Colorado River; metric units are used for all other measures. Use of river mile has considerable historical precedent (Stevens, 1990) and provides a reproducible method of describing the location of tributaries with respect to the Colorado River. The location of tributaries was described using river miles downstream from Lees Ferry and a descriptor of "L" for river-left and "R" for river-right. The left and right sides of the Colorado River are determined as one faces downstream.

We typically refer to "Grand Canyon" in broad reference to both Marble and Grand Canyons. "Marble Canyon" is the canyon reach of the Colorado River between Lees Ferry and the juncture with the Little Colorado River (river miles 0 to 61.5; fig. 1); we refer to Marble Canyon only for specific tributaries in that reach. Grand Canyon, which is formally designated between the juncture with the Little Colorado River and the Grand Wash Cliffs (river miles 61.5 to about 280), is considerably larger and better known than Marble Canyon. For geological and statistical reasons described in the text, we divide Grand Canyon into eastern Grand Canyon, between Lees Ferry and Crystal Rapid (river miles 0 to 98) and western Grand Canyon, between Crystal Rapid and Surprise Canyon (river miles 98 to 248; fig. 1).

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SETTING

Grand Canyon has formed where the Colorado River cuts deeply through the southwestern corner of the Colorado Plateau in northern Arizona (fig. 1), exposing nearly 2 km of Paleozoic and Proterozoic stratigraphy (fig. 3). The combination of the slow downcutting of the Colorado and the gradual rise of strata toward the Kaibab uplift in the west results in the rapid exposure of Paleozoic strata as one moves downstream (Huntoon and others, 1986). Numerous resistant strata — the Paleozoic Kaibab Formation, Coconino Sandstone, and especially the thick Redwall and Muav limestones — are exposed at river level, resulting in a narrow, steep-sided canyon. Owing to the steepness of the canyon walls, the divides for most drainages in Marble Canyon are at the rim, exposing the maximum extent of the stratigraphy. Marble Canyon encompasses much of eastern Grand Canyon.

The entire Paleozoic section and some Proterozoic units are exposed west of Phantom Ranch (river mile 87; fig. 1). The exposure of the Bright Angel Shale near river level results in a distinctly wider canyon. The drainage divides of many smaller tributaries are not at the rim; therefore, these tributaries do not contain some of the younger geologic units. The maximum dip in the regional structure is mostly to the southwest (Huntoon and others, 1986). From eastern to western Grand Canyon, increased faulting results in large changes in the elevation of stratigraphic units from one rim to the other (Huntoon and others, 1986). Western Grand Canyon lies entirely within Grand Canyon proper.

Elevations in Grand Canyon range from 975 to 2,804 m above sea level at the rim, and from 939 m to 402 m along the river. The river itself drops an

