U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

QUATERNARY GEOLOGY OF THE GRANITE PARK AREA, GRAND CANYON, ARIZONA: AGGRADATION-DOWNCUTTING CYCLES, CALIBRATION OF SOILS STAGES, AND RESPONSE OF FLUVIAL SYSTEM TO VOLCANIC ACTIVITY

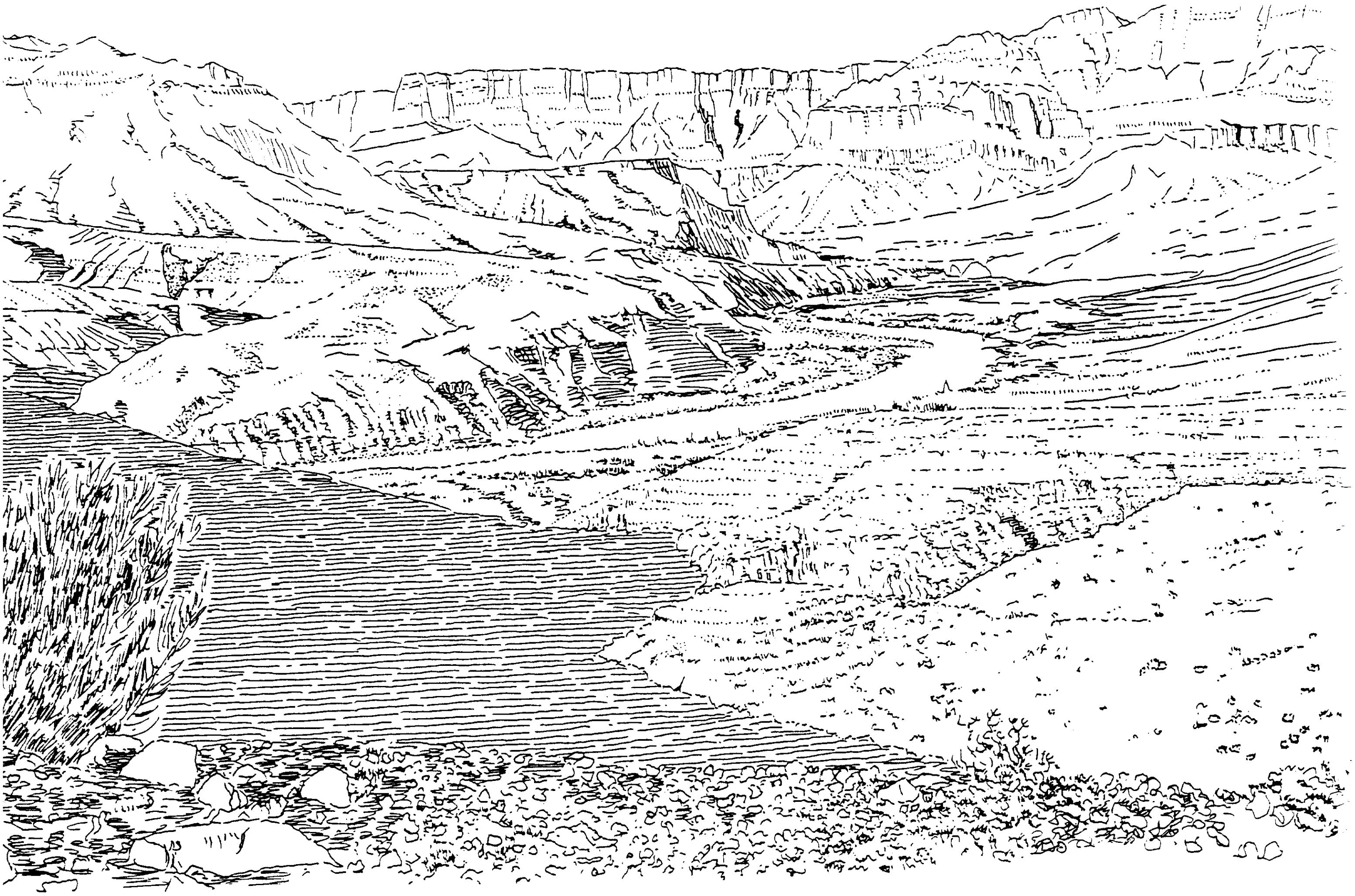
By

Ivo Lucchitta[1], G.H. Curtis[2], M.E. Davis[3], S.W. Davis[3], and Brent Turrin[4].

With an Appendix by Christopher Coder, Grand Canyon National Park, Grand Canyon, AZ 86040

Open-file Report 95-591

[1] *U.S. Geological Survey, Flagstaff, AZ 86001*
[2] *Berkeley Geochronology Center, Berkeley, CA 94709*
[3] *Davis[2], Georgetown, CA 95634*
[4] *U.S. Geological Survey, Menlo Park, CA 94025*



GLEN CANYON ENVIRONMENTAL STUDIES

QUATERNARY GEOLOGY-GEOMORPHOLOGY PROGRAM

REPORT 2

QUATERNARY GEOLOGY OF THE GRANITE PARK AREA, GRAND CANYON, ARIZONA: DOWNCUTTING-AGGRADATION CYCLES, CALIBRATION OF SOIL STAGES, AND RESPONSE OF FLUVIAL SYSTEM TO VOLCANIC ACTIVITY

CONTENTS

PLATES AND FIGURES

ABSTRACT

Field studies of Quaternary geology and geomorphology in the Granite Park area, river miles 207.5 to 209 in western Grand Canyon, have led to the construction of five detailed cross sections in which the elevation of contacts above a fixed datum has been determined by total-station survey. This work has been accompanied by field and laboratory soil analyses and by precision geochronometry of a basalt flow incorporated in the Quaternary section. This flow is critical to calibrating soil-carbonate stages in the Grand Canyon.

The sections depict four downcutting-backfilling cycles, each consisting of erosion of older deposits by the Colorado River, forming a new river channel in which a new and characteristic suite of deposits is laid down. Cycle I, the youngest, records downcutting that started about 700 years ago and is still going on today. No significant deposition has yet occurred during this cycle. Cycle II includes formation of the archeological unit, an unusual fine-grained deposit that is present throughout the Grand Canyon and was the material farmed by prehistoric puebloan cultures. Cycle III is characterized by thick fluvial gravels that include and are overlain by basalt-cobble gravel and basalt sand -- the youngest evidence for volcanic activity preserved in Granite Park. Cycle IV includes the 600 (525?) ka Black Ledge basalt flow, which is overlain by basalt-cobble gravel and basalt sand. When the basalt was emplaced, the river channel was about 30 m above its present location.

Cycle IV deposits are truncated by a planation surface with Stage V carbonate soil, which is about 525 (600?) ka. The deposits are also truncated by a lower surface with Stage IV carbonate, which is less than 525 (600?) ka, and more than or equal to 250 ka. Cycle III deposits are truncated by a planation surface with Stage III carbonate soil, which is very much less than 525 (600?) ka, less than 250 ka, and probably about 100 ka on the basis of many ^{10}Be and ^{26}Al determinations upstream in the Colorado River drainage.

The basalt-cobble gravel and basalt sand require unusual processes of formation. We propose that both represent overloading of the Colorado River as a consequence of volcanic events in the Toroweap-Whitmore area, about 30 miles upstream. The basalt sand represents overloading by volcanic ash during an eruption, possibly augmented by sand-size material produced by thermal shock as flows came in contact with water. The basalt-cobble gravel represents overloading by material derived from breaching and rapid destruction of lava dams.

The basalt-cobble gravel and basalt sand show how the Colorado River responds to overloading: vigorous aggradation while the overload exists, and equally vigorous downcutting when the overload ends. In the Granite Park area, the downcutting since the end of Cycle IV aggradation has occurred at an overall average rate of 1.6 cm\ka. The actual rate during downcutting events was higher because the interval includes the Cycle-III and Cycle-II aggradation.

Deposition and subsequent removal of the archeological unit during cycle II probably represent a similar response of the river to overloading as the volcanically-driven Cycle IV. However, this aggradation could not have resulted from volcanic activity, nor from glacially induced overloading. Instead, we propose destabilization of ice-age colluvial aprons of regional extent owing to disappearance of vegetative cover and onset of torrential rains related to monsoonal weather systems. Once the colluvial aprons were mostly eroded, sediment supply waned and the Colorado River and its tributaries embarked on a regimen of vigorous downcutting that has resulted in about 10 m of incision in about 750 years (1300 cm/ka) and is still going on today. Glen Canyon Dam has exacerbated this process by further decreasing sediment supply to the river, but its effect is merely an addition to the naturally occurring intense erosion.

INTRODUCTION

In 1962, when Glen Canyon Dam was built across the Colorado River, attention was focused on the effects of the dam on Glen Canyon, the stretch of the Colorado upstream from the dam that would be inundated by Lake Powell. It was not long, however, before major effects began to be felt downstream, in Glen Canyon National Recreation Area and Grand Canyon National Park. These changes affect both the physical and the biological systems. Some impact archeological sites and endangered species, both of which are protected by law. Others, notably the erosion of beaches, have a negative effect on the more than 15,000 people who float down the Grand Canyon annually. Because of these impacts, the Bureau of Reclamation was charged with conducting studies (Glen Canyon Environmental Studies, or GCES) aimed at understanding the effects brought about by the Dam. The long-term purpose of GCES is to provide information that will allow operating Glen Canyon Dam in a way that will minimize negative impacts in the Grand Canyon, consistent with the need to generate power and provide water storage.

The Quaternary Geology-Geomorphology program, of which this report is a result, is a series of studies carried out under the auspices of GCES and aimed at providing an insight into the long-term functioning of the Colorado River and its tributaries within the Grand Canyon. Understanding how the River system operates in its natural state provides a baseline against which to evaluate the changes brought about by the Dam. The consequences of failing to develop the baseline over a long enough time interval are best illustrated by the Colorado River Compact, which apportions water between the lower and upper basin states on the basis of flows averaged over a time interval that in retrospect turned out to be non-representative.

In Quaternary studies, accurate numerical ages for deposits and surfaces are essential, yet such ages are difficult to obtain and of suspect reliability because many of the techniques involved are still experimental and require a knowledge of the history of the boulder from which the sample was taken. Our approach, then, has been to utilize a variety of techniques and cross-check the results. Modern Quaternary studies also require the simultaneous application of varied disciplines to yield satisfactory results. Accordingly, we have assembled a team consisting of geomorphologists/geologists, soil scientists, cosmogenic-radionuclide-, ^{14}C, and $^{30}Ar/^{40}Ar$ geochronologists, surveyors, and even a geophysicist experienced in paleoseismology to help with slope-stability problems and the possible occurrence of earthquakes in the geologically recent past. This, and subsequent reports, are the result of the team's efforts.

In this paper, we have done our best to avoid using technical jargon, excepting instances such as soil descriptions, where technical terms are unavoidable. This is not a popular approach in some quarters, but we justify it on the grounds that these reports are to be used by people who are not professional earth scientists, and that simplicity is the daughter of understanding.

PURPOSE

Our work in the Granite Park area (Fig. 1) came at the urging of the Archeology staff of the Grand Canyon National Park, who pointed out that Granite Park is one of the few places in the lower Grand Canyon that contains a variety of Quaternary deposits and surfaces of various ages. Furthermore, these features are locally associated with archeological remains. Our interest in this area was whetted by the knowledge that it contains basalt flows within the Quaternary section. Such basalt flows can be dated with great precision by means of laser-fusion ^{39}Ar-^{40}Ar techniques, which provides a means for calibrating the methods we have been using for determining ages of Quaternary features elsewhere in the Grand Canyon. Another purpose was to investigate whether the morphostratigraphy that we have developed in the eastern Grand Canyon is valid and recognizable in the western Grand Canyon, where the fluvial system has been disrupted repeatedly by Quaternary basalt flows cascading into the Canyon from the Toroweap Overlook - Whitmore Canyon area (River miles 177 to 188). Finally, we were interested in determining whether the known volcanic events that influenced the River in the lower Grand Canyon can shed light on the river's response to changing conditions.

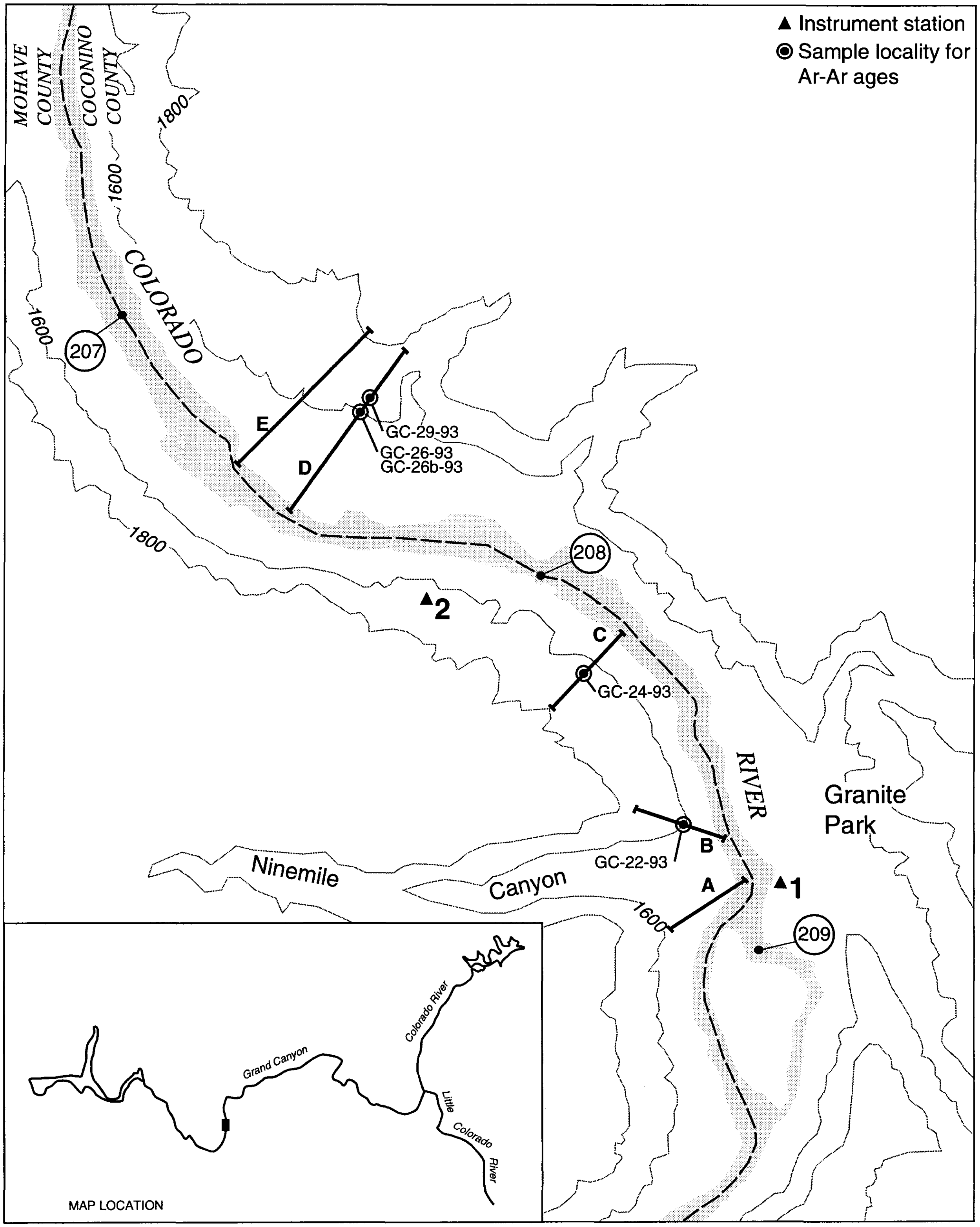


Figure 1. Location map of the Granite Park area showing cross section lines, instrument stations, and sample localities for Ar-Ar ages. River level in area of sections approximately 1400'.

