SPECIAL PUBLICATION 46

Geology of the 1994 South Canyon Fire Area, and a Geomorphic Analysis of the September 1, 1994 Debris Flows, South Flank of Storm King Mountain, Glenwood Springs, Colorado

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With an Eyewitness Account of the September 1, 1994 Debris Flows
By Kevin White of Glenwood Springs, Colorado

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ABSTRACT

Debris flows that formed in response to a heavy rainstorm late in the evening on September 1, 1994 traveled down several channels on the south flank of Storm King Mountain west of Glenwood Springs, Colorado, and spilled onto or next to Interstate Highway I-70. The debris trapped thirty cars on the highway, and at least two people were swept into the river. Smaller debris flows occurred in this same area during 1995, causing additional delays on the highway. Materials carried by the debris flows were largely eroded from hillslopes and channels that had burned during the July 1994 South Canyon fire.

Immediately following the 1994 storm the Colorado Geological Survey and U.S. Geological Survey initiated a cooperative investigation to evaluate the geologic and geomorphic characteristics of the debris flows, investigate the stability of a large landslide complex within the burned area, and assess the potential for future debris-flow activity. The surficial and bedrock geology of the area and the 1994 debris-flow paths were mapped at a scale of 1:5,000.

The late Paleozoic Maroon Formation, Eagle Valley Formation, and Eagle Valley Evaporite, and an unnamed late Tertiary sedimentary deposit here in called the conglomerate of Storm King Mountain crop out in the study area. Surficial deposits that are at least three feet thick cover nearly half of the mapped area. Thick accumulations of deeply dissected older landslide deposits and older colluvium and sheetwash deposits are locally preserved where a prominent structural terrace within the Grand Hogback Monocline extends across the study area. These thick surficial deposits, along with dry ravel and younger debris-flow deposits found in and adjacent to stream channels and residuum that mantled the Maroon Formation, were major sources of the material carried by the 1994 debris flows.

Geomorphic analysis and field observations of the distribution of the September 1 debris flows indicate that the majority of debris flows from the 1994 event initiated in 1st-order drainages within the burned area through the process of progressive sediment bulking, rather than by failure of discrete landslides. Although 58 small, shallow soil-slip scars formed during the September 1994 storm, material from these scars is estimated to account for only about seven percent of the debris deposited at the canyon mouths. Drainages showing the highest susceptibility to debris-flow initiation have south and south-west aspects, and gradients between 25 and 40 degrees in the Maroon Formation and less than 30 degrees in the older landslide deposits. This agrees with field observations of abundant sheet and rill erosion on slopes cut into these units. Slightly more than 50 percent of the total length of all the debris-flow paths occurred as first-order segments, 30 percent occurred as second-order segments, and 19 percent occurred as third-order segments. More than one-half the length of available main channels was occupied by debris flows during the September 1994 event. Values for debris-flow path density and path frequency indicate that even small, partially burned basins are susceptible to debris-flow activity that involves a significant proportion of its drainage network.

Although stream incision and lateral erosion locally destabilized the large landslide complex, we observed no evidence to indicate that it had been reactivated to any great extent since the 1994 fire. However, several smaller landslide slump blocks within the large landslide complex have recently moved, including one that blocked a drainage channel sometime between the 1994 and 1995 debris flows.

Steep slopes cut into the Maroon Formation, older landslide deposits, and older colluvium and sheetwash deposits will continue to produce debris flows in the future, given adequate precipitation. As demonstrated by the debris flows in 1995, Basin F is particularly susceptibility to on-going debris-flow activity, perhaps because of the small, unstable landslides and deeply dissected older landslide deposits found within it.

INTRODUCTION

OVERVIEW

During the evening of September 1, 1994, debris and hyperconcentrated flows originating in response to a heavy rainstorm flowed down several channels on the south flank of Storm King Mountain west of Glenwood Springs and emptied onto or next to Interstate Highway 70 in numerous places. Materials carried in this event were largely eroded from the hillslopes recently burned by the July, 1994 South Canyon fire. Shortly after the fire scientists from the Colorado Geological Survey (CGS), U.S. Geological Survey (USGS), and U.S. Bureau of Land Management (BLM) inspected the geologic aspects of the area burned by the fire. Following the flooding on September 1, several scientists conducted a preliminary investigation into the debris-flow events and released their results in USGS Open-file Report 95-508 (Cannon and others, 1995).

Further investigations of the geology and debris-flow events on Storm King Mountain were organized by W. P. Rogers of the CGS and funded by the CGS, USGS, BLM, and Colorado Department of Transportation, Region 3. The primary goals of these studies were to (1) prepare detailed topographic and geologic maps of the burn area, (2) map the paths of the 1994 debris flows, (3) evaluate geologic and geomorphic influences on the debris-flow events, (4) assess the potential for future debris-flow activity, and (5) investigate the stability of large landslides previously mapped within the burn area.

A series of 1:8,000-scale, black and white, aerial photographs were taken of the burn area on November 11, 1994. A 1:5,000-scale, digital topographic map of the area was prepared from the survey-controlled aerial photographs. Color aerial photographs flown for the BLM on September 23, 1978 were also used during the project. The geologic map of the area was prepared by inspection and interpretation of the aerial photography and was supported by fourteen days of field investigations during the late spring and early summer of 1995. Selected parts of the study were revisited for short time periods during 1995. Geologic data collected during the field investigation were inked onto the 1:8,000-scale aerial photographs and later transferred to the base map using a PG-2 photogrammetric plotter.

A Digital Elevation Model (DEM) with 32.8-feet (10-meter) resolution was also generated from the detailed topographic data. The topographic and geologic maps, the DEM, and maps of the debris-flow paths were elements were used for the geomorphic study of the area and the morphometric analysis of the debris-flow paths.

The study area lies on the south flank of Storm King Mountain, north of the Colorado River and about 3.2 to 6.6 miles west-northwest of downtown Glenwood Springs (Figure 1) and encompasses about 2,995 acres or 4.7 square miles (Table 1). It includes the watersheds of all drainage basins that were significantly burned by the fire (48 percent or more of each of these basins were burned), one drainage basin west of the South Canyon fire area (basin A) that was only very slightly burned by the fire (about 3 percent of basin), and a watershed front (basin I) that was not burned at all. Basin A was included in the study as a control area because (1) it received a high amount of precipitation during the rainstorm that triggered the debris flows in adjacent basins and (2) only a very small part of it was burned by the fire. Six watershed fronts that lie between the mouths of the larger drainage basins along the steep valley wall immediately north of the Colorado River also were included within the study area. Highway I-70 was chosen as the south and southwest boundary of the study area because construction activities associated with the building of the highway had disturbed and concealed the geologic deposits within this corridor, and the debris-flow deposits that spilled onto or crossed the highway were quickly removed by highway clean-up crews, precluding accurate mapping of their original extent.

The preliminary report on the Storm King Mountain debris-flows (Cannon and others, 1995) used the four types of flow in the sediment-water flow continuum as described by Pierson and Costa (1987). For simplicity, we herein simply use the term “debris flow” or “debris-flow deposits” to describe all types of the flow processes or deposits that occurred during the September 1, 1994 Storm King Mountain events.

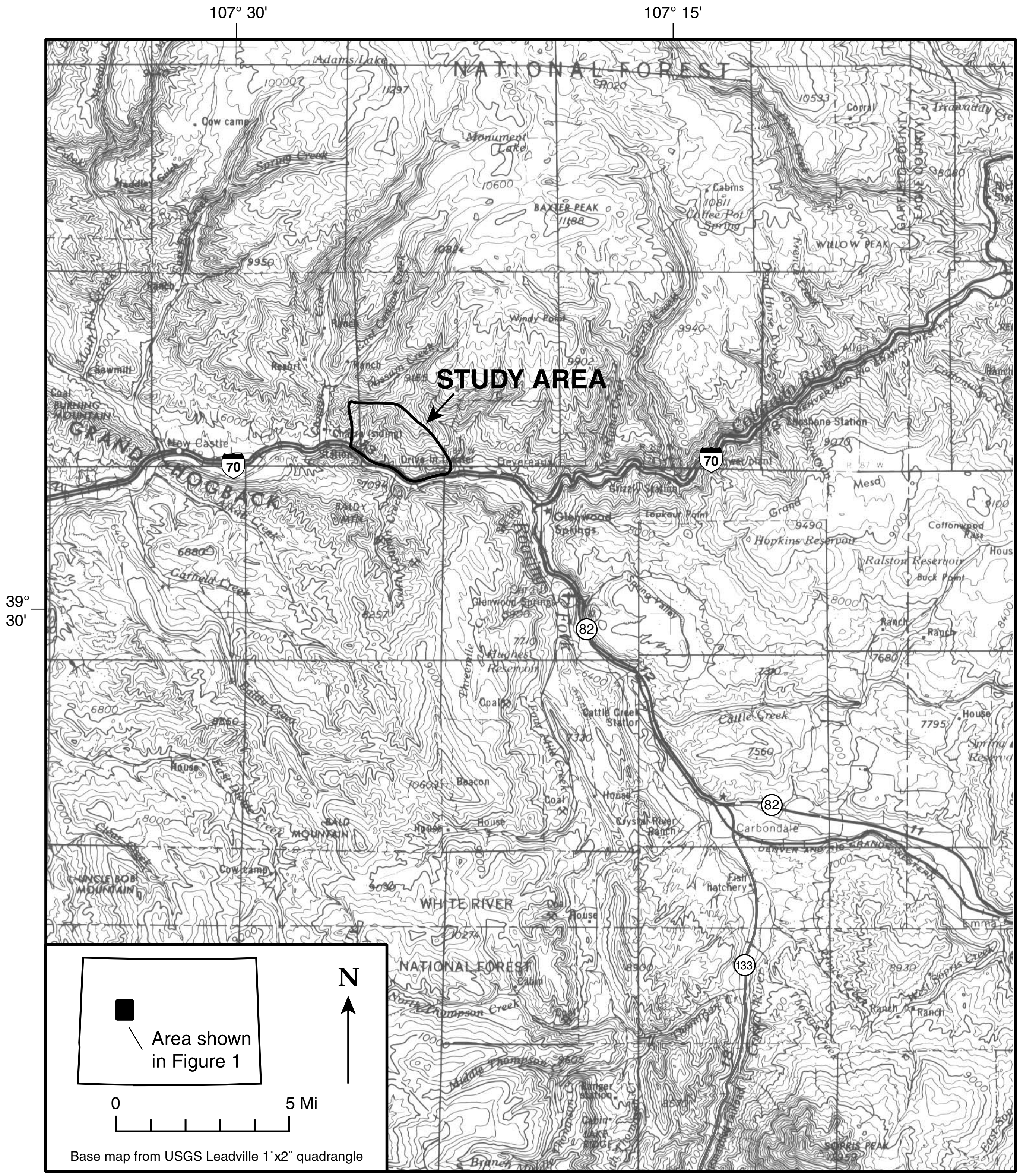


Figure 1. Location map of the study area.

Table 1. Areas of drainage basins and watershed fronts, percent of study area, burned area, and percent of drainage burned within the study area.

Drainage Basin	Area (acres)	Percent of Study Area	Burned Area (acres)	Percent Burned
A	502	16.8	15	3.0
B	552	18.4	516	93.5
C	609	20.3	562	92.3
D	191	6.4	182	95.3
E	115	3.8	72	62.6
F	523	17.5	252	48.2
G	77	2.6	58	75.3
Watershed Front				
H	154	5.1	127	82.5
I	181	6.0	0	0.0
J	31	1.0	7	22.6
K	35	1.2	5	14.3
L	8	0.3	4	50.0
M	17	0.6	0	0.0
Total Area	2,995	—	1,800	60.0

AKNOWLEDGEMENTS

The Storm King Mountain debris-flow project was funded jointly by the CGS, USGS, BLM, and Colorado Department of Transportation, Region 3. Acquisition of new aerial photography and development of a digital topographic base map was contracted to Merrick & Company. Randy Streufert, CGS, and Bill Smith, USGS, assisted Merrick & Company with establishment of ground control and field logistics. Susan Rhea, USGS, produced a reproducible version of the base map from the digital topographic file. John Michael, USGS, provided guidance and expertise for the GIS analysis. Photogrammetric models used to transfer geologic data from aerial photographs to the base map were set by James Messerich, USGS, on a Kern PG-2 plotter.

Pat Rogers, CGS, organized this project, arranged for acquisition of the large-scale aerial photographs and development of the digital base map, and contributed many helpful scientific susggestions to the authors throughout the project. We appreciate the cooperation of Richard Dever, landowner, who allowed us access onto his property. Jim Scheidt, BLM, and Chris Tomlinson, Daily Sentinel newspaper in Grand Junction, provided copies of photographs of the 1994 debris flows that were taken the day after their deposition. Bruce Bryant and Ralph Shroba, with the USGS, and Roger Pihl, Randy Streufert, and Jim Cappa, with the CGS, provided valuable comments that aided our interpretations of the geology of this area. Mr. Bryant also contributed a large number of strike and dip measurements on bedding surfaces and the schematic structural cross section. This report benefited from reviews by Bruce Bryant, Gerald Wieczorek, and Pat Rogers. Larry Scott, CGS, designed the book format and cover. Matt Morgan, CGS, compiled the geologic map, which was digitized by the USGS, in GIS software and did final cartographic production. Cheryl Brchan, CGS, edited the book and map and assisted in map production.

CONDITIONS LEADING UP TO THE STORM KING MOUNTAIN DEBRIS FLOWS

THE SOUTH CANYON FIRE, JULY 1994

On July 2, 1994 lightning from a summer storm started a fire on the south flank of Storm King Mountain. For the next few days the fire slowly spread across the mountain. Firefighters were brought in to protect homes in the Canyon Creek area west of the fire. On July 6 a strong cold front accompanied by a sudden shift in the direction and intensity of the wind passed through the area and caused the fire to spread rapidly. It quickly grew from around 200 acres to about 1,800 acres, threatening west Glenwood Springs and causing portions to be evacuated. Tragically, 14 firefighters lost their lives while battling this fire. Temperatures generated by the fire must have been tremendously high at least locally. While conducting field work, we observed melted and fused soils in a small area on one ridge within the burn area, and aluminum cables used while fighting the fire were melted.

GEOMORPHIC SETTING AFTER THE FIRE AND BEFORE THE RAINSTORM

In the days following the fire, residents of Glenwood Springs reported seeing huge clouds of white dust flying above the mountain; presumably the ash and loose, friable, and virtually unprotected burned mineral soil on the hillsides were being transported by wind and deposited in the tributary drainages. In addition, the processes of dry ravel both during and after the fire resulted in the downslope transport and accumulation of material. Accumulations of loose, silty sand and ash up to about 3 feet deep along the sides of most tributary drainages were observed (R. Pihl, 1994, written commun.). This material was at its angle of repose, measured between 26 and 32 degrees (Cannon and others, 1995). The dry-ravel material was primarily well sorted, silty sand and sandy, slightly gravelly silt. It generally lacked the larger clasts present in the in-place soils (Cannon and others, 1995). Aprons of this loose material were also observed mantling many sideslopes. In addition, larger material in the form of loose boulders, cobbles, and channel alluvium had been deposited in the channel over the years by either gravity-driven colluvial processes or by fluvial and debris-flow processes. Material in and adjacent to the channel was available for entrainment by channel runoff during the storm. Material on the steep side slopes was susceptible to erosion, followed by transport downslope and into the channel by overland flow.

Our study area on the south flank of Storm King Mountain can be divided into seven major, intermittent stream drainages, labeled Basins A through G on Plate 1 and Figure 2. All seven drainages are direct tributaries of the Colorado River. These drainages typically have steep stream channels and precipitous side slopes. This topographic configuration is conducive to a rapid concentration of runoff and, when combined with intense rains, can be a primary cause of high peak discharge and erosion rates (Rowe and others, 1954). In addition, six watershed front areas (H through M) are shown on Figure 2 and Plate 1. Approximately 1,800 acres, or 60 percent of the entire study area was burned, with drainage basins B, C, and D being nearly completely burned (Table 1). The remaining basins experienced between 0 and 82 percent burn coverage.

Both the burned and unburned portions of the Storm King Mountain watershed are characterized by an average topographic gradient of 15 degrees, with some hillsides, particularly in the lower portion, having gradients greater than 35 degrees. Soils in the lower one-third to one-half of the burned area are generally very shallow, recent, poorly developed, contain a high percentage of rock particles, and supported before the fire a sparse pinyon-juniper vegetative community (M. McGuire, BLM, 1995, written commun.). The upper watershed soil is a stony loam that supported a mountain shrub vegetative community. Large deposits of older colluvium and sheetwash in basin B and extensive older landslide deposits on the south side of Storm King Mountain are the thickest surficial deposits in the area. Bedrock crops out in many parts of the area and locally is mantled by a thin veneer of residuum.

