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THE 1983 HYDRAULIC JUMP IN CRYSTAL RAPID: IMPLICATIONS FOR RIVER-RUNNING AND GEOMORPHIC EVOLUTION IN THE GRAND CANYON[1]

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ABSTRACT

For the last 1,000 to 10,000 years, dozens of large debris fans have severely constricted the path of the Colorado River in the Grand Canyon, Arizona. At most of these fans, the narrowest part of the channel eroded by the river is 0.5 of the upstream width. At Crystal Creek, a debris fan was emplaced in 1966, constricting the channel of the Colorado River to about 0.25 of its upstream width between 1967 and 1983, forming a major rapid. In this paper the hydraulics of Crystal Creek rapid are described, and an analysis is presented to support the hypothesis that the major wave in the rapid was a normal wave (one type of hydraulic jump). Hydraulic jumps rarely occur in natural river channels with erodible beds, but one was present at Crystal Rapid because of the unusually severe constriction of the Colorado River by the 1966 debris fan. Observations on the hydraulics of the river during this time (including mid-1983, when progressively higher discharges culminated in excess of 96,000 cubic feet per second) have demonstrated that the velocity of water going through the constriction and into the hydraulic jump was so great that there was erosion of the Crystal debris fan in the vicinity of the jump. Each new level of record high discharges caused the river to erode a channel of sufficient width to reduce flow velocities below a threshold value required for movement of the larger boulders of the debris fan, thus contouring the fan toward a configuration more in equilibrium with the high discharges. A quantitative model for river debris fan shapes is proposed and is used to estimate prehistoric flood levels from the observed constrictions: the 0.5 value of river constriction found at the more mature debris fans in the Grand Canyon suggests that peak flood discharges of approximately 400,000 cubic feet per second (11,320 m^3/s) have occurred.

INTRODUCTION

In the first 400 km of its course below Lee's Ferry, Utah, the Colorado River passes about 60 large debris fans formed by the flooding of its tributaries (location map in fig. 1). Such tributary floods are a major source of boulders in the river channel through the Grand Canyon. Although the major features of the flood-produced fans can be stable for more than 100 years (Leopold 1969; Dolan et al. 1978; Graf 1979, 1980; Howard and Dolan 1979, 1981), the river has eroded them, with remarkable uniformity, so that the narrowest part of the channel as it passes through these debris fans is about 0.50 of the mean upstream width (fig. 2). This geometric relationship has not previously been noted or explained by theories of dynamics of rapids in canyon rivers, and observations on the fate of large boulders and the erosional modification of the large debris fans have been lacking because of the rarity of the modifying events (Shoemaker and Stevens 1969).

The 1966 mudflow down Crystal Creek was the most recent in the series of major tributary floods that have built debris fans into the Colorado River at Crystal Creek (Cooley et al. 1977), with the narrowed channel being thus called Crystal Rapid. Since about 1965, discharges into the Colorado River through the Grand Canyon (and hence through Crystal Rapid) have been controlled at less than 30,000 cfs by the U.S. Bureau of Reclamation

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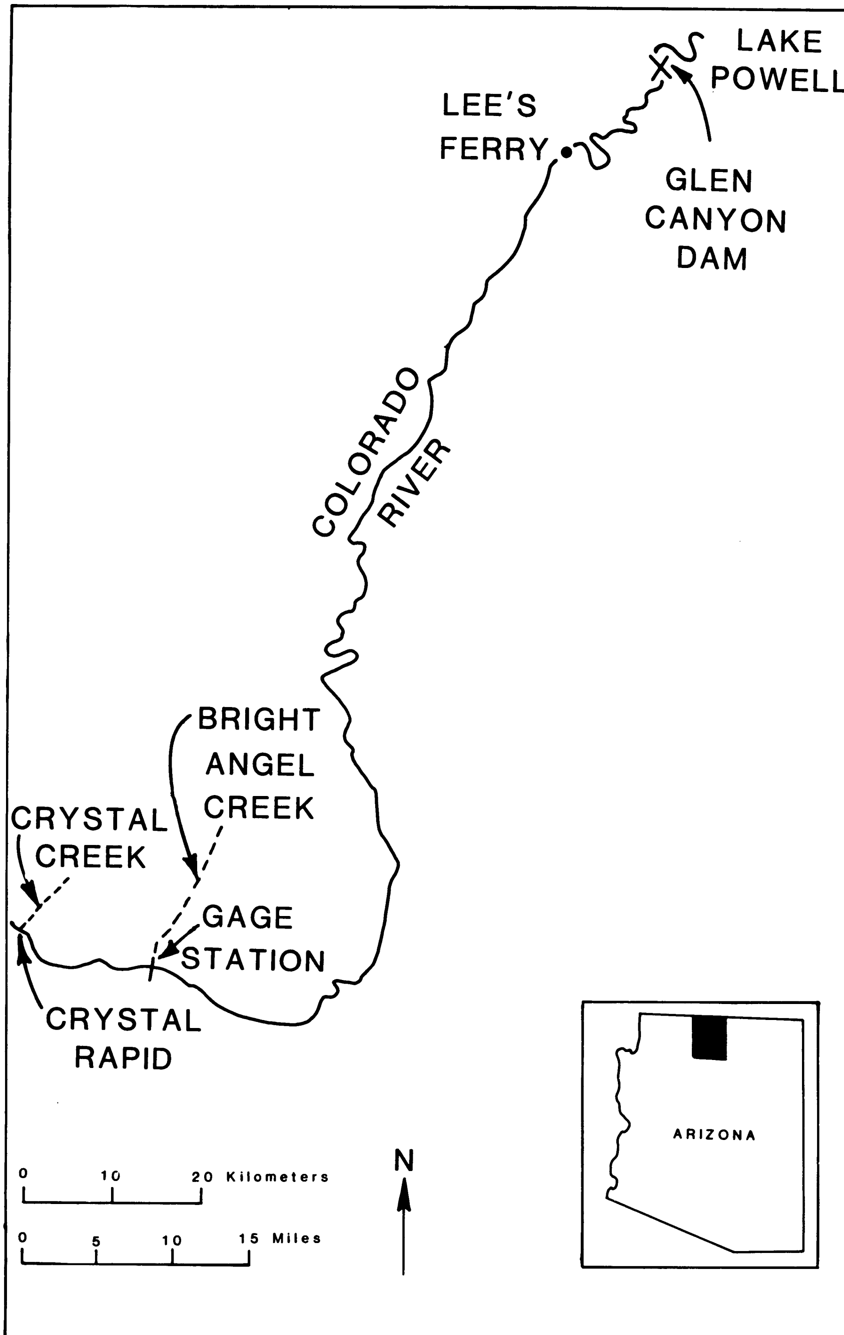

FIG. 1.—Location map of sites discussed in text.

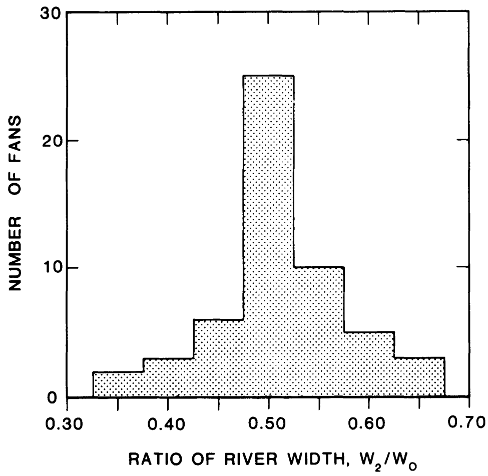

FIG. 2.—Histogram of constriction values of the Colorado River as it passes 59 of the largest debris fans in the 400-km stretch below Lee's Ferry. These values are based on the widths of the surface water in the channel on 1973 air photos (such as in fig. 4). As discussed in the text, the surface width of the water is not identical to the width of an idealized channel. Thus, in this histogram, Crystal Rapid has the value $w_2/w_0 = 0.33$, whereas elimination of shallow channelized flow over the debris fan and idealization of the channel to a rectangular cross-section suggests that an average channel constriction is about 0.25. At the present time, a histogram based on actual channel constrictions cannot be made because of lack of detailed surveys of river bottom topography.

to optimize water use for power generation at Glen Canyon Dam. Discharges typical of natural floods (e.g., as high as 300,000 cfs in 1884) had not flowed through Crystal Rapid before 1983 (U.S. Geological Survey, Water Resources Data for Arizona 1980). In June and July, 1983, however, record-high controlled discharges of up to 96,200 cfs were required to prevent Lake Powell from overtopping the Dam, causing rarely seen or documented geologic and hydraulic events and providing the opportunity to address the hydraulic relationship between the Colorado River and its debris fans.

In addition to their geomorphic significance, however, the hydraulic events during 1983 had a significant effect on commercial and private rafting in the Grand Canyon, where about 10,000 people each year navigate the 400-km stretch through the canyon. Boulders, waves, and eddies in Crystal Rapid have made raft navigation difficult even at normal levels of controlled discharges (Collins and Nash 1978). In 1983 Crystal Rapid became unusually hazardous, with one wave reaching trough-to-crest heights of more than 6 m as the discharge reached 50,000 to 70,000 cfs (fig. 3), drowning one rafter and seriously injuring dozens of others (Wolf 1983). Rare geologic events are only fortuitously documented, and they usually offer little opportunity for the rigorous observations required by the scientific method. The observations of the river-runners who navigated Crystal Rapids before and during this time have provided important and partially quantitative support for the hydraulic model presented in this paper.

A Note on Units and Directions.—The discharge of the Colorado River is accurately measured by the U.S. Geological Survey at the Bright Angel gage station, and the measurements are published in units of cubic feet per second (cfs). River-runners, who provided many eyewitness observations for this report, also estimate the discharges in cubic feet per second. Therefore, English units of discharge are used (10,000 cfs = 283 m^3/s), but all other variables are given in metric units. In river navigation, "right" is the right side of the river when facing downstream—generally north in this case; left is generally south. "Above" means "upstream of," and "below" means "downstream of."

CHANNEL GEOMETRY AT CRYSTAL RAPID

The Pre-1983 Channel.—Since few survey data are available, the pre-1983 geometry of the Colorado River channel is unknown. The geometry has now changed substantially so this information is beyond recovery, except that which can be inferred from an interpretation of surface features present then.

When the discharge was 10,000 cfs, the *surface* width of the river narrowed from about 87 m upstream to about 35 m as the river passed around the debris fan (fig. 4). At all discharges, much of the surface width included shallow flow across the debris fan. Even at the peak discharge of 96,200 cfs the flow remained slow and shallow, as can be seen from the texture of the water surface in figure 5. However, the shallow water is not important in considering larger-scale features of the flow: field estimates of velocity, depth, and area of fan covered show that, at all discharges, less than 10% of the total flux is involved in the shallow flow. Most of the pre-1983 discharge was contained within a channel cut in the distal end of the debris fan on the south side of the river. This channel was substantially narrower in width than the surface extent of the water, even at the rate of only 10,000 cfs shown in figure 4.

