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EVIDENCE OF CATASTROPHIC EROSIONAL EVENTS IN THE GRAND CANYON OF THE COLORADO RIVER, ARIZONA

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ABSTRACT

Gigantic slump blocks, river anticlines, toppled crystalline rock slopes, and travertine deposits found in the Grand Canyon are evidence of a large lake within the Canyon. The lava and/or pyroclastic dams may have met sudden ends with overtopping and subsequent removal by hydraulic cavitation.

Slump blocks of stratigraphically intact Paleozoic sediments have been noted in the vicinity of Surprise Valley. The volume of this slide mass is something over 5.5 bilion cubic yards. Vertical displacement amounts to 1500 feet off of the North Rim of the Canyon. The blocks appear to have rotated along classical semi-circular slip surfaces with the critical shear resistance lying within the Bright Angel Shale. The upper part of the slide plane appears to be joint controlled and only frictional resistance along intersecting joint planes assumed. Shear failure of the Bright Angel Shale under the known overburden can by analytically demonstrated. A drop in shear strength corresponding to saturation of the Bright Angel Shale seems to be a likely cause.

The long recognized river anticlines along the Colorado channel between Kanab and Stairway Canyons can also be explained by the release of elastic strain energy within the Bright Angel Shale. Elastic strain release could have been generated by a rapid downcutting of the channel - either by enormous flood quantities or by the breachment of a volcanic dam some 8 to 20 miles downstream. Since this erosional episode the channel has been aggrading. Preferential directionality of the anticlinal structures is the result of de-stressed zones along directions of pre-existing discontinuites.

1. INTRODUCTION

Dam the Grand Canyon! This subject conjures up the usual cast of characters, Friends of the Earth vs. the U.S. Bureau of Reclamation, Edward Abbey blowing up Glen Canyon Dam and Georgie White pulling water skiers 3,000 feet above Lava Falls. What none of these diverse groups realize is that damming the Colorado in the vicinity of Grand Canyon National Park has happened, not once, but many times in the past. During the late Pleistocene, temporary impoundment of the ancient Colorado was made possible by basaltic lava erupting out onto a plateau and cascading over a 3,000 foot near-vertical escarpment into the western inner gorge of the Grand Canyon. The geologic magnitude of such an event has not been duplicated in historic time. These lava dams were stort-lived (Hamblin, 1979), but they left sufficent evidence for an interdisciplinary approach to reconstruct the locations, reservoirs and impact on today's Grand Canyon.

1.1 EXISTENCE OF LAVA DAMS

Virtually all of the geologically-oriented scientists who have explored the depths of the Grand Canyon of the Colorado have mentioned the extensive lava flows cascading into the the present river gorge from the Shivwitts Plateau. Powell (1875) rhapsodized about the steaming cataclysim that certainly took place when the red-hot lavas met the river below. Dutton (1882) was the first geologist to map the Canyon and its lava flows, which extended out to Toroweap on the Esplanade. The first detailed investigation of the lava dam sites and positive recognition of their existence and scale was done by McKee and Schenk (1942). Subsequent detailed reconnaissance of the lavas was done by Koons (1943) on the Shivwitts plateau for his Ph.D. Three decades later, a remarkable series of papers by Hamblin (Hamblin, McKee, Damon [1968], and Hamblin [1969, 1970, 1974]) elucidates the meticulous mapping and geomorphic analysis originally initiated by McKee in his Grand Canyon work. Hamblin set topographical and age-synchronous limits on the erruptive events; both he and McKee postulated the repeated existence of reservoirs in the Canyon. Hamblin, Lucchitta, McKee, Shoemaker, and Damon have all contributed to the various age-dating work done in the past 13 years that has provided a clear picture of the river's history in the western reaches of the Colorado Plateau.

1.2 PRELIMINARY STATEMENT OF EVIDENCES OF RIVER IMPOUNDMENT

Due to inaccessable terrain, blazing days and frozen nights, the depths of the canyon have escaped careful scientific scrutiny. Also, for reasons of their own, the Park Service does little to maintain adequate trails. The authors do not advocate paved trails, but for those of us who enjoy a wilderness experience and find it necessary for survival to pack in drinking water in the arid sections of the canyon, a regular trail maintenance program would be greatly appreciated.

Evidence for the lava dams has been observed by geologists, but not quantitatively explained or analyzed. This is where the applied sciences, such as engineering, can be utilized, specifically the discipline of the geological/geotechnical engineer. Geomorphology may prove to be the ultimate interdisciplinary science. This paper encompasses hydrology, limnology, water quality, channel hydraulics, soil mechanics, rock mechanics, as well as many facets of geology.

Two field expeditions were made by the authors, one by boat in 1978, and on foot in 1979. We believe that we can demonstrate the related nature of the structures listed below wholly or in part to successive river impoundments of enormous proportions and consecutive catastrophic failures.

The inferred evidences cited in this paper for impoundment of the Colorado River are as follows:

1. Massive toppling of crystalline schistose slopes in the Granite Gorge at Miles 84, 95, and 111 [1].

2. Massive Toreva [2] style slumping, **progressive wedge slumping**, successive sliding, and possible gravity faulting in the vicinity of Surprise Valley —river miles 134 through 139.

3. Travertine deposits of tremendous vertical reach that correlate elevations and not of stratigraphy; miles 56 through 159.

4. River gravels and river terrace deposits that also posses topographical correlations and are of sufficient elevation to be antecedent to the recent [3] river regimen.

5. Localized anticlines in the lower Muav limestone occurring at river level between Kanab and Stairway Canyons (miles 144 to 171) on southwest trending stretches of the channel.

6. A curious convex-upwards trend of thee Colorado River surface profile immediately upstream of the Toroweap-Prospect lava dam sites. The Colorado channel is abnormally quiescent and aggrading between Kanab Canyon and the lava flows (miles 144 to 179).

7. There is ample recognized evidence for lava dams at Toroweap by McKee and Schenk (1942), for Esplanade level dams at Toroweap and Whitmore Washes by Hammblin (1974), a succession of younger intra-canyon flows by Hamblin (1969, 1974), and unpublished evidence on reach, slope, and age of the most extensive flows by Hamblin (1979).

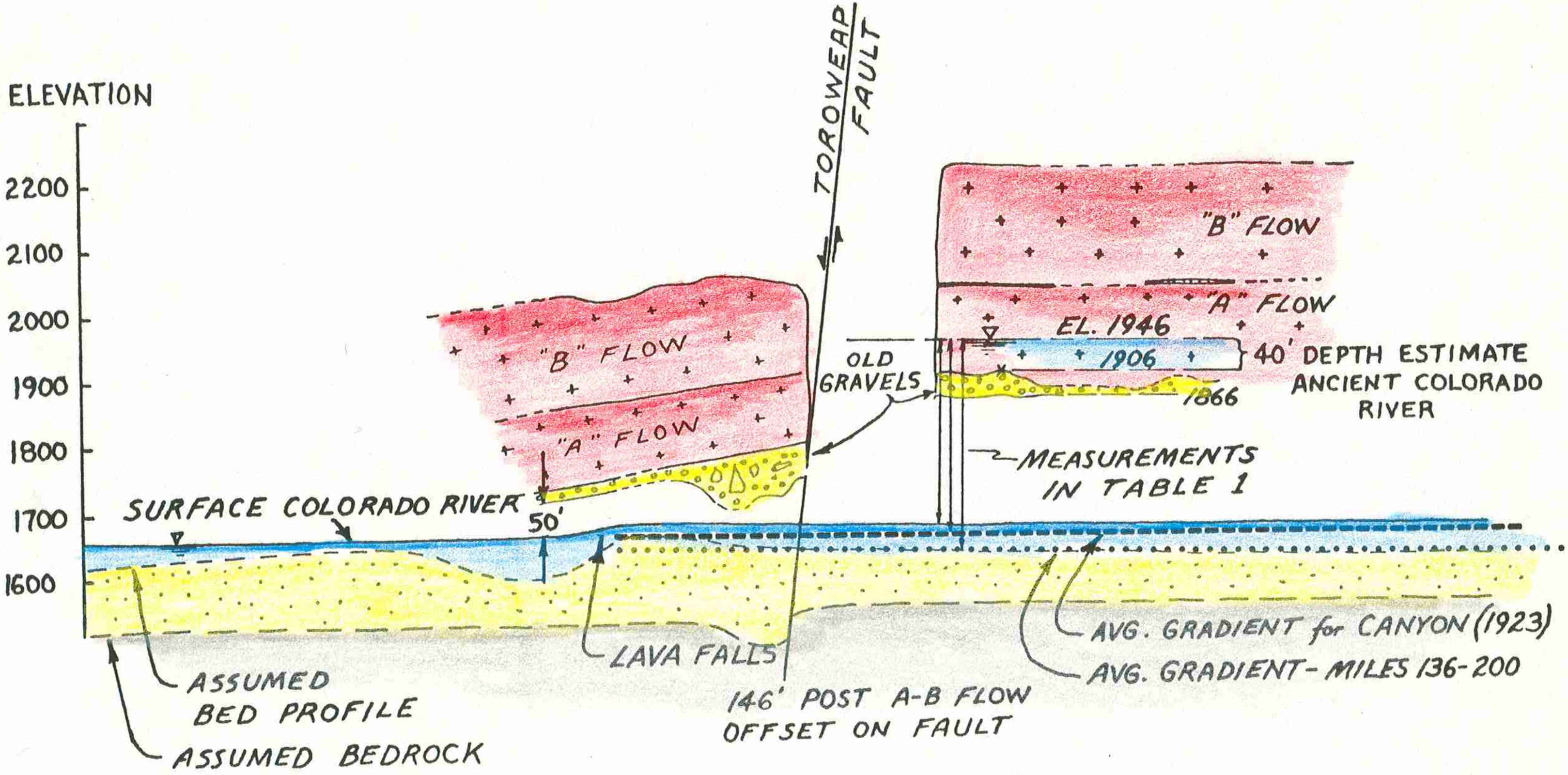


Figure 1 - Position of Ancient Channel Bed below initial Lava Flows in the Inner Gorge at Toroweap.

2. THE EMPLACEMENT OF THE LAVA DAMS

Remnants of volcanic activity have been preserved on the near-vertical walls of the inner Colorado gorge between mile 178 downstream and mile 263. Using Potassium-Argon dating, the lowest flows were dated at 1.2 ± .16 million years before present (McKee, Hamblin, Damon [1968]. This is the time-limiting boundary initially applied to the oldest of all the lava flows recognized within the Inner Gorge at Toroweap (mile 179).

2.1 Generalized Sequence of Lava Flows

By approximately 1.2 million years ago, [4] the Colorado River had excavated a Grand Canyon much as we know it today. However, the river elevation before the lava flows [5] was miscalculated by McKee and Schenk (1942) on page 271-2. Regarding the Toroweap fault, they summarized:

1. The Toroweap fault developed as a normal north-south trending fault with its down-thrown side to the west and with a displacement of about 486 feet.

2. The Inner Gorge of the Grand Canyon was cut to within 50 feet of its present depth {23}.

An important footnote at the bottom of page 272 read:

> {23} Measurement of the down-thrown side of Toroweap fault on assumption that later fault movement was up. If movement was down, canyon bottom would have been 200 feet above present river level.

McKee and Schenk's 50 foot value is an absolute value involving elevations above today's sea level (the presently employed datum). It would appear, however, in actual physical terms that both the Kanab and Kaibab Plateaus have continually been UPLIFTED throughout late Pliestocene (post lava-flow) time (see Figures 1 and 2).

Table One summarizes the authors' calculations regarding the amount of rock the Colorado River has cut down through in the past 1.2 million years **east of the Toroweap Fault.** Other data presented later suggests slightly greater uplift in the Kaibab Plateau.

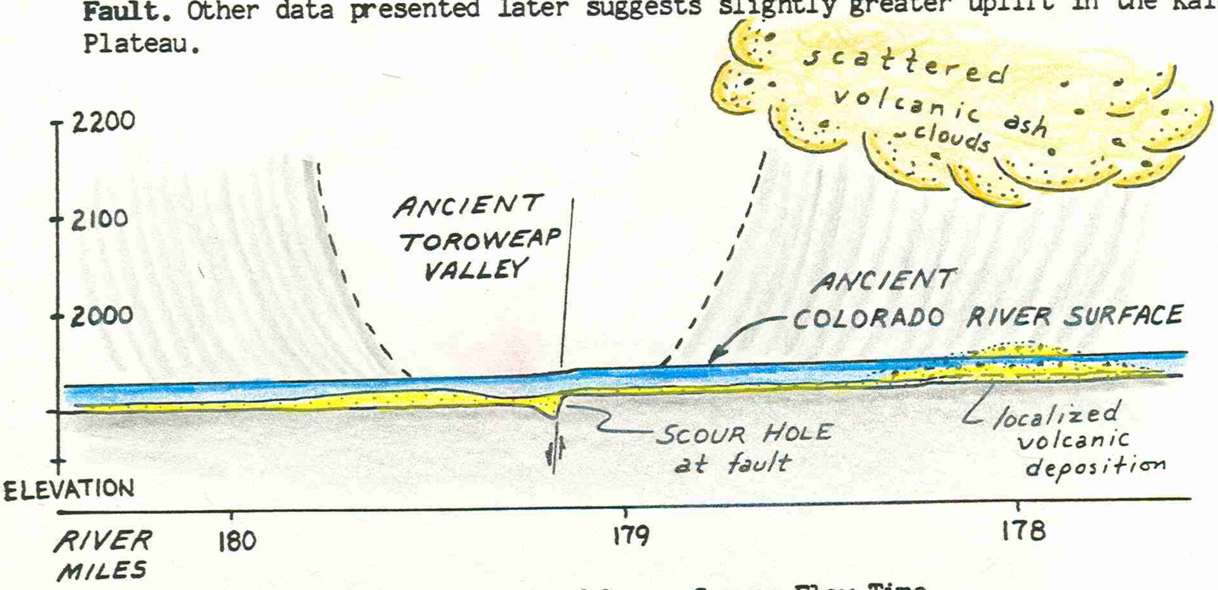


Figure 2 - River Profile at outset of Lower Canyon Flow Time

TABLE ONE

Ancient Colorado River Level Reconstructions

- - measurements taken from Figures 1 and 2 at miles 178.93 - -

Method	Elevation at Milepost 178.93	Presumed Ancient Channel Elevation	Elev Difference Between Old and New Channels
Mean Surface Profile	1663.09	1946	282.9
1923 Hydrographic Survey Surface	1677.5	1946	268.5
Regional (local) Mean Surface Profile	1647.75	1946	298.25

From Table One, therefore, it would be reasonable to assume that the Colorado River has cut its gorge from 250-300 feet LOWER in the past 1.2 million years in the greater part of the Kanab and Kaibab Plateaus.

Observations by the senior author in the vicinity of the much-studied (Hamblin, [1969, 1974]) mile 183 area support the preceding hypothesis [6]. The Colorado channel exhibits considerable aggradation of the previous channel west of the Toroweap fault (see Figures 29-L and 28 in Hamblin [1969]). This would appear to support McKee andd Schenk's supposition of relative displacement on the Toroweap fault, (up on east, constant on west) but does not explain the popular opinion that the Colorado has only incised 50 feet in the past 1.2 ± .16 million years (McKee, Hamblin, and Damon [1968] and Leopold [1969]).

3. CHRONOLOGICAL SEQUENCE OF LAVA DAMMING OF THE INNER GORGE

Some sort of dam was built up that was eventually breached and precipitated McKee and Schenk's (1942) "Basal Conglomerate" by means of a high-quantity rock-debris flow with ash, lava, and river cobbles ranging in size from 1 inch to 10 feet. The extent of this deluge deposit is unknown -- it fills an apparent scour hole on the west side of the Toroweap fault surface trace — but is completely absent at mile 183 where the basal intra-canyon lava flow lies atop a fresh, cleanly-scoured bedrock channel. The basal conglomerate may be a pre-lava extrusion mudflow - one that scoured and filled locally.

A partial breachment of the Flow A-B dam (Fig 3) is inferred from the presence of McKee and Schenk (1942) "First Interflow Sediments" lying in irregularities atop the eroded surface of "B" flow. The low heights [9] of the A-B lava dam and the almost certain high flow and bed load of a Pleistocene Colorado River would have collaborated to create a reservoir upstream [10] that quickly filled up with an advancing series of density/turbidity current fins overlain by a cross-bedded series of reworked river gravels [11]. A close inspection shows these "sediments" to consist of cobbles of well-rounded Shinumo Quartzite [12] and sub-rounded clasts of olivene basalt, presumably of local origin. Above the more dense quartzites and basalts are less-commonly included clasts of Paleozoic limestone and some sandstone. Boulders 2-3 feet in diameter are commonly included while some range up to 10 feet [13]. The sizes are suggestive of high energy/flow breachment [14] or catastrophic breakout [15] upstream creating the scoured surface on "B" flows. Evidence for an upstream dam is as follows:

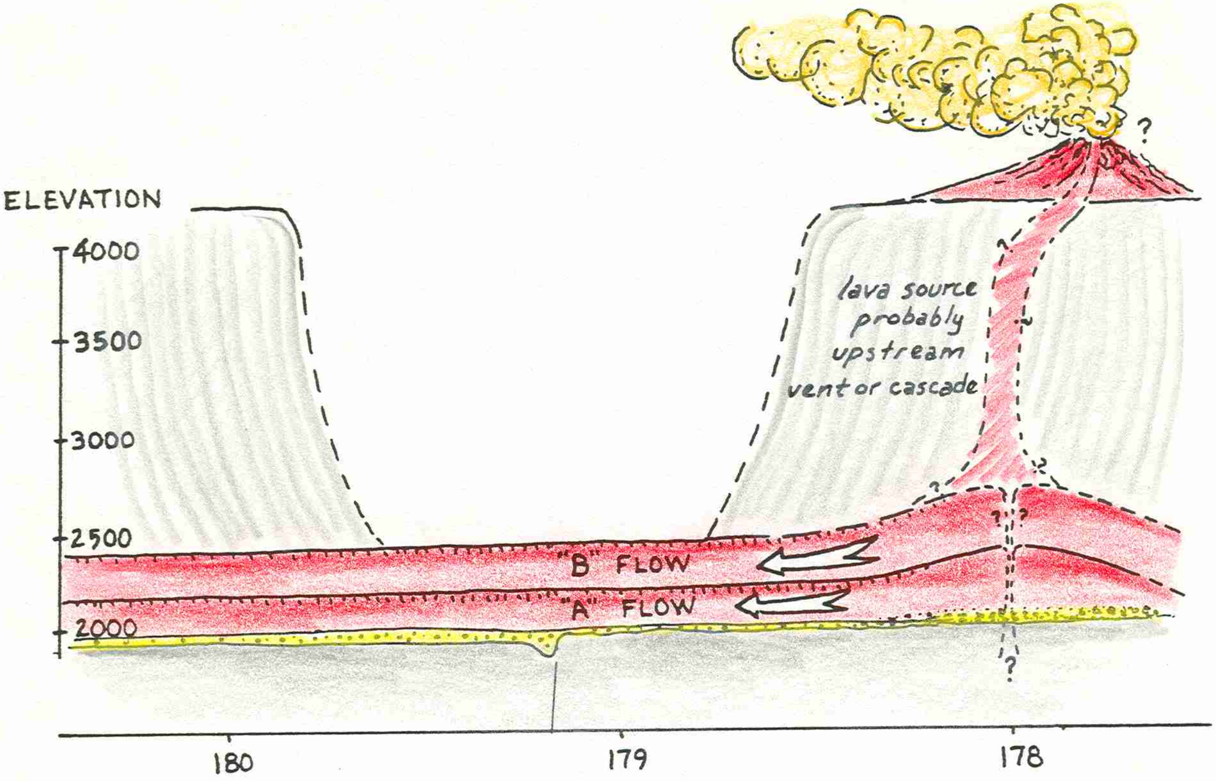


Figure 3 - Emplacement of A and B Flows at Toroweap

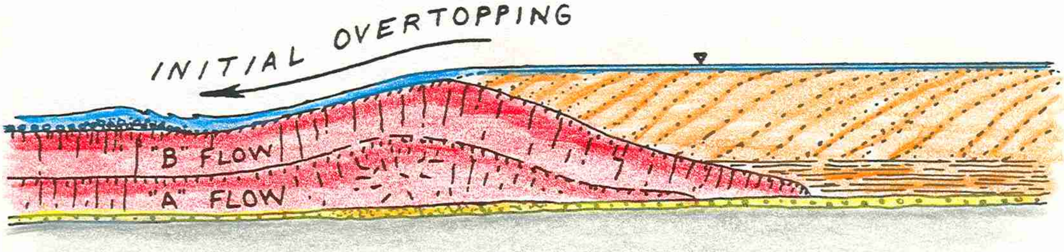


Figure 4a - Initial Overtopping with Sediment over the A-B Dam

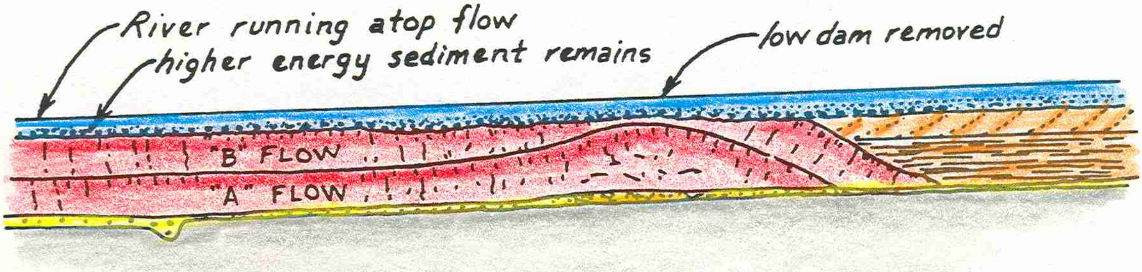


Figure 4b - Planation of the A-B Flows, the first in a series of such events

3.1 Both "A" and "B" flows are close to being level and continuous, apparently thinning downstream [16]. It is hard to imagine, although not impossible, a lava flow proceeding UPSTREAM in such a fashion [17].