The generation of a hydrophobic or water-repellent, layer in the soil during a fire can affect the erosion potential of a site during an intense rainstorm by increasing rainsplash, rill, and sheetwash erosion, as well as surface runoff (Wells, 1987; Morris and Moses, 1987). Even under unburned conditions, organic substances leached from plant litter can induce a non-wettable condition in soils, and microbial by-products may coat mineral soil particles. Naturally-occurring, non-wettable soil is particularly common in chaparral communities, in part due to the high resin content of the organic litter (Spittler, 1995). Under unburned conditions, the non-wettable substances generally form a noncontinuous layer because rodent, worm, insect, and root activity continuously disrupts the soil-column structure, and forms conduits for water to enter (Spittler, 1995). However, when a high-temperature fire sweeps through an area the existing organic water-repellent materials volatilize. These materials then condense on mineral soil particles and produce an extremely water-repellent layer.

Water-repellent soils were detected at some sites in the burned area on Storm King Mountain, but not all (Cannon and others, 1995). Field evidence of variations

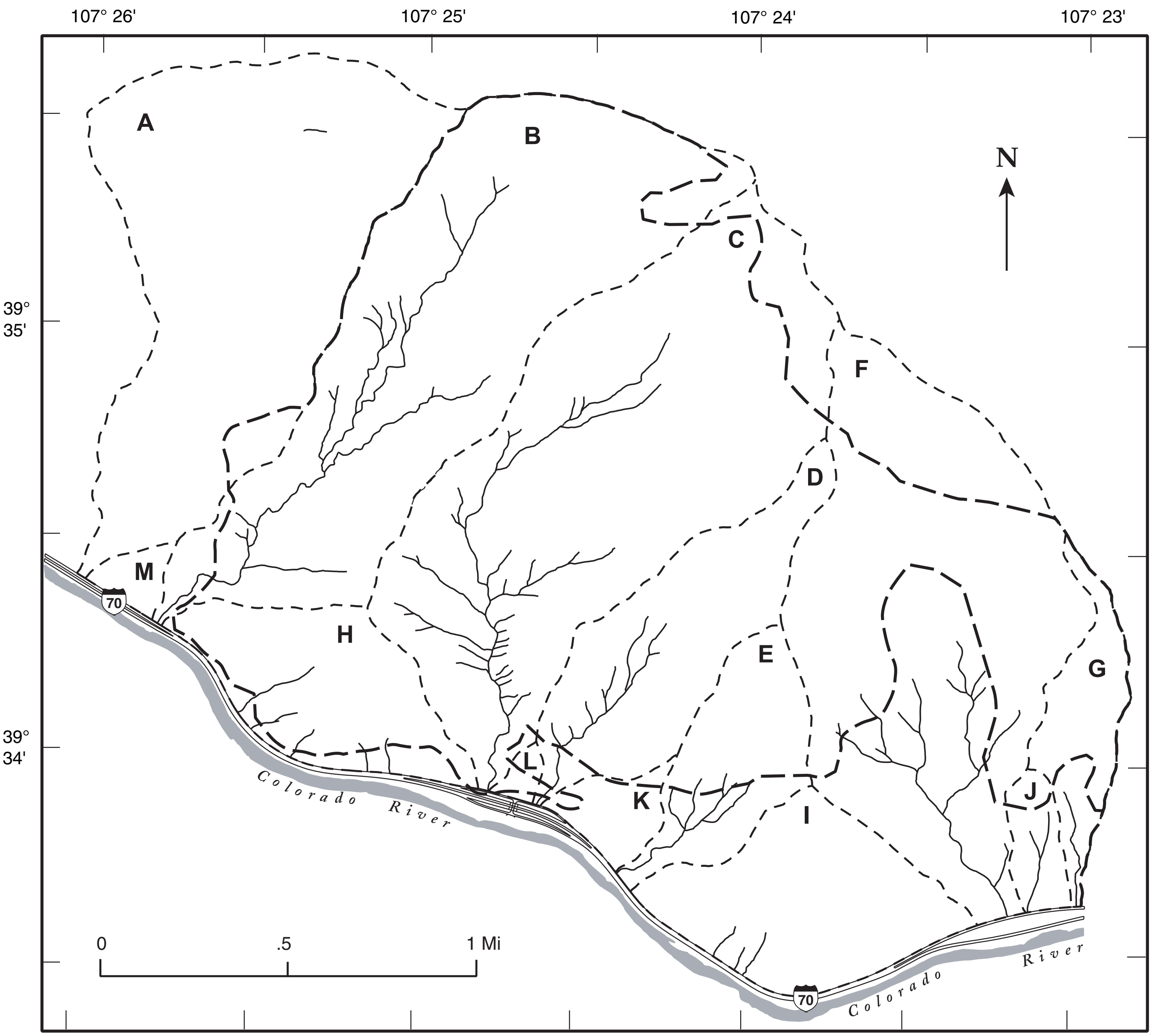


Figure 2. Drainage basins, extent of the burn area, and debris-flow paths on the south flank of Storm King Mountain. Drainage basins and watershed fronts on the south-facing flank of Storm King Mountain are labeled A through M and delineated by dashed lines. Paths of the debris flows that occurred during the September 1, 1994 event are shown by solid lines. Heavy dashed line marks the extent of the South Canyon fire of July, 1994.

in fire temperature, soil materials, and vegetation could not explain their presence or absence. At one unburned site located under a juniper tree, a patchy hydrophobicity was detected. This occurrence is probably due to natural hydrophobic compounds in the existing organic materials.

RAINSTORM EVENT ON SEPTEMBER 1, 1994

The only available precipitation records from the vicinity of Storm King Mountain are daily rainfall totals recorded at a National Weather Service site at the corner of 13th and Grand Avenues in Glenwood Springs. This location is about 3.4 miles from the eastern edge of the study area. The 24-hour period of record for this station began at 5 p.m. No rain fell in the month of July following the fire, and in the month of August only 1.3 inches were measured, half of which occurred on August 9. Thus, before the September 1 event, soil-moisture conditions were fairly dry.

Between 5 p.m. on September 1 and 5 p.m. on September 2 (which corresponds to the 24-hour recording period at the measurement site), a total rainfall of 0.67 inches was recorded at the Glenwood Springs station. Eyewitness accounts suggest that rainfall conditions on the west end of Glenwood Springs (and closer to Storm King Mountain) were more severe than are indicated by this total. A motorist described the rain as "... so hard you almost couldn't see. It came down like a monsoon". The first and strongest pulse of intense rainfall was reported by an eyewitness to have occurred between 8 and 9 p.m., another pulse of intense rainfall occurred at 10:30 p.m., and rain was still falling heavily at 11 p.m.

The recurrence interval for the measured 24-hour rainfall total reported in Glenwood Springs for this storm is fairly short, indicating that the 24-hour total was not an unusual event (N. Doeskin, Assistant State Climatologist, personal communication, 1995). Observations that this amount of rainfall fell in a very abbreviated time period, however, would suggest a less frequent recurrence of short duration, intense rainfall. The lack of detail at the recording station and of site-specific data for Storm King Mountain, preclude this determination, however.

After the 1994 debris-flow event, the BLM installed two climatic monitoring stations, one near the top of Storm King Mountain and a second on a ridge high above but near the Colorado River along the drainage divide between basins B and C and watershed front H.

DEBRIS FLOWS ON STORM KING MOUNTAIN, SEPTEMBER 1, 1994

On the night of September 1, 1994 at approximately 10:30 p.m., in response to a torrential downpour, debris flows originating on the burned hillslopes on Storm King Mountain and consisting of mud, rocks and burned trees emptied down onto or next to I-70 from 15 channels (Figure 2; Plate 1). Thirty cars traveling on the highway at the time of the debris flows were engulfed, trapped, or turned over by the mud. At least two of the people travelling in these vehicles were swept into the river by the debris flows (see Appendix 1, an eye witness account by Kevin White). Although some travelers were seriously injured, fortunately no deaths resulted from this event.

According to Colorado Department of Transportation personnel, burned logs and branches and up to boulder-sized material in a very fluid, muddy matrix continued to flow out of the canyons as a series of pulses throughout the night of September 1 and the early morning hours of September 2. Material was deposited at the mouth of every major drainage with burned upper reaches (Figure 2; Plate 1), as well as at the base of unburned watershed front I (Cannon and others, 1995). A total area of approximately 35 acres was inundated with approximately 91,300 cubic yards of material (Cannon and others, 1995). The mostly unburned drainage adjacent to the burned area, herein called basin A , showed evidence of high-water flows, attesting to the high intensity of the rainstorm, but only a very minor debris flow 338 feet long and with levees up to a few inches high occurred in it.

Figure 3 is a photograph of the Colorado River valley near the mouth of basin B looking east. Debris-flow deposits from basin B are visible in the center of the photograph and left or north side of the highway. Note the steep slopes with prominent rock outcrops on watershed front H, which lie beyond the channel of basin B on the north (left) side of the river. A close-up view of the debris-flow deposits discharged from basin B is shown in Figure 4. The debris-flow deposits were derived primarily from red soils, yet they are gray, a result of their high ash and charcoal content. The debris-flow fan created by the 1994 events at the mouth of basin B extended about half-way across the river. Most of the fine-grained sediments in the fan have since been eroded away by the river, but large boulders in the fan deposits remain in the channel, creating new rapids for river rafters. The debris flows discharged from basin B carried at least two people into the river, as described in the eyewitness account by Kevin White contained in Appendix 1.

Debris-flow deposits flushed out of basins C (channel on left side of photograph) and D (right side) are shown in Figure 5. Note the near-vertical, bedrock dip slope that forms the channel bed of basin D a short

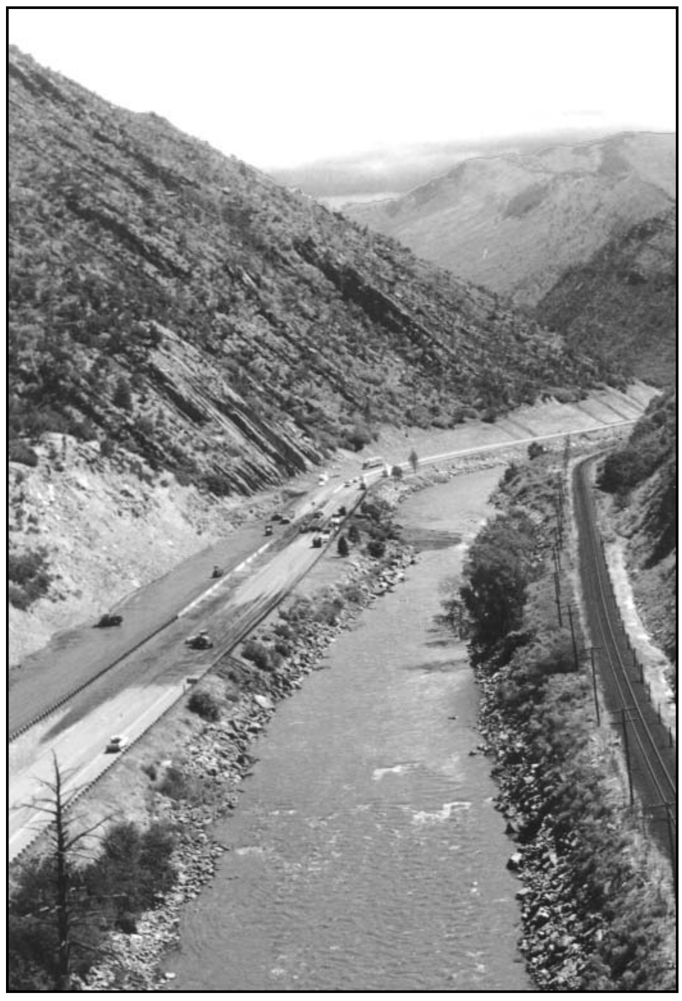


Figure 3. Photograph of the Colorado River valley near the mouth of drainage basin B. Debris-flow deposits from basin B are visible in the center of the photograph and on the left or north side of the highway. Note the steep slopes with excellent rock outcrops on watershed front H, which is on the north (left) side of the river beyond the mouth of Basin B. Photograph by Jim Scheidt, BLM.

Figure 4. Photograph of debris-flow deposits at the mouth of drainage B. The debris-flow deposits were derived primarily from red soils, yet they are gray, a result of their high ash content. The debris-flow delta created by the 1994 events extended about half way across the river. Most of the fine-grained sediments in the delta have since been eroded away by the river, but large boulders from the deposits remain in the channel, creating a new section of whitewater for river rafters. The debris flows discharged from basin B carried at least two people into the river (see the eyewitness account by Kevin White in Appendix 1). Photograph by Jim Scheidt, BLM.

distance above the highway exit ramp. This steep slope likely created a waterfall effect or extreme turbulence in the debris flows discharging from basin D, causing the flows to violently cascade downslope. None of the material flushed from basins C or D spilled onto the traffic lanes of I-70, because the South Canyon Creek highway interchange fortuitously served as a mitigative structure for the debris flows. Debris from basin C flowed eastward down the westbound entrance ramp, while debris from basin D ran westward down the westbound exit ramp. The deposits then flowed beneath the traffic lanes of the highway by way of the underpass, illustrating how diversion structures, even unintended ones, can mitigate debris-flow hazards to highways.

When the senior author first entered the lower end of basin E a disturbing odor of decaying animal flesh was noted. A short distance up the drainage the remains of several elk and a few deer were observed within debris-flow deposits from the 1994 event. The ungulates may have been swept down the canyon by the debris flows while they were still alive, attesting to the sudden and powerful character of the flows.

Scars left by the evacuation of thin, areally small, translational landslides, herein called soil slips, are common on steeper slopes in the area. Figure 6 is a photograph of a typical soil-slip scar developed in older landslide deposits. Material mobilized from the soil slips appears to have been very fluid in that only a few traces of the deposits from soil slips were observed on the hillsides downslope from the scars. This is in contrast with the debris flows in the main channels, which left nearly continuous, up to one-inch thick veneers of mud on the channel banks. Most material from the soil slips apparently traveled over the hillsides and into adjacent channels. No significant deposits from the soil slips were observed in the channels. The soil exposed in the soil-slip scars was not burned, indicating that the soil slips occurred after the fire. When coupled with the observation that most material derived from the soil slips was not preserved

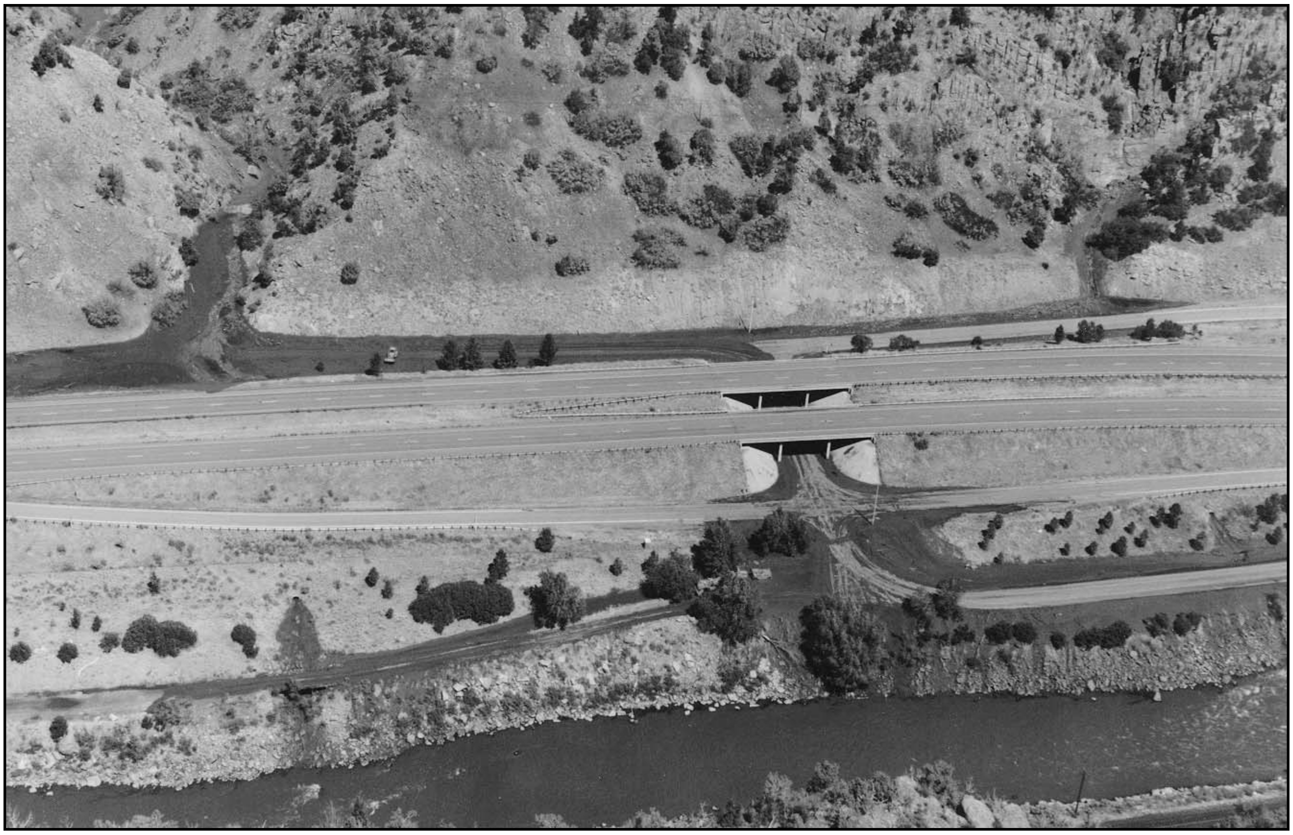


Figure 5. Photograph of debris-flow deposits that discharged from drainages C and D at the South Canyon Creek exit. Note the near vertical dip slope that forms the channel bed of basin D a short distance above the highway exit ramp. This steep slope likely created a waterfall effect for the debris flows discharging from basin D and caused the flows to violently cascade downward. None of the deposits flushed from basins C or D spilled onto the through-going traffic lanes of I-70. The South Canyon Creek highway interchange fortuitously served as a mitigative structure for the debris flows. Debris from basin C flowed eastward down the westbound entrance ramp, while debris from basin D ran westward down the westbound exit ramp. The deposits then flowed beneath the traffic lanes of the highway through the underpass, illustrating how diversion structures, even unintended ones, can mitigate debris-flow hazards to highways. Photograph by Christopher Tomlinson, Daily Sentinel.

