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13. Research on hermatypic coral growth studies was supported by NSF grant ATM75-22210 and research on deep-sea corals was supported by ONR grant N00014-76-C-0216. Contribution No. 5 from the Harold C. Urey Laboratory for Isotopic Paleotemperature Research, Department of Geology, University of Miami.

1 February 1978; revised 21 August 1978

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 (~450 m³/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 ±0.3 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 (~450 compared to ~1500 m³/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 ~150 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

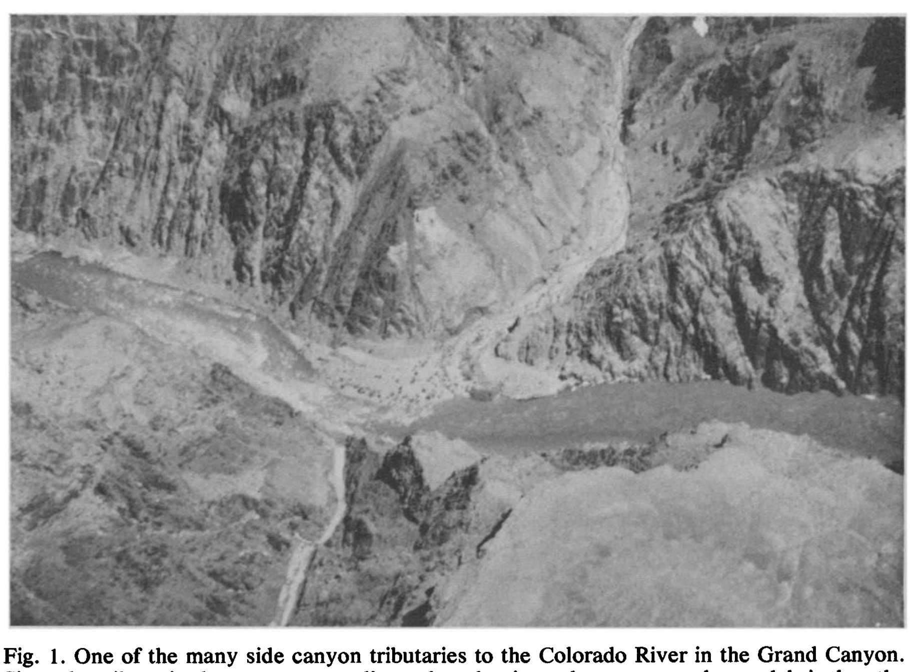

Fig. 1. One of the many side canyon tributaries to the Colorado River in the Grand Canyon. Since the tributaries have steeper gradients than the river, they transport larger debris than the river. This large debris forms the alluvial fans and thus the rapids.

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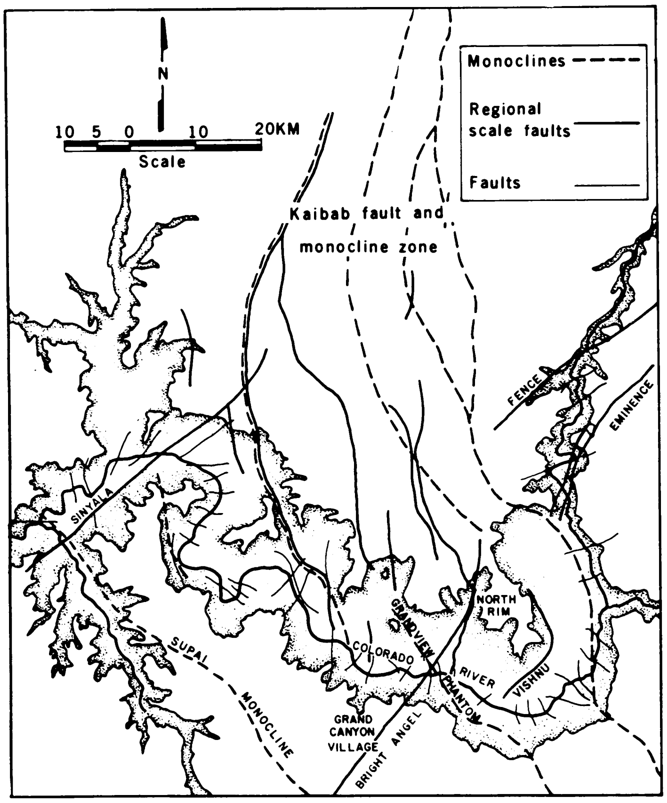

Fig. 2. Principal structural trends of the Colorado Plateau and the Grand Canyon.

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 Eminence 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 sequences 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 converge 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.

