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Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado

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Abstract

A torrential rainstorm on September 1, 1994 at the recently burned hillslopes of Storm King Mountain, CO, resulted in the generation of debris flows from every burned drainage basin. Maps (1:5000 scale) of bedrock and surficial materials and of the debris-flow paths, coupled with a 10-m Digital Elevation Model (DEM) of topography, are used to evaluate the processes that generated fire-related debris flows in this setting. These evaluations form the basis for a descriptive model for fire-related debris-flow initiation.

The prominent paths left by the debris flows originated in 0- and 1st-order hollows or channels. Discrete soil-slip scars do not occur at the heads of these paths. Although 58 soil-slip scars were mapped on hillslopes in the burned basins, material derived from these soil slips accounted for only about 7% of the total volume of material deposited at canyon mouths. This fact, combined with observations of significant erosion of hillslope materials, suggests that a runoff-dominated process of progressive sediment entrainment by surface runoff, rather than infiltration-triggered failure of discrete soil slips, was the primary mechanism of debris-flow initiation. A paucity of channel incision, along with observations of extensive hillslope erosion, indicates that a significant proportion of material in the debris flows was derived from the hillslopes, with a smaller contribution from the channels.

Because of the importance of runoff-dominated rather than infiltration-dominated processes in the generation of these fire-related debris flows, the runoff-contributing area that extends upslope from the point of debris-flow initiation to the drainage divide, and its gradient, becomes a critical constraint in debris-flow initiation. Slope-area thresholds for fire-related debris-flow initiation from Storm King Mountain are defined by functions of the form $A_{cr}(\tan\theta)^3 = S$, where A_{cr} is the critical area extending upslope from the initiation location to the drainage divide, and $\tan\theta$ is its gradient. The thresholds vary with different materials.

Keywords: Wildfire; Erosion; Debris flow; Initiation

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1. Introduction and approach

During the evening of September 1, 1994, debris flows originating in response to a heavy rainstorm occurred on Storm King Mountain west of Glenwood Springs, CO. These flows traveled down channels on the south flank of the mountain and emptied onto or next to Interstate Highway 70 in several locations. The flows originated in drainage basins recently burned by the July 1994 South Canyon fire. Every drainage basin burned by this fire, and even some that were not burned, produced debris flows. The primary focus of this study is to examine processes that lead to the generation of fire-related debris flows in this setting and to develop a descriptive model for their initiation.

The process most commonly associated with the generation of debris flows from unburned hillslopes in the United States is that of failure of a landslide as an intact block which then mobilizes into a fluid debris flow with travel downslope. When this process occurs, the debris-flow path can be traced up a channel to a discrete landslide-scar source. Campbell (1975) referred to this process as soil slip–debris flow; we adopt this terminology here because it reflects both the transition from landslide to debris flow and the observation that the landslide involved primarily the surficial soil. Considerable research effort has gone into the development of hypotheses to explain both the failure and mobilization of soil slips into debris flows, many of which are discussed in Iverson et al. (1997).

Two initiation processes specifically for fire-related debris flows have been identified in the literature: infiltration-triggered soil slip, as described above, and runoff-dominated erosion by surface runoff. These two processes are reported in widely disparate environments. The process of soil slip-debris flow has been documented in burned areas in southern California by Wells (1987), Morton (1989), Booker (1998), and Cannon (1999); the occurrence of soil slips on the hillslopes points to failure triggered by rainfall infiltration. Debris-flow generation by failure of a discrete landslide in burned areas has also been attributed to reduced evapotranspiration rates and the consequent increase in soil moisture (Klock and Helvey, 1976; Helvey, 1980; Swanson, 1981; Megahan, 1983) and decay of roots that anchor colluvium (e.g., Swanson, 1981; DeGraff, 1997). These processes are generally thought to occur a few years after the fire.

An alternative process for debris-flow initiation based on significantly decreased rainfall infiltration rates has also been proposed for burned areas. Johnson (1984), working in Big Sur, Monterey County, CA, and Wells (1987), working in the San Gabriel Mountains of southern California, traced debris-flow deposits directly upslope through small gullies and into a series of rills. These workers concluded that the debris flows initiated high on the hillslopes from material eroded by surface runoff, and that the debris flows increased in volume by entraining larger material from the channels. In Wells' model (1987), debris flows initiate by failure of a saturated layer of soil a few mm thick above a subsurface water-repellent zone as miniature soil slips. Material from these tiny soil-slips forms rills and travels downslope as shallow, narrow debris flows.

More recently, Meyer and Wells (1997), working in Yellowstone National Park, observed the first appearance of debris-flow features such as levees and mud coatings in the middle reaches of the main basins. These workers concluded that debris flows would thus initiate through a process of progressive sediment bulking of surface runoff and rill erosion in steep upper basin slopes, followed by deep incision as flows progressed down channels. Parrett (1987) also noted the lack of landslide scars in a burned area that experienced debris flows in Montana and suggested a similar mechanism. Meyer and Wells (1997) and Parrett (1987) emphasize that both hillslope sediment input from rills and gullies, as well as material entrained by extensive channel incision are important in the bulking process that led to the formation of debris flows. Meyer and Wells (1997) further hypothesized that addition of fine-grained sediment eroded from hillslopes to the generally coarser-grained channel material was important in both the development of debris-flow conditions and in maintaining the mobility of the flow.

On Storm King Mountain, we observed evidence of both runoff- and infiltration-dominated initiation processes. In this paper, we examine the relative contributions of materials generated by both processes to the debris-flow deposits, and the effects of topographic configuration and lithology on fire-related debris-flow initiation. We then explore the idea that the runoff-contributing area extending upslope from the initiation location to the drainage divide, and its gradient, constrained debris-flow initiation during the September events. These evaluations, coupled with field observations and measurements, are used to build a descriptive model for the generation of fire-related debris flows from Storm King Mountain.

The analyses are based on digital compilations of 1:5000-scale geologic mapping of the south flank of Storm King Mountain and of the debris-flow paths from the September 1, 1994 events. We used a 10-m resolution Digital Elevation Model (DEM) and Digital Line Graph (DLG) with 20-ft contours obtained from survey-controlled, 1:8000-scale aerial photographs taken on November 10, 1994 for topographic information.

2. Study area

The study area lies on the south flank of Storm King Mountain, north of the Colorado River and about 5–10 km west-northwest of downtown Glenwood Springs (Fig. 1)

2.1. 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, and 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. The fire quickly grew from around 1 to about 7 km^2, threatening West Glenwood Springs and resulting in the evacuation of parts of the city. Tragically, 14 firefighters lost their lives while battling this fire.

2.2. Geomorphic and geologic setting

The study area consists of seven major intermittent stream drainages with basin areas from 0.31 to 2.46 km^2, labeled A through G in Fig. 1. All seven drainage basins are direct tributaries of the Colorado River and have steep stream channels and precipitous side slopes (Table 1). This topographic configuration is conducive to a rapid concentration of runoff, and when combined with intense rains, can lead to high peak discharge and erosion rates, even without the exacerbating effects of wildfire. Drainage basin A experienced only 3% burn; basins E, F, and G experienced between 48% and 75% burn; and basins B, C, and D were nearly completely burned (Table 1).

