Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Rickenmann & Chen (eds)
 ISBN 90 77017 78 X

Wildfire-related debris-flow generation through episodic progressive sediment-bulking processes, western USA

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Keywords: debris flow, wildfire, runoff, erosion, channel incision

ABSTRACT: Debris-flow initiation processes on hillslopes recently burned by wildfire differ from those generally recognized on unburned, vegetated hillslopes. These differences result from fire-induced changes in the hydrologic response to rainfall events. In this study, detailed field and aerial photographic mapping, observations, and measurements of debris-flow events from three sites in the western U.S. are used to describe and evaluate the process of episodic progressive sediment bulking of storm runoff that leads to the generation of post-wildfire debris flows. Our data demonstrate the effects of material erodibility, sediment availability on hillslopes and in channels, the degree of channel confinement, the formation of continuous channel incision, and the upslope contributing area and its gradient on the generation of flows and the magnitude of the response are demonstrated.

1 INTRODUCTION

Wildfires can result in profound changes of the runoff response of a burned watershed. Removal of the rainfall-intercepting canopy and of the soil mantling organic litter and duff, the presence of wood ash on burned soils, and the generation of water-repellent soils can result in significant changes in infiltration and runoff characteristics from pre-fire conditions (e.g. Helvey 1980, Moody & Martin 2001, Martin & Moody 2001). One of the most hazardous consequences of the changes wrought by wildfire can be the generation of debris flows (Conedera et al. 2003, Cannon 2001, Meyer and Wells 1997, Parrett 1987).

In studies of recently burned basins throughout the western United States, workers have described debris flows that are generated through a process of progressive bulking of storm runoff with material eroded from hillslopes and channels, rather than from the mobilization of discrete landslides on hillslopes (Parrett 1987, Meyer and Wells 1997, Cannon et al. 2001a, b). In addition, Cannon (2001) demonstrated that debris flows are much more frequently generated from recently burned basins by the runoff-dominated process of progressive sediment bulking than by the infiltration-dominated process of landslide failure. Although this paper focuses exclusively on debris flows generated from burned basins, debris flows generated through what appears to be a similar process have also been described on unburned, yet primarily unvegetated, hillslopes (e.g. Coe et al. 2003, Davies et al. 1992).

To further examine this poorly understood process of debris-flow generation, detailed field and aerial photographic mapping of debris-flow events from three sites in the western U.S. were used to characterize the process, investigate the conditions which result in variations in the process, and assess the relative hazards posed by debris flows under these variable conditions. This study provides a qualitative assessment of the controls on the transitional process from clear water runoff to the generation of debris flow and is intended to foster further work to understand the mechanics of the processes observed in the field. Note that the work presented here differs from that which addresses channel initiation and gully formation processes (e.g. Istanbulluoglu et al. 2002) in that we focus on the elements of channel erosion that result specifically in the production of debris flows. Further, this work presents a view unique from that of Tognacca et al. (2000) who documented the process of debris-flow generation in response to a cascade of water over a readily erodible bed.

2 EXAMPLES OF DEBRIS FLOW GENERATION THROUGH PROGRESSIVE SEDIMENT BULKING

Three detailed case studies of post-wildfire debris flow generation are presented here through descriptions of detailed maps of the events. In each case, the debris flow producing basins were of similar size and average gradient, were all nearly completely burned at moderate to high severities, and although the rainfall accumulations in the storms that resulted in the debris flows are different, the storms all had similar recurrence intervals (Table 1). The erodibility of the materials that mantle the hillslopes differs, however, and differences in basin configuration exist (Table 2). Each of the case studies reveals variations in the process that allow a better understanding of the processes involved in debris-flow generation from recently burned basins.

Table 1. Case study similarities.

Basin	Area (km^2)	Average hillslope gradient (degrees)	Average channel gradient (degrees)	Percent area burned at high severity	Percent area burned at moderate severity	Percent area burned at low severity	Storm recurrence interval
Sula Complex-Sleeping Child Creek	0.24	25	15	71	10	19	~2 years
Coal Seam-South Canyon fires	0.20	28	18	87	5	8	~2 years*
Cerro Grande fire- Rendija Canyon	0.38	27	16	85	10	5	1-10 years

*data for Coal Seam fire only

2.1 *Sula Complex, Sleeping Child Creek, Hamilton, Montana*

The Sula Complex is the name given to a number of coalescing fires that burned throughout the summer of 2000 in the Bitterroot Valley of Montana. The fires burned primarily through thick stands of lodgepole pine, Engleman spruce and mixed conifer. In response to a convective thunderstorm on July 18, 2001, which dropped 16 mm of rainfall in one hour (return period of 2 years), debris flows were produced from a series of low-order tributaries to Sleeping Child Creek. Peak discharges of up to 250 m^3/s ($Q/A \sim 0.0010 m/s$) were estimated for these events. The debris flows deposited thousands of cubic meters of up-to-boulder sized material in abundant muddy matrix along a 2 km length of the Sleeping Child Creek valley floor. In several places, the deposits completely blocked the main channel and forced the stream to cut a new channel along the south side of the valley. The area is underlain by metamorphic rocks, primarily schists and gneisses (Lewis 1998), and the hillslopes of Sleeping Child Creek are mantled with a thin, silty clay loam soil (USDA Forest Service, unpublished data).

