HISTORICAL DEBRIS FLOWS ALONG THE INTERSTATE-70 CORRIDOR IN CLEAR CREEK COUNTY, CENTRAL COLORADO

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Key Terms: debris flow, Interstate 70, Clear Creek County, Idaho Springs, Georgetown, Brownville, rainfall, monsoon, snowmelt

ABSTRACT

We have compiled information on 19 historical debris-flow events along the Interstate-70 corridor in Clear Creek County. Twelve of these events were triggered by rainfall, and seven by snowmelt. Of the twelve triggered by rainfall, ten were caused by rainstorms during July and August. At least five of the seven snowmelt-triggered events involved failures of mine dumps that were located in drainage channels. Debris flows were most common on steep, south-facing hillslopes above the maximum extent of Pleistocene glaciation. Observations of recent debris flows suggest that most flows were initiated by erosive processes of rilling and/or a "fire-hose" effect, in which overland flow that is concentrated in bedrock-lined channels impacts and mobilizes debris from talus deposits and the heads of debris fans.

INTRODUCTION

The Interstate-70 (I-70) corridor in Clear Creek County (Figure 1) has been repeatedly identified by the Colorado Geological Survey (CGS) as one of the most serious landslide hazard areas in Colorado (Colorado Water Conservation Board, 1985; Jochim et al., 1988; Rogers, 2003). The CGS uses the term "landslide" to include all types of slope failures, including debris flows. The I-70 corridor in Clear Creek County is listed by the CGS as a debris-flow and rockfall hazard area. In this area, I-70 transects the Front Range along Clear Creek, an eastward-flowing, formerly glaciated drainage. Debris flows initiate in tributary drainages of Clear Creek and can transport debris from above timberline to multiple lanes of I-70. This paper documents historical debris flows that have occurred along the I-70 corridor in Clear Creek County. We include debris flows that occurred within the corridor prior to the construction of I-70 in the 1960s and 1970s. Our hope is that the information contained in this paper will contribute to an understanding of debris-flow triggers, processes, frequencies, and hazards in Clear Creek County.

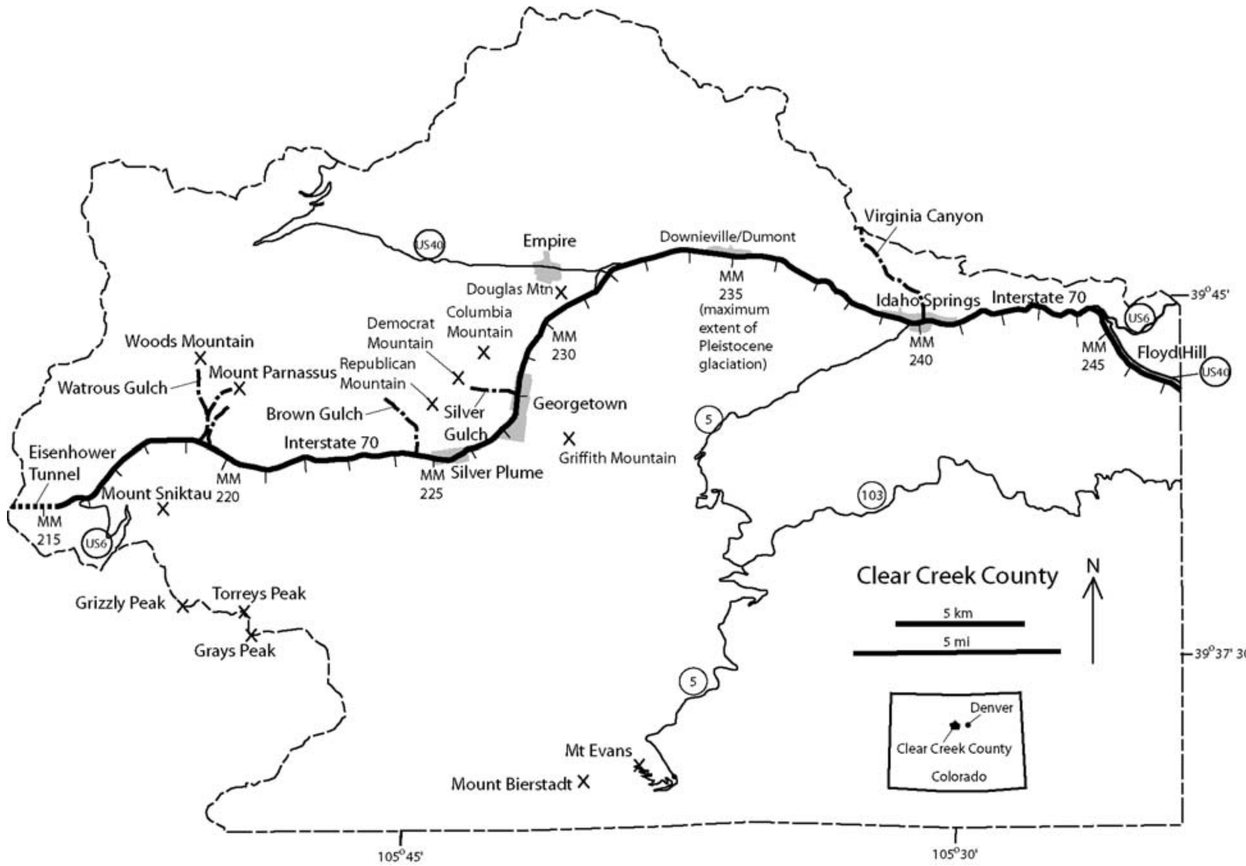

Figure 1. Map showing location of Clear Creek County and Interstate 70. The area is within the north-south trending Front Range, the eastern-most mountain range in Colorado. Shaded areas are towns. Road and highway numbers are labeled. Mile markers (MM) are shown as tick marks along I-70.

SETTING

Physiographic

The Clear Creek valley in Clear Creek County is located from about 19 mi (30 km) to 47 mi (75 km) west of Denver. The upper part of the Clear Creek valley (elevations above about 7950 ft (2420 m)) was repeatedly glaciated during the Pleistocene (Madole et al., 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 et al., 1998). The maximum extent of Pleistocene glaciation is located near Dumont (elevation of about 7950 ft (2420 m), Figure 1, Madole et al., 1998). Above this boundary, the Clear Creek valley typically has steep walls and small, 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, moderately steep tributary drainage basins. Below the glacial limit, Pleistocene gravels are present 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.

