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This study used distinctive patterns on side-scan sonar charts and depth-finder charts to delineate the distribution of movable sediment that forms parts of the Colorado River bed. Three types of bed were delineated: smooth bottom, sediment waves, and boulder and bedrock outcrops. A set of 189 sonar-pattern maps were produced covering 75% of the 225 miles from Lees Ferry to Diamond Creek. Profile depths ranged from 5-106 feet at an average discharge of 25,000 cfs. The bottom is irregular in metamorphic rock reaches with near-vertical depth changes up to 50 feet. Scour holes more than 1.5 times deeper than the local mean depth occur below many rapids and riffles. Rough bottom of boulders and bedrock slopes downward to the scour-hole bottom on the upstream side. Smooth bottom begins in the bottom of the scour hole or at the base of the downstream side and continues downstream as depths decrease until sediment waves appear. Moveable sediment during a discharge of 25,000 cfs consists of sand and rounded gravel and forms smooth bottom or sediment waves. Little sand is stored in scour holes during that discharge.

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SONAR PATTERNS OF THE COLORADO RIVERBED IN THE GRAND CANYON

Distinctive patterns on side-scan sonar charts and depth-finder charts were used to delineate smooth bottom, sediment waves, and boulders and bedrock outcrops on the bed of the Colorado River in the Grand Canyon, Arizona.

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INTRODUCTION

The sand banks and bars, locally called "beaches," along the Colorado River in the Grand Canyon, Arizona, are composed of sand that is both deposited and eroded by the river. The riverbed serves as a reservoir of sand that is available to be transported to the beaches. This sand is one component of the movable sediment carried by the river. During floods, large volumes of sediment enter and are transported by the river. During sustained flow, material on the riverbed is sorted and redistributed. Although small boulders and cobbles move during floods, sub-rounded to well-rounded gravel and sand constitute the movable sediments at lower sustained discharges.

In this study, distinctive patterns on side-scan sonar charts and depth-finder charts were used to delineate the distribution of movable sediment that forms parts of the Colorado riverbed. We collected bed material samples to provide a qualitative description of the sediment and calibration of bed material to side-scan sonar patterns. This study resulted in a set of 189 sonar-pattern maps, covering about 75 percent of the 225 miles of river from Lees Ferry to Diamond Creek. The gaps resulted from poor or no sonar image in rapids or places where the flow is highly turbulent, and from removal of the sonar fish from the water through major rapids. The maps and data are part of the input to the sediment transport model used by the U.S. Bureau of Reclamation and the U.S. Geological Survey (USGS) to define the movement of sediment through the canyon.

The USGS performed the first detailed survey of the Colorado River in the Grand Canyon in 1923 using alidades and plane tables (Birdseye 1923). They produced maps showing river miles below the USGS gage at Lees Ferry and profiles of the water surface adjusted to a discharge of 10,000 cubic feet per second (cfs). Water-surface profiles were adjusted by discharge because the stage commonly changes more than 10 ft in response to changes in discharge. Leopold (1969) made the first systematic measurements of river depths in 1965.

He measured depths approximately every 0.1 mile using a nonrecording depth finder at a discharge of about 48,000 cfs. His locations were from aerial photographs and his mileage from the 1923 USGS river maps. Leopold described scour holes and discussed their formation by high-velocity, downward-directed flow below rapids. In 1975, Dolan et al. (1978) made a continuous-depth profile with a recording Fathometer using the same location methods as Leopold. Their location errors were as great as 0.06 mile. Discharge during their trip was about 16,000 cfs. Howard and Dolan (1981) discussed distribution and transport of sand, cobbles, and boulders by current flow and the change in sediment transport caused by construction of Glen Canyon Dam. They related origin and location of scour holes to both geologic structure and position below rapids and constrictions.