METHODS

Given the week of field time available for the project and the absence of a suitable base map, we felt that our aims would best be served by inspecting the Quaternary geology and geomorphology of Granite Park, and depicting our findings on calibrated cross sections. We felt that attempting to produce a geologic map would be costly, time-consuming, and add relatively little to our knowledge in relation to expense.

The result of the work is five cross sections spanning the river interval between Miles 207.3 and 208.8, situated where the Quaternary deposits are thickest and best exposed (Fig. 1).

Geologic units and their relations were inspected and described in the field, as were the soils developed on the units. The elevation of contacts and location of soils descriptions were determined by means of a total station situated at two instrument stations (Fig. 1). Station 1 was tied in to a Banner leveling-survey point. Selected units were sampled for soils analyses, paleomagnetism, and radiometric age determinations.

Results from the field determinations were plotted on the five cross sections (Figs. 2 through 6), which are drafted to scale in the vertical direction using the total-station data. This gives accurate figures for the elevation of important geologic contacts above a reference datum, which is the High-Water Line (HWL), i.e. the highest level generally reached by the river during the fluctuating-flow regimen. This corresponds to about 30,000 cfs (cubic feet/second). The line is marked in the field by the lowest bushes and small trees. The surface of the river cannot be used as a datum because of its constant fluctuation. Horizontal distances are not relevant and are not plotted to scale. Instead, horizontal dimensions were chosen to give vertical exaggerations adequate for showing the locally complex details of the stratigraphy.

The elevations, geomorphic and geologic characteristics, soils, and radiometric ages of units were evaluated in terms of their correlation with Quaternary units studied and described in the Eastern Grand Canyon, and of the unusual geologic story that they record.

Soils were described, sampled and analyzed according to standards of the National Cooperative Soil Survey. Soil descriptions in the Granite Park area include two formal descriptions. Soil classification follows Soil Taxonomy (USDA Soil Survey Staff, 1994). Classification of relative secondary carbonate development follows Gile (1981), modified by Machette (1985). Laboratory facilities at the Department of Land, Air and Water Resources, University of California, were made available by Dr. Randy Southard, who provided data on particle size distribution, percent carbonate, aluminium, and iron. Soils data are presented in Appendix B.

Seven samples of the Black Ledge basalt flow were collected from the locations shown in Fig. 1. ^{39}Ar-^{40}Ar ages of the samples were determined by whole-rock step-wise incremental laser heating and fusion. These procedures were carried out at the Berkeley Geochronology Center in Berkeley, California. Analytical data, step-heating spectra, isochrons and comments for the samples are given in Appendix C.

RESULTS

Geology and geomorphology

The Granite Park area contains Quaternary units exposed over a vertical distance of 83 m (274 feet) and spanning more than 600 ka of time, as determined by radiometric ages and soil development. In the eastern Grand Canyon, this time span is represented by units exposed over a greater vertical interval.

The most noticeable Quaternary geologic unit in the Granite Park area is a basalt composed of several flow units that collectively are at least 30 m (100 feet) thick. Mostly, the flows have little or no sedimentary material separating them; in places, as much as 3.5 m of gravel and debris is interbedded with the upper flows. A conspicuous feature of the thickest flows is a well developed coarse columnar structure, which makes large basalt blocks that have slumped off the eroded cliff look rather like pinecones. The basalt is part of Hamblin's Black Ledge flow (1994), which is the farthest-traveled of the intracanyon lavas.

River gravels that form steep bluffs near the water's edge are conspicuous, as are sloping planation surfaces at various elevations above present river grade. But the most interesting and unusual geologic features generally are not visible from the River. These are 1) coarse black sand composed predominantly to exclusively of basaltic ash, generally cross bedded; and 2) basalt-cobble gravel, commonly well rounded, with <1% clasts of Paleozoic rocks, quartz, quartzite, igneous rocks, and other lithologies typical of Colorado River gravels. In several exposures, the basalt-cobble gravel overlies the basalt sand; elsewhere, the opposite is true. Commonly, sand and cobbles are intermixed in various proportions. The basaltic sand-gravel association occurs directly above the basalt stratigraphically and topographically (Sections B, C, and D and E, Figs. 3 through 6); inset into it and topographically lower (Sections D and E); and not directly associated with basalt but topographically lower and interpreted as stratigraphically younger (Section A, Fig 2).

Basalt flows, basalt-cobble gravel and basalt sand are absent from the Quaternary section upstream from Vulcan's Throne, i.e. upstream from the vents that produced the volcanic materials. In contrast, other Quaternary units that are part of the Granite Park section do occur upstream in the Grand Canyon. These include river gravels in terraces at various elevations, fine to very fine river sand of the archeological or 'striped' unit, debris-flow terraces along major washes, and the various levels associated with the most recent downcutting by the Colorado River.

The framework against which the Granite Park Quaternary deposits are to be viewed is this: The Colorado River has an overall history of vigorous downcutting since the end of the Miocene, when it became established in its present course (Lucchitta, 1972, 1990) . The result has been the carving of the Grand Canyon in a time interval ranging from a maximum of 4.3 MA to a minimum of about 2.8 MA (Lucchitta, 1988, 1990). The overall downcutting has been interrupted several times during that part of the Quaternary for which there is a record (at least the last 800 ka) by episodes of aggradation, which we believe are caused directly by overloading of the river with sediment, and indirectly by climate. Intervening downcutting reflects climate-induced underloading or depletion of sediment sources. Each downcutting-aggradation couplet represents a cycle. Deposits and surfaces of each cycle are inset into and topographically lower than those of previous cycles.

In addition to the events described above, the area downstream from Toroweap Overlook has been affected by violent events of volcanic nature, including ash falls accompanying eruptions; the emplacement of basalt flows, some of which coursed down the Canyon for tens of kilometers, whereas others formed dams that impounded the Colorado River; and the eventual overtopping and probably catastrophic destruction of the lava dams, followed by renewed vigorous erosion to attain the pre-dam river grade.

The interaction between volcanic activity and the river system is of great interest, but is difficult to reconstruct in the area where the lavas cascaded into the Canyon, where flow is piled chaotically upon flow, dam upon dam. In contrast, the Granite Park area, some 20 river miles downstream from the lava cascades, has a simpler and more orderly stratigraphy, and one more promising for sorting out relations between volcanic products, sedimentary deposits, and geomorphic features. This, in turn, provides an opportunity for understanding the processes by which the rivers of molten rock and the river of water interacted and interfered with each other and, by extension, how rivers function during periods of extreme overloading and periods of very-high-energy discharge.

The five sections measured in the Granite Park area contain the record from which river processes can be reconstructed. The sections are labelled and discussed going upstream from Granite Park (mile 209). This order generally corresponds to increasing complexity.

Section A (Mile 208.8)

Section A (Fig. 2 and Plate 1) is the thinnest of the sections studied, and the only one lacking the basalt flow sequence. Three downcutting-backfilling cycles are represented: in descending order, that containing the non-volcanic river gravel,

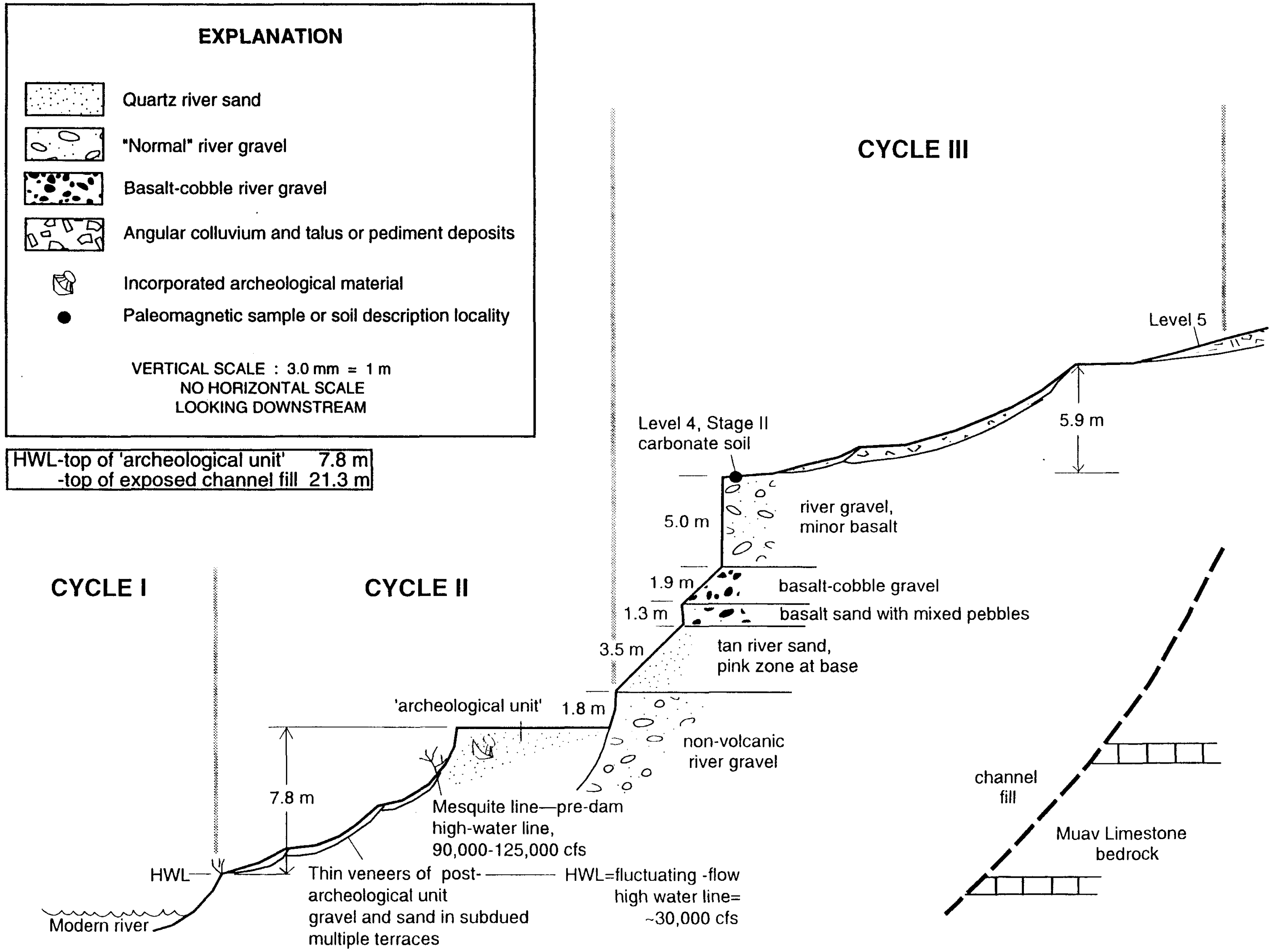


Figure 2. Cross section A, Granite Park, river right, mile 208.8. Vertical gray bars separate cycles. Horizontal black lines denote boundaries of intervals (shown in meters).

together with basaltic gravel and sand (cycle III); that containing the archeological unit (cycle II); and that containing the modern river channel (cycle I). The top of the gravel sequence is 21.3 m above HWL.

In the absence of basalt flows, it is impossible to determine directly whether the gravel and sand exposed are stratigraphically below the basalt, and therefore older, or inset into the basalt, and therefore younger. In our opinion, they are inset and younger because that is the position of thick non-volcanic river-gravel in the other sections (Fig. 7). Gravel above the flows is composed predominantly of basalt cobbles, and the non-volcanic gravel stratigraphically beneath the flows is merely a thin veneer separating the flows from bedrock.

The river sand, black sand, and basalt-cobble gravel within the river-gravel sequence are not present in the other sections at comparable elevations. One possible explanation is that this section was deposited in a marginal part of the river where deposits were laid down and preserved that have been eroded elsewhere. The black sand and basalt-cobble gravel attest to a volcanic event that took place long after emplacement of the Granite Park basalt flows.

The section comprising the river gravel and sand, the black sand, and the basalt-cobble gravel represents one overall aggradational event which, however, very likely includes minor episodes of downcutting. The aggradation filled a channel that had been cut down to, or even below, the present river grade.

The second downcutting-backfilling cycle recorded is that represented by the archeological unit, which was deposited within a valley cut into the previous gravel sequence. We apply the name 'archeological unit' to this deposit because throughout the Grand Canyon it is the oldest deposit that includes archeological material, and because such material generally is abundant. In contrast to older fluvial units, this one is composed predominantly of fine to very fine sand. Charcoal layers within the unit are common in the Grand Canyon and its tributaries and attest to farming by prehistoric people (see Appendix on archeology). We believe that the layers result from either initial clearing of the fields, or the annual burning of stubble. We do not know when the unit started being deposited, but believe this took place four to eight thousand years ago on regional grounds. However, the time when the unit stopped being deposited and started being affected by downcutting of the present cycle is established at 700 to 800 BP on the basis of ^{14}C and archeology.

Modern downcutting amounts to about 10 m. The archeological unit is well preserved only above the 'mesquite line', which is the lower limit for large and abundant mesquite trees. The line corresponds to the common pre-Glen Canyon Dam flood discharges of the Colorado River, in the 90- to 125,000 cfs range. Below the mesquite line are several strandlines and minor terraces that mark post-dam floods of the River, including that of 1983. The lowest bushes and very young trees mark the high-water line (HWL) of the fluctuating discharges of Glen Canyon Dam, at about 30,000 cfs.