The area is underlain predominantly by Precambrian biotitic gneiss and quartz monzonite with scattered Tertiary intrusions (Spurr et al., 1908; Lovering, 1935; Sims, 1964; Braddock, 1969; Sheridan & Marsh, 1976; Bryant et al., 1981; Widmann et al., 2000; Widmann & Miersemann, 2001) with associated hydrothermal alteration and silver-and-gold mineralization (Harrison & Wells, 1956; Sims & Gable, 1967). The zone of mineralization that encompasses the area extends from southwestern Colorado to the Front Range northwest of Denver, and is known as the Colorado Mineral Belt (Tweto & 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 7220 ft (2200 m) at Floyd Hill to about 10,990 ft (3,350 m) at the east entrance to the Eisenhower tunnel. Mountain peaks adjacent to the Clear Creek valley range up to about 14,270 ft (4350 m) in elevation. Mean annual precipitation ranges from about 15 in (380 mm) in Idaho Springs (elevation 8150 ft (2,484 m)) to about 33 in (840 mm) near Grizzly Peak (elevation 11,949 ft (3642 m)) near the Arapahoe Basin ski area (Western Regional Climate Center, 2003, 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. Timberline is at an elevation of about 11,480 ft (3,500 m). Above timberline, 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 soil conditions that are cooler and wetter on the south side, and warmer and drier on the north side.

Interstate 70

Interstate 70 (I-70) in Colorado is the main east-west highway 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 (Figure 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 & Lovekin, 2002; Arndt et al., 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 individual tunnels that 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 & Lovekin, 2002).

Previous work on debris flows along Interstate 70

Recent debris flows, as well as Holocene debris-flow deposits, have shown that the Front Range part of the I-70 corridor is susceptible to debris-flow hazards (Soule, 1975; Hecox, 1977; Pelizza, 1978; Coe & Godt, 1997; Coe et al., 1998; Soule, 1999; Henceroth, 2000; Coe et al. 2002; Godt & Coe, 2003; Andrew & Lovekin, 2002; Widmann & Rogers, 2003). Debris flows along I-70 in Clear Creek County initiate on hillslopes 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. An analysis of historical 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 et al., in press). Mean recurrence intervals ranged from about 7 to 2900 yrs. 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 et al., 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 is unitless and is defined as $H/(A)^{0.5}$, where H is basin height upstream from the fan and A is basin area upstream from the fan (Melton, 1965). Melton's Numbers can be easily derived from a Digital Elevation Model (DEM). Basins that are small and steep have higher Melton's Numbers than larger basins with low-to-moderate relief. A regression analysis of mean recurrence intervals and Melton's Numbers from the 19 fans and corresponding basins yielded the equation $y=19{,}400\exp^{-4.67x}$, where y is mean recurrence interval in years and x is Melton's Number (Figure 2). Following verification through further work (see Coe et al., in press), it may be possible to use this equation to estimate the mean recurrence interval for debris flows on fans with no historical or stratigraphic records from the Melton's Numbers of the corresponding drainage basins.

Observations of debris flows along I-70 that we have made since the summer of 1996 (described in Coe et al., 2002; Godt & Coe, 2003; and Coe et al., in press) 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 were to occur 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 are dominated by flood events (Coe et al., in press), rather than 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.

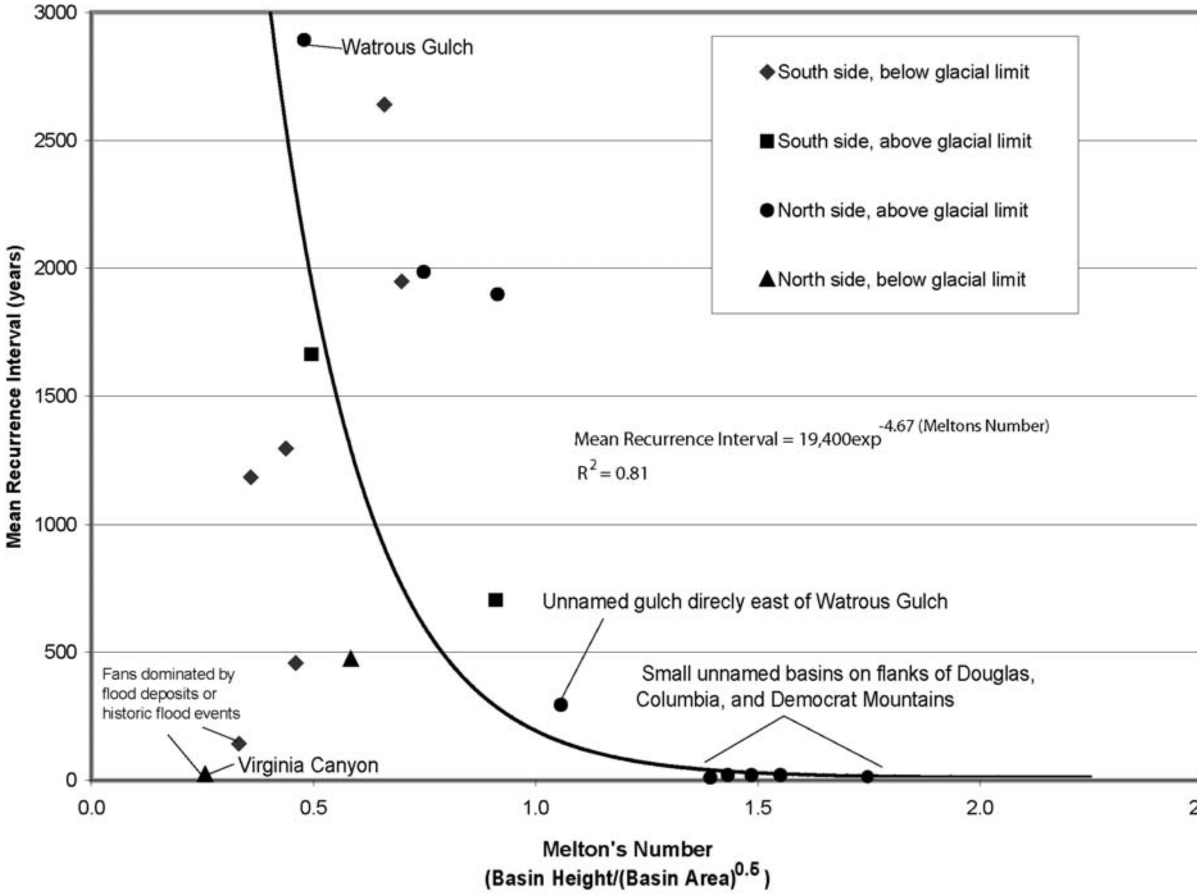

Figure 2. Scatter plot showing mean recurrence interval data from fans, and Melton's Number data from corresponding basins along I-70 in Clear Creek County (from Coe et al., in press). Mean recurrence interval data were derived from stratigraphic and/or historical data at each fan. A regression analysis yielded the best-fit line and equation. Fans dominated by flood deposits or historical flood events were not used in the regression analysis. Fans/basins with historical debris-flow events discussed in the text are labeled. Location of fans on the north or south side of I-70, and above or below the glacial limit, is also shown.

