ORIGIN, STRUCTURE, AND EVOLUTION OF A REATTACHMENT BAR, COLORADO RIVER, GRAND CANYON, ARIZONA[1]

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ORIGINAL

ABSTRACT: In a channel expansion, flow can separate from the bank, creating a zone of relatively weak recirculating current. Bars that accumulate in this weak flow near the point where flow reattaches to the bank are called reattachment bars. As a reattachment bar evolves, the recirculation zone may fill with sediment and restrict flow from the main channel. The increasingly restricted flow over the bar causes ripples to replace dunes and causes the sediment size to fine; the resulting vertical sequence resembles that of point bars. Seasonal and daily flow fluctuations in the Grand Canyon complicate this idealized sequence. Changes in discharge alter the geometry of recirculation zones, flow within the recirculation zones, the location of depositional and erosional sites, the kind of bedform and migration direction of bedforms on the bar, and the transported sediment size.

Dunes and ripples within a recirculation zone migrate in a rotary pattern in response to the recirculating flow. Ripples near the reattachment point often resemble oscillation ripples in morphology and dynamics. The reversing flow that creates these ripples is caused by fluctuations in location of the reattachment point. These fluctuations cause flow near the reattachment point to reverse in an upstream–downstream direction, thereby producing symmetrical, reversing ripples with crests that trend normal to the bank. Low rates of ripple migration in the reversing flow, accompanied by rapid deposition, cause these ripples to climb at a high angle. At increasing distances from the reattachment point, the reversing flow is less balanced, and the ripples climb at lower angles as they migrate upstream and downstream.

Although these observations were made in a bedrock canyon, the same processes operate in alluvial and tidal channels and are important in adjusting the shape of channels on point bars and concave benches and behind bedforms that become emergent at low stage. Reattachment bars can be recognized by the rotary flow patterns and by symmetrical, reversing, vertically climbing ripples.

INTRODUCTION

Purpose

Recirculation zones form in channel expansions where flow separates from and then reattaches to the bank (Fig. 1). High-velocity flow from the constricted channel impinges on the bank at the reattachment point, where flow decelerates and sand is deposited. Velocities are also low and deposition is induced near the center of the main recirculating current, in secondary eddies, and in nearly stagnant flow that may be present immediately downstream from the separation point. The purposes of this paper are to describe flow processes that produce bars in recirculation zones, to describe internal structure of the bars, to present a model of the evolution of one such bar, and to argue that the same depositional processes are important in controlling the curvature of alluvial channels.

Previous Work and Terminology

Flood deposits formed in low-velocity areas or in recirculating currents in bedrock gorges have been described throughout the western United States and in Australia (McKee 1938; Howard and Dolan 1981; Baker et al. 1983; Baker 1984; Schmidt 1990). Baker's studies have described "eddy bars" that form in the mouths of tributary canyons and downstream from bedrock spurs. In many recirculation zones, deposition is localized near the separation point, reattachment point, eddy center, or along the "eddy line" (the shear surface that separates the recirculating eddy flow from the adjacent downstream flow in the main channel; this surface was called the separation surface by Rouse et al. 1951). Deposits that mantle the debris fan near the separation point have been termed "separation deposits"; deposits that are centered at or are topographically highest at the reattachment point have been termed "reattachment deposits"; and deposits that are topographically highest near the center of the eddy have been termed "eddy-center deposits" (Schmidt 1986). Where subdivision is unnecessary or impossible, the composite bar can be termed an eddy bar, following Baker's usage. A channel divides the separation and reattachment components of the eddy bar at our study site; this paper considers only the reattachment bar.

Recirculation zones and their deposits have also been described from point bars and concave benches in alluvial channels (Taylor et al. 1971; Leeder and Bridges 1975; Page and Nanson 1982; Nanson and Page 1983). These alluvial recirculation deposits have many similarities with those in bedrock canyons, as discussed below.

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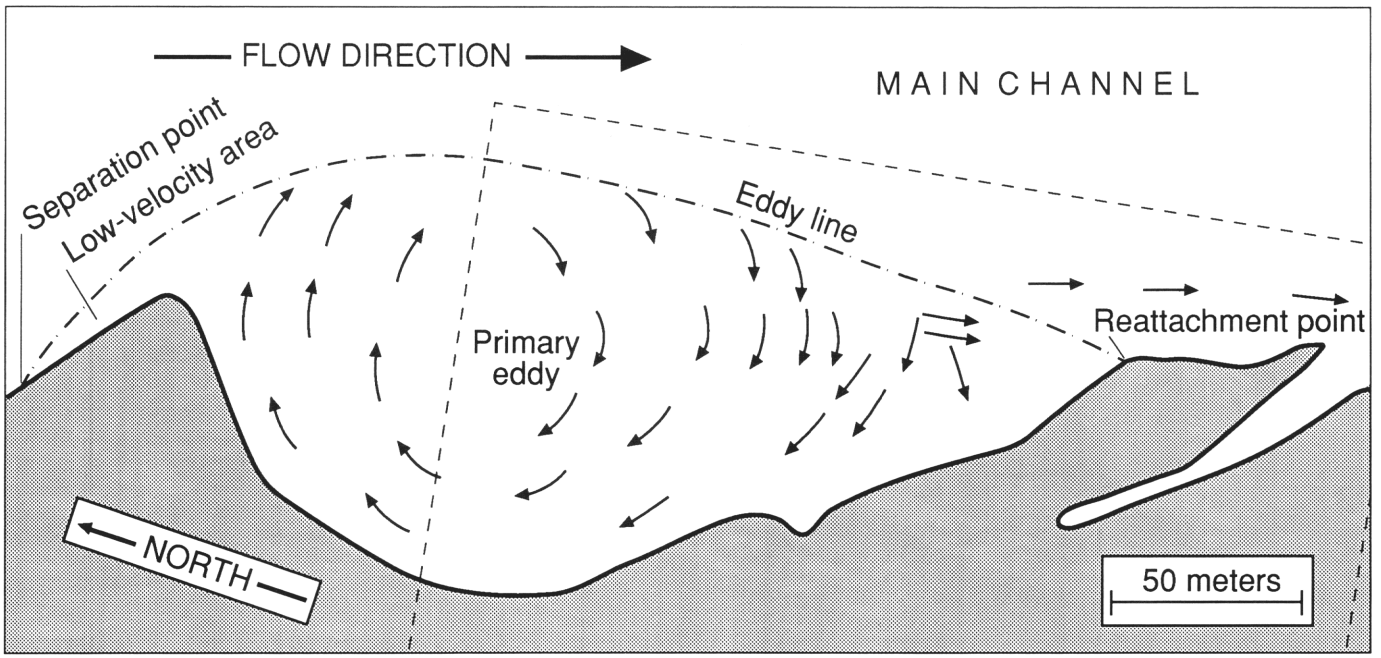


FIG. 1.—Surface flow pattern at study site at a discharge of 620 m^3/s, mapped by observing the water surface in April 1987. Dashed rectangle shows area of Figure 4.

