on the basis of increased information content), the extraneous variables were eliminated from further consideration. Variables measuring distance or area, such as drainage area, channel distances, channel gradient, and fault distance, are distributed logarithmically. Logistic regression is not dependent on normally distributed data, but log transformation of these variables reduces the redundancy identified by principal-component analysis. We therefore chose to use the log-transformed values in modeling the probability of debris-flow occurrence. To properly evaluate zero values in log-transformed data, zero values were replaced with a value one order of magnitude smaller than the smallest non-zero variable. For source-lithology channel distances and gradients this value was 0.001, resulting in a log-transformed value of -3. For fault lengths, these values were 0.01 and -2.

We used a step-backward elimination process in our logistic regression (SAS, 1990). Variables of least statistical significance are removed from the model until only variables with significance (ρ_v) less than a given threshold (0.10 in this study) remain. We used the χ^2 measure of the Wald statistic (Hosmer and Lemeshow, 1989; SAS, 1990) to evaluate variable significance. We employed several statistics to evaluate the quality of the resulting models. These statistics include measures of the overall significance of the final model compared with the model containing all initial variables (ρ_m); a percentage of accurately predicted debris-flow occurrence as a rough measure of model accuracy (α); and the Hosmer/Lemeshow model goodness-of-fit statistic (C), which can be expressed as a χ^2 significance measure (ρ_C) (Hosmer and Lemeshow, 1989).

We also calculated the odds ratio (Ψ) for each variable in the model. This statistic measures the change in the odds of outcome occurrence per unit increase of the variable. We evaluated how robust the models were by attempting to reproduce model results using larger data sets drawn from the same population of drainages. For this purpose, we determined debris-flow probability for the "verification set," an additional 50 drainages — 25 each in eastern and western Grand Canyon — using a variety of non-photographic methods, including radiometric dating, stratigraphic evidence, and other field evidence (Melis and others, 1994). Unfortunately, a verification set of only 25 observations is too small for reliable logistic regression modeling alone. We therefore added each set of 25 drainages to the original calibration data and formed two larger verification data sets (fig. 7). This overlap of calibration and verification data limits the usefulness of the model comparison.

INITIATION OF DEBRIS FLOWS

Debris flows in Grand Canyon are initiated by a combination of intense precipitation and subsequent slope failure. The intensity of rainfall necessary to initiate debris flows in Grand Canyon is poorly known because few climatic stations are in debris-flow producing tributaries. Previous studies have reported rainfall that initiates debris flows to have intensities greater than 25 mm/hr with a total rainfall of at least 16 to 50 mm (Webb and others, 1989; Melis and others, 1994). The recurrence interval of precipitation on the days when debris flows have occurred in Grand Canyon ranges from less than one year to more than sixty years (table 2). Multiday storms that precede debris flows had larger recurrence intervals, typically greater than 100 years.

Intense precipitation may occur in summer or winter throughout Grand Canyon. Three types of storms can cause floods in the southwestern United States: localized or widespread convective thunderstorms in summer, regional frontal systems in winter, and dissipating tropical cyclones in late summer and early fall (Hansen and Shwarz, 1981; Hirschboeck, 1985; Webb and Betancourt, 1992; Thomas and others, 1994). Most historic debris flows in Grand Canyon are associated with the intense precipitation of convective summer thunderstorms that affect only one or two drainages at a time. These storms are fed by large quantities of moisture, evaporated from the northern Pacific and Gulf of California by monsoonal circulation patterns. Debris flows also occur during prolonged precipitation produced in winter by regional frontal systems (Cooley and others, 1977). These widespread storms sweep across the Colorado Plateau from the west along the Pacific storm track, which is shifted south during the winter by the Aleutian Low in the North Pacific Ocean (Webb and Betancourt, 1992). Rain that can be both