Figure 6. Photograph of a soil-slip scar developed in older landslide deposits in basin F. Note the absence of burned soil in the soil-slip scar, indicating the slip occurred after the wildfire. Note also that the material removed from the scar is not present on the slope below the scar and that the hillslope below the scar was little affected by the downslope transport of the material removed by the soil slip. Photograph by Robert Kirkham.

GEOLOGIC SETTING

in any channel, we conclude that the slips developed during the storm of September 1, 1994. Permian and Pennsylvanian red beds of the Maroon Formation underlie most of the study area and evaporitic rocks of the Pennsylvanian Eagle Valley Evaporite crop out in the northern part of the mapped area. The Eagle Valley Formation mapped between the Maroon Formation and Eagle Valley Evaporite is transitional between the red bed and evaporitic formations and contains rock types found in both of the formations.

A late Tertiary conglomerate containing cobbles and pebbles of limestone mantles the upper reaches of the south shoulder of Storm King Mountain.

Bedrock is locally well exposed in bold outcrops, notably on the steep slopes adjacent to the Colorado River and on the southwest side of Storm King Mountain. However, in much of the area outcrops are scarce, as the bedrock rapidly weathers to residuum. Weathering rates appear to be very high in the region that coincides with the structural terrace, perhaps due to increased fracturing. Prior to the rainstorm on September 1, 1994 many of the steep hillslopes adjacent to drainage channels within the structural terrace that were underlain by Maroon Formation had surprisingly thick veneers of residuum (thickness up to 3 or 4 feet). This residuum was locally eroded off these steep slopes during the rainstorm.

Table 2. Distribution of geologic units within the study area.

Geologic Unit	Area (acres)	Percent of Study Area
af	2	0.1
IPe	230	7.7
IPee	203	6.8
PIPm	1228	41.0
Qcs	417	13.9
Qcso	237	7.9
Qdfo	2	0.1
Qdfr	4	0.1
Qdfy	40	1.3
Qls	32	1.1
Qlso	534	17.8
Qlsr	5	0.2
Qt	3	0.1
Tc	58	1.9

Surficial deposits other than residuum cover about 43 percent of the study area (Table 2). Older landslide deposits (Qlso) blanket 17.8 percent of the area. Colluvium and sheetwash (Qcs), the second most common type of surficial deposits, occupy 13.9 percent of the area, and older colluvium and sheetwash (Qcso) cover 7.9 percent. Others types of surficial deposits are much less widespread, as none cover more than 1.3 percent of the area. The older landslide deposits on the south flank of Storm King Mountain and the older colluvium and sheetwash that floors much of basin B where it overlies the structural terrace are deeply dissected and were major sources of material for the 1994 debris flows. Other significant sources of material include residuum and various types of deposits, such as dry ravel, younger debris-flow deposits, colluvium and sheet wash, landslide deposits, and recent landslide deposits that were adjacent to or that had filled the stream channels. These deposits were directly eroded by sheetwash on hillslopes and by water flowing down the first, second, and third order tributaries. Lateral erosion of the streams into these deposits and bank caving during the storm also contributed material to the debris flows.

STRUCTURE

A schematic SW-NE cross section shows the general regional structural setting of the study area (Figure 7). The study area lies astride part of the Grand Hogback Monocline, a late Laramide structure that separates the Piceance Basin on the south from the White River Uplift on the north. There is over 20,000 feet of down-to-the-south structural relief across the monocline from the White River Uplift to the Piceance Basin.

Originally we intended to focus our mapping efforts on the soils and surficial deposits in the study area and examine the bedrock in only a cursory manner. As field work began, it became evident that (1) the structural geology of the area was more complex than previously mapped, (2) the burning of the very heavy vegetative cover and erosional removal of soil veneers during the storm greatly improved bedrock exposures,

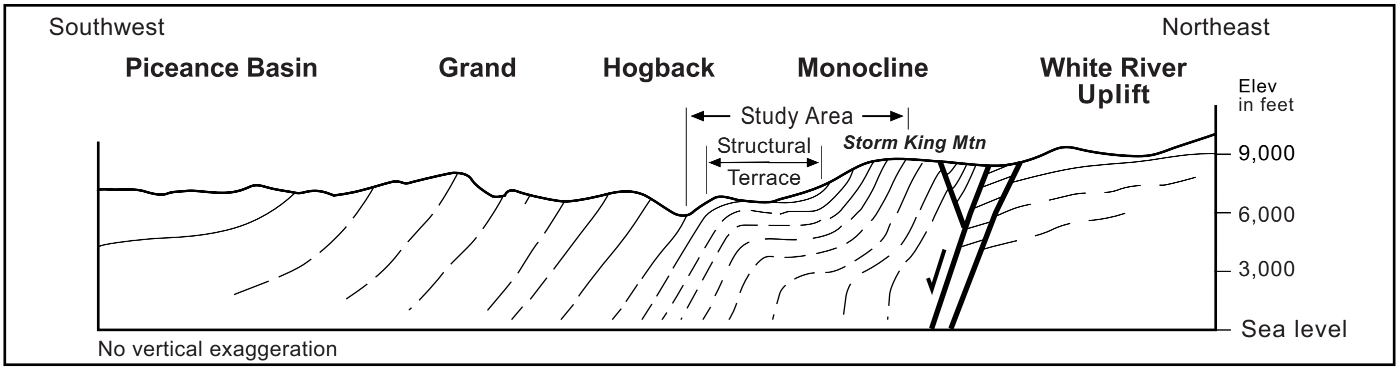


Figure 7. Schematic structural cross section from the Piceance Basin on the southwest to the White River Uplift on the northwest, showing the relative position of the structural terrace within the Grand Hogback Monocline and the location of the study area. Individual formations are not depicted; only the generalized attitudes of bedding and major faults are shown. Cross section based upon Bryant and others, 1998.

(3) the structural geology of the area played an important role in the distribution of the thicker surficial deposits, and (4) the bedrock exposures would rapidly become obscured as slopes revegetated and as surficial deposits and bedrock weathered. Therefore we adjusted our mapping schedule to allow for more time to be spent examining the bedrock.

Bass and Northrop (1963) mapped the Storm King thrust fault as extending through our study area. Fairer and others (1993) did not recognize this thrust fault in the Storm King Mountain 7.5-minute quadrangle, but did map several faults on the south flank of Storm King Mountain. We found no evidence of the Storm King thrust fault mapped by Bass and Northrop (1963), and several of the faults mapped by Fairer and others (1993) could not be confirmed during our mapping. We did, however, observe a broad, west-northwest-trending structural terrace within the Grand Hogback Monocline. Subsequent mapping by Bryant and others (1998) supported this interpretation, and they suggested it may have resulted from collapse due to dissolution and flowage of underlying evaporite rocks. The southern limb of the structural terrace roughly coincides with the location of the thrust fault mapped by Bass and Northrup (1963).

South of the structural terrace bedrock generally dips 30 to 60 degrees south. Within the structural terrace beds are usually much flatter lying and in many areas actually dip northward, opposite of the regional fold direction of the monocline. North of the structural terrace bedrock in the eastern part of the area again dips 30 to 60 degrees south, similar to beds south of the structural terrace. In the western part of the study area, however, beds north of the structural terrace commonly are overturned with most dips varying from 35 to 75 degrees northward.

Several small anticlines, monoclines, and faults occur within the hinge zone along the southern edge of the structural terrace. Most faults are downthrown to the north, opposite of the overall structural relief on the Grand Hogback Monocline. A well-exposed drag fold is on the upthrown side of one of these faults just above the mouth of basin C. We mapped several small, down-to-the-south faults in the hinge zone along the northern edge of the structural terrace (Plate 1). Bryant and others (1998) interpret this northern hinge zone as a sharp fold without faulting. Beds are commonly overturned on the north side of the northern hinge zone in the western part of the study area.

Although bedding within the structural terrace is generally more or less flat-lying, a number of small-scale, discontinuous folds and faults occur within it. The limbs of these small folds typically dip 15 to 20 degrees and rarely as much as 45 degrees. Areas with more complicated structure were observed more frequently in the canyon bottoms and less frequently on the drainage divides within the structural terrace. At the junction of the two major tributaries within basin B is an intriguing exposure with a prominent fault and overlying fold structure. The fault could be a low-angle thrust fault with small displacement, but since Maroon redbeds are faulted against other Maroon redbeds, the character of this structure is difficult to decipher. A complex zone of folding and faulting was noted in the east fork of basin F.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

Surficial deposits shown on the map are generally more than 3 feet thick, but may be thinner in a few locations. Residuum, which locally is pervasive and thick and is transitional to bedrock, was not mapped. Although thin deposits of debris from the 1994 event remain on the channel walls in many areas, they are mapped only where they are at least 3 feet thick and are wide enough to be shown at the scale of the map (at least 8 to 10 feet in width).

Mapping is based upon aerial photos taken on November 10, 1994 and upon field work undertaken during the spring and summer of 1995. Debris-flow deposits both on and immediately north of the highway in the borrow ditch were removed by CDOT before the aerial photographs were flown and prior to initiation of field work for this project. Because of this, the original extent of the 1994 debris-flow deposits was not observed during this study. The approximate distribution of the deposits from the 1994 event that were removed by CDOT, as shown on Plate 1, is modified from Cannon and others (1995) using oblique aerial photographs taken by Jim Scheidt, BLM, and Chris Tomlinson, Daily Sentinel newspaper in Grand Junction, immediately following the 1994 debris flows.

Contacts between some surficial units may be gradational, and mapped units may locally include deposits of another type. Precisely locating the downhill contact of colluvium and sheetwash (Qcs) was a particularly difficult task, because these deposits tend to gradually thin as they run out over other units. Similarly, determination of the contact between Maroon bedrock and overlying surficial deposits located within the structural terrace was sometimes very uncertain because (1) the bedrock rapidly weathers to residuum, (2) overlying surficial deposits shed debris that usually obscures the contact, and (3) there is very little color difference between weathered Maroon redbeds and the reworked Maroon materials that compose the surficial deposits.

Divisions of the Pleistocene used herein correspond to those of Richmond and Fullerton (1986). Age assignments for surficial deposits are based primarily upon the degree of erosional modification of original surface morphology, height above modern drainages, and to a lesser extent the relative degree of soil development. Correlation of stream terraces and interpretations of their ages is hindered by their limited and discontinuous distribution and poor outcrops.

Human-made Deposits

af — **Artificial fill (latest Holocene)—**Fill deposited by people during the construction of U.S. Highway 6, 24, and I-70, a small pond, a dirt road, and a home site. Artificial fill is composed mostly of unsorted local silt, sand, and rock fragments, but may include construction materials. Maximum thickness is about 20 feet.

Alluvial Deposits—Silt, sand, and gravel deposited in terraces along the Colorado River.

Qt — **Terrace alluvium (late Pleistocene)—**This unit is composed of stream alluvium underlying remnants of terraces about 35 to 80 feet above the Colorado River. It is exposed in roadcuts along I-70 between the mouths of basins B and C and near the South Canyon Creek exit on both sides of the mouth of basin C. The unit consists of poorly sorted, clast-supported, occasionally bouldery, pebble and cobble gravel with a sand matrix. Clasts are chiefly subround to round and consist of various rock types found in the drainage area of the Colorado River. Clasts generally are only slightly weathered at shallow depths. Maximum thickness of the unit is about 20 to 30 feet. These deposits were mapped by Fairer and others (1993) as older terrace alluvium, which supposedly occurs about 130 ft above river level and is of Bull Lake age (140 to 150 ka, Pierce and others, 1976; Pierce, 1979 or about 130 to 300 ka, Richmond, 1986). In that these deposits are actually only 35 to 80 feet above river level, they probably correlate with terrace deposits T6 and T7 in the Carbondale-Glenwood Springs area of Piety (1981), and with younger and intermediate terrace deposits of Kirkham and others (1995). As such, these deposits may be of Pinedale age (12 to 35 ka; Richmond, 1986).

Colluvial Deposits—Silt, sand, rock debris, and clay deposited by landslides.

Qlsr — **Recent landslide deposits (latest Holocene)—**Includes active and recently active landslides having morphological features suggestive of historical movement. Deposit is a heterogeneous unit consisting of unsorted, unstratified silt, sand, and rock debris with minor clay. Unit includes rotational and translational landslides. Most of the recent landslides are very small and occur on steep slopes eroded into either older landslide deposits (Qlso), older colluvium and sheetwash deposits (Qcso), or younger colluvium and sheetwash deposits (Qcs). A few recent landslides have involved residuum developed on Maroon Formation red beds. Maximum thickness is about 40 feet.

Recent landslides probably provided a small percentage of the material mobilized during the 1994 debris flows. However, in the spring of 1995 a few of the recent landslides extended into and partially or completely blocked adjacent stream channels. The relatively large, recent landslide in the east fork of basin F blocked the channel in May, 1995, but a 5 to 6 feet wide by 5 to 15 feet deep channel was incised through the slide mass when it was examined in November, 1995. This suggests this landslide was probably a source of material for one or more of the 1995 debris-flow events in basin F. Recent landslide deposits may continue to be a source of debris for future events.

Qls **Landslide deposits (Holocene)—**Highly variable deposits similar in texture and lithology to recent landslide deposits (Qlsr). They possess distinctive landslide morphology, but do not appear to have moved during the past few decades. Unit includes rotational and translational landslides. Maximum thickness is around 60 feet. Sheet and rill erosion of landslide deposits, along with direct erosion of their toes, probably contributed minor amounts of material to the 1994 debris flow. These deposits will probably continue to yield only minor quantities of sediment during future events, unless they are reactivated and slide into active channels.

Qlso **Older landslide deposits (Pleistocene)—**Highly variable deposits similar in texture and lithology to recent landslide deposits (Qlsr), but which appear to have been stable for thousands of years and are locally deeply dissected by streams. Unit includes a very large landslide complex that heads on the south side of Storm King Mountain in the upper reaches of basins C, D, E, F, and G. Older landslide deposits underlie the drainage divides between parts of these basins. Unit chiefly consists of heterogeneous deposits of unsorted, unstratified, matrix-supported, gravelly sandy silt. Older landslide deposits contain a high percentage of bouldery and cobbly rock debris in their upper reaches. The relative amount of coarse rock debris decreases downslope. Thickness is estimated to range from 50 to perhaps as much as 180 feet, but generally is 80 to 120 feet thick.

Older landslide deposits have been deeply dissected by erosion along the active stream channels, creating steep, angle-of-repose slopes along much of its southerly edge. The upper surfaces on these deposits are mostly gently sloping and little eroded; much of the original hummocky topography on the landslide is now subdued, a result of minor erosional modification of the higher ground and deposition of thin veneers of sheetwash and colluvium in lower areas. Two prominent escarpments extend across parts of the older landslide deposits. The origin of these escarpments is poorly understood. The upper escarpment coincides with the north limb of the structural terrace and may somehow be related to it.

