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# QUATERNARY GEOLOGIC MAP OF THE PALISADES CREEK-COMANCHE CREEK AREA, EASTERN GRAND CANYON, ARIZONA

*by*

Ivo Lucchitta[1], Carol M. Dehler[1], Marie E. Davis[2], Kelly. J. Burke[1], and Peggy O. Basdekas[1]

Prepared in Cooperation with
Glen Canyon Environmental Studies, U.S. Bureau of Reclamation
Grand Canyon National Park
Lawrence Livermore National Laboratory
The University of California at Davis



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[1] U.S. Geological Survey, Flagstaff, Arizona 86001
[2] Davis[2], Georgetown, CA. 95634

## FOREWORD

The meat of the report that follows is the Geologic Map (Plate 1) and the Surveyed Map Points (Plate 2), together with the Description of Map Units and the Correlation of Map Units. These items jointly make up the geologic data base.

We suspect, however, that many users of the report are likely to be intersted primarily in the interpretations and conclusions derived from the primary data. Accordingly, the interpretations and so on take first place, in the expectation that the maps and correlative data will be looked at only as a second step.

Plate 2 should be of interest to those for whom it is important to know the level that is reached by the river at various discharges. Examples of applications are beach building, erosion of archeological sites, and preservation or destruction of habitats such as wetlands along the river corridor.

Doing the fieldwork that has led to this report has been fun. We have enjoyed the opportunity and are grateful to the Glen Canyon Environmental Studies Program, the National Park Service, and our astonishing river-guide friends for making it all possible.

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### INTRODUCTION

This map is a result of a program of Quaternary studies carried out in the Grand Canyon National Park in cooperation with the Glen Canyon Environmental Studies group, U.S. Bureau of Reclamation, and the Grand Canyon National Park, National Park Service.

The purpose of the studies is to reach a historical understanding of the processes that have been active in the Grand Canyon during the Quaternary. This understanding provides a background against which to evaluate the effects of Glen Canyon Dam, completed in 1963, on the physical and biological systems along the Colorado River in the Grand Canyon, downstream from the Dam. This objective has been approached through mapping of surficial geologic and geomorphic features in four key areas along the Colorado River corridor in the eastern Grand Canyon, each selected on the basis of range and excellence of exposure of Quaternary features. The Palisades-Comanche Creeks map is the first in a series of these maps to be completed.

Informal studies began in the mid-Eighties. The field mapping was done between 1990 and 1995. As is common in modern Quaternary geologic studies, geological mapping alone does not provide the degree of precision needed to clarify issues adequately. Accordingly, the mapping was supported by:

Geodesy, surveying, and trilateration (to provide an accurate topographic framework on which to construct a large-scale topographic base) — Joseph Mihalko and Brenda Mihalko, National Park Service

Geochronology, paleomagnetism, and soils analyses (to date surfaces and materials numerically, thus allowing determination of rates at which processes take place) — Dr.Robert Finkel and Dr. Mark Caffee, Lawrence Livermore National Laboratory: cosmogenic radionuclides and $^{14}C$; Professor Garniss Curtis, Berkeley Geochronology Center: high-precision $^{39}Ar/^{40}Ar$; Dr. Jack Hillhouse, U.S. Geological Survey: paleomagnetic reversals; Dr. Randy Southard, U.C. Davis: quantitative soil analyses

Soils description, classification, mapping, and interpretation (to help classify surfaces, illuminate erosional processes, and refine understanding of paleoagricultural practices) — Sid and Marie Davis, Davis² Consulting Earth Scientists

Palynological analyses (to help define paleoclimate and agriculture) — Jim Hasbargen and Susie Smith, Northern Arizona University

The topographic base was especially prepared for this project by the Photogrammetry section of the U.S. Geological Survey, Flagstaff, using photogrammetric techniques applied to aerial photographs provided by the U.S. Bureau of Reclamation, and calibrated by the high-precision trilateration network.

Other geological studies going on simultaneously in the area include those of Richard Hereford (young fluvial deposits), and Robert Webb (debris-flow processes, and historic changes in the river corridor).

Construction of Glen Canyon Dam has profoundly altered the Colorado River's operating regimen. Before the dam, the river experienced annual high-discharge floods in the spring, followed by very low discharges in the fall and winter, commonly with a discharge ratio of 30:1, and often more. After the dam, discharges varied on a daily basis, reflecting diurnal variations in power demand; peak discharges typically were one-quarter or less of the pre-dam discharges, and the discharge ratio was mostly in the 2:1 to 4:1 range. Sediment load has been drastically reduced, because most sediment is now trapped in Lake Powell upstream from the dam. And pre-dam fluctuations in water temperature have been replaced by a near-constant low temperature in the 42-45 °F range in the eastern Grand Canyon. In other words, the Colorado River in the Grand Canyon now is cleaner, colder, doesn't flood much, but fluctuates regularly all year long. Among the consequences attributed to these changes are the erosion of beaches and archeological sites along the river corridor, as well as a profound alteration of the ecologic system.

## METHODS

Units shown on the map are morphostratigraphic, i.e. defined by morphologic position as well as by lithology (Figure 1, and Appendix A). Contacts were plotted in the field on aerial photographs at 1: 5,000 scale and also directly on the topographic base map. Selected important contacts were located by total-station survey. To maintain objectivity, terraces along tributaries to the Colorado River were numbered in the field in ascending order, starting with the present wash level as 1. Each major wash was assigned its own numbering system because terraces do not necessarily track form one wash to another. The same numbering technique was used for terraces along the river. Although one can expect an overall similarity of terrace levels from one wash to another, because all washes must reflect the grade set by the Colorado River, exact correspondence of levels is not a given because individual washes may lack a terrace level or have an extra one. Accordingly, elevations of all terrace levels for all washes were tabulated from field data, and the table was used to identify terrace levels of general validity (Appendix A). The map shows these interpreted level assignments. Field assignments, where different, are shown by the observed level in parentheses following the lithologic symbol containing the interpreted level assignment (eg. ld6 (5)).

To bring the level of detail of the map in conformity with the map's scale, the younger deposits and features along the Colorado River were subdivided into only 3 units that, however, reflect distinct flow regimes of the river (Figure 1). The youngest extends up to the post-dam fluctuating-flow high-water line at about 30,000 cfs (cubic feet/second). The next youngest extends up to the common pre-dam high flood stage at about 125,000 cfs ('mesquite line'), but includes features produced by the major post-dam floods, including that of 1983 at somewhat more than 90,000 cfs. Last is a deposit that reflects the river's most recent (but prehistoric) major aggradational event, which produced a floodplain farmed by the Anasazi people, and lasted until 1200-1250 AD on the basis of Pueblo II sites and artifacts within the upper part of the unit and on top of it. Each of these units contains strand- and driftwood lines and terraces that document intermediate events. Selected features of this kind are shown where appropriate.

Soils data result from many formal and detailed descriptions of profiles visible in soil pits, combined with laboratory analyses of critical soils parameters. Together with field mapping, these characteristics have led to the delineation of soil units that are portrayed in a separate map (Davis and others, 1995).

The age of morphostratigraphic units is critical in helping establish the processes by which the units have been formed. We have used $^{26}Al$ and $^{10}Be$ to determine exposure ages, and $^{14}C$ to pinpoint the age

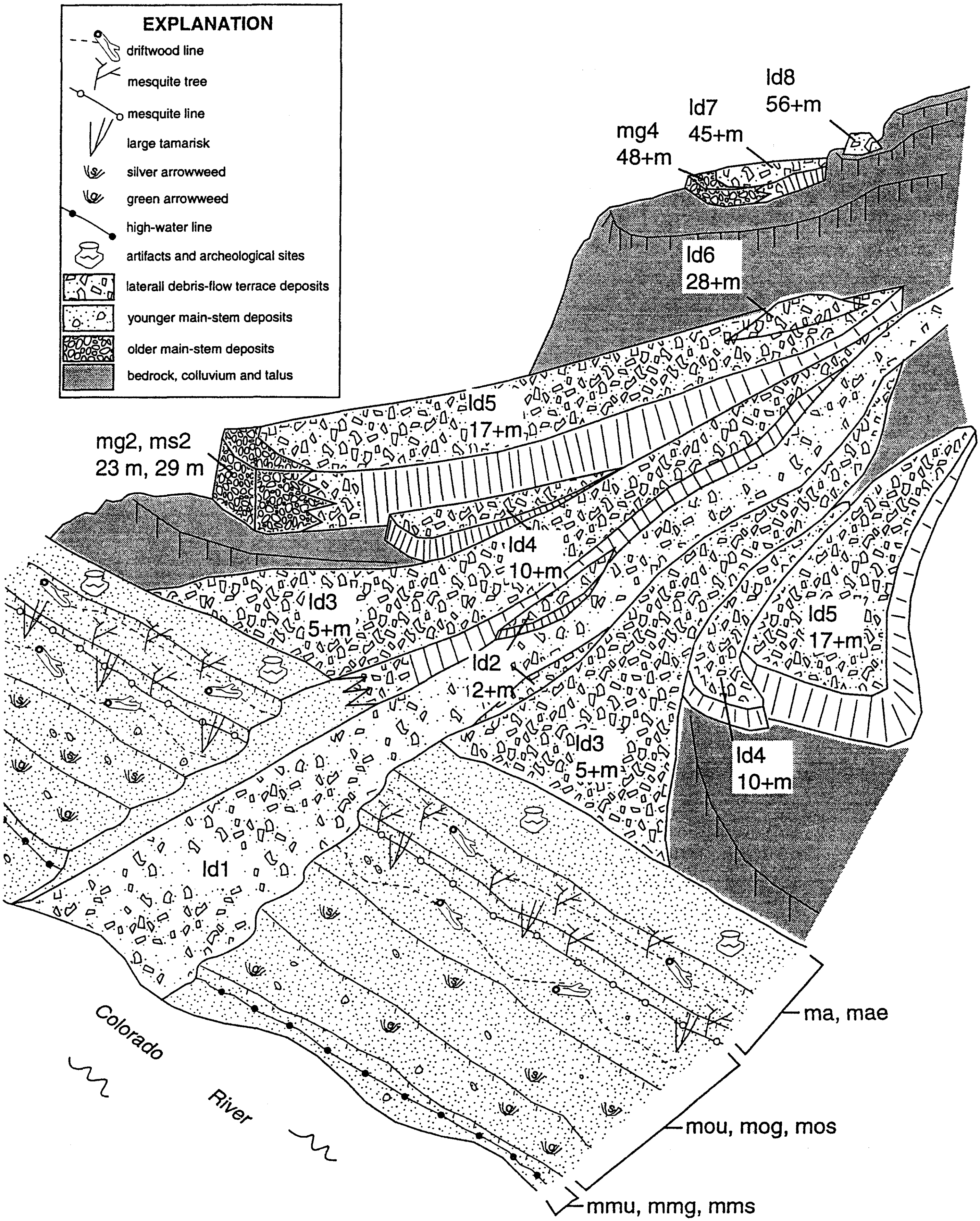


Figure 1. Schematic diagram illustrating morphostratigraphic relations between main-stem and lateral components of the Colorado River system.

of younger units (Caffee and Finkel, personal communication, 1995), high-precision laser-fusion Ar-Ar to calibrate soil stages in the western Grand Canyon (Lucchitta and others, 1995), and paleomagnetic reversal stratigraphy to determine whether surfaces and associated soils are older or younger than the 780-ka reversal (Hillhouse, personal communication, 1995). We have also incorporated palynologic analyses of the deposit farmed by the Anasazi to shed light on what they farmed and when (Appendix C).