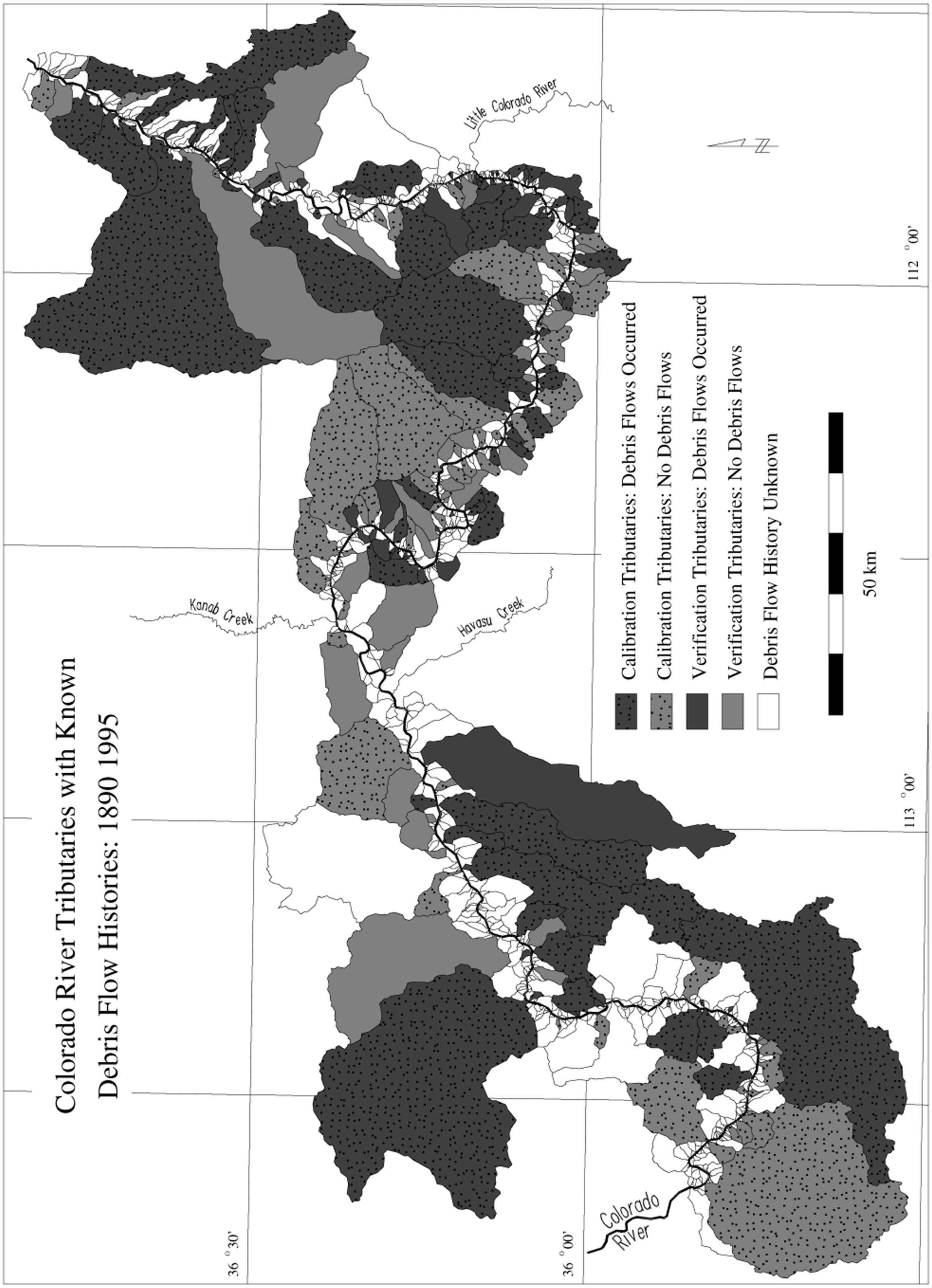

Figure 7. Map of Grand Canyon showing the locations of tributaries with histories of debris flows between 1890 and 1990.