Table 2. Case study differences.

Basin	Vegetation	Bedrock	Surficial materials	Erodibility of surficial materials*	Channel fill thickness	Degree of channel confinement, c**
Sula Complex-Sleeping Child Creek	Lodgepole pine, Engelman spruce, mixed conifer	Schist and gneiss	Silty clay loam	Low	Up to 7m	Tightly confined along length; c = 3.1-4.4
Coal Seam-South Canyon fires	Piñon juniper, oak brush	Fine-grained sedimentary	Silty fine sand, silty sand, abundant dry gravel	Moderate	Up to 2m	Tightly confined along length; c = 1.1-3.7
Cerro Grande fire- Rendija Canyon	Ponderosa pine, mixed conifer	Volcanic	Silty sandy gravel	High	Up to 1m	Variable, with tightly confined reaches (c = 2.1-3.3), and reaches with broad, flat bases (c = 4.2-8.3)

*Erodibility characterized by relative presence and abundance of loose, unconsolidated materials.
**c, the degree of confinement, measured as the cross-sectional width at 0.5 m height above bed prior to any channel erosion.

The erosional and depositional processes in a debris flow producing tributary to Sleeping Child Creek were characterized through detailed mapping from 1:6000-scale aerial photographs taken immediately after the event, augmented with field measurements and observations (Fig. 1). The majority of the other debris flow producing tributaries in the watershed showed a similar progression to that described here. High on the hillslopes, overland flow coalesced into numerous small rills. The rills then converged in the shallow, low gradient (10-20 degree) swale that serves as the channel in the upper part of the small basin. The runoff, once concentrated, began eroding the channel bed as a series of down-channel progressing plunge pools (A in Fig. 1). The plunge pools resemble steps with the nearly vertical headscarp as the riser and the nearly flat floor as the tread. The upper-most plunge pools were just a few square centimeters in area and a few centimeters deep, but with progression down the swale, the pools increased in depth and area, and the distance between them decreased. In most cases, the pools were observed to form immediately below roots or rocks within the flow path. Less frequently, plunge pools formed immediately below locations where the flow dammed and then breeched. Localized deposits of material were observed immediately downslope of some of the plunge pools or along the path behind obstructions such as trees or rocks. In the upper part of the basin, the deposits consisted primarily of well-sorted sands and silts (B in Fig 1). With progression down channel, the sorting of the deposits decreased, and the size of the entrained materials and the amount of matrix increased. At a distance about midway between the ridge crest and the channel mouth, the deposits, although discontinuous, were characterized by poor sorting, random orientation of the clasts, and fine-grained matrix support of the larger clasts (C in Fig. 1). These features are common indicators of fire-related debris-flow activity (Meyer & Wells 1997, Cannon 2001). At a distance about two-thirds of the distance from the ridge crest to the channel mouth, depositional levees become continuous along the channel (D in Fig. 1). The cores of the levees consisted of up-to-boulder sized material in abundant fine-grained matrix, and the rims consisted of openwork boulders and cobbles. A series of cross sections measured along the length of the channel indicate that the transition to continuous debris flow occurred in the tightly confined section of the channel (c, the degree of channel confinement measured as the width of the channel bed at 0.5 m height prior to any channel erosion, ranges between 3.1 and 4.4 m). A final transition, from channel erosion as a series of discrete plunge pools, to continuous channel incision leaving steep, nearly vertical banks, also occurred with downchannel progression (E in Fig. 1).

Bedrock was exposed in places along the freshly eroded channel, usually at depths greater than about 2 m. At the narrow junction with Sleeping Child Creek, the tributary channel had incised as much as 7 meters. This deep channel incision revealed that prior to the debris-flow events of July 2001 the channels were filled with thick accumulations of colluvium.

