

Mackin stated clearly how he conceived base level and the equilibrium profile to be related.

A rise in base level is equivalent to the rising of a barrier across the path of the graded stream . . . the final readjusted profile will tend toward parallelism with the original profile . . . but because of secondary effects of aggradation . . . , precise parallelism will usually not be achieved (Mackin, 1948: p. 496). Lowering of base level is, insofar as the response of the stream is concerned, essentially the same as the lowering of a barrier in its path. . . . Downcutting must continue until slope is again completely adjusted to supply just the velocity required to transport all of the debris shed into the stream; as in the last case, and with the same qualifications, the final adjusted profile will tend to parallel the original profile (Mackin, 1948: p. 498).

This conclusion is inferred in part from the fact that in many river systems, stratigraphic and morphologic evidence shows that when a master stream aggraded, so also did entering tributaries. If a terrace or level of an abandoned flood plain occurs along the valley sides of a master stream it is usual to see a similar terrace along the sides of tributary valleys and, at the junction of the valleys, the terraces are at the same elevation.

Similarly most tributaries enter the master stream at the elevation of the master stream and are said to be "graded to the master stream." Only where a tributary is at its mouth traversing a resistant layer of rock, or whose elevation was determined by some process operating in the past such as glacial action, does the tributary discharge over a waterfall into the master stream. Such "hanging valleys" are seen in glaciated terrain and in deep gorges as in the Grand Canyon system.

When a tributary meets the master stream at grade, the usual case, it is not possible to say whether the effect of the master stream is felt far upstream or merely a short distance. A rise or lowering of the level of the master stream constitutes a base-level change for the tributary. Therefore it cannot be ascertained whether the observed change in the tributary system was caused by change of base level or by a combination of base-level change and concurrent discharge-sediment relations affecting both tributary and master stream simultaneously. The separate effect of such base-level changes cannot be isolated.

PURPOSE AND SCOPE

The influence of local base level and the effects of a change of base level can be separated from the influence of hydrologic and geomorphic processes within the basin under certain conditions.

These include the following situations: 1) observed changes in the longitudinal profile by aggradation or degradation when a local base level is lowered or raised while the basin conditions remain unchanged. 2) observed changes in aggradation and/or degra-

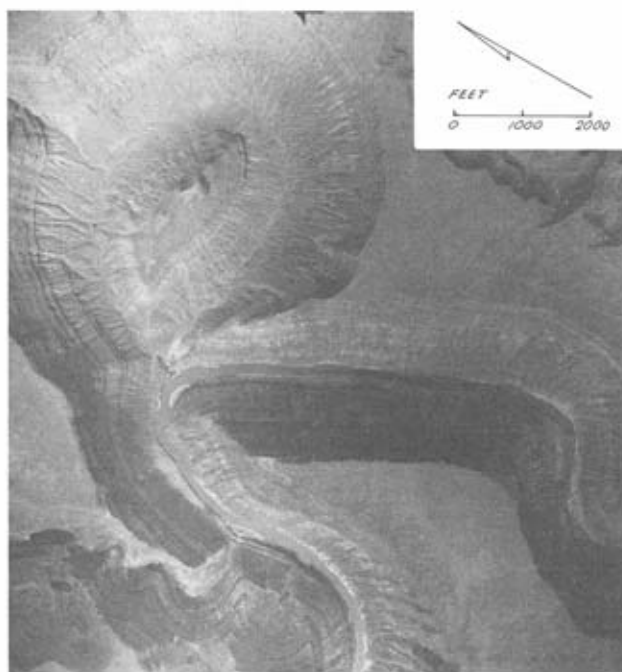


FIG. 1. Aerial photograph of the Loop, an abandoned meander, showing its relation to the present canyon of the San Juan River.

dation of valley fill alluvium during periods of unchanging local base level.

By the analysis of field examples in which the separation of base level from basin changes can be made, we propose to draw some inferences that may clarify the relations between local base levels and base-level processes, and between a base-level change and the longitudinal profile upstream.