Table 3. Precipitation associated with selected debris flows in Grand Canyon

Tributary	River mile -side	Basin area (km^2)	Date of debris flow	Nearest climate station	Daily precip-itation (mm)	Recurr-ence interval (years)	Storm[1] precip-itation (mm)	Recurr-ence interval (years)
Badger Canyon	7.9-R	47.0	8/18/94	Lees Ferry	45	46	45	16
18-Mile Wash	18.0-L	5.1	8/24/87	Desert View	14	<1	17	<1
Unnamed	19.9-L	3.8	8/24/87	Desert View	14	<1	17	<1
Unnamed	62.5-R	0.7	9/18/90	Desert View	19	<1	61	34
Crash Canyon	62.6-R	1.8	9/18/90	Desert View	19	<1	61	34
Unnamed	63.4-R	0.7	9/18/90	Desert View	19	<1	61	34
Lava Canyon	65.5-L	54.7	12/5/66	Grand Canyon	43	16	118	157
Tanner Canyon	68.5-L	19.3	8/22/93	Desert View	28	3	56	8
Cardenas Creek	70.9-L	3.9	8/22/93	Desert View	28	3	56	8
Unnamed	71.2-R	1.1	8/21/84	Grand Canyon	35	3.2	69	7.6
Unnamed	72.1-R	1.2	8/21/84	Grand Canyon	35	3.2	69	7.6
75-Mile Creek	75.5-L	11.5	8/24/87	Desert View	14	<1	16	<1
			9/18/90	Desert View	19	<1	61	34
Monument Creek	93.5-L	9.7	7/27/84	Grand Canyon	27	1	39	1
Hermit Creek	95.0-L	32.0	7/15/96	Grand Canyon				
Crystal Creek	98.2R	111.6	12/6/66	Tuweep	96	63	157	63
Forster Canyon	122.7-L	10.0	9/8/91	Grand Canyon	13	<1	18	1.9
Fossil Canyon	125.0-L	34.4	8/19/89	Grand Canyon	46	8	92	25
Unnamed	126.9-L	0.6	8/19/89	Grand Canyon	46	8	92	25
Unnamed	127.3-L	0.8	8/19/89	Grand Canyon	46	8	92	25
Unnamed	127.6-L	1.8	8/19/89	Grand Canyon	46	8	92	25
Bedrock Canyon	130.5-R	21.1	8/19/89	Grand Canyon	46	8	92	25
Unnamed	157.6-R	11.1	8/6/93	Peach Springs	20	<1	22	<1
Unnamed	160.8-R	3.4	8/6/93	Peach Springs	20	<1	22	<1
Prospect Canyon	179.4-L	257.2	9/6/39	Grand Canyon	32	7	98	158
			7/24/54	Grand Canyon	27	1	27	--2
			7/24/55	Mount Trumbull	111	100	112	100
			9/17/63	Mount Trumbull	23	<1	23	<1
			3/5/95	Tuweep	43	5	--[2]	--[2]
Unnamed	207.8-L	3.1	9/23/91	Peach Springs	35	3	--[2]	--[2]
Diamond Creek	225.8-L	716.7	7/20/84	Tuweep	53	10	90	24

[1] Storm is defined as consecutive days with measurable rainfall.
[2] One day storm.

widespread and intense is produced by occasional dissipating tropical cyclones in the late summer and early fall (Smith, 1986), but these storms have only caused debris flows in Prospect Canyon (Melis and others, 1994; Webb and others, 1996).

In general, moisture and storm systems travel across Grand Canyon from west to east and south to north. Strong orographic lifting occurs in the vicinity of the Kaibab Plateau, with greater rainfall falling at higher elevations (table 1). It should be noted that, although intense or prolonged rainfall is necessary for the occurrence of a debris flow, rainfall alone is not a sufficient cause because a slope failure is also required (Melis and others, 1994). The occurrence of debris flows cannot be predicted solely on the basis of rainfall.

Figure 8. Debris-flow source areas exposed in Monument Creek (river mile 93.5-L), Grand Canyon, Arizona. The Supai Group forms the dark, ledgy unit in the middle of the section; the overlying slope is Hermit Shale. The 1984 debris flow was initiated in the Hermit Shale and the lowest member of the Supai Group (Webb and others, 1988).