3.2 Ten foot diameter boulders would require a considerable amount of water in the absence of a high gradient (which there is evidence **against**). A dam breachment's fantastic energy flow is a very localized and short-lived phenomenon immediately downstream [18] of the failed structure. Considering the apparently low height of the A and B flow dam, the water quantities required could only be generated by sudden failure and not geologiccal downcutting consistent with the rest of the region.

3.3 The absence of any typical reservoir bottom sediments [19] atop the "B" flow.

3.4 Later "C" flow basalts lie on both the north and south sides of the Colorado River downstream at mile 179.8 of the Toroweap. The south exposure fills a cave in the Muav limestone [20] at an elevation continuous [21] with the eroded top of "B" flow on the north side of the river. On this side of the river, "C" flows are tentatively mapped [22] atop the "B" flows in a horizontally contiguous fashion.

The most numerous of the Lower Intracanyon Flows (Fig. 5) are the "D" Flows [23], a succession of thin lavas 2-15 feet thick with a thickness of 137 feet [24]. These flows appear less weathered [25], are chiefly of scoriaceous character and are found lying atop receded Muav scarps for some distance downstream of Toroweap on the south wall of the Inner Gorge. The "D" flows appear to have been widespread and continuous in nature, apparently flowing down the canyon on a relatively shallow gradient [26]. The emplacement of the "D" flows created a dam at least 750 feet high [27], presumably backing water up to Bright Angel Creek [28], 91 miles distant.

Throughout the Toroweap area the "D" series flows are capped a third series of "Interflow Sediments" [29] about 25 feet thick. These sediments are a very angular and heterogenous mixture of volcanic ejecta, river-worn limestone pebbles, and very angular assemblages of locally derived Supai sandstone [30]. It would appear that this asseeblage is a composite of pyroclastics mixing with moderate-sized river gravels being taken over the crest (of the lava dam) followed by larger and more angular material as the flow increased [31]. Localized widening of the channel is indicated (possibly on a seasonal intermittent braided channel bed) that probably helped to oversteepen the slopes, thereby precipitating slope failures of (cascaded) lavas and the Supai enscarpment (Esplanade). This debris was subsequently washed and reworked little by the river.

Hamblin (1969, 1974) reports on two more flows he terms "E" and "F" that were a continuous part of the above sequence. These columnar basalts, like those preceding, flowed down the channel on very slight gradients and are continnuously correlable intermittently on both walls of the Inner Gorge from

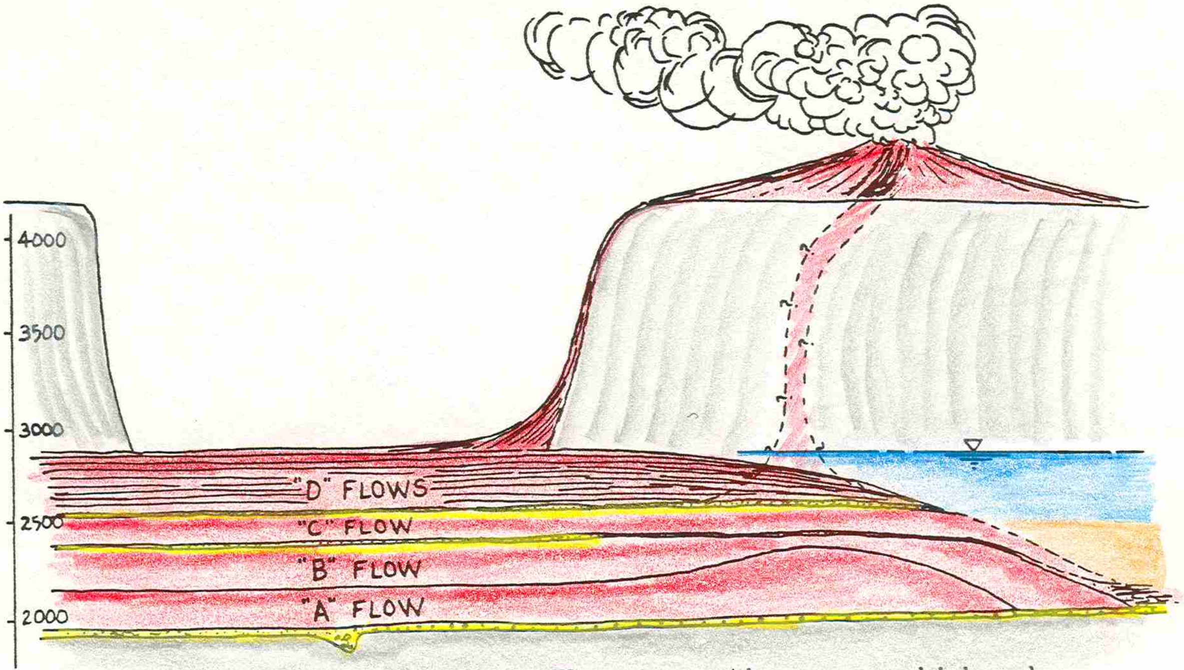


Figure 5 - Emplacement of the C-D Flows - creating an even higher dam

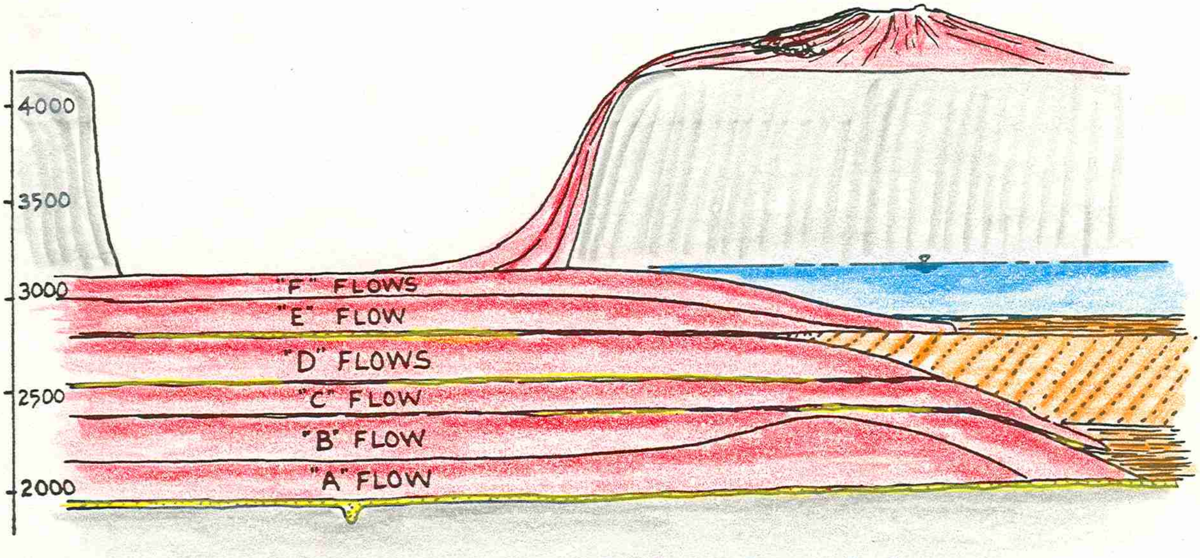


Figure 6 - The 1138 foot high dam of the Lower Canyon Series

miles 178 to 184. Hamblin (1974) states:

> "These high-level remnants are especially significant in that they provide evidence of former lava dams across the Grand Canyon 1,413 feet above present river level". [32]

Further evidence accumulated by Hamblin (1974) in mapping the older intracanyon flows along the Inner Gorge indicates that the above flows decrease in absolute elevation to the west [33]. It can be inferred that:

1. The older intracanyon flows had a source area somewhere upstream of or in the vicinity of Toroweap (mile 178).

2. Intermittent damming of the Colorado River took place and following at least three episodes of erruption, flowage, and river impoundment, the river overtopped the lava dams, but did not completely destroy them.

3. Preservation of the lava flows was most likely made possible by:

    a. The low height differential between the dam and the downstream flow surface.

    b. The great extent of the flows prevented toe-headward erosion of the entire flow masss by overtopping waters. The greatest amount of erosion probably occurred at the toe overflow.

    c. Once the waters breached the high point of the flow-dam, the gradient atop to lava flows was not sufficient to support large-diameter bed-loads. The resulting scour atop the flows was small as compaired to the potential energy in the river system.

    d. More lava flows accumulated than the river system could remove.

It is not known how the first 1000 foot plus dam was eventually removed. The only good evidence lies in the vicinity of the abandoned buried channel of the Colorado River at mile 183 described by Hamblin (1969, 1974) and shown in fig. 7.

The post-lower canyon series lava dam alluvial history appears to support a successive overtopping-removal genesis similar to those postulated for interflow sediment sequences cited previously.

The 1,140'+ dam appears to have been overtopped and 150'+ of basalt flows were removed in the vicinity of mile 183 — presumably in high-flow stages caused by sudden failure of an upper part of the composite lava dam upstream. This was followed by the usual aggradation of the flood channel as the debris load accumulated behind the dam would have been beyond the capacity of a normal flowing Colorado River [34] to handle.

4. A LAVA FLOW HIATUS

The flows of the Lower Canyon Group were followed by long periods of continuous

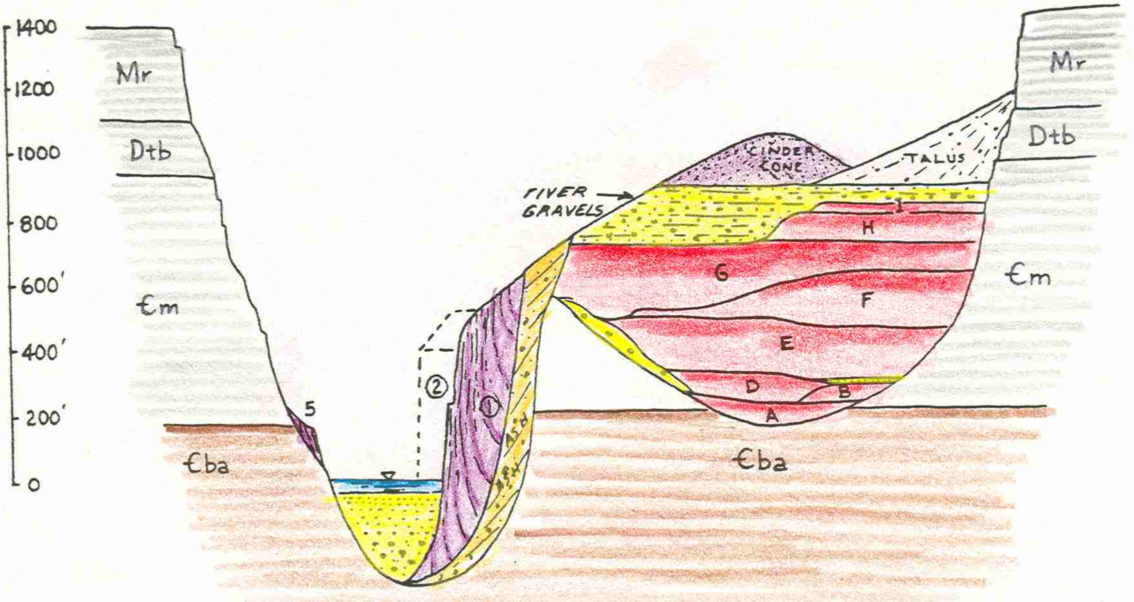
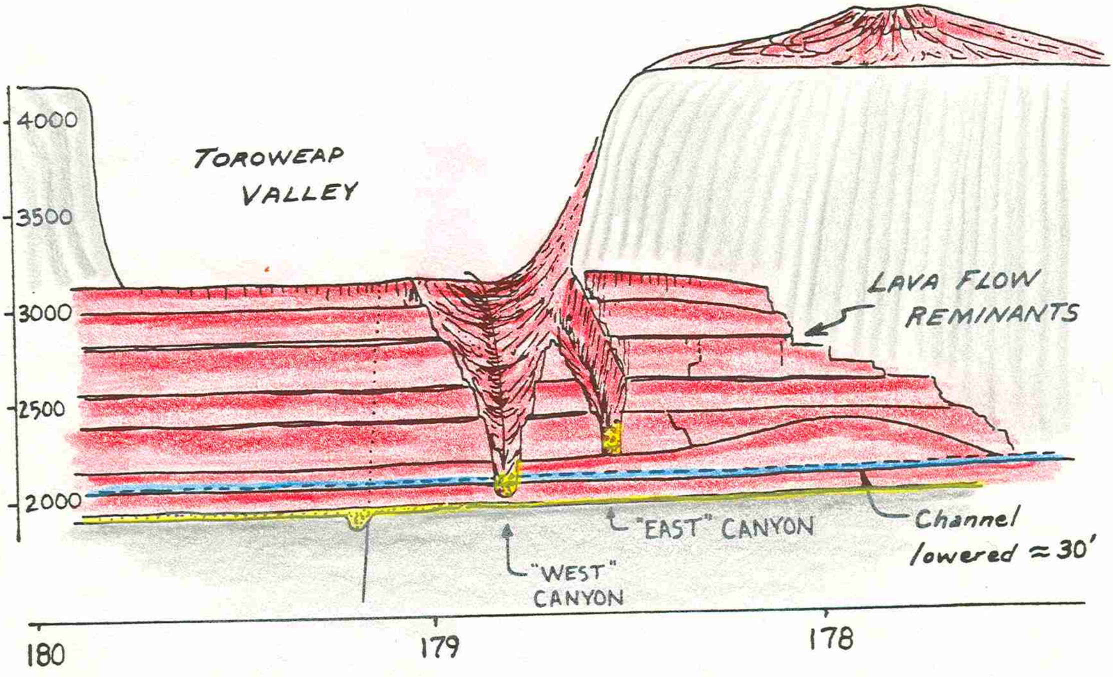


Figure 7 - A generalized section at Mile 183 taken from Hamblin's (1969) Figure 28, page 60 with recent corrections (Hamblin, [1979]).



Rejuvination of Toroweap Valley

Figure 8 - Frontal view of North Wall of the Inner Gorge at Toroweap during the hiatus between Lower and Middle Canyon Flows.

downcutting as the Colorado reseeked its previous gradient.

Figure 8 shows the approximate locations of two post-lower Canyon Group tributary channels at Toproweap that were subsequently covered by Middle Canyon flows. These channels were most likely the result of Toroweap Valley waters [35] re-establishing a drainage through the lavas to the downcutting river. The "eastern channel" (see Figure 8) cut down to the top of "A" flow [36] while the "western channel" appears to have pirated the sister channel and excavated itself down to a new base level slightly below [37].

Both of the post-Lower-Canyon Toroweap channels became choked with locally derived debris. The easternmost one probably filled after capture of its drainage while the western channel most likely aggraded after a low level (<200 feet?) damming of the river downstream (a marked increase in local base level). Toroweap Valley was subsequently filled by later volcanic eruptions.

What happened after the Lower Canyon Series flows is still not entirely clear. The evidence is summarized as follows:

1. Toroweap and Prospect Vally were excavated to approximmately within 225 feet of the present channel surface.

2. The river cut a new channel at mile 183 along the old basalt flow/South Wall bedrock contact. This channel is extremely incised [38] (see Figure 7). Hamblin (1974) on page 161 states:

   > "This canyon was deeper than the present channel of the river, as is indicated by remnants of younger intracanyon flows which extend an unknown distance below water level".

3. A relative downcutting of over 1200 feet vertically is inferred at mile 183.

The magnitude of the last statement is immense. No suitable theory other than the natural course of canyon downcutting is evidenced. A considerable hiatus between the Lower Canyon Lavas and the next episode of vulcanism is inferred.

5. MIDDLE CANYON FLOWS

A period of renewed volcanism eventually erupted that was more explosive. This sequence is hereafter termed the "Middle Canyon Flows" after the type locality investigations at Toroweap made by McKee and Schenk (1942) [39]. The entire sequence is typified by alternating sequences of basalt flows and stratified tuffaceous ash. An approximate sequence is outlined below.

At Mile 178–179 Toroweap-Prospect

An alternating sequence of columnar basalt flows and pyroclastic ash was built up to an elevation of approximately 3600 feet. This cyclic sequence was apparently localized and it filled Toroweap and Prospect Canyons.

At Mile 180

A 200' thick series of interflow river gravels is covered by a thin veneer of 10' diameter lava boulders, evidently the result of a high flow breakout. This is overlain in turn by 20' of flat lying tuffs apparently deposited in a lake followed by more inteflow gravel accumulations that were apparently partally dissected by subsequent localized planation of the channel. Another eruption of ash apparently coincided with a damming downstream as the resulting tuff beds appear to have been deposited in a lacustrine environment. Several hundred feet of additional tuff, cinder, and ash were subsequently overlain on the lake deposits. The lacustrine nature of these deposits was first noted by McKee and Schenk (1942), page 267-8.

At Mile 183

Hamblin (1969, 1979) has documented a similar, but more complete series of events at mile 183. His recognition of a 600' thick intracanyon stratified ash flow may be construed as an event occurring in Middle Canyon Flow time. It was almost completely removed in the long hiatus until Younger Intra Canyon Flow time.

At Mile 187.5 Whitmore Wash

Here a successive series of thin basalts flowed down ancient Whitmore Wash and filled up the canyon to a depth of 960+ feet, almost the level of the Esplanade. A tremendous dam must have been created here in early "Middle Lava Flow" time. The removal of the dam was completed before Hamblin's younger intracanyon flows #1 and 2 are juxtaposed against a completely downcut and dissected Whitmore Wash dam. Theories on the removal of this dam will be presented later.

It appears then that during the time of McKee and Schenk's (1942) "Middle Canyon Group", there was a build-up of composite ash/flow deposits which were excavated locally or built upon by subsequent flows. In the vicinity of Toroweap the elevation of the build-up was some 1785 feet to elevation 3450. Our model for the toe-headward breakdown of the basalt dams (if valid), explains how the ancient Colorado concentrated its energies upon removal of the great dam at Whitmore, thus preserving the buildup at Toroweap during this period [40].

6. UPPER CANYON FLOWS

Soon after the cessation of the ash/flow cyclic eruptions that stratigraphically typify the Middle Canyon Group [41] a series of tight, intact basaltic flows erupted. These are cited below.

At Mile 178–179 Toroweap-Prospect

Four hundred feet of thin scoriaceous basalts were extruded presumably in a southwards direction along a surface of Middle Canyon tuffaceous ash in Toroweap Valley. These apparently continued across into Canyon (indicating a relatively intact Middle Canyon flow base within the Gorge) and then presumably this very viscous mass made its way downstream. The resulting high dam was about 2,460 feet high rising to a fault-corrected elevation of 4125 feet [42].

7. YOUNGER INTRACANYON FLOWS

Hamblin (1969, 1974) describes a series of five basalt flows that are the youngest correlative events in the Inner Gorge. These appear to have moved down a Colorado River very similar to today's channel (after removal of the large dams at Whitmore and Toroweap). The lower bounds and location of lava dams that these flows must have created are tabulated in Table 2. Flow 3 appears to have been built upon an eroded, gravel filled channel atop flow 2, much like that described in the Lower Canyon flows [43]. The rest of these younger flows appear to have been extruded after a sufficient hiatus to permit re-excavation of the river channel [44].

TABLE TWO

The Major Lava Dams in the Western Grand Canyon

Listed in Time-Chronological Order

Location	Type	Elevation (feet)	Height Above Ancient River Level (feet)
Mile 177-8	Basalt Flow "A&B"	2225+	350+
Mile 178	Basalt Flow "C"	2350+	475+
Mile 178	Basalt Flow "D"	2690+	750+
Mile 178	Basalt Flow "E&F"	3078+	1138+
Mile 182-3	Stratified Ash	2225+	600+
Mile 187.5	Basalt Flows	2560+	960+
Mile 178	Ash & Basalt Flows	4125	2460+
Mile 178(188)	Basalt Flow #1	2075+	450+
Mile 178(263)	Basalt Flow #2	1965+	370+
Mile 188	Six Thin Flows River Gravels	2130+	536+
Mile 182	15 Small Diabase Flows #4	1991+	298+
Mile 178(195)	Basalt Flow #5	1837+	165+
Mile 178 (?)*	Minor Recent Flows	1830+	150+

*150 feet of stratified river gravels cover Flow #5 in places.