Both the burned and unburned hillslopes of the Storm King Mountain watershed are characterized by an average gradient of 15°, with some hillsides, particularly in the southern portion, having slopes greater than 35°. Before the fire, southeast-facing hillslopes supported a sparse pinyon–juniper vegetative community. The northern two-thirds to one-half of the burned area supported a nearly impenetrable thicket of oak brush. Soils in the lower one-third to one-half of the burned area are generally very shallow, poorly developed, and contain a high percentage of gravel- and larger-sized material. Using the Unified Soil Classification System (Craig, 1987), Cannon et al. (1995) classified two samples of unburned soil as silty fine sand and silty sand and one sample of burned soil as silty sand. The climate is semiarid; and the majority of precipitation occurs in July, August, and September as convectional thunderstorms.

Erosion following wildfires is often attributed to the development, or enhancement, of a water-repellent layer in the soil by the fire (e.g., DeBano and Letey, 1969; DeBano, 1981; Morris and Moses, 1987; Wells, 1987; Robichaud, 1996). The presence and extent of water-repellent soils at Storm King Mountain was assessed by digging small pits with clean, inclined sides in areas where burned soil and ash were in place. Pits were, in general, 10 cm deep, 20 cm wide, and with one side inclined at about 3:1. Water from a squirt bottle was dripped along the incline. Water repellency was identified if the water beaded on the surface and did not infiltrate for at least 30 s. Where water-repellent material was found, its lateral extent was evaluated by dripping more water along the 20-cm wide inclined surface.

Water-repellent soils were detected in approximately 35% of the test pits in the months following

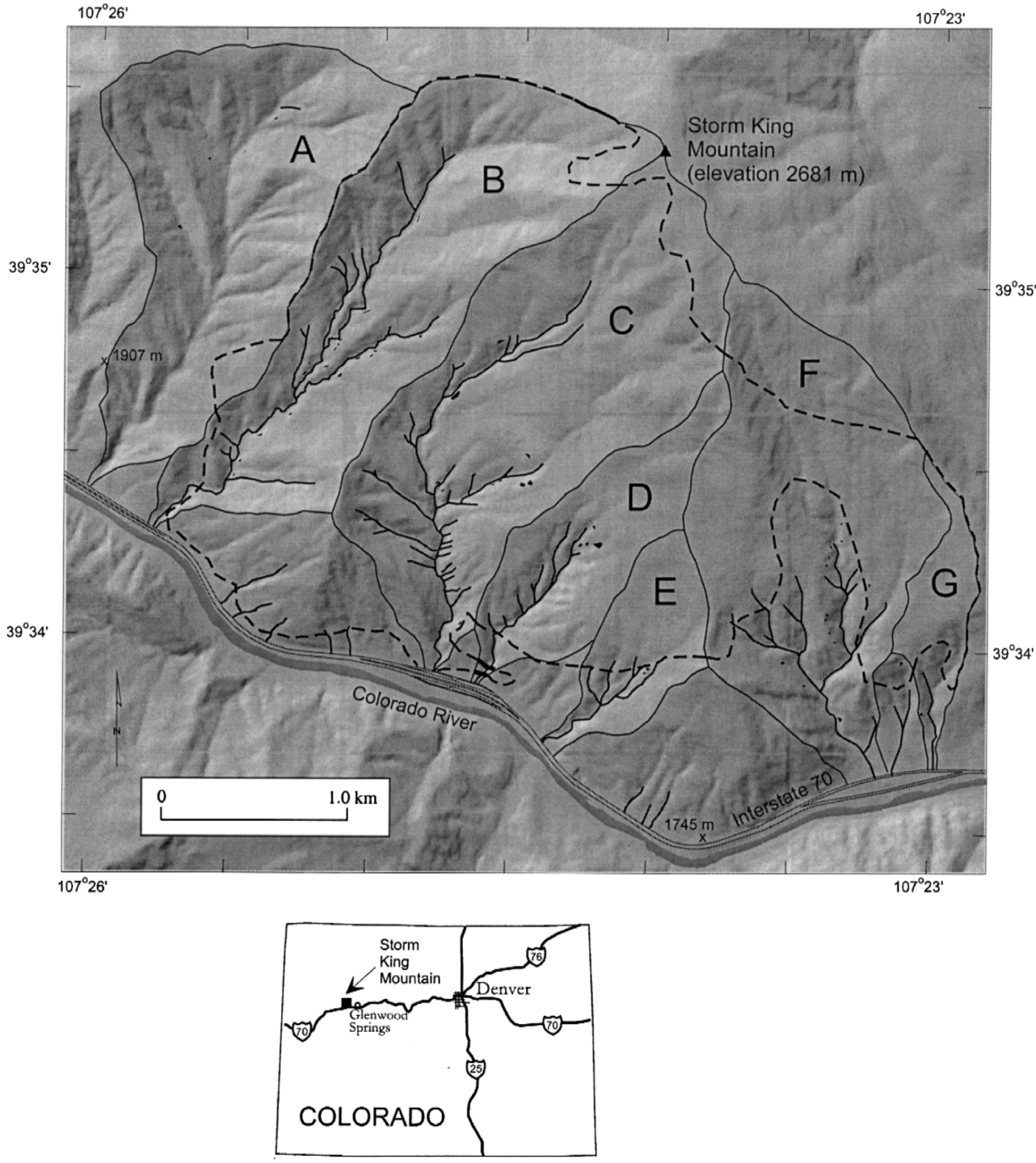

Fig. 1. Storm King Mountain study area. Drainage basins are labeled A through G and are delineated by thin solid lines. Small watershed fronts along the Colorado River between the major drainage basins are outlined but not labeled. Heavier black solid lines show paths of the debris flows that occurred during the September 1, 1994 event. Soil-slip scars are shown as solid black polygons. Heavy dashed line marks the extent of the South Canyon fire of July 1994.

Table 1
Area, height, and relief ratio of drainage basins, burned area, and percent of drainage basin burned

Drainage basin	Area (km^2)	Relief (m)	Relief ratio	Burned area (km^2)	Percent burned (%)
A	2.03	842	0.32	0.06	3.0
B	2.23	950	0.27	2.08	93.5
C	2.46	941	0.30	2.27	92.3
D	0.77	772	0.38	0.73	95.3
E	0.46	449	0.33	0.29	62.6
F	2.11	853	0.30	1.02	48.2
G	0.31	526	0.32	0.23	75.3

Relief ratio is calculated as basin relief divided by length. Basin length is measured from the drainage mouth along the length of the longest channel extended to the drainage divide.

the fire (Cannon et al., 1995, 1998). The water-repellent soils that were observed were not extensive nor laterally continuous. Field evidence of variations in fire temperature, soil materials, and vegetation could not explain their presence or absence. At one unburned site located under a juniper tree, a discontinuous water-repellent soil was detected, probably caused by hydrophobic compounds in the unburned organic materials.

