and freeze-thaw action breaks up and is transported downslope by earth slides (Figs. 15 and 16).

As noted earlier near the beginning of the field trip, earth slides cause damage to CO 65 by depositing debris on its inboard lane and undermining the outboard lane.

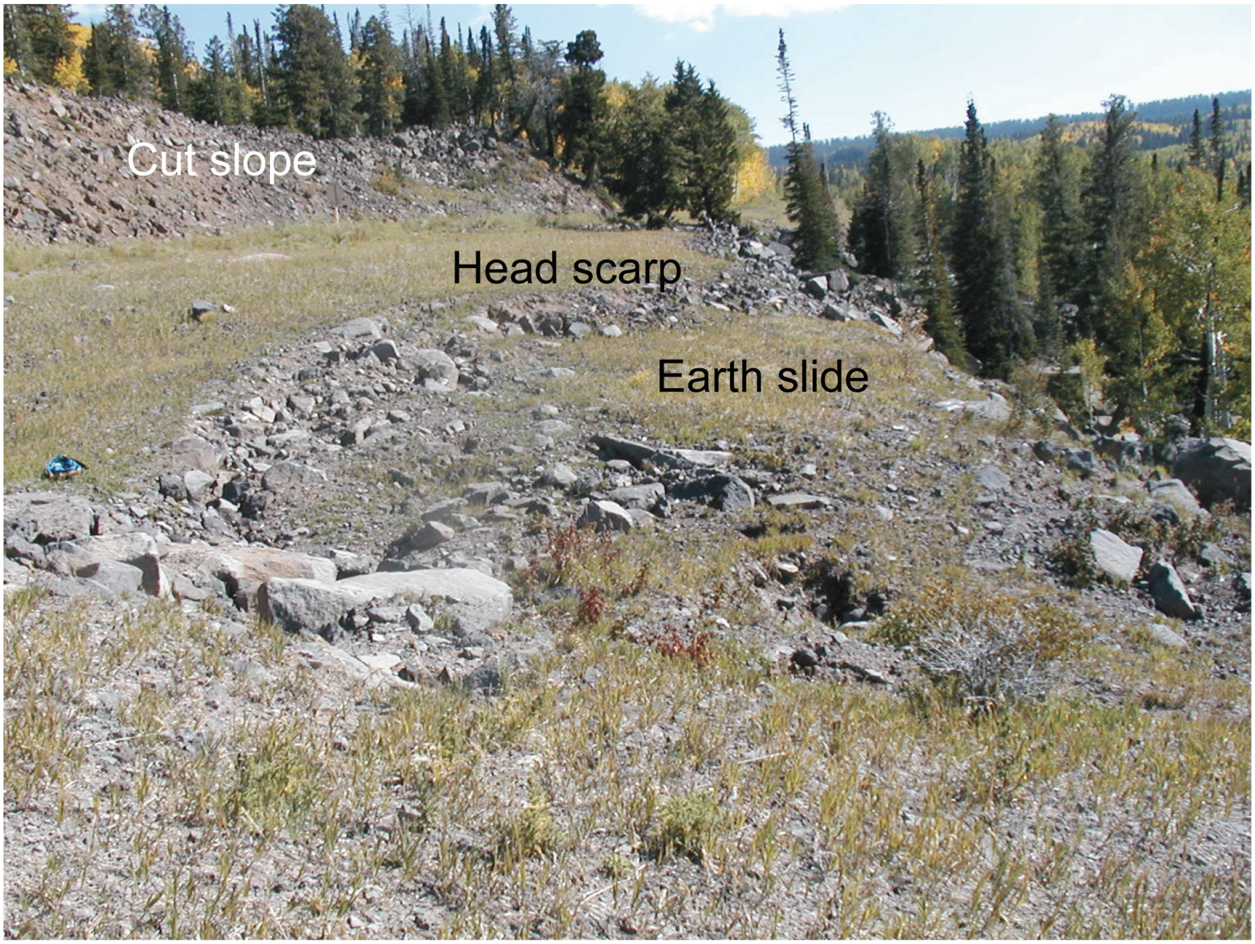

Figure 15. Head of active earth flow at Stop 1. Many earth flows like this one surround Grand Mesa. Active head scarp in center of photograph, road embankment in upper left part of photograph.

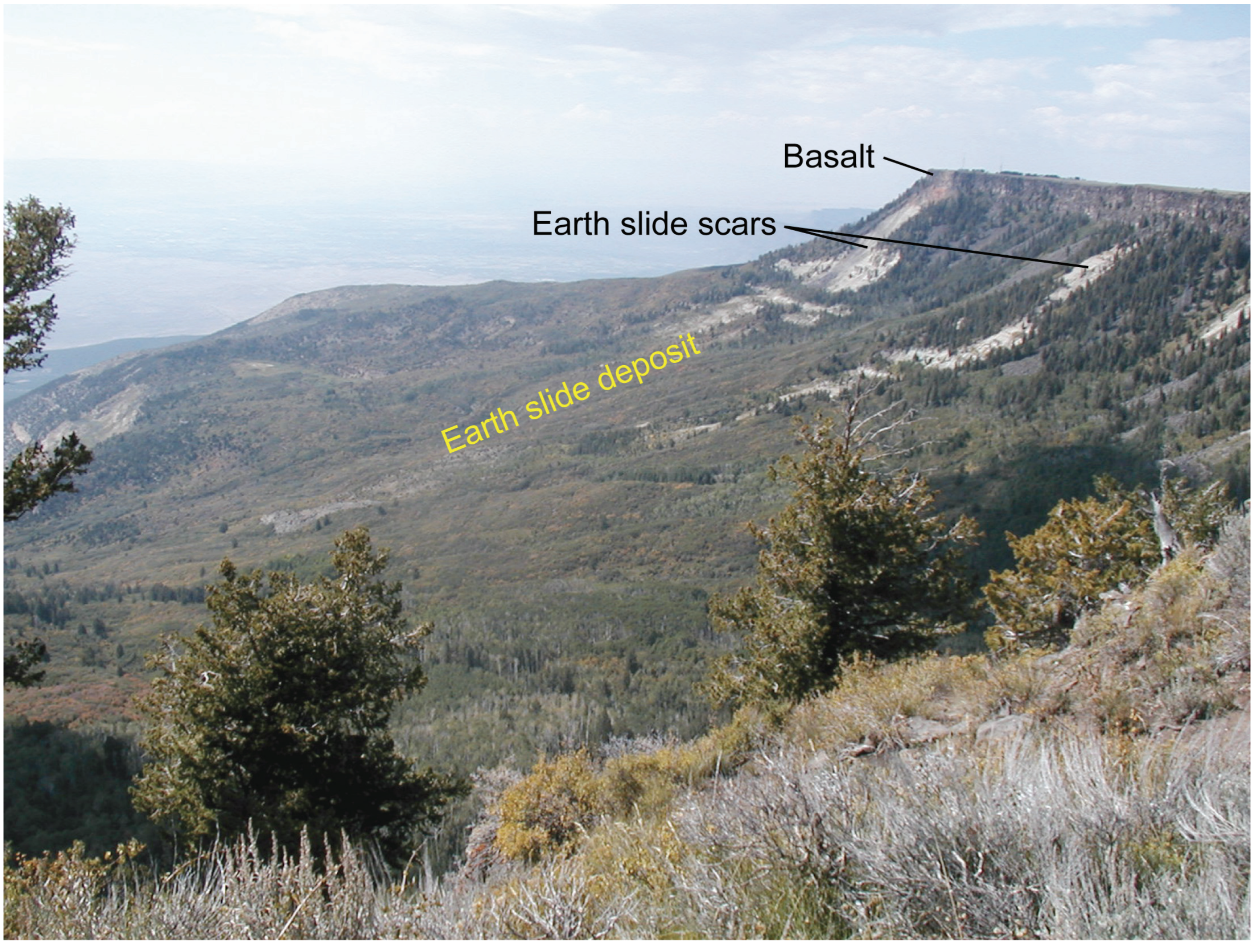

Figure 16. View north from Lands End (west end of Grand Mesa) illustrating the kinds of shallow earth slides /earth flows that transport material downslope from the edge of the landslide bench. In this view, earth slides head at the base of the basalt cap; no landslide bench exists because the claystone beds are very thin. Scars at the heads of the earth slides expose the claystone, and the Uinta and Green River beds in the steep slopes. Earth slide deposits cover the Wasatch Formation, which underlies the gently sloping apron in the center of the photograph.

This is the last stop of the field trip. Leave the parking area and head north on CO 65. Retrace your earlier route along CO 65 back to I-70.

ACKNOWLEDGEMENTS

Jeff Coe and Bill Schulz offered helpful suggestions in planning this field trip. Steve Personius and Jason Kean reviewed the field trip guide and offered constructive suggestions for improvement.

REFERENCES

Baum, R.L., 1997, Retrogressive slumping at Grand Mesa, Delta and Mesa Counties, Colorado: Association of Engineering Geologists program with Abstracts, 40th Annual Meeting, p.82.

Baum, R.L., and Odum, J.K., 1996, Geologic map of slump-block deposits in part of the Grand Mesa area, Delta and Mesa Counties, Colorado: U.S. Geological Survey Open-File Report 96-017, 12 p., 2 oversize plates, 1:24,000.

Baum, R.L., Odum, J.K., and Savage, W.Z., 1996, Evidence for tensile failure and forward rotation during early stages of slumping at Grand Mesa, Mesa County, Colorado. Geological Society of America Abstracts with programs, v. 28, no. 4, p. 2.

Baum, R.L., and Odum, J.K., 2003, Retrogressive slumping at Grand Mesa, Colorado, in Boyer, D.D., Santi, P.S., and Rogers, W.P., eds., Engineering Geology in Colorado Contributions, Trends and Case Histories: Association of Engineering Geologists Special Publication No. 15 and Colorado Geological Survey Special Publication 55, (CD-ROM), 17 p.

Cole, R.D., and Sexton, J.L., 1981, Pleistocene surficial deposits of the Grand Mesa Area, Colorado, in Epis, R.C., and Callendar, J.F., eds., Western Slope Colorado: New Mexico Geological Society Guidebook, 32nd Field Conference, pp. 121-126.

Donnell, J.R., 1969, Paleocene and lower Eocene units in the southern part of the Piceance Creek basin, Colorado: U.S. Geological Survey Bulletin 1274-M, pp. M1-M18.

Ellis, M.S., and Gabaldo, Virginia, 1989, Geologic map and cross sections of parts of the Grand Junction and Delta 30' x 60' quadrangles west-central Colorado: U.S. Geological Survey Coal Investigations Map C-124, scale 1:100,000.

Marvin, R.F., Mehnert, H.H., and Mountjoy, W.M., 1966, Age of Basalt Cap on Grand Mesa, in Geological Survey Research 1966: U.S. Geological Survey Professional Paper 550-A, p. A81.

Schuster, R.L., 2006, Interaction of dams and landslides—Case studies and mitigation: U.S. Geological Survey Professional Paper 1723, 107 p.

Yeend, W.E., 1969, Quaternary geology of the Grand and Battlement Mesas area, Colorado: U.S. Geological Survey Professional Paper 617, 50 p.

Yeend, W.E., 1973, Slow-sliding slumps, Grand Mesa, Colorado: The Mountain Geologist, Vol. 10, No. 1., pp. 25-28.

GEOLOGIC HAZARDS BETWEEN GLENWOOD SPRINGS AND MARBLE, COLORADO

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Wulfsohn debris fan, Glenwood Springs, Colorado (Photograph by Jon White and Dave Noe, Colorado Geological Survey).

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

This field trip will examine geologic hazards, related mitigation, and land-use issues between Glenwood Springs and Marble, Colorado. This field trip guide contains narrative descriptions of 6 stops and several drive-by points of interest (Tables 1 and 2). Our trip will start with a description of the geologic framework of the area and discussion of the engineering geology issues that affect development and land use. We will view a large mitigation project on the huge Wulfsohn debris fan. Just outside of Glenwood Springs, we will look at hillslopes burned by the South Canyon and Coal Seam wildfires of 1997 and 2002, and describe the debris-flow response to these fires, the rainfall triggers and initiation processes, and a method for emergency hazard assessments. Nearby, we will examine sites that have problems with rockfall and hydrocompactive soils. The main destination of the trip will be the little town of Marble. This scenic old mining town, with its considerable debris-flow, landslide, avalanche, and flooding hazards, has been "Ground Zero" for geology-related land use issues in Colorado since the early 1970s. In Marble, we will examine historic buildings that were associated with the world famous Yule Marble Quarry, which is still active above the town. The dazzling white marble has been used for numerous monuments and buildings in Denver and Washington, D.C., and is the Colorado State Rock.

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Glenwood Springs Overlook (Stop 1)	Geologic setting; evaporite collapse; engineering geology, debris-flow mitigation works	Bob Kirkham, Ralph Mock
South Canyon (Stop 2)	Post-fire debris flows	Bob Kirkham, Sue Cannon
The Terrace Apartments (drive by)	Foundation settlement and mitigation	Steve Pawlak
Midland Avenue (Stop 3)	Rockfall	Ralph Mock
Iron Bridge (drive by)	January 2005 sinkhole	Ralph Mock
CR 109 south of Glenwood (drive by)	Hydrocompaction and slope failures	Steve Pawlak
SH-133 (drive by)	Mt Sopris and rock glaciers	Bob Kirkham
SH-133 (drive by)	"Overshot" debris flow mitigation structures	Pat Rogers
SH-133 (drive by)	Penny Hot Springs	Pat Rogers
SH-133 (drive by)	USFS Redstone Campground	Pat Rogers
Redstone (Stop 4)	Debris-flow and flood hazards	Pat Rogers
Marble, Slate Creek (Stop 5)	Debris-flow deposition	Pat Rogers
Marble, Carbonate Creek (Stop 6)	Debris-flow hazards to town site and Marble quarry	Ralph Mock, Pat Rogers

TRIP ROUTE DESCRIPTION AND MAPS

This one-day trip starts and ends in Vail, in Eagle County, but will travel through Garfield County, with Glenwood Springs as its seat, parts of Pitkin County, and Gunnison County, where the town site of Marble is located (Figures 1, 2 and 3).

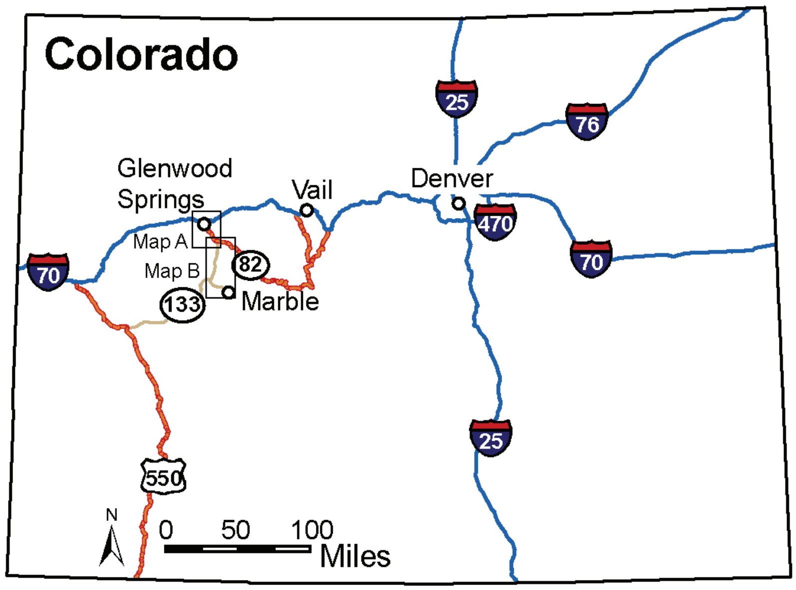

Figure 1. Field trip route from Vail west to Glenwood Springs, and south on State Highways 82 and 133, and County Road 3 to Marble.

The first leg of the field trip will take us from Vail west along Interstate 70 through the spectacular Glenwood Canyon to the town of Glenwood Springs, where we will make three stops (Figure 2). We will hear about the geologic setting and engineering geology issues in the area, the impact of wildfires on debris-flow generation, efforts to mitigate debris-flow hazards on an active debris fan, and ongoing problems with rockfall, sinkholes, road settlement and hydrocompation along SH 82 along the Roaring Fork River Valley. If the weather is cooperative, we will have stunning views of Mt Sopris and its beautiful rock glaciers. The first leg will end with lunch in the town of Carbondale's town park.

The second leg of the field trip will travel south from Carbondale along SH 133, which parallels the Crystal River. Along the way, we will see the 'overshot' debris-flow mitigation structures built to protect irrigation canals, the fog-producing Penny Hot Springs, and the rockfall-producing pinnacles above a USFS campground. We will stop at the town of Redstone for a discussion of debris flow and flood hazards at this site. We will reach the town of Marble by turning off SH133 onto CR3. Our two stops, at Slate and Carbonate Creeks, will allow us to examine hazard issues on an active debris fan (Figure 3). We will return to Vail on the same route.

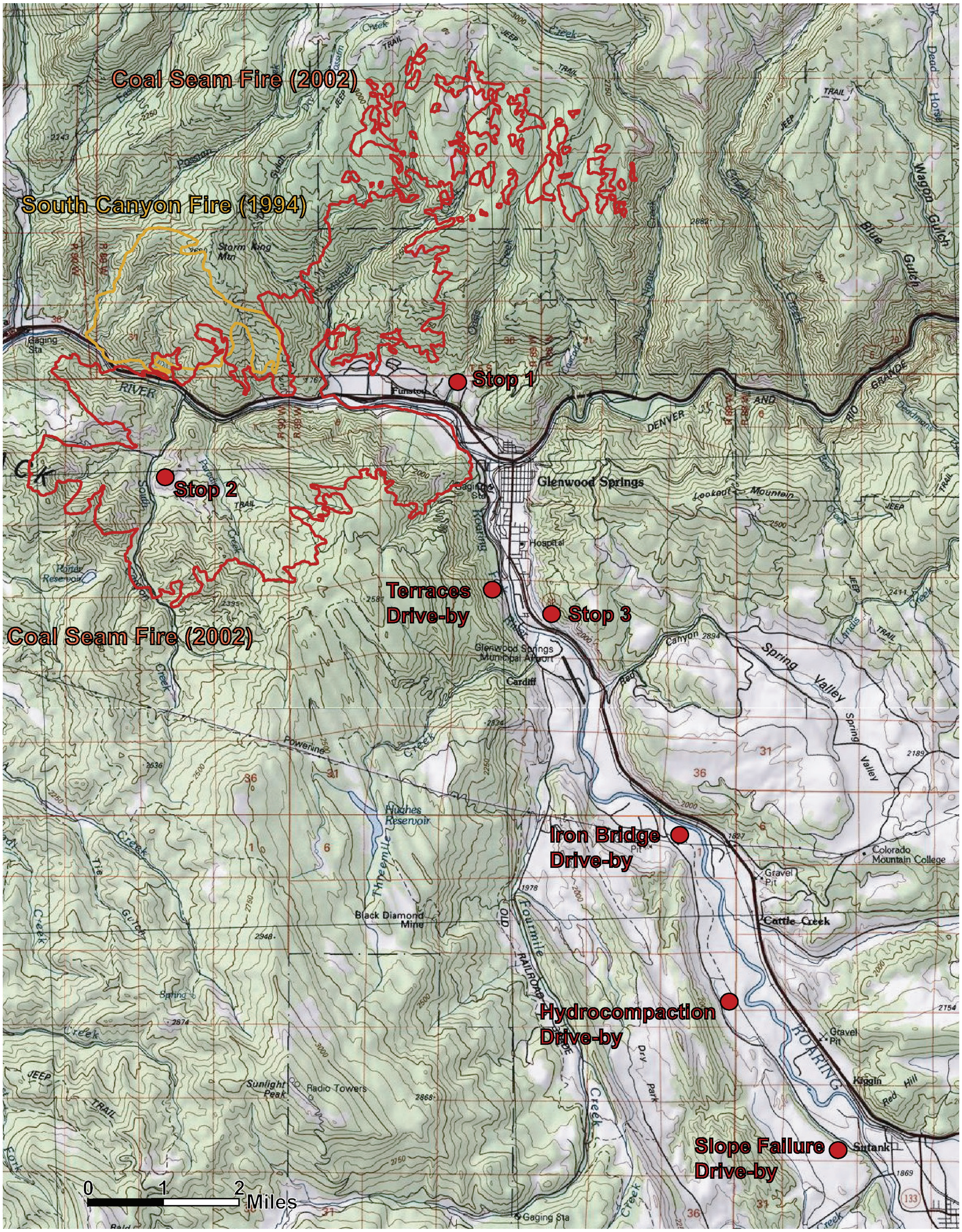

Figure 2. Map A (see Figure 1) showing field trip stops and drive-bys, and perimeters of Coal Seam and South Canyon Fires, on Leg 1 of the trip.

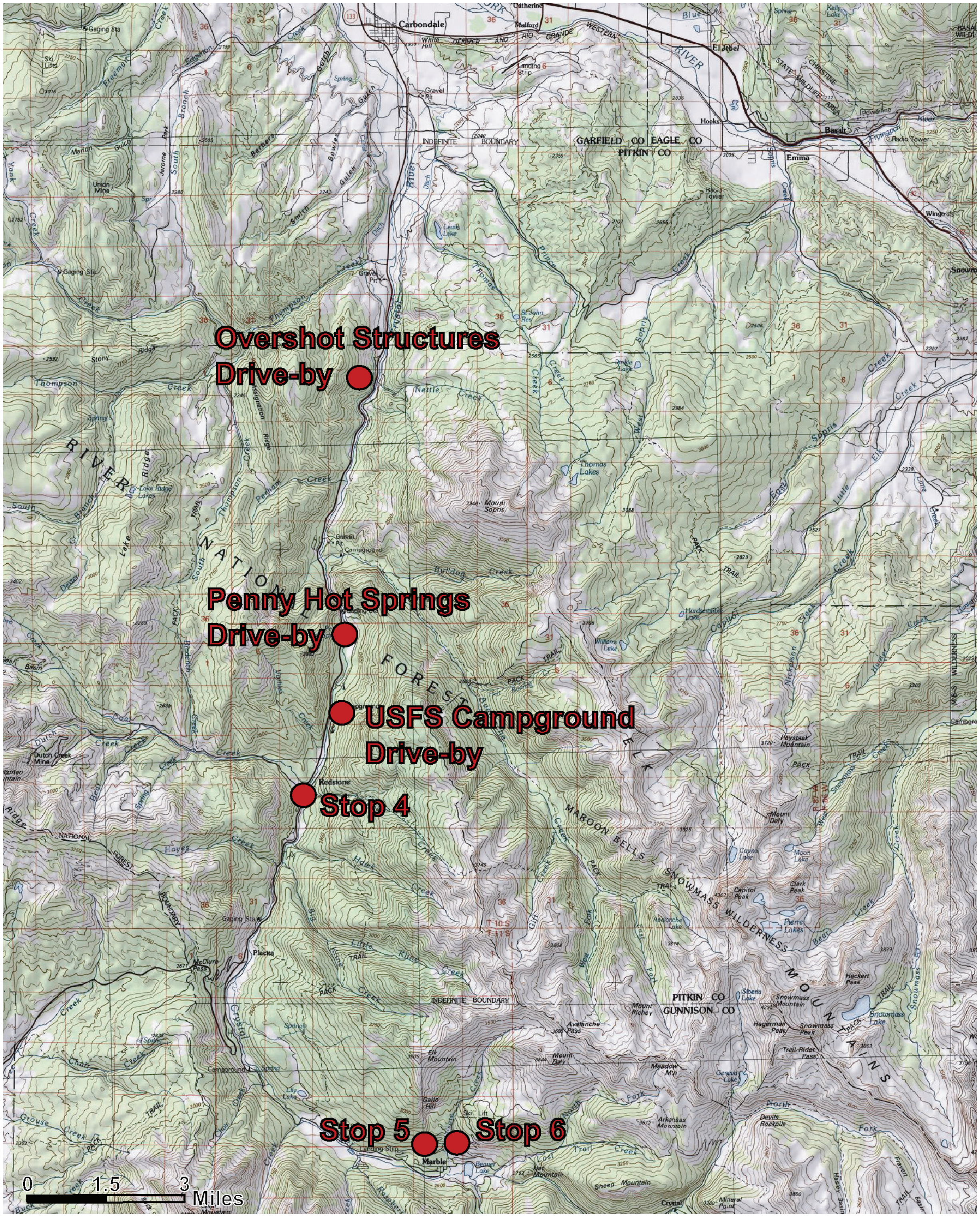

Figure 3. Map B (see Figure 1) showing field trip stops and drive-bys on Leg 2 of the trip.

The following stop and drive-by descriptions include directions and mileages (stop-to-stop and cumulative) for the two legs of this trip (Tables 1 and 2). In deference to American odometers, units are given as miles rather than kilometers.

Table 1. Leg 1 mileage from start of field trip at Vail Marriott Mountain Resort to Glenwood Springs (Stops 1, 2 and 3 and drive bys).

Mileage	Description
0 (start) 56.5 (cumulative)	Leave Vail Marriot Resort. Go west on I-70 toward Glenwood Springs for 56.5 miles.
0.4 (from last stop) 56.9 (cumulative)	Take Exit 119 for CO-82 East. At stop light, go west on West 6th Ave for 0.4 miles to intersection of West 6th Ave and North Traver Trail. Park at parking areas at this intersection. Walk ~300 m up Traver Trail to turnout on south side of road. This will be Stop 1, and will provide an overlook of Glenwood Springs and the Roaring Fork River Valley.
4.9 (from last stop) 61.8 (cumulative)	From parking area go west on West 6th Ave 1.8 miles and get back on westbound I-70 at the Midland Avenue entrance. Travel 2.6 miles to the South Canyon Creek Road (CR 134) exit. Take this exit and go south underneath the freeway to follow South Canyon Creek Road ~0.5 miles to pull off. This will be Stop 2, and will provide an overlook of Storm King Mountain to the north.
6.3 (from last stop) 68.1 (cumulative)	Drive down South Canyon Creek Road ~0.5 miles to I-70 and get back on freeway heading east. Travel 2.6 miles to the Midland Avenue exit (exit 114). Go southeast on Midland Ave 2 miles to the traffic light at the intersection of West 7th Street and Midland Ave. Midland Ave crosses the toe of the Wulfsohn debris fan discussed at Stop 1. Continue south on Midland Ave 1.7 miles to the intersection with 27th Street. The Terrace Apartments (drive by) are located southwest of this intersection.
0.8 (from last stop) 68.9 (cumulative)	Turn east onto 27th Street and travel 0.3 miles to the intersection with Glen Ave (State Highway 82). Go south on Glen Avenue for 0.5 miles to the traffic light at McDonalds. Turn east into the shopping center and then south into the parking lot for American Furniture. This will be Stop 3, and will provide an overlook of the Midland Ave rockfall initiation areas and paths.
4.2 (from last stop) 73.1 (cumulative)	Return to South Glen Ave (SH 82) and turn south. Go south on SH 82 for ~2.8 miles to traffic light at intersection of SH 82 and CR 154 (Old SH 82). Turn west at this intersection and go ~0.6 miles south on CR 154 to stop sign at intersection with CR 109 (Hardwick Bridge Road). Turn west at stop sign and immediately cross Roaring Fork River on CR 109. Continue south on CR 109 for ~ 0.8 miles. The Iron Bridge Golf Course is on the east side of the road. This is the site of the Iron Bridge sinkhole (drive by)
4.8 (from last stop) 77.9 (cumulative)	Continue south on CR 109 for 4.8 miles. The first 3 miles of the road is the CR 109 Hydrocompaction (drive by). An additional 4.8 miles on CR 109 takes us past CR 109 Slope Failure and Debris Flow (drive by).

Table 1. – continued

Mileage	Description
1.9 (from last stop) 79.8 (cumulative)	Continue south on CR 109 a distance of 0.7 miles to the junction with CR 108. Take a left on CR 108 to cross the river, followed by an immediate right onto CR 106 (North Thompson Creek Road). Follow CR 106 for 0.6 miles. It will make a sharp turn to the east and become Main Street/Avenue of the town of Carbondale. Continue east on Main Street for 0.3 miles and cross SH 133 at the traffic light. Continue east on Main Street 0.3 miles into the old part of Carbondale. Make a right turn on South 7th Street, and the town park (the lunch stop) will be on the left.

Table 2. Leg 2 mileage from Carbondale Town Park to Marble (Stops 4, 5, and 6 and drive bys).

Mileage	Description
6.0 (from last stop) 85.8 (cumulative)	From Carbondale Town Park go west on Euclid Ave to SH 133. Make a left onto SH 133, and travel south for ~6 miles to view the 'overshot' debris flow mitigation structures on the right side of the valley (drive by)
5.0 (from last stop) 90.8 (cumulative)	Continue south on SH 133 to where the valley floor widens on the east side of the Crystal River. This is the location of Penny Hot Springs (drive by)
2.0 (from last stop) 92.8 (cumulative)	Continue south on SH 133 and observe the towering pinnacles of the Maroon Formation red rock above the USFS campground (drive by)
4.0 (from last stop) 96.8 (cumulative)	Continue south on SH 133 for ~ 4 miles and pull off at Coal Creek Road on the right for Stop 4.
10.0 (from last stop) 106.8 (cumulative)	Resume south travel on SH 133 for ~3.5 miles to CR 3. Take a left onto CR 3, and proceed 6.5 miles to the crossing with Slate Creek. This will be Stop 5.
11.0 (from start) 117.8 (cumulative)	Continue south on CR for ~ 1 mile to the crossing with Carbonate Creek. This will be Stop 6.

LEG 1: GEOLOGIC HAZARDS IN GLENWOOD SPRINGS AND VICINITY

GLENWOOD SPRINGS OVERLOOK, STOP 1.

Regional Geology

Stop 1 is located on the southern margin of the White River uplift. The south-dipping middle to early Paleozoic sedimentary rocks to our north are within the south flank of the uplift. To the south is the Roaring Fork River valley (Figure 4), whose glaciated headwaters are in the Sawatch Range and Elk Mountains. Middle and late Pleistocene outwash terraces are well preserved in the Roaring Fork River valley. Debris fans built by sediment flushed from tributary valleys locally overlie the terraces. Much of the town of Glenwood Springs is built on debris fans. A prominent remnant of an older debris fan is visible on the east side of the valley. This fan remnant hosts the cemetery in which Doc Holliday is buried. Several landslides exist on the flanks of the valley, but none are known to have moved historically. Rockfall hazards exist below cliffs of rocks exposed on the valley walls.

Figure 4. View from near Stop 1, looking south up the Roaring Fork River valley. The valley is carved into the axis of the Cattle Creek anticline, a Laramide-age fold modified by late Cenozoic evaporite diapirism. Glaciated Mount Sopris, the mountain with twin summits that extend above treeline, lies between the Roaring Fork River (on left) and Crystal River (on right). The town of Glenwood Springs is mostly built upon coalescing debris fans. Numerous historical debris flows on these fans have periodically plagued the city. Note the remnant of an older debris fan surface perched above the drainage in the left center of the image. Photograph by Jonathan White, Colorado Geological Survey.

The Roaring Fork River valley coincides with the crest of the Cattle Creek anticline (Figure 5). West of the White River uplift and the Cattle Creek anticline is the Grand Hogback monocline. This major Laramide fold accounts for over 6 km of structural relief between the White River uplift and the Piceance basin.

Spectacular outcrops of Permian and Pennsylvanian red beds in the Maroon Formation are visible on the walls of the Roaring Fork River valley. Hints of the underlying Pennsylvanian Eagle Formation also are glimpsed from Stop 1. South of Glenwood Springs excellent exposures of the Eagle Valley Formation and underlying Eagle Valley Evaporite are on the walls of the Roaring Fork River valley. On upland areas adjacent to the valley Miocene and Pliocene basaltic flows unconformably overlie the Maroon Formation, Eagle Valley Formation, and Eagle Valley Evaporite, as well as Mesozoic and Tertiary sedimentary rocks.

The twin summits of Mount Sopris, the 3,948-m high mountain framed by the walls of the Roaring Fork River valley, are held up by ~35 Ma granodiorite (Streufert, 1999). Mount Sopris is surprisingly well glaciated considering its relatively low altitude. Other high peaks visible in the distance beyond the shoulders of Mount Sopris also are formed by middle Tertiary granitic plutons in the Elk Range.

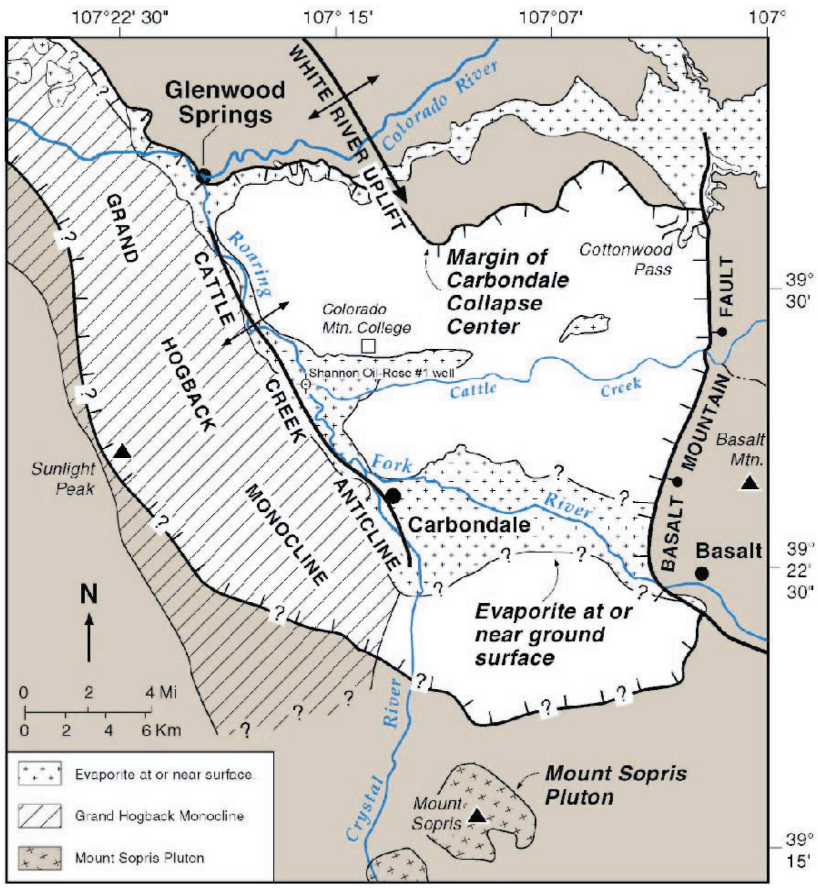

Figure 5. Simplified structure map of the Roaring Fork River valley. The margin of the southern part of the Carbondale collapse center and areas with evaporite at or near the surface also are shown. (from Kirkham et al., 2002b).

Evaporite Collapse

Both the Cattle Creek anticline and Grand Hogback monocline are affected by late Cenozoic evaporite tectonism (Kirkham et al., 2002b). The anticline is enhanced by evaporite upwelling in the crest of the fold (Figure 5). Close to the Roaring Fork River, Quaternary terraces are folded upward and dip away from the river. An upwarped middle Pleistocene terrace creates the shaded area on the west side of the river in the center of the right side of Figure 4. The downstream end of this terrace is over 30 m higher than its upstream end.

Where fresh water encountered evaporate beds, they were dissolved. The combined effects of evaporite flow and dissolution led to regional collapse of the ground surface and creation of the Carbondale (Figure 5) and Eagle collapse centers (Kirkham et al., 2002a). Active sinkholes caused by evaporite dissolution pose hazards to the works of humans (Mock, 2002; White, 2002). Saline ground water discharges from evaporate bedrock as springs and as inflow into alluvial aquifers (Eisenhauer, 1986; Kirkham et al., 1999). For example, Yampah hot spring, which supplies water for the Glenwood hot springs pool, discharges ~240 metric tons of dissolved halite and gypsum daily (Kirkham et al., 2002b). This is the equivalent of the formation of one new sinkhole with volume of ~108 m^3 every day.

The total volume of evaporite collapse in the combined Carbondale and Eagle collapse centers is estimated at 2,300 km^3 (Kirkham and Scott, 2002). An estimated 0.8 million metric tons of evaporite mineral are dissolved in the collapse area and removed by the Colorado River each year (Chafin and Butler, 2002). Kirkham and Scott (2002) concluded that if the modern salt loads in the Colorado River are representative of prehistoric salt loads, then it would take only 6.4 m.y. to dissolve the estimated 2,300 km^3 of evaporite that has been removed from the collapse areas.

Removal of evaporite from beneath the west-dipping Grand Hogback monocline, either by dissolution and/or flow, has caused the monocline to relax or unfold. Flexural slip faults that formed along bedding planes in the folded Mesozoic and lower Tertiary sedimentary rocks cut Miocene volcanic rocks that unconformably overlie the monocline (Figure 5). Other types of features related to evaporite flow and dissolution include synclinal sags, depositional bowls, overturned volcanic flows, and sinkholes.

Engineering Geology Considerations

Potential geologic hazards that are considered for developments in Glenwood Springs and the adjoining Colorado and Roaring Fork River valleys are debris flows, rockfall, hydrocompactive soils, and sinkholes. Geologically young alluvial fans are common in the area and are potential sites of debris flows. The debris flows are usually triggered by intense thunderstorms between June and September, but some result from rapid snowpack melt in the late spring. Rock outcrops on the steep, upper valley sides are potential source areas for rockfalls that can reach developments on the lower valley sides. The alluvial fan deposits on the lower valley sides can be hydrocompactive and buildings on the fan may experience unacceptable foundation settlement if the fan deposits are deeply wetted after construction. Most of the lower valley sides and the valley floors are underlain by the Eagle Valley Formation and Eagle Valley Evaporite. Both formations contain evaporite interbedded with clastic sediments. The evaporite is relatively soluble in circulating groundwater and subsurface voids have locally developed in the evaporite. Over time, caving and piping above the voids has resulted in sinkholes at the ground surface.

Historic Debris Flows

On July 24, 1977 an intense thunderstorm triggered debris flows that reached several alluvial fans in Glenwood Springs and nearby areas (Figure 6). The total rain recorded at the Glenwood Springs weather station for July 24 was 1.08 inches. More significantly, 0.85 inches of this rainfall occurred in about one-half hour which is about fifty percent of the 100-year, one-hour rainfall. Based on this, Mears (1977) concluded that the July 24, 1977 debris flows have a statistical recurrence interval of about 50 years. Flow depth on the upper parts of the larger fans was between 1 to 2 meters (Lincoln DeVore, 1978). Flow velocity estimates based on super elevations at channel bends above the larger fans was between 4 and 8 meters per second (Mears, 1977).

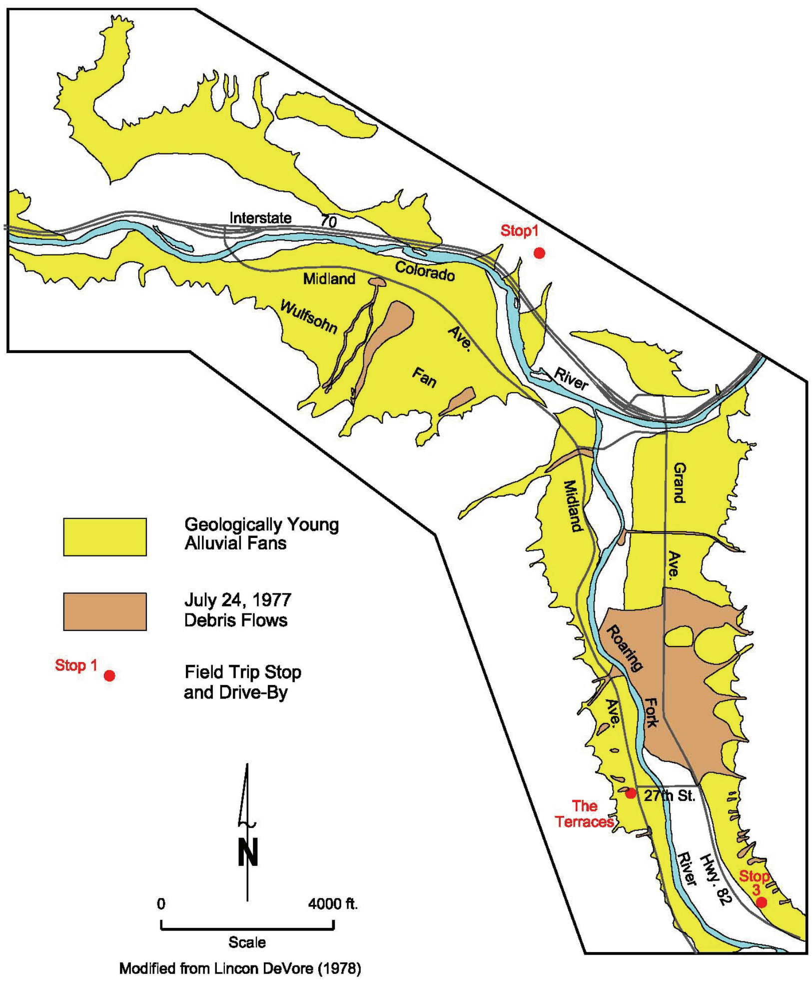

Figure 6. Geologically young alluvial fans in the Glenwood Springs area that are potential sites of debris flows, and the approximate extent of major debris flows that occurred on July 24, 1977.

Review of newspapers by ESA Geotechnical Consultants (1982) and our observations indicate that, in addition to the July 24, 1977 debris flows, three other major debris-flow events have occurred in the Glenwood Springs area since 1903 and twenty small, but significant events have occurred during this time. From this, it appears that major debris flows occur on the average of about every 25 years and significant debris flows occur about every 5 years. Recurrence times on individual fans may be longer than the regional averages.

The Glenwood Springs Municipal Code regulates development in geologic hazard areas that include debris flows. The code requires that buildings within 300 feet of the fan heads be designed to resist a horizontal force of 900 psf for a height of 6 feet, and that buildings constructed between 300 and 600 feet of the fan head be designed to resist a horizontal force of 400 psf for a height of 6 feet. These performance specifications can be modified if a report is submitted by a qualified geologist and engineer that shows other performance specifications are appropriate for the proposed development. Following the July 24, 1977 debris flows, ESA Geotechnical Consultants (1982) developed a drainage and debris control plan for the city. The 1982 plan has not been implemented. Risk mitigation is typically done by developers of individual projects.

Wulfsohn Fan Debris Flow and Hydrocompaction Mitigation

Development on the Wulfsohn alluvial fan started in the early 1990's with construction of the Midland Avenue bypass to Interstate 70 and the Glenwood Springs Community Center on the east side of the fan. Subsequent development has included other municipal and county maintenance facilities and the recently completed shopping center. Parts of the fan were the site of debris flows in 1977 (Figure 6). Initial debris flow mitigation for the community center was an interim deflection berm. All development on the fan is now protected by a series of linear debris basins (frontispiece).

The Wulfsohn fan deposits are also hydrocompactive. In the lower parts of the fan the hydrocompactive deposits are usually less than 20 to 30 feet deep and overlie dense Colorado River gravels. In the upper parts of the fan, the hydrocompactive deposits are greater than 100 feet deep. Various mitigations have been used to reduce the risk of foundation settlement. Because of the considerable grading for the new shopping center, excavation and compaction was the primary mitigation for this facility. Facilities that are owner-built and occupied have been placed on heavily reinforced, low bearing pressure, spread footings if the owner accepted the risk of foundation settlements and repair. Facilities where little risk was acceptable to the owner have been placed on pile foundations that bear on the river gravels.

Evaporite Sinkholes

Location of known evaporite sinkholes in the Carbondale and Eagle evaporite collapse centers where detailed geologic maps are available are shown on Figure 7. The highest sinkhole density is three sinkholes per square mile along the Roaring Fork evaporite diapir that trends along the Roaring Fork River valley between Glenwood Springs and Carbondale. The overall region has a sinkhole density of one sinkhole every 1.5 square miles. These sinkhole densities should be considered a lower limit estimate of the actual sinkhole density in the region.

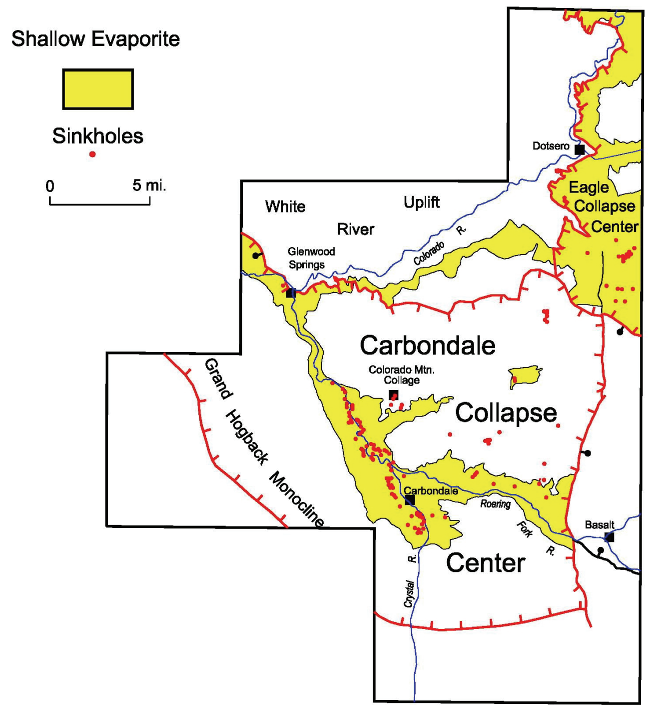

Figure 7. Known sinkhole locations in Carbondale and Eagle evaporate collapse centers where 7.5 minute quadrangle geology maps by the Colorado Geological Survey are available. Boundary of evaporite collapse centers are from Kirkham and Scott (2002).