Table Two is chiefly a summary of data presented by McKee and Schenk (1942), McKee et al. (1968), and Hamblin (1969, 1974, 1979). Miles in parenthesis indicate known downstream reach of individual flows as reported by Hamblin.

8. SUMMARY

A preliminary tabulation of the (major) lava dams cited in this section is presented in Table 2. A discussion of the genesis of their removal will be presented later in this paper.

9. THE EFFECTS OF RIVER EMPOUNDMENT

The emplacement of the lava dams created repeated impoundments of the Colorado River and intermittent drowning of the Canyon as far upstream as Cataract Canyon. Depending on the dam heights, the Pleistocene waters of the Colorado filled the new reservoir in the matter of a few years. The tremendous bed-load capacity of the river then served to fill up the reservoir with sediments [45] in a few hundred years [46], depending on the volumes involved.

Sudden increases in water level of such magnitude must have had a profound effect upon slope stability in certain specific topographical cases. Saturation of argillaceous units would promote a decrease in their shear strength while ponding of water would increase the weight acting upon the toe of a slope (stabilizing force).

The complex interactions involved tend to preclude the possibility of a shoreline-wide sequence of slope failure and mass wastage. However, certain geomorphological situations in the Canyon were "ripe" for reservoir-induced slope failures. Most of these failures are long gone today; likely because of the excessive steepness of the Canyon walls, and the relative ease with which the hydrologic regimen can remove broken rock debris in lieu of intact (unfailed) masses. [47]

Most catastropic events leave some clues, and an erosional remnant of these ancient slope failures is preserved in the vicinity of the Surprise Valley.

10. PURPOSE

The purpose of this section is to determine the evolution of the landforms in Surprise Valley. The investigation consisted of five phases. The first phase was a review of the literature on the Surprise Valley; the second was field reconnaissance expeditions including low level air photography; the third was a laboratory program (still in progress) to determine the strength of the Bright Angel Shale under dry and saturated conditions; the fourth was an engineering slope stability analysis of the Surprise Valley Slides; and, the the fifth was the reduction of the data into a final hypothesis.

11. DESCRIPTIVE GEOLOGY OF SURPRISE VALLEY

Surprise Valley is located in the west part of Grand Canyon just west of the Kaibab Uplift (river mile 135). The valley is bounded on the west by Deer Creek and on the east by Tapeats Creek (Figure 9). Because of the geologic similarity, the valley boundary has been extended (Ford et al 1974) west of Deer Creek approximately one mile to include a large landslide feature on the north side of the Colorado River.

Spectacular landslides form the topography in Surprise Valley.

> In Geology of the Grand Canyon Ford states: "The Surprise Valley slide is the most spectacular example of landsliding in the Grand Canyon. The jumbled debris that comprises the slide occupies between 3 and 4 square miles of terrace north of the Colorado River that extends 4.5 miles westward from Thunder River to an unnamed canyon 1/2 mile east

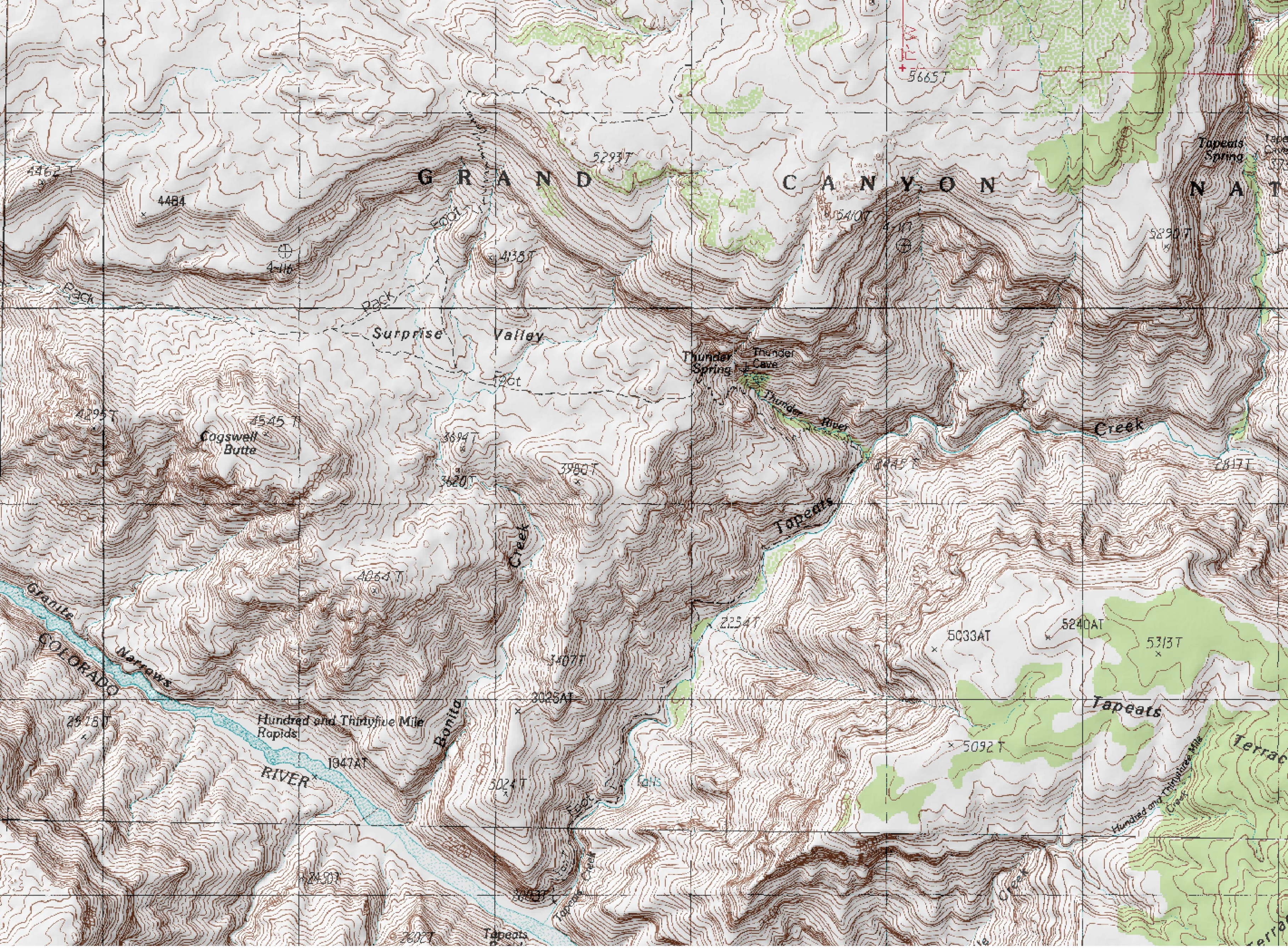


Figure 9 - Surprise Valley Site Map

of Fishtail Rapids. The maximum breadth of the disturbance is over 1.5 miles in Surprise Valley." (Ford et al, 1974).

12. PREVIOUS STUDIES OF SURPRISE VALLEY

Previously, little effort has been made to map the Surprise Valley slides in detail. The entire area is shown on the most recent geologic map of the canyon as undifferentiated landslide debris (Museum of Northern Arizona 1976).

Ford et al (1974) have suggested that the slide debris in Surprise Valley is the result of a massive collapes into a former east-trending tributary of Tapeats Creek. They further suggest that the slides north of the Colorado River and west of Deer Creek may be totally independant of the Surprise Valley slides.

In addition, Ford also points out the following important features of the Surprise Valley locality. Upriver of the Surprise Valley, the inner gorge is broad with slopes that can be termed gentle near river level. These are dominated by the relatively soft younger pre-Cambrian rocks of the Grand Canyon series and the older Cambrian rocks of the Tapeats Sandstone and the Bright Angel Shale. Down river, where the Bright Angel Shale and older formations dip below river level, the inner gorge narrows with steep slopes in the hard limestone and sandstone rocks of upper Cambrian to Pennsylvanian age. The change in slope of the river gorge upstream and downstream of Surprise Valley is illustrated in Figure 10.

Ford states that the presence of outcrops of Bright Angel Shale are of major importance in determining the configuration of the inner gorge.

The Ford paper is the only previous geologic description of the Surprise Valley. Unfortunately, the discussion of this area is part of a larger study on mass wasting in the canyon and is therefore quite cursory with respect to Surprise Valley. Although the authors agree that the presence of the Bright Angel shale was important in the formation of Surprise Valley, there were other vital factors which played a part in that formation.

13. FIELD, OFFICE, AND LABORATORY INVESTIGATIONS

13.1 Field Investigations

Two field trips and one airborne reconnaissance trip were made to investigate the Surprise Valley. The first was a river reconnaissance in the Spring of 1978. The second field reconnassance was made in the fall of 1979 by hiking down from the canyon rim. During the field trips, samples were taken of the Bright Angel shale for laboratory analysis.

After the completion of the fall 1979 excursion into the canyon, an airborne reconnaisance trip was made. Approximately 200 oblique low level aerial photographs were taken of the Surprise Valley features. Using sequential frames, stereo pairs were obtained for photo-interpretation of the geologic features of the area. The photographs gave excellent detail of the slide areas.

13.2 Geologic Map of Surprise Valley

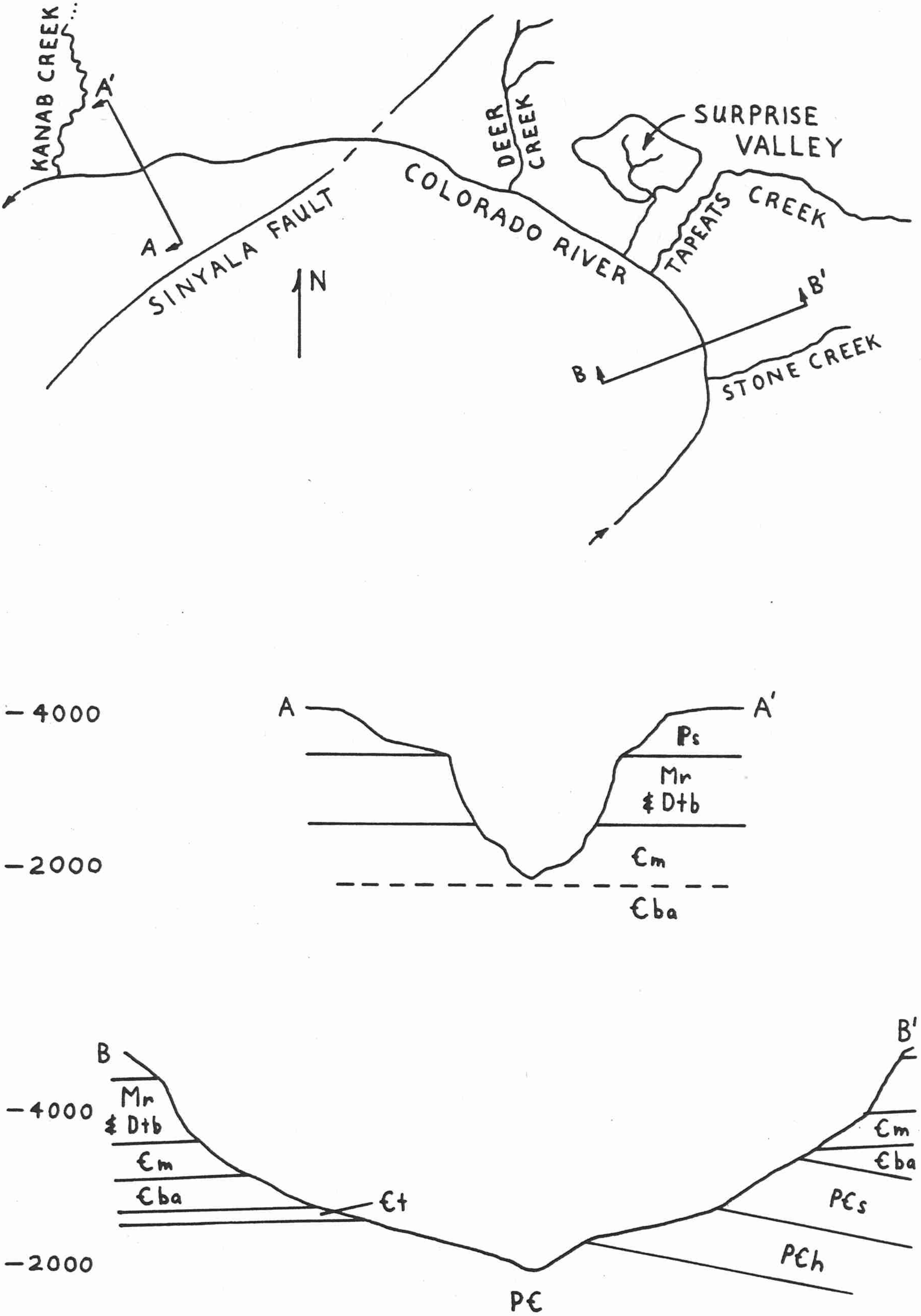


Figure 10 – Inner Gorge Cross Sections Upstream and Downstream of Surprise Valley.

Based upon the airphoto analysis and field reconnaisance, a new geologic map is presented (Figure 11). The map is much like the previously published work with the principal differences being better delineation of the slide debris in Tapeats, Bonita, and Deer Canyons; and, the mapping of lacustrine sediments in the center of the valley. In addition to the geologic map, a slide debris classification map is presented in Figure 12. Five types of slide debris have been identified in Surprise Valley. They are:

1) Talus debris that is the result of rock slope raveling and small rock falls. Some of this may be very old.

2) Relatively intact, rotated slide blocks that generally could be classified as Toreva Blocks (Reiche, 1937).

3) Successive rock wedges that slid with little rotation.

4) Block-glides wherein the sliding surface is relatively flat and little or no rotation is observed.

5) Graben debris associated with high angle gravity faulting (Huntoon, 1973).

In addition, there are areas of landslide debris where the slide type can not be differentiated. Where possible, the probable direction of sliding is also indicated.

An exceptional slide at the Northest margin of Surprise Valley near Thunder Spring exhibits both block glide and Toreva block characteristics. This slide is marked with a dual symbol and is illustrated in Figure 13.

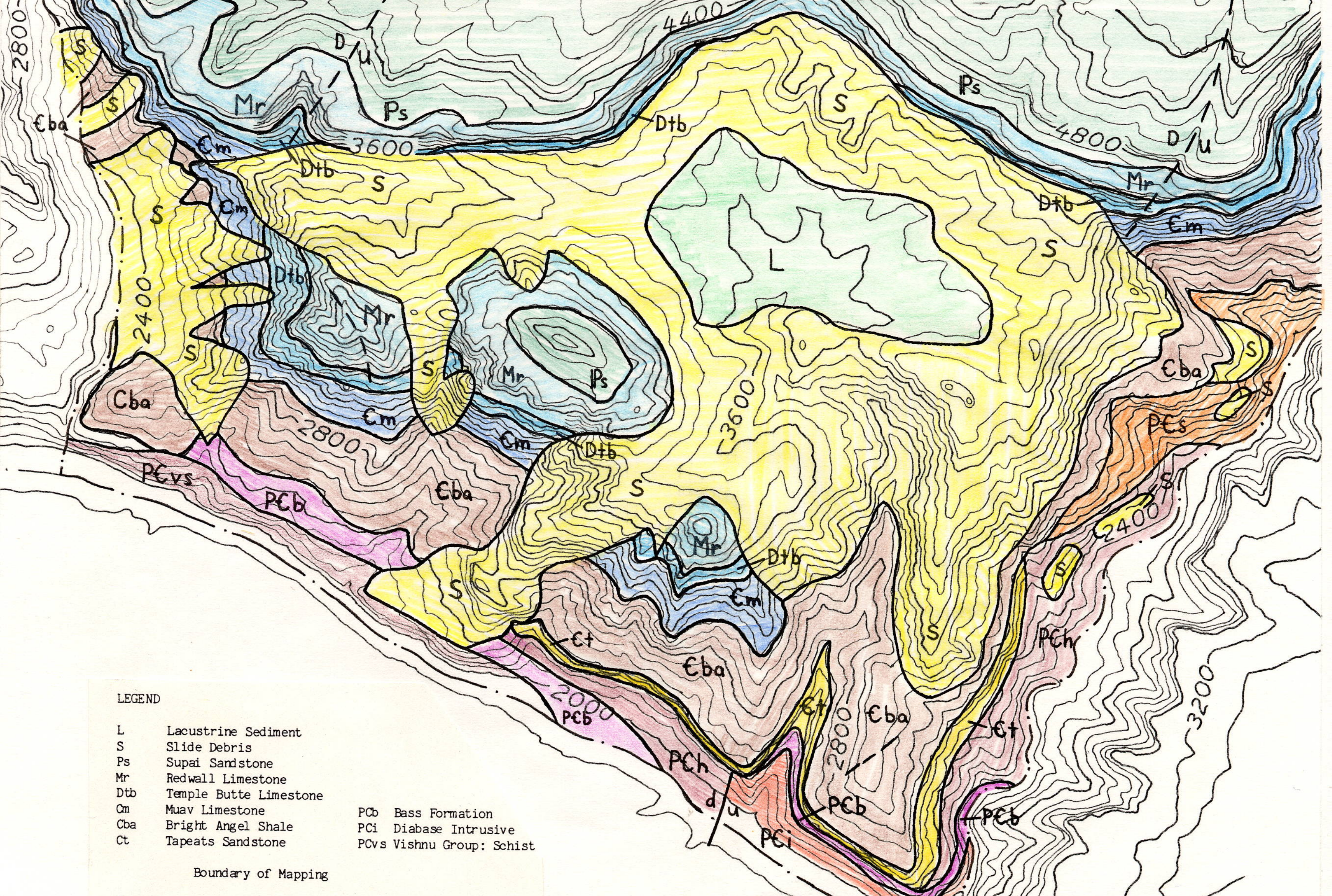
13.3 Laboratory Investigation

To date, one sample of the Bright Angel Shale has been tested using direct shear (November 1979). Additional samples are being prepared for soaking and will be tested when saturated. Figure 14 presents the results of the direct shear test on dry Bright Angel Shale. A strength envelope was obtained by testing a single sample at a range of confining pressures. Only the first loading of the intact sample gives results for both friction and cohesion. Subsequent tests give results for friction alone. Under the assumption that cohesion is not a function of confining pressure, the friction strength envelope is ajusted upward by the amount of the cohesion to obtin the strenght envelope in Figure 14.

An estimate of the saturated strength of the Bright Angel Shale can be made based upon the work of Morgenstern and Eigenbrod (1974). Their work indicates that strength reductions of the order of 30 to 40 percent can occur for non-swelling Cambrian shales upon saturation and softening.