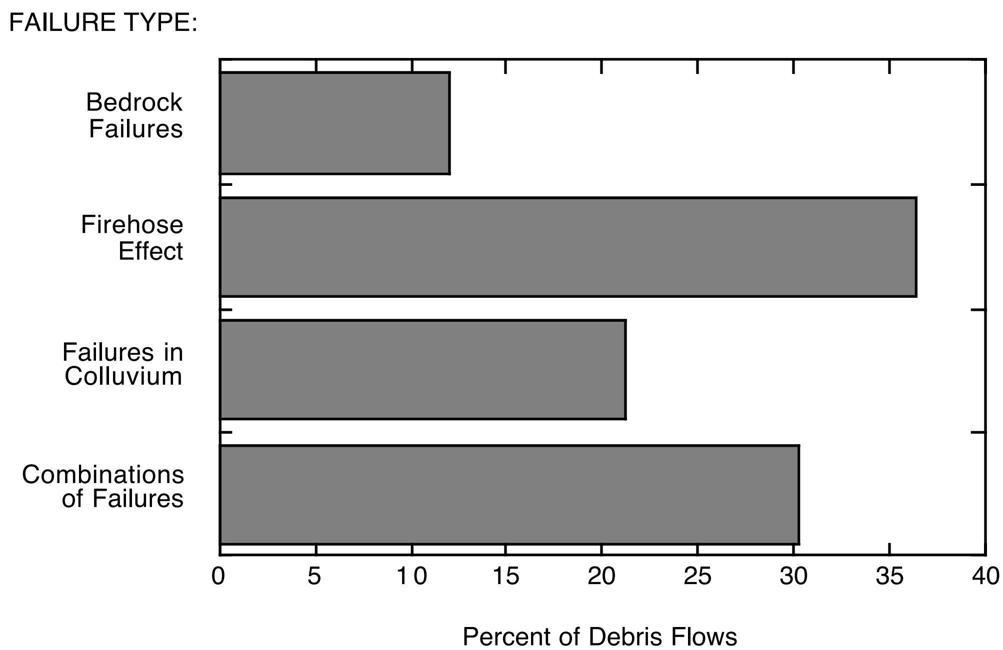

Figure 9. Failure mechanisms that have initiated debris flows in Grand Canyon from 1939 through 1996 (modified from Melis and others, 1994).

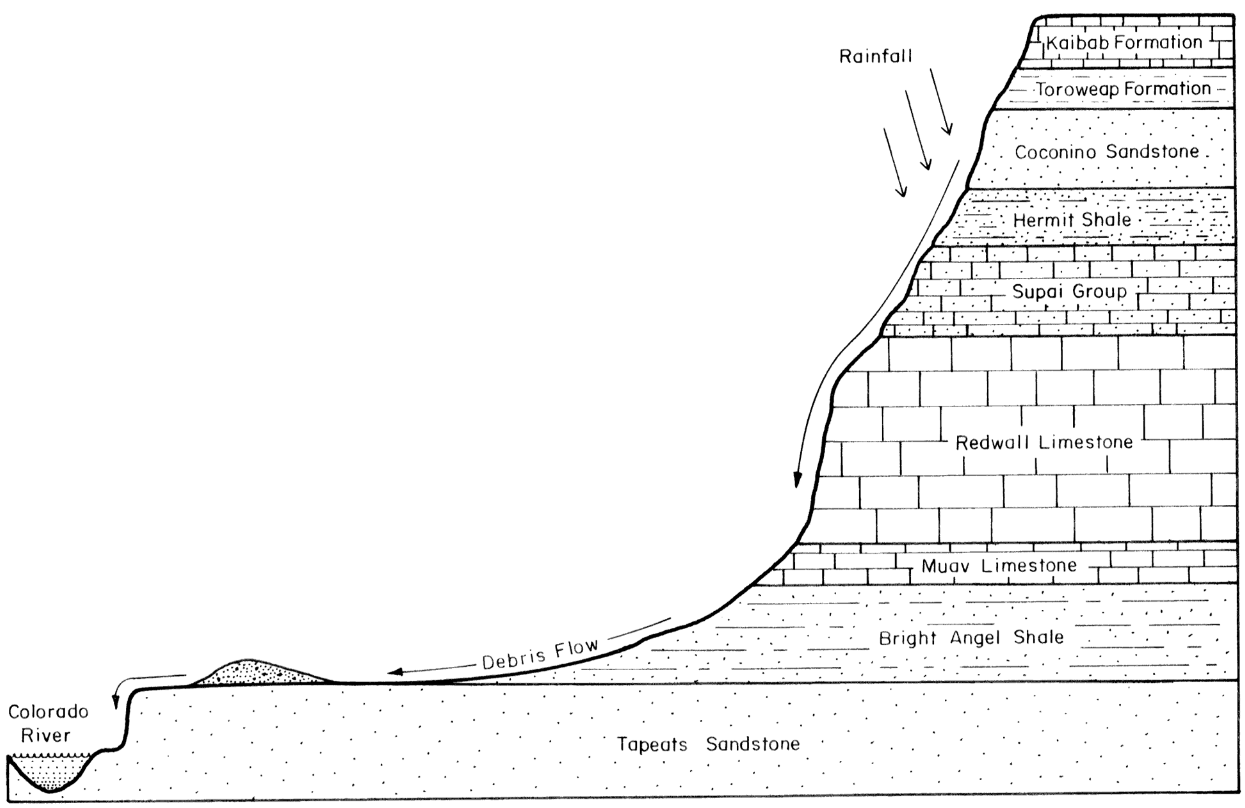

Figure 10. Schematic diagram illustrating the initiation of debris flows by the failure of bedrock - usually the Hermit Shale and Supai Group - during intense rainfall.

