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INITIATION OF DEBRIS FLOWS IN TRIBUTARIES OF THE COLORADO RIVER IN GRAND CANYON, ARIZONA

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ABSTRACT

Debris flows are initiated in tributaries of the Colorado River in Grand Canyon when intense rainfall causes failures in colluvium and (or) bedrock. Most debris flows occur in the summer during localized convective thunderstorms with rainfall intensities as high as 40 mm/hr. Rarer and larger debris flows occur during unusually warm frontal storms in winter. Hourly precipitation data suggest that storms that cause debris flows terminate with a period of intense rainfall, a characteristic that complicates the use of daily rainfall records in assessing debris-flow hazard. Recurrence intervals for 1-day rainfall associated with 37 recent debris flows range from <1 to >50 years, with most <10 years. Recurrence intervals for the multi-day rainfall of storms associated with debris flows range from <1 to 158 years, but most were >10 years. The low recurrence intervals of debris-flow producing rainfalls, compared with the 10-50 yr recurrence intervals for most debris flows, underscores the co-dependence of debris-flow initiation on geologic factors, including bedrock type and antecedent soil-moisture conditions. The primary geologic factor influencing debris-flow initiation in Grand Canyon is the exposure of shale units at heights >100 m above the river. Exposed shale bedrock fails readily, either producing debris flows directly or contributing source material to wedges of colluvium that may fail later. Shales also provide silt- and clay-size particles that in part determine the rheological properties of debris flows.

INTRODUCTION

Debris flows occur in at least 600 tributaries of the Colorado River in Grand Canyon between Lees Ferry and Surprise Canyon, Arizona (fig. 1; Melis et al., 1994; Griffiths et al., 1996). These mass movements transport poorly sorted sediment, including very large boulders that form rapids at the mouths of tributaries and control the longitudinal profile of the Colorado River. In most tributaries, debris flows reach the Colorado River on average once every 10-50 years, contain up to 80 percent sediment by weight, and transport particles ranging in size from fine clay to

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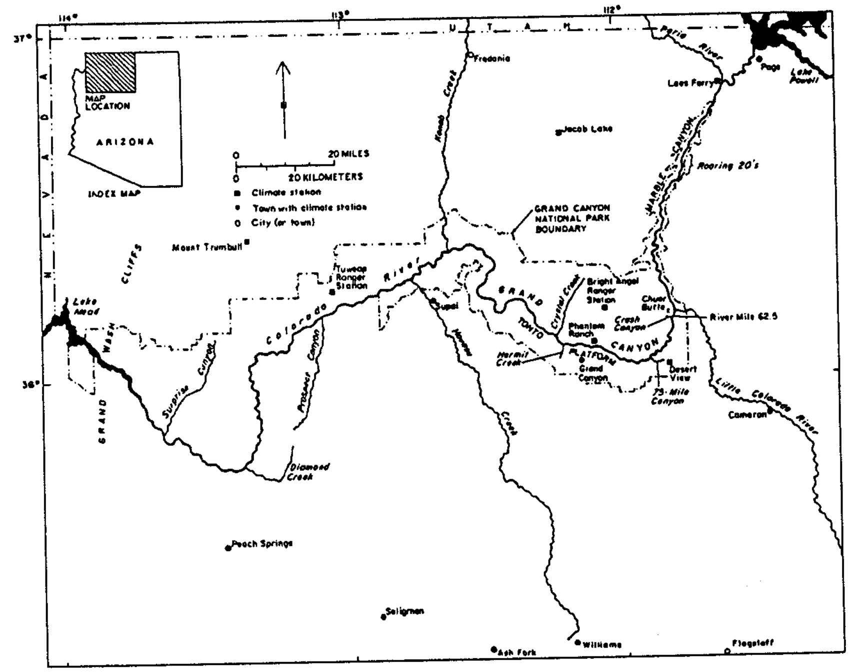

Figure 1. The Colorado River in Grand Canyon, Arizona.

