Debris Flows along the Interstate 70 Corridor, Floyd Hill to the Arapahoe Basin Ski Area, Central Colorado – A Field Trip Guidebook

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Open-File Report 02-398

October 2002

U.S. Department of the Interior
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Cover: Debris-flow deposit on Interstate 70 about 2.1 miles west of the Bakerville exit (exit #221). Debris flow was triggered by an afternoon thunderstorm on July 28, 1999. The Interstate was closed about 25 hours while debris was cleared from the highway surface. See vehicles for scale. Photograph by Ed Harp on July 29, 1999.

[1] USGS, Denver, Colorado
[2] Arapahoe Basin Ski Area

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INTRODUCTION

As the title indicates, this field trip guide will focus on debris flows in the Interstate 70 (I-70) corridor between Floyd Hill and the Arapahoe Basin ski area in the Front Range of Colorado (fig. 1). We prepared this guide to accompany a Geological Society of America field trip during the October 2002 annual meeting in Denver, Colorado. Most of the field trip stops will be at fans adjacent to I-70 where we will examine Holocene, historic, and recent debris-flow deposits. Two stops, Watrous Gulch (Stop 9, fig. 1) and the Arapahoe Basin ski area (Stop 10, fig. 1), will be made to examine debris flows triggered by a July 28, 1999 thunderstorm. This storm triggered about 480 debris flows in the field-trip area (Godt and Coe, in press) at elevations above 3,350 m (11,000 ft). Although the Arapahoe Basin ski area is not directly adjacent to I-70, we include it as a stop because it provides a rare and convenient opportunity to examine high altitude debris-flow processes and deposits.

In this guidebook, we first describe the setting of the field-trip area and then follow with a detailed road log including descriptions of each stop. Stop descriptions focus on the origins of deposits, radiocarbon dating and debris-flow recurrence intervals, debris-flow initiation processes, basin morphology, and debris-flow hazards.

SETTING

Physiographic

The field-trip area is located west of Denver along I-70, which is adjacent to Clear Creek, an east-flowing, formerly glaciated, stream drainage in the Front Range of Colorado (fig. 1). The upper part of the Clear Creek valley (elevations above about 2400 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). The maximum extent of Pleistocene glaciation is located near the center of the field-trip area (fig. 1, Madole and others, 1998). Above this boundary, the Clear Creek valley typically has steep walls and small and steep tributary-drainage basins. Most drainages contain glacial deposits, and talus deposits are common at the foot of steep bedrock hillslopes. The lower, non-glaciated part of the Clear Creek valley is generally characterized by moderately steep hillslopes and large and moderately steep tributary drainage basins. Below the glacial limit, Pleistocene gravels are common along the valley bottom and on hillslopes adjacent to Clear Creek. Hillslopes in both the glaciated and non-glaciated parts of the area are commonly mantled by matrix-supported colluvium. Fans are present at the mouths of tributary-drainage basins in both parts of the valley.

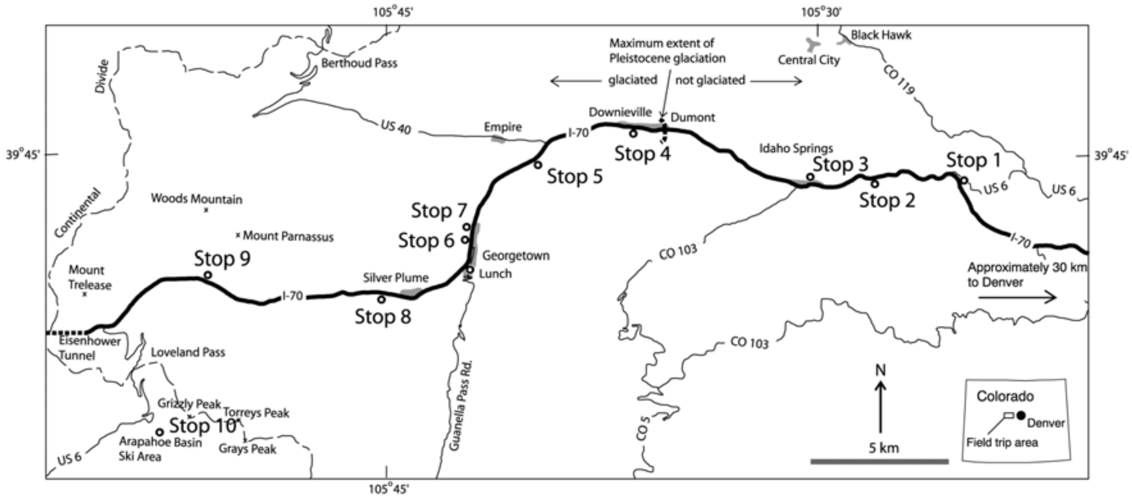


Figure 1. Map showing location of the field trip. Stops are labeled and shown as black dots with white centers. The area is within the north-south trending Front Range, the eastern-most mountain range in Colorado. Shaded areas are towns. Road and highway numbers are labeled.

The area is underlain predominantly by Precambrian biotitic gneiss and quartz monzonite with scattered Tertiary intrusions (Spurr and others, 1908; Lovering, 1935; Sims, 1964; Braddock, 1969; Sheridan and Marsh, 1976; Bryant and others, 1981; Widmann and others, 2000; Widmann and Miersemann, 2001) with associated hydrothermal alteration and silver and gold mineralization (Harrison and Wells, 1967; Sims and Gable, 1967). The zone of mineralization that encompasses the field-trip area extends from southwestern Colorado to the Front Range northwest of Denver, and is known as the Colorado Mineral Belt (Tweto and Sims, 1963). Mining activity was common in the area in the late 1800s and early 1900s and numerous abandoned mines and mine dumps are present on hillslopes in the area.

Elevations within the Clear Creek valley range from about 2,200 m (~7,220 ft) at Floyd Hill to about 3,350 m (10,990 ft) at the east entrance to the Eisenhower tunnel. Mountain peaks adjacent to the Clear Creek valley range up to about 4350 m (~14,270 ft) in elevation. Mean annual precipitation ranges from about 380 mm (15 in) in Idaho Springs (elevation 2,484 m, 8,150 ft) to about 840 mm (33 in) near Grizzly Peak (elevation 3,642 m, 11,949 ft) near the Arapahoe Basin ski area (Western Regional Climate Center, unpublished data).

Tree cover in the area ranges from a Ponderosa Pine, Juniper, Douglas Fir assemblage at lower elevations, to an Englemann Spruce, Limber Pine, Subalpine Fir assemblage at higher elevations. Tree line is at an elevation of about 3,500 m (~11,480 ft). Above tree line, hillslopes are bare or are covered by alpine tundra. In general, hillslopes on the south side of I-70 (north facing) have more vegetation than hillslopes on the north side (south facing) of I-70, presumably because the difference in solar exposure results in variable soil-moisture conditions (cooler and wetter on the south side, warmer and dryer on the north side).

Interstate 70

Interstate 70 (I-70) in Colorado 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 which are jointly referred to as the Eisenhower Tunnel). Assessments of geologic hazards provide critical baseline information that can be used to evaluate the proposed infrastructure modifications within the corridor (Andrew and Lovekin, 2002).

The presence of I-70 in the Clear Creek valley is both an advantage and disadvantage for debris-flow hazard assessments. It is an advantage because highway construction activities created cuts through many fans, either by direct excavation for installation of highway lanes, or by excavation of fan material for fill. These cuts provide subsurface exposures of fans that can be used to study debris-flow history. However, like many roads in Colorado, I-70 was aligned along the north side of the valley, presumably to take advantage of southerly exposure to quickly melt snow and ice on the highway surface. Thus, many of the fans along the north side have therefore been removed or are covered by highway fill, and information such as fan slope, area, and volume cannot be collected at these fans. However, morphometric parameters for drainage basins above these fans are easily determined from Digital Elevation Models (DEMs) and can be used to assess debris-flow potential (Coe and others, in press).

Previous work on debris flows along I-70

Recent and historic debris flows, as well as Holocene debris-flow deposits, show that the Front Range part of the I-70 corridor is susceptible to debris-flow hazards (Soule, 1975; Hecox, 1977; Pelizza, 1978; Coe and Godt, 1997a; Coe and others, 1998; Soule, 1999; Widmann and others, 2000; Henceroth, 2000; Godt and Coe, in press; Andrew and Lovekin, 2002). Debris flows between Floyd Hill and the Eisenhower Tunnel (fig. 1) initiate in tributary drainage basins of Clear Creek and form fans at the mouths of the basins along the north and south flanks of the Clear Creek valley.

All documented recent and historic debris flows that have occurred immediately adjacent to I-70 have initiated in tributary basins above the glacial limit on the north side of the highway (Godt and Coe, in press; Coe and others, in press). Most of these flows have been triggered by summer thunderstorms related to the flow of monsoon moisture (Adams and Comrie, 1997) from the south. The summer thunderstorm that triggered widespread, high-altitude debris flows in July 1999 dropped about 43 mm of rain in 4 hours, although most (35 mm) fell in two hours (Godt and Coe, in review).

An analysis of historic and stratigraphic records of debris-flow events at 19 fans in the corridor resulted in estimates of mean recurrence intervals (the average time between debris-flow events) at the fans (Coe and others, in press). Following methods described by Crovelli (2000), Coe and others (in press) calculated the mean recurrence interval by dividing the period of record (length of historic or stratigraphic records) by the number of debris-flow events that occurred during the period of record. Field observations made during the same study indicated that mean recurrence intervals tended to be shortest on fans at the mouths of small and steep basins and longest on fans at the mouths of large basins with low-to-moderate relief. Following these observations, a method was developed (Coe and others, in press) to estimate the probability of future debris flows on fans along Clear Creek using a measure of drainage-basin ruggedness, called Melton's Number. Melton’s number, defined as $H/(A)^{0.5}$, where H is basin height above the fan and A is basin area above the fan (Melton,1965), can be derived from a DEM. Basins that are small and steep have higher Melton’s numbers than basins that are large and have low-to-moderate relief. A regression analysis of mean recurrence interval data and Melton's numbers from the 19 fans and corresponding basins (fig. 2) yielded the equation $y=19,400\exp^{-4.67x}$, where y is mean recurrence interval in years and x is Melton's number. Using this equation, the mean recurrence interval for debris flows on all fans along the corridor can be estimated from the Melton's numbers of the corresponding drainage basins. Once a mean recurrence interval is estimated, the Poisson probability model (Ross, 1972) can be used to estimate the probability of future debris flows (see table 1, and previous landslide application by Crovelli, 2000; Coe and others, 2000). For example, according to the Poisson probability model (table 1), a fan with a mean debris-flow recurrence interval of 200 years, would have a 0.50 percent chance of one or more debris flow events in any given year, and about a 39 percent chance in any 100-year period (see table 1).

The method for estimating future debris-flow probabilities has several limitations. The number of debris-flow events identified on individual fans are minimum numbers because we are confident that not all debris-flow events are documented in historic records or in the typically limited exposures of fan stratigraphy. Because the number of debris-flow events identified are minimums, the mean recurrence intervals calculated from the records are maximums, and the estimates of probability made on the basis of the mean recurrence intervals are minimums.