ALLUVIAL HISTORY OF A CHANNEL DURING SLOWLY LOWERING BASE LEVEL WHEN SEPARATED FROM THE MASTER STREAM

The Loop of the San Juan River, Utah

Preliminary remarks

Rivers have a heritage but no beginning. Through geologic time even the first incipient channel system appearing on an emerging landmass changes in form, drainage network, and gradient as relief increases. There is continual modification, but at any stage the existing system is different from that which existed at a previous state, but has been influenced by that earlier stage.

Therefore there is a special interest attached to any fluvial system that, owing to some geologic accident, has a definite and known origin. A singular case of this is an abandoned meander loop that becomes isolated from the river of which it was once a part. Three examples exist in the canyon country in the middle reaches of the Colorado River in Utah; the Rincon of the main Colorado River, the Gooseneck in

the Labyrinth Canyon of the Green River, and the Loop of the San Juan River. All are abandoned meander bends which had been superimposed on structurally rising landscapes, and before abandonment, had incised into horizontally bedded sedimentary rocks many hundreds of feet. They are thus encased by steep, nearly vertical cliffs that form the boundaries for the isolated valleys. By far the simplest and most symmetrical is the Loop of the San Juan River, located between Bluff and Mexican Hat, Utah.

Physical character

The Loop is an elliptical gorge, the circumference of which along the central axis is about two miles. The Loop was cut into horizontally bedded sandstones, limestones, and shales of carboniferous age with steep, and in places vertical, bounding cliffs hundreds of feet in height. It is a cutoff meander of the San Juan River, which, since abandonment of this curve, has continued to downcut and now flows at a level 130 feet lower in elevation than it did at the time this cutoff occurred (figs. 1 and 2). The separation of the abandoned segment and the present river is in the form of a series of vertical falls over a bed of resistant rock (fig. 3).

Thus, at a moment in time in the Pleistocene a confined segment of a river valley became isolated from the main river that had formed it, leaving a small independent drainage basin the boundaries of which were the cliff tops on each side. Its central



FIG. 3. View to the east from the mouth of the Loop of the San Juan River. In the foreground the two ephemeral stream channels draining the east and west sides of the Loop end abruptly at a dry waterfall, the top of which is 130 feet above the San Juan River.



FIG. 4. Well-sorted gravel and sand deposited by the ancestral San Juan River, and exposed in the West Arroyo of the Loop.

axis was a former river bed having a width of 180 feet and, as will be shown, a gradient of about .001 (five feet per mile).

The flat floor of the gorge, being a former river bed, was covered with well-rounded gravel averaging one hundred mm. in diameter, derived not from the local cliffs but from the far headwaters in the San Juan Mountains of Colorado. The gravel consists primarily of quartzite with a small percentage of conglomerate and vein quartz rocks. This gravel of the ancestral river crops out in a few places (figs. 4 and 2), and where it is in contact with underlying bedrock establishes the elevation of the former river bed.

Debris derived from the adjacent cliffy slopes continued to wash and fall into this gorge after abandonment, and alluviation on the valley floor began. The debris included large sandstone blocks riven off the cliffs by frost action and weathering, steep talus and debris sheets of heterogeneous rubble that can be seen now throughout the canyons of the Colorado River and its tributaries. Cliffs are more common along the San Juan River than in the headwaters of the Loop. The processes of cliff retreat since meander abandonment have furnished fine as well as coarse materials, which have accumulated in the Loop to depths of as much as 150 feet, and have furnished an unknown amount of sediment load to the San Juan River. Since meander abandonment, the footslopes of the cliffy hillsides in the headwaters of the Loop have eroded in a manner different from those adjacent to the San Juan River, which has continued to downcut. Bull (1975: pp. 1495, 1496) shows that the slopes adjacent to the San Juan River are steeper and more concave than those adjacent to the backfilled gorge of the Loop.

tion. But in some places the tread is sufficiently level to provide a reasonable estimate of its original height. Different symbols are used on figure 9 to distinguish scarp from tread height. The tread of the low terrace is sufficiently flat in most places to establish with some surety the original height of that alluvial fill.

The low terrace follows the profile of the present stream closely in the central reaches of both East and West Arroyos. Even in the unusually steep portion between station 15+00 and 30+00 the profile of the high terrace appears to follow suit. In both basins the heights of the terraces decrease in the two thousand feet closest to the watershed divide, extinguishing to zero at the divide.