Beyond the obvious bedrock boundaries, the path available for the river was narrowed by a rock ridge that extended from the south shore into the narrowest part of the channel (fig. 4). Water poured over the southern part of this ledge, creating the Crystal Rapid "Pour-Over." The projection of this ledge into the channel caused two eddies—one above the ledge in the mouth of Slate Creek, and one below. These eddies were present at all water levels, although their detailed configuration changed with discharge (figs. 4, 5, 6). The main part of the flow (see fig. 4*a*) was thus confined to a narrow, high-velocity channel between the eddies on the south and the debris fan on the north. Although the bottom profile was laterally irregular (see fig. 4*c*), in the following calculations it is assumed that this high-velocity channel was rectangular at all cross-sections and that it narrowed from an average width of 80 m upstream to 20 m at its narrowest point; the calculations can easily be done for a channel of arbitrary cross-section, but only the simplest assumption is justified by the scant data.

Little was known about the longitudinal slope of the main channel in 1983. The shoreline was measured to drop 2.5 m from Crystal Creek to a beach north of the main wave of interest (see figs. 4, 5, and 6), and the water surface was estimated to have dropped another 2.5–3 m through the Rock Garden. Fathometer data obtained before the 1966 mudflow (in 1965) suggest that the river bed dropped 7 m between the mouth of Crystal Creek and the bottom of the Rock Garden (Leopold 1984).

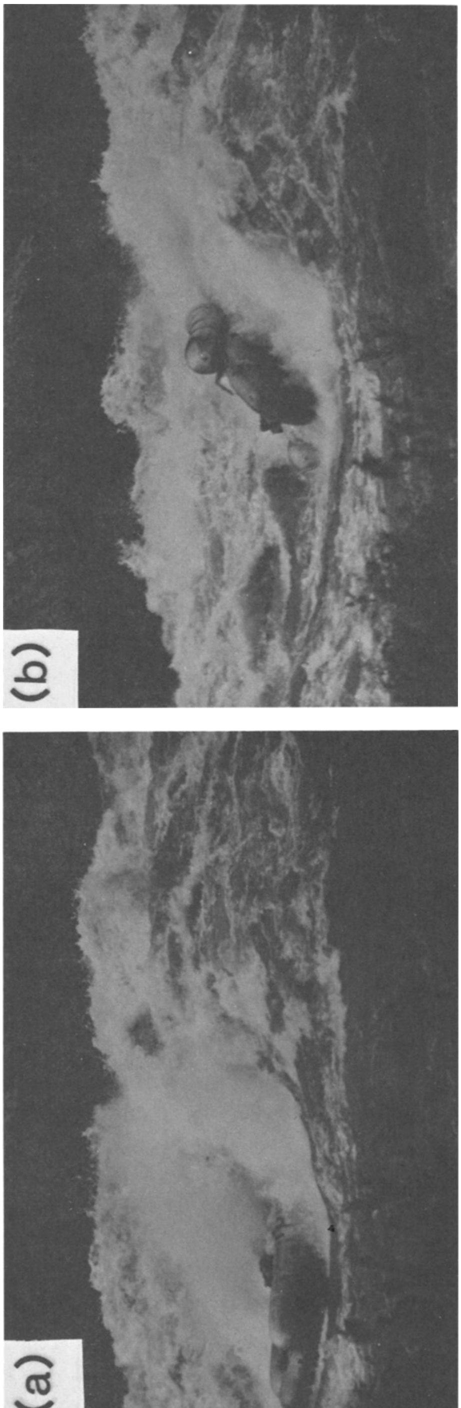

FIG. 3.—River raft (*a*) entering and (*b*) trapped in the large wave at Crystal Rapid on June 25, 1983 (photograph copyrighted by Richard Kocim; reprinted with permission). Pontoons on the raft are each 1 m in diameter; mid-section is about 3 m in diameter. More than 30 passengers are on board; one head is visible on lower left side of raft. From the scale of the raft, the trough-to-crest height of the wave can be estimated at more than 5–6 m.

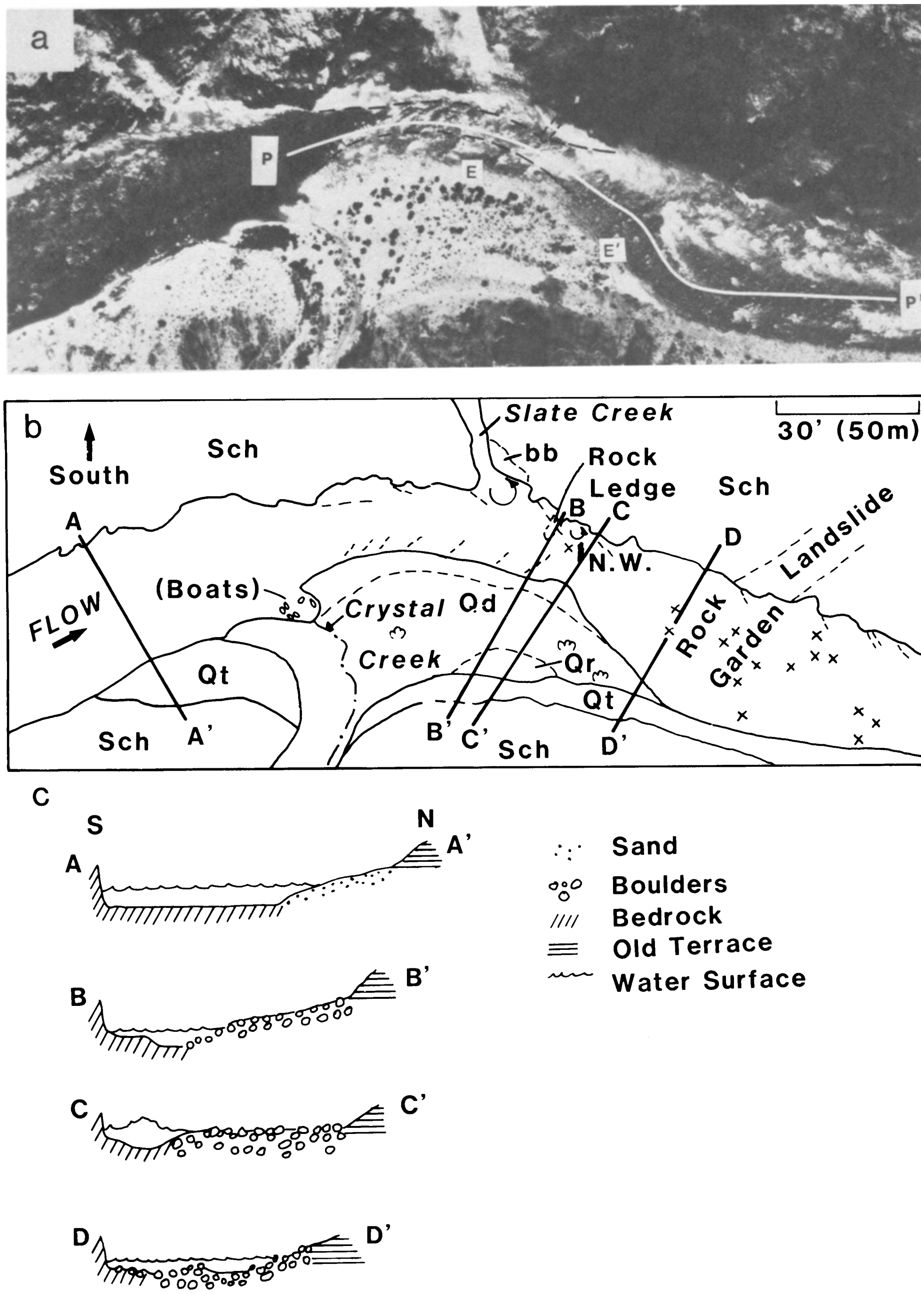

FIG. 4.—(*a*) Crystal Rapid on June 16, 1973 (U.S. Geological Survey Water Resources Division (air photo)); discharge was about 10,000 cfs. (*b*) Key to features on (*a*). Other symbols are explained in figure 5. (*c*) Schematic cross-sections. Relative widths correct; vertical scale exaggerated. The river level at 30,000 cfs is shown by the limit of growth of tamarisk. Surface width of river upstream of rapid is about 87 m; surface width at narrowest point is about 29 m. Rise of debris fan from this river level to old alluvial terrace is about 5.5 m. Below the rapid, the river expands back toward more than 90-m width; the channel bottom is very irregular in this area and littered with boulders (the "Rock Garden"). Rocks in the Rock Garden are visible at 10,000 cfs, cause substantial waves at 30,000 cfs, and are submersed by 92,000 cfs (see fig. 5). Underwater extension of rock ledge is outlined, and assumed boundaries for deep channel are shown by light dashed line in (*a*). P-P′ is the preferred navigation route. The normal wave of interest in this paper (indicated by N.W.) in (*b*) is not easily visible in (*a*). E-E′ indicates the span of shore eroded by the 1983 high discharges; compare with figure 10.

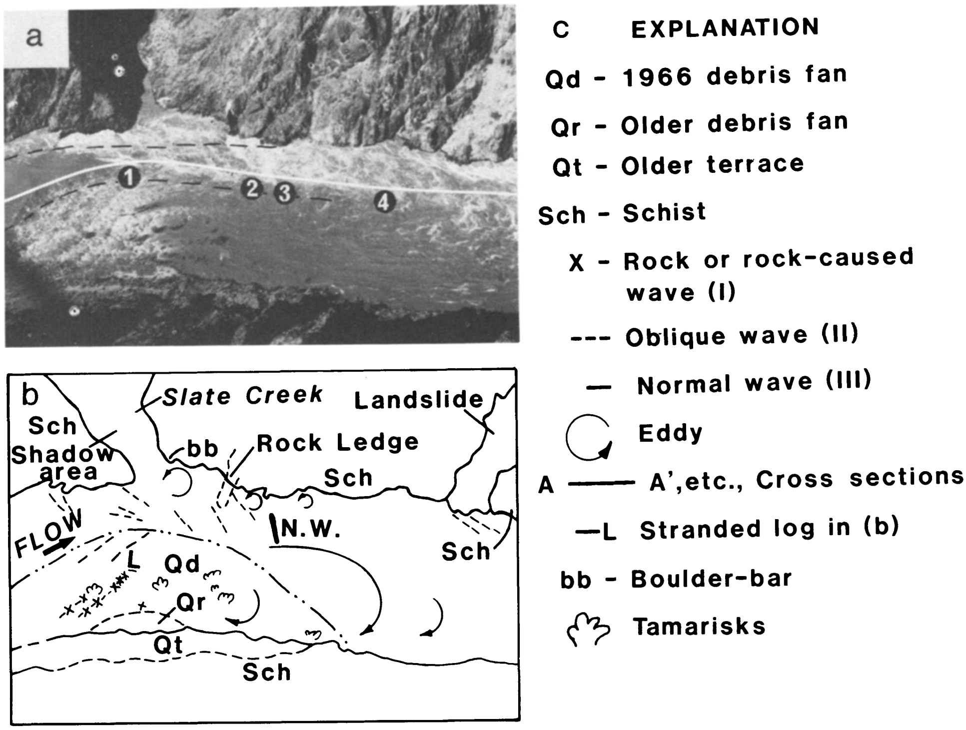

FIG. 5.—(*a*) Crystal Rapid at about 92,000 cfs on June 27, 1983. Scale is approximately the same as in figure 4(*a*) but altitude at which photo was taken and orientation differ slightly. (*b*) Key to features on (*a*), (*c*) Explanation of symbols. In (*a*) water laping at the base of the alluvial terrace indicates a rise in level of about 5 m from the level shown in figure 4(*a*). Flow across upper half of debris fan is slow and channelized. Three types of waves discussed in the text are shown by different symbols; the wave that is the subject of this report is the normal wave (N.W.). Although this wave appears to be continuous with an oblique wave from the south shore, it was much larger than that oblique wave. The white line labeled with numbers refers to a path taken by kayaks, discussed in the text.