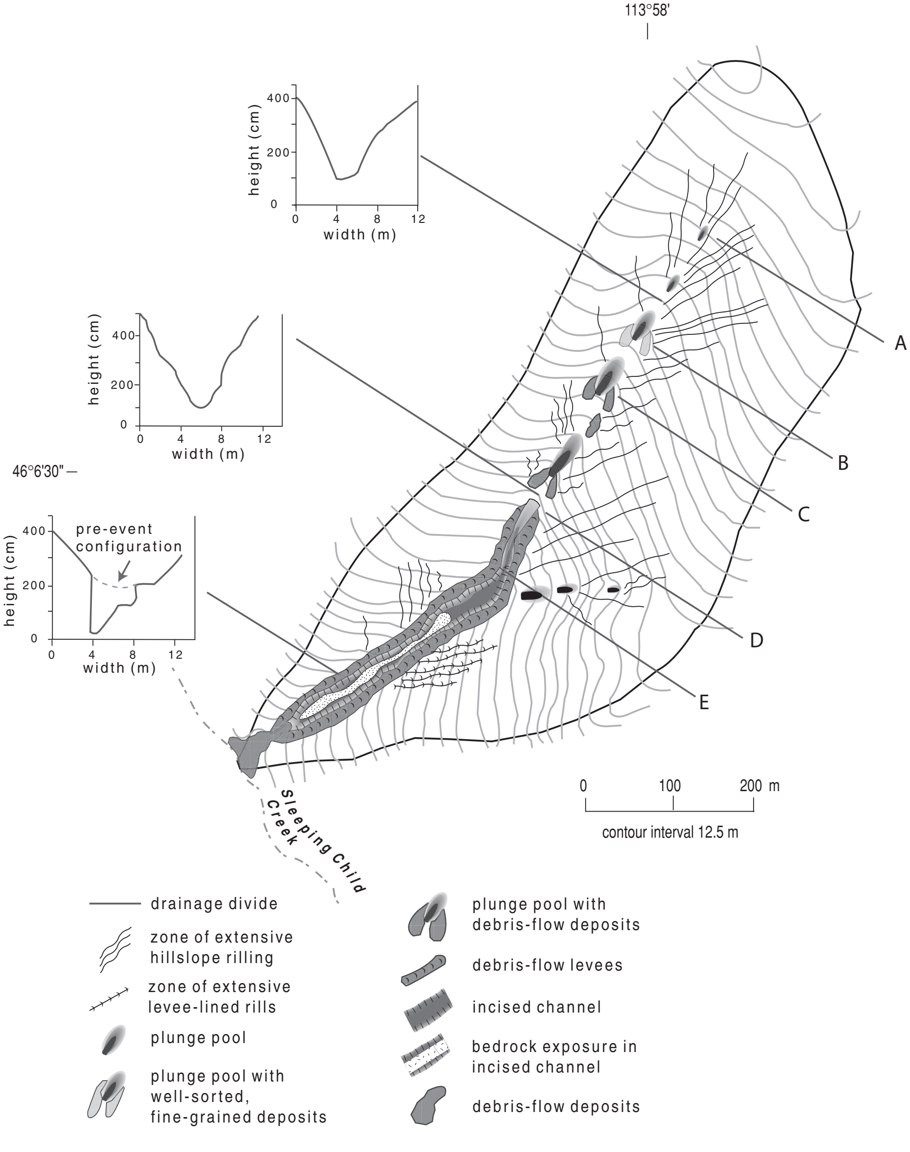

Figure 1. Map of a debris-flow producing basin in the Sleeping Child Creek watershed. Evidence is shown of progression from concentrated flow to the generation of debris flows. Features are somewhat exaggerated and schematized for illustrative purposes. Letters A, B, C, D and E are transitions referred to in text.

2.2 *South Canyon and Coal Seam Fires, Glenwood Springs, Colorado*

The South Canyon fire of July 1994 and the adjacent Coal Seam fire of June 2002 together burned approximately 6000 ha of Piñon juniper and Oak brush outside the town of Glenwood Springs, Colorado (Cannon et al. 2001a). Rainstorms in September 1994 produced debris flows from all of the steep basins burned by the South Canyon fire, and an August 2002 storm resulted in debris flow activity from the Coal Seam fire. The 1994 debris flow event inundated a 2 km long stretch of Interstate highway I-70 with approximately 70,000 m^3 of boulders, mud and burned vegetation washed from the hillslopes. The debris flow response in 2002 was less areally extensive than that of 1994, but debris flows with estimated peak discharges up to about 30 m^3/s ($Q/A \sim 0.0002 m/s$) were produced from many basins. No rain gages were located near the burned basins at the time of the 1994 events, but two gages installed in the area burned by the Coal Seam fire recorded storm rainfall of 8.35 mm in 17 minutes (32mm/hr), and 8.89 mm in 11 minutes (45mm/hr), which resulted in the 2002 debris flows. These rainfall values have a return period of about 2 years (Miller et. al. 1973). The area burned by both fires is underlain primarily by fine-grained sedimentary rocks; hillslopes are mantled with an abundance of loose, unconsolidated colluvium and soils are primarily silty sands and silty fine sands (Kirkham et al. 2000).