Most of the sinkholes are prehistoric, but since 2003 three sinkholes have developed with little or no advance warning. These recent sinkholes were typically about 30 to 40 feet in diameter and from 10 to 40 feet deep (Figure 8a).

Figure 8a. Sinkhole that formed in February 2003 in an athletic field at the Colorado Mountain College. Diameter about 30 feet, depth about 10 feet. The risk to people was mitigated by backfilling. *(Photo by Jonathan White, Colorado Geological Survey)*

The sinkholes are most common on glacial outwash terraces along the Roaring Fork and Crystal Rivers but sinkholes are also present in the adjacent uplands (Figure 7). Three sinkhole types are recognized in the evaporite region (Mock, 2002). As shown in Figure 8b, Type A sinkholes have rubble pipes that extend through the entire outwash; Type B sinkholes involve only the finer grained alluvial fans and loess that overlie the outwash; Type C sinkholes are the result of direct roof collapse above large solution cavities in the evaporite.

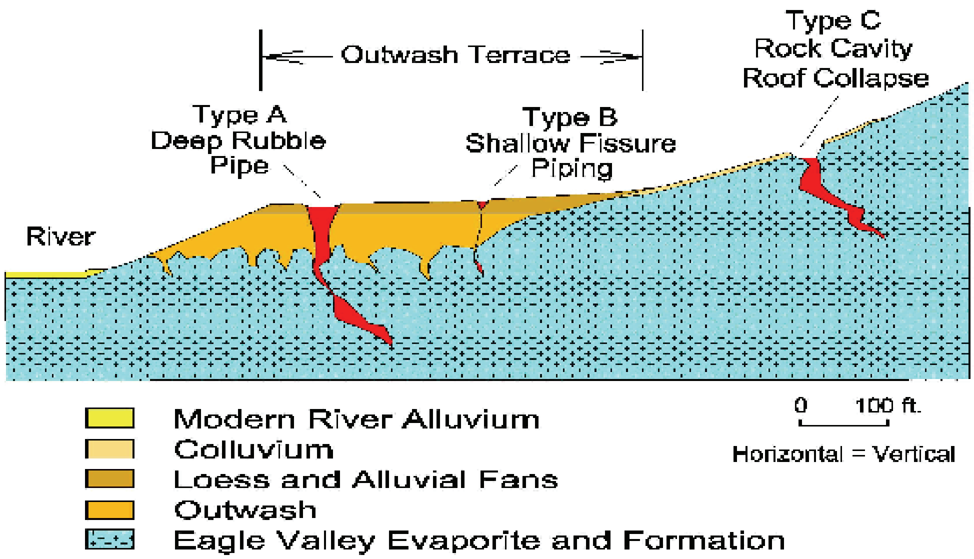

Figure 8b. Geologic setting and three sinkhole types found in the Carbondale and Eagle evaporite collapse centers (from Mock, 2002).

Geotechnical consultants usually evaluate the sinkhole risk to developments by geologic mapping and exploratory borings. Several geophysical methods for detecting subsurface voids have been tried with limited success. Risk mitigation is typically accomplished by:

- Not locating buildings near known sinkholes
- Not locating unlined ponds near buildings
- Control of landscape irrigation near buildings
- Mat or other rigid foundation systems
- Deep foundation systems
- Stabilization by backfilling and grouting
- Stabilization by backfilling
- Timely remedial actions if ground movements are detected
- A combination of the above

STOP 2. SOUTH CANYON AND COAL SEAM FIRES OVERLOOK

The 1997 South Canyon Fire

The South Canyon fire burned slowly for several days on the north side of the Colorado River west of Glenwood Springs before exploding into a fire storm on July 7, 1994, when a cold front passed through. Fourteen firefighters were killed in the blazing inferno, which burned about 13 km^2 of pinion, juniper, and gambel oak on the south side of Storm King Mountain. Temperatures were locally high enough to melt and fuse quartz grains in soil. Large clouds of blowing ash were reported on the mountain in the days following the fire. Ash drifted into and accumulated on the bottoms of the drainages within the burn area (Cannon et al., 1995).

During the evening of September 1, 1994, debris flows originating in response to a heavy rainstorm flowed down several channels on the south flank of Storm King Mountain west of Glenwood Springs. The debris flows spilled onto or next to a nearly 5-km-long stretch of Interstate Highway 70 (Figure 9), trapping thirty cars on the highway. Material from Basin B (Figure 10) crossed the Interstate, and swept two people into the Colorado River; the resulting delta nearly dammed the river. Fortunately, there were no deaths and only a few serious injuries resulting from the debris flows. Materials carried in this event were largely eroded from hillslopes and channels burned by the South Canyon Fire.

Immediately following the 1994 storm the Colorado Geological Survey and the U.S. Geological Survey initiated a cooperative investigation of the geologic and geomorphic characteristics of the debris flows, the potential for on-going debris-flow activity, and the stability of a large landslide complex within the burned area. Burning of the thick vegetative cover and erosional removal of soil during the storm exposed significantly more bedrock, providing a unique opportunity for detailed mapping of both bedrock and surficial materials. For example, the site lies within the Grand Hogback monocline, and all strata within the area were thought to dip south at a moderately steep angle. However, a structural terrace within the monocline, wherein bedrock was more fractured than in adjacent areas, was discovered while mapping the area. Much of the sediment carried by the debris flows was stripped from surficial materials overlying the structural terrace.

Figure 9. Debris flows from Basin B flowed over Highway I-70 and built a delta that extended about half way across the Colorado River (Photograph by Jim Scheidt, Bureau of Land Management).

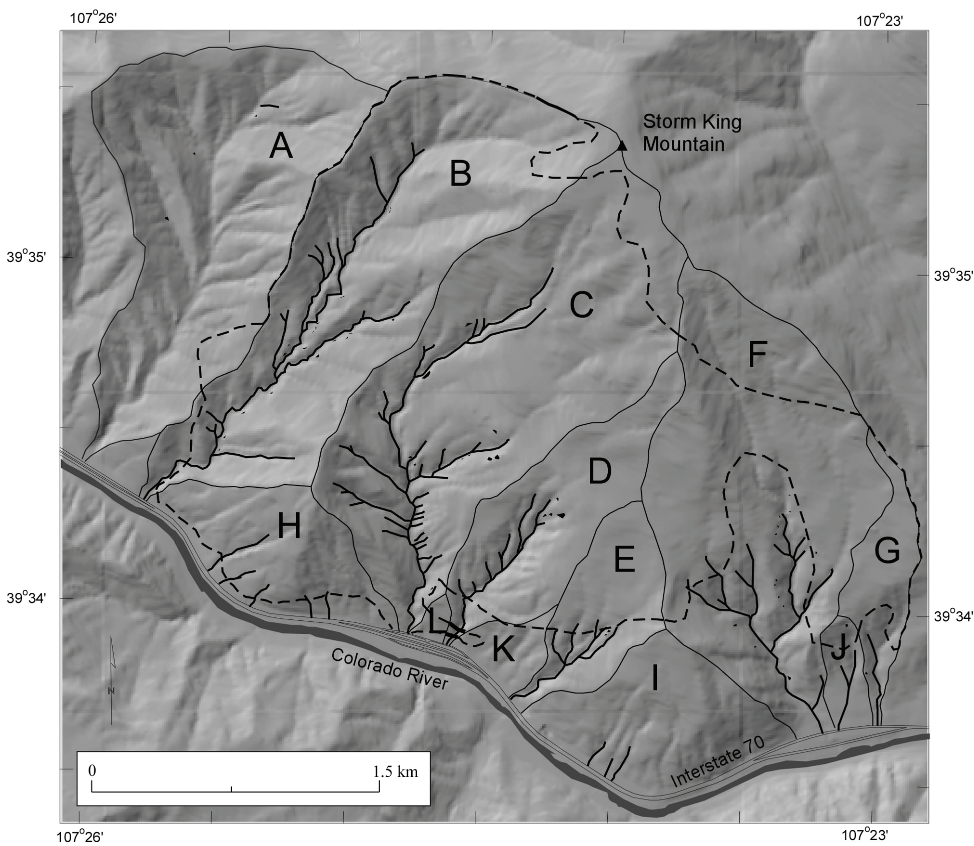

Figure 10. Map showing outlines of drainage basins A through J (thin dashed lines), paths of debris flows that occurred during the September 1, 1994 event (solid thin lines), soil slip scars (black polygons), and extent of the burn area (heavy dashed lines) (modified from Kirkham et al., 2000).

The 2002 Coal Seam Fire

The 2002 Coal Seam Fire burned 4941 hectares between June 9 and July 15, 2002 during the height of a severe drought in Colorado. It was one of 30 wildfires that occurred in the state during the spring and summer of 2002. The fire started at a burning coal seam south of the Colorado River. In response to high winds, the fire jumped Interstate 70 and the Colorado River, burning the hillslopes and canyons on both sides of the river (Figure 11). The fire burned through piñon-juniper woodlands at lower elevations, mountain shrublands, and aspen, Douglas fir, and spruce-fir forests at higher elevations. Approximately 75 percent of the area was burned at high and moderate burn severity. Twenty-nine homes, one commercial structure, and 14 outbuildings were destroyed by this fire.

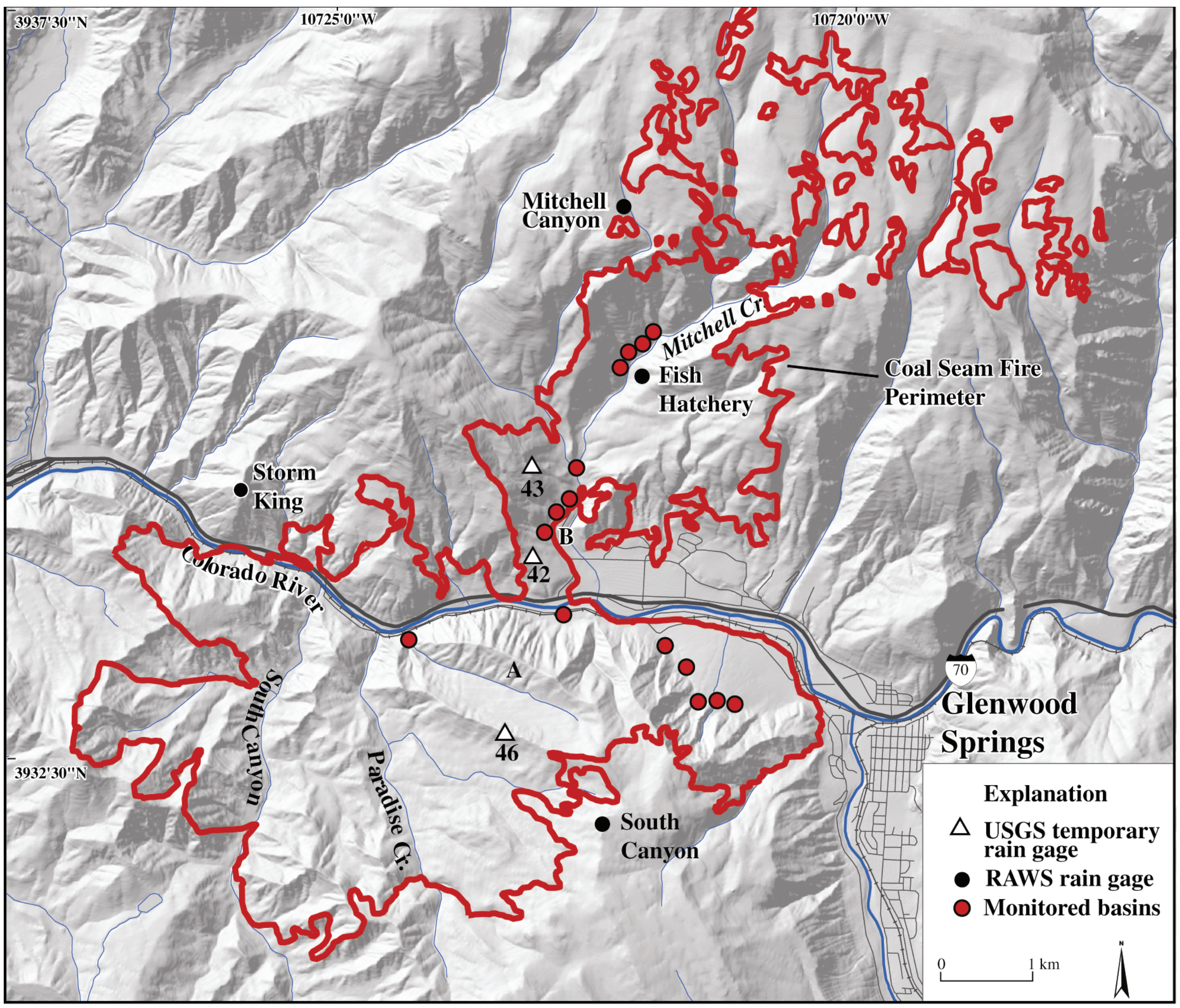

Figure 11. Map of area burned by the 2002 Coal Seam Fire in south central Colorado, locations of rain gages, and outlets of monitored basins *(from Cannon et al., 2003).*

Figure 12. Debris-flow deposits produced during August 5, 2002 storm from Basins B and C (Photograph by Andrea Holland-Sears, USDA Forest Service).

The Coal Seam Fire increased the frequency and volume of debris-flow events in the burn area. During the first summer following the fire, six convective thunderstorms (August 5, September 7, 11, 12 and 17, and October 2-3, 2002) triggered debris flows and floods from many of the basins burned by the Coal Seam Fire (Cannon et al, 2003) (Figure 12). The storms were extremely localized, as evidenced by the variable responses of the rain gages and basins to storms throughout the summer.

Debris flow triggering rainfall conditions

Identification of measures of storm rainfall that are reliable predictors of destructive flood or debris-flow response is critical for issuing warnings and planning for emergency response. Shortly after the Coal Seam Fire was extinguished and before any rainstorms had impacted the area, a network of tipping bucket rain gages was installed throughout the burned area (Figure 11). After each significant rainfall event, we documented which basins produced debris flows, sediment-laden floods, and which showed no response. We use this information to define the rainfall conditions that lead specifically to the generation of post-wildfire debris flows in this setting (Cannon et al., in press).

To define rainfall intensity-duration thresholds for the Coal Seam burned area, we compared measures of peak storm rainfall of different durations recorded by gages located within 1.5 km of basins that produced either debris flow, sediment-laden flood, or showed a negligible response. For the Coal Seam Fire, the storm rainfall intensity-duration threshold that defines the rainfall conditions unique to the debris-flow and flood-producing storms is: $I = 6.5D^{-0.7}$, where I = rainfall intensity (in mm/hr) and D = duration of that intensity (in hours). The filled red circles on Figure 13 show the rainfall conditions leading up to the two known times of occurrence of debris-flow events from basins burned by the Coal Seam Fire. These points fall above, and close to the threshold, indicating that the position of the threshold adequately represents those rainfall conditions that can potentially result in significant post-fire debris-flow and flood activity.

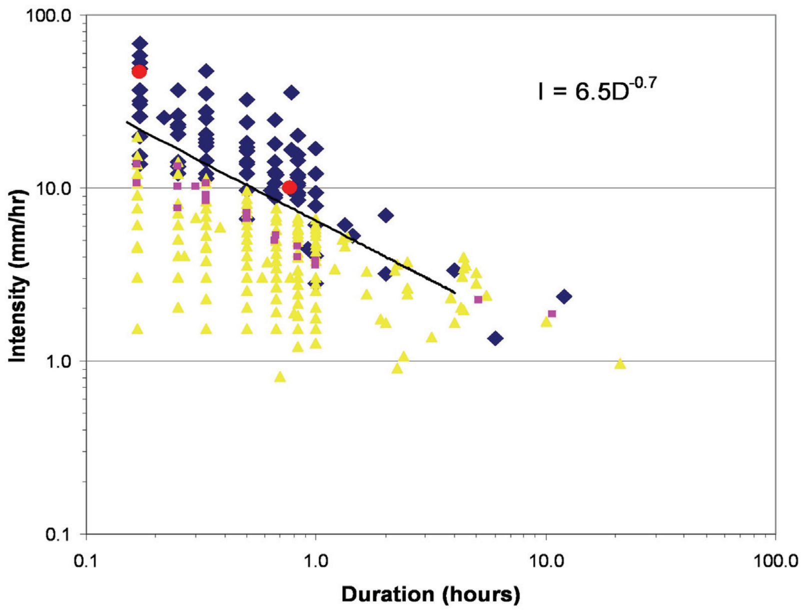

Figure 13. Rainfall intensity-duration thresholds for the generation of fire-related debris flows from the Coal Seam Fire in Colorado. Blue diamonds are measures of storm rainfall from rain gages near basins that produced debris flows; pink squares are measures of storm rainfall from gages near basins that produced sediment-laden flows and yellow triangles are measures of storm rainfall from gages near basins that showed a minimal or no response. Each storm is represented by several data points representing peak intensities of different durations within the storm. Measurements from different storms can occupy the same location, but at least one measure of storm rainfall from the debris flow and flood producing storms lies above the threshold line. Red dots indicate rainfall conditions preceding known times of debris-flow occurrence (from Cannon et al., in press).

The threshold is best defined for durations of less than one hour, but delineates a range of rainfall combinations, from high-intensity, short-duration (20 mm/hr for 10 minutes or, 3.4 mm total) to lower-intensity, longer-duration (3 mm/hr for three hours, or 9 mm total), any of which can result in the triggering of debris flows and floods. This threshold can be used to identify when destructive post- fire floods and debris flows are possible during the first rainy season to impact recently-burned basins in south-central Colorado that have similar soil, burn severity and basin characteristics.

This rainfall threshold for the occurrence of debris flows and floods following wildfires is among the lowest, in terms of intensity and duration, when compared to thresholds for unburned settings. The difference between the processes found in burned areas, where runoff and sediment entrainment can be nearly instantaneous, and the longer-timeframe, infiltration-dominated processes on unburned hillslopes may account for these differences.

SETTLEMENT AT THE TERRACE APARTMENTS (DRIVE BY)

The apartment complex is located on an alluvial fan at the base of the steep western Roaring Fork River valley side in an area susceptible to rockfall and hydrocompactive foundation soils. Initial construction of this twelve building apartment complex was started in 2000. By 2002 building distress was apparent in several of the buildings. The distress was attributed to deep wetting of low to highly collapsible foundation soils as a result of precipitation infiltration and landscape irrigation. Eventually eight buildings were severely damaged, two buildings were moderately damaged and the remaining two buildings sustained minor damage. In some areas differential foundation settlement was less than one inch, but in other areas as much as eight inches of differential settlement occurred. The subsurface soil profile at the project site consisted of 25 to 60 feet of hydrocompactive alluvial fan deposits that overlie dense, Roaring Fork River outwash gravels.

Factors contributing to the building damage were:

- Deep hydrocompactive foundation soils
- Landscape irrigation close to building foundations
- Inadequate roof gutters and downspouts
- Poor surface drainage away from the buildings
- Inappropriate foundation drain construction (no impervious membrane)
- Inappropriate foundation drain locations
- Split level ground floors
- A structural framing system that provided poor resistance to differential foundation movements

Remedial actions to repair the building damage were completed in 2006. The remediation was paid for as part of a litigation settlement. The remediation included:

- Compaction grouting the alluvial fan down to the top of the outwash gravels
- Foundation levelling of the most severely damaged buildings
- Replacement or elimination of inadequate foundation drains
- Installation of additional roof gutters and downspouts to solid pipe drains
- Improvement in surface drainage
- Xeriscaping around the buildings

STOP 3. MIDLAND AVENUE ROCKFALLS AND HYDROCOMPACTION

Historic Rockfall

Outcrops of the Maroon Formation at the ridge line on the west side of the Roaring Fork river valley have produced at least four rockfall events during the past 20 years. Rockfall events occurred in the mid-1980’s, in the spring of 1995, on April 6, 2004 and on October 5, 2007 and it is possible that other rockfall events have occurred during this time. Buildings in the vicinity of Midland Avenue were struck and damaged by the mid-1980's, 2004 and 2005 rockfall events, but to date no injuries or deaths have occurred. After detaching from the outcrop, the rockfalls typically break up into several individual rock blocks that range from 4 to 8 feet in diameter. The individual blocks are estimated to weigh between 2 to 10 tons. The blocks stopped at and below Midland Avenue and some have reached the Roaring Fork River.

A six-foot-high, earthen catchment wall with a stacked boulder facing was installed in 1999 to protect a new, down-slope residential development. The April 6, 2004 rockfall event broke into at least six large, individual blocks. Several of these blocks hit and damaged the catchment wall on the east side of Midland Avenue. The rockfall block that hit the north end of the wall was deflected and damaged a house located down slope on Hager Lane (Figures 14a and b).

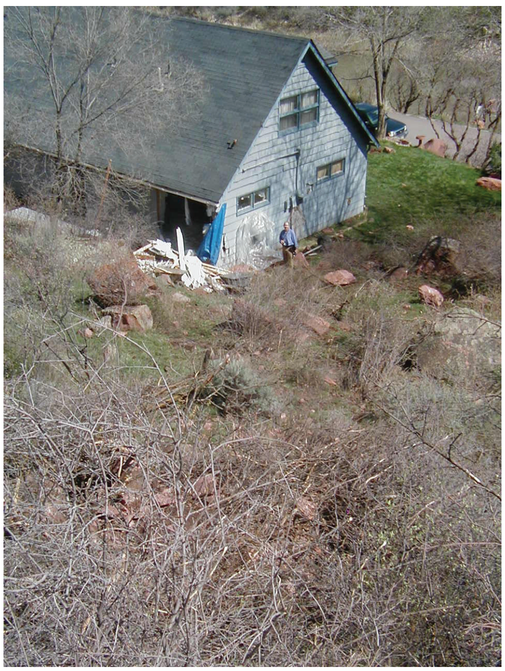

Figure 14a. Two rock blocks from April 6, 2004 event damaged the house after glancing off of the Midland Avenue catching wall.

Figure 14b. The two rock blocks stopped in the house and one almost traveled through the house. The rock blocks are estimated to be between 4 and 6 tons.

Rockfall mitigation used in the Glenwood Springs area, in addition to mechanically stabilized earth catching walls, include cross-slope ditches with compacted earth berms and woven wire-rope catching nets. Another option is outcrop stabilization, which is often not feasible because of access and property ownership constraints.

Hydrocompaction

Hydrocompaction problems in the Roaring Fork River Valley are usually associated with alluvial fans that have drainage basins in the Eagle Valley Evaporite and Eagle Formation, both of which contain gypsum and anhydrite. However, hydrocompaction can also be associated with fans that have other rock formations in their drainage basins. The hydrocompactive fan deposits consist of rock fragments from gravel- to boulder-size supported in a fine-grained soil matrix. The fan matrix, at its typically dry moisture content, will support building foundations with acceptable settlements. However, if the soil matrix becomes wetted to a significant depth after construction, the matrix can lose strength and collapse, resulting in unacceptable settlements. The key factors governing hydrocompaction susceptibility are fan deposits with moisture contents less than about 16 percent and dry densities between 65 and 120 pcf. In addition to alluvial fan deposits, colluvium and loess in the region can be hydrocompactive.

Most geotechnical engineers use the one dimensional consolidation test (oedometer test) to evaluate collapse potential in conjunction with susceptibility graphs similar to the CGS Collapse Susceptibility Graph. Plate bearing field tests have been used to evaluate the hydrocompaction severity at a few important project sites.

The main factors that should be considered in assessing the hydrocompactive risks at a specific building site are:

- Hydrocompactive severity of the foundation soils
- Depth of hydrocompactive soils
- Site grading and surface drainage
- Foundation loads and foundation configuration
- Ability of the structural system to resist differential foundation settlements

Some risk must be accepted when building at a site with a high hydrocompaction potential. In the Glenwood Springs area these sites are typically alluvial fans with greater than 20 feet of moderate to high severity hydrocompactive soils. At these sites, mitigation measures to reduce potential hydrocompaction damage should take precedence over other architectural and development considerations. Mitigation measures can include:

- Deep foundation systems or shallow spread footings with bearing pressures of 1,000 psf or less
- Heavily reinforced foundation walls in a *box-like* configuration or a rigid mat foundation
- Ground floors on a single level
- Good compaction of foundation backfill and positive surface drainage away from the building
- Adequate roof gutters with downspouts that discharge well away from the building
- Avoid landscape irrigation close to the building or eliminate irrigation with xeriscape
- Use of impervious linings below foundation drains
- Use of impervious linings in landscape ponds and other water features and locating the ponds well away from buildings
- Use of positive joint restraints on water and sewer lines

In addition to the above mitigation measures, some sites could require ground modification such as:

- Complete or partial removal and replacement of the hydrocompactive soils
- Compaction grouting
- Dynamic compaction
- Prewetting and surcharge loading

IRON BRIDGE SINK HOLE (DRIVE BY)

During construction of the Ironbridge Golf Course a sinkhole developed near the temporary golf cart storage tent (Figure 15). There was little indication of ground movement in this area until the sinkhole caved to the surface early in the morning on January 9, 2005. At that time, the sinkhole was bell-shaped and had a diameter of about 10 feet. By mid-morning the sinkhole had enlarged to a diameter of about 40 feet. About a month later the sinkhole had enlarged to a diameter of about 75 feet and was about 40 feet deep. The subsurface profile next to the sinkhole consisted of about 45 feet of alluvial fan deposits overlying about 10 feet of outwash gravel deposited on the Eagle Valley evaporite. One of the borings drilled next to the sinkhole encountered a 20 foot deep void in the evaporite. During geotechnical studies for the development, sinkholes had been mapped in the general area but there was no indication of a sinkhole at the site of the January 9, 2005 sinkhole. Since permanent buildings would not be located near the sinkhole, it was stabilized by backfilling with road base and compaction grouting up from the soil/evaporite contact at depths between about 50 and 100 feet.

Figure 15. 40-ft diameter sinkhole that formed on January 9, 2005 at corner of Ironbridge Golf Course temporary cart storage tent.

COUNTY ROAD 109 HYDROCOMPACTION (DRIVE BY)

The three mile stretch of County Road 109 starting at the Ironbridge Golf Course and extending to the south crosses many small, coalescing alluvial fans with drainage basins in the Eagle Valley Evaporite and Eagle Valley Formation on the western Roaring Fork River valley side. The fan deposits along this part of the road are particularly susceptible to hydrocompaction. Differential road settlement and ground cracks occur in many areas along the road where surface runoff ponds in the road ditches. Some houses in this area have been damaged by foundation settlements. The geology along this part of the road is similar to many other parts of the Roaring Fork River valley that have not experienced a similar degree of road settlement and hydrocompaction damage. The reasons for the pronounced hydrocompaction along this three mile stretch of road is uncertain at this time.

COUNTY ROAD 109 SLOPE FAILURE AND DEBRIS FLOW (DRIVE BY)

On July 11, 1998 a large debris flow on an alluvial fan blocked about 600 feet of County Road 109 and inundated irrigated hay fields to the east of the road (Figure 12). The flow extended about 1,000 feet from the fan head to where it stopped at the lower irrigation ditch. The flow deposit at the road was about 9 feet deep and consisted of gravel- to boulder-size rocks in a mud matrix (Figure 16). The flow resulted from a slope failure on the north side of a draw that extends about 700 feet back from the top of the upper terrace escarpment. The 1998 slope failure started about 200 feet back from the top of the escarpment. The flow was about 400 feet long and 150 feet wide and involved about 65,000 cubic yards of material (White, 1998). The 1998 slope failure formed a new, branching draw to the north of the pre-existing draw. The draw is likely the site of one or more older, but similar, slope failures that built the alluvial fan at the base of the terrace escarpment. The soil profile exposed in the slope failure escarpment consisted of about 10 feet of loess and alluvial fan deposits over 20 feet of Bull Lake-age, glacial outwash that overlies the Eagle Valley Evaporite. The Eagle Valley Evaporite forms the base of the failed area.

The most likely cause of the 1998 slope failure was higher than usual groundwater levels in the upper terrace. Groundwater recharge to the upper terrace is from natural precipitation and infiltration of flood irrigation water that has gone on for at least 100 years. Tree ring analysis indicates that western Colorado has experienced cyclic droughts and wet periods during the past 600 years (Woodhouse et al., 2004). On the average, a drought cycle lasts about 20 $\pm$10 years followed by a 20 $\pm$10 year wet period. The twenty-one year period between 1982 and 2003 was the second longest wet cycle in the 600 year tree ring record. The 1998 County Road 109 slope failure and debris flow, and several other landslides in western Colorado in the late 1990's, occurred around the peak of this wet cycle. Western Colorado is currently in a drought cycle that has lasted three years.

Figure 16. July 11, 1998 County Road 109 debris flow looking to the west. (Photo by Jonathan White, Colorado Geological Survey)

MT. SOPRIS AND ROCK GLACIERS (DRIVE BY)

The twin summits of Mount Sopris are at an identical altitude of 3,948 m (12,953 feet). The mountain is formed by a middle Cenozoic granodiorite stock, with slightly metamorphosed Pennsylvanian sedimentary rocks concordantly draped over the south side of the stock. An $^{40}Ar/^{39}Ar$ age of 34.74 ± 0.19 Ma on biotite probably records the time of cooling through 350^{o} C. The north flank of the mountain coincides with the southwest margin of the Carbondale collapse center, which may help to explain the dramatic relief of the mountain. In spite of its relatively low altitude, Mount Sopris was glaciated during the Pleistocene, and spectacular latest Pleistocene and Holocene rock glaciers spill off the north flank of the mountain (Figure 17).

Figure 17. Rock glaciers from north flank of Mt Sopris (Photo by Jonathan White and David Noe, Colorado Geological Survey)

LEG 2: GEOLOGIC HAZARDS OF MARBLE TOWNSITE AND VICINITY

"OVERSHOT" DEBRIS FLOW MITIGATION STRUCTURES (DRIVE BY)

Where the Crystal River valley narrows, starting about 6 miles south of Carbondale, we can see the "overshot" structures near the mouths of small tributaries on the right (west) side. Frequent debris flows occur on these small but steep and erosive streams and the "overshots" are designed to pass the debris flows over the canals without obstructing and washing out the irrigation canal. Severing of the canal can cause extensive breaching of the canal and increased threat of flooding on the fans below.

PENNY HOT SPRINGS (DRIVE BY)

Penny Hot Springs are located about 5 miles past the "overshot" structures where the valley floor widens on the east side of the Crystal River. Under certain weather conditions these multiple hot springs create a dense fog bank in the valley flats.

USFS REDSTONE CAMPGROUND (DRIVEBY)

Two miles south of the hot springs, signs identify the USFS Redstone Campground. Note the towering pinnacles of Maroon Formation red rock comprising the high upper slopes approximately ¾ mile to the left (east). These pinnacles and similar ones along this reach of the Crystal River are subject to toppling failures that launch long runout distance rockfall events. The very large equi-dimensional blocks have the longest runouts and frequently can be seen as surviving 15+ ft. "boulders" in the Crystal River channel. About 20 years ago a rockfall event occurred above this campground. Blocks as large as 15 ft. in diameter traversed a proposed expansion area for the campground. After an evaluation by the Colorado Geological Survey, the USFS altered their expansion plan.

STOP 4. REDSTONE GEOLOGIC HAZARDS

The town of Redstone was founded in the late 19th century to support the mining of premium quality coking coal from the Mesa Verde Group of the Grand Hogback to the west. Mines were active in the area until the late 20th century when they were closed for safety concerns from cave-ins and explosive gases. Damage to surface facilities from debris flows and snow avalanches were also a factor.

The mines were abandoned about 15 years ago and the reclamation bonds forfeited. Reclamation has now been completed by the Colorado Division of Mines and Geology, Department of Natural Resources. The long row of Cardiff beehive coking ovens (cica 1890) at Redstone are the chief reminders of the once thriving coking industry of the area.

The town was built by John C. Osgood, Chairman of the Colorado Fuel and Iron Company of Pueblo. He created it as a "utopian community". The Tudor-style Redstone Inn was built as a residence for unmarried workers and included a clubhouse for cultural and educational activities. Detached single family homes were provided for workers with families. Imagine a late 19th century industrial baron with a social ethic!

Redstone is our first stop and we will view and discuss the debris flow and flood hazards on the Crystal River. The upper basin of Coal Creek experiences very frequent debris flows, debris avalanches, and snow avalanches that feed an immense volume of wood debris and rock material to the main channel. During heavy spring run-off, much of this material is re-mobilized and swept downstream. At the confluence of Coal Creek and the Crystal River, the wood and rock debris piles up, often causing backwater and erosion on both streams and CO Hwy 133. Town, County and CDOT maintenance staff are aware of the problem and manage to cope with it each year.

MARBLE GEOLOGIC HAZARDS

Location and historical sketch

The upper Crystal River valley starts at the foot of McClure Pass near the coal mining ghost town of Placita. At this point the Crystal River departs from its path along the Grand Hogback and begins to carve its way easterly into the towering Elk Mountains. By any standards, this is one of the most rugged and scenic areas in Colorado (Figure 18). Today this area is a favorite haunt for numerous summer-home dwellers, miners, prospectors, backpackers, overnight campers, big game hunters, geology field camps, and aspen-gazers in the fall. There are still a determined few residents who stay on through the long and bitter winters. Despite this rather light current usage by man, the town of Marble and its environs has at times in the past seen a population numbering in the thousands, was served by a railroad, and even challenged Gunnison as the commercial center of Gunnison County. Within its 140 years of recorded history, this valley has seen a wide variety of development activity and human drama. Players in this saga have included Mountain Ute hunting parties and hard-bitten prospectors, explorers and entrepreneurs, miners of white marble and black coal, visionaries and confidence men, skilled artisans and bootleggers, railroad builders and fast-talking modern resort developers. As diverse as this history is in detail, in overview it simply records man's challenges and struggles to conquer an unbelievably beautiful and enticing, but hostile and deadly environment. From George Yule's first dream of wealth from the incomparable marble of Treasure Mountain to the inglorious demise of Marble Ski, Inc. in a sea of mud and red ink a hundred years later – the Crystal River country has spawned a thousand dreams – and eventually destroyed all those dreamers who sought to tame it. The silent past speaks to today's casual sojourner in the valley through the crumbling ruins of mines, mills and smelters, of electric tramway foundations and corduroy roads; but most impressive of all these memorabilia are the cavernous depths of the old Yule quarry and the Romanesque ruins of the marble works that extend for more than half a mile along the Crystal River in the town of Marble.

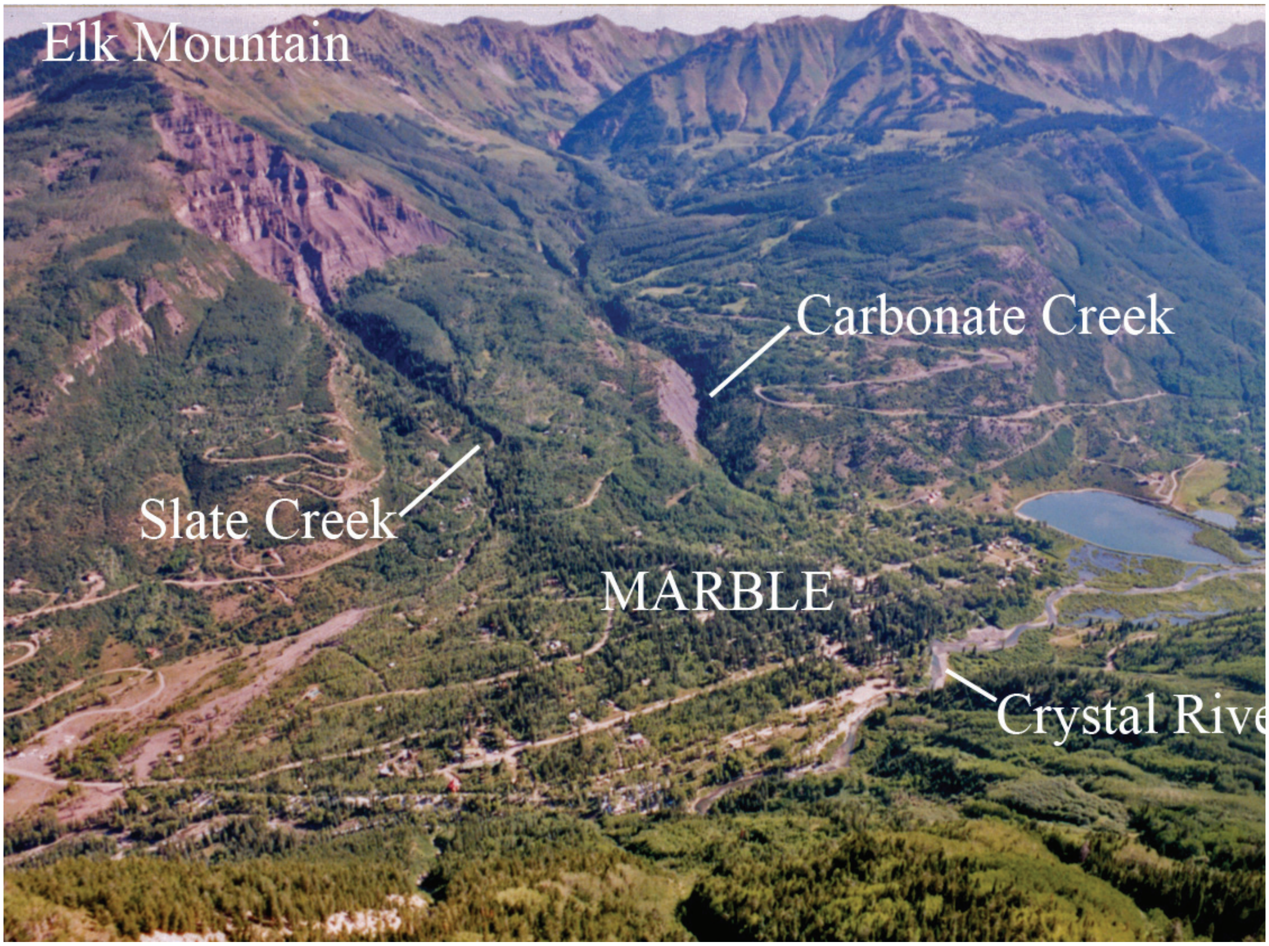

Figure 18. Aerial view of Marble townsite, including view of Elk Mountain and the Slate and Carbonate Creek drainages.

Dr. W.P. Rogers first visited the vicinity of Marble in 1971 when reports of potentially dangerous and ill-advised land use were directed to the Colorado Geological Survey for investigation. A quick field reconnaissance of the area and comparison with the "Master Plan" of Marble Ski, Inc. confirmed that the plan was fraught with numerous serious geologic hazards that had been unrecognized or unheeded. Intensive subdivision into lots, road building, and lot sales demonstrated that the developers were indeed serious in their announced intention of creating a major destination ski resort on the 2,000 acres or more of private lands they controlled. Their Master Plan depicted base facilities and housing for a year-round resort population of 25,000 or more.

The name of this community is derived from the marble producing and processing industry (Figure 19), which operated under very difficult conditions and with varying degrees of success between 1880 and 1941 and was reactivated in the 1990's (McGee, 1999). Production is from high quality marble deposits which are located on Yule Creek approximately three miles southeast of the townsite. The marble deposits consist of metamorphosed Leadville Limestone which occurs on the southwest flank of the Treasure Mountain Dome.

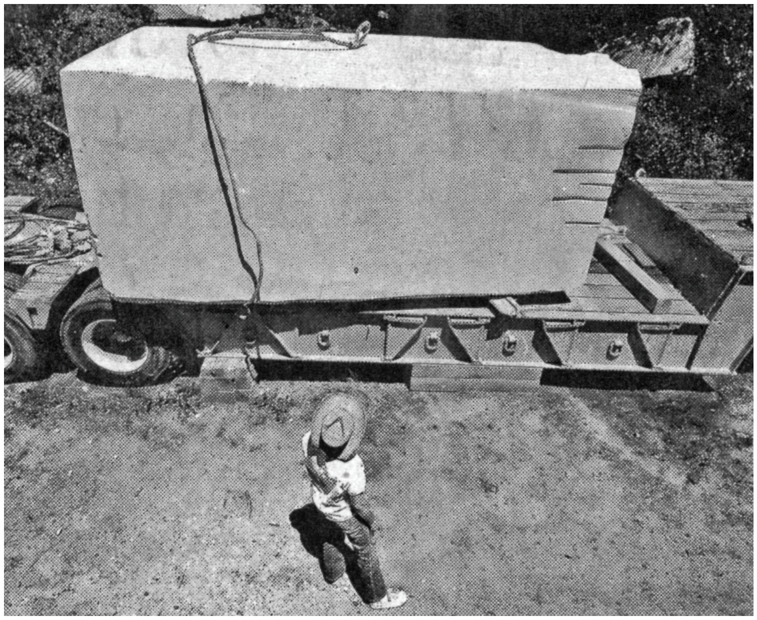

Figure 19. The 57-ton block of marble, cut two years ago from the Yule Marble Quarry, sits in a storage yard in the town of Marble. For the stone to be accepted, it will have to be examined for flaws.

The town and its marble industry reached maximum development immediately before the start of World War I when Marble attained a population of 1500 to 2500. The marble works, and with it the town, declined between the World Wars and finally closed after a "mud flood" in 1941. After 1941, the town rapidly dwindled to the extent that it was considered essentially a ghost town. A subsequent debris flow in 1945 destroyed much of the remaining town on Carbonate Creek.

Geologic and geomorphic setting

Marble is located in the Elk Mountains of Western Colorado, approximately 35 miles by air south of Glenwood Springs (Figure 1). We will focus on the combined watersheds of Slate Creek and Carbonate Creek. This basin forms a southwest-facing bowl having an area of approximately 4,000 acres. The Slate Creek drainage, which consists of only about 600 acres, exerts a significant influence on the area, because it heads in the rapidly eroding Gallo Bluff area that feeds the Slate Creek mudflows. It seems quite probable that in the geologic past, Slate and Carbonate Creeks were part of the same stream system that contributed to the early growth of the major debris-flow fan upon which Marble is situated. The Slate-Carbonate drainage basin descends from an elevation in excess of 12,000 feet at the basin rim to approximately 7,950 feet on the Crystal River near Marble. Precipitation charts indicate an average annual rainfall of approximately 30 inches, with major rainfall occurring during the peak thunderstorm season of July and August. All mud floods that we have been able to date have occurred in July or August.

Bedrock geology of the area is complex, but the area is underlain for the most part by strata of the Mancos Shale and Mesa Verde Formation, both of Cretaceous age. Structurally, these strata occur along the northwest-trending axis of the broad Treasure Mountain Dome, which lies to the southeast. The Mancos Shale underlies most of the area, with Mesa Verde strata cropping out high on Gallo Bluff and in a narrow band south of the Crystal River. The Mesa Verde also probably subcrops beneath the extensive talus debris north of the Crystal River in the vicinity of the landing strip (Figure 20). There is intensive minor faulting of the Cretaceous strata in Gallo Bluff – a condition that presumably extends under the landslide, colluvial, mudflow, and other surficial deposits which mask the bedrock surface over most of the area between Gallo Bluff and the main mass of Treasure Mountain Dome east of Marble. Porphyritic intrusive rocks occur within the area on both sides of the Crystal River west of Marble in the vicinity of the landing strip. These outcrops consist of the synclinal limbs of the Raspberry Creek Phacolith. Other intrusive igneous rocks occur in the upper reaches of Carbonate Creek, along with Pennsylvanian sedimentary strata. These rocks have been thrust over Cretaceous beds along the Elk Range Thrust Zone. Igneous rocks of minor importance occur as occasional dikes cutting the Cretaceous strata.