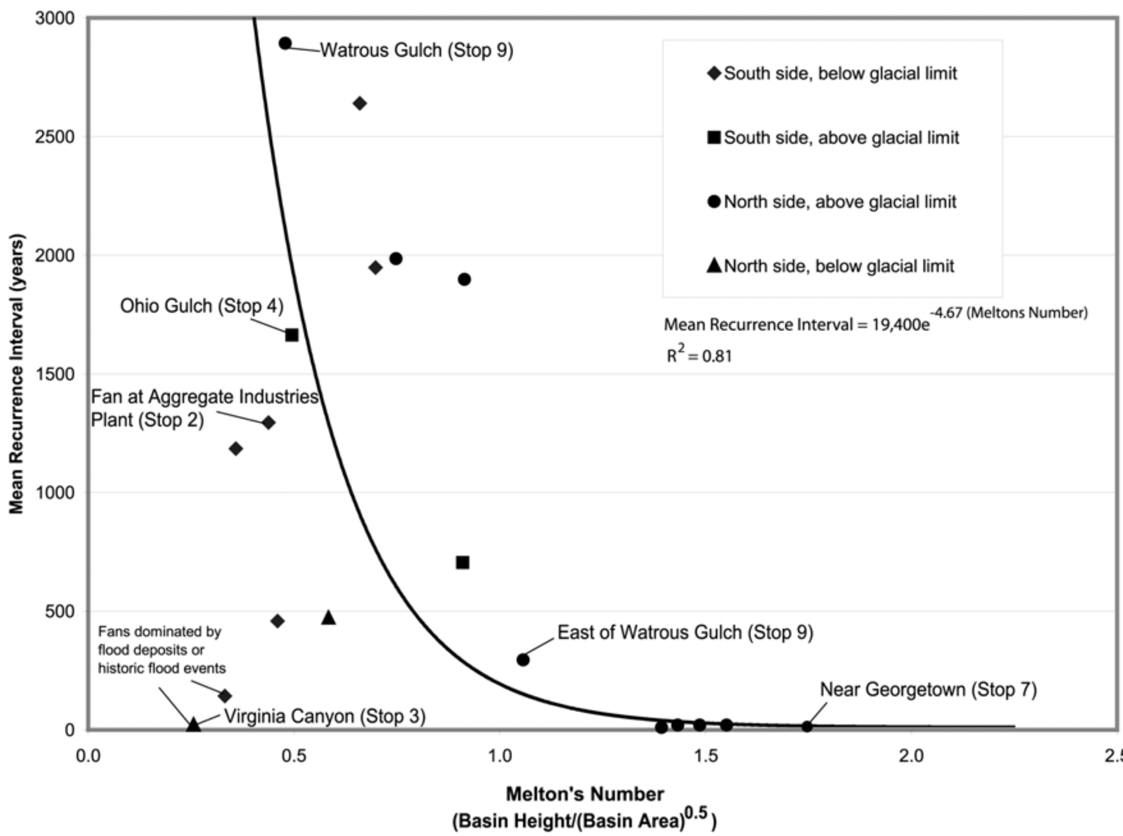


Figure 2. Scatter plot showing mean recurrence interval and Melton's number data from fans in the field-trip area (from Coe and others, in press). Best-fit line and equation from regression analysis is shown. The regression equation can be used to predict the mean recurrence interval (from Melton's number) at fans where there are no historic or stratigraphic records. Fans dominated by flood deposits were not used in the regression analysis. Fans at field-trip stops are labeled. Location of fans on the north or south side of I-70, and above or below the glacial limit, is also shown.

Mean Recurrence Interval (years)	Probability (percent chance of one or more debris flows on an individual fan during specified time)				
	1 yr.	10 yrs.	25 yrs.	50 yrs.	100 yrs.
10	9.52	63.21	91.79	99.33	100.00
50	1.98	18.13	39.35	63.21	86.47
100	1.00	9.52	22.12	39.35	63.21
200	0.50	4.88	11.75	22.12	39.35
300	0.33	3.28	8.00	15.35	28.35
400	0.25	2.47	6.06	11.75	22.12
500	0.20	1.98	4.88	9.52	18.13
1,000	0.10	1.00	2.47	4.88	9.52
1,500	0.07	0.66	1.65	3.28	6.45
2,000	0.05	0.50	1.24	2.47	4.88
2,500	0.04	0.40	1.00	1.98	3.92
3,000	0.03	0.33	0.83	1.65	3.28
3,500	0.03	0.29	0.71	1.42	2.82
4,000	0.02	0.25	0.62	1.24	2.47
4,500	0.02	0.22	0.55	1.10	2.20
5,000	0.02	0.20	0.50	1.00	1.98

Table 1. Debris-flow probabilities for fans in the I-70 corridor. Probabilities calculated for a range of mean recurrence intervals (from Coe and others, in press) using the Poisson probability model, $P = 1-e^{-t/\mu}$, with probability (P) defined as the percent chance of one or more debris flows occurring on an individual fan during a specified time t, where μ is mean recurrence interval (from Crovelli, 2000).

Observations of debris flows in the field-trip area that we have made since the summer of 1996 (described in Godt and Coe, in press; Coe and others, in press, Godt and Coe, in review) suggest that one of the reasons that debris flows occur frequently on fans at the mouths of basins with relatively large Melton's numbers is that they have a greater likelihood of flowing to the fan than do debris flows in basins with relatively small Melton's numbers. We suspect that if debris flows occurred with equal frequency on hillslopes in all basins, many of the debris flows in the large basins with low to moderate relief (small Melton's numbers) would deposit material at the base of hillslopes within the basins, not on fans at the mouths of basins. This would also explain why fans at basins with very small Melton's numbers (less than about 0.35, fig. 2) are dominated by flood events, not debris-flow events. In basins with high Melton's numbers, the base of the hillslope and the mouth of the basin are essentially the same. Debris flows in these basins simply flow down the hillslopes and are deposited on fans.

ROAD LOG

Coordinates for each stop are given in the World Geodetic System of 1984. Elevations are given in the National Geodetic Vertical Datum of 1929. Grain-size data are given on the basis of engineering soil classification (see Terzaghi and others, 1996) with size distinctions as follows: sand, 4.76 mm to 0.074 mm; silt, 0.074 mm to 0.002 mm; and clay, less than 0.002 mm. We use the term *matrix* when referring to the sand- through clay-sized portion of material in deposits.

Cumulative
Mileage

0.0 Begin trip at I-70 Exit 248 at Beaver Brook/Floyd Hill. Turn right at the top of the exit ramp onto County Road 65, then immediately turn left (west) on U.S. Highway 40. Set mileage to 0.0 at junction of County Road 65 and U.S. Highway 40. Proceed west on U.S. Highway 40.

1.5 Entering the Clear Creek valley.

3.1 Junction of U.S. Highway 40 with U.S. Highway 6 in the Clear Creek valley. Turn right (east) on U.S. Highway 6 and pull into a parking area on the left (north) side of the highway about 0.1 mile east of the junction.

3.2 **Stop 1**. **Base of Floyd Hill - Introduction to the Clear Creek valley**. Latitude: N 39º 44' 33.0", Longitude: W 105º 25' 47.3", Elevation: 2,201 m (7,220 ft). The Clear Creek valley in the Front Range can be split into three major physiographic divisions, 1) Clear Creek Canyon, located downstream from here to Golden, 2) the non-glaciated, generally V-shaped valley upstream from here to Dumont, and 3) the glaciated, U-shaped valley located from Dumont upstream to the Continental Divide. On this trip we will examine debris-flow deposits and processes in the non-glaciated V-shaped and glaciated U-shaped parts of the valley. In general, debris flows affect fans at the mouths of tributary basins in the U-shaped part of the valley more frequently than fans in the V-shaped part of the valley. Fans with relatively high debris-flow frequencies (relatively short mean recurrence intervals) have higher estimated probabilities of future debris-flow occurrence (table 1) than fans with relatively low debris-flow frequencies (relatively long mean recurrence intervals).

Throughout the field-trip area, Clear Creek cuts predominantly Precambrian gneisses and quartz monzonites. At this first stop, the foliation of Precambrian gneiss dips about 35º towards the northwest. To the south is the Floyd Hill landslide, which is a foliation- and joint-controlled rockslide (Robinson and others, 1974) that moves roughly a centimeter per year towards I-70 (unpublished USGS GPS data). The Colorado Department of Transportation (CDOT) has placed concrete barriers along the south side of I-70 to prevent landslide debris from being deposited on the highway lanes. The debris piles up on the asphalt pavement behind the barriers and is periodically scraped off by CDOT.

Just to the west of this stop is USGS stream-flow monitoring station 06718300. The drainage area above the station is 692 km^2 (267 mi^2, USGS, unpublished data). Records from this station indicate that daily mean streamflow between October 1, 1994 and September 30, 2001 ranged from about 0.9 m^3/s (30 cfs, Winter, 1995) to 56.6 m^3/s (2000 cfs, Spring, 1995). The current (October 10, 2002) discharge is about 1.7 m^3/s (60 cfs).

Proceed west on U.S. Highway 6 and merge onto I-70 westbound.

5.0 Exit I-70 at Hidden Valley (exit 243). Turn left (south) at the bottom of the off-ramp, go under I-70, then turn right (west) on County Road 314.

5.9 Bear left as County Road 314 becomes a dirt road along Clear Creek.

6.3 **Stop 2. Fan exposure near the Aggregate Industries Plant**. Latitude: N 39º 44' 36.9", Longitude: W 105º 28' 37.9", Elevation: 2,256 m (7,400 ft). This fan exposure reveals sediments that we interpret to be debris-flow deposits. These deposits are generally poorly to moderately sorted, matrix supported, and contain randomly oriented clasts. Grain size analyses of the matrix of the deposits (USGS, unpublished data from 4 samples) indicates that silt-sized material makes up most of the matrix (41 to 72 percent), followed by sand- (7 to 41 percent) and clay-sized material (5 to 10 percent). Prominent, dark gray to black, buried A-soil horizons separate the debris flow deposits. Charcoal is present throughout the exposure, but most common in fine-grained deposits. Charcoal and buried A horizons tend to be most common on fans along the south side of I-70 (north-facing), presumably where solar exposure creates soil conditions that are cooler and wetter than on fans along the north side of I-70 (south-facing). The abundance of charcoal suggests a strong temporal link between forest fires and debris-flow events. Radiocarbon dating of the charcoal suggests that the exposed deposits are Holocene in age (fig. 3) and that the mean recurrence interval between debris-flow events is about 1,300 years. On the basis of the mean recurrence interval, the estimated probability (percent chance) of one or more future debris flows on this fan is about 4 percent in any given 50-year period (table 1, Coe and others, in press).

The drainage-basin upslope from the fan is forested, and has moderate size and relief as indicated by a Melton's number of 0.44 (figs. 2 and 3). For tributary basins along Clear Creek, there is a negative correlation between Melton's number and the mean recurrence intervals of debris flows on fans (Coe and others, in press). That is, fans with the shortest mean recurrence intervals tend to be at basins with the highest Meltons numbers (small and steep basins). Also, in general, mean recurrence intervals between debris-flow events on fans at the mouths of vegetated basins (such as this one) are longer than those on fans at the mouths of sparsely-vegetated basins.

Continue west on the County Road 314.

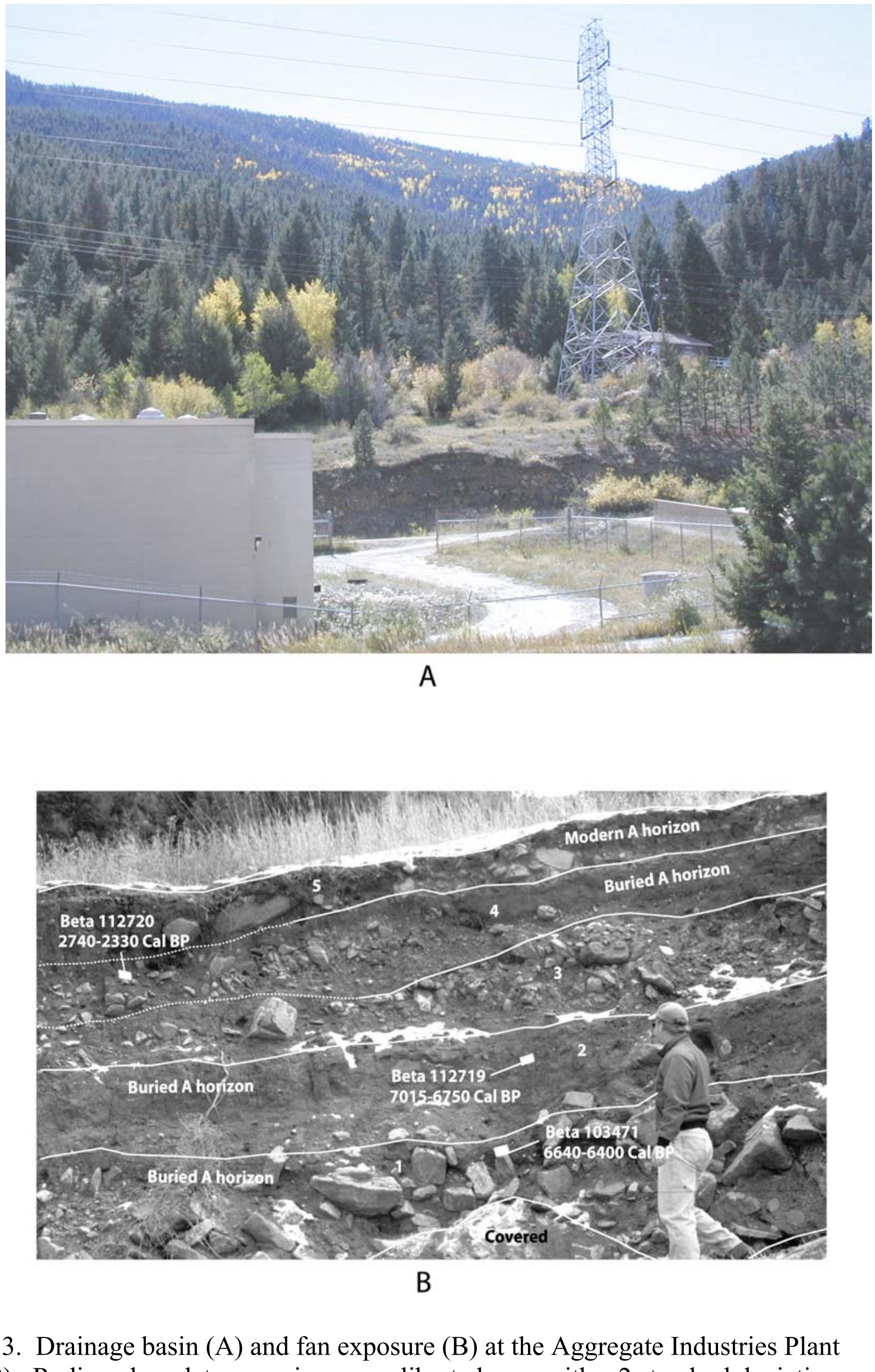


Figure 3. Drainage basin (A) and fan exposure (B) at the Aggregate Industries Plant (Stop 2). Radiocarbon dates are given as calibrated ages with a 2 standard deviation range.