Physical and Hydraulic Setting

The Colorado River flows within the Grand Canyon for 400 km downstream from Lees Ferry, Arizona to Lake Mead (Fig. 2A). Geology and geomorphology of the river corridor are detailed elsewhere (Leopold 1964; Hamblin and Rigby 1968, 1969; Howard and Dolan 1981; Kieffer et al. 1989) Although the Colorado River is well known for its steep rapids, the average slope through the Grand Canyon is only 1.5 m/km; except in major rapids, Froude numbers are commonly less than 0.1.

The study site is located approximately 1 km upstream from Kwagunt Rapids and is situated downstream from a debris fan that was deposited in the main channel by a small unnamed ephemeral tributary (Fig. 2B). The debris fan constricts both the width and depth of the main channel; the study site occurs in the channel expansion downstream from the constriction. Since deposition of the debris fan, tributary flow has had negligible influence on the bar at the study site. The bar has existed at least since 1965, although its surface has episodically been eroded. In the first 170 km downstream from Lees Ferry, 91 reattachment bars have been identified (Schmidt and Graf 1990). The study bar is larger than average, but its morphology and setting are otherwise representative of reattachment bars throughout the Grand Canyon.

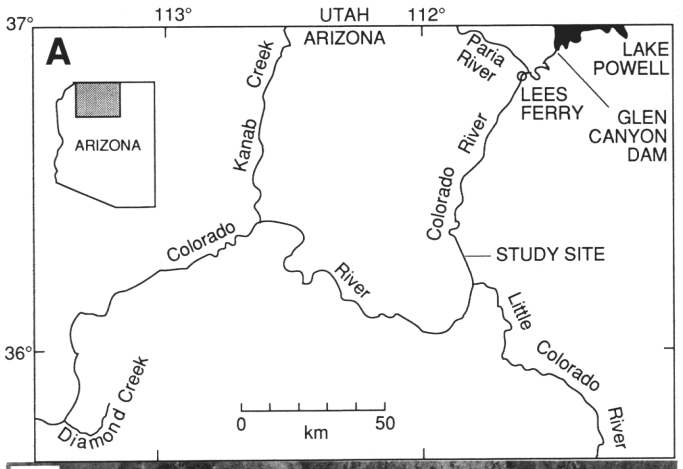
When the Colorado River was dammed at Glen Canyon in 1963, the natural high flows and sediment transport into the Grand Canyon were reduced (Turner and Karpiscak 1980). While the dam was filling between 1963 and 1965, flows were generally very low. From then until May 1983, flows generally fluctuated daily (from lows of 30–150 m^3/s to highs of 400–900 m^3/s). Maximum flows during the summer of 1983 were very high (2,800 m^3/s), and high again in 1984–86 (approximately 1,500 m^3/s). Between our two field surveys in 1987, dam discharge fluctuated daily (Fig. 3).

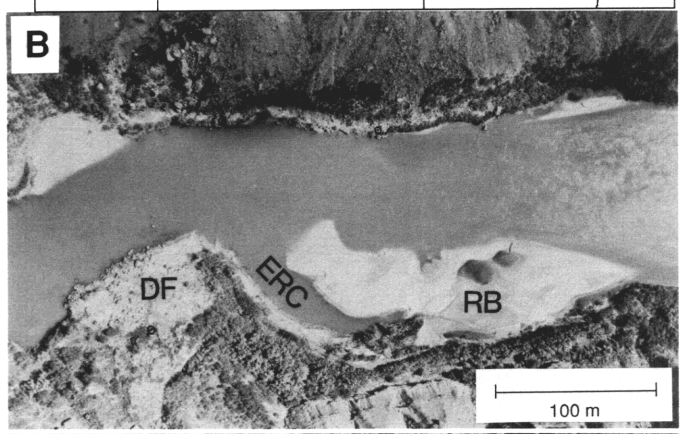
METHODS

This study included examination of aerial photographs taken in 1965, 1973, 1980, and 1984 and more than six weeks of field observation of bars throughout the Grand Canyon. Field studies were conducted at numerous sites in 1985 and 1986 and at a single site April 23–25, and October 21–24, 1987. These detailed studies form the core of this paper, but the ideas relating bar formation to internal structure were developed from observations of many bars on the Colorado River and other rivers in the western U.S.

The detailed field studies consisted of topographic surveys using a laser theodolite; bathymetric surveying of the main channel using a sonar depth recorder; measurements of surface flow made by observing the direction and speed of floating sticks; and examination of internal structures exposed in pits, trenches, and horizontal sections. The longest trench extended 55 m across the study bar.

Estimates of discharge during bar formation were based on discharge recorded at Lees Ferry (90 km upstream) and on observations of travel time of hydrograph peaks and troughs to the study site. Flow patterns over the bar were observed in April 1987 and determined in October 1987 from orientations of rib-and-furrow structures in horizontal sections excavated through climbing-ripple structures within the bar.





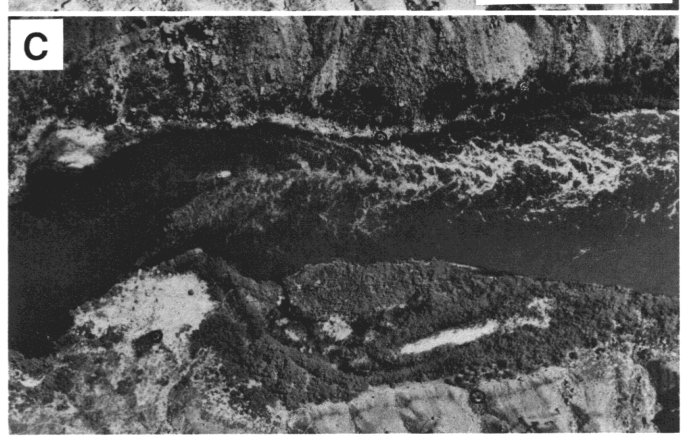


FIG. 2.—(A) Location map showing the Grand Canyon and study site. (B) Air photograph of study site in 1984 shows reattachment bar (RB), eddy-return channel (ERC), and debris fan (DF); the debris fan is mantled by a separation bar. Flow in main channel is from left to right. Aerial photograph by U.S. Bureau of Reclamation (October 21, 1984). Discharge at time of photograph was 85 m^3/s. (C) Air photograph of study bar in 1980; same area and scale as (B). Bar is covered with tamarisk trees and other vegetation. Floods in 1983 eroded much of this bar, but by 1984 the new bar (B) was well developed.