METHODS

For this paper, we compiled information on historical debris flows using newspaper articles, published reports, eyewitness accounts, and personal observations. We searched for newspaper articles that described slope failures using the keywords "avalanche", "mudslide", "earth movement", "landslide", "rockslide", and "flood". If an article described a generally fast-moving slope failure and that carried debris (mud, rocks, vegetation, etc.), we classified the failure as a debris flow. Newspaper articles in the *Rocky Mountain News* and *Denver Post* were reviewed using on-line, hard copy (annual book), and card catalog versions of subject indices available through the Denver Public Library. Publication of the *Rocky Mountain News* and *Denver Post* began in 1859 and 1895, respectively. The *Rocky Mountain News* is indexed in on-line form from 1989 to present, whereas the *Denver Post* is indexed in either book or on-line form from 1979 to present. Card catalog subject indices available at the library were sporadically created throughout the 1990s, and are therefore incomplete. Microfilm versions of both newspapers are available from the initial publication date to the present. We attempted a comprehensive search of each newspaper by visually scanning microfilm tapes and found that it took about 1 hr to review 20 days of daily newspapers (two microfilm tapes). At this rate, it would take about 1800 hrs to review 100 yrs of daily newspaper articles. For this reason, we have not done a comprehensive review of newspaper articles available on microfilm.

Transcripts of landslide-related articles from Clear Creek County newspapers from the late 1880s through the early 1900s were provided by Christine Bradley, the Clear Creek County Archivist. She provided articles from the *Colorado Miner* and *Georgetown Courier* (both Georgetown newspapers) and the *Silver Standard* (a Silver Plume newspaper).

The record of historical debris flows documented in this paper is incomplete because newspaper articles prior to 1979 were not systematically indexed or searched, and because there have undoubtedly been debris flows that were not observed or recorded in any report or newspaper.

HISTORICAL DEBRIS FLOWS

We have documented 19 historical debris-flow events that occurred adjacent to the location of I-70 in Clear Creek County (Table 1). We define a debris-flow event as an occurrence of debris flow(s) in one or more basins. Fourteen of the debris-flow events initiated in tributary basins above the glacial limit on the north side of the highway (Figure 1). There were two types of triggers for debris flows along I-70: rainfall (12 events) and snowmelt (seven events). Ten of the 19 debris-flow events were triggered by rainstorms during July and August, storms that are commonly associated with the northerly flow of monsoon moisture from the Gulf of California and Eastern Pacific Ocean (referred to as the North American Monsoon by Adams & Comrie (1997)). This pattern has also been observed in the San Juan Mountains of southwestern Colorado, where more than 90 percent of historical debris flows have been triggered by rainstorms in the months of July and August (Coe & Burke, 2003). At least five of the seven snowmelt-triggered debris flows were related to failures of mine dumps located in channels.

There were debris flows that we identified during our compilation that were in Clear Creek County, but not directly along I-70, and therefore not listed in Table 1. These debris flows included several hundred that were triggered by a rainstorm on July 28, 1999 (see Godt and Coe, 2003, for map and description), as well as two more that occurred on July 16, 2000, and resulted in closures of Colorado Highways 5 and 103 near Mount Evans (Vaughan & Kass, 2000).

Our compilation also revealed information on several historical deep-seated landslides in Clear Creek County. Although we did not systematically compile these landslides for this paper, several are worthy of mention. These include the Floyd Hill landslide (Rocky Mountain News, 1947; Robinson et al., 1974), the Loveland Basin landslide (Robinson & Lee, 1972), the Clear Creek Forks landslide (Savage et al., 1998), and a landslide near the Lower Cabin Creek Dam south of Georgetown that killed three people in 1965 (Myers, 1965).

Below, we describe the historical debris-flows locations that have had repeated events or single events that have greatly impacted the I-70 corridor. We begin with locations near the eastern edge of the County and proceed to the west.

Idaho Springs and vicinity

The historical debris-flow event located farthest east in Clear Creek County is on the north flank of Floyd Hill near mile marker 245 (Figures 1 and 3, Event 1 in Table 1). To our knowledge, this was the only debris flow triggered by a rainstorm in late July 2000. This debris flow initiated as a shallow landslide (also referred to as a soil slip, Campbell, 1975; also see Reid et al., 1988 and Iverson et al., 1997) in fill material beneath I-70 (Figure 3). Another debris flow occurred at Floyd Hill on July 8, 2001 (Event 2, Table 1). This debris flow deposited debris on the eastbound lane(s) of the highway.

Figure 3. Debris flow along the north flank of I-70 at Floyd Hill. View is to the south. Photo taken August 4, 2000. See guard rails along I-70 and US Highway 40 for scale.

Small drainage basins on the north side of Idaho Springs, as well as the basins directly west of town along I-70, have had historical debris-flow occurrences (Events 3 and 4 in Table 1). These basins tend to be small and steep.

A much larger drainage basin near Idaho Springs that is recognized as a hazardous area is Virginia Canyon (Figure 1). Hillslopes in Virginia Canyon have a long history of mining activity (Stewart & Severson, 1994), and the Virginia Canyon channel contains an abundance of debris, some of which originated from mine dumps. The mouth of Virginia Canyon in Idaho Springs has a history of water-dominated (flood) or hyperconcentrated flow (Pierson and Costa, 1987) events, but to our knowledge, not debris-flow events. Herron et al. (2001) reported that *"… in recent years that there have been several thunderstorms that have resulted in flooding of the housing area near the confluence …"* of Virginia Canyon and Clear Creek. There have been water-dominated or hyperconcentrated flows in the Canyon and on the fan in August 1994, possibly in July 1997, and in July 1998. We have visited the fan and canyon multiple times and have observed deposits following the 1998 event. The hazardous area during flow events is along the channel near the mouth of the canyon. During such events, water and debris run down the channel, as well as on the road. This presumably occurs because culvert pipes get clogged with debris. Houses near the channel are also impacted by these events. One structure is built on top of the channel and others have structural components anchored within the channel. Once flows reach the fan, they are contained within a concrete-lined channel.