Section B (Mile 208.7)

Section B (Fig. 3) records three downcutting-backfilling cycles: in descending order, that containing basalt flows and associated basalt-cobble gravel; that containing the 'striped' or archeological unit; and that related to the modern river. The basalts are about 0.6 MA old (see below) and flowed down a river channel that had been carved into the Bright Angel Shale to no more than about 30 m above present grade. Two flow units are preserved in this section. The top of the basalt is about 53 m above the HWL; the base is not exposed. Conformably above the

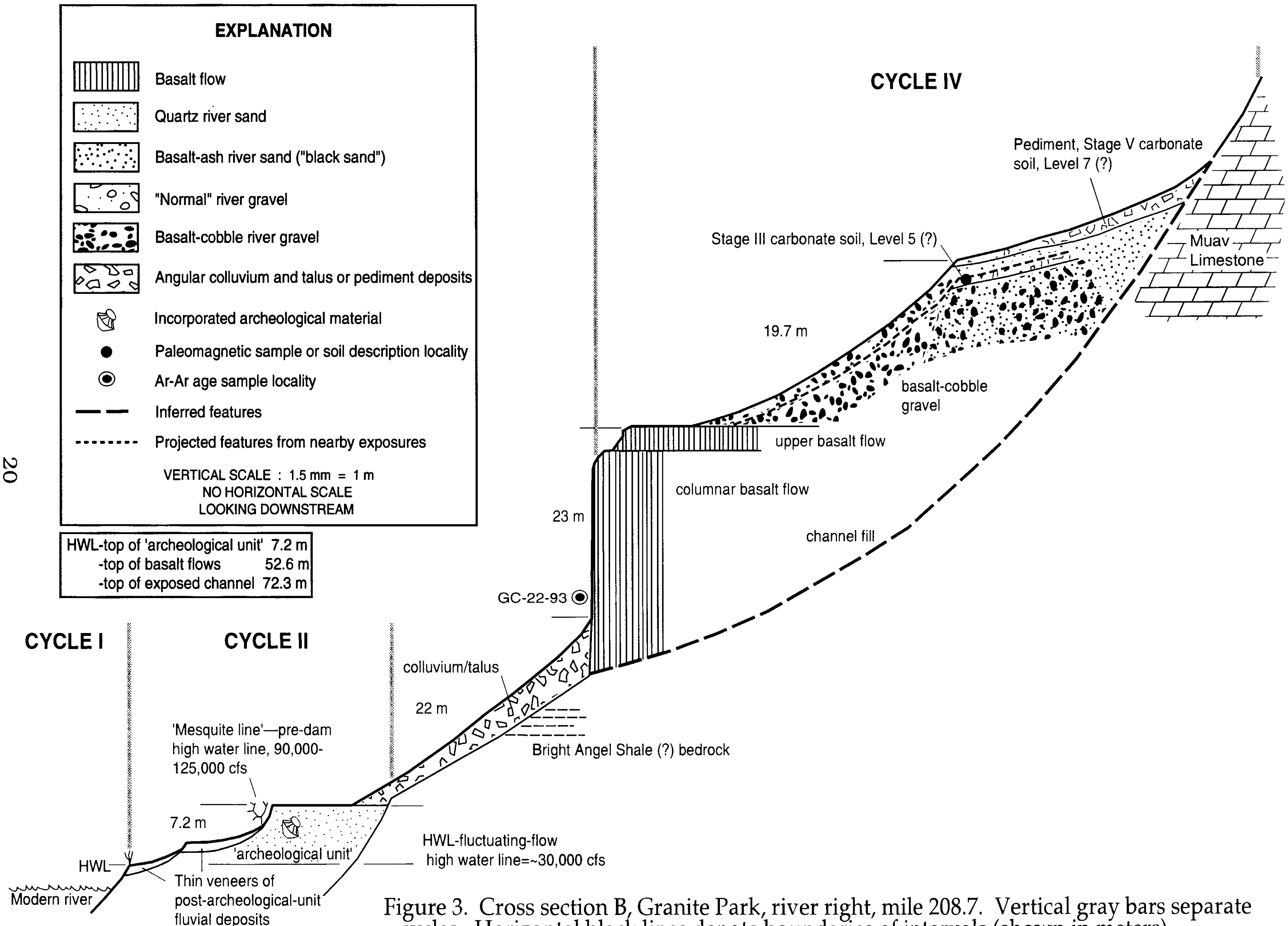


Figure 3. Cross section B, Granite Park, river right, mile 208.7. Vertical gray bars separate cycles. Horizontal black lines denote boundaries of intervals (shown in meters).

flows is at least 20m of basalt-cobble gravel that grades upward in the section and toward the edge of the channel into basalt-ash black sand. Gravel and sand are truncated by a planation surface mantled by local debris that shows a Stage V carbonate soil. This surface probably represents Level 7. A lower surface is inset into Level 7 and probably represents Level 5 because of its Stage III carbonate soil.

The river gravel sequence is not exposed here. The archeological unit is present, however, as are the deposits and surfaces related to post-archeological-unit downcutting.

<u>Section C (Mile 208.2)</u>

No fluvial deposits inset into and younger than the basalt flows are present in this section (Fig. 4), so only two downcutting-backfilling cycles are represented -- the oldest, which contains the basalt flows, and the youngest, consisting of the modern channel of the Colorado River. The base of the basalt is about 35 m above HWL, where the basalt rests on a thin layer of river gravel that in turn rests on bright Angel Shale. The top is at about 59 m. Two basalt flow units are in evidence, as well as a thin layer of gravel and basaltic debris that separates them. Above the basalt are black sand, basalt-cobble gravel, and intermixed black sand and basalt-cobble gravel. The package is truncated by a planation surface with Stage V carbonate soil. Within the gravel and sand is an unusual deposit composed of angular boulders and cobbles representing chiefly Paleozoic lithologies and subordinate basalt. Rounded river cobbles are present but rare. Exposures are poor, so it is not possible to determine whether the deposit is part of the basaltic gravel-sand sequence, or inset into it. A normal, river origin for this deposit is hard to reconcile with the angularity of the clasts -- all river deposits in these sections contain rounded to subrounded clasts. A more likely origin is as a debris flow issuing from a canyon entering the River from the West and upstream and carrying Paleozoic rocks and Shivwits Plateau lavas.

Near the River is a normal fault of the Hurricane fault system that juxtaposes Bright Angel Shale to the West against Vishnu Schist to the east. This fault is responsible for the alignment of the river valley in this area.

Section D (Mile 207.5)

Section D (Figure 5) contains the most complete section of Quaternary deposits studied in the Granite Park area. Four downcutting-backfilling events are recorded. The oldest contains the basalt flows and overlying basaltic gravel and sand. The next oldest contains the non-volcanic gravel and overlying black sand, then comes the archeological unit, and finally the modern river channel.

Two main basalt flows in the oldest sequence range in elevation from 30m above HWL at the base to about 60 m at the top. A thin third flow locally overlies the other two. Above the basalts are basalt gravel and sand, which are truncated by a planation surface that slopes down to nearly the top of the main basalt flows and shows a Stage V carbonate soil.

The top of the non-volcanic gravel in the next sequence is 23.6 m above HWL, and erosional remnants of the overlying black sand reach about 35 m. The sequence is truncated by a Level IV surface.

The top of the archeological unit is 9.8 m above HWL.

The down-to-the-west normal fault of sections C and D is also present in section E, but not exposed.

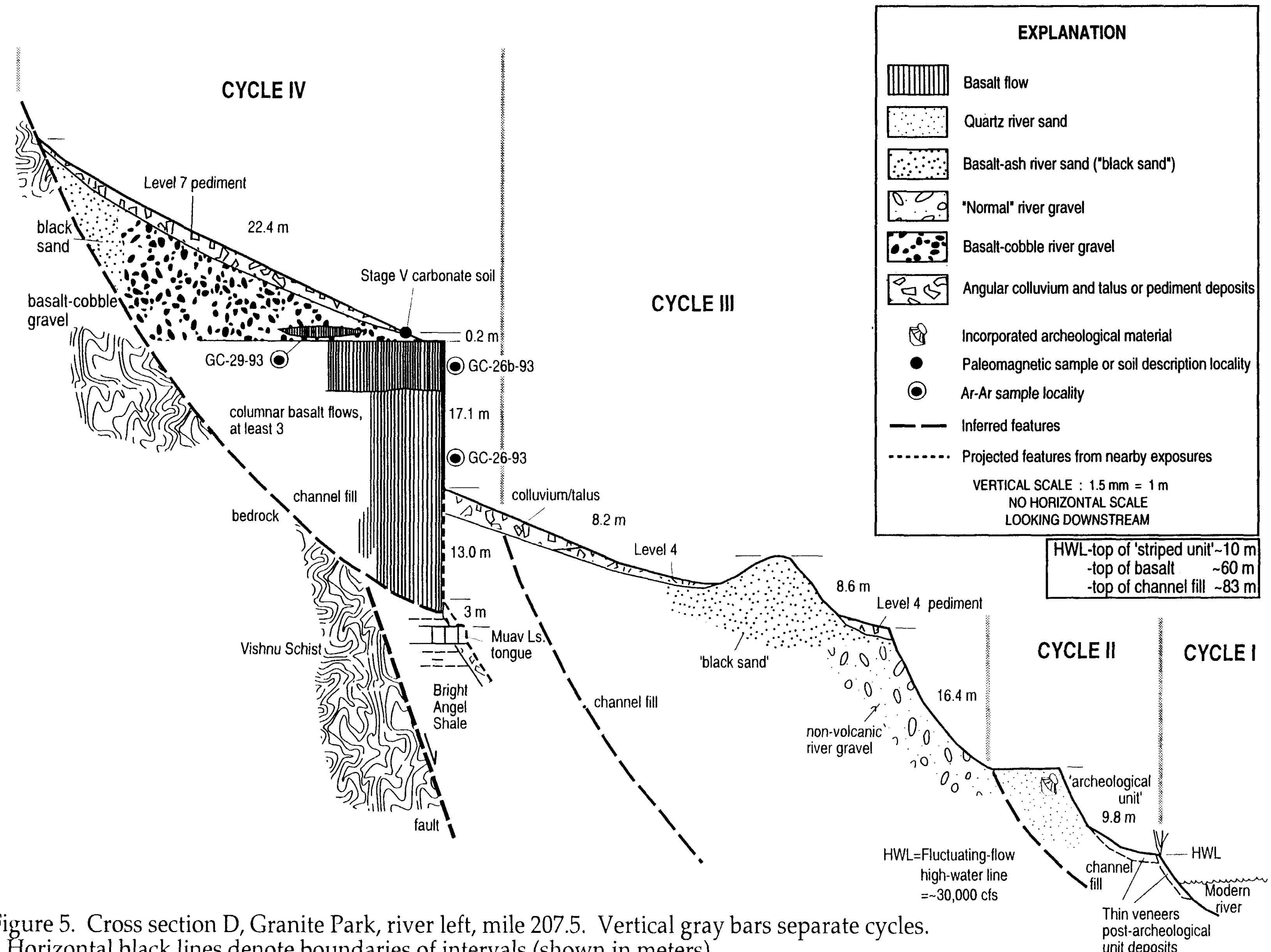


Figure 5. Cross section D, Granite Park, river left, mile 207.5. Vertical gray bars separate cycles. Horizontal black lines denote boundaries of intervals (shown in meters).

Section E (Mile 207.3)

Section E (Figure 6) records three downcutting-backfilling events. The oldest is that represented by the basalt and associated volcanic gravel and sand. Next is the channel cut into the basalt and containing the non-volcanic gravel package seen in section A, together with overlying basaltic sand. The youngest cuts the non-volcanic gravels and is occupied by the modern river channel.

The base of the basalt section is about 30 m above HWL, and the top at 55.7 m. Three distict flow units are present. The top of the channel sequence containing the basalts is 82.7 m above HWL, as preserved. The sequence is truncated by a planation surface that represents Level 7, and a younger one that is inset into Level 7 and shows a Stage IV carbonate soil. The top of the non-volcanic gravel of the intermediate sequence is about 25 m above HWL, and the top of the sequence, as preserved, is 36.3 m. This sequence also is truncated by a planation surface representing Level V.

The normal fault exposed in section C is present in this section also, but is not exposed. Along the fault, Bright Angel Shale and included tongue of Muav Limestone are dropped down against the Vishnu Schist to the east.

Soils

Soils associated with the various levels track closely with what has been described in the Palisades-Unkar area upstream (Davis and others, 1995). Essentially no subsoil is developed along the frequently flooded to occasionally flooded surfaces near the River (Cycle I). Soils on the archeological unit (Cycle II) are deep and sandy textured, with stratified charcoal layers indicative of farming by prehistoric Indians. Such charcoal

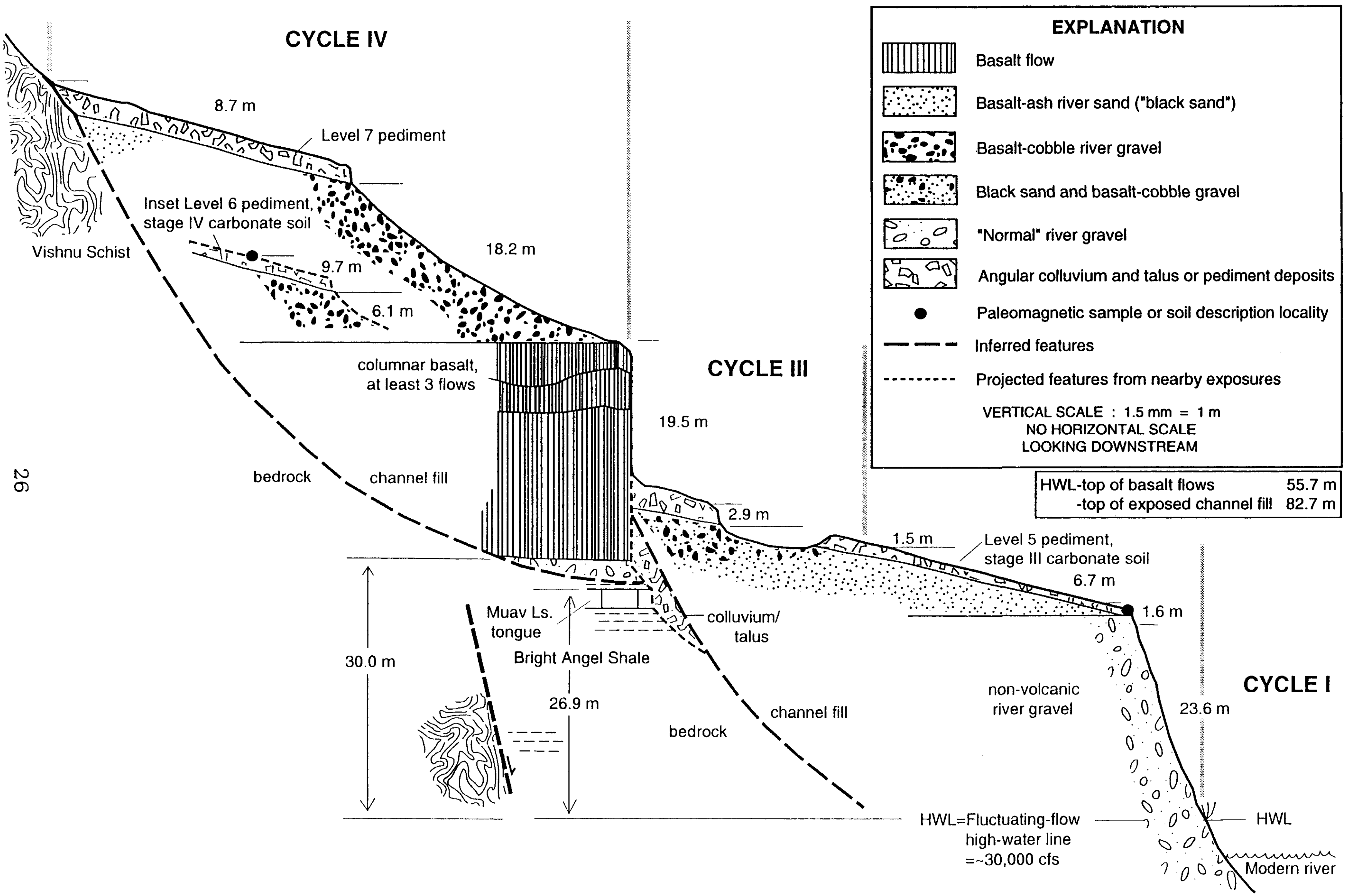


Figure 6. Cross section E, Granite Park, river left, mile 207.3. Vertical gray bars separate cycles. Horizontal black lines denote boundaries of intervals (shown in meters).

layers are common at the same stratigraphic position in the Palisades-Unkar area. Level 4 (Cycle III, cross section A) was examined qualitatively; this level has Stage II carbonate development, with lime present in thin laminations under clasts and with common small concretions within the near-surface soil matrix.