METHODS

Data for this study were collected during three trips on the Colorado River for 225 miles below Lees Ferry (Figure 1). Side-scan sonar images and depth profiles were run concurrently March 1-10, 1984. Discharge during that trip was 24,300 to 25,800 cfs, averaging 25,000 cfs. Cross sections were taken April 28-May 7, 1984, while discharge was 25,500 to 33,200 cfs. Bottom samples were collected September 4-11, 1984, during a discharge of 24,000 cfs. Locations along the river were determined by annotating approximately 1,050 navigation points on aerial photographs taken in 1973 and on recorder charts as data were collected. River miles were assigned to the navigation points on the basis of the 1923 USGS river maps (Birdseye 1923). Probable location accuracy is within 0.03 mile.

A Klein 100-khz side-scan sonar unit was used to acquire sonic images of about 80 percent of the riverbed. The side-scan sonar fish was removed from the water for many of the larger rapids. Images made in or just below rapids or large riffles were unusable, probably because air bubbles entrained in the water absorbed the returning sonic signal.

A Raytheon 208-khz Fathometer was used to record a depth profile of about 95 percent of the river. The profile was taken concurrently with the side-scan sonar data. An attempt was made to measure the depth profile near the thalweg. An assumed sound velocity in water of 4,800 feet per second was used to convert travel time to depth or to distance. Cross sections of the river were taken in pools between rapids or large riffles at 224 locations with the Fathometer and a continuous seismic (subbottom) profiler. The sonic pulse of the profiler was produced by a boomer and had most of its energy concentrated in the frequency range of 900 to 2,000 hz. The profiler was to be used to