The overall slopes of the terraces of figure 9 are not as steep as the gradient of the present day arroyos. For example, the high terrace of the West Arroyo progressively diverges from the present stream in the downstream direction. In the 3,900 feet between station 51+00 and station 90+00 the high terrace falls 179 feet and the stream falls 216 feet, thus the overall gradient has increased about twenty-one per cent. When the downstream reaches of the West Arroyo were aggrading, it was not possible for the stream to increase its sediment capacity by channel entrenchment. Subsequent channel entrenchment may have occurred as a result of a decrease of sediment load being supplied from the hill-slopes, or an increase in stream discharge.

Gradient of the ancestral San Juan River

Patches of river gravel of exotic lithologies are exposed in both west and east basins (figs. 2 and 4).



FIG. 7. View of coarse grained valley fill in the West Arroyo of the Loop at station 83+50.



FIG. 8. View downstream of the East Arroyo of the Loop. The prominent horizontal outcrops on the ridge to the right of center in the background are part of a nose that separates the present San Juan River from the Loop.

Their areal extent is shown on figure 2 and their vertical extent on the profile of figure 9. To establish the gradient of the ancestral river one might use the elevations of the gravel-bedrock contact or use the top of the gravel. The former may include errors due to uneven surface of the eroded bedrock, while the latter may have been eroded in post-abandonment time. With the exposures available, the top of the gravel gives the most reasonable estimate shown as the line on figure 9 which has a slope of 0.0012. The present San Juan River in the vicinity of the Loop has a slope of 0.0015.

The thickness of San Juan River gravel exposed in the Loop varies from fifteen to forty feet. The present San Juan River in the reaches near the Loop is flowing on bedrock or on a foot or two of sand and gravel above bedrock. However, along the sides of the river are patches of sand and gravel, five to twenty feet thick, that have been deposited at times of higher discharge. It appears, then, that the ancestral San Juan River was comparable to the present river both in gradient and in the thickness of alluvial fill above the bedrock.

Analysis of the ephemeral streams

It is in respect to the longitudinal profile that the geologic accident of the meander cutoff is of particular interest, because the new profile was developed by the ephemeral streams in a relatively short period of geologic time with none of the usual influences of previous history. The streams did not inherit any relief ratio, for at the beginning the gradient of the

they cannot either roll to or be transported over the gentle gradients of the central valley. The debris from rockfalls accumulated on top of the valley fill. The extensive stripping and deep gullying of the hillslope colluvium that has occurred during the Holocene furnished the debris for the surficial deposits that cap the fine grained valley fill; it also exposed the bedrock ledges that allowed rockfalls to become a more important geomorphic process. These rockfalls may have been induced by seismic shaking if the monocline under the Loop vicinity is associated with an earthquake-generating fault at still greater depths.

Implications of the high terrace

The age of the meander cutoff has been determined only in general terms. Speaking of the canyons upstream from the Grand Canyon, specifically illustrated by the San Juan in the vicinity of the Loop, Hunt (1969; p. 92) states that, "About five hundred feet of canyon deepening (occurred) during Quaternary time (the last two million years)." The level of the San Juan at the time of cutoff was at 4,340 feet, the top of the adjoining cliffs are at five thousand feet, and the present river is at 4,175 feet. Thus, the cutoff occurred when the canyon was about ninety per cent of its present depth. We place the cutoff in the late Pleistocene. The cutoff of the Rincon on the main Colorado appears older from several lines of evidence. It stands about five hundred feet above the present river and about it, Hunt says, "I assume . . . (it is) at least as old as early Pleistocene" (1969: p. 101). His discussion of the late Pleistocene events includes the statement that,

There must have been snowfields on many of the north-facing cliffs, several of which contain ancient debris avalanches. . . . These deposits are deeply dissected and deeply weathered, but they record a middle or late Pleistocene episode when the climate was more moist than now and the canyon walls were mantled with the weathering products of the period (p. 105).

These observations are useful, but the most direct evidence comes from the rudimentary soil profile developed on the surface of the fill of the high terrace (see appendix 2). The combined evidence of highly dissected debris and talus slopes on the walls of the Loop gorge and the Holocene soil profiles developed on the surface of the high terrace fill are clear evidence that the canyon walls were mantled with debris before the Holocene. Part of this debris has been stripped from the slopes and has furnished the alluvium rich in debris-flow deposit that caps the valley fill. Such a sequence of events implies that the hillslopes during the latest Pleistocene had a more protective vegetative cover and/or a greater rate of weathering.