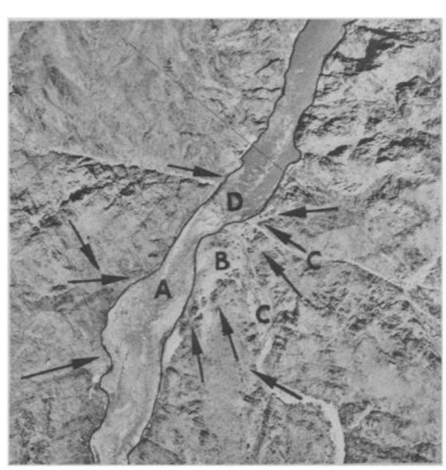

Fig. 3. Vertical aerial photograph of the Colorado River at mile 935. The rapid (*D*) and the deep pool (27 m) at *A* are clearly related to the many structural trends that determine the stream courses (*C*). Arrows indicate faults and *B* indicates a debris fan.

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 (*1*); 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 concident 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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27 February 1978; revised 24 May 1978

Hypophysial Responses to Continuous and Intermittent Delivery of Hypothalamic Gonadotropin-Releasing Hormone

Abstract. *In rhesus monkeys with hypothalamic lesions that abolish gonadotropic hormone release by the pituitary gland, the constant infusion of exogenous gonadotropin-releasing hormone (GnRH) fails to restore sustained gonadotropin secretion. In marked contrast, intermittent administration of the synthetic decapeptide once per hour, the physiological frequency of gonadotropin release in the monkey, reestablishes pituitary gonadotropin secretion. This phenomenon is attributable to the pattern of GnRH delivery rather than to the amounts of this hormone to which the cells of the pituitary are exposed. Moreover, the initiation of continuous GnRH administration in animals with lesions and in which gonadotropin secretion is reestablished by intermittent GnRH replacement can result in a "desensitization" or "down regulation" of the processes responsible for gonadotropin release.*

Lesions induced by radio-frequency current in the medial basal hypothalamus of rhesus monkeys (*1*) abolish the secretion of the gonadotropic hormones [luteinizing hormone (LH) and follicle-stimulating hormone (FSH)] by the pituitary gland, presumably by interfering with the release of the hypothalamic gonadotropin-releasing hormone, GnRH. Attempts to restore gonadotropin secretion in such animals by the continuous infusion of synthetic GnRH succeeded only in eliciting an evanescent release of LH and FSH despite the continued administration of the decapeptide (*1*). When, on the other hand, GnRH was administered once per hour (*2*), a rate equivalent to the physiological frequency of episodic LH release in ovariectomized monkeys (*3*), sustained increases in plasma LH and FSH concentrations were achieved for the duration of the replacement regimen (up to 7 weeks). The study described here was designed to determine whether the refractoriness of the pituitary to the continuous infusion of GnRH is attributable to the pattern of hypophysiotropic hormone stimulation per se or to the quantity of the decapeptide delivered to the pituitary.

Cardiac catheters were implanted in seven ovariectomized rhesus monkeys (4.2 to 6.8 kg of body weight) in which gonadotropin secretion had been abolished or severely curtailed by placement of radio-frequency lesions in the hypothalamus (*1*). By means of an infusion-withdrawal device that permits continuous access to the venous circulation without the animal being restrained, GnRH (*4*) was infused continuously by way of the cardiac catheter at rates of 0.001, 0.01, 0.1, and 1.0 μg per minute as described (*2*). Each infusion rate was maintained for 10 days (*5*). Blood samples were taken daily by way of the catheter, or by femoral venipuncture after the animal was sedated (30 to 40 mg of sodium thiamylal per animal, intravenously), and plasma concentrations of LH and FSH were determined by use of established radioimmunoassays (*6*). The pituitary response to GnRH administered at the rate of 1 μg per minute for 6 minutes once per hour was determined in similar fashion.

The mean circulating LH and FSH concentrations during the last 5 days of each continuous GnRH infusion, which reflected the steady-state response of the pituitary to this mode of hypophysiotropic stimulation (*7*), are shown in Fig. 1A. None of the continuous infusions of releasing hormone produced a sustained increment in plasma LH and FSH concentrations. In sharp contrast, however, long-term restoration of gonadotropin secretion was achieved in the same animals by the intermittent administration of GnRH (Fig. 1B). These observations lead to the conclusion that the failure of continuous GnRH infusion, regardless of infusion rate, to initiate sustained gonadotropin secretion in ovariectomized monkeys bearing hypothalamic lesions is the consequence of the pattern of GnRH administration rather than of the total mass of the decapeptide delivered to the gonadotrophs.

The effects on gonadotropin secretion of a shift in GnRH administration from the intermittent to the continuous mode, without a change in the infusion rate, were investigated in four similarly prepared monkeys in which gonadotropin secretion had been reestablished by pulsatile hypophysiotropic stimulation. The institution of continuous GnRH administration was followed by a brief increase in plasma LH and FSH lasting approximately 5 hours. Thereafter, however, circulating gonadotropin declined, reaching a nadir within 7 to 10 days where they remained for the duration of the continuous infusion period. This inhibition was reversed when pulsatile GnRH administration was reinstituted (Fig. 2).

These influences of pattern of hypophysiotropic stimulation may be related to the phenomenon of "desensitization" or "down regulation" (*8*), whereby pro-

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