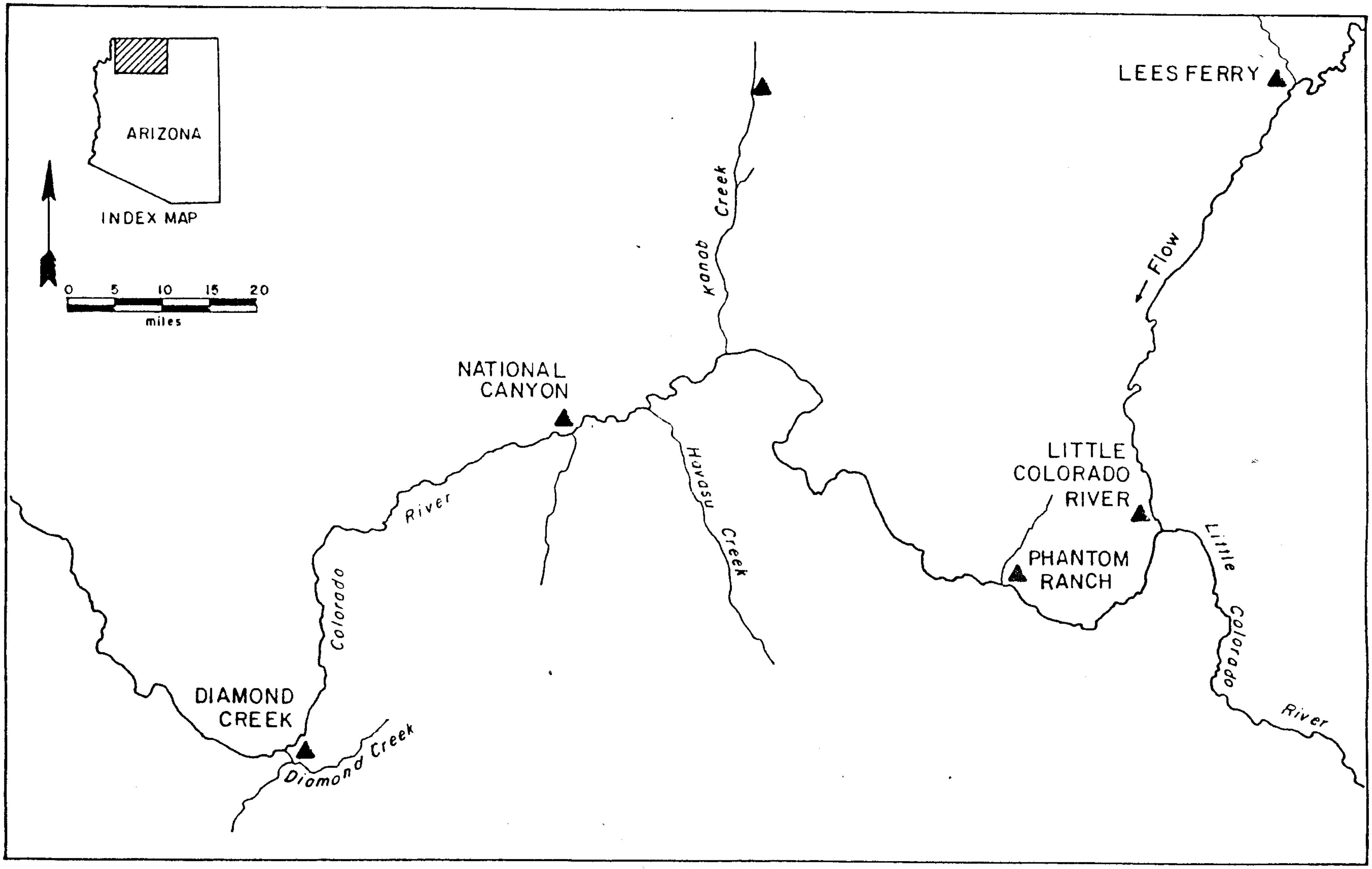


Figure 1. Map of the Colorado River through Grand Canyon National Park (study area).

determine thickness of movable sediment on the riverbed, but poor penetration of the sonic pulses into the sediment resulted in weak returning signals. The signals produced by subsurface layers were commonly obliterated by the strong multiple reflections between the bottom and the water surface.

Fifty bed material samples were taken with a 10-in pipe dredge in order to calibrate patterns delineated on the side-scan sonar charts to the bed material. Sampling depths ranged from 12-64 ft. Quantitative samples of sand and fine gravel and qualitative samples of large pebbles and cobbles were taken by the dredge. Two small boulders were recovered. A typical sample volume was 0.3 to 1.2 cubic feet. At several sites, bed material was not recovered in the dredge, presumably because the riverbed consisted of bedrock outcrops or boulders too large to enter the dredge. Positive contact with the riverbed was made during three sampling attempts before a "no return" was declared. Bed material samples taken with BM-54 samplers at five sediment-collection stations (Figure 1) also were used in calibration of the sonar patterns.

RESULTS

SIDE-SCAN SONAR PATTERNS. A side-scan sonar pattern is produced by multiple sonic reflections from particles and surface features of an area of riverbed. The location and shape of accumulations of movable sediment on the riverbed that produce side-scan sonar patterns are a function of sediment particle size, current-velocity pattern, and length of time a particular velocity pattern has existed. The particles are stored and distributed in an organized way in the sediment accumulations as a result of the variations in local current velocity. Side-scan sonar images on the chart are divided visually into three patterns: B = boulders and bedrock; S = smooth bottom; and SW = sediment waves. See Figure 2 for an example of a side-scan sonar pattern.

Boulders and bedrock outcrops are large in size compared to the resolution of the sonar unit and produce a broken pattern of stripes and spots (pattern B). A diver's observations at a test section above Lees Ferry, BM-54 bed material samples at the Grand Canyon, National Canyon, and Diamond Creek sediment-collection stations (Figure 1), and observations at cross sections indicate that the boulders and bedrock outcrops are commonly covered with a thin layer of sand. The irregular shapes, however, show through the sand to produce the B-pattern. Boulders and bedrock are most extensive along the banks where talus enters the water or bedrock outcrops are exposed. The riverbed of rapids and of the upstream side of scour holes is commonly composed of boulders or bedrock. Boulders form the bed of some riffles.

