FIGURE 86.—Flow-measurement gear being readied for observations of velocity and depth. The 100-pound weight hangs below the current meter from a cable on the winch.

Types of Waves and Causes of Rapids

In attempting to ascertain the causes of rapids, it would be helpful if one knew the details of the sizes and types of boulders or the configuration of bedrock making up the riverbed through the rapids. As only depth soundings are available, one must infer what he can about the bed from other evidence. The character of the shoreline and the distribution of wave forms at the water surface provide some indication of what is hidden under water. To aid in drawing inferences about the causes of rapids, it is useful to categorize the forms seen on the surface, especially the relation of waves to the shoreline and to what is known about water depth.

Four types of waves can be distinguished in rapids. This fourfold classification is descriptive of the hydraulic form rather than the geomorphic cause of the rapids. It is a classification based on the origin of large waves or wave trains in rapids rather than an explanation of why rapids occur at a given place in a canyon. Each type of wave is shown diagrammatically in figure 91.

Waves below large rocks or outcrops.—A common cause of large waves is the chance occurrence of extremely large boulders or rock outcrops in the channel. These rock masses or blocks force water to pass over and around the obstruction. The water speeds up on the downstream side, causing a hole or deep trough in

FIGURE 88.—Hance Rapids, caused principally by the debris cone from a tributary entering on the left bank.

of the rapids in the Grand Canyon can be explained by these, as will now be shown.

A channel obstruction causing a rapid can be formed by large blocks of rock falling into the river from adjacent high cliffs. In many places along the Colorado, one sees bedrock blocks whose dimensions are in hundreds rather than tens of feet. Sometimes these are seen as great blocks protruding from the river, but more often, their size can be appreciated when they are on the river margin or on the slopes beneath the enclosing cliffs. The depth soundings through some rapids show that the depth changes instantly from very deep to very shallow and just as quickly increases again. This strongly suggests that the boat has just passed a large block of cliff rock which fell into the river and is completely submerged. Even some of the big rapids seem to be caused primarily from rockfalls from the cliffs. Many rapids are so far from adjoining cliffs, however, that this explanation is improbable.

The second obvious reason for rapids in the great canyons is the occurrence of a fan of rock debris debouched from an entering tributary and partly blocking the river. Many tributaries, however, do not cause a rapid at all, although they are apparently equal in size to those that do.

Some rapids must be the result of outcrops of especially hard rock locally, but because such outcrops are submerged, the cause must be inferred. Lava Falls, one of the largest and most dangerous rapids in the Grand Canyon, seems to be of this sort. In middle Pleistocene time, basalt from a lava eruption partly filled the canyon. This lava flow later was eroded away. Its occurrence suggests such a cause for this steep and violent rapid.

Many rapids, however, do not seem to be explained by the three types of circumstances mentioned. Rather, they are associated with what seems at first glance to be a random occurrence of gravel accumulations, either as a central bar across the channel or as the channelward extension of a lateral gravel bar. In fact, these gravel accumulations are not random when viewed in terms of a long reach of channel. They have a roughly regular spacing as has long been observed in the occurrence of gravel riffles in small streams. Some support for this inference comes from the data on the number of rapids per unit distance mentioned earlier. In the first 150 miles below Lees Ferry, a reach dominated by the sedimentary rock in Marble Canyon, rapids average 1.6 miles apart. In the next 178 miles downstream, a reach dominated by the metamorphic rock of Granite Gorge,

