Lunar and Planetary Laboratory
Department of Planetary Sciences

Planetary Field Geology Practicum

PTYS 594a - Spring 1994

Colorado Plateau - Grand Canyon

The University of Arizona
Tucson, Arizona

17854

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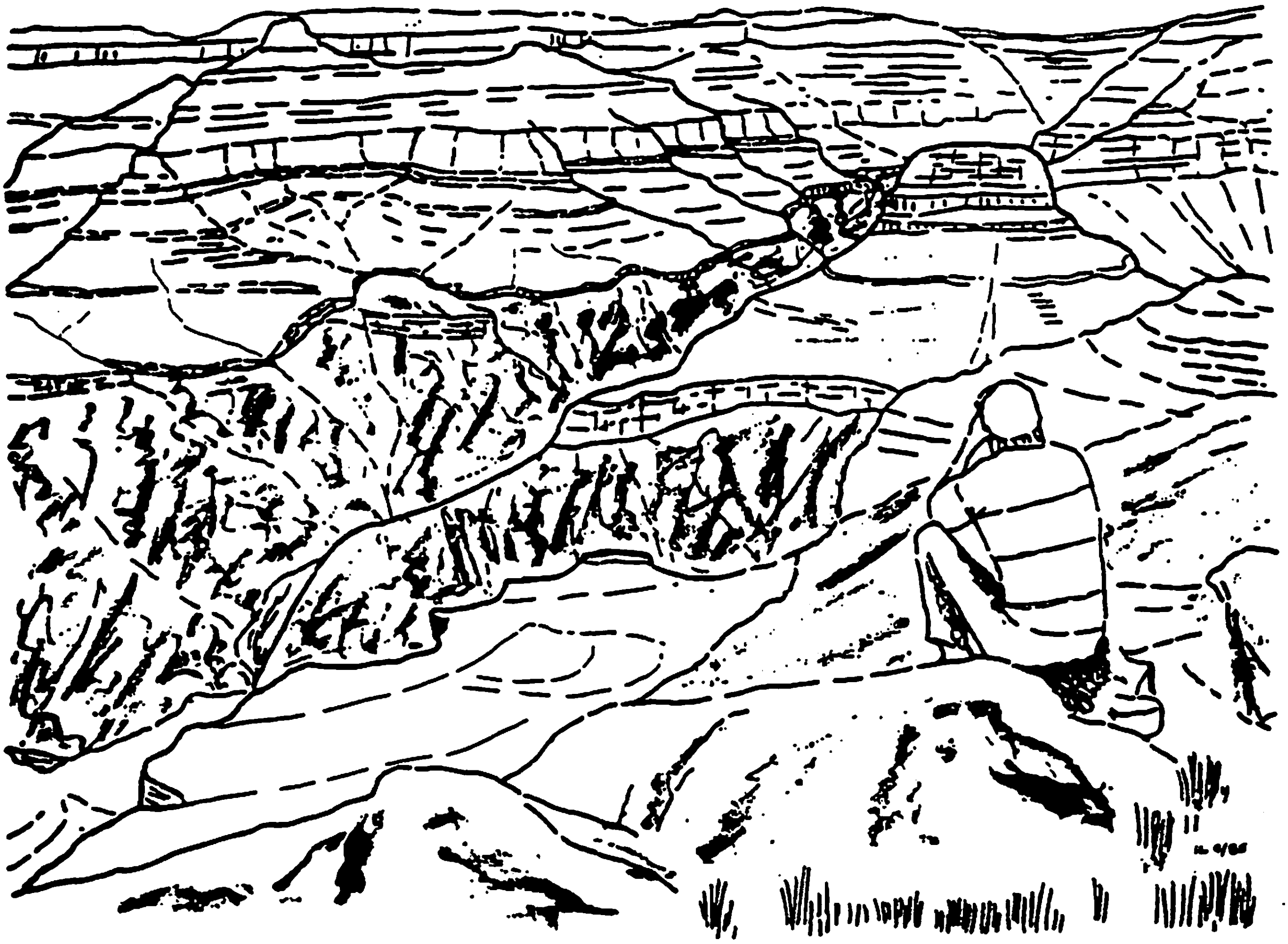


FIGURE 10. Sketch of view from end of hike on the Kaibab Trail, looking about north. Prominent gash in middle distance is Bright Angel Canyon, along fault of the same name. The view point is a little above the Redwall Limestone stratigraphically, and about half-way down into the Canyon.