Debris flows on the flanks of Douglas, Columbia, and Democrat Mountains

The most active debris-flow area along I-70 is on the north side of the highway between the US Highway 40/I-70 junction and Georgetown along the southern and eastern flanks of Douglas, Columbia, and Democrat Mountains (Figures 1, 4-6, Events 5-11 in Table 1). The valley in this area has been glaciated and is U-shaped with small and steep tributary basins (Figure 4). Tributary basins in this area tend to have Melton's Numbers greater than 1, are sparsely vegetated, and are dominated by bedrock slopes in their upper portions and fan aprons in their lower portions. The mean recurrence interval between recent debris-flow events in this area is about 7 yrs or less (Coe et al., in press).

Debris flows in this area tend to initiate from hillslope and channel erosion, not from discrete landslide source areas as documented in many other parts of the United States. Two processes are responsible for mobilizing debris, a "fire-hose" process (Johnson & Rodine, 1984; Fryxell & Horberg, 1943; and Curry, 1966), and a progressive rilling process. The fire-hose process begins when flowing water in steep bedrock channels crosses talus or debris-fan material at the base of steep bedrock slopes. When the concentrated water-dominated flows impact these materials, they erode and mobilize debris. Progressive rilling is the concentration of flow that mobilizes loose sediment primarily at knickpoints and plunge pools (Horton, 1945; Johnson & Rodine, 1984; Cannon et al., in press). Debris flows that initiate by these processes in this area tend to travel short distances (less than 0.6 mi (1 km)) and deposit volumes of material less than 1300 yd^3 (1000 m^3).

Figure 4. Oblique aerial photo showing historical debris-flow areas near Georgetown. U.S. Geological Survey photograph taken on August 18, 1999 by Intrasearch, Inc. View is to the north.

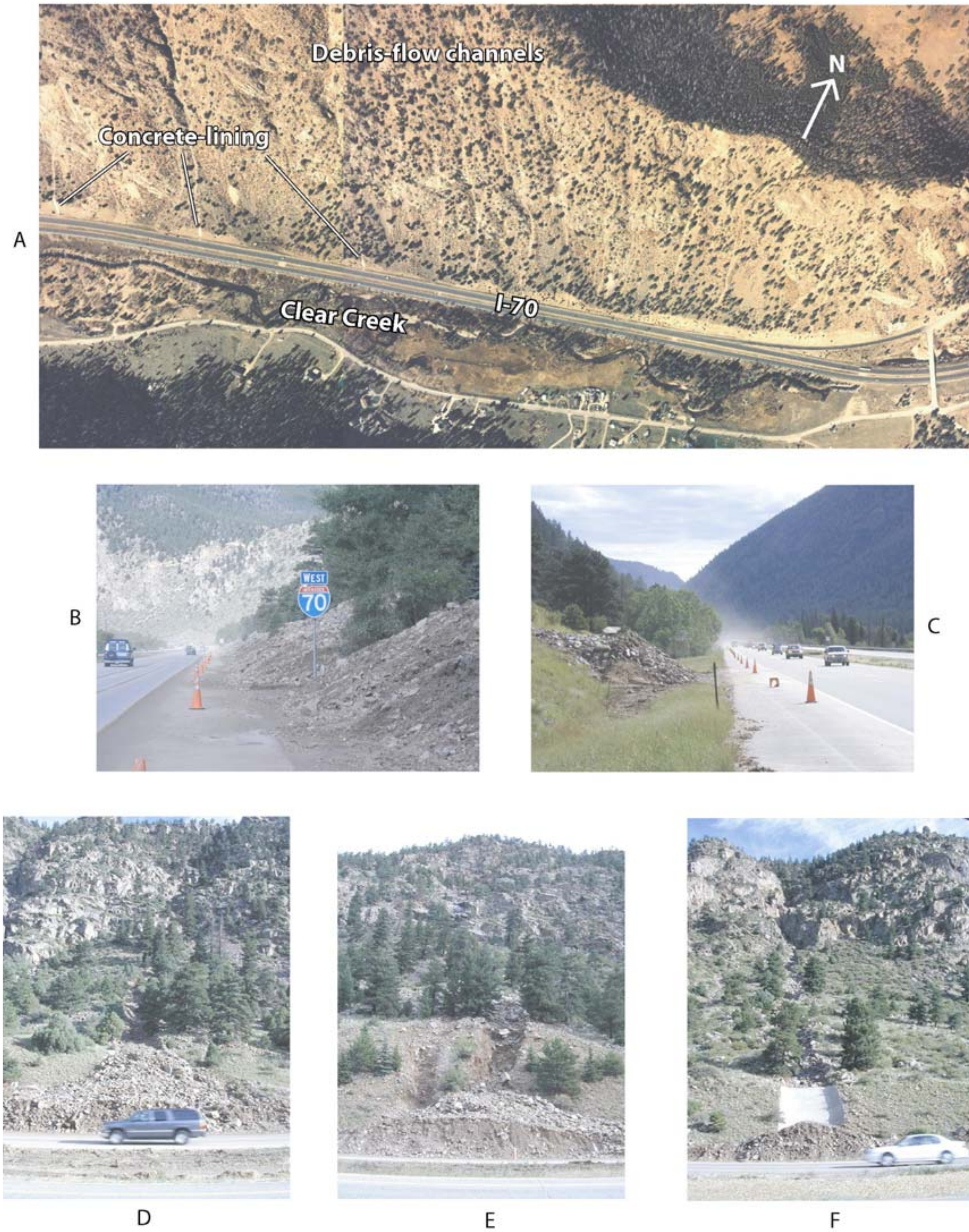

Figure 5. Debris flows along I-70 on the south flank of Douglas Mountain near the junction of I-70 and U.S. Highway 40. A) Aerial photograph of the area. Photograph taken October 12, 1996. B) Piles of debris from flows on July 13, 2001. View to southwest. C) Deposit and dust from July 13 debris flows.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