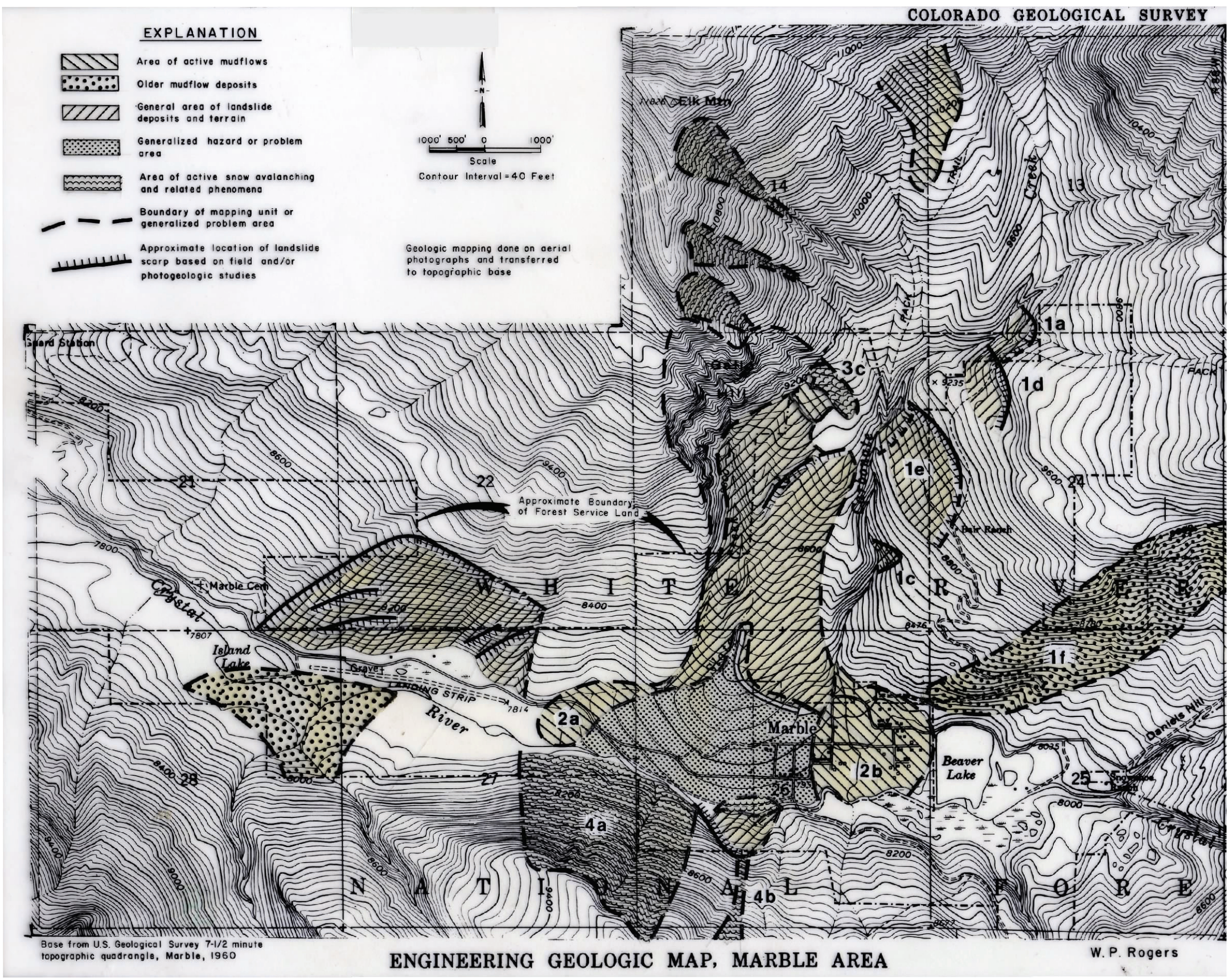

Figure 20. Engineering Geologic Map of the Marble Area (from Rogers and Rold, 1972).

Surficial deposits of the area are also complex but are much younger, being of Pleistocene and Holocene age. These deposits consist of residual soils formed on Mancos Shale, talus and other colluvial soils, landslide and debris-flow deposits, and older morainal material which occur as discontinuous deposits mostly on the higher slopes Junge, 1978).

Geomorphic evolution of the area has been affected by rock type and structure, by multiple glaciations during Pleistocene time, and finally by intensive fluvial action and vigorous mass wasting. The vigorous fluvial and mass wasting processes that have dramatically modified the area since the last glaciation are continuing, and are closely related to the geologic hazard conditions of the area (Figure 20).

<u>STOP 5.</u> SLATE CREEK – ACTIVE DEBRIS FLOW DEPOSITIONAL AREA

The Marble townsite and environs is dominated by two large debris-flow producing creeks that form a large coalescing debris/alluvial fan (Figure 18). The 2nd stop of this leg of the field trip is on lower Slate Creek at the western edge of the fan. Slate Creek enters near the apex of the major fan and follows an entrenched course along its western edge. It emerges from this steep-sided and erosive channel about 2,000 feet north of the Crystal River and deposits coarse debris plugs and alternating hyper-concentrated flows along shifting distributaries of the active fan. Slate Creek produces debris flows of serious consequence at about 3- to 5-year intervals and smaller ones yearly (Figures 21 and 22). The active channel has recently shifted eastward and is now threatening the few remaining houses on the active fan.

Figure 21. Fresh abrasion marks and mud on trees indicate at least a 9-ft thick debris front at this location on Slate Creek.

The long defunct Marble Ski Resort sold lots on 1/4- to 1/3–acre sites in the early 1970's on the entire active fan (Figure 17). This land-use activity was a major factor in Colorado passing stringent land use-laws at that time (SB-35, HB-1041, et al.).

At this stop we will discuss the source area and other factors resulting in this very active debris fan. There will also be time to walk over the active fan as far as the entrenched section.

Figure 22. Large blocks of Mesa Verde Sandstone in recent mudflow debris of Slate Creek, twelve year old boy in foreground. Recency of the deposit is indicated by fine debris on top of blocks.

<u>STOP 6.</u> CARBONATE CREEK FAN – EXISTING TOWNSITE, RUINS OF MARBLE WORKS

Carbonate Creek descends from a steep and sizeable drainage basin (approximately 3,500 acres) on the slopes of Mt. Daly and Elk Mountain, and follows a deeply entrenched and actively eroding channel adjacent to and east of the major debris flow fan (Figure 18). Just north of the Marble townsite, Carbonate Creek emerges from the steep-walled canyon it has cut into the Mancos Shale, and flows through the town to its confluence with the Crystal River. The area between the mouth of the canyon and the Crystal River has a history of similar but much larger mud and debris flooding than those described on Slate Creek (Figure 23). The area affected by periodic recent mud floods from Carbonate Creek covers approximately twice the area of the Slate Creek flows. The most recent catastrophic mud floods on Carbonate Creek occurred in 1936, 1941 and 1945, and smaller floods are reported nearly every year.

Figure 23. Top of park bandstand in town of Marble, lower part was buried by coarse debris of 1945 mud flood on Carbonate Creek.

At this stop we will view and discuss historic debris flows and avalanche paths as well as the perpetual debris-flow events on the Marble Ski Resort's property. We will also walk through the ruins of the marble processing works.

REFERENCES

Cannon, S.H., Gartner, J.E., Holland-Sears, A., Thurston, B.M., and Gleason, J.A., 2003, Debris-flow response of basins burned by the 2002 Coal Seam and Missionary Ridge fires, Colorado, *in* Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering Geology in Colorado–Contributions, Trends, and Case Histories: AEG Special Publication 15, Colorado Geological Survey Special Publication 55, 31 pp., on CD-ROM.

Cannon, S.H., Gartner, J.E., Wilson, R.C., and Laber, J.L., in press, Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California: Geomorphology.

Cannon, S.H., Powers, P.S., Pihl, R.A., and Rogers, W.P., 1995, Preliminary evaluation of the fire-related debris flows on Storm King Mountain, Glenwood Springs, Colorado: U.S. Geological Survey Open-file Report 95-508, 38 p.

Eisenhauer, R.J., 1986, Characterization of Glenwood springs and Dotsero springs source aquifers: U.S. Bureau of Reclamation, report REC-ERC-86-1, 35 p.

ESA Geotechnical Consultants, 1982, Final Report - Drainage and Debris Control Plan for the City of Glenwood Springs: Prepared for the City of Glenwood Springs, Glenwood Springs, Colorado (Project No. G208, December 1982).

Junge, W.R., 1978, geologic hazards, Upper Crystal Rivers Area, Gunnison County, Colorado: Colorado Geological Survey Open-File report 78-11, 2 maps.

Kirkham, R.M., Parise, Mario, and Cannon, S.H., 2000, Geology of the 1994 South Canyon fire area, and a geomorphic analysis of the September 1, 1994 debris flows, south flank of Storm King Mountain, Glenwood Springs, Colorado: Colorado Geological Survey Special Publication 46, 39 p.

Kirkham, R.M., and Scott, R.B., 2002, Introduction to late Cenozoic evaporite tectonism and volcanism in west-central Colorado, *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America, Special Paper 366, p. 1-14.Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., 2002a, Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America, Special Paper 366, 234 p.

Kirkham, R.M., Streufert, R.K., Kunk, M.J., Budahn, J.R., Hudson, M.R., and Perry, W.J., Jr., 2002b, Evaporite tectonism in the lower Roaring Fork River valley, west-central Colorado, *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America, Special Paper 366, p. 73-99.

Kirkham, R.M., Zook, J.M., and Sares, M.A., 1999, Reconnaissance field investigation of surface-water specific conductance in the Snowmass-Glenwood Springs area, west-central Colorado: Colorado Geological Survey Information Series 49, 21 p.

Lincoln DeVore, 1978, Geologic Hazards of the Glenwood Springs Metropolitan Area - Garfield County, Colorado: Colorado Geological Survey Open File Report 78-10.

McGee, E.S., 1999, Colorado Yule marble – building stone of the Lincoln memorial: U.S. Geological Survey Bulletin 2162, 41 p.

Mears, A. I., 1977, Debris-Flow Hazard Analysis and Mitigation - An Example from Glenwood Springs, Colorado: Colorado Geological Survey Information Series 8.

Mock, R.G., 2002, Geologic setting, character, and potential hazards for evaporite-related sinkholes in Eagle and Garfield Counties, Colorado, *in* Kirkham, R.M., Scott, R.B., and Judkins, T.W., eds., Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Geological Society of America, Special Paper 366, p. 157-166.

Rogers, W.P., and Rold, J.W., 1972, Engineering geologic factors of the Marble area, Gunnison County, Colorado: Colorado Geological Survey, In-house Report, 11p., map

White, J.E., 2002, Collapsible soils and evaporite karst hazards map of the Roaring Fork River corridor, Garfield, Eagle, and Pitkin Counties, Colorado: Colorado Geological Survey, Map Series 34, scale 1:50,000.

White, J. L., 1998, County Road 109 Earth Failure and Resultant Debris Flow: Field Trip Guidebook, Geologic Hazards and Engineering Practices in Western Colorado, Colorado Geologic Survey, Denver, Colorado.

Woodhouse, C. A. et al., 2004, TreeFlow Colorado Stream flow Reconstructions: IGBP PAGES/World Data Center for Paleoclimatology, Data Contribution Series No. 2004-029, NOAA/NGDC Paleoclimatology Program, Boulder, Colorado.

Ye, H., Royden, L., Burchfiel, C., and Schuepbach, M., 1996, Late Paleozoic deformation of interior North America: The greater ancestral Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 80, p. 1397-1432.

GEOLOGIC ROAD GUIDE FOR THE HIGHWAY 82 CORRIDOR, GLENWOOD SPRINGS TO ASPEN, COLORADO

Trip Leaders:

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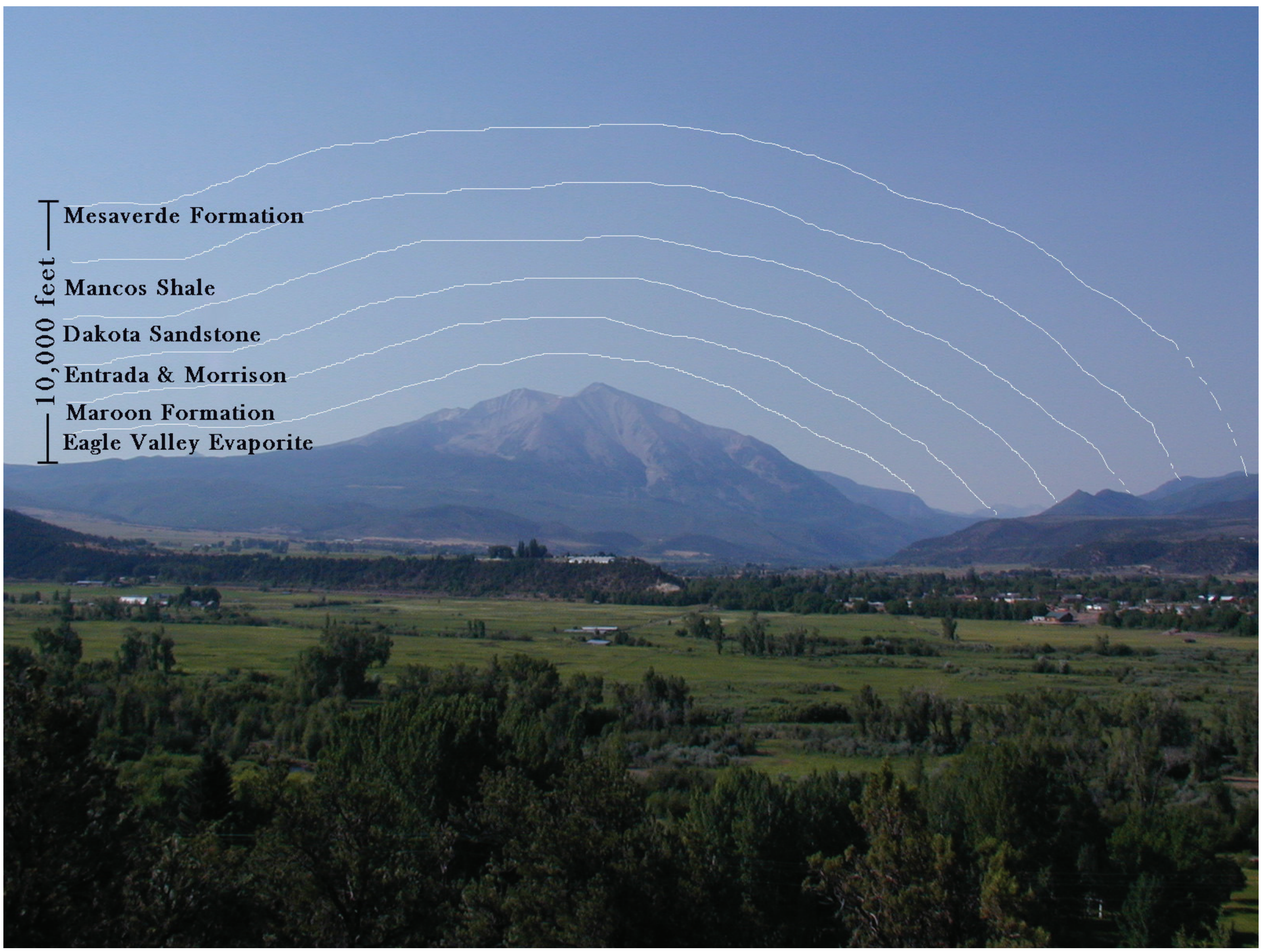

Mt. Sopris (12,953 ft) in the Roaring Fork Valley just south of Carbondale, Colorado

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

This one-day field trip covers the geology of the Roaring Fork valley from Glenwood Springs to Aspen, Colorado. The geology is spectacular, consisting of Middle to Upper Paleozoic rock units near Glenwood Springs to Middle to Upper Paleozoic, Mesozoic and Cenozoic rock units toward Aspen. Glenwood Springs (elevation 5,763 ft) is located at the confluence of the Colorado and the Roaring Fork rivers and is situated on the western edge of the Southern Rocky Mountain Province. Just west of Glenwood Springs is the Grand Hogback, a 90-mile long monoclinal ridge of west dipping Mesozoic rock units that marks the boundary between the Southern Rocky Mountain and the Colorado Plateau provinces. East of Glenwood Springs is the Glenwood Canyon, formed as the Colorado River eroded into the faulted and folded southern edge of the White River Uplift, a circular topographic and structural dome. The canyon shows a fairly complete geologic section of Precambrian and Paleozoic outcrops, which the Colorado River has exposed during the past 3 million years. Aspen is located at the western edge of the Sawatch Mountain Range, which consists mainly of Precambrian rock units, and is northeast of the Elk Mountains that are Tertiary intrusive and volcanic rock. Alluvial and colluvial filled valleys of the Roaring Fork River have experienced major growth over the last 20 years, which has resulted in many problems arising from construction in geologic hazard areas that include landslides, rockfall, debris flows, sink hole development and flooding. Above 7,500 ft, glacial features and valleys dominate the upper Roaring Fork valley. Aspen (7,907 ft) is located at the base of Aspen Mountain, a faulted, north plunging syncline. This field guide contains narrative of drive-by points of interest between Glenwood Springs and Aspen (Table 1).

Table 1. Field Trip and Topics

Location	Topic	Presenter
Glenwood Springs	Geologic setting; hot springs	Garry Zabel and Sylvia White
Near Carbondale, Highway 133 and Hwy 82 intersection	Eagle Valley Evaporite – collapse center, sinkholes, slope failures	Garry Zabel and Sylvia White
Basalt	Basalt flows	Garry Zabel and Sylvia White
Snowmass Village	Geologic setting, Highway 82 construction	Garry Zabel and Sylvia White
Approach to Aspen	Glaciation of upper Roaring Fork Valley; faults and folds	Garry Zabel and Sylvia White

TRIP ROUTE DESCRIPTION AND MAPS

The trip route will take us on State Highway 82 from Glenwood Spring to Aspen, Colorado (Figure 1). Highlights of this trip will include folds, faults, landslide and debris flows, glaciofluvial terraces, gypsum piercement, rock glacier, faults, glacial moraines and glacial erosional features.

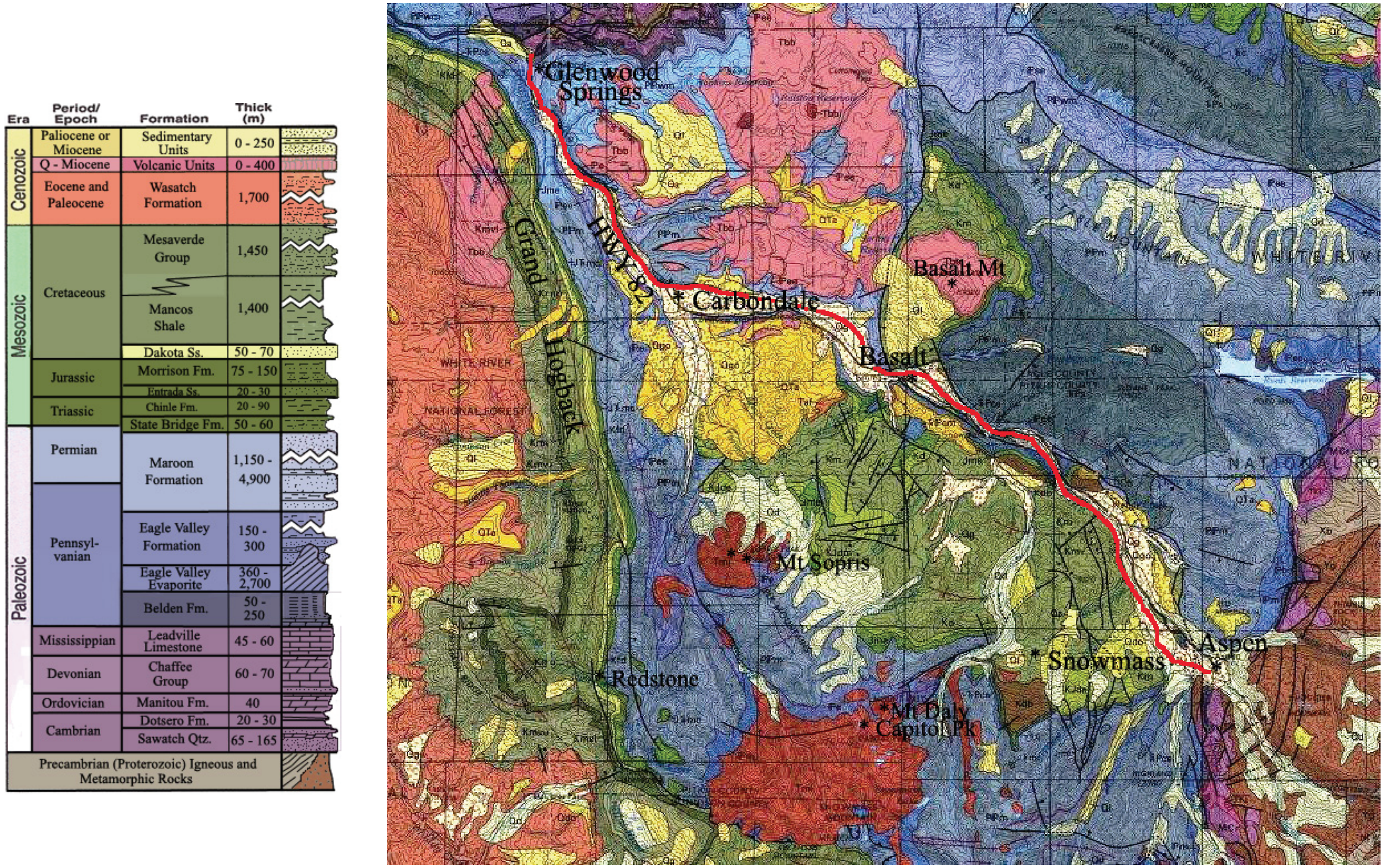

Figure 1. Geologic map and route map from Glenwood Springs to Aspen. (Mod. from Tweto, 1978) and General stratigraphic column of the Glenwood Springs area (mod. from Kirkham and others, 2002).

Table 2. Mileage from the start of the field trip at stoplight on State Highway 6 and Interstate 70 off ramps in Glenwood Springs, Colorado to Roaring Fork River terraces overview.

Cumulative Mileage	Mileage Difference	Description
0.0	0.0	Start field trip mileage at stoplight at intersection of State Highway 6 (6th Street), and off ramps of Interstate 70 at Exit 116, Glenwood Springs. Turn right (east) on 6th Street.
0.1	0.1	Turn right (south) onto Grand Avenue Bridge and continue south through Glenwood Springs on Grand Avenue (State Highway 82).
1.4	1.3	Continue south as Grand Avenue becomes Glen Avenue and is also State Highway 82.
1.7	0.3	Major slump feature to right (west) in the Maroon Formation. (Figure 2)
3.4	1.7	Coke ovens to the right (west) past Glenwood Springs air field
4.1	0.7	Driving along axis of Cattle Creek Anticline within the Maroon Formation.
5.3	1.2	Roaring Fork River glaciofluvial (outwash) terraces on right (west) with view of Mount Sopris (12,953 ft) to south (see cover photo), a 34 Ma granodiorite laccolith.
7.4	2.1	Gradational contact between the Eagle Valley and the Maroon formations.
8.3	0.9	Multiple Pinedale glaciofluvial terraces and gravel pit to the right (west).

Figure 2. Condominiums just north of the slump feature.

Table 3. Mileage from Roaring Fork River terraces overview to El Jebel turnoff.

Cumulative Mileage	Mileage Difference	Description
8.7	0.4	Folded beds of Eagle Valley Evaporite to left (east) – gypsum dome or gypsum piercement. Note the south dipping contact with the overlying Eagle Valley and Maroon formations to the left just ahead.
10.4	1.7	Coryell Ranch debris flow 1998 to the right (west). (Figure 3)
11.6	1.2	Intersection of HWY 82 and 133 to Carbondale. Stay on HWY 82.
12.0	0.4	Basalt Mountain (10,866 ft) in skyline to east, ahead.
13.2	1.2	Gravel pit to left (north) in Bull Lake (?) glaciofluvial deposits.
15.5	2.3	Eagle Valley Evaporite exposed on both sides of valley
18.4	2.9	Sinkhole in the Eagle Valley Evaporite (Figure 4) on the edge of the Roaring Fork Valley to the left (north) is part of the Carbondale Collapse center (Figure 5).
18.8	0.4	Rock glacier on Mount Sopris to right (south). Figure 6)
18.9	0.1	Intersection of HWY 82 and turnoff to El Jebel.

Figure 3. Aerial photo of the 1998 Coryell Ranch debris flow (Kirkham and others, 2000).

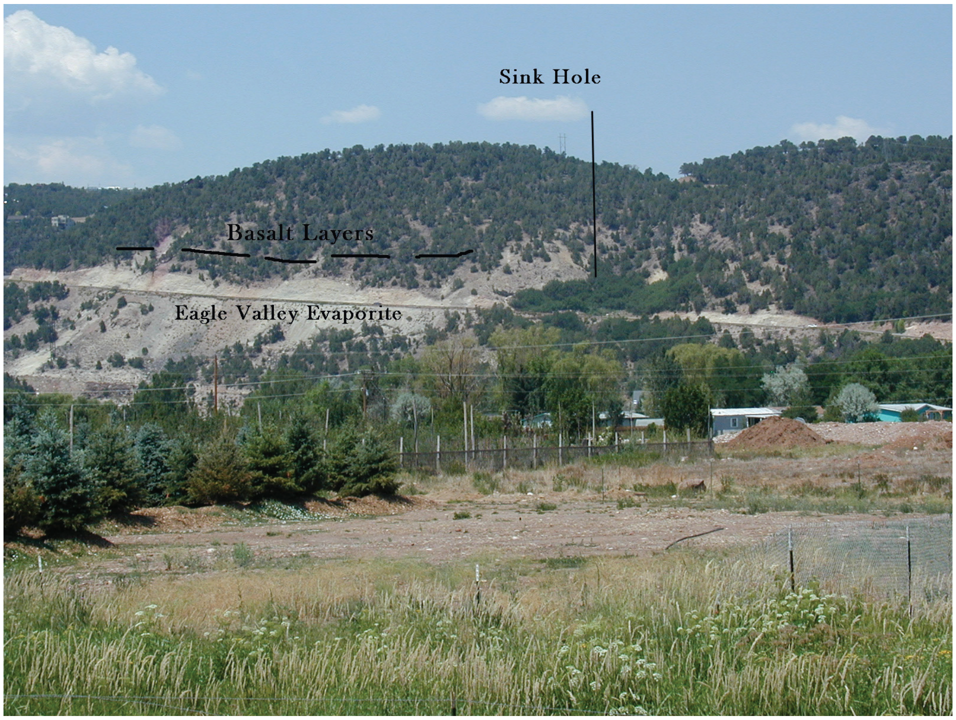

Figure 4. Sink hole along Upper Cattle Creek road north of El Jebel.

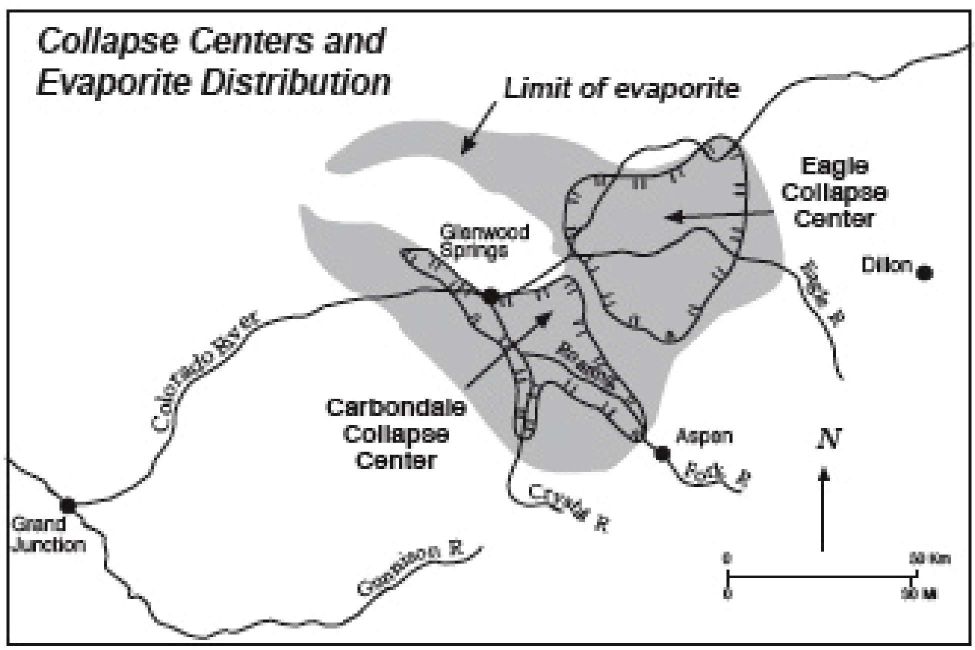

Figure 5. Map showing the Carbondale and Eagle collapse centers
(Kirkham and others, 2000).

Figure 6. Aerial view of the rock glacier below the east peak of Mt. Sopris
(http:www.ngdc.noaa.gov/seg/cdroms/geohazards_v3/images/647006/jpg/64700618.jpg)

Table 4 Mileage from El Jebel turnoff to Basalt Mountain Fault view.

Cumulative Mileage	Mileage Difference	Description
20.7	1.8	View to the right (southwest) of exposures of Maroon Formation up through Mancos Shale on the side of the Roaring Fork Valley. (Figure 7)
21.0	0.3	Junction State Highway 82 and Willits Lane
21.2	0.2	Highway 82 crosses Roaring Fork River
23.1	1.9	Junction State Highway 82 and Basalt Ave.
23.6	0.5	Highway 82 crosses Roaring Fork River. Basalt Mountain (9.7 – 10.5 Ma) to the left (north) with basalt talus slopes and outcrops of Maroon up through Dakota formations on the southeast flank. (Figure 8)
24.8	1.2	Steeply dipping Morrison Formation in Basalt Mountain fault to right (south).

Figure 7. Formations exposed to the right (southeast) at Emma, Colorado.

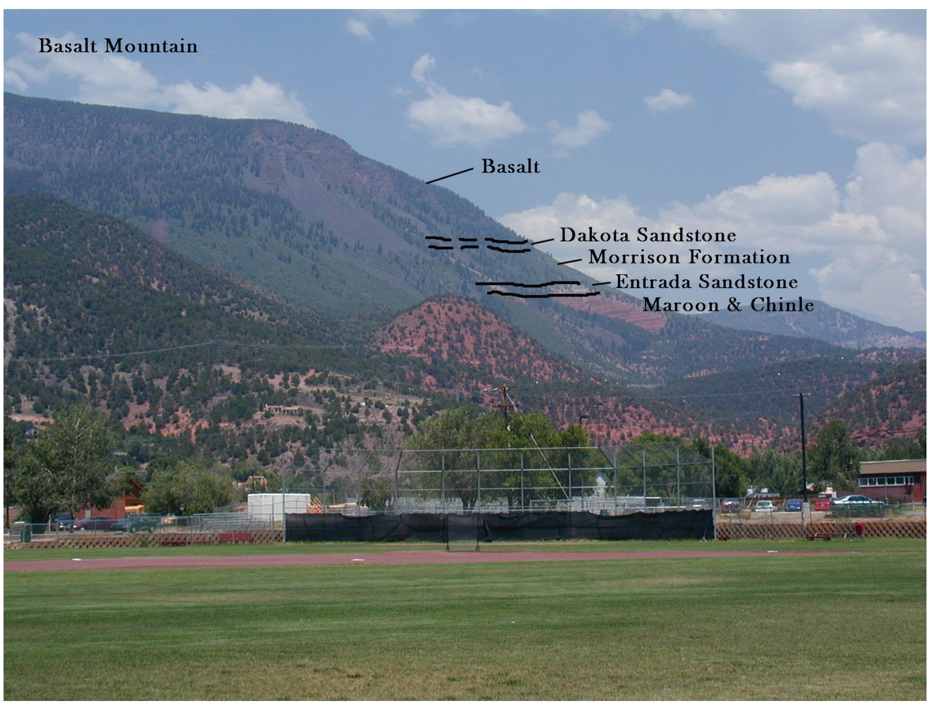

Figure 8. Basalt Mountain to the northeast at Basalt, Colorado

Table 5. Mileage from Basalt Mountain Fault to Aspen Ski Area.

Cumulative Mileage	Mileage Difference	Description
26.7	1.9	Junction of HWY 82 and Old Snowmass turn at Lower River Road.
27.1	0.4	Snowmass Canyon in Maroon Formation.
31.1	4.0	The Roaring Fork valley widens due to glaciation in the Illinoian Period. Triangle Peak (9,225 ft) to the left (north) is a remnant cinder cone dated at 1.5 Ma.
33.1	2.0	Glaciofluvial terraces on both sides of the Roaring Fork River of Late Bull Lake and Pinedale stages melting cycles. (Figure 9)
35.2	2.1	Junction of State Highway 82 and turn to Snowmass Village.
35.4	0.2	Shale Bluffs area with good exposures of Mancos Shale cliffs.
36.7	1.3	Mancos Shale overlain by glaciofluvial deposits left (north). (Figure 10)
37.4	0.7	Mt.Daly (13,300ft) a granodiorite stock with felsic dike. (Figure 11)
37.6	0.2	Aspen Airport Business Center.
38.1	0.5	Recessional moraine (Late Bull Lake) to the left (northeast) and two lateral moraines (Bull Lake and Early Pinedale) to the right (southwest).
39.1	1.0	Red Butte to the left (north) composed of an overturned sequence from red Chinle Formation on top to the Mancos Shale on the bottom. The Castle Creek fault to the northeast of Red Butte overturned this sequence now dipping 45 to 55 degrees northeast.
39.6	0.5	Pyramid Peak (14,018 ft) composed of Maroon Formation to the right (south).
40.4	0.8	Cross Castle Creek bridge. View of Hunter Creek hanging valley to the left (northeast). Entering the city of Aspen.

Figure 9. Glaciofluvial terraces west of Aspen

Figure 10. Glaciofluvial deposits overlying the Mancos Shale.

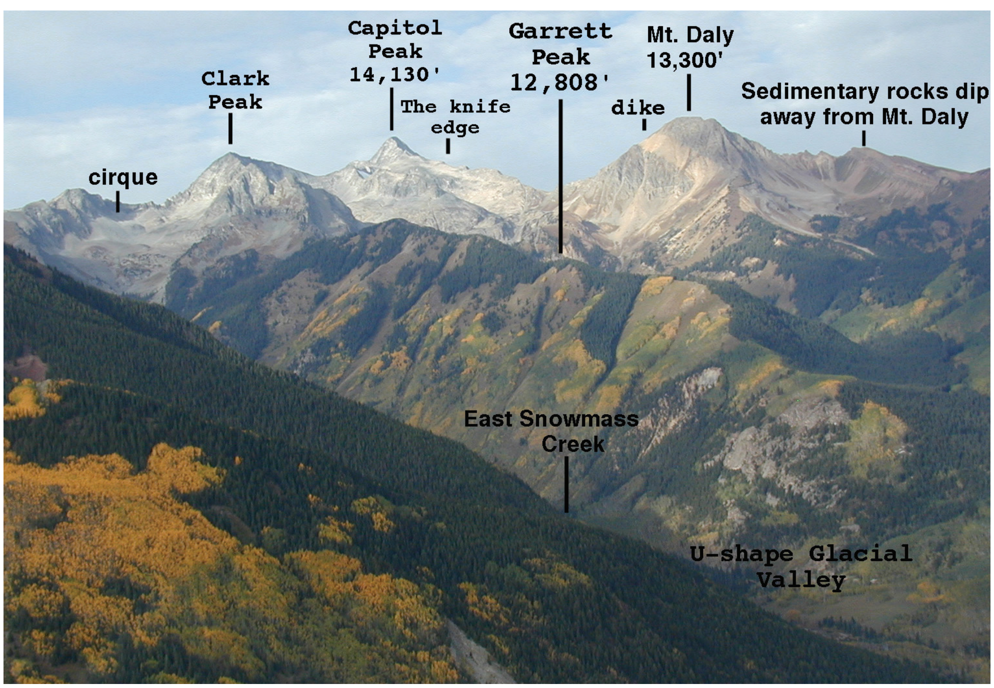

Figure 11. Aerial photo of Mt. Daly and Capitol Peak west of the Snowmass Ski Area.

REFERENCES

Kirkham, R.M., Scott,R.B., and Judkins, T.W., eds., 2002, Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Boulder, CO, Geological Society of America Special paper 366, 234 p.

Kirkham, R.M. and Matthews, V., 2000, Guide to the geology of the Glenwood Springs area, Garfield County, Colorado, Earth Science Week Field Trip October 13, 2000, Colorado Geological Survey.

Kirkham, R.M., Streufert, R.K., and Cappa, J.A., 1997, Geologic map of the Glenwood Springs quadrangle, Garfield County, Colorado, Open file report MS-31, Colorado Geological Survey.

Streufert, R.K., Widmann, B.L., and Kirkham, R.M., 1998, Geologic map of the Basalt quadrangle, Eagle, Garfield and Pitkin Counties, Colorado, Open-file report 98-1, Colorado Geological Survey.

Tweto, O., Moench, R.H. and Reed, J.C., 1978, Geologic map of the Leadville 1 degree x 2 degrees quadrangle, northeastern Colorado, Miscellaneous Investigations Series Map I-999, U. S. Geological Survey.

Zabel, G.E. and White, S.A., 2004, Geology of the Snowmass area, Snowmass Village: Wild at Heart, WHO Press and Town of Snowmass Village, p. 21-30.

Zabel, G.E. and White, S.A., 2003, Stratigraphy and Engineering Geology of the Glenwood Springs I-70 Corridor October 5, 2003, Geology in the Next Decade, Field Trips and Abstracts, American Institute of Professional Geologists

ASPEN—SKI AREA GEOLOGY

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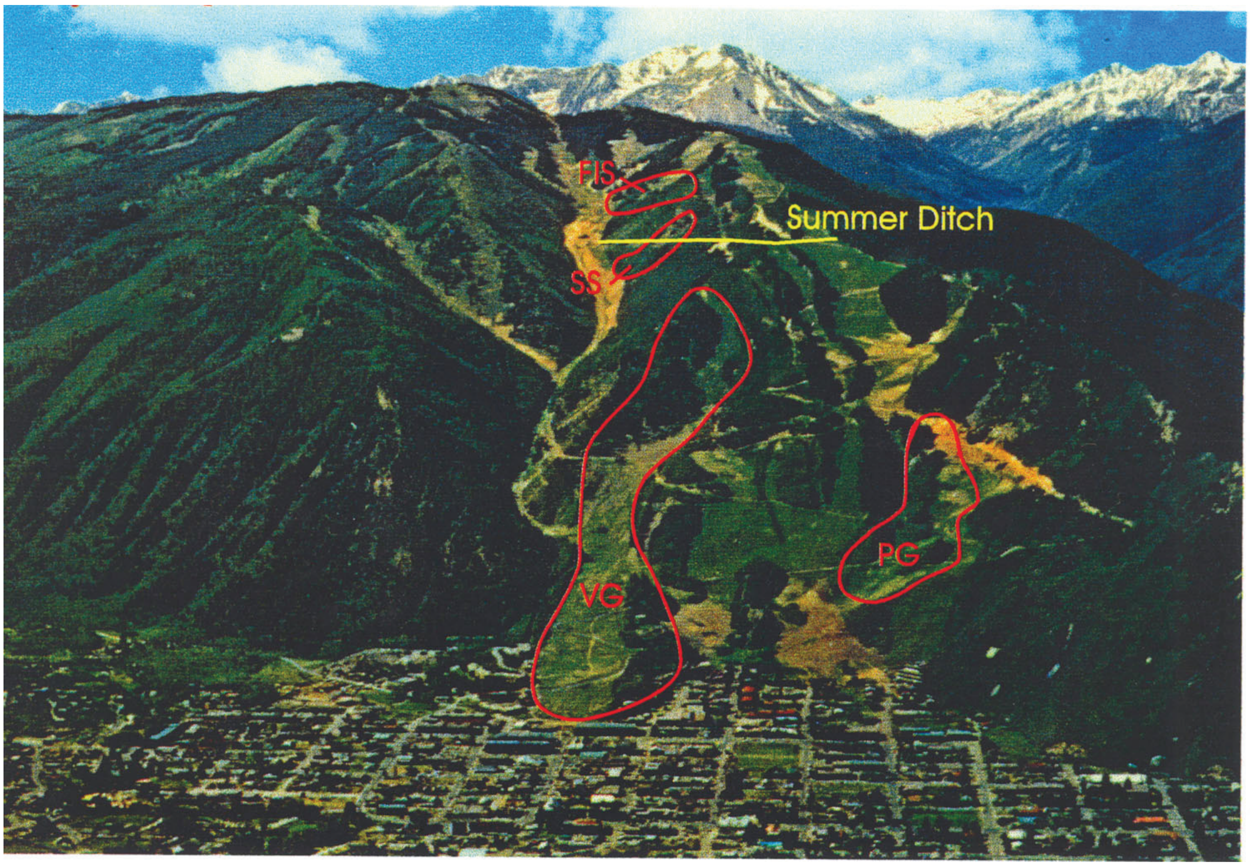


View of Aspen Mountain Ski Area, looking south. Town of Aspen is in foreground. Red lines outline post-glacial landslides (VG, Vallejo Gulch; PG, Pioneer Gulch; SS, Short Snort; FIS, FIS landslide). Yellow line shows the Summer Ditch. The final leg of our field trip route descends Aspen Mountain on a road faintly visible at right center. This road (the Summer Road) zig-zags its way down the mountain, passing through the FIS slide, past the right (west) end of the Summer Ditch, past the head of the PG slide, and then back across its toe to the VG slide.

1st North American Landslide Conference
Vail, Colorado, June 6, 2007

OVERVIEW

Aspen, Colorado was originally founded in the 19th Century as a silver-mining town, but its 20th-Century reputation results from its 3 ski areas, and from the rich and famous people who come to ski in the winter and visit their vacation homes and ranches in other seasons.

Like most Colorado ski areas, the 3 ski areas near Aspen all contain landslides. In fact, the original ski area (Aspen Mountain, directly south of downtown; see cover) would never have been developed, if landslides had not reduced the mountain slopes to a skiable grade. Each of the mountains we will visit on this trip has a different geologic setting, and thus, landslide style and history:

1—Aspen Mountain, the original ski area, where deep-seated, postglacial landslides occur in Paleozoic shale in the axis of a north-dipping syncline

2—Aspen Highlands, for years Colorado's record holder for vertical drop, where sackungen have formed on the arête between two 1000 m-deep glacial valleys

3—Buttermilk, the "beginner's mountain", a planar dip slope on Cretaceous sandstone characterized by shallow dipslope landslides

This trip will be led by James P. McCalpin, President of GEO-HAZ Consulting, Inc., Crestone, Colorado. During the 1990s, Dr. McCalpin was engaged by the U.S. Forest Service (USFS) and the Aspen Skiing Company (ASC) to perform landslide and geologic hazard mapping on all 3 ski mountains. These geohazards studies were part of the Environmental Impact Assessment (EIS) process required by the USFS, because much of the 3 ski areas lie in the National Forest on public land leased by USFS to the ASC. Normally, only the land at the base of a Colorado ski area is privately owned. Most of the observations we make on this trip result from those EIS studies.

The trip will begin at the base of the Buttermilk ski area, and then will drive to the top of the Aspen Highlands ski area (Figure 1). After descending Aspen Highlands we will drive up Castle Creek, stop briefly at the Aspen Music School, and then drive up the "backside" of Aspen Mountain to its summit. The last leg of the trip descends the "frontside" of Aspen Mountain into downtown Aspen.

Table 1. Field Trip 6A1, Stops and Topics (see route map, Figure 1).

Location	Topic	Presenter
Buttermilk Parking Lot	Welcome to Aspen; 4 mountains	Jim McCalpin
Tiehack Landslide (Stop 1)	Creeping post-glacial landslide	
Aspen Highlands Parking Lot	Geology of Aspen Highlands	
Loge Peak (Stop 2)	Sackungen	
Aspen Music School (Stop 3)	1996 debris flows	
Backside of Aspen Mountain—drive by	Mining history	
Top of Aspen Mountain (Ajax) (Stop 4)	Geology of Aspen Mountain	
Frontside of Aspen Mountain—look at landslides and panoramas (optional Stops 4a, 4b, 4c along the road)	1998 landslide mapping and snowmaking expansion	
Downtown Aspen bar	End of trip	

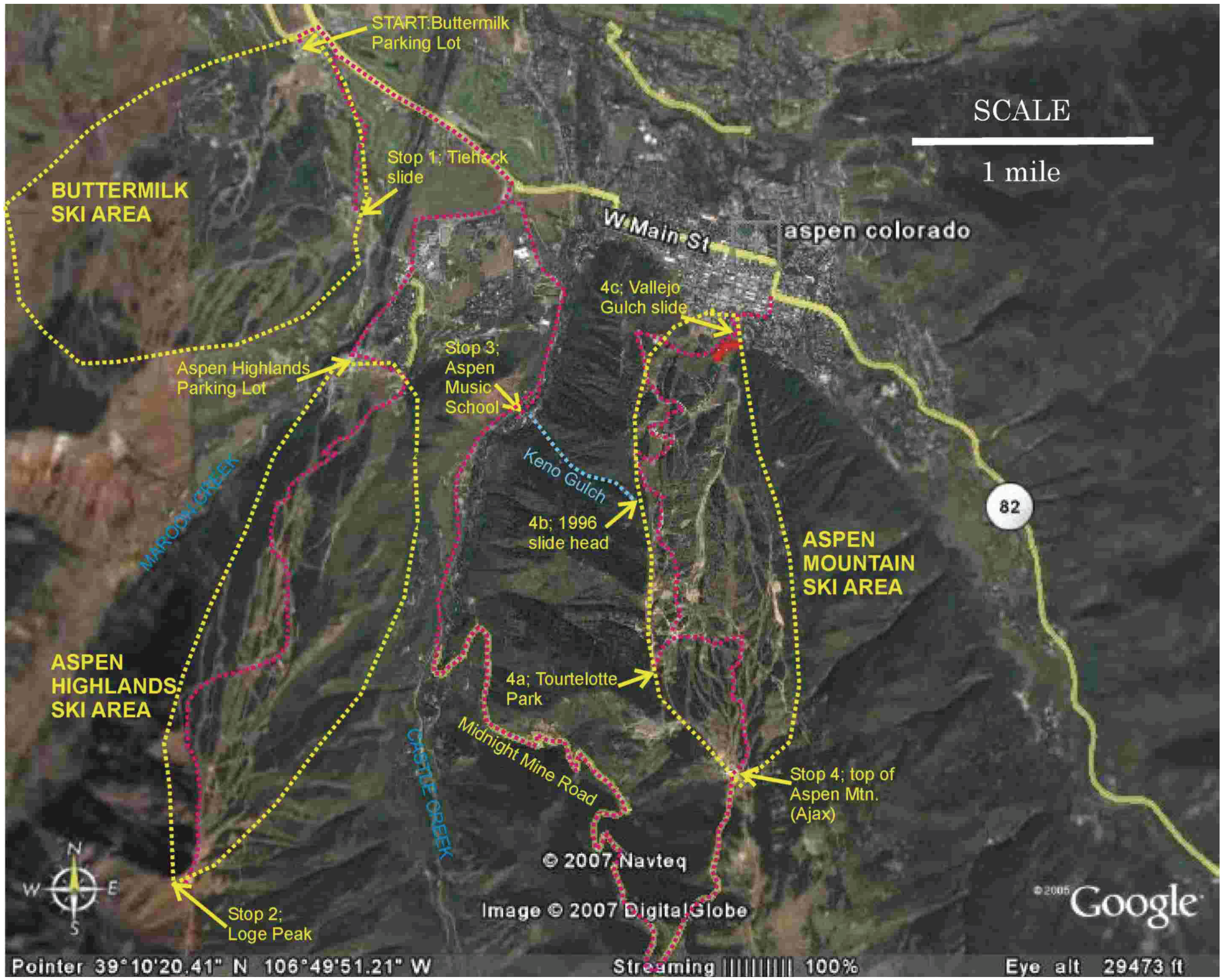


Figure 1. Route map of the field trip. Route ishown by pink dotted line. Start is at Buttermilk ski area, upper left; end is at Town of Aspen, upper right center.