There is no evidence for sharp vertical drops (ledges) in the bed within this distance, except for the Pour-Over restricted to the south shore. A large rock set in the center of the main channel about 30 m below the Pour-Over, the avoidance of which (and of the hole and wave associated with it) was the primary goal of river-runners prior to 1983. The hole and wave were known as the "Crystal Hole." It was observed that this rock was just submerged at 6,000 cfs, from which its diameter can be estimated roughly at 2 (± 1) m.

The Post Mid-1983 Channel.—After the high discharges of 1983, surface wave patterns were changed (fig. 6), indicating changes in the channel configuration. Most notable of these changes is the steepening of the rapid at its head: most of the drop through Crystal Rapid now occurs above Slate Creek. After peaking at 96,200 cfs, the discharge did not drop below about 45,000 cfs for most of 1983. At this discharge a new, strong oblique wave appeared on the north side of the entrance to the rapid, opposite Slate Creek (fig. 6). It is, in late 1984, the largest wave in the rapid. At lower discharges this wave moves farther upstream and diminishes in size, but it is appreciable even at a discharge of only 6,000 cfs (these changes are addressed in the "Conclusions" section).

Although the depth of water in the channel at various discharges was not measured at Crystal Rapid itself, data are available from the U.S. Geological Survey's gaging station near Bright Angel Creek, 16 km upstream (table 1). Because of the similarity in channel size, gradient, and wallrock, similar conditions are assumed to have existed there and above Crystal Rapid. A loose constraint on

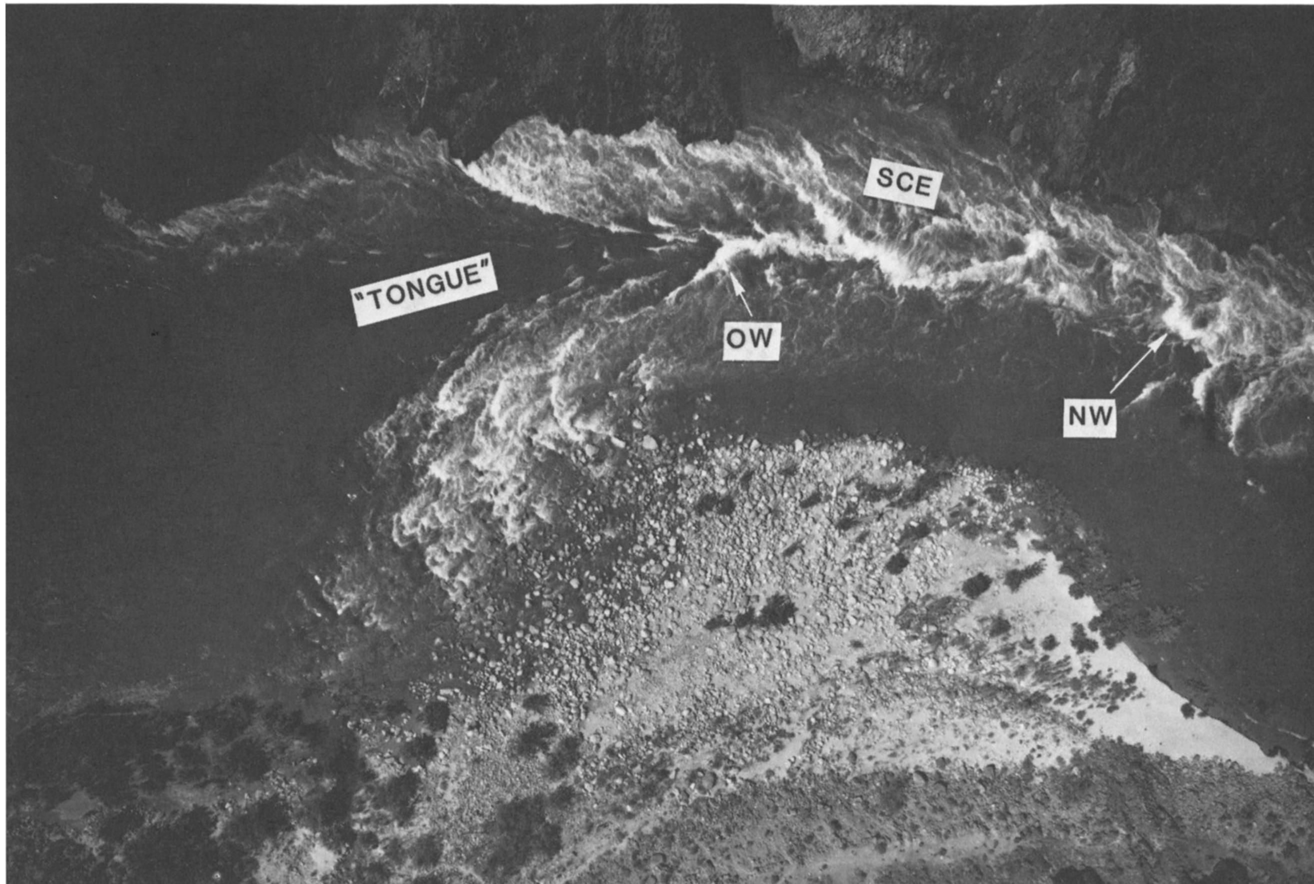

Fig. 6.—Air photo of the new configuration of Crystal Rapid at a discharge of about 45,000 cfs, taken on May 11, 1984. Photo courtesy of the National Park Service. NW indicates the normal wave discussed in this paper; its strength has diminished as a result of the high discharges of 1983. OW indicates the strong oblique wave that has become a major problem for navigation since the high discharges of 1983. SCE is centered on the large Slate Creek eddy.

TABLE 1

DISCHARGE OF THE COLORADO RIVER AT BRIGHT ANGEL CREEK GAGING STATION

Date	A^a (m^2)	Q^b (cfs, m^3)	$\bar{u}^c$ (m/s)	$\bar{D}^d$ (m)	$D_{gh}{}^e$ (m)	$D_{gb}{}^f$ (m)	$H_r{}^g$ (m)
1982							
2/14	345.6	9060, 256	0.741	4.36	2.45	−1.91	4.39
7/21	472.0	20400, 577	1.23	5.96	3.91	−2.04	6.03
1983							
6/8	631.8	48700, 1378	2.18	7.97	5.92	−2.05	8.21
6/16	711.0	57600, 1630	2.29	8.97	6.52	−2.45	9.24
6/17	705.2	59700, 1690	2.40	8.90	6.41	−2.49	9.19
6/18	733.4	62300, 1763	2.41	9.25	6.37	−2.88	9.55
6/24	829.6	70000, 1981	2.39	10.47	6.72	−3.75	10.76
6/25	835.2	71500, 2023	2.42	10.54	6.69	−3.85	10.84
7/28[h,i]	901.2	83000, 2349	2.69	11.37	7.50	−3.87	11.73

[a] The cross-sectional area, A, is measured by plumbing for depth D_i at intervals j across the width, w_j, of the river; velocity, u_{ij}, is measured at each width-depth station.
[b] The discharge, Q, is calculated from individual w_j, D_i, and u_{ij} measurements.
[c] The mean velocity, $\bar{u} = Q/A$.
[d] The mean depth, $\bar{D}$, is taken as A/80, where 80 m is taken as the average width of a hypothetical rectangular channel.
[e] The gage height, D_{gh}, was provided by E. Buell, U.S. Geological Survey.
[f] The gage bottom, D_{gb}, is average gage bottom $= D_{gh} = \bar{D}$.
[g] H_r is the specific head: $H_r = \bar{D} + \bar{u}^2/2g$.
[h] Peak discharge of 96,200 cfs occurred on 6/29/83 at 0400; at this time only stage was measured and discharge extrapolated from the measurements shown in this table (U.S. Geol. Survey Water Data Rept. AZ-83 in press).
[i] For estimation of the specific head at high levels of discharge, the average depths ($\bar{D}$), velocities (u), and specific heads H_r given in table 1 were fit with simple power functions relating them to discharge. The measured average depths ($\bar{D}$), velocities (u), and specific heads (H_r) listed in table 1 were fit as follows: $u = (8.23 \times 10^{-2})(Q)^{0.30}$, $\bar{D} = (4.27 \times 10^{-3})(Q)^{0.70}$, and $H_r = (4.88 \times 10^{-3})(Q)^{0.69}$, for Q in cfs.

the increase in water depth with discharge is also available from estimates of the elevation change of the water across the debris fan.

During the peak discharge of 96,200 cfs, for example, water covered the debris fan up to the base of an old alluvial terrace (fig. 5). Relative to the river level at 10,000 cfs, the following estimates are used: at 30,000 cfs, 1 m higher; at 50,000 cfs, 4 m; at 92,000 cfs, 5.5 m.

At Bright Angel, approximately 2.4 m of material was scoured from the main channel at discharges between 60,000 and 70,000 cfs, but further scouring did not occur at higher discharges. The changes in the bed observed since the high discharges suggests that erosion of a similar magnitude occurred in Crystal, and this assumption is used in the calculations presented below.

Water velocity varies through the length of Crystal Rapid, but the velocity in different regions has not been measured at most discharges because of the remoteness of the area and the difficulty of making systematic measurements in high velocity flows. On June 27, 1983, when the flow was at 92,000 cfs, the author obtained films of three kayaks going through the rapid. For a kayak following approximately the route shown in figure 5*b*, the average velocities were as follows: immediately upstream of point 1, 8.5 m/s; point 1 to 2, 9.8 m/s, point 3 to 4, 8.7 m/s. The kayaks stalled to an average velocity of 3.3 m/s between the trough and crest of the wave before accelerating down the backside of the wave to a velocity of 8.5 m/s.

