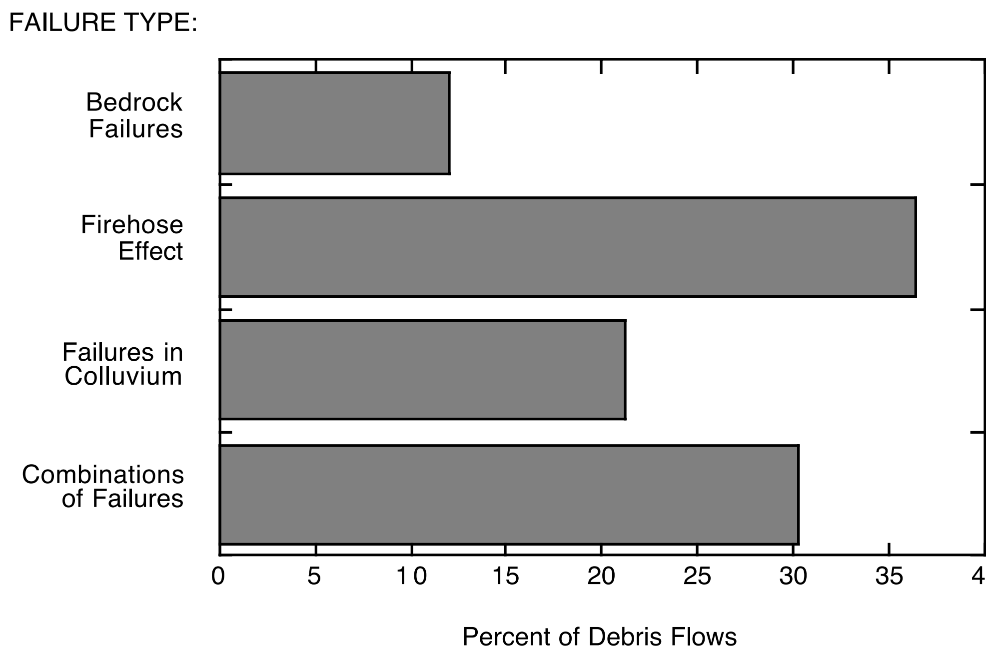

Figure 9. Failure mechanisms that have initiated debris flows in Grand Canyon from 1939 through 1996 (modified from Melis and others, 1994).

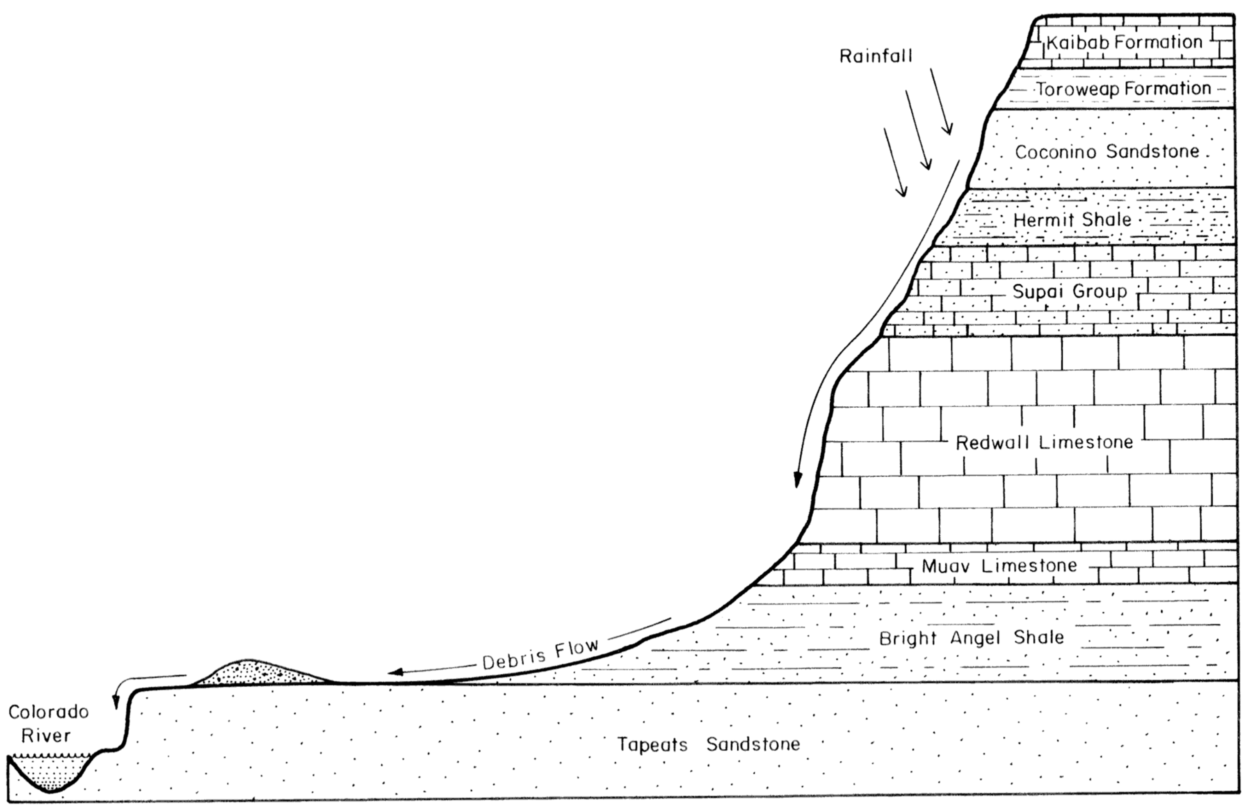

Figure 10. Schematic diagram illustrating the initiation of debris flows by the failure of bedrock - usually the Hermit Shale and Supai Group - during intense rainfall.

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