7.1 Turn right near I-70, then make a quick left and cross over I-70 and proceed into Idaho Springs onto Colorado Blvd.

8.4 Turn right on Placer St. and then make a quick left onto Canyon St. Proceed north on Canyon St.

8.9 **Stop 3. Virginia Canyon.** Latitude: N 39º 45' 00.5", Longitude: W 105º 30' 56.8", Elevation: 2,377 m (7,800 ft). Park along left side of road near culvert at turn off to Central City. The fan below our parking area is dominated by historic, water-dominated flow events (floods). The hazardous area during flood events is along the channel downslope from the parking area. During flooding events, water and debris runs down the channel as well as on the road. This presumably occurs because culvert pipes get clogged with debris. Houses in close proximity to the channel (fig. 4) are also affected by flooding. One structure is built on top of the channel and others have structural components anchored within the channel (fig. 4c and d). Once flood waters reach the fan, they are contained within a concrete lined channel (fig. 4b). On the basis of historic events, the mean recurrence interval between flood events on the fan is about 7 years.

The basin upslope from the fan is relatively large with moderate relief, as indicated by a Melton's number of 0.26 (figs. 2 and 4a). From our data, fans at the mouths of basins with Melton's numbers less than about 0.35 are dominated by flood events, whereas basins with Melton's numbers greater than about 0.35 are dominated by debris-flow events (fig. 2).

Proceed back down Canyon St. to Placer St. and then to Colorado Blvd. Turn right on Colorado Blvd. and proceed west through Idaho Springs.

10.5 Turn left onto Stanley Road.

11.5 Waste piles from the Stanley Mine are on the left side of the road. The piles have been affected by rilling but have had no obvious landslide failures. Rilling is the typical erosive process acting on mine waste piles within the I-70 corridor.

14.6 Intersection of Stanley Road and County Roads 312 (to the right) and 310 (straight ahead). Proceed straight through the intersection onto County Road 310.

15.1 Turn left (south) onto a small dirt road.

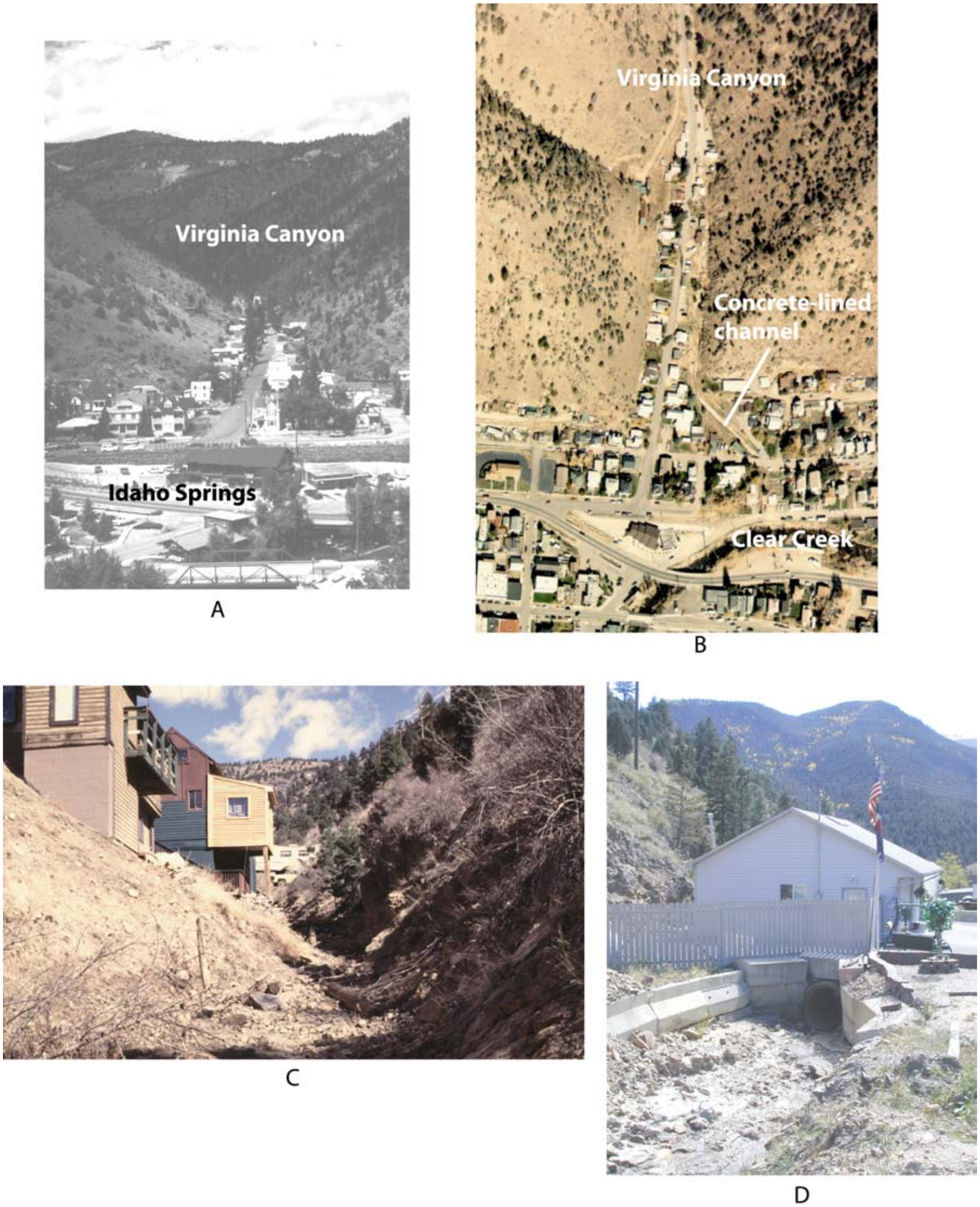


Figure 4. Drainage basin, fan, and structures at Virginia Canyon (Stop 3). A) Drainage basin. Photo taken in 1997. B) Aerial photograph of the mouth of the basin in Idaho Springs. Photo taken October 13, 1996. C) Houses along the west bank of the drainage channel. Photo taken in March, 1997. D) Garage built over the channel. Photo taken October 7, 2002.

15.2 **Stop 4. Fan at mouth of Ohio Gulch.** Latitude: N 39º 45' 46.9", Longitude: W 105º 36' 31.9", Elevation: 2,445 m (8,020 ft). Park along the side of the road and walk downslope to the northeast (over a fence) to the exposure of fan stratigraphy. This stop is on private property and permission must be obtained to visit the exposure. The exposure contains a record of at least 4 debris-flow events separated by well-preserved, buried A horizons (fig. 5). On the basis of radiocarbon dates from charcoal within the generally fine-grained A horizons, the mean recurrence interval between debris-flow events is about 1,700 years. On the basis of the mean recurrence interval, the estimated probability (percent chance) of one or more future debris flows on the fan is about 3 percent in any given 50-year period (table 1, Coe and others, in press).

The drainage-basin upslope from the fan is forested, and has moderate size and relief as indicated by a Melton's number of 0.50 (figs. 2 and 5). This basin has morphologic and vegetation characteristics that are very similar to those of the basin at Stop 2 (fig. 3). The recurrence interval of debris-flow events and estimated probability of future debris flows are also very similar.

The maximum extent of Pleistocene glaciation lies about 1 km east of this stop. As we proceed to the next stop, the valley walls and tributary basins of Clear Creek become steeper and the valley floor becomes wider.

Proceed back to the intersection of Stanley Road and County Roads 310 and 312.

15.8 Turn left (north) on County Road 312 and cross over I-70.

15.9 Turn left on the Frontage Road on the north side of I-70. Proceed west on the Frontage Road through Dumont and Downieville.

17.5 Pass through the small town of Lawson.

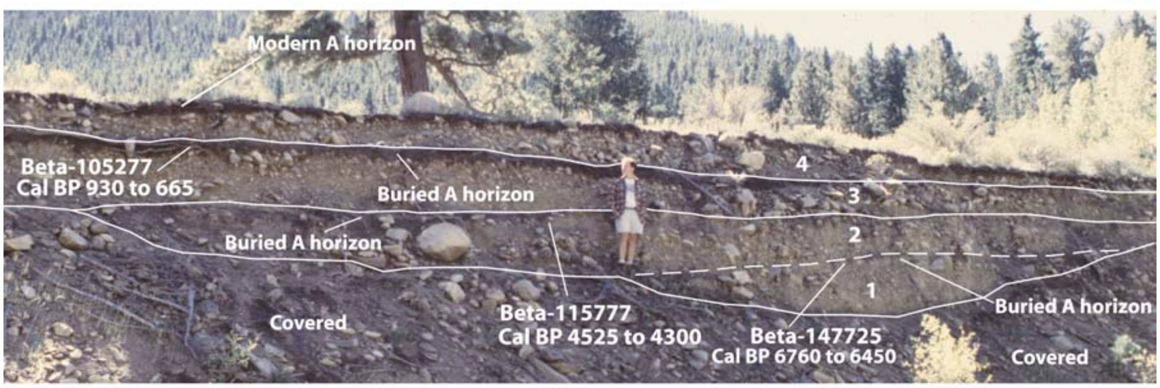
17.8 Turn left on County Road 306.

18.2 Note the large boulder above the trailer park on the north side of I-70. The boulder has been periodically monitored by the Colorado Geological Survey.

19.2 Terminal moraine of late Pleistocene Clear Creek valley glacier. The most recent Pleistocene glaciers (Pinedale glaciation) in the Front Range melted between 14,000 and 12,000 ^{14}C yr BP (Madole and others, 1998). The deposit at this exposure is poorly sorted, matrix supported, contains sub-rounded to rounded clasts, and has a poorly developed soil formed at the surface.

Proceed west on County Road 306.

A



B

Figure 5. Drainage basin (A) and fan exposure (B) at Ohio Gulch (Stop 4). Basin photographed October 7, 2002. Fan photographed in 1997. Radiocarbon dates are given as calibrated ages with a 2 standard deviation range

19.6 Junction of County Road 306 and an unnamed Road crossing over I-70 and leading to a westbound I-70 onramp. Park along the northwest corner of the intersection. **Stop 5. Overview of debris-flow channels between Empire and Georgetown.** Latitude: N 39º 45' 07.6", Longitude: W 105º 39' 38.9", Elevation: 2,530 m (8,300 ft). The most active debris-flow area along I-70 lies along the north side of the highway between this stop and Georgetown (fig. 6). Along this section of highway, the mean recurrence interval between debris-flow events is about 7 years or less. The most recent debris-flow event that affected this portion of I-70 was triggered by an afternoon thunderstorm on July 13, 2001. The storm triggered about 13 debris flows that deposited debris on the west-bound lane of I-70 (fig. 6) between mile markers 230.5 and 231.5. Debris on westbound lanes was up to about 3 m thick and extended to the highway's centerline. CDOT closed the Interstate between the Empire and Georgetown exits for about 4 hours while debris was cleared from one westbound lane.