Erosional and depositional processes in a debris flow producing tributary burned by the Coal Seam fire are shown in Figure 2. This map was generated primarily by field measurements and observations, and most of the debris-flow producing tributaries burned by the Coal Seam and South Canyon fires showed a similar progression (Cannon et al. 2001a). The majority of the other debris-flow producing tributaries in the area showed a similar progression. Runoff and erosion of surficial material by rainsplash and erosive sheetwash started high on the steep (32-42 degree) upper hillslopes, and coalesced into numerous small rills. The rills then converged in the steep (30-40 degree) 0-order drainages. The concentrated runoff began eroding the channel bed as a progressive series of stepped plunge pools (A in Fig. 2). However, at distances only between about 200 to 300 m from the ridge crest, and where the channel is tightly confined (c between 1.1 and 3.7 m), the passage of the flow was marked by a deposit of a distinct muddy veneer up to 2.5 cm thick on the channel sidewalls, and small levees composed of poorly-sorted, matrix-supported material (B in Fig. 2). This is considered as the starting location of the debris flow. The path left by the debris flow was continuous from the first trace extending downstream to the canyon mouth. Further down the channel, the path widened and the levees increased in size and in the size of material contained. Bedrock was exposed in many places in the channel, and localized incision from the progressively larger plunge pools cut into colluvium to depths up to about 3 m (C in Fig. 2). This incision reveals that prior to the debris flow event, the channels were filled with a minimum of 3 m of colluvium. However, unlike Sleeping Child Creek, the incision was extremely variable and laterally discontinuous along the length of the channel.

In contrast to the case of Sleeping Child Creek, in this basin the transition to debris flow occurred very high in the basin, only a few hundred meters from the drainage divide, but again where the channel was tightly confined. Once the flow developed, it maintained debris-flow characteristics along the length of the path.