large boulders (intermediate-axis >3 m) (Melis et al., 1994). These tributaries take the form of steep canyons (mean channel slope = 0.41) in which are exposed numerous near-horizontal strata of sedimentary rock (fig. 2). Most bedrock units are exposed as vertical cliffs, broken occasionally by steep slopes and benches where softer units, predominantly shales, have eroded. As bedrock cliffs weather and erode, unconsolidated material accumulates on the slopes and benches as steep wedges of colluvium, perched in settings of high potential energy. As with debris flows in many other locales (Caine, 1980), debris flows in Grand Canyon are readily initiated when rainfall of sufficient intensity triggers single or multiple slope failures in either the weathered bedrock cliffs or the wedges of colluvium. The climatic conditions that trigger failures are typically very localized, making estimates of the triggering precipitation difficult in this rugged terrain. The mechanisms by which precipitation results in slope failures vary, and are enhanced by the sparse vegetation and steep relief of these arid bedrock canyons.

PRECIPITATION

Historically, most Grand Canyon debris flows have occurred during localized, convective summer thunderstorms that affect only one or two drainage basins at a time. These storms typically occur from July through October (fig. 3a). Rainfall from summer thunderstorms typically is intense, but localized, and has durations of less than several hours (fig. 4a). Debris flows in summer months are not related to

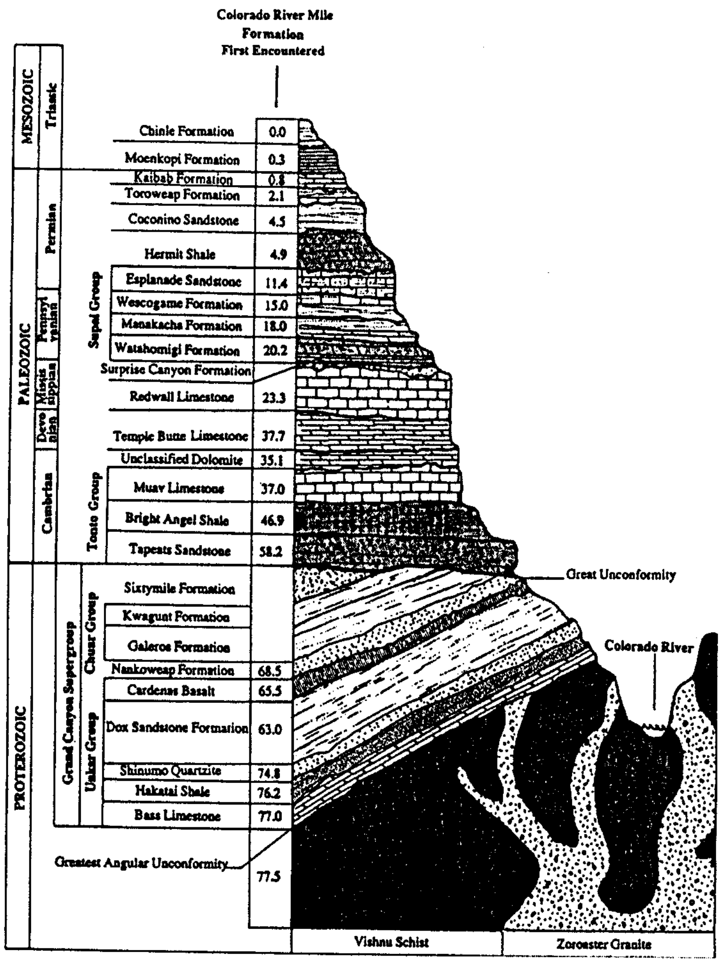

Figure 2. A stratigraphic column of rocks exposed in Grand Canyon, Arizona, with the location in river miles from Lees Ferry where they first appear at river level (from Billingsley and Elston, 1989).

the level of seasonal precipitation; instead, debris flows are as likely to occur in wet, average, or dry summers (fig. 3a).