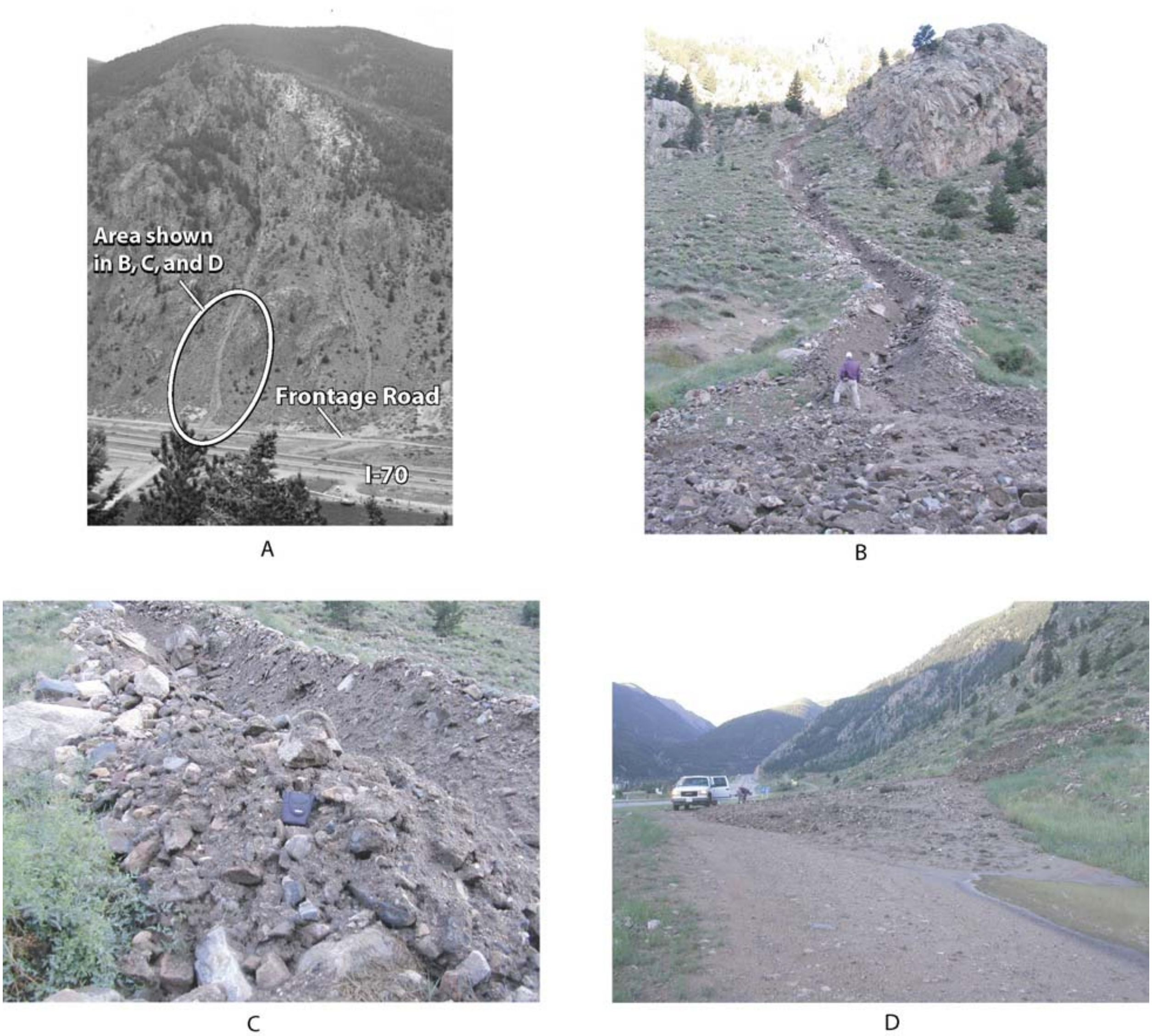

Figure 6. Drainage basin and July 13, 2001, debris-flow deposits near Georgetown (see Figure 4 for location). A) Drainage basin. Photograph taken August 30, 1996. B) Debris-flow channel. C) Matrix-supported debris-flow levee. Note camera case for scale. D) Fan formed by deposit. Photos B, C, and D were taken July 14, 2001.

A recent debris-flow event that affected this portion of I-70 was triggered by an afternoon rainstorm on July 13, 2001 (Event 7 in Table 1). The storm triggered about 13 debris flows that deposited debris on the west-bound lane of I-70 (Figure 5) between mile markers 230.5 and 231.5. Debris on westbound lanes was as much as about 10 ft (3 m) thick and extended to the highway centerline. The Colorado Department of Transportation (CDOT) closed the Interstate between the Empire and Georgetown exits for about 4 hrs while debris was cleared from one westbound lane. Much of the mobilized debris came from the oversteepened, cut-slope portion of the talus fan directly adjacent to I-70 (Figure 5e). In order to minimize the amount of material mobilzed from the cut-slope part of the talus fans, CDOT had previously installed concrete linings in cut-slope channels along the most active debris-flow paths (Figures 5a and 5f).

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 Figures 5e and 5f).

One of the best locations to observe July 2001 debris-flow features in the area is on the north side of I-70 near Georgetown (Figure 6). The fan at this location is matrix-supported, poorly sorted, and contains randomly oriented clasts. Grain-size analysis (U.S.Geological Survey, 1999, unpublished data) of a similar deposit at the same location that resulted from a July 27 or 28, 1999, rainstorm (Event 11, Table 1) 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 (e.g., see Figure 6c).

Grain-size data throughout this paper are presented on the basis of an 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.

Silver Gulch

A type of debris flow that differs from those described above was triggered by spring snowmelt in Silver Gulch (Figures 1 and 4) in May 1872 (Event 9 in Table 1). Silver Gulch is an atypical basin for the area in that it is relatively large (Melton's Number: 0.76). On May 28, 1872, snowmelt and runoff from streams and springs triggered a landslide along the bank of Silver Creek near the Beecher Silver Mine. The landslide dammed Silver Creek about noon on May 28. The landslide dam failed and the rushing water carried wood, logs, and debris downstream where it formed another dam estimated to be about 40 ft (12 m) high. This second dam failed about 12:30 pm and the rushing water mobilized debris and carried it to the fan at the mouth of the basin where it damaged several houses and deposited debris as much as about 6 ft (2 m) deep.

Brown Gulch

Brown Gulch (Figures 1, 7, and 8, Melton's Number: 0.53) was the site of at least 5 debris-flow events between 1889 and 1912 (table 1, Events 14-18). The primary source of debris in the flows was mine-waste dumps located within the Gulch. Most of the mobilized debris came from the waste dump of the Seven-Thirty mine (Figure 7) located at an elevation of about 10,450 ft (3,185 m), about 1200 ft (365 m) upstream from the fan (Figure 7) 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* (1892) 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 (Figure 8) revealed that a large part of the dump is still present (Figures 8a and 8b) and that it lies adjacent to the channel (Figure 8c). 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.

Mount Parnassus and vicinity

On July 28, 1999, about 480 alpine debris flows were triggered by an afternoon rainstorm along and near the Continental Divide in Clear Creek and Summit Counties (Godt & Coe, 2003). The rainstorm dropped 1.7 in (43 mm) of rain in 4 hrs, most of which (1.4 in (35 mm)) fell in the first 2 hrs (Event 19, Table 1). Field observations of debris-flow source areas indicate that the debris flows were initiated by three processes, fire hose, coalescing rills, and soil slips, with the first two processes being responsible for most of the debris flows (Godt and Coe, 2003).