BUTTERMILK PARKING LOT (START OF TRIP 6A)

The Buttermilk ski area lies on a large dipslope dipping 20°-24° NE. This planar slope is just the right gradient for beginner and intermediate skiing. The lower 2/3 of the ski area is underlain by the Mancos Formation, which can be divided into three members, an upper shale member about 4000 ft thick (map unit Kmu), a limestone member about 40 ft thick (the Fort Hays limestone member, map unit Kmf), and a lower shale member about 400 ft thick (map unit Kml). The upper shale member forms the lowest slopes at Buttermilk and is a dark gray shale and silty shale with a few lenticular beds of fine- to medium-grained olive-gray sandstone, with some thin-bedded shaly limestones in the lower part. The Fort Hays Limestone Member forms small resistant ridges in the central part of Buttermilk, and is composed of dark gray limestone beds 1-2 ft thick that contain thin interbeds of shaly limestone. The upper 2/3 of the mountain is underlain by the upper shale member, a dark gray silty shale with thin beds of silstone and fine-grained sandstone near the base (i.e., its contact with the underlying Dakota sandstone).

The shaly members of the Mancos Formation are known for widespread slope instability in Colorado (Colton et al, 1976), particularly in areas of relatively high precipitation as at Buttermilk. As shown in Figure 2, the lower half of the mountain is occupied by 5 large landslide complexes that originate in the Mancos Formation (McCalpin, 1999). Only part of one of these complexes, the middle of the Tiehack complex (A on Figure 2), has demonstrated historic movement.

Table 2. Mileage from Buttermilk Parking Lot to Stop 1.

Mileage	Description
0.4 (from Parking Lot) 0.4 (cumulative)	Leave Buttermilk Parking Lot and drive east to Colo Highway 82. Turn right (south) and proceed 0.2 mi on Colo 82
1.0 (from Colo 82) 1.4 (cumulative)	Turn right (west) onto Tiehack Road, and proceed to parking lot at base of Tiehack trail. STOP 1, Tiehack landslide.

<u>STOP 1.</u> TIEHACK LANDSLIDE

The only earthflow that has a known depth and rate of activity is the flow beneath the Upper Tiehack ski lift, which is 16-28 ft thick and had an average displacement rate between 1979 and 1981 of 3-5"/yr (Chen & Associates, 1981). Rates increased to 3-7"/month during the spring and accompanying rise in groundwater level. Chen & Associates (1981, p. 1) state "Continued landslide movements of similar pattern and magnitude can be expected, and greater landslide movement could occur in years of large than normal precipitation". It should be noted that from 1979-1981 (when the initial movement rates were measured) Colorado precipitation was below normal. Despite conclusive evidence for historic downslope movement, the surface of the Upper Tiehack earthflow does not exhibit fresh cracks, tilted trees, or other typical manifestations of active movement.

It is important to note that Bryant (1971) had mapped this same area as intact bedrock of the lower Mancos Formation (Kml). However, aerial photographs clearly show that the toe of this landslide has advanced approximately 500 ft downslope and buried part of the latest glacial outwash terrace of Maroon Creek. This discrepancy raises the possibility that other areas mapped as Mancos Formation bedrock by Bryant at Buttermilk are, in fact, slow-moving (creeping) landslides. New inclinometers were installed at Upper Tiehack in May 1983 and continuing movement was documented through June 1984 (Chen & Associates, 1985).

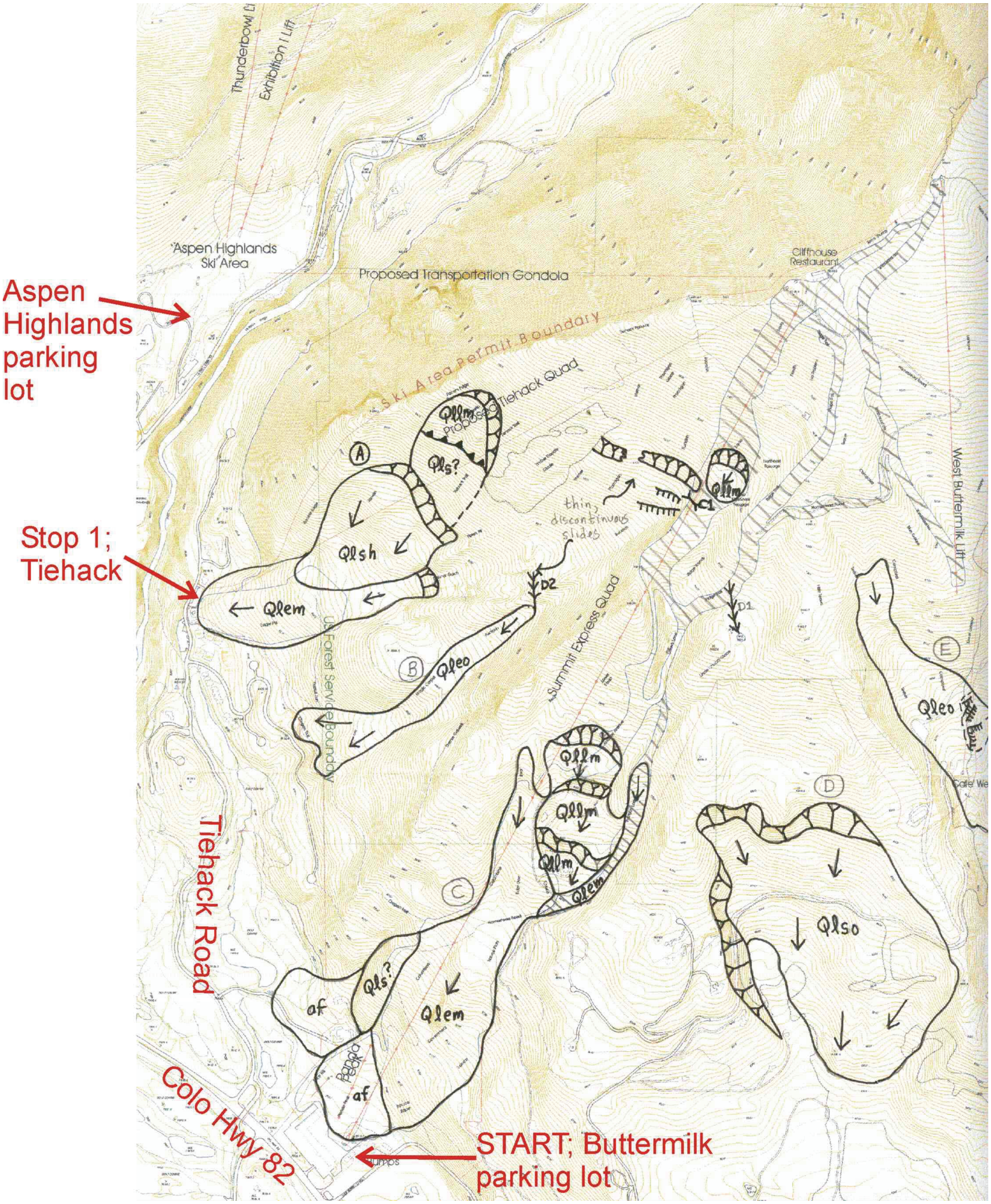


Figure 2. Map of the five landslide complexes (A-E) at Buttermilk; south is at the top. Ql, landslide; s, slump; e, earthflow; h, historic; m, mature; o, old; af, alluvial fan.

Prior to 1996, the four lowest towers of the Tiehack lift were on the 1200 ft-long, slow-moving Tiehack landslide. The cumulative slow movement of this slide from the inception of the lift up to 1981 was sufficiently large and damaging to lift operations that the slide was studied in detail by Chen & Associates (1981, 1985), with remedial work (grading, interceptor drains) performed in 1991-92 (Chen-Northern, 1991). In addition to the earthwork, several of the original towers on the slide were replaced with towers that had adjustable bases. In Aug. 1996 the towers of Adjustable Towers 2 and 3 were adjusted to the southeast end of their travel run, and they were still in that position as of Oct. 1998. Therefore, the landslide near these towers has probably not moved sufficiently to require adjustment in the 6 years since the towers were constructed. This lack of movement suggests that the remedial work performed by Chen-Northern in 1991-92 was successful in slowing down or stopping slide movement.

Table 3. Mileage from Stop 1 to Aspen Highlands Parking Lot.

Mileage	Description
1.0 (from Stop 1) 2.4 (cumulative)	Leave Tiehack parking lot and retrace route to Colo Highway 82.
1.0 (from Tiehack Rd) 3.4 (cumulative)	Turn right (south) on Colo 82 and drive over Maroon Creek Bridge.
1.3 (from Colo 82) 4.7 (cumulative)	Turn right (west) at traffic circle onto Maroon Creek Road. Proceed 0.4 mi to the Aspen Highlands Parking Lot. Transfer from bus to 4WD vehicles.

ASPEN HIGHLANDS PARKING LOT (VIEW OF PROPOSED HIGHLANDS-BUTTERMILK-SNOWMASS GONDOLA; TRANSFER TO 4WD VEHICLES)

In 1996, ASC proposed a gondola that would link 3 ski areas, Aspen Highlands, Buttermilk, and Snowmass. The impetus was to relieve traffic congestion, from skiers driving their cars between ski areas. The gondola would ascend from the base of Aspen Highlands, across Maroon Creek to the high point of Buttermilk (Cliff House), and then across the top of Buttermilk to the eastern edge of Snowmass (Elk Camp). Numerous slope stability hazards affect this alignment. The Highlands-Buttermilk section was most threatened by rockfalls from the 3 cliff-forming units (from top to bottom, Dakota sandstone [Cretaceous], Entrada sandstone [Jurassic], and State Bridge Fm. [Permian]). Based on loose rocks measured on the slopes, the median size of a rockfall boulder is about 2 ft in diameter and the 84th percentile (mean + 1 sigma) is about 3 ft in diameter (McCalpin, 1996b). To decrease exposure to rockfall, 2 alternative alignments were proposed that included expensive turn stations; however, the gondola has not yet been built.

Table 4. Mileage from Aspen Highlands Parking Lot to Loge Peak (Stop 2).

Mileage	Description
0.3 (from AH parking lot) 5.0 (cumulative)	Leave parking lot and drive S on Thunderbowl Lane to cul-de-sac; pass through gate to unpaved mountain access road.
0.6 (from start of access road) 5.6 (cumulative)	Ascend access road to 1st switchback.
1.0 (from 1st switchback) 6.6 (cumulative)	Ascend access road to 3rd switchback
1.4 (from 3rd switchback) 8.0 (cumulative)	Ascend road up 7 switchbacks through ski trails, to Midway.
1.7 (from Midway) 9.7 (cumulative)	Ascend road to top of Cloud 9 Lift.
0.8 (from top of Cloud 9 Lift) 10.5 (cumulative)	Ascend road to Loge Peak. Park at lift terminal. STOP 2.

STOP 2. LOGE PEAK AT ASPEN HIGHLANDS

For many years, Aspen Highlands boasted the largest vertical drop of any Colorado ski area (3,635 ft; 1,108 m). Like Buttermilk, Aspen Highlands is basically a north-dipping homoclinal sequence sedimentary rocks (Figure 3), ranging from Cretaceous Mancos Shale at its base (dip 15° NE), to Pennsylvanian Maroon Formation at its summit (dip 30° NE; Highland Peak). Currently, ski lifts end at Loge peak, underlain by Permian State Bridge Formation. Unlike Buttermilk, however, the homoclinal ridge has been eroded by deep U-shaped glacial valleys to the east (Castle Creek) and west (Maroon Creek). As a result, the ridge narrows southward, until south of Loge Peak it is an arête.

Due to the severe removal of mass from the lower ridge flanks, and the weak character of the rocks, the ridge south of Loge Peak has undergone post-glacial, deep-seated gravitational spreading (sacking, Figure 4). This spreading has flattened sections of the ridge crest and made them attractive for development; in fact, a restaurant complex was planned for the large depression SE of Loge Peak. In 1994 we identified and mapped the sackung landforms (McCalpin, 1994), and tried to determine if the sackungen were recently active, and if so, if they posed a geologic constraint to development (McCalpin, 1996a; McCalpin and Irvine, 1995).

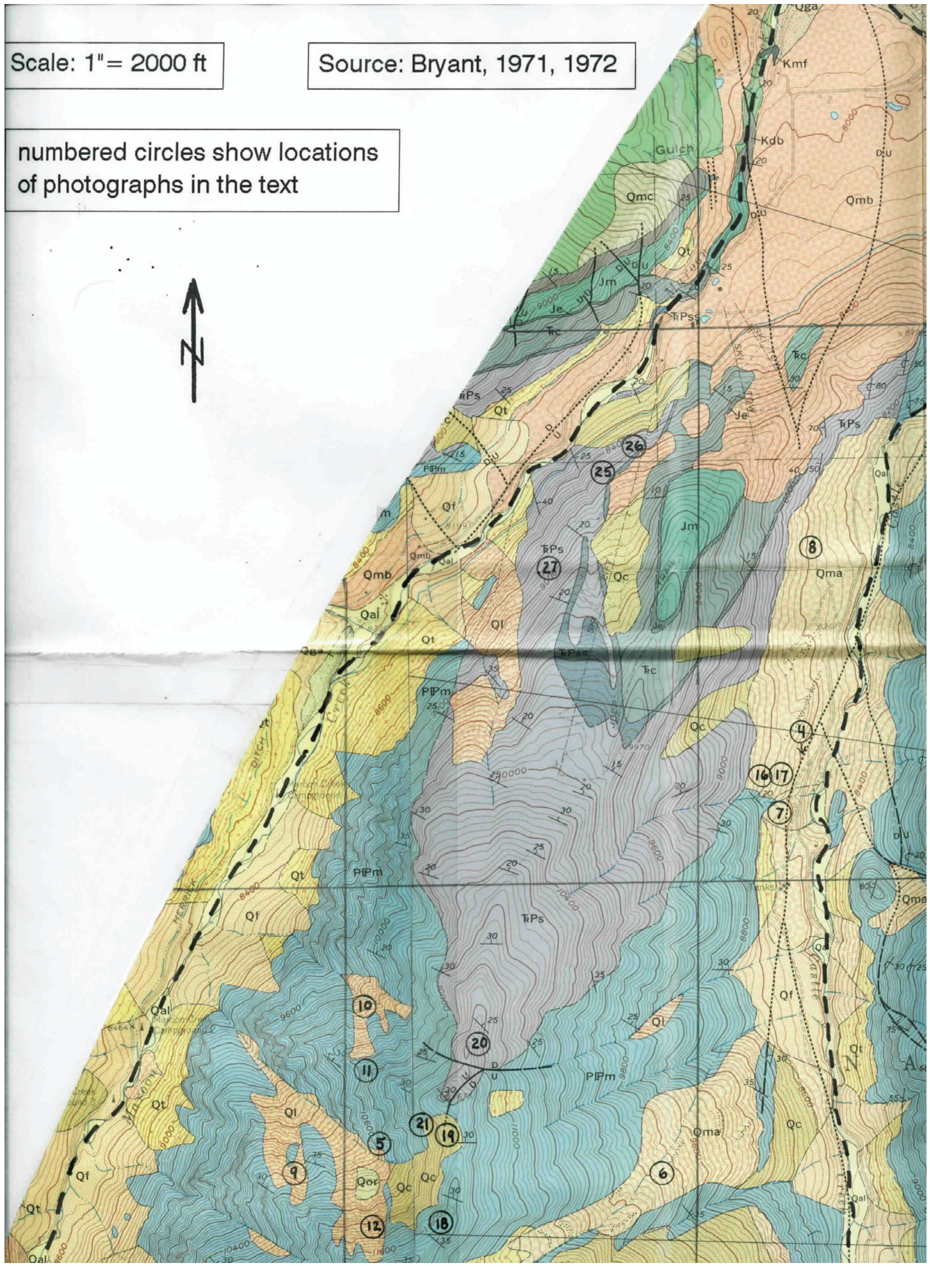


Figure 3. Geology of Aspen Highlands. Formations in ascending order: Maroon (blue), State Bridge purple), Chinle (olive), Entrada (d. olive), Morrison (green). Quaternary deposits in yellow.

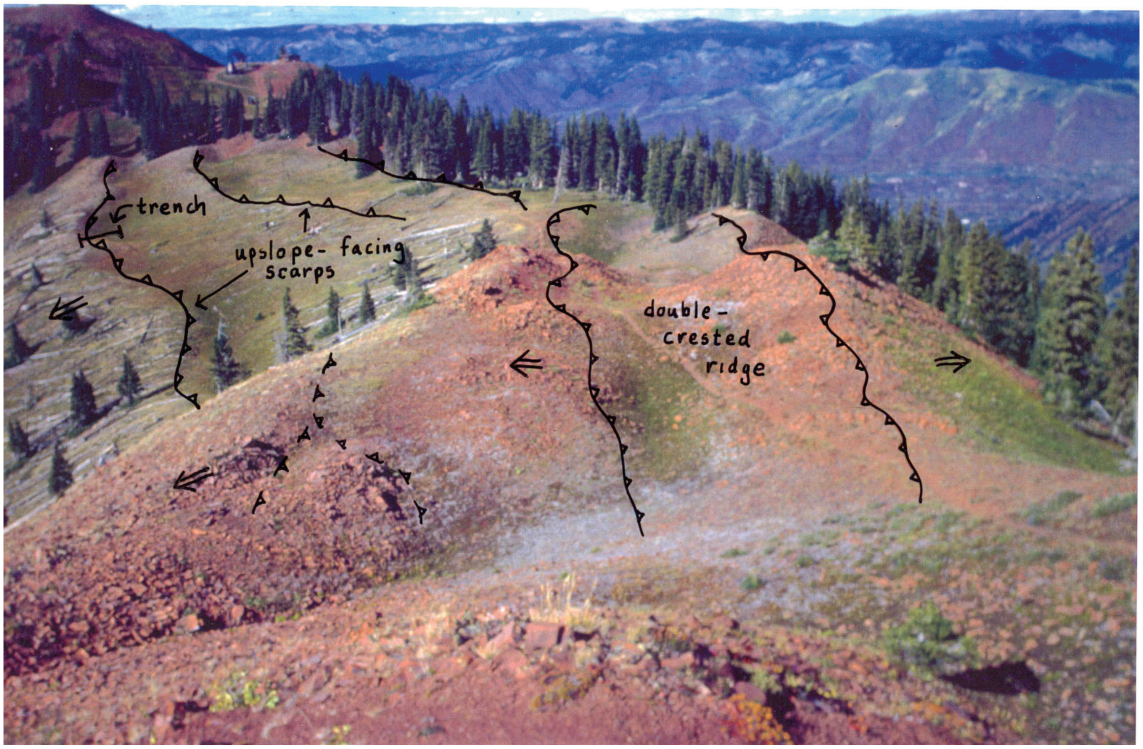


Figure 4. View of sackungs on the arête south of Loge Peak, looking north toward Loge Peak (upper left). Site of 1994 trench is shown at far left, across the leftmost antislope scarp.

DESCEND ASPEN HIGHLANDS (DRIVE BY)

Retrace route down access road, and proceed to Castle Creel and Stop 3.

Table 5. Mileage from Stop 2 to Aspen Music School (STOP 3).

Mileage	Description
5.8 (from Stop 2) 16.3 (cumulative)	Descend access road to Aspen Highlands Parking Lot.
1.2 (from AH parking lot) 17.5 (cumulative)	Turn right (NE) onto Maroon Creek Road and return almost all the way to Colo 82.
1.1 (Maroon Creek Road) 18.6 (cumulative)	70 m before reaching the traffic circle on Colo 82, turn right (E) onto Castle Creek Road. Proceed 1.1 mi to Music School Road.
0.2 (from Castle Creek Road) 18.8 (cumulative)	Turn left (S) onto Music School Road and drive 0.2 mi to parking lot (STOP 3)

STOP 3. ASPEN MUSIC SCHOOL

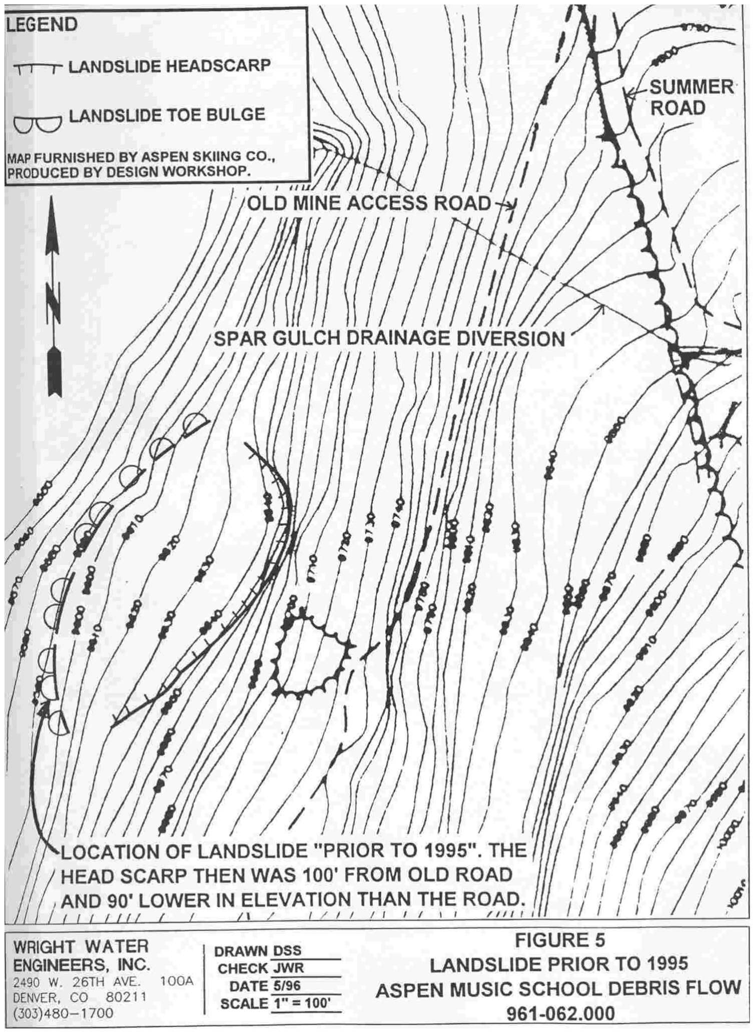
About 4 pm on May 13 a large, viscous debris flow issued from the mouth of Keno Gulch, jumped out of the channel, and flooded a parking lot at the Aspen Music School. This debris flow resulted from liquefying of a landslide mass in the head of Keno Gulch basin at about 9800 ft elevation. Estimates of the volume of the landslide ranged from 15,000-30,000 cubic yards (Mears, 1996) to 91,500 cubic yards (B. Savage and A. Chleborad, as quoted in Wright and Rold, 1996, p. 11). The initial catastrophic failure of the landslide and its transition into a debris flow high in the basin on May 13 were not observed. However, increasing displacements in the headscarp area were noted on May 10-12, 1996. By about noon on May 14 Arthur I. Mears (A.I. Mears, Inc.) and Jeffrey L. Hynes (Colorado Geological Survey) were on site and observing the landslide head and its interaction with ski area runoff. They left the site before the second large debris flow event, which occurred about 4 pm on March 14 and deposited additional material at the Aspen Music School.

According to Mears (1983) "debris flows... are a common geologic process in Keno Gulch. Inspection of 1973 and 1951 photos showed that debris flows have occurred regularly in the past, and field inspection of the basin found many areas susceptible to both landslide and debris flows". In a later report, he states "The alluvial fan at the bottom of Keno Gulch... has accumulated as a result of debris flows which have occurred over the past 10-20,000 years (since glaciers retreated from Castle Creek Valley)" (Mears, 1992). A test hole drilled on the alluvial fan at the mouth of Keno Gulch showed 14 ft of material that Wright and Rold (1996) interpreted as pre-mining debris flow deposits, with an additional 15 ft of similar material inferred below the bottom of the hole (Chen Northern, 1993). Although several episodes of debris flow deposition have been documented at the mouth of Keno Gulch (Table 6), it is interesting to note that Bryant (1971, 1972c) did not map an alluvial fan at this location, nor did he identify any "potentially unstable slopes" in Keno Gulch.

Based on reports furnished to me by ASC, there appear to have been at least three episodes of debris flows in Keno Gulch since shortly before 1973 (before 1973, 1983-84, and 1996). Both Mears (1983) and Bussone (1989) state that the 1973 aerial photographs show relatively recent debris deposition on the fan surface, which I take as evidence for a pre-1973 episode of debris flows. Jim Blanning (ASC) is quoted as recalling a debris flow in 1983 or 1984 (Wright and Rold, 1996, p. 6), years in which many landslides were reactivated elsewhere in Colorado. Finally, the largest and best-documented debris flows occurred on May 13-14, 1996 (Wright and Rold, 1996).

Table 6. Past Locations of Slope Instability on Aspen Mountain (from McCalpin, 1997).

Location	Detachment Elev. (ft)	Deposit Elev. (ft)	Date	Failure Style	Geologic Unit Failed	Groundwater Control	Remarks	Reference
Pioneer Gulch	1. unknown 2. unknown 3. 8600 4. 9300?	8400 8400 8300 9260?	Prehistoric 1985 5/22-25/89 1990s?	Slump slump slump slump	Belden Fm. " colluvium "	flow in syncline " " "	Strawpile area broke sewer line	Bryant, 1971 Robinson, 1989 Robinson, 1989 Gerdin, p. comm.
Vallejo Gulch (STOP 4c)	1. 8600-9400	7950-8600	Prehistoric	rockslide	aplite porphry	flow on faults	toe goes to Aspen	Bryant, 1971
Keno Gulch (STOP 4b)	1. unknown 2. unknown 3. 9630-9680	8065-8200 8065-8200 9590-9620	pre-1973 1983 or 1984 5/13-14/96	debris flow debris flow slide-debris flow	unknown unknown aplite-Belden	? ?	well-studied	Mears, 1983; Bussone, 1989 Blanning (unpub.) Wright & Rold, 1996
Short Snort trail	10,000	9550-9940	Prehistoric	slump-flow	Belden	flow on fault		Bryant, 1971
F.I.S. trail	10,340	10,000-10,200	Prehistoric	slump-flow	Belden	flow on fault		this study
Deer Park trail	10,460	10,260-10,400	Prehistoric	slump-flow	Belden-Leadville	?		this study
Tourtelotte Park trail (STOP 4a)	1.10,680 2.10,560	10,420-10,640 10,520	Prehistoric spring 1997	slump-flow slump-flow	Belden	?		this study
Castle Butte	10,840	9200-9700	Prehistoric	rock wedge	Leadville-Dyer	flow on faults		Bryant, 1971



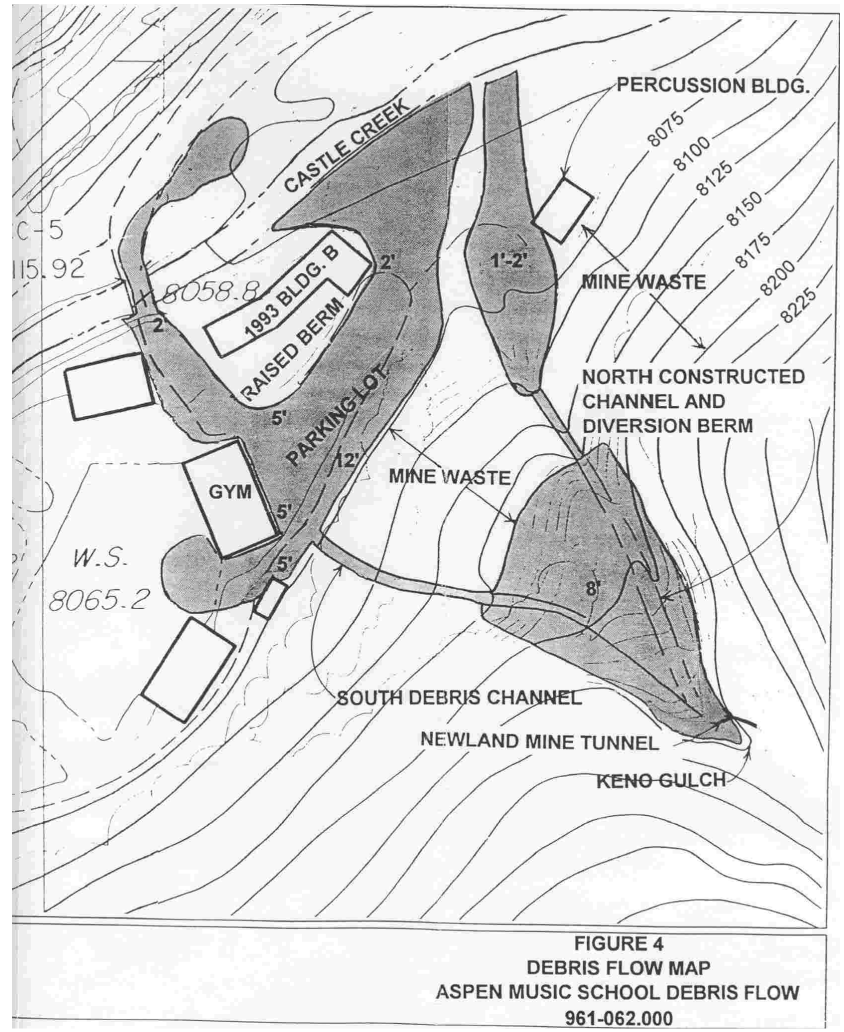


Figure 5. Left—Map of the headscarp area of the 1996 debris slide (see Stop 4b); Right—Debris-flow deposition at the Aspen Music School on May 13-14, 1996 (Stop 3).

Table 7. Mileage from Stop 3 to Ajax (top of Aspen Mountain ski area) via Midnight Mine Road.

Mileage	Description
0.2 (from Stop 3) 19.0 (cumulative)	Return on Music School Road to Castle Creek Road
1.6 (from Music School Road) 20.6 (cumulative)	Turn left (S) onto Castle Creek Road and proceed 1.6 mi to Midnight Mine Road
3.8 (from Castle Creek Road) 24.4 (cumulative)	Turn left (E) onto Midnight Mine Road; cross Castle Creek. Proceed up unpaved road for 3.8 mi
1.2 (from fork in road) 25.6 (cumulative)	Fork in road; bear left (N) onto Aspen Mountain Road; proceed 1.2 mi to Ajax (top of Aspen Mountain ski area)

ASCEND BACKSIDE OF ASPEN MOUNTAIN (DRIVE BY)

From Castle Creek Road, the Midnight Mine Road descends through till to Castle Creek and then ascends through till to 8400 ft (big switchback to S), where the Maroon Formation outcrops. The road reaches the toe of a large (unstudied) landslide at 9200 ft elevation. Beyond the head of the landslide, the road passes over a complexly-faulted terrain of lower Paleozoic strata and Tertiray intrusive porphyry, in the Castle Creek fault zone.

STOP 4. TOP OF ASPEN MOUNTAIN (AJAX)

Aspen Mountain is located at the border between two geologic terranes, the crystalline rock-cored Sawatch Uplift (to the east) and the sedimentary rock-filled Eagle Basin (to the west). The border between these two terranes is formed by the Castle Creek fault zone, a 4000-8000 ft-wide zone of four to 11 faults that trend roughly north-south (Figs. 6 and 7). Due to its location adjacent to this fault zone, the geology of Aspen Mountain is much more complex than that of the other Aspen ski areas. This stop is located on the contact between the Leadville Limestone (Mississippian) and the Dyer Dolomite (Devonian), which dip NW at 20°.

Most of Aspen Mountain lies east of the Castle Creek fault zone and is thus underlain at depths of 500-1000 ft by Precambrian igneous rocks of the Sawatch Uplift (quartz monzonite, map unit pCq on Figure 6). This old igneous rock unit (termed "granite" by Spurr, 1898) only outcrops relatively far down on the east and west flanks of Aspen Mountain. Elsewhere the upper 500-1000 feet beneath the surface is composed of seven formations of Paleozoic sedimentary rocks. These formations range from the basal quartzite (Sawatch Quartzite), through mixed dolomites (Peerless Formation, Manitou Dolomite, Dyer Dolomite) and quartzites (Parting Formation), to limestone (Leadville Limestone), and to a shaly formation at the top (Belden Formation). With the exception of the Belden Formation, these old sedimentary rocks are massive, well-cemented and competent, and are not generally prone to slope failure. The Belden Formation, however, is composed of dark gray to black "thin bedded carbonaceous limestone, dolomite, and shale with a few beds of sandy shale and sandstone" (Bryant, 1979, p. 23). Breccias are common in the Belden where exposures are good (such as in mine tunnels), with some breccias resulting from faulting and others (as at the Belden-Leadville contact) being related to dissolution and collapse (Bryant, 1979, p. 23). The overall effect of shale beds, shaly interbeds in more competent units, and breccias is to make the Belden Formation prone to erosion and slope failure.

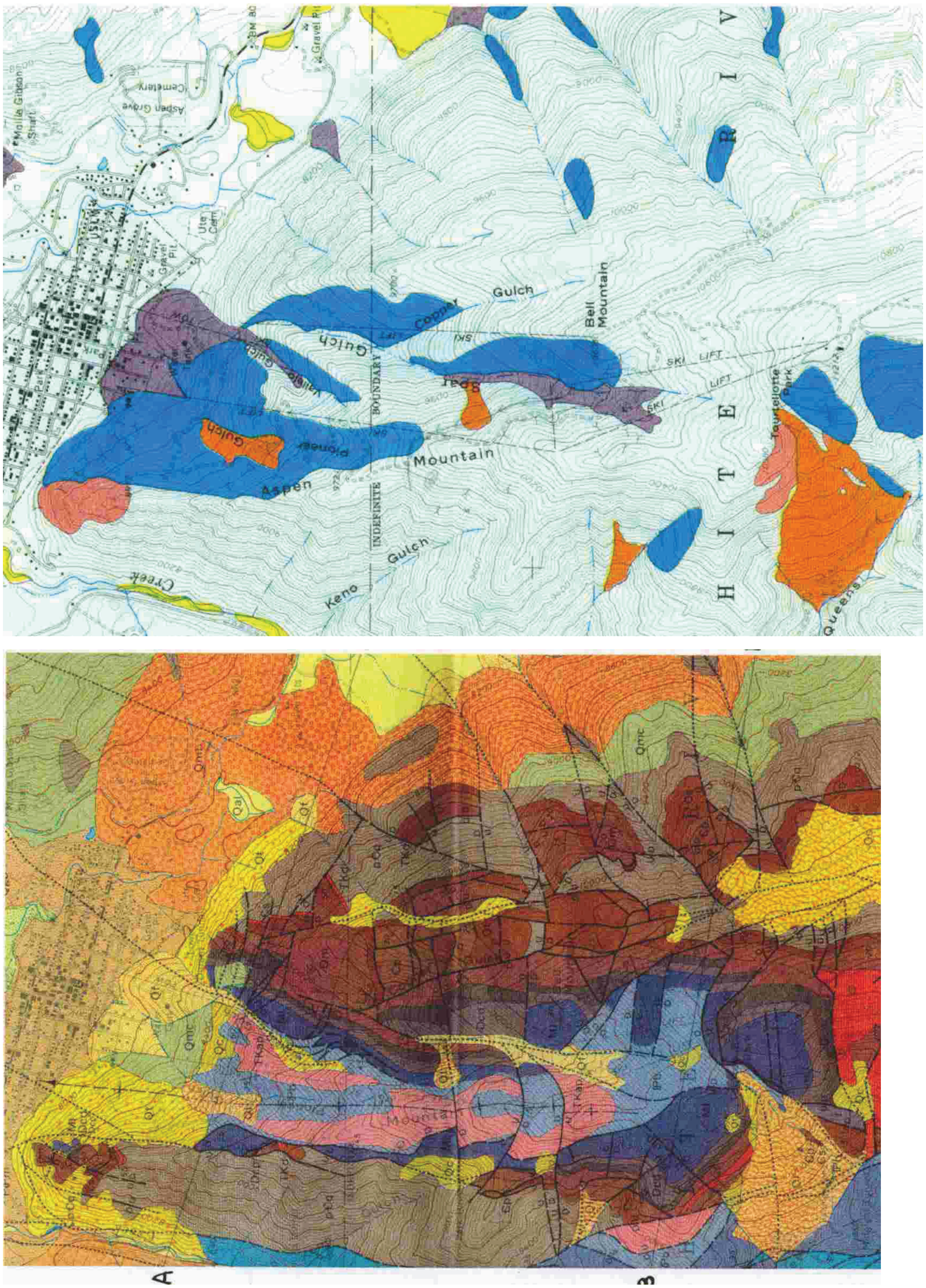


Figure 6. Left—Geologic map of Aspen Mountain, from Bryant (19710. Right—Geologic hazards on Aspen Mountain, from Bryant (1972). Orange, landslides; purple, alluvial fans; blue, potentially-unstable slopes; pink, rockfall areas.

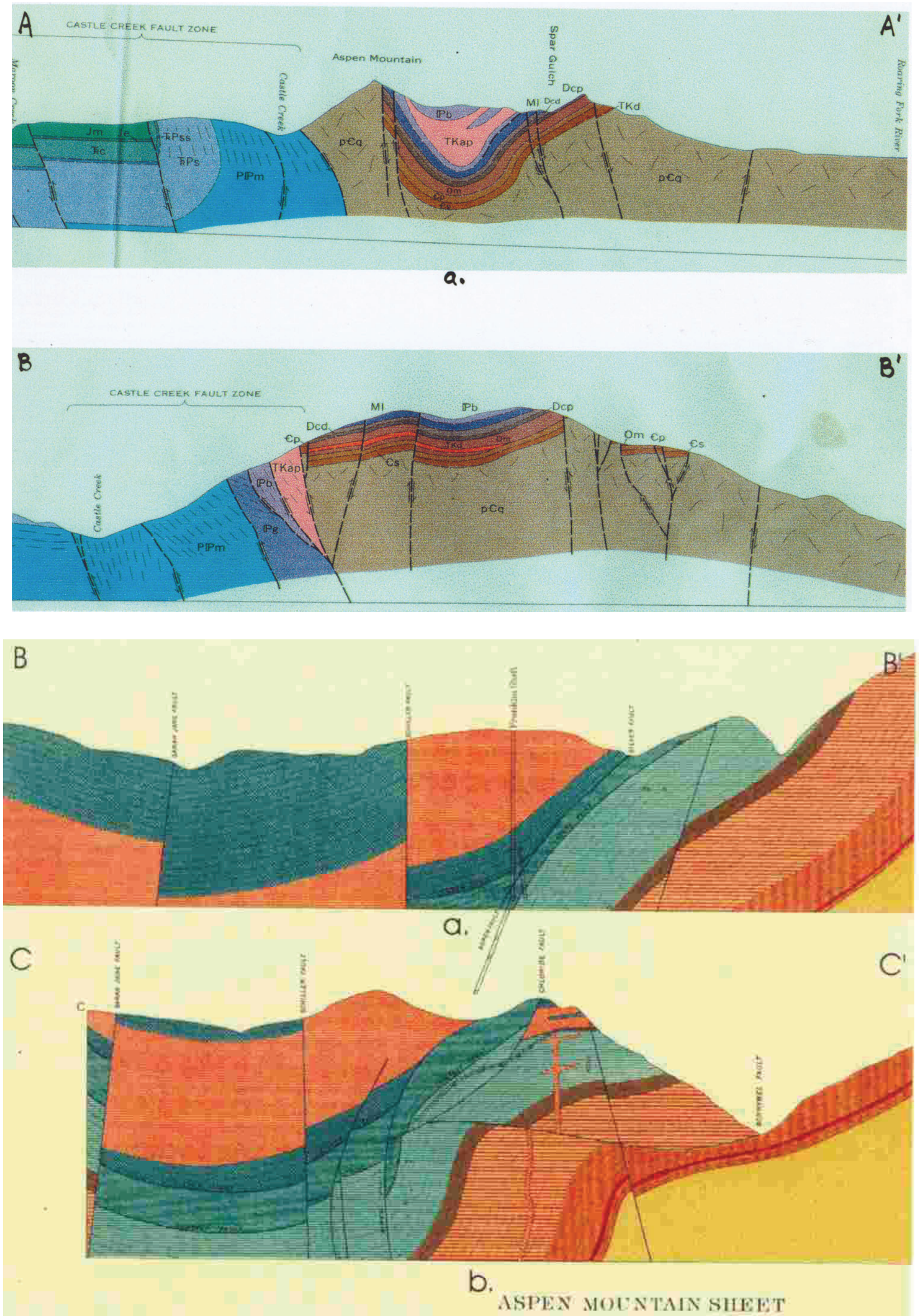


Figure 7. East-west cross-sections through Aspen Mountain. Top, A-Ai, lower Aspen Mountain; B-B’, upper Aspen Mountain (Bryant, 1972); Lower, B-B’ and C’C’, from Spurr (1898).

The sedimentary strata are folded into a north-trending, north-plunging syncline which is tightly folded on lower Aspen Mountain but opens up on upper Aspen Mountain (Figure 6). The syncline is cut by near-vertical faults of two orientations, a north-south set that approximately parallels the axis of the syncline, and an east-west set. A unique feature of Aspen Mountain is the sill of Tertiary igneous rock (aplite porphyry; unit TKap on Figs. 3 and 4) that intrudes the sedimentary section. The sill ranges in thickness from 100-1000 ft and is folded concordantly with the Paleozoic sedimentary rocks, indicating that the sill was intruded (mainly into the soft Belden Formation) before the syncline formed.

The ski trails above about 10,800 ft elevation, and those on the ridge south of Bell Mountain (which contains the Summer Road) lie on a west-dipping series of massive, hard Paleozoic strata (from west to east the Leadville Limestone, Dyer Dolomite, Parting Quartzite, Manitou Dolomite, Peerless Formation, and Sawatch Quartzite). On these formations slopes are relatively steep, soils are thin, and slopes are dry and stable. Most of the ski trails below 10,800 ft (Pussyfoot, Summit, Rip's Run, Ruthie's Road, North American, Tourtelotte Park, Pump House Hill, Blazing Star) lie on the Belden Formation. These runs pass through a relatively gentle, rolling terrain that is marked by lush grass cover, occasional springs and seeps, and some small earthflow-type landslides.

Mining

An extensive system of tunnels, inclines, shafts, and stopes underlies Aspen Mountain. These workings from the 1880s and 1890s are concentrated in a linear band trending NNE, roughly centered beneath Vallejo Gulch. The ore zone targeted by these workings is a complexly faulted and mineralized area of the Leadville Limestone and adjacent strata bounded by the Silver fault and Contact fault. According to Spurr (1898) almost all tunnel levels are interconnected by shafts, inclines, and stopes.

DESCEND "FRONTSIDE" OF ASPEN MOUNTAIN (OPTIONAL STOPS 4A-4C)

From Ajax we descend Aspen Mountain on the Summer Road, and will either drive by several small landslides, or stop at them (optional stops 4a-4c) if time permits.

Slope Instability

Due to weak bedrock units on Aspen Mountain (particularly the Belden Shale), the complex faulting and shattering of rocks, and steep slopes, there have been numerous past incidents of slope failure within and adjacent to the ski area. The following discussion is not comprehensive but highlights the locations and styles of several failures (Table 6).

Table 8. Mileage from Ajax (STOP 4, top of Aspen Mountain ski area) to downtown Aspen, via the Aspen Mountain Road (Summer Road).

Mileage	Description
0.9 (from Stop 4) 26.5 (cumulative)	Descend Aspen Mountain Road to north to saddle S of Bell Mountain (4-way intersection)
0.4 (from saddle) 26.9 (cumulative)	Turn left (W) and cross Tourtelotte Park to Bonnie's Restaurant
0.2 (from Bonnie's Restaurant) 27.1 (cumulative)	Turn left (S) on unpaved road to head of Tourtelotte Park and Tourtelotte Park earthflow (**Stop 4a**).
0.2 (from Stop 4a) (cumulative)	Return to Bonnie's Restaurant.
0.3 (from Bonnies) 27.3 (cumulative)	Turn left (N) onto Aspen Mountain Road (Summer Road) and continue downslope' road crosses FIS landslide (0.3 mi)
0.3 (from FIS landslide) 27.6 (cumulative)	Continue downslope to junction of jeep road up Ruthie's Run; head of SS landslide downslope and to right (east); head of large bedrock landslide downslope and to left (west)
0.15 (from junction) 27.75 (cumulative)	Summer Ditch intersects Summer Road from right
0.12 (from Summer Ditch) 27.87 (cumulative)	Road bends to west; junction of old mine road; park in beginning of mine road.
0.0	Walk 135 m SW on mine road, to head of 1996 landslide (**Stop 4b**)
0.9 (from Stop 4b) 28.77 (cumulative)	Return to vehicles; continue down Summer Road to switchback; overlook of Compromise Mine
0.55 (from overlook) 29.32 (cumulative)	Continue down Summer Road, across head of Pioneer Gulch and landslide, to next switchback
0.47 (from switchback) 29.79 (cumulative)	Continue east on Summer Road, traversing across face of Aspen Mountain; reach west edge of Vallejo Gulch landslide
0.15 (from road junction) 29.94 (cumulative)	Bear to left (N) at road junction and descend the toe of the Vallejo Gulch landslide to switchback (**Stop 4c)**
0.3 (from switchback) 30.24 (cumulative)	Continue down Summer Road into Town of Aspen (S. Original St.)