In contrast, a few of the large debris flows have occurred during prolonged precipitation produced in winter by unusually warm frontal systems (Cooley et al., 1977; Griffiths et al., 1996; Webb et al., 1996; fig. 3b). These storms typically occur from November through March and cause heavy rain and snow over several days (fig. 4b,c). Winter storms can affect large drainage basins (fig. 5a), triggering multiple hillslope failures, high-volume debris flows, and sustained runoff (Cooley

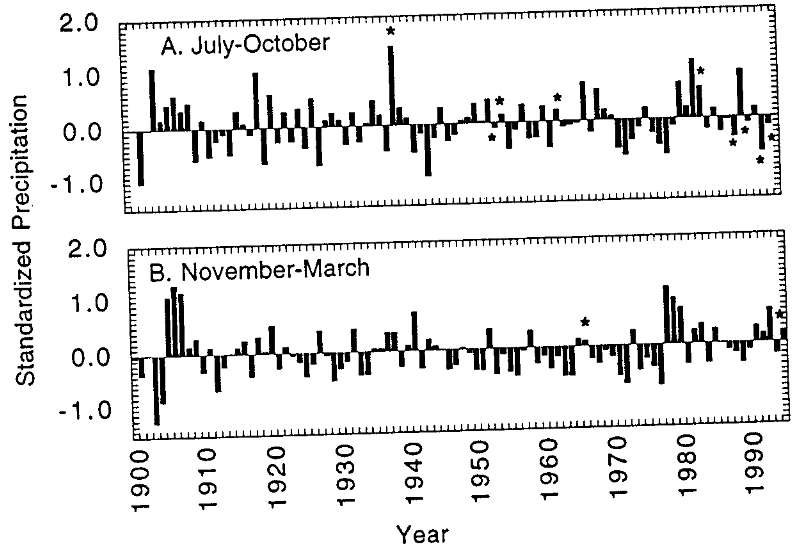

Figure 3. Standardized seasonal precipitation averaged from eight stations in the vicinity of Grand Canyon. Positive values represent above average seasonal precipitation; negative values represent below average seasonal precipitation. Asterisks indicate seasons during which debris flows have occurred.

et al., 1977; Webb et al., 1989). Like summer debris flows, the occurrence of winter debris flows apparently is unrelated to the amount of seasonal precipitation (fig. 3b).

The intensity of rainfall necessary to initiate Grand Canyon debris flows is poorly known because only a few weather stations are near the initiation sites. Previous studies have reported intensities >25 mm/hr and total rainfalls of 16 to 50 mm associated with debris flow initiation (Melis et al., 1994). Peak rainfall intensity associated with three additional historic debris flows ranged from 10 to 40 mm/hr (fig. 4a-c). However, rainfall intensities at the debris flow locations are unlikely to be as low as 10 mm/hr. This minimum was recorded more than 40 km distant from the initiation site and it is unlikely that the rain gage recorded the peak intensity of the storm.

We calculated recurrence intervals (RI) for precipitation associated with 37 historical Grand Canyon debris flows (fig. 5) using one-day and multi-day storm precipitation data (Griffiths et al., 1996). Storm precipitation is totaled over consecutive days of precipitation (ranging from 2 to 9 days). The RI of precipitation on single days when debris flows occurred ranged from <1 yr to 100 yrs, with 88 percent of the RIs <10 yrs, (fig. 5b). Precipitation from multi-day storms associated with debris flows had larger RIs, ranging from <1 to 168 yrs, with 51 percent of the events <10 yrs (fig. 5b). However, it is unlikely that precipitation intensity at the point of initiation is as common as daily RIs suggest, because most regional gages