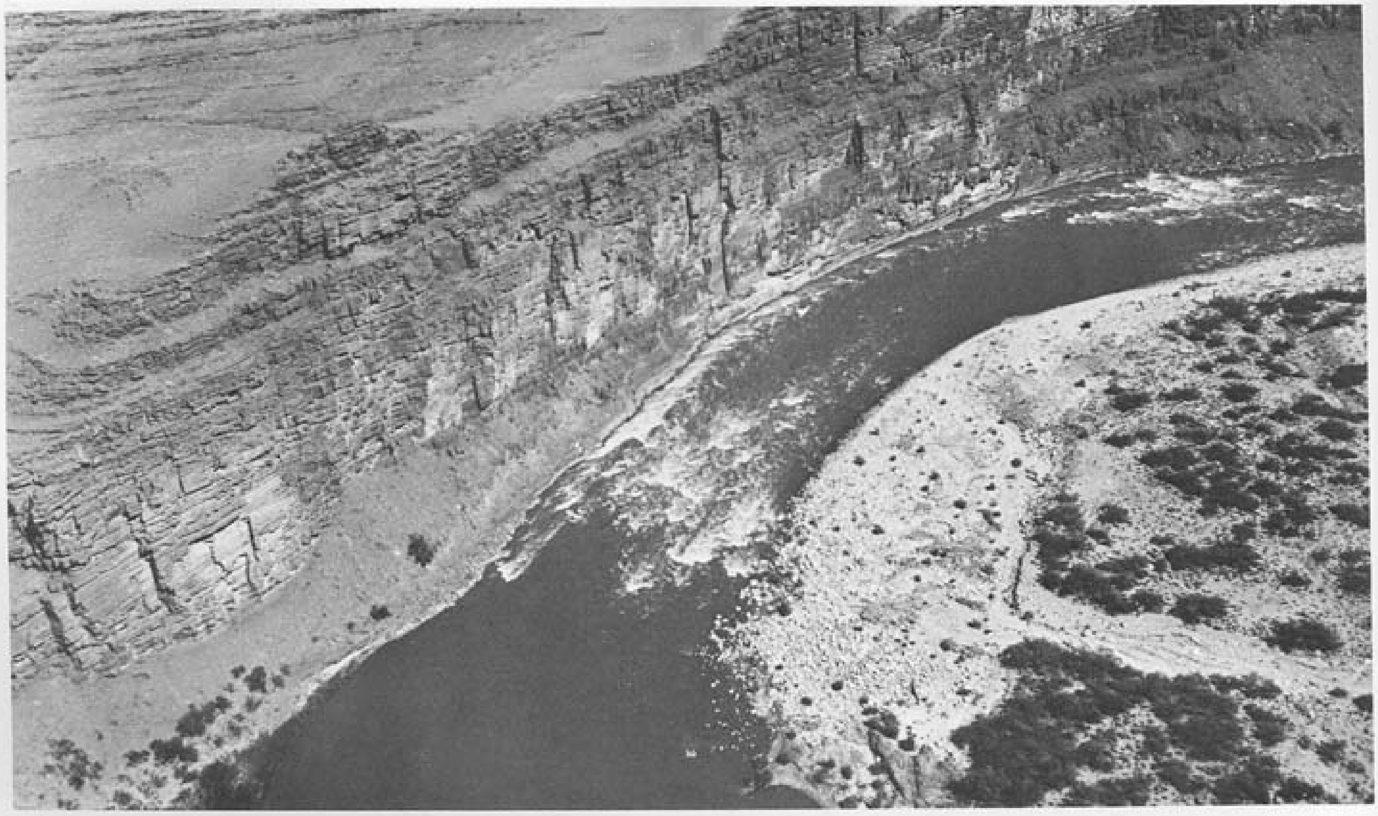

FIGURE 90.—Looking downstream at Unkar Rapid, which was caused by tributary fan forcing river against cliff on the left bank.

To explain in different words the importance of this age determination: the river has had a long time to smooth out breaks in gradient resulting from outcrops of hard rock and from tributary fans or big rockfalls. The erosion of more than 500 feet of hard basalt would require more time and the expenditure of more stream power than would be necessary to dispose of even the largest tributary fan or rockfall observed anywhere in the canyon. Accordingly, one finds it difficult to avoid the conclusion that the river profile is essentially graded and that the alternation of smooth pools and steep rapids is a natural habit of the river, related to the achievement of an equilibrium condition probably equatable to a tendency toward minimum work.

The rapids in the Grand Canyon constitute the most important element in the river's approach to sea level. Considering the whole length of the Grand Canyon, the decrease in elevation of the water flowing through all the pools is small compared with the decrease resulting from even a few of the principal rapids. Figure 94 is a graph showing the proportion of the total elevation attributable to various distances. It can be seen that 50 percent of the total decrease in elevation takes place in only 9 percent of the total river distance. In half the total river length, 86 percent of the total elevation decrease is achieved. The asymmetry of this curve demonstrates the importance of the rapids in accounting for a large proportion of the total elevation drop. For example, in those rapids that have a slope of .01 or more (1 foot drop in 100 feet), 28 percent of the total elevation drop is accounted for.

The 10 largest rapids are listed below in order of decreasing water-surface gradient; these alone account for 19 percent of the total fall in the 150-mile river reach used as a sample.

