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).

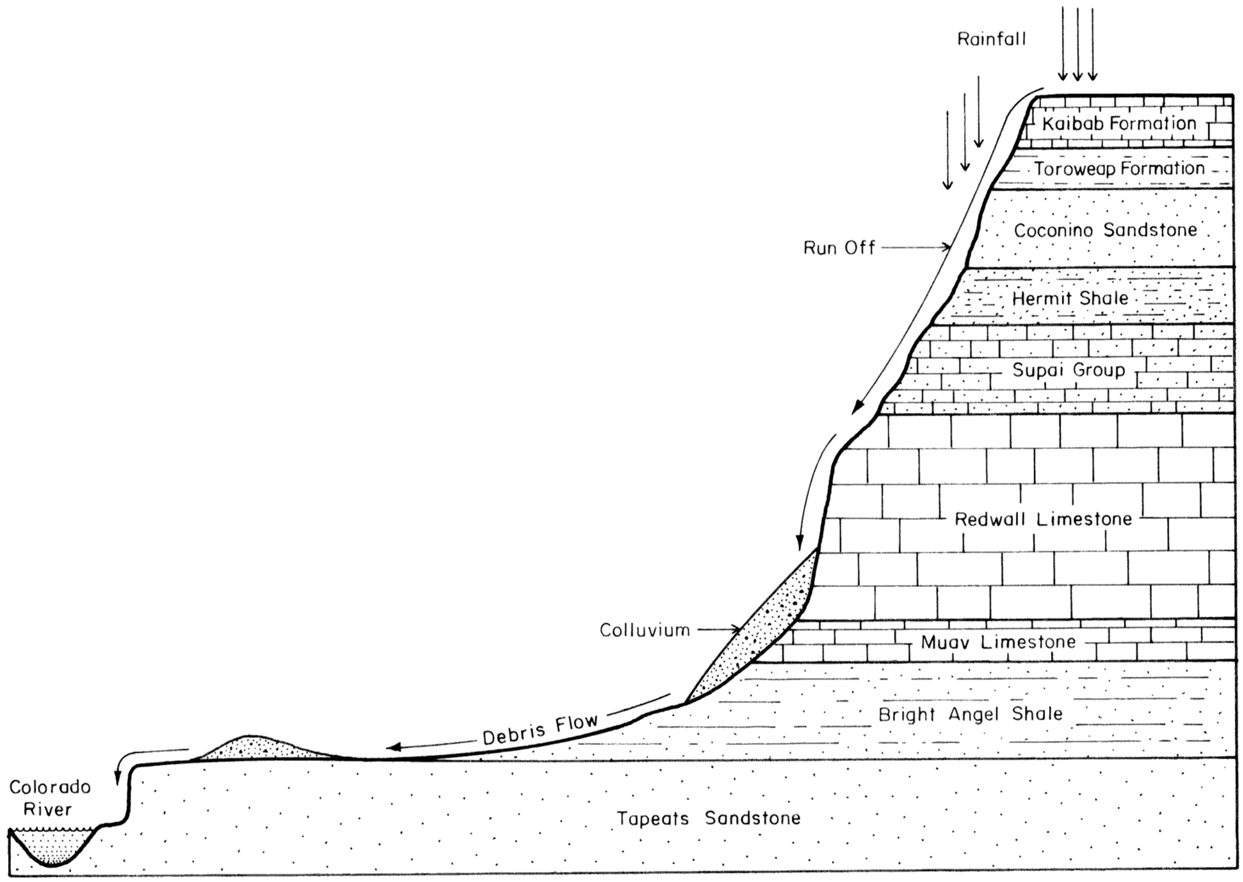

Figure 12. Schematic diagram illustrating the initiation of debris flow by colluvial wedge failure during intense rainfall.

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.