We saw no evidence to indicate the older landslides moved after the 1994 forest fire. They appear to have been stable for many hundreds and perhaps thousands of years. Very small, localized, recent landslides have formed on the steep slopes cut into the toe of the older landslide deposits, but this activity does not have direct bearing on the stability of the entire older slide mass. Older landslide deposits were a major source of sediment for the 1994 debris flows. Considerable material was stripped by sheet and rill erosion and by soil slips off the steep slopes eroded into the toe of the deposit. The gently sloping surfaces on top of the older landslide deposits appear to have contributed very little or no sediment to the 1994 debris flows. A tremendous amount of soil material remains on the steep slopes eroded into the older landslide deposits and is readily available for mobilization during future rainstorms.

Alluvial and Colluvial Deposits—Silt, sand, gravel, and clay on debris fans, hillslopes, valley floors, and ridge lines deposited by debris flows, hyperconcentrated flows, colluvial activity, and sheetwash.

Qdfr **Recent debris-flow deposits (latest Holocene)—** Includes debris-flow and hyperconcentrated-flow deposits associated with the September 1, 1994 storm. Recent debris-flow deposits range from poorly sorted, matrix- and clast-supported, silty, sandy, bouldery, cobbly, and pebbly gravel to sandy silt. Clasts are angular to subangular pieces of sedimentary rock as much as 6 feet in diameter. Maximum thickness of preserved exposures of recent debris-flow deposits is about 8 feet. The recent debris-flow deposits generally have a light-gray or grayish-red color, a result of their high ash and charcoal content.

Flow paths for the 1994 debris-flow events are shown on the geologic map (Plate 1) and on Figure 2. The estimated extent of deposits removed by clean-up activities along I-70 prior to the aerial photography of November 10, 1994 is shown by the stipple pattern on Plate 1. The distribution of the removed recent debris-flow deposits is based upon 1:10,000-scale mapping by Cannon and others (1995) and oblique aerial photographs by Jim Scheidt, BLM, and Chris Tomlinson, Daily Sentinel. Thin veneers of deposits associated with the 1994 debris-flow events are found along on the banks of many of the channels which carried debris, but these deposits were not mapped on

Plate 1 either because they were less than 3 feet thick or were too narrow to be shown on the map.

Qdfy **Younger debris-flow deposits (Holocene)—** Sediments deposited by debris flows, hyper-concentrated flows, mudflows, and sheetwash on active debris fans and in stream channels before the September 1, 1994 event. Younger debris-flow deposits occur in all large basins but are most extensive in basin A and in the coalescing fan complex at and between the mouths of basins F and G. Unit ranges from poorly sorted, matrix-supported, gravelly, sandy, slightly clayey silt to clast-and matrix-supported, pebble and cobble gravel in a sandy, clayey silt or silty sand. Locally it is very bouldery. Distal parts of some fans are characterized by mudflow and sheetwash and tend to be finer grained. Clasts are mostly angular to subround sedimentary rock up to about 6 feet in diameter. Maximum thickness of this unit is about 30 feet. Erosion of channel banks composed of younger debris-flow deposits contributed a small percentage of the sediment during the 1994 debris flows, but may have played a somewhat larger role in the 1995 debris flows in basin F. Younger debris-flow deposits would likely provide similar small quantities of material during future events.

Qcs **Younger colluvium and sheetwash deposits (Holocene and late Pleistocene)—**Includes deposits derived from weathered bedrock and surficial materials that are transported as colluvium and sheetwash and deposited on hillslopes and in drainage channels. Typically they consist of poorly sorted, poorly to moderately well bedded, matrix-supported, gravelly silty sand and sandy silt, but range to matrix-supported sandy, silty, cobbly and bouldery gravel. Clasts are chiefly angular to subangular sedimentary rocks as much as about 3 feet in diameter. Deposit on east wall of basin A about 800 feet north of I-70 contains well rounded clasts gravel that originally was deposited by the Colorado River, but later reworked as colluvium. Maximum thickness is probably about 25 to 30 feet. During the 1994 debris flows, younger colluvium and sheetwash deposits probably contributed only minor quantities of the sediment that was eroded from channel banks.

Qdfo **Older debris-flow deposits (early Holocene and late Pleistocene)—** Includes remnants of formerly more extensive debris-flow and hyperconcentrated-flood deposits that lie up to about 50 feet above modern channels. Similar in texture, sorting, and clast rounding to younger debris-flow deposits (Qdfy). Since the original depositional surfaces on these deposits range from about 5 to 50 feet above active debris-flow channels, they generally are not susceptible to future debris-flow activity unless a major channel blockage develops or an unusually large debris flow occurs. Older debris-flow deposits were a minor source of sediment during the 1994 event, and likely will yield only minor sediment in future debris flows.

Qcso **Older colluvium and sheetwash deposits (Pleistocene)—**Occurs on hillslopes, ridge lines, and basin floors as erosional remnants of formerly more extensive deposits that once filled basinal areas. These deposits were transported primarily by gravity and sheetwash. Older colluvium and sheetwash deposits locally include fluvial, debris- and hyperconcentrated-flow deposits along the axes of former stream channels. Texture, bedding, sorting, and clast lithology are similar to younger colluvium and sheetwash deposits (Qcs). Unit averages 10 to 30 feet thick, but locally is as much as 125 feet thick along the mainstem drainages of basins B and C and in the west fork of basin F.

Areas underlain by older colluvium and sheetwash generally are not subject to significant future depositional activity, except where they are adjacent to eroding hillslopes. Older colluvium and sheetwash deposits may be covered by a wedge of younger colluvium and sheetwash deposits in these locations. Although the original depositional surface is locally preserved, older colluvium and sheetwash deposits generally are deeply dissected, and steep slopes have been cut into them along many of the channels.

A photograph taken in May 1995 of deeply dissected older colluvium and sheetwash deposits in basin B (Figure 8) shows remnants of the original depositional surface of the deposit preserved on the right (east). Erosion caused by and deposits left by the 1994 events can be seen in both of the major tributaries to basin B. Hillslopes where thin veneers of soil were removed during the rainstorm are visible in the lower left and center of the photograph. Trees burned by the South Canyon fire stand as stark reminders of the intensity of the fire. At the time of the photograph stands of grasses and forbs were beginning to establish on the flatter slopes in the basin and locally on the steeper slopes that were less affected by erosion during the storm.

Older colluvium and sheetwash deposits were a major source of sediment during the 1994 debris flows. Materials were stripped from steep slopes by sheet and rill erosion, minor gullying, and small soil slips. Where adjacent to active channels, surface water flowing in the channels directly eroded slopes comprised of older colluvium and sheet-wash deposits by lateral erosion and bank caving. These deposits will probably be major sources of sediment during future debris flows.

BEDROCK

Tc **Conglomerate of Storm King Mountain (late Tertiary)—**This unit includes a previously unrecognized, very poorly exposed, conglomeratic unit found on the south flank of Storm King Mountain at altitudes ranging from about 8,200 to 8,700 feet. Identification of this unit was based on the presence of limestone cobbles in residuum and on a single piece of sandy, limestone-pebble conglomerate found in a road cut. The conglomerate of Storm King Mountain appears to overlie moderately to steeply dipping Maroon and Eagle Valley Formations at a major angular unconformity. All cobble-sized clasts and most pebble-sized clasts are limestone. Other lithologies noted in the pebble- and granule-sized fraction included minor amounts of basalt, feldspar, quartz, and chert. Clasts within this unit are subangular to subrounded. The matrix consists of very fine to medium-grained sand that is cemented with

Figure 8. Photograph of older colluvium and sheetwash deposits in basin B taken in May, 1995. Remnants of the original depositional surface of the deposit are preserved on the right (east) side of the photograph. Erosion caused by the 1994 events and deposits left by it can be seen in both of the major tributaries to basin B. Hillslopes where thin veneers of soil were removed during the flood are visible in the lower left and center of the photograph. Trees burned by the South Canyon fire stand as stark reminders of the intensity of the fire. At the time of the photograph stands of grasses and forbs were beginning to be established on the flatter slopes in this basin, but were much less well established on the steep slopes. Photograph by Robert Kirkham.

calcite. The unit appears to be weakly to moderately indurated. Age of the conglomerate of Storm King Mountain is very poorly constrained. It must be younger than major folding of the Grand Hogback Monocline during the late Laramide and erosional beveling of the monoclinally folded beds and older than incision by Dolan Gulch 0.6 miles to the northeast and 2,200 feet deep. Presence of basalt clasts suggests a post-early Miocene age, in that the oldest basalt in this region is around 24 Ma.

PIPm **Maroon Formation (Lower Permian and Pennsylvanian)—** The Maroon Formation consists of red beds of sandstone, conglomerate, siltstone, mudstone, and shale and minor, thin beds of gray limestone. Conglomeratic beds within the formation contain pebble- and cobble-sized clasts. Commonly the Maroon Formation is arkosic and very micaceous. Total thickness ranges from about 3,000 to 4,000 feet, including the 125- to 150-feet-thick Schoolhouse Member at the top of the formation; however, only the lower three-quarters of the formation crops out within the mapped area.

The Maroon Formation rapidly weathers to residuum, particularly where it crops out in the structural terrace within the Grand Hogback Monocline. Thickness of the mantle of residuum probably averages about 4 or 5 feet, but locally may be much thicker. Sheet and rill erosion on steep hillslopes and small soil slips in residuum derived from the Maroon Formation residuum were significant sources of material for the 1994 debris flows. Abundant residual materials remain on these slopes and are available for mobilization during future debris flows.

IPe **Eagle Valley Formation (Middle Pennsylvanian?)—** Interbedded reddish-brown, gray, reddish-gray, and tan siltstone, shale, sandstone, gypsum, and carbonate rocks comprise the Eagle Valley Formation. This unit represents a stratigraphic interval in which the red beds of the Maroon Formation grade into and intertongue with the dominantly evaporitic rocks of the Eagle Valley Evaporite. It includes rock types of both formations. Formation thickness is variable, ranging from about 500 to 1,500 feet. The Eagle Valley Formation is conformable and intertonguing with the overlying Maroon Formation and underlying Eagle Valley Evaporite. The contact with the Maroon Formation is placed at the top of the uppermost evaporite bed or light-colored clastic bed. Although the Eagle Valley Formation weathers to residuum rapidly, it appears to have contributed only very minor sediment to the 1994 debris flows, primarily because it crops out in only a limited part of the study area above where most debris flows initiated.

IPee **Eagle Valley Evaporite (Middle Pennsylvanian)—**The Eagle Valley Evaporite includes a sequence of evaporitic rocks consisting mainly of massive to laminated gypsum, anhydrite, and halite, interbedded with light-colored mudstone and fine-grained sandstone, thin carbonate beds, and black shale. Only the upper part of the formation crops out in the mapped area. Beds commonly are intensely folded, faulted, and ductily deformed by diapirism, flowage, load metamorphism, hydration of anhydrite, and Laramide tectonism (Mallory, 1971; Kirkham and others, 1996). In the Glenwood Springs area the formation thickness ranges from about 1,200 feet to perhaps 9,000 feet (Mallory, 1971), where it is tectonically thickened along the axis of the Cattle Creek Anticline between Glenwood Springs and Carbondale. The Eagle Valley Evaporite rapidly weathers to residuum, but, due to its very limited aerial extent within the upper reaches of the mapped area, was only a very minor source of sediment during the 1994 debris flows.

ANALYSIS OF THE SEPTEMBER 1, 1994 DEBRIS-FLOW EVENTS

APPROACH

Debris-flow susceptibility in a burned watershed depends on the interaction of several factors. They include the types of geologic materials within the drainage basin, slope characteristics, availability of unconsolidated materials on the hillslopes and in the channels, and condition of the soils following the fire, particularly the development of hydrophobic properties (Cannon, 1997; Spittler, 1996). The debris flows that occurred during the September, 1994 events on Storm King Mountain consisted of material from three primary sources: 1) the abundant loose, friable dry ravel, ash, and charcoal that accumulated in the channels during and after the fire, 2) material eroded from the steep hillslopes of the mountain, and 3) material stored in the stream channels from years of smaller flooding and debris-flow events (Cannon and others, 1995). Neither the volume nor spatial distributions of the dry-ravel deposits nor the pre-event channel configuration are known. Therefore, this analysis will focus on determining where, within the topography, the debris flows initiated and resolving which geologic units were most susceptible to debris-flow initiation.

Digital compilations of the 1:5,000-scale mapping of the geology and of the debris-flow paths were used in this analysis. These data were coupled with a 20-feet contour interval Digital Line Graph (DLG) representation of the topography and a Digital Elevation Model (DEM) with 32.8-feet (10-meter) resolution that were obtained from survey-controlled, 1:8,000-scale aerial photographs. Tools available through ARC-Info for analyzing spatial data were used to measure areas of the geologic units, lengths of the debris-flow paths, and slopes of debris-flow initiation areas and of soil-slip scars.

The geomorphic setting of the area before the fire and after the September 1, 1994 rainstorm, along with the accompanying debris-flow events are described in a previous section. The geologic and topographic controls on debris-flow initiation, as derived from the geologic and topographic coverages, are discussed below. Three morphometric parameters commonly attributed to clear water drainage networks are computed for the drainages occupied by the debris flows. These parameters provide descriptive information about debris-flow occurrence within the drainage basins. A detailed comparison of two morphologically similar drainages that experienced different burn coverages is presented, as is an evaluation of sources of material contributed to the debris flows as they traveled down the drainages.

GEOLOGIC AND TOPOGRAPHIC INITIATION CONTROLS

The analysis presented in this section will focus on determining where, within the topography, the debris flows initiated, and which geologic units were most susceptible to debris-flow initiation. Our analysis starts with a consideration of the role of the soil slips shown on the geologic map in contributing material to the debris flows. We then consider the initiation locations of the debris flows. At the point of origin of each mapped debris flow, the slope gradient at the path's upper limit, the slope aspect, the underlying geologic unit, and the location within burned or unburned areas were computed and/or evaluated.

Debris-flow paths from the September events could not be traced up-channel to discrete landslide sources. This factor, when combined with observations of spatially extensive hillslope erosion and flushing of channel material that occurred during the September events, led Cannon and others (1995) to conclude that most of the material involved in the debris flows was derived from the loose, unconsolidated dry-ravel materials generated after the fire, the burned soils on the hillslopes, and the materials stored in the channels over the years.

However, fifty-eight soil-slip scars were discovered in the study area while conducting the detailed mapping for this investigation; it is likely that more exist.

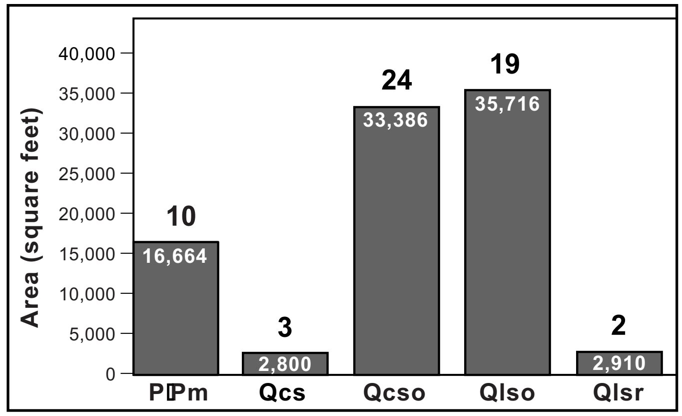


Figure 9. Calculated areas of soil-slip scars and frequency of occurrence by geologic unit and drainage basin.

Table of statistical data for Figure 9.

PIPm

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	1	2,377	—	4	—	2	—	10
Area (sq ft)	2,210	2,377	—	8,550	—	3,526	—	16,664

Qcs

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	2	—	1	—	—	—	—	3
Area (sq ft)	1,398	—	1,402	—	—	—	—	2,800

Qcso

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	1	19	2	—	—	1	1	24
Area (sq ft)	1,019	18,495	10,053	—	—	2,054	1,764	33,386

Qlso

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	—	—	7	1	—	11	—	19
Area (sq ft)	—	—	18,684	6,098	—	10,934	—	35,716

Qlsr

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	—	—	—	—	2	—	—	2
Area (sq ft)	—	—	—	—	2,910	—	—	2,910

Totals

Drainage	A	B	C	D	E	F	G	Unit Total
Frequency	4	22	10	5	2	14	1	58
Area (sq ft)	4,628	20,872	31,140	14,648	2,910	16,514	1,764	91,477

The spatial frequency and calculated areas of these scars in each drainage, as well as in the host geologic units, are shown in Figure 9 . Older colluvium and sheetwash deposits (Qcso) and older landslide deposits (Qlso) were particularly susceptible to failure by soil slips. The soil slips developed on slopes ranging from 10 to 57 degrees, with an average slope of 30 degrees and standard deviation of 8.5 (Figure 10).