## BACKGROUND PHILOSOPHY

The Colorado River corridor is composed of two separate but interdependent components that respond to entirely different sets of circumstances (Figure 1). The first is the Colorado River itself, which we label the main-stem component.

The Colorado River depends on precipitation in its source mountains, the Rocky Mountains of Wyoming and Colorado, for most of its water, and, in its natural state, on the spring melt for the annual flood. Consequently, the activities of the Colorado River before the Dam was built depended largely on what happened in far-away source mountains.

Conversely, the behavior of washes, slopes, cliffs, in short, everything in the Grand Canyon other than the Colorado River, depends on local circumstances, which now and in the past differ greatly from what happens in the Rocky Mountains. This is the lateral component.

The connection between the two components is the grade established by the Colorado River: when it cuts down, the lateral component must be lowered as well. The interdependent behavior of the two components is useful in clarifying the processes that affect the system as a whole.

## RESULTS

### Processes

The Quaternary deposits preserved within the eastern Grand Canyon give an insight into the processes that have been operating in the Canyon during the past half-million years, perhaps even three-quarter million. This is to be viewed against the overall scenario that the Grand Canyon is at most 5.5 Ma old, and was as deep as it is today at least in the western part by about 1 Ma, requiring an overall downcutting rate of 1 to 3 ft/ka (Lucchitta, 1990).

The downcutting has been interrupted several times by periods of backfilling (aggradation) during which the River built up its bed by many tens of meters mostly with gravel that commonly grades upward into sand. Only the most recent (Holocene) aggradational event consists principally of sand.

Each aggradation event resulted from overload of the river with gravel and sand. During aggradation, the Colorado River most likely was a braided stream, and may well have resembled modern rivers issuing from steep mountain terrane or from glaciers. When the overload ceased, downcutting resumed. It is likely that the river typically reattained its pre-aggradation grade very quickly, as shown by the $\geq$ 10 m of downcutting in the ~750 years since deposition of the archeological unit (ma, mae). A high rate of downcutting is also inferred for the Granite Park area once the Colorado River stopped being overloaded by volcanic products (Lucchitta and others, 1995).

While the Colorado River was going through its backfilling cycles, tributary washes were also forced to aggrade, resulting in terraces that correspond in a general way to the river terraces and associated planation surfaces (Figure 1). Tables 1 and 2 show the terrace levels that are most common and reliable, and Table 3 shows elevations of the interface between lateral and mainstem components, which represent ancient flood plain edge (Appendix A). There is considerable variability in the terrace-level data. In our experience, this results from the following factors: presence/absence of terraces in any particular drainage, which affects terrace-level assignment; terraces present only as erosional remnants in which original tops are not preserved; elevation of river terraces measured above river high-water line, whereas elevation of wash terraces is measured above wash level; and decrease in wash-terrace elevations upstream along the washes, which results in upstream convergence of terraces. The latter characteristic is consonant with the hypothesis that at least some of the wash terraces were formed in response to aggradation by the Colorado River. In spite of the variability, the terrace elevation data define distinct families of levels. These families are the ones shown on the map.

At or near the end of some of the backfilling events, the grade of the river remained stable long enough for extensive planation surfaces (pediments) to be carved in the softer rock such as the Dox Formation within the river corridor. These surfaces merged with the river floodplain at their lower end; at the higher end, they were bounded by bedrock cliffs. While the pediments were being cut, river grade was stable because sediment load was in equilibrium with transport energy. Under these conditions, sand probably was a major component of the channel fill. Some of this sand was blown far up the pediment slopes downwind from the river, resulting in sheets of eolian sand interlayered with pediment gravel deposits. These sheets were stabilized when the surface of pediments developed an armor of desert pavement, and when the pediments were isolated from the sand supply by renewed downcutting, at which time the river typically carried more gravel than sand.

The workings of wind transport are much in evidence today, when sand from current sandbars, especially that derived from the archeological unit, is reworked into dunes, climbing dunes, falling dunes, and sand sheets. The sand that forms these features is important for the preservation of archeological sites, because shifting sand is extremely effective in preventing gullying owing to its self-sealing properties. Since the building of Glen Canyon Dam, however, the sand supply has been drastically curtailed owing to the decrease in sand carried by the river, and the stabilization of sandbars owing to riparian vegetation. Consequently, many of the dunes and sand sheets are now inactive and subject to severe gullying, with possibly serious effects for archeological sites buried by the sand.

## Soils

According to Davis and others (1995), soils in the Grand Canyon are characterized by development of calcium carbonate (caliche). They range in development from non-existent in the youngest units to massive calcrete in the oldest. In several instances older soils show evidence of multiple histories: soils form, are stripped or buried, then new soils form again. The stripping of soils results from the decrease in permeability on geomorphic surfaces as calcretes form, which promotes sheetwash and greatly increases erosion of the surfaces.

In the area of this map, soils attain Machette's (1985) carbonate Stage IV. Well-documented relations between soil-carbonate stages and a precisely dated basalt flow in the Granite Park area (river miles 207-209) have enabled us to date this carbonate stage at less than 525 ka and more than 250 ka (Lucchitta and others, 1995).

Stage III carbonate, which underlies the more prominent planation surfaces, is less than 250 ka old, and more than about 85 ka.

## Archeogeology

Only the archeological unit (ma, mae) and terrace levels 3, 2, and 1 (ld3, ld2, and 1d1; respectively) are young enough to have witnessed the presence of human beings. However, some older units help to understand the stage against which human activity took place.

The most important aspects of the river with regard to human activity are its level relative to present grade; the characteristics of the river valley, notably during the last aggradation, in contrast to the present rugged and incised aspect related to strong downcutting; and the erosion that accompanies downcutting events.

Paleolevels. Our data show that the river was flowing ≥ 10 m (33 feet) above present grade as recently as about 750 years BP, 13-17 m (43-56 feet) at 20-30 ka, 25-30 m (80-100 feet) about 80 ka, and 45-50 m (150-165 feet) about 100 ka.

One of the archeological questions that has arisen in the Marble Canyon section of the Colorado River is how driftwood, $^{14}$C dated at 43.7 ka BP (Elston, 1984), was deposited in Stanton's Cave, 144 feet (44 m) above the present river grade (Euler, 1985a). This driftwood is associated with Archaic figurines that yield $^{14}$C ages of about 4,000 years BP (Euler, 1985b). Two chief hypotheses have been advanced to explain the presence of driftwood so far above the river grade: major Pleistocene-age floods (Euler, 1978); and ponding by a rockfall in the Nankoweap area (Hereford, 1984). In both cases, the assumption was that the river flowed then at the grade it has today. Our data indicate instead that the river was flowing at least ~15 m above its present grade, and possibly nearly ~30 m, which makes it much easier to reach the cave level by more or less routine large glacial (?) discharges, and minimizes or eliminates the need for a ponding event. Furthermore, the unit interpreted by Hereford as a rockfall is about 11,000 years too old to match the age of the driftwood in Stanton's Cave, so cannot be used to to explain the driftwood.

Characteristics of the floodplain during aggradation and their influence on paleoagriculture. During aggradational events, the Colorado River was overloaded with sediment. Modern overloaded streams suggest that the River at these times was braided, and flowed in multiple and shifting shallow channels. The deposits of most events consist largely of gravel, which in several instances grade upward into several meters of coarse sand. This indicates a decrease in transport energy. Because unconsolidated sand is easy to erode, it is possible that sand may have been more common at the top of aggradational sequences than the preserved record indicates.

The Holocene backfilling event represented in the Grand Canyon by the archeological unit (ma. mau) is widely in evidence in much of the Colorado Plateau. According to Luna Leopold (personal communication, 1995), this unit may be present in Utah and Wyoming as well. Periods of erosion probably occurred during the overall aggradation.

Deposits of the Holocene aggradation differ from those of previous such events in grain size -- fine to very fine sand, instead of gravel and coarse sand, and in derivation -- Mesozoic eolian sandstone units of the Colorado Plateau. The sand grades laterally into clay, silt, sand and gravel brought into the river floodplain by tributary streams of the lateral component. During deposition, river level was little below that of the floodplain, and the floodplain itself was of low relief, so the river frequently flooded the plain, perhaps on an annual basis.

These characteristics of the archeological unit (ma, mae) had a major influence on human activity in the region. The combination of fertile soil, abundant water, and a probable warm sunny climate makes the unit uniquely well suited for agriculture, and indeed was exploited by the prehistoric inhabitants of the region (Anasazi etc.) for that purpose. In fact, we suspect that these factors may have led to the development of agriculture itself along the main drainages of the Colorado Plateau, much as they did in the Fertile Crescent of the Middle East.

End of deposition of the archeological unit occurred around AD 1200-1250 because Pueblo II sites and artifacts are the youngest that are incorporated in the top of the unit. Beginning of deposition of this unit is not known. We have obtained a $^{14}C$ age of 4500 years B.P. (Caffee and Finkel, personal communication, 1995) from a charcoal layer about 2.5 meters below the top of the archeological unit at river mile 2.5, river left. Because another 7.5+ meters of sediment still remains below this dated layer, and assuming constant rates of deposition, the base of the archeological unit could well date to >8,000 years B.P.

Soil analyses that we have obtained from the Grand Canyon show that much of the archeological unit is suitable for farming. Multiple, laterally extensive charcoal layers suggest clearing of fields or burning of stubble. High concentrations of salts near the layers suggest irrigation. Corn and cotton pollen indicate that the areas were farmed. And common Basketmaker through Pueblo II artifacts and structures indicate that people did live in the area in substantial numbers (Fairley, et al., 1994). An interesting preliminary result of our work is the presence of one grain of cotton pollen at the 56-cm depth near Little Nankoweap Creek, as identified by Hasbargen and Smith, 1995. This layer has been dated by $^{14}C$ at 1390±90 yr BP (Caffee and Finkel, personal comm., 1995). This age is about 500 years earlier than previously reported cotton cultivation by Pueblo II people (Fairley, et al., 1994).