13.4 Engineering Analysis of Slope Stability in Surprise Valley

The engineering analysis was performed to determine the conditions under which the failures could occur. To complete these calculations, strength parameters were required for the various formations not tested in the laboratory. To obtain these parameters, a back calculation analysis of standing slopes was performed. The object of that analysis was to determine the angle of internal



LEGEND

L	Lacustrine Sediment
S	Slide Debris
Ps	Supai Sandstone
Mr	Redwall Limestone
Dtb	Temple Butte Limestone
Cm	Muav Limestone
Cba	Bright Angel Shale
Ct	Tapeats Sandstone
PCb	Bass Formation
PCi	Diabase Intrusive
PCvs	Vishnu Group: Schist

Boundary of Mapping

Figure 11 - Geologic Map; Surprise Valley

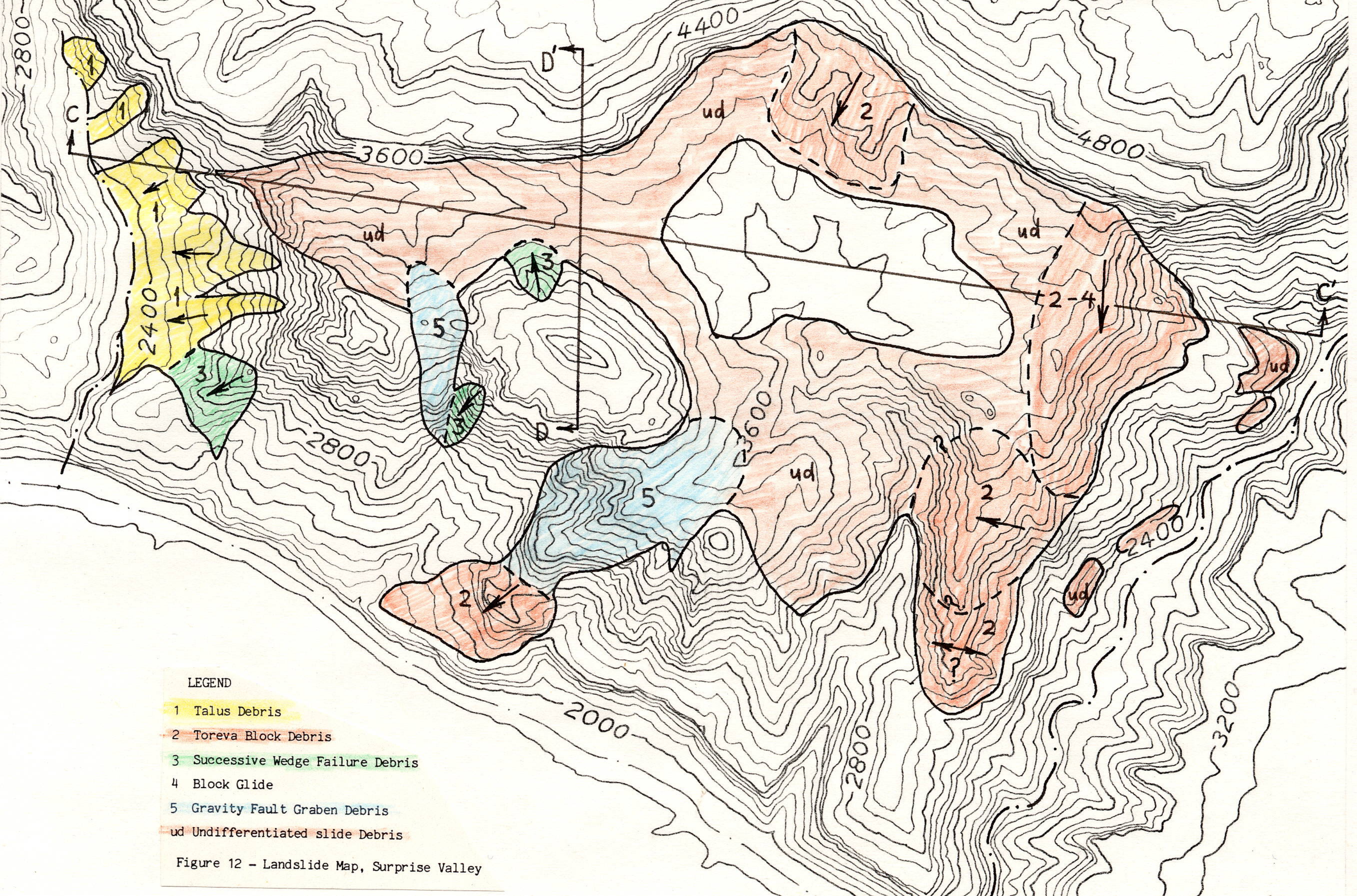


Figure 12 - Landslide Map, Surprise Valley

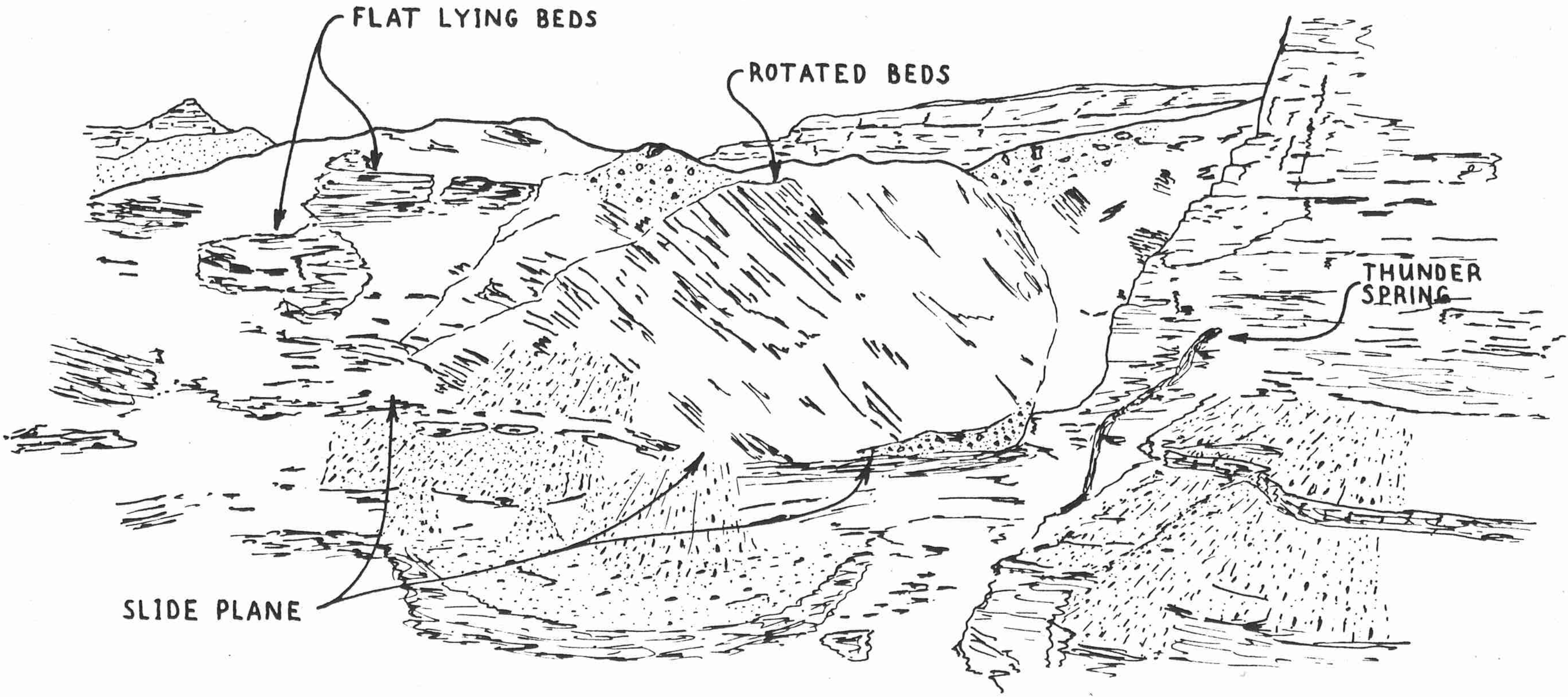


Figure 13 - Illustration of Thunder Slide Showing both Flat Lying and rotated blocks.

friction and cohesion for the materials in the failure zones. Because one of the two parameters must be estimated for back calculations, the angle of internal friction was extracted from published data (Hoek and Bray, 1977). A factor of safety of 1.5 was assumed for the standing slopes. This factor of safety was chosen to reflect the fact that the slopes are stable, but under some distress as evidenced by gravity faulting.

The values of strength used and determined in the back calculations are presented in table 3.

TABLE 3

Rock Formation	Strength Parameters Phi (degrees)	Cohesion, ksf
Supai Sandstone	45(a)	4.0(c)
Redwall Limestone	45(a)	29.0(c)
Temple Butte Limestone	45(a)	29.0(c)
Muav Limestone	35(a)	3.5(c)
Bright Angel Shale (Dry)	26(b)	21.5(b)

(a—interpreted, b—laboratory tests, c—back calculated)

Using the average shear strengths given in Table 3, the failed sections were analized to determine what environment would be required for failure. The shape of the canyon wall prior to failure can not, of course, be directly measured. In order to have a reasonable estimate of the slope, values were measured of the inclination of the various rock formations at several different locations. The mean inclinations were used to develop the slope used for analysis (see Figure 15). The potential for failure was analyzed for dry and saturated Bright Angel Shale and also for sudden drawdown. (During sudden drawdown, large hydrostatic forces are created perpendicular to the free face as the water tries to reestablish equilibrium conditions after a sudden lowering of the water level by dam failure or other cataclysmic event).

Non-circular sliding surfaces were analized by force polygon solutions of the equations of slice equilibrium in the failure mass. One of the potential sliding surfaces is presented in Figure 15.

Based upon this analysis, the following conclusions were reached. First, under dry conditions, the slopes are stable. Second, immediately upon submergence, the slopes will remain stable; however, as the Bright Angel Shale becomes saturated, a 30 to 40 percent reduction in the shear strength of the Bright Angel shale would be enough to cause the massive slides found in Surprise Valley. Third, the analysis showed that sudden drawdown was not a likely cause of the failures.

14. EVOLUTION OF SURPRISE VALLEY

Part of the evolution of Surprise Valley is explained by the analysis of the gap between Cogswell Butte and the north wall of the valley. The most likely explanation for the gap north of Cogswell Butte is that Tapeats Creek once flowed through Surprise Valley between Cogswell Butte and the north wall, and into Deer Creek. The orientation of the slide blocks mapped in the gap area indicate the direction of sliding and thusly indicate the downslope direction in

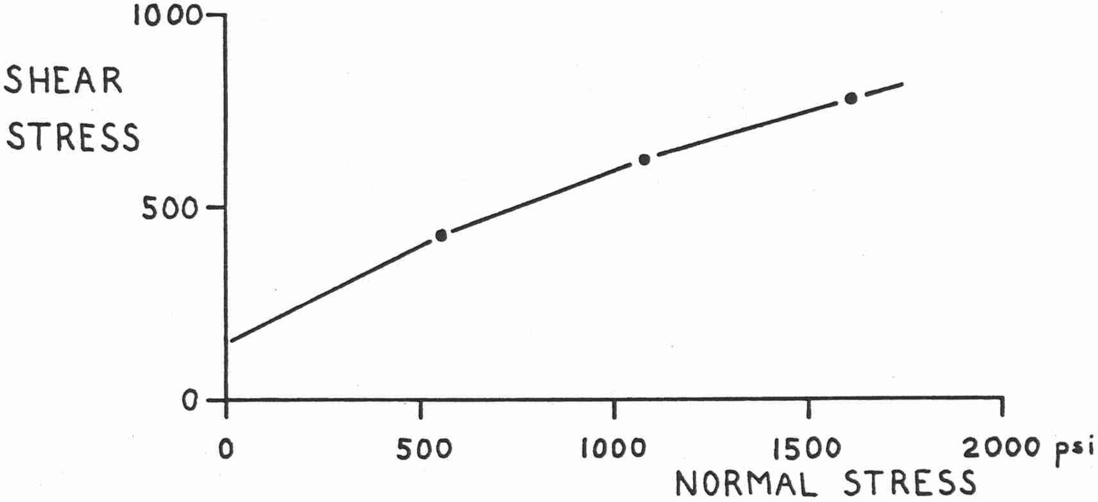


Figure 14 - Strength Envelope Along Bedding: Bright Angel Shale

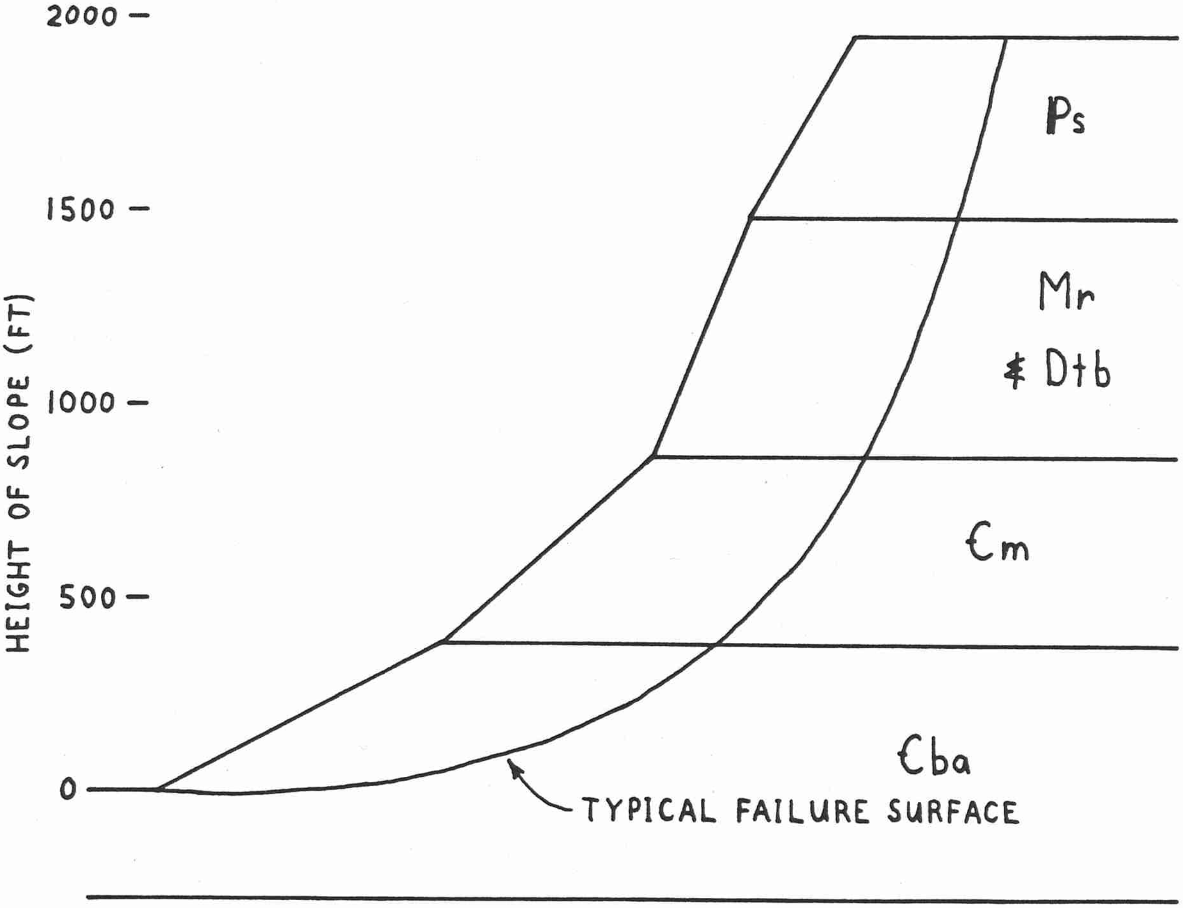


Figure 15 - Slope used for Stability Analyses with typical failure surface.

the vacinity. All relatively intact blocks of slide debris strike east-west. this implies that motion was north or south. Thus a valley and not a drainage divide must have existed in the gap.

The depth of excavation of the valley at the west end is approximately at elevation 2900. At the average stream gradient in this region, the stream bed at the east end of the valley near Thunder Spring would have been approximately elevation 3500, (Figure 16). The elevation of this channel at the Cogswell Butte gap is shown in section in Figure 17. Also shown is a section from an existing canyon with the same stratigraphic location. The mass balance between slides at Cogswell Butte gap and the existing geometry at the other canyon is remarkable.

Further evidence that Tapeats Creek flowed through Surprise Valley can be seen in the linearity of the valley and upper Tapeats Creek.

The elevation of the hypothesized Tapeats channel through Surprise Valley is about 500 feet higher than the observed slide planes near present day Tapeats Creek. This difference can be accounted for by downcutting from an ancient Thunder Spring at the preslide cliff face.

Tapeats Creek was probably diverted from Surprise Valley to its present alignment by stream capture. Although normal geologic evidence of stream capture such as alluvial deposits is missing, the topographic features in Surprise Valley support the hypothesis.

The Thunder Fault is near the alignment of lower Tapeats Creek. Headward erosion of the Colorado Tributary which captured Tapeats Creek could have been aided by fault induced weakness in the Cambrian through Pennsylvanian rocks. The source of flow for this tributary would no doubt have been springs existing at the base of the Muav limestone.

The deepest point of erosion in the west end of Surprise Valley is at elevation 2900. This point is approximately 1.2 miles from the Colorado River along along a fairly straight extension of Surprise Valley to the west. At the average stream gradient in the region, the stream fall between the west end of Surprise Valley and the river would be between 385 and 535 feet. Without an unprecedented waterfall along the stream, the Colorado river would have been from 425 to 575 feet higher than present level when Tapeats Creek last flowed through the valley.

The lower canyon group lava flows in the vacinity of Toroweap Valley have been dated at approximately 1.2 million years before present (McKee, Hamblin, Damon, 1968). At the time these flows occurred, the Colorado river channel bottom was a minimum of 250 feet higher than at present. Based upon the assumption that the lower canyon group lava and subsequent lava flows were eroded relatively quickly, an erosion rate can be computed for the last 1.2 million years. Extrapolating this erosion rate back in time, the Colorado river would have been 500 feet above its present level (when Tapeats Creek was captured) approximately 2.4 million years ago.

The east end of Surprise Valley is dominated by a ridge between Tapeats and Bonita Creeks. The ridge is composed of slide debris which can be differentiated into 2 or 3 slide blocks (Figure 12). The slide planes are

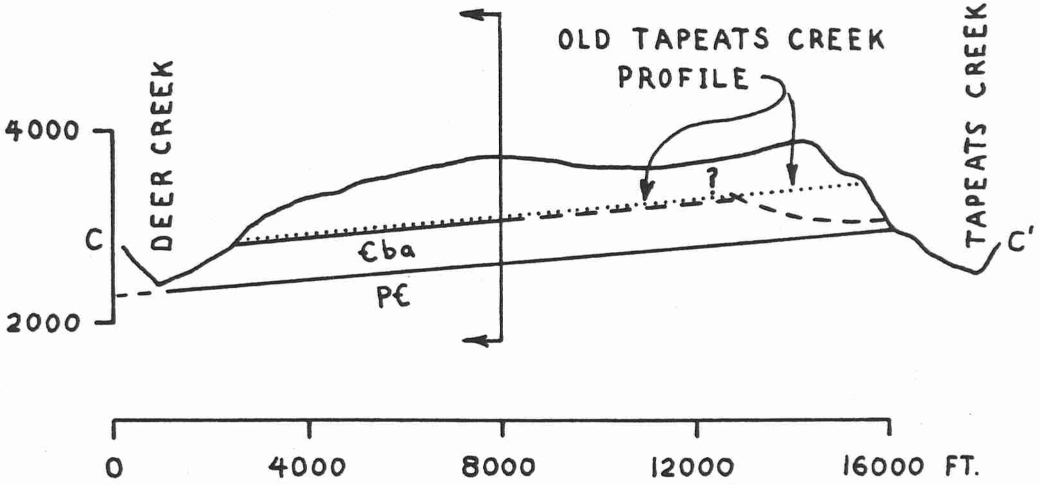


Figure 16 - East-West Profile; Surprise Valley

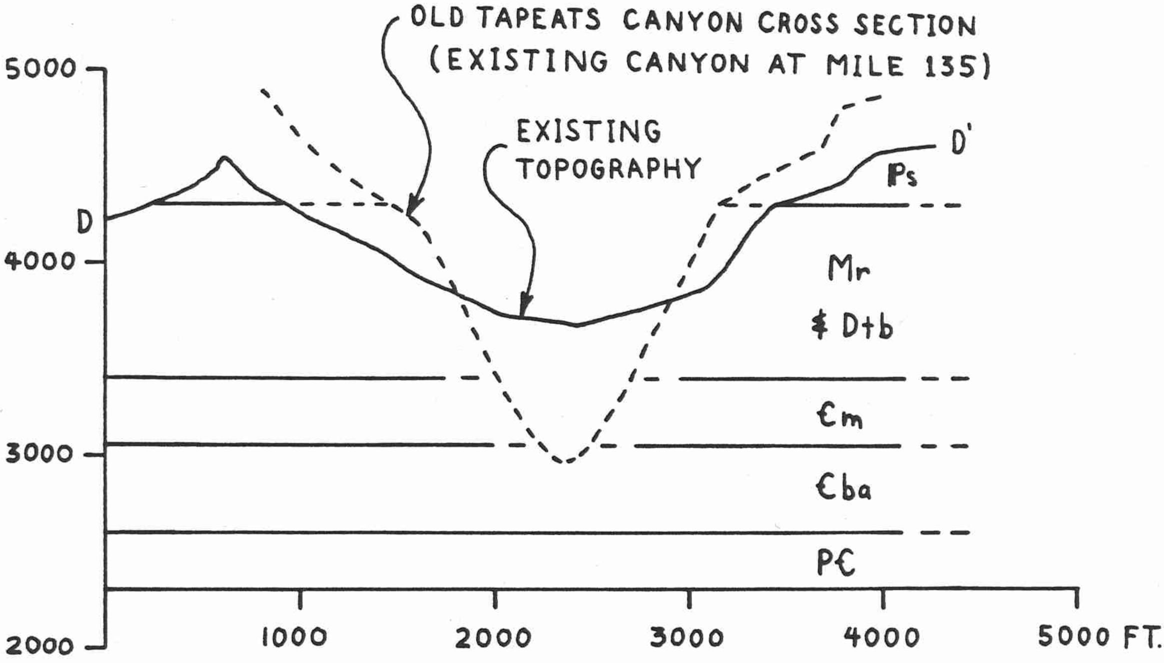


Figure 17 - Cross Section through Surprise Valley at Cogswell Butte Gap

Figure 18 - Illustration of Tapeats Creek Buried Channel

located in the Bright Angel Shale, but vary from the upper third near Thunder Spring to near the base of the formation beneath the southernmost slide block. Intact rock can be seen all along the east face of the ridge below the slide debris, but in four locations there are isolated pockets of brecciated slide debris. One of these pockets is a buried stream channel, and is shown on Plate I, and illustrated in Figure 18. The bottom of the buried stream channel is about 250 feed above the present level of Tapeats Creek. Thus the slides probably occured when the Colorado river was 250 feet above its present elevation.