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 exposed burned mineral soil on the hillsides were being transported by wind and redistributed on hillslopes, deposited in the tributary drainages, and removed from the area. In addition, the processes of dry ravel both during and after the fire resulted in the downslope transport and accumulation of material. Dry-ravel deposits are formed by the particle-by-particle transport of material downslope by gravity. Dry ravel has been described as an important post-fire process in southern California where channels are loaded with sediment, increasing available sediment for transport in large runoff events (e.g., Wells, 1987; Florsheim et al., 1991). After the fire on Storm King Mountain, accumulations of ash and dry-ravel material up to about 1 m deep along the sides of most tributary drainages were observed (Fig. 2). This material was at its angle of repose, measured between 26° and 32°. The dry-ravel material was primarily well-sorted, silty sand and lacked the larger clasts present in the in-place soils (Cannon et al., 1995, 1998). 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 channels prior to the fire by either gravity-driven colluvial processes or by fluvial and debris-flow processes (Fig. 2).

Field and aerial photographic geologic mapping of the study area at a scale of 1:5000 was completed in 1995 (Kirkham et al., 1999) (Fig. 3) 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

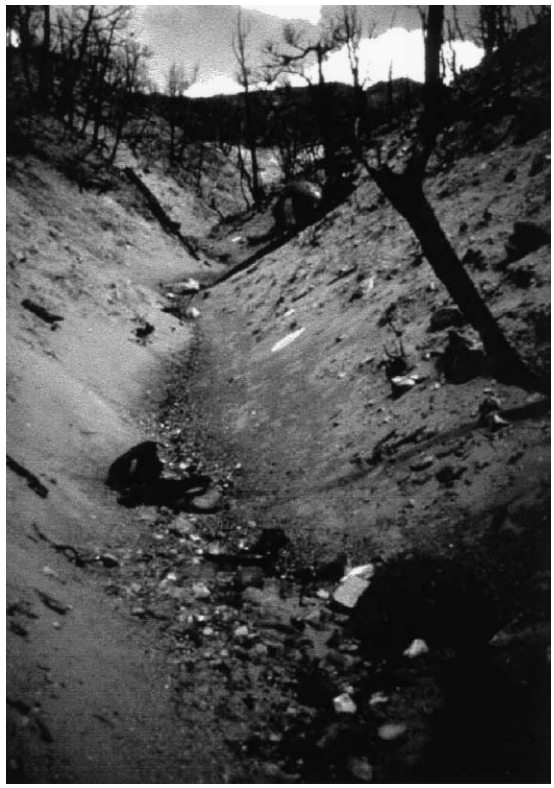

Fig. 2. Photograph of loose, noncohesive material transported by dry ravel and wind that forms aprons along tributary channels and larger material stored in channel prior to the September 1994 debris-flow event. Photograph was taken on August of 1994. These deposits supplied material for debris-flow events in September of 1994. Photograph by Roger Pihl, Colorado Geological Survey.

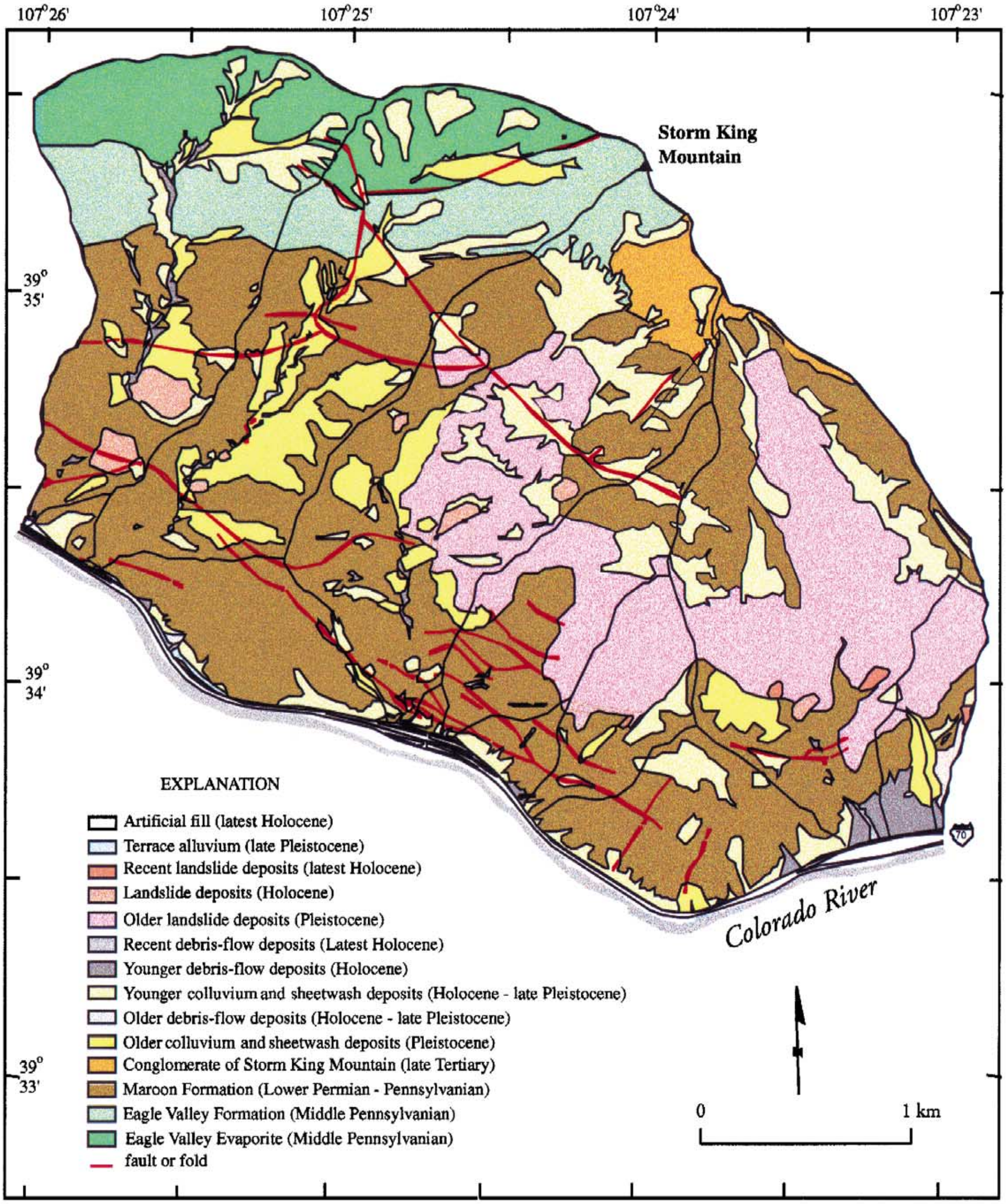

Fig. 3. Geologic map of the south flank of Storm King Mountain (simplified from Kirkham et al., 1999).