THE WAVES OF CRYSTAL RAPID

It is not commonly recognized that where a river passes across a debris fan waves can arise from different physical causes, and that for this reason, different waves can respond differently to changing discharges. At Crystal Rapid, there are three major causes of waves: (1) substantial obstacles in the bed, such as rocks (fig. 7*a*); (2) a converging or irregular shoreline, or a strong eddy that acts as an effective shoreline (fig. 7*b*); and (3) contraction and expansion of the flow as it goes through a channel of varying area (fig. 7*c*).

In all three instances, wave behavior depends on the Froude number of the flow:

$$Fr = u/(gD)^{1/2} \quad (1)$$

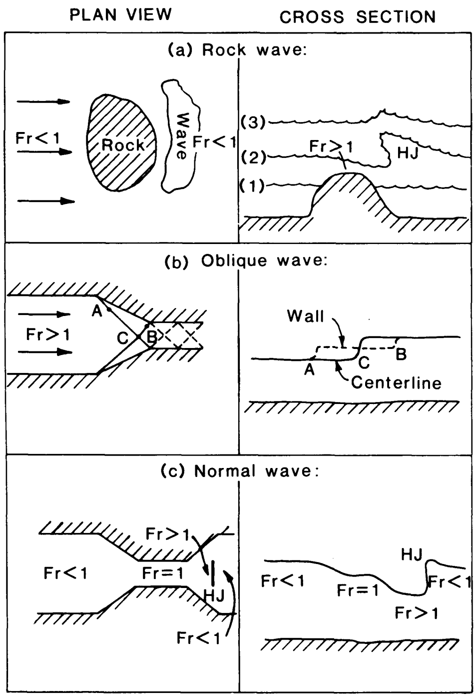

FIG. 7.—Schematic diagram of three types of waves found in river rapids. (left; plan view; right, cross-section) (*a*) Type 1 waves, caused by rocks. (*b*) Type 2 wave, caused by deflection of supercritical flow by convergence of a shoreline. These are oblique waves inclined downstream, commonly called "laterals" by river runners. (*c*) Type 3 wave, caused by severe convergence of the channel.

where u is mean flow velocity, g is the acceleration due to gravity, and D is mean depth of flow. The Froude number is the ratio of mean flow velocity to *critical velocity,* which, in turn, depends on water depth. Strikingly different wave phenomena occur in *subcritical* ($Fr < 1$), *critical* ($Fr = 1$), and *supercritical* flow ($Fr > 1$) regimes.

At Crystal Rapid, waves of the first type (fig. 7*a*) arise from boulders and from projections of underwater extensions of ridges on the south shore (fig. 4). Along the north shore, even small (0.5-m-diameter) rocks created problems for rafts at low discharges, but the main obstacles were rocks 1 to 2 m in diameter. The infamous rock in the center of the constriction described above, and an equally infamous "orange rock" at the top of the Rock Garden (fig. 4) were the most prominent, but many others substantially complicated the flow.

Consider first a rock embedded in subcritical flow, which is the ambient condition of the flow in the Colorado River in the unconstricted channel. At a discharge that just submerges such a rock, the water that flows over the rock becomes supercritical because the upstream velocity is nearly maintained but the water becomes shallow (fig. 7*a*). The flow returns to subcritical conditions through a *hydraulic jump* (discussed in detail below), which is the wave associated with the rock. The height of the wave depends on the Froude number of the flow over the top of the rock. As discharge increases, the Froude number decreases because the depth of water over the rock increases rapidly with discharge, whereas the velocity remains approximately constant or increases only slowly. At the discharge at which the Froude number returns to unity, flow over the rock returns to subcritical conditions, and the wave disappears ("washes out"). Although it is difficult to quantify these ideas for a particular rapid without detailed measurements of water depth and flow velocity at specific rocks, it is useful to note that waves from boulders as high as 2 m in the "Rock Garden" below the constriction (see fig. 4) are strong at 10,000 cfs, moderate at 30,000 cfs, and are washed out at 92,000 cfs.

The behavior of waves around rocks embedded in supercritical flow is more complex because depth changes with discharge are less easily predicted. Flow can be supercritical near a shore where it maintains nearly the velocity of the main current but becomes shallow, e.g., along the north shore of the channel at Crystal. Many of the boulders in figure 4 show a prominent V-shaped wake typical of supercritical flow. (Note how their wakes resemble the waves emanating from an object in supersonic flow; there is a semiquantitative comparison between supercritical and supersonic flow that the reader might find useful, e.g., Loh 1969). The problem of obstacles in supercritical flow will be dealt with below in "Application to the Hydraulics of Crystal Rapid."

Numerous oblique waves of the second type (fig. 7*b*) occur where the Crystal Creek debris fan deflects the flow southward and where the curving south shoreline deflects the flow northward (figs. 4–6). Several rock buttresses that extend into the water above and below Slate Creek are the sources of oblique waves. The height of these waves increases with Froude number. The flow velocity decreases substantially across an oblique wave; therefore, moveable bed material transported into the wave at high velocity may be dropped downstream in the lower velocity region. Oblique waves thus can become stabilized by rocks and boulders, and a rather long oblique wave may consist of many smaller rock waves.

Another type of oblique wave is formed where fast-moving water in the main channel meets slow or stagnant water, such as where the main current collided with the Slate Creek eddy at high discharges (figs. 5 and 6). If the angle of intersection is small or if the velocity gradient across the boundary of the zones is small, the intersection of two different flows may be characterized only by a zone of shear without a prominent wave; such zones are known as "eddy fences" to river runners. If the angle of intersection is large or if the velocity gradient is large, a substantial wave may arise; waves of this type in the main channel surged as high as 3 m at 92,000 cfs (fig. 5).

Waves of the third type arise where flow is constricted by narrowing of the channel. If the constriction is severe, subcritical flow can accelerate to critical and then to supercritical conditions in passing through and out of the constriction. A strong wave will form downstream of the constriction; flow returns to subcritical condition as it passes through this wave. Such a wave stands approximately perpendicular to the flow direction and, because of this orientation, is called a "normal" wave. It is a hydraulic jump. The normal wave may not stand near any obvious source of perturbation of the flow (although it may be connected to weak lateral waves), and the height and position of the wave may change with discharge. This behavior was observed for the largest wave at Crystal Rapid during the high discharges of 1983, suggesting that it was a normal wave.

The size, location, and sound of this normal wave at Crystal Rapid changed with discharge. The trough-to-crest height was about 3 m at 20,000 cfs, and about 1 m higher at 30,000 cfs. At 50,000 to 60,000 cfs, boatmen and passengers reported that the wave surged to a height between 5 and 9 m; it was verified photographically to about 5–6 m (fig. 3 and other photographs collected by the author). At 96,000 cfs, the wave surged between 3 and 4.5 m in height. At discharges over 50,000 cfs, the wave was located about 30 m downstream from its pre-1983 position at 30,000 cfs. Observers reported that at 50,000 to 60,000 cfs the wave emitted a low roar like a jet engine, but it did not generate the same loud roar at 96,000 cfs. However, loud, cannon-like booms that appeared to originate in the main channel occurred several times per minute. These sounds did not correlate with surges or declines in wave height and presumably originated from large boulders moving in the channel.

GENERAL ANALYSIS OF THE BEHAVIOR OF THE NORMAL WAVE

The behavior of the normal wave at Crystal Rapid can be analyzed by using the well-known equations of shallow-water flow (e.g., Rouse 1950; Brater and King 1976), although the channel geometry must be much simplified. The generalized geometry used is shown in figure 8*a*. Note the explicit assumption that there are no significant abrupt changes in bed elevation, i.e., that changes in water velocity are due to the overall slope of the bed and to width variations. In this analysis, the approximations of shallow-water theory are used: wavelengths of disturbances are assumed to be long and surface tension effects are assumed to be unimportant. The surface of the water is assumed to be at constant atmospheric pressure.

Quantitative analysis of the flow requires distinction of six different flow regimes, as shown in figure 8*a*: (0) an upstream state of unconstricted uniform flow; (1) the convergent section of the channel upstream from the constriction; (2) the constriction [the ratio of width at a cross section taken through the constriction to upstream width in region 0 (w_2/w_0) will be called the *constriction* of the river]; (3) the beginning of the divergence out of the constriction; (4) the end of the divergence; and (5) a downstream state of uniform flow not influenced by the constriction. Regimes (3) and (4) may be separated by a hydraulic jump, HJ.

At any cross section, the total energy of the

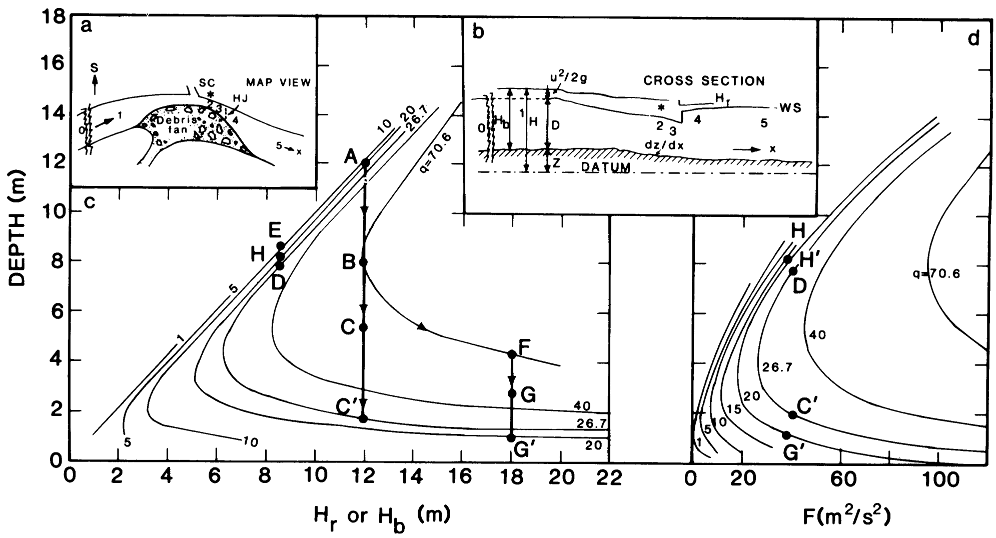

FIG. 8.—(*a*) Schematic map view of the river-debris-fan relations at Crystal Rapid. (*b*) Schematic cross-section. Regions 0,1,2,3,4,5 defined in text. HJ indicates a possible hydraulic jump; SC indicates position of Slate Creek. Water profile is for conditions of supercritical flow through the channel. (*c*) Depth-energy diagram. (*d*) Depth-force diagram. The curves are for different values of discharge per unit width, q. See text and appendix for discussion and explanation of symbols and paths shown.