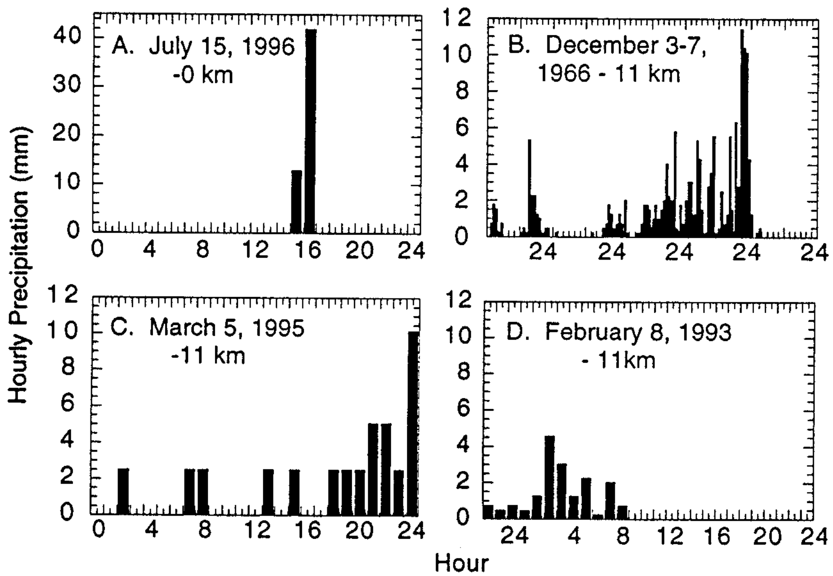

Figure 4. Hourly precipitation at nearest stations during three historic debris flows (A-C) and one stream flow flood (D) in tributaries of the Colorado River in Grand Canyon. Distance between station and tributary indicated.

are several kilometers from initiation points. Webb et al. (1996) indicate that Grand Canyon debris flows are only weakly related to larger regional storms. Nevertheless, on the basis of regional precipitation alone, Grand Canyon debris flows (RI = 10-50 yrs) are better related to the recurrence interval of multi-day storms than to single-day rainfall.

Although monthly precipitation was high when most historic debris flows occurred (Webb et al., 1996), seasonal precipitation was not consistently high (fig. 3). Grand Canyon debris flows do not necessarily require season-long buildup of antecedent soil moisture; however, the importance of above-average rainfall in the days preceding the debris flow is reflected in the RIs for storm precipitation. The true RI for daily precipitation for summer debris flows may not be known because the storms are localized and the climate stations typically are kilometers from the affected drainage basins. Storms that produce debris flows typically end in a strong microburst of high rainfall intensity (fig. 4a-c). It is most likely that slope failures occur during this period. Storms that do not have a terminal microburst tend to produce large stream floods rather than debris flows (fig. 4d).

SLOPE FAILURES

Importance of Shale

Debris flows in Grand Canyon are initiated when sufficiently intense rainfall triggers a slope failure in either bedrock or colluvial, though not all slope failures result in debris flows. The occurrence of a debris flow is highly dependent on the

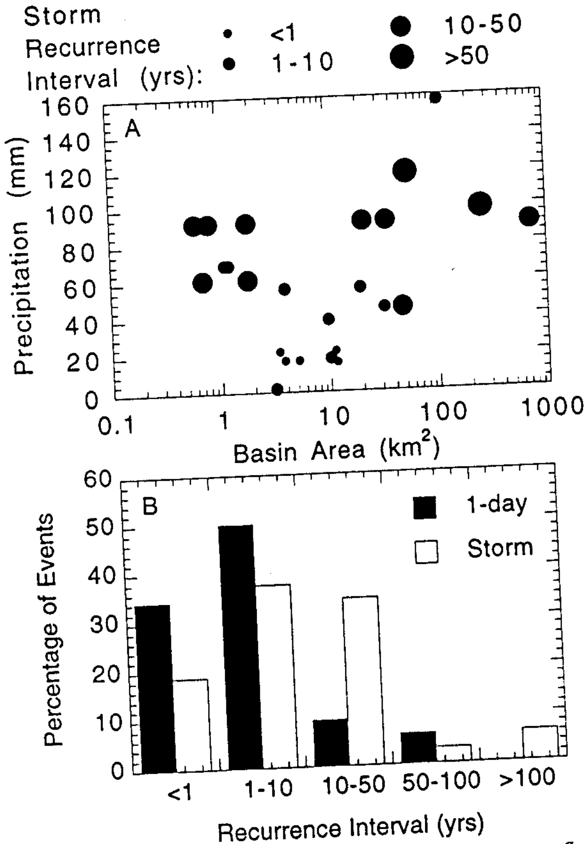

Figure 5. Precipitation associated with Grand Canyon debris flows measured at nearest gage.

presence of shale bedrock (Griffiths et al., 1996). Exposed shale bedrock fails readily, either producing debris flows directly or contributing source material as colluvium. Shales erode into slopes that store unconsolidated source material. If these colluvial wedges do not fail, the underlying shale bedrock may fail, mobilizing the overlying colluvium. Erosion of shale units also can undercut more-indurated, cliff-forming lithologies, contributing to their failure.