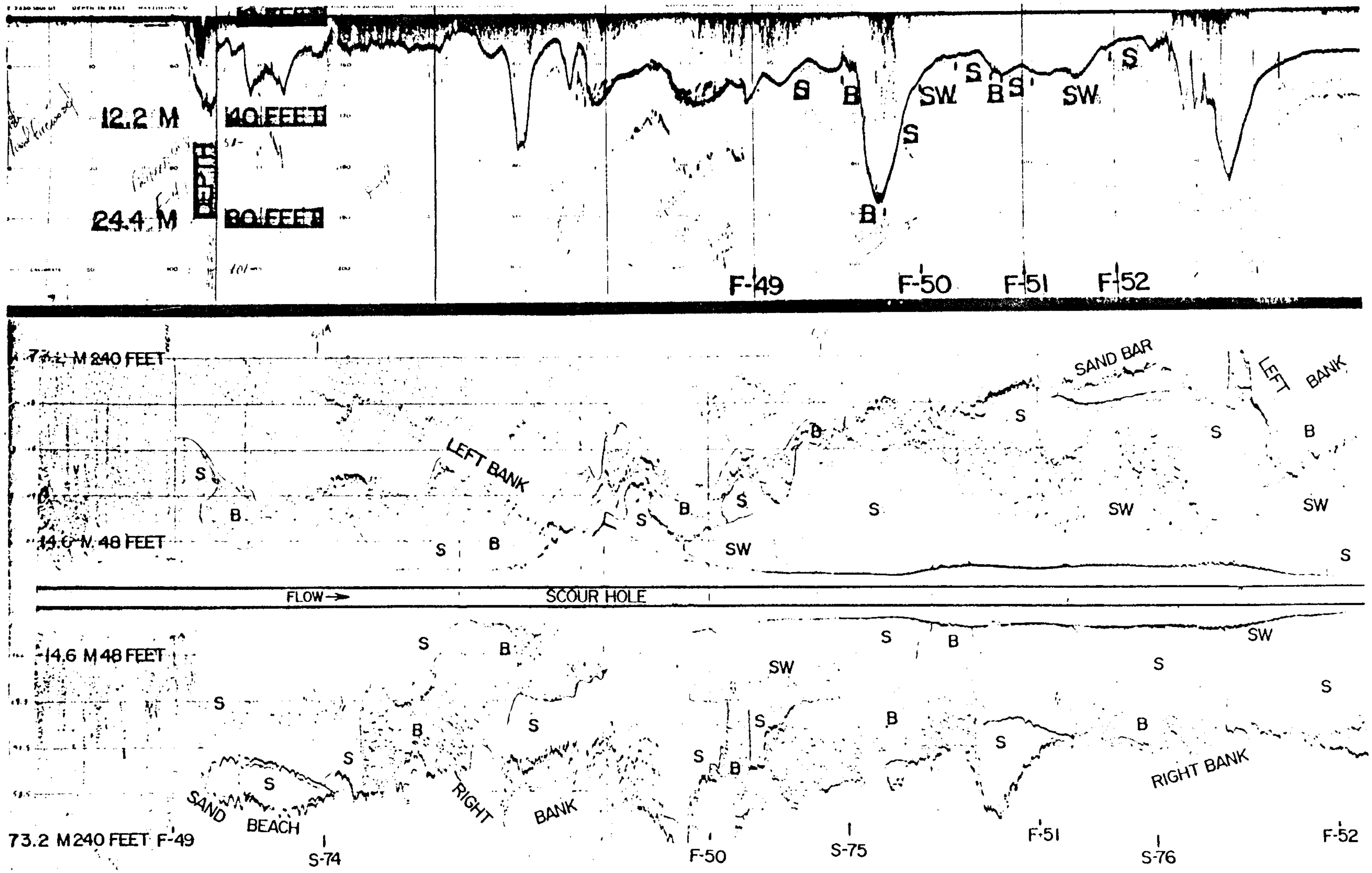


Figure 2. Uncorrected side-scan sonar and Fathometer charts.