PTYS 594a,

PLANETARY FIELD GEOLOGY PRACTICUM

Itinerary, Grand Canyon Field Trip 15-18 April 1994

H. J. Melosh, 353 Space Sciences, 621-2806

We will assemble at 8:00 am on Friday, 15 April from the LPL loading dock off Warren St. in five 8-passanger Suburban vans. Try to be at LPL by 8:00 am to get the vans loaded. Please be sure that you have had breakfast beforehand, have ice for the coolers, etc. before we are scheduled to leave: Breakfast and ice runs just before departure have caused long delays in the past!

Our approximate itinerary, as worked out at the last class meeting is:

Friday, 15 April:

8:30 am Distribute handouts, Depart LPL, turn right on Cherry to Speedway, then travel East on Speedway to I-10, proceed North on I-10.
10:00 am Exit I-10 to Route 93 in Phoenix
12:00 noon Lunch stop near Wickenburg on Route 93
2:00 pm Intersect I-40 at exit 71, drive West on I-40 toward Kingman. Take Exit 52, drive North on Stockton Road.
3:00 pm Arrive Red Lake Playa. Check condition of playa, proceed <u>cautiously</u> onto central playa surface. Discussion of Giant Dessication Polygons by McLarty and Wood.
4:30 pm Proceed North from Red Lake Playa on Stockton road, turn right on Pierce Ferry Road, drive 6 miles to road toward Quartermaster overlook.
5:00 pm Meet Stansberry and Spencer at intersection of Antares and Pierce Ferry roads.
5:30 pm Camp on Grapevine Mesa in Joshua tree forest.

Saturday, 16 April:

8:00 am Break Camp, continue to Quartermaster overlook. Discussion of volcanism and river erosion by Johnson, mechanics of rapids by Lemmon.
9:30 am Depart Quartermaster overlook, return to Pierce Ferry Road, drive 5 miles West to Antares road, proceed South at foot of Grand Wash Cliffs. Stop and disussion of Plateau Uplift by Nolan and Zhang.
11:00 am Continue South on Antares Road to Route 66 near Hackberry. Proceed East on Route 66 to Peach Springs. Stop at Wildlife Office in Peach Springs to obtain Tribal Permit, proceed 1 mile North on Diamond Creek Road to outcrop of Peach Springs Tuff.
12:30 pm Lunch at outcrop. Discussion of Peach Springs Tuff by Pedecino.
2:30 pm Return to Peach Springs. Drive East on Route 66 to Seligman, then join I-40 East to Williams. At Williams turn North on Route 64 to Grand Canyon National Park. Drive 4 miles North of Kaibab National Forest boundary, turn left on Forest Service road 347.
5:30 pm Camp in Kaibab National Forest
7:00 pm Campfire history of exploration of the Grand Canyon by Howell.

Sunday, 17 April:

8:00 am Break camp, return to Rte 64 and proceed North to Grand Canyon Villiage. Proceed East on rim road to Grandview point overlook

9:00 am Park vehicles, descend Grandview trail to Horseshoe Mesa. Elevation change is about 2000' and length 2.5 miles one way. Trail is steep, narrow and no water is available along the route, which is not maintained by the Park service. Described as a "strenuous" hike in the guidebooks. On return trip, overall geologic guidance to the Paleozoic stratigraphy will be given by Rivkin and Cohen. Bottke will discuss the geologic history of the Colorado river, Fischer and Grundy will describe mass wasting on the canyon walls, Grier will describe the role of catastrophism in cutting the canyon, Karkoschka will describe historic landslides and Turtle will discuss faulting. Bring lunch and plenty of water. Hats and sunscreen may also be helpful.

3:00 pm Return to the rim, drive East then West to view overlooks. Proceed on route 64 to Kaibab National Forest, find campsite in the National Forest unit.

6:00 pm Camp in Kaibab National Forest west of Navajo Reservation boundary.

Monday, 18 April:

8:00 am Break camp, continue East on route 64 to Cameron. Turn North on route 89 to junction with route 160, then drive East on route 160 to Tuba City.