Several debris flows triggered by the storm affected I-70, U.S. Highway 6, and the Arapahoe Basin ski area. Several debris flows initiated on the south flank of Mount Parnassus (Figures 1 and 9, Event 19 in table 1), traveled about 1.5 mi (2.5 km) down Watrous Gulch and an unnamed gulch directly to the east of Watrous Gulch, and deposited about 34,000 yds (26,000 m^3) of debris on I-70 (Al Chleborad, 1999, written communication), closing the highway for about 25 hrs. Fortunately, little permanent damage to public or private property and no injuries or fatalities resulted from any of the flows.

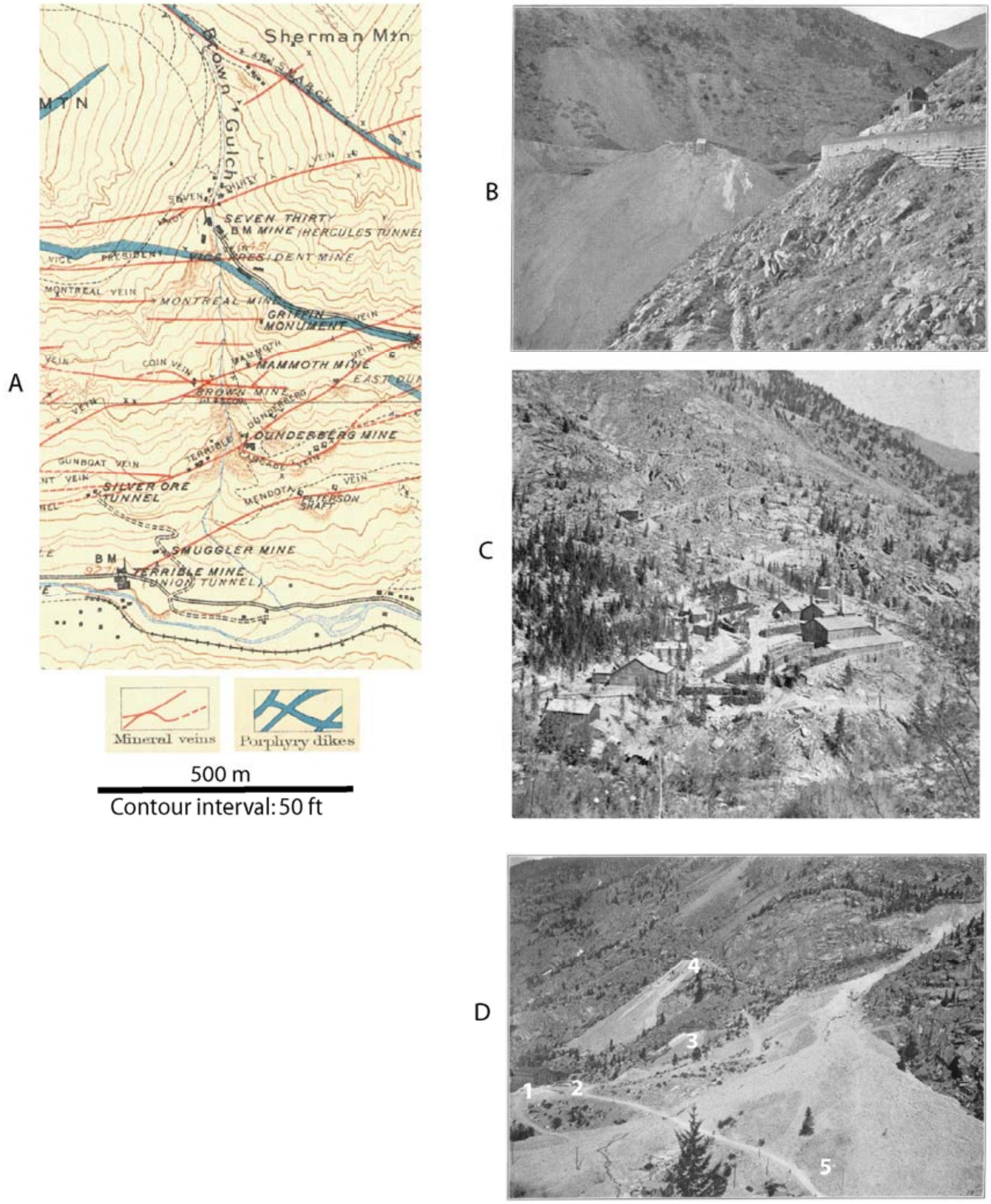

Figure 7. Map and photos of Brown Gulch in late 1800s and early 1900s (A, B, and D from Spurr et al. (1908); C from Denver Public Library Historical Photograph Collection, number X-7236). A) Map made in 1906 showing topography, mines, and veins and dikes in Brown Gulch and vicinity. B) Seven-Thirty mine and dump in Brown Gulch looking northwest from the Griffin monument. C) Fan at the mouth of Brown Gulch taken between 1886 and 1898. View to the northeast. Compare to Figures 7D and 8F. D) 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.