flow, H, relative to an arbitrary datum is

$$H = H_r + z \tag{2}$$

where z is the elevation of the bed relative to the datum and H_r is the combined kinetic energy and potential energy of the water (relative to the bed), the *specific energy* (fig. 8*b*). Along the path of the river, the balance of energy is given by

$$\frac{dH}{dx} - \frac{dz}{dx} = \frac{dH_r}{dx} \tag{3}$$

where x is the distance downstream. The energy dissipation, dH/dx, in regions outside of flow discontinuities (discussed below) can be estimated from a Chezy, Manning, or Darcy-Weisbach equation if the flow is assumed to be gradually varied in these regions (e.g., see Brater and King 1976 or Richards 1983). Then,

$$\frac{dH}{dx} \sim \frac{u^2n^2}{R^{4/3}} \tag{4}$$

where u is flow velocity, R is the hydraulic radius (approximately equal to depth), and n is the Manning coefficient. At high discharges in the main channel of the Colorado the Manning coefficient averages 0.03. The bed of Crystal Rapid is much rougher than the main channel, and a value of n as high as 0.06 is plausible. In Crystal, u ~ 10 m/s and R ~ 10 m, so dH/dx ~ 0.017. This value is comparable to that of the slope (dz/dx) in the upper part of the rapid (e.g., a drop of 2.5 m over the upper 150 m of the rapid), and the near equality of dH/dx and dz/dx suggests that the potential energy gain and energy dissipation approximately cancel. In this case

$$\frac{dH_r}{dx} \sim 0 \text{ i.e., } H_r \sim \text{constant} \tag{5}$$

This approximation greatly simplifies the analysis. Further examination of this assumption is given in the Appendix as an illustration of the use of figure 8*c* and 8*d*.

Values of specific head, H_r, are obtained from the Bright Angel measurements of flow depth (which give potential energy) and flow velocity (which give kinetic energy) (table 1). These measurements show that the ambient conditions of flow in regions 0 and 5 are subcritical at all discharges.

At a specific cross-section water depth and velocity are obtained from the equations of mass continuity and energy conservation. Mass continuity for steady flow across two cross-sections of areas A_1 and A_2 requires that:

$$A_1u_1 = A_2u_2 = D_1w_1u_1 = D_2w_2u_2 \quad (6)$$

where w is the mean channel width and D is the mean water depth. The discharge is Q = Au. The specific energy of the flow, H_r, is then:

$$H_r = \frac{u^2}{2g} + D = \frac{q^2}{2gD^2} + D \quad (7)$$

where q = Q/w = Du is the volume flux per unit width, or *specific discharge*. For a given value of H_r, there are three roots D allowed by eq. (7); two are real and positive. These roots can be shown as a function of specific discharge on a depth-energy graph (fig. 8*c*).

For flow with constant specific head (that is, everywhere except across a hydraulic jump) the variation in depth is controlled solely by the specific discharge, q. For a given head, H_r, equations (6) and (7) show that the specific discharge, q, must be less than a limit, q_{max}, given by:

$$\left(\frac{{q_{max}}^2}{g}\right)^{1/3} = \frac{2}{3}H_r = D_c = \frac{u_c^2}{g} \quad \text{(for } H_r \text{ constant)} \quad (8)$$

A *critical depth,* D_c, and *critical velocity,* u_c, are implicitly defined in this equation. If Q/w_2 is greater than q_{max}, the ambient river head, H_r is not sufficient to allow all of the discharge through the constriction. Then H_r must be increased by the formation of a backwater to a new head (the *backwater head,* H_b) in region 0 (illustrated in fig. 8*b*):

$$H_b = \frac{3}{2}\left[\frac{(Q/w_2)^2}{g}\right]^{1/3} \quad (9)$$

Equation (8) then describes the flow with H_r replaced by H_b.

Flow with a given head can be in either of two regimes (called *conjugate states*) separated by the critical conditions at q_{max}: in one state (subcritical flow, Fr < 1) the water is deeper than D_c; in the other state (supercritical flow, Fr > 1), it is shallower. In a channel of the general shape of the Colorado River at Crystal Rapid, flow may be entirely subcritical, or entirely supercritical, or it may change from one state to the other. The specific discharge, q, will be greatest at the constriction, region 2. For a given specific head, H_r, if the total discharge, Q, divided by the constriction width, w_2, is less than q_{max} given by equation (8), and if the flow is subcritical in region 1, critical conditions will not occur in the constriction. The subcritical flow of region 1 accelerates to higher velocities and shallower depths through the constriction, and then decelerates back to greater depths in the diverging part of the channel.

On the other hand, if Q/w_2 is greater than q_{max} allowed by H_r, water will pond behind the constriction until a backwater is formed that just allows Q/w_2 to equal q_{max} for the backwater head, H_b. The backwater is essentially stagnant, and subcritical flow in regions 0 and 1 accelerates to critical conditions in region 2. The relative energies of the main channel flow upstream and downstream of the constriction determine whether the flow will return along a subcritical or supercritical path. In the case where a backwater has formed so that the energy of the river downstream, H_r, is less than the energy of the backwater, H_b, the flow will expand supercritically into the divergence. The return to ambient head is accomplished through a discontinuous transition—a *hydraulic jump.*

The depth change across the jump can be obtained from conservation of momentum. For any given discharge, there will always be two depths at which the forces at a given cross-section are the same (fig. 8*d*). The ratio of depth downstream of the jump (D_4) to depth upstream of the jump (D_3) is:

$$\frac{D_4}{D_3} = -\frac{1}{2} + \left(\frac{1}{4} + 2Fr^2\right)^{1/2} \quad (10)$$

(In this context, Fr = Fr_3; the position of the jump defines the boundary between the end of region 3 and the beginning of region 4.)

The velocities before and after the jump are simply related by the continuity equation (2). The new specific head in region 4, H′, is given by Bernoulli's equation applied to the flow after the jump:

$$u_4^2 = 2g\,(H' - D_4) \quad (11)$$

The location of the jump will be determined by the condition that $H' = H_r$. The equations were solved by computer, but an illustration of their solution by graphical techniques is shown in figures 8*c* and 8*d* and discussed in the Appendix as the justification for assuming constant specific energy in the analysis.

APPLICATION TO THE HYDRAULICS OF CRYSTAL RAPID

At a given discharge (Q), the flow state is completely specified when the specific head (H_r), the river width (w_0), and the change in discharge through the constriction (q_0/q_2) are given. The average river width used here for regions 0 and 5 is 80 m; the constriction of the river at the onset of the 1983 high discharges is assumed to have been 0.25. The specific energy of the flow is assumed to be given by the values at Bright Angel gage station, table 1. Calculated flow variables are shown as a function of discharge and ratio of specific discharges, q_0/q_2 (fig. 9). As discussed above, it is assumed that all of the water goes through the constriction, so that $q_0/q_2 = w_2/w_0$. This assumption will be reexamined below, but, anticipating the validity of the assumption, the geometric term "constriction" will be used for this ratio.

The calculations indicate that at discharges of less than 12,000 cfs, flow through the assumed idealized channel should be subcritical if the constriction is 0.25. In detail, the potential energy gain arising from the drop in bed elevation at the top of the rapid is probably not compensated by the energy losses over this section, and the flow becomes weakly supercritical at the top of the rapid because of this energy gain (an illustration of this effect is discussed in the Appendix). Thus, in figure 4 (taken at 10,000 cfs), the "tongue" of smooth water extending into the rapid indicates supercritical flow. Over the course of the rapid, energy dissipation takes the flow back to subcritical conditions without need for a hydraulic jump at low discharge. The mid-channel rock caused a wave at the "Crystal Hole," of the type illustrated in figure 7*a*, but no obvious normal wave was present.

The calculations indicate that the available head, H_r, was not sufficient to allow the required flux through the constriction when discharges exceeded 12,000 cfs. A substantial backwater (up to 5 m deep) was necessary (fig. 9*a*). Critical flow through the convergence, supercritical flow downstream of the convergence, and a normal wave to bring the supercritical flow back to subcritical downstream conditions resulted (fig. 9*b*–*e*). River runners experienced the backwater as the tranquil slow water above Crystal Rapid ("Lake Crystal") before the acceleration down the tongue of the rapid into the convergence. They experienced the normal wave, i.e., hydraulic jump, as the major obstacle in the rapid. The subcritical flow regime in the diverging section of the rapid below the hydraulic jump was either difficult to negotiate (at low to moderate discharges when the Rock Garden was exposed) or surprisingly simple and smooth (at high discharges when the Rock Garden was washed out).

As discharge increased from 12,000 to 50,000 cfs, the calculations indicate that the normal wave should have moved about 33 m downstream, which is in good agreement with observations.

The calculations suggest that the height of the jump would have increased continuously with increasing discharge if the channel geometry were constant at a constriction of 0.25 (the heavy line in fig. 9*b*). The observed wave heights were in good agreement with those calculated for a normal wave in a channel—until the discharge exceeded 60,000 cfs. At higher discharges the wave height was observed to decrease, rather than to increase toward the calculated value of 9 to 10 m. The observed decrease in wave height suggests that this quantity that I have been calling the "constriction," which is really the ratio of q_0/q_2, increased from 0.25 to about 0.40. If the effect of spillover of water across the debris fan was significant, the ratio of specific discharges q_0/q_2 would not be equal to the geometric ratio, w_2/w_0 because water that passed through region 0 would be detoured around region 2 and the ratio q_0/q_2 could vary while w_2/w_0 remained constant. For example, if the proportion of water bypassing region 2 increased with discharge, q_0/q_2 would increase with discharge. Figure 9*b* shows that this would cause the wave height to decrease with increasing discharge. However, the estimated upper limit on spillover—about 10% of the total discharge—would correspond to an effective increase in the channel constric-