9:00 am Explore dinosaur footprints and trails in vicinity of Tuba City under guidance of Kring and Navajo guides. Observe aeolian features, sand dunes and yardangs under the direction of Dawson.

11:00 am Return to vehicles, drive west on 160 to junction with route 89, drive south to Cameron. Time permitting, a side trip to view the spectacular aeolian features at Paiute Trail Point commences at dirt road just to the North of the bridge over the Little Colorado River. Dawson will host this possible trip over 20 miles (each way) of dirt road.

1:00 pm Continue South on route 89 to Flagstaff, travel through town then turn right (North) to pick up route 180 (towards Grand Canyon). Travel about 3 miles North on route 180 to Museum of Northern Arizona. Parking lot and entrance on left.

2:00 pm Meet curator at Museum for a private exposition on dinosaur traces on the Colorado Plateau.

3:00 pm Return to Flagstaff on route 180. Continue South on I-17 to Phoenix, then I-10 to Tucson. Exit Speedway Blvd. and return to the LPL loading dock.

8:00 pm Arrive Tucson, unpack and clean vans, go home.

Primary Drivers: Converse, Dawson, Gurndy, Karkoschka and Nolan

Participants:

E. Asphaug
E. Bus (Howell)
V. Converse
D. Durda
J. Grier
J. Johnson
D. Kring
J. McLarty
J. Melosh
J. Pedicino
T. Ruzmaikina
J. Stansberry
D. Wood
B. Bottke
B. Cohen
D. Dawson
M. Fischer
W. Grundy
E. Karkoschka
M. Lemmon
J. McGuire
M. Nolan
A. Rivkin
J. Spencer
E. Turtle
S. Zhang

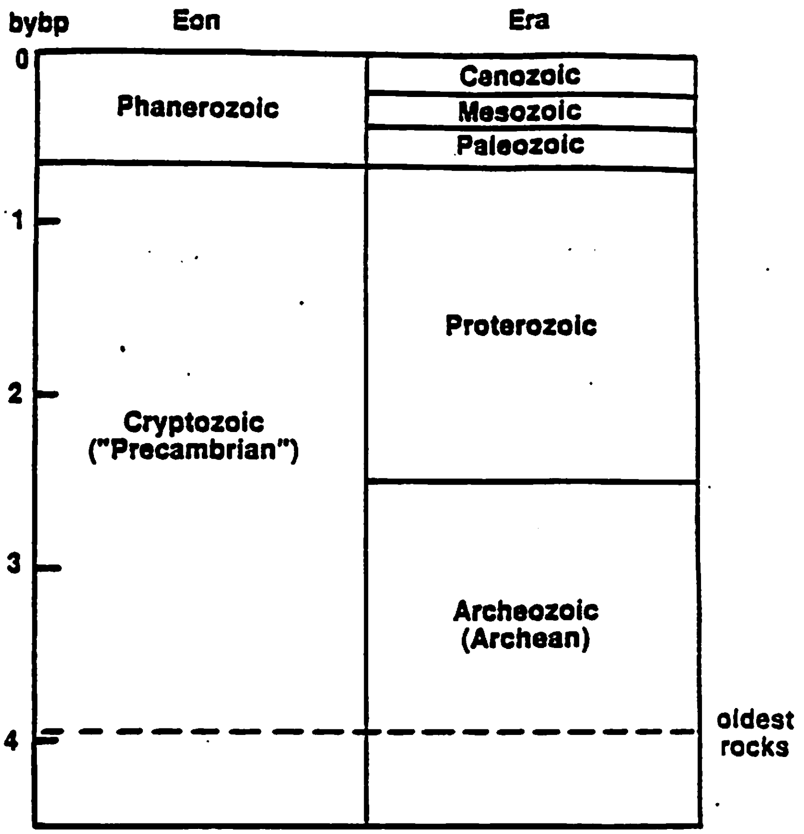


Figure 8-10 The geologic time scale, in broadest outline.

Figure 8-11 The geologic time scale for the Phanerozoic Era.