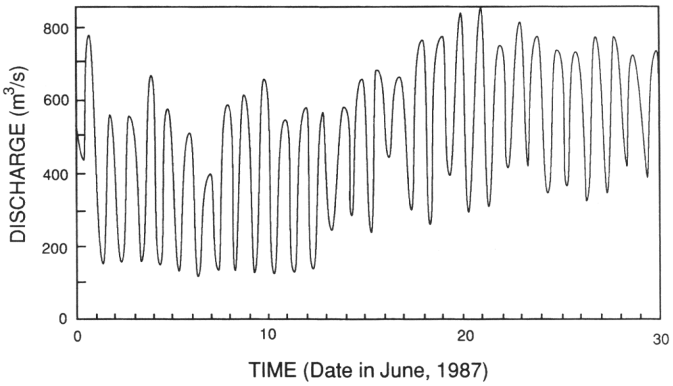


FIG. 3.—Hydrograph showing discharge at Lees Ferry for June, 1987. Discharge above approximately 600 m^3/s inundated the main platform of the study bar; cyclic discharge caused cyclic inundation and emergence of the study bar. Discharge fluctuated daily because of releases from Glen Canyon Dam.

FLOW PROCESSES IN A CHANNEL EXPANSION

The channel expansion at the study site contains a separation point, a reattachment point, a zone of recirculating flow, and an area of low-velocity, directionally variable flow upstream from the primary eddy, near the separation point (Fig. 1). Mean velocities are zero at the points where flow separates from and reattaches to the bank and in the center of the primary eddy. Throughout the eddy, instantaneous velocities also are relatively low, and deposition occurs as the flow from the main channel decelerates.

Recirculating flow at the study site occurs over our entire range of observations (from less than 110 m^3/s to 1,260 m^3/s); the flow pattern at a discharge of 620 m^3/s in April 1987 is shown in Figure 1. Maximum surface velocities in the main channel were 1.5 m/s; maximum surface velocities in the upstream part of the eddy over the bar were 0.3 m/s. As discussed below, however, the geometry of the recirculation zone varies with discharge.

The lengths of recirculation zones (measured from separation point to reattachment point) increase with discharge (Schmidt and Graf 1990, fig. 6; Schmidt 1990). The increase in length is caused more by downstream migration of reattachment points than by upstream migration of separation points. Downstream migration of reattachment points as a function of increasing flow velocity is commonly observed in laboratory experiments (Abbott and Kline 1962; Chang 1966; Allen 1968, figs. 3–13). Slight upstream migration of separation points in the Colorado River results from geometry of the constrictions. Debris fans that constrict the river are typically asymmetric cones skewed downstream. As stage increases, the separation point migrates upstream, toward the apex of the cone. Upstream migration of the separation point may also be a function of flow velocity. Experiments have shown that the point of flow separation (in flows around circular cylinders and spheres at much lower Reynolds numbers) shifts upstream as velocity increases (Batchelor 1967, figs. 4.12.1 and 4.12.8).

Stage-discharge relations suggest that at high discharges (such as those in excess of 2,000 m^3/s that occurred in 1983) the debris fan at the study site becomes flooded; without the constriction, the bar is subjected to downstream flow. Sand that was previously stable within the

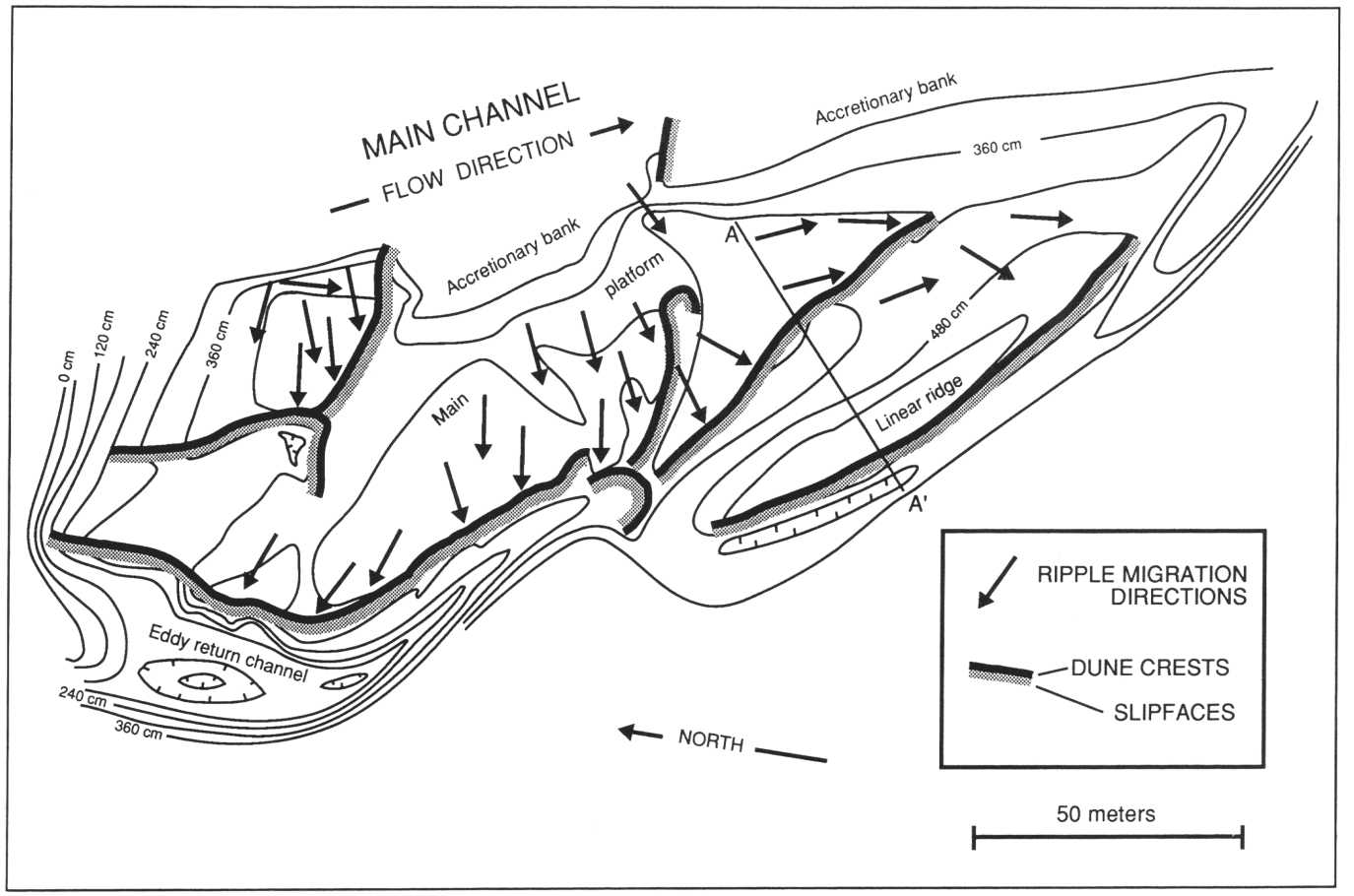


FIG. 4.—Topographic map of study bar. A–A′ shows location of stratigraphic sequence in Figure 5. Ripple migration directions were inferred from the orientation of symmetrical rib and furrow structures that were examined in horizontal section, as discussed by Rubin (1987, figs. 39 and 54). Elevations were measured relative to an arbitrary datum.