That the climate of the recent geologic past has been more moist than the present is indicated by the



FIG. 11. Headwaters of the East Arroyo of the Loop. Sandstone blocks derived from the cliffs have accumulated at the foot of the hillslope and on the fine grained valley fill, which has a Holocene soil profile.

presence of fossil juniper stems and seeds in the middens of pack rats, which we found in rock niches and openings in the cliffs of the Loop. There are at present no such trees in the Loop. The use of vegetal material in pack rat middens as indicators of Quaternary climates has been developed by Wells and Rainer (1967), and by Van Devender (1977). The fine grained deposits in the high terrace materials also imply more precipitation than at present, but its admixture with debris-flow material suggests a still semiarid climate rather than a sub-humid one.

The subsequent trenching of the high terrace and its partial removal is quite in accord with the evidence that relative aridity is associated with high intensity storm rainfall and the absence of low intensity, long duration storms that succor the vegetation (Leopold, 1951; Cooke and Reeves, 1976).

The accumulation of low terrace material in the trenched valley is also interpreted as a shorter period of increased sediment yield. A similar low terrace lying within the trench of a high terrace exists in Gypsum Canyon, a tributary to the Colorado River fifty miles to the west, and charcoal at a paleo-indian burial within that low terrace has been dated at 640 ± 200 BP (Nieuwenhuis, 1978). This implies that the low terrace is comparable in age to the Tsegi Formation of Hack (1942), or Deposition II of Bryan (1941), and that the trenching of the terrace took place at about the time alluvial valleys in Arizona and New Mexico were trenched.