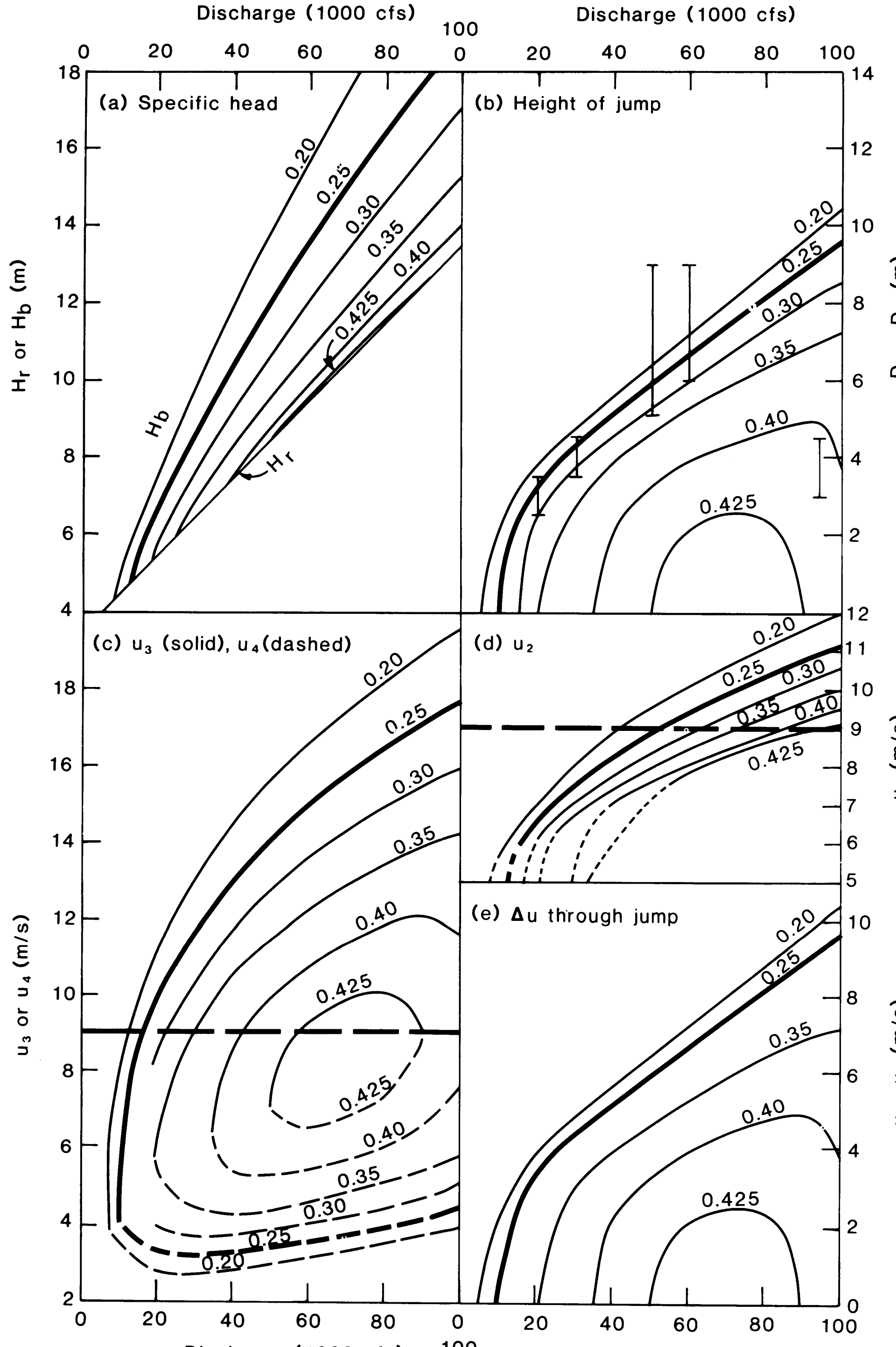

FIG. 9.—(*a*) Specific head (H_r) measured at Bright Angel Creek vs. discharge, with backwater heads (H_b) calculated for Crystal Rapid for the constrictions, $w_2/w_0 = q_0/q_2$, indicated. (*b*) Calculated height of the hydraulic jump for constrictions indicated. Bars denote observed values. (*c*) Calculated values of flow velocity in region 3 (top curves, solid lines) and region 4 (bottom curves, dashed lines) for constrictions indicated. Dashed line at 9 m/s indicates velocity at which larger boulders at Crystal Rapid can probably be moved by the current. (*d*) Calculated values of velocity in region 2 (the constriction) for constrictions indicated. Flow subcritical where dashed. (*e*) Velocity change through hydraulic jump that separates regions 3 and 4.

tion ratio of about 10% (e.g., from 0.25 to 0.275) and could not account for the substantial decrease in wave height observed.

It appears most plausible, therefore, that the path available for flow in the constriction widened, that is, that w_2/w_0 actually changed. A change in w_2/w_0 from 0.25 to 0.40 corresponds to about 12 m of widening. The widening could have occurred in two ways: (1) the size of the eddies constraining the flow along the south shore could have decreased with increasing discharge; or (2) erosion of the debris fan on the north shore could have occurred. Available photographs suggest that the eddy sizes remained relatively constant (perhaps because the eddy size is determined by the lateral dimension of the underwater protrusion of the rock ridge sketched in fig. 4*a*). Therefore, flow widening by eddy shrinkage is discounted.

Channel widening by erosion of the debris fan is the more likely process. Although data are sparse on conditions required for movement of large particles, velocities on the order of 9 m/s are required to move a 2-m diameter boulder, 11 m/s to move a 3-m boulder, and 13 m/s to move a 4-m boulder. These estimates are based on extrapolation of data from Schumm and Stevens (1973); Hjulstrom's criteria as extrapolated in Blatt et al. (1972), field observations on a natural stream by Helley (1969); and estimates of tractive force on large boulders. The calculations of conditions at Crystal Rapid during 1983 indicate velocities of exactly this range: at 50,000 cfs, with a constriction of 0.25, the velocity in the constriction (u_2) is calculated to be 9 m/s and would increase to 14 m/s in region 3 (u_3), figures 9*c* and 9*d*. These numbers, and figures 9*c* and 9*d*, emphasize the important control that a constriction has on flow velocities and, by implication, on channel erosion.

If the channel contoured itself to keep u_2 equal to the threshold velocity for transport of the major boulders, then by 60,000 cfs the channel would have enlarged to a constriction of about 0.30, a widening of 4 m; by 92,000 cfs, the constriction would have enlarged to 0.40, a widening of about 12 m. For contouring to reach these threshold values, erosion must occur rapidly compared to the duration of the high discharges. A rough calculation of erosion rate based on the number of rock impacts heard (about 1/minute; boulders assumed to be 1 m diameter) suggests that 2200 m^3 could have been removed in 3 days. At this rate, the distal sector of a highly idealized fan, about 220 m^2 in area and 10 m in height, could have been eroded back the required 12 m during the few days that the maximum discharges were maintained.

On the basis of historical highest discharge and shoreline the documented post-1966 history of the Crystal debris fan can be divided into two parts: (1) pre-1983, when the maximum discharge had been at about 30,000 cfs and the highest shoreline had been at about the limit of salt cedar growth (fig. 4); and (2) post-1983, when the maximum discharge had been at 96,200 cfs and the highest shoreline had been at about the limit of currently preserved salt cedars (fig. 5). "Shoreline" as used here excludes slow channelized runoff and therefore does not correspond to river "stage." Evidence for the proposed channel erosion is preserved in the shorelines. Comparison of figs. 4 and 10 along the shore between E and E′ and use of fig. 5 to demonstrate that this region was indeed between the constriction and hydraulic jump during the high discharges show that a substantial amount of material is missing. The shore prior to 1983 and the current shore here are much steeper than the general slope of the debris fan, and I interpret the steep banks to be channel walls carved during river erosion. Thus, the available evidence, though not conclusive or quantitative, supports the proposed idea that the channel was substantially widened by the 1983 discharges, and that in the past the channel has been subjected to erosion in the vicinity of the constriction.

High flow velocities cause channel widening, but channel widening in turn decreases flow velocities, as can be seen in figures 9*c* and 9*d*. Erosion should cease at a constriction when the constriction becomes sufficiently wide to pass the given discharge at a velocity equal to the threshold velocity for erosion. Erosion can continue, however, in region 3 of supercritical flow even after it ceases in region 2, because water accelerates from the constriction through the supercritical region (fig. 9*c*). As cited above, at 50,000 cfs, with the constriction still at 0.25, calculations indicate that the velocity u_3 increases from 9 m/s at region 2 to 14 m/s just in front of the hydraulic jump. At 60,000 cfs, the con-

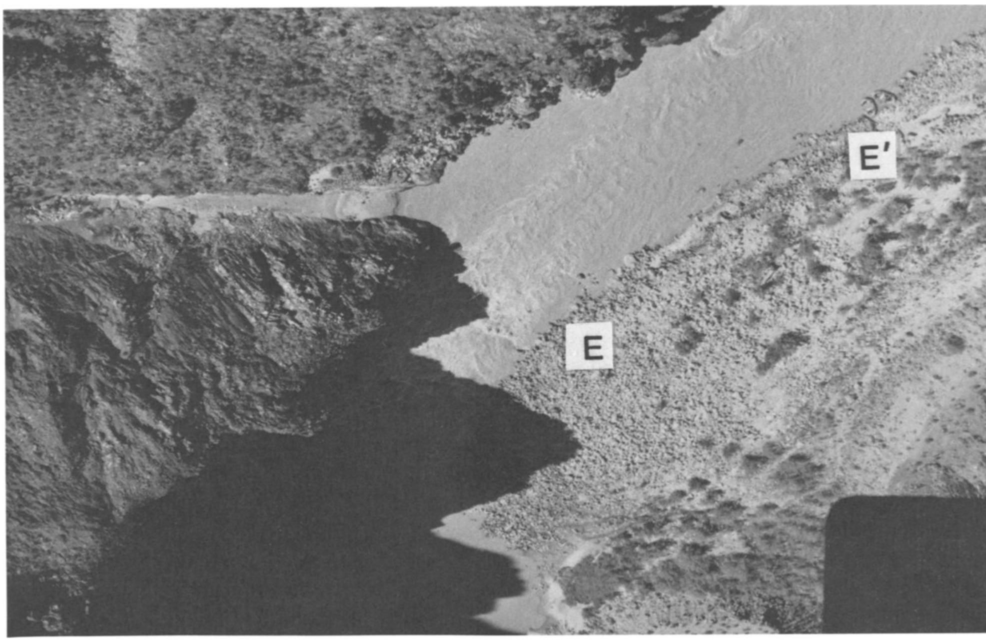

FIG. 10.—Photograph of part of Crystal Rapid obtained on Oct. 22, 1984 at a discharge of 6,000 cfs. Compare with figure 4*a*, taken in 1973 at 10,000 cfs. The equality of stage for the two different discharges suggests that either the bed in this photo is higher than in figure 4*a*, which could have resulted from post-flood sedimentation of fine material (e.g., as described by Howard and Dolan 1981, fig. 7), or that the depth-velocity relations within the rapid have substantially changed due to the change in channel shape. The author prefers the later explanation. Having noted the approximately equal stages in this figure and figure 4*a*, compare the span of shore between E and E′ for evidence of erosion.

striction should enlarge to 0.3 to reduce u_2 to 9 m/s, but u_3 in front of the normal wave remains high at 13.6 m/s. At 90,000 cfs, a constriction of 0.40 will hold u_2 to 9 m/s, but u_3 is 11.6 m/s in front of the normal wave. Thus, under conditions of progressively higher discharge in the history the Crystal debris fan, the Colorado River should contour a nozzle of a shape appropriate to keep u_2 equal to the threshold velocity for boulder transport and to keep region 3 of supercritical velocities as small as possible. It is therefore probably not a coincidence that at 92,000 cfs, the kayak velocities were 9.8 m/s from Slate Creek to the trough of the wave—a stretch that includes region 2 and the faster region 3. Given that the kayakers did not exactly follow flow streamlines and that they were paddling with great vigor when upright, this value of 9.8 m/s can be considered in reasonable agreement with the inferred threshold velocity of 9 m/s.