The departure of the Anasazi from their fields along the Colorado River, the San Juan, and other rivers in the Southwest is commonly attributed to the onset of drought (Cordell, 1984; Dean, 1988; Fairley, et al., 1994; Hasbargen and Smith, 1995). Drought may well have set in at that time, but it can hardly be used to explain directly the Anasazi departure from the banks of rivers that are most unlikely to have dried up. In our opinion, a more promising direct explanation hinges on the end of aggradation and the onset of downcutting that followed and continues to this day. From the Anasazi farmer's point of view, the effects would have been these:

The rivers no longer routinely overtopped their banks, which previously had revitalized the soil in the fields

Water levels dropped more and more, making it difficult or impossible to irrigate the former floodplain and its fields

Erosion and gullying began destroying the fields

The dropping water level lowered the local water table, which previously had been close to the surface in the cultivated floodplain. The sand in the fields, no longer stabilized by being moist at shallow depth, began blowing around forming dunes and making cultivation difficult and residence unpleasant. At some point, these factors collectively became too much for the farmers: the Anasazi left, and the abandoned structures on and near the floodplain were gradually buried by blowing sand and dunes.

Downcutting. Downcutting begins when a river ceases to be overloaded. Our experience in the Grand Canyon suggests that the Colorado may well have stopped aggrading and started downcutting even when its overload did not end, but merely decreased relative to previous values. In any case, once it began, downcutting took place at a very rapid rate. This is suggested in the Granite Park area (Lucchitta and others, 1995), and shown for the archeological unit (ma, mae), which has been dissected more tham 10 m since 1200-1250 AD, for a downcutting rate of about 13m/ka.

If one assumes that the archeological unit occupied most of the floodplain of the river, ther greater part of the unit has been eroded away. Only remnants survive, in wider parts of the valley, in protected areas, and clinging to canyon walls. We interpret this to have happened primarily by lateral erosion as the river migrated across its floodplain. Another process, probably secondary for the floodplain but of primary importance along washes and slopes of the lateral component, is the development of and extension of arroyos by headward erosion. We believe headward erosion to be the significant process for drainage development regionally, and not only at the small scale of arroyos and gullies, but for the Grand Canyon as a whole (McKee and others, 1964; Lucchitta and others, 1995; Hanks and others, in prep.). Some of the arroyos are working their way headward into remnants of the archeological unit or other deposits where sites are preserved, thus threatening them. This is evidenced by archeological material exposed in arroyo walls. Much of this erosion is the consequence of the severe post-archeological unit downcutting and was going on long before Glen Canyon Dam was built. Nevertheless, the Dam has probably worsened the situation by decreasing sand supply that helps retard erosion either indirectly by means of eolian sand that blankets gullies, or directly by means of high-level fluvial sand deposited across them.

## Causes of Aggradation and Downcutting

Exposures of Quaternary deposits in the Granite Park area of western Grand Canyon suggest that the Colorado River responds very rapidly to sediment overload, building up its bed by meters or even tens of meters and forming a braided stream plain, then cuts down equally rapidly when the overload ends (Lucchitta and others, 1995). It is likely that the various aggradation episodes recorded in the terrace levels reflect similar mechanisms. The question is: what caused the overload in the first place?

The most likely explanation is that the terrace-building overloads were caused by increased glacial activity in the source mountains during or late in glacial stades (Lucchitta, 1991). Glaciers are very efficient at producing debris, which clogs rivers issuing from glaciers. Braided streams that issue from valleys heading in glaciers are common in glaciated terrain. Conversely, shrunken glaciers during interglacial stades generate much less sediment, so rivers cut down vigorously through the material deposited during the previous glaciation.

The chronologic framework constructed so far suggests that lateral terrace level 4 (ld4), and probably river terrace 2 (mpg2) have ages appropriate for the Pinedale glaciation, whereas lateral terrace levels 6 and 7 (ld6, ld7) and river terrace 4 (mpg4, mps4) have ages more appropriate for the Bull Lake glaciation. However, these results are tentative, pending completion of the geochronologic determinations now in progress.

A glacial origin for the latest aggradational event (mainstem archeological unit, ma) is not likely because this unit probably is entirely Holocene in age. We suggest that this unit represents temporary overload of the drainage network by Holocene erosion of Pinedale-age alluvial and colluvial aprons present regionally (Lucchitta, 1991; Lucchitta and others, 1995). Such colluvial aprons are conspicuous in the Grand Canyon on slopes below cliffs, and are being eroded vigorously today. The aprons were formed during the glacial stades, as shown by travertine spring deposits where there are no springs now, when more pluvial conditions resulted in vegetative cover that stabilized the slopes. With the onset of warmer and drier Holocene climate, the vegetative cover waned, exposing the aprons to erosion. Catastrophic erosion began with the torrential rains resulting from the onset of monsoonal precipitation patterns. The products of this erosion overloaded all drainages in the region. Once the supply of easily erodible material was exhausted, sediment supply decreased and the drainages began vigorous downcutting that is still going on today.

## ACKNOWLEDGMENTS

Sid Davis' work on the development of soils, Marc Caffee's and Bob Finkel's cosmogenic-radionuclide age determinations, and Jack Hillhouse's paleomagnetic reversal determinations give us a means for assigning ages to our morphostratigraphic units and thus testing hypotheses on their genesis. Renate Kostrewa helped with the collection of sedimentologic data. George Billingsley reviewed this map and made valuable suggestions for improving it. Jack Coffman provided total-station control for the location of driftwood lines, strandlines and geologic contacts, and made systematic observations of weathering characteristics. Baerbel Lucchitta also examined the weathering characteristics of boulders at various terrace levels. Finally, Brenda and Joseph Mihalko and the photogrammetry section, U.S.G.S., Flagstaff, were instrumental in constructing the topographic base without which this map would not be possible. To all these people we extend a heartfelt 'thankyou'.

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## DESCRIPTION OF MAP UNITS

All map units are Quaternary, excepting Cambrian and Proterozoic bedrock units, which are so labeled. Quaternary units are mapped on the basis of morphostratigraphic characteristics that combine geomorphic and lithologic features. The major categories of morpho-stratrigraphic units are the Mainstem Component, representing all units deposited by Colorado River processes, and the Lateral Component, which constitutes all units deposited by tributary-specific and local processes. Mainstem and Lateral Component units are identified below and on the accompanying map by the first letters "m" and "l" in the lithologic symbol, repectively

### MAIN-STEM COMPONENT

#### ALLUVIAL DEPOSITS OF THE COLORADO RIVER

Includes deposits of the Colorado River that are distinguished on the basis of terrace elevation and to a lesser extent on lithology

**Modern sediments — Deposits related to fluctuating-flowoperation of Glen Canyon Dam (upper Holocene)** — Thin veneer of deposits whose maximum elevation above river level at 5,000 f³/second release is 2.5 m, typically about 1.5 m. Distribution and thickness of sand and gravel deposits change with time depending on deposition and erosion

**mmu** **Modern Colorado River sediments, undifferentiated** — Unconsolidated, poorly sorted, rounded to subangular silt, sand, gravel and boulder gravel. Bars below confluence of major tributaries include high percentage of subangular to subrounded clasts of locally derived limestone, sandstone, siltstone, and basalt as much as 1 meter in diameter. Far-travelled lithologies include very well-rounded clasts of "San Juan" hypabyssal porphyry, quartzite, and granite that typically range from 10 to 30 cm in diameter. Deposits form sand and gravel bars and are sparsely vegetated by young tamarisk and coyote willow trees, and abundant horsetail grass. Sand deposits reworked by wind action to varying degrees. Upper contact with older deposits marked by high-water line created by flows as large as 30,000 ft³/second. Grades laterally into Level 1 debris-flow deposits (ld1), modern Colorado River sand (mms) and modern Colorado River gravel (mmg).

**mms** **Modern Colorado River sand**— Moderately to well-sorted, rounded to subangular silt and fine-grained sand composed chiefly of quartz. Deposits form sand bars and grade laterally into modern Colorado River gravel deposits (mmg) and modern Colorado River sediments, undifferentiated (mmu)

**mmg** **Modern Colorado River gravel** — Predominantly gravel, local sand lenses. Forms gravel bars and grades laterally into modern Colorado River sand (mms) and modern Colorado River sediments, undifferentiated (mmu)

**Older sediments — high-discharge deposits, pre-dam and post-dam (upper Holocene)** — Deposits related to frequent pre-dam and rare post-dam flood stages. Unit includes several terraces (not mapped separately) and driftwood lines. In descending order, main terraces are charaterized by: large tamarisk trees and, locally, young mesquite trees (terrace produced by pre-dam annual floods of as much as 125,000 ft³/second); dead (silver-colored) arrowweed shrubs (1983 flood, 90,000+ ft³/second); live (green-colored) arrowweed shrubs (probably 30-40,000 ft³/second discharges). Upper contact with older deposits determined by base of scarp and by lowest elevation of large and medium-sized mesquite trees that grow on scarp face cut into archeological unit (ma, mae). Contact mapped at base of scarp, even where mesquite tree line is higher on scarp face. Sand locally reworked by wind action. Maximum elevation above high-water line 5 meters, typically about 2.5 m. Exposed thickness typically about 2.5 m

mou **Older Colorado River sediments, undifferentiated** — Unconsolidated to weakly consolidated, moderately to poorly sorted, rounded to subangular silt, sand, gravel and boulder gravel. Locally derived clasts include Paleozoic and Proterozoic rock types and are as much as 3 meters in diameter. Far-travelled clasts include "San Juan" hypabyssal porphyry, quartzite, and granite 10 to 30 cm in diameter on average. Grades laterally into older Colorado River sand (mos) and older Colorado River gravel (mog)

mos **Older Colorado River sand**— Moderately to well-sorted, rounded to subangular silt and fine-grained sand composed predominantly of quartz. Grades laterally into older Colorado River gravel (mog) and older Colorado River sediments, undifferentiated (mou)

mog **Older Colorado River gravel**— Predominantly gravel. Grades laterally into older Colorado River sand (mos) and older Colorado River sediments, undifferentiated (mou)

**Archeological sediments (middle to upper Holocene)** — Deposit is entirely pre-dam in age. As mapped, includes driftwood lines and terraces related to very large pre-dam floods, including that of 1884, whose discharge was estimated at 300,000 $ft^3$/second (Dickinson, 1944). Top of deposit forms terrace level that typically is a prehistoric occupation horizon containing artifacts and archeological sites. Artifacts and sites also present within upper part of unit. Upper part of unit commonly includes multiple charcoal layers probably related to clearing fields and/or burning stubble. Layers have yielded dates as old as 4,500 years B.P. (Caffee and Finkel, 1995). Deposit commonly insets into or interfingers with Level 3 debris-flow deposits (ld3). Maximum height above high-water line as much as 11 m, typically about 9 m. Exposed thickness typically about 9 m

ma **Archeological sediments** — Weakly to moderately consolidated, moderately to well-sorted silt and rounded to subangular very-fine to fine quartz sand, and rare moderately sorted, well-rounded medium-grained sand to pebbles of far-travelled lithologies (fluvial deposits), interbedded with locally derived mud and moderately to poorly sorted, angular to subround very coarse sand, granules, and pebbles as much as 15 cm in dia (debris-flow deposits). Fluvial deposits are very pale orange and show low-angle and trough-crossbeds as well as planar horizontal beds in sets averaging 15 cm thick. Debris-flow deposits are pale-reddish-brown, matrix-supported, and locally contain flat-lying chips of Dox Sandstone in beds from 5 cm to 1m thick. Debris-flow deposits wedge out towards river. Unit probably contains erosional disconformities

mae **Archeological sediments, reworked at top into eolian deposits** — Top of unit complexly reworked by deflation and dune-building