Debris flows in this area initiate as water-dominated flows in steep bedrock channels (fig. 6). When these water-dominated flows cross the talus fan at the base of the steep bedrock slope, they erode and mobilze debris from the talus fan. That is, the concentrated flow of water impacts and mobilizes debris and deposits it on I-70. This type of debris-flow initiation has been described by Fryxell and Horberg (1943) and Curry (1966), and was termed the "firehose effect" by Johnson and Rodine (1984). Much of the mobilzed debris comes from the oversteepened, cut slope portion of the talus fan directly adjacent to I-70 (fig. 6e). In order to minimize the amount of material mobilzed from the cut slope part of the talus fans, CDOT has installed concrete linings in cut-slope channels along the most active debris-flow paths (figs. 6a and 6f). Observations of the amount of material deposited on I-70 during the July 13 storm suggest that these concrete linings are effective in reducing the amount of debris eroded and mobilized from the cut slope during rainstorms (compare figs. 6e and 6f).

Continue west on County Road 306 towards Georgetown.

21.8 Georgetown Dam, also known as the Harry M. Locke Dam. The east end of this earthen dam is built on the toe of a large landslide. Two previous dams at this site have failed (Woodward-Clyde consulting report, 1970). One previous dam failed because it was breached by flooding in June, 1956 (Woodward-Clyde consulting report, 1970). The current dam was built in 1974.

22.0 Georgetown Lake viewpoint.

23.1 Turn right and proceed under I-70 to the dirt Frontage Road on the north side of the highway. Turn right on the Frontage Road and proceed to the top of the first hill.

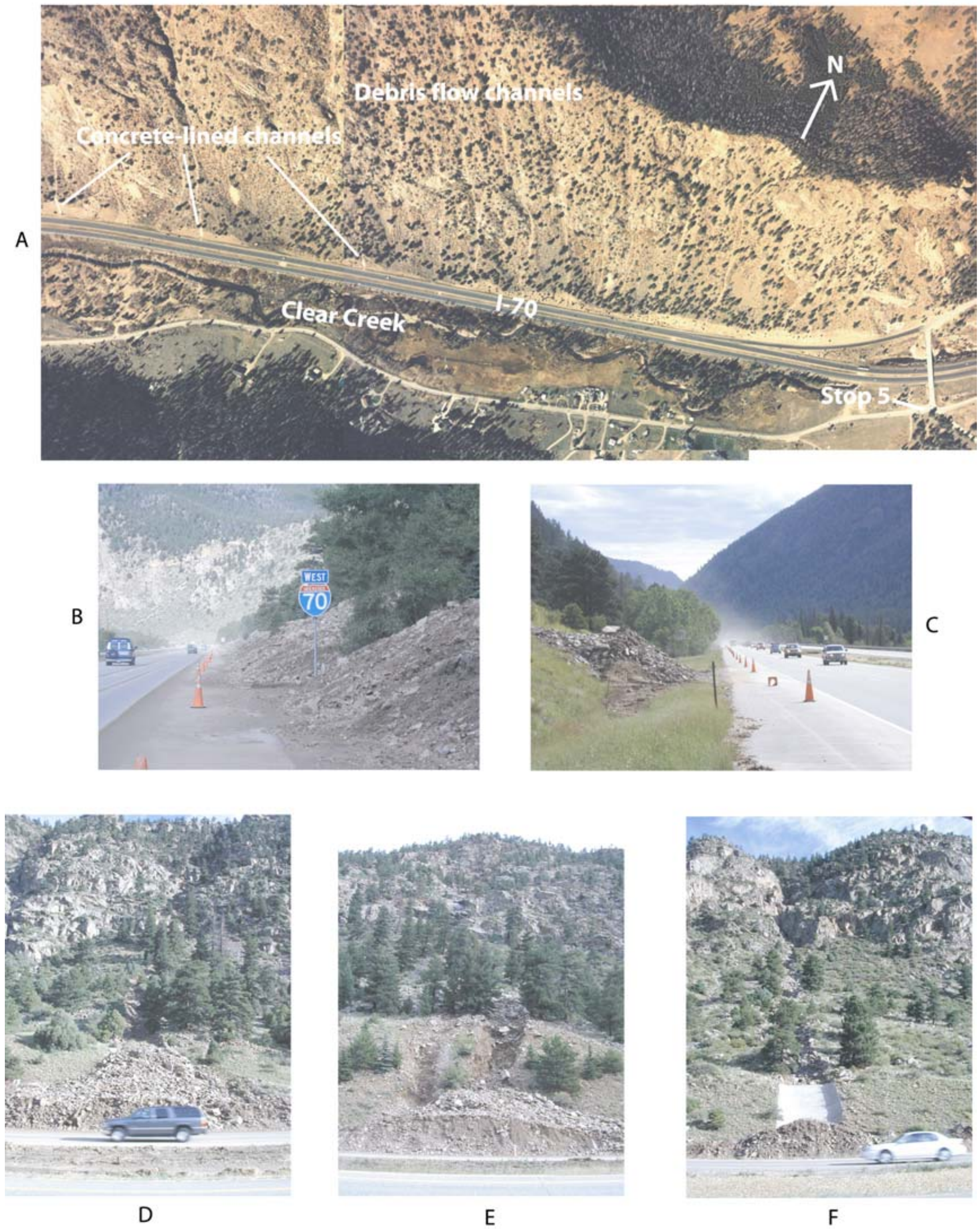


Figure 6. Debris flows along I-70 near the junction of I-70 and U.S. Highway 40 near Empire (Stop 5). A) Aerial photograph of the area. Photograph taken October 12, 1996. B) Piles of debris from flows on July 13, 2001. View to southwest. C) Deposit and dust from July 13 debris flows. View to northeast. D,E,F) July 13, 2001 debris-flow channels and deposits. View to northwest. Concrete-lined channel shown in E. Photographs B through F were taken on July 14, 2001.

23.3 **Stop 6. Georgetown debris flow and rockfall overview.** Latitude: N 39º 43' 01.6", Longitude: W 105º 41' 49.4", Elevation: 2,615 m (8,580 ft). We have stopped on a large fan along an east-facing slope overlooking Georgetown. On the west-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 directly across from us (fig. 7), radiocarbon dating of charcoal from fan deposits (Coe and others, in press) 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. The Melton's number of the drainage basin upslope from the fan is 0.91.

Debris-flow channels to our left (north) and right (south) 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 the some of the channels. As at stop 5, 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 rilling). Progressive rilling is the concentration of overland flow that mobilizes loose sediment primarily at knickpoints and plunge pools (Horton, 1945; Johnson and Rodine, 1984; Cannon and others, in press).

The heads of the fans near this stop are also susceptible to rockfall hazards as evidenced by numerous rock-fall deposits. Just to the left of the fan directly across from us, 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. Several fatalities from rockfall have occurred along this portion of I-70, with the most recent occurring on May 16, 1999.

Proceed northeast along the dirt frontage road.

A

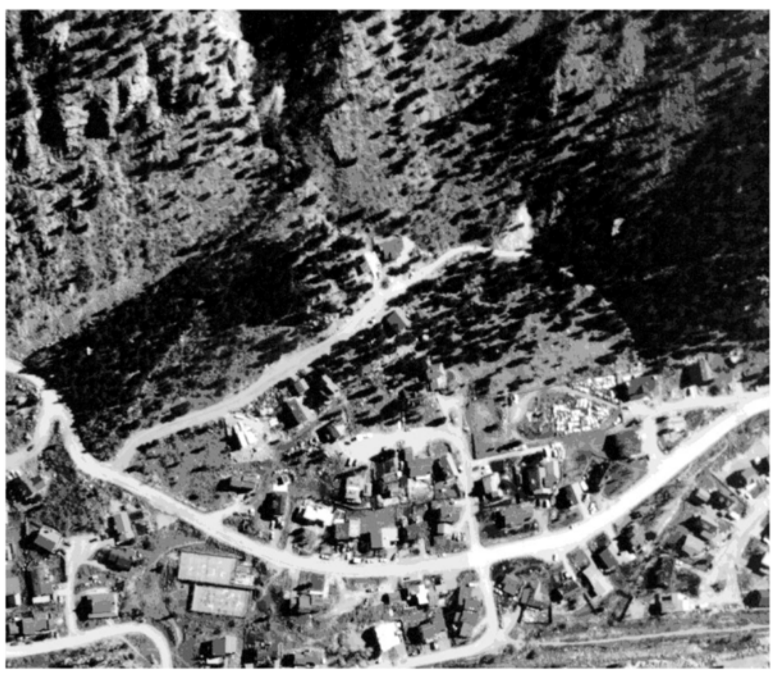


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Figure 7. Aerial photograph showing residential development on a fan in Georgetown (fan is visible to the east from Stop 6). A) Photograph from 1961. B) Photograph from 1996. Distance covered by the width of the photos is about 0.5 km (~0.3 miles) on the ground.

23.9 **STOP 7. Debris-flow channel with deposit from July 13, 2001 debris-flow event.** Latitude: N 39º 43' 31.9", Longitude: W 105º 41' 43.2", Elevation: 2,597 m (8,520 ft). The debris-flow that deposited this small fan has characteristics that are typical of debris flows in the area along the north side of I-70 between Empire and Georgetown. That is, it traveled a short distance (less than 1 km) and deposited a volume of material less than 1000 m^3. The fan deposit is matrix supported, poorly sorted, and contains randomly oriented clasts (fig. 8). Grain-size analysis of a similar deposit (at the same location) that resulted from the July 28, 1999 storm (USGS, unpublished data) indicated that sand-sized material makes up most of the matrix (74 percent), followed by silt- (21 percent), and clay-sized material (5 percent). Unlike some of the other debris-flow channels in the area, this channel has matrix-supported levees that seemingly receive fresh material with each debris-flow event (for example, see fig. 8c).

The basin is also typical for the area; it is small and steep, sparsely vegetated, and has bedrock slopes in its upper half and a fan apron in its lower half. This basin has a Melton's number of 1.75 (fig. 2). Debris flows in the basin initiate by progressive rilling and fire hose processes. Because the basin is so small and steep (relatively large Melton's number), debris flows that initiate within the basin have a greater likelihood of flowing to the fan at the mouth of the basin than do debris flows that initiate in very large basins with moderate relief (relatively small Melton's numbers, for example see basins in figs. 3, 4, and 5). The estimated probability of future debris-flow events on the fan is greater than 99 percent in any given 50-year period.

Turn around and proceed back along the Frontage Road to I-70. Proceed up the ramp onto I-70 westbound.

26.8 Exit I-70 at the Silver Plume exit (exit 226). At the bottom of the offramp go straight along the Frontage Road on the north side of I-70.