At river mile 207.3 detailed profile descriptions and sampling substantiate a Stage III carbonate soil on Level 5 (Cross section E, Figure 6). This profile is extremely gravelly and composed largely of black basaltic material. Soils consist of pale brown to brown very gravelly sandy loam, underlain by light gray to yellowish brown extremely gravelly coarse loamy sand, to a depth of approximately 1.5 m. Clay increases from 5 to 10 percent between 3 and 12 cm depth, which is not thick enough to qualify the layer as an argillic horizon. Secondary carbonate content ranges from 12 to 18 percent in the upper 12 cm, abruptly increases to nearly 30 percent to a depth of 1.5 m, then drops back to approximately 17 percent in the underlying sandy gravels. Secondary lime occurs as many large concretions with moderate cementation in the Bk horizons at depths of 12 to 150 cm. The Bk horizons lack platy structure and are considered to be Stage III (Machette) as a maximum. These soils classify as loamy-skeletal, mixed, hyperthermic, Typic Haplocalcids.

Level 6 (inset, Section E, Figure 6) has petrocalcic subsoils with platy structure, representing at least Stage IV (Machette) secondary carbonate development. No good escarpment exposures of these soils were found, and time constraints precluded hand excavation in these calcretes.

Level 7 in cross section B (Figure 3) was examined in detail because of a good escarpment exposure along a drainage swale cut into this deposit. This exposure shows a petrocalcic subsoil that represents the thickest and most advanced example of pedogenesis that we have encountered in our studies in the Grand Canyon. This subsoil is strongly cemented, platy, more than a meter thick, and with Stage V morphology. Surface soil is being stripped by accelerated sheet, rill, and gully erosion. As a consequence, exposed calcrete occupies about 3 percent of the surface plain.

Secondary carbonate in this subsoil ranges from 14 to 20 percent in the upper 12 cm of the profile, abruptly increases to more than 71 percent between 12 and 140 cm, then gradually decreases to 44 percent below the 150 cm level, where it is developed in weakly cemented calcareous and mixed colluvium.

A similar soil was observed at Level 7 in Section D (Figure 5). These soils classify as Loamy-skeletal, mixed, hyperthermic, Typic Petrocalcids.

Geochronology

^{39}Ar-^{40}Ar ages of the seven samples analyzed are:

GC-22-93 (plateau, ±1 σ)	**0.585±0.014** MA
GC-24-93 (plateau, ±1 σ)	**0.609±0.006** MA
GC-22-93 and GC-24-93, weighted average	**0.603±0.008** MA
GC-26-93 (plateau, ±1 σ)	**0.604±0.008** MA
GC-26b-93 (plateau, ±1 σ)	**0.607±0.009** MA
GC-26-93 and GC 26b-93 weighted average	**0.605±0.008** MA
GC-29-93 (plateau, ±1 σ)	**0.525±0.013** MA
GC-34-93 (plateau, ±1 σ)	**0.559±0.009** MA
GC-35-93 (plateau, ±1 σ)	**0.500±0.007** MA
GC-34-93 and GC-35-93 weighted average	**0.524±0.007** MA

SUMMARY AND CONCLUSIONS

Geochronology

Our laser-fusion data (Appendix C) show that most of the Black Ledge flow in the Granite Park area has an age of about 600 ka. The data also suggest that there may be small, local remnants of a flow that is younger, about 525 ka. Both flows were mapped as the Black Ledge flow by Hamblin (1994), who reports an age of 549±32 ka obtained by Damon, without specifying the level from which the sample was obtained. The possible presence of a flow 75 ka younger than the main body of the Black Ledge flow is puzzling in light of the lack evidence for substantial erosion between the two flows.

Geology and geomorphology

When pieced together (Figure 7), the five sections studied show that the Quaternary record in the Granite Park area consists of four fluvial cycles, which we label Cycles I (youngest) through IV. Each of the Cycles II through IV represents the carving of a channel and its subsequent filling with tens of meters of deposits. Cycle I is incomplete because the Colorado River most likely is still engaged in the downcutting phase and no back-filling phase has yet started. Each channel cuts, and is inset into, older deposits.

Cycle I consists of the modern river channel and its fill, which includes both gravel and sand. The channel is cut into deposits of Cycle II. Gravel bars are common in deposits of Cycle I. Volcanic cobbles are present but not common in these bars. This cycle contains the record of modern activities of the Colorado River, including the water level reached by pre-Glen Canyon Dam

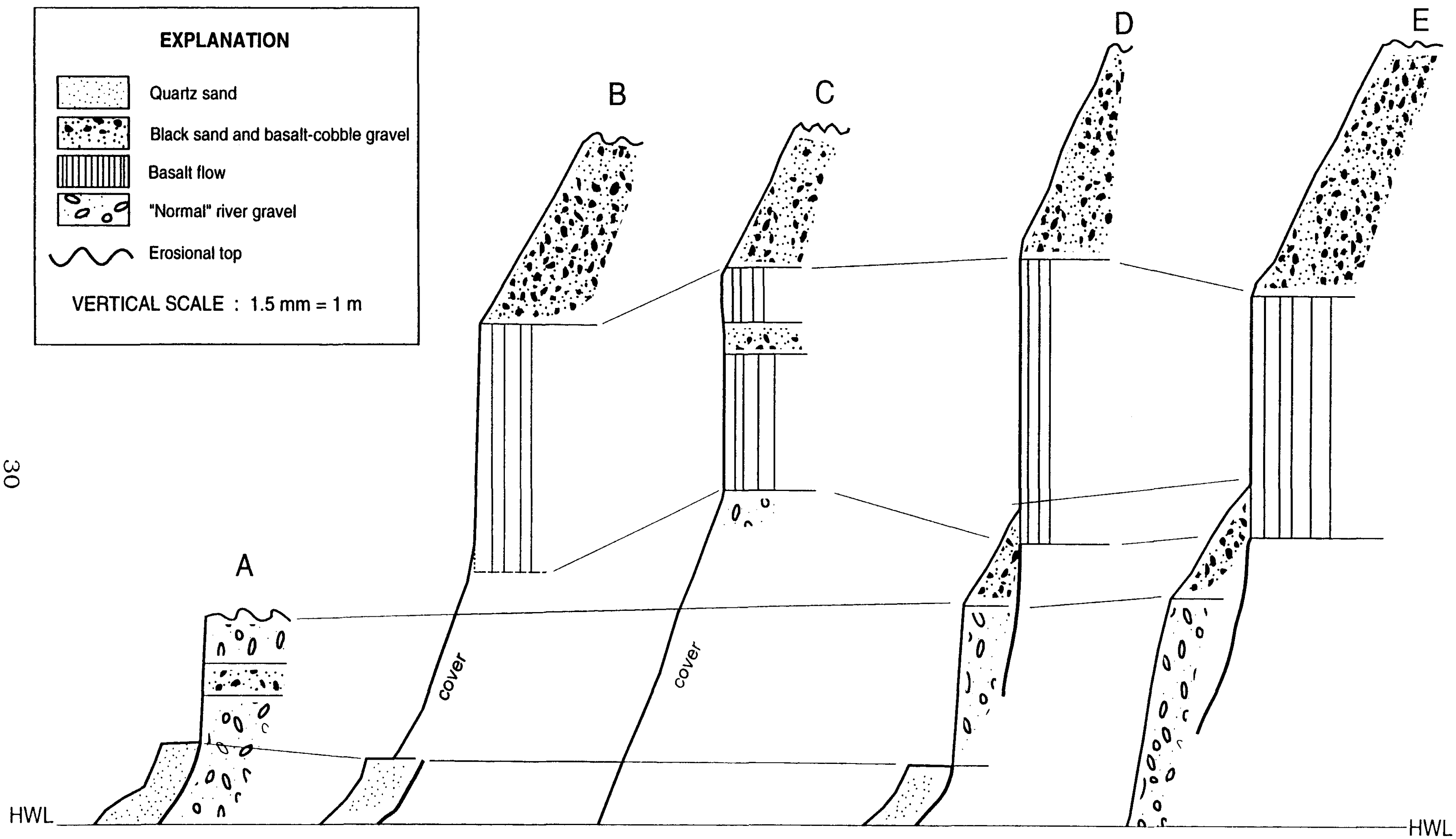


Figure 7. Correlation chart for the five cross-sections

floods, typically in the 90,000 to 125,000 cfs range. This level is marked by the line below which large, old mesquite trees do not grow, and by one or more scarps cut into the archeological unit, the fill of Cycle II. We refer to this level as the 'mesquite line'. Below the line are scarps and driftwood lines marking post-dam high water stands, including that of 1983, when discharge from the dam exceeded 90,000 cfs for several days. The lowest level is marked by the line below which bushes and small trees are not found. This level marks the 'high-water line', i.e. the highest discharge released by the dam during its routine fluctuating-flow operations. This is about 30,000 cfs. Fluctuating flows occur because the dam varies its discharge on a daily basis as a function of demand for electric power. Permanent non-acquatic vegetation cannot become established in the fluctuating flow zone. We have used the high-water line (HWL) as the datum for elevations of fluvial features because it is the only reference level that is related to the river and fixed.

During Cycle II, the river cut its channel into Cycle-III deposits to below the present river grade, but we do not know by how much. Once cut, the channel was filled by more than 10 m of fine and very fine sand, which shows fine lamination and ubiquitous current cross-lamination, as well as interlayering of light-colored sand, brought in by the river, with darker or redder and more poorly sorted layers of local derivation. This is the archeological unit. The interlayering gives the unit a distinctive striped appearance, hence the informal name 'striped unit'. The time when deposition began is not known precisely. On regional considerations, it would be before about 2,000 BP because an equivalent deposit in the Tanner Canyon area (Mile 69) contains Archaic hearths (Hereford and others, 1993). We suspect beginning of deposition was considerably earlier because the artifacts are far from the bottom of the unit. Deposition probably was not continuous, but was interrupted by occasional erosion, as witnessed by minor erosional disconformities within the section. End of deposition occurred about 750 BP because the upper part of the deposit contains abundant Pueblo II material in the eastern Grand Canyon. Charcoal layers are common in the unit, which we interpret as resulting from burning of stubble in mile 246. The flows filled the channel with more than 30 m of basalt. The last of these flows may have been emplaced are recently as about 525 ka on a surface that shows little evidence of significant erosion of the older flows. Aggradation continued after emplacement of the flows with at least 27 m of basalt-cobble gravel and basalt-ash sand, with at best minor admixture of normal river-channel material. This indicates unusual and probably catastrophic events upstream, which resulted in major accumulation of volcanic products within the river system while excluding both the material that normally transits down the river channel, and material introduced into the channel by tributary drainages. Downcutting resumed after deposition of the basaltic gravel and ash, forming a planation surface (level 7). This surface truncates the basalt-cobble gravel and black sand down to the top of the basalt and has a Stage V carbonate soil. A lower and younger planation surface (level 6), also above the basalt, has a Stage IV carbonate soil.

Soils

Examination and analysis of soils from geomorphic levels 5 and 7 show relative pedogenesis of carbonate Stage III and V (Machette), respectively. Stage III soils classify as Typic Haplocalcids, and Stage V as Typic Petrocalcids.

Stage III soils have been described upstream in the Grand Canyon in the Palisades-Unkar area, where ^{26}Al-^{10}Be exposure ages from surface boulders have a maximum range from 85 to 120 ka (Caffee and others, 1994). These are considered minimum ages for the surfaces because accelerated erosion of the surfaces begins when secondary carbonate cements and plugs subsurface pores, decreasing permeability of the soil. When this happens, sheet flow, rilling and gullying all are enhanced on these old surfaces.

Stage IV carbonate soils also have been described in the Palisades-Unkar area, and in the Rainbow Plateau of Utah, near Lake Powell, where the associated surfaces have yielded ages ≥250 Ka (Caffee and others, 1994). Again, this is considered a minimum age because of erosive processes. Stage IV carbonate soils observed on Level 6 geomorphic surfaces in the Granite Park area are inferred to be of similar age.

The Stage V calcrete is important to the study and age calibration of soils in the Grand Canyon because of its association with a datable basalt flow, which places a constraint on the time needed for very advanced carbonate pedogenesis. The basalt (600 ka, possibly 535 ka) provides an upper limit for the age of the Stage V carbonate.

Calibration of soil-carbonate stages

As is well known, obtaining quantitative ages for deposits and surfaces is one of the most difficult yet most essential aspects of Quaternary geology and geomorphology. Because of this, our studies in the eastern Grand Canyon and in the Rainbow Plateau of Utah include a major effort to obtain such ages. The strategy was to employ a variety of different techniques and to use them in extended and concerted fashion on units of different ages and topographic levels. These techniques are: morphostratigraphy; soils; ^{10}Be and ^{26}Al cosmogenic-radionuclide geochronology; ^{14}C; and archeology. We now have more than 200 radiometric age determinations, 34 formal soil descriptions and a dozen magnetic-reversal determinations for this region. Each technique has strengths and weaknesses. Morphostratigraphy gives results that are accurate but imprecise: no absolute ages are obtained, only relative ones. Soils are ubiquitous and relatively insensitive to the exposure age versus formation age problem; but they, also, only give relative ages unless calibrated and are subject to errors introduced by possible polycyclic origin. Radionuclide geochronology gives quantitative ages, but these reflect exposure rather than formation ages, giving rise to uncertainties that stem from the history of the particular rock being sampled. ^{14}C and archeology give precise numerical ages but only apply to the youngest material.

Because of these uncertainties, we consider it important to calibrate our geochronologic scheme by anchoring it to reliable numerical ages at the young and the old end. The young end has been dealt with by anchoring soils and geochronology to the archeological unit, whose age is known with great precision through Pueblo II pottery, ^{14}C, and dendrochronology. The Granite Park area provides a means for anchoring the old end through association of soil-carbonate stages and morphostratigraphic levels with basalt flows that can be dated very accurately by ^{39}Ar-^{40}Ar geochronometry.

Figure 8 shows the relation of soil carbonate stages V, IV, III and II to the 600 (525?) ka basalt. These stages correspond to morphostratigraphic levels 7, 6, 5 and 4, respectively.

The stage-V carbonate occurs within Cycle IV, in the level-7 pediment surface, which is graded to the top of the basalt and truncates the basalt-cobble gravel and black sand that accumulated after the basalt was emplaced. The stage-V carbonate clearly postdates the basalt; the question is by how much.