This elevation corresponds to two different times in the history of the Grand Canyon. The Colorado River was 250 feet above its present level when the lower canyon lava flows at Toroweap occurred, and again after the lower canyon flows had been eroded but before the middle canyon flows. The lower canyon flows dammed the Colorado river to elevation 3080, and the post middle canyon flows dammed the river to elevation 4125. The stability analysis presented herein concluded that the most probable condition for slope failure existed when the slope was submerged and strength was reduced due to saturation and softening of the Bright Angel Shale. This condition could have occurred only during the impoundment from the higher lava dam. Thus the age of the slides is significantly less than 1.2 million years before present.

15. TRAVERTINE DEPOSITS

Previous observers of Canyon geology have noted the widespread occurence of travertine. Reilly (1961) wrote detailed descriptions of the travertine morphology while on a river trip between Lee's Ferry and Lake Mead. Most of the deposits he cited were still actively accumulating, though presumably at retarded rates when compaired to the entire masss accumulations. Ford, et al. (1974) relates that it is widely felt that the travertine deposits are somehow related to the lava dam impoundments. During the course of this study some surprising correlations were discovered.

15.1 Probable Pleistocene Reservoir Chemistry

We can make some correlations on the probable water quality in a Grand Canyon Reservoir by comparing notes with what has been observed at Lakes Mead [52] and Powell [53], [54], and other reservoirs [55], [56], keeping in mind that the Pleistocene climate was much more humid and that local volcanic eruptions of gas clouds could have complicated the chemistry equilibrium temporarily.

A summation of data pertaining to reservoirs in arid/temperate climates and exposed to phreatic systems that percolate through carbonate or carbonate-cemeted rocks:

Salinity increases with depth.

Temperature decreases with depth, then increases near the density current deposit interface (at the bottom) due to increased biologic activity.

Dissolved oxygen content (DOC) is **replenished** at depth during winter months.

Dissolved oxygen content is **depleted** in the summer.

Silica is extracted from the lake water by diatoms.

Photosynthesis in surface waters produces **high pH conditions** and **precipitation of calcite** [53],[54],[57].

Calcite Precipitation is apparently controlled by pH, [58] temperature, and surface area of calcite nuclei.

16. PRECIPITATION OF TRAVERTINE CARBONATES

The reservoirs in the Grand Canyon during the Pleistocene would have been integrated [59] with the previously developed phreatic drainage systems so well developed in the limestones, [60], [61], [62]. Travertine was most likely precipitated from carbon dioxide rich groundwaters which dissolved CaCO3 from the limestones before seeping into the ancient reservoirs. At the rock/lakewater interface the phreatic water released carbon dioxide (back) into the lake water and precipitated carbonate [63]. Fungal growth in the (warmer) upper regions of the water column certainly enhanced carbonate deposition [64]. All of this suggests that a progressive increase in the potential for travertine formation was made possible by the increasingly more temperate climate since the initial reservoir ponding in the cooler Pleistocene of 1.2 m.y.b.p.

As the weather continued to warm it is a likely conclusion that the subsequent moderate-height dams in the Canyon impounded increasingly warmer reservoirs where perennial photosynthetic production enhanced carbonate deposition. In the Holocene this potential has been counteracted by severe decreases in phreatic water accumulation, thereby drawing the travertine depositional sequence to a slow close [65].

Figure 19 shows a longitudinal profile of the present-day river surface, travertine and river gravel deposits from miles 55 to 157. Table 4 and Figure 20 summarize the correlations that can be drawn. The travertine deposits show that no strong stratigraphic correlation over the 101 miles sampled can be drawn (see Table 4), but strong similarities arise when comparing elevations of the heights of the deposits. This clustering is shown on the frequency plot in Figure 20. It is suggestive of different lake elevations with the 2350-2480 and 3320-3480 sets predominating [66]. The 140± feet of scatter may be attributable to the subsequent uplift of the Kaibab Plateau. Across the Plateau the travertine outcrops start AND terminate at the "higher" (130-160') elevations than their up or downstream counterparts [67]. This anomaly, along with the steeper gradient of the river may be the result of onging adjustments to recent further uplift.

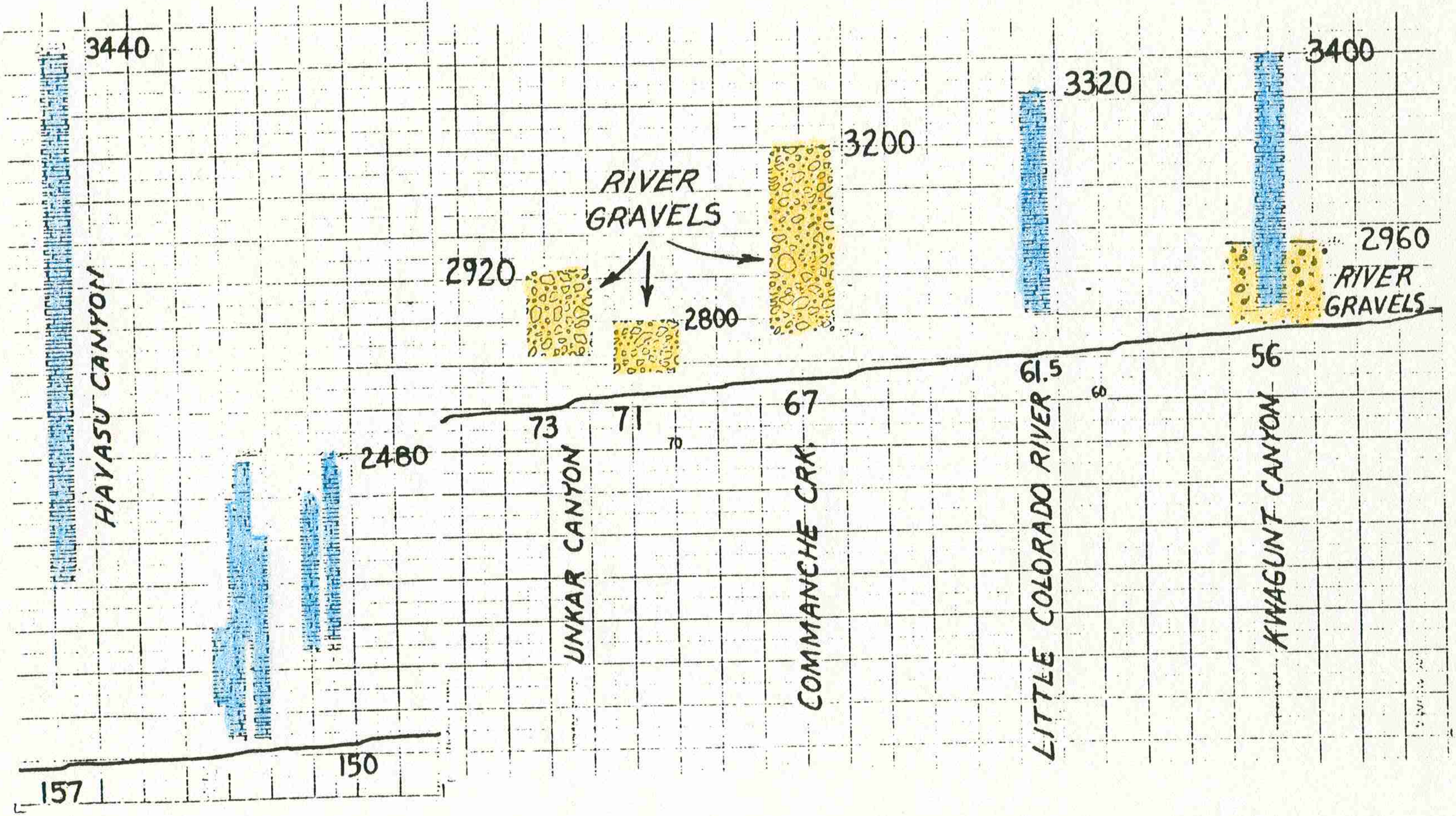


Figure 19a - Longitudinal profile segments of present day river surface, travertine, and river gravel deposits for miles 56-73 and 150-157.

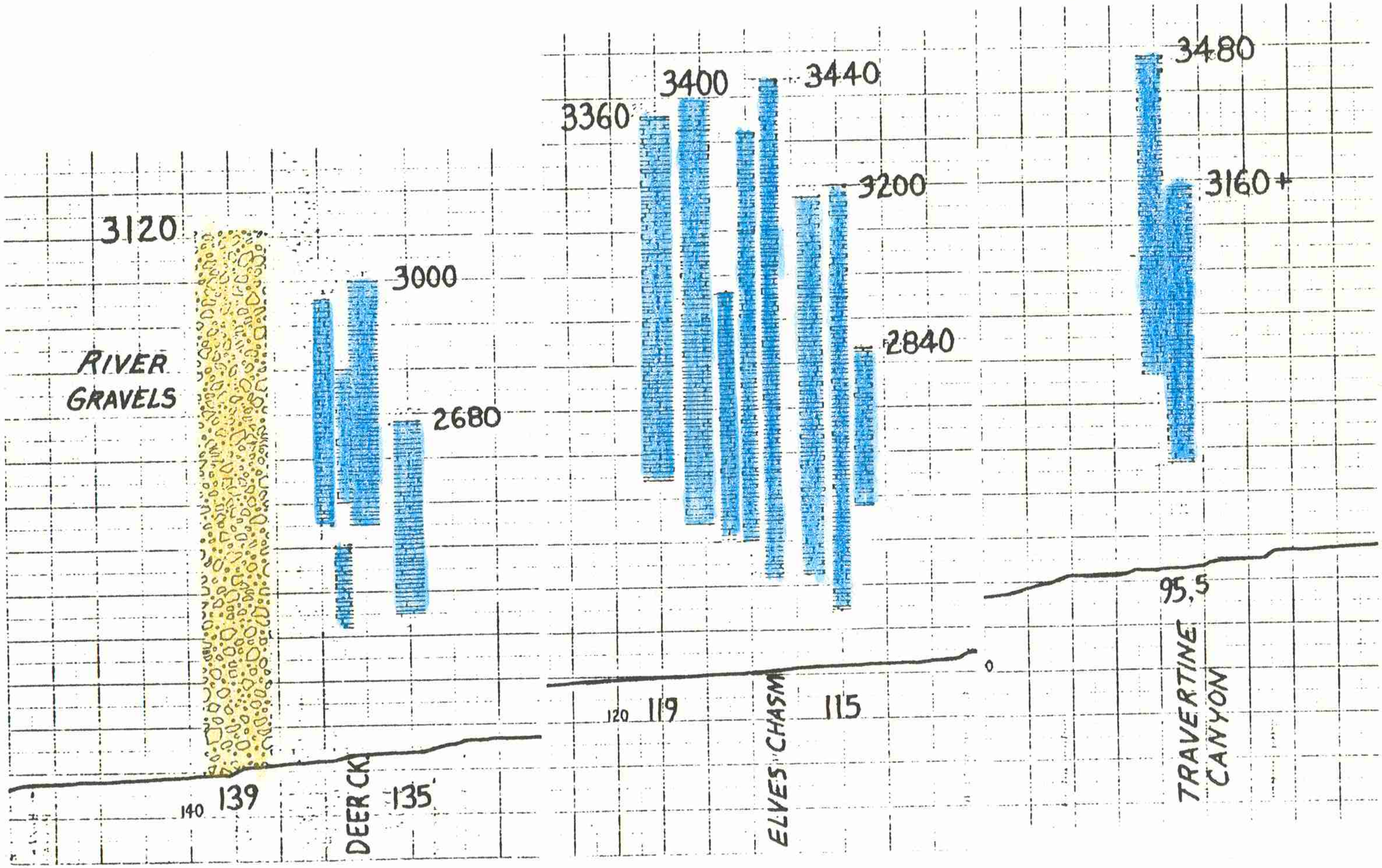


Figure 19b - Longitudinal profile segments of present day river surface, travertine, and river gravel deposits for miles 95.5 -95.7, 114-119, and 135-139.

TABLE FOUR
TABULATION OF TRAVERTINE FORMATION OUTCROP ELEVATIONS AND GEOLOGY

Grand Canyon - miles 56-157

Location (miles)	Geology	River Elev	Apex Elev	Bottom Elev	Closest Vertical Distance Above River
56	Mr	2750'	3400'	2300	50'
61.5	Cm	2710	3320	2800	90
95.5	Ct,pCvs	2365	3160+	2560	195
96	Ct,pCvs	2363	3480	2760	397
114.6	Cba	2120	2840	2480	360
114.7	Cba	2120	3200	2240?	120+
115	Cm,Cba,Ct	2118	3175	2320	202
115.4 to 116.4	Dtb,Cm,Cba	2114	3440	2320	206
116.7	Cm,Cba	2110	2960	2400	290
117	Cm,Cba	2107	3320	2400	293
118	Cm,Cba	2103	3400	2440	337
119	Cm,Cba	2098	3360	2540	442
135	Cba,Ct,pCh	1940	2680	2240	300
136.5	Cm,Cba	1930	2800	2500	570
136.5	Ct,pCva	1930	2400	2250	290
136.7	Cm,Cba	1930	3000	2450	520
136.8	Cm,Cba	1930	2960	2450	520
150.5	Dtb,Cm	1820	2480	2040	220
151	Dtb,Cm	1818	2400	2040	222
152.2	Dtb,Cm	1814	2320	1840	26
152.3	Dtb,Cm	1813	2540	2080	267
152.4	Dtb,Cm	1810	2480+	2000	190
152.5	Mr/Dtb,Cm	1810	2400	1840	30
153.1	Cm	1805	2080	1920	115
156.8	Dtb,Cm	1785	2400	2240	455
Havasu	Ps,Mr,Dtb	1785	3440	2215	430

Geologic Legend

Ps	Pennsylvanian Supai Formation
Mr	Mississippian Redwall Limestone
Dtb	Devonian Temple Butte Limestone
Cm	Cambrian Muav Limestone
Cba	Cambrian Bright Angel Shale
Ct	Cambrian Tapeats Sandstone
pCh	Upper pre-Cambrian Hakati Shale
PCvs	pre-Cambrian Vishnu Schist

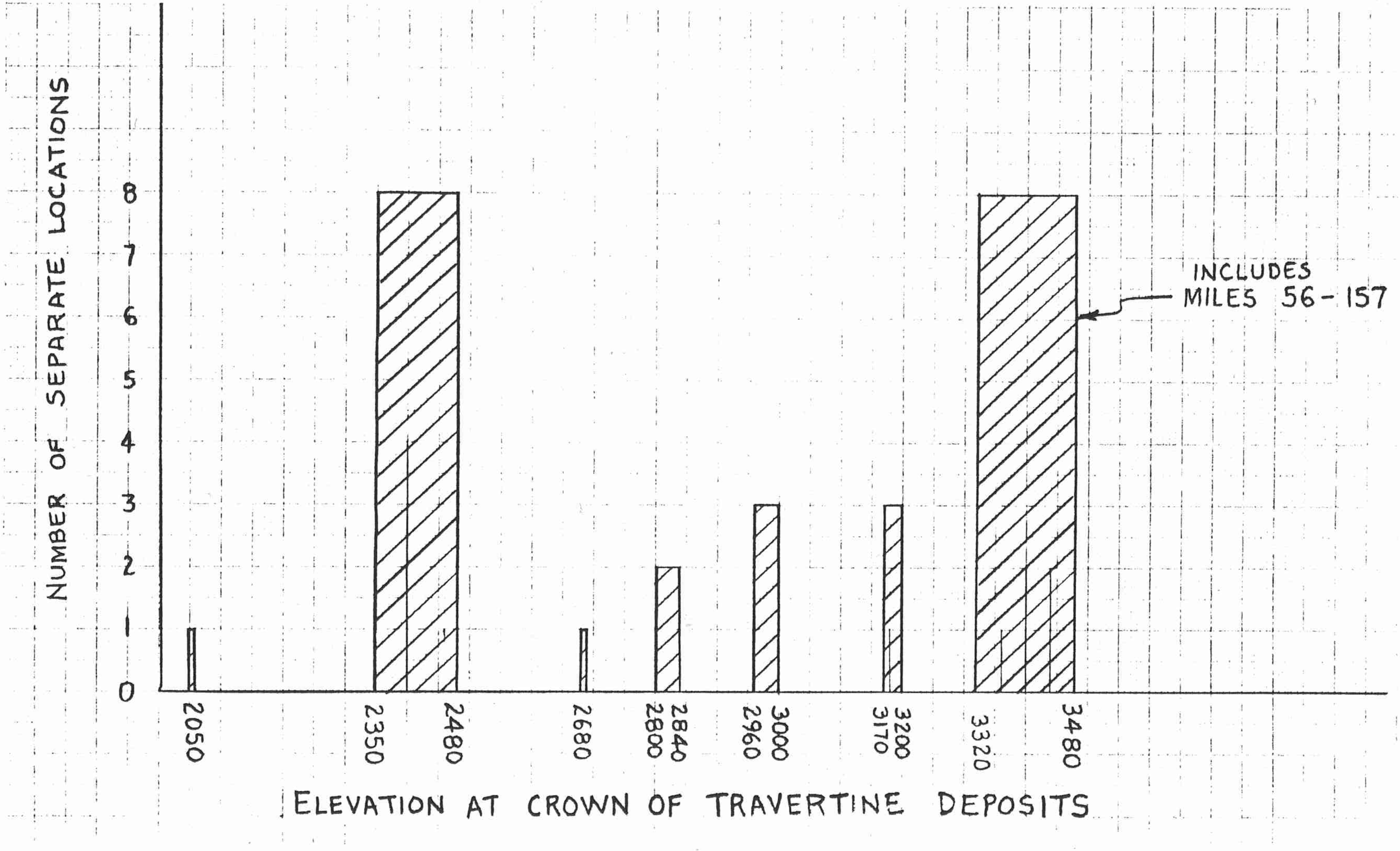


Figure 20 - Frequency diagram of the top elevations of travertine formations from mile 56-157.

17. LAKE SEDIMENTS

The Colorado River was once a river with a tremendous bed-load capacity and high salt content. Unlike most major integrated drainage systems, the Colorado flows through the Grand Canyon without any appreciable tributary flow [68]. When the ancient Colorado was dammed it must have dispelled its bed load into the reservoir. This delta was probably built up in much the same manner that Smith et al. (1960) describes at Lake Mead and is schematically shown in Figure 21.

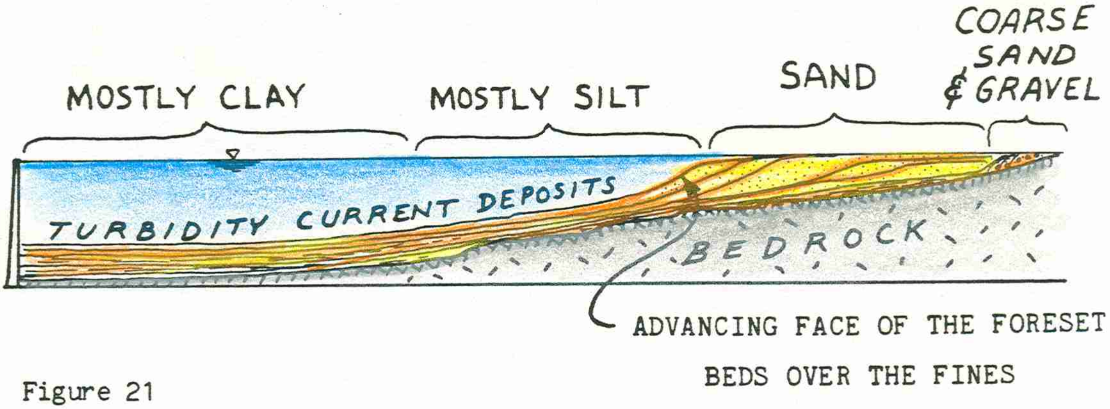


Figure 21

Many outcrops of "river gravels" and perched "terrace deposits" exist in the Canyon. The assemblages at Commanche Creek (mile 67) and at Fishtail Canyon (mile 139) are extensive and reach elevations of 3200 feet. Those mapped [69] gravel and terrace deposits of sufficient height above the present day channel are shown along with the travertine in Figure 19.

Many of the low-level river terraces are suggestive of Pleistocene-Holocene climatic changes and not lacustrine deposition.

Bull and Schick (1978) state ". . . stripping of colluvium suggests a change to a drier and/or warm climate". This presumably pre-Holocene colluvial cover is preserved at several spots in the Canyon by travertine cementation and over-riding landslides.

