Figure 5. Replicate photographs showing the debris fan at Ruby Rapid (river mile 104.8-L) (Webb, 1996). A. Photograph taken on February 15, 1890 at 1:00 PM by Robert B. Stanton. Lack of sand in the canyon mouth, and fresh-looking gravels all the way to the river, indicates a flash flood had recently occurred in Ruby Canyon, probably in the summer of 1889.

Colorado River in Grand Canyon (fig. 6). These 164 fans form the "calibration set" of our data.

One important limitation of this data set is that the photographic record captures only the mouths of the tributary canyons. Thus, binomial-frequency estimates are skewed to record only those debris flows large enough to reach the Colorado River. Therefore, we do not include all debris flows generated in tributaries, but only those that have reached the river.

Morphometric, Lithologic, and Climatic Variables

We measured 21 variables representing the morphometric, lithologic, climatic and structural drainage-basin characteristics that may control or influence debris-flow initiation in Grand Canyon (table 2). These include standard drainage-basin measures such as area, channel length, and channel gradient. All three major debris-flow source lithologies (Hermit Shale, the Supai Group, and Muav Limestone) are represented by their height above river level, a measure of the potential energy of source failures. We also included the height above river level of the highest point in each drainage basin. Although this variable does not relate directly to source failures, it does reflect the potential for intense rainfall and the potential energy of runoff, which are factors in some types of failures. A large amount of initial energy may not translate into a debris flow, however, if the transit distance to the river is sufficiently long. The greater the distance, the more energy is lost in transit (Savage and Hutter, 1987), and fewer and smaller debris flows reach the river. Therefore, we also measured channel distance from each source lithology to the river. The inter-dependence of source height and channel distance from river are represented in a third class of variable, channel

B. Replicate view taken on February 14, 1991 at 2:11 PM by T.S. Melis. Despite higher water in 1991, the rapid and debris fan are unchanged after a century. Erosion and deposition by the Colorado River have caused the only changes in the debris fan. Instead of fresh-looking gravels at the mouth of the canyon, cobbles and boulders are now exposed. A large sand bar has been deposited at right center, obscuring a clear view of the channel mouth.

Figure 5. Continued.

gradient from source area to river, a simple ratio of channel distance to source height.

Few Grand Canyon tributaries have climatic stations, so precipitation associated with debris flows must be estimated using data collected many kilometers away. Because of this, we derived proxy variables to measure climatic effects on debris-flow initiation. Elevations of source lithologies and basin headwaters above sea level are included to reflect orographic effects on precipitation. Higher elevations are likely to intercept more moisture as precipitation and so produce more debris flows. Additionally, tributaries which open into the dominant paths of weather systems and moisture vectors may actively trap precipitation, particularly smaller storms. Tributaries facing other directions may be orographically shielded from many storms.

We calculated the aspect, F, for each drainage as the angle from true north of a ray drawn from the basin centroid to its confluence with the river. This radial measure was then transformed into a linear value more appropriate for logistic regression modeling: southwestern aspect (θ), the degree to which a given drainage faces southwest using

$$\theta = \sin[(\Phi - 45°)/2]. \quad (3)$$

An orientation to the southwest was chosen to reflect the southwest to northeast travel vectors of severe weather across Grand Canyon. Similarly, we measured the aspect of the canyon or river-corridor itself as the angle from true north of a vector drawn parallel to the river at the confluence of each tributary. This value, which we termed Θ, was linearized into a variable of southwest/northeast trend in the river corridor runs using