Eagle Valley Formation, which is 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 mantles the upper south shoulder of Storm King Mountain. The areal extent of these units within the study area is shown in Table 2.

Table 2
Areal distribution of geologic units within the Storm King Mountain study area

Geologic unit	Area (km^2)	Percent of study area (%)
Artificial fill	0.01	0.1
Eagle Valley Formation	0.93	7.7
Eagle Valley Evaporite	0.81	6.8
Maroon Formation	4.91	41.0
Conglomerate of Storm King Mountain	0.23	1.9
Younger colluvium and sheetwash deposits	1.67	13.9
Older colluvium and sheetwash deposits	0.95	7.9
Recent debris-flow deposits	0.02	0.2
Younger debris-flow deposits	0.16	1.3
Older debris-flow deposits	0.10	0.1
Recent landslide deposits	0.20	0.2
Landslide deposits	0.13	1.1
Older landslide deposits	2.13	17.8
Terrace alluvium	0.01	0.1

Structurally, the study area lies astride part of the Grand Hogback Monocline, and a west-northwest-trending structural terrace within the monocline extends across the study area. Several folds and faults are associated with the hinge zones on either side of the structural terrace, which may be a collapse feature related to dissolution or flowage of underlying evaporitic rocks (Bryant et al., 1998). Within this collapsed structural terrace, bedrock is intensely fractured.

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. Within the structural terrace, however, outcrops are scarce. Bedrock in this area, most notably the Maroon Formation, weathers rapidly, probably due to the intense fracturing associated with the collapsed structural terrace. Colluvium, sheetwash, and landslide deposits, locally as much as 38 m thick, and deeply weathered bedrock (residuum) mantle the bedrock in most of the study area. Prior to the rainstorm on September 1, 1994, many of the steep hillslopes underlain by the Maroon Formation within the structural terrace had covers of residuum up to about 1.2 m thick.

Surficial deposits other than Maroon Formation residuum cover about 43% of the study area (Table 2 and Fig. 3). These units include the following (Kirkham et al., 1999): (i) Younger colluvium and sheetwash deposits (Holocene and late Pleistocene age) consisting primarily of poorly sorted, poorly to moderately well bedded, matrix-supported gravelly silty sand and sandy silt. These units cover approximately 14% of the study area, mantling hillslopes and infilling drainage channels. (ii) Older colluvium and sheetwash deposits (Pleistocene age) on hillslopes, ridge crests, and basin floors that are erosional remnants of formerly more extensive deposits that once filled basins. (iii) Recent debris-flow deposits (latest Holocene) associated with the September 1, 1994 storm are poorly sorted, matrix- and clast-supported, and range between a silty sand, a bouldery, cobbly, and pebbly gravel, and a sandy silt. (iv) Younger debris-flow deposits (Holocene age), deposited prior to the September 1, 1994 storm occur in the channels of the seven major drainage basins and on fans at the mouths of some. (v) Older debris-flow deposits (early Holocene and late Pleistocene age) include remnants of formerly more extensive deposits that lie up to about 15 m above modern channels. (vi) Recent landslide deposits (latest Holocene age) include active and recently active landslides having morphological features that suggest movement during the previous few years. (vii) Landslide deposits (Holocene age) exhibit distinctive landslide morphology but do not appear to have moved during the last few decades. (vii) The older landslide deposits (Pleistocene age) include 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 and covers 17.8% of the study area. This old landslide complex appears to have been stable for thousands of years and is locally dissected by stream channels up to a depth of a few tens of meters. (ix) Minor amounts of artificial fill and Quaternary terrace deposits also occur in the study area.

3. September 1–2, 1994 debris-flow event

On September 1, 1994 at approximately 10:30 p.m., in response to a torrential downpour, debris flows originated on the burned hillslopes on Storm King Mountain. These flows (consisting of mud, rocks and burned vegetation) emptied down onto or next to Interstate Highway 70 from 15 channels (Fig. 1). Thirty cars traveling on the highway at the time of the debris flows were engulfed or trapped by the mud. At least two of the people travelling in these vehicles were swept into the river by the debris flows. Although some travelers were seriously injured, fortunately no deaths resulted from this event.

Unfortunately, the only available rainfall records are daily totals recorded at a site 5–10 km southeast of Storm King Mountain in downtown Glenwood Springs. This record does not reflect an unusual event. However, a motorist traveling on the highway at the time of the storm described the rain as "... so hard you almost couldn't see."

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 all of the burned basins. A total area of approximately 0.13 km^2 was inundated with approximately 68,000 m^3 of debris-flow deposits generated from the burned areas (Cannon et al., 1995, 1998). Material deposited at canyon mouths was generally flat-lying, indicating low shear strength (perhaps due to high water content), and was comprised primarily of silty sand with extremely variable amounts of gravel, cobbles, and boulders (Fig. 4)

The passage of the debris flows down channels was marked by a distinct path on the channel sidewalls consisting of a muddy veneer up to 2.5 cm thick (Fig. 5) Material was also deposited locally in the channels. This material consisted of cobble- and boulder-sized material in an abundant silty sand matrix (Cannon et al., 1995, 1998) (Fig. 6) These deposits were in the form of levees and lobes, indicating a more significant shear strength than those deposited at the canyon mouths. The boulders and cobbles in the deposits from the September 1994 event probably came from material that had been deposited in the channels prior to the fire by either gravity-driven colluvial processes or by fluvial and debris-flow processes (Cannon et al., 1995, 1998).

A particular focus of the field mapping was to identify the upper extent of flow paths where surface runoff could be characterized as debris flow (Kirkham et al., 1999). These points, which we refer to as initiation locations, are where debris-flow features consisting of nearly continuous levees comprised of primarily matrix-supported material and a mud ve-

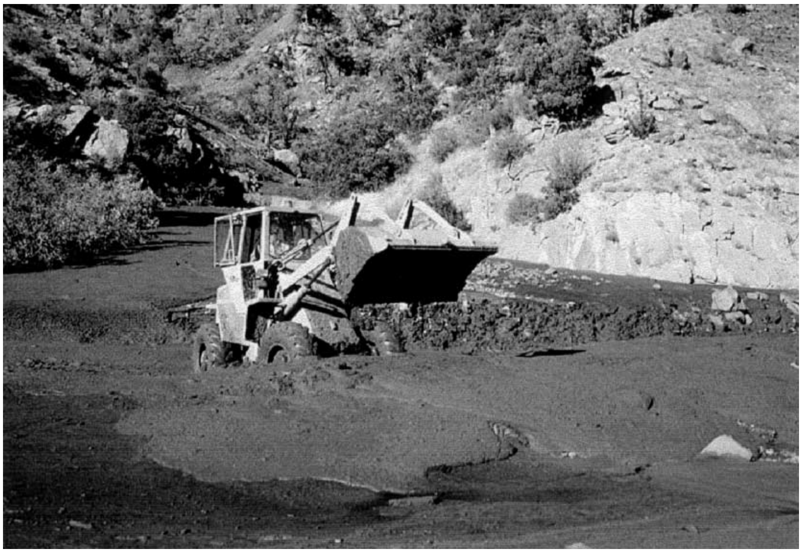

Fig. 4. Photograph of very fluid debris-flow deposits at mouth of canyon. Deposits consisted of abundant silty sand with variable amounts of gravel, cobbles, and boulders.