Era	Period	Epoch		
Cenozoic	Neogene	Holocene		Quaternary
		Pleistocene	1.8	
		Pliocene	5	Tertiary
		Miocene	24	
	Paleogene	Oligocene	37	
		Eocene	58	
		Paleocene	65	
Mesozoic	Cretaceous		144	
	Jurassic		208	
	Triassic		245	
Paleozoic	Permian		286	
	Pennsylvanian		320	
	Mississippian		360	
	Devonian		408	
	Silurian		438	
	Ordovician		505	
	Cambrian		570	

-From Southard: MIT Intro to Geology
Lecture Notes

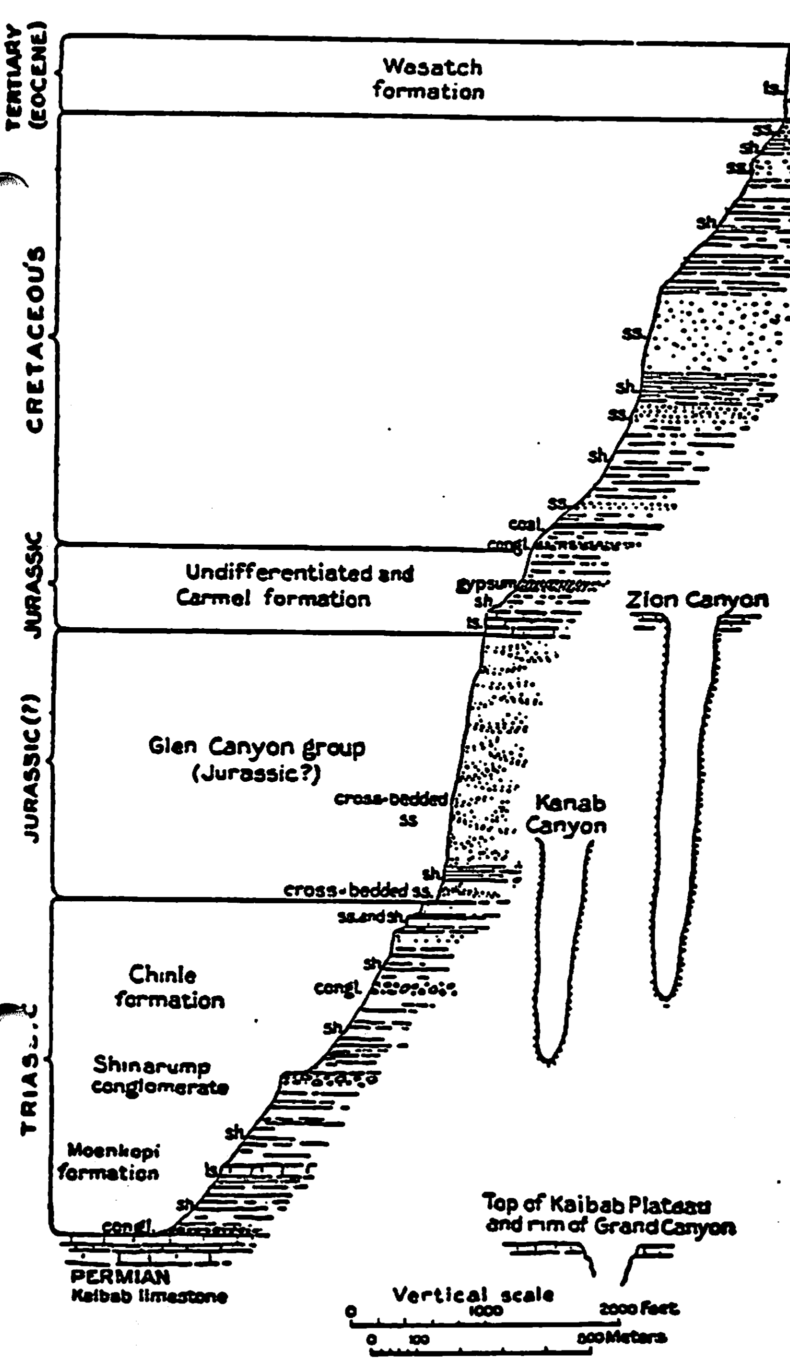
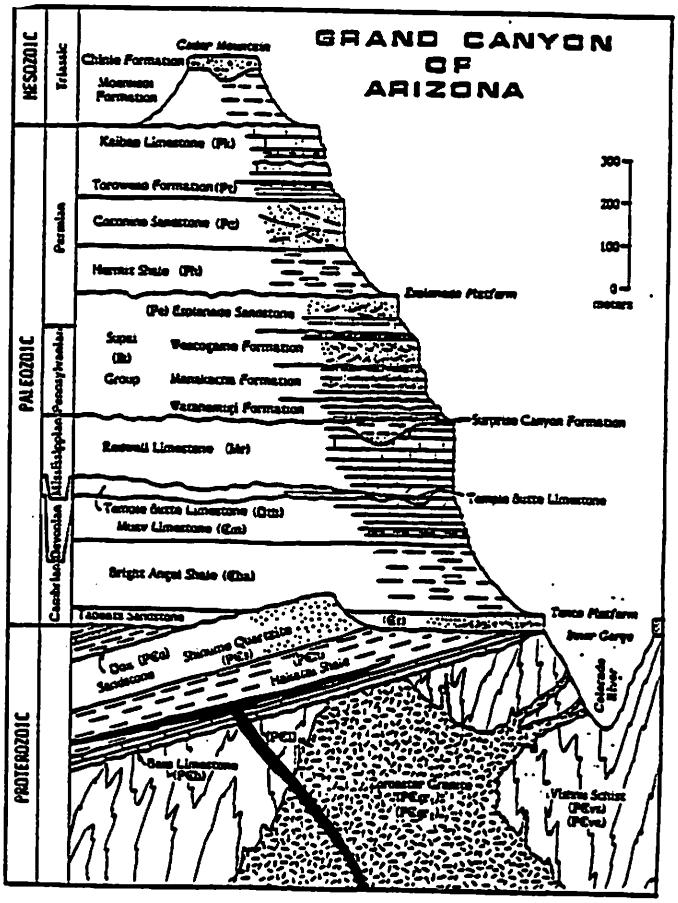