Tourtelotte Park (Optional Stop 4a)

A prehistoric landslide on the Tourtelotte Park run was partly reactivated in spring of 1997 (Figure 9, bottom).

Head of Keno Gulch Debris Slide of 1996 and the role of the Summer Ditch (optional Stop 4b)

Since the 1890s, the surface water flow from the upper 1/3 of Aspen Mountain has been diverted westward off the mountain by a man-made ditch at an elevation of 9980 ft. This ditch (the Summer Ditch) was dug by miners to divert water out of lower Spar Gulch and the extensive mines there. The Summer Ditch traverses NE across the west wall of Spar Gulch for about 2330 ft, descending at a grade of 200 ft/mile (4%). Except for the last 400 ft the ditch is an open slightly asymmetrical channel. The Ditch ends at about 9900 ft in the head of Keno Gulch and the water is allowed to flow downslope, where it eventually reaches a natural channel. After the

Two opposing interpretations have been proposed for explaining the effect of Summer Ditch water on the debris flows of May 13-14, 1996. On the one hand, Jeff Hynes (pers. comm., 1997) and Art Mears (Mears, 1996) propose that the landslide moved downslope as a solid mass, where it dammed the channel carrying Summer Ditch water. This water then backed up behind he slide toe, saturated it, and caused it to fail as a debris flow. On the other hand, Wright and Rold (1996) propose that the landslide became a debris flow several hundred feet upslope of the confluence with Summer Ditch water, and that this water had no role in creating the debris flows, although it may have increased their fluidity downstream of the confluence Based on the written reports of Mears (1996), Wright and Rold (1996) and a phone conversation with Jeff Hynes (Nov. 20, 1997), I believe that these opposing interpretations are both correct, but apply to different landsliding events. Mears and Hynes were on site after the initial failure (4 pm on May 13) and observed its after-effects, as well as small failures occurring between about noon and 2 pm on May 14. John Rold did not visit the source area until May 17, three days after the second large debris flow event (4 pm on May 14). By this time, the field evidence of the first landsliding event (observed by Mears and Hynes) had been destroyed by the second large sliding event.

According to the three-phase interpretation of McCalpin (1997), the Phase 1 landslide was not caused by Summer Ditch runoff, but its transformation into a debris flow was thus caused. Without Summer Ditch runoff it is unlikely that the frozen toe of the Phase 1 slide would have liquefied. It is clear from eyewitness reports (Mears, 1996) that the smaller debris flow pulses of Phase 2 were caused by chunks of landslide material falling into the runoff from the Summer Ditch. Without this water the slide toe moving at 10 ft/sec would either have maintained this velocity, or more likely come to a stop in the narrow, gentler-sloped tributary channel to Keno Gulch. Only during Phase 3 were debris flows initiated without the assistance of Summer Ditch water.

Figure 9. Top—photo of Bell Mountain looking east from the top of Tourtelotte Park; note small slump-earthflow at tight. Bottom—Small reactivated earthflow at the head of Tourtelotte Park, in the Belden Shale (Stop 4a)

Background to the 1997 Slope Stability Studies

The 1997 Aspen Mountain Master Plan proposed new snowmaking on 57.5 acres of trails in the uppermost part of the ski area (Figure 8). Trails to be covered are Buckhorn (4.3 acres), Ruthie's Road (8.1 acres), Dipsy Doodle (16.1 acres), One & Two Leaf (17.5 acres), and Silver Bell (11.5 acres). Approximately 24.2 acres of new snowmaking (42% of the total area) will occur on U.S. National Forest land, with the remaining 33.8 acres (58%) on private land. Approximately 18 inches of artificial snow would be added to each run early in the ski season.

Figure 8. Areas of new snowmaking (red diagonal pattern) proposed by ASC in 1997. Gondola Building is Ajax (Stop 4). Note Bonnie's Restaurant at lower right.

Pioneer Gulch (Optional Overlook)

The portion of Pioneer Gulch above 8400 ft elevation (the glacial trimline) has probably been the site of repeated landsliding since glacial ice melted away from the undercut face of Aspen Mountain. Pioneer Gulch is developed along the axis of the north-plunging syncline in the Belden Formation (Figure 6). Bryant (1971) maps a landslide roughly 500 ft wide and 1500 ft long in Pioneer Gulch astride the axis of the syncline between about 8400 ft and 9000 ft elevation. Landsliding in Pioneer Gulch is caused by three factors: 1) presence of the weak Belden Formation, 2) slope undercutting by glacial ice, and 3) funneling of surface water and ground water into the axis of the syncline.

At least two periods of historic slope movement have been documented in consulting reports. One episode of movement occurred in 1985 (mentioned, but not described, by Robinson, 1989). A second episode of movement from May 22-25, 1989 was described in a three-page letter report by Robinson (1989) in the so-called "Strawpile" area. Robinson concluded that the sliding material was colluvium derived from the Belden Formation and aplite porphyry. He also concluded that removal of vegetation, dressing of slopes, and snowmaking had increased the rate of downslope movement of the colluvium.

Finally, Bryant (1972c) mapped the remainder of the Belden Formation upslope of 9000 ft elevation in the syncline axis (i.e., above the landslide) as "potentially unstable slopes", along with most of the face of Aspen Mountain below an elevation of 8800 ft (Figure 6). This latter area includes thin deposits of permeable colluvium, talus, and glacial till (map units Qc, Qt, and Qmc on Figure 6) that overlie the impermeable Belden Formation.

Vallejo Gulch (optional Stop 4c)

At some time after the retreat of glacial ice from the base of Aspen Mountain (ca. 15,000-20,000 years ago) a large landslide occurred in Vallejo Gulch. The source area for the landslide is above the Compromise Mine between elevations of 8600 and 9400 ft, and occupies all of Vallejo Gulch (Figure 6). The source area is dominantly underlain by aplite porphyry (Sec. 3.1), a fine-grained granitic rock (Spurr, 1898; Bryant, 1971). This 600 ft-wide body of porphyry is bounded by two NNE-trending faults, the Schiller fault on the west and the Silver fault on the east. These two faults have caused considerable fracturing and shattering of rock, as observed by the author in the Upper Durant Tunnel. This fracturing presumably weakened the porphyry rock mass and was a contributing cause of failure.

The other two inferred causes of failure are glacial erosion and oversteepening of lower Aspen Mountain, and the valleyward plunge of the synclinal fold axis. According to Bryant (1971), when the Roaring Fork glacier was actively building the moraines that now flank the Aspen Airport (Bryant's moraine Qmc, Figure 6), glacial ice was at least 500-700 ft thick at Aspen and extended up to an elevation of 8400-8600 ft on the face of Aspen Mountain. Glacial till of the Qmc advance mantles the slope up to an elevation of 8400 ft. Below 8400 ft the glacier presumably eroded some material from the mountain face and slightly undermined the slope. The third cause of landsliding is an abrupt steepening of syncline plunge around 9050 ft elevation. South of the 9050 ft contour the syncline has a very slight northward plunge but north of that location plunge increases to 25° north. This 25° plunge of shattered porphyry overlying the weak Belden Formation (called Weber Formation by Spurr, 1898) would encourage sliding of rock masses. Due to the drastic thinning of the porphyry, groundwater travelling atop the impermeable Belden Shale is forced toward the surface, leading to saturation of near-surface materials.

The material that slid out of Vallejo Gulch came to rest as an elongate, tongue-shaped ridge that protrudes into the town of Aspen. The Little Nell ski trail occupies the near-level top of the deposit and the Ski Queen gondola sits on the tip of the lobe. Roadcuts along the Summer Road show that the deposit consists of angular blocks of porphyry floating in a matrix of brown sand and gray silt and clay, the latter derived from the Belden Formation. Bryant (1971) mapped this deposit as "alluvial fan deposits", but the flat top, steep sides, and internal composition of the deposit clearly show it is a landslide toe. This toe buries the postglacial downvalley end of Spar Gulch and pinches off the present drainage, which below 8400 ft elevation is the size of a small ditch that hugs the eastern margin of the landslide toe.

To my knowledge the landslide toe has not experienced movement in historic time (post 1860). For example, the upper 250 ft of the Homestake Deep Shaft is located in this deposit and no mention is made in written accounts of mining (e.g., Spurr, 1898; Rohrbough, 1986) that the shaft had to be abandoned or replaced due to downslope movement.

REFERENCES

Bryant, B., 1971, Geologic map of the Aspen quadrangle, Pitkin County, Colorado: U.S. Geological Survey Map GQ-933, scale 1:24,000.

Bryant, B., 1972c, Map showing areas of selected potential geologic hazards in the Aspen quadrangle, Pitkin County, Colorado: U.S. Geological Survey Map I-785-A, scale 1:24,000.

Bryant, B., 1979, Geology of the Aspen 15-minute quadrangle, Pitkin and Gunnison Counties, Colorado: U.S. Geological Survey Professional Paper 1073, 146 p.

Chen & Associates, 1981, Landslide investigation, Upper Tiehack Ski Lift No. 5, Buttermilk Ski Area, Aspen, Colorado: unpublished report submitted to the Aspen Ski Corporation by Chen and Associates Consulting Engineers, Denver, CO, Job. No. 18,737B, Aug. 28, 1981, 12 p. plus appendices.

Chen & Associates, 1985, Review of geotechnical investigation and slope monitoring, Tiehack Ski Lift no. 5, Buttermilk Ski Area, Aspen, Colorado: unpublished letter report submitted to the Aspen Ski Company by Chen and Associates Consulting Engineers, Denver, CO, Job. No. 18.737, Nov. 14, 1985, 2 p.

Chen-Northern, 1991, Geologic reconnaissance and subsoil study, proposed grading and Lift No. 4 relocation, Eagle Hill ski trail, Tiehack ski area, Pitkin County, Colorado: unpublished report submitted to Maroon Creek Development Corporation, Aspen, CO by Chen-Northern, Inc., Glenwood Springs, CO, Job. No. 4-203-90-14,Feb. 11, 1991, 9 p. plus figures

Chen-Northern, 1993, Subsoil study for foundation design, proposed school building, Aspen Country Day School, 1038 Castle Creek Road, Aspen, Colorado: unpublished report submitted by Chen-Northern, Inc., Glenwood Springs, CO to Aspen Country Day School, Aspen, CO, Job. no. 4-191-93, Jan. 11, 1993, 13 p. plus appendices

Colton, R.B., Holligan, J.A., Anderson, L.W. and Patterson, P.E., 1976, Preliminary map of landslide deposits in Colorado: U.S. Geol. Survey Map I-964, scale 1:500,000.

Mears, A.I., 1983, unpublished letter report on geologic hazards at the music school camp, submitted by A.I. Mears, P.E., Inc., Gunnsion, CO to Mr. Ford Schumann, Music Associates of Aspen, Aspen CO, Oct. 6, 1983, 3 p. plus figures.

Mears, A.I., 1992, unpublished letter report submitted by A.I. Mears, P.E., Inc., Gunnison, CO to Mr. Joe Wells, Wells Land Planning, Aspen, CO, Nov. 10, 1992, 3 p. plus figures.

Mears, A.I., 1996, Re: debris flow hazard: unpublished letter report submitted by A.I. Mears, P.E., Inc., Gunnison, CO to Aspen Music Festival and School, Aspen, CO, May 15, 1996, 3 p. plus figures.

McCalpin, J.P., 1994, Geology, geologic hazards, and hydrology of the Aspen Highlands Ski Area, Pitkin County, Colorado: unpublished report submitted to Aspen Highlands Skiing Corp., Aspen, CO by GEO-HAZ Consulting, Inc., Estes Park, CO, Job No. 2006, Feb. 16, 1994, 69 p. plus 3 oversized maps at 1:7200 scale.

McCalpin, J.P., 1996a, Geology, geologic hazards, and soil hazards associated with proposed expansion of the Aspen Highlands Ski Area, Pitkin County, Colorado: unpublished report submitted to Pioneer Environmental Services, Logan UT by GEO-HAZ Consulting, Inc., Estes Park, CO, Job No. 2016, Feb. 15, 1996, 54 p. plus 3 oversized maps at 1:7200 scale.

McCalpin, J.P., 1996b, Geology, geologic hazards, and soils of the Snowmass-Buttermilk gondola interconnect project, Pitkin County, Colorado: unpublished report submitted to Pioneer Environmental Services, Logan UT by GEO-HAZ Consulting, Inc., Estes Park, CO, Job No. 2019, Nov. 30, 1996, 59 p. plus one oversized map at 1:7200 scale.

McCalpin, J.P., 1997, Geologic and hydrologic impacts of proposed snowmaking on upper Aspen Mountain, Pitkin County, Colorado: unpublished report submitted to Aspen Skiing Co., Aspen, CO by GEO-HAZ Consulting, Inc., Estes Park, CO, Job. No. 2023, Dec. 6, 1997, 53 p. plus one oversized map at 1:3600 scale.

McCalpin, J.P., 1999, Geologic and hydrologic impacts of the 1999 Master Plan, Buttermilk Ski Area, Pitkin County, Colorado: unpublished report submitted to Aspen Skiing Company, Aspen, CO by GEO-HAZ Consulting, Inc., Estes Park, CO, Job No. 2030, Oct. 12, 1999, 48 p.

McCalpin, J.P. and Irvine, J.R., 1995, Sackungen at Aspen Highlands Ski Area, Pitkin County, Colorado: Environmental and Engineering Geoscience, v.I, no. 3, p. 277-290.

Robinson, C.S., 1989, Re: Pioneer Gulch slope failure: unpublished letter report submitted by Mineral Systems, Inc., Golden, CO to the Pitkin County Engineer, Aspen, CO, May 26, 1989, 3 p.

Rohrbough, M.J., 1986, Aspen-- The history of a silver-mining town, 1879-1893: Oxford University Press, New York, 263 p.

Spurr, J.E., 1898, Geology of the Aspen mining district, Colorado, with atlas: U.S. Geological Survey Monograph, vol. 31, 260 p.

Wright, K.R. and Rold, J.W., 1996, Report on the Aspen Music School debris flow investigation (draft): unpublished report submitted by Wright Water Engineers, Inc., Denver, CO to Fireman's Fund Insurance Company, Denver, CO, May 1996, 17 p. plus appendices.

LANDSLIDES, GEOLOGY, AND MINING BETWEEN VAIL AND LEADVILLE, COLORADO

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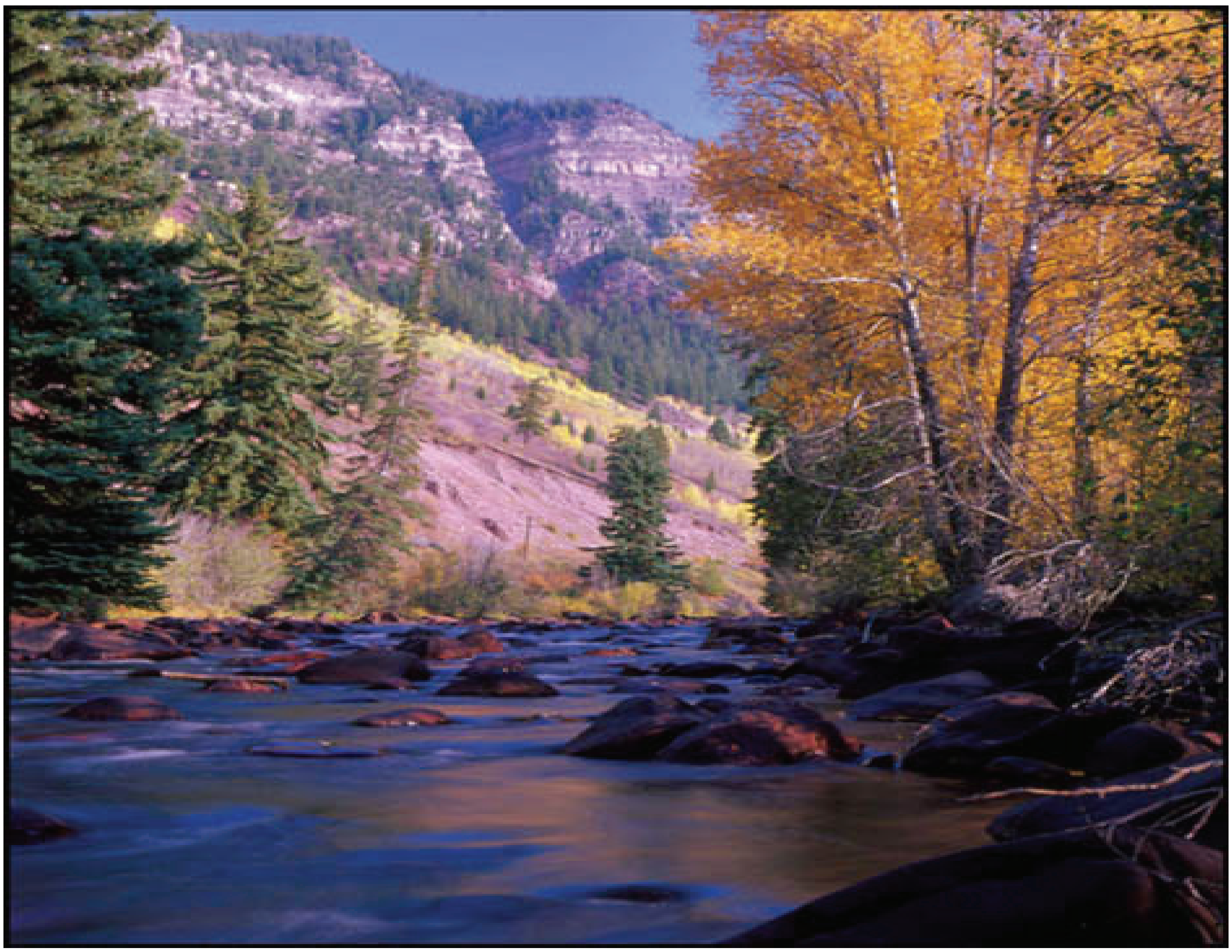

The Eagle River near Minturn, Colorado, in the fall. This picture was taken before the current onslaught of the pine beetle. During the trip, note the devastation currently being inflicted on the Ponderosa Pines along the Eagle River.

1st North American Landslide Conference

Vail, Colorado, June 6, 2007

OVERVIEW

This one-day field trip offers a combination of landslide discussions, Leadville mining district geology and the history of the Leadville Mining District. The trip will loop around some of the most rugged scenery in central Colorado. The main destination is Leadville (also known as the Cloud City, disputably the highest incorporated city in the U.S.A.), a boomtown several times over that was Colorado's second-largest city during the 1870's, and is now looking for one more resurrection. The route is roughly triangular with Vail located in the northern leg. We will follow I-70 to the junction with Highway 24 near Minturn. From there we journey southeasterly over Tennessee Pass and into Leadville where we will lunch. In the afternoon we will use Highway 91 from Leadville to Climax and Fremont Pass and down to the junction once more with I-70, and finally back along the interstate over Vail Pass back to Vail.

Table 1. Field Trip Stops and Topics.

Location	Topic	Presenter
Dowd's Junction – Stop 1	Landslides/Earthflows along I-70 and Hwy. 24	John Rold
Minturn (drive-by)	Area History	Bob Valentine
Eagle Mine Overlook –Stop 2	Mining, Superfund Remediation, Development	Fred Meisner/Bob Valentine
Camp Hale – Stop 3	10th Mountain Division – training site	Bob Valentine
Leadville Vicinity – Stop 4	Mineralization/History	Fred Meisner
National Mining Museum – Stop 5	Lunch/History	Sam McGeorge
Climax Mine –Stop 6	Mining History, Geology, Reclamation	Gordon Stinnett
Copper Mountain (drive by)	Landslides, development	John Rold
Vail Pass (drive by)	Landslides, highway construction	John Rold
West Vail (drive by)	Avalanche chutes, construction	John Rold

TRIP ROUTE DESCRIPTION AND MAPS

Our first stop will be about four miles west of Vail at the junction of I-70 and Hwy. 24 (Dowds Junction), where we will observe landslides that could have a very significant impact on the economy of Colorado were they to fail (Figure 1). We will then proceed through the old railroad/mining town of Minturn and begin our upward climb on Highway 24 to the Eagle Mine overlook. The site provides a view of the Eagle Valley and the Eagle Mine superfund site, which now is also proposed as a major resort facility. We will proceed along the Eagle River valley past Camp Hale, the training area for the 10th Mountain Division (famous for their exploits during World War II), and on into Leadville. Normally, Leadville receives an abundance of snow in the winter, which often lasts into the summer. If snow conditions cooperate, that is, if the snow has melted sufficiently, we will visit a couple of the gold discovery areas around Leadville.

We will lunch at the renowned National Mining Hall of Fame & Museum and spend some time understanding the history of the Leadville area. After lunch, we will depart Leadville on Highway 91 headed for Fremont Pass and the Climax Mine. We will stop at the crest of the pass to view the mine area and the reclamation efforts involved with the tailings ponds. Departing from the mine area, it is all downhill to the junction of Highways 91 and I-70. Along the way we will discuss some of the problems associated with the road relocation. Copper Mountain ski area is located at the foot of Tennessee Pass and Vail Pass at the junction of the two highways. We return to Vail over Vail Pass and discuss some of the landslide problems at Copper Mountain, as well as the major slide problems associated with the Vail Pass Highway. As we near Vail, we will observe and discuss the geologic hazards posed by avalanche chutes in West Vail and the resolution of the problem.

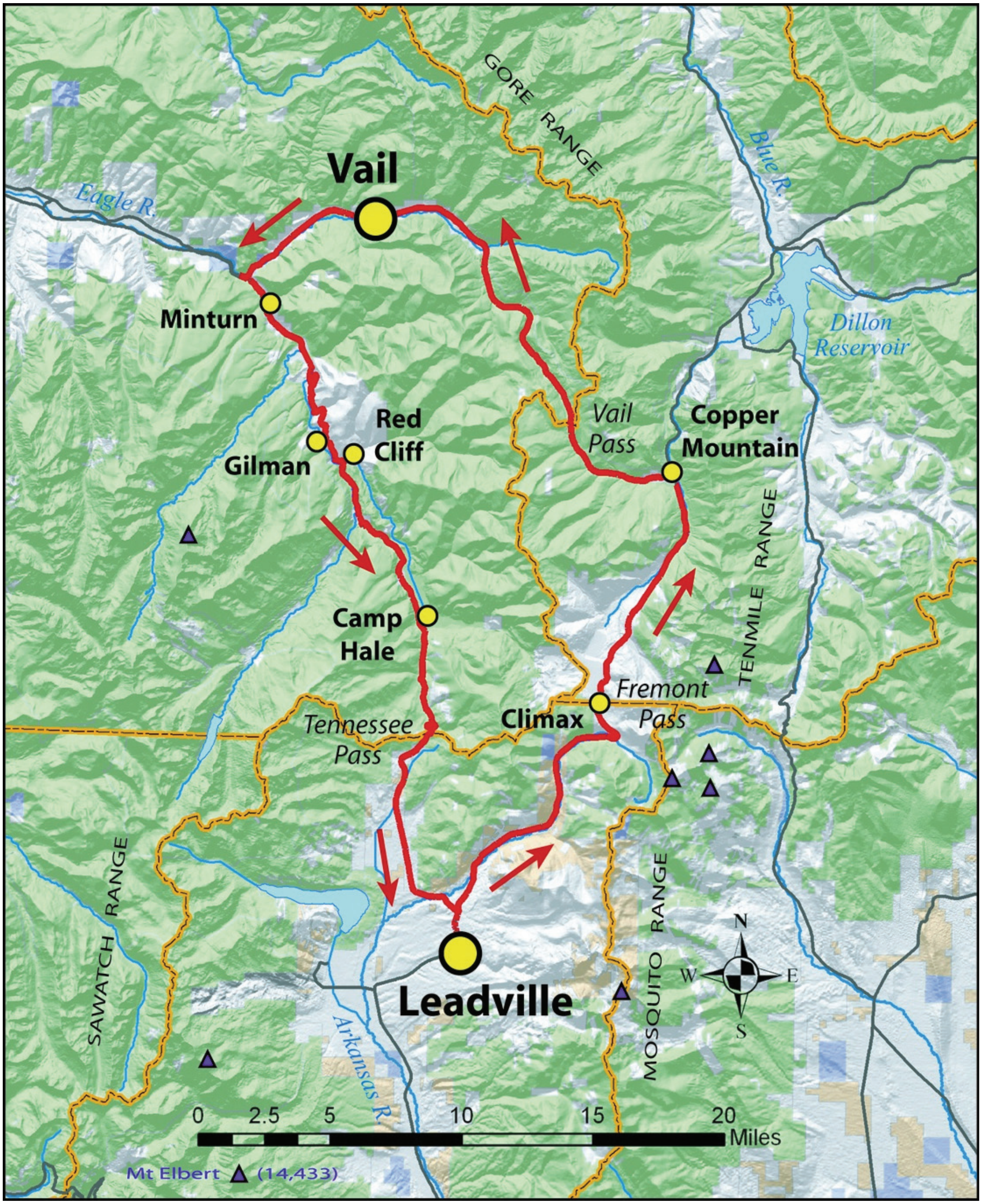

Figure 1. Map of Central Colorado showing field trip area and route.

Table 2. Mileage from Start of Field Trip at Vail Marriott Mountain Resort to Dowd's Junction, and Minturn.

Mileage	Description
0.0 (from start) 5.0 (cumulative)	Leave Vail Marriott Resort. Drive west on frontage road to I-70 access, access I-70 west to Minturn Exit (Dowd's Junction). Elevation 7750, Stop 1
2.0 (from Stop 1) 7.0 (cumulative)	Minturn. Note the town squeezed in between the Eagle River and the hillside to the west. Drive-by
7.2 (from Stop 1) 12.2 (cumulative)	Eagle Mine Overlook – Stop 2. Mining, Superfund Remediation, Proposed Development.
1.3 (from Stop 2) 13.5 (cumulative)	Battle Mnt. Summit, elev. 9000'. Notch Mnt. elev. 13237, to the west. Drive–by.
2.7 (from Stop 2) 16.2 (cumulative)	High bridge over Eagle River. Town of Red Cliff is one mile east of bridge. Highly rated kayak stream this location.
9.8 (from Stop 2) 22 (cumulative)	Camp Hale. Elev., 9250. Site of 10th Mountain Div. Training. Stop-3
4.6 (from Stop 3) 26.6 (cumulative)	Union Pacific (formerly D&RGW) RR tunnel to right of highway to pass under Continental Divide.
5.5 (from Stop 3) 27.5 (cumulative)	Tennessee Pass, elev., 10424. Continental Divide. Ski Cooper to east of highway. 10th Mountain Division granite monument is on highway at the left.
6.4 (from Stop 3) 28.4 (cumulative)	Descending into Arkansas Valley (drains to east). Views of Mr. Elbert (14,433') and Mt. Massive (14,421) to the southwest. These are the tallest peaks in Colorado.
15.5 (from Stop 3) 37.5 (cumulative)	Leadville. Stop 4. Possible short stops at famous gold localities. Lunch stop at National Mining Hall of Fame and Museum. Lunch stop.

VAIL VALLEY – DOWD'S JUNCTION SETTING

The Vail Valley and the Town of Vail occupy the deep, narrow, formerly glaciated valley of Gore Creek (Figure 1). The geology of the area has recently been mapped at 1:24,000-scale by the U.S. Geological Survey (Scott and others, 2002; Kellogg and others, 2003).

Minturn Formation

Just to the west of Vail, the valley of Gore Creek narrows. The interstate is bounded to the north (right) by high, vertical cliffs that expose the Pennsylvanian Minturn Formation, which is jointed and fractured, predominantly gray in color, and contains interbedded sandstone, shale, and conglomerate lenses with minor, persistent limestone beds and localized bioherms. The Minturn Formation is nearly a mile thick in this area. It was deposited as fan deltas and marine deposits along the margins of the Ancestral Rocky Mountains.

A large rockslide in this canyon closed the westbound lanes of I-70 in 1989.

STOP 1. DOWDS JUNCTION LANDSLIDE COMPLEX

Dowds Junction marks the intersection of I-70 with US-24, where Gore Creek enters the larger valley of the Eagle River. Along the western side of the valley are four large earthflow landslides: the Meadow Mountain, Dowds number 1 and 2, and Whiskey Creek (Figure 2). These slides have formed within the weak claystone beds of the Minturn Formation. They predate the construction of Interstate 70 and have experienced reactivations and failures when the highway construction altered and cut into the landslide toes.

These landslides have been extensively studied by the Colorado Department of Transportation (CDOT) and the Colorado Geological Survey (CGS) since the interstate was constructed and certain remedial actions have been taken such as rock buttresses and horizontal drains. A potentially catastrophic hazard scenario, particularly associated with the Meadow Mountain landslide, involves earthflow movements damming the Eagle River. Activation of the toe of the Whiskey Creek landslide could threaten Battle Mountain High School in Avon as well as the interstate highway.

The fall/winter period of 1984/85 experienced record-breaking precipitation characterized by unusually heavy snowfall in the fall before the ground had frozen. As the heavy snowfall melted, it soaked much more deeply into the ground than later snowfalls after the ground had frozen. Unusually large and more numerous occurrence of freezing groundwater springs issuing from normally dry cliffs, road cuts, and hill slopes were observed in several locations along the I-70 corridor. Based on the history of prior landslides and high maintenance required in the area, a task force was organized by the governor to analyze the potential for catastrophic failure and to evaluate future courses of action (Minturn Earthflows Task Force, 1986). A number of immediate actions were initiated, and the subsequent options presented in the report fell into four general response categories: Option 1: No structural solutions. Option 2: Stop the slide from moving. Option 3: Don't let it flood. Option 4: Wait until the last minute. Each recommendation was examined with regard to its feasibility, timeframe for implementation, responsible party and estimated cost (Minturn Earthflows Task Force, 1986)

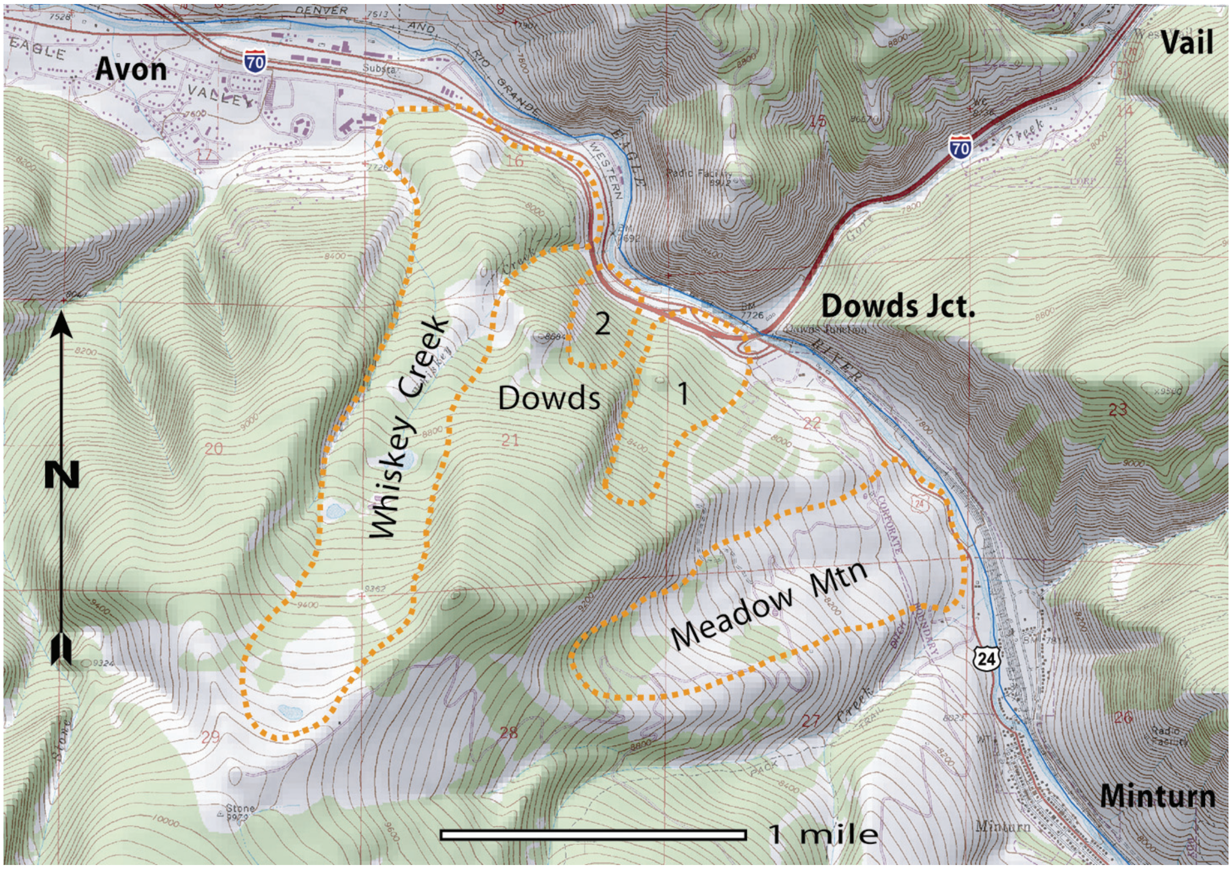

Figure 2. Shaded topographic map of landslides near Dowds Junction. (Image from Colorado Geological Survey)

The Dowds Junction area is the focus of a recent geotechnical investigation by Yeh and Associates, as part of an assessment of potential traffic improvements along the I-70 Corridor. The abundant and serious geologic hazards here will affect many of the potential alternative designs, which include highway widening and construction of a Fixed Guideway Transit (FGT) line along the highway route. One option is to avoid the rockfall and landslide hazards utilizing a tunnel realignment. The study is in its second phase.

MINTURN (DRIVE BY)

Minturn burst to life during Eagle County's mining boom in the late 1800's and was an essential railroad division point for the Rio Grande Railroad. Minturn has adapted to several major changes in the local economy, including the development of Vail and Beaver Creek ski resorts, the closing of the Gilman mine, and the abandonment of rail lines through Minturn. Nevertheless, Minturn has retained its reputation as one of the friendliest towns in the Rocky Mountains. Summer months offer magnificent vistas and an incredible show of wildflowers. The Eagle River, which runs through the town, provides outstanding kayaking and rafting.

STOP 2. GILMAN EAGLE MINE

The abandoned mining camp of Gilman (elevation 8970 ft.) is perched on the steep side of Battle Mountain (Fig. 3), high above the Eagle River. The Eagle Mine at this location principally produced zinc, lead, and copper. Mining first began in the Gilman area in the late 1870's with the discovery of gold and silver deposits. By the mid-1890's production from these mines declined, but picked up in 1905 with the mining of lead and zinc deposits. Four roasting and magnetic separation plants, used to process the ore, were constructed, and the roaster process continued until 1919. An underground mill, constructed to extract lead and zinc metals, operated from 1919 to 1979. Copper-silver production continued until 1984 when the mine workings were allowed to flood. The State of Colorado filed notice and claim against the former mine owners for natural resource damages under the Superfund law in 1985. The site was placed on the National Priority List of Superfund sites in June 1986 (Colorado Department of Public Health and Environment, 2004).

The Eagle Mine site consists of the Eagle Mine and associated mining wastes between Gilman and Minturn. The 235-acre site includes the Eagle Mine workings, the town of Gilman, eight former mine tailings piles, Rock Greek Canyon below Highway 24, and at least 14 waste rock piles.

Environmental Concerns and Site Remediation.

The major contaminants of concern are heavy metals such as lead, zinc, cadmium, arsenic, and manganese associated with the mining wastes. The major pathways of concern are surface water contamination to the Eagle River, alluvial groundwater contamination, and ingestion/inhalation of mining wastes. The State of Colorado and the previous mine owner/operator (Gulf + Western Industries, now Viacom International, Inc.) entered into a Consent Decree and Remedial Action Plan to conduct remedial actions in June 1989. The cleanup plan included flooding the mine workings by bulkheading mine adits, relocating all processed mine wastes and contaminated soils to one main on-site tailings pile, capping this pile with a multi-layer clean soil cap, and re-vegetating all disturbed areas with native plant species. The cleanup began in 1988 and was generally completed in 1994. Flooding of the mine workings resulted in unacceptable seepage into the Eagle River beginning in late 1989. A water treatment plant was constructed in 1990 to collect mine seepage, groundwater at the main tailings pile, and precipitation accumulation on tailings removal and relocation areas. Subsequently, water quality in the Eagle River has shown improvement beginning in 1991 and is expected to continue to improve as the remedial actions are completed. The first 5-year review for the site was completed in October 2000. The review concluded that public health risks have been removed and that significant progress has been made in restoring the Eagle River.

Figure 3. Gilman and the Eagle Mine prior to Superfund remediation. View looking east across Eagle River. (Colorado Rockhounding)

STOP 3. CAMP HALE

Camp Hale History

When the War Department decided to establish a unit of mountain troops trained in skiing and winter warfare, a search for an appropriate site for the military post began. Various locations in the western states were investigated. The area around Pando, Colorado, a railway stop on the Denver and Rio Grande Railroad, proved to be the ideal location, meeting all the criteria set forth by the War Department. A foremost consideration was snowfall, and the area near Tennessee Pass had consistent and heavy snow throughout the winter as well as topography conducive to ski training (Fig. 4). Since much of the surrounding land was national forest, acquisition of land and room for maneuvers and training was not a problem. One advantage the site had over others reviewed was accessibility. The Denver and Rio Grande Railway and Highway 24 provided ready access to the valley. This was important for the construction phase on the camp because building crews and materials could be brought to the site without additional costly construction of transportation. Natural water sources from the Eagle River and Homestake Creek were deemed sufficient for camp use, and regional supplies of coal existed in sufficient quantities to meet fuel demands. The only drawback noted in the investigative report was Leadville. It was thought to be lacking in appropriate social and recreational amenities, and the report presented the town negatively stating, "The morals of Leadville are said to be on a rather low plane." Before the Army would allow soldiers into Leadville, the city council and police had to clean up the town by enforcing gambling and liquor laws and finding a solution to end the prostitution problem.

Building the camp was an enormous undertaking. The contract was awarded April 7, 1942 and completion date was November 15, 1942. In addition to all the regular facilities required in a camp site, there were also facilities for mules as the mountain division would be using them. Due to the relative isolation of the area, the camp also had to provide for recreational needs of the troops. A new city sprang up practically overnight. Another challenge included the remoteness of the area making it necessary to bring in workers and materials from long distances. By summer there were nearly 12,000 workers on the construction payroll. As the completion date approached, workers were guaranteed an ever-increasing number of hours per week. The contractor completed work within a month of the objective.

Nothing like this project had been tried before. The entire area was a swamp in need of draining in order to lower the ground water level and landfill had to be added where necessary. Part of the solution involved rechanneling the Eagle River to provide for proper drainage of the valley. Five wells were dug at one end of the valley for water supply, and a new sewage system was constructed with 13.5 miles of sewer lines. One of the challenges was the snowfall which averaged 163.5 inches per year, which required modification of structural designs for the buildings. One problem not anticipated or overcome was the pollution in the valley during the winter. Because the camp relied on burning coal for its primary source of energy, air inversions held the smoke and particulates over the camp.

The decision to locate the cantonment in national forest proved wise in that thousands of acres of national forest were opened for the army to use as necessary. This led the way for development of a ski facility on Cooper Hill. The 240-acre facility adjacent to the camp serviced ten runs with four rope tows. (Note: Ski Cooper has been upgraded and is now run by the City of Leadville, at very modest fees.)

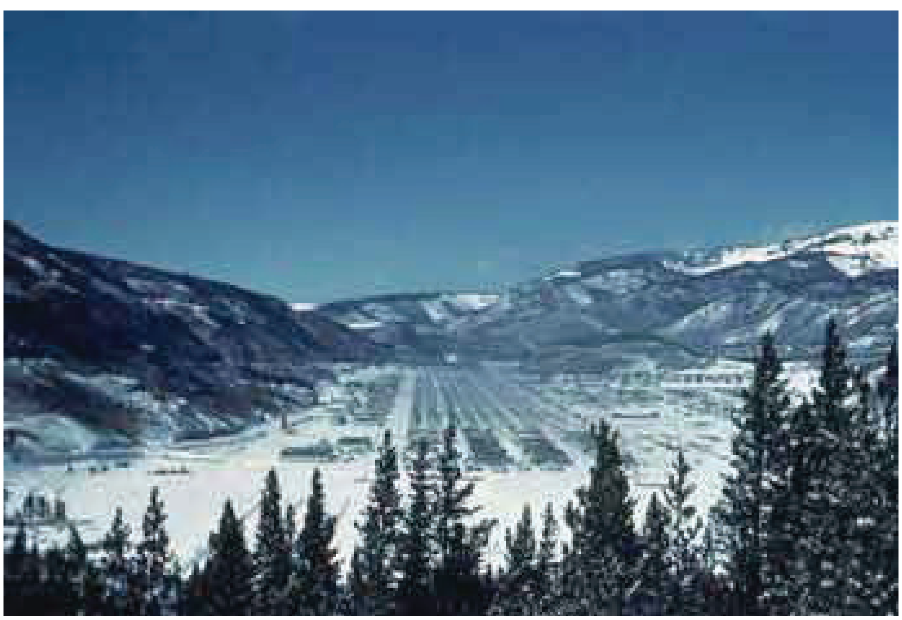

Figure 4. Camp Hale, winter of 1944. (U.S. Corps of Engineers Photo)

The name selected for the post was Camp Hale, named for the late brigadier general Irving Hale, a veteran of the Spanish American War. Camp Hale eventually housed approximately 16,000 soldiers and 3,900 animals. Approximately 13,000 military personnel stationed there were members of the famed 10th Mountain Division. The 10th Mountain Division had been among the last American troops mobilized for combat in World War II. The division fought valiantly, routing the Germans from the Italian Alps at Riva Ridge and Mounts Belvedere, Gorgolesco, della Torraccia, Castello, and della Spe before advancing into the Po Valley. Their victories were instrumental in defeating the Germans on the Western front.

A fact not generally recognized is that approximately 200 women of a Woman's Army Corp (WACS) Detachment were also stationed at Camp Hale (Fig. 5). Undoubtedly they received considerable attention from the soldiers. Reportedly several marriages occurred after the war. Ladies were also bussed in from Leadville for the dances held on the base (Metropolitan State College of Denver, 2004).

Another major impact from the Camp Hale cantonment was the development of the ski industry in Colorado. Recruitment efforts by the Army brought some of the world's best skiers into the 10th Mountain Division, and thence into some of the world's best ski terrain and snow conditions. After the war many of those same people returned to Colorado and helped develop existing and new ski facilities in Colorado. Graduates of the 10th Mountain Division developed Aspen Highlands, Buttermilk, Vail and Arapahoe Basin, and although Colorado was the main beneficiary, nationally 17 ski areas and 33 ski schools were founded and/or managed by the those former soldiers.

Figure 5. WAC on hill overlooking Camp Hale. (Metro College of Denver Photo)

STOP 4. LEADVILLE, COLORADO

Leadville History

Leadville's origins date to the gold rush of California in 1846. Miners rushed from all over the world to make their fortune from gold in California. Although most of the prospective miners didn't make a fortune, it opened up the west and started prospectors looking throughout the western mountains. It was just such a group of prospectors who left Denver early in 1860 and who worked up the Arkansas Valley to an area just southeast of present day Leadville. They split up to sample the streams, and it was Abe Lee who discovered the first strike in California Gulch. And so began the first rush to Leadville. Some 8,000 prospectors arrived in “Oro City – their name for the instant town” of tents and cabins and that began the first of several booms for the area. That first gold was discovered by sluice and pan, a relatively simple and easy way to access the gold, and the early claims divided up the alluvial soils along the creeks to develop the placer deposits. Within a half decade, however, that source of gold ran out and the area dwindled to fewer than 100 miners. The prospectors remaining realized that the “mother lode,” the source of the placer gold deposits, had not been tapped, and with persistence they continued to search. Finally, some of the gold veins were located and another rush began.

However, removing the ore from the hard rock was a much more difficult task than panning and required teams of miners to drill and blast the rock, haul it to the surface and transport it to a mill where the gold could be separated from the host rock. Thus it also required more financial resources to conduct the mining.

It was in 1877 that prospectors north of Oro City found an unusually high content of silver in their samples, and thus the next boom ensued. Prospectors again descended on the area, sinking some 135 mines between 1877 and the mid-1890’s. The informally named “Cloud City” was renamed Leadville (Figs. 6 and 7), apparently believing that the associated lead ore would have more future than the silver. By 1880, Leadville had over 30,000 residents and was the second largest city in Colorado.