In our opinion, the basalt-cobble gravel and black sand represent catastrophic events that caused the river to aggrade rapidly (see below). Consequently, the time represented by these deposits probably is small and may well be measured in weeks or months. On the other hand, once the catastrophic events related to volcanism were over, the river was no longer overloaded and began downcutting energetically to re-establish its old grade. The rate of downcutting presumably was high in the just-deposited and unconsolidated basalt-cobble gravel and black sand, which were rapidly cleared from the river channel. The Level 7 pediment and associated Stage V carbonate soil are graded to the top of the basalt flows and represent the time when the river had regained this level. Consequently, the Stage V carbonate soil can be taken to have essentially the same age as the basalt flow -- 525 ka and no more than 600 ka. The Black Ledge basalt flow was much harder to cut through, however, not only because the basalt is tough to erode, but also because the flow has a length of at

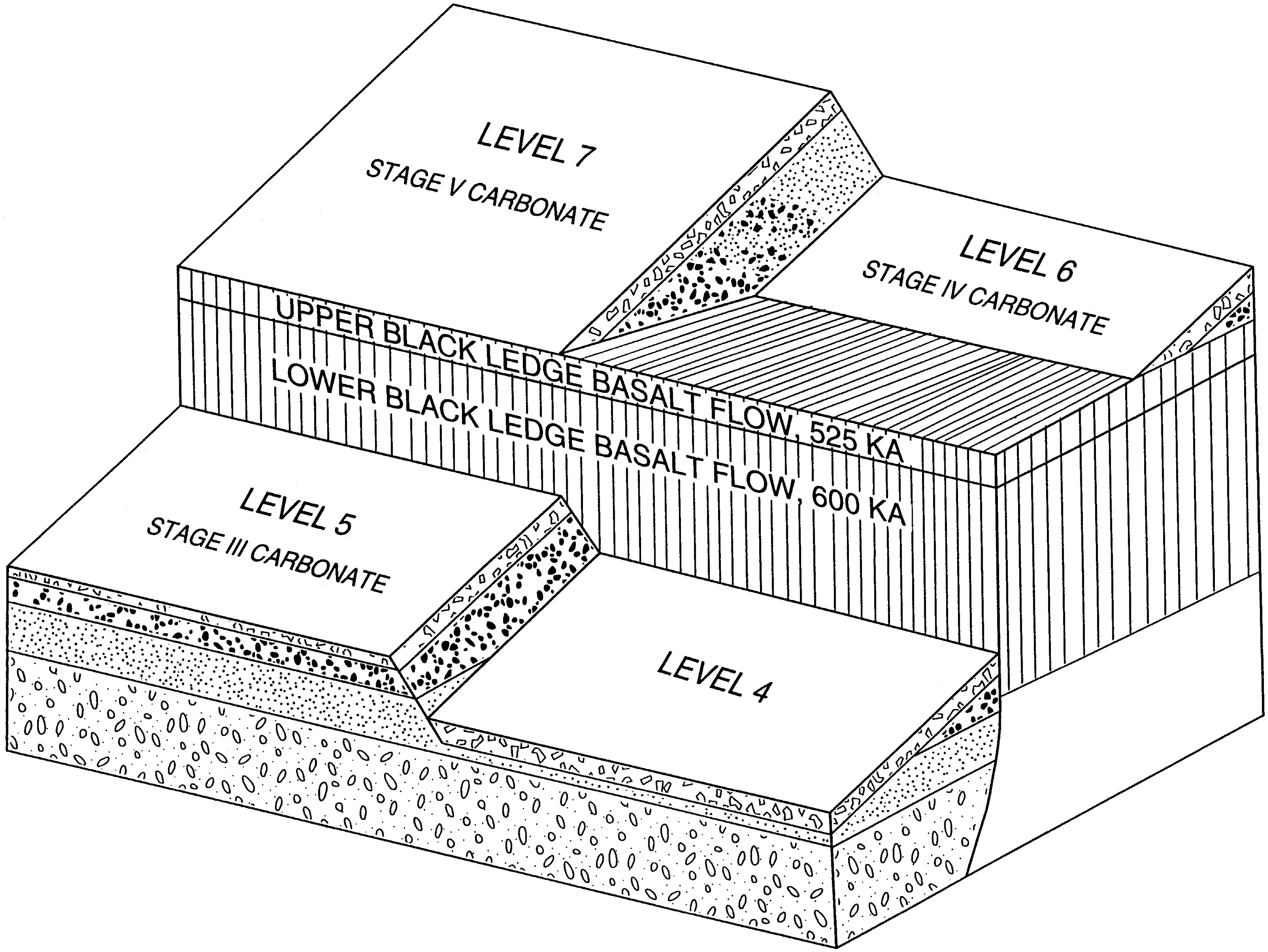


Figure 8. Relations between soil-carbonate stages and Black ledge basalt flows

least 68 miles, of which at least 37 are below the exposures studied by us. This is a very long dam. The consequence is that the river probably was stuck on top of the basalt for a considerable time, as shown by Level 6 and associated Stage IV soil, which are graded to a level not much below that of level 7.

Once the basalt was sliced through, the river continued downcutting during Cycle III to well below its previous channel level. Later in the cycle, the river resumed aggrading, depositing the non-volcanic gravel and the overlying basalt-cobble gravel and black sand. These were truncated by the Level 5 surface, which has a Stage III soil, and later by a Level 4 suface, with associated Stage II soil. Stage III carbonate soils in the Eastern Grand Canyon have yielded abundant cosmogenic ages in the 85-120 Ka range (see above). This indicates that the time represented by the Cycle III downcutting through the basalt, and the subsequent backfilling and pedimentation, was much greater than the time taken to cut down through the Cycle IV gravel and sand to the top of the basalt in Cycle IV time.

The overall framework for soil ages in the Granite Park area is this:

Stage V carbonate	~525 ka, <600 ka
Stage IV carbonate	<525 (600) ka, ≥250 ka
Stage III carbonate	<<525 (600) ka, <250 ka, ≥~85 ka

Processes

The Quaternary record of Granite Park resembles that of the rest of the Grand Canyon in having multiple downcutting-backfilling cycles. Cycles I (modern river), II (archeological unit) and III (non-volcanic gravel) correspond to similar cycles well expressed elsewhere, especially in the Palisades-Unkar area, mile 65 to 73 (Lucchitta and others, unpublished mapping). However, Cycle IV and the volcanic material in Cycle III attest to profound changes in the river's activity that resulted directly or indirectly from volcanism in the Vulcan's Throne-Whitmore Wash area upstream from Granite Park. The most significant aspect of the volcanism was the repeated cascading of lavas into the Grand Canyon. Each of the major cascades produced dams that ponded the river, which in turn resulted in deposition of lacustrine beds upstream from the dams (Hamblin, 1994). In contrast, the area downstream from the dams was affected not by lakes but by entirely different processes, which, however, also resulted from the dams and eruptions that created them. The Granite Park sections provide a means for deciphering these processes.

The most conspicuous Quaternary feature in the Granite Park area is the vertical black cliff formed by the Black Ledge flow. The mechanism of emplacement of this flow presents no great difficulty of interpretation. This, however, is not the case for the monolithologic basalt-cobble gravels and basaltic sand that overlie the basalt of Cycle IV and the non-volcanic gravel of Cycle III, and are interbedded with Cycle-III non-volcanic gravel. A mechanism must be found that allows deposition of volcanic debris while excluding the Proterozoic, Paleozoic and Tertiary material that normally forms the overwhelming majority of the channel fill of the Colorado River. This material is brought in by the River itself axially and by tributaries laterally.

The mechanism that can best accomplish major but temporary overloading of the river with basaltic debris is the introduction of volcanic material, either directly during or shortly after an eruption, or indirectly, between eruptions, through the breaching of lava dams.

Choking the river during an eruption can occur with direct fall of ash into the river, with remobilizations of ash blanketing terrain surrounding the river, and to a lesser extent with basaltic debris produced by the quenching and thermal shattering typical of flows in contact with water. Preserved vents in the Vulcans Throne-Whitmore Wash field are cinder cones. As observed in many parts of the world, the activity of cinder cones is known to include major venting of ash clouds. The ash blanket resulting from such eruptions is unconsolidated and not stabilized by vegetation soon finds its way into drainage systems, overloading them and turning them into aggrading braided streams while the supply of ash lasts (Segestrom, 1960; Kuenzi and others, 1979; Vessel and Davies, 1981; G.A. Smith, 1991; Inbar and others, 1993). This aggradation is likely to be a very fast process, especially when mudflows are involved in bringing volcanic ash to a drainage -- meters of ash could be deposited in a matter of weeks or months. When the ash blanket is depleted or stabilized by vegetation, aggradation of streams slows down or ceases. The black sand deposits in Granite Park are likely to be the record of such events, especially direct ashfall and erosion of ash blankets. If mudflows made a significant contribution, the Colorado winnowed the fine fraction and transported it beyond the Granite Park area.

Another way to overload the river is illustrated by the basalt-cobble gravel, which is a high-energy deposit. We believe these gravel deposits represent overtopping of basalt dams and consequent extremely vigorous erosion of the basalt, probably by headward erosion and plunge-pool action. This erosion cut and scoured the basalt in the area of the dam, but the products of erosion overloaded the river downstream from the dam, where the gradient of the channel was less steep. Under such circumstances, deposition is likely to be rapid.

Our conclusion is that the black sand deposits signal an eruption, whereas basalt-cobble gravel deposits signal the breaching of a lava dam following an eruption. Under ideal conditions, black sand should therefore underlie basalt-cobble gravel if they both result from a single eruption. This indeed is the case in several of our sections. In other cases, however, relations are less simple, and the deposits probably represent multiple eruptions occurring simultaneously with damming and breaching events, so gravel resulting from breaching of a dam produced from one volcanic eruption could be intermixed with black sand resulting from another eruption.

Our interpretations of the processes that occur when a lava dam is destroyed differ to some extent from those advanced by Hamblin (1994). A lava dam must be overtopped for erosion of the dam to begin. Overtopping implies filling the reservoir impounded by the dam, which a function of the discharge of the river that is dammed. Hamblin does not quote the discharge figures used in his calculation, other than stating that they are based on 'modern discharge measurements'. USGS records from the stream gage at Lees Ferry show that the average peak discharge of the Colorado River since systematic readings began in 1923 is 78,000 cfs. But the records also show a peak discharge of nearly 120,000 cfs in 1922, 220,000 in 1921, and an estimated 300,000 cfs in 1884. Such large discharges in an interval of only 80 years suggest that floods such as these, and even larger ones, would be not infrequent over an interval of several hundred years. Because annual discharge is sensitive to peak discharge, it is likely that the lava-dam reservoirs filled in even less time than given by Hamblin in Table 1 (p.30). In reality, modern discharges are a very poor guide to discharges of the river in the interval between 500,000 ka and 1.8 MA, the range in age of the lava dams. Discharges during glacial times are likely to have been very much greater than the present ones, which are taken during an interglacial stade. In our opinion, the net result is that the lakes produced by the lava dams were filled faster than calculated by Hamblin, making the creation of lava dams and their destruction essentially simultaneous events. This is what we see in the downstream record.

The basalt-cobble gravel and basalt sand represent valuable experimental evidence of how the Colorado River responds to changes in its load: vigorous aggradation as long as a temporary overload exists, and equally vigorous downcutting once the overload ends. In the case of Cycle IV in the Granite Park area, the aggradation and downcutting amounted to at least 27 m (Figure 6). There is no direct way to determine the rate of this downcutting. The overall rate from that time to today is 1.6 cm/ka, but the actual rate of downcutting is much greater because the time interval includes periods of aggradation and of stasis.

We have proposed a similar relation between river activity and load for the eastern

Grand Canyon (Lucchitta, 1991). In this area, however, the overload was not caused by volcanic activity; we interpret it as resulting from introduction of abundant glacial debris into the river during glacial or late glacial stades. The downcutting that followed each of these aggradation events would then result from decreased load during interglacial stades. The glacial mechanism cannot apply, however, for the latest aggradation event, which resulted in deposition of the archeological unit (Cycle II in the Granite Park area). The reason is that deposition of this unit took place after the end of the last (Pinedale) glaciation. But this glaciation did result indirectly in the regional accumulation of extensive colluvial deposits, partly because of increased frost action on the source outcrops, partly because the colluvial aprons were stabilized by the vegetative cover that resulted from the more pluvial climate of the region. Remnants of such aprons are readily visible throughout the Grand Canyon, wherever a slope is developed at the foot of cliffs (Bright Angel under Muav-Redwall, upper Supai-Hermit under Coconino). Preliminary results indicate that the aprons are graded to surfaces that have yielded radiometric ages consistent with the Pinedale glaciation (Lucchitta, unpublished mapping; Caffee and Finkel, 1994). The aprons are not stable under present conditions and have been extensively eroded. We propose that erosion of the Pinedale-age colluvial blanket is related to the aggradation resulting in the archeological unit: after the waning of the Pinedale glaciation, climate in the Colorado Plateau became warmer and drier and the vegetative cover gradually waned, making the colluvial blanket vulnerable to erosion. Catastrophic erosion began with the onset of the monsoonal precipitation pattern, probably in mid-Holocene time, when the abundant and unprotected blanket was exposed to torrential monsoon rains. The resulting heavy sediment load caused all drainages in the area to aggrade, resulting in deposition of the archeological unit within the Grand Canyon, and equivalent units in tributary drainages. Once the supply or easily-erosible material was exhausted, sediment load decreased, and the drainages began vigorous downcutting, starting with the master streams and extending up tributaries of all sizes by headward erosion. This downcutting is still going on today and amounts to more than 10 m in about 750 years in the Grand

Canyon, for an remarkable average downcutting rate of more than 13 m/ka. This inexorable erosion of the archeologic unit and the archeologic material that it contains is exacerbated by Glen Canyon Dam, which has further decreased sediment supply to the Colorado River, but this effect is only a temporary addition to the naturally occurring long-term erosion.

ACKNOWLEDGMENTS

This work was done in cooperation with the U.S. Bureau of Reclamation, Glen Canyon Environmental Studies program, and with the National Park Service, Grand Canyon National Park. The Hualapai Tribe allowed us to work on their lands. Jack Coffman ran the instrument during surveys of the geologic contacts. Prof. Randy Southard carried out laboratory analyses of soils and interpreted reults in light of his expertise. Ms. Carol Dehler did a literature search on the interaction between volcanic activity and fluvial systems, and applied her wizardry to the illustrations. Ms. Kelly Burke reduced and organized the total-station data. We are indebted to these organizations and individuals.

REFERENCES

Caffee, M.W., Finkel, R.C., Lucchitta, I., Davis, S.W., and Davis, M.E., 1994, Investigation of the Quaternary history of the Colorado River: EOS Transactions, v. 75, no. 44, p. 273

Finkel, Robert C., Caffee, M.C., Curtis, G., Davis, M., Davis, S., Hanks, T.C., Turrin, B.D., and Lucchitta, I., 1994, Geochronology of downcutting in the Colorado River System: Geological Society of America Abstract with Programs, V. 26, no. 7, p. A-258

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the Basin and Range area of Southern New Mexico - Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral resources Memoir 39.

Hamblin, W.K., 1994, Late Cenozoic lava dams in the western Grand Canyon: Geological Society of America Memoir 183, 139 p.

Hereford, Richard, Fairley, H.C., Thompson, K.S., and Balsom, J.R., 1993, Surficial geology, geomorphology, and erosion of archeological sites along the Colorado River, Eastern Grand Canyon, Grand Canyon National Park, Arizona: U.S. Geological Survey Open-file report 93-517

Inbar, Moshe, Hubp, J.L., and Ruiz, L.V., 1994, The geomorphological evolution of the Paricutin cone and lava flows, Mexico, 1943-1990: Geomorphology, v.9, p. 57-76

Kuenzi, D.W., Horst, O.H., and McGehee, R.V., 1979, Effect of volcanic activity on fluvial-deltaic sedimentation in a modern arc-trench gap, southwestern Guatemala: Geological Society of America Bulletin, v. 90

Lucchitta, Ivo, 1972, Early History of the Colorado River in the Basin and Range Province: geological Society of America Bulletin, v. 83

Lucchitta, Ivo, 1988, Canyon Maker: Plateau, v. 59, no. 2

Lucchitta, Ivo, 1990, History of the Grand Canyon and of the Colorado Rivert in Arizona in Grand Canyon Geology, Beus and Morales, eds.: Oxford University Press

Lucchitta, Ivo, 1991, Quaternary geology, geomorphology, and erosional processes, eastern Grand Canyon, Arizona: U.S. Geological Survey Administrative Report, 32 p.