Water decelerates rapidly as it passes through the normal wave into region 4, and the strong deceleration, as well as the great wave height, contributed to the rafting accidents at discharges of 50,000 to 60,000 cfs. The calculated velocity change through the wave was 10.7 m/s (35 feet/s or 24 miles per hour) at 50,000 cfs (fig. 9*e*). At 96,000 cfs with the constriction at 0.41, the calculated velocity change across the wave is 4.8 m/s. The kayaks were measured to decelerate from 9.8 to 3.3 m/s as they passed through the trough-crest region, in reasonable agreement with the calculated velocity change. Movies obtained by the author, as well as the sequence of photographs of which figure 3 is a part, show the large raft suddenly stopping as it hit the wave—a manifestation of the large velocity decrease across the hydraulic jump.

The large decelerations calculated for water when it passes through the normal wave from region 3 of supercritical flow into region 4 of subcritical flow suggest that this boundary will be a site of deposition of material scoured from regions 2 and 3. Experienced

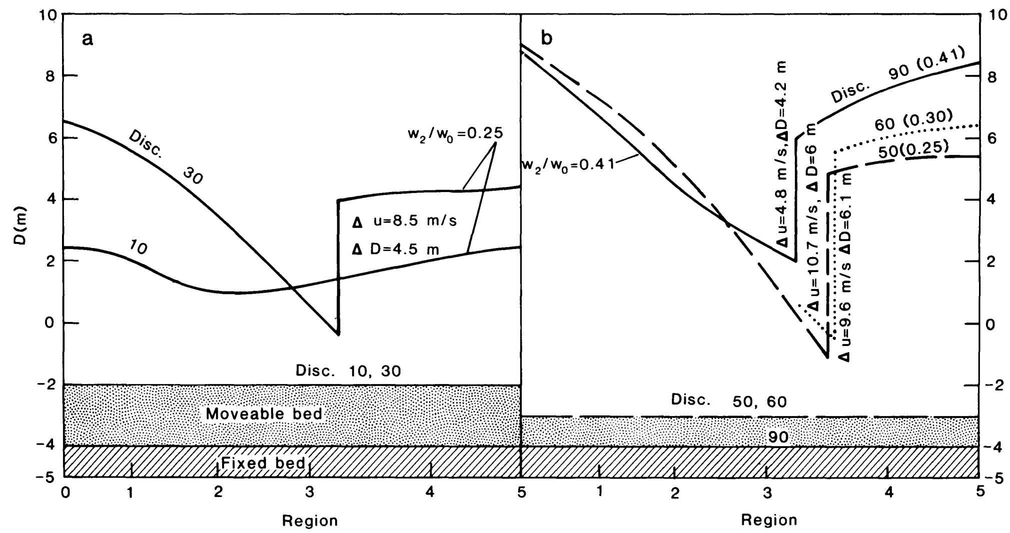

FIG. 11.—Schematic diagram of hydraulics at Crystal Rapid to discharges of 90,000 cfs. In each part, level of the water surface is obtained by taking the depth relative to a bottom whose behavior is that measured at Bright Angel Creek gaging station. Thus, erosion that occurred above 50,000 cfs is shown as a decrease in bottom level. (*a*) Subcritical flow at 10,000 cfs and supercritical flow at 30,000 cfs with a constriction of 0.25 in both cases. (*b*) Supercritical flow at 50,000, 60,000, and 90,000 cfs, with constriction widening as described in the text to maintain u_2 at 9 m/s. For each supercritical-flow curve, height of hydraulic jump and velocity change across it are shown.

boatmen reported that the Rock Garden in the lower part of the rapid was substantially modified by the 1983 high discharges, and that it contains many new large boulders, some estimated to be greater than 2 m in diameter. These observations qualitatively support the erosion concepts developed above.

The major observation not explained by the calculations is the shape of the normal wave and the observed acceleration of the kayaks to 8.7 m/s downstream of it. The steepness of the wave on its back side cannot be accounted for by the two-dimensional theory used here. One possible cause of the interesting shape is stabilization by large boulders; however, observations of the river bed at 6,000 cfs by the author in October 1984 did not reveal any evidence of substantial material at this position in the bed. Descent of this steep backside by the kayaks undoubtedly contributed somewhat to their excess velocity beyond that predicted by the calculations. Part of the excess velocity may also have been obtained as the kayaks entered water that had high velocity but did not go through the wave.

The proposed hydraulic region in the various parts of Crystal Rapid is summarized in figure 11. The calculated rise of the water surface across the debris fan with increasing discharge is about 6.5 m. A rise of about 5.5 m was observed. The agreement of the calculated and observed values must be considered good in view of the simplicity of the model, the uncertainty in extrapolating the bottom erosion from Bright Angel to Crystal, and the lack of observations and topographic control to estimate elevations of the flow at various discharges.

IMPLICATIONS FOR RIVER DEBRIS-FAN EVOLUTION

The dynamic interactions between the Colorado River and its tributaries have been described by Howard and Dolan (1979, 1981, esp. fig. 7), Dolan et al. (1978), and Graf (1979, 1980). The widely recognized pool-and-rapid sequence near tributary canyons (Leopold 1969; Dolan et al. 1978) arises from the rare emplacement of large debris fans at tributary mouths and their modification by large floods on the main river (see also Shoemaker and Stevens 1969), both events probably having time scales on the order of 10^2 to 10^4 years. A tributary flood raises the bed of the main river at the debris fan, dam-

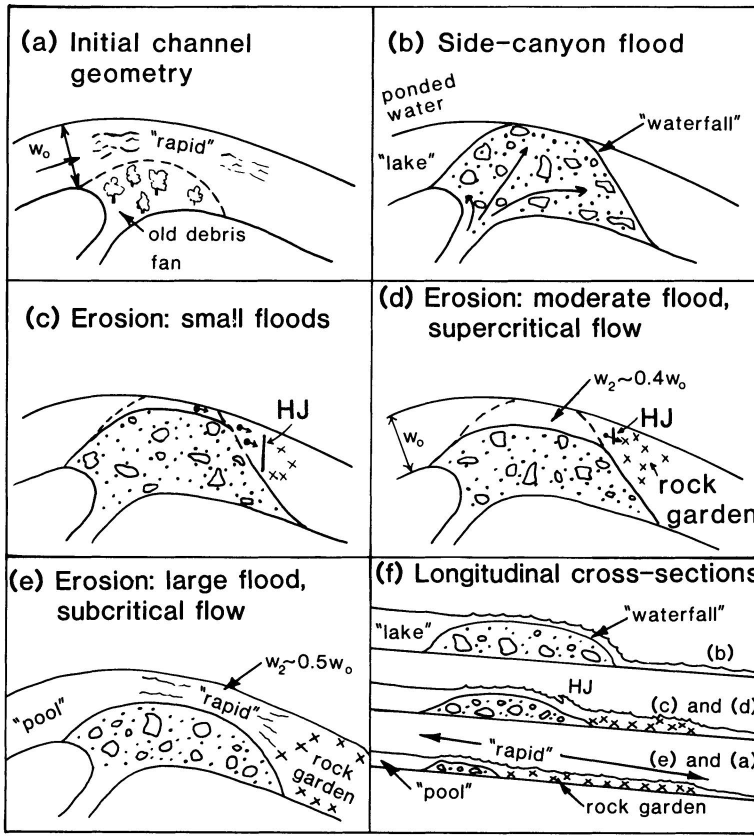

FIG. 12.—Emplacement and modification of the Crystal Creek debris fan.

ing the river; we might call this the "lake-and-waterfall" phase of "pool-and-rapid" evolution. Main-stream floods then remove the finer debris far from the fans and can shift some coarse debris downstream. Thus, the dam of tributary debris is lowered by erosion and the river bed below it raised by deposition. This general sequence of events has been confirmed by the events at Crystal between 1966 and 1984, and the analysis in this paper suggests a quantitative model for some intra-fan dynamics not previously recognized.

The proposed concept of river-debris-fan evolution in the Grand Canyon is summarized in the sequence shown in figure 12. This sequence represents but one cycle in recurring episodes in which debris fans are enlarged by floods in the tributaries and then modified by floods in the main channel. The beginning of the sequence is arbitrarily chosen as a time when the main channel is relatively unconstricted (fig. 12*a*). The river is suddenly disrupted and ponded by catastrophic debris-fan emplacement (fig. 12*b*), forming a "lake" behind the debris dam. The surface of the debris fan is the "waterfall" in this model. As the ponded water overtops the debris dam, it erodes a channel, generally in the distal end of the debris fan (fig. 12*c*); this is the beginning of evolution of the "rapid" from the "waterfall."

Unless the debris dam is massively breached by the first breakthrough of the ponded water, the constriction of the main river is initially severe. Floods of differing sizes and frequency erode the channel to progressively greater widths, as shown in figures 12*c*, 12*d*, and 12*e*. Small floods (fig. 12*c*) enlarge the channel somewhat, but constricted, supercritical flow is still present (e.g., the annual discharges from Glen Canyon dam brought Crystal to the constriction of 0.25 between 1966 to 1983). Moderate floods (fig.

12*d*) enlarge the channel further and may widen the channel so that at lower discharges the flow is weakly supercritical or even subcritical (e.g., the 1983 high discharges at Crystal widened the channel and weakened the waves characteristic of the 20,000 and 30,000 cfs discharges). At the same time that lateral widening is occurring, vertical scouring and headwall erosion of the channel are occurring (fig. 12*f*). Thus, the local gradient in the channel is changing, and new waves can arise as the channel geometry changes (e.g., the new, strong oblique waves at the tongue in Crystal can be attributed to concentration of the 2–3 m drop in bed elevation that had previously been distributed over much of the constriction into a small region at the head of the rapid by headward migration of the laterally widening channel, as in fig. 12*f*). Rare large floods (fig. 12*e*) carry this process further, possibly widening the channel sufficiently to allow subcritical flow at all discharges. This state has not been reached at Crystal.

A rapid like Crystal therefore evolves into two parts: the original debris deposit, and the rock garden below it consisting of reworked debris. In early episodes of small floods, flow through the constricted channel is strongly supercritical, and velocities are high enough in the constriction and in region 3 of supercritical flow so that large boulders can be moved by the river. They will be eroded from the constriction and region 3 and deposited downstream of the normal wave in region 4 of subcritical flow where flow velocities are smaller. Thus, it is plausible to believe that the rock garden grows or is modified with the changing position of the normal wave. The reports of changes in the configuration of the Crystal Rock Garden during the 1983 high discharges support this idea. Since the position of the hydraulic jump changes with discharge (which increases and decreases on many different time scales) and with channel constriction (which becomes less severe with time), changes in the rock garden can occur over a substantial distance in the rapid. At Crystal Rapid, the distance between the constriction and the furthest rocks in the Rock Garden is on the order of 1 km.