recirculation zone may then be eroded. At very low discharges, reattachment points migrate upstream, and the downstream ends of bars are subjected to erosive downstream flow (Schmidt and Graf 1990, fig. 20). Thus, the flow direction at any one point on the bar varies with discharge.

BAR TOPOGRAPHY

In a transect toward the main channel, the topographic features of the reattachment bar are: 1) an eddy-return channel, 2) a linear ridge, 3) a main platform, and 4) an accretionary bank (Figs. 4, 5). The eddy-return channel is the main pathway for upstream circulation in the main eddy (Figs. 1, 2B). Water circulates bankward over the bar surface in a broad, non-channelized, shallow flow into this channel. The depth and width of this eddy-return channel increase toward the separation point; this upstream increase in cross-section of the channel is characteristic of eddy-return channels and probably results from the increase in discharge of the return channel, which is caused by the flow across the bar converging with the upstream flow in the return channel. Eddy-return channels in bedrock canyons are analogous to the "secondary channels" in concave benches (Page and Nanson 1982; Nanson and Page 1983). In both settings, the channels are maintained by recirculating flow along the bank. Whereas the secondary channels along concave benches are continuous along the bank, however, eddy-return channels typically terminate where reattachment bars connect to the bank.

Most of the bar consists of a broad, relatively flat, platform that gradually steepens toward the main channel (Figs. 4, 5). At the highest elevations, the main platform projects into the channel and upstream (near "A" in Fig. 4). This projection was formed by deposition of sand near the reattachment point. Although the projection resembles a spit topographically, repeated topographic profiling and internal structures indicate that it is advancing upcurrent, opposite to the direction of advance of a spit. The linear ridge is a raised topographic feature that occurs bankward of the main platform. Bar stratigraphy (discussed below) suggests that most of the ridge is the erosional remnant of a platform formed at high discharge, probably during 1983.

The main platform and accretionary bank support 4–5 dunes that are migrating obliquely bankward, out of the main channel (Fig. 4). These dunes have several bar-like

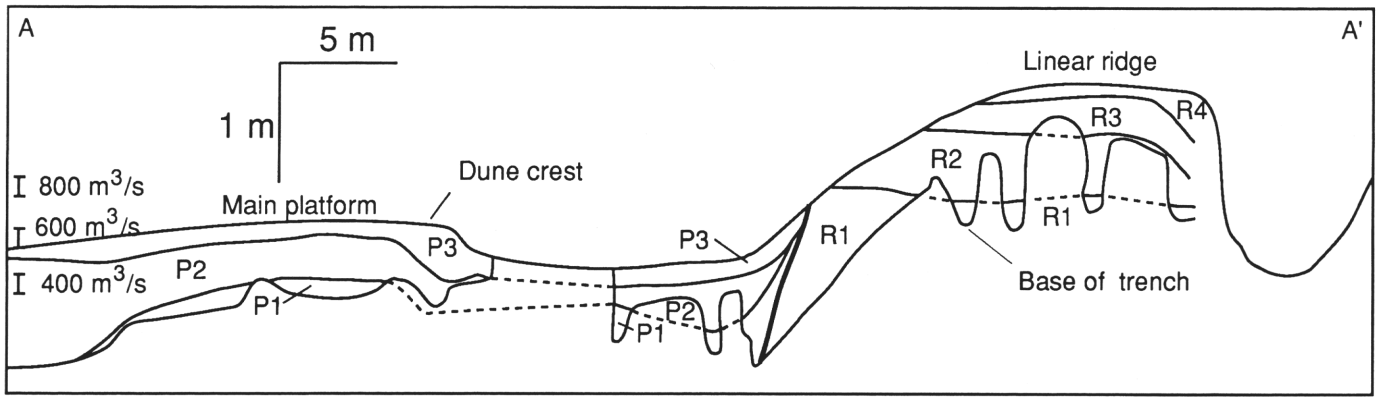


FIG. 5.—Stratigraphic sequence in bar. Units in linear ridge are designated R1–R4; units in main platform are designated P1–P3. Unit R1 is fluvial, cross-bedded, relatively coarse sand that was deposited by dunes and bars that migrated bankward to fill the channel expansion during high flows in 1983 (Fig. 6). Overlying units in the ridge are primarily fluvial climbing ripples and bankward-dipping foresets but contain three thin beds of climbing wind ripples. Structures in the main platform are climbing ripples and dune foresets (Fig. 7). Brackets at left show the estimated water-surface elevation for three discharges.

characteristics: at some times and locations, dune height approaches the flow depth; and at some discharges the dune topography functions as the channel margin.

INTERNAL STRUCTURES

Cross-Bedding

Cross-beds in the study bar originate by migration of the bar and by migration of superimposed dunes. Sets of foresets observed in trenches are as thick as 1.5 m; sets as thick as 4 m would form if the bar were to advance into the deeper parts of the eddy-return channel. As might be expected from the circulation pattern and dune orientations (Figs. 1, 4), upstream-dipping foresets are more abundant on upstream areas near the bank, and downstream-dipping beds are more abundant downstream and away from the bank.