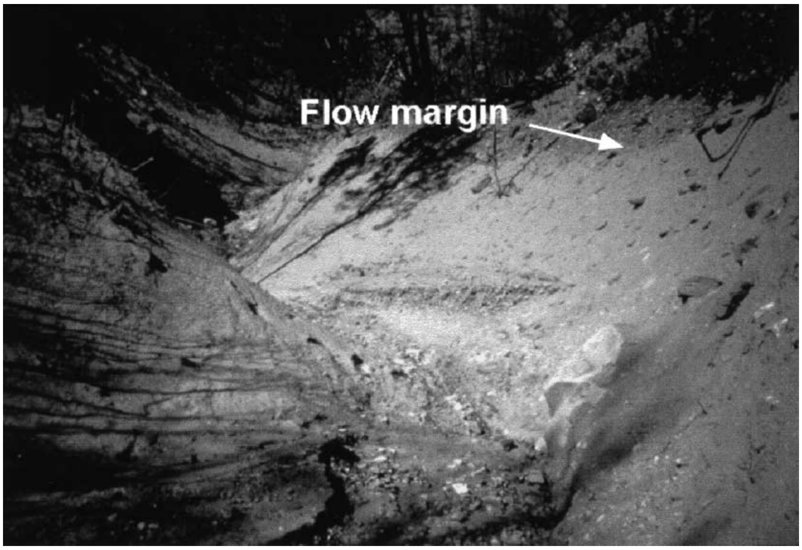

Fig. 5. Photograph of debris-flow path flow through high-order channel. Note thin, muddy veneer deposited by debris flow on channel sidewalls. Photograph by Roger Pihl, Colorado Geological Survey.

neer lining the path persist down channel. We identified 84 debris-flow initiation locations, shown as the upper ends of the debris-flow paths in Fig. 1. All of the initiation locations occurred in pre-existing 0- and 1st-order channels (Fig. 7). Nearly complete removal of burned soil and ash from the drainages immediately upslope of the initiation locations indicated the occurrence of concentrated overland flow.

Fig. 6. Photograph of debris-flow deposits in channel axis. Deposits consisted of cobble-to boulder-sized material in a silty sand matrix.

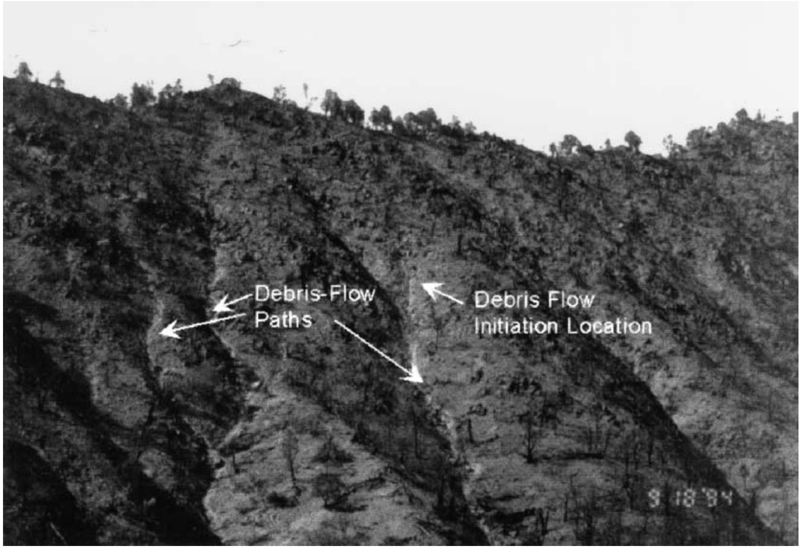

Fig. 7. Photograph of extensively eroded hillslopes in basin C showing debris-flow paths and initiation locations in 0- and 1st-order drainages. Before the September rainstorm, the hillslopes were mantled with dark-colored burned soil and ash.

Abrupt headcuts, like those described for channel initiation by Montgomery and Dietrich (1994), or small headcuts, like those attributed to very small-scale landslides or Coulomb failure at the onset of rill initiation by Johnson (1984) and Wells (1987), were not observed at the initiation locations.

With the exception of some localized lateral stream erosion and bank caving and flushing of the dry-ravel material and loose material stored in the stream channels, there did not appear to be significant amounts of channel incision during the September 1994 event. The channels did not exhibit extensive areas of freshly exposed, continuous, steep to near vertical walls with dangling tree roots that usually indicate incision. Rather, even at steep gradients, the channels were generally V- or U-shaped and coated with a thin veneer of debris-flow deposits, as seen in Fig. 5. Bedrock was exposed in places in the channel, but the lack of incised channel banks indicated that there likely was not more than about 0.5 m of material mantling the surface before the passage of the debris flows. In addition, U.S. Bureau of Land Management personnel familiar with the canyons reported that bedrock was exposed in places in the main channels prior to the September events, and they also saw little evidence for extensive channel erosion or incision following the September event. Cannon and Reneau (2000) also observed fire-related debris-flow deposits in a channel that did not exhibit extensive incision.

Field estimates made following the September events suggested that approximately 15% of the surface of the mineral soil in the burned area was removed to an approximate average depth of 4 cm by erosive sheetwash, rilling, and raindrop impact (Cannon et al., 1995, 1998). Rill networks developed in both the in-place, burned mineral soil and the aprons of dry ravel material on the sideslopes. Rills started high on the hillslopes; and, in general, their frequency, depth, and width increased with distance down slope to a maximum width of 30–40 cm and maximum depth of approximately 5 cm. Field observations also indicated that erosion by sheetwash and rilling was particularly severe on the steep slopes cut into the toe of the older landslide deposits, in the older colluvium and sheetwash deposits, and in the residuum developed on the Maroon Formation (Kirkham et al., 1999).

Fifty-seven soil-slip scars were mapped on steeper slopes in the area (Fig. 1). The soil slips typically involved a 0.3- to 1.0-m thick veneer of surficial deposits over areas of 29–828 m^2 (Kirkham et al., 1999). Material mobilized from the soil slips apparently was very fluid in that only a few traces of the deposits were observed on the hillsides downslope from the soil slip scars. This contrasts with debris flows in the main channels that deposited a nearly continuous, up to 2.5-cm thick, veneer of mud on the channel banks and sidewalls. Most material from the soil slips apparently traveled over the hillsides and into adjacent channels, and no significant deposits from the soil slips were observed remaining in the channels. The soil exposed in the soil-slip scars was not burned, indicating that they formed after the fire and most likely during the September storm.