Soil slips typically involved only a thin, 1- to 3-feet-thick veneer of surficial deposits. Based on an estimated average thickness of two feet and a measured areal extent of 91,477 square feet (Figure 9), the combined volume of material mobilized by the soil slips is 6,780 cubic yards. This is approximately 7 percent of the total volume of material deposited at the canyon mouths, which was estimated at 91,300 cubic yards by Cannon and others (1995). Thus, only a relatively small amount of the material deposited by the debris flows came from the soil-slip scars. Apparently the large majority of the debris flows initiated without the development of a well-defined landslide source area. This agrees with the general observation that in the years immediately following a fire, landsliding due to water infiltration and Coulomb failure is less likely to occur in burned areas than in unburned ones (Morton, 1989), a process generally ascribed to an increase of surface runoff at the expense of infiltration after a fire.

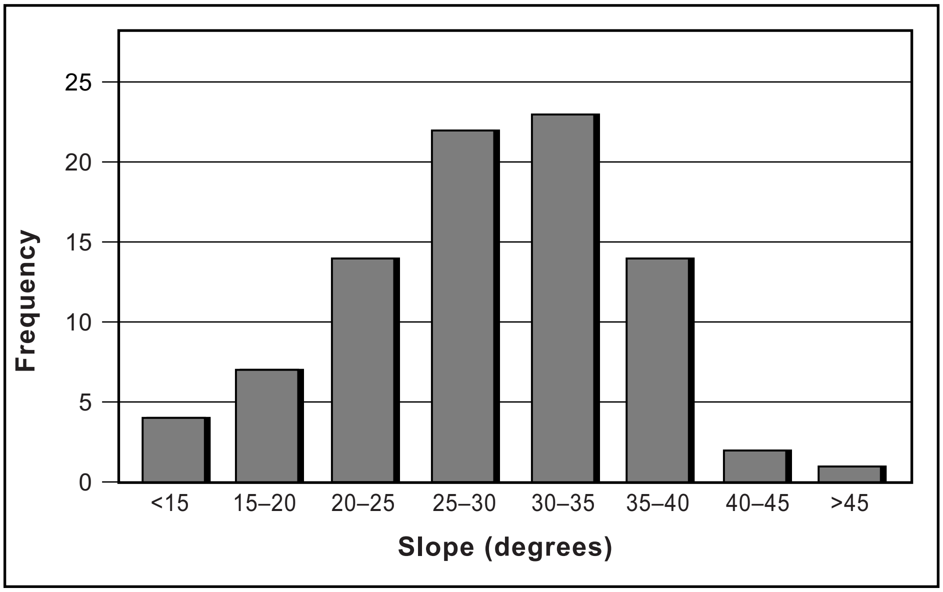


Figure 10. Frequency distribution of soil-slip scars relative to slope angle.

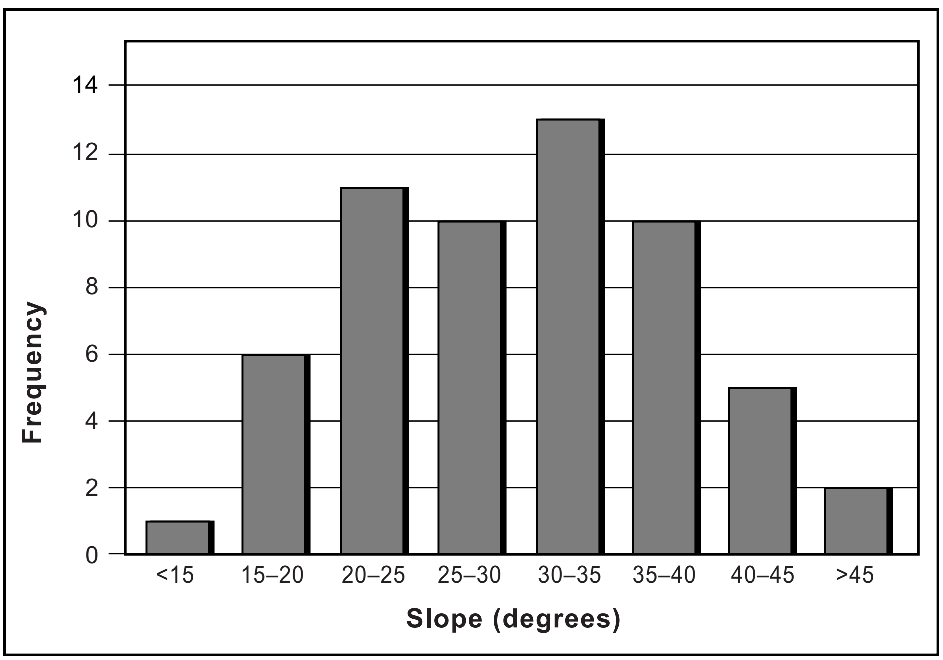


Figure 11. Frequency distribution of debris-flow initiation locations relative to slope angle.

Throughout the study area, most of the debris flows originated on slopes between 20 and 40 degrees, with a majority between 25 and 35 degrees. A few debris flows initiated on slopes flatter than 15 degrees, but only one originated on a slope steeper than 45 degrees (Table 3 and Figure 11). The debris-flow initiation areas occurred primarily on the south- and southwest-facing slopes, with a secondary concentration in the southeast- and west- facing slopes (Table 3).

The great majority, or 82 percent, of the debris flows from the September event originated in areas within the boundaries of the South Canyon Fire (Figure 2). However, in the eastern portion of the study area in drainages E, F, G, and J, both the initiation areas and debris-flow paths occurred at the margin of or downslope from the burned areas. Even though only 48 percent of drainage basin F was burned, significant debris-flow activity occurred in this drainage. Additional debris flows also developed in basin F during 1995. Watershed front I also produced debris flows in 1994, even though it was not burned. This suggests that either the storm was sufficiently intense at this end of the watershed, or the slopes of this watershed front were steep enough to produce debris flows even without the exacerbating effects of the wildfire.

Most of the debris-flow paths originated within first order drainages underlain by either the Maroon Formation or older landslide deposits (Table 3). This is supported by field observations of abundant sheet and rill erosion off the steep slopes cut into the toe of the older landslide deposits and the residuum developed on the Maroon Formation. Considerably fewer debris flows initiated in colluvium and sheetwash deposits (Qcs), older colluvium and sheetwash deposits (Qcso), and the Eagle Valley Evaporite. Within the Maroon Formation, most debris flows initiated in tributary drainages with gradients between 25 and 40 degrees, while in the older landslide deposits (Qlso) the majority of the debris flows originated in tributary drainages with gradients less than 30 degrees (Table 3).

The total number of debris flow paths occurring in a particular geological unit depends at least in part upon the areal extent of that unit within the study area. For example, the Maroon Formation hosted the largest number of flows (55; Table 3) and also by far covered the highest proportion of the study area (41 percent; Table 2). To compensate for this effect, we developed an "initiation susceptibility index" by dividing the number of debris-flow initiation locations in each geologic unit by the relative proportion of the host unit exposed in the study area (Table 4). This index thus defines the number of initiation locations that occurred per unit area of each geologic unit and allows for a comparison of their susceptibility to debris-flow initiation. This approach is similar to that described by Wieczorek and others (1988).

The initiation susceptibility index indicates that in addition to generating the majority of the debris flows, the Maroon Formation and older landslide deposits (Qlso) produced the most debris flows per unit area during the storm. Older colluvium and sheetwash deposits (Qcso) and colluvium and sheetwash deposits (Qcs) were less vulnerable to debris-flow initiation. The Eagle Valley Evaporite had the lowest number of debris flows per unit area of all the geologic units in which debris flows initiated. This order of geologic units is essentially the same sequence indicated by the data that was not normalized by area of exposure.

Our analysis indicates that the slopes with the highest susceptibility to debris-flow initiation following the wildfire on Storm King Mountain were burned, south and south-west facing hillslopes with gradients between 25 and 40 degrees where underlain by the Maroon Formation and less than 30 degrees where underlain by older landslide

Table 3. Distribution of debris-flow initiation locations by geologic unit, slope, and slope aspect in the study area.

Geologic Unit	Frequency	Slope		Slope Aspect	
		Degrees	Frequency	Quadrant	Frequency
IPee	1	<15	—	SW	1
		15–20	—		1
		20–25	—		
		25–30	—		
		30–35	—		
		35–40	—		
		40–45	—		
		>45	—		
PIPm	55	<15	—	W	10
		15–20	7	SW	17
		20–25	3	S	18
		25–30	15	SE	5
		30–35	15	E	5
		35–40	12		
		40–45	2		
		>45	1		
Qcs	6	<15	—	S	4
		15–20	—	SW	2
		20–25	1		
		25–30	1		
		30–35	3		
		35–40	1		
		40–45	—		
		>45	—		
Qcso	4	<15	1	S	4
		15–20	—		
		20–25	1		
		25–30	—		
		30–35	2		
		35–40	—		
		40–45	—		
		>45	—		
Qlso	18	<15	1	W	1
		15–20	1	SW	6
		20–25	5	S	6
		25–30	5	SE	5
		30–35	3		
		35–40	3		
		40–45	—		
		>45	—		

Table 4. Debris-flow initiation susceptibility index for each geologic unit. The index is calculated as the number of debris flows hosted by a particular unit divided by the relative proportion of the unit exposed in the study area.

Geologic Unit	No. of Initiation Sites	Percent of Study Area	Suscepti-bility Index
IPee	1	6.8	0.1
PIPm	55	41.0	1.3
Qcs	6	13.9	0.4
Qcso	4	7.9	0.5
Qlso	18	17.8	1.0

deposits (Qlso). Material derived from soil slips accounted for about 7 percent of the total volume of material deposited at canyon mouths. Older colluvium and sheetwash deposits (Qcso) and older landslide deposits (Qlso) were particularly susceptible to soil-slip failure. A drainage basin of which only 23 percent was burned experienced major debris-flow activity, although this occurrence may be due to particularly high-intensity rainfall at the eastern end of the watershed or to varying topographic, geomorphic, or soil characteristics.

MORPHOMETRIC ANALYSIS APPLIED TO DEBRIS-FLOW PATHS

The fact that the debris flows traveled through the pre-existing drainage network during the September 1994 events at Storm King Mountain allows for evaluation of the paths left by the debris flows using a morphometric analysis (Figure 12). In this analysis the debris-flow paths are treated as fluvial segments and are subdivided into orders as defined by Strahler (1957). The lengths of the debris-flow paths in each order were measured from the digital representation of the mapped debris-flow paths. This analysis is used to describe the occurrence of debris flows within the drainage network.

Ordering of the debris-flow path segments shows that most of the segments are first order (Figure 13; Table 5). The maximum observed order is third, which occurred in drainage basins B, C, D, E, and F. Drainage basins C and B, which hosted the most debris flows, show the largest overall number of segments (38 in drainage C and 22 in drainage B).

Slightly more than 50 percent of the total length of all the debris-flow paths occurred as first-order segments, 30 percent occurred as second-order segments, and 19 percent occurred as third-order segments (Table 6). In most of the geologic units, where more than one order is present, there is a general tendency towards a decrease in both length and the length percentage in the higher orders (Table 6).

Three morphometric parameters commonly used for describing clear water drainage networks were computed for the drainages occupied by debris-flow paths: debris-flow path density (D), debris-flow path frequency (F), and the percentage of the main channel occupied by debris flows (PL). These parameters give information about debris-flow occurrence within the individual drainage basins. The values for these parameters and their definitions are shown in Table 7.

The debris-flow path density relates the cumulative length of the debris-flow paths in the drainage to the drainage area, and it corresponds to the proportion of drainage area occupied by debris-flow paths. The highest values of debris-flow path density are in the following drainages (listed in decreasing order): J, E, B, and C. Interestingly, only a small percentage of the upper reaches of drainages E and J were burned, and the debris flows occurred downslope of the burned areas. In comparison, drainages B and C were nearly completely burned and produced the highest volume of material during the storm (Cannon and others, 1995).

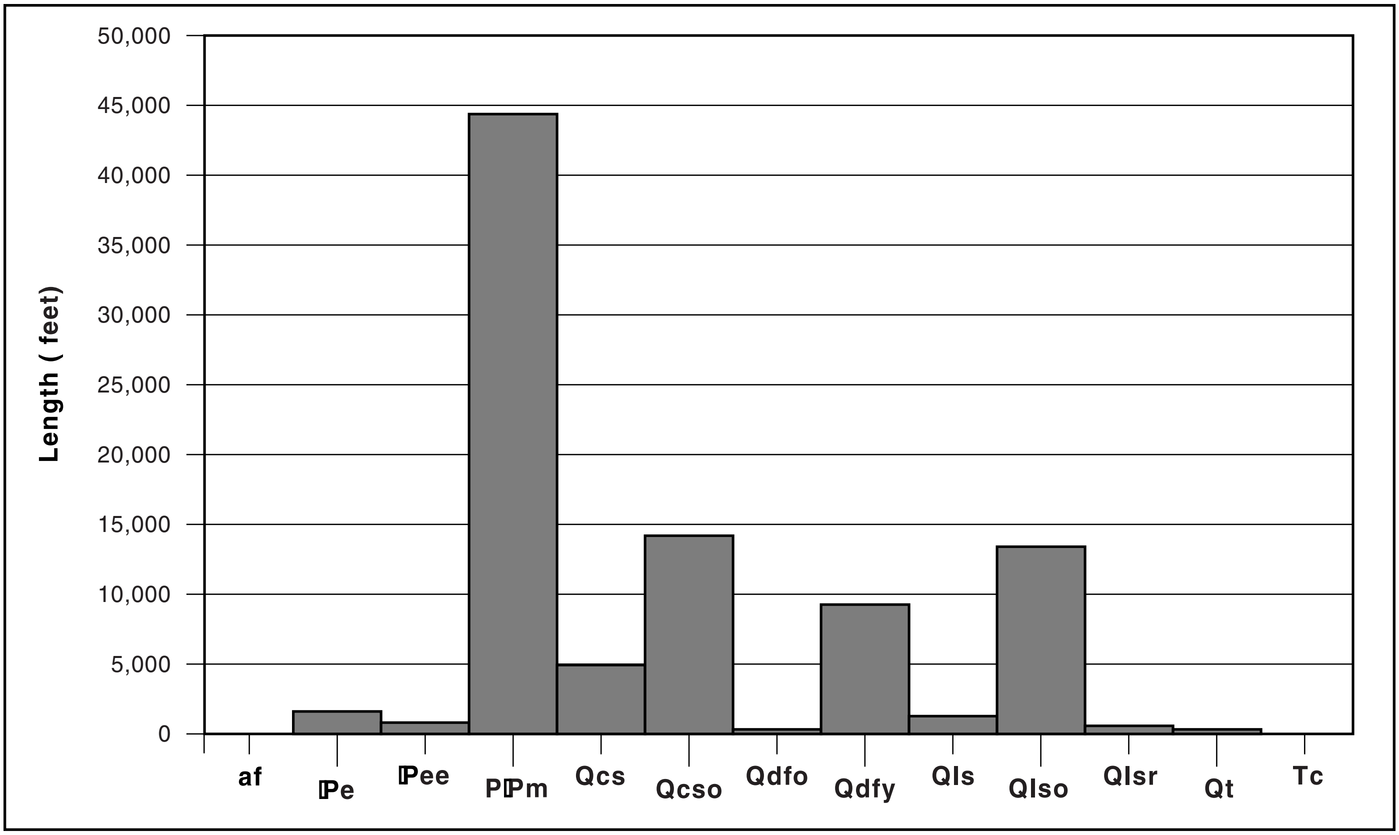
The debris-flow path frequency is the ratio between the number of debris-flow path segments in a drainage basin and the areal extent of that drainage basin. This parameter is less significant than the path density in that it does not take into account the length of the debris-flow path segments, only their frequency. Drainages J, E, B, C, and H show the highest values of debris-flow frequency. Again, drainages E and J were only partially burned, while B, C, and H were nearly completely burned.

The relatively high values of each of these parameters in drainages E and J points to the fact that even small, partially burned drainages were susceptible to debris-flow activity that involves a significant proportion of the drainage network in that basin. The fact that unburned basin A did not produce any significant debris flows indicates the presence of the fire, rather than the rainfall, was the controlling factor for debris-flow initiation.

A parameter of particular interest is the length percentage of the main channel occupied by the debris-flow paths. This parameter was not computed for drainage basins H and I due to the lack of a main channel in such watershed front areas, and is equal to 0 in drainage A, where the main channel was not affected at all by debris flows. Values ranged from greater than 40 percent to greater than 80 percent in drainages C and J. Thus, for the entire study area, more than one half of the length of available main channels were occupied by debris flows during the September 1, 1994, event. This result can be used in future assessments of sediment yields from burned watersheds with similar geological and geomorphic frameworks.