Bedrock outcrops that project above the bottom sediments or large boulders that rest on the riverbed create isolated occurrences of pattern B.

Smooth bottom (pattern S) consists of sand, gravel, or cobbles that are smaller than the smallest particle that can be resolved by the sonar unit. The pattern is typically pale, low contrast, and stippled. Pattern S generally is shaded because the return signal gradually increases in strength as the distance from the fish (range) increases. The ripples and irregularities of the riverbed return a stronger signal as the angle of incidence increases. Areas of the bed near exposed sand beaches and bars commonly have underwater cutbanks that show on the sonar charts as bold smooth stripes. These areas are included in the smooth-bottom pattern.

Low-flow aerial photographs taken in October 1984 and dredged bed material samples show that cobble and gravel cannot be reliably distinguished from sand on the side-scan sonar charts. The inability to distinguish between the two bed materials is probably due to the limited resolution and the low dynamic response of the chart paper. In some areas, however, the image does appear to show two types of smooth bottom. An imaging system that would respond to the full dynamic range of the returning signal could probably distinguish sand bottom from gravel and cobble bottom.

Smooth bottom is found near the banks, on the downstream side of scour holes, in some riffles, and in shallow areas just above many rapids. The location of smooth bottom appears to correlate with low current velocity near banks and higher velocity between areas of boulders and bedrock and areas of sediment waves. The sequence of patterns--boulders and bedrock to smooth bottom to sediment waves to smooth bottom to boulders and bedrock--is repeated many times through the canyon. Smooth bottom that extends from low-velocity areas to the beginning of sediment waves probably represents the tranquil-flow transition from plane bed to dunes (Simmons et al. 1961). Smooth bottom near the banks is mainly sand and commonly extends above water where sand bars and beaches are exposed. The aerial photographs taken in October 1984 indicate that smooth bottom in the lower canyon is commonly composed of cobbles. Basalt flows provide an abundant supply of tough cobble- and boulder-size clasts to the river below River Mile (RM) 179.

Sediment waves (pattern SW) are efficient reflectors of sound and produce a strong returning signal. The cyclic alternation of sloping surfaces produces a moderate- to high-contrast striped pattern. The sonar unit resolved sediment waves of amplitudes as small as 0.5 ft, with the largest amplitude observed being 4 ft. Sediment waves are most common near the center of the river in areas of intermediate current velocity and depth. The waves typically begin downstream from short reaches of rising smooth bottom on the downstream side of scour holes and change back into smooth bottom at constrictions or riffles where the depth decreases and current velocity increases. Dredged bed material samples indicate that the sediment waves are composed of medium to very coarse sand, fine gravel, and a few medium to large pebbles. The granules and pebbles show evidence of sustained transport; they are mostly sub-rounded to well-rounded, smooth surfaced, and free from algae or coatings. The fine gravel is probably being transported as bedload. Neither the samples recovered from sediment waves nor the behavior of the dredge during sampling indicated the existence of an armored bottom.

DEPTH PROFILE. The depth profile of the river was taken concurrently with the side-scan sonar images and was used in interpreting the sonar patterns. The Fathometer chart showed sediment waves of amplitude of about 0.3 ft and bottom features of about 0.5 ft in size. The unit commonly showed depths and bed forms in turbulent areas where the side-scan sonar unit produced poor or no records. Profile depths ranged from 5-106 ft at an average discharge of 25,000 cfs. The bottom is irregular in metamorphic rock reaches with near-vertical depth changes of as much as 50 ft.