It is important to note that the mapped soil-slip scars did not coincide with the mapped debris-flow initiation locations, nor could the debris-flow paths be traced up channel to the scars (Fig. 1).

4. Relative contribution of materials from hillslope soil slips to debris-flow deposits

We calculated the volume of material mobilized from the soil-slip scars using an estimated average thickness of 0.6 m (Table 3) to compare the volume of material contributed from the soil slips to the volume of deposits at the canyon mouths estimated by Cannon et al. (1995, 1998). With this approach, we assume that the bulk densities of the material mobilized from the soil-slip scars and the deposits are similar. This assumption seems reasonable given the accuracy of the method. The comparison indicates that, with the exception of basin F, only between 5% and 12% of the deposits could have come from the soil-slip scars. In basin F, nearly one quarter of the material could have come from discrete soil slips (Table 3). In this basin, however, the great majority of the soil-slip scars are located outside the burned area, suggesting that these failures occurred in response to heavy rainfall, independent of the effects of the fire.

The fact that the majority of the debris-flow material deposited at the mouths of the canyons at Storm King Mountain did not originate as soil slips on the hillslopes and the observation that the debris-flow paths did not originate at the soil-slip scars suggests that mass movements, or infiltration-triggered processes (as described by Morton, 1989; Booker, 1998; Cannon, 1999), were a minor component in debris-flow initiation on Storm King Mountain. However, observations of extensive erosion by rainsplash, sheetwash, and rilling on the hillslopes indicate that a process of progressive sediment entrainment by surface runoff (as suggested by Parrett, 1987; Meyer and Wells, 1997) was the primary mechanism of debris-flow initiation on Storm King Mountain.

At Storm King Mountain, channel erosion was laterally discontinuous, extremely variable, and the pre-event channel configuration was not known. These conditions make any evaluation of the relative contribution to deposits at channel mouths from channel incision beyond the scope of this study.

5. Lithologic and topographic controls on debris-flow initiation

We determined the geologic unit at the point of origin of each of the 84 mapped debris-flow paths. Most of the debris-flows originated within pre-existing drainages underlain by either Maroon Formation

Table 3
Evaluation of contribution of soil-slip scars to fire-related debris-flow deposits

Drainage basin	Area of soil-slip scars (m^2)	Estimated volume of soil-slip scars (m^3)	Volume of deposit at basin mouth (m^3)	Ratio of scar volume to deposit volume at basin mouth
B	1878	1127	20,824	0.05
C and D	4031	2419	39,064	0.06
E	262	157	1368	0.12
F	1486	892	4256	0.21
G	159	95	1064	0.09
Total	8232	4690	67,944	0.07

Average depth of each soil-slip scar assumed to be 0.6 m. Note that drainages C and D were combined because the deposits merged.

or older landslide deposits (Table 4). Considerably fewer debris flows initiated in younger colluvium and sheetwash deposits, older colluvium and sheetwash deposits, and the Eagle Valley Evaporite. The number of debris-flow initiation locations within in a particular geologic unit depends at least in part upon the areal extent of that unit within the study area. To compensate for this effect, we divided the percent of the total number of debris-flow initiation locations in each geologic unit by the percent exposure of the host unit within the study area to obtain a dimensionless index of relative susceptibility (Table 4). These susceptibility indices indicate that the Maroon Formation and older landslide deposits were the most susceptible geologic units to debris-flow initiation. The remaining geologic units that produced debris flows were considerably less susceptible. Field observations of abundant sheetwash and rill erosion on steep slopes cut into the toe of the older landslide deposits and the residuum on the Maroon Formation support the high susceptibility of these units.

Although the hillslope gradient at the location of failure is a primary control on the initiation of rainfall infiltration-triggered debris flows (e.g., Ellen et al., 1988; Wieczorek et al., 1988), the evaluations presented above indicate the importance of runoff-dominated rather than infiltration-triggered process in the generation of the fire-related debris flows from Storm King Mountain. With this consideration, we explored the idea that the runoff-contributing area extending upslope from the initiation location to the drainage divide, and its gradient, constrained debris-flow initiation during the September events. We assume that runoff and material eroded from the contributing areas were necessary to generate the debris flows, which then propagated downslope. The upslope contributing area is similar to the critical support area defined by Montgomery and Foufoula-Georgiou (1993) and Montgomery and Dietrich (1992, 1994) in their work on the runoff-controlled generation of channels and to the topographic index used in the hydrologic model TOPMODEL for runoff generation (Beven and Kirkby, 1979).

Contributing areas were delineated on the 1:5000-scale, 20-ft contour DLG generated from survey-controlled aerial photographs taken after the September events (Fig. 8) Lateral boundaries of contributing areas were defined as the pair of flow lines essentially perpendicular to the contour lines that converge at the debris-flow initiation location. The areas and slopes of the contributing areas were measured using a planimeter and scale. Although attempts were made to use automated commercially available watershed definition tools, these tools did not satisfactorily delineate the subtle 0- and 1st-order channels or hollows occupied by the debris-flow initiation locations.

Montgomery and Foufoula-Georgiou (1993) show theoretically and empirically that channels are initiated with smaller drainage areas on steeper slopes. An empirical relation between the upslope contributing area and its gradient can be defined for the debris-flow initiation locations on Storm King Mountain (Fig. 9) A regression analysis of the area and gradient data yields the relation

$$A = 1726(\tan\theta)^{-2.90}, \quad (1)$$

where A is the upslope contributing area in square meters and $\tan\theta$ is its gradient. In this form, 1726

Table 4
Distribution of debris-flow initiation locations within the geologic units and debris-flow susceptibility index for each geologic unit

Geologic unit	Number of initiation locations	Percent of initiation locations (%)	Index of relative susceptibility
Eagle Valley Evaporite	1	1	0.15
Maroon Formation	55	65	1.60
Younger colluvium and sheetwash	6	7	0.51
Older colluvium and sheetwash	4	5	0.60
Older landslide deposits	18	21	1.20

The index is calculated as the percentage of the total number of debris flows in each geologic unit divided by the percentage area of the unit within the study area (see Table 2).