In Grand Canyon, three shale units dominate debris-flow initiation sites. The Hermit Shale is the most influential unit of the three source units, and is prone to both bedrock and colluvial failures. Along the Colorado River, successively older rock units crop out at river level and rise in elevation as one moves downstream from Lees Ferry, Arizona (figs. 1 and 2). Where the Hermit Shale reaches elevations >100 m above the Colorado River (about river mile 20), the frequency of debris-flows increases significantly (Griffiths et al., 1996). Although the lithology and

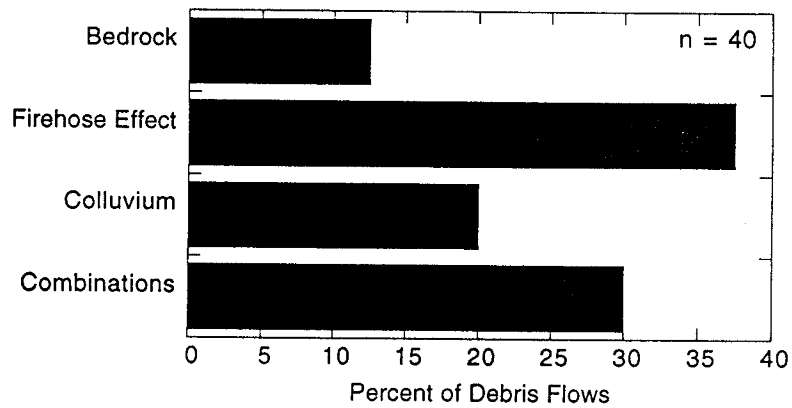

Figure 6. Failure mechanisms that have initiated debris flows in Grand Canyon from 1939 through 1996 (Griffiths et al., 1996).

structure of the canyon have not changed significantly at this location, the elevation of the Hermit shale above a threshold height above the river gives failures the potential energy necessary to transform into debris flows (Griffiths et al., 1966). The expression of this potential energy as debris flows is dependent on the angle of slope below the source area. However, slope becomes a significant factor only in the largest canyons of western Grand Canyon, where the Hermit Shale is far removed, both horizontally and vertically, from the river.

In tributaries where the Hermit Shale is either sufficiently far from the river or nonexistent, other shale units contribute to debris flows. Shale beds in the Supai Group —particularly the basal unit of the Esplanade Sandstone — are subject to bedrock failures, providing both fine particles and large boulders from interbedded shale and sandstone beds. The Muav Limestone contains thin, interbedded mudstone and shale beds and grades into the underlying marine Bright Angel Shale, forming part of the Tonto Platform. This broad, erosional shelf at the base of the Redwall Limestone stores abundant colluvium throughout Grand Canyon downstream from the Little Colorado River (fig. 1).

Most importantly, shale units provide the fine particles and clay minerals that are essential to the mobility and transport competence of debris flows. Most Grand Canyon debris-flow deposits contain 1-8% silt- and clay-size particles by weight (Griffiths et al., 1996). These fine particles occupy interstitial spaces in debris-flow slurries, increasing the density of the matrix and the buoyant forces that contribute to the suspension of larger particles (Hampton, 1975; Rodine and Johnson, 1976). Electrochemical attraction among clay particles may influence matrix rheological properties, and strong water absorption by clay particles helps maintain high pore pressures, one condition deemed necessary to support large clasts (Hampton, 1975; Major and Pierson, 1992).

Initiation Mechanisms

Melis et al. (1994) identified four mechanisms of debris-flow initiation in Grand Canyon: 1) the failure of weathered bedrock; 2) the "firehose effect" of run-

off falling onto unconsolidated colluvial wedges, 3) direct failure of colluvial wedges, 4) combinations of the first three mechanisms (Fig. 6). Here, we extend the data of Melis et al. (1994) by adding information from 1994-1996 debris flows.

Many of the largest debris flows begin with the failure of weathered shale bedrock or interbedded shale and sandstone units. These bedrock failures occur most often in either the Hermit Shale or Supai Group, although failures also occur in formations such as the Bright Angel Shale. Bedrock failures are most often triggered by the intense, localized rainfall of convective summer thunderstorms, but some of the largest bedrock failures have occurred during warm winter storms (Cooley et al., 1977).