We conclude that the meander cutoff was in late

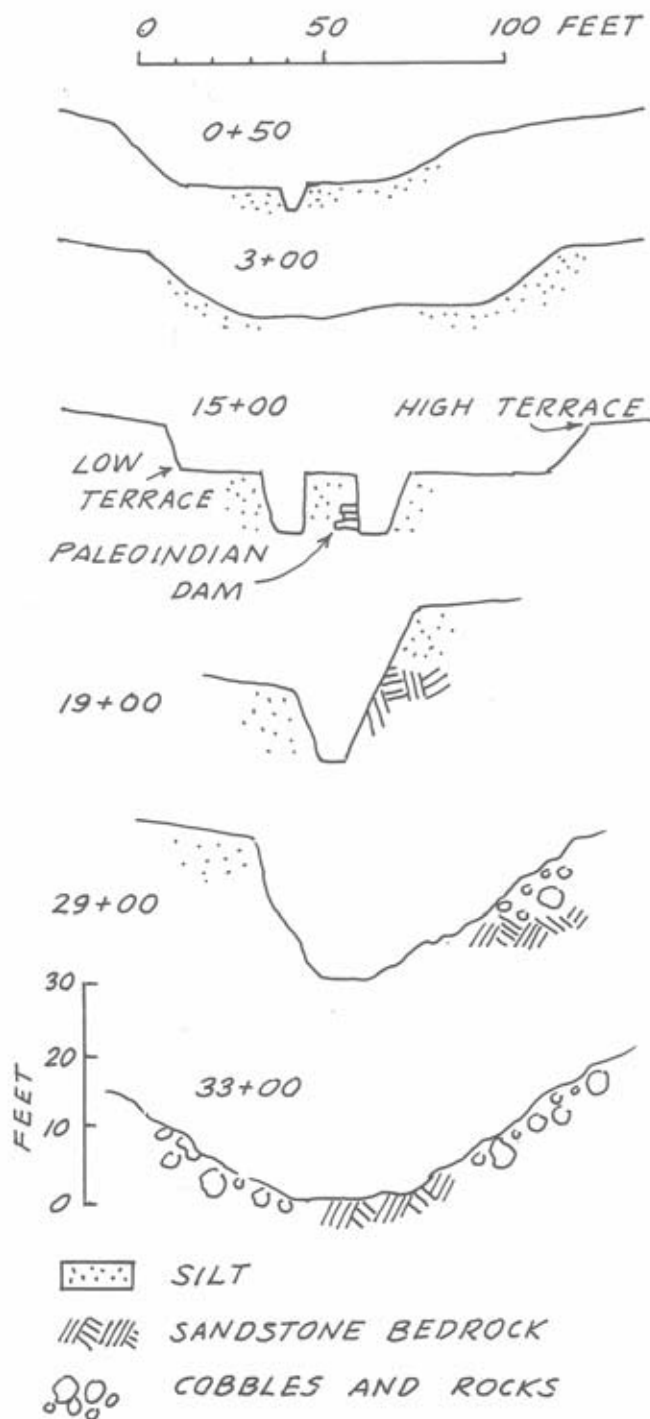


FIG. 13. Cross section of the channel of Madame Walk Arroyo at several positions along its length. Location of cross sections relative to the longitudinal profile is indicated by the distance scale (abscissa) of figure 12. Low and high terraces and present channel bed can be seen on the cross sections.

The average gradients of bedrock floor, present channel thalweg and the two terraces are all about equal at 0.033.



FIG. 14. Photograph of gully in Madame Walk Arroyo looking upstream at station 15+00 in vicinity of paleo-indian dams. One dam is exposed in arroyo wall near the rod in center right of the photograph.

Age of the alluvium

The age relations of the alluvium underlying the two terraces could not be determined from exposures. But the presence of the paleo-indian dams embedded in the alluvium under the low terrace and the corn pollen in that alluvium prove that the older alluvium



FIG. 15. Bedrock comprising the floor of Madame Walk Arroyo near station 30+00, looking downstream.

was deposited first, then eroded to bedrock, and the newer alluvium deposited as a fill within the erosional trench. From associated pottery shards date of the dam construction was between A.D. 1000 and A.D. 1100. The dams were built in the broad swale eroded in the earlier fill. They were three to four feet high and built on an alluvial channel bed that stood 1.3 feet above bedrock. The purpose of the dams was to form small silt deposits that could be planted to crops, apparently corn. The dams were spaced so that the toe of an upstream dam was at the level of the lip of a downstream one. Such a series of small dams is found in several similar swales in the tableland of Mesa Verde National Park.

The pollen profiles, summarized in appendix 7, were determined by Dr. Estella B. Leopold in the laboratory of the U. S. Geological Survey. Progressively upward from the base of the older alluvium, *Pinus* (probably *ponderosa*) changed progressively to juniper, sage, and some chenopods, thence to pine, probably pinon. The sequence suggests an initial mixed woodland giving way to a drier climate characterized by open brushland, and then a slight in-

crease in moisture leading to an open pinon-juniper woodland and sage at the end of the depositional period. No C^{14} dates associated with this high terrace have been determined but presumably are Holocene.

The alluvium under the low terrace began deposition in a brushland of sage and a diverse herbaceous flora, followed by a steady increase in woodland elements ending with a peak in pinon-juniper at the end of alluviation. The climate suggested by this latter sequence is

a gradual increase in precipitation from the beginning of alluviation to the end of it. . . . The highest stratigraphic occurrence of corn pollen (sample 0 at eighty-four inches) may date from the time of the Indian exodus from Mesa Verde, about A.D. 1250, a time when tree rings suggest severe droughts. The nature of the pollen rain at that level certainly looks like drier than present conditions (E. B. Leopold, by letter report dated Oct. 6, 1972).

The erosion of the younger fill and the development of the present gully system undoubtedly is associated with the widespread epicycle of erosion that began in the late nineteenth century.