Debris-flow source sediments in Grand Canyon consist of weathered and jointed bedrock, colluvial wedges, or sediment stored in or adjacent to channels. Numerous exposed Paleozoic and Proterozoic strata, ranging from shale to sandstones and limestones, provide many types of source rock in a setting of high topographic relief (figs. 3, 8). Weathering and erosion are constantly at work on these strata as the canyon continues to widen (Ford and others, 1974; Webb and others, 1989; Hereford and Huntoon, 1990; Melis and others, 1994). Elevational and temperature gradients, along with a high degree of annual and inter-annual climatic variability, promote rock expansion/contraction as well as precipitation-related infiltration and frost action. All Grand Canyon drainage basins, particularly the largest ones, are influenced to some extent by regional and localized faults, folds and joints, which weaken bedrock to various degrees. Soft shale units erode quickly, and can destabilize overlying cliffs of more indurated sandstones and limestones. These processes result in rockfalls and rock avalanches that occur in all seasons, and under a wide variety of weather conditions, but are especially common during the winter due to prolonged precipitation and freezing temperatures. Larger slab failures also occur in the more indurated sandstones, especially the Coconino and Esplanade Sandstones, as compressive stresses are released during erosive unloading.

Rockfalls and slab failures do not necessarily produce debris flows, but they do produce large amounts of colluvium that is an important source material for debris flows. This colluvium collects where softer units have eroded to form benches, particularly the Hermit Shale and the distinctive Tonto Platform formed by the Muav Limestone and Bright Angel Shale (figs. 1, 3). Various shale units within the members of the Supai Group form smaller, high-angle slopes that also collect loose debris (fig. 8).

Other sources of loose, poorly sorted debris are shear zones in the many fault-controlled drainages present in Grand Canyon, such as 75-Mile Canyon (river mile 75.5-L). This tributary has formed along the strike of east-trending 75-Mile Fault, and drainages have formed preferentially along the highly fractured, footwall-side of the fault. Since 1959, three debris flows have been initiated exclusively in colluvium accumulated in these footwall sub-basins (Melis and others, 1994). Alluvial deposits, especially old debris-flow levees along the sides of tributary channels, also provide source sediments. Once initiated, debris flows in Grand Canyon often "bulk up", entraining sediments from terrace deposits and gaining volume and velocity as they head toward the river (Melis and Webb, 1993; Melis and others, 1994; Webb and others, 1996).

Melis and others (1994) identified four main mechanisms of debris-flow initiation in Grand Canyon: 1) the failure of weathered bedrock; 2) the "firehose effect" of runoff falling onto unconsolidated colluvial wedges, 3) direct failure of colluvial wedges, 4) combinations of the first three mechanisms (fig. 9). We extend the data from Melis and others by adding information from debris flows that occurred between 1994 and 1996. The largest debris flows — which are few in number — begin with the failure of weathered Paleozoic shales and sandstones, most often in either the Hermit Shale or Supai Group, although failures also occur in other formations such as the Bright Angel Shale (fig. 10). Bedrock failures are most often triggered by intense, localized rainfall from convective summer thunderstorms, although bedrock failures occurred in the December 1966 debris flow (Cooley and others, 1977). One example of this failure mechanism occurred during the Monument Creek (river mile 93.5-L) debris flow of 1984 (Webb and others, 1988, 1989). On July 25, runoff from a thunderstorm centered over the eastern part of Monument Creek caused a slope failure in the Esplanade Sandstone. The failure became an avalanche that fell 650 m and mobilized into a debris flow upon reaching the creek channel. The debris flow traveled 4.5 km to the Colorado River where deposition of boulders significantly altered flow in Granite Rapid (Webb and others, 1988).

Most debris flows in Grand Canyon are produced by the "firehose effect." In this mechanism, runoff pours over a cliff face and impacts colluvium at the base of the cliff, causing bulk failure (Johnson and Rodine, 1984). This process frequently occurs in drainages that have high-elevation catchments, leading to waterfalls over the Redwall Limestone, with runoff falling on colluvium that overlies slopes of Muav Limestone and Bright Angel Shale (figs. 11, 12). As with bedrock failures, 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 pourover. The firehose effect triggered a debris flow in “Crash Canyon” (river mile 62.6-R) on or about September 18, 1990 (Melis and Webb, 1993). Runoff from convective thunderstorms poured over the Redwall Limestone cliffs of Chuar Butte, falling onto massive colluvial deposits overlying Muav Limestone. The colluvium failed, resulting in a debris flow (Melis and others, 1994).