In the same interval, the river has apparently seen more **reduction in flow** than **vertical downcutting**. One of many case examples is shown in Figures 22 and 23.

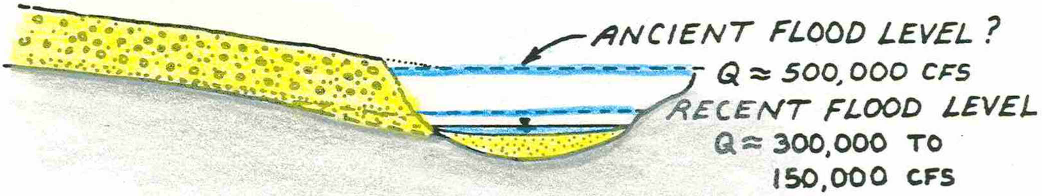


Figure 22 - Section of typical side canyon entry in the Grand Canyon, in this case at Kwagunt (mile 56). The depth of the bedrock channel suggests lowering of the base level (reduced flow quantities in the Colorado River). In the last 13 years we would expect a significant increase in this erosional trend due to Glen Canyon Dam permanently lowering the base level to a $Q_{max} \cong 23{,}000$ cfs, or < 1/4 of the 2-year flood (USBR [1950], page 153).

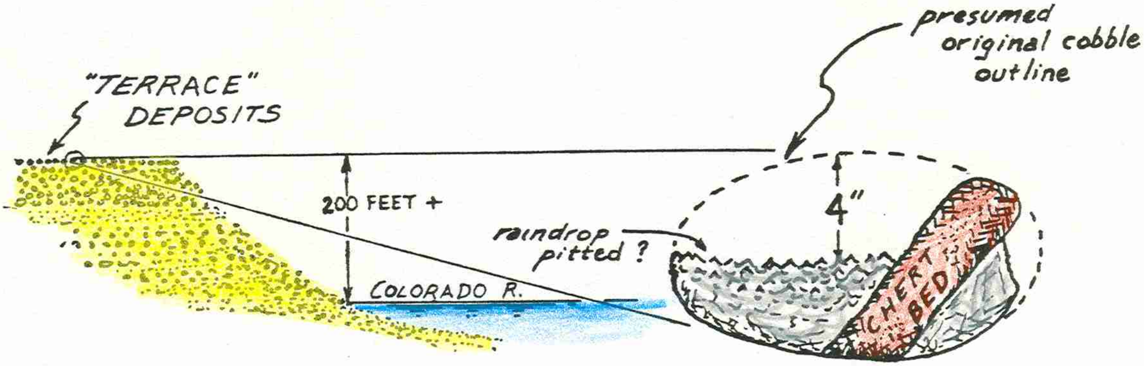


Figure 23 — Weathered cobble recovered from old river terrace opposite Escalante Creek. The limestone matrix has been dissolved 4 inches vertically. The cobble has a very sharp pitted surface that is 4" below the siliceous chert. This sort of weathering appears to have been produced by slightly acidic rainfall. Data from Leopold (1979).

18. THE CATACLYSMIC REMOVAL OF THE LAVA DAMS

Different basaltic dam compositions and structures precipitated an equally diverse suite of failure modes.

The first failure occurrs for a low lava dam with a sizable downstream reach of flow, Figure 24. These dams most likely ponded and sedimented rather quickly. The highest section was soon overtopped and scoured to a level approximately equal in grade to the rest of the flow (low gradient). The river's initial pour over created some large cobbles and a pothole and rill scour surface was created where the water ran over the flow.

The principal point of erosion would have been at the toe where the river pored over, locally increased velocities and gradient promoting scour of the channel alluvium under the snout of the flow. Less viscous, ropy flows possessed lower snouts and were thereby preserved longer.

Figure 25 shows that the much larger dams were of a composite nature; either built of succeding lava flows or with cyclicaly emplaced pyroclastics such as ash. These much larger structures took a much longer period of time to fill with both sediment and water. Probably, the largest (4124') never filled completely with sediment (the highest of which are found at 3200'). These dams impounded a full reservoir in a matter of 5-15 years, then began to pour over reaching volocities of up to 15 feet per second. Once the overtopping was initiated it is probably that something close to the natural flow of the river began passing over the dam and down the basalt flow(s). At the toe of the flow the water spilled over a short waterfall where scour of the alluvial base beneath the flow undercut the flow until basalt colum with low cohesion columnar jointing, were toppled into the plunge pool. The whole process was progressive and the potential energy available for scour was always increasing. The waterfall worked its way back upstream always becoming larger and more powerful. The basalt columns acted like carbon chips in the envronment of sedimentary

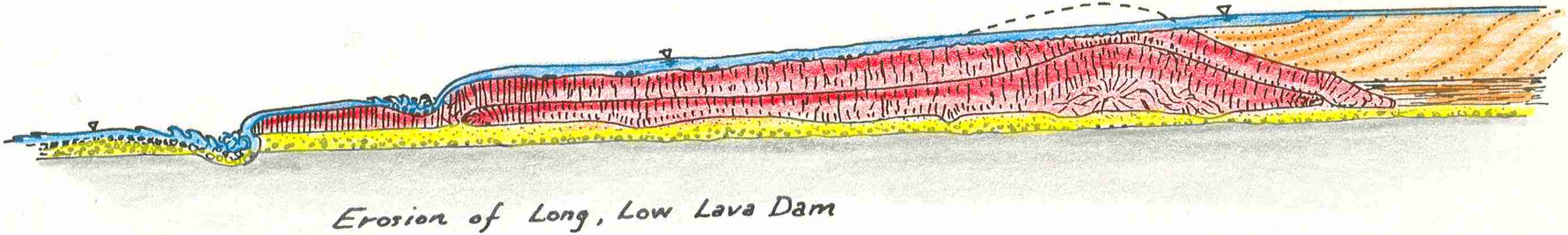


Figure 24a - Initial stages of erosion of long, low lava dam.

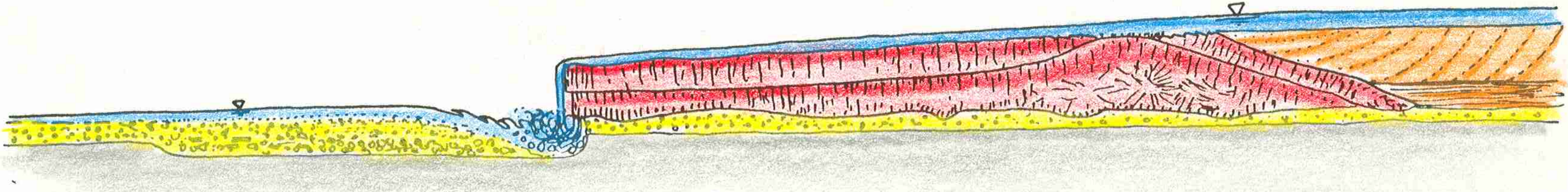


Figure 24b - Toe headward erosion of long, low lava dam. Note plunge pool scour of the bedrock.

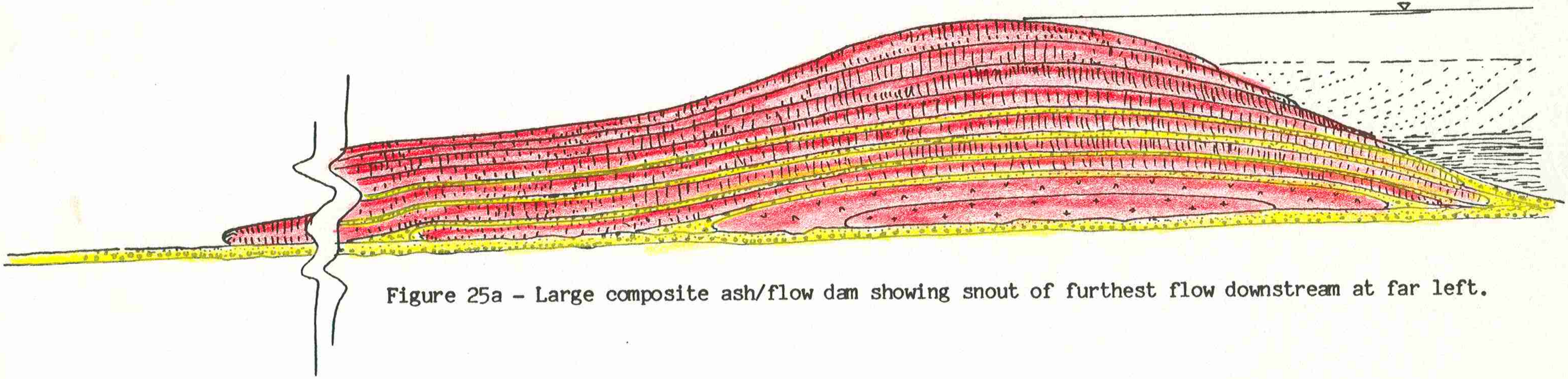


Figure 25a - Large composite ash/flow dam showing snout of furthest flow downstream at far left.

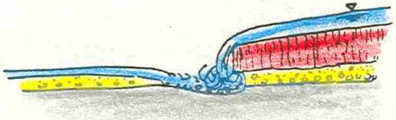


Figure 25b - Snout starts to erode

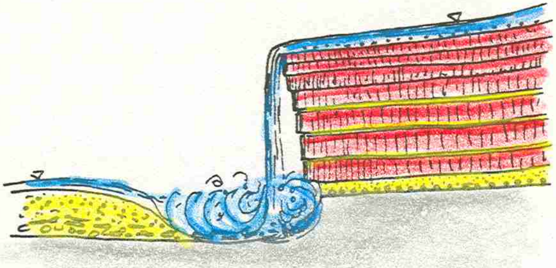


Figure 25c - The waterfall and plunge pool enlarge in a headward direction

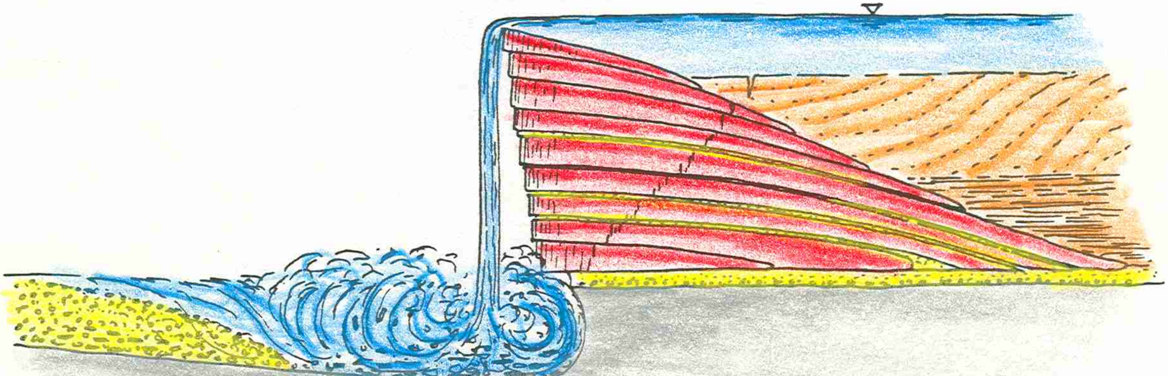


Figure 25d - Waterfall and plunge pool attain maximum dimensions. Dam structure approaches the point of critical stability. Tensile separation starts to occur between columnar joints initiating from the haunch towards the highly stressed toe area.

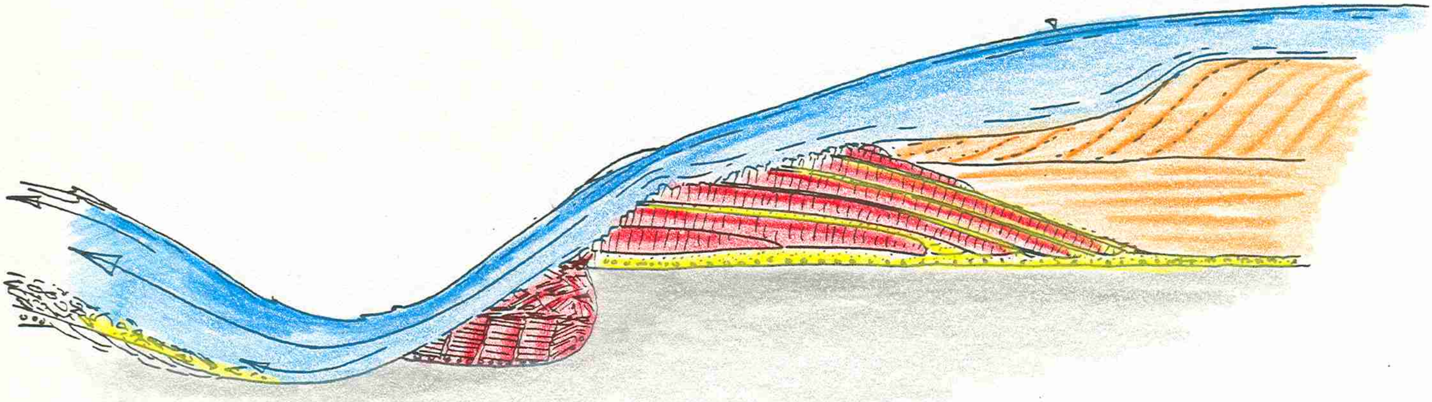


Figure 25e - Hypothetical rendition of the cataclysmic breakout upon failure of the summit mass of the dam.

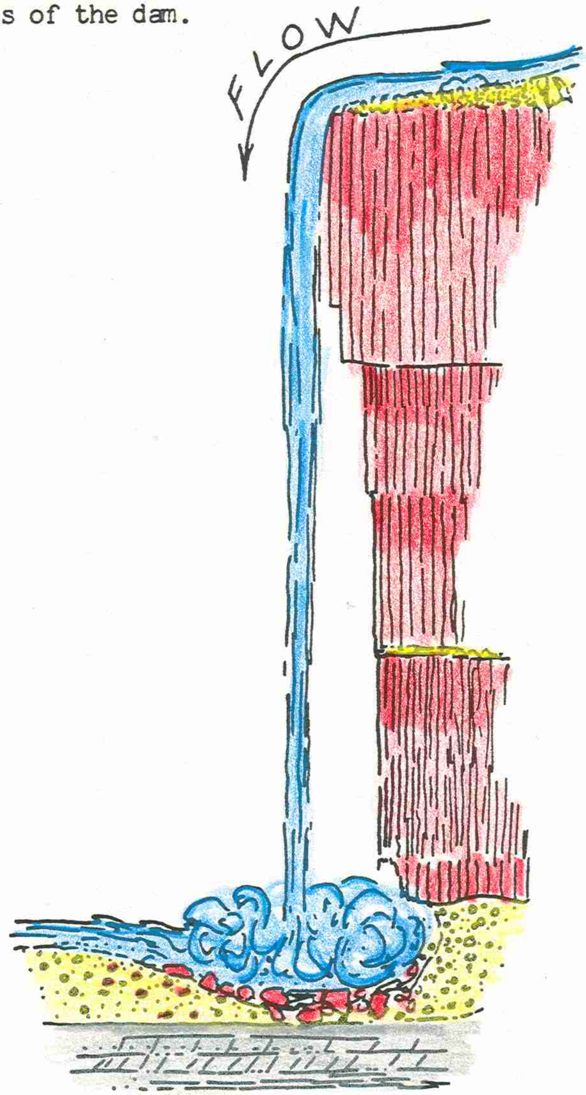


Figure 26 - Typical basaltic cliff exhibiting a negative slope angle as seen in (dry) outcrop in the Western Grand Canyon.

cobbles and bedrock helped to excavate the ever-enlarging plunge pool. The process would have been more rapid in the big dam at Toroweap that was built on cyclic sequences of ash and lava as the ash would also promote undercutting of the basalt flows.

Evidence that the pour over lava falls was so vertical is seen on the basalt cliffs today. Their morphology is most strongly controlled by the pervasive columnar jointing. The cliffs retreat by toeward erosion due to oversteepening and many possess negative slope angles as shown in Figure 26.

As the waterfall advanced towards the highest section of the dam a tremendous scour hole must have been generated, the likes of which no one has witnessed - a 2500 foot waterfall with approximately 500,000 cfs plunging into a huge hole. The stability of the dam to base-shear and overturning became critical, especially considering the enormous pore pressures of the still-intact reservoir in all of the columnar joints. At some critical point the dam finally separated and fell into the plunge pool. The fall itself would have disaggregated much of the dam mass to say nothing of the resulting deluge.

The flood quickly expelled the tremendous sediment load that was accumulated behind the dam. This expulsion created a widened, braided, and elevated channel downstream for a considerable distance. As the flood waters subsided (in a few days) the natural decrease in sediment production triggered a rejuvination of the stream bed.

19. UPSTREAM EFFECTS OF THE DAM BREACHMENT

19.1 Description of the Anticlines

Immediately upstream (miles 171-144) of the lava dams lies the most quiet reach of the Colorado River within the Grand Canyon. Small anticlines have been formed in the Muav limestone near river level. These structures quite regularly follow the sinuous course of the channel with the present midstream, an approximate axis. The anticlines posses some very curious features from a rock mechanics viewpoint:

1. They are well developed only in southwesterly trending reaches of the Gorge and are not well developed in northerly trending sections of the channel. This is suggestive of a preferential stress field oriented with a high horizontal component along a northwest-southeast axis.

2. They contain two sets of structures that could not have been the result of the same uniaxial stress field. The first set of structures are high angle reverse faults (see Figure 35) inclined at about 60 degrees away from the channel (parallel to the steep cliffs of the Inner Gorge). These reverse faults are suggestive of a highly differential vertical stress field. The second set of structures are low-angle thrust faults which are indicative of a high horizontal stress field locally dominating strain.

A host of previous workers [70] have attempted to explain how the anticlines were formed, but have fallen short in attempting to explain their absence in the north-trending reaches, in stratigraphically similar situations in other parts of the Canyon, or the two distinctively different fault structures [71].

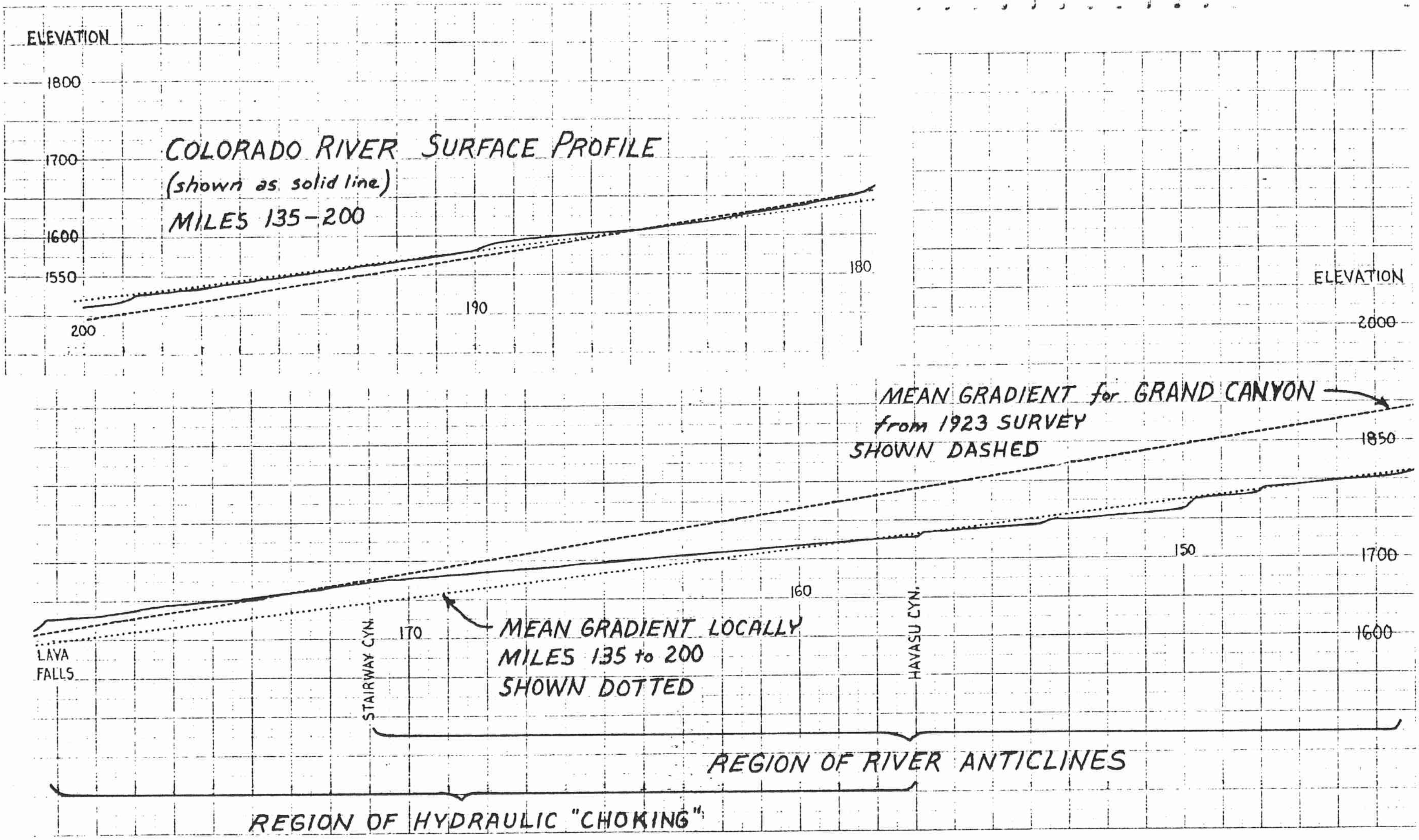


Figure 27 - shows a surface profile of the Colorado River from mile 200 to 145 with the mean gradient for Grand Canyon dashed in. It can be seen that the region from Toroweap upstream to Kanab Cannyon is on a very low gradient.