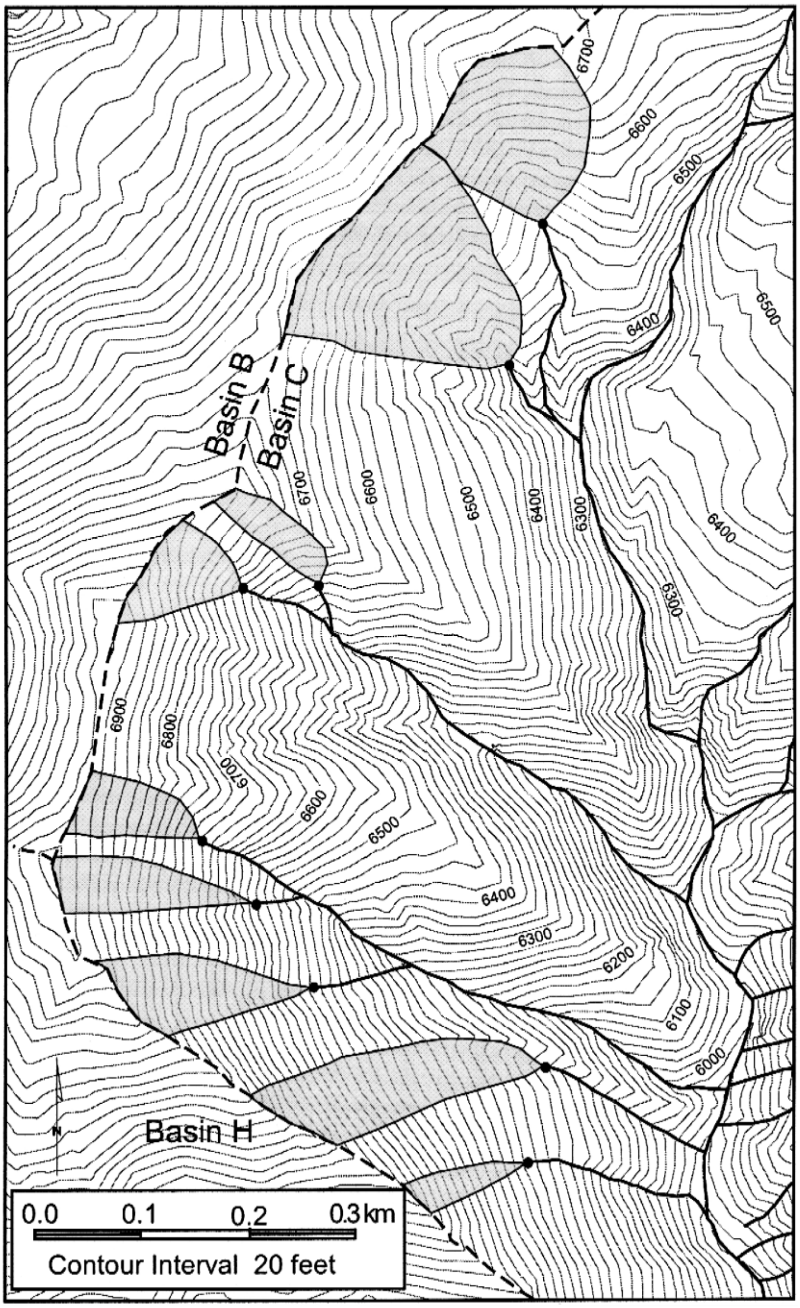

Fig. 8. Example of mapping of upslope contributing areas to debris-flow initiation locations in basin C. Topographic base is from 1:5000-scale DLG generated from survey-controlled aerial photographs. Solid circles mark the debris-flow initiation locations, and solid black lines are the debris-flow paths. Shaded polygons denote the contributing areas above each initiation location. Dashed line shows the drainage divides between basins C, B, and H.

m^2 is the value of the upslope contributing area at $\tan\theta = 1$ (45° slope). A correlation coefficient, R, of 0.58 indicates that Eq. (1) describes the relation between the independent and dependent variables

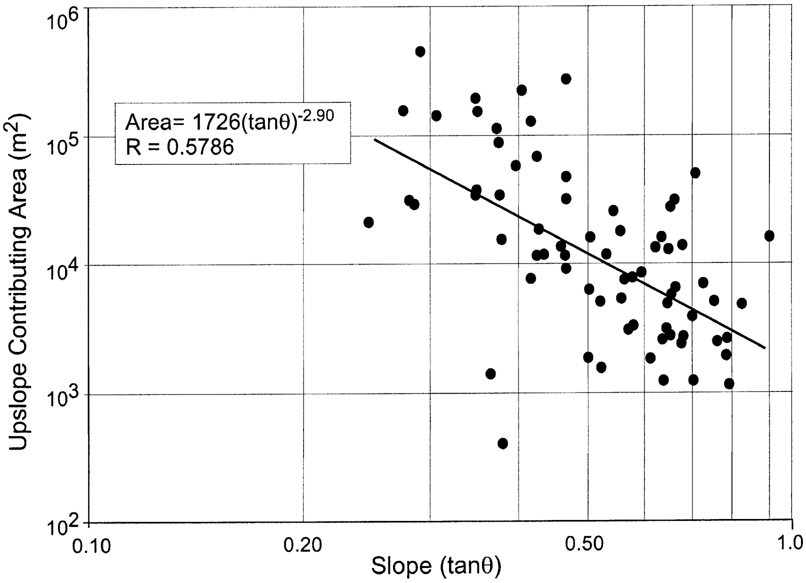

Fig. 9. Graph of upslope contributing area as a function of its average gradient for all 84 debris-flow initiation locations.

with some scatter. The F-statistic (F_{calc}) is greater than $F_{1,69;0.05}$, indicating that the independent variable contributes significantly in predicting the dependent variable (Table 5). A P value of <0.001 indicates that there is little probability of being wrong in concluding that there is a true relation between the independent and dependent variables.

Eq. (1) can also be written as

$$A(\tan\theta)^{2.90} = 1726, \qquad (2)$$

or generalized into the form

$$A_{cr}(\tan\theta)^{3} = S, \qquad (3)$$

where A_{cr} is the critical contributing area, and S is the value of upslope contributing area at $\tan\theta = 1$.

Table 5
Analysis of variance for relation between upslope contributing area and gradient

	df	Sum of squares	Mean square	F_{calc}	$F_{1,69;0.05}$	*P*
Regression	1	10.487	10.487	35.309	4.00	< 0.001
Residual	69	20.493	0.297			
Total	70	30.980	0.443			

The physical significance of the cubed slope term in unknown; this is simply an empirical result.

On Storm King Mountain, we found that the geologic unit underlying the contributing area affects its gradient and area characteristics. (Fig. 10) shows the relation between area and slope for contributing areas underlain entirely by either Maroon Formation or older landslide deposits, the two geologic units that hosted the most debris flows. This graph shows a distinct cluster of contributing areas within the Maroon Formation on slopes between 27° ($\tan\theta =$ 0.51) and 42° ($\tan\theta = 0.90$), while the contributing areas within the older landslide deposits are larger than those in the Maroon Formation and form on slopes between 14° ($\tan\theta = 0.25$) and 37° ($\theta = 0.75$). Some of this distinction may be the result of overall lower slopes on the older landslide deposits. Note also that the ambiguous inverse slope–area relation for the data from the Maroon Formation alone may indicate that other factors, such as variations in rainfall intensity and sediment availability, may also affect initiation locations.