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 is focused at the intersection of colluvial wedge and cliff face, augmenting direct precipitation and increasing the rate of saturation. The probability of slope failure is enhanced by the low density of vegetation on talus slopes in Grand Canyon. Multiple source areas combined with the extreme topographic relief of Grand Canyon can result in combinations of the three basic initiation mechanisms.

Importance of Shale

Shales are a critical factor in the initiation of debris flows in the Colorado River drainage basin. Weathered shale bedrock fails readily, either producing debris flows directly or contributing source material to colluvial wedges. Shales form the slopes in Grand Canyon and store unconsolidated source material. If colluvial wedges do not fail, the underlying bedrock may fail, mobilizing the overlying colluvium. Eroding shales also undercut more-indurated, cliff-forming lithologies, contributing to their failure. Of most importance, shales in Grand Canyon provide abundant fine particles and clay minerals that are essential to the mobility and transport competence of debris flows, giving them the internal strength necessary to transport large boulders over long distances. Electrochemical attraction among clay particles increases debris-flow matrix strength, and strong water absorption helps maintain high pore pressures, one condition deemed necessary to support large clasts (Hampton, 1975; Pierson and Costa, 1987; Major and Pierson, 1992). Most Grand Canyon debris flow deposits contain 1-8 percent silt- and clay-size particles by weight (fig. 13); the exception is Prospect Canyon, which has a unique setting for debris-flow initiation (Webb and others, 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 (Beverage and Culbertson, 1964; Hampton, 1975; Rodine and Johnson, 1976). Fine-grained constituents of these debris flows are 60-80 percent illite and kaolinite by weight, reflecting the terrestrial source shales and colluvial wedges (table 4).

Three lithologic units dominate the initiation sites for debris flows in Grand Canyon. The Hermit Shale is the most important unit of the three source areas in terms of generating debris flows. This shale is prone to both bedrock and colluvial failures, and undermines the overlying Coconino Sandstone, a source of many large boulders in eastern Grand Canyon, as it erodes. Where the Hermit Shale is first elevated to heights over 100 m above the Colorado River (about river mile 20.0), a set of some of the most closely-spaced rapids in Grand Canyon, informally termed “the Roaring Twenties,” begins (fig. 1). Although the lithology and structure of the canyon have not changed significantly at this point, the elevation of the Hermit shale beyond a threshold height above the river gives failures sufficient potential energy to transform into debris flows. Beyond this stretch of river, the Hermit Shale remains a key factor in debris-flow initiation, but may be too high on the cliffs to occur in the smaller drainages. In smaller tributaries without exposures of Hermit Shale, the lower units of the Supai Group or colluvial wedges of the Tonto platform become more important in generating debris flows. Terrestrial shales in the Supai Group — particularly the basal unit of the Esplanade Sandstone — are also major sources of bedrock failures, providing both fine particles and large boulders from interstratified shale and sandstone units. Many failures occur in the Esplanade Sandstone, which is undercut by erosion of the basal shale unit. The Muav Limestone contains thin, interbedded shales and grades into the underlying marine Bright Angel Shale. The

Figure 11. Failure scars caused by the “firehose effect” on colluvial wedges overlying Muav Limestone at river mile 62.5-R, Grand Canyon, Arizona (photograph is by T.S. Melis).