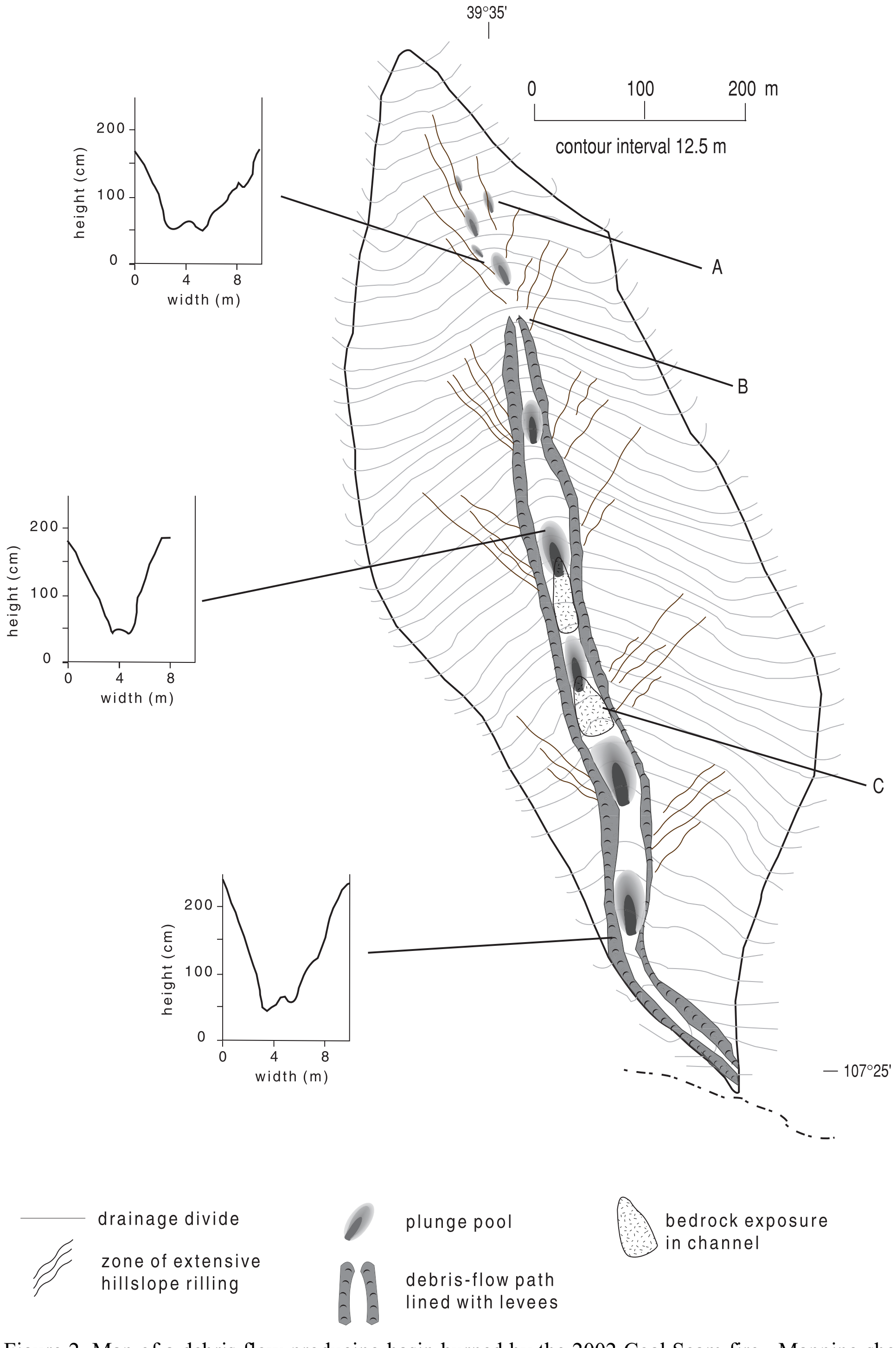

Figure 2. Map of a debris flow producing basin burned by the 2002 Coal Seam fire. Mapping shows debris flow origination high in 0-order basins where the channel is tightly confined, and continuous deposits lining the channel. Features are slightly exaggerated and schematized for illustrative purposes. Letters A, B, and C are transitions referred to in the text. Channel cross sections were surveyed prior to the August 2002 event.

2.3 *Cerro Grande Fire, Rendija Canyon, Los Alamos, New Mexico*

The Cerro Grande fire burned approximately 17,200 ha of Ponderosa pine, mixed conifer forest and Piñon juniper woodlands between May 4 and June 6, 2000 near the town of Los Alamos, New Mexico (Los Alamos National Laboratory 2000). Monitoring of the hillslope and channel response to convective rainstorms throughout the summer of 2000 revealed that debris flows were produced from many 0 to 3rd order tributaries to Rendija Canyon during a rainstorm on July 16, 2000. A rain gage located in the case study basin described below recorded 25.4 mm of rain in 1 hour and 26 minutes, for an average storm intensity of 20.16 mm/hr. Maximum 30-minute rainfall intensities of between 20mm/hr and 50mm/hr were recorded for this storm by a network of 14 gages located throughout upper Rendija Canyon (John Moody 2001, pers. comm.). Return periods for these rainfall accumulations varied from between 1 and 10 years. Rendija Canyon and its tributaries are underlain by fine-grained volcanic rocks (Smith et al. 1970), and the hillslopes are mantled with a loose, unconsolidated, coarse gravel- to cobble-sized lag that overlies up to 0.5 m of silty, sandy gravel.

Erosional and depositional processes in a debris-flow producing tributary to Rendija Canyon are shown in Figure 3. This map was generated primarily by field measurements and observations, and most of the debris-flow producing tributaries to Rendija Canyon showed a similar progression. The dominant response to the July 16, 2000 storm was the development of an extensive rill network on the hillslopes (Cannon et al. 2001b). Between 5 and 10 m from the ridge crest, overland flow coalesced into numerous small rills. At downslope distances between 20 and 50 m from their origin, the rills were lined with continuous levees that consisted of poorly sorted, gravel- and cobble-sized material in an abundant fine-grained matrix that supported the clasts (A in Fig. 3). Again, the lack of sorting and matrix support of clasts is taken to indicate debris flow movement. Some of the material transported over the hillslope then converged into the 0-order channel that drains the basin. As in the previous cases, the runoff from the hillslopes began eroding the channel bed as a progressive series of stepped plunge pools, and discontinuous deposits of material were observed immediately downslope of these pools. In addition, poorly sorted, matrix-supported deposits were evident behind breeched debris dams within the channel. In contrast to the two previous cases, a series of cross sections show that the channel is not tightly confined along its entire length; a broad channel floor exists at some locations (c between 4.2 and 8.3 m) (B in Fig. 3). Deposits were mapped at these locations. Deposits were not continuous along the channel, and a transition to continuous channel incision occurred approximately 150m from the junction of the tributary with the main stem of Rendija Canyon (C in Fig. 3). Bedrock was exposed in many places in the channel, usually at depths less than 1 m. At the valley floor of Rendija Canyon, the tributary channel had cut down as much as 1.5 meters.