In most sets of cross-beds in the bar, only foresets and bottomsets are preserved, but in some beds topsets also occur (Fig. 6). Where present, the topsets usually consist of climbing-ripple structures. Many of the foresets were produced by avalanching; these foresets dip at the angle of repose, contain internal shear surfaces, and are relatively uniform in composition and grain size (Fig. 6). Other foresets resulted from fluctuations in discharge; these foresets contain drapes of mud or organic matter and commonly dip at angles lower than the angle of repose (Fig. 7). Both kinds of foresets may be quite uniform in thickness. Uniformity in thickness of the fluctuating-discharge foresets results from regularity of diurnal variations in discharge (Fig. 3); uniformity of thickness of av-

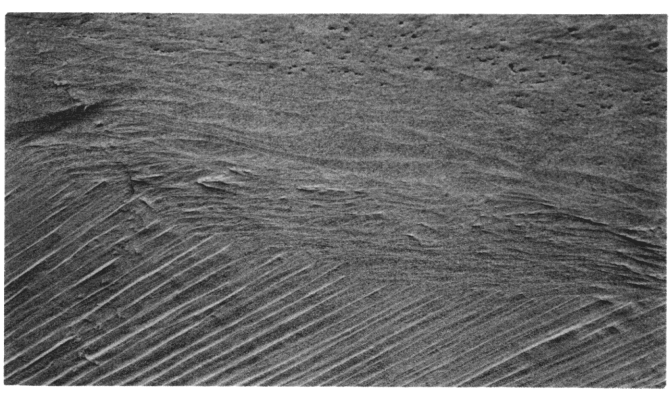


FIG. 6.—Grain-flow foresets and climbing-ripple topsets in unit R1. Steeply dipping foresets in lower bed were produced by avalanching as a bar or dune migrated bankward in the recirculation zone. Where the ripples migrated to the brink of the larger bedform, climbing-ripple topsets interfinger with the grain-flow foresets (most clearly visible at the left side of photograph). Faint laminae within grain-flow foresets are interpreted as shear surfaces. Area shown is 70 cm wide.

FIG. 7.—Regularly spaced mud drapes (dark layers) deposited by a dune in unit P3. Repeated topographic profiling indicates that these beds were deposited during a time when daily discharge variations caused the bar to be inundated daily. To the right of the compass, the horizontal section shows trough-shaped sets of cross-laminae deposited by ripples that were climbing down the lee slope of the dune; the climbing ripples are also visible in the upper right corner of the vertical section. Mud drapes were deposited on lower foresets and bottomsets. Compass is 20 cm long.

alanche foresets in steady flows has been attributed to cyclic avalanching processes (Hunter 1985).

Climbing-Ripple Structures

The surfaces of reattachment bars are commonly covered with ripples, ranging from asymmetrical ripples formed by unidirectional flow to symmetrical ripples formed by reversing flow. Although current ripples are most common, symmetrical, reversing ripples are considerably more abundant than might be expected in a fluvial environment. Some of these ripples are created by waves, but more commonly they are created by reversing flow that results from fluctuations in location of the reattachment point. Even when discharge is constant, the location of the reattachment point is not fixed; rather, it migrates upstream–downstream. Observations for up to an hour at different sites demonstrate that the excursion of the reattachment point ranges from as little as a few meters to as much as tens of meters. The duration of fluctuations ranges from a few seconds to more than ten minutes. One possible cause of some of these reattachment-point fluctuations is the vortices that form along the eddy line. As these vortices impact the bank in the vicinity of the reattachment point, the instantaneous location of the reattachment point would shift. The complete process is more complex and irregular, however, because the vortices decay and become deformed as they impact the bank and collide with other deformed vortices in the vicinity of the reattachment point. The resulting reattachment-point fluctuations are commonly much longer in duration than the vortex-shedding period.

When the instantaneous location of the reattachment point is downstream from the mean location, flow at the mean location is directed upstream; when the reattachment point moves upstream, flow at the mean location is directed downstream. Unlike wave-generated reversing flow that creates ripples with crests that parallel shore, this upstream–downstream reversing flow creates ripples with crests that trend normal to the bank. Some ripples formed at the reattachment point are as symmetrical and straight-crested as wave ripples; others have the plan form of interference ripples (Rubin 1987, fig. 64B). Evidently, the flow reverses too frequently for the ripples to adopt the morphology of current ripples. This inference is also suggested by internal structures (lamina-to-lamina zigzags at the ripple crests) which indicate that the ripples experience many flow reversals while ripple morphology and location remain relatively constant (Fig. 8). Thus, in both morphology and dynamics, these ripples are more akin to oscillation ripples than to current ripples. Indeed, we would argue that the resulting ripples should be called oscillation ripples, if that term did not imply formation by wave-generated reversing flow.

Symmetrical ripples in fluvial environments previously have been interpreted as wave ripples and attributed to backwater and overbank environments, "where wind-generated or other waves can over-ride any influence of the river current" (Allen 1984). The presence of ripples on the bed, however, is not sufficient to insure that climbing-ripple structures are preserved in the subsurface (McKee 1965); a unidirectional component of flow is necessary to introduce the sediment that is essential for the observed high angles of climb (Rubin 1987). The reattachment point is an ideal environment for creating such ripples. The reversing flow creates symmetrical ripples; the balanced upstream–downstream flow causes ripples to migrate very slowly or not at all, and relatively rapid deposition contributes to a high angle of climb. For this reason, we suspect that most fluvial ripples that are steeply climbing and symmetrical (or reversing) are produced by the reversing flow at reattachment points (for example, Davies 1966, plate 1C).

The character of climbing-ripple structures varies systematically with location. At increasing distances from the reattachment point, the flow becomes increasingly unidirectional, resulting in ripples that migrate more rapidly and therefore climb at lower angles. Upstream from the reattachment point and near the bank of the river, ripples are asymmetric and migrate upstream. Near the reattachment point, ripples migrate bankward or are symmetrical and reversing. Downstream from the reattachment point, ripples are asymmetric and migrate downstream. This spatial pattern in migration directions is shown in Figure 4; on bars that have natural cut-bank exposures, these lateral variations in ripple asymmetry and angle of climb are often displayed clearly, sometimes within a single bed.

The migration directions of ripples preserved within the bar are useful indicators of flow directions during formation of the bar. Such flow directions were determined by excavating horizontal sections and mapping the axes of trough-shaped sets of cross-laminae (rib-and-furrow structures) deposited by migration of three-dimensional ripples. Ripple-migration directions were mapped only from such structures where symmetry of the structures (in sections parallel to the generalized depositional surface) indicated that the ripples were transverse—not oblique—to flow (Rubin 1987, figs. 39 and 54). The circulation pattern defined by ripple-migration directions (Fig. 4) is similar to the flow pattern observed over the bar (Fig. 1). The patterns are not identical, however, because some climbing-ripple structures were deposited when discharge was relatively low, and the reattachment point shifted upstream.