Machette, M.N., 1985, Calcic soils of the southwestern United States in D.L. Weide. ed., Soils and Quaternary Geology of the Southwestern United States: Geological Society of America Special Paper 203

Segerstrom, Kenneth, 1960, Erosion and related phenomena at Paricutin in 1957: U.S. Geological Survey Bulletin 1104-A

Smith, G.A., 1991, Facies sequences and geometries in continental volcaniclastic sediments: Sedimentation in Volcanic Settings, Society of Economic Paleontologists and Mineralogists Special Publication No. 45

U.S. Department of Agriculture Soil Survey Staff, 1994, Keys to Soil Taxonomy, Agency for International Development, Soil Conservation Service, SMSS Technical Monograph No. 19, Fifth Ed.: Pocahontas Press, Inc., Blacksburg, VA

Vessel, R.K., and Davies, D.K., 1981, Nonmarine sedimentation in an active fore arc basin in Ethridge and Flores, eds., Recent and ancient nonmarine depositional environments: models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication No. 31

APPENDIX A

Synopsis of Granite Park Archeology

by

Christopher Coder

There are eight recorded archeological sites at Granite Park proper, as well as an additional eight or ten more that are located upstream and on the opposite bank at 209-Mile Canyon.

In the main, these sites are various groups of roasting features and associated artifacts that generally indicate Hualapai use prehistorically and historically. Artifacts are various shards, chipped and groundstone tools, a copper dress tinkler, purple glass, wire, milled lumber, cans, and other historic debris.

Most of these cultural properties are open sites located on the upper terraces covered by and situated on the reworked dunes. The exception to this is G:03:003, a rockshelter located in the Bright Angel shale on the downstream side of the delta [of Granite Park Canyon]. The shelter has been used extensively over the last 11 centuries and probably a lot longer. Sherds present on the surface include materials belonging to the Anasazi, Cohonina, Hualapai (Cerbat), Southern Paiute, and Hopi (the Hualapai have traded with the Hopi for centuries).

Granite Park has been utilized by the Hualapai people since just after 1300 as a seasonal grocery store and base of operations for families belonging to the Pine, Peach, Clay, and Milkweed Springs bands. Bighorn sheep were hunted, hematite mined, mesquite, agave (viyal), seeds, and prickly pear tuna were collected and processed. During hard times, bands of Southern Paiute would winter over at Granite Park, with permission of course and vice versa.

During the Federal war on the Hualapai, 1865-1874, several families used the Park as a refugium from the depradations of the U.S. Army.

In the 1890's Granite Park was the site of at least one episode of the controversial

APPENDIX B

Representative Soil Profile Descriptions*

Grand Canyon River Mile 208.7 (river right), Level 7
Cross section B
3/22/93-1

A 0 to 3 cm, light brown (7.5YR 6/4) very gravelly sandy loam, brown (7.5YR 4/4) when moist; fine to medium moderate fine subangular blocky structure; slightly hard, friable, nonsticky and nonplastic; many very fine and fine roots; common very fine and fine interstitial and tubular pores; some gravels are caliche fragments; clear smooth boundary.

Bk 3 to 12 cm, brown (7.5YR 5/4) very gravelly sandy loam, brown (7.5YR 4/4) when moist; massive; soft, loose, slightly sticky and nonplastic; many large lime concretions; abrupt wavy boundary.

2Bkm 12 to 140 cm, weak red (10R 5/4) freshly broken faces, red (10R 4/6) when moist; strong coarse platy structure, grading to massive; very hard, very firm, strongly cemented (petrocalcic); gradual wavy boundary.

3Btk 140 to 150 plus cm, light reddish brown (5YR 6/4) extremely gravely loam, red (2.5YR 4/6) when moist; massive; hard, frim, slightly sticky and slightly plastic; common fine tubular and interstitial pores; lime occurs as many large concretions.

Notes: Stage V calcrete. Petrocalcic layer outcrops randomly and represents 3 percent of the plain surface. Soil developed in debris flow parent materials above basalt flow. ^{40}Ar-^{39}Ar date on basalt (Curtis and Turrin) ~ 525 Ka. Loamy-skeletal, mixed, hyperthermic, Typic Petrocalcids.

Grand Canyon, River Mile 207.3, river left, bluff, Level 5
Cross section E
3/22/93-2

A 0 to 3 cm, pale brown (10YR 6/3) very gravelly sandy loam, brown (10YR 4/3) when moist; moderate fine platy to moderate fine granular structure; slightly hard, very friable, nonsticky and nonplastic; common very fine roots; common very fine and fine interstitial pores; 20 percent gravel; clear smooth boundary.

Btk 3 to 12 cm, light brown (7.5YR 6/4) very gravelly sandy loam, strong brown (7.5YR 4/6) when moist; massive; hard, firm, nonsticky and nonplastic; few very fine and fine roots; common very fine and fine interstitial pores; lime occurs in common medium soft masses; 30 percent gravel; gradual smooth boundary.

2Bk1 12 to 60 cm, light brown (7.5YR 6/4) extremely gravelly coarse sandy loam, strong brown (7/5YR 4/6 when moist; massive, hard, firm nonsticky and nonplastic; few very fine interstitial pores; many large lime concretions; 83 percent gravel; clear smooth boundary.

2Bk2 60 to 100 cm, light gray (10YR 7/2) extremely gravelly coarse sandy loam, very pale brown (10YR 7/4) when moist; massive; hard, firm, nonsticky and nonplastic; few very fine interstitial pores; lime occurs as many large concretions; 50 percent cobbles and 24percent cobbles; clear smooth boundary.

3Bk 100 to 150 cm, light yellowish brown (10YR 6/4) very cobbly loamy coarse sand, yellowish brown (10YR 5/4) when moist; massive; slightly hard, friable, nonsticky and nonplastic; few very fine interstitial pores; many medium lime concretions; 50 percent cobbles and 23 percent gravel; clear smooth boundary.

4Ck 150 plus cm, black (10YR 2/1) extremely gravelly coarse sand, black (10YR 2/1) when moist; massive; soft, loose, nonsticky and nonplastic; many very fine interstitial pores; lime as many medium 1 mm laminations under gravels; 30 percent cobbles and 32 percent gravel; gradual smooth boundary.

Notes: Gravel pavement on surface with weak varnish and carbonate scatter mostly lining gravel clasts. Moderate cementation 12 to 100 cm, weakly cemented below 100 cm (Stage III carbonate). Black basaltic gravels throughout. Loamy-skeletal, mixed, hyperthermic, Typic Haplocalcids.

Soil Sample Laboratory Data†

208.7 River Rt. Cross section B
3/22/93-1

Depth (cm)	Sand	Silt	Clay	VCS	CS	MS	FS	VFS	Gravel	$CaC0_3$	Fe_d	Al_d
	%											
0-3	64.2	28	7.8	8.9	3.2	1.7	13.1	37.2	44	20.3	0.56	0.02
3-12	56.1	34.7	9.2	4.5	1.7	1	11.4	37.5	45	14.3	0.55	0.02
12-140	nd	nd	nd	nd	nd	nd	nd	nd	nd	71.2	nd	nd
140-150	46.4	38	15.6	9.3	4.7	2.7	8.7	21	86	44	0.27	0.01

207.3 River Lt. Cross section E
3/22/93-2

Depth (cm)	Sand	Silt	Clay	VCS	CS	MS	FS	VFS	Gravel	$CaC0_3$	Fe_d	Al_d
	%											
0-3	70.1	24.8	5.1	5.8	5	3.1	14.9	41.3	42	12.4	0.47	0.03
3-12	67.3	23	9.7	7.5	7.1	4.1	14.6	34	60	18.4	0.37	0.02
12-60	72.3	21.9	5.7	25.9	16.1	6.6	9	14.8	88	29.2	0.45	0.03
60-100	74.8	20.8	4.4	26.3	18.2	8.1	8.5	13.5	85	29.9	0.45	0.04
100-150	86.6	8.3	5.1	17.1	32.4	6.2	10.1	20.9	84	28	0.56	0.03
150	87.5	9.8	2.7	25.8	33.9	14.9	8.6	4.4	76	16.7	0.49	0.03

* Sid and Marie Davis, $DAVIS^2$ Consulting Earth Scientists, 1993
† R.J. Southard, UC Davis, 1994.

APPENDIX C

Step-heating spectra, isochrons, and sampling comments for ^{39}Ar-^{40}Ar age determinations on Black Ledge basalt flow, Granite Park area, Grand Canyon

by

Garniss Curtis and Brent Turrin

Sample **GC-22-93** is from the southern end of the thick flow remnant on river right, across from Granite Park camp, mile 209 [actually, mile 208.7; Section B]. This flow unit has been mapped at the Black ledge unit by Hamblin, (1994). The plateau age, total fusion (integrated) age and isochron age are concordant within analytical uncertainties. The best age for this sample is the plateau age [±1σ: **585±14 ka**]

Sample **GC-24-93** is from the northern end of the flow remnant on river right [mile 208.2; Section C]. This sample is of a thin flow unit that overlies sample GC-22-93. These two units are separated by a thin basaltic cobble conglomerate. This flow unit is one of the thin flows that overlies the Black Ledge flow as described by Hamblin (1994). The plateau age, total fusion (integrated) age and isochron age are concordant within analytical uncertainties. The best age for this sample is the plateau age [±1σ: **609±6 ka**].

The ages for **GC-22-93** and **GC-24-93** are concordant within analytical uncertainties...use the weighted average of the two results for the best age of the flow unit on river right, **603±8 ka**

Sample GC-26-93 is from the lower thick flow remnant on river left, near the southern half of the body, mile 207 [actually mile 207.5; Section D]. This flow unit has been mapped as the Black Ledge unit by Hamblin (1944). The plateau age, total fusion (integrated) age and isochron age are concordant within analytical uncertainties. The best age for this sample is the Plateau age [±1σ, **604±8 ka**

Sample GC-26b-933 is from a massive 0.4 m ledge approximately 1.5 m above sample GC-26-93 [river mile 207.5; Section D]. There is no obvious temporal break between these two units. The ages for GC-26-93 and GC-26b-93 are concordant within analytical uncertainties....use the weighted average of the two results for the best age of the flow unit on river right, **605±8 ka**

Sample GC-29-93; unfortunately, the field notes are not clear as they should be. The notes [Turrin's] indicate that this sample is from a basalt that underlies a lapilli ash interbedded with the gravels that overlie the basalt of GC-26b-93. The plateau age, total fusion (integrated) age and isochron age are concordant with analytical uncertainties. The best age for this sample is the plateau age, **525±13 ka**

Samples GC-34-93 and GC-35-93 are from the isolated southernmost basalt outcrop on river left, near mile 208 [actually about mile 207.7, downstream from Section D]. At this locality there are two lava flows, GC-34-93 is from the stratigraphically younger flow, GC-35-93 is stratigraphically older. There is no indication of any time between the two flow units. Internally, the individual samples have concordant plateau ages, total fusion (integrated) ages and isochron ages within analytical uncertainties. The ages, however, are stratigraphically reversed and analytically distinct...use the weighted average of the two results for the best age of this outcrop, **524±7 ka**

L#	Sample	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	% $^{40}Ar^*$	Age ±1σ	% ^{39}Ar	Temp °C
7667-02A	GC-22-93	44.221	0.0387	0.9027	0.1441	3.9	0.607 ±0.107	25.3	675
7667-02B	GC-22-93	11.682	0.0188	1.7973	0.0343	14.4	0.595 ±0.035	7.5	701
7667-02C	GC-22-93	10.468	0.0179	1.4418	0.0296	17.4	0.644 ±0.032	7.2	726
7667-02D	GC-22-93	9.721	0.0178	1.2020	0.0277	16.8	0.578 ±0.031	7.0	750
7667-02E	GC-22-93	11.324	0.0185	1.0497	0.0327	15.3	0.613 ±0.049	3.5	775
7667-02F	GC-22-93	10.763	0.0188	1.0169	0.0315	14.3	0.547 ±0.047	3.7	801
7667-02G	GC-22-93	12.390	0.0192	0.9928	0.0368	12.7	0.559 ±0.033	9.5	851
7667-02H	GC-22-93	18.182	0.0241	1.1135	0.0569	8.1	0.518 ±0.054	10.2	902
7667-02I	GC-22-93	32.563	0.0340	4.7249	0.1060	4.9	0.565 ±0.076	18.9	1050
7667-02J	GC-22-93	71.126	0.0615	55.3261	0.2517	1.5	0.387 ±0.199	7.0	1276
7667-02K	GC-22-93	1370.771	0.8803	11.3436	4.6716	-0.6	-3.141 ±19.960	0.3	1501

Plateau Age ±1σ: 0.585 ±0.014

L#	Sample	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	% $^{40}Ar^*$	Age ±1σ	% ^{39}Ar	Temp °C
7674-01A	GC-24-93	29.933	0.0313	1.3612	0.0948	6.8	0.732 ±0.089	3.2	599
7674-01B	GC-24-93	8.481	0.0169	0.8157	0.0199	31.4	0.956 ±0.082	1.7	652
7674-01C	GC-24-93	5.764	0.0160	0.7331	0.0139	29.8	0.618 ±0.014	21.5	701
7674-01D	GC-24-93	5.678	0.0161	0.7677	0.0139	28.6	0.585 ±0.014	19.2	725
7674-01E	GC-24-93	3.496	0.0142	0.6212	0.0064	47.3	0.594 ±0.012	13.2	752
7674-01F	GC-24-93	3.857	0.0139	0.6355	0.0074	44.5	0.616 ±0.012	14.9	801
7674-01G	GC-24-93	5.839	0.0153	0.9184	0.0140	30.5	0.640 ±0.021	8.1	850
7674-01H	GC-24-93	15.185	0.0218	1.3972	0.0464	10.4	0.570 ±0.045	5.5	899
7674-01I	GC-24-93	23.680	0.0280	5.7410	0.0757	7.4	0.632 ±0.061	7.4	1051
7674-01J	GC-24-93	52.097	0.0481	46.6152	0.1819	3.8	0.732 ±0.150	5.3	1475

Plateau Age ±1σ: 0.609 ±0.006

L#	Sample	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	% $^{40}Ar^*$	Age ±1σ	% ^{39}Ar	Temp °C
7675-01A	GC-26-93	-314.818	-0.4745	0.0000	-0.1852	82.6	-95.975 ±113.618	0.0	501
7675-01B	GC-26-93	148.943	0.1077	1.3936	0.4975	1.4	0.732 ±0.507	3.3	651
7675-01C	GC-26-93	22.486	0.0267	1.0253	0.0708	7.4	0.596 ±0.054	13.4	700
7675-01D	GC-26-93	7.724	0.0177	0.9123	0.0207	21.6	0.599 ±0.018	14.3	726
7675-01E	GC-26-93	6.841	0.0171	1.2588	0.0176	25.5	0.628 ±0.016	14.8	750
7675-01F	GC-26-93	6.570	0.0170	0.7340	0.0168	25.4	0.600 ±0.015	19.4	802
7675-01G	GC-26-93	7.527	0.0177	0.8228	0.0202	21.7	0.588 ±0.018	12.7	851
7675-01H	GC-26-93	9.871	0.0195	1.3277	0.0292	13.6	0.484 ±0.033	7.1	900
7675-01I	GC-26-93	11.975	0.0228	5.6180	0.0377	10.7	0.464 ±0.030	11.7	1050
7675-01J	GC-26-93	54.152	0.0492	85.7431	0.2009	2.7	0.563 ±0.171	3.2	1475