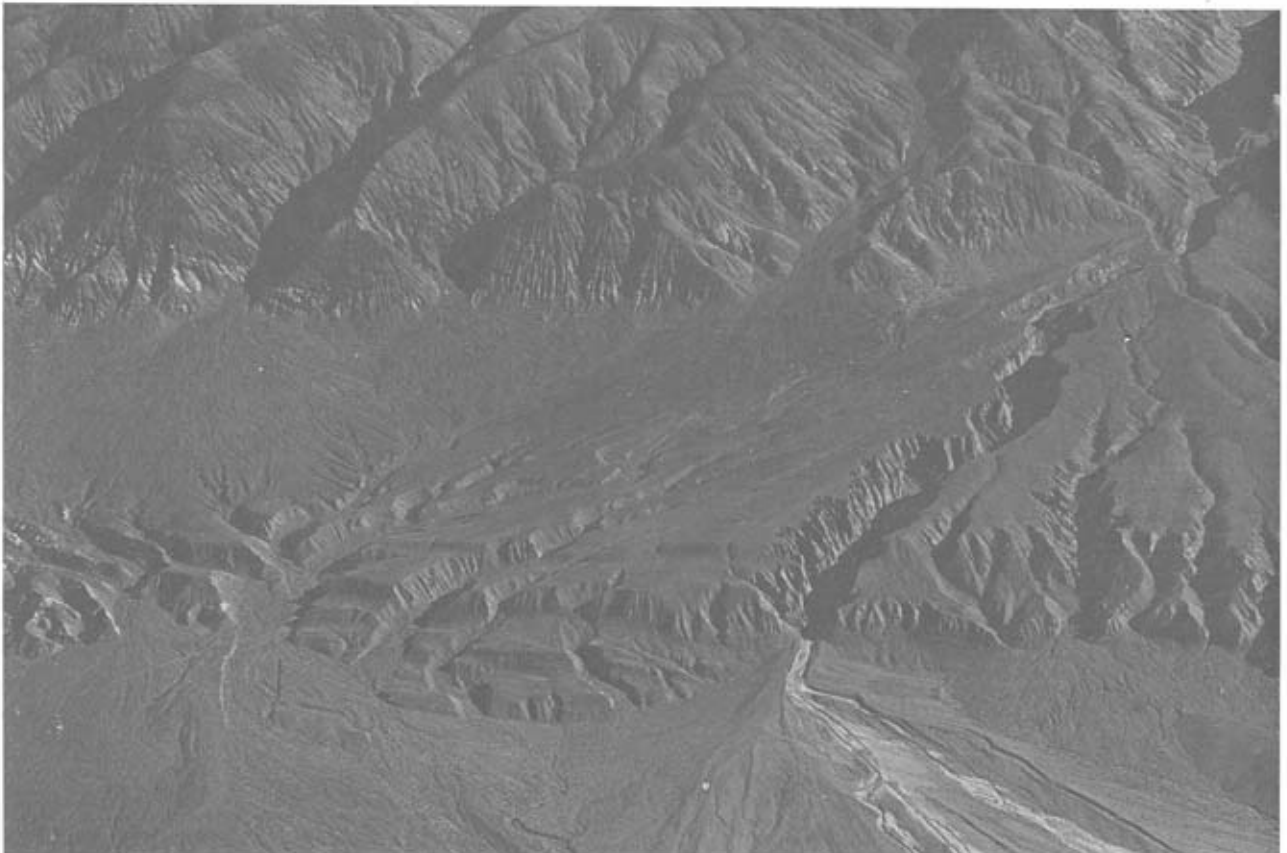


FIG. 16. Aerial view towards the east of the area where Tuber Canyon (right center) enters the Wildrose Graben, west side of Panamint Range, eastern California. Dirt road on fan at lower left provides scale as does mining camp at mountain front just to left of Tuber Canyon. The mountain-bounding fault stretches horizontally at the foot of the steep mountain in the upper part of the photograph. In the lower part of the photograph, the scarp line running horizontally across the photograph is caused by faulting of the piedmont (coalescing fans).

had been affected fifty feet upstream and after four years eighty feet. By that time the gradient of new deposition had attained a value of 0.033 which remained constant thereafter, a smaller value than the original gradient, 0.045. In the next ten years the gradient of deposition remained constant, and it did not extend upstream beyond one hundred feet as can be seen on the lower profile of figure 18. The progressive change with time of gradient at various distances above the dam are shown in table 1, in which it can be seen that the gradient in the reach from 110-220 feet and that in the reach 220-330 respectively were never altered by the dam.

In summary, the sediment wedge extended upstream for the first four years after which its gradient remained stable at seventy-nine per cent of the original value. The maximum distance its effect was felt was 110 feet and the dam had no effect on the other 640 feet to the watershed divide. Deposition above the other dam nearby not shown here had similar effects.