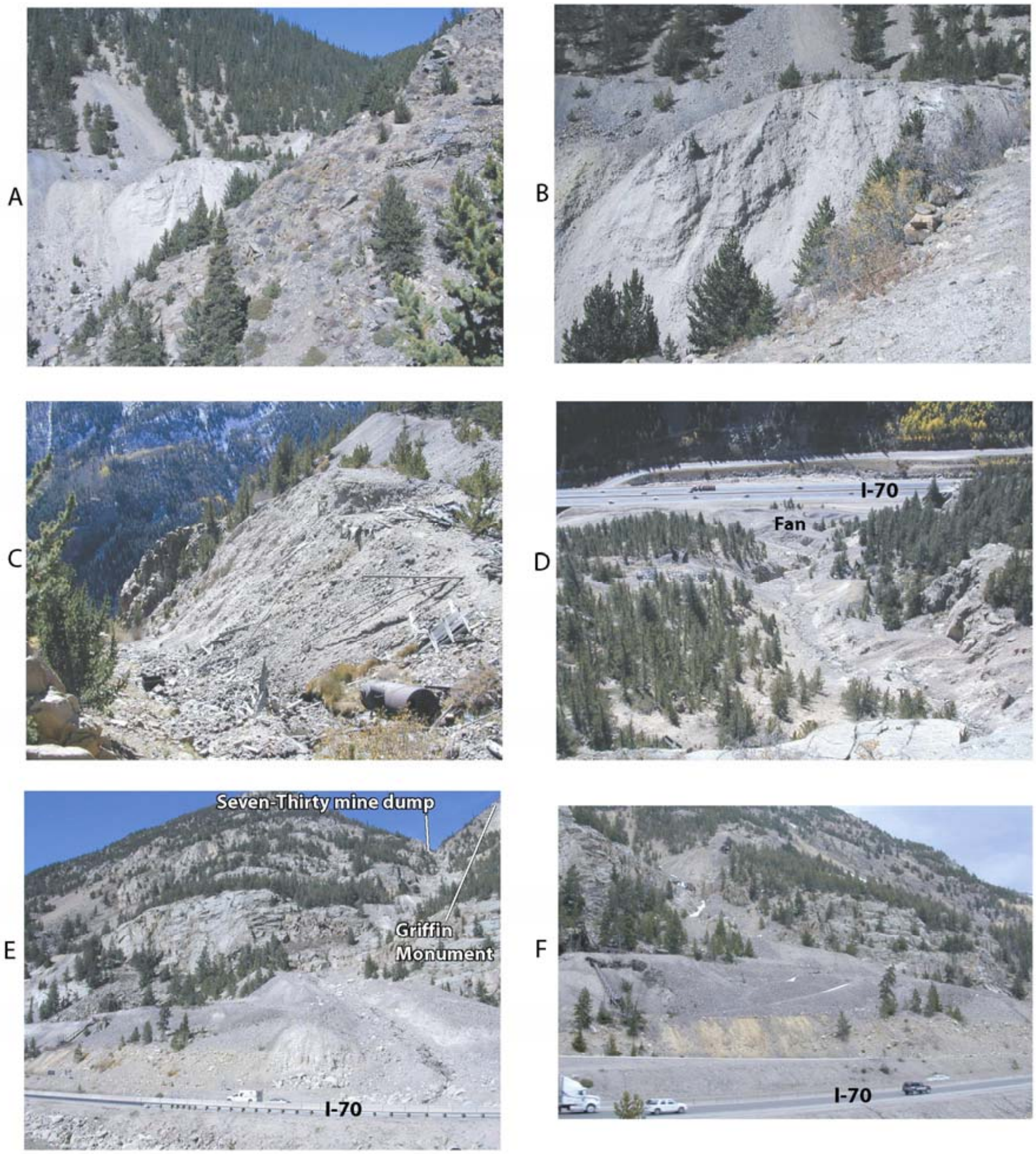

Figure 8. Brown Gulch in 2002 and 2003. Photos A-E taken on October 10, 2002. A) Seven-Thirty mine dump (compare to figure 7b). B) Close-up of Seven-Thirty mine dump. C) View of the Seven-Thirty mine dump (at right) looking downstream to the south. Dump is roughly 25 m high. D) Brown Gulch looking downstream 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. F) Fan at the mouth of Brown Gulch. Photo taken April 21, 2003. Compare to Figures 7C and 7D.

A
B


Figure 9. July 28, 1999 debris flows on the south flank of Mount Parnassus. A) Oblique aerial photo of Mount Parnassus. U.S.Geological Survey photograph taken on August 18, 1999 by Intrasearch, Inc. B) Debris-flow deposit on I-70 at the mouth of Watrous Gulch. See vehicles on I-70 for scale. Photo taken on July 29, 1999, by Ed Harp, U.S. Geological Survey.

The flows on the south flank of Mount Parnassus that fed into Watrous Gulch initiated as large rills on steep, non-vegetated slopes above timberline (Figures 10a, b, and c). The matrix of colluvium at the head of the largest rill included 84 percent sand-sized material, 8 percent silt-sized material, and 8 percent clay-sized material (U.S. Geological Survey, 1999, unpublished data). Clasts made up about 50 percent of the colluvium. As the Watrous Gulch debris flow(s) progressed downslope, it eroded material from the channel. Parts of the channel were incised several meters by the flow (Figures 10d, e, f, g). Material eroded from the channel included deposits of layered sandy-silt (Figure 10d), as well as matrix-supported deposits containing sub-angular to sub-rounded boulders (Figure 10d). The matrix of the flow became finer-grained as it progressed downslope. The matrix of the deposit on I-70 (Figure 10h) included 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 Figure 10b with Figure 10h).

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 (Figures 10f and 10g) indicated a velocity for the Watrous Gulch debris flow of 32 ft/s (10 m/s). This compares favorably with video footage shot of the debris-flow from I-70 (Denver television station "News 4" footage). This footage shows what appears to be a hyperconcentrated flow coming from the mouth of the basin and mobilizing debris flows on the fan. It is unclear at what time during the debris-flow event the footage was shot.

The debris flow in Watrous Gulch, as well as a debris flow in the gulch directly east of Watrous Gulch, exposed fan stratigraphy that displayed a record of past debris flows (see Figure 13 in Coe et al. (2002)). This stratigraphy indicates that the mean recurrence intervals for debris flows in Watrous Gulch, and the gulch to the east, are about 3,000 yrs and 300 yrs, respectively. The Melton's Numbers for the basins are 0.48 and 1.1, respectively. The negative correspondence 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 (Figure 2). 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 yrs BP) that affected both fans.

SUMMARY

This paper documents historical debris-flow events along the I-70 corridor in Clear Creek County. The majority of the 19 documented events were triggered by rainstorms in the months of July and August. These storms are commonly associated with the flow of moisture from the North American Monsoon. Observations of recent debris flows suggest that the predominant mechanisms of debris-flow initiation in the area are rilling and fire-hose processes.

Figure 10. 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).

Figure 10 – continued. 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. Note geologist for scale. 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.

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Table 1. Historical debris-flow events along I-70 in Clear Creek County. Debris-flow events are listed from east to west and are sequentially numbered. Rainfall data were included as available.