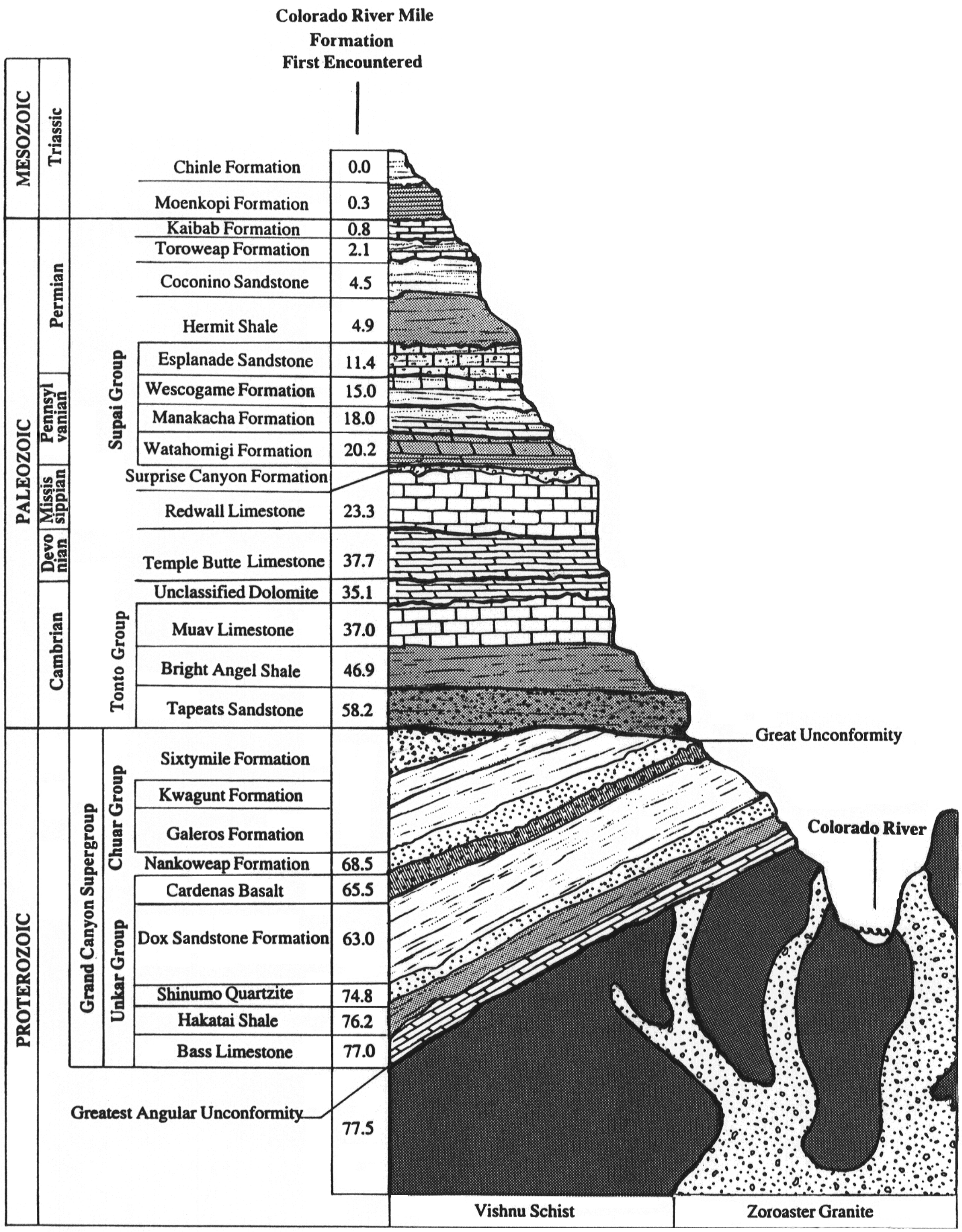

Figure 3. Stratigraphic column showing rocks exposed in Grand Canyon and the distances in river miles downstream from Lees Ferry where they first appear along the Colorado River (from Billingsley and Elston, 1989).

Table 1. Characteristics of climate stations in the vicinity of Grand Canyon National Park

Station Name[1]	Elevation (m)	Record Length	Mean Annual Precipitation (mm)	Summer Precipitation (%)	Winter Precipitation (%)
Bright Angel RS	2,726	7/48-3/95	646	29	60
Desert View	2,271	9/60-7/95[2]	347	40	48
Grand Canyon	2,204	10/04-3/95	403	42	46
Lees Ferry	978	4/16-3/95	148	50	38
Mount Trumbull	1,818	10/20-12/78[3]	297	49	37
Peach Springs	1,613	7/48-3/95	280	45	43
Phantom Ranch	834	8/66-3/95	234	39	49
Tuweep RS	1,551	7/48-12/86[4]	306	42	43

Notes:
1 All stations are in Arizona (Fig. 1).
2 Daily data from September 1, 1960, to July 1, 1975, have been lost at this station, which is not part of the NOAA network of climate stations. Monthly data is available after September 1960 from the National Park Service.
3 Station discontinued.
4 In 1986, Tuweep Ranger Station was discontinued as a cooperative observer station, which records rainfall in 0.01 in. accuracy and reports in increments of daily rainfall. A tipping-bucket recording rain gage, which records rainfall in 0.10 in. increments and reports hourly as well as daily rainfall (e.g., U.S. Department of Commerce, 1966), remains in operation.

average of 1.5 m in every linear kilometer. The climate is semiarid to arid, producing a wide range of annual and seasonal precipitation (table 1). Melis and others (1994) and Webb and others (1996) discuss the regional hydroclimatology in relation to debris-flow initiation. Precipitation generally increases with elevation, and the amount of summer precipitation generally decreases towards the west.

METHODS

Initiation Mechanisms and Precipitation Recurrence Intervals

During the course of this study (1986-1995), 25 debris flows occurred in Grand Canyon (Melis and Webb, 1993; Melis and others, 1994; Webb and Melis, 1995; Webb and others, unpublished data). For as many of these events as feasible, we traced the debris flow to its initiation point to evaluate the failure mechanism and source material. Using other reports (for example, Cooley and others, 1977), we augmented our data with data on other notable, historic debris flows.

We obtained climatic data from the National Climatic Data Center in Asheville, North Carolina, and from their reports (for example, NOAA, 1996). We used daily rainfall data, and we calculated storm precipitation by summing over consecutive days with rainfall preceding historical debris flows. We estimated the probability of daily and storm precipitation using the modified Gringorten plotting position (U.S. Water Resources Council, 1981),

$$p = ((m - 0.44)/(n + 0.12)) \bullet d, \qquad (1)$$

where p = probability of the event, m = the ranking of the event, n = the number of days in the record, and d = the number of days in the season per year. The recurrence interval, R (yrs), is

$$R = 1/p. \qquad (2)$$

Selection of Geomorphically Significant Tributaries

Melis and others (1994) identified 529 geomorphically significant tributaries to the Colorado River in Grand Canyon from Lees Ferry to Diamond Creek, excluding the four largest tributaries (the Paria and Little Colorado Rivers, and Kanab and Havasu Creeks). They selected tributaries that have the potential to produce debris flows that affect the geomorphology of the river channel. Their criteria include: 1) drainage areas larger than 0.01 km^2; 2) mapped perennial or ephemeral streams; 3) previously designated