In the Rendija Canyon basins, debris flows initiated high on the hillslopes as levee-lined rills. Debris flows generated in this fashion have also been described by Johnson (1984) and Wells (1987). In this case, however, these sediment-rich flows were not able to persist through the channel into which they traveled. Although additional sediment was contributed to the runoff through the erosion of the plunge pools and the breaching of dams, significant deposition of material behind the debris dams and at locations where the channel widened out precluded the generation of debris flows that could persist along the entire length of the channel. And last, the relatively minor amounts of channel incision to shallow bedrock exposures indicate very little accumulation of material in the channel prior to the July 2000 storm.

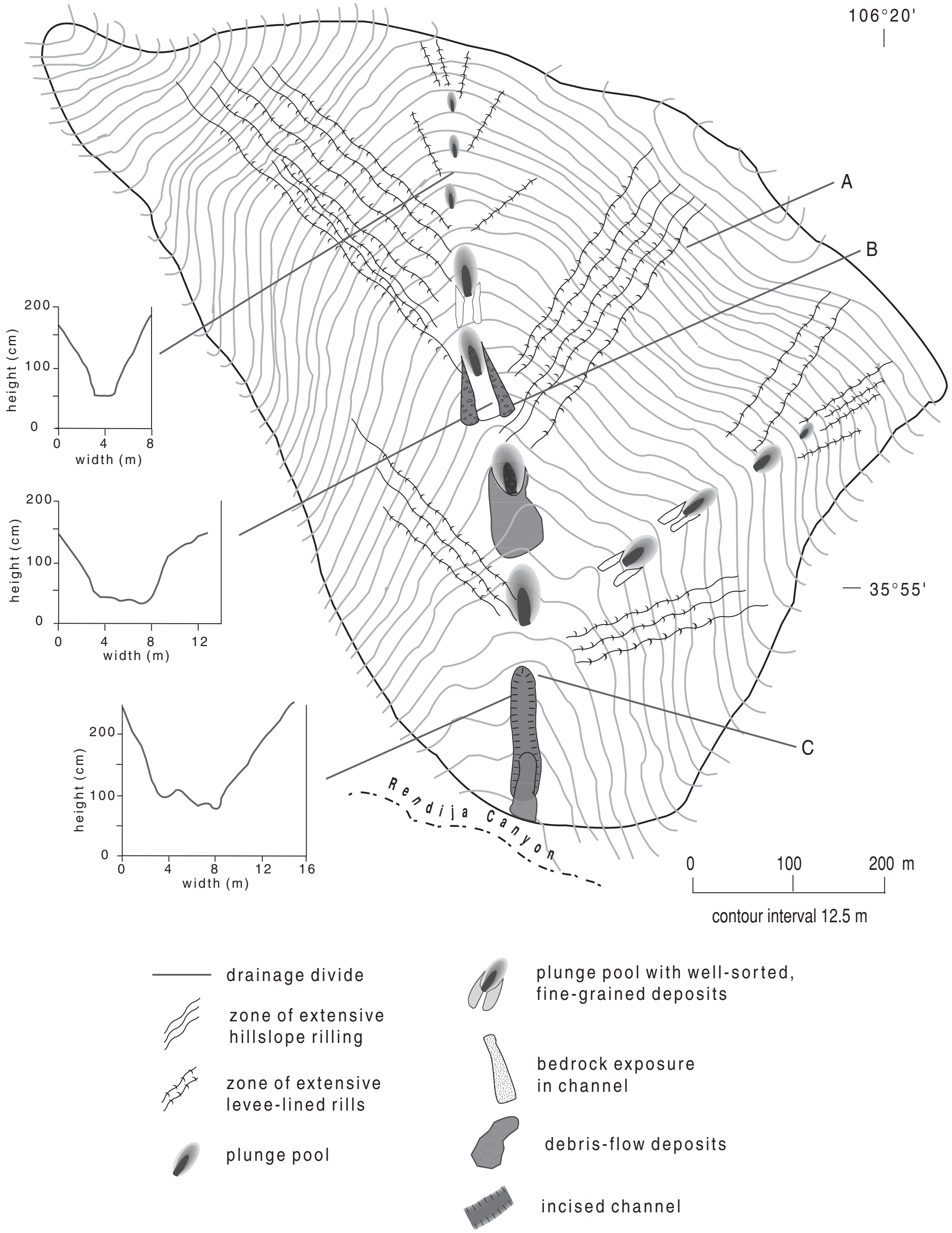

Figure 3. Map of a debris flow producing tributary to Rendija Canyon. Evidence of progression from levee-lined rills on hillslopes to small- to moderate-sized plunge pools in the 0- and 1st order channel is shown. Features are slightly exaggerated and schematized for illustrative purposes. Letters A, B, and C are transitions referred to in text. Channel cross sections were surveyed prior to the July 2000 event.