Where changes in discharge produce changes in eddy geometry, the structure of climbing-ripple beds can be quite complex. For example, a decrease in discharge can cause topographic obstructions to become emergent, thereby producing eddies—and reversing or upstream flow—at sites where the flow was previously downstream. Vertical sequences deposited at such sites consist of downstream-climbing ripples overlain by vertically climbing, symmetrical, reversing ripples, which are in turn overlain by upstream-climbing ripples (Fig. 8). At sites that are immediately upstream from the reattachment point, decreases in discharge can produce the reverse vertical sequence; the local change in flow direction occurs because of the upstream migration of the reattachment point at lower discharges. Changes in discharge

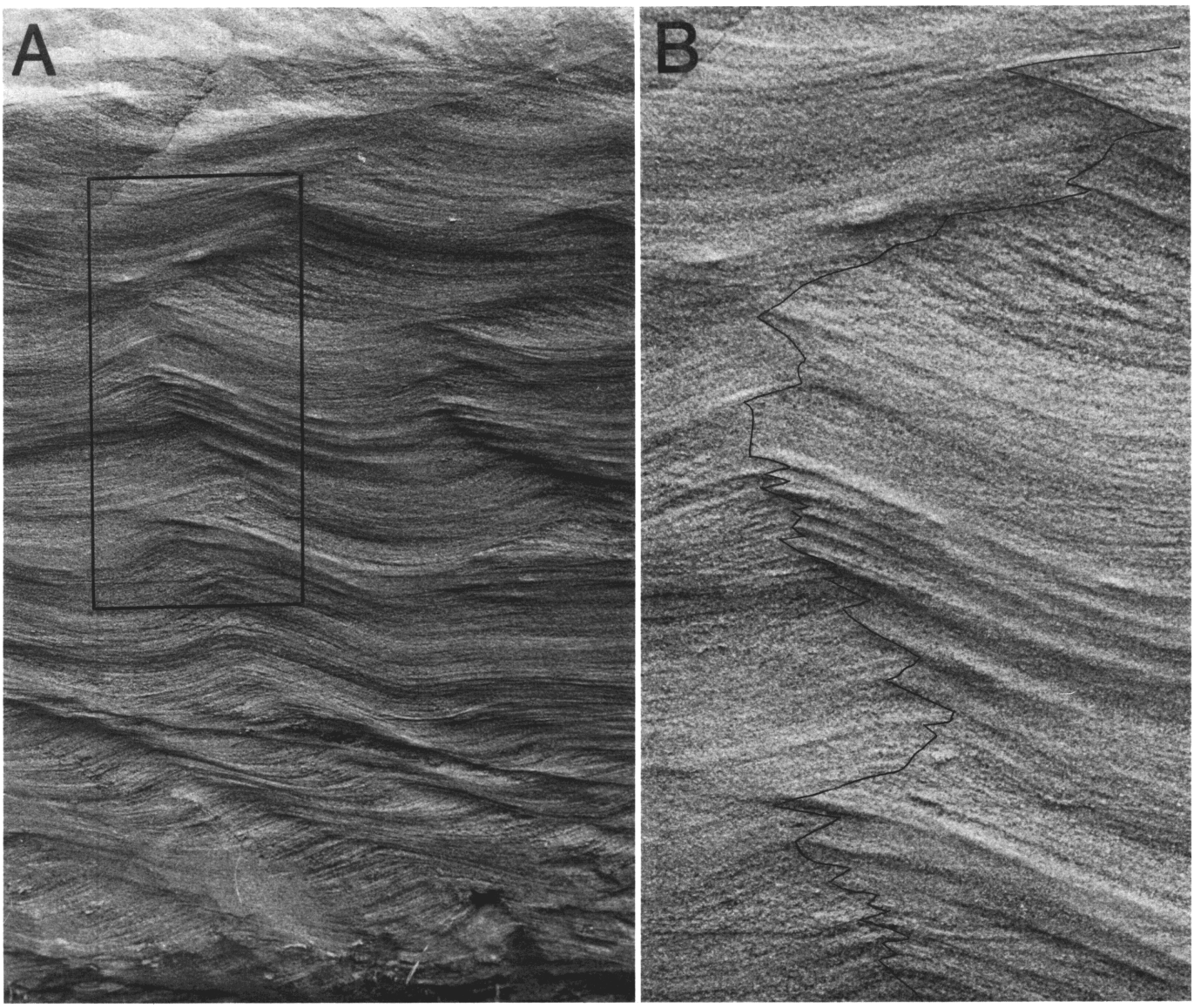


FIG. 8.—Vertical sequence showing reversals in ripple migration direction. The reversals occur over a wide range of scales. (**A**) On the largest spatial scale and longest temporal scale, the ripples reverse from right-to-left (downstream) in lower part of photograph to left-to-right (upstream) at top. Upstream flow at the top of the bed is presumed to have started when the reattachment point migrated downstream and the depositional site was incorporated within a recirculation zone. Area shown is 27 cm wide. (**B**) Enlargement of area outlined in (A); approximately actual size. Line on photograph—along the contact between left- and right-dipping cross-laminae—represents the path of climb of the ripple crest. The ripples are relatively symmetrical and reverse upstream–downstream with excursions as large as a few centimeters and as small as a few millimeters. The smallest reversals that can be recognized are visible as lamina-to-lamina zig-zags at the ripple crests. These reversals in migration are presumed to result from flow reversals caused by fluctuations in location of the reattachment point. Although these ripples resemble wave ripples in morphology and dynamics, waves are not involved in their formation. This example is from another reattachment bar in the Grand Canyon.

can also cause parts of the bar surface to undergo erosion; ripples at such sites scour into underlying sediment, thereby producing a ripple-form erosional surface (Rubin 1987, fig. 11).

Upstream-climbing ripples are extremely common in reattachment bars, because these ripples occur where the preservation potential is relatively high (near the bank in the upstream part of the recirculation zones). This part of the bar is less subject to erosive downstream flows that rework the downstream part of the bar when discharge decreases and the reattachment point shifts upstream. As a result of this high preservation potential, upstream-climbing ripples are extremely common—possibly more abundant than downstream-climbing ripples—in the exposures along the banks of the Colorado River. Upstream-climbing ripples are common in recirculation zones in alluvial rivers as well as in bedrock canyons. Ripples and dunes that migrate or climb upstream have been reported from recirculation zones on point bars and concave benches in meandering alluvial and tidal channels (Davies 1966; Taylor et al. 1971; Leeder and Bridges 1975; Page and Nanson 1982; Nanson and Page 1983).

HISTORY OF THE STUDY BAR AND MODEL OF BAR FORMATION

Air photography shows that in 1980 a marsh occupied the channel expansion at the study site (Fig. 2C). Tamarisk trees grew on the marsh at an elevation of only 1–2 m above the present surface. The marsh was eroded from the expansion by high flow in 1983, and all of the beds observed in the bar (Fig. 5) evidently post-date 1983, because they are undisturbed by roots.

