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## Structural Control of the Rapids and Pools of the Colorado River in the Grand Canyon

**Abstract.** *Most of the major rapids along the 450-kilometer course of the Colorado River in the Grand Canyon are within fracture zones that run perpendicular to the river. Steep tributaries flowing within the zones of bedrock weakness move large debris to the Colorado, forming the rapids. Accelerated flow through the rapids scours the deep pools that are located below them.*

The Colorado River in the Grand Canyon slopes from an elevation of about 1000 m near Lee's Ferry, Arizona, to less than 300 m at Lake Mead 450 km downstream. The 161 rapids along the route are responsible for most of the elevation change; in fact, 50 percent of the decrease takes place in 9 percent of the distance (1). With few exceptions, the rapids are produced by tributary debris fans that partially obstruct the main channel (Fig. 1). These rapids are the premier white water in North America and one of the major attractions in Grand Canyon National Park (2).

In his 1969 U.S. Geological Survey (USGS) report, Leopold (1) concluded that the longitudinal profile of the Colorado River was in a state of quasi-equilibrium of which the alternating deep pools and rapids are a necessary part and that the occurrence of rapids and pools is independent of the bedrock types and the valley characteristics associated with the bedrock types. In this report we present evidence that many of the pools and rapids in the Grand Canyon are located where the river crosses regional and local fracture zones.

The USGS expedition down the Grand Canyon in 1965 included the first measurements of water depths along the length of the Colorado River. Leopold's measurements, taken before construction of the Glen Canyon Dam, were made with a nonrecording Fathometer at 5-second intervals as their boat progressed down the river. We made a similar set of measurements in 1976 with a recording Fathometer, using the same method for determining the locations of the boat as we progressed downstream (1).

There is a problem in recording exact locations from a boat that is moving downstream at varying speed; however, we minimized the location problem by using a powerboat, and there was a fairly constant discharge ( $\sim 450 \text{ m}^3/\text{sec}$ ) during our trip. Locational errors are limited to the sections of the river between points that were keyed to aerial photographs. Since our concern was regional-scale patterns over a distance of 450 km, locational errors of up to 100 m were not disturbing. The continuous records provide excellent profiles of the riverbed at a vertical resolution of  $\pm 0.3 \text{ m}$ .

Our profile data show that although the average depth of the river is about 10

to 12 m, the longitudinal profile is highly irregular. We defined a deep pool as any place where the water depth exceeded twice the average depth of the river (20 m). On this basis we found 86 deep pools within the 360-km section sampled (mile 0 to mile 225 below Lee's Ferry), but the number would almost double if we chose 15 m as the depth. Ten pools equal in depth to the deepest reported by Leopold (about 35 m) were found when we corrected for the difference in discharge between the two data sets ( $\sim 450$  compared to  $\sim 1500 \text{ m}^3/\text{sec}$ ). Most of the deep pools occur in pool-and-rapid sequences. Three are located just upstream of the rapids and the others are immediately (within  $\sim 150 \text{ m}$ ) downstream.

Sixty-eight of the 86 deep pools occur in close association with "rated rapids"; this is a subjective classification ranging from 1 to 10, with 1 a riffle and 10 a large and extremely dangerous rapid (3). Sixteen of the 86 deep pools occur in sections of the river without rapids. Of the 40 largest rapids (rated 4 and higher), 31 have deep pools. Of the nine remaining, three have pools at least 14 m deep, and six occur along the river where the bedrock is weakest and the canyon widest (mile 50 through mile 90). We were not able to record water depths at 13 rapids because of equipment problems and extreme turbulence. Water depths for the deep pools closely associated with the ten steepest rapids (1) are House Rock, 24 m; Horn Creek, 20 m; 75-Mile Rapid, 13 m; Badger Creek, no record; Zoroaster Creek, 25 m; 76-Mile Rapid, no record; Unkar, no record; Tuna Creek, 25



Fig. 1. One of the many side canyon tributaries to the Colorado River in the Grand Canyon. Since the tributaries have steeper gradients than the river, they transport larger debris than the river. This large debris forms the alluvial fans and thus the rapids.

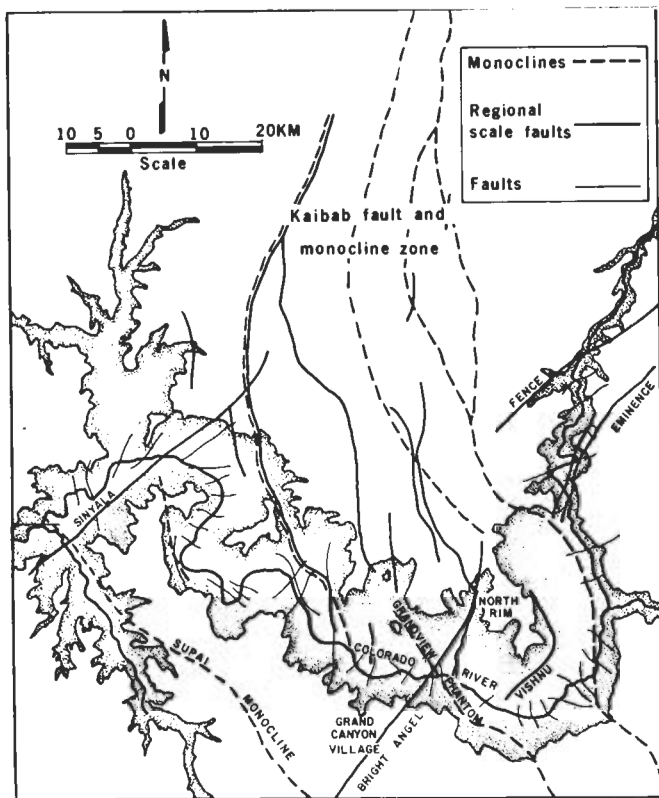


Fig. 2. Principal structural trends of the Colorado Plateau and the Grand Canyon.

m; Sockdolager, 20 m; and Grapevine, 24 m.