DETAILED COMPARISON OF DRAINAGES B AND F

In this section we compare the debris-flow path characteristics described above for two drainage basins, B



Geologic Unit	Drainage Basin													
	A	B	C	D	E	F	G	H	I	J	K	L	M	Study Area
af	—	—	—	—	—	—	—	—	—	—	—	—	—	
₽e	—	1,668	—	—	—	—	—	—	—	—	—	—	—	1,668
₽ee	—	784	—	—	—	—	—	—	—	—	—	—	—	784
P₽m	—	10,992	14,929	6,251	4,375	4,475	242	2,279	710	137	—	—	—	44,390
Qcs	—	1,073	1,181	—	500	—	174	1,108	916	—	—	—	—	4,952
Qcso	338	9,571	1,879	—	541	876	607	—	—	408	—	—	—	14,220
Qdfo	—	—	—	148	—	—	—	173	—	—	—	—	—	321
Qdfy	—	2,094	2,861	171	498	1,735	517	—	—	1,366	—	—	—	9,242
Qls	—	109	324	—	—	840	—	—	—	—	—	—	—	1,273
Qlso	—	—	5,896	83	110	6,666	635	—	—	—	—	—	—	13,390
Qlsr	—	—	219	—	206	155	—	—	—	—	—	—	—	580
Qt	—	—	—	—	—	—	—	333	—	—	—	—	—	333
Tc	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total	338	26,291	27,289	6,653	6,230	14,747	2,175	3,893	1,626	1,911	—	—	—	91,153

Figure 12. Cumulative lengths of debris-flow paths by geologic unit and drainage basin. The table shows the cumulative lengths of debris-flow paths (in linear feet) in each drainage basin and the entire study area through each geologic unit. The graph shows the cumulative length of debris-flow paths through each geologic unit for the entire study area.

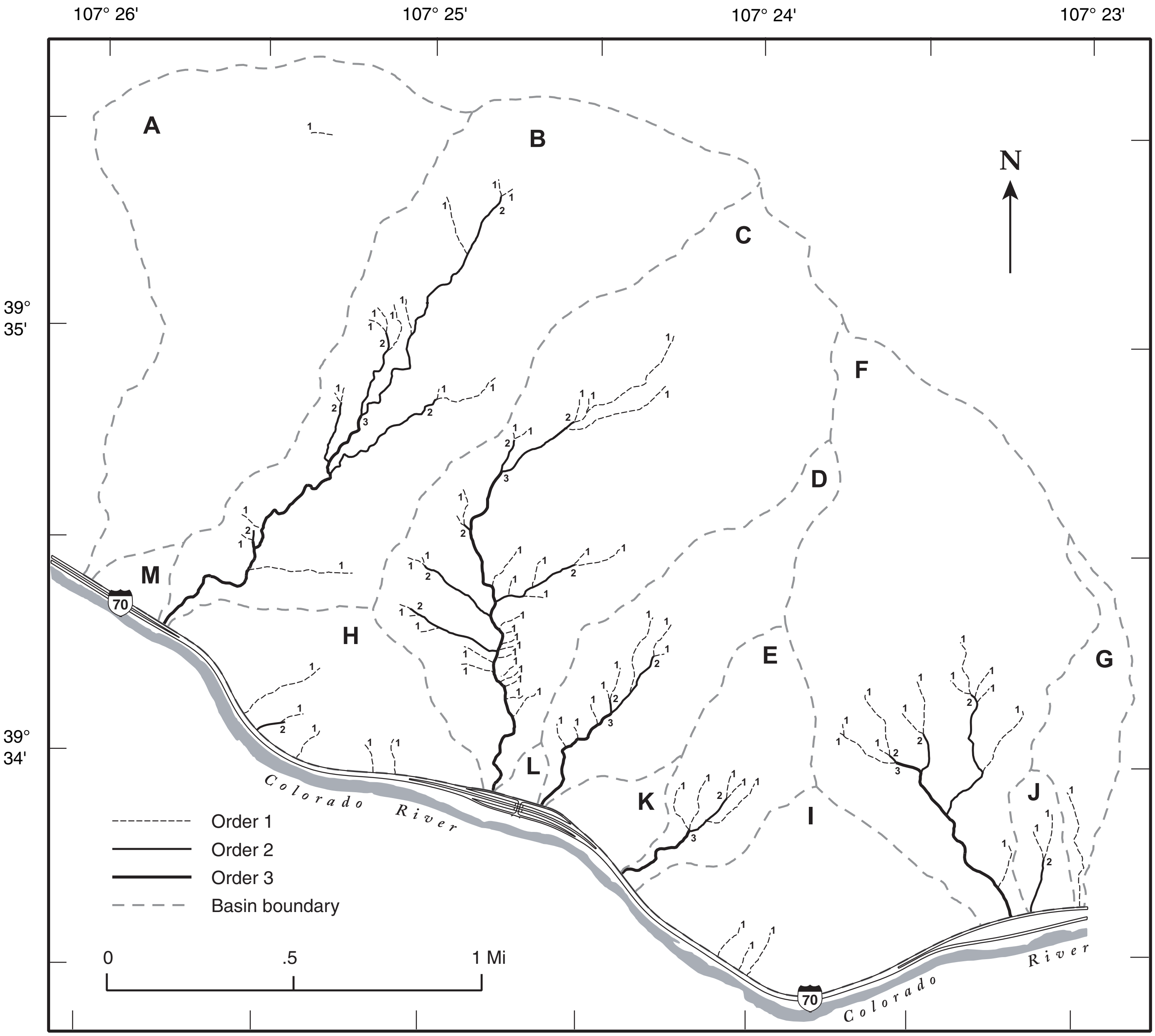


Figure 13. Ordering of debris-flow path segments (methodology from Strahler, 1957).

and F, which exhibit considerable differences in geologic configuration and experienced strong differences in burn percentage. This comparison gives interesting results applicable in estimating debris-flow susceptibility following wildfire.

Drainage basins B and F both cover approximately 500 acres, but 94 percent of basin B burned, while only 48 percent of basin F, mostly the upper reaches, were burned (Table 1 and Figure 2).

The percentages of geological units in the two drainage basins are shown in Table 8. In both the basins, the Maroon Formation occupies more than 30 percent of the drainage basin area. However, in basin B the Maroon Formation underlies the ground surface in much of the lower two-thirds of the basin, and it makes up the majority of the slopes adjacent to the main channel. In contrast, the Maroon Formation crops out as isolated areas of bedrock in the upper and lower reaches of basin F. Nearly 45 percent of basin F is underlain by a blanket of older landslide deposits (Qlso), which has been deeply dissected by the existing drainage network. Older landslide deposits are absent from basin B.

The geologic control of initiation locations for the debris-flow paths varies considerably between basins B and F, even though the Maroon Formation underlies nearly the same percentage of basins B and F.

Table 5. Distribution of ordering and lengths of debris-flow path segments in drainages within the study area.

Drainage Basin	Order 1		Order 2		Order 3		Total	
	Length (ft)	No.	Length (ft)	No.	Length (ft)	No.	Length (ft)	No.
A	338	1	—	—	—	—	338	1
B	6,558	15	9,163	5	4,933	1	20,655	21
C	12,438	31	5,879	6	5,287	1	23,605	38
D	3,399	8	1,239	2	1,867	1	6,504	11
E	3,108	5	760	2	1,280	1	5,148	8
F	7,050	12	3,271	4	2,599	1	12,920	17
G	1,736	1	—	–	—	—	1,736	1
H	3,252	6	360	1	—	—	3,612	7
I	1,627	3	—	–	—	—	1,626	3
J	1,114	2	798	1	—	—	1,912	3
K	—	—	—	–	—	—	—	—
L	—	—	—	–	—	—	—	—
M	—	—	—	–	—	—	—	—

Table 6. Distribution of ordering and lengths of debris-flow path segments by geologic unit.

Geologic Unit	Order 1		Order 2		Order 3		Total
	Length (ft)	Percent	Length (ft)	Percent	Length (ft)	Percent	Length (ft)
af	—	—	—	—	—	—	—
Pe	363	22	1,304	78	—	—	1,667
IPee	458	58	325	41	—	—	783
PIPm	19,395	43	13,533	30	11,462	26	44,390
Qcs	4,160	84	576	12	216	4	4,952
Qcso	6,320	44	6,651	47	1,249	9	14,220
Qdfo	73	23	–	–	248	77	321
Qdfy	2,296	25	2,976	32	3,971	43	9,243
Qls	727	57	242	19	305	24	1,274
Qlso	11,536	86	1,853	14	—	—	13,389
Qlsr	293	50	288	49	—	—	581
Qt	263	79	70	21	—	—	333
Tc	—	—	—	—	—	—	—
Total	46,391	51	27,818	30	17,451	19	91,660

In drainage B, most of the debris flows initiated within the Maroon Formation, whereas in basin F, the majority of debris flows originated in older landslide deposits (Qlso; Table 9).

An index of debris-flow initiation susceptibility was calculated for both these basins by normalizing the number of debris-flow initiation locations in each geologic unit by the percentage of exposure of a geologic unit in that basin (Table 10). This index indicates that, per unit area, most debris flows in basin B originated primarily in colluvium and sheetwash (Qcs) and the Maroon Formation. In comparison, older landslide deposits (Qlso) were the most susceptible unit to debris-flow initiation in basin F. The Maroon Formation exhibited a very low susceptibility value in basin F.

Perhaps reflecting the inconsistent geographic distributions of the Maroon Formation and older landslide deposits (Qlso), the locations of the debris-flow path initiation locations varied considerably between the two basins. In basin B the paths initiated in first-order drainages located all along the main channel, and debris-flow paths were mapped extending nearly to the head of the drainage (Figure 2). The debris-flow paths in basin B all originated within the burned area

Table 7. Morphometric parameters calculated for debris- flow paths in each drainage basin. D, path density, is the total length of the debris-flow paths in each drainage (see Table 5) divided by the drainage basin area (see Table 1). F, path frequency, is the number of debris-flow paths in each drainage (see Table 5) divided by the drainage basin area (see Table 1). PL, percent length of the main channel occupied by debris-flow paths, is the length of the debris-flow paths in the main channel divided by the length of the main channel, and multiplied by 100.

Drainage Basin	D	F	PL
	(1/feet)	(1/square feet)	Length (%)
A	1.55×10^{-5}	4.57×10^{-8}	—
B	8.60×10^{-4}	8.73×10^{-7}	75.5
C	1.03×10^{-3}	1.43×10^{-6}	81.5
D	8.01×10^{-4}	1.32×10^{-6}	65.1
E	1.24×10^{-3}	1.60×10^{-6}	54.3
F	6.47×10^{-4}	7.46×10^{-7}	55.4
G	6.50×10^{-4}	2.99×10^{-7}	43.2
H	5.53×10^{-4}	1.04×10^{-6}	—
I	2.07×10^{-4}	3.81×10^{-7}	—
J	1.40×10^{-3}	2.19×10^{-6}	80.4
Total area	7.02×10^{-4}	8.51×10^{-7}	—

and on slopes between 15 and 40 degrees (Figure 14). In contrast, the majority of the debris-flow paths in basin F initiated at the change in slope at the head of the incision into the toe of the old landslide deposits in the basin (Figure 2), on slopes between 20 and 40 degrees. Although the majority of these paths occurred downslope from the burned area, the area of the drainage basin upslope from the initiation locations is considerable.

Intensely burned and steep hillslopes are generally susceptible to debris-flow processes following a wildfire (Cannon, 1997). The result presented above indicates that an unburned but steeply sloping, erosion-susceptible geologic unit (i.e. Qlso) exposed downslope from an intensely burned area with gentle slopes is still susceptible to significant debris-flow activity. This susceptibility can almost certainly be attributed to increased surface runoff generated from the burned area above.

In another comparison of the two drainage basins, the contribution of material to the debris-flow deposits at the canyon mouths from soil-slip scars on the hillslopes was computed for both basins. In basin B the majority of the soil-slip scars occurred in older colluvium and sheetwash deposits (Qcso). The volume of material contributed by the soil slips in basin B is approximately 4 percent of the total volume of material deposited at the canyon mouth (Figure 9). This is close to the value for all the drainages combined (7 percent). In contrast, the soil slips in basin F originated primarily in older landslide deposits (Qlso) and accounted for approximately 16 percent of the material deposited at the canyon mouths (Figure 9).

Since almost all of the soil-slip scars mapped in basin F are located in unburned areas, the value of 16 percent suggests a greater susceptibility to infiltration-initiated landslides in this basin, regardless of the occurrence of the wildfire. This conclusion is supported by the recurring debris-flow activity in drainage basins F, G, and J since the September 1994 event. In

Table 8. Distribution of geologic units and percent exposure in drainage basins B and F.

Drainage Basin B

Geologic Unit	Area (acres)	Percent of Exposure
af	0.07	0.01
IPe	107.6	19.5
IPee	73.7	13.3
PIPm	198.0	35.9
Qcs	48.9	8.8
Qcso	117.9	21.4
Qdfr	2.1	0.4
Qdfy	2.4	0.4
Qls	1.6	0.3
Qlsr	0.04	0.01
Total	552.3	

Drainage Basin F

Geologic Unit	Area (acres)	Percent of Exposure
af	0.2	0.04
PIPm	169.1	32.3
Qcs	79.4	15.2
Qcso	18.0	3.4
Qdfr	1.2	0.2
Qdfy	7.3	1.4
Qls	2.4	0.5
Qlso	228.7	43.7
Qlsr	3.5	0.7
Tc	13.4	2.6
Total	523.2	

Table 9. Distribution of debris-flow initiation locations by geologic unit, slope, and slope aspect for drainage basins B and F.

Drainage Basin B

Geologic Unit	Frequency	Slope		Slope Aspect	
		Degrees	Frequency	Quadrant	Frequency
IPee	1	<15	—	SW	1
		15–20	1		
		20–25	—		
		25–30	—		
		30–35	—		
		35–40	—		
		40–45	—		
		>45	—		
PIPm	8	<15	—	W	1
		15–20	1	SW	1
		20–25	1	S	4
		25–30	3	E	2
		30–35	2		
		35–40	1		
		40–45	—		
		>45	—		
Qcs	3	<15	—	S	2
		15–20	—	SW	1
		20–25	1		
		25–30	1		
		30–35	1		
		35–40	—		
		40–45	—		
		>45	—		
Qcso	3	<15	2	S	3
		15–20	—		
		20–25	1		
		25–30	—		
		30–35	—		
		35–40	—		
		40–45	—		
		>45	—		

Drainage Basin F

Geologic Unit	Frequency	Degrees	Frequency	Quadrant	Frequency
PIPm	1	<15	—	W	1
		15–20	—		
		20–25	—		
		25–30	—		
		30–35	1		
		35–40	—		
		40–45	—		
		>45	—		
Qlso	11	<15	—		
		15–20	—	SW	2
		20–25	5	S	6
		25–30	2	SE	3
		30–35	1		
		35–40	3		
		40–45	—		

Table 10. Debris-flow initiation susceptibility index for drainage basins B and F. The index is calculated as the number of debris-flow initiation sites hosted by a particular geologic unit divided by the relative proportion of the unit exposed in each basin.

Basin	Geologic Unit	Number of Initiation Sites	Percent Exposure in Basin	Susceptibility Index
B	IPee	1	13.3	0.08
	PIPm	8	36.8	0.22
	Qcs	3	8.8	0.34
	Qcso	3	21.8	0.14
F	PIPm	1	32.2	0.03
	Qlso	11	44.7	0.25

contrast, no debris-flow activity has occurred in drainage basins B, C, and D following the September 1994 event.

A comparison of the three morphometric parameters described above for drainages B and F indicates a higher value of debris-flow path density (D) in basin B than in basin F, whereas debris-flow frequencies (F) for the two basins are comparable (Table 7). This result indicates that the path lengths in basin B are generally longer than those in basin F. The percent length of the main channel occupied by debris flows (PL) is 75.5 percent in basin B and 55.4 percent in basin F. This difference appears to reflect the fact that some debris flows in basin B extended nearly to the head of the drainage, whereas in basin F the paths originated in the lower third of the basin at the change in slope. Both of these results are apparent on the Plate 1.