Figure 6. Leadville, Chestnut Street in 1879. (The National Mining Hall of Fame & Museum Photo)

A major factor in the Leadville boom of the 1870's and 1880's was the arrival of the railroad. Up to that point, all supplies had to be freighted into Leadville from Denver by horse-drawn wagons over very primitive road or trails. The last great obstacle was getting over 11,000'+ Mosquito Pass, difficult in good conditions, essentially impassable in winter. At least four railroads started for Leadville and the Colorado and Southern High Line, a narrow gauge line, won the race in the late 1880's. Subsequently, the Denver and Rio Grande Western arrived with a standard gauge line and eventually forced out the competition.

In 1893, repeal of the Sherman Silver Purchase Act brought the silver boom to a quick end. The price of silver dropped to such a low level that it was uneconomical to mine it. Sporadic mining of other minerals – lead, zinc, copper - continued at a reduced scale but the gold and silver era was over.

The final Leadville boom occurred owing to a different ore discovered a few miles north of Leadville (See Stop 5). Molybdenum was mined at Climax and as demand for that mineral gained over the first half of the 20th century, the fortunes of Leadville gained as well. When the Climax Mine swallowed the primitive town of Climax, Leadville became the residence of choice, and once more Leadville boomed. Some 3,000 workers were employed at the peak of operations. However, as previous booms were followed by busts, so it was in the mid-nineteen eighties. The price of molybdenum dropped as more sources of the metal came on the market and with closure of the mine, Leadville once more went bust. But Leadville is resilient. Phelps Dodge, owner of the Climax Mine, has indicated that mining may resume in 2009, and the residents are looking forward to another boom.

Figure 7. Leadville in 1879. (The National Mining Hall of Fame & Museum Photo)

Some of the notables from the Silver Era in Leadville include the following:

Horace A.W. Tabor, “the Silver King”. Farmer/rancher, prospector/miner, store keeper, postmaster of Leadville, millionaire, investor, first mayor Leadville, elected Lt. Governor of Colorado, appointed U.S. Senator, philanthropist. Tabor made his initial money principally by “staking “prospectors to food and equipment for a share in any strike they might find. This proved successful, but Tabor was a gambler and he began buying and selling leases, and by good fortune, and a lot of luck, made millions in his trading. For example, Tabor bought the Matchless Mine for $117,000, but it paid back $1 million per year during the peak years of its 14-year operation. Along the way, Tabor divorced his first wife, **Louisa Augusta (Pierce) Tabor**, who received a generous settlement and moved to Denver where she became an investor and philanthropist. She died in 1895, a millionaire. Tabor was infatuated with **Elizabeth Bonduel (McCourt) Doe Tabor** (Baby Doe) and their wedding in Washington was lavish, such as their wedding invitations fashioned from solid silver. Tabor also invested in Leadville and constructed the Tabor Opera House, the Bank of Leadville and the Tabor Grand Hotel. He rose from local to state to national political figure. He and Baby Doe build a mansion in Denver, and lived a wealthy lifestyle. When the silver market crashed in 1893, Tabor lost his fortune and died in 1899, a pauper. Reportedly, one of the last things Tabor told Baby Doe was to hold on to the Matchless Mine, apparently believing that silver would make a comeback. So Baby Doe did do just that, living in poverty in a one-room shack at the mine for some 36 years until she froze to death in the winter of 1935.

J.J. Brown and Margaret (Tobin) Brown. “Molly” Brown arrived as a teenager in the early 1880’s, working as a boardinghouse waitress. She married J.J. Brown, superintendent of the Little Jonny Mine. He was given an eighth interest in the mine, based on his innovative mining techniques, and that proved to be so lucrative that the Browns were able to move into Denver’s high society. Margaret, who never went by the Molly nickname, survived the sinking of the Titanic and thereby gained her “unsinkable” reputation.

Meyer Guggenhiem and Sons. Guggenhiem was the owner of the A.Y. and Minnie mines in California Gulch. Later he consolidated the smelters in Leadville and other places, and eventually gained control of the American Smelting and Refining Company (ASARCO).

David May. May started an auction house and dry goods store in Leadville in 1878. Later he merged his company with his competitors, Daniels and Fisher, which became the national May D&F Company.

Charles Boettcher. Boettcher opened a thriving hardware business, later moving to Denver where he became a successful business man and philanthropist.

John Henry Holiday. “Doc Holiday”, dentist and professional gambler, shot and wounded Billy Allen in August 1884. Supposedly penniless, he was nonetheless released on bail of $5,000 and in March 1885, was acquitted of the shooting owing to self-defense, and released. Soon after the trial, he moved to Glenwood Springs, CO where he died of TB in 1887.

Table 3. Mileage and Directions from Leadville (Stop 4) to Vail.

Mileage	Directions
4.0 (from Stop 4) 41.5 (cumulative)	Highway 91. Following E. Fork of Arkansas River. Ahead is the massive of the Mosquito Range with peaks over 13,700'. Mosquito Pass, elev., 13,185' connects Leadville to Fairplay, is the highest pass in the US. Completed in 1879 as a toll road, and was used by freight wagons from Denver.
12.3 (from Stop 4) 49.8 (cumulative)	Fremont Pass, elev., 11,318', the Continental Divide. Stop-5. The Climax Mine. Closed in 1986, may reopen in 2009.
0.5 (from Stop 5) 94.7 (cumulative)	Begin descent from Fremont Pass. We have passed the Continental Divide and are back on the west slope. Note the extensive tailings ponds of the Climax Mine in the valley west of the road. Extensive studies of landslide deposits and soil conditions this area for relocation of highway.
10.7 (from Stop 5) 60.5 (cumulative)	Pass Copper Mountain. Turn on I-70 westbound. (Begin "Wheeler Junction and Copper Mountain" drive-by)
16.1 (from Stop 5) 65.9 (cumulative)	Continue past Vail Pass (Exit 190). Rest area is available at the Pass if needed. Begin descent from Vail Pass along the valley of Black Gore Creek.
22.6 (from Stop 5) 72.4 (cumulative)	I-70 curves to the left (west) and enters the larger valley of Gore Creek. This marks the eastern edge of the town of Vail. (Begin "Gore Creek Valley and Vail" drive-by.)
30.5 (from Stop 5) 80.3 (cumulative)	Town of Vail, main exit (Exit 176). Exit from I-70. Enter the first traffic circle and drive ¾ of the circle. Drive south under the interstate to the second traffic circle.
30.8 (from Stop 5) 80.6 (cumulative)	From the second traffic circle, turn right (west) directly onto the South Frontage Road. Follow this road for about a mile.
31.5 (from Stop 5) 81.3 (cumulative)	Turn left (south) onto West Lions Head Circle immediately after driving under the pedestrian overpass. Keep to the right after one block. The Vail Marriott Hotel is on the left. Welcome back to Vail!

STOP 5. CLIMAX

When one thinks of Climax, it follows that one also thinks of Molybdenum. Just what is molybdenum (or "moly") and what are its uses. Molybdenum is a silver to white-colored metallic element. It is hard, malleable, ductile, and has a high melting point. Its chief ore mineral is molybdenite, a soft, shiny, greasy appearing, blue-gray mineral. Although it was first recognized in 1778, it wasn't until the turn of the Twentieth Century that its value as a steel toughener and hardener for armaments was realized during World War I. Today, along with other alloying elements, moly gives steel alloys a combination of strength, toughness, and wear and temperature resistance.

Geology of the Climax Molybdenum Deposit

Molybdenum ore deposits occur associated with an igneous rock called porphyry (a rock composed of usually well shaped, large crystals set in a very fine-grained matrix). The term porphyry describes the texture of the rock. Mineralogically, most of the porphyries in Colorado are rhyolitic or granitic, which are similar chemically, but with rhyolites being fine-grained and granites being coarse grained.

About 30 million years ago a granitic porphyry – the Climax Stock – was intruded into the 1,700 million-year-old metamorphic rocks of the Mosquito Range. Four separate phases of the Climax Stock have been identified. Many of the minerals that make up the granite porphyry of the Climax Stock show evidence of hydrothermal alteration. Metallic minerals, such as molybdenite, are usually introduced during episodes of high-temperature hydrothermal alteration with the introduction of quartz and feldspar. Most of the molybdenum mineralization occurs as molybdenite in quartz-filled veinlets formed before and during the main event of hydrothermal alteration.

History of Molybdenum Mining at Climax

In 1879 a prospector by the name of Charles Senter was searching for gold on Bartlett Mountain, part of the Mosquito Range in central Colorado. He discovered a yellow-stained outcrop, which is usually a good sign of the presence of sulfide minerals and gold. He hiked up the outcrop and found a crystalline gray rock faced with thin veinlets of a dark bluish-gray greasy mineral and pyrite. Senter staked three claims over this outcrop because of the presence of the pyrite. He thought the gray mineral was some sort of lead or even graphite. It took Senter an additional 14 years to get his samples analyzed. The strange gray mineral was a sulfide of molybdenum, now recognized as molybdenite.

The small settlement of Climax (Fig. 8) was established at 11,318 feet near Fremont Pass just below Bartlett Mountain in 1884. Climax was only a couple of bunkhouses at a railroad siding on the Denver-Leadville rail route.

Figure 8. The town of Climax in 1916. (The National Mining Hall of Fame & Museum Photo).

In the 1890's molybdenum was just starting to be used in industrial processes for hardening steel. Other prospectors and businessmen had heard of the strange metal on Bartlett Mountain near Climax. They staked claims around Senter's original discovery, dug adits and in 1911 shipped some ore to a mill in Denver. However, it was in 1916 with World War I raging in Europe, when a German company with American headquarters in New York became interested in the molybdenum deposits at Climax. Molybdenum's steel hardening properties made moly steel excellent for armaments. They conducted test mining and eventually gained control of the deposit. The company was "Americanized" in 1917 as America entered World War I against Germany and Climax Molybdenum Company was formed. A schoolhouse, post office, and residences were established at Climax in 1918.

The new Climax Mine produced about 250 tons of ore per day. The first rail cars of molybdenum concentrate were shipped from the Climax Mine in April 1918 beginning the long history of mining and milling at Climax (Fig. 9).

When World War I ended in November 1918, the demand for, and the price of molybdenum crashed. The industry slowly recovered during the 1920's and 1930's as Climax Molybdenum Company developed new uses for moly. In 1929, the Climax Mine instituted a new system of bulk underground mining – the block caving method. The highly efficient block cave method allowed production to climb to over 6,000 tons of ore per day. As the depression of the 1930's came to end, Climax Mine was making its first significant profits and was supplying 90 percent of the world demand for molybdenum. As production increased at the Climax Mine more miners and mill workers were needed. A company town grew up at Climax and families soon settled into the routine of life in the high Rockies.

World War II and the ensuing Korean War fostered new uses for moly in pigments, fertilizers, and high temperature alloy steel for jet engines. Recovery circuits for the small amounts of tin and tungsten – important metals for the war effort – in the Climax ore body were installed in the mill. Production during those war years and the following Cold War years was deemed a high priority by the American government and in 1987 production reached 35,000 tons per day, making Climax the world's largest underground mine. In 1960 the Company expanded the mine and mill workings onto the site of the village of Climax. Most of the miners and other workers moved to the nearly town of Leadville creating a boom in that venerable old mining town. In 1964 Climax engineers designed and set the world's largest non-nuclear explosion in the Climax Mine. They used 416,000 pounds of explosives to blast 1.5 million tons of ore leaving behind a semi-circular depression of broken rock called the Glory Hole (Figure 9). During the boom years of the 1970's production increased to a spectacular 50.000 tons of ore per day. The price for molybdenum rose from $2 per pound to $9.50 and up to $30 on the spot market. An open pit mine was constructed and employment increased to 3,000 persons in the underground and open pit mines and the mill.

Because of the high price of molybdenum in the 1970's, many large porphyry copper mines in Arizona, Chile, and British Columbia installed molybdenum recovery circuits to their mills. Those copper mines produced what is known as by-product molybdenum. A national recession began in the early 1980's. With increasing molybdenum supplies and decreased demand, the mine began a series of painful layoffs that eventually led to the closure of the mine. In spite of these difficulties, mining from Climax continued on a sporadic basis through the early 1990's. The last ore containing about 3 million pound of molybdenite was mined in 1995.

The Climax Mine produced 500 million tons of ore that yielded about a million tons of elemental molybdenum with a "year-mined' value of $4 billion. There is still ore in the open pit mine – 137 million tons with about 500,000 pounds of contained molybdenum. Recently, molybdenum prices have stabilized and the Phelps Dodge Corporation (current owners of the mining properties) announced they intended to renew mining and milling operations at Climax, perhaps as soon as 2009. Meanwhile environmental remediation of the tailings ponds and other features is an ongoing operation.

Figure 9. The glory hole rising above the tailings ponds and mill in the foreground. Photo prior to World War II. (Colorado Geological Survey)

Wheeler Junction and Copper Mountain

During the 1880s, when both the Denver, South Park and Pacific and the Denver and Rio Grande Western railroads laid track through this valley between Frisco and Leadville, this place was called Wheeler Flats or Wheeler Junction (elev. 9,800 ft). Today, most residents and visitors know it as Copper Mountain, after the ski area and resort that were started here in the 1970s.

Copper Mountain has many of the same geologic constraints and considerations for development as other resort areas in the Rocky Mountains. The valley bottom, consisting of outwash gravel and extensive wetlands (Widmann and others, 2003b), has been developed over a 30-year span. The surrounding land has certain limitations, including federal land holdings, protection of remaining wetlands, and geologic hazards. The base of the ski mountain has landslides, and the flat land on the eastern side of the resort, at the base of the Tenmile Range, has potentially serious avalanche and rockfall hazards.

Vail Pass Landslides and I-70 Construction

Vail Pass was not the first choice for the interstate highway route between Vail and Frisco, in part because of the numerous landslides that were recognized along the alignment (Barrett, 1968). The favored route, Red Buffalo Pass, was not used because it lies within the Gore Range-Eagle Nest Primitive Area. The subsequent building of the interstate over Vail Pass (Fig. 10) during the 1970s is notable in that it was the first project to make use of engineering geology expertise throughout – from planning to design to construction (Turner and Rogers, 2003).

The route closely follows the Gore fault on the west side of the pass. Precambrian crystalline rocks are exposed to the east of the fault trace, whereas the Pennsylvanian Minturn and Maroon Formations are exposed to the west. Among the many challenging conditions encountered were a) sheared and structurally deformed bedrock, b) oversteepened bedrock slopes from glaciation, c) colluvium and moraine deposits found at close to their natural angles of repose, d) numerous landslide deposits, e) easily erodible soil deposits, and f) difficult revegetation due to the high altitude (Robinson and Cochran, 1983).

As a result of these conditions and the accompanying environmental constraints, a number of innovative design concepts were used or developed. These included a) widely separated lanes to reduce sizes of cuts and fills, b) avoidance of large rock cuts, c) slope contouring and sculpting, d) use of long, viaduct bridges to span problem areas, e) use of pre-cast, post-tensioned bridge segments, f) use of reinforced earth retaining walls, and g) coordination between geologists and landscape architects to enhance the visual effect of the highway (ibid.).

Landslides were recognized in metamorphic/igneous rock, sedimentary rock, and surficial deposits. The sedimentary rock landslides are the most significant in terms of number and areal distribution. One landslide complex occupies the highway alignment for nearly 4 miles. Most of the landslides were found to be inactive. Nonetheless, care was taken to minimize cutting and loading, and a variety of drainage and slope sculpting schemes were used. At one location, fill was added to the valley bottom, effectively raising the stream profile of Black Gore Creek. This decreased the erosive power of the stream and allowed two landslides on the opposite sides of the valley to buttress each other.

Figure 10. Looking southeast (eastbound) from 10,666-foot Vail Pass toward Copper Mountain Ski Area (left) and Jacque Peak. The widely spaced eastbound and westbound lanes of I-70 not only provide a pleasing visual aesthetic for travelers, they are also part of an integrated landslide mitigation design. (Colorado Geological Survey Photo).

Gore Creek Valley and Vail

The Town of Vail occupies the deep, narrow, valley of Gore Creek. To the east, the rugged Gore Range is composed of Proterozoic migmatitic biotite gneiss and the Cross Creek Granite. Closer to town, sandstones, conglomerates, and shales of the Pennsylvanian Minturn Formation form ledgy slopes along the valley. The Pennsylvanian to Permian Maroon Formation forms distinctly red ledges and slopes to the northwest of town.

The valley itself shows a distinctive “U” shape from Pleistocene alpine glaciers that carved its lower walls (Fig. 11). The floor is made up of Pinedale-age (upper Pleistocene) outwash deposits and modern alluvium. On the valley walls to the north, there are scattered deposits of Pinedale and older, Bull Lake-age (middle Pleistocene) glacial till. Vail Ski Area is distinctive in that it does not have steep valley walls. Instead, the mountainside is dominated by landslide and colluvial deposits. Quaternary (post-glacial) movement of the landslide complex has created a large-scale, “hummocky” terrain that is ideal for skiing.

A series of small, first-order drainages along the valley wall serve as avalanche chutes during the winter and debris flow chutes during the summer. At the base of these drainages are well-formed alluvial fan deposits. The cliffs are potential sources of rockfall.

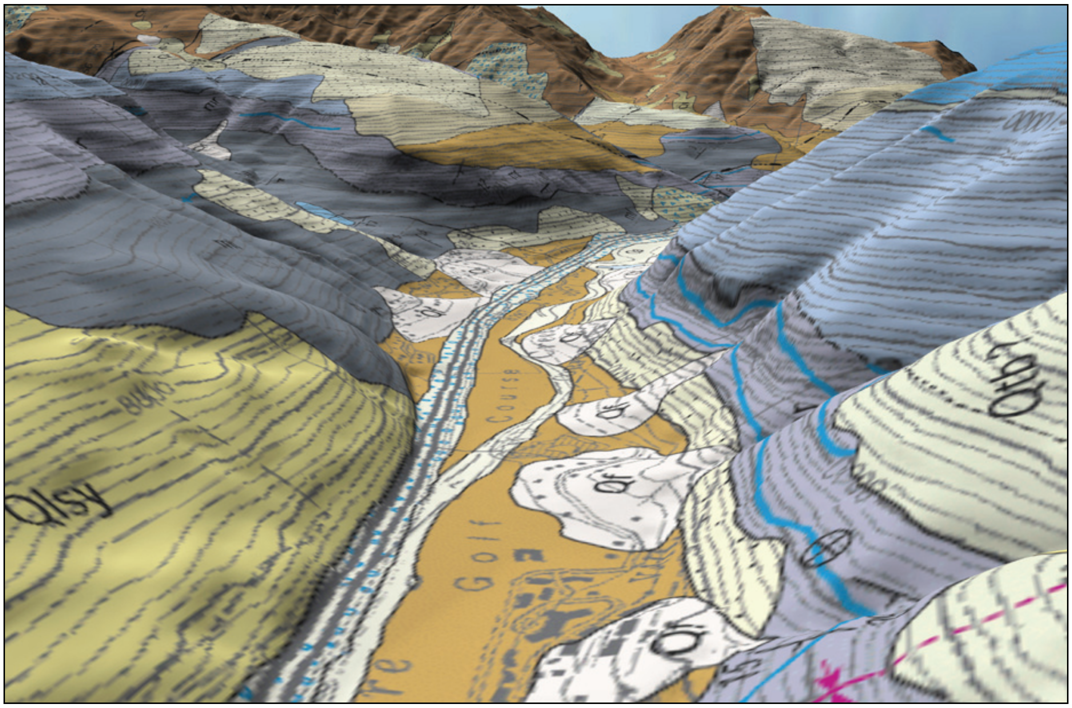

Figure 11. 3-D geologic map looking east from Vail, up the U–shaped glacial valley of Gore Creek. Debris fans spill onto the valley floor from side slopes of Pennsylvanian-age, syntectonic sedimentary rocks (blue and gray). Proterozoic crystalline rocks (dark brown) form the core of the Gore Range in the distance. Geology from Kellogg and others (2003).

The Town of Vail has enacted specific zoning regulations that address geologically sensitive areas, including these potential debris flow and avalanche areas (Fig. 12). The town's master hazard plans delineate areas where development is to be restricted, such as avalanche "red" zones. In hazard fringe areas, such as avalanche "blue" zones, structures may be built providing that proper mitigating measures have been taken. These are among the most stringent avalanche-hazard regulations in the United States.

Figure 12. An alluvial fan in east Vail. Because of the dual threat of debris flows and avalanches, Vail has enacted specific land-use regulations in such areas. On this particular fan, a pair of earthen berms has been built to channel flows away from built-up areas. (Colorado Geologic Survey Photo).

Booth Creek Rockfall Area

Notice the large, earthen berm near the base of the slope on the northern side of the valley, to the right of eastbound I-70. In May 1983, before Vail enacted its geologic-hazard regulations, a major rockfall from the cliffs (Fig. 13) above caused serious damage to several structures (Stover, 1988). In response, the town and the owners of one subdivision subsequently formed a Geologic Hazard Abatement District (GHAD) and constructed the large ditch and berm, which has performed effectively through the intervening years.

In March, 1997, another major rockfall event formed a swath of debris more than 500 ft across. All of the rocks that entered the existing ditch and berm were retained. The rest of the rockfall, however, was unchecked in the area of the condominiums. There were two major impacts, and a five-ft-diameter block of rock broadsided one of the buildings (White, 1997). Amazingly, there were no injuries. After this potentially catastrophic incident, two Mechanically Stabilized Earth (MSE) inertial impact barriers have been constructed just uphill from the condominiums.

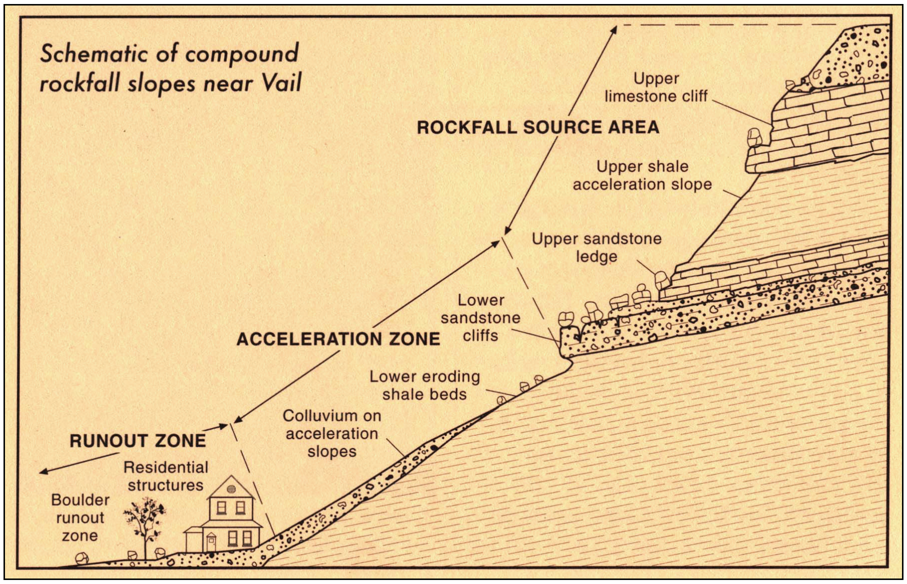

Figure 13. Rockfall hazard setting at Booth Creek, Vail (modified from Stover, 1988).

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REFERENCES

American Whitewater, 2006, Gilman Gorge, Description of River Running Conditions, Eagle River at Gilman Gorge, article posted to internet.

Andrew, R.D. and Lovekin, J.R., 2002, Geologic hazards and geologic constraints, I70 mountain corridor, programmatic environmental impact statement (PEIS): Association of Engineering Geologists Program with Abstracts v. 45, p. 53.

Barrett, R.K., 1968, Preliminary geologic report – Gore Creek Campground to Wheeler Junction: Colorado Department of Highways, Report for District 3, 20 p.

Bergendahl, M.H., 1963, Geology of the Northern Part of the Tenmile Range, Summit County, Colorado: USGS Bulletin 1162-D.

Colorado Department of Public Health and Environment, 2004, Eagle Mine Superfund Site, Site summary including 5-year review, summary of activities and progress posted to internet.

Colorado Geological Survey, 2001, Unsinkable Moly – Colorado's World-Class Metal Resource, in Rocktalk, v. 4, no. 3, p. 1 – 7.

Colorado Rockhounding, undated, mineral locations in Eagle County, article posted to internet.

Holmquist, D.V., 1983, Slope stability consideration of the Colorado State Highway 91 relocation, in Hynes, J.L., ed., Proceedings of the 33rd Annual Highway Geology Symposium, Colorado Geological Survey, Department of Natural Resources, Denver, Colorado, p.62-76

Kellogg, K.S., Bryant, B., and 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 1.0, scale 1:24,000.

Klauber, W., 1975, Unpublished surficial geologic map of the "Tenderloin" Area, +/- Sta. 110+00, +/- Sta. 146.00; including results of Climax and CHD geophysical surveys, and Climax test pit program (prepared for AMAX).

Metropolitan State College of Denver, 2004, Camp Hale History, article posted to the internet.

Metropolitan State College of Denver, 2004, Colorado Ski & Recreation History, article posted to the internet.

Metropolitan State College of Denver, 2004, The WAC, The Women's Army Corps Detachment at Camp Hale, article posted to the internet.

Noe, D.C., Matthews, V., Steele Weir, S., and McCalpin, J.P., 2003, Geology, geologic hazards, and water resources in the mountains of central Colorado: Field Trip Guidebook, Association of Engineering Geologists Annual Meeting, Vail, Colorado, September 16, 2003, 37 p.

Robinson, C.S., and Cochran, D.M., 1983, Engineering geology of Vail Pass I-70, in Hynes, J.L., ed., Proceedings of the 33rd annual highway geology symposium – engineering geology and environmental constraints: Colorado Geological Survey Special Publication 22, p. 116-135.

Rogers, W.P., 2003, Map of critical landslides in Colorado - A year 2002 review, in Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering Geology in Colorado: Contributions, Trends, and Case Histories: Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55, on CD-ROM.

Stover, B.K., 1988, Booth creek rockfall hazard area: Geological Society of America Field Trip Guidebook, Colorado School of Mines Professional Contributions, No. 12, p. 395-401.

Turn er, A.K., and Rogers, W.P., 2003, History of engineering geology development in Colorado, in Boyer, D.D., Santi, P.M., and Rogers, W.P., eds., Engineering Geology in Colorado – Contributions, Trends, and Case Histories: Association of Engineering Geologists Special Publication 15 and Colorado Geological Survey Special Publication 55, on CD-ROM, 73 p.

Tweto, O., 1979, Geologic map of Colorado: U.S. Geological Survey, scale 1:500,000.

Tweto, O., 1983, Geologic cross sections across Colorado: U.S. Geological Survey. Available as Colorado Geological Survey Miscellaneous Investigation Series MI-63.

Tweto, O., and Sims, P.K., 1963, Precambrian ancestory of the Colorado Mineral Belt: Geological Society of America Bulletin, v. 74, p. 991-1014.

Tweto, O., Moench, R.H., and Reed, J.C., Jr., 1978, Geologic map of the Leadville 1° by 2° quadrangle, northwestern Colorado: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1199, scale 1:250,000.

U.S. Corps of Engineers, undated, Camp Hale Military Munitions Project, article posted to internet.

Voynick, S.M., 1996, Climax–The history of Colorado's Climax molybdenum mine: Missoula, Montana, Mountain Press Publishing Co., 366 p.

Wallace, S.R., Muncaster, N. K., Jonson, D.C., MacKenzie, W.B., Bookstrom, A.A., and Surface, V.E., 1968, Multiple intrusion and mineralization at Climax, Colorado, in Ridge, J.D. (ed.), Ore Deposits of the United States, 1933-1967, The Graton-Sales Volume, vol. 1: American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, p 605-640.

White, J.L., 1997, Rockfall hazard assessment at Booth Falls condominiums and proposed mitigation: Colorado Geological Survey, unpublished report for the Town of Vail, 9 p.

Widmann, B.L., Bartos, P.J., McCalpin, J.P., and Jackson, J., 2003b, Geologic map of the Copper Mountain quadrangle, Summit, Eagle, Lake, and Park Counties, Colorado: Colorado Geological Survey Open-File Map 03-20, scale 1:24,000.

GEOLOGY, GEOLOGIC HAZARDS, AND NARRATIVE OF THE VAIL AREA

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OVERVIEW

This one-day field trip involves visiting sites of interest in and around the Town of Vail and the Gore Valley in Eagle County Colorado. These sites were selected because they are thought to well represent the general geology, Quaternary geology and geologic hazards found in the area. Other stops provide general information on the Town of Vail and Vail Mountain past and present. The general area and the trip route is shown on Figure 1 and summarised below.

Figure 1. Aerial photo of Vail Mountain and the Town of Vail looking to the southeast. Image provided by Jim Wark, Airphoto.

Numerous developed and undeveloped sites within the jurisdiction of the Town of Vail are subject to "high-velocity" mass-wasting hazards such as:

- Snow Avalanches
- Debris-Avalanches
- Soil Slides
- Debris-Flows
- Rockfalls

This field trip visits several of these sites in the eastern portion of Vail and describes the geological hazards at each site. Methods used to mitigate the hazard, as required by the Town of Vail hazard regulations, are also discussed.

TRIP ROUTE DESCRIPTION

Leaving from the Vail Marriott Mountain Resort, this one-day field trip will involve travel to East Vail with eight stops and discussions along the way. After a short in-town bus ride to the Vail Transportation Center, we will disembark for a walking tour through the Town of Vail, up to Mill Creek Circle and Golden Peak where we will board a bus to take us east to the Vail Golf Course via Vail Valley Drive. From the golf course we will continue east on the East Frontage Road to the Booth Falls trailhead where we will look at areas prone to rockfall and preventive mitigation measures, debris flows and the general geology of the Gore Creek Valley. Afterwards we will continue east on the East Frontage Road to Bighorn Road, and further east to Main Gore Drive (the last East Vail turn off on the right). We will then continue to Snowshoe Lane for a short hike to the East Vail water tower, where we will discuss snow avalanche hazards and mitigation measures. Next: Bighorn Park for lunch!

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Town of Vail Transportation Center, walk through town to base of Vail Mountain.	Area History, Town of Vail, Vail Mountain, Geologic Setting.	J.P. O'Brien
Mill Creek Circle, Golden Peak	Alluvial Fan, Debris Flows, and Landslide Complexes.	J.P. O'Brien
Vail Golf Course	Large Recent Landslide Complex, Debris Avalanche, Rockfall Hazards.	Art Mears, J.P. O'Brien
Booth Creek	Rock Fall Hazard Area, Debris Avalanche, Glacial Features.	Art Mears, J.P. O'Brien
East Vail Water Tower	Snow Avalanche's and Mitigation Measures	Art Mears
Bighorn Park	Lunch	Everyone
Juniper Lane Meadow Drive	Town of Vail Hazard Regulations Snow Avalanches & Debris Flows	Art Mears, J.P. O'Brien
Timber Falls Court	Debris Avalanches & Mitigation Measures	Art Mears
Bighorn Creek	Floods and Debris Flows	J.P. O'Brien
Lupine Drive	Avalanche Guiding Structures	Art Mears

After lunch we will view designated avalanche and debris flow hazard areas and discuss hazard regulations the Town of Vail has implemented. Our first afternoon stop will be southeast of the park near the intersection of Juniper Lane and Meadow Drive to see an area with high hazard rating for snow avalanche and debris flow. Walking northeast on Meadow Drive to Timber Falls Court we will look at several areas with various hazards and the measures that have been taken to mitigate or avoid them. From Timber Falls we drive by Bighorn Road and cross

Bighorn Creek where flooding and debris flows caused a sinkhole closing I-70 for several days and the evacuation of over 220 homes. Our last stop will be on Lupine Drive where we will study a recent avalanche chute and mitigation measures implemented there.

STOP 1. VAIL TRANSPORTATION CENTER

Historical and Present Day Perspective's

Although the Town of Vail was only founded as recently as 1962, the Gore Creek Valley and the surrounding areas have been populated with Indians, explorers, miners and ranchers for hundreds of years. In the 1940's the 10th Mountain Division trained nearby at Camp Hale and by the 60's and 70's the Vail Ski area and Town of Vail were built and growing. The following excerpt is a short history of the Vail area taken from the Town of Vail website (www.vailgov.com 2007).

"Vail was the hunting ground and summer residence of the Ute Indians before the arrival of the white man in the mid-19th century. Irishman George Gore, known as Lord Gore, and American frontiersman Jim Bridger were among the first explorers to venture into the mountainous region. From 1854 to 1856, they spent the summers hunting and exploring the peaks northeast of what is now known as Vail. A few years later, Bridger returned to the region and named the mountain range and valley after Gore.

By the 1870s, the Gore Range was attracting fortune seekers as the news spread that its hills contained both gold and silver. Mines were set up and railroad tracks laid down to transport the precious metals. The greedy intruders drove the Ute Indians from the land; upon their departure, the Utes allegedly set fire to thousands of acres of trees, resulting in the deforested area today known as Vail's famous Back Bowls.

It wasn't long before the miners depleted the area's mineral resources and abandoned the valley. It remained a peaceful home for sheep ranchers until 1939, when construction began on Highway 6, running from Denver through the Gore Valley. Charlie Vail, the project's engineer, lent his name to the road--the Vail Pass--and eventually to the Town of Vail, too.

During World War II, the Army's Tenth Mountain Division used the Vail area for backcountry survival training. After the war, many of the men who trained there were drawn back to the mountain valleys. Pete Seibert, one of Vail's founding fathers, was one such veteran; he returned to the Valley along with fellow troopers Bill "Sarge" Brown and Bob Parker. The three vets shared a great vision of a mountain ski community. In 1954, Earl Eaton, a uranium prospector with a similar vision, teamed up with Seibert to draw up a plan for a ski resort.

Construction began in spring 1962, and by fall 1966, the town of Vail was incorporated. Vail had the first gondola in the United States, along with two double chairlifts and a beginner poma lift, serving six square miles of terrain. Several restaurants, hotels and a medical clinic opened their doors soon thereafter.

By the mid-1970s, discriminating skiers had discovered Vail, and the town had earned the reputation as one of Colorado's best ski areas. When Gerald Ford, who owned a house in Vail, became President of the United States in 1974, the ski town made front-page news. Vail was soon recognised world-wide as **the** ski resort.

During the early 1980s, the area blossomed as a year-round resort. Golf courses were laid out and mountain-biking trails were added; gondolas and chairlifts began transporting sightseers instead of skiers; hot-air balloon rallies, tennis tournaments and concerts featuring everything from chamber music to rock became part of the Vail summer scene."

Table 2, shows some mountain facts that help Vail maintain it's number 1 ski resort ranking (Vail Resorts, www.snow.com Town of Vail, www.vailgov.com).

Table 2. Vail Mountain by the numbers.

Elevations Base Elevation: 8,120 ft./2,476 m Peak Elevation: 11,570 ft./3,527 m Vertical Rise: 3,450 ft./1,052 m	**Snow** Snowmaking: 390 acres/158 hec Average Annual Snowfall: 348 inches / 29 feet / 881 cm
Trail Classification (Total Mountain Acreage) 53% Expert/Advanced 29% Intermediate 18% Beginner Conventional Trails: 193 Longest Run: Riva, 4 miles/6.4 km	**Acreage** Total Skiable Area: 5,289 acres/2,141 hec Front Side: 1,627 acres/658 hec Back Bowls: 3,017 acres/1,221 hec Blue Sky Basin: 645 acres/261 hec
Total Skier/Snowboarder Visits 2005-2006: 1,676,118 2004-2005: 1,568,192 2003-2004: 1,555,513 2002-2003: 1,610,961 2001-2002: 1,536,024 2000-2001: 1,645,902 1999-2000: 1,371,702	**Lifts** Total Number of Lifts: 33 Gondola: 1 High-speed quads: 14, Fixed-grip quad: 1 Triple chairs: 3, Double chairs: 4 Surface lifts: 5, Magic Carpets: 5 Total Uphill Capacity Per Hour: 53,381
Climate (Temperatures in Fahrenheit) Daytime low temperatures in the teens with averages in the 20's and 30's, below 30 degrees at night. In summer, average temperatures are 75 degrees daytime, 45 degrees nighttime Vail sees more than 300 days of sunshine per year.	**Monthly Snowfall Averages (measured at mountain top and historical totals)** November: 58 inches December: 59 inches January: 64 inches February: 57 inches March: 63 inches April: 40 inches

Today Vail Mountain commonly exceeds 1.5 million skier visits per year on over 5,100 acres of lift accessible terrain. The Town of Vail now has a population of 4,531 full time and 3,000 part-time residents, the population of Eagle County is 41,659 residents, including 9,813 part-time. During the winter ski season the town's population often surges past 20,000 with guests and visitors. Vail is the largest ski area in North America and has been rated as the number 1 ski area in North America over the past several years. The Town of Vail is approximately five miles long and two miles wide encompassing 13 square miles (Figure 1). There are 2,200 developed acres and 1,100 undeveloped acres with 400 acres of town-owned parks within town limits. Most of the undeveloped acres not suitable for development; are due in part to the hazards we will be looking at today. Current build out within the town limits is over 96 percent.

General Geology

The Vail Valley and the Town of Vail occupy the deep, narrow, formally glaciated valley of Gore Creek. Geology of the area has recently been mapped at 1:24,000 scale by the U.S. Geological Survey (Scott and others, 2002; Kellogg and others, 2003).

The bedrock near Vail is Precambrian and upper Paleozoic in age. Along the skyline to the east, the rugged Gore Range is composed of Precambrian migmatitic biotite gneiss and the Cross Creek Granite (early Proterozoic). Closer to town the ledgy hill slopes to the north and south of Gore Creek are composed of the Minturn Formation (middle Pennsylvanian). A few miles to the west, near Avon, the Minturn Formation grades laterally into bedded evaporite deposits of the Eagle Valley Formation (Scott and others, 2002). Northwest of Vail the Minturn Formation is overlain by the middle Pennsylvanian to lower Permian aged Maroon Formation which contains redbeds of coarse clastic sandstone and conglomerate, distinguishing it from the Minturn by its uniform color and relative lack of carbonate beds (Noe and others, 2003). A general stratigraphic column for the central Colorado Mountains is shown on Figure 2. A generalised cross-section for the central Colorado Mountains is shown on Figure 3.

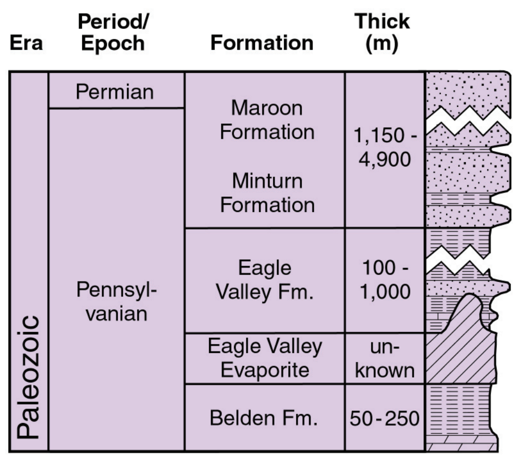

Figure 2. General stratigraphic column for the central Colorado mountains (mod. from Kirkham and others, 2002).

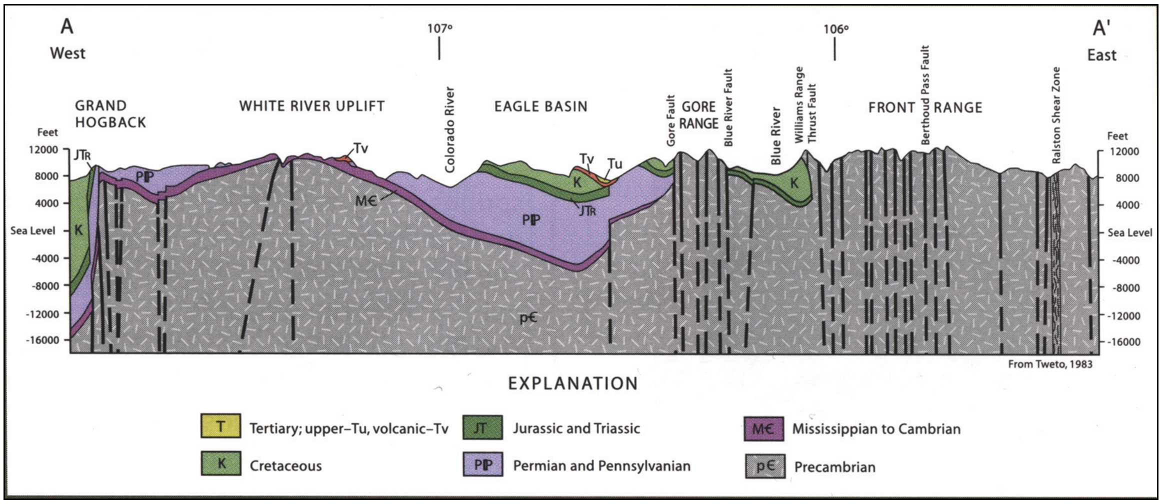

Figure 3. General stratigraphic cross section for the central Colorado mountains along the Interstate 70 corridor, from Glenwood Springs to Golden (modified from Tweto, 1983).

Several types of surficial deposits (unconsolidated deposits of Quaternary age, 1.5 million years or younger in age) are found in the valley. The valley itself shows a distinctive "U" shape from alpine glaciers that carved the lower valley walls during the Pleistocene epoch. The flat valley floor is covered with Pinedale-age (upper Pleistocene) outwash deposits and modern alluvium. On the valley walls north of Gore Creek, there are scattered deposits of Pinedale and older, Bull Lake (middle Pleistocene) glacial till (Noe and others, 2003).

In other areas adjacent to the Gore Valley, such as on the ski mountain south of Gore Creek, steep valley walls give way to a gentler hummocky topography that is perfect for skiing. Quaternary (post glacial) movement of landslide complexes creates this terrain. Further, glacial over-steepening has caused a number of types of slope failure. In many areas, such as above Game Creek Bowl, open tension fissures have led to the formation of active and inactive landslide complexes. On the front side of Vail, from Game Creek Bowl to the slopes south of Mill Creek, mass movement has occurred in strata with northward dipping bedding planes, causing many incipient slides in these areas (Tweto and Lovering, 1977).

East of the Town of Vail the valley walls steepen markedly and show their glacial profile. Along the south wall, there are a series of small, first-order drainage's that enter the main valley. These drainage's, which head on steep slopes and continue down steep lower cliffs, serve as avalanche chutes during the winter and debris flow chutes during the summer. At the base of these drainages are well-formed alluvial fan deposits. The cliffs on the north and south sides of the valley are potential sources of rockfall (Noe and others, 2003).

A Walk Through Town

As we proceed down the main south stairs towards the covered bridge, note the statue commemorating the elite 10th Mountain Division to our right. The 10th Mountain Division won many decisive battles in WWII and contributed greatly to the American ski industry. Riva Ridge, one of first and a famous ski run at Vail, is named after one of the great battle the 10th fought in the Apennines north of Florence Italy. Vail Skier Penny Tweedy named one of her horses after this run, Riva Ridge, which went on to win the Kentucky Derby in 1972. Over two thousand 10th Mountain veterans became instructors, patrolman and industry leaders, notably (Seibert, 2000):

- Fitz Benedict, an architect and developer in Aspen
- Bill "sarge" Brown, Vail mountain manager
- Larry Jump, president of Arapahoe Basin Ski Area
- Merril Hastings, founded SKIING magazine
- Friedl Pfeifer, director Aspen ski school and created Buttermilk Ski Area
- Bob Parker, editor of SKIING magazine and Vail marketing director
- Jack Tweedy, vice president and attorney of Vail Corporation

From the memorial we head west on Meadow Drive to the intersection with Willow Bridge Road where a small part of Vail's billion dollar renewal is being completed. On our right is the old Crossroads development, built in 1968 and scheduled for demolition this summer, it will be rebuilt and renamed Solaris. In front of us is the soon to open One Willow Bridge Road project, and both developments will have retail space, grocery and liqueur stores, condominiums and hotel rooms. Heading south on Willow Bridge Road we cross a stretch of Gore Creek on the International Bridge that is a designed kayak park and plays host to several competitions held during the Teva Mountain Games. Continuing south we arrive at Check Point Charlie at the intersection with Gore Creek Drive, where looking south we can see the large excavation for Vail's new Front Door Project, which will contain skier and mountain services, restaurants, a spa and condominiums.

From Check Point Charlie heading west on Gore Creek Drive we enter the core village area (observe the Gore Range on the skyline); turn south on Wall Street to enter Earl Eaton Plaza. Earl Eaton was the "finder" of Vail and first showed it to Pete Seibert, the "founder" of Vail, in the winter of 1957. Note the new streetscape and water features that have recently been installed. Continue south past the ticket offices then west to Seibert Circle where we will gather for a short discussion concerning development on alluvial fans.

Southeast is The Mill Creek Development, one of the first residential developments in Vail; houses here sell in the 10 plus million-dollar range. Alluvial deposition on this fan has been controlled by the installation of culverts and by incising a deep straight channel through areas that were previously shallow and anastomosing. The Mill Creek fan is shown on Figure 4, where the Town of Vail maps the upper portions as a hazard area. The toe of the fan is immediately in front of us (although altered by construction of the skier yard and chair lift) and high hazard debris flow areas extend up the access road to the top of chair 12 (the beginner lift to the southeast where Mill Creek enters the valley). Closer to us, a moderate hazard debris flow area has been mapped in areas encompassing several home sites (TOV code, 12-21-15). Generally, in many areas on this and other nearby fans, piping may occur in fine-grained material on older fan alluvium and debris-flow deposits, whereas hydrocompaction may occur in younger fan alluvium and debris-flow deposits (Scott and others, 2002).