The river profile posseses a curious convex-upwards trend from Havasu Canyon (mile 157) to Lava Falls (mile 179). This appears to be a "hydraulic choke" of river gravel (?) that is slowly being taken out in a headward fashion. The unusually large debris fan [72] at Prospect Canyon (mile 179, opposite Toroweap) acts as a temporary plug preventing normal downstream translation of the accumulated upstsream bedload.

It is hereby postulated that the actual **bedrock** channel upstream of Prospect-Toroweap is very deep and filled with accuumulated debris. In this reach the channel exhibits slower velocities and a very eddying flow - typical of an aggrading stream. Depth meassurements [73], [74] in the region are highly interpretive since the data obtained only indicates depth to the sand bed and **not** to bedrock. How deep the actual rock gorge is can only be speculated. Evidence elsewhere in teh Grand Canyoon suggests a very strong tendency for deep, incised rock channels in the Muav limstone - taperiing to a wider profile once into the thicker, more argillaceous facies of the middle Bright Angel Shale [75]. This channel was apparently cut following the collapse of major lava dams downstream. These events precipitated localized catastrophic denudation of the river gravels immediately upstream catastrophically and the adjusting to a new base level downstream.

Such a deep channel and increased gradient would better line up with the local mean gradient showed as the dotted line in Figure 27. It is the author's opinion that the **base level** the river reacts to is a localized phenomenon [76]. The river retakes its steeper mean gradient as it ascends the West Kaibab Uplift [77].

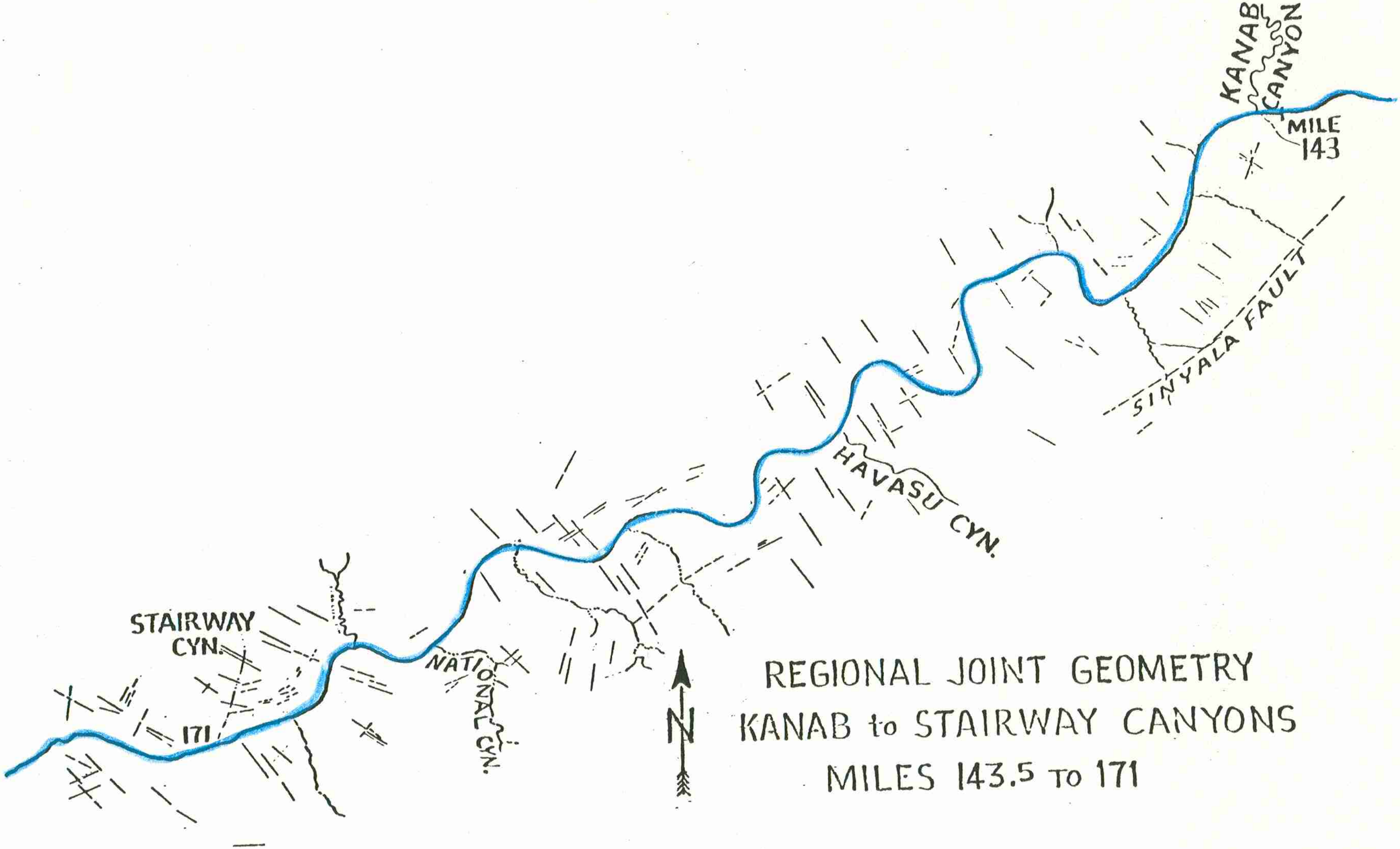
20. EVIDENCES OF A LOCALLY ANISOTROPIC HORIZONTAL STRESS FIELD

Figure 28 shows a plan view of the Colorado River between Kanab and Stairway Canyons. Superimposed upon this map are short straight black lines representing the local trends of systematic [78] regional joints cutting through the Paleozoic and possibly [79] the pre-Cambrian basement rocks as well. The regional joint pattern shows a northwesterly-preferred trend. Joint suites orthogonal to the northwesterly set are much less well-developed with reduced traces and spacings. The northwesterly set also exhibits more signs of phreatic percolation (indicating a very interconnective network).

It can be seen that southwesterly trending reaches of the Colorado channel cross the strong regional joint set in a normal (90 degrees) fashion. More northerly [80] trending parts of the channel either parallel localized secondary joint sets or cut the regional joint set at a low angle.

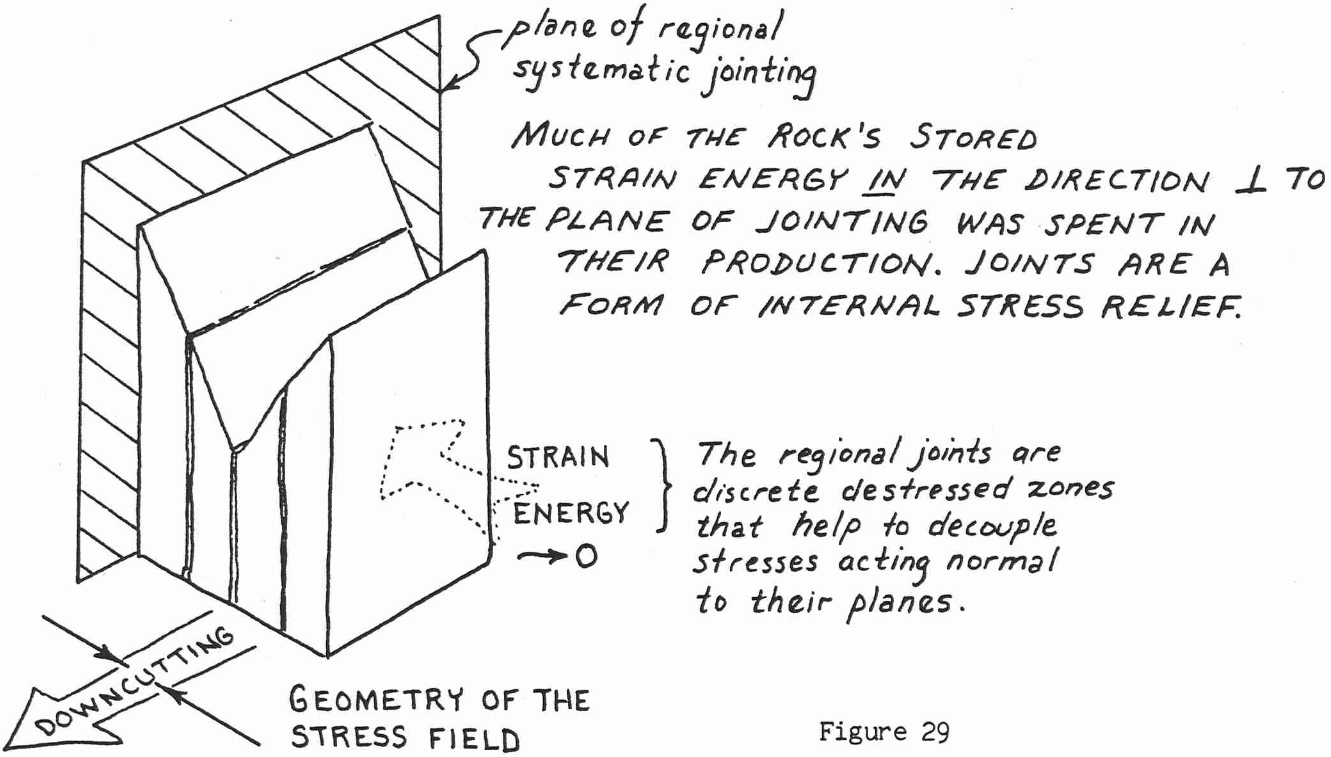
We could not reasonably exxpect high horizontal stresses or stored elastic strain energy [81], [82], [83] to be translated across the through-going systematic joints, as the joints would act as discrete destressed zones. Elastic strain could not be available in a destressed or relieved zone of rock [85], [86], [87]. (See Figure 29).

On the other hand, a river channel cutting the regional joint set at or near 90 degrees would simply unload lateral confining forces at the bedrock/channel interface. A unidirectional [88] stress field is assumed with the river channl forming the free face and the rock masses behaving according to plane strain



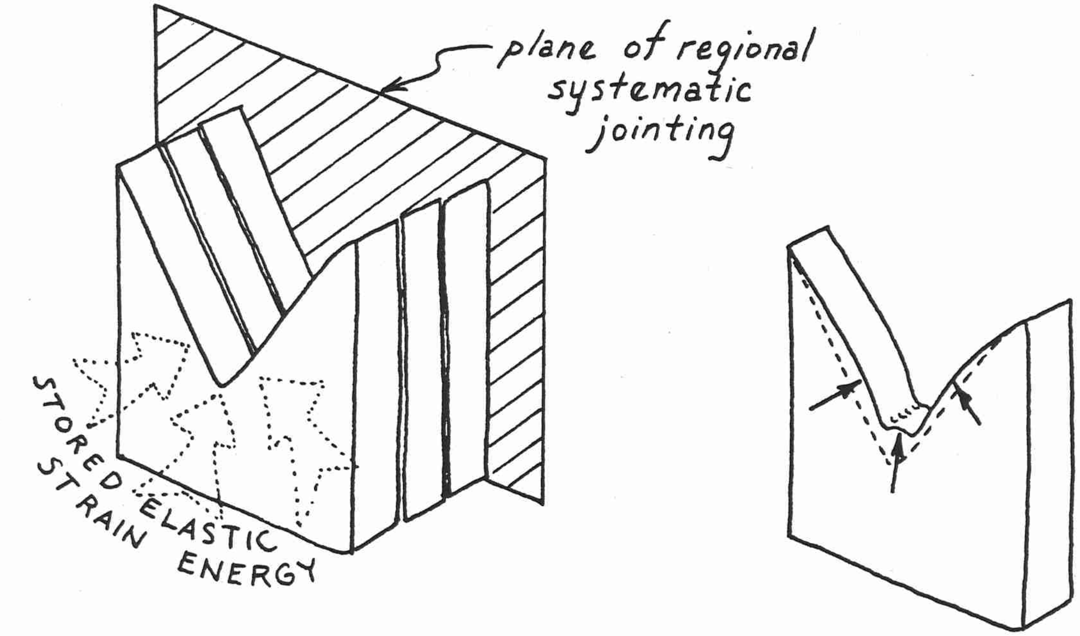
REGIONAL JOINT GEOMETRY
KANAB to STAIRWAY CANYONS
MILES 143.5 to 171

Figure 28



GEOMETRY OF THE STRESS FIELD
A PLANE STRAIN CONDITION

Figure 29



RAPIDLY-CUT NOTCH IN AN ELASTIC PLATE

NOTCH AFTER STRAINING

Figure 30

(two dimensional) theory (see Figure 30). This stress picture only serves to explain the geometry of the structures.

Most rock mechanicians [89], [90], [91], [92] who have worked with elastic strain energy agree by what mechanism we can see it manifested - sudden load removal. Sudden removal of constraint precludes normal intergranular adjustments [93] - a mechanism that is evidenced in normal erosional processes. Such are the problems in interfacing perfectly elastic finite elements between a slowly downcutting river valley and an "instant gravity-on" loading [94] - the model does not truly simulate a natural geoological process.

Most natural geological processes do act to erode, denude or otherwise pertubate the natural stress field quickly enough that the rock cannot readjust internally by any other means than straining suddenly - this then is the release of elastic strain energy presumably held in the rock matrix. The potential capacity for storing strain energy appears to be a property dependent on the rock type and its load history. How much of it we see evidenced by (seemingly) anomalous strain is dependant on the **unloading** history. Elastically-stored strain is, therefore, most often generated by catastrophic or accelerated events. Some examples would be:

1. Sudden removal of constraint; a large block breaking away from its parent mass on a cliff.

2. A rapidly rising diapir or tectonic uplift can cause accelerated denudation rates.

3. A flood can instantaneously (geologically speaking) erode a new or deeper channel in rock or serve to remove gravels or talus that provide vertical or lateral constraint.

Statement three may be applicable to the case of the anticlines. If a rapidly incising channel were being excavated through the Muav and into the Bright Angel Shale we may see the most recently liberated (eroded) cliffs move inward (strain) and thrust over the more constrained strata below. this release of strain could only occur in the direction of accumulated high horizontal stress - in a northwest-southeast direction parallel to the regional joints. A high horizontal stress field could not be generated in a northeast-southwest direction because of decoupling - the tensile stresses set up by lateral elastic straining can not be transmitted across joints.

The Bright Angel shale at the base of the channel wouuld strain upwards under elastic relief. It has been postulated by many [95], [96], [97] that less-stiff rocks like shale or coal possess much greater amounts of strain energy due to the very close joint spacings. The strain these types of rock exhibit upon unloading when other more stiffer rocks nearby exhibit less deformation (each rock type was subjected to the same loading/burial). The correlation may be complicated by the tensile strengths [98] of the respective rock types.

If the above theory is correct, much of the energy involved in the formation of the anticlines came from elastic strain evergy stored in the nearby [99] Bright Angel Shale.

We may not see elastic strain upstream in Marble Canyon because of destressing due to the nearby Eminence Fault System, the slower downcutting rates of the channel (evidenced in the wider cross-section of the Canyon), or possibly a facies change of the Bright Angel Shale eastward.

20.1 Evidences of Hydrostatic Loading by the Reservoirs

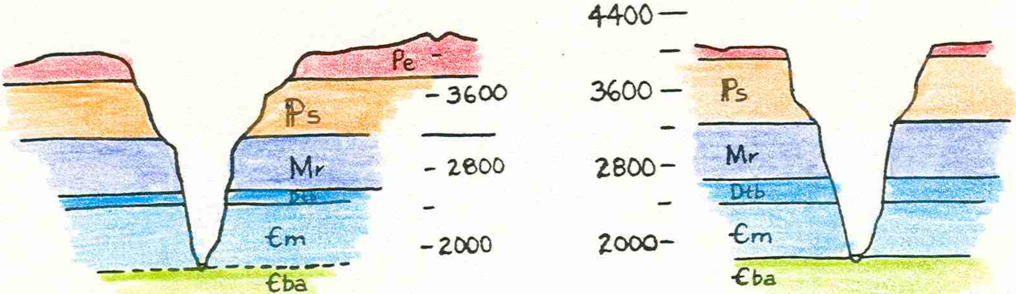
Figures 31 and 32 shows cross-sections of the Inner Gorge in the vicinity of the river anticlines and upstream where a similar stratigraphic sequence exists. The reservoir-induced bydrostatic pressures would have been predictably great as would hav been the loading caused by a succession of silts and gravels filling the Innner Gorge. Figure 33 shows a stratigraphic section at Toroweap of the lower Muav and complete Bright Angel Shale sequence. Complete saturation of all of these strata most certainly took place during the several hundred years of complete inundation before a dam was removed. Figure 34 shows the sequences of channel filling and dam breakout. The resulting increases in stress due to hydrostatic and detrital loading are also indicated at mid-channel (Figure 34b). If a catastrophic breakout occurred [100] some rather rapid removal of the sediment directly behind the dam structure would be expected; especially in a **confined** channel situation with a lake 360 miles long! [101] We may apply "directly behind the dam" in this case to mean maybe 20 to 35 miles upstream (up to mile 144 for a Toroweap dam) considering the duration of the deluge and the extremely **narrow cross-section** area of the Inner Canyon below Kanab Creek.

The immediate post-breakout situation is detailed in Figures 34c. Figure 35 shows in more detail how the more-thoroughly fractured liimestones would have quickly drained and thereby relieved their high hydrostatic pore pressues. The slightly swelling [102] Bright Angel shale strata would not be able to relieve their excess pore pressures due to their impermeable nature [103].

What the Bright Angel would do, and probably did, was to strain upwards under the tremendous differential load. Although plastic straining of the uplifting unit usually acts to dissipate pore pressures (due to increased volume), the situation in actuality was made worse by the cyclic nature of the shale strata downwards (as shown in Figure 33), and the fact that the intervening crytalline sequences could relieve themselves downstream where they "daylighted" out of the channel bottom.

This uplift probably created the high-angle reverse faults and much of the anticlinal bulging seen today. Once again, the process would have been less effective where systematic joint clusters parallel the channel (in northerly trending segments of the channel) for they would help to relieve any upward stresses.

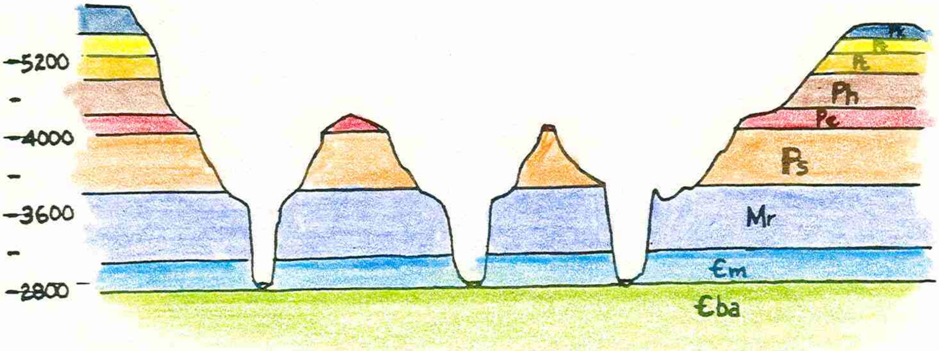
The downstream effects of the dam breachment will be discussed in a future paper.