Of the beds observed in the study bar, the oldest are found in the core of the linear ridge (unit R1 in Fig. 5). This unit consists of bankward-dipping foresets that were deposited by bankward migration of the bar or superimposed dunes, overlain by climbing-ripple topsets (Fig. 6). Younger units in the ridge (R2–R4) consist of subaqueous beds (dune or bar foresets and climbing-ripple structures) separated by three beds of climbing wind-ripple structures several centimeters or tens of centimeters thick. These wind-ripple structures, like examples reported from classic eolian deposits (Hunter 1977), are recognizable by their regularity of thickness, which gives the bedding a "pin-stripe" appearance (Rubin and Hunter 1987); by inverse grading that results from inverse grading on the lee side of the migrating wind ripples; and, rarely, by faintly preserved ripple foresets. These subaqueous-eolian couplets are inferred to have formed annually. The subaqueous beds in the ridge must have been deposited during the late spring, because the beds occur at elevations that were inundated only by discharges in excess of 1,150–1,230 m^3/s; such high flows occurred only during the late springs of 1983–86. The eolian beds were formed during other seasons, when discharge was too low to drown the ridge. A complete sequence would have included an eolian-subaqueous couplet for each of the four years when flow over-topped the ridge (1983–86), but we could only identify three such couplets.

Although deposition occurred on the crest and bankward side of the ridge between 1983 and 1987, much of the opposite side experienced net erosion. This erosion is evidenced by truncation of units R1–R4 (Fig. 5) and by differences in ridge topography observed between 1984 and 1987. We do not know the original extent of these truncated beds, but we suspect that at least the lowermost beds in the ridge (R1) are the remnants of a central platform that formed during 1983, at a higher elevation than the present platform. As the 1983 high flows receded, this higher platform was eroded, forming the truncation surface between units P1–P3 and R1 (Fig. 5). Units P1–P3 were subsequently deposited, producing the present platform. In 1986–87, discharges were not high enough to top the ridge, and fluvial deposition was restricted to the central platform and accretionary bank; approximately 15 cm of sediment in unit P3 were deposited on the central platform between April and October 1987.

The depositional history described above can be related to both the sedimentary structures and grain size of the bar. Large-scale cross-beds were deposited by bankward-migrating dunes or bars in the early history of the bar (unit R1), presumably because flow in the recirculation zone was relatively deep and unrestricted, and velocities were high both in the main channel and in the recirculating flow. In contrast, during 1986–87 when discharges were low, only shallow restricted flows occurred over the bar surface, depositing muddy rippled sediment (unit P3). This pattern holds throughout the canyon; foresets deposited by dunes and bars have a slightly coarser mean grain size (0.28 mm) than do climbing-ripple beds (0.20 mm).

Several of the bars that have been trenched contain beds of massive sand; these beds have only been found at depths of 1–2 m within the bars, however. Basal contacts of these beds are commonly erosional and exhibit high relief. One such basal surface contained abundant potholes scoured into the cohesive underlying sediment. The erosional contacts and massive bedding suggest that these beds represent the early phases of development of the bars. The scour surfaces are inferred to form when pre-existing bars are flushed out of the channel expansion; the massive beds are then deposited from suspension under conditions in which dunes cannot form. If present in the study bar, massive beds would be expected to be at the base of the 1983 deposits, below the base of the trench.

An idealized sequence for the development of a reattachment bar begins with extensive scour of older deposits during high discharge, followed by deposition of a bar during the receding flows. If discharge receded gradually and if enough sediment were available, the channel expansion might fill with sediment. A complete vertical sequence would consist of a scoured surface overlain by massive beds deposited from suspension and then by foresets deposited by dunes migrating in a rotary pattern. Eventually, deposition within the expansion would restrict circulation to such an extent that the flow could no longer maintain the large bedforms and could no longer transport the coarser grain sizes; the large bedforms would be replaced by ripples, and the grain size would become finer. The final phase would consist of deposition of mud and organic matter, colonization by vegetation, and the formation of a marsh or floodplain. This sequence has several similarities to the idealized sequence expected of bars in meandering channels: channel facies are overlain by overbank facies; grain size fines upward; dune-scale cross-bedding is overlain by climbing ripples; and bedform migration directions diverge from the direction of bar advance. The presence of structures indicating rotary and reversing flow, however, can be used to identify recirculation deposits.

Evolution of the bars on the Colorado River is considerably more complicated than this idealized model, because discharge has decreased since the high flows of 1983. The general pattern of deposition-erosion is: 1) erosion of part of the bar during peak discharge, 2) deposition within a large recirculation zone when the debris fan emerges, 3) deposition within a smaller recirculation zone and erosion of sand at the downstream end of the bar when discharge is low and the reattachment point retreats upstream. Even this pattern is complicated by seasonal flow fluctuations in 1984–86 and daily fluctuations in 1986–87.

RELEVANCE TO ALLUVIAL RIVERS

Although bars in bedrock canyons are unlikely to be preserved in the rock record—except overlying unconformities, as noted by Baker (1984)—the same processes that create reattachment bars in bedrock canyons also operate in alluvial rivers. Deposition in recirculation zones is fundamental in adjusting channel morphology and smoothing channel irregularities on alluvial rivers. For example, recirculation zones occur on point bars in meandering channels, as shown by theoretical studies (Bagnold 1960), experimental studies (Leopold et al. 1960), and field studies (Davies 1966; Taylor et al. 1971; Leeder and Bridges 1975). The reattachment bars that form in bedrock canyons are even more akin—both morphologically and dynamically—to bars in recirculation zones in concave benches (Page and Nanson 1982). Recirculation zones also occur downstream from dunes, mid-channel bars, and other topographic features that become emergent during receding flows. We have seen an example of such a recirculation zone and upstream-climbing ripples in the lee of an emergent dune on a point bar in the Sacramento River, California. Recirculation deposits could also be expected to fill channel expansions at the mouths of abandoned channels and migrating tributaries.

Like the recirculation zones in bedrock canyons, those in sandy channels are effective in trapping sediment (Leeder and Bridges 1975) and occur on accreting surfaces of migrating channels (Page and Nanson 1982); deposits of the recirculation zones therefore can be expected to be preserved in the rock record. Because the alluvial channel recirculation zones contain upstream-migrating bedforms and symmetrical, vertically climbing ripples (Davies 1966, plate 1C), deposits of recirculation zones—and reattachment points in particular—should prove to be an identifiable sub-facies of alluvial channels.