Plateau Age ±1σ: 0.604 0.008

L#	Sample	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	% $^{40}Ar^*$	Age ±1σ	% ^{39}Ar	Temp °C
7676-01A	GC-26b-93	135.463	0.0988	2.2055	0.4518	1.6	0.761 ±0.491	1.6	599
7676-01B	GC-26b-93	74.419	0.0596	1.7950	0.2420	4.1	1.091 ±0.340	1.1	651
7676-01C	GC-26b-93	11.806	0.0190	1.0469	0.0345	14.4	0.610 ±0.030	16.4	701
7676-01D	GC-26b-93	5.370	0.0145	0.7228	0.0128	30.8	0.595 ±0.014	21.0	725
7676-01E	GC-26b-93	4.242	0.0139	0.6802	0.0090	38.9	0.593 ±0.015	15.4	752
7676-01F	GC-26b-93	6.375	0.0150	0.8032	0.0157	28.2	0.646 ±0.018	15.9	801
7676-01G	GC-26b-93	10.563	0.0176	1.0600	0.0285	21.1	0.802 ±0.034	7.8	851
7676-01H	GC-26b-93	10.600	0.0190	1.8780	0.0308	15.6	0.595 ±0.052	4.5	902
7676-01I	GC-26b-93	15.396	0.0227	5.9923	0.0493	8.5	0.471 ±0.043	10.9	1051
7676-01J	GC-26b-93	64.408	0.0548	60.7462	0.2277	2.9	0.701 ±0.195	5.5	1475

Plateau Age ±1σ: 0.607 ±0.009

7677-01A	GC-29-93	32.432	0.0332	0.6180	0.1050	4.5	0.521 ±0.081	7.1	601
7677-01B	GC-29-93	12.517	0.0198	0.4773	0.0366	13.8	0.622 ±0.053	2.9	651
7677-01C	GC-29-93	10.802	0.0189	0.7017	0.0317	13.9	0.540 ±0.025	20.6	700
7677-01D	GC-29-93	12.629	0.0200	1.1920	0.0381	11.5	0.521 ±0.032	10.9	725
7677-01E	GC-29-93	13.546	0.0206	1.3372	0.0412	11	0.534 ±0.036	8.1	750
7677-01F	GC-29-93	14.206	0.0209	1.0523	0.0433	10.6	0.540 ±0.037	8.6	802
7677-01G	GC-29-93	15.707	0.0223	1.0734	0.0492	8	0.454 ±0.042	7.6	851
7677-01H	GC-29-93	17.135	0.0234	0.9921	0.0541	7.2	0.443 ±0.044	8.5	902
7677-01I	GC-29-93	24.314	0.0289	3.8660	0.0781	6.3	0.551 ±0.058	13.8	1050
7677-01J	GC-29-93	39.836	0.0380	21.4363	0.1333	5.3	0.771 ±0.098	11.9	1476

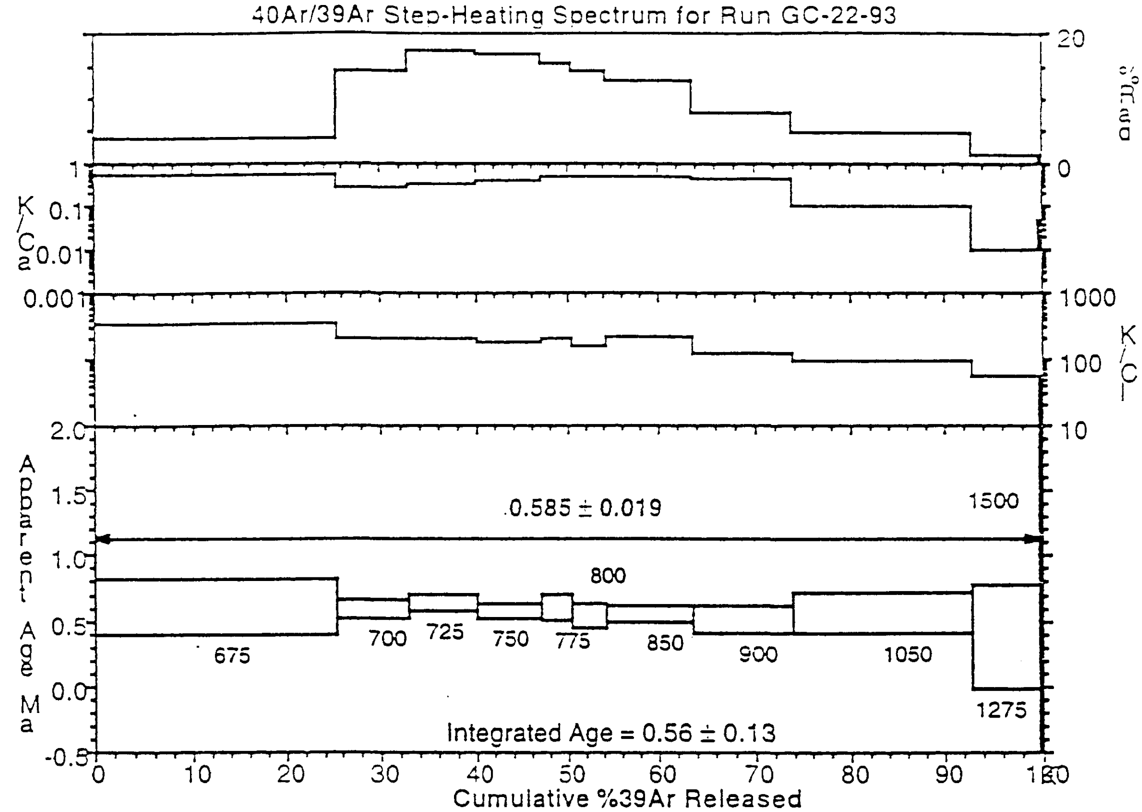
Plateau Age ±1σ: 0.525 ±0.013

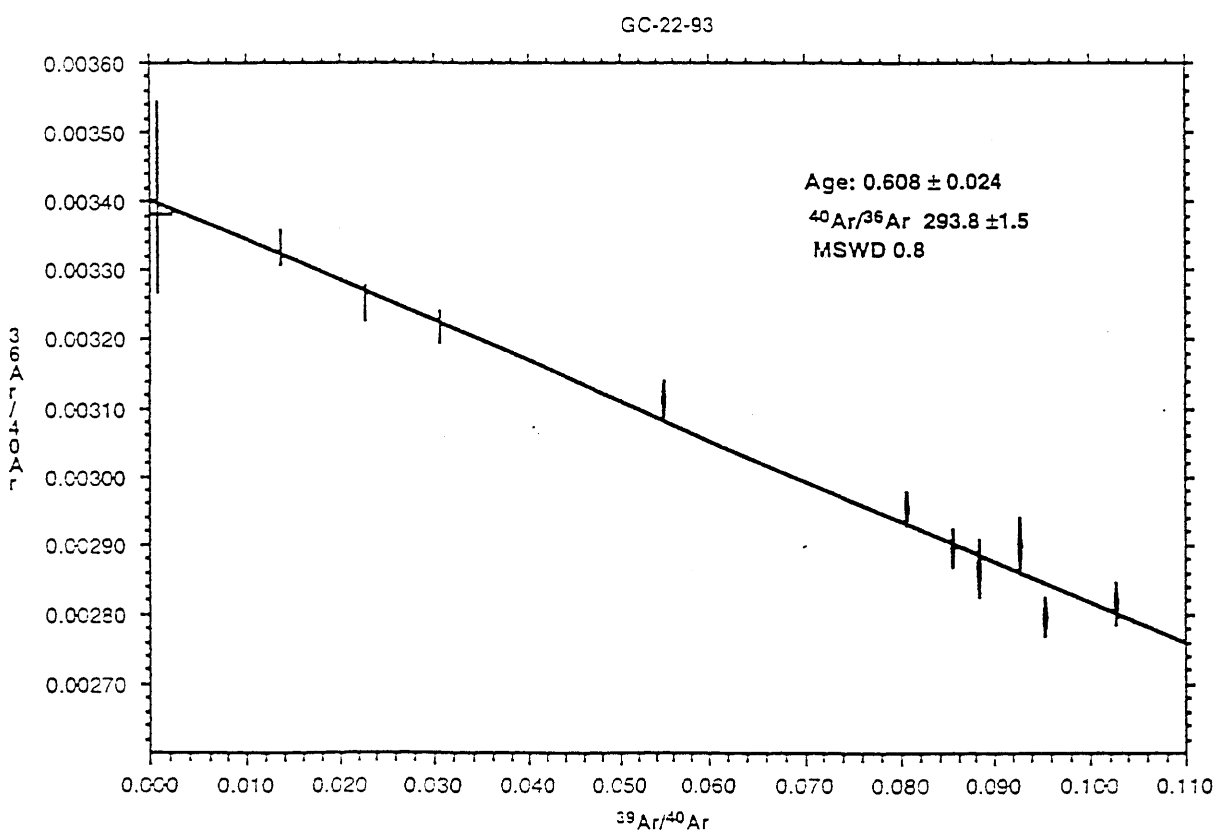
L#	Sample	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	% $^{40}Ar^*$	Age ±1σ	% ^{39}Ar	Temp °C
7678-01A	GC-34-93	41.928	0.0387	0.6509	0.1378	3	0.451 ±0.135	1.6	601
7678-01B	GC-34-93	24.861	0.0277	0.5683	0.0796	5.6	0.502 ±0.074	2.8	650
7678-01C	GC-34-93	9.547	0.0180	0.4963	0.0271	16.4	0.562 ±0.021	24.3	701
7678-01D	GC-34-93	7.225	0.0170	0.5977	0.0193	21.8	0.567 ±0.016	18.9	725
7678-01E	GC-34-93	7.663	0.0173	0.8304	0.0210	19.9	0.548 ±0.017	16.2	752
7678-01F	GC-34-93	9.570	0.0187	0.7289	0.0273	16.2	0.558 ±0.022	15.0	802
7678-01G	GC-34-93	18.764	0.0245	0.9161	0.0582	8.7	0.589 ±0.046	7.5	851
7678-01H	GC-34-93	28.528	0.0315	1.3936	0.0919	5.2	0.537 ±0.073	4.5	902
7678-01I	GC-34-93	55.776	0.0509	10.0406	0.1842	3.8	0.766 ±0.143	4.1	1051
7678-01J	GC-34-93	44.054	0.0422	39.7288	0.1540	3.7	0.606 ±0.119	5.2	1476

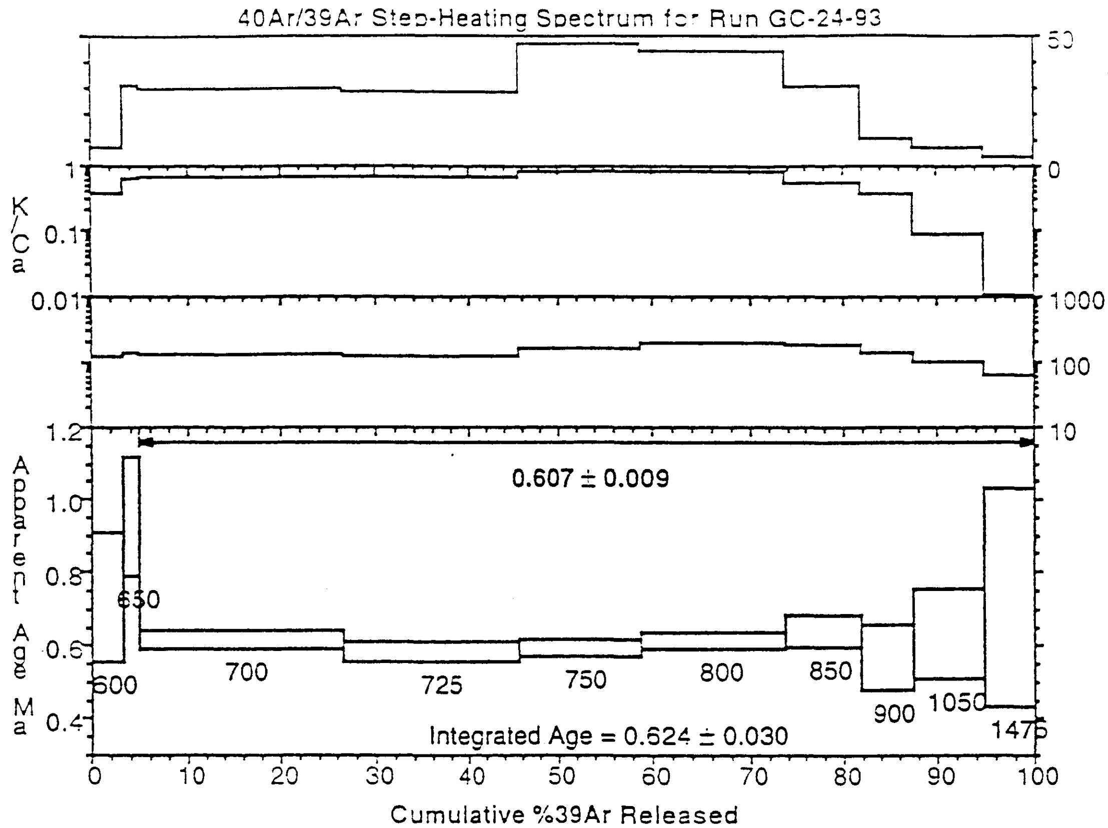
Plateau Age ±1σ: 0.559 ±0.009

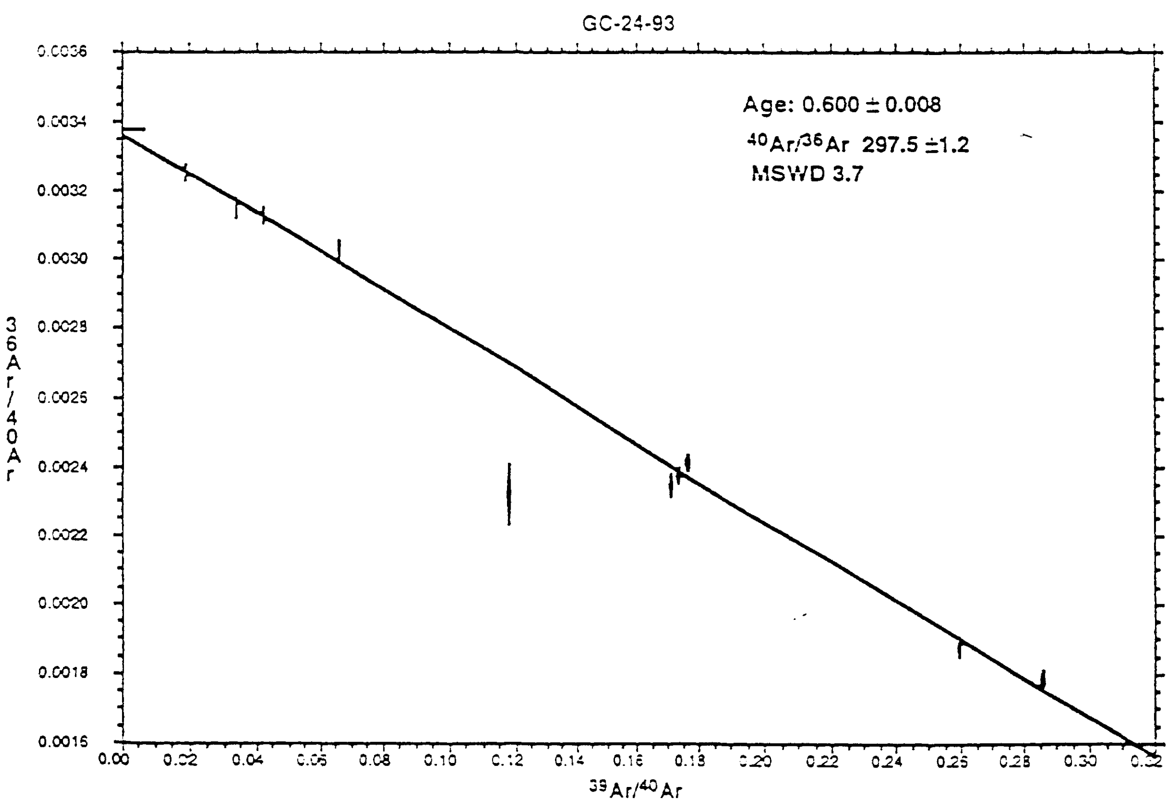
7686-01A	GC-35-93	43.463	0.0396	0.8229	0.1424	3.3	0.494 ±0.115	15.7	601
7686-01B	GC-35-93	18.448	0.0229	1.0004	0.0579	7.7	0.492 ±0.055	3.7	650
7686-01C	GC-35-93	21.501	0.0266	1.3139	0.0681	6.9	0.511 ±0.057	8.6	700
7686-01D	GC-35-93	11.826	0.0193	0.9050	0.0352	12.6	0.516 ±0.038	3.5	725
7686-01E	GC-35-93	8.627	0.0175	0.6755	0.0249	15.2	0.451 ±0.035	3.0	750
7686-01F	GC-35-93	6.477	0.0162	0.6623	0.0171	22.8	0.510 ±0.021	5.7	801
7686-01G	GC-35-93	4.575	0.0141	0.5439	0.0105	32.9	0.518 ±0.013	9.7	851
7686-01H	GC-35-93	5.299	0.0153	0.5338	0.0133	26.6	0.486 ±0.016	9.9	900
7686-01I	GC-35-93	5.500	0.0157	2.7617	0.0145	26	0.494 ±0.012	26.9	1051
7686-01J	GC-35-93	12.802	0.0199	9.0073	0.0402	12.6	0.559 ±0.035	13.3	1475