List of steepest rapids, Lees Ferry to mile 150, Grand Canyon

	Slope in feet	*Length in miles*
House Rock Rapid	0. 0170	0. 3
Horn Creek Rapid	. 0168	. 4
75-Mile Rapid	. 0164	. 2
Badger Creek Rapid	. 0162	. 2
Zoroaster Creek Rapid	. 0150	. 2
76-Mile Rapid	. 0130	. 3
Unkar Rapid	. 0130	. 4
Tuna Creek Rapid	. 0130	. 2
Sockdologer Rapid	. 0126	. 4
Grapevine Rapid	. 0120	. 7
Total		[1] 3. 3

[1] Or 2.2 percent of 150 miles.

NOTE.—Total drop through 10 steepest rapids is 246 feet or 19.3 percent of total drop in 150 miles.

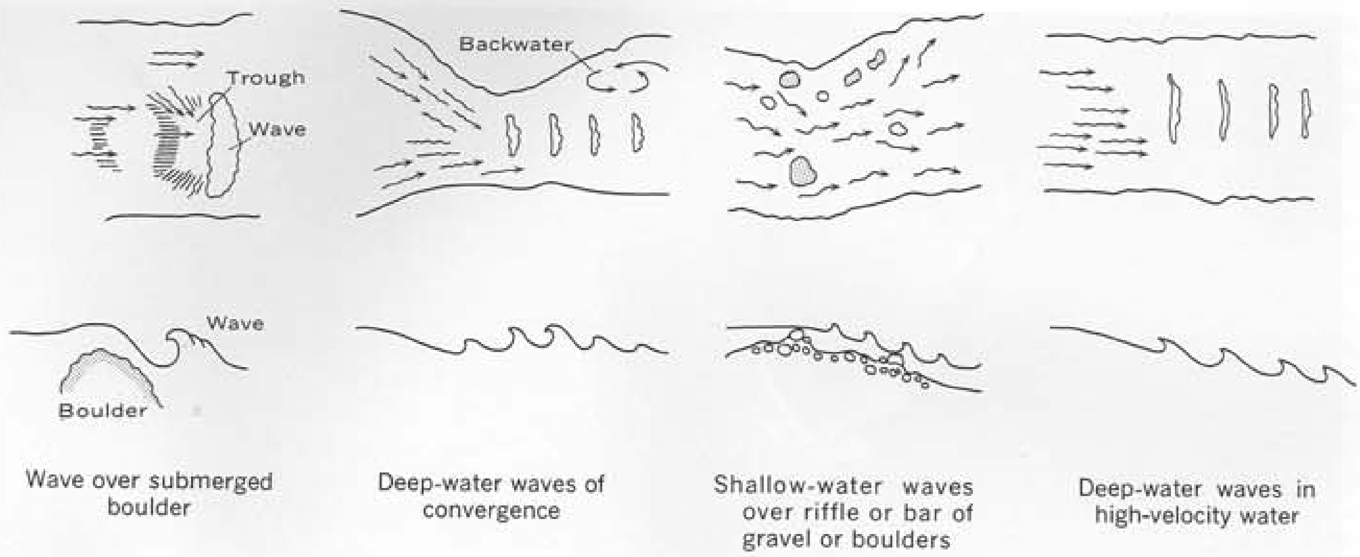

FIGURE 91.—Diagrams showing four types of water waves in rapids. Upper sketches show a plan view of the river; lower sketches indicate the inferred relation of waves to the bed configuration.