SOURCES OF DEBRIS-FLOW MATERIAL

Based on field observations, the geologic map, and the geomorphic analysis, material mobilized and carried by the 1994 debris flows was derived from a number of sources. During and after the fire, dry gravel deposits accumulated as aprons along the channels that were adjacent to steep slopes. These were flushed from the channels by surface water flowing down the channels during the intense rainstorm. Part of the ash and burned soil from the fire remained on hillslopes, but much of it had also drifted into the channel bottoms during the strong winds in the days following the fire. Ash within the channels was incorporated into the debris flows along with the dry gravel. The ash, charcoal, and burned soil were stripped from the hillslopes by surface-water runoff during the storm. Other surficial deposits that occurred adjacent to the stream channels were eroded by and entrained in the surface water

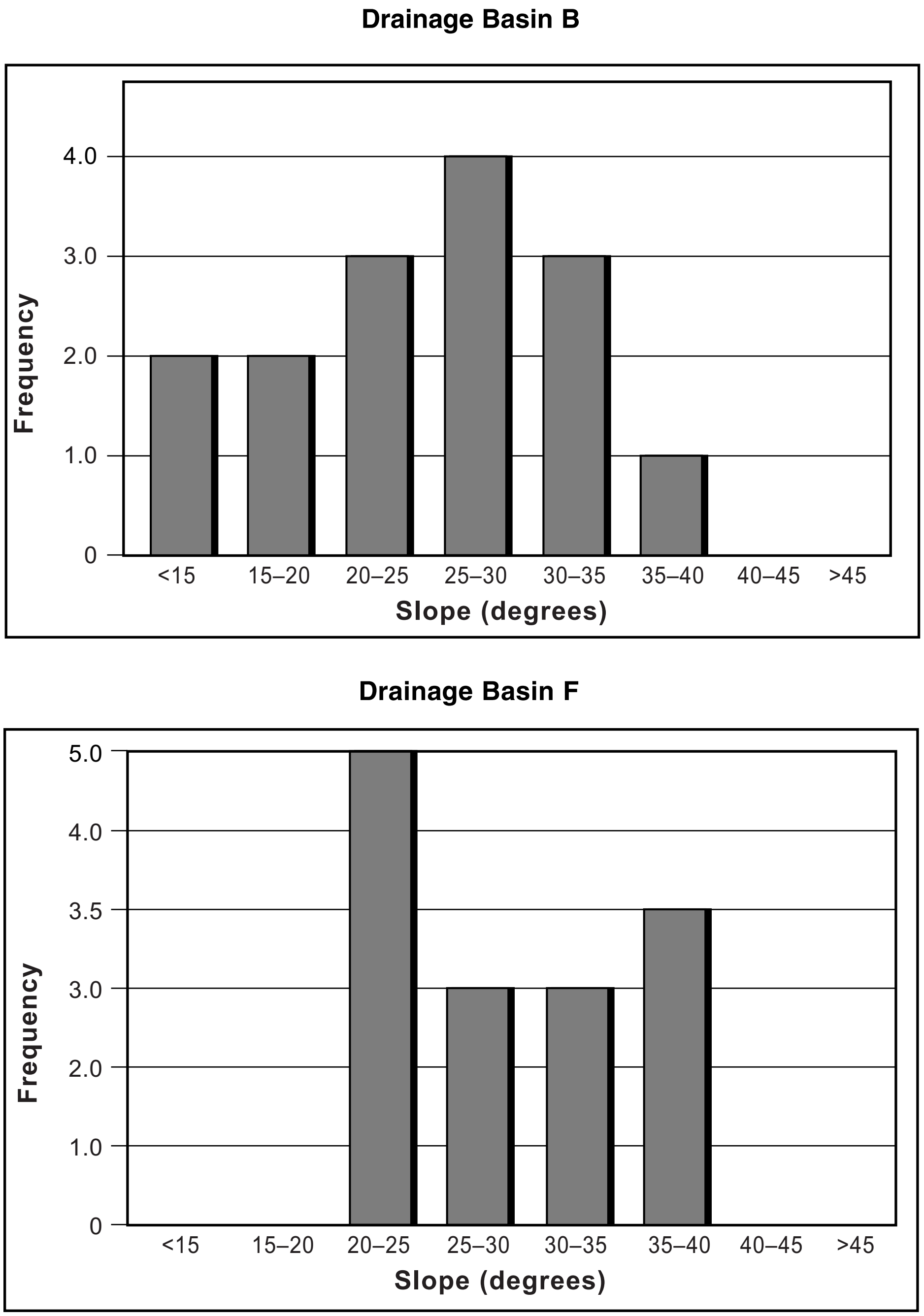


Figure 14. Distribution of debris-flow initiation locations relative to slope for drainages B and F.

flowing down the channels. These deposits included younger and older debris-flow deposits (Qdfy and Qdfo), landslide deposits (Qls), older landslide deposits (Qlso), younger and older colluvium and sheetwash deposits (Qcs and Qcso), and residuum weathered from the Maroon Formation. Lateral stream erosion and bank caving played important roles in the erosion occurring adjacent to stream channels. Sheet erosion, rill erosion, and minor gullying of loose surficial deposits on steep slopes cut into older landslide deposits (Qlso), older colluvium and sheetwash deposits (Qcso), and residuum formed by weathering of Maroon Formation redbeds also contributed significant quantities of material to the debris flows. Very little or no material was eroded from the gentle slopes in the upper parts of the basins.

Soil slips developed on hillslopes cut into older colluvium and sheetwash deposits, older landslide deposits, and residuum overlying the Maroon Formation, also contributed material to the 1994 debris flows. As described in a previous section, about 7 percent of the total volume of the all the material involved in the 1994 debris flows. Soil slips in basin F, which largely formed in older landslide deposits, accounted for up to about 16 percent of the material deposited at the mouth of basin F.

POTENTIAL FOR FUTURE DEBRIS FLOWS

A tremendous volume of sediment remains on steep hillslopes on the south flank of Storm King Mountain and is available for mobilization during future intense rainstorms. Steep slopes cut into older landslide deposits (Qlso), older colluvium and sheetwash deposits (Qcso), and residuum-covered red beds of the Maroon Formation are particularly prominent sources of future debris-flow material. Although much of the dry ravel and ash formerly present in and adjacent to stream channels and some of the residuum overlying the Maroon Formation were removed by the 1994 floods, significant deposits of residuum still exist on the steep slopes the and could be mobilized in future storms.

As demonstrated by the debris flows that occurred in 1995 in basin F, the south flank of Storm King Mountain continues to be capable of generating debris flows, given adequate precipitation. Basin F was especially prone to debris flows in 1995. At least three debris flows occurred in basin F during 1995, with some of the debris-flow material burying parts of I-70 on May 31 and causing the highway to be partially closed. During a traverse up basin F in the spring of 1995 it was noted that the recent landslide in the east fork of the channel immediately above the zone of complex folding and faulting had slid since the 1994 floods and was blocking the channel. Upon returning to this area in November of 1995, a 5- to 6-feet-wide by 5- to 15-feet-deep gorge had been cut through the toe of the slide, probably during one of the debris-flow events that occurred during the summer of 1995.

Figure 15. Photograph of older landslide deposits on the south flank of Storm King Mountain taken in May, 1995. Note the prominent, transverse ridges and swales that extend across the landslide. Excellent stands of

One of the original concerns following the 1994 debris flows was the effect of the fire and debris flows on the stability of large landslides recognized on the south flank of Storm King Mountain by Soule and Stover (1985) and Fairer and others (1993). If destabilized, these landslides, by continuing to slide into and block drainages, could become major sediment sources for future debris flows. Figure 15 is a photograph of some of the older landslide deposits where prominent, transverse ridges and swales extend across the landslide. During our field work we observed no evidence to indicate that these large landslides have been reactivated to any large extent. Because of their apparent age relative to other landslides in the study area, we have mapped these large landslides as older landslide deposits (Qlso) on Plate 1.

The older landslide deposits have been locally destabilized where steep hillslopes have been cut into them along the active channels. Numerous landslides (Qls) and a few recent landslides (Qlsr) have developed on the steep slopes cut into the older landslide deposits. As described above, one of the recent landslides experienced movement after the 1994 debris flows and prior to the 1995 events.

However, the older landslide deposits were and will continue to be important sources of sediment during debris flows. Where streams have carved steep-walled valleys into the older landslide deposits, there is an abundant supply of loose soil material exposed on the steep slopes that is readily available for mobilization during future storms. This channel incision is a natural process that has been active for many thousands of years.

The burn area was aerially seeded in November of 1994. By the early summer months of 1995 good stands of grasses and forbs were becoming established on the flatter slopes where good soil profiles were preserved. Also, new shoots of oak brush sprouted up from the roots of much of the burned oak during the summer of 1995. Re-growth of the coniferous trees will be much slower. Re-establishment of any vegetation on steep hillslopes, especially where it is rocky, will be a slow and difficult task. Even when the vegetative cover returns to pre-fire conditions, the very steep slopes on the south flank of Storm King Mountain will still be capable of generating debris flows, given the right set of soil and precipitation conditions.

SUMMARY AND CONCLUSIONS

Late in the evening on September 1, 1994, debris flows that formed in response to an intense rainstorm flowed down several channels on the south flank of Storm King Mountain west of Glenwood Springs and spilled onto or next to Interstate Highway 70. Materials carried by the debris flows were largely eroded from hillslopes that had recently burned during the July, 1994 South Canyon fire.

Thirty cars traveling on the highway at the time of the debris flows were engulfed, trapped, or turned over by the mud. At least two of the people travelling in these vehicles were swept into the river by the debris flows. Fortunately no deaths resulted from this event, but there were serious injuries.

According to CDOT personnel, burned logs and branches and up to boulder-sized material in a very fluid, muddy matrix continued to flow out of the canyons as a series of pulses throughout the night of September 1 and the early morning hours of September 2. Material was deposited at the mouth of every major drainage with burned upper reaches, as well as at the base of unburned watershed front I (Cannon and others, 1995). A total area of approximately 35 acres was inundated with approximately 91,300 cubic yards of material (Cannon and others, 1995). The mostly unburned drainage adjacent to the burned area, basin A , showed evidence of high-water flows, attesting to the high intensity of the rainstorm, but only a very minor debris flow occurred in it.

The Colorado Geological Survey and U.S. Geological Survey initiated an evaluation of the debris-flow event immediately following the storm. A preliminary report describing the initial investigation was released as USGS Open-File Report 95-508 (Cannon and others, 1995). This report contains the findings of the more detailed cooperative investigation.

Structurally, the study area lies astride part of the Grand Hogback Monocline. A west-northwest-trending structural terrace within the Grand Hogback Monocline extends across the study area. This structural terrace may be related to collapse due to dissolution or flowage of underlying evaporitic rocks. Several folds and faults are associated with the hinge zones on either side of the structural terrace. Bedrock formations on the south flank of Storm King Mountain include the late Paleozoic Maroon Formation, Eagle Valley Formation, Eagle Valley Evaporite, and an unnamed late Tertiary sedimentary deposit herein called the conglomerate of Storm King Mountain. Bedrock formations in the area, particularly the Maroon Formation, locally tend to weather rapidly to residuum. Surficial deposits generally are fairly thin in much of the area; however, thick accumulations of deeply dissected older landslide deposits (Qlso) and older colluvium and sheetwash (Qcso) locally overlie the structural terrace.

A geomorphic analysis of the distribution of the September 1, 1994 debris flows relative to geologic units and topography was conducted out to 1) identify geologic and topographic initiation controls for these fire-related debris flows; 2) describe the occurrence of debris-flow paths within the drainage network through a morphometric analysis; and 3) compare the debris-flow characteristics for two basins that vary both geologically and in the percentage burned.

The conditions that indicate the highest susceptibility to debris-flow initiation following the wildfire on Storm King Mountain are burned, south and southwest facing hillslopes with gradients between 25 and 40 degrees in the Maroon Formation and less than 30 degrees in older landslide deposits (Qlso). This determination agrees with field observations of abundant sheet and rill erosion in these units. Significantly, a watershed front that was only 23 percent burned experienced debris-flow activity, although this occurrence may also be attributed to localized more intense rainfall.

The fact that the debris flows traveled through the pre-existing drainage network during the September 1994 events at Storm King Mountain allows for evaluation of the debris-flows using a morphometric analysis which treats the debris-flow paths as fluvial segments and subdivides them into orders. Within the Storm King Mountain watershed, slightly more than 50 percent of the total length of all the debris-flow paths occurred as first-order segments, 30 percent occurred as second-order segments, and 19 percent occurred as third-order segments.

High values of three morphometric parameters of debris-flow path density, debris-flow path frequency, and the percentage of the main channel occupied by debris flows indicate that even small, partially burned drainages are susceptible to debris-flow activity that involves a significant proportion of the drainage network. The length percentage of the main channel occupied by debris flows indicates that more than one half of the length of available main channels were occupied by debris flows during the September 1, 1994, event. This result can be used in future assessments of sediment yields from burned watersheds with similar geological and geomorphic frameworks.

A detailed comparison of basins B and F, two morphologically similar drainages that experienced different burn coverages, indicates the initiation locations for the debris-flow paths varies considerably between the basins. In drainage B, most of the debris flows initiated within the Maroon Formation. Even though the Maroon Formation underlies nearly the same percentage of both basins B and F, the majority of debris flows in basin F originated in older landslide deposits (Qlso). Perhaps reflecting this changing geologic configuration, the locations of the debris-flow path initiation locations varied considerably between the two basins. In basin B the paths initiated in first-order drainages located all along the main channel, and debris-flow paths were mapped extending nearly to the head of the drainage. The debris-flow paths all originated within the burned part of basin B. In contrast, the majority of the debris-flow paths in basin F initiated at the change in slope at the head of the incision into the toe of the old landslide deposits. Although the majority of these paths occurred downslope from the burned area, the area of the drainage basin upslope from the initiation locations is considerable. This result indicates that an unburned but steeply sloping, erosion-susceptible geologic unit such as older landslide deposits (Qlso) exposed downslope from an intensely burned area with gentle slopes is still susceptible to significant debris-flow activity. This susceptibility may be attributed to increased surface runoff generated from the burned area above.

The contribution of material to the debris-flow deposits at the canyon mouths from soil-slip scars on the hillslopes was also evaluated for both basins. In basin B the majority of the soil-slip scars occurred in older colluvium and sheetwash deposits (Qcso), and the volume of material contributed by the soil-slip scars is approximately 4 percent of the total volume calculated at the canyon mouth. In contrast, the soil-slip scars in basin F originated primarily in older landslide deposits (Qlso) and accounted for approximately 16 percent of the material deposited at the canyon mouth. In that almost all of the soil-slip scars mapped in basin F are located in unburned areas, the value of 16 percent suggests a greater susceptibility to infiltration-initiated landslides in this basin, regardless of the occurrence of the wildfire.

Based on field observations and the geomorphic analysis, material mobilized and carried by the 1994 debris flows was derived from a number of sources. During and subsequent to the fire, dry ravel deposits accumulated as aprons along the channels that were adjacent to steep slopes. They were flushed from the channels by surface water flowing down the channels during the intense rainstorm. Part of the ash from the fire remained on hillslopes, but much of it had drifted into the channel bottoms during the strong winds in the days following the fire. Ash within the channels was also incorporated into the debris flows along with the dry ravel. The ash, charcoal, and burned soil was stripped from the hillslopes by surface-water runoff during the storm.

Other surficial deposits that occurred adjacent to the stream channels were eroded by and entrained in the surface water flowing down the channels. These deposits included younger and older debris-flow deposits (Qdfy and Qdfo), landslide deposits (Qls), older landslide deposits (Qlso), younger and older colluvium and sheetwash deposits (Qcs and Qcso), and residuum weathered from the Maroon Formation. Lateral stream erosion and bank caving played important roles in the channel erosion. Sheet erosion, rill erosion, and minor gullying of loose surficial deposits on steep slopes cut into older landslide deposits (Qlso), older colluvium and sheetwash deposits (Qcso), and residuum formed by weathering of Maroon Formation red beds also contributed significant quantities of material to the debris flows. Very little or no material was eroded from the gentle slopes in the upper parts of the basins.

Although soil slips are common on steeper slopes eroded into older colluvium and sheetwash deposits (Qcso), older landslide deposits (Qlso), and residuum overlying the Maroon Formation, the prominent debris-flow paths from the 1994 event could not be traced up-channel to a discrete landslide source. Our observations indicate the soil slips developed during the 1994 storm and likely had a very high water content. Material mobilized by the soil slips apparently was transported downslope into the channels by sheetwash or overland flow. The soil slips account for about 7 percent of the total volume of material deposited at canyon mouths. Thus, the debris flows appear to have developed through a process of progressive sediment bulking of high discharge runoff with material derived from the hillslopes and channels.

A tremendous volume of sediment remains on steep hillslopes in the area and is available for mobilization during future intense rainstorms. Steep slopes cut into older landslide deposits (Qlso), older colluvium and sheetwash deposits (Qcso), and residuum-covered red beds of the Maroon Formation are particularly prominent sources of future debris-flow material.

Much of the dry ravel and ash formerly present in and adjacent to stream channels, and some of the residuum overlying the Maroon Formation were removed by the 1994 floods. Yet dry ravel continues to slowly accumulate in some channels, and residuum gradually forms as the exposed bedrock begins to weather.

An original concern following the 1994 debris-flows was the effect of the fire and debris flows on the stability of large landslides mapped on the south flank of Storm King Mountain by previous investigators. If destabilized, these landslides could become sources for potentially massive future debris flows. Our field work indicated that these large, old, landslide complexes have not been reactivated to any large extent; however, they have been locally destabilized where steep slopes have been cut into them along the active channels. Numerous landslides (Qls) and a few recent landslides (Qlsr) have developed on the steep slopes cut into the older landslide deposits. One of the recent landslides experienced movement after the 1994 debris flows, but before the 1995 events.