Depending on the relative upstream and downstream heads of the water and on the velocity required to move debris, two different flow regimes and channel geometries could result from the highest discharges: (a) As widening occurs, flow velocities in the constriction could become lower than the threshold velocity for erosion, and erosion could cease while the channel geometry still required supercritical flow (as suggested in fig. 12*d*). (In this case, even though erosion no longer occurred in the constriction, modification of the debris fan could continue downstream of the constriction if velocities in the supercritical region 3 were sufficiently high for boulder transport.) (b) Alternatively, as widening occurs, velocities could remain sufficiently high for erosion to channel a width sufficient for subcritical flow (as suggested in fig. 12*e*). The choice of alternatives is determined by the relative upstream and downstream heads of the river at the rapid, and by the threshold erosion velocity. Calculations presented below suggest that alternative (b) is the general case for debris fan evolution on the Colorado River in the Grand Canyon—that is, that subcritical flow is obtained in the widening process. At some relatively arbitrary time in this sequence, the configuration of the river at the debris fan has evolved from lake-and-waterfall to pool-and-rapid, and, depending on the relative frequencies of the large floods on the main river and tributary, the sequence of fig. 12*a–e* is repeated.

The shape of the main stream at a debris fan at any instant of geologic time therefore reflects the contouring that occurred at the maximum discharge of the river since the last emplacement episode in the history of that debris fan, unless effects of sedimentation of the finer-grained, more transient material partially mask the larger scale erosion (e.g., Howard and Dolan 1981, fig. 7). The observation, summarized in figure 2, that the Colorado River is less constricted at most of the tributary debris fans than it is at Crystal Rapid suggests that these fans have seen higher discharges than Crystal, i.e., higher than 100,000 cfs. We know this to be true—a flood of 220,000 cfs occurred in 1921, and a flood estimated at 300,000 cfs occurred in 1884. It is reasonable to assume that even larger floods have occurred since the emplacement of many of these debris, a time that may exceed 10^4 years (Hereford 1983). (Note: the observations in fig. 2 and this dis-

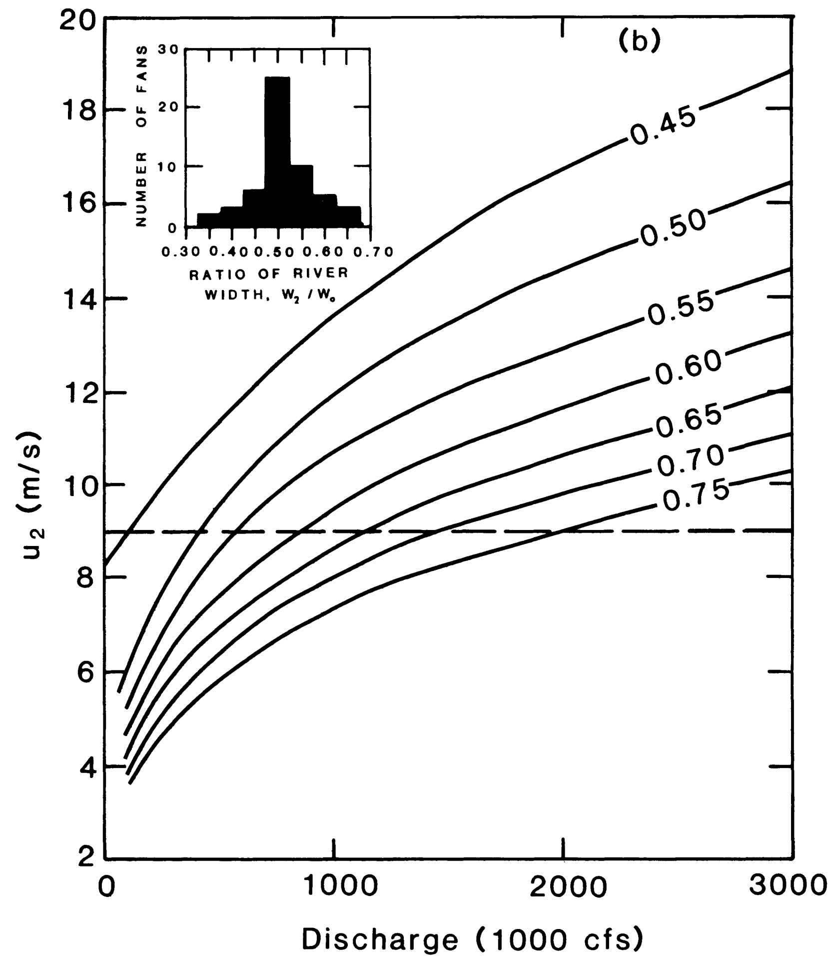

FIG. 13.—(*a*) Histogram of figure 2 reproduced. (*b*) Velocity in narrowest part of a constriction for flows extrapolated beyond 100,000 cfs, in comparison with threshold velocity (dashed line) assumed required for constriction erosion. Curves are labeled with values of constriction.

cussion apply only to those recent fans that emerge from tributaries and are currently active, not to some of the more ancient terraces along the Colorado that may have formed under substantially different climatic conditions.)

These observations suggest that the largest discharge in the life of these fans could be estimated from extrapolation of this analysis for Crystal discharges sufficiently high to obtain a constriction of 0.50 (fig. 13). In so doing, an assumption is made that channel erosion was sufficiently rapid to reduce the flow velocity to the threshold level at each flood. Extrapolation was done with the standard power functions relating depth, velocity, and head to specific discharge as described in table 1, footnote i. In addition to the uncertainty introduced by these functions, there are uncertainties due to lack of knowledge of the vertical cutting of the bed at high discharges and to the role of overflow across the debris fan, which could become more significant at higher discharges.

The calculations show that if the discharges through Crystal Rapid were increased above 100,000 cfs, the present channel constriction of about 0.40 is too severe to prevent velocities in the constriction from rising above those required for erosion. For example, if the discharge rose to 300,000 cfs, u_2 would rise to 10.6 m/s in a channel with 0.41 constriction; therefore, the channel would widen. A widening to a constriction of 0.47

would reduce the velocity back to 9 m/s. The hydraulic jump and supercritical flow regimes would disappear under these conditions. A constriction of 0.50 would be obtained at a discharge of slightly over 400,000 cfs (11,320 m^3/s). Assuming that similar conditions hold at the other debris fans represented in the histogram of figure 2, this discharge represents an estimate for the largest flood in the Grand Canyon since these fans were formed.

As the channel widens, flow at low discharges becomes subcritical. Supercritical flow, even at the highest discharges, ceases when the constriction has reached 0.45. In the absence of supercritical flow, there is no normal wave. It is thus consistent with the calculations presented that there are few normal waves other than at Crystal Rapid on the Colorado River in the Grand Canyon—the river channel is sufficiently wide around the debris fans that supercritical flow does not occur (except the weakly supercritical conditions that arise when potential energy and dissipation are not exactly balanced in the upper reaches of rapids, as described in the text).

The constrictions of the Grand Canyon tributary debris fans are remarkably uniform at a value of $w_2/w_0 = 0.5$ (fig. 2), especially when one considers variations in rapid size, fan size and composition, and vertical drop through the rapid. Variations in river constriction at different debris fans may indicate: (1) different erosional thresholds (e.g., due to different particle sizes or cementation of the fans); (2) different specific heads of the Colorado River along different reaches; (3) different flood histories of the Colorado in the vicinity of different debris fans (e.g., if the debris fans are of different ages or if temporary obstruction of parts of the Colorado River by debris or lava flows resulted in different flood levels along the Colorado); (4) different ages of the fans. For refinement of the estimate of peak discharge discussed above, these factors need to be examined at each fan of interest.

In conclusion, the ability of the Colorado River to contour its own channel probably accounts for the remarkable uniformity of constriction that the river exhibits as it passes around each of the major debris fans along its 400 km length in the Grand Canyon. During the high discharges of 1983, supercritical flow of the Colorado River at the Crystal Creek debris fan brought the river and the debris fan substantially closer to a configuration characteristic of the one that would be obtained if natural flooding of the river still occurred.

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APPENDIX

As an example of the use of the depth-energy and depth-force diagrams of figure 8*c* and 8*d*, consider the discharge of 50,000 cfs (1415 m^3/s) flowing through a channel at Crystal assumed to narrow from 80 to 20 m. First consider the case of constant specific energy. The discharge per unit width in region 0 is 17.7 m^2/s; in region 2 it is 70.6 m^2/s. The ambient river head H_r is 8.4 m. This is insufficient to allow a flow of 70.6 m^2/s through the constriction, so a backwater forms to increase the head to 12 m (point A). At this head the water flows through the constriction at a critical depth of 8.0 m, with a critical velocity of 8.8 m/s. Upon expansion into the divergence, the flow becomes supercritical as q increases (path B-C-C′). A hydraulic jump forms at the conditions C′ where the dissipation across the jump returns the backwater head to the ambient downstream head of 8.4 m. The height of the jump formed for a given initial depth in front of the jump (e.g., C or C′) can be found in part (d) of the figure. For example, at C′, the depth in front of the jump D_3 is 1.9 m at a discharge of $q_3 = 26.7$ m^2/s. The conjugate state on (b) is 7.9 m (point D), giving a jump height of 6 m. Referring back to part (c), point D plots at a new head of 8.4 m, as required to restore the flow to the ambient head. The flow then expands subcritically to the ambient downstream discharge, E.

The effect of increasing the specific head if the potential energy gain in the vertical drop through the rapid is not dissipated is shown by the alternate trajectory A-B-F, where B-F represents an extreme gain of 6 m head while the flow is in the constriction. A reasonable simplification of the geometry is that the steep downhill section is within the narrowest part of the channel (fig. 8*b*). The flow then becomes supercritical in the constriction, in this case at F, with Fr = 2.5. The depth is 4.3 m and velocity is 16.4 m/s. In the divergence the flow expands along path F-G-G′ to a state where a hydraulic jump, if formed, would return the head from 18 m back to 8.4 m. By the same procedure as before, point G′ is plotted on (c) where the conjugate depth (H) of 8.1 m is found. Expansion to state E (fig. 8*c*) in the divergence follows. Even for this case, in which the potential energy gain is about twice that plausible for Crystal, the calculated jump height (on c) is within 1 or 2 meters of that calculated without inclusion of the vertical drop of the bed and energy dissipation in the water. The height of the hydraulic jump is relatively insensitive to the potential energy gain. The few existing observations are insufficient to distinguish between the calculations with and without the potential energy gain. Therefore, the flow equations in the text are for the simplified case of H_r = constant.

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