We calculated the lower bounds for debris-flow initiation on Storm King Mountain using values measured for each contributing area and its gradient

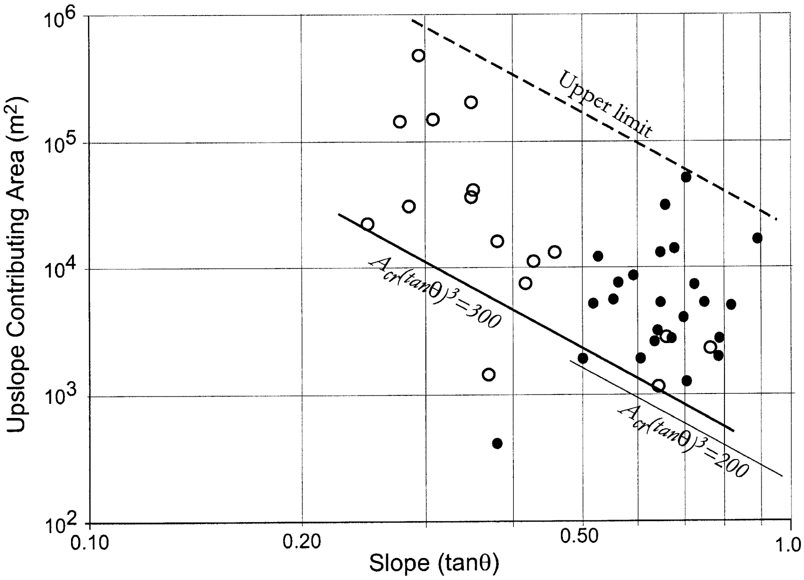

Fig. 10. Graph of contributing area as a function of slope for contributing areas underlain entirely by either the Maroon Formation (●) or the older landslide deposits (○). Thin solid line marks the lower initiation threshold for the Maroon Formation; thick line marks the threshold for the older landslide deposits. Dashed line marks the upper limit of contributing areas that produced fire-related debris flows.

in Eq. (3). With the elimination of the lowest, and errant, value for each unit, a slope–area threshold for debris-flow initiation locations in the Maroon Formation is

$$A_{cr}(\tan\theta)^3 = 200 \qquad (4)$$

for values of θ between 27° and 42°. The threshold for the older landslide deposits is

$$A_{cr}(\tan\theta)^3 = 300 \qquad (5)$$

for values of θ between 14° and 37° (Fig. 10).

Although the initiation threshold lines are similar for the two units, debris flows were produced from the Maroon Formation from contributing areas that were generally smaller and with steeper gradients than those that produced debris flows from the older landslide deposits.

Eqs. (4) and (5) define slope-dependent thresholds for fire-related debris-flow initiation for different materials. The equations are similar in form to thresholds for critical support area defined by Montgomery and Dietrich (1994) for channel initiation by overland flow, the exception being that in their paper $\tan\theta$ is squared rather than cubed. Note also that an upper limit of slope–area characteristics exists for the contributing areas on Storm King Mountain (Fig. 10), indicating that specific combinations of large, steep contributing areas will not produce runoff-dominated debris flows.

6. Conclusions and discussion

From field observations and measurements, and the evaluations above, we suggest that the generation of debris flows at Storm King Mountain started with significant sheetwash, rill, and rainsplash erosion and transport of burned mineral soil and dry-ravel materials from the hillslopes high within the contributing areas. Surface runoff bulked with material eroded from the hillslopes converged into small, 0- and 1st-order hollows and channels that were mantled with dry-ravel material. The flowing water easily incorporated this material. At the point within the drainages defined by a threshold value of upslope contributing area and its gradient, sufficient eroded material had been incorporated, relative to volume of contributing surface runoff, to generate debris flows. The dependence of the threshold on gradient suggests three possibilities: (i) The amount of post-fire sediment mobilized depended on the erosive ability of runoff at each point within the contributing area, which in turn depended on shear stress and hence on flow depth and gradient. (ii) Within the contributing areas, the down-gradient increase in available sediment was greater than the down-gradient increase in surface runoff, which resulted in a progressive increase in the sediment/water ratio. (iii) A combination of both. The location of the threshold thus reflects variations in sediment supply related to gradient, in that steeper slopes provide more erodible material per unit area. The slope–area threshold also varies with geologic materials.

As the flows traveled through higher-order channels, discharges increased as runoff and additional eroded material was contributed from the sideslopes and tributary channels and from soil slips on the hillslopes. Larger material stored within the channel was incorporated into the flows and subsequently flushed out of the canyon mouths as cobble- and boulder-sized material in an abundant fine-grained matrix. The material deposited at the canyons mouths was more fluid and contained relatively less large material than deposits within the canyons, indicating that the downchannel contribution of sediment might have decreased somewhat relative to the downchannel increase in discharge. However, the sediment/water ratio was sufficient to maintain debris-flow conditions.

It is also plausible that the debris-flow material exiting the channel mouths was of lower strength and contained less large material due to segregation of the flows within the channel into less mobile bouldery flow fronts, with more mobile and gravel-poor surges and midsections and dilute tails, as documented by Pierson (1986). Other debris-flow studies document how boulders and cobbles are typically deposited at higher gradients and flow depths (e.g., Sharp and Nobles, 1953), while the debris flows minus these coarser materials continue downchannel. Meyer and Wells (1997) also document this depositional pattern, and based on a sediment budget infer that the large volume of gravel-poor debris-flow deposits observed in fire-related events resulted from a significant contribution of fine sediment from the hillslopes to debris flows.

Although erosion following wildfires is frequently attributed to the development of a water-repellent soil, water-repellent soils were not extensive at Storm King Mountain. Thus, the process of debris-flow initiation described above does not depend on the presence of such soils. This is consistent with conclusions reached in southern California by Cannon (1999), and Meyer and Wells (1997) who found that the presence of water-repellent soils were not a prerequisite for debris-flow occurrence.

In contrast to the mechanism for debris-flow initiation proposed by Meyer and Wells (1997), the majority of the debris flows from Storm King Mountain initiated in 0- and 1st-order channels and hollows, in contrast to Yellowstone where Meyer and Wells (1997) described the first recognition of debris-flow features within higher-order channels. The origination of debris flows on Storm King Mountain in 0- and 1st-order channels and hollows also differs from the mechanism proposed by Wells (1987) and Johnson (1984), where debris flows are thought to initiate as rills high on burned hillslopes.

In addition, while Meyer and Wells (1997) concluded that a significant volumetric contribution to the flow by erosion of channel material was important to the initiation process, observations at Storm King Mountain indicate that extensive erosion of the channels did not occur, and thus, contribution of material from the channels was of secondary importance. Interestingly, the total volume of sediment produced per unit basin area for basins B, C, and D at Storm King Mountain is 1.5–2 times greater than for a debris-flow producing basin in Yellowstone of comparable size and near-total burn ("12 km" basin, Meyer and Wells, 1997). This would suggest perhaps significant differences in degree of weathering and thus considerably greater erodibility of the Storm King Mountain hillslopes relative to the thin mantle of colluvium and soil in glaciated Yellowstone. Another possibility for this contrast might be that large intense fires may have been more common in the late Holocene at Yellowstone (Meyer et al., 1995) than at Storm King Mountain, leaving smaller volumes of erodible materials available for entrainment into individual debris-flow events.

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