Two structural trends are evident in the Grand Canyon area of the Colorado Plateau (4): a set of northeast-trending normal faults and grabens with displacements generally less than 100 m, and a set of north-trending monoclines and faults (Fig. 2). In addition, the Precambrian rocks exposed along portions of the canyon bottom were faulted during at least two episodes prior to the deposition of Paleozoic strata.

The structural controls act at several scales commensurate with the size of the streams affected. The Colorado River from Nankoweap Rapid to Desert View is forced to follow the East Kaibab Monocline. The Emence and Sinyala fault zones have also influenced the course of the river both upstream and downstream (Fig. 2), and most of the major tributaries are clearly aligned along either monoclines or faults. The linearity of many smaller streams indicates that they, too, follow unmapped fracture or fault systems.

To document these patterns we examined low-altitude aerial photographs taken along the river in 1965 and 1973 for faulting near the rapid-pool-tributary sequences. We found definite evidence of local structural control for 80 of the 86 deep pools on the aerial photographs and, as indicated earlier, 68 of the pools are associated with rapids. Eighty-two of the pools and all 68 of the rapid-pool se-

quences occur in close association with side canyon tributaries. The evidence of structural control includes well-defined straight and intersecting fault traces, rectangular stream patterns, offset beds, and sharp transitions in color and texture of the rocks. Figure 3 is an example of the relationship between local lineation patterns and pool-rapid-tributary sequences. The deep pool (27 m) at A is located immediately downstream from the debris fan at B. Numerous faults, indicated with arrows, are visible, and it is clear that the two streams (C) that con-



Fig. 3. Vertical aerial photograph of the Colorado River at mile 935. The rapid (D) and the deep pool (27 m) at A are clearly related to the many structural trends that determine the stream courses (C). Arrows indicate faults and B indicates a debris fan.

verge at the debris fan are fault- or joint-controlled. The rapid (D) is Granite Rapid, one of the largest (rated 9) within the Grand Canyon.

The side canyon tributaries, which are mostly structurally controlled, deliver debris that is too large to be transported by the Colorado River with its existing gradient. Therefore, large debris can be dislodged only by the highest river discharges. The channel is narrower and the river gradient is greater through the rapids than between them. The flow emerges into the wider channel downstream as a jet that is directed toward the bed (I); a velocity of 3.4 m/sec has been measured just above the bed in a pool immediately below Unkar Rapid. The resulting bed scour forms the pools; however, we believe that the deeper pools also require the coincident occurrence of brecciation associated with the faulted bedrock that initially localized the tributary stream and therefore the alluvial fan.

The greatest density of deep pools occurs in the highly fractured Precambrian gneisses and schists along 70 km of channel. In the metamorphics, deep pools occur 2.3 times as frequently as the average of 0.3 deep pool per kilometer along other sections of the river.

The junctions of large tributaries to the Colorado River lack both steep rapids and deep pools because they do not transport the large debris to the Colorado and there is in-transit sorting, abrasion, and weathering within the channels.

The section of the river with a wide channel also lack deep pools and have fewer rapids, so that weaker bedrock is associated with fewer deep pools. Along 100 km of channel wider than the average width of the river through the canyon (120 m), only 12 deep pools are found, about 30 percent of the average frequency. The wider channels mean that the flow is less constricted and therefore has a lower velocity through the debris fans. Furthermore, along sections of the inner canyon that are wider and of lower relief, the tributaries supply a smaller amount of debris with a smaller average particle size to their debris fans.

The final condition that reduces the frequency of deep pools is the occurrence of resistant, unfractured bedrock at stream level. Between mile 140 and mile 160 below Lee's Ferry, the river flows through a narrow gorge (80 m) in the Muav Formation. Only one deep pool occurs in this section, 12 percent of the average frequency. The cause is fourfold: (i) fewer tributaries enter the river because of the low density of fracture zones; (ii) where rapids do occur,

scouring is less pronounced because of the lack of fracturing; (iii) the narrowness of the river allows more of the debris to be swept away; and (iv) the limestone, although resistant, appears to shed less large-size debris.

With the evidence of a consistent structural influence, we offer this generalized model for the rapid-pool-tributary sequences along the Colorado. Large faults determine zones of bedrock weakness within the Grand Canyon. Structures that run perpendicular to the river provide an advantage for side canyon drainage. The side canyon tributaries, flowing within the brecciated zones, deliver material to the main river that is too large to be carried downstream. This material forms a channel constriction, accelerated flow, and a rapid. Part of the accelerated flow at the foot of the rapids is directed downward against the bed. These high velocities, coupled with the zone of brecciation associated with the faulted bedrock, lead to deep scour below the rapids, and thus the deep pools. The hydraulic processes (autogenic) that produce regularly spaced riffles (5) on most streams, therefore, may dominate a

few sections of the Colorado River in the Grand Canyon, but along most of its course these processes appear to be superimposed on, or modified by, local external (exogenic) controls.

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#### References and Notes

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#### COVER

Within the Grand Canyon, 161 rapids account for most of the drop in elevation of the Colorado River. The rapids occur in bedrock fracture zones where steep side-canyon tributaries deliver large debris to the parent stream. Before the existence of Glen Canyon Dam (1963), the mean annual flood height was 3.5 times the present 800 cubic meters per second, so the large alluvial fan debris was periodically moved down the river. Since this process is no longer occurring, the alluvial fans are growing and the rapids are becoming larger. See page 629. [Robert Dolan and Alan Howard, University of Virginia, Charlottesville; David Trimble, North American Exploration, Charlottesville, Va.]