**Pre-archeological gravel and sand (Pleistocene)** — Unconsolidated to well-cemented, poorly to moderately sorted, subangular to well-rounded fine-grained sand to cobble-gravel in terraces and erosional remnants whose tops are 21 to 70.5 meters above high-water line. Matrix- to clast-supported. Gravels typically composed of locally derived Paleozoic and Proterozoic rock types as much as 1 m in diameter, intermixed with well-rounded, far-travelled clasts (quartzite, "San Juan" porphyry, granite) as much as 50 cm in diameter, 10 cm average. Gravel with substantial proportion of locally derived rocks indicates ancient bars near or below the mouth of major tributaries. Thin to thick, horizontal tabular beds and channel forms with internal fining-upward sequences common. Units mps2 and mpg2, and mps4 and mpg4, form fining-upward sequences. Exposed thickness generally less than 30 m

**mpgu** **Colorado River gravel, level 1 and 2, undifferentiated** — Thick package of gravels downstream of Lava Creek, river right. Upper and lower gravels separated by a thin band of Dox Sandstone suggesting possible lower, younger deposit (level 1). Grades upward into level 2 Colorado River sand (mps2). Erosional remnant of lower gravel package within unit is 3.5 m above high-water line

**mps2** **Colorado River sand, level 2** — Light gray, moderately to well-sorted, medium- to coarse-grained sand and granules. Clast lithologies predominantly quartz, with lesser amounts of chert and Dox Sandstone. Lower half of unit is finely laminated with rare lenses of granule-sized material; upper part is structureless with rare high-angle crossbeds. Inset into level 3 Colorado River gravels (mpg3). Time equivalent of level 5 debris-flow deposits (ld5). Erosional remnants of terrace level range in elevation from 23 to 34.5 m above high-water line, typically 29 m

**mpg2** **Colorado River gravel, level 2** — Weak desert varnish developed on Dox Sandstone and Cardenas Lava clasts; breadcrust weathering on limestone clasts. Grades laterally into Comanche planation surface (lpc) north of Espejo Creek, river left. Grades upward into level 2 Colorado River sand (mps2) and is inset into level 3 Colorado River gravels (mpg3). Erosional remnants of terrace range in elevation from 21 to 28 m above high-water line, typically 23 m

**mpg3** **Colorado River gravel, level 3** — Moderate yellowish-brown. May be time equivalent of level 6 debris-flow deposits (ld6). Erosional remnants of terrace range in elevation from 30 to 41 m above high-water line, typically 36 m

**mps4** **Colorado River sand, level 4** — Pale yellowish-brown, moderately to well-sorted, fine-grained sand and rare pebbles. Time equivalent of level 7 debris-flow deposits (ld7). Erosional remnants of terrace level 43 m above modern high water line

**mpg4** **Colorado River gravel, level 4** — Grayish-orange-pink. Deposit grades laterally into level 7 debris-flow deposits (ld7) south of Comanche Creek, river left. Erosional remnants of terrace range from 41 to 53 m above high-water line, typically 48 m

**mpg5** **Colorado River gravel, level 5** — Small erosional remnants that may be time equivalents of level 8 debris-flow deposits (ld8). Elevations range from 60.5 to 70.5 m above high-water line, typically 66 m

## LATERAL COMPONENT

DEPOSITS REFLECTING LOCAL PROCESSES ADJACENT TO COLORADO RIVER

The Lateral component includes: debris-flow terrace deposits (d), planation-surface deposits (p), colluvial and talus deposits (c), and eolian deposits (e); all of which are identified below and on accompanying map by the second letter of the lithologic symbol. Debris-flow terraces were numbered in the field on the basis of their elevation above the modern bed (level 1) for each wash. Correlation of debris-flow terraces throughout the area resulted in recognition of populations of terrace elevations that are valid throughout the map area and a few anomalous ones. We interpret the anomalous elevations as actually belonging to other populations and have assigned them accordingly on the map. The levels are represented below and on the accompanying map by the third number in the lithologic symbol. The number "1" indicates the modern drainage deposits; higher numbers indicate successively older terrace deposits perched above the modern drainage. Planation surfaces are identified by proximity to Palisades or Comanche Creek and are therefore labelled with the third letter "p" or "c", respectively.

**Debris-flow terrace deposits (Holocene and Pleistocene)** — Unconsolidated to moderately consolidated, very poorly sorted deposits of angular to subrounded pebbles, cobbles and boulders of local derivation in mud matrix. Clasts most commonly derived from Redwall Limestone, Muav Limestone, Tapeats Sandstone, and Supai Group, and less so from other Paleozoic and Proterozoic rock types. Matrix typically reddish and derived principally from the Hermit Shale, Supai Group, and Dox Formation. Clast size distribution is bimodal: coarse fraction diameter averages 2 m and finer fraction diameter averages 30 cm. Each debris-flow unit contains smaller debris-flow deposits separated by scour contacts. Individual deposits generally have fabric of chaotically oriented clasts and commonly are capped at top by 3 to 10 centimeters of parallel-bedded, imbricated gravels and sand indicative of fluvial reworking. The fluvial gravel commonly is associated with incipient soil horizons. Except for level 1 (ld1), deposits form terraces along tributary washes that slope gently toward Colorado River. In many cases, original terrace surface is not preserved. Deposits near Colorado River may include lenses of far-travelled gravel (granite, "San Juan" porphyry, and quartzite) and quartz sand. For many terraces, height above present wash grade decreases upstream along wash. Deposits generally less than 10 m thick

**ld1** **Debris-flow terrace deposits, level 1 (Holocene)** —Material in active stream channel. Clasts in Lava Creek mostly Dox Sandstone and Cardenas Lava

**ld2** **Debris-flow terrace deposits, level 2 (Holocene)** — Deposit cut by level 1 debris-flow deposits (ld1), forming cutbank in modern washes. Deposited during time interval in which Main-stem older Colorado River gravel and sand (mou, mos, mog) were laid down. Vegetated by tamarisk trees, coyote willow trees and arrowweed shrubs. Clasts in Lava Creek typically subangular to angular. Dominant clast lithologies include Dox Sandstone and Cardenas Lava.Maximum elevation above present wash level: 3 m, typically 2 m.

**ld3** **Debris-flow terrace deposits, level 3 (Holocene)**—In general, unusually coarse clasts. Minor desert varnish. Commonly inset by level 2 debris flow deposits (ld2). Archeological unit (ma, mae) inset to interfingering. Typically exposed in cutbank. Clast lithology in Lava Creek predominantly Cardenas Lava and Dox Sandstone. Clast size as large as 14 m in diameter; 1 m common. Comanche Creek deposit coarser-grained than other level-3 deposits. Maximum elevation above present wash level: 11 m, typically 9 m

**ld4** **Debris-flow terrace deposits, level 4 (upper Pleistocene)**— Relief on chert layers within limestone clasts as much as several centimeters. Breadcrust weathering of limestone clasts. Desert varnish common. Deposit commonly cut by level 3 debris-flow deposits (ld3). Clasts in Lava Creek predominantly subrounded and composed of Paleozoic limestone with lesser amounts of Dox Sandstone and Cardenas Lava. Maximum elevation above present wash level: 15 m, typically 10 m

**ld5** **Debris-flow deposits, level 5 (upper Pleistocene)** — Limestone heavily pitted. Chert relief as much as 10 cm. Desert varnish common. Time equivalent to level 2 Colorado River gravel and sand (mpg2, mps2). Clasts in Lava Creek predominantly subrounded and composed of Paleozoic limestone with lesser amounts of Dox Sandstone and Cardenas Lava. Maximum elevation above present wash level: 25+ m, typically 17+ m ('+' indicates that values shown are minimum values) ld6 **Debris-flow deposits, level 6 (Pleistocene) —** Well-developed desert pavement. Chert relief as much as 10 cm. Limestone boulders disintegrating. Limestone "blades" common. Tapeats Sandstone clasts mostly worn down to level of surface. Clasts in Lava Creek predominantly subrounded and composed of Paleozoic limestone with lesser amounts of Dox Sandstone and Cardenas Lava. Maximum elevation above present wash level: 34+ m, typically 28+ m

ld7 **Debris-flow terrace deposits, level 7 (Pleistocene)** Grades laterally into level 4 Colorado River gravels (mpg4) south of Comanche Creek, river left. Many limestone boulders completely disintegrated, leaving chert scatter. Limestone "blades" common. Tapeats Sandstone boulders as much as 5 m in dia are weathered down to level of surface. Clasts in Lava Creek predominantly subrounded and composed of Paleozoic limestone with lesser amounts of Dox Sandstone and Cardenas Lava. Maximum elevation above present wash level: 48+ m, typically 45+ m

ld8 **Debris-flow terrace deposits, level 8 (Pleistocene) —** Clasts in Lava Creek predominantly subrounded and composed of Paleozoic limestone with lesser amounts of Dox Sandstone and Cardenas Lava. Maximum elevation above present wash level: 58+ m, typically 56+ m

**Planation-surface deposits (upper Pleistocene) —** Unconsolidated to strongly consolidated, calcite-cemented. Very poorly sorted, angular to subrounded sand- to boulder-sized clasts . Clast diameters as large as 1.5 m. Desert varnish common. Forms extensive but dissected bajada-like surface. Time equivalent to level-5 debris-flow deposits (ld5)

lpp **Deposits of Palisades Creek planation surface (upper Pleistocene) —** Common clast lithologies include Dox Sandstone, Tapeats Sandstone and Redwall Limestone. To south, truncated by debris-flow terrace deposits of Palisades Creek (ld1p, ld3p). To north, grades into colluvium and talus apron (lc). Minimum elevation above high-water line 20.6 m

lpc **Deposits of Comanche Creek planation surface (upper Pleistocene) —** Dominant clast lithology is limestone (especially Redwall Limestone), with lesser amounts of Tapeats Sandstone, Coconino Sandstone and Supai Group rocks. Limestone deeply pitted. Chert relief several cm Tapeats Sanstone clasts worn down to level of surface. Grades into level 2 Colorado River gravel (mpg2) north of Espejo Creek. Minimum elevation above high-water about 15 m