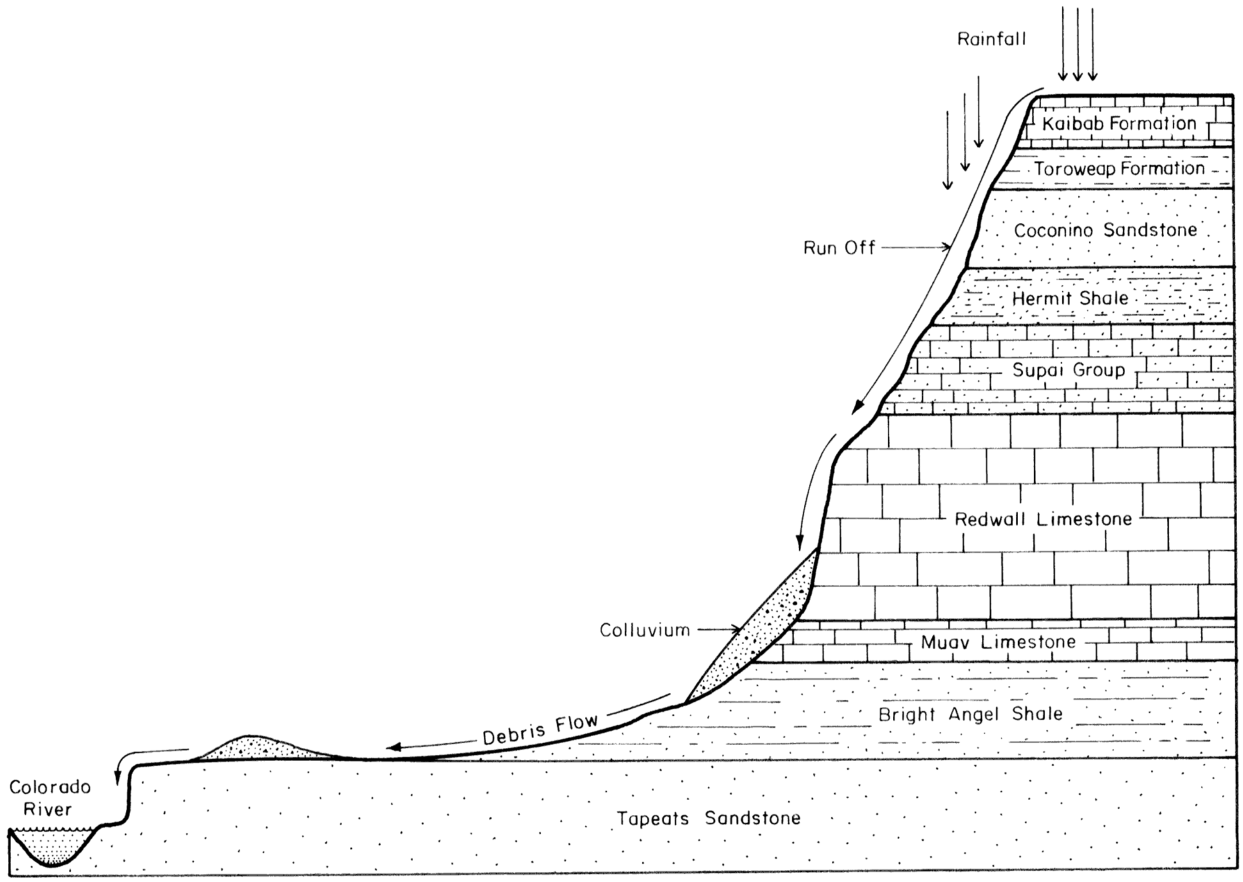

Figure 12. Schematic diagram illustrating the initiation of debris flow by colluvial wedge failure during intense rainfall.

erosional shelf formed by these units is the Tonto Platform, a broad shelf at the base of the Redwall Limestone that stores abundant colluvial material throughout Grand Canyon downstream from river mile 60 (fig. 1).

From the time of the first exploration of Grand Canyon by John Wesley Powell in 1869, the occurrence of rapids in Grand Canyon has been linked to the presence of resistant bedrock at river level (Powell, 1875). The large boulders that form rapids are well-indurated and derive from resistant bedrock units, but they have been rafted down to the river from tributary side canyons, often over many kilometers, by debris flows. The initiation of these debris flows is dependent on the presence of exposed shale units as both points of initiation and sources of fine materials. Debris flows in Grand Canyon, and ultimately the rapids they form, depend on the presence of shale source units exposed at greater than 100 m above the Colorado River. Without the combination of exposed shale units at height and boulder-producing sandstones and limestones, debris flows that form rapids will rarely occur.

LOGISTIC-REGRESSION ANALYSES

Eastern Grand Canyon

A principal-component analysis of the drainage-basin data for eastern Grand Canyon identified 9 redundant variables (fig. 14). Variables measuring height above and channel distance to the river were eliminated in favor of elevation and gradient variables, respectively. The river kilometer variable was also removed, as it strongly reflects the variation in Muav Limestone. The elevation and gradient of Muav Limestone were also strongly related, but both were retained as their removal had no effect on model outcome.