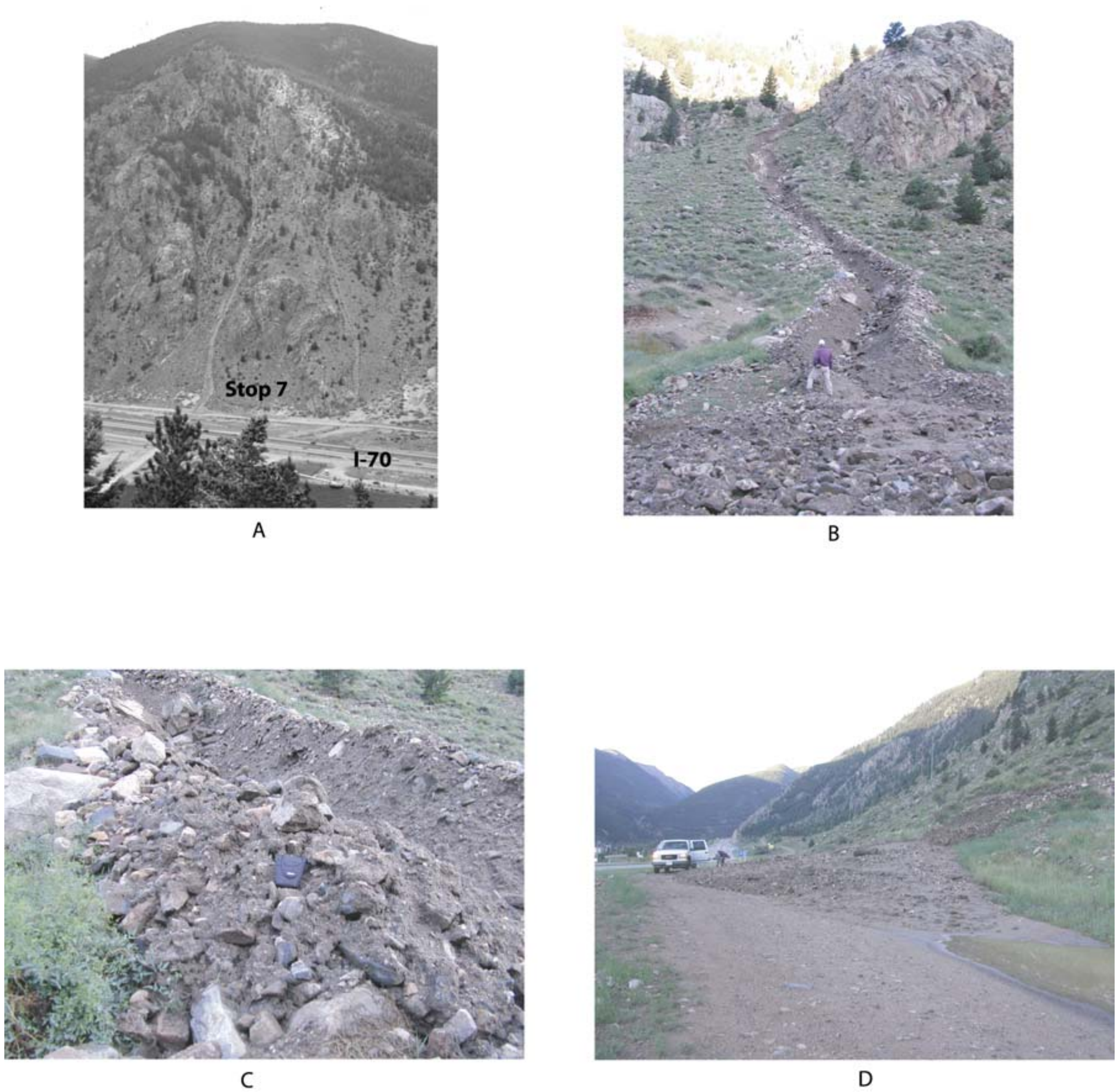


Figure 8. Drainage basin and July 13, 2001 debris-flow deposits at Stop 7. A) Drainage basin. Photograph taken August 30, 1996. B) Debris-flow channel. C) Matrix-supported debris-flow levee. See camera case for scale. D) Fan formed by deposit. Photos B,C, and D where taken July 14, 2001.

27.9 Park along the berm on the north side of the Frontage Road on the south side of I-70. **Stop 8. Brown Gulch Debris Flows**. Latitude: N 39º 41' 44.5", Longitude: W 105º 44' 30.4", Elevation: 2,816 m (9,240 ft). Brown Gulch (fig. 9) was the site of at least 4 debris-flow events between 1889 and 1912 (1889, 1892, 1895, 1912; Christine Bradley, Clear Creek County Archivist, written communication). The primary source of debris in the flows was mine-waste dumps located within the Gulch. According to newspaper articles published in the *Silver Standard* and the *Georgetown Courier*, most of the mobilized debris came from the waste dump of the Seven-Thirty mine (fig. 9b) located at an elevation of about 3,185 m (10,450 ft), about 365 m (1,200 ft) above the fan (fig. 9c) at the mouth of the Gulch. At least one of the debris-flow events buried buildings in the small town of Brownville, located on and near the fan. All of the documented debris-flow events occurred in the month of June and were apparently triggered by snowmelt. Part of a *Silver Standard* article from June 25, 1892 mentions the " first really warm day" of spring followed by a "rapid rise of water" in creeks. Part of the discussion of Brown Gulch is quoted as follows. "*On Wednesday morning the dump of the Seven-Thirty mine began to wash away and Brown Gulch was a scene of ruin. The water in the gulch seemed to reach its highest point after midnight and when the first dump started to go the mass of rock and timbers was added to from other dumps as it went down. The ore houses and blacksmith shops of the Coin, Brown, Mammoth and Dunderberg were situated in the gulch, as are also the mouths of numerous tunnels going into the mines. The latter were speedily covered over and the buildings either buried where they stood or washed down the gulch. Most of the debris washed down on Wednesday stopped at the lower end of the gulch above the Terrible, and on Thursday morning about 3 o'clock it began to move under the influence of the volume of water then coming down. It was expected that it would go toward the Union tunnel of the Terrible but it took a course toward the Terrible mill and granite quarry, burying the house occupied by William Payne and the office of the company. The mass of rock flowed out over the railroad track running into the quarry and filled up the wagon roads going across the bridge and by the Terrible Mill to a depth of many feet. One corner of the mill is mashing in, and 2 cars of rock standing on the track were buried.*

An examination of the Seven-Thirty mine dump in October 2002 (fig. 10) revealed that a large part of the dump is still present (figs. 10a and 10b) and that it lies adjacent to the channel (fig. 10c). Presumably, when the debris flows occurred in the late 1800s and early 1900s, the dump was closer to, or covered part of the channel. Thus, the high volume of runoff from snowmelt eroded the edge of the dump and caused it to fail into the channel and contribute debris to the runoff. The dump could still contribute debris to the channel if it failed as a landslide, however, because the dump is now located farther from the edge of the active channel, it appears that "normal" spring runoff would no longer erode the edge of the dump and be the cause for such a landslide failure. Modern debris flows in Brown Gulch would most likely be triggered by intense or prolonged rainfall.

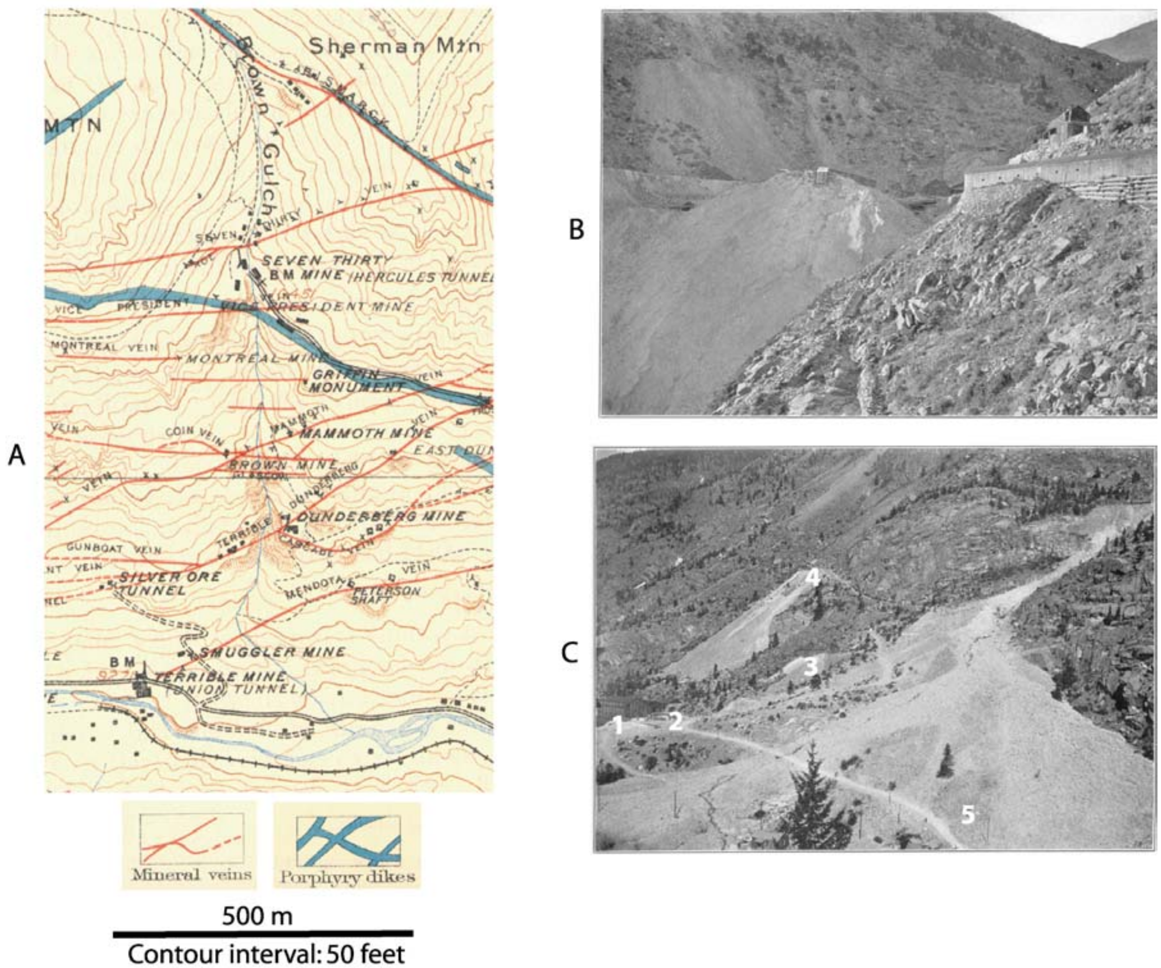


Figure 9. Map and photos of Brown Gulch (Stop 8) in the early 1900s (all from Spurr and others, 1908). A) Map made in 1906 showing topography, mines, and veins and dikes in Brown Gulch and vicinity. B) Seven-Thirty mine and dump in Brown Gulch looking northwest from the Griffin monument. C) Fan at the mouth of Brown Gulch showing; 1, Terrible mill; 2, Union tunnel of the Terrible mine; 3, Smuggler mine; 4, Silver Ore tunnel of the Terrible Mine; 5, deposit of debris mobilized from mine dumps in Brown Gulch.

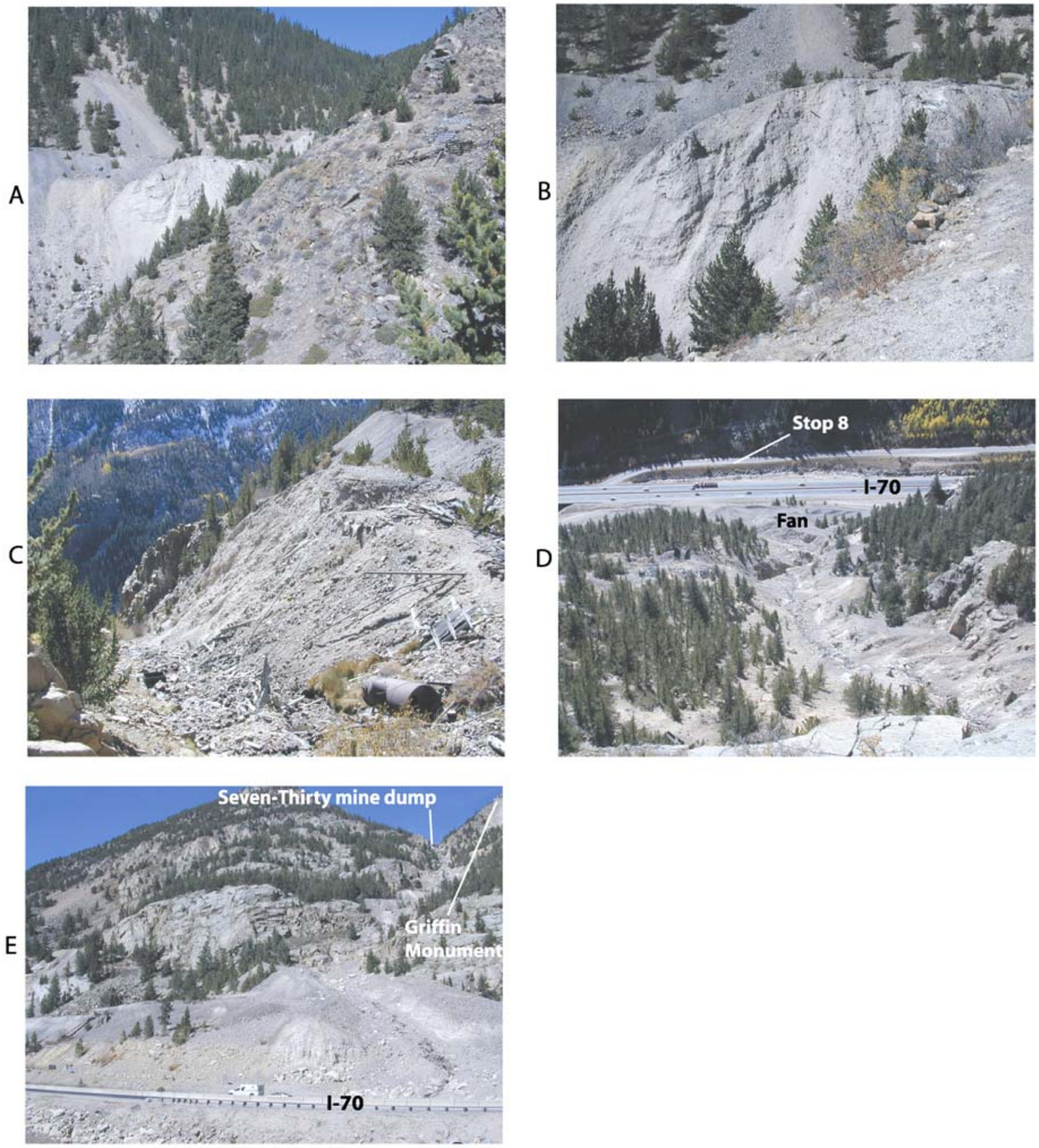


Figure 10. Photos of Brown Gulch on October 10, 2002. A) Seven-Thirty mine dump (compare to figure 9b). B) Close-up of Seven-Thirty mine dump. C) View of the Seven-Thirty mine dump (at right) looking downstream to the south. Dump is roughly 25 m in height. D) Brown Gulch looking downstream to the south from the Griffin monument (see E for location of monument). Horizontal distance from the monument to I-70 is roughly 600 m. E) Brown Gulch and fan looking upstream to the north.