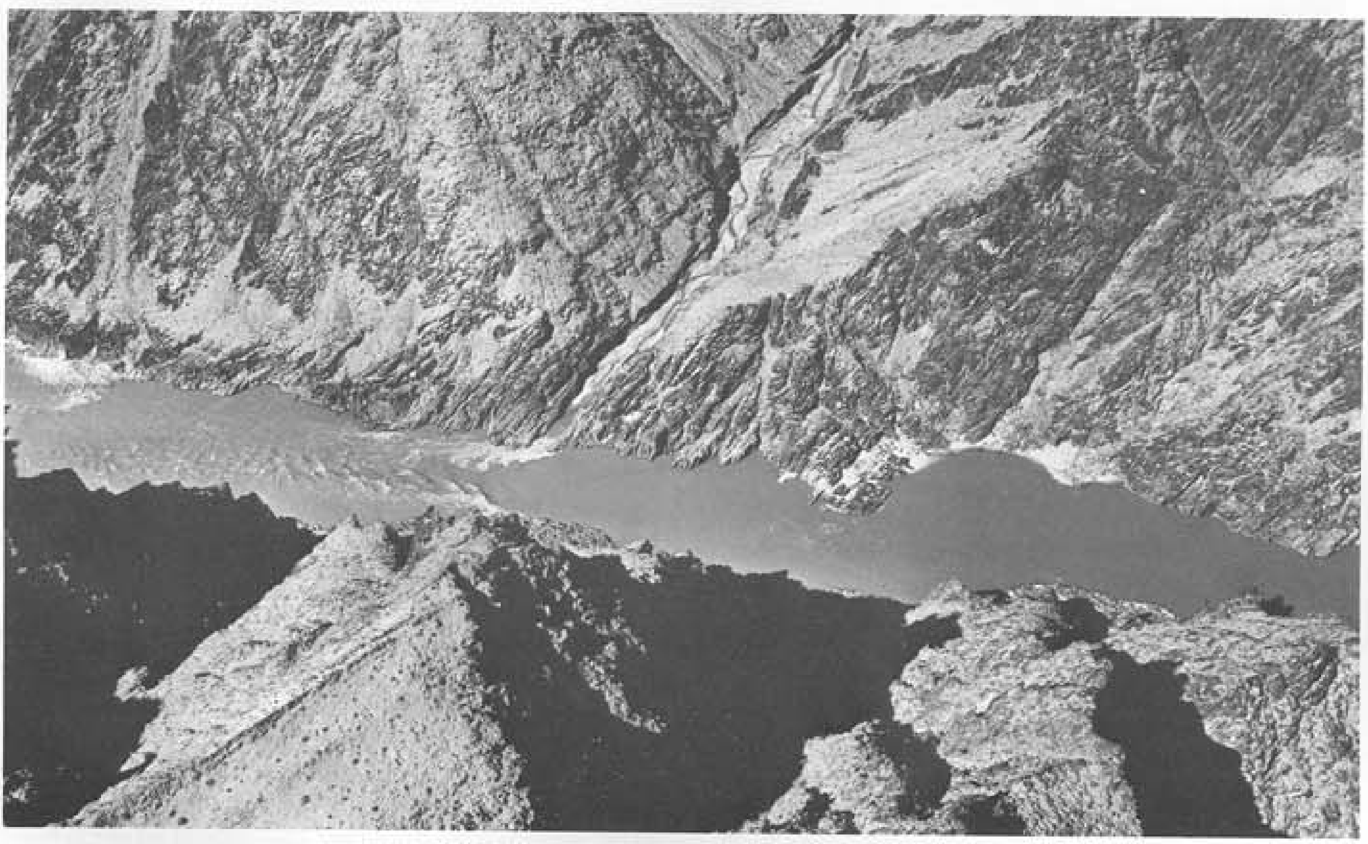

FIGURE 92.—A rapid due primarily to convergence where rockbound channel narrows in a part of Granite Gorge.

FIGURE 93.—Rapids unrelated to any tributary entrance and presumably caused by large gravel bar deposited on streambed.

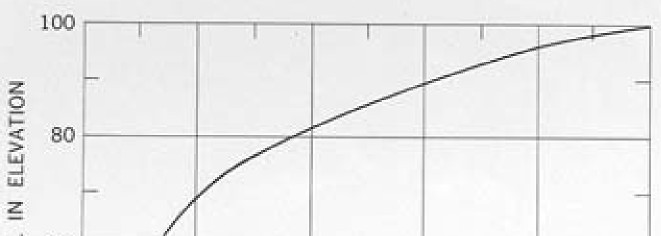

FIGURE 94.—Relation between the fall in elevation of the Colorado River and distance along the channel in the first 150 miles of the Grand Canyon below Lees Ferry.

The direction and speed of water through and below a rapid in the Grand Canyon illuminates some aspects of the bed form and profile. Commonly, immediately below a very steep rapid, a large part of the downstream flow will be thrown against one bank, particularly if that bank is a vertical cliff. When this occurs, the opposite side of the stream will invariably have a strong upstream current at the water surface, often forming half the total stream width. Between the downstream and upstream surface currents, then, a strong shear zone exists that will be characterized by boils or round domes of upwelling water. These boils are sporadic in size and intensity, as would be expected of turbulent eddies. The boils in the Grand Canyon may be as small as 3 feet in diameter or as large as 40 feet in diameter. The vertical component of upwelling water is distinctly shown by the dome-shaped topography of the water surface over the eddy. The amount of surface elevation or vertical superelevation of the water surface over the boil is a direct indication of the strength of the vertically directed upward current. We estimated that this vertical superelevation was as much as 1 foot, indicating a vertical velocity of 8 fps.