FIG. 17. Photograph of Big Sweat Dam, basin of Arroyo de los Frijoles, near Santa Fe, N. Mex. The dam is shown in foreground; view is looking upstream at wedge of sediment deposited behind the dam. Vertical rods are steel pins used as permanent markers for resurveys.

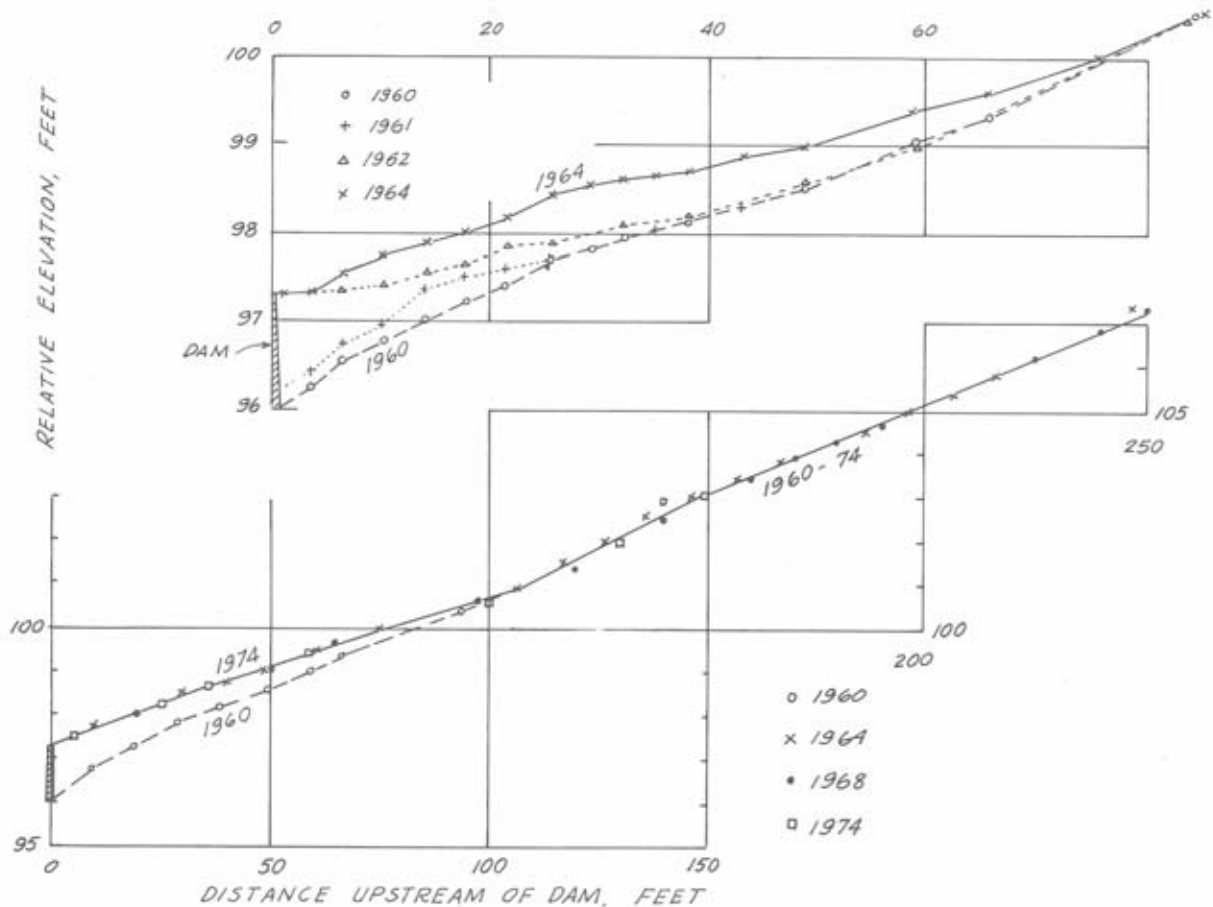


FIG. 18. Successive channel-bed profiles above Big Sweat Dam built on an ephemeral tributary to Arroyo de los Frijoles near Santa Fe, New Mexico. The upper diagram shows the progressive changes in the profile of the building sediment wedge behind the dam. The lower diagram shows less detail immediately behind the dam but at a smaller scale the relation of depositional wedge to profile upstream.