**Colluvium and talus deposits (Holocene to Pleistocene)**

lc **Colluvium and talus deposits (Holocene to Pleistocene) —** Very poorly sorted, very angular pebbles and boulders, and angular to well-rounded fine- to medium-grained sand. Clasts as large as 5 m, composed of local bedrock lithologies. Well-developed desert varnish common. Forms apron against or at foot of bedrock slopes and cliffs. Grades laterally into deposits of the Palisades Creek planation surface (lpp) and mixed colluvium, talus, alluvial and pediment deposits (lca, lcp). Deposits result from a combination of alluvial and colluvial processes including sheet wash and mass wasting. Deposits generally less than 10 m thick

lca **Colluvial, talus and alluvial deposits (Holocene) —** Deposits form sloping sheet- and cone-shaped colluvial and talus deposits that grade towards Colorado River into gently sloping deposits on bajada-like surface. These deposits overlap top of archeological unit (ma), or are graded to modern drainage of Espejo Creek (ld1e)

lcp **Colluvium, talus and pediment deposits (Pleistocene) —** Erosional remnants of steeply to moderately sloping apron that grades towards Colorado River into gently-sloping pediment surface graded to level 2 Colorado River gravels (mpg2). May be time-equivalent of level 5 debris-flow deposits. Minimum elevation above modern high water line about 15 m

**Eolian deposits (Holocene)**

le **Eolian deposits, undifferentiated** — Pale yellowish-brown, well- to moderately sorted, subangular to well-rounded, fine- to medium-grained sand. Deposit probably derived mostly from archeological unit (ma). Exposed thickness no greater than 5 m

led **Eolian dune deposits** — Unstabilized to partly stabilized dunes, typically above mesquite line

ledf **Falling-dune deposits** — Sand masses on lee side of steep slopes

les **Sand sheet deposits** — Sand sheets on blanketing older units. Thin (cm to tens of cm) on windward slopes, thicker (tens of cm to a few m) on lee slopes

**Playa deposits (Holocene)**

ll **Playa-lake deposits** — Medium reddish-brown to tan, weakly cemented by salts. Well-sorted, subangular to rounded, fine-grained sand and silt. Forms relatively smooth unvegetated surface with deflation hollows and minor drainage channels on eroded top of archeological unit (ma)

## BEDROCK

Description of Tapeats Sandstone supplemented by information from Middleton and Elliott (1990), and Precambrian descriptions supplemented by information from Hendricks and Stevenson (1990), and Lucchitta and Hendricks (1983)

Ct **Tapeats Sandstone (Cambrian)** — Medium- to coarse-grained quartz-rich sandstone. Granule- to pebble-sized arkosic conglomerate present locally near base. Medium to thick beds with internal planar, trough-cross, and horizontal stratification. Forms cliff. Present in Palisades Creek area in northeast corner of map area. Exposed thickness as much as about 60 m

Yc **Cardenas Lavas (Middle Proterozoic)** — Basaltic to basaltic andesite flows interbedded with minor laminated siltstone and sandstone. Forms slopes and cliffs. Thickness in the eastern Grand Canyon as much as 300 m

Ycs **Cardenas Lavas, sill** — Basalt to basaltic andesitic; intrudes Dox Sandtone (Yc) north of Palisades Creek area in northeast corner of map area

Yci **Cardenas Lavas, intrusion** — Basalt to basaltic andesite; intrudes Dox Sandtone (Yc) north of Palisades Creek area in northeast corner of map area

Yd **Dox Formation (Middle Proterozoic)** — Red to maroon shaly siltstone, mudstone and sandstone interbedded with minor gray stromatolitic dolomite. Mudstone is micaceous and contains salt crystal casts, asymmeterical ripple marks, mud cracks and mud curls. Small-scale crossbeds and ripple marks present in sandstone and siltstone. Forms cliffs and steep slopes. Gradational upper contact with Cardenas Lava (Yc). In northeast corner of map area, upper contact with Tapeats Sandtone (Ct) is an angular unconformity (The Great Unconformity). Lower contact not exposed. Thickness in the eastern Grand Canyon as much as 985 m

## EXPLANATION

**Contact**

**High water line** — Dashed where inferred or where within unit

**Mesquite line** — Dashed where within unit

125 K

**Driftwood line** — number, where shown, indicates interpreted water flow in cubic feet per second (K=1000), (see Appendix C)

— <125,000 $ft^3$/second -- various post-dam discharges. Driftwood on older Colorado River sediments (mou, mos, mog) and modern Colorado River sediments (mmu, mms, mmg) characterized by abundant worked wood and other modern artifacts such as plastic items

— 125,000 $ft^3$/second -- highest common pre-dam discharge. Driftwood near mesquite line and base of scarp at lower contact of archeological unit (ma) characterized by moderate amount of worked wood and modern artifacts

— 300,000 $ft^3$/second -- pre-dam discharge from the 1883 flood. Driftwood on archeological unit (ma) characterized by little worked wood and few historical artifacts

**Erosional scarp** — Teeth on face of scarp

U d / D u ?

**High angle fault** — Dashed where approximately located, dotted where concealed, queried where inferred. U, upthrown side of fault block; D, downthrown side of fault block. Lower case u and d indicate Precambrian displacement

.P17 .C046 **Survey data point**

+ **Soil description locality**

**Agricultural sample locality**

* **Cosmogenic sample locality**

P **Pollen and Carbon 14 sample locality**

**ld6 (5)** — In lithologic symbols for debris-flow terrace deposits the number following the lithologic symbol indicates an interpreted level assignment that correlates between tributaries whereas the number within parentheses indicates the objectively mapped level within each individual tributary. Where number in parentheses is absent, then the interpreted level and the objectively mapped level are the same

# APPENDIX A
# ELEVATION DATA

| Level | Above La/Pal | Lava | Palisades | Down --L/P | Espejo | Coman-che | Arithmetic mean |
|---|---|---|---|---|---|---|---|
| ld2 | | 2.5+(u), 3+(u) 2+(u) 2 | 1.25 | 2.5+(u) 1+(u) | | 2.5, 1.5 | **2+** |
| ld3 | | 7.5+(u), 8.5+(u) | 3+(u) | 2+(u) 1+(u) | 1.5+(u), 3+(u) 1+(u) 2+(u) 11, 7+(u) | 11.1, 8+(u) | **5+** |
| ld4 | | 10.3 | 7.7, 5+(u) | | 10+(u), 15+(u) 12.5+(u) | 11+(u), 7.5+(u) | **10+** |
| ld5 | | 13.9, 15.9+(u) 16.4 | 14.4, 17.5+(u) 18.4 15+(u) | | | 25+(u) | **17+** |
| ld6 | 30+(e) | 34,30 27.5 | 29.3, 33.1 | | 21+(e) 23+(e) | 32+(u) 16+(e) | **28+** |
| ld7 | | 47.8+(u) 42.5+(u) | 42+(e) | | | | **44+** |
| ld8 | | 57.6+(u) 58+(u) 52.5+(u) | | | | | **56+** |

Table 1. Selected elevation data from debris-flow terrace deposits in the Palisades Creek-Comanche Creek area. Elevations were measured from the highest point of each deposit relative to the nearest modern wash level and represent minimum terrace elevations. Elevations are in meters. +-minimum elevation; u-upstream; e-erosional remnant (terrace top not preserved). Figures given to 1 decimal place are from surveyed elevation points and are rounded up when mentioned in the text.

| Level | Near Lava | Palisades | Down --L/P | Espejo | Comanche | Arithmetic mean |
|---|---|---|---|---|---|---|
| mg1-mg2, undif. | 13 | | | | | **13** |
| mps2 | 31.9<br>26.8<br>32.3<br>34.3 | | 26.5<br>28<br>23 | | | **29** |
| mpg2 | | | 28<br>21<br>21 | | | **23** |
| mpg3 | 40.9<br>32.9<br>29.7<br>34.8<br>39.4 | | 35.7<br>40.1 | | | **36** |
| mps4 | | | | 43+(e) | | **43+** |
| mpg4 | 49.4+(e) | 53.1+(e) | 52+(e) | 42+(e),<br>52.1+(e)<br>52.1+(e)<br>49.1+(e) | 41.8+(e)<br>40.8+(e) | **48+** |
| mpg5 | | 60.6+(e)<br>70.6+(e)<br>65.6+(e) | 64.4+(e)<br>68+(e) | | | **66+** |

Table 2. Selected elevation data from Colorado River gravel terrace deposits in the Palisades-Comanche area. Elevations were measured from highest point of each deposit relative to the modern high water line and represent minimum terrace elevations. Elevations are in meters. +-minimum elevation; e-erosional remnant (terrace top not preserved). Figures given to 1 decimal place are from surveyed elevation points and are rounded up when mentioned in text.

| Level | Palisades | Espejo | Comanche | Arithmetic mean |
|---|---|---|---|---|
| ld3/ma | 8.1, 7.6<br>6.8, 7.7 | 9.6, 10 | 11.1 | **9** |
| lpc/mpg2 | | 26 | | **26** |
| ld7/mpg4 | | | 47.8, 44.8 | **46** |

Table 3. Selected elevation data from interface between mainstem (Colorado River gravel terrace deposits) and lateral (planation surfaces and debris-flow deposit terraces) features in the Palisades-Comanche area. Elevations were measured relative to the modern high water line and represent the flood plain edge. Elevations are in meters. Figures given to 1 decimal place are from surveyed elevation points and are rounded up when mentioned in the text.

# APPENDIX B

# COSMOGENIC-RADIONUCLIDE AGE DATA

Obtaining numerical ages for Quaternary deposits and surfaces is a difficult task: most such deposits are too old for $^{14}C$ methods and unsuitable for coventional methods of geochronology, which usually require a geologic event, such as volcanism, to reset the radiometric clock.

Quaternary deposits in the eastern Grand Canyon generally are associated with geomorphic surfaces such as terraces and planation surfaces. This association raises the possibility of dating the deposits by dating the correlative surfaces. A relatively new technique for dating surfaces is based on exposure of surficial matarials to cosmic-ray-produced neutrons. These neutrons have enough energy to penetrate the upper half-meter of solid material and produce, generally through spallation reactions, a variety of nuclides. The *in situ* cosmogenic radionuclide dating technique is thus based on the production of rare nuclides, generally radionuclides, as a result of this exposure. The technique yields exposure ages for materials lying on the surfaces. Such ages may depart from the actual age of formation of the surfaces because the material dated may have been buried originally, and subsequently exposed by erosion; or it may have been exposed by rolling or otherwise moving on the surface; or it may have been exposed by disintegration or weathering of a large boulder. In all these cases, the exposure ages obtained are younger than the real age of the surface, so represent lower limits to this age. The converse is true if the material sampled has a history of pre-exposure before landing on the surface. These considerations show that ages based on only a few samples may be problematic. The most robust results are obtained for individual surfaces by making numerous age determinations on as many surfaces as possible. This allows evaluating the validity of the ages by comparing them with morphostratigraphic observations.

We have dated surfaces and deposits within the area of this map by means of simultaneous $^{10}Be$ and $^{26}Al$ determinations (27 separate locations), as well as $^{14}C$ measurements on 4 samples from the archeological unit (ma).