3 CONTROLS ON DEBRIS-FLOW GENERATION BY PROGRESSIVE SEDIMENT BULKING

Comparing and contrasting the features illustrated in the detailed maps above, and evaluation of less-detailed maps of the paths of all of the debris flows produced during these events (e.g. Cannon et al. 2001a and unpublished), allows for a qualitative evaluation of the processes that led to the generation of debris flows from these basins. Through this procedure, we are able to evaluate the controls on the initiation process and the resulting relative degree of hazard.

3.1 *Episodic contribution of sediment from channels*

In the three cases presented above, sediment was eroded from the plunge pools and entrained into the runoff, resulting in increased sediment bulking with travel down the channel. Contributions of sediment to the runoff were episodic, and the down-channel increase in size of the plunge pools indicates that sediment contributions increased in volume with distance down the channel. In the upper reaches of the basins, fluctuations in the proportions of sediment to runoff occurred as a result of localized erosion, deposition, and the contribution of additional runoff and sediment from side slopes. However, at locations along the channel where poorly-sorted deposits with abundant fine-grained matrix appeared, it is assumed that sufficient material had been entrained, relative to the amount of runoff, to impart debris-flow characteristics to the flow. The still fluctuating sediment-to-runoff proportions in these channel reaches generally precluded the persistence of travel as debris flow for more than a few meters down channel. However, in the Sleeping Child and Coal Seam/South Canyon cases, with increasing distance down channel, additional sediment contribution from the progressively-larger plunge pools resulted in debris flows that were able to persist along the remaining length of the channel, as evidenced by the continuous mud veneers and levees.

This episodic contribution of material to the flow through the excavation of the stepped plunge pools appears to be a necessary element in the generation of debris flows. Incorporation of material at concentrations beyond that of turbulent suspension is not possible with the shear forces exerted by water on even a steep channel bed (J.D. Smith 2002, pers. comm.). The case studies illustrated here suggest that it is necessary to episodically increase the sediment concentrations to attain debris-flow conditions.

3.2 *Upslope contributing area and materials*

The detailed mapping of the three case studies indicates that under different conditions debris flows are generated from varying positions within basins. Based on this result, and the importance of runoff-dominated processes in the generation of wildfire-related debris flows (Cannon et al. 2001a), we investigated the idea that the runoff-contributing area extending upslope from the first appearance of debris-flow deposits to the drainage divide, and its gradient, constrained debris-flow initiation in the three study areas. It was assumed that runoff and material eroded from the contributing areas were necessary to generate the debris flows, which then propagated downslope. Although the upslope contributing area used for this study is somewhat similar to the critical support area defined by Montgomery & Foufoula-Georgiou (1993) and Montgomery & Dietrich (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 (Bevin & Kirkby 1979), it differs with the important distinction that this study examined the conditions above the point where the proportions of sediment entrained into the runoff were sufficient to impart debris-flow characteristics to the flow, rather than the conditions above the first indication of erosion within a swale. In this study the upslope contributing area and the gradient were measured from 10 and 30 m digital elevation models (DEMs) of each area.

From data collected from detailed mapping of the initiation locations of all of the debris flows that occurred in the study areas, it was found that the upslope contributing area and its gradient constrain the initiation locations of debris flows (Fig. 4). A regression analysis of the area and gradient data yields a statistically significant relation between upslope contributing area and the gradient of the form $A = 1700(\tan\theta)^{-3}$, where A is the upslope contributing area in m^2, and $\tan\theta$ is the gradient.

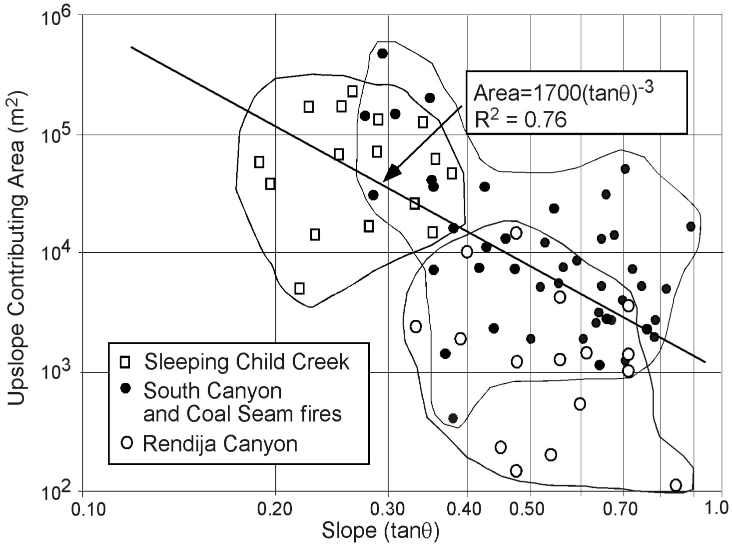

Figure 4. Graph of upslope contributing area as a function of the gradient of the contributing area (expressed as $\tan\theta$) underlain by metamorphic rocks and mantled with consolidated materials (Sleeping Child Creek), fine-grained sedimentary rocks and abundant loose, unconsolidated materials (South Canyon and Coal Seam fires), and fine-grained volcanic materials and abundant loose gravel lag (Rendija Canyon).