Looking further up the mountain, under and to the east of the Vista Bahn chairlift, the steep slopes here contain many seeps and springs within and adjacent to recently active (Holocene) and currently inactive (Quaternary) landslide complexes. The ski runs in this area are referred to as the "chutes", the ski run "Mudslide", in front of us to the southeast, is on a recently active landslide on the southwest flank of this mountain side. Further to the east is Golden Peak, although obscured by ski run grading, the entire upper face of Ruder's Route is a landslide complex as evidenced by the hummocky topography, reflecting Holocene movement. No evidence was found by Kellogg and others (2003) or Scott and others (2002) for ongoing large-scale landslide activity on Vail Mountain.

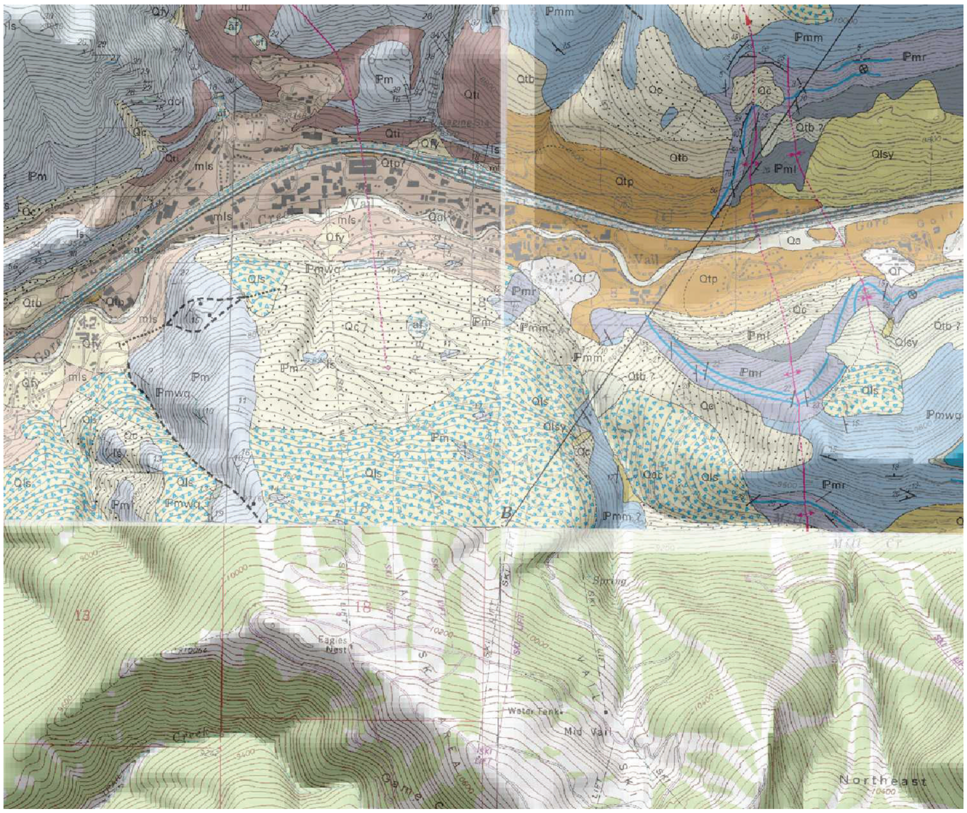

Figure 4. Geologic map of the Vail Mountain and Golf Course areas. Modified from Scott and others, 2002 (west side) and Kellogg and others, 2003 (east side).

Near the base of the Vista Bahn, we head east on the bike path, past the pirate ship and on to the base at Golden Peak to catch a bus to the Golf Course. Going east on Vail Valley Drive we are travelling on Pinedale Till (Upper Pleistocene), turn right on to Sunburst Drive, park at clubhouse parking lot.

<u>STOP 2.</u> VAIL GOLF COURSE

Landslides

Looking north across I-70 a large active landslide complex is clearly visible on the south-facing slope, it was recently mapped by Kellogg and others (2003) and is shown on Figure 4. The toe of the landslide has been cut by construction of I-70 and it is currently failing by a combination of deep rotation and shallow soil slumping (Jurich and Miller, 1987). Jersey barriers have been placed to keep debris off the Interstate highway. The catchment area, a narrow alley between the hillside and highway, is cleaned out as needed. This slide may be up to 120 feet thick and is located in the lower member of the Minturn Formation (Kellogg and others, 2003). Note the hummocky topography and the stressed, pistol butted or fallen aspen trees. Looking to the south-southwest, about 400 feet up, a smaller recently active landslide can be seen on the west flank of the drainage (Figure 4.).

Constructions of roads and houses at the toes of landslide deposits may reactive older slide surfaces or cause new ones to form without proper mitigation and best management practices. In some cases multi-storey houses are being built against cuts in the toes of these landslide deposits (Scott and others, 2002).

Back on the bus we head west to the East Frontage Road, turn east and drive past the I-70 overpass to Booth Falls Road, park, and walk to the Booth Falls Trailhead at the end of the road.

STOP 3. BOOTH CREEK AREA

Booth Creek Rockfall Area

The following is a largely unmodified excerpt from a previous AEG field trip prepared by Noe and others (2003).

A number of single- and multi-family housing developments were built at the mouth of Booth Creek, where it enters the main valley of Gore Creek, in the 1970s and 1980s. This was before the Town of Vail enacted its geologic-hazard zoning regulations. In May 1983, a major rockfall event from the cliffs above the valley caused serious damage to several structures (Stover, 1988). Other damaging rockfall events occurred over subsequent years. This prompted the town to work with property owners to find workable solutions for this existing, serious hazard area. The result was that the town and the owners of one of the single-family residence filing formed a Geologic Hazard Abatement District (GHAD). The GHAD constructed a large ditch and berm across the slope above the subdivision, as shown on Figure 5. These were designed using modeling results from the Colorado Rockfall Simulation Program (CRSP). The owners of a multi-family condominium facility on an adjoining filing declined to join in on the GHAD and the mitigation project.

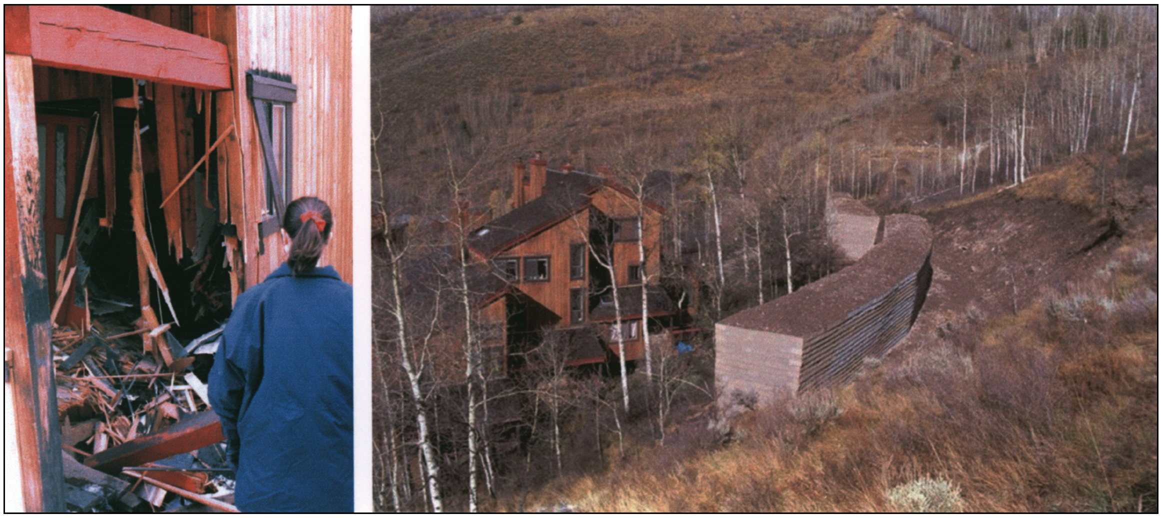

Figure 5. a) Aftermath of the March 1997 rockfall event at the Booth Falls Condominiums, where a large boulder broadsided a condominium. Luckily, the owner was away at the time. b) New impact barriers at the condominiums. Photos by Jonathan White, Colorado Geological Survey.

The rockfall ditch and berm on the hillside has performed effectively through the intervening years. Most of the events, in fact, have gone unnoticed because the ditch caught all of the rocks. In March 1997, another major rockfall event occurred above the western edge of the berm. A limestone block, about 8 ft x 8 ft x 20 ft, broke from the top of the cliff, knocking loose several other blocks from the cliff. As this mass of rocks tumbled down the slope below, it fanned out to form a swath of rockfall debris more than 500 ft across. All of the rocks that entered the existing ditch-and-berm area were retained. The rest of the rockfall debris, however, was unchecked in the area of the condominiums. There were two major impacts, and a five-ft-diameter block of rock (Figure 6a) broadsided one of the buildings. Smaller fragments sheared off the tops of some aspen trees in the vicinity at up to 25 feet above ground level (White, 1997). Amazingly, there were no injuries. After this potentially catastrophic incident, the Colorado Geological Survey assisted the town and the condominium owners in assessing and modeling the rockfall hazard and creating mitigative design parameters. Two Mechanically Stabilized Earth (MSE) inertial impact barriers have been constructed just uphill from the condominiums (Figure 5b). The barriers have overhanging impact walls on the uphill sides to better control and contain rocks having high rotational velocities, and are reinforced internally with geotextile membranes.

The rockfall source area consists of a bedrock nose where the valleys of Booth and Gore Creeks come together. There are two prominent cliffs, consisting of limestone and sandstone beds in the Minturn Formation. The limestone beds produce the largest and hardest rockfall blocks. These beds are overlain at the top of the cliff by a deposit of glacial till, which is capable of producing granite and metasedimentary boulders as rockfall. Below the cliffs are acceleration zones of shale deposits capped by a thin veneer of colluvium. The residential structures are built on the run-out zone at the base of the slope, as shown on the schematic in Figure 6.

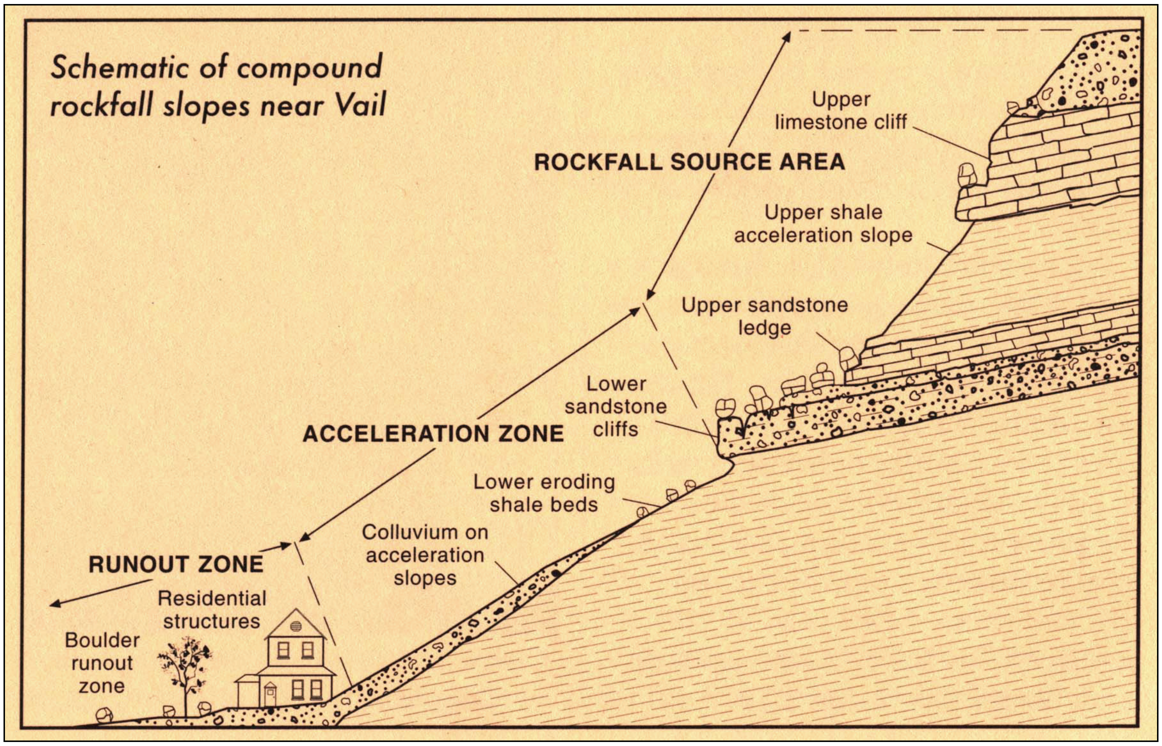

Figure 6. Rockfall hazard setting at Booth Creek, Vail (modified from Stover, 1988).

Booth Creek Valley Hike

We will take a short (~1/3 mile) scenic hike along the Booth Falls trail to a valley-floor bench where we can look at the surrounding geology. The debris flow scar across the valley on the west side of Booth Creek dates back to the early to mid 1980s. During this period, several debris flows impacted Vail. This was at the same general time that wet conditions affected much of the western U.S., causing numerous landslides such as the one at Thistle, Utah (James Soule, Colorado Geological Survey, personal communication). This particular debris-flow chute has a broad, bowl-like scar at its head, indicating that soil-slip processes in the hillside colluvium initiated it.

The bench at the mouth of Booth Creek is the lip of a hanging valley where a smaller glacier flowed into the larger and deeper-cutting, Gore Creek glacier. We are approximately 500 feet above the main valley floor at this spot, as shown on Figure 7.

The Minturn Formation

The surrounding cliffs consist of resistant sandstone, conglomerate, and limestone beds of the Minturn Formation. There is ample evidence of rockfall from these cliffs in the recent past along this trail. Some of the sandstone and conglomerate beds have a distinctive geometry consisting of large-scale bottomset, foreset, and topset beds. These are classic "Gilbert"-type deltas, deposited as fan deltas into a restricted, low-energy seaway along the margin of the Ancestral Rocky Mountains during Pennsylvanian time. Lacking hard evidence about this ancient uplift (which has since eroded away), geologists have used paleocurrent measurements from foreset beds in the Minturn, Maroon, and other age-equivalent clastic formations in Colorado to reconstruct the footprint of the highland areas (Noe and others, 2003).

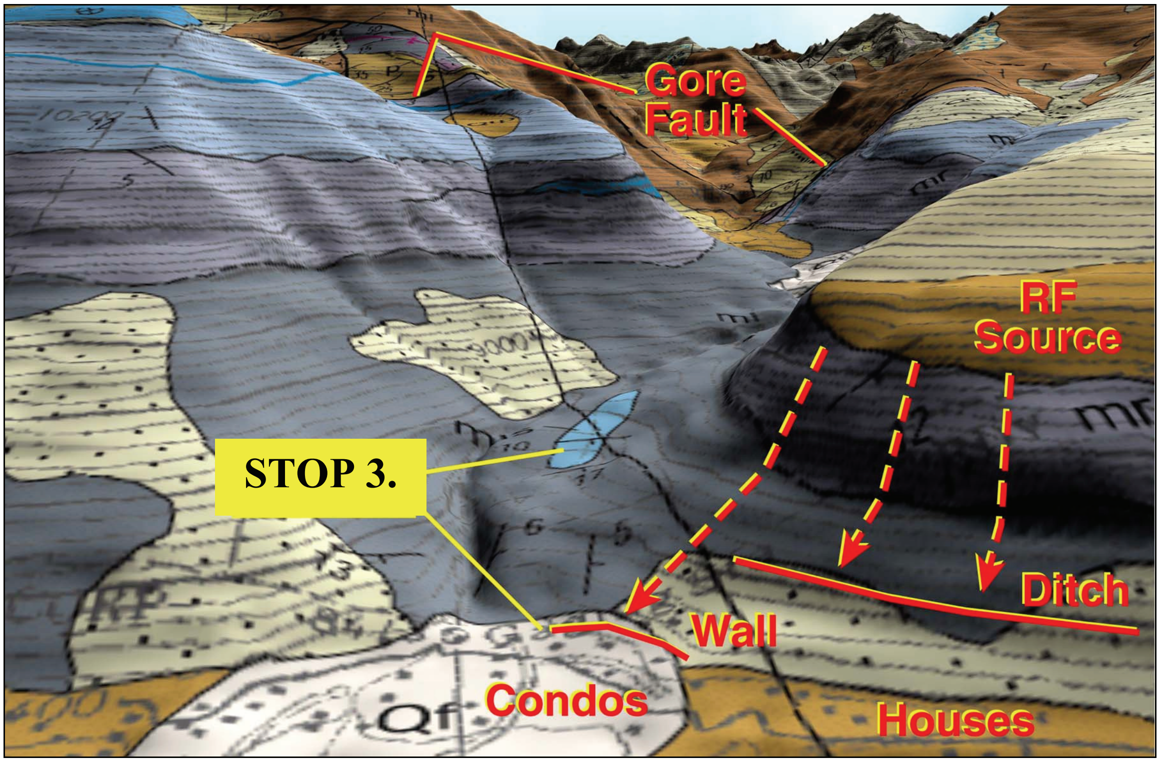

Figure 7. 3-D geologic map of the valley of Booth Creek where it meets Gore Creek, looking north. Note the hanging valley bench (upper stop location), the rockfall source zone on the steep slopes to the right, the Pennsylvanian sedimentary rocks (blue and gray colors) in the lower valley, and the Proterozoic crystalline rocks (dark brown) in the upper valley. These two rock types are separated by the Gore fault. Geology from Kellogg and others (2003).

The Minturn Formation contains up to 6,300 feet of tan to gray clastic rocks with subordinate interbedded carbonate rocks of Pennsylvanian age lying above the Belden Formation and below the Maroon Formation, it inter-tongues with the Eagle Valley Formation just west of Dowds Junction (Scott and others, 2002). Although the Minturn Formation primarily consists of interbedded grit (coarse-grained, poorly sorted arkosic sandstones), conglomerate, shale and siltstone; several laterally persistent marker beds of gritty marine limestone and dolomite are intercalated in the coarse clastic rocks (Tweto and Lovering, 1977).

Many clastic rocks in the Minturn Formation are cross-bedded and often occur as lens shaped beds. Cross-bedding is high-angle, medium scale planer, simple and trough cross-beds are also commonly found. In some areas small and large-scale scour structures are incised up to several feet into underlying strata. Entire beds or lenticular deposits of grit or conglomerate often fill the incised channels. Other sedimentary structures commonly found are ripple marks, desiccation cracks, small clastic dikes and rain drop impressions (Tweto and Lovering, 1977).

The limestone and dolomite beds are laterally traceable in this area but are not persistent throughout the region. The primary marine marker beds in this area include:

- The Jacque Mountain Limestone
- The White Quail Limestone Member
- The Robinson Limestone Member
- The Reef Dolomite of Lionshead
- And the Dolomite bed at Dowds Junction

These sequences are separated by clastic sequences of conglomerate, sandstone, siltstone and shale (Tweto and Lovering, 1977).

Sequences within the Minturn Formation are asymmetric and characterised by thin transgressive units and thick regressive units. The thickening-upward trend of sequences and the stacking of Pennsylvanian aged alluvial fan deposits in the uppermost sequences are attributed to progressively increasing tectonism. From these and other data it is inferred that during the Middle Pennsylvanian increasing tectonism along the margin of the Ancestral Rocky Mountains in and adjacent to the Central Colorado Trough resulted in deposition of alluvial fan, braid-plain, Gilbert-delta, fan-delta and shallow marine sediments of the Minturn Formation. These clastic rocks are inferred to be marine margin piedmont deposits derived from a highland east of the Gore Fault (Johnson and others, 1988; Tweto and Lovering, 1977).

The Minturn Formation contains many incompetent shaley beds that make ideal surfaces for landsliding where beds dip toward valleys e.g. Vail Mountain. Further, the weak and platy weathering of beds forms thick deposits of colluvium that creeps down slopes accumulating in debris flows and falls in the valleys (Tweto and Lovering, 1977).

Gore Fault

About 1 mile up Booth Creek from our stop on the hike is the Gore fault, which crosses the valley at approximately a 90-degree angle (see Figure. 7). Here the fault places Proterozoic crystalline rocks against Pennsylvanian rocks (Figure. 8), with approximately ½ mile of vertical displacement. Determining the age of movement is a challenge, especially when younger formations or deposits that might date the fault are missing or have been eroded away. The exposure up-valley has been interpreted alternatively as a Laramide fault (Cretaceous-Tertiary) and an Ancestral Rocky Mountains fault (Pennsylvanian). A fault further up-valley may be a Neogene fault (Noe and others, 2003).

Back on the bus, we head east on the East Frontage Road under the I-70 overpass, where the road name changes to Bighorn Road, and proceed east to Main Gore Drive (the last East Vail turn off). Turn right onto Main Gore Drive to Snowshoe Lane and walk a short distance to the East Vail water tower.

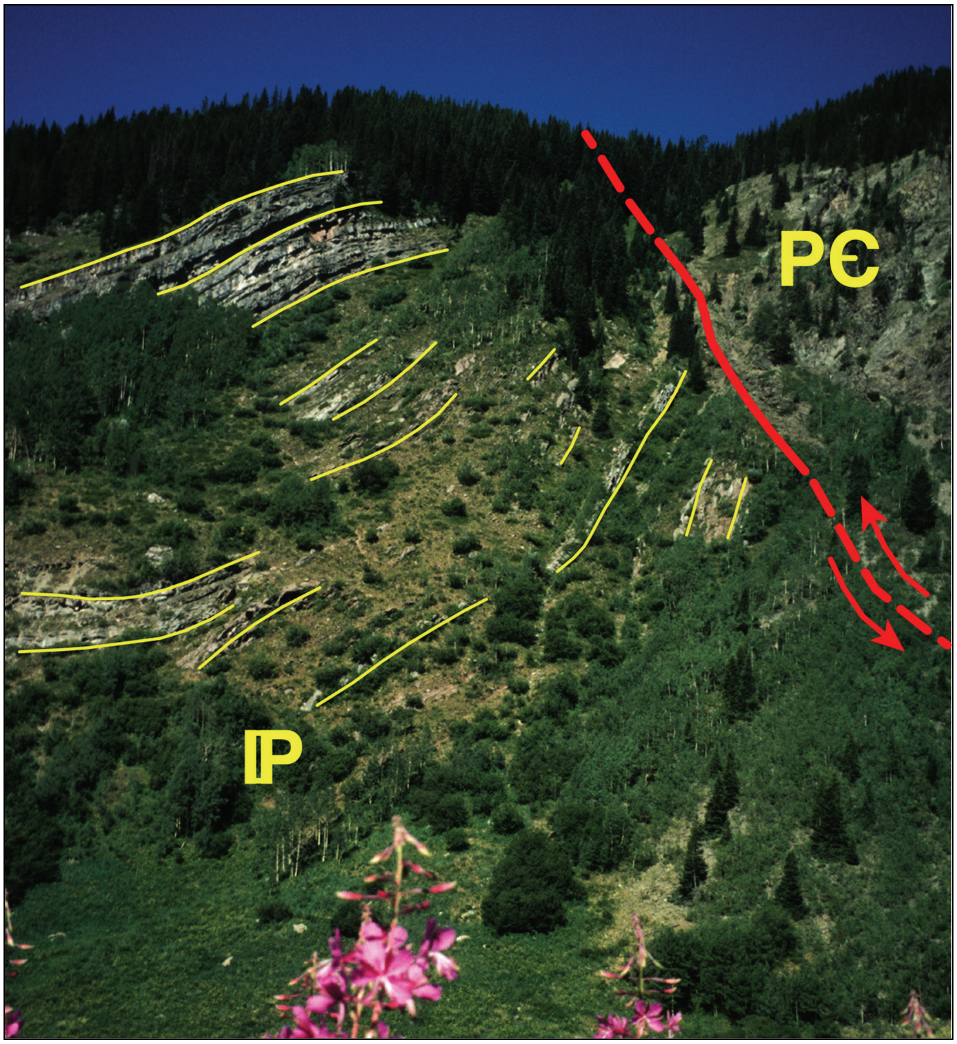

Figure 8. The Gore fault (red), as exposed on the west wall of the valley of Booth Creek. The Pennsylvanian Minturn Formation (P) is on the left of the fault (individual beds are highlighted in yellow) and the Proterozoic Cross Creek Granite (PC) is on the right. The Minturn, which is nearly flat lying farther down valley, is folded spectacularly against the fault (from Noe and others, 2003).

<u>STOP 4.</u> EAST VAIL WATER TOWER

This moderate-sized snow avalanche has a vertical displacement of approximately 2,400 feet (730 m) and impacts a small hill in the runout zone. The last major avalanche occurred in the 1950's. A municipal water-storage is located in the runout zone and has been designed for avalanche impact and static forces. The East Vail water tank is mostly within an avalanche area, as well as a debris flow.

Back to Juniper Lane or Meadow Drive (west) and finally to Bighorn Park where we will stop for lunch.

STOP 5. LUNCH AT BIGHORN PARK

Lunch in Bighorn Park on Pinedale Till

Lunches provided under the pavilion by the lake, rest rooms are to the east. After lunch we will walk across Meadow Drive then west to Timber Falls Court to look at three or four well developed alluvial fans (Figure 9.), their associated avalanche chute run out areas and debris-flows.

On the hillside to our southeast, note the Cross Creek Granite is exposed in the form of a glacial flute that has a house on top of it (Figure 9.).

General Tectonic Environment

The rocks in Eagle and Summit Counties have endured multiple periods of deformation. The oldest, crystalline rocks suffered at least two periods of ductile deformation associated with metamorphism during the Proterozoic.

Early Paleozoic tectonism certainly occurred in Central Colorado (and probably more than once), but the evidence is woefully incomplete. One finds only tantalising bits and pieces of evidence here and there.

During the Pennsylvanian/Permian periods the Ancestral Rocky Mountains rose as fault blocks out of a shallow sea. Colorado was dominated by the Ancestral Uncompahgre and Ancestral Front Range uplifts with a restricted evaporite basin trapped between the two ranges. Most of the evidence of this uplift is stratigraphic rather than structural. The rocks in the Vail Valley record the uplift of the Ancestral Front Range. It is rare to find a fault that can unequivocally be assigned to the Ancestral Rocky Mountain deformation. The Ancestral Rocky Mountains were pretty well worn away by the end of the Triassic.

The next major deformation (Laramide Orogeny) began with fault blocks rising out of the Late Cretaceous seaway about 80 million years ago. This period of uplift and crustal shortening continued into the early Cenozoic. The structural style is dominated by high angle reverse faults with a few, low-angle thrust faults. Faulting was accompanied by igneous intrusions and mineralization, as well as deposition of syntectonic sedimentary units. By about 38 million years ago the Laramide mountains were pretty well worn away and Colorado was fairly featureless once again.

The last major tectonic event, and the one we are in today, began about 25 million years ago with major east-west extension. This extension broke the crust into large blocks that are subsiding into basins and rising into some of the most impressive mountains in North America. Fifty-eight peaks in Colorado soar above 14,000 feet in elevation and the entire state averages 6,800 feet above sea level. Colorado has the areally largest heat-flow anomaly in North America. The distance between the lowest and highest points is more than two vertical miles. The structural style is dominated by normal faults and basaltic volcanism. The Colorado Geologic Survey's current catalogue of Late Cenozoic deformation includes 92 Quaternary faults. The youngest basalt in the state, located about 45 miles to the west at Dotsero, is only 4,150 years old.

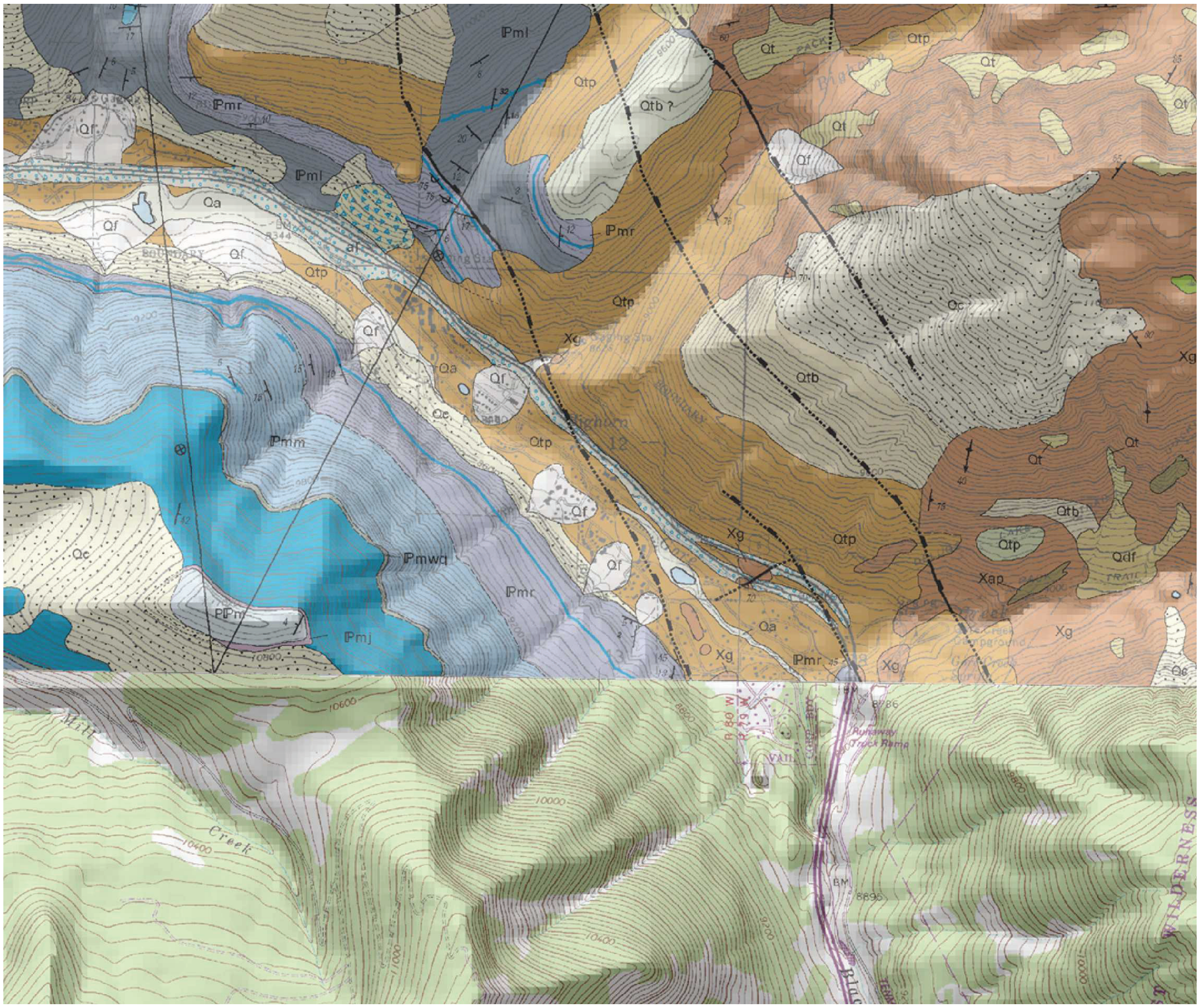

Figure 9. Geologic map of the East Vail Bighorn Area, modified from Kellogg and others, 2003.

The great challenge in evaluating earthquake risk in Colorado is to decipher when a particular fault last moved and what its slip rate is. Because Colorado is such an active tectonic area, erosion is a dominant process. As Tom Steven, USGS Emeritus, recently stated, "By its nature, erosion progressively destroys the history of its own evolution."

<u>STOP 6.</u> JUNIPER LANE / MEADOW DRIVE

Prior to annexation into the Town, this area was planned for residential development. The U.S. Forest Service recognised the avalanche potential of this area in the early 1970's and brought the exposure of the site to the attention of Eagle County and the Town. This and other conspicuous avalanche paths in the eastern portion of the valley stimulated identification and mapping of avalanche paths.

The area directly above the Racquet Club is both a snow avalanche and debris-flow area. The numerous scars in the aspen forest below the cliff outcropping 400 ft above the valley probably resulted from debris slides and wet snow avalanches. A recent scar (from 1984) is located immediately east of the Waterfall. Old scars of this type are common above the golf course.

Walk west on Meadow Drive approximately 0.1 mile to our next fan.

This site is exposed to rare snow avalanches and muddy debris-flows. A young boy was caught in a mud-flow in approximately 1970. Buildings are located beyond the expected boundaries of avalanches.

Continue walking west on Meadow Drive to Timber Falls Court, approximately 0.2 mile to our next stop.

STOP 7. TIMBER FALLS COURT

A relatively small soil-slip debris avalanche descended into this site in May 1984. The avalanche released under a deep, wet spring snowpack and completely removed the aspen forest. Avalanche guiding structures have been built to prevent lateral expansion of this avalanche into developed areas.

To protect the Timber Falls Complex, berms have been built on the lateral sides of the avalanche path to contain it. Again, long return periods and no major events in this area for 50 years or more.

Head west on bus past Bighorn Creek, to Lupine Drive.

BIGHORN CREEK AREA (DRIVE BY)

On June 1st, 2003 flooding and debris flows on Bighorn Creek caused a breach in a culvert under I-70 leading to the formation of a 22-foot wide sinkhole on the west bound lanes of the Interstate. Due to the sinkhole both west and eastbound lanes of I-70 were closed for 3 days, westbound lanes were closed for three weeks. As shown on Figure10, flooding closed several neighbourhood roads, the bike path, and over 200 homes were evacuated for a few days. Costs for repairs to I-70 exceeded $400,000, other repairs to local streets, infrastructure and private homes exceeded $600,000. The nearly 100 year old culvert, which was extended in 1976 during highway construction, was replaced with a 72" culvert.

Continue west to Lupine Drive turn in, continue to the confluence of Pitkin and Gore Creeks.

Figure 10. Figure 10 a. (top) Bighorn Creek floods Spruce Way. Figure 10 b. (bottom) Bighorn Creek Floods East Vail Bike Path..

<u>STOP 8.</u> LUPINE DRIVE

At this site an avalanche released under a deep, wet spring snowpack and completely removed the aspen forest. Avalanche guiding structures have been built here to prevent lateral expansion of this avalanche into developed areas.

End of trip, return to the Marriot Resort.

ACKNOWLEDGEMENTS

Special thanks goes to Dave Noe of the Colorado Geological Survey whose help with text; figure and illustration preparation was invaluable.

REFERENCES

Johnson, S.Y., Schenk, C.J., Karachewski, J.A., 1988, Pennsylvanian and Permian depositional systems and cycles in the Eagle Basin, Northwest Colorado, in Holden, G.S., ed., Geological Society of America, Centenial Meeting Field Trip Guidebook, Professional contributions of Colorado School of Mines, Number 12, p. 156-174.

Jurich, D., M., and Miller, R., J., 1987, Acoustic monitoring of landslides: Transportation Research Record 1119, Transportation Reseach Board, National Research council, Washington D.C., p. 30-38.

Kellogg, K.S., Bryant, B., and Redsteer, M.H., 2003, Geologic map of the Vail West quadrangle, Eagle County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2375, version 1.0, scale 1:24,000.

Kirkham, R.M.; Scott, R.B.; and Judkins, T.W., eds., 2002, Late Cenozoic evaporite tectonism and volcanism in west-central Colorado: Boulder, CO, Geological Society of America Special paper 366, 234 p.

Noe, D., Matthews, V., Steele, S., McCalpin, J., 2003, Geology, Geologic Hazards, and Water Resouces in the Mountains of Central Colorado, Field Trip Guide Book, First North American Landslide Conference, Vail, Colorado, 38p.

Seibert,P.,W.,2000, Vail, Triumph of a Dream, Mountain Sports Press, Boulder, Colorado, 192p.

Scott, R.B., Lidke, D.J., and Grunwald, D.J., 2002, Geologic map of the Vail West quadrangle, Eagle County, Colorado: U.S. Geological Survey Miscellaneous Field Studies Map MF-2369, version 1.0, scale 1:24,000.

Stover, B. K., 1988 Booth Falls Rockfall Hazard Area: Geological Society of America Field Trip Guidebook, Colorado School of Mines Professional Contributions, No. 12, p 395-401.

Town of Vail, 1985, as revised 2/15/07, Town Code, 12-21-15, Restrictions in Geologically Sensitive Areas: all inclusions, 5p.

Tweto, O., 1983, Geologic cross sections across Colorado: U.S. Geological Survey. (Available as Colorado Geological Survey Miscellaneous Investigations MI-63.)

Tweto, O., Lovering, T.H., 1977, Geology of the Minturn 15-Minute Quadrangle, Eagle and Summit Counties: Colorado, U.S. Geological Survey Professional Paper 956, 96 p.

Tweto, O., Moench, R.H., and Reed, J.C., 1978, Geologic Map of the Leadville Quadrangle, Northwestern Colorado: U.S.Geological Survey, Miscellaneous Investigations Series, Map I-999

White, J.L., 1997, Rockfall hazard assessment at Booth Falls Condominiums and proposed mitigation: Colorado Geological Survey, unpublished report for the Town of Vail, 9 p.

THE SLUMGULLION LANDSLIDE, HINSDALE COUNTY, COLORADO

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The disrupted surface of the Slumgullion landslide. Photo by J.A. Coe, U.S. Geological Survey

1st North American Landslide Conference
Vail, Colorado, June 9-10, 2007

OVERVIEW

This two-day field trip visits the Slumgullion landslide located in the San Juan Mountains of southwestern Colorado (Figure 1). The landslide moves continuously at rates as high as about 7 m/yr, making it an exceptional location for landslide research. The trip will provide opportunities to observe and evaluate the landslide, as well as learn some of the results of research studies performed during the past sixty years. The first day of the trip will include overviews of the landslide and its geologic setting, and the second day will include a hike down part of the landslide. We will see some of the monitoring equipment used to study the landslide and features that indicate the kinematics involved with landslide movement.

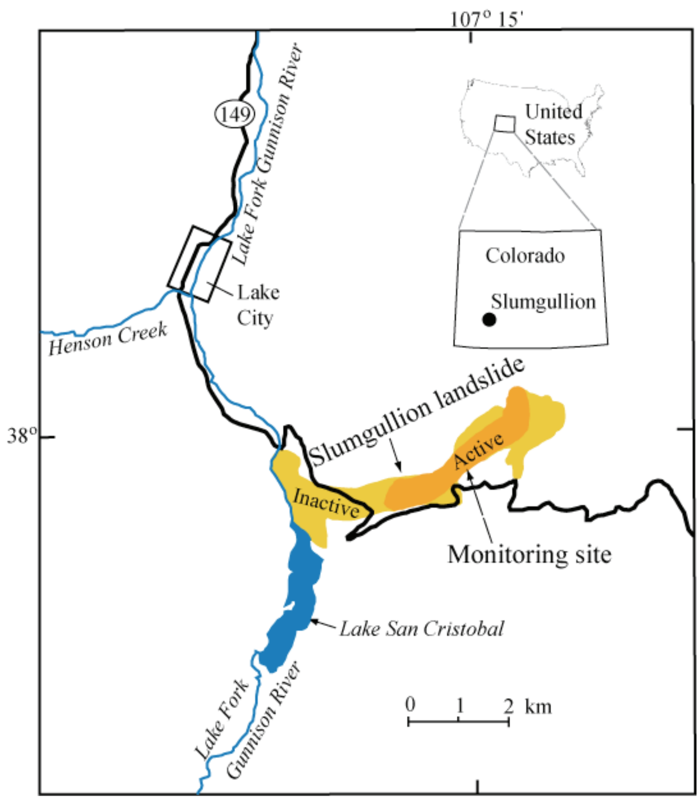

Figure 1. Map showing the location of the Slumgullion landslide (from Schulz and others, 2007).

The Slumgullion landslide (Figure 2) is a translational debris slide (Cruden and Varnes, 1996) and has been described by numerous investigators (for example, Endlich, 1876; Howe, 1909; Atwood and Mather, 1932; Burbank, 1947; Crandell and Varnes, 1960, 1961; Savage and Fleming, 1996; Fleming and others, 1999; Coe and others, 2003; Schulz and others, 2007). The landslide occurs in Tertiary volcanic rocks and consists of a younger, active, upper part that moves on and over an older, larger, inactive part. The entire landslide is 6.8 km long, averages about 400 m wide, has an estimated depth of up to 120 m, and has an estimated volume of 170×10^6 m^3 (Williams and Pratt, 1996). The active landslide (Figures 1 and 2) is about 3.9 km long, averages about 300 m wide, has an estimated average depth of about 14 m, and has an estimated volume of 20×10^6 m^3 (Parise and Guzzi, 1992). Radiocarbon dating suggests that the older, inactive landslide dammed the Lake Fork of the Gunnison River and created Lake San Cristobal about 700 years ago (Crandell and Varnes, 1960, 1961).

Figure 2. View of the Slumgullion landslide. Photograph by J.A. Coe, U.S. Geological Survey.

Summary of Research Studies of the Active Part of the Slumgullion Landslide

In general, the active upper part of the Slumgullion landslide extends, the lower part compresses, and the middle part moves as a plug and has the greatest velocity. This style of movement produces normal faults and tension cracks in the upper part of the landslide (Figure 3) and imbricate thrust faults (Figure 4) and lateral spreading in the lower part of the landslide. The landslide is laterally bounded by strike-slip faults and prominent flank ridges (Figure 5). Low-permeability clay striated by landslide movement is exposed at many locations along these faults. This clay and the continuous movement of the landslide suggest that the landslide may be hydrologically isolated from adjacent areas (Baum and Reid, 2000). Pull-apart basins are common on both sides of the landslide where it widens (Fleming and others, 1996, 1999). At several locations on the lower part of the active landslide, pond sediments are carried downslope while the associated ponds remain stationary. This and other observations (Fleming and others, 1996, 1999) suggest that sub-basal topography strongly controls deformation in the Slumgullion landslide.

Figure 3. Downhill-facing normal fault scarps in the upper part of the Slumgullion landslide. Photograph by J.A. Coe, U.S. Geological Survey.

Figure 4. Imbricate thrust faults in the lower part of the Slumgullion landslide. Photograph by W.Z. Savage, U.S. Geological Survey.

Figure 5. Flank ridges along the southern margin of the Slumgullion landslide (landslide is left of the ridges). Photograph by Giulia Biavati, Università di Bologna, Italy.

The first detailed measurements of landslide movement were begun in 1958 by D.R. Crandell and D.J. Varnes (Crandell and Varnes, 1960, 1961), who established lines of survey markers in the middle part of the active landslide. They found that during the period 1958-1968 movement of up to 6 m/yr occurred in the narrow part of the landslide and that the active toe advanced at about 1 m/yr. From a mapping effort carried out in the early 1990s, Fleming and others (1999) concluded that annual displacement of the active landslide had been about constant during the previous one-hundred years and found that the active landslide consists of several independent kinematic units that can have differing velocities. Coe and others (2003) established a global positioning survey network across the landslide and observed a range of displacement rates of about 6 m/yr among these kinematic units.

Fleming and others (1999) inferred that velocity varies seasonally, presumably due to changes in pore-water pressures, and Savage and Fleming (1996), Coe and others (2003), and Schulz and others (2007) documented seasonally varying velocity through continuous displacement monitoring. Coe and others (2003) established two instrumentation stations to study relationships between landslide displacement, air and soil temperature, snow depth, rainfall, soil water content, and perched ground-water pressure and identified generally direct, positive correlation between ground-water pressure measured at a depth of 2.2 m and landslide velocity. Schulz and others (2007) installed ground-water pressure monitoring devices at depths up to 9.1 m. They found that at these greater depths there was no direct correlation between surface infiltration events and measured ground-water pressures, or between ground-water pressure and landslide velocity. However, they did observe that changes in ground-water pressure inversely correlated with landslide acceleration, suggesting dilatant behavior of shearing landslide debris. They also observed cycles of acceleration, ground-water pressure decrease, and deceleration, suggesting dilatant strengthening and pore-pressure feedback during shear.

Table 1. Field Trip Stops and Topics

Location	Topic	Presenter
Lake San Cristobal Overlook (Stop 1, day 1)	Landslide overview; Lake San Cristobal; geologic setting	Bill Schulz
Slumgullion Landslide Overlook (Stop 2, day 1)	Active landslide characteristics	Bill Schulz
Lower Landslide Walk - Monitoring station to active landslide toe (Stop 3, day 2)	Landslide monitoring; active landslide characteristics	Bill Schulz, Bill Ellis

TRIP ROUTE DESCRIPTION AND MAPS

Our field trip begins and ends in Vail, Colorado, while the focus of the trip is located outside Lake City, Colorado (Tables 1 and 2, Figure 6). Drive time from Vail to the Slumgullion landslide is about 4.5-5 hrs so we will make only 2 stops during the drive, one for a mid-morning break and the other for lunch. Our drive takes us through several geologic provinces, spectacular scenery, and historic towns. We will try to provide some interesting background about these places during the drive. A brief overview of the geologic, historic, and scenic features is given below. Upon our arrival in Lake City, we will stop at our hotel to check in and unload luggage. Then we will drive to the landslide and make 2 stops that provide overviews of the landslide and its geologic setting (Tables 3 and 4). We should return to Lake City about 6 pm. This should allow adequate time for independent exploration of the quaint, historic mining town and dinner. Although limited in number, there are several restaurant choices in town.

To allow ample time to explore the landslide, we will leave the hotel early on Sunday and have a group breakfast. We will be dropped off near the middle of the landslide (Table 5) and will hike down beyond the landslide toe where we will meet the bus. Afterward, we will return to Lake City for a late lunch and then return to Vail. We expect to arrive in Vail between 6 pm and 7 pm.