Production rates for $^{10}Be$ and $^{26}Al$ are relatively high, so sample-size requirements are reasonable. However, $^{10}Be$ is also produced in the atmosphere, so it is necessary to separate the $^{10}Be$ produced in the atmosphere from that produced in the rock. In the case of $^{26}Al$, little is produced in the atmosphere, but an abundance of stable $^{27}Al$ in the rock can pose a problem: if the sample contains too much stable $^{27}Al$, the $^{26}Al/^{27}Al$ ratio becomes too low to be measured by accelerator-based mass spectrometry (AMS). Quartz is a good mineral for dating because atmospheric $^{10}Be$ can be leached out easily and because stable Al is present in only very small concentrations if at all. Cryptocrystalline quartz in the form of chert is abundant in the Grand Canyon surfaces.

Using both systems on the same sample gives a measure of the quality of the age obtained. For this work, we only consider determinations for which the $^{10}Be$ and $^{26}Al$ ages differ by no more than 20%.

Radiometric ages have been crosschecked with morphostratigraphic position and soil-carbonate development to establish a valid chronology. Nevertheless, some ages are anomalous and cannot be fitted into the overall scheme; an example is the 88.7 ka for unit ld4, which should be younger than the 80.3 ka unit lpc.

| Geomorphic unit | Location | Elevation above present grade, m | Age, ka | Soil-forming carbonate stage |
|---|---|---|---|---|
| ma | Espejo Cr. | ~10 | >modern to 3580±60 $^{14}$C yr (3) | I |
| ld4 | Comanche | 10+ | 88.7* | |
| lpp | Palisades | ≤30 | 60.5 | |
| lpc | Comanche | >17-26 | 81.6±16.5 (7)** | II |
| ld6 | Comanche | 28+ | 81.9±8.1 (3) ** | |
| ld7/mg4 | Comanche | 46 | 101.0±32.2 (5) | Weak III |
| ld7 | Lava Cr. | 45+ | 98.9 | |

* *Does not match ld4 determinations elsewhere, which are in the 25-30 ka range. May indicate pre-exposure of rock sampled.*
** *Identical ages suggest that levels lpc and ld6 are essentially identical in Comanche Creek area.*

Table 4. Radiometric ages of terraces and planation surfaces in the Palisades Creek-Comanche Creek area. All ages, other than for unit ma, are $^{26}$Al and $^{10}$Be exposure ages. Number in parentheses denotes number of determinations averaged to obtain age listed. No number indicates single determination. Table does not include determinations rejected because $^{26}$Al age/$^{10}$Be age is <0.8 or >1.2.

# APPENDIX C
# PALYNOLOGICAL DATA

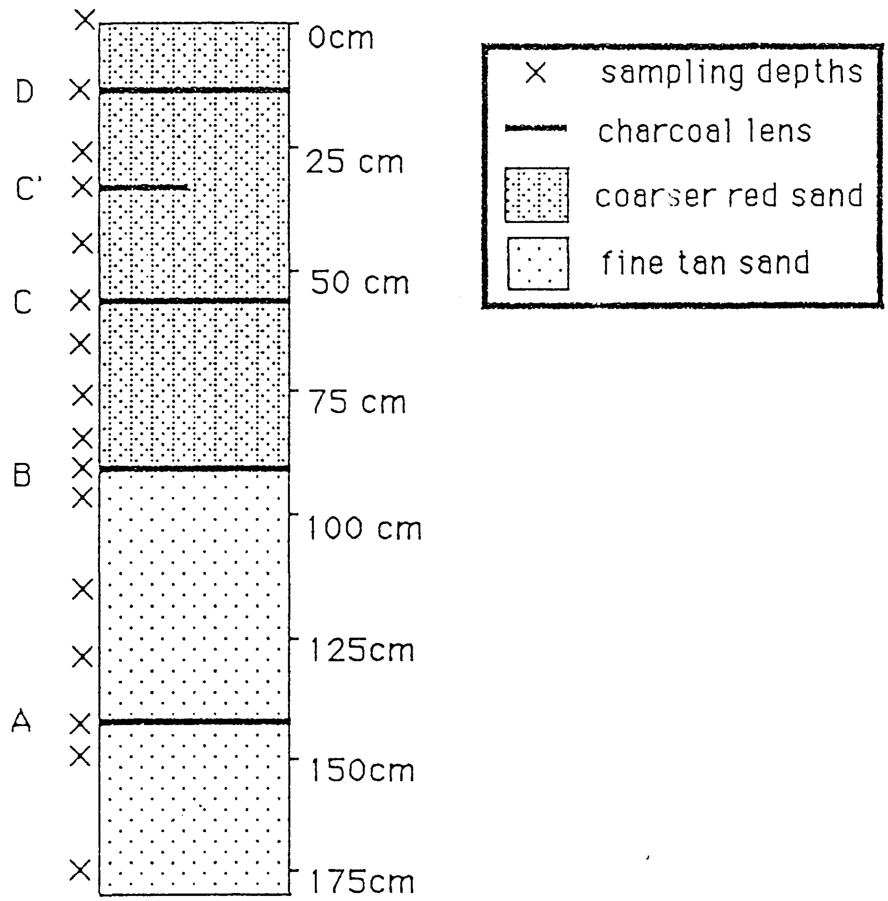


Figure 2. Pollen sample locations within "Sediment Profile 1" at Comanche/Espejo sample site, (see accompanying map for exact site location). (From Hasbargen and Smith, 1995)

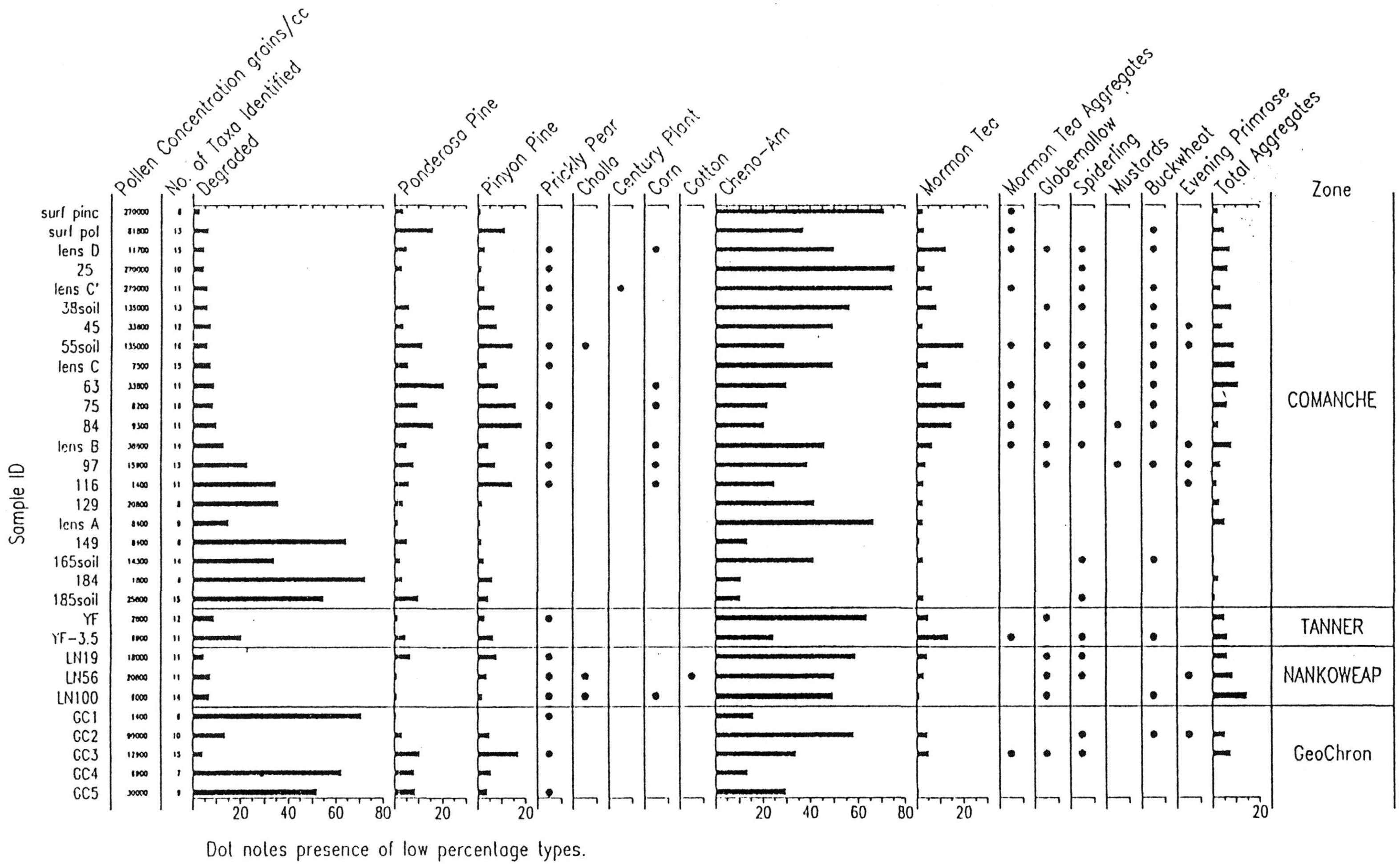


Table 5. Pollen percentage diagram from Comanche-Espejo Sediment Profile 1. Dot denotes presence of pollen in low concentration.

## APPENDIX D
## SURVEY DATA

| Survey Data Point | Geologic significance | Elevation in meters |
|---|---|---|
| *Lava Creek Area* | | |
| L1 | mpg1 | 819 |
| L2 | mog | 820.5 |
| L3 | mpg1 | 822.5 |
| L4 | mpg3 | 826 |
| L5 | mpg1 | 826.5 |
| L6 | mpg3 | 834 |
| L7 | ld4 base | 838.5 |
| L8 | ld4 top | 844 |
| L9 | ld5 base | 863 |
| L10 | ld5 top | 878 |
| L11 | ld6 base | 882 |
| L12 | ld6 top | 888 |
| L13 | ld4 top | 841.5 |
| L14 | ld4 top | 838 |
| L15 | ld5 top | 853 |
| L16 | ld5 base | 845.5 |
| L17 | ld3 | 827 |
| L18 | ld3 | 829 |
| L20 | high water line | 819.5 |
| L21 | high water line | 819.5 |
| L22 | ld4 top | 830.1 |
| L23 | mpg1 base | 817.5 |
| L24 | mpg1 top/mpg2 base | 821.5 |
| L25 | mpg2 top | 825.5 |
| L26 | high water line | 817.5 |
| L27 | driftwood line (100K?) | 820 |
| L28 | mpg2 base | 822.5 |
| L29 | mpg2 top | 840.5 |
| L30 | mpg3 base | 844.5 |
| L31 | mpg3 top. | 847.5 |
| L32 | high water line | 817.5 |
| L33 | mpg2 base | 831.5 |
| L34 | mpg2 top | 839.5 |
| L35 | mpg5 base | 875.5 |
| L36 | mpg5 top | 883.5 |
| L37 | mpg5 top | 881.5 |
| L38 | mpg5 base | 870.5 |
| L39 | mpg3 top | 852.5 |
| L40 | mpg3 base | 850.5 |
| L41 | mpg2 base | 827 |
| L42 | mpg2 top | 843.5 |
| L43 | high water line | 817 |
| L44 | mpg3 base | 848 |
| L45 | mpg3 top | 857 |
| L46 | mpg4 | 868 |
| *Palisades Creek Area* | | |
| P1 | ld1 | 842.5 |
| P2 | ld2 | 845 |