CONCLUSIONS

Recirculation zones are sites of deposition in bedrock canyons and alluvial rivers. Deposition is commonly focused at the separation point, reattachment point, eddy center, or along the shear surface that separates the recirculation zone from the downstream flow in the main channel. Recirculation deposits are characterized by a rotary flow pattern that includes upstream flow. Fluctuations in location of the reattachment point produce upstream–downstream reversing flow; this flow produces symmetrical, reversing ripples with relatively straight crests that trend normal to the bank. The most diagnostic feature of reattachment bars is the morphological and directional pattern of climbing ripples. At the reattachment point, ripples migrate toward the bank or are symmetrical, reversing, and vertically climbing. They grade laterally into more asymmetric ripples that climb upstream and downstream from the reattachment point.

Flow patterns within channel expansions vary with discharge. Increases in discharge generally increase the length of the recirculation zone. Under steady conditions, reattachment bars evolve with a fining-upward sequence because flow over the bar becomes increasingly restricted.

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REFERENCES

ABBOTT, D. E., AND KLINE, S. J., 1962, Experimental investigation of subsonic turbulent flow over single and double backward facing steps: Jour. Basic Engineering, v. 84, p. 317–325.

ALLEN, J. R. L., 1968, Current Ripples; Their Relation to Patterns of Water and Sediment Motion: Amsterdam, North-Holland Publishing, 433 p.

———, 1984, Sedimentary Structures. Their Character and Physical Basis: Amsterdam, Elsevier, 663 p.

BAGNOLD, R. A., 1960, Some aspects of the shape of river meanders: U.S. Geol. Sur. Prof. Paper 282-E, p. 135–144.

BAKER, V. R., 1984, Flood sedimentation in bedrock fluvial systems, *in* Koster, E. H., and Steel, R. J., eds., Sedimentology of Gravels and Conglomerates: Can. Soc. Petroleum Geol., Mem. 10, p. 87–98.

BAKER, V. R., KOCHEL, R. C., PATTON, P. C., AND PICKUP G., 1983, Paleohydrologic analysis of Holocene flood slack-water sediments, *in* Collinson, J. D., ed., Modern and Ancient Fluvial Sediments: IAS Spec. Publ. 6, p. 229–239.

BATCHELOR, G. K., 1967, An Introduction to Fluid Dynamics: Cambridge, Cambridge Univ. Press, 615 p.

DAVIES, D. K., 1966, Sedimentary structures and subfacies of a Mississippi River point bar: Jour. Geol., v. 74, p. 234–239.

CHANG, P. K., 1966, Separation of Flow: New York, Pergamon, 777 p.

HAMBLIN, W. K., AND RIGBY, J. K., 1968, Guidebook to the Colorado River, part 1, Lee's Ferry to Phantom Ranch in Grand Canyon National Park: Brigham Young Univ. Geology Studies, v. 15, pt. 5, 84 p.

HAMBLIN, W. K., AND RIGBY, J. K., 1969, Guidebook to the Colorado River, part 2, Phantom Ranch in Grand Canyon National Park to Lake Mead Arizona-Nevada: Brigham Young Univ. Geology Studies, v. 16, pt. 2, 126 p.

HOWARD, A. D., AND DOLAN, R., 1981, Geomorphology of the Colorado River: Jour. Geol., v. 89, p. 269–298.

HUNTER, R. E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, p. 362–387.

———, 1985, A kinematic model for the structure of lee-side deposits: Sedimentology, v. 32, p. 409–422.

KIEFFER, S. W., GRAF, J. B., AND SCHMIDT, J. C., 1989, Hydraulics and sediment transport of the Colorado River, *in* Elston, D. P., Billingsley, G. H., and Young, R. A., eds., Geology of Grand Canyon, Northern Arizona: A.G.U. 28th Int'l. Geol. Cong. Field Trip Guidebook T115/315, p. 48–66.

LEEDER, M. R., AND BRIDGES, P. H., 1975, Flow separation in meander bends: Nature, v. 253, p. 338–339.

LEOPOLD, L. B., 1964, The rapids and the pools—Grand Canyon: U.S. Geol. Sur. Prof. Paper 669-D, p. 131–145.

LEOPOLD, L. B., BAGNOLD, R. A., WOLMAN, M. G., AND BRUSH, L. M., 1960, Flow resistance in sinuous or irregular channels: U.S. Geol. Sur. Prof. Paper 282-D, p. 111–134.

MCKEE, E. D., 1938, Original structures in Colorado River flood deposits of Grand Canyon: Jour. Sed. Petrology, v. 8, p. 77–83.

———, 1965, Experiments on ripple lamination, *in* Middleton, G. V., ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation: SEPM Spec. Publ. 12, p. 66–83.

NANSON, G. C., AND PAGE, K., 1983, Lateral accretion of fine-grained

concave benches on meandering rivers, *in* Collinson, J. D., ed., Modern and Ancient Fluvial Systems: IAS Spec. Publ. 6, p. 133–143.

PAGE, K., AND NANSON, G. C., 1982, Concave-bank benches and associated floodplain formation: Earth Surface Processes and Landforms, v. 7, p. 529–543.

ROUSE, H., BHOOTA, B. V., AND HSÜ, EN-YUN, 1951, Design of channel expansions: Transac. Amer. Soc. Civil Engineers, v. 116, p. 347–363.

RUBIN, D. M., 1987, Cross-Bedding, Bedforms, and Paleocurrents: SEPM Concepts in Sedimentology and Paleontology, v. 1, 187 p.

RUBIN, D. M., AND HUNTER, R. E., 1987: Field guide to sedimentary structures in the Navajo and Entrada Sandstones in Southern Utah and Northern Arizona: G.S.A. Field Trip Guidebook, 1987 meeting, Phoenix, Arizona, publ. by Arizona Geological Survey, p. 126–139.

SCHMIDT, J. C., 1986, Changes in alluvial deposits, upper Grand Canyon, *in* Proceedings of the Fourth Federal Interagency Sedimentation Conference: Water Resources Council, p. 2-48 to 2-57.

———, 1990, Recirculating flow and sedimentation in the Colorado River in Grand Canyon, Arizona: Jour. Geol. v. 98.

SCHMIDT, J. C., AND GRAF, J. B., 1990, Aggradation and degradation of alluvial sand deposits, 1965–1986, Colorado River, Grand Canyon National Park, Arizona: U.S. Geol. Sur. Prof. Paper 1493, 100 p.

TAYLOR, G., CROOK, K. A. W., AND WOODYER, K. D., 1971, Upstream-dipping foreset cross-stratification: origin and implications for paleoslope analyses: Jour. Sed. Petrology, v. 41, p. 578–581.

TURNER, R. M., AND KARPISCAK, M. M., 1980, Recent vegetation changes along the Colorado River between Glen Canyon Dam and Lake Mead: U.S. Geol. Sur. Prof. Paper 1132, 125 p.