Scour holes more than 1.5 times deeper than the local mean depth occur below many rapids and riffles. The scour holes are a local feature that owe their location to the high-energy level generated by fall through rapids. Scour is displaced and concentrated below the rapids because the boulder bed of the rapids is resistant (Howard and Dolan 1981). Many of the holes display a characteristic pattern on the depth profile. Rough bottom of boulders and bedrock slopes downward to the scour-hole bottom on the upstream side. Smooth bottom begins in the bottom of the hole or at the base of the downstream side and continues downstream as depths decrease until sediment waves appear. The slope of the downstream side changes smoothly from about one-half the upstream value to 0 (Figure 3). Bed material samples suggest that the bottoms of the holes consist of cobbles and gravel that become finer downstream and change to fine gravel and sand that form sediment waves. Only a small amount of sand is stored in the holes during a sustained discharge of 25,000 cfs. Current velocity in the holes remains greater than in the pools downstream and prevents significant accumulation of sand. The sediment deposited in the hole by a previous flood probably coarsens downward to the point of maximum scour because the particles that accumulate on the bottom become smaller as velocity and discharge decrease during the flood recession.

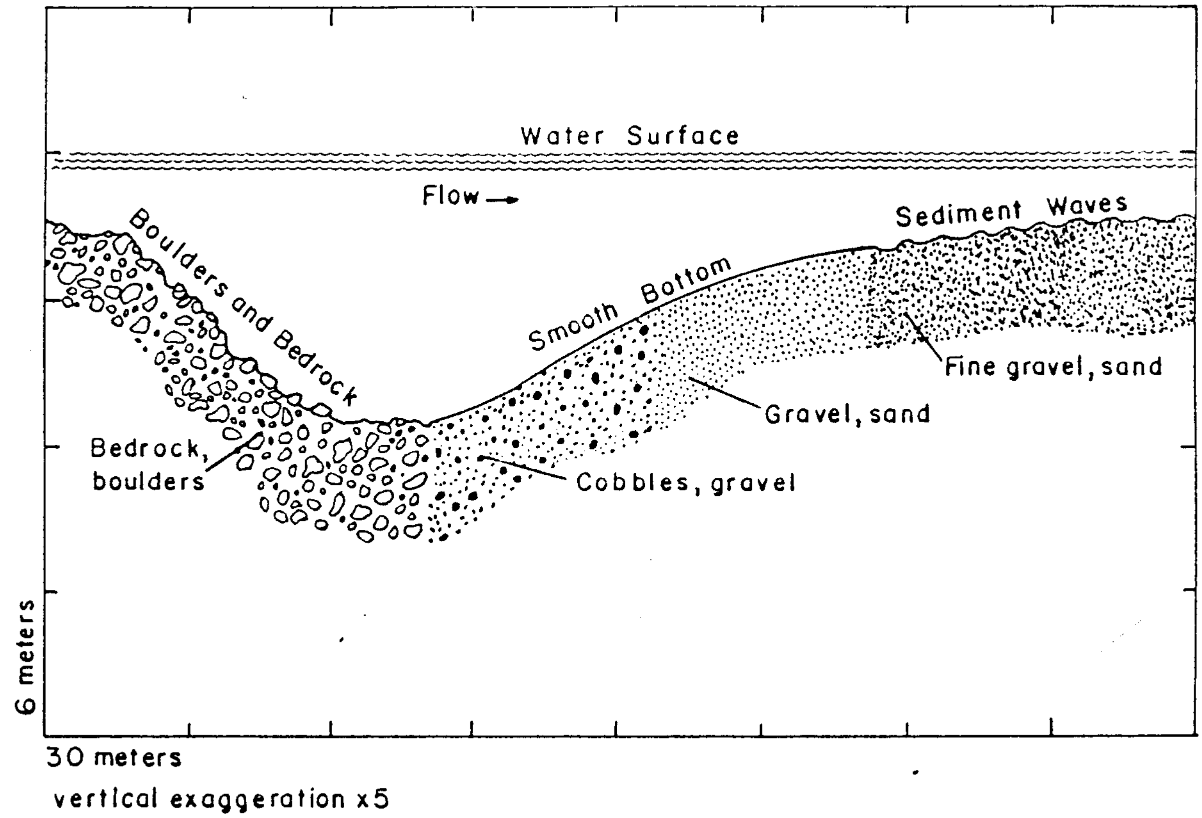
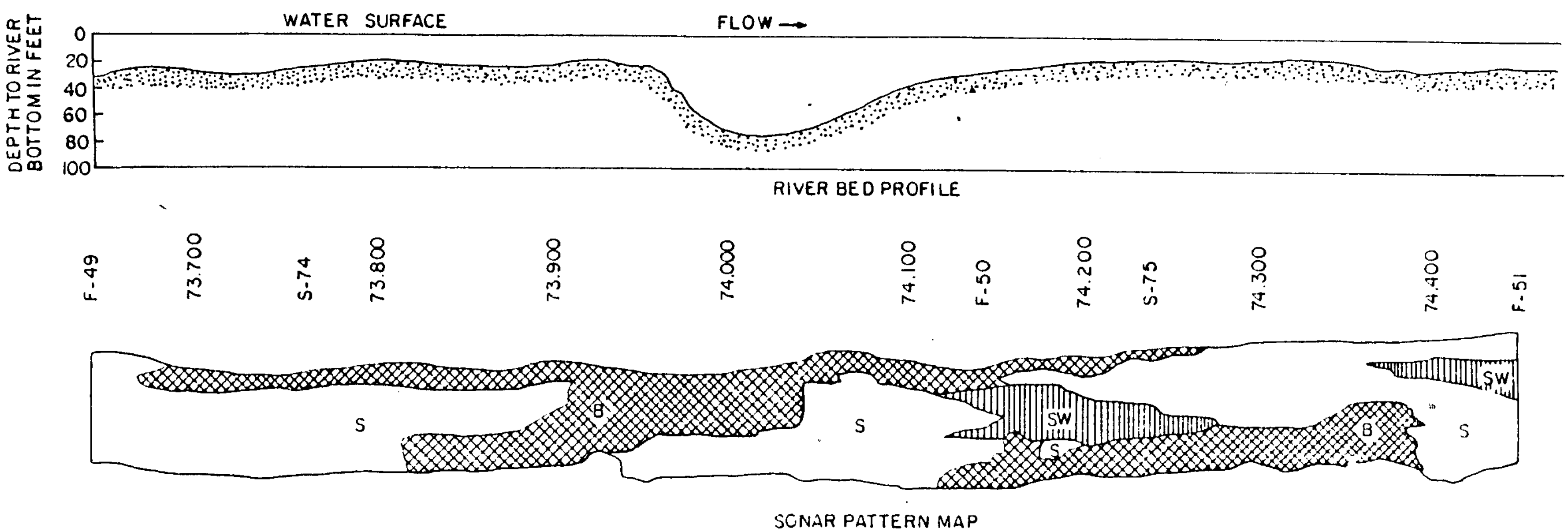


Figure 3. Generalized scour-hole profile, location of side-scan sonar patterns, and bed material.