FIG. 157. Generalized columnar section showing the nature and relations of the rock systems from Late Permian to Early Tertiary in the Colorado Plateau. Note the stratigraphic positions of the Jurassic system, and of Grand, Kanab, Zion, and Bryce Canyons. (After H. E. Gregory, U. S. Geological Survey.)

(Miller, 1942)

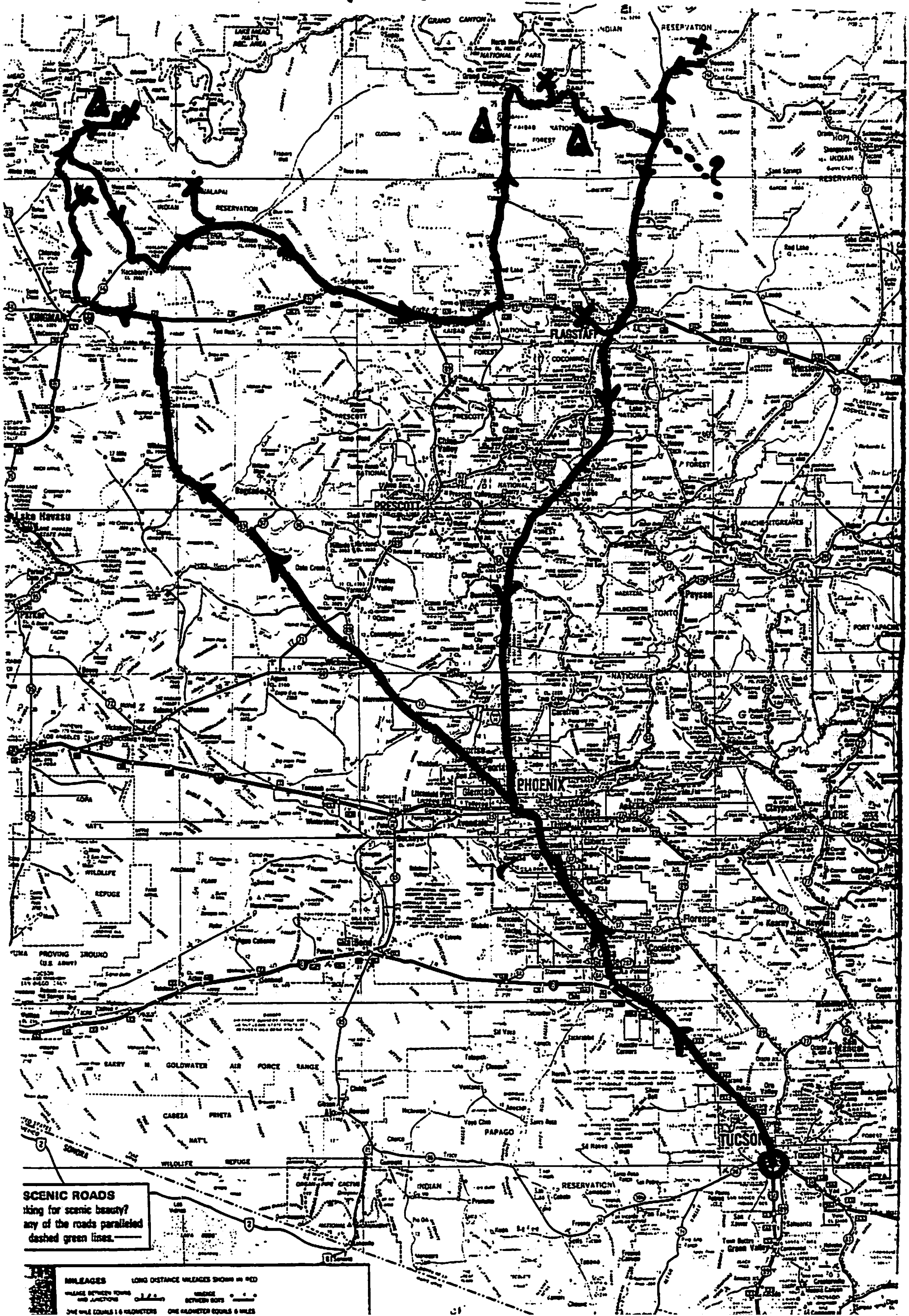
Proterozoic – Tertiary of Colorado Plateau, mostly to correct relative scale



from Geologic Diversity of Arizona... (passive margins, etc.

7. Stratigraphic section for the Grand Canyon near the Kaibab Trail. Tilted rozoic rocks exposed in this area are part of the Unkar Group. Not visible here ost of the Dox Sandstone, and the Cardenas Lavas, also part of the Unkar Group, as ell as the Nankoweap Formation and the overlying Chuar Group, which add up to several m of section. These rocks are exposed in the eastern Grand Canyon.

X = geologic stop
Δ = campsite



RED LAKE PLAYA AND DESICCATION POLYGONS

Janet E. McLarty
David A. Wood, Jr.

Red Lake Playa is one of four playas with desiccation polygons exceeding 100 meters in diameter. Sediments on the surface of the playa shrink during desiccation forming a network of cracks with polygonal structures. These "giant desiccation polygons" appear to be similar to those seen in the northern Martian plains. Understanding the formation of these terrestrial features should provide insight into the formation of the Martian features.

Giant desiccation polygons are almost exclusively found in fine grained hard surface playas. As the fine grained silt dries at the surface, the sediments undergo volume reduction (i.e. they shrink) and then crack. The large cracks formed by the shrinking sediments cross one another in orthogonal networks outlining roughly polygonal patterns.

The polygonal structures found in Red Lake Playa can be classified into (approximately) three types according to diameter: mud-crack polygons (5-10 cm), moderate size polygons (0.3-0.9 m), and giant desiccation polygons (30-300 m). Mud-crack polygons are attributed to surficial wetting and drying. Moderate size polygons are believed to be the surficial expression of prismatic or columnar structures that developed within the playa soil. These structures are probably unrelated to the mud-cracking observed at the surface since they are affected by non-surficial processes. The giant desiccation polygons are apparently analogous to the small scale mud cracks. However, giant desiccation polygons tend to occur in homogenous deposits and exhibit desiccation to greater depths than the mud-cracks.

Desiccation polygons are formed with the removal of water, either by natural or (theoretically) artificial processes. In the past couple of decades, four well were dug around the playa. Recent aerial photographs show cracking in regions of the playa around these wells where no cracking previously existed. For example, there are newly