In addition, the dissimilar fields occupied by data from the three debris-flow events indicate that the contributing area/gradient conditions vary with different materials. The abundance of loose, unconsolidated materials mantling the hillslopes in the Coal Seam/South Canyon and Cerro Grande cases resulted in the attainment of debris-flow conditions with relatively small contributing areas with steep gradients. Debris-flow generation in the Sleeping Child case, however, occurred with larger contributing areas with gentler gradients. This difference can conceivably be attributed to the less erodible soils in the area. It is also possible that variations in rainfall amounts and intensities produced these differences.

3.3 *Hillslope and channel material availability*

The erodibility of the materials mantling the hillslopes appears to strongly influence the location of debris-flow initiation (Table 2). The hillslopes in the Coal Seam/South Canyon and Cerro Grande cases were mantled with abundant, loose, unconsolidated, and thus easily erodible, materials. In these cases, debris-flow conditions were attained high on the hillslopes or within the drainages, reflecting the abundance of material that could readily be entrained to attain debris-flow conditions. The surficial materials in the case of Sleeping Child creek, in contrast, were not nearly as loose and unconsolidated, and debris flow conditions were not attained until well down the channel.

In contrast, the abundance of material available in the channel for incorporation into the flow appears to affect the magnitude of the debris-flow response, and thus the relative degree of hazard. The largest debris flow events documented here were produced from a setting with thick accumulations (up to 7 m) of colluvium stored in the channel (Sleeping Child Creek tributaries). However, debris flows of sufficient magnitude to persist along the length of their channels were produced from basins with only up to 3 m of stored material (Coal Seam and South Canyon fires). In the case of the Rendija Canyon, however, debris flows were generated from hillslopes mantled with abundant loose, unconsolidated material, but because there was not a substantial accumulation of material in the channel available for entrainment, these debris flows did not attain a significant size, and thus posed a negligible downstream hazard.

3.4 *Channel confinement*

The degree of channel confinement also appears to be an important control in the generation of post-wildfire debris flows. In the Sleeping Child Creek and Coal Seam/South Canyon cases where debris flows of significant size were generated, continuous debris-flow deposits were mapped at, and down channel from, tightly confined channel reaches. Flows generated in the Rendija Canyon case, in contrast, consistently deposited materials at locations where the channel widened and the gradient decreased; these flows did not attain continuous debris flow along the length of the channel.

3.5 *Continuous channel incision*

Field observations of the dramatic channel incision at Sleeping Child Creek leads to the initial impression that such incision, with associated bank failures, is necessary for the generation of debris flows. However, the detailed mapping reveals that the transition to continuous debris flow in this case occurred up channel from the continuous channel incision. In addition, significant debris-flow activity occurred from the Coal Seam and South Canyon fire areas without the establishment of continuous channel incision. These observations indicate that although the occurrence of deep, continuous channel incision along a significant length of channel were associated with the most significant debris-flow events, and thus the greatest hazard, debris flows can be generated through progressive sediment bulking in the absence of this feature.

4 SUMMARY AND CONCLUSIONS

The process of progressive sediment bulking in the generation of wildfire-related debris flows has been explored through examinations of three detailed case studies. It has been demonstrated that sediment input to flows was generally episodic in nature, and these episodic fluxes increased in volume with travel down channel. These episodic sediment contributions appear to be necessary in order to entrain sufficient material, relative to the amount of runoff, to impart debris flow characteristics to the flow. The upslope contributing area, its gradient and materials, the volume of material available on hillslopes and in channels for entrainment, and the degree of channel confinement all affect the development of debris flows through this process. Continuous channel incision, and associated bank failures, does not appear to be a necessary condition for the generation of debris flows through this process.

This presentation of the process of debris-flow generation through progressive bulking of runoff with material eroded from hillslopes and channels is in no way complete; the conclusions presented here are based on qualitative evaluation of three case studies, and it is likely that additional variability will be noted with additional cases. In addition, to adequately characterize runoff and erosion processes, and the associated generation of debris flows from recently burned basins, it will be necessary to develop a physical framework that accounts for episodic contribution of sediment of varying volumes and size distributions to runoff, as well as flow through rapidly varying scales of channel confinement. This work further demonstrates the need for methodologies to characterize the amount of material stored in channels in order to define the magnitude of the potential hazards posed by post-wildfire debris flow.

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