| Survey Data Point | Geologic significance | Elevation in meters |
|---|---|---|
| P3 | ld3 | 847 |
| P4 | ld4 base | 850 |
| P5 | ld4 top | 852.5 |
| P6 | ld5 base | 855.5 |
| P7 | ld5 top | 866.5 |
| P8 | ld6 base | 870 |
| P9 | ld6 top | 881 |
| P10 | ld7 top | 905 |
| P11 | ld5 base | 848.5 |
| P12 | ld5 top | 854.5 |
| P13 | ld6 base | 856.5 |
| P14 | ld1 | 826 |
| P15 | ld2 | 828 |
| P16 | top of mesquite scarp | 822 |
| P17 | base of mesquite scarp | 821 |
| P18 | base of arroweed scarp | 817 |
| P19 | high water line | 815.5 |
| P20 | old driftwood line on arroweed terrace | 817 |
| P21 | base of mesquite scarp, end of arroweed terrace on trail | 818.5 |
| P22 | top of mesquite scarp=mesquite line | 820 |
| P23 | end of arroweed terrace, base of mesquite scarp | 818 |
| P24 | old driftwood line at mesquite scarp | 821 |
| P25 | cutbank, inboard end of arroweed terrace | 818 |
| P26 | high water line-driftwood | 817.5 |
| P27 | old driftwood line near mesquite line | 821 |
| P28 | oldest driftwood line, just above mesquite line | 823 |
| P29 | mesquite line | 821.5 |
| P30 | driftwood line near mesquite line, 125K? Abundant worked wood with nails | 821 |
| P31 | high water line | 817.5 |
| P32 | oldest driftwood line (300K?) | 822.5 |
| P33 | driftwood line near mesquite line above arroweed terrace | 821.5 |
| P34 | high water line-driftwood | 818 |
| P35 | driftwood line near base of mesquite scarp; Anasazi sites here | 821.5 |
| P36 | driftwood at scarp inboard from arroweed terrace; large tamarisk immediately behind, not mesquite | 818 |
| P37 | highwater line-small driftwood | 818 |
| P38 | old driftwood inboard of arroweed terrace, can represent mesquite line here | 821.5 |
| P39 | highwater line-driftwood | 818 |
| P40 | old driftwood inboard of arroweed terrace; large tammies behind-use as mesquite line here | 821 |
| P41 | oldest driftwood just above mesquite line | 823 |
| P42 | near top of ma, against Palisades fan (ld3) | 824.5 |
| P43 | top of ma against Palisades fan (ld3) | 825.5 |
| P44 | mesquite line | 823 |
| P45 | highwater line-small driftwood line | 817.5 |

| Survey Data Point | Geologic significance | Elevation in meters |
|---|---|---|
| P46 | highwater line | 819.5 |
| P47 | highwater line | 820 |
| P48 | inboard edge of arroweed terrace; base of mesquite scarp | 820.5 |
| P49 | mesquite line | 823 |
| P50 | top of ma against Palisades fan (ld3) | 826 |
| P51 | highwater line | 819.5 |
| P52 | mesquite line | 822 |
| P53 | top of ma against ct | 827 |
| P54 | highwater line | 819.5 |
| *Comanche Creek Area* | | |
| CO6 | ld4 | 880 |
| CO8 | ld5 | 877 |
| CO9 | ld5-very few river gravels | 863.5 |
| CO10 | ld5 | 858.5 |
| CO11 | ld3 | 839.5 |
| CO13 | ld3 | 834 |
| CO14 | ld2 | 831.5 |
| CO15 | ld1 | 830 |
| CO16 | ld1 | 834.5 |
| CO17 | ld2 | 836.5 |
| CO18 | ld2 | 839.5 |
| CO19 | ld3 | 846 |
| CO20 | ld3 | 859.5 |
| CO21 | ld2 | 856 |
| CO22 | ld3 | 856.5 |
| CO23 | ld3 | 861 |
| CO24 | ld3 | 852 |
| CO25 | ld1 | 846 |
| CO26 | ld2 | 847.5 |
| CO27 | ld4-unit with weathered clasts between 3&4 | 858.5 |
| CO28 | ld4-unit possibly below ld4 at fort (north side) | 867 |
| CO29 | ld4 | 868 |
| CO30 | ld4-break in slope, trail | 862 |
| CO31 | ld4 | 857 |
| CO32 | ld4-unit possibly under 4 at fort (north side). | 873 |
| Station 12A | Control Station | 860 |
| CO33 | top of ld4 below Comanche Fort | 868.5 |
| CO34 | top of ma north of Comanche | 828 |
| CO35 | top of ma—flat area in Espejo-Comanche "garden" | 822 |
| CO36 | top of ma, Espejo-Comanche "garden"; charcoal layer site | 822 |
| CO37 | top of river gravel | 840 |
| CO38 | top of ma, north end Espejo-Comanche "garden" ~50 m from area sampled for charcoal by H. Fairley | 823.5 |
| CO39 | mesquite line, add 1 m (cutbank top) | 817 |

| Survey Data Point | Geologic significance | Elevation in meters |
|---|---|---|
| CO40 | medium-sized driftwood line at base of cutbank; small-medium tamarisks along bank; arroweed on terrace above, 30-40K? | 814 |
| CO41 | arroweed terrace (upper?) | 815 |
| CO42 | mesquite line (top of scarp) | 820 |
| CO43 | arroweed terrace (base of scarp) | 818.5 |
| CO44 | base of upper-lower arroweed scarp | 814.5 |
| CO45 | top arroweed scarp-mesquite here may include mesquite line | 817 |
| CO46 | highwater line | 813 |
| CO47 | mesquite line | 816.5 |
| CO48 | driftwood line (medium to large) | 815.5 |
| CO49 | highwater line | 812 |
| CO50 | approximate top of ma south of Comanche Creek | 823.5 |
| CO51 | approximate top of ma between dunes | 821 |

APPENDIX E

RIVER CORRIDOR SHORELINE FEATURES

## BACKGROUND INFORMATION AND PROCEDURES

Precise knowledge of river level for any given discharge is of great importance for many issues relating to sound management of the Colorado River downstream from Glen Canyon Dam, and specifically within the Grand Canyon National Park. Among such issues are

- Erosion of archeological features
- Erosion/formation of beaches
- Effects on riparian vegetation
- Effects on habitats such as fish spawning grounds.

For example, the 45,000 cfs flow of 1996 was designed not only to determine whether sand would be entrained from the channel and deposited in beaches, but also to find out whether the level above normal water level at which the beaches formed was high enough the protect the beaches from subsequent rapid erosion. In other words: would beaches form, and would any beaches formed have an adequate lifespan?

Unfortunately, it is not possible to measure the relation between stage (i.e., water elevation above a fixed datum) and discharge at some one place, then apply this relation throughout a drainage, because stage as a function of discharge depends on channel geometry: the narrower the channel, the higher the stage for a given discharge.

The only pratical way to determine stages along the river is by mapping 'fossil' shoreline features and inferring from these the discharge that corresponds to each shoreline, making use of known discharges such as those of 1983 and 1996, and the personal experience of river runners. Shoreline features that we have used include

Lowest elevation of large mesquite trees ('Mesquite line')
Driftwood lines
Scarps
Terraces

We have also used vegetation types growing on terraces to relate the terraces to discharges.

Discharges vary greatly with stage, especially in the wide reaches of the river corridor, where a difference in stage of one meter might well correspond to differences in discharge of tens of thousands of cfs. Consequently, even large-scale topographic maps with contour intervals of five meters, or even one meter, are not detailed enough to allow reading elevations of the features accurately enough to be of use. Furthermore, it is difficult or impossible accurately to plot the features on the map, given that most occur in areas of subdued topography and thus few contour lines.

To get around this problem, we embarked on a surveying program using a total station and prism pole to locate features between Palisades Creek, at the upstream end of the maps, and lower Unkar Beach at the downstream end. This has yielded hundreds of elevation readings; some are of tops and bottoms of geologic contacts, but most locate shoreline features. The total station was located on or near trilateration-survey stations; the geologist placed the prism pole on features whose position was to be determined.

The total station is capable of reading elevations to the millimeter, but this precision is unrealistic for the features being described, which tend to be irregular or diffuse. Consequently, elevations are presented rounded off to the nearest ½ meter. The value of the technique was to quickly locate a great number of points as precisely as needed needed.

## SHORELINE FEATURES

Most known shoreline features in the Grand Canyon postdate the beginning of incision of the archeological unit (ma). The archeological unit represents the last episode of significant aggradation in the Grand Canyon. Its incision began about 700 years BP. The top of the unit typically is about 10 m above present river grade. We have determined this elevation in many places to define an upper limit to the range within which the River has operated in its modern, downcutting, phase.

Figure 3 shows that the Colorado River has operated in two entirely different modes, separated by construction of Glen Canyon Dam in 1962. Before that date, peak annual discharges varied widely. The mean was 78,000 cfs, but the river reached 125,000 cfs or so about once every ten years. High discharges tend to modify or destroy features produced by earlier smalled discharges, so the bulk of the pre-dam shoreline features that are still preserved are likely to be related to the 125,000 cfs discharges. According to the record available, the 220- and 300,000 cfs discharges are not common events. Both predate the measured 125,000 discharges, so their shoreline features should still be preserved, subject only to the decay caused by many decades of exposure. The most prominent feature is high driftwood. Our study has been carried out in an open part of the river corridor, where the cross-sectional area of the river increases rapidly with stage. Therefore, we suspect that the stages represented by the 220- and 300,000 cfs discharges are close and probably not distinguishable in most places.

After 1962, the river has been much more controlled, and the annual maxima typically have been around 25,000 cfs. However, maxima in the 40,000 cfs range are common enough to have left their mark on topography and vegetation. The 1983 flood that exceeded 90,000 cfs and peaked at around 97,000 provides a useful marker, as does the 1996 flood of 45,000 cfs. In the more open parts of the river corridor, the 1983 shoreline and the pre-dam 125,000 shoreline are close together, and the corresponding driftwoods are stacked together or even intermixed.

Before 1996, river flow fluctuated on a daily basis, generally reaching daily maxima in the 12 to 15,000 cfs range: This line marks the point below which there is little or no vegetation, especially bushes and trees. We call this the High Water Line, or HWL, and use it as a datum.

A brief description of specific shoreline features follows (Fig.4 ), starting with the oldest and highest.