ANALYSIS AND DISPLAY OF PATTERN DATA. The sonar patterns contain three distortions that must be corrected in order to make geometrically correct maps. A sonar-pattern map derived from part of the uncorrected chart in Figure 2 is shown in Figure 4. The distance axis is traced out by the fish as the boat travels down the river. The plotting position of the distance-coordinate values (miles below Lees Ferry) vary because of changes in boat speed and flow velocity. The digitized distance coordinates were corrected by linear interpolation between navigation points using assigned mileages interpreted from the 1923 USGS maps. Bottom reflections on each side of the fish appear on the range axis of the chart at a point farther than their true position from the distance axis (Figure 5). The range-coordinate value is decreased by an amount that varies from 0 near the river banks to the distance of the fish above the bottom for reflections directly beneath the fish. The corrections are determined from the depth profile and the bottom and bank slopes. Data from the 224 cross sections are used to estimate the slopes. Generalized cross section geometry and range-correction equations are shown in Wilson (1986). The third correction required is to bend the distance axis to conform to the actual curving course followed by the boat as it traveled down the river. The river generally is narrow with respect to bend radii, and only a few miles of wide meandering channel are present in the canyon. The error in computation of pattern areas caused by this distortion is probably small compared to the errors of range and distance. This third correction was not made and the patterns are plotted and areas are computed using the distance axis as a straight line.