Proceed west on the Frontage Road.

31.4 Small town of Bakerville. Turn right and cross over I-70 to the westbound onramp on the north side of the highway. Proceed west on I-70.

33.5 Pull off I-70 and park on the dirt berm on the right side of the highway**. Stop 9. The July 28, 1999 thunderstorm and debris-flow event in Watrous Gulch.** Latitude: N 39º 42' 10.0", Longitude: W 105º 50' 23.6", Elevation: 3,109 m (10,200 ft).

On July 28, 1999, about 480 alpine debris flows were triggered by an afternoon thunderstorm along and near the Continental Divide in Clear Creek and Summit Counties (Godt and Coe, in press; Godt and Coe, in review). The thunderstorm dropped about 43 mm of rain in 4 hours, most of which (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, in review). 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.

Several debris flows triggered by the storm affected I-70, U.S. Highway 6, and the Arapahoe Basin ski area. One debris flow (which is the primary subject of this stop) initiated on the south flank of Mount Parnassus (above us to the north at this stop, fig. 11), traveled 2.5 km down Watrous Gulch, and deposited about 26,400 m^3 of debris on I-70 (Al Chleborad, written communication), closing the highway for about 25 hours. Fortunately, little permanent damage to public or private property and no injuries or fatalities resulted from any of the flows.

On the south flank of Mount Parnassus the flows initiated as rills on steep, non-vegetated slopes above tree line (figs.12a, b, and c). The matrix of colluvium at the head of the largest rill contained 84 percent sand-sized material, 8 percent silt-sized material, and 8 percent clay-sized material (Godt and Coe, in press). Clasts made up about 50 percent of the colluvium. As the debris flow(s) progressed downslope, it eroded material from the channel. Parts of the channel were incised several meters by the flow (figs. 12d, e, f, g). Material eroded from the channel included deposits of layered, sandy-silt (fig. 12d), as well as, matrix-supported deposits containing sub-angular to sub-rounded boulders (fig. 12d). The matrix of the flow became finer-grained as it progressed downslope. The matrix of the deposit on I-70 (fig. 12h) contained 69 percent sand-sized material, 24 percent silt-sized material, and 7 percent clay-sized material. Clasts made up about 70 percent of the deposit on I-70 and were larger and more rounded than those in the colluvium at the source area (compare fig. 12b with fig. 12h).

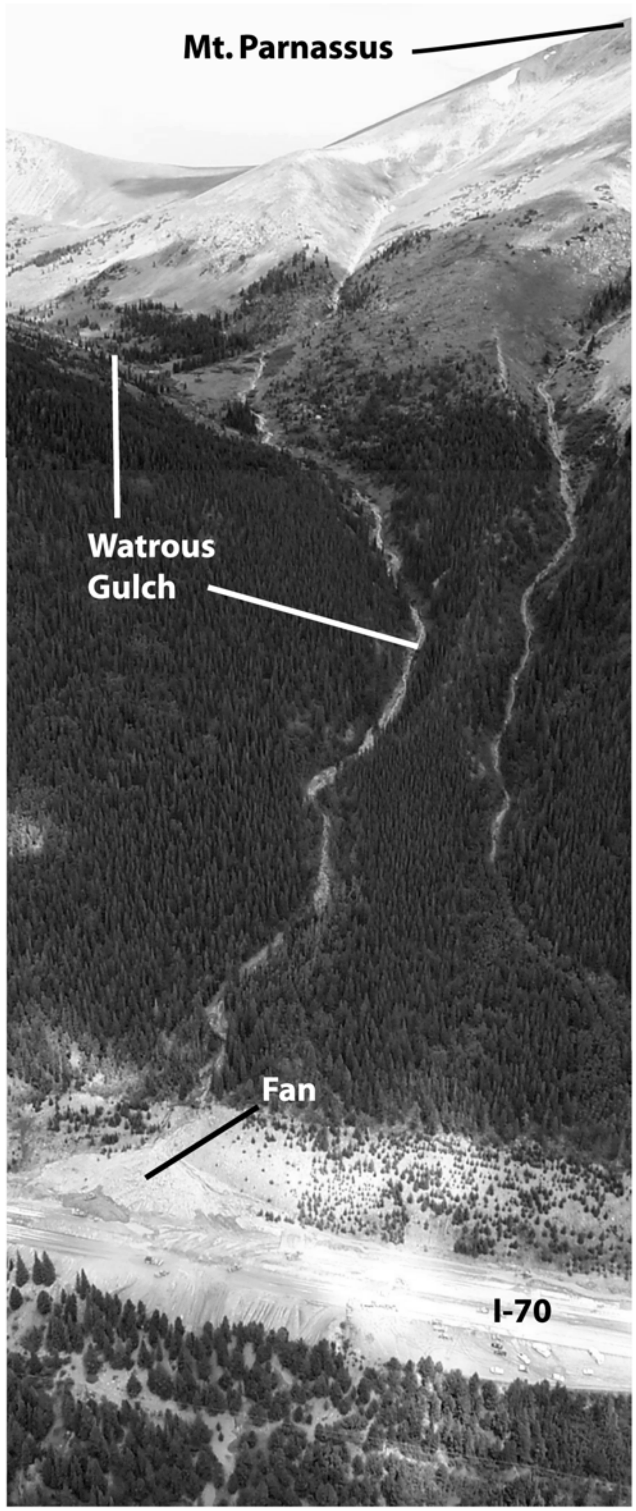


Figure 11. Watrous Gulch drainage basin and fan (Stop 9). Fan on the highway is from the July 28, 1999 debris-flow event. See vehicles on I-70 for scale. Photo taken July 29, 1999 by Ed Harp.

Figure 12. Photographs of Watrous Gulch taken after the July 28, 1999 debris-flow event. A) Rills in the source area. View to the east. Relief visible is about 610 m (2,000 ft). B) Head of the largest rill in the source area (see quart-sized sample bag at lower left for scale). View to the north. C) View upstream along the largest rill. See geologist for scale.

Figure 12 – continued. D) Deposits exposed by the July 1999 debris-flow event located about half way between the head of the largest rill and the fan. Channel is about 3 m deep. Matrix-supported boulder-rich deposit on top, sorted, stratified, silt-rich deposit at base. View to the northwest. E) Bedrock-lined channel exposed by the July 1999 debris flow. F) Matrix-supported levee deposits along a bend in the channel above the fan. View downstream to south. Channel depth (thalweg to top of levee) is about 4 m. G) Matrix-supported levee deposits along a bend in the channel above the fan. View upstream to north. H) Fan on I-70. Photos A through D taken on August 4, 1999. Photos E through H taken July 29, 1999.

An analysis of superelevation of debris-flow levees (see Costa, 1984 for description of the method) at a bend in the channel of Watrous Gulch directly above I-70 (figs. 12f and 12g) indicated a velocity for the Watrous Gulch debris flow of 9.7 m/s. This compares favorably with video footage shot of the debris-flow from I-70 (Denver television station “News4” footage).

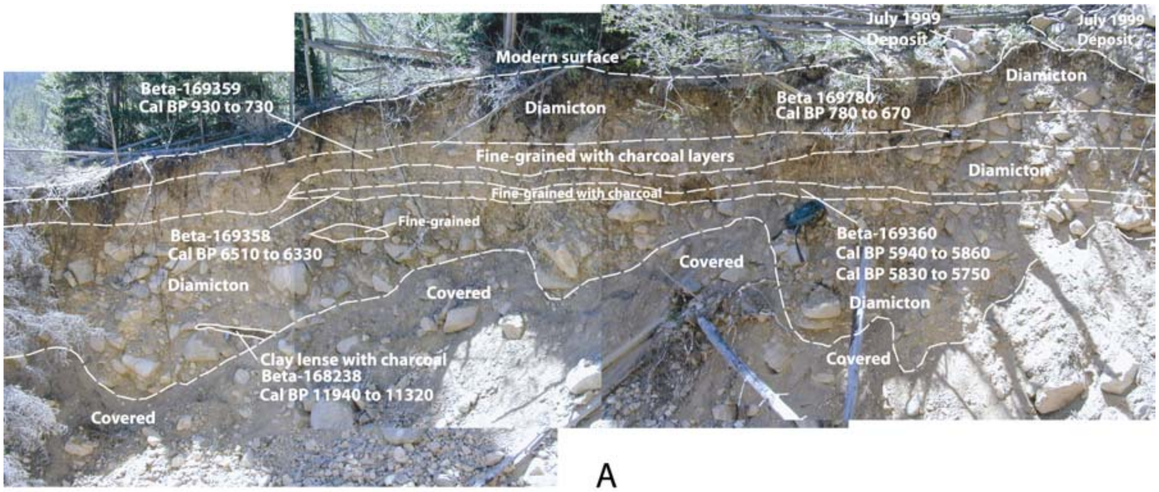
The debris flow in Watrous Gulch, as well as a debris flow in the gulch directly east of Watrous Gulch (Latitude: N 39º 42' 04.7", Longitude: W 105º 50' 14.5", Elevation: 2,846 m (9,336 ft), exposed fan stratigraphy containing a record of past debris flows (fig. 13). This stratigraphy indicates that the mean recurrence intervals for debris flows in Watrous Gulch, and the gulch to the east, are about 3,000 years and 300 years, respectively (fig. 13 and fig. 2). The Melton’s numbers of the basins are 0.48 and 1.1, respectively (fig. 2). The negative correlation between Melton’s number and mean recurrence interval at these two basins fits the overall pattern for the corridor as a whole, that is, fans at the mouths of basins with larger Melton’s numbers have shorter debris-flow recurrence intervals than fans at the mouths of basins with smaller Melton’s numbers (fig. 2). The estimated probabilities of future debris-flow events are about 2 percent in any given 50-year period for the fan at the mouth of Watrous Gulch, and about 15 percent in any given 50-year period for the fan at the mouth of the gulch to the east of Watrous Gluch (see table 1). Additionally, the fan stratigraphy at the mouths of the two gulches also suggests that there was at least one previous debris-flow event (between 720 and 930 cal BP) that affected both fans (fig. 13).

Proceed west on I-70.

35.0 Passing a snow avalanche chute on the right. Avalanches initiate on the south-facing flank of Mount Bethel (elevation 3,872 m, 12,705 ft).

36.2 Exit I-70 at the Loveland Pass/Loveland Basin exit (exit 216). Proceed west on U.S. Highway 6.

37.4 Pass the Seven Sisters snow avalanche chutes on the right. Look back to the east to see Mount Parnassus and the initiation area of the July 28, 1999 Watrous Gulch debris flow.