**Ma, top**. Top surface of the last major aggradational deposit of the Colorado River and other drainages in the area. All shoreline features mapped are inset into this deposit, which typically is truncated by a scarp descending toward the River. The upper few meters contain Pueblo material, and Pueblo sites are built on top of the unit. The youngest sites found are Pueblo II, indicating that the unit stopped being deposited as early as 700 to 750 years BP.

**Oldest driftwood**. Probably deposited mostly by the 1884 300,000 cfs flood. May also include material from an older flood and from the 1921 220,000 cfs flood. Consists predominantly of large

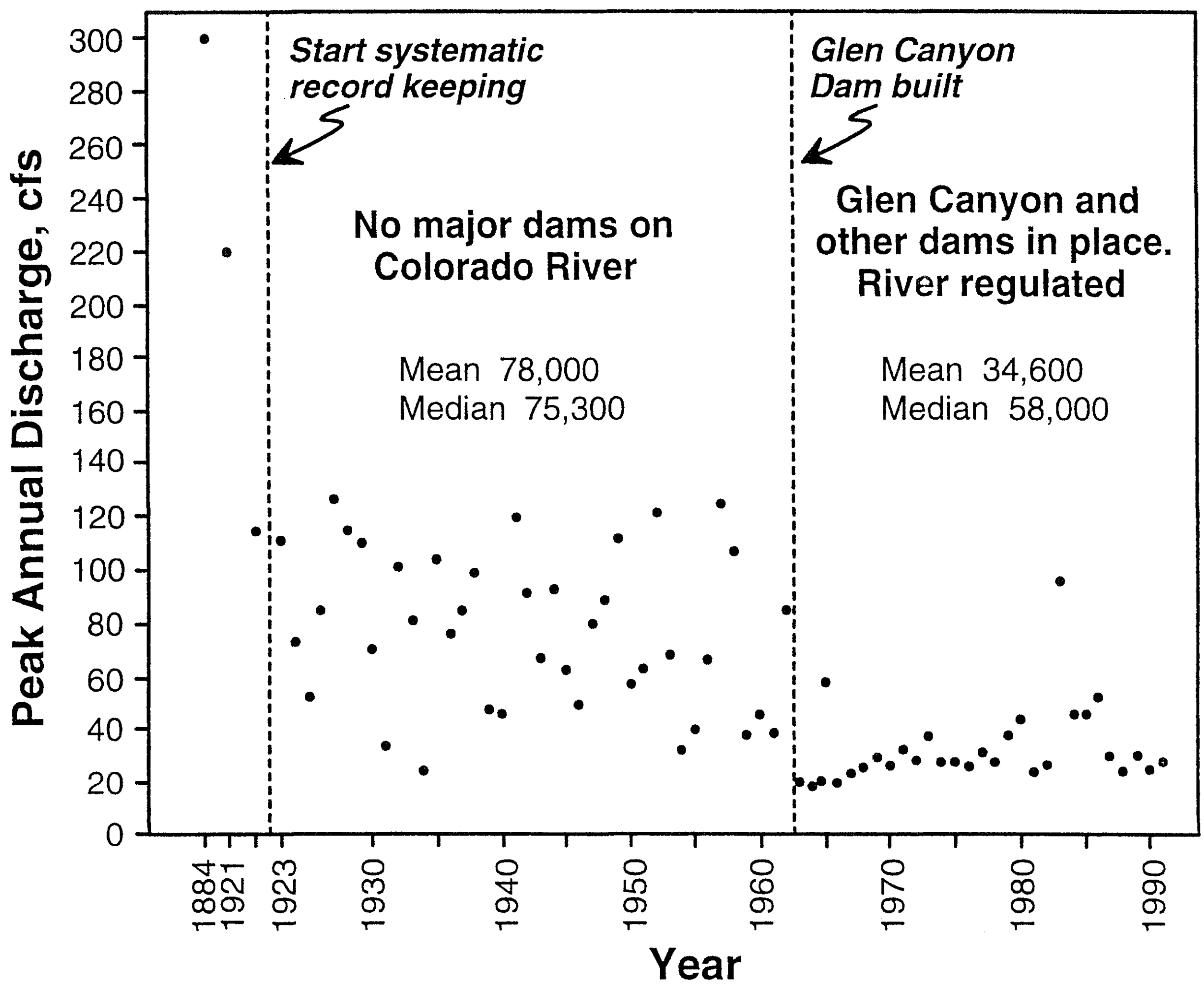


Figure 3. Peak annual discharges, Colorado River at Lee's Ferry, 1884-1992.

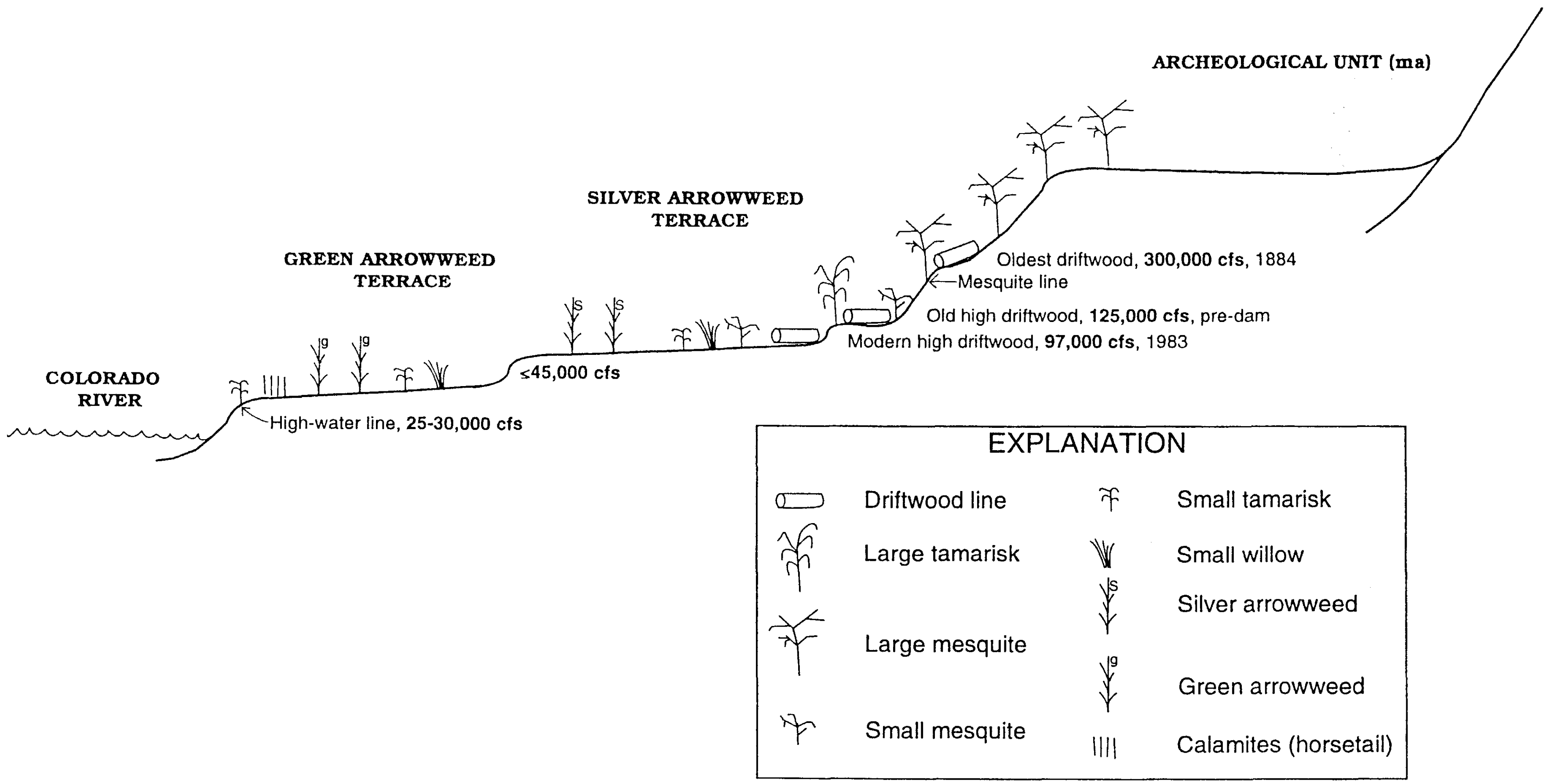


Figure 4. Schematic diagram showing relations between shoreline features along the Colorado River corridor.

and highly weathered logs. Worked wood scarce but present, some hand-shaped. Other artifacts present but scarce.

**Mesquite line.**
Diffuse line on scarp cut into ma unit that marks lowest level at which large mesquite grow. Generally, close to base of scarp. Where mesquite does not grow, line is marked by other bushes and trees. Where ma unit is absent, line is defined by vegetation zone growing in colluvial or alluvial deposits. Line approximates the level above which mesquite could grow successfully because they could germinate, their taproots could reach groundwater during low-flow stages, and they were not killed by floods. Interpreted to be a little above the level of frequent large pre-dam floods, about 125,000 cfs.

**Old high driftwood**. Typically large, well-weathered logs and branches. Machine-worked wood common, as well as cans and other artifacts. Writing and logos on cans etc. weathered. Plastic containers absent. Marks level of frequent large pre-dam floods, interpreted at approximately 125,000 cfs.

**Modern high driftwood**. Deposited by 1983 flood. Generally close or nested in old high driftwood. Wood relatively small and unweathered. Machine-worked wood, cans and other artifacts common. Writing and logos on cans etc. relatively fresh. Plastic containers common. Lower limit of old, large tamarisk and willow trees is near this line. Young mesquite trees in places. Corresponds to 97,000 cfs peak discharge, but locally may include slightly lower shorelines corresponding to discharges in the 90 thousands.

**Silver arrowweed terrace**. Characterized by dead or dying large arrowweed bushes. Moderate-sized tamarisks locally. Arrowweed probably sprouted as a result of 1983 flood, but terrace is above routine major post-dam peak discharges of about 40,000 cfs, causing death of arrowweed. Many discontinuous strand lines composed of small- to medium driftwood, probably emplaced by receding waters of 1983 flood. Includes several scarplets locally.

**Green arrowweed terrace**. Characterized by green, living arrowweed bushes, small to large. Small coyote willow and tamarisk in places. Horsetails (*calamites*) present il lower part locally. Flooded by routine peak annual discharges in the 20-40,000 cfs range. Strandline of 45,000 cfs research flood of 1996 is near top of this this terrace. Numerous discontinuous strandlines composed of small to medium driftwood. Includes several scarplets locally.

**High-water line**. Characterized by lowest bushes. Represents high level routinely attained by fluctuating-flow discharges. Probably corresponds to 25-30,000 cfs discharges. Zone below the high-water line is flooded routinely, preventing establishment of tamarisk and other trees and bushes. Horsetails and other small water-loving plants are present in places. High-water line commonly marked by driftwood composed mostly of small wood. Plastic oil cans, beer cans, tires, and other modern debris common in backeddies.