Most Grand Canyon debris flows are produced by the "firehose effect" (Johnson and Rodine, 1984). This mechanism occurs in Grand Canyon when runoff pours over a cliff face, impacts colluvium at the base of the cliff, and forces a failure. This process frequently occurs in drainage basins that contain catchments at high elevations above the Redwall Limestone. Runoff from these catchments typically pours as a waterfall over the vertical Redwall cliffs and may impact colluvial deposits below. As with failures in bedrock, the firehose effect is usually triggered by small summer thunderstorms but can also occur during less-intense regional storms, especially in large tributaries that concentrate runoff at a single waterfall (particularly Prospect Canyon; Webb et al., 1996).

Failures of colluvial wedges occur during either intense or prolonged rainfall, and usually result in smaller debris flows. In the case of low-intensity, sustained rainfall, saturation may be hastened by concentrated sheetflow runoff from cliff faces. This substantial runoff may be concentrated at the intersection of a colluvial wedge and a cliff face, augmenting direct precipitation. Multiple source areas combined with the extreme topographic relief of Grand Canyon commonly result in combinations of the three basic initiation mechanisms, particularly in larger drainage basins and during widespread winter storms.

SUMMARY AND CONCLUSIONS

Debris flows in the canyons tributary to the Colorado River are initiated when intense rainfall causes a failure in weathered bedrock cliffs and (or) slopes of colluvium. Intense rainfall that initiates most Grand Canyon debris flows comes from convective summer thunderstorms and is highly localized. However, some of the largest debris flows have been caused during unusually warm winter frontal storms. In both cases, failures in source material occur during a microburst of rainfall as intense as 40 mm/hr at the end of the storm. The local nature of these conditions makes it very difficult to predict accurately when and where debris flows may occur solely on the basis of precipitation unless there is a recording rain gage close to the failure point(s). However, this is rarely the case, and regional precipitation may sometimes be useful in predicting debris flows if used with caution. On the basis of regional precipitation, debris flows are better related to extreme multi-day storms than to single days of high precipitation. Grand Canyon debris flows do not necessarily occur in the wettest months or seasons, but rainfall several days before the debris flow is extremely important.

Most Grand Canyon debris flows are the result of failures in colluvial wedges, but some of the largest involve the direct failure of exposed bedrock. In all cases, the presence of shale units exposed at heights >100 m above the Colorado River is an essential factor. Shale units either fail directly or erode to form slopes on which colluvium accumulates. Shales also provide most of the fine sediment that is essential to the mobility and transport competence of debris flows.

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THE INFLUENCE OF HILLSLOPE SHAPE ON DEBRIS-FLOW INITIATION

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ABSTRACT

A severe storm of June 27, 1995, in Madison County, Virginia, triggered more than 1,000 debris flows. Sites were sampled to determine which topographic factors contributed most to soil-slip initiation. Logistic regression analyses of failure/non-failure conditions indicate that hillside curvature, distance to ridge, and drainage area predict soil-slip initiation. The model from logistic regression confirmed field observations in this area that planar slopes were more prone to failure than concave slopes. The probability of failure in the model increased with drainage area and decreased with distance from ridge. The influences of drainage area and distance to ridge based on the model are difficult to interpret because the soil-slip process is very complex and involves other geologic and hydrologic factors.

INTRODUCTION

Debris flows frequently initiate in topographic concavities filled with colluvial soils on steep hillsides (Pierson, 1980; Reneau and Dietrich, 1987; Ellen, 1988; Sitar et al., 1992), although in some environments, planar slopes are more prone to failure (Jacobson et al., 1993). Based on local usage in the eastern United States, Hack and Goodlett (1960) termed these topographic features above the permanent stream network "hollows", and noted that they have surface runoff only during storms of high rainfall intensity. Concentration of surface and subsurface water flow may theoretically account for initiation of debris flows along the axes of these topographic depressions or swales (Wilson and Dietrich, 1987). As found by Dengler et al. (1987), thickness of soil over bedrock may vary greatly on steep hillsides adjacent to hollows. Thick colluvial soils may accumulate in the center of these swales from a variety of slope

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