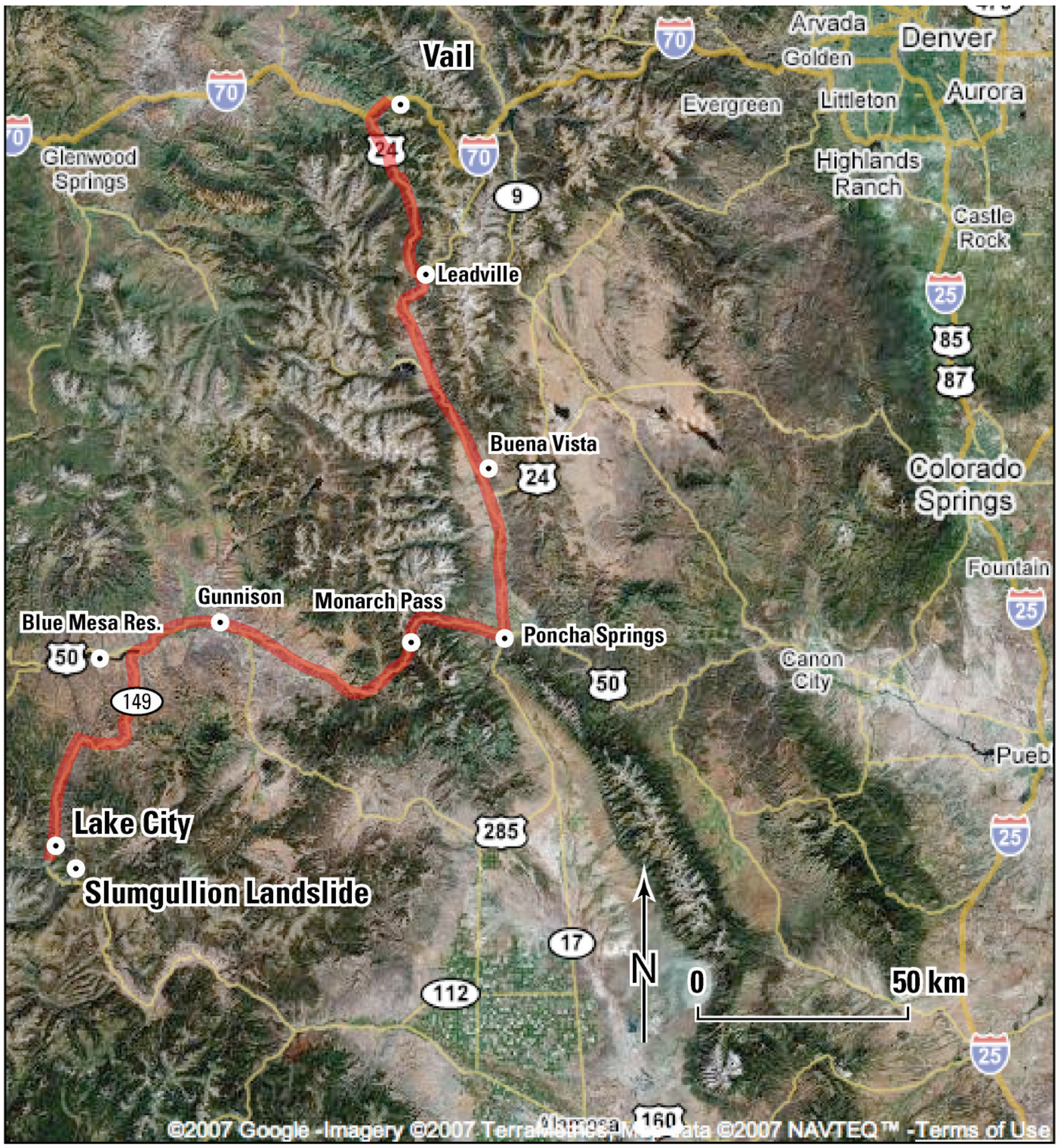

Figure 6. Satellite image and road map showing field trip route from Vail to Lake City, Colorado (image from Google Maps).

Table 2. Mileage from Start of Field Trip at Vail Marriott Mountain Resort to Lake City.

Mileage	Description
5.8	Leave Vail Marriot Resort heading north on West Lionshead Circle and follow signs to I-70 west. Take I-70 west to exit 171 onto US-24 east.
72.8	Follow US-285 south (continue heading straight) when US-24 splits off to east.
93.8	Turn right onto US-50.
162.6	Turn left onto CO-149.
208.1	Arrive in downtown Lake City at intersection of CO-149 (Gunnison Ave.) and 2nd St.

VAIL TO LAKE CITY HIGHLIGHTS

Our field trip begins the morning of June 8 with a short jaunt west from Vail on Interstate 70 west (Table 2). We then head south on U.S. Highway 24 east (we really do go south, though) toward the town of Minturn. Minturn predates Vail by almost a century and was originally a homestead in the 1800's. In 1887, the Denver & Rio Grande Western Railroad arrived in Minturn, which was named for Robert B. Minturn, a shipping millionaire responsible for raising the money to bring the rails west. We continue south on U.S. 24 through the town of Gilman, perched high on the side of the canyon, and then through the town of Redcliff. Both towns figure prominently in Colorado mining history. We then pass Camp Hale, the WW II training area for the famous 10th Mountain Division of the U.S. Army. Concrete pads for the buildings and barracks are all that remains of this military facility. We then proceed over Tennessee Pass (elevation 10,424 ft) and the continental divide. Leadville is the next large town we pass through. The Leadville Mining District is home to the famous Matchless Mine of "Unsinkable Molly Brown", and also hosts the National Mining Museum. Colorado's highest peak, Mount Elbert (elevation 14,433 ft), is clearly visible just to the southwest of town.

South of Leadville, U.S. 24 follows the northern end of the Rio Grande Rift. The rift formed during the mid-Tertiary uplift of the mountains on either side of the rift. The Arkansas River now flows through this part of the rift. The valley bottom is underlain mostly by glacial outwash deposits, and the upper part of the valley is underlain by moraines and till deposited by glaciers that flowed down from the western peaks. The Collegiate Peaks (Mounts Oxford, Harvard, Columbia, Yale, and Princeton) are west of the Rio Grande Rift and the Mosquito Range is on the east. U-shaped glacial valleys and moraines can be observed along most of the Collegiate Peaks. The northern parts of both ranges are comprised of Precambrian gneiss and schist, and the southern parts are mostly granite.

U.S. 24 passes through the small town of Granite (where granite is exposed along the Arkansas River) and the next large town of Buena Vista, a gateway to Colorado's varied and exciting outdoor recreational activities—mountain climbing, skiing, river rafting and kayaking, mountain biking, hiking, fishing, hunting, fossil and gem collecting, camping and snowmobiling are all easily accessible from this area. If time permits, we are planning a short stop in Buena Vista. With its mild winters, the upper Arkansas River valley is amenable for grazing and hay farming, and cattle and sheep ranching are still actively pursued in this area.

At Poncha Springs we leave the main valley and turn west on U.S. Highway 50, heading upwards to the summit of Monarch Pass (11,312 ft). Monarch Pass Ski Area is located just before the summit of the pass. Originally named Monarch Mountain, the ski area was built in 1939 by Works Project Administration workers. Upon completion of the project, the ski area was given to the city of Salida, which is about 5 miles east of Poncha Springs. Our climb up Monarch Pass follows a formerly glaciated valley upon a Tertiary granite batholith intruded into sedimentary rocks (mostly limestone). We'll pass a large inactive limestone quarry (on the left) and a lead, zinc, and silver mine located above the quarry.

At the summit of Monarch Pass we again cross the continental divide. The valley we follow down from the pass was not glaciated. At the base of the mountain, however, is the terminal moraine of a glacier that flowed down from the north along the Tomichi Creek drainage. We will follow Tomichi Creek from this point to the town of Gunnison. Tomichi Creek and roadcuts along U.S. 50 generally reveal Precambrian igneous and metamorphic rocks, but also some Paleozoic sedimentary rocks. Tertiary volcanic rocks (mostly tuffs) are also common and become more common as we head west.

The next large town we come to is Gunnison, which is a welcome place to stop for a lunch break. The city was named after John W. Gunnison, a United States Army officer who surveyed for the transcontinental railroad in 1853. It is home to Western State College. One of Gunnison's claims to fame is that it is one of the coldest places in the United States during the winter. This is due to its geographical location; it sits at the confluence of two low river valleys between several high mountain ranges from which the cold air descends into town.

On the final leg of our drive we travel a short distance west of Gunnison and then turn south and travel along Colorado State Highway 149. The upper reaches of the Blue Mesa Reservoir can be seen for a short distance along Highway 149. From Blue Mesa to Lake City we enter the San Juan Mountains, which are primarily comprised of Tertiary volcanic rocks. This becomes readily apparent when we drop into the canyon of the Lake Fork of the Gunnison River about 30 miles after leaving Blue Mesa Reservoir. The canyon walls are mostly welded tuffs dissected by vertical columnar joints. The river has eroded through the rim of the Lake City caldera, and a few miles after we leave the canyon we'll reach Lake City and the interior of the caldera. When we drive into Lake City you might notice the valley that we've driven down forks to the right (west) and left (southeast). These forks skirt the edge of the resurgent dome that grew within the caldera; the dome is straight ahead.

As we approach Lake City, the flat-topped mountain to the left (east) is named Cannibal Plateau, which is a bit misleading since Alferd Packer had his meals at the confluence of Deadman Gulch (named after Alferd's former companions) and the Lake Fork, less than a thousand feet from the inactive toe of the Slumgullion landslide. Alferd Packer was one of only two (thankfully – or maybe they never caught the others!) Americans imprisoned for cannibalism. Actually, he claimed he was imprisoned for cannibalism, but he was really imprisoned for murder. During the winter of 1873-1874, Packer was part of a poorly planned expedition through the San Juan Mountains destined for Gunnison. After becoming snowbound, Packer apparently became hungry enough to kill and eat his five comrades. He claimed that one of the men killed the other four while Packer was away searching for food then tried to kill Packer when he returned. Packer claimed to have killed the man in self-defense and had to resort to cannibalism to survive the winter. Packer was convicted of murder in the Hinsdale County Courthouse in Lake City (the big white building that still serves as the courthouse and which is located left of CO 149 at 3rd St.). There has been debate amongst historians regarding the guilt of

Packer, and a mock trial organized by several historians recently found that he was innocent of murder. We'll drive by the site of the massacre on our way to the landslide. The site is on the left just before we cross the Lake Fork (Table 3).

Table 3. Mileage from Lake City to Lake San Cristobal Overlook (Stop 1, day 1).

Mileage	Description
2.5	Leave Lake City (intersection of CO-149 (Gunnison Ave.) and 2nd St.) on CO-149 south. Cross Lake Fork of the Gunnison River. Yellow deposits to right comprise the downstream limit of Slumgullion landslide deposits.
4.1	Drive onto inactive Slumgullion landslide deposits.
4.5	Leave inactive Slumgullion landslide deposits.
5.0	Lake San Cristobal Overlook (Stop 1) is the parking area on the right.

STOP 1. LAKE SAN CRISTOBAL OVERLOOK

This stop provides a view of some of the active part of the landslide (Figure 7), some of the toe of the inactive part of the landslide, and Lake San Cristobal (Figure 8). Also visible from this stop is the general setting of the Slumgullion landslide. Directions to the stop are given in Table 3.

The Slumgullion landslide is located along a flank of the collapsed Lake City caldera. The mountains visible to the west from the overlook were mostly formed during post-collapse resurgent dome building. The landslide occurs within Tertiary volcanic rocks including basalt, rhyolite, and andesite, much of which has been highly altered by hydrothermal activity (Lipman 1976; Diehl and Schuster 1996). The 230-m-high headscarp of the landslide is visible from this stop and exposes faulted, generally flat-lying, interbedded basalt and ash-flow tuff that overlie highly altered andesite and rhyolite (Diehl and Schuster, 1996).

The toe of the active part of the Slumgullion landslide is marked by the light-colored soil, disturbed trees, and an abrupt hill upslope from CO-149. The inactive landslide extends downslope to the valley bottom. The toe of the inactive part of the landslide impounds Lake San Cristobal, which is the second largest natural lake in Colorado. The channel of the Lake Fork of the Gunnison River was completely blocked by the landslide and was subsequently re-established where the toe abuts the opposite valley slope. At the toe, landslide deposits extend about 0.5 km upstream and 0.9 km downstream from the projected landslide margins. Failure of the landslide dam is not expected (Schuster, 1996).

Lake San Cristobal was originally about 4.3 km long but shrunk to 3.3 km long as sediment filled the lake beyond the mouth of the Lake Fork of the Gunnison River. A much smaller sediment fan occurs at the mouth of Slumgullion Creek, which runs along the south flank of the landslide. We crossed Slumgullion Creek just downslope from this stop; the creek flows through a culvert beneath CO-149. The maximum depth of Lake San Cristobal is 27 m and it has a volume of 14 x 10^6 m^3 (Schuster, 1996).

Figure 7. View of the Slumgullion Landslide from Stop 1. Photograph by W.Z. Savage, U.S. Geological Survey.

Figure 8. View of Lake San Cristobal from Stop 1. Photograph by Giulia Biavati, Università di Bologna, Italy.

Table 4. Mileage from Lake San Cristobal Overlook (Stop 1, day 1) to Slumgullion Landslide Overlook (Stop 2, day 1).

Mileage	Description
1.0	Return to southbound CO-149 (heading the same direction as the drive to stop 1). Slumgullion Landslide Overlook (Stop 2) is the large parking area on the left.

<u>STOP 2.</u> SLUMGULLION LANDSLIDE OVERLOOK

This stop (Table 4) provides a closer view of some of the active part of the Slumgullion landslide than did Stop 1. The active nature of the landslide is readily apparent from this location and is indicated by disturbed soil, hummocky topography, freshly exposed rock and soil, and jumbled orientation of trees on the landslide (Figure 9). Also apparent from this location is a series of flank ridges located along the near margin of the landslide. These ridges are also located along the margins of most of the active landslide. A monitoring station where nearly continuous displacement, groundwater pressure, soil temperature, soil moisture, and climatic conditions have been recorded is visible (but barely discernible) to the northeast and an additional monitoring station is similarly visible to the west. The flatter area located to the west may mark the location where the active part of the landslide emerged from the subsurface and began overriding the ground surface located downslope.

Figure 9. View of part of the Slumgullion landslide from the Slumgullion Landslide Overlook. Photograph by J.A. Coe, U.S. Geological Survey.

Table 5. Mileage from Lake City to Lower Landslide Walk (Stop 3, day 2).

Mileage	Description
6.8	Leave Lake City (intersection of CO-149 (Gunnison Ave.) and 2nd St.) on CO-149 southbound. Parking area for the Lower Landslide Walk (Stop 3) is the wide shoulder of northbound CO-149 (on left while southbound) at the sharp right turn.

<u>STOP 3.</u> LOWER LANDSLIDE WALK

Stop 3 (Table 5 provides directions to the starting point) will involve a several-hour walk down the lower half of the active part of the Slumgullion landslide (Figures 10 and 11). We will cover about 2.5 km on the landslide, gain about 40 m in elevation, and drop about 200 m in elevation. Only our initial ascent (about 40 m elevation over 200 m) and final descent (about 35 m elevation over 300 m) will be off of the active landslide.

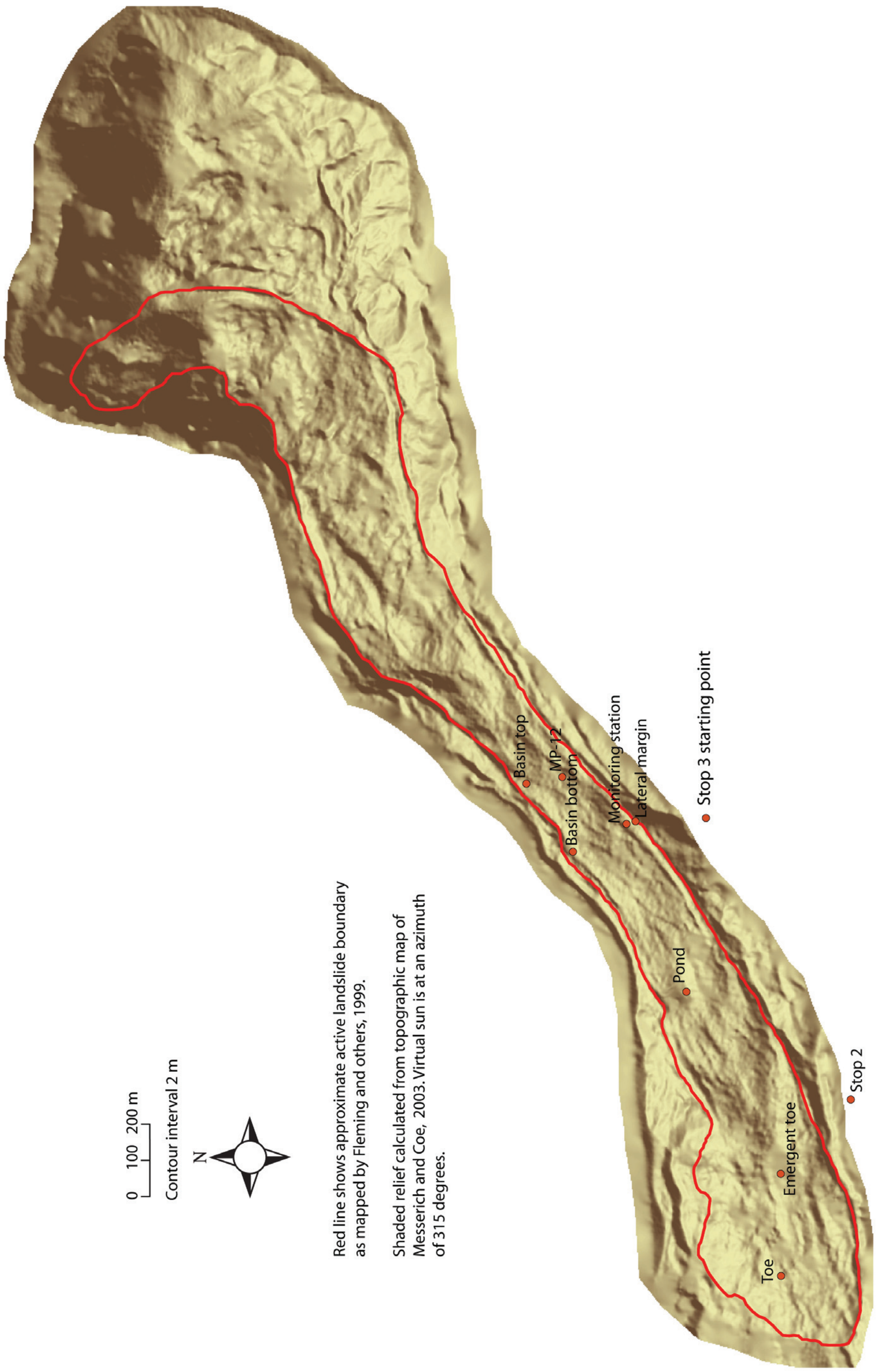

Figure 10. Shaded relief map of the active part of the Slumgullion landslide (outlined in red) showing locations of features that may be evaluated during the field trip. "Stop 3" marks the location of the Stop 3 starting point.

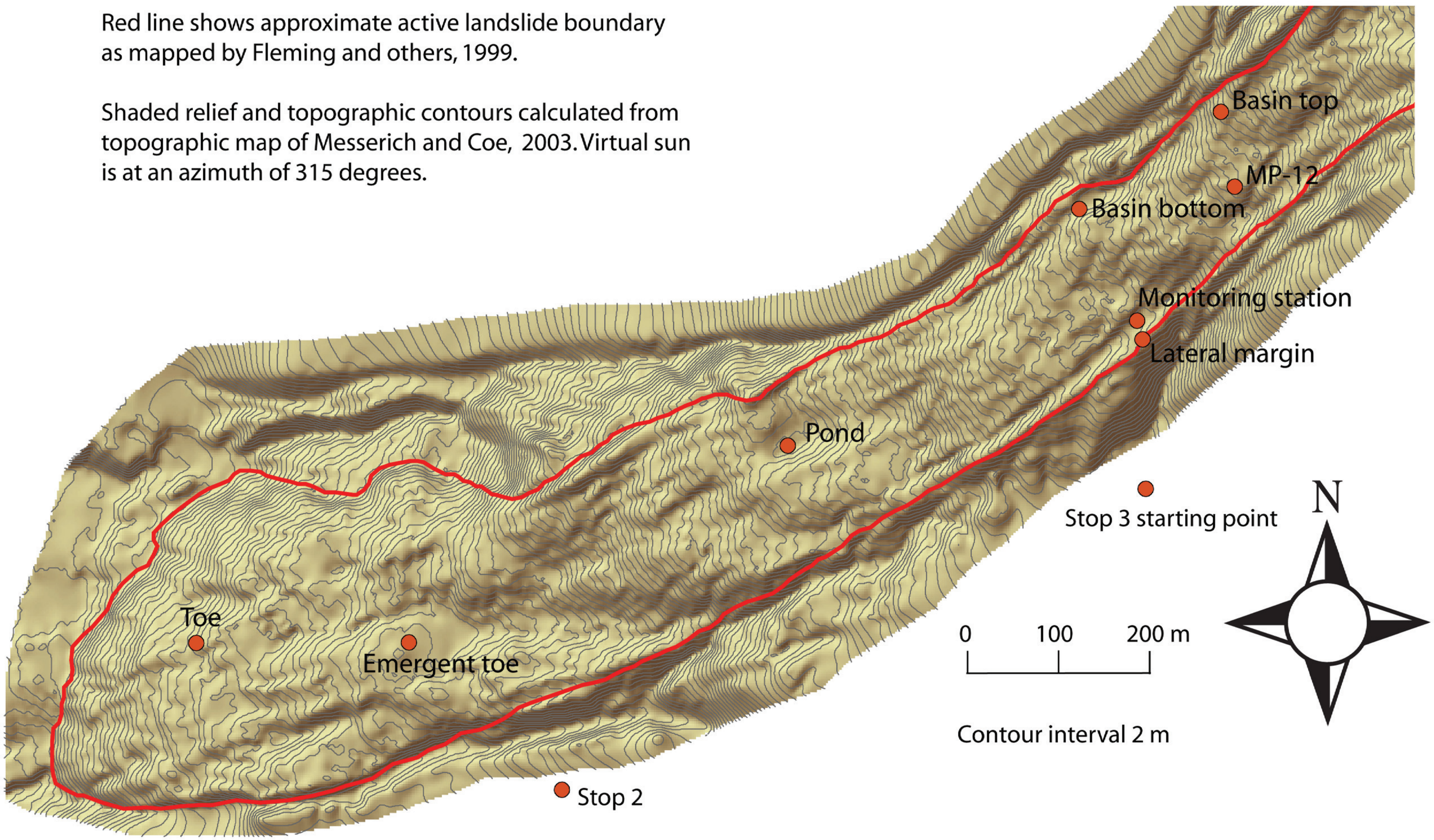

Figure 11. Map of the lower part of the active Slumgullion landslide (outlined in red) showing locations of features that may be evaluated during the field trip.

Landslide Margin and Monitoring Station

We will cross a few flank ridges as we come onto the landslide (Figures 5 and 12). This is one of the few locations where the boundaries of the active and inactive parts of the Slumgullion landslide are nearly coincident. We should be able to locate an active, discrete strike-slip fault or zone of en echelon fractures marking the active landslide margin (Figure 12). Both forms of ground rupture have been observed at this location and along different parts of these flank ridges. Fleming and Johnson (1989) provide an excellent evaluation of flank ridges formed along landslide margins. Mechanisms proposed to explain the development of flank ridges include helical flow of moving landslide debris, dilation within a shear zone, buckle folds, landslide debris spilling over the landslide margin, and upward intrusion of clay within a shear zone. The series of flank ridges here suggests changing conditions during landslide movement, such as narrowing of landslide debris or changing stress conditions.

This is the location of much of the monitoring performed by the U.S. Geological Survey (Figure 13). Various pieces and types of equipment have been located here periodically for the past several decades. Currently, we measure landslide displacement, positive and negative ground-water pressures, soil and air temperature, rainfall, soil water content, and snow depth (Coe and others, 2003; Schulz and others, 2007). Measurements are made hourly and results are stored on a datalogger. Previous studies in this area included measurements of hydrogeologic properties of landslide debris (Schulz and others, 2007) and of slidequakes associated with landslide movement (Gomberg and others, 1996). Earlier, nearly continuous monitoring of landslide movement was also performed near here using modified tide gauges (Savage and Fleming, 1996) and episodic monitoring using an automatic camera.

Figure 12. View to northeast of southern lateral margin. Photograph by J.A. Coe, U.S. Geological Survey.

Figure 13. Equipment at the monitoring station. Photograph by Giulia Biavati, Università di Bologna, Italy.

Pull-Apart Basin

Pull-apart basins occur in a few places along the flanks of the Slumgullion landslide and are both structural and topographic basins that form to accommodate downhill widening of the landslide (Fleming and others, 1996, 1999). These basins reflect controls on landslide kinematics exerted by lateral boundary conditions. The location of this stop marks probably the most well-developed basin on the landslide (Figures 14-16). It appears that abrupt widening of the landslide here is accommodated by thinning of landslide debris and resultant secondary sliding of adjacent landslide debris that has been oversteepened by the thinning (Fleming and others, 1996, 1999). This conclusion is suggested by the series of crescent-shaped tension cracks and normal faults above the south part of the basin and thrust faults and soft-sediment folding at the bottom of the basin, all of which are subparallel to the overall landslide margin. A pond is generally present at the bottom of the basin and its sediments extend downslope beyond the basin, while basin structural features do not. These features are destroyed at and just beyond the downslope end of the basin during landslide movement. Detailed mapping of this area performed recently and about ten years ago shows that structural features have changed very little in character and location, although the landslide has moved about 40 m through here in the intervening years.

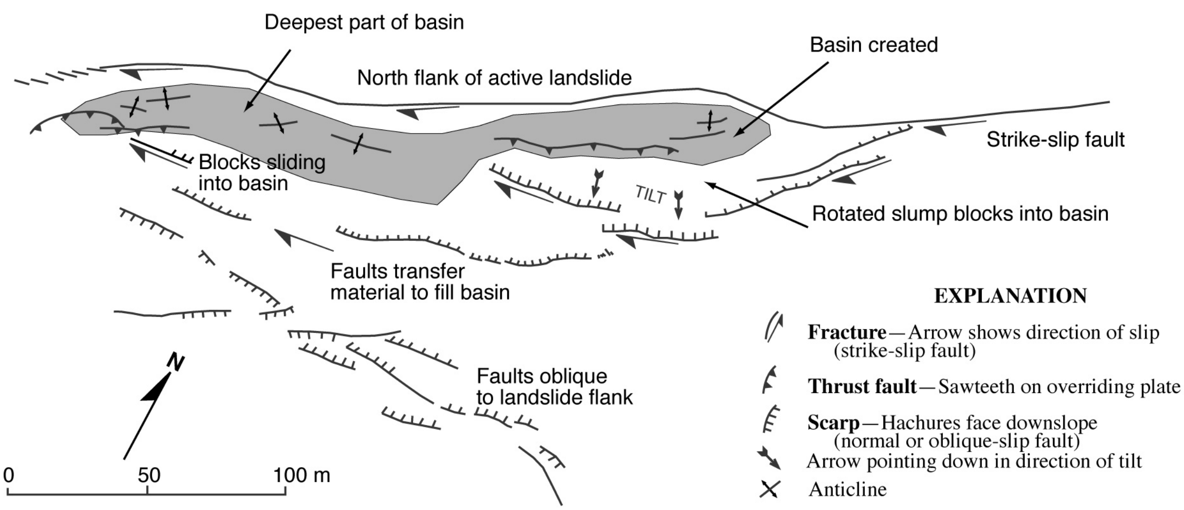

Figure 14. Idealized map of pull-apart basin. From Fleming and others, 1999.

Figure 15. View to southwest of pull-apart basin from its upper end. Photo by J.A. Coe, U.S. Geological Survey.

Figure 16. View to northeast of pull-apart basin from its lower end. Photo by J.A. Coe, U.S. Geological Survey.

Upper Pond

We saw at the basin how lateral boundary conditions appear to affect landslide structural and geomorphic characteristics. At this location we can see how basal boundary conditions apparently also affect landslide characteristics. Observations of this pond (Figure 17) indicate that it has remained generally the same and at the same location for at least the last few decades. During this time, the landslide has moved about 150 m here, or several times farther than the length of the pond. In addition, thrust faults have been observed just upslope from the pond for many years, as have been normal faults at the slope break located just downslope from the pond. We are near the inferred location of the former surface-water divide between Slumgullion Creek and the unnamed creek just to the north (Fleming and others, 1999). Perhaps the landslide overrides this divide and creates the features we see here.

Figure 17. View to the southwest of a pond located on the active Slumgullion landslide. Photograph by J.A. Coe, U.S. Geological Survey.

Emergent Toe

Based on detailed mapping, Fleming and others (1999) concluded that a large area of the landslide headscarp collapsed and resulted in mobilization of the reactivated part of the Slumgullion landslide. This reactivation does not involve the entire length or width of the original landslide, as we have seen, nor does it appear to involve the entire depth. Our stop at the upper pond provided evidence for basal boundary conditions controlling kinematics of the active landslide, and similar conditions appear to occur here. However, rather than overriding a bump in original topography below the landslide, it has been proposed that features here are due to the toe of the reactivated part of the landslide rupturing through the ground surface near here a few hundred years ago. As we'll see when we descend the active toe of the landslide, the landslide is clearly moving along the ground surface at its downslope end. It has been proposed (Parise and Guzzi, 1992) that the location where the landslide originally moved out of the subsurface and onto the ground surface occurred in this area (Figure 18). This change of displacement style is associated with significant changes in the geometry of the base of the landslide. This changing geometry results in the features seen here. Thrust faults occur upslope of the large back-tilted area on which a small pond occurs. Pond sediments extend for at least 250 m downslope from the pond due to displacement of the landslide mass past this location (Fleming and others, 1999). These sediments are well exposed in a gully eroded just downslope (Figure 19). Based on the current rate of landslide movement here, this pond must have persisted for at least the last hundred years (Fleming and others, 1999).

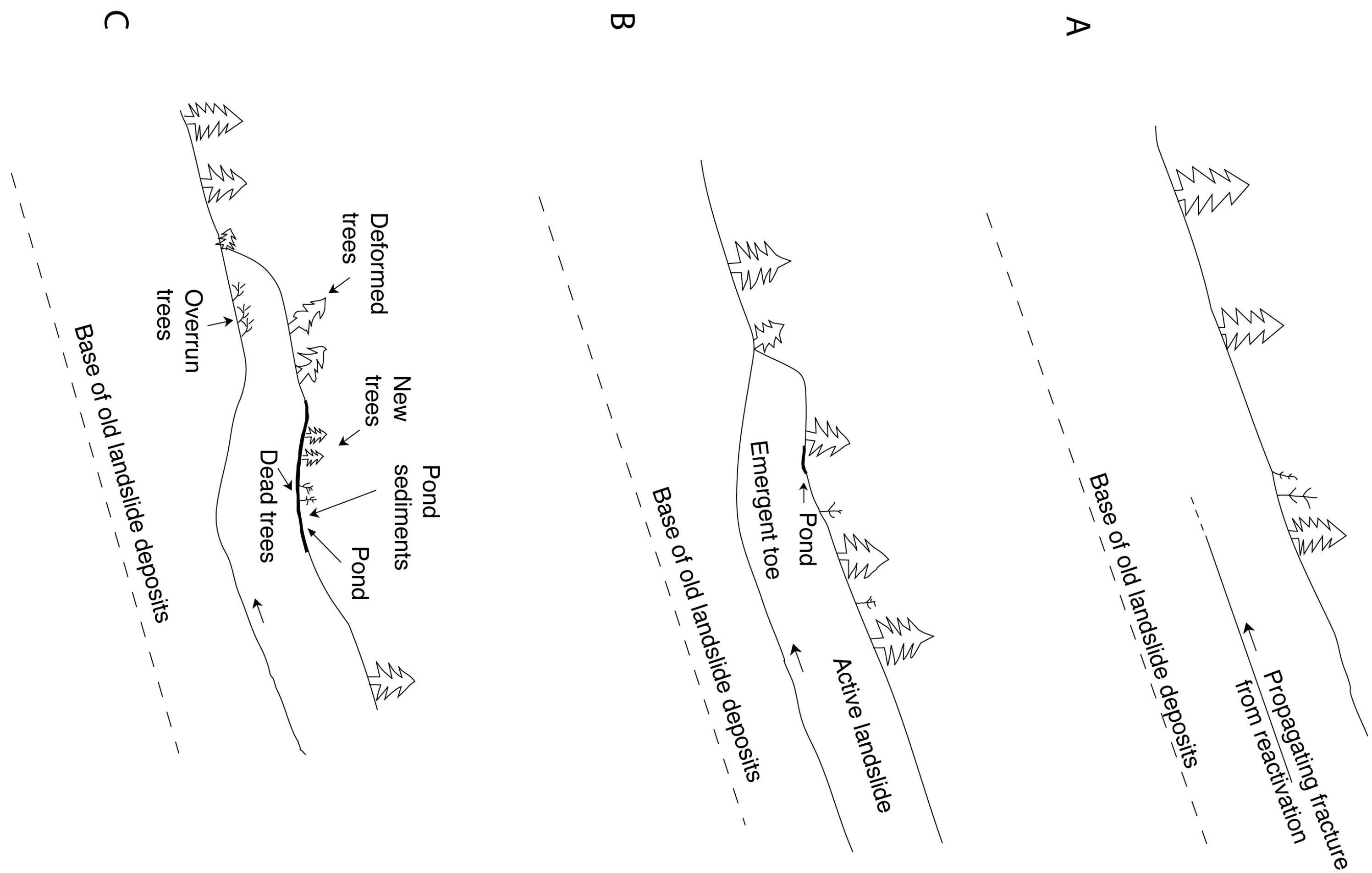

Figure 18. Idealized cross-section showing conceptual sequence of reactivation of the Slumgullion landslide at the location of the emergent toe. From Fleming and others, 1999.

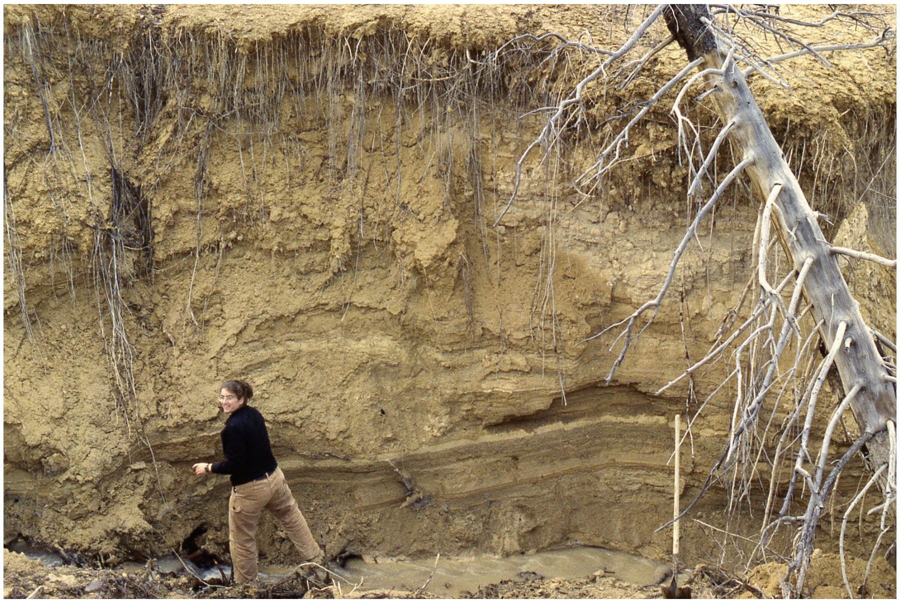

Figure 19. Exposure of pond sediments in the emergent toe area of the active Slumgullion landslide. Photograph by J.A. Coe, U.S. Geological Survey.

Active Toe

The active toe of the landslide is a zone of both transverse spreading and longitudinal shortening (Fleming and others, 1996, 1999). A major strike-slip fault zone extends from the north flank of the landslide through the toe and generally marks the boundary between spreading to the north and downslope sliding to the south (Figure 20). Spreading of the toe north of the boundary even causes trees to split upward from their bases and the separate parts to move away from one another. Surveying of the active toe found that, rather than moving slope parallel as might be expected, points on the ground surface are moving horizontally, indicating that the toe is thickening as it moves (Fleming and others, 1996, 1999). Continuing downslope, the top of the toe becomes nearly flat due to this thickening until a region is encountered where superficial sliding occurs nearly everywhere along the distal end of the toe. This superficial sliding obscures some of the features of the overall landslide as it plows over trees and the old ground surface, but many areas can be found where this overriding is clear.

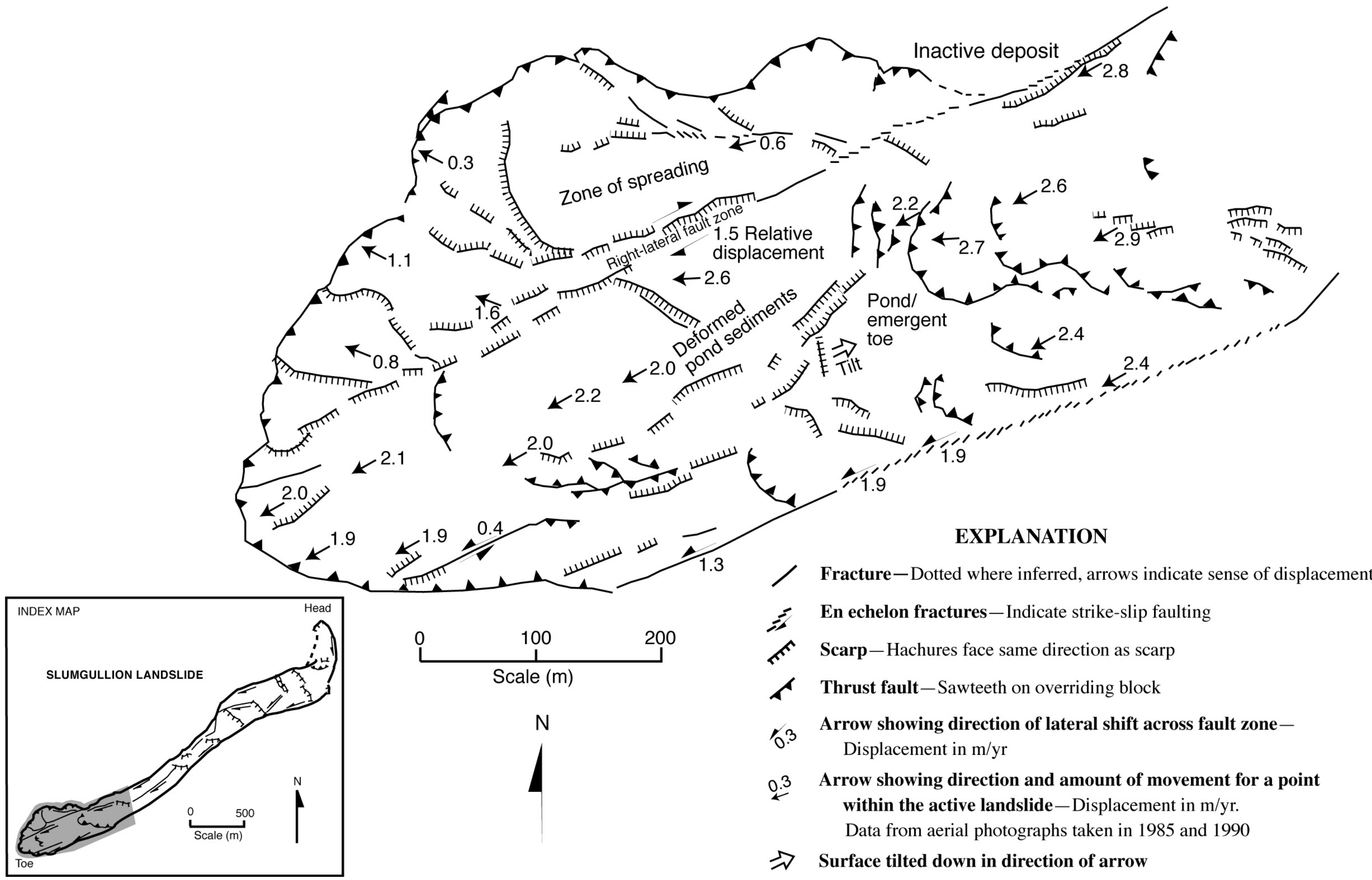

Figure 20. Idealized map of the lower part of the active Slumgullion landslide. From Fleming and others, 1999.

REFERENCES

Atwood, W.W., and Mather, K.F., 1932, Physiography and Quaternary geology of the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 166, 176 p.

Baum, R.L., and Reid, M.E., 2000, Ground water isolation by low-permeability clays in landslide shear zones, *in* Bromhead, E.N., Dixon, N. and Ibsen, M-L., eds., Landslides in research, theory and practice: London, Thomas Telford, p. 139-144.

Burbank, W.S., 1947, Lake City area, Hindsdale County, *in* Mineral Resources of Colorado: Colorado Mineral Resources Board, p. 439-443.

Coe, J.A., Ellis, W.L., Godt, J.W., Savage, W.Z., Savage, J.E., Michael, J.A., Kibler, J.D., Powers, P.S., Lidke, D.J., and Debray, S., 2003, Seasonal movement of the Slumgullion landslide determined from Global Positioning System surveys and field instrumentation, July 1998-March 2002: Engineering Geology, v. 68, p. 67-101.

Crandell, D.R., and Varnes, D.J., 1960, Slumgullion earthflow and earthslide near Lake City, Colorado: Geological Society of America Bulletin, v. 71, no. 12, p. 1846.

Crandell, D.R., and Varnes, D.J., 1961, Movement of the Slumgullion earthflow near Lake City, Colorado, *in* Short papers in the geologic and hydrologic sciences: U.S. Geological Survey Professional Paper 424-B, p. 136-139.

Cruden, D.M., and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A.K. and Schuster, R.L, eds., Landslides: Investigation and mitigation: Washington, D.C., Transportation Research Board National Research Council, p. 36-75.

Diehl, S.F., and Schuster, R.L., 1996, Preliminary geologic map and alteration mineralogy of the main scarp of the Slumgullion landslide, *in* Varnes, D.J. and Savage, W.Z., eds., The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130, p. 13-19.

Endlich, F.M., 1876, Report of F.M. Endlich, *in* U.S. Geological and Geographical Survey (Hayden) of the Territories, Annual Report 1874, p. 203.

Fleming, R.W., and Johnson, A.M., 1989, Structures associated with strike-slip faults that bound landslide elements: Engineering Geology, v. 27, p. 39-114.

Fleming, R.W., Baum, R.L., and Giardino, Marco, 1999, Map and description of the active part of the Slumgullion landslide, Hinsdale County, Colorado: U.S. Geological Survey Geologic Investigations Series Map I-2672, 34 p., scale 1:1,000.

Fleming, R.W., Baum, R.L., and Savage, W.Z., 1996, The Slumgullion landslide, Hinsdale County, Colorado: Colorado Geological Survey Open-File Report 96-4, no. 11, unpaginated.

Gomberg, J.S., Bodin, P.W., Savage, W.Z., and Jackson, M.E., 1996, Slidequakes and fault creep at the Slumgullion landslide: An analog to crustal tectonics, *in* Varnes, D.J., and Savage, W.Z., eds., The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130, p.85-92.

Howe, Ernest, 1909, Landslides in the San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 67, 45 p.

Lipman, P.W., 1976, Geologic map of the Lake City caldera area, Western San Juan Mountains, Southwestern Colorado: U.S. Geological Survey Miscellaneous Investigation Series Map I-962, scale 1:48,000.

Messerich, J.A., and Coe, J.A., 2003, Topographic map of the active part of the Slumgullion landslide on July 31, 2000, Hinsdale County, Colorado: U.S. Geological Survey Open-File Report 03-144, scale 1:1,000.

Parise, Marco, and Guzzi, Rafaella, 1992, Volume and shape of the active and inactive parts of the Slumgullion landslide, Hinsdale County, Colorado: U.S. Geological Survey Open-File Report 92-216, 29 p.

Savage, W.Z., and Fleming, R.W., 1996, Slumgullion landslide fault creep studies, *in* Varnes, D.J., and Savage, W.Z., eds., The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130, p. 73-76.

Schulz, W.H., McKenna, J.P., Biavati, G., and Kibler, J.D., 2007, Characteristics of Slumgullion Landslide inferred from subsurface exploration, in-situ and laboratory testing, and monitoring, *in* Proceedings of the First North American Landslide Conference, Landslides and Society: Integrated Science, Engineering, Management, and Mitigation, Vail, Colo., June, 2007, American Society of Civil Engineers.

Schuster, R.L., 1996, Slumgullion landslide dam and its effects on the Lake Fork, *in* Varnes, D.J., and Savage, W.Z., eds., The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130, p. 35-42.

Varnes, D.J., and Savage, W.Z., eds., 1996, The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130.

Williams, R.A., and Pratt, T.L., 1996, Detection of the base of Slumgullion landslide, Colorado, by seismic reflection and refraction methods, *in* Varnes, D.J., and Savage, W.Z., eds., The Slumgullion earth flow: A large-scale natural laboratory: U.S. Geological Survey Bulletin 2130, p.77-84.