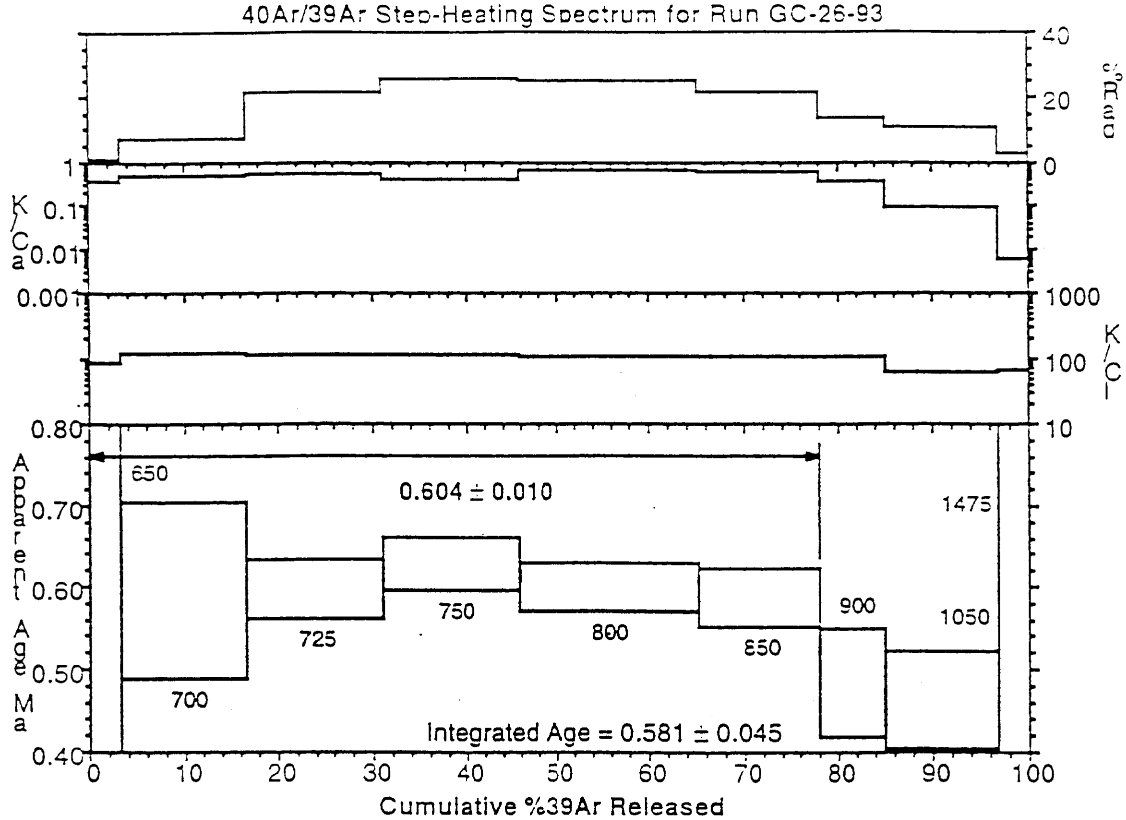
Plateau Age ±1σ: 0.500 ±0.007

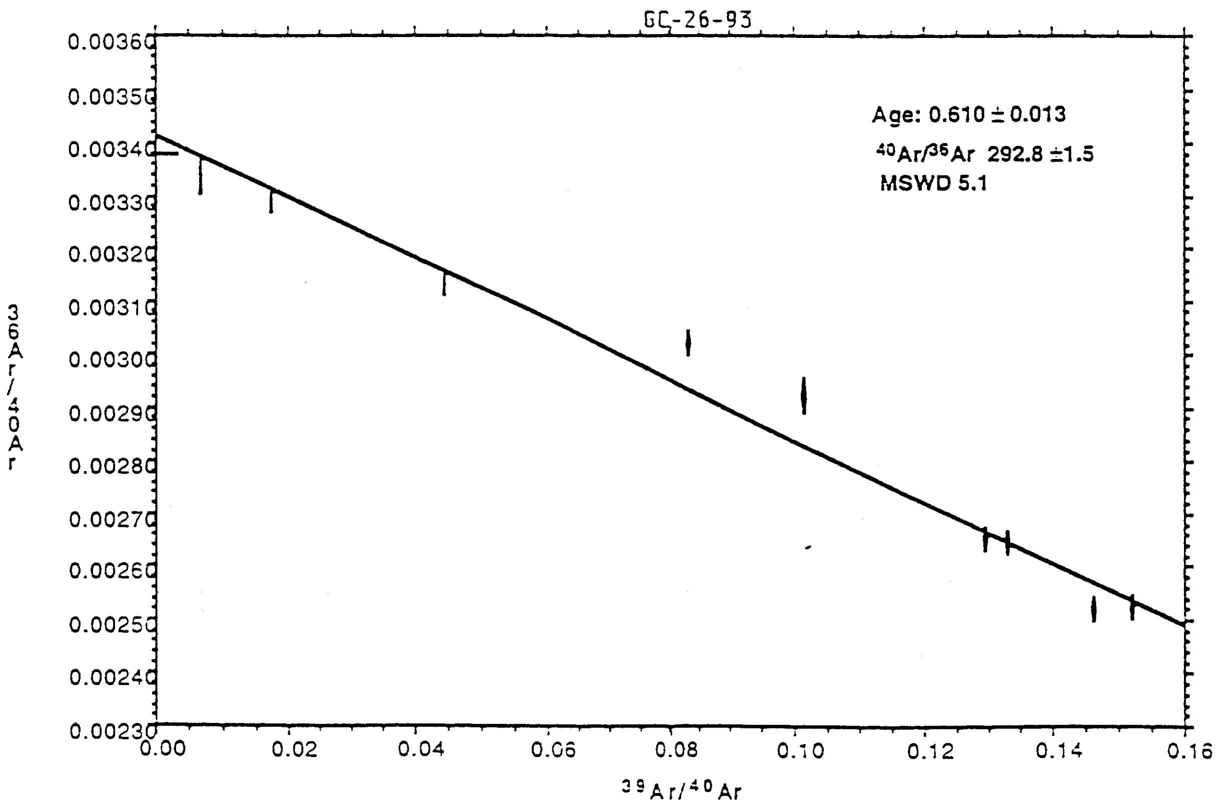

40Ar/39Ar Step-Heating Spectrum for Run GC-22-93
K/Ca
K/Cl
Apparent Age Ma
0.585 ± 0.019
1500
800
675
700
725
750
775
850
900
1050
1275
Integrated Age = 0.56 ± 0.13
Cumulative %39Ar Released

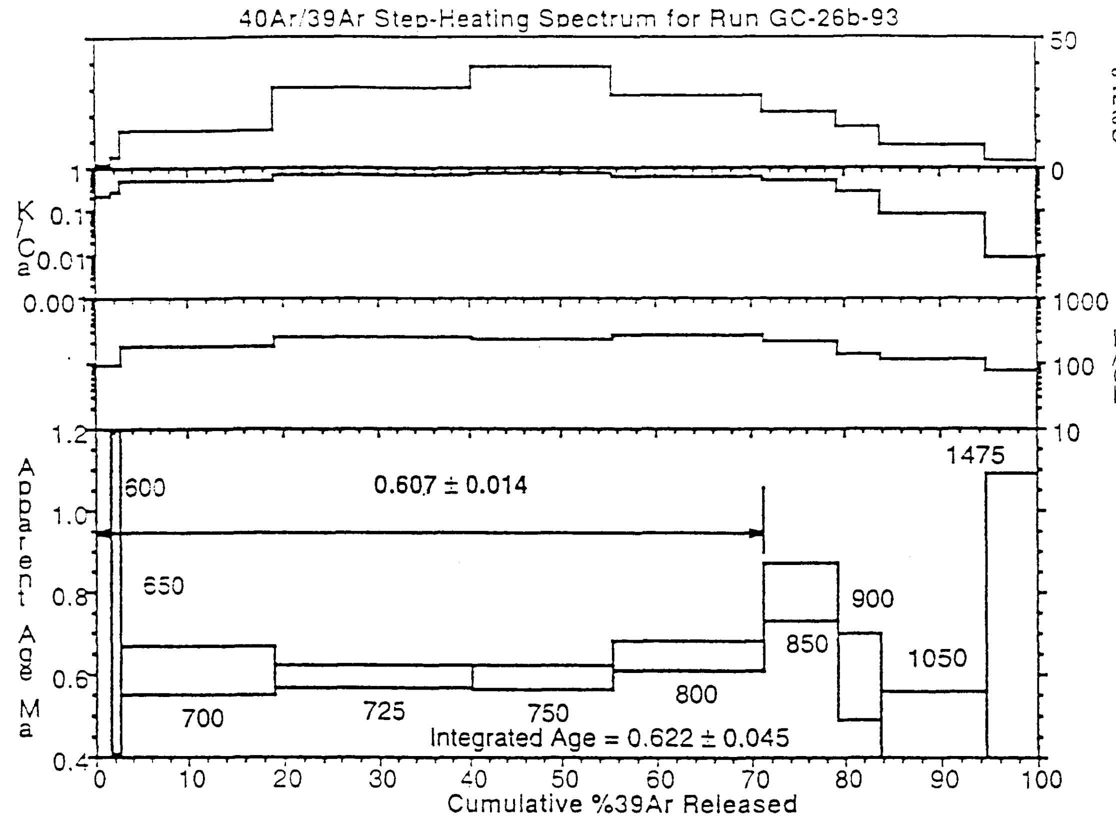

GC-22-93
Age: 0.608 ± 0.024
40Ar/36Ar 293.8 ±1.5
MSWD 0.8
36Ar/40Ar
39Ar/40Ar

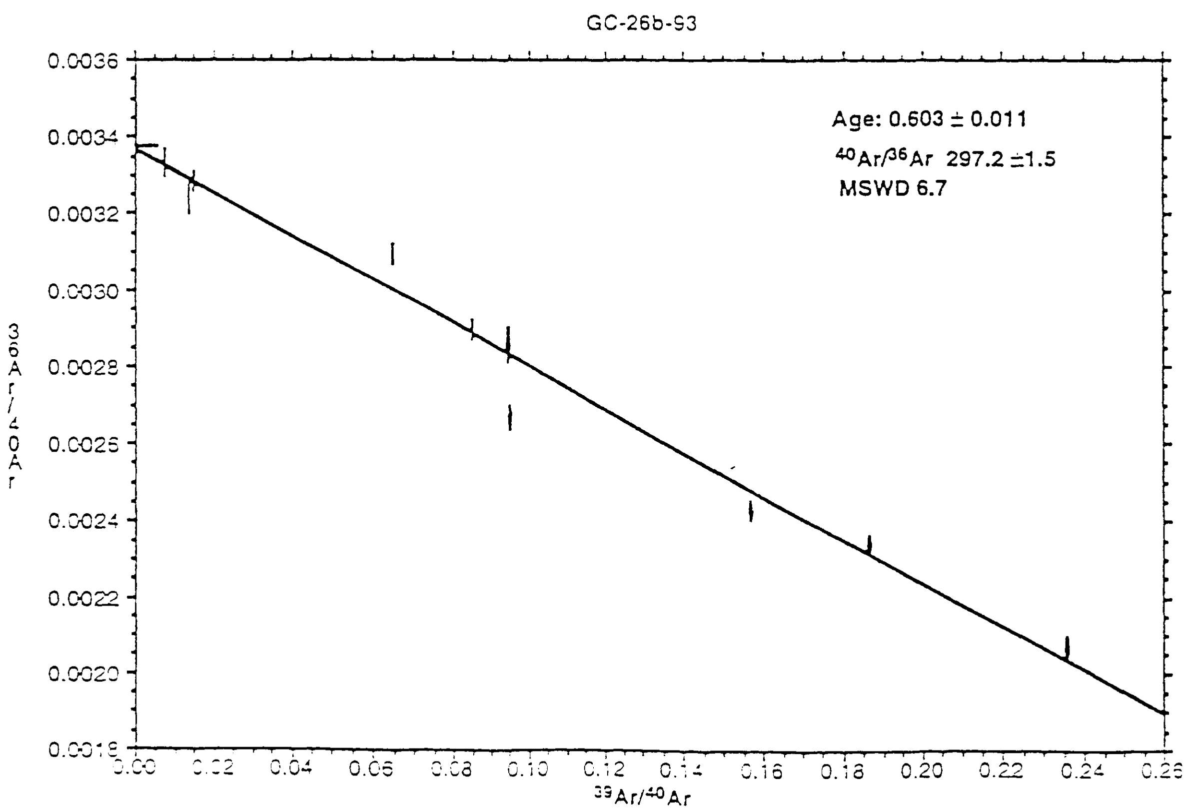

40Ar/39Ar Step-Heating Spectrum for Run GC-24-93
% rad
K/Ca
K/Cl
0.607 ± 0.009
Apparent Age Ma
600
650
700
725
750
800
850
900
1050
1475
Integrated Age = 0.624 ± 0.030
Cumulative %39Ar Released


GC-24-93
Age: 0.600 ± 0.008
40Ar/36Ar 297.5 ±1.2
MSWD 3.7
36Ar/40Ar
39Ar/40Ar


40Ar/39Ar Step-Heating Spectrum for Run GC-26-93
% Rad
K/Ca
K/Cl
Apparent Age Ma
650
700
725
750
800
850
900
1050
1475
0.604 ± 0.010
Integrated Age = 0.581 ± 0.045
Cumulative %39Ar Released


GC-26-93
Age: 0.610 ± 0.013
40Ar/36Ar 292.8 ±1.5
MSWD 5.1
36Ar/40Ar
39Ar/40Ar


40Ar/39Ar Step-Heating Spectrum for Run GC-26b-93
K/Ca
K/Cl
Apparent Age Ma
600
650
700
725
750
800
850
900
1050
1475
0.607 ± 0.014
Integrated Age = 0.622 ± 0.045
Cumulative %39Ar Released


GC-26b-93
Age: 0.603 ± 0.011
40Ar/36Ar 297.2 ±1.5
MSWD 6.7
36Ar/40Ar
39Ar/40Ar