DISCUSSION

Calibrated side-scan sonar patterns can be used to delineate boulders and bedrock, smooth bottom, and sediment waves on the bed of the Colorado River in Grand Canyon, Arizona. The patterns interpreted in this study, however, cannot be used to reliably differentiate sand from gravel on smooth bottom or sediment waves. A 10-in pipe dredge can be used to collect bed material samples of cobbles, gravel, and sand from smooth bottom or sediment waves, but many more samples will be required to define the fraction of sand in movable sediment. Movable sediment during a discharge of 25,000 cfs consists of sand and rounded gravel and forms smooth bottom or sediment waves. Scour holes more than 1.5 times deeper than local mean depth contain cobbles and gravel in and near the bottom; little sand is stored in them during that discharge.



KEY

B,S,SW	Side-Scan Sonar Patterns - B, boulders and bedrock; S, smooth bottom; SW, sediment waves
F-50	Navigation point
74.100	River mile
S-75	Cross Section location

Figure 4. Example of a sonar-pattern map of reach F49F51.

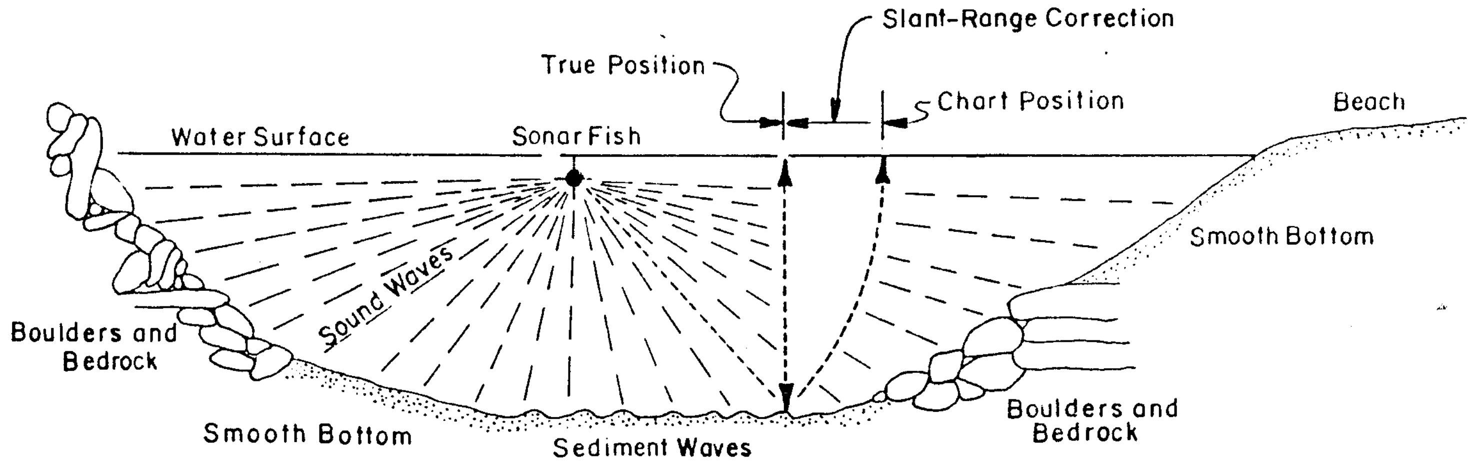


Figure 5. Sonar slant-range correction.

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