Debris-Flow Event Number	Location	Time and Date of Debris-Flow Event	Trigger	Comments	Source(s) of Information
1	North flank of I-70 at Floyd Hill, just below west-bound lanes	Late July, 2000	Rainfall	Initiated as a soil slip (Campbell, 1975) in highway fill; traveled about 260 ft (80m, slope distance) downslope, and deposited debris just above US Highway 40 (Figure 3).	Personal observations by authors
2	Eastbound lanes of I-70 at Floyd Hill and westbound lanes of I-70 near Silver Plume	Afternoon of July 8, 2001	Rainfall	Debris-flow deposits on I-70 disrupted traffic.	Whaley, 2001
3	Small basins in and near Idaho Springs	Afternoon of June 17, 1993	Rainfall	Debris-flow deposits on westbound lanes of I-70 near Idaho Springs.	Mehle, 1993
4	Small basins in and near Idaho Springs	1:15 p.m. to 2:00 p.m., August 1, 1994	Rainfall, about 1 inch (25 mm) in 45 minutes	Debris-flow deposits on I-70 near Idaho Springs; Virginia Canyon Road closed, probably due to flooding or hyperconcentrated flow.	Garner, 1994
5	Small unnamed basins on southeast flank of Douglas Mountain (Figures 4 and 5)	About 6 pm on August 14, 1983	Rainfall, 1.8 in (45 mm) of rain in 35 minutes at Empire.	Debris covered one westbound lane between mile markers 229 and 232. Both westbound lanes were closed from about 6 to 8 pm.	*Rocky Mountain News*, 1983

Debris-Flow Event Number	Location	Time and Date of Debris-Flow Event	Trigger	Comments	Source(s) of Information
6	Small unnamed basins on southeast flank of Douglas Mountain (Figures 4 and 5)	Night of September 2/3, 1990	Rainfall	Blocked Interstate 70 in both directions east of Georgetown (estimate between mile markers 229 and 232.	*Rocky Mountain News*, 1990
7	Small unnamed basins on southeast flank of Douglas Mountain and east flank of Democrat Mountain (Figures. 4, 5 and 6)	About 2 pm on July 13, 2001	Rainfall, on July 13; mid-day shower (0.21in (5 mm)); afternoon-evening thunderstorms (0.50 in (13 mm)); total rainfall between July 13 (8 am) and July 14 (8 am) was 0.71in (18 mm); total rainfall between July 11 (8 am) and July 13 (8 am) was 0.49 in (12 mm)	Debris closed I-70 for about 4 hrs, debris about 3 m deep on westbound lanes as well as within center median; eastbound lanes closed during clean-up of westbound lanes; highway opened at 6:15 pm.	Multiple, including personal observations by authors; Vaughan and Flynn, 2001; Sherry & Juozapavicius, 2001; rainfall data from Bill Wilson, observer at the National Weather Service station in Georgetown.
8	Unnamed basin(s) on flank of Columbia Mountain	August 3, 1909	Rainfall	Earth washed down Columbia Mountain.	*Georgetown Courier*, 1909
9	Silver Gulch (Figure 4)	About 12 pm, May 28, 1872	Snowmelt	Bank failure dammed Silver Creek near Beecher Silver Mine, dam failed and created a second dam that then failed, triggering a debris flow in Sliver Gulch that flowed to the fan where it damaged several houses.	*Colorado Miner*, 1872

Debris-Flow Event Number	Location	Time and Date of Debris-Flow Event	Trigger	Comments	Source(s) of Information
10	Unnamed basin(s?) on flank of Democrat Mountain	July 28, 1919	Rainfall, 0.7 in (17.8 mm) in 1 hr.	Debris flow closed highway, trapped an automobile, and delayed a train.	*Georgetown Courier*, 1919
11	Small unnamed basins on east flank of Democrat Mountain	Evening of July 27 and/or afternoon of July 28, 1999	Rainfall; total rainfall between July 28 (8 am) and July 29 (8 am) was 0.41 in (10 mm); total rainfall between July 27 (8 am) and July 28 (8 am) was 1.42 in (13 mm) from thunderstorm between 5:40 pm and 10 pm.	Deposits briefly closed westbound lanes of Interstate 70 near Georgetown on afternoon of July 28 (Gutierrez, 1999; Lofholm, 1999); storm system triggered debris flows throughout Colorado (Godt and Savage, 2003; Gutierrez, 1999; Lofholm, 1999).	Multiple, including personal observations by the authors; Gutierrez, 1999; Baca and McCrimmon, 1999; Lofholm and Kirksey, 1999; Lofholm, 1999; News 4 video coverage; Coe et al., 2002; rainfall data from Bill Wilson, observer at the National Weather Service station in Georgetown.
12	Griffith Gulch at Georgetown (Griffith Gulch not shown on maps, but probably located on the west flank of Griffith Mountain (fig. 1) on the east side of Georgetown)	Late May/early June, 1876	Snowmelt?	Debris flow carrying large boulders comes down with "… a roar and force that appalled the inhabitants living in the lower portion of the town."	*Rocky Mountain News,* 1876
13	Unnamed basin(s?) on flank of Republican Mountain	July 26, 1919	Rainfall	Debris flow and rockslide deposited debris (including mine dump debris) about 5 ft (1.5 m) deep near the Kelly Tunnel.	*Georgetown Courier*, 1919
14	Brown Gulch (Figures 7 and 8)	June 13, 1889	Snowmelt	Failure and mobilization of Seven-Thirty Mine dump destroyed ore houses.	*Silver Standard*, 1889

Debris-Flow Event Number	Location	Time and Date of Debris-Flow Event	Trigger	Comments	Source(s) of Information
15	Brown Gulch (Figures 7 and 8)	June 22, 1892	Snowmelt	Failure and mobilization of Seven-Thirty Mine dump; damage to ore houses, blacksmith shops, and Terrible Mill.	*Silver Standard*, 1892
16	Brown Gulch (Figures 7 and 8)	June 26,1895	Snowmelt	Failure and mobilization of Seven-Thirty Mine dump; destroyed Desmoineaux house and Terrible Mill; covered county and mill roads with debris.	*Silver Standard*, 1895
17	Brown Gulch (Figures 7 and 8)	5 am on June 1, 1900	Snowmelt	Debris flow destroyed the shaft house of the Seven Thirty Mine and flowed to Clear Creek. Damage estimated at several thousand dollars.	*Denver Times*, 1900
18	Brown Gulch (Figures 7 and 8)	June 24 and 25, 1912	Snowmelt	Failure and mobilization of Seven Thirty Mine dump; destroyed Griffin cabin, a blacksmith shop, the Lampshire boarding house, the Granite Polishing Works, and the Fox and Hound saloon.	*Georgetown Courier*, 1912; Martin, 1982
19	South and SW flanks of Mt. Parnassus with flows in Watrous Gulch and the gulch immediately to the east (Figures 9 and 10).	Afternoon of July 28, 1999	Rainfall, about 1.4 in (35 mm) in 2 hrs	Rainstorm triggered widespread debris flows in Clear Creek and Summit Counties; flows from Mt Parnassus deposited about 34,000 yd^3 (26,000 $m^{3)}$ of debris on I-70, closing it for about 25 hrs.	Multiple, including personal observations, Gutierrez, 1999; Baca and McCrimmon, 1999; Lofholm and Kirksey, 1999; Lofholm, 1999; NEWS 4 video coverage, Henceroth, 2000; Coe et al., 2002; Godt and Coe, 2003; rainfall data from Grizzly Peak Snotel station near the Arapahoe Basin ski area