As demonstrated by the debris flows that occurred in 1995, the south flank of Storm King Mountain continues to be capable of generating debris flows, given adequate precipitation. Basin F was especially prone to debris flows in 1995; at least three occurred in that basin during 1995, with some of the debris-flow material burying parts of I-70 and causing the highway to be partially closed. During a traverse up basin F in the spring of 1995 it was noted that the recent landslide in the east fork of the channel immediately above the zone of complex folding and faulting had slid since the 1994 floods and was blocking the channel. Upon returning to this area in November of 1995, a small gorge had been cut through the toe of the slide, probably during one of the debris-flow events that occurred during the summer of 1995.

The burn area was aerially seeded in November of 1994. By the early summer months of 1995 stands of grasses and forbs had become established on the flatter slopes where good soil profiles were preserved. Also, new shoots sprouted up from the roots of the burned oak brush during the summer of 1995. Re-establishment of vegetation on steep hillslopes, especially where rocky, will be a more difficult task. Even when the vegetative cover returns to pre-fire conditions, the very steep slopes on the south flank of Storm King Mountain will still be capable of generating debris flows, given the right set of soil and precipitation conditions.

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APPENDIX I

EYEWITNESS ACCOUNT OF THE SEPTEMBER 1, 1994 DEBRIS FLOWS

By Kevin White, Glenwood Springs, Colorado

"On the evening of September 1, 1994, four friends and I were returning to Glenwood Springs on eastbound I-70 when traffic was stopped. In the headlights of the semi-truck ahead of us, we could see part of the mud stream and debris that was moving across the highway. We also saw an overturned vehicle with passengers and we left our car to help them. As I approached the vehicle the mud flow was about ankle deep but the flow increased rapidly and soon it was thigh deep. The chunks of rocks and trees that I could feel knocked me off my feet and I was carried by the mud flow across the road, over the edge and into the river. My friends, who had been behind me, stopped when the flow deepened and they could no longer see me.

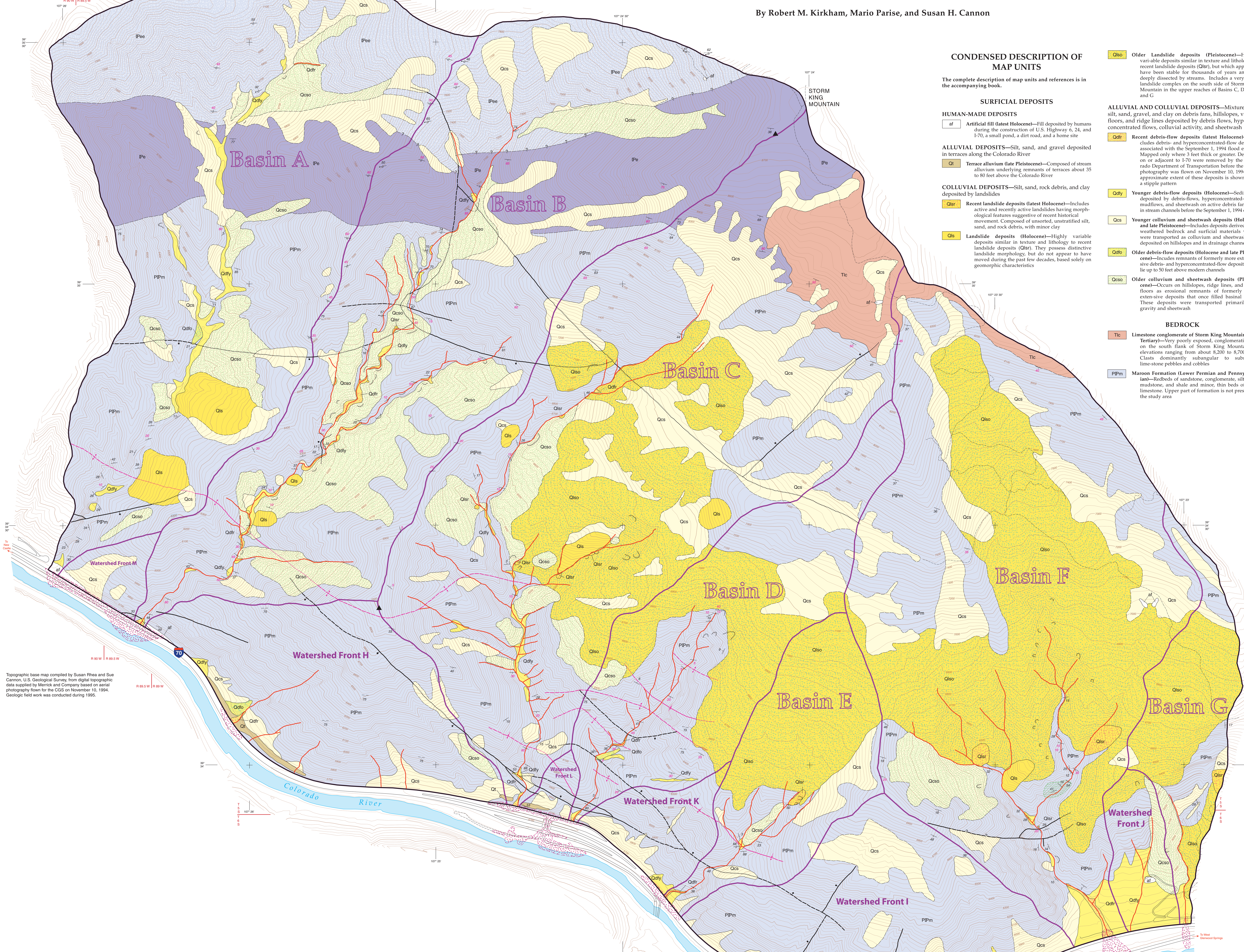
I remembered my family's instructions given when we rafted the same stretch of river and tried to keep my feet ahead of me, but I could not move in the debris and mud. As I moved over the rock ledge in the churning mud, rocks and logs, debris hit under my chin, pushing my head backward. I felt like all of my teeth were broken and I knew one was gone, but did not realize I had any other injury. I was actually relieved to be in the river where I could move and the water washed away the muck from the flow. I swam to the river bank where I saw another person in the river near me. I made my way to her and we sat together on a rock until the rain stopped. I climbed back up to the highway to get help and I was eventually reunited with my friends who sat with me, singing, until the ambulance arrived. A few days later I had surgery to repair three breaks to my jaw. I hope to be finished with the repair work for my jaw and teeth by the upcoming third anniversary of the most bizarre ride of my life."

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
DENVER, COLORADO

SPECIAL PUBLICATION 46
PLATE 1 OF 1
2000

GEOLOGIC MAP OF THE SOUTH FLANK OF STORM KING MOUNTAIN, GLENWOOD SPRINGS, GARFIELD COUNTY, COLORADO

By Robert M. Kirkham, Mario Parise, and Susan H. Cannon



Topographic base map compiled by Susan Rhea and Sue Cannon, U.S. Geological Survey, from digital topographic data supplied by Merrick and Company based on aerial photography flown for the CGS on November 10, 1994. Geologic field work was conducted during 1995.

CONDENSED DESCRIPTION OF MAP UNITS

The complete description of map units and references is in the accompanying book.

SURFICIAL DEPOSITS

HUMAN-MADE DEPOSITS

af — **Artificial fill (latest Holocene)**—Fill deposited by humans during the construction of U.S. Highway 6, 24, and I-70, a small pond, a dirt road, and a home site

ALLUVIAL DEPOSITS—Silt, sand, and gravel deposited in terraces along the Colorado River

Qt — **Terrace alluvium (late Pleistocene)**—Composed of stream alluvium underlying remnants of terraces about 35 to 80 feet above the Colorado River

COLLUVIAL DEPOSITS—Silt, sand, rock debris, and clay deposited by landslides

Qlsr — **Recent landslide deposits (latest Holocene)**—Includes active and recently active landslides having morphological features suggestive of recent historical movement. Composed of unsorted, unstratified silt, sand, and rock debris, with minor clay

Qls — **Landslide deposits (Holocene)**—Highly variable deposits similar in texture and lithology to recent landslide deposits (Qlsr). They possess distinctive landslide morphology, but do not appear to have moved during the past few decades, based solely on geomorphic characteristics

Qlso — **Older Landslide deposits (Pleistocene)**—Highly vari-able deposits similar in texture and lithology to recent landslide deposits (Qlsr), but which appear to have been stable for thousands of years and are deeply dissected by streams. Includes a very large landslide complex on the south side of Storm King Mountain in the upper reaches of Basins C, D, E, F, and G

ALLUVIAL AND COLLUVIAL DEPOSITS—Mixtures of silt, sand, gravel, and clay on debris fans, hillslopes, valley floors, and ridge lines deposited by debris flows, hyper-concentrated flows, colluvial activity, and sheetwash

Qdfr — **Recent debris-flow deposits (latest Holocene)**—Includes debris- and hyperconcentrated-flow deposits associated with the September 1, 1994 flood events. Mapped only where 3 feet thick or greater. Deposits on or adjacent to I-70 were removed by the Colorado Department of Transportation before the aerial photography was flown on November 10, 1994. The approximate extent of these deposits is shown with a stipple pattern

Qdfy — **Younger debris-flow deposits (Holocene)**—Sediments deposited by debris-flows, hyperconcentrated-flows, mudflows, and sheetwash on active debris fans and in stream channels before the September 1, 1994 event

Qcs — **Younger colluvium and sheetwash deposits (Holocene and late Pleistocene)**—Includes deposits derived from weathered bedrock and surficial materials which were transported as colluvium and sheetwash and deposited on hillslopes and in drainage channels

Qdfo — **Older debris-flow deposits (Holocene and late Pleistocene)**—Incudes remnants of formerly more extensive debris- and hyperconcentrated-flow deposits that lie up to 50 feet above modern channels

Qcso — **Older colluvium and sheetwash deposits (Pleistocene)**—Occurs on hillslopes, ridge lines, and basin floors as erosional remnants of formerly more exten-sive deposits that once filled basinal areas. These deposits were transported primarily by gravity and sheetwash

BEDROCK

Tlc — **Limestone conglomerate of Storm King Mountain (late Tertiary)**—Very poorly exposed, conglomeratic unit on the south flank of Storm King Mountain at elevations ranging from about 8,200 to 8,700 feet. Clasts dominantly subangular to subround lime-stone pebbles and cobbles

PIPm — **Maroon Formation (Lower Permian and Pennsylvanian)**—Redbeds of sandstone, conglomerate, siltstone, mudstone, and shale and minor, thin beds of gray limestone. Upper part of formation is not present in the study area

IPe — **Eagle Valley Formation (Middle? Pennsylvanian)**—Interbedded reddish-brown, gray, reddish-gray, and tan siltstone, shale, sandstone, gypsum, and carbonate rocks. Unit represents a stratigraphic interval in which the red beds of the Maroon Formation grade into and intertongue with the dominantly evaporitic rocks of the Eagle Valley Evaporite. It includes rock types of both formations

IPee — **Eagle Valley Evaporite (Middle Pennsylvanian)**—Sequence of evaporitic rocks consisting mainly of massive to laminated gypsum, anhydrite, and halite, interbedded with light-colored mudstone and fine-grained sandstone, thin carbonate beds, and black shale. Only the upper part of the formation crops out in the mapped area. Beds commonly are intensely folded, faulted, and ductily deformed by diapirism, flowage, dissolution, load metamorphism, hydration of anhydrite, and Laramide tectonism (Mallory, 1971; Kirkham and others, 1996)

MAP SYMBOLS

Formation contact—Dashed where approximately located; queried where very uncertain

Fault—Dashed where approximately located; queried where uncertain; dotted where concealed; ball and bar on downthrown side

Anticline—Showing axial trace; dashed where approximately located; dotted where concealed

Syncline—Showing axial trace; dashed where approximately located; dotted where concealed

Monocline—Anticlinal bend; Showing shorter arrow on steeper beds; dashed where approximately located; dotted where concealed

Monocline—Synclinal bend; Showing shorter arrow on steeper beds; dashed where approximately located; dotted where concealed

Strike and dip of beds—Angle of dip shown in degrees; measurements contributed by B. Bryant (1998, written communication) are in magenta

33 — **Inclined beds**

Vertical beds

75 — **Inclined beds**—Showing approximate attitude of bedding plane as determined from photo-grammetric models set on a Kern PG-2 plotter; "15" indicates estimated dip is between 0° and 30°, "45" indicates estimated dip is between 31 and 60°, "75" indicates estimated dip is between 61° and 90°

68 — **Overturned beds**—Showing strike and dip in degrees

57 — **Overturned beds**—Showing strike and dip in degrees; top of beds known from local features

Area of complex folding and faulting

Path of debris-flows associated with the September 1, 1994 rainstorm

Approximate extent of debris-flow deposits on and adjacent to Interstate Highway 70 that were removed by the Colorado Department of Transportation immediately following the September 1994 events

Headscarp of shallow soil-slip scar

TOPOGRAPHIC AND CULTURAL SYMBOLS

Boundary of study area

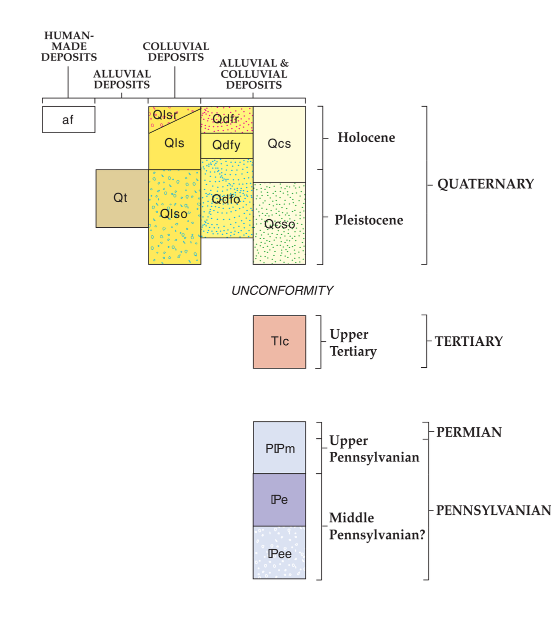
Boundaries of drainage basins and watershed fronts

Approximate location of weather station

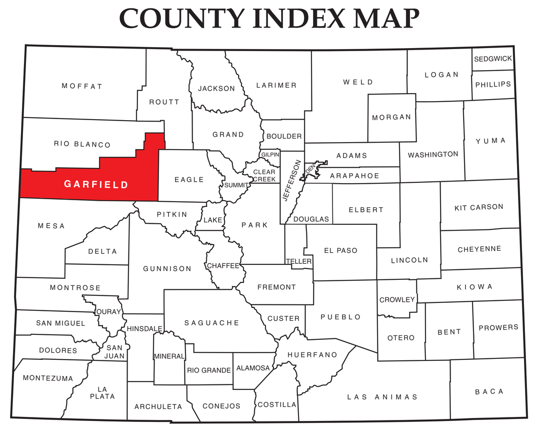
Highway

Trail

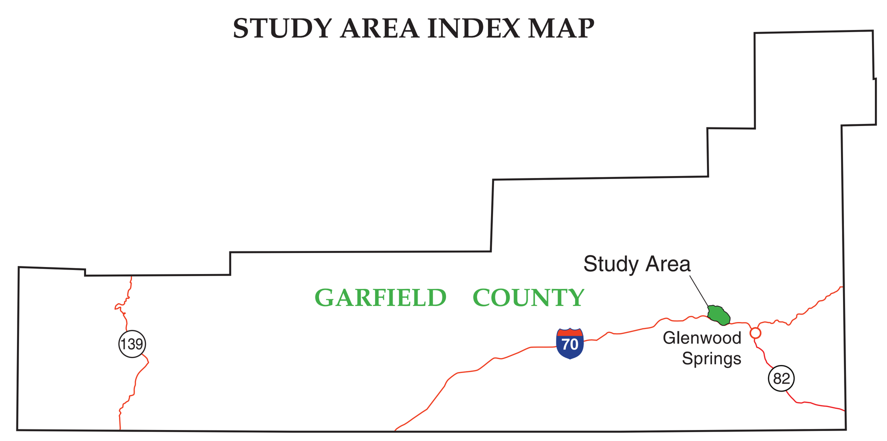
CORRELATION OF MAP UNITS



COUNTY INDEX MAP



STUDY AREA INDEX MAP



SCALE 1:5,000

GIS compilation by Matt Morgan
Digital cartography by Matt Morgan and Cheryl Brchan

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Department of Natural Resources, Greg E. Walcher, Director
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