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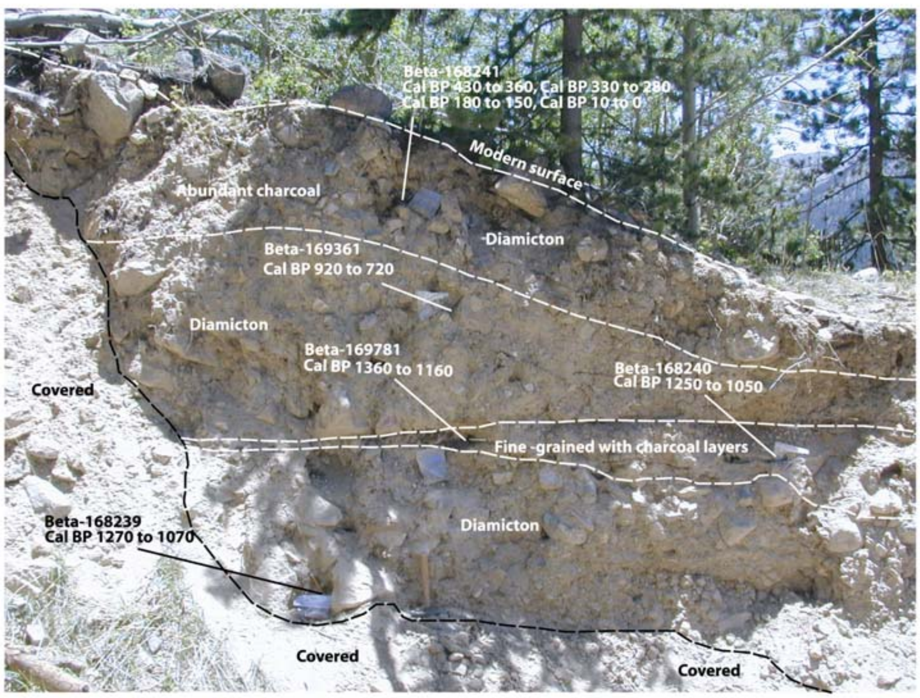

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Figure 13. Fan stratigraphy exposed by the July 1999 debris-flow event. Radiocarbon dates are given as calibrated ages with a 2 standard deviation range. A) Stratigraphy at mouth of Watrous Gulch. See green backpack for scale. B) Stratigraphy at mouth of unnamed gulch immediately east of Watrous Gulch. Unit boundary between Beta-169361 and Beta-168241 is inferred. See quart-sized sample bags and rock hammer for scale.

41.0 Loveland Pass – Continental Divide. Stop here briefly to observe debris flows triggered by the July 1999 storm along the west-facing flanks of Grizzly Peak (fig. 14) and Lenawee Mountain above the Arapahoe Basin ski area (figs. 15 and 16). Proceed west on U.S. Highway 6 toward the Arapahoe Basin ski area.

44.0 Debris flow that closed U.S. Highway 6 and covered the ski area parking lot with debris on July 28, 1999 (fig. 15).

44.1 Turn left onto a small dirt service road leading into the Arapahoe Basin ski area. Permission must be obtained from the Director of Mountain Operations at the Arapahoe Basin ski area base lodge (about 0.9 miles farther west on U.S. Highway 6) to drive motor vehicles on this road. In the summer, hiking and biking are allowed without permission.

45.0 Bear left at the fork in the road.

45.1 Lenawee Mountain ski lift. Park near the base of the lift. **Stop 10. Debris flows in and near the Arapahoe Basin ski area.** Latitude: N 39º 38' 00.8", Longitude: W 105º 52' 02.8", Elevation: 3,493 m (11,460 ft). About 70 debris flows (defined by the number of mappable source areas) were triggered by the July 28, 1999 storm on the west flanks of Grizzly Peak and Lenawee Mountain in and near the Arapahoe Basin ski area. The flows caused about $200,000 worth of damage to ski area facilities, including parking lots, service roads, ski trails, a water treatment plant, and the Arapahoe Basin first-aid room (Henceroth, 2000). Most of the damage was related to clogged culverts that forced the Snake River out of its channel.

Debris flows in and near the ski area were initiated by two different processes, soil-slip processes and fire-hose processes (Godt and Coe, in review). Flows were mobilized from soil slips on steep, tundra-covered slopes (fig. 14), and were mobilized by fire-hose processes on steep, non-vegetated, bedrock slopes with footslope talus (fig. 16). The debris flow that closed U.S. Highway 6 and the upper Arapahoe Basin parking lot (fig. 15) was a composite flow that contained material from both types of processes.

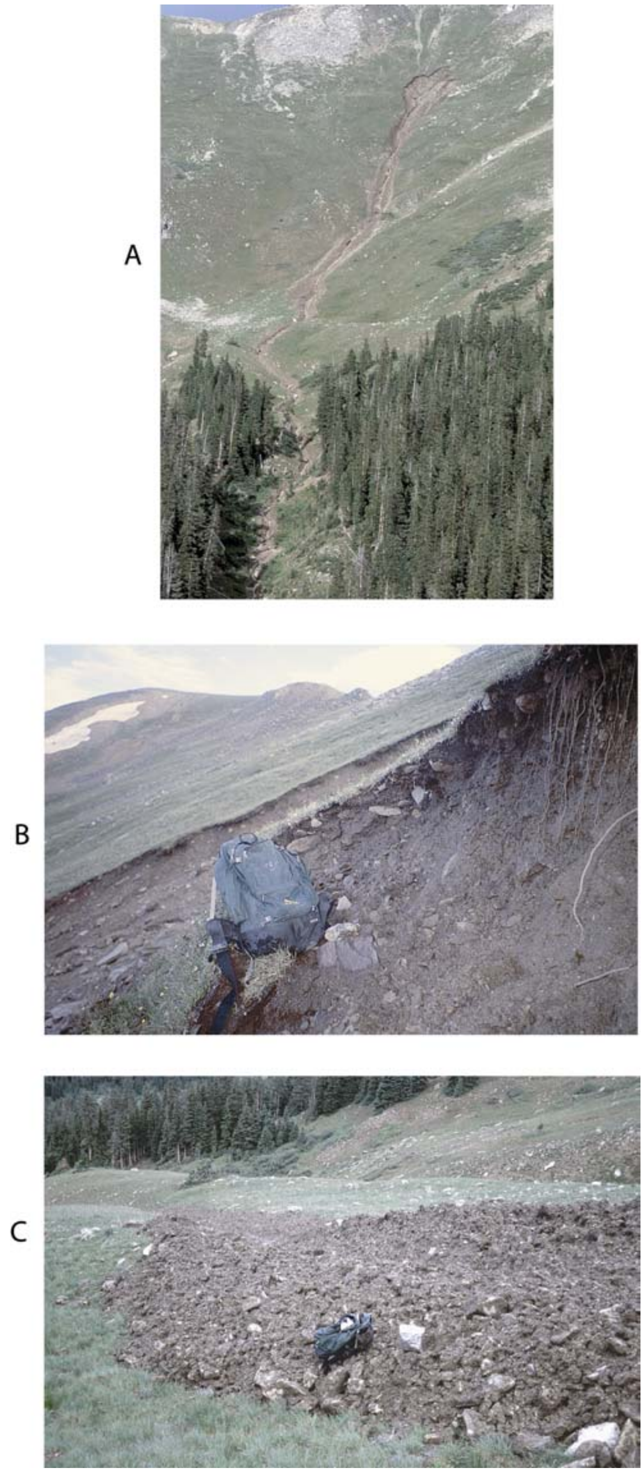

Figure 14. Debris flow mobilized from a landslide (soil-slip) on the west flank of Grizzly Peak near the Arapahoe Basin ski area. Eyewitness accounts indicate that the flow was mobilized on July 29, 1999, instead of July 28, 1999, as were most other debris flows that were triggered by the July 28 storm. A) Overall view of the flow. View to the east. B) Landslide head scarp. View to the north. C) Matrix-supported levee along the south edge of the debris-flow channel. All photos taken on August 10, 1999.

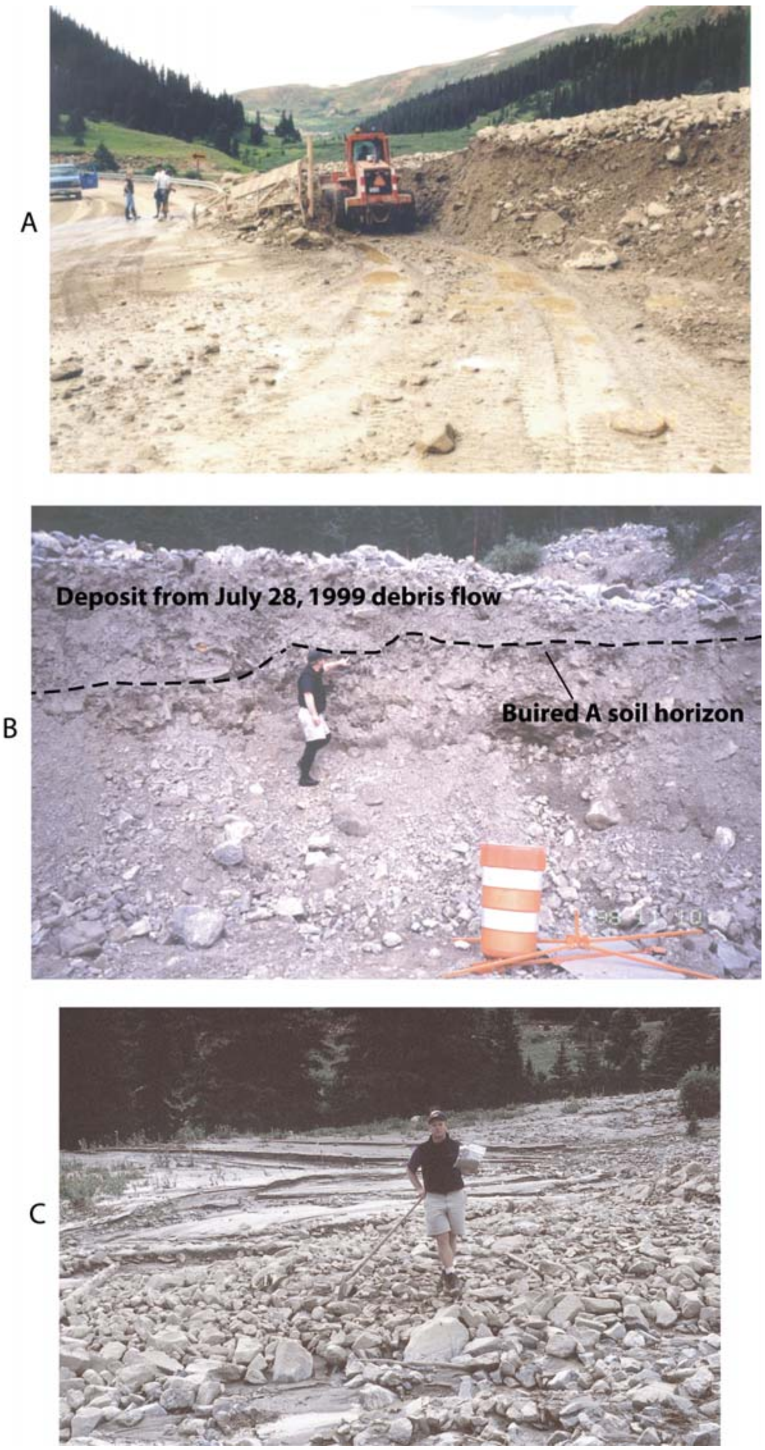

Figure 15. Deposits from July 28, 1999 debris flows near the Arapahoe Basin ski area. A) Deposit that closed U.S. Highway 6. Photograph by CDOT on July 28 or 29, 1999. View to the north. B) Soil horizon buried by July 1999 deposit (same deposit as shown in A but with view to the east). C) Deposit in the upper Arapahoe Basin parking lot. Photos in B and C taken July 29, 1999.