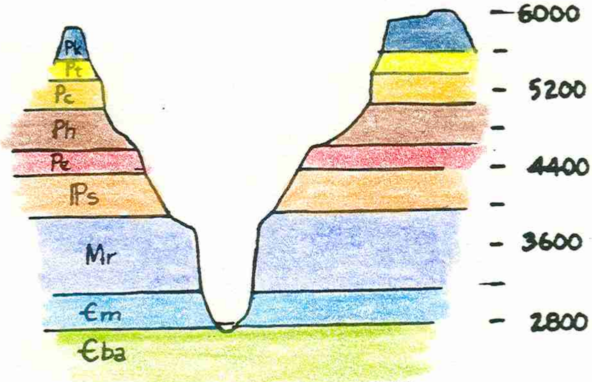
SECTION AT MATKATIMIBA
MILE 151

SECTION at NATIONAL
CANYON
mile 166.7

Figure 31 - Typical cross sections of the Inner Gorge in the region of the River Anticlines. (vertically exagerated 2.58x)



SECTION IN MARBLE CANYON - miles 40.5 to 45.5



SECTION JUST ABOVE THE
TRIPLE ALCOVES
mile 46.5

Figure 32 - Typical sections in similar statigraphy 100 miles upstream from those shown above. No river anticlines are observed. (vert. exageration 2.58x)

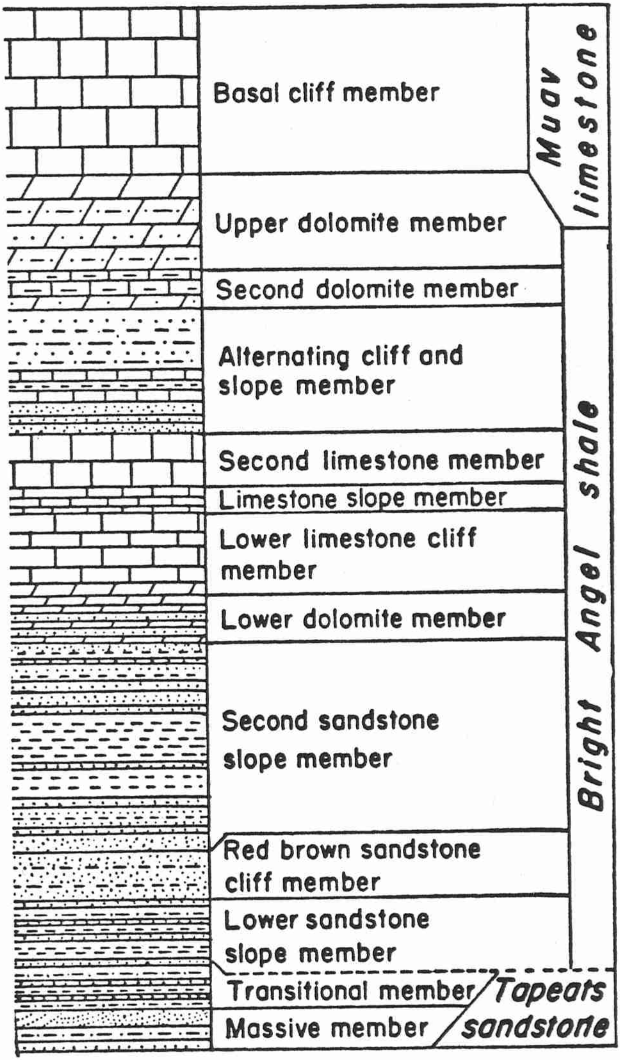


Figure 33 - Stratigraphic section of lower Muav limestone and entire Bright Angel Shale sequence at Toroweap, mile 178. This figure is taken from McKee and Schenk (1942), p. 248.

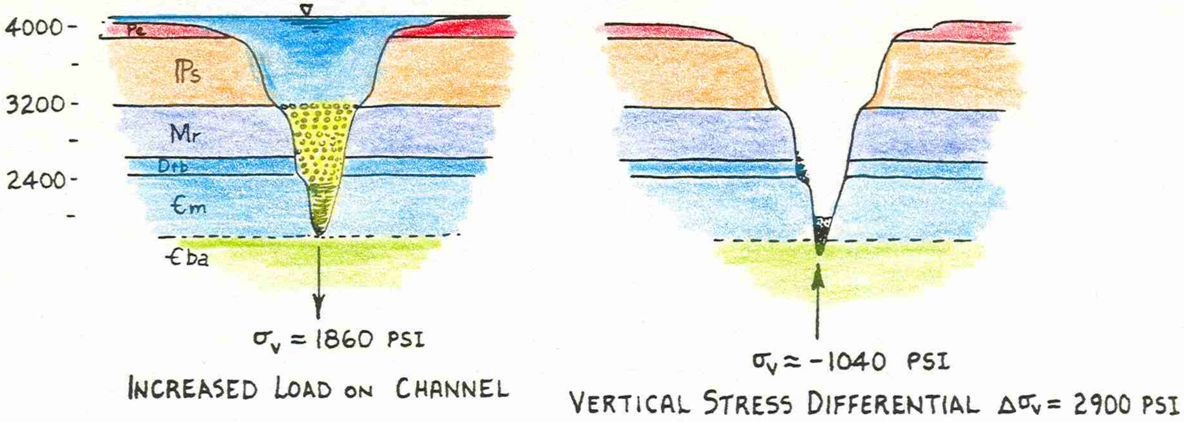


Figure 34 - Cross sections of Inner Gorge at Havasu Canyon (mile 156.5) showing differential vertical stress field generated by reservoir sedimentation followed by sudden breakout, incision of gorge, and pore pressure uplift. (vertical exageration 2.58x)

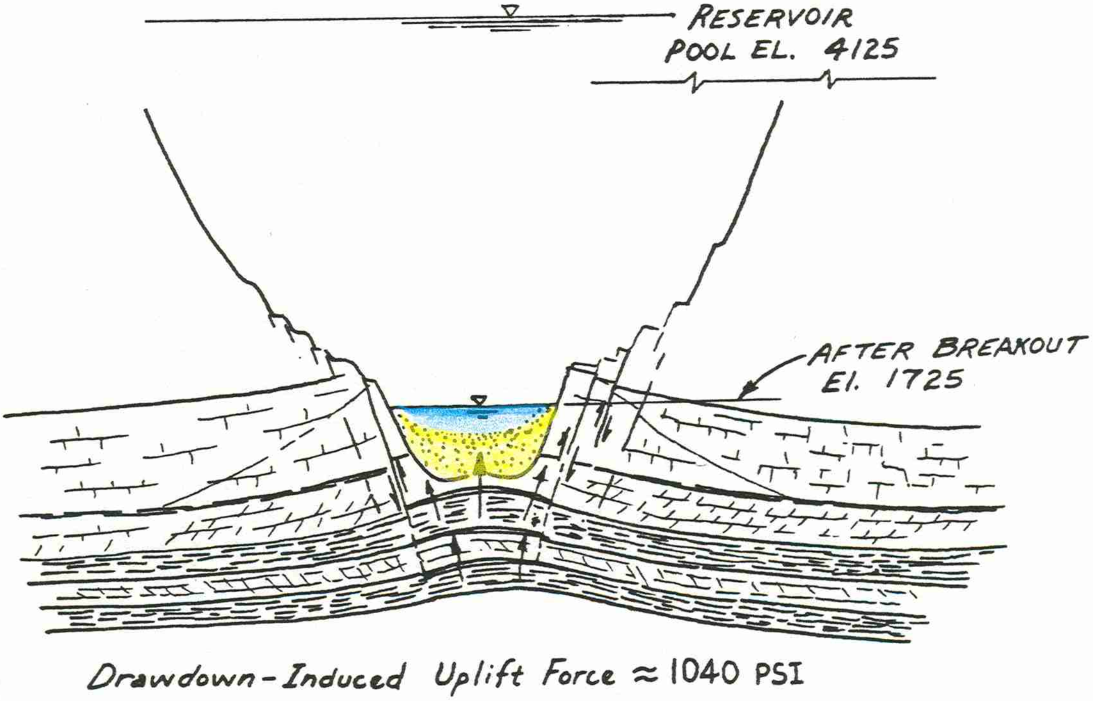


Figure 35 - Detail of local deformation caused by rapid drawdown-induced uplift.

ACKNOWLEDGEMENTS

The authors wish to thank the following people for discussions that contributed to this project.

Professor W. Kenneth Hamblin of the Geology Department at Brigham Young University, Professor Luna B. Leopold of the Geology and Geophysics Department at U.C. Berkeley, and Professor D.H. Trollope of the Department of Civil and Systems Engineering of James Cook University of North Queensland, Australia. Each gave generously of their time and knowledge.

Robert B. Rogers, P.E., graduate student in Geotechnical Engineering at Berkeley, developed the hypothesis on the hydraulics involved in the removal of the lava dams.

Eric D. Savage assisted in both expeditions to the Canyon as the photographer. His generous donations of time, money, and computer equipment were above and beyond the call of duty.

Janet M. Rogers worked unselfishly as she always does, entering, editing, and printing the manuscript.

This research has been carried out entirely as an outside project of the authors and all expenses incurred were from personal funds. This research will continue in the spirit of science and friendship.

FOOTNOTES

[1] River mileposts cited in this paper are in accordance with the Colorado River Compact and are taken in successions from the Upper/Lower Colorado River Division Point at Lee's Ferry, Arizona (mile 0) to the Mexican border. Mean river surface elevations recognized herein were made by the USGS geologic/hydrologic expedition of 1923. At this time, the peak Colorado River flows were higher, non regulated, and carrying a greater bed load.

[2] Term presented by Reiche (1937).

[3] The definition chosen by the authors for "recent" (Holocene) in this paper is any mappable stratigraphic unit(s) (not gravitites or colluvium) lying less than 200 feet above the nearest channel water surface (1923 datum [1]), or presumed intermittent channel water surface (spring flood level). This is based on offset evidence on the Toroweap Fault cited by McKee and Schenk (1942).

[4] McKee, Hamblin, Damon (1968).

[5] The "first" lava flow cited herein is McKee and Schenk's continuous "A" flow. This basal flow was the subject of the 1968 paper cited above. Large lava and ash blocks are entrained in the gravels of the pre-"A" flow channel bed in a large ancient scour hole immediately downstream of the Toroweap fault.

[6] An ancient Colorado River channel at mile 183 contains older intracanyon flows of Hamblin (1969). The bottom of this channel lies at least 130 feet **above** the present day channel **surface** indicating an ancient Colorado River channel <u>at least</u> 150 feet higher at the outset of intracanyon lava flow time (presumably 1.2 mybp) west of the Toroweap fault.

[7] McKee and Schenk (1942) p. 255.

[8] Ibid. p. 256.

[9] At least 350 feet above the ancient channel bottom and apparently located upstream of Toroweap (mile 179).

[10] A 400 foot high lava dam at mile 178 would have backed up water to 122-Mile Creek. The cross-sectional area available for deltaic accumulations would be minimal in this region of the canyon (see Figure 31).

[11] Smith, et al. (1960).

[12] The nearest outcrops of Shinumo Quartzite lie in Tapeats Creek, 45 miles upstream.

[13] McKee and Schenk (1942).

[14] Okuda, et al. (1977), Suwa, Okuda, and Yokoyama (1973), and Johnson (1973).

[15] An instantaneous catastrophic breakout (which is rare) would easily have the capacity to carry large solids downstream a good distance. Two dam failures are known (St. Francis in 1925, and Malpasset in 1959) that failed

catastrophically and concrete blocks up to 40x40 feet were carried one half mile downstream. See Committee Report for State of California (1928), Thomas (1966), and Ministere de L'Agriculture (1960).

[16] Hamblin (1969), Figure 28, page 60.

[17] The average gradient of the Colorado River in the Grand Canyon is 7.89 feet per mile taken from Grand Wash to Lee's Ferry.

[18] Wittke, et al. (1977), Schiedegger (1973), and Chadwick, et al. (1976).

[19] Density current deposits cited by Smith, et al. (1960).

[20] McKee and Schenk (1942), pp. 256-7.

[21] Including approximate allowances for downstream slope.

[22] McKee and Schenk (1942), Figure 7, page 257.

[23] Term applied by McKee and Schenk (1942).

[24] McKee and Schenk (1942), p. 259.

[25] A considerable hiatus is assumed between "C" and "D" flows (Hamblin [1969], p. 147).

[26] Visual observation of the upper exposed surface of the "D" flow "pendants" on the south side of the river suggests that the flows follow the slight western dip of strata fairly continuously.

[27] The upper exposed (eroded) surface of the "D" series flows lies at elevation 2540 just west of the Toroweap Fault. Adding 150 feet for post-"D" flow vertical fault offset yields a minimum elevation of 2690 feet, from which the mean pre-lava flows channel bottom elevation, 1946, is subtracted.

[28] This assumes that the entire river surface profile was raised an average of 275 feet based on the values cited in Table 1.

[29] McKee and Schenk (1942), p.259.

[30] Ibid. A type section is described in detail.

[31] This could be due to widening of the overflow channel, localized braiding of a choked channel following breakout of the reservoir, or the subsequent breakdown of a hydraulic choke (flow obstruction) downstreamm. Successive surges of large-scale debris "flows" could have been made possible due to normal seasonal flooding of the Colorado followed by drops in flow that created sudden localized choking (aggradation) of the channel, thereby creating a temporary debris dam until the next year's flood.

[32] Not considering subsequent upthrow/downthrow on the Toroweap fault of 146 feet as measured by McKee and Schenk (1942), p. 262.

[33] Actual heights above ancient Colorado River Channel can be estimated by

subtracting 275' (from Table 1). A hieght of 1138'+ above (ancient) river is subsequently cited for this dam.

[34] A Pleistocene Colorado River probably delivered yearly floods in the 300,000 to 500,000 cfs range. The greatest flood of historical record was 384,000 cfs in 1884 at Toppock, California, 289 miles downstream, (USBR [1950], p. 154).

[35] Present-day Toroweap Valley has a watershed of 253 square miles.

[36] Now eroded away exposing Cambrian Bright Angel Shale.

[37] A considerable hiatus is assumed here. A deepening of 50 feet could be postulated depending on all sorts of speculation as to the exact whereabouts of the center of the new channel and the revised flow regimen. Hamblin's work (1975) demonstrated post-Pliocene normal offsets on the nearby Hurricane fault can be construed as a mechanism whereby the river's local base level could be taken down significantly in a short period (geologically) of time.

[38] This statement is made with the realization that the channel has been literally "drowned" 150 feet by downward throw of the Toroweap fault during post-Lower Canyon Series Time.

[39] This same sequence has been termed "Younger Intracanyon Flows" by Hamblin (1969), who has mapped their extent up and down the gorge in considerable detail.

[40] More work needs to be done on this dilemma, especially in dating and correlative mapping of specific lava flow extents.

[41] The terms Middle and Upper Canyon Groups were applied by McKee and Schenk (1942).

[42] Assuming horizontal lineation across the Inner Gorge and 150 feet of subsequent fault movement. This unit appears correspondingly across the gorge.

[43] Interflow (sediments) river gravels were described between Lower Canyon Flows B and C, C and D, and D and E respectively.

[44] Flow 5 appears to have emplaced a debris-choked river bed about 50 feet above the present river surface. This implies that the river system had not yet transported enough detritus downstream to re-seek its pre-flow base level in a bedrock channel.

[45] The first recognition of lacustrine deposits was made by McKee and Schenk (1942), pages 269-270. The basic mechanism of river-borne sedimentation was first put forth by Hamblin and Rigby (1969b) page 77.

[46] Hamblin (1979).

[47] Farrington and Savina (1978) concluded that "The fewest effects occur where landslides enter steep reaches with bedrock channels and valley slopes." This statement appears to be perfectly suited to the Canyon.

[48] See Goodman and Bray (1976).

[49] Rogers and Goodman (1978).

[50] Rogers and Goodman (1979).

[51] Hittenger and Goodman (1978).

[52] Smith, et al. (1960).

[53] Condit, et al. (1975).

[54] Kidd (1975).

[55] Prokopovich (1975).

[56] Pyles (1979) personal communication on seepage solutioning in a carbonate rock environment at Tarbella Dam, Indus River, Pakistan.

[57] Precipitating calcite is of course evidenced by high water "bleach lines" at Lake Mead and Lake Powell and high on the walls in the Marble Gorge. Calcite precipitation has also been noted by the senior author in the foundation adits at Glen Canyon Dam. The natural continual deposition of salts in the foundation rock at Glen Canyon has acted to steadily decrease seepage around the abutments, even though the growing reservoir provides increased head each year.

[58] pH measurements made by the senior author showed a dominant alkaline trend in Lake Powell waters (pH=6-7.5) while the downstream river water in the Canyon varied from pH=4.0 to 4.5 taken from Lee's Ferry to the Little Colorado River. The anomally would be expected between ponded surface water in a calcareous environmment and the deeper waters of the lake that pass through the powerhouse and then into the river.

[59] The assumption is made that the Pleistocene gradient of the groundwater near the Plateaus sloped toward and fed into the lakes. Jacoby and Spydell (1975) found this situation in today's more arid climate at Lake Powell, even though the Kaiparowits Plateau dips gently towards the north.

[60] Reilly (1961).

[61] Lange (1956).

[62] Huntoon (1970).

[63] The temperate to arid climate invading the Canyon since the Pleistocene would tend to suppress high carbon dioxide concentrations in the reservoir system due to a year-round continuence of photosynthesis (too much warm weather).

[64] Reilly (1961) mentions the observation of intertwined fungi in the travertine deposits.

[65] Reilly (1961) states that he believed the great bulk of the travertine deposition is a thing of the past and noted few actively accumulating springs

today.

[66] Possibly because of more favorable environments for calcite deposition.

[67] The travertine deposits come closet to the river at the only two reaches of the channel that are convex upwards and suggestive of aggradation. The western end may be aggrading due to debris choking at Prospect-Toproweap (as discussed previously) while the Marble Canyon segment may be aggrading due to uplift of the central Kaibab Plateau. A number of scientists have proposed that the steeper gradient throughout the river's course in the Kaibab Plateau is a result of more resistant bedrock. This thesis has come under much criticism recently and the reader is directed to Keller (1977) of U.C. Santa Barbara whose data would suggest that the stream gradient indicies can be related to recent tectonic activity.

[68] Tributary flow additions appear to be more than offset by bank losses.

[69] On the 1:62,500 scale map of the Grand Canyon published by the Museum of Northern Arizona (1976).

[70] Ford, et al. (1974) pp. 126-7 have summarized theories of McKee, Hamblin and Rigby (1969b), Ford, Shoemaker, and Huntoon.

[71] Sturgl and Grinshpan (1975) demonstrated how finite elements could be utilized to demonstrate elastic rebound with a certain set of assumptions. This paper is a very good starting place to analytically unravel the problem of how the anticlines and all of their preferably oriented structures were generated.

[72] This debris fan also created Lava Falls, the largest rapid on the entire Colorado River (37 foot drop).

[73] The 1965 USGS Water Resources Division expedition did not record depth data beyond mile 150. (Leopold [1979].

[74] Dolan et al. (1978) reports on a second depth measurement survey conducted in 1976. This is the only available data past mile 150.

[75] It must be remembered that all of the lower Paleozoic sediments thicken towards the west and that the upper Bright Angel "Shale" is really limestone and dolomites with thin shale partings between. See McKee and Schenk's (1942) stratigraphic section taken at Toroweap, Figure 3.

[76] The author cannot imagine how sea level could exert greater influence than the 3.5 mile thickness of lava flows that the river excavated in this area in the last million years. The surface profile is **remarkably planar** through the entire lava dam area, suggesting temporary equilibrium working its way upstream.

[77] Pleistocene movements on the Hurricane and Toroweap faults, the increased heights of travertine above the river and increased gradients only where it transgresses the Kaibab Plateau, the aggrading nature of the river profile and the evidences for temporary flow reversal east of the Kaibab Plateau could all be construed as evidences for recent continuing uplift of the Kaibab block.

[78] Hodgson (1958).

[79] Hodgson (1962).

[80] There is actually a moderate range either side of true north inferred in this statement.

[81] Emery (1964).

[82] Price (1966).

[83] Ibid. (1959).

[84] Cloete et al (1973).

[85] Roering (1978).

[86] Obert and Stephenson.

[87] Varnes and Lee (1972).

[88] The term is used here in a broad sense. It can be applied on the basis of statistical frequency; the northwest trending joint sets outnumber their counterparts by a ratio in excess of 10 to 1.

[89] Price (1966).

[90] Emery (1964).

[91] Rogers (1979).

[92] Obert and Stephenson.

[93] Such as dilatancy, generation of secondary joints (exfoliation or "discing"), fissuring, very viscous flow (creep), or as folding (where the potential strain energy can be liberated in the deformation process).

[94] Sturgul and Grinshpan (1975) - a criticism NOT of the paper, but of the state-of-the-art in 1975.

[95] Price (1966)

[96] Price (1959).

[97] Ferguson (1978).

[98] This is one of the subjects being addressed by the senior author's Ph.D. dissertation.

[99] The Colorado Channel is presumably entrenched into or quite close to the Bright Angel shale below water level.

[100] In this situation a scientist can **only** speculate on the actual effects as the numbers involved are unprecedented. Channel hydraulics is an

empirically-derived science. Also, most of the dams that have failed in historic time have not been in place sufficient time to have accrued high volumes of sediment.

[101] This distance is based on the dam at elevation 4125 backing up water to mile 175 in Cataract Canyon. This mileage is according to that adopted in 1922 for the Upper Colorado River Division and are asigned sequentially from Lee's Ferry, Arizona in an UPSTREAM direction.

[102] Qualitative judgement based on swell tests performed on the Bright Angel Shale in the Rock Mechanics laboratory at the University of California, Berkeley. The Bright Angel Shale might swell enough to close open joints, but that is all. It does not contain appreciable amounts of swelling clay minerals.

[103] In fact, preliminary tests would indicate that the shale might not have experienced internal stress relief naturally for a period of months, or even years.

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