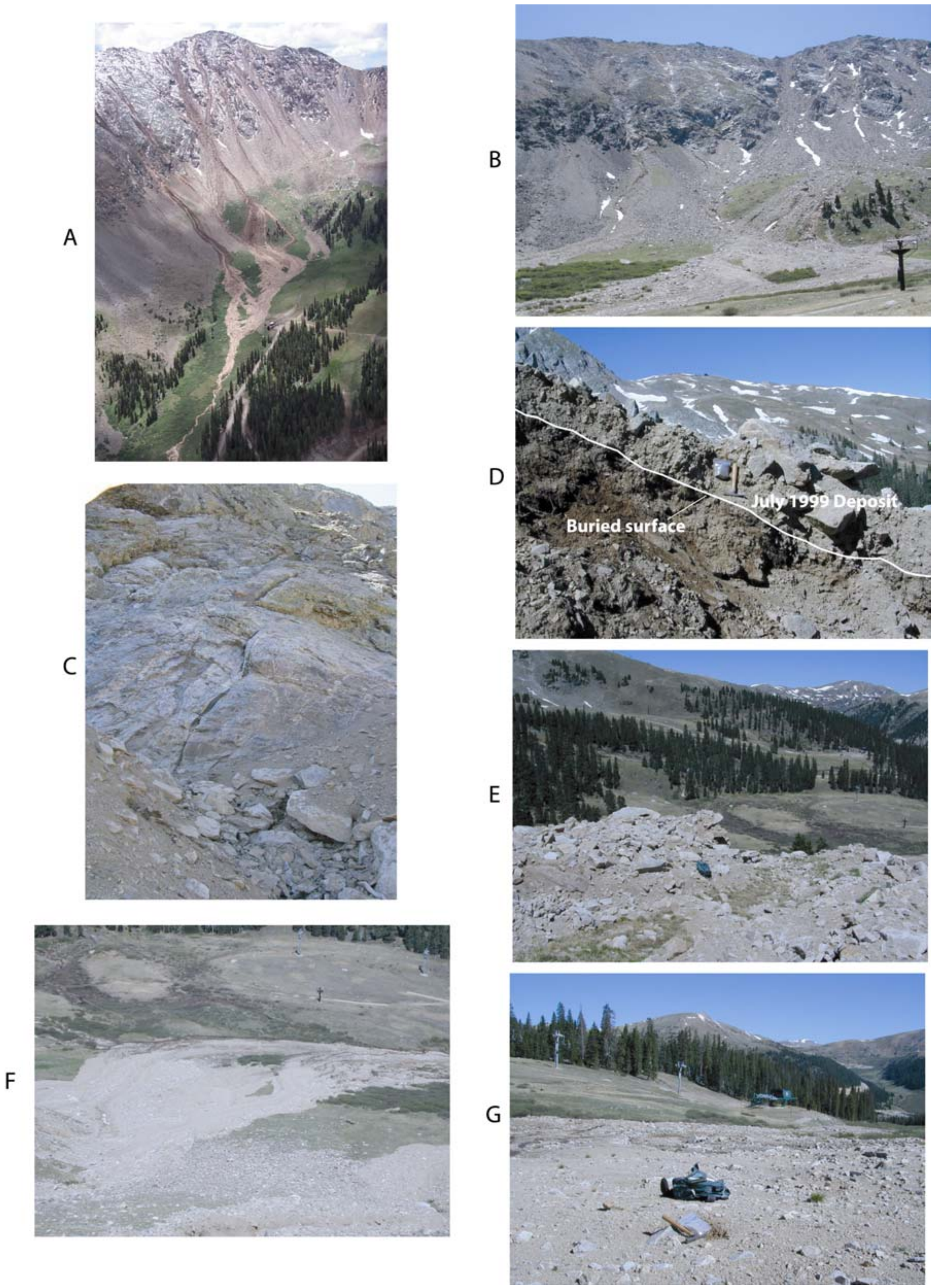

Figure 16. Debris flows within the Arapahoe Basin ski area triggered by the July 28, 1999 storm. A) Overall view of flows on the west flank of Lenawee Mountain.

Figure 16 – continued. Photo by Ed Harp on July 29, 1999. B) Flows on west flank of Lenawee Mountain. Note large talus and debris fans at the base of steep bedrock channels. C) Interface between steep bedrock channel and fan. D) levee deposit on fan immediately below bedrock channel. E) Approximately 2-m thick deposit that was transported over, but did not erode, tundra. F) Main fan deposited by the July 28 debris flow event. Water from the upslope talus fan flows through the fan and emerges at the distal end of the July 1999 fan. G) Surface of fan deposit near the Lenawee Mountain ski lift. Photos B through G taken on June 13, 2002.

The soil-slip variety of debris flows are well studied in different parts of the U.S., but to our knowledge, have not been previously documented in the alpine zone of the U.S. In more temperate parts of the U.S. (for example, the San Francisco Bay area and the Appalachian Mountains), soil-slip debris flows have been described as being caused by a decrease in effective normal stress in hillslope colluvium which leads a reduction in strength and failure (according to Terzaghi's effective stress law, Lamb and Whitman, 1969). The decrease in normal stress is typically attributed to the infiltration of surface water or the perching of a shallow water table (Campbell, 1975; Reid and others, 1988; Iverson and others, 1997). Near Arapahoe Basin, the soil-slip debris flows initiated in colluvium with a thin A soil horizon (fig. 14). The matrix of colluvium exposed at the headscarp of the largest soil slip (fig. 14b) is composed of 61 percent sand-sized material, 31 percent silt-sized material, and 8 percent clay-sized material (Godt and Coe, in press). The basal slip surface of the soil slips was typically 1-2 meters below the ground surface but still within the colluvium, and not at the boundary between colluvium and bedrock as frequently described for soil slips in other areas. The flows deposited poorly sorted, matrix supported levees and lobes (fig. 14). The matrix of the levee deposit shown in figure 14c is composed of 59 percent sand-sized material, 31 percent silt-sized material, and 10 percent clay-sized material (Godt and Coe, in press).

The soil-slip debris flow shown in figure 14 was reported by Mark Atkins of the Asphalt Paving Company to have failed on July 29, 1999, one day after the rainstorm. This observation suggests that the decrease in effective normal stress that caused the soil slip to fail may have resulted from slow, topographically forced convergence of flow, rather than the infiltration of rainfall. The position of the soil slip in a channel (fig. 14a) makes such a mechanism possible.

The fire-hose variety of debris flows have been documented in many parts of the US (Fryxell and Horberg, 1943; White, 1981, Johnson and Rodine, 1984; Coe and others, 1997b), including Colorado (Curry, 1966), but are generally not considered as common as soil-slip debris flows. Fire-hose debris flows are generally described as being caused by the mobilization of material when it is impacted by the concentrated flow of water. Near Arapahoe Basin, the hillslope morphology is favorable to fire-hose debris flows because it is characterized by steep, bare or nearly bare, bedrock (Tertiary quartz monzonite, Bryant and others, 1981) slopes that collect and concentrate snowmelt or rainfall into channels or couloirs (fig. 16a, b and c). The July 1999 debris flows occurred when intense rainfall was concentrated in the couloirs, flowed down the slopes, and impacted footslope talus deposits (Godt and Coe, in review). Debris flows were mobilized from the footslope talus, deep gullies were eroded into the heads of the talus deposits (fig.16b, c, and d), and debris-flow levees and fans were formed downslope (fig. 16d, e, f, and g). In some locations, debris was transported over gentle to moderately sloping tundra surfaces (without incision into the surfaces) and deposited as levees and lobes up to several meters thick (fig. 16e). The matrix of the debris-flow deposits (fans and levees, 1 sample each) is composed of 67-73 percent sand-sized material, 23-25 percent silt-sized material, and 2-10 percent clay-sized material (Godt and Coe, in press).

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. Because snowfall between 2000 and 2002 has been at or below average (Arapahoe Basin ski area, unpublished data), 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.

End of field trip.

ACKNOWLEDGEMENTS

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REFERENCES

Adams, D.K. and Comrie, A.C., 1997, The North American Monsoon: Bulletin of the American Meteorological Society, v. 78, p. 2197-2213.

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.

Braddock, W.A., 1969, Geology of the Empire quadrangle, Grand, Gilpin, and Clear Creek Counties, Colorado: U.S. Geological Survey Professional Paper 616, 56 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., Parett, C., and Parise, M, in press, Wildfire-related debris-flow generation through episodic progressive sediment bulking processes, western USA: Proceedings of the Third International Conference on Debris-flow hazards mitigation, mechanics, prediction, and assessment, September 10-15, 2003, Davos, Switzerland.

Coe, J.A. and Godt, J.W., 1997a, Characteristics of alluvial fans from tributaries of Clear Creek, Floyd Hill to Georgetown, Colorado: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A-316.

Coe, J.A., Glancy, P.A., and Whitney, J.W., 1997b, Volumetric analysis and hydrologic characterization of a modern debris flow near Yucca Mountain Nevada: Geomorphology, v. 20, p. 11-28.

Coe, J.A., Godt, J.W., Parise, M., 1998, Evaluation of stream and debris flow hazards on small fans along the Interstate-70 highway corridor, Central Colorado, U.S.A., 23rd General Assembly, European Geophysical Society, Nice, France, April, 1998, Annales Geophysicae, v. 16, Supplement IV, p. C1215.

Coe, J.A., Michael, J.A., Crovelli, R.A., and Savage, W.Z., 2000, Preliminary map showing landslide densities, mean recurrence intervals, and exceedance probabilities as determined from historic records, Seattle, Washington: U.S. Geological Survey Open-File Report 00-303, 25 p.

Coe, J.A., Godt, J.W., Parise, M., Moscariellio, A., in press, A method for estimating debris-flow probability using fan stratigraghy and drainage-basin morphology, Interstate 70 highway corridor, central Colorado, U.S.A.: Proceedings of the Third International Conference on Debris-flow hazards mitigation, mechanics, prediction, and assessment, September 10-15, 2003, Davos, Switzerland.

Costa, J.E., 1984, Physical geomorphology of debris flows, *in* Costa, J.E. and Fleisher, P.J., eds., Developments and applications of geomorphology: Springer-Verlag, Berlin, p. 268-317.

Crovelli, R.A., 2000, Probability models for estimation of number and costs of landslides: U.S. Geological Survey Open-File Report 00-249, 23 p.

Curry, R.R., 1966, Observation of alpine mudflows in the Tenmile range, central Colorado, Geological Society of America Bulletin, v. 77, p. 771-776.

Fryxell, F.M. and Horberg, L., 1943, Alpine mudflows in Grand Teton National Park, Wyoming: Geological Society of America Bulletin, v. 54, p. 457-472.

Godt, J.W. and Coe, J.A., in press, 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.

Godt, J.W. and Coe, J.A., in review, Alpine debris flows triggered by a July 28, 1999 thunderstorm in the Central Front Range, Colorado: Earth Surface Processes and Landforms.

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.

Hecox, G.R., 1977, Engineering geology and geomorphology in northeast Clear Creek County, Colorado, Colorado School of Mines Masters Thesis T-1962, 131 p.

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

Horton, R.E., 1945, Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology: Geological Society of America Bulletin, v. 56, p. 275-370.

Iverson, R.M., 1997, The physics of debris flows: Reviews in Geophysics, v. 35, p. 245-296.

Johnson, A.M. & Rodine, J.R., 1984, Debris Flow, *in* D. Brunsden & D.B. Prior (eds.), Slope Instability: John Wiley and Sons Ltd., Chichester, p. 257-361.

Lamb, T.W. and Whitman, R.V., 1969, Soil Mechanics: John Wiley & Sons, New York, 553 p.

Lovering, T.S., 1935, Geology and ore deposits of the Montezuma quadrangle, Colorado: U.S. Geolgoical Survey Professional Paper 178, 119 p.

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.

Melton, M.A, 1965, The geomorphic and paleoclimatic significance of alluvial deposits on southern Arizona: Journal of Geology, v. 73, p. 1-38.

Pelizza, M.S., 1978, Environmental and surficial geology in east central Clear Creek County, Colorado, Colorado School of Mines Masters Thesis T-1895, 102 p.

Reid, M. E., Nielsen, H.P., and Dreiss, S.J., 1988, Hydrologic factors triggering a shallow hillslope failure: Bulletin of the Association of Engineering Geologists, v. 25, p. 349-361.

Robinson, C.S., Rife, D.L., and Johnson, T.D., 1974, Mining and mountain development, Field Trip Number 2: unpublished field-trip guidebook for the Association of Engineering Geologists Annual Convention, Denver Colorado, October, 1974.

Ross, S.M., 1972, Introduction to probability models: Academic Press, Inc., New York, 273 p.

Sheridan D.M. and Marsh, S.P., 1976, Geologic map of the Squaw Pass quadrangle, Clear Creek, Jefferson, and Gilpin Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-1337.

Sims, P.K., 1964, Geology of the Central City quadrangle, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-267.

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.

Soule, J. M., 1975, Idaho Springs area geologic hazards, Colorado Geological Survey Open File Map #5.

Soule, J.M., 1999, Active surficial-geologic processes and related geologic hazards in Georgetown, Clear Creek County, Colorado: Colorado Geological Survey Open-File Report 99-13.

Spurr, J.E., Ball, S.H., and Garrey, G.H., 1908, Geology of the Georgetown quadrangle (together with the Empire district), Colorado: U.S. Geological Survey Professional Paper 63, 422 p.

Terzaghi, K., Peck, R.B., Mesri, G., 1996, Soil mechanics in engineering practice: John Wiley, New York, 549 p.

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

White, S.E., 1981, Alpine mass movement forms (noncatastrophic):Classification, description, and significance: Arctic and Alpine Research, v. 13, no. 2, p. 127-137.

Widmann, B.L., Kirkham, R.M., Beach, S.T., 2000, Geologic map of the Idaho Springs Quadrangle, Clear Creek County, Colorado: Colorado Geological Survey Open-File Report 00-2, 22 p.

Widmann, B.L. and Miersemann, U., 2001, Geologic map of the Georgetown Quadrangle, Clear Creek County, Colorado: Colorado Geological Survey Open-File Report 01-5, 22 p.

Woodward-Clyde & Associates consulting report, 1970, Engineering and geologic investigation for the proposed Georgetown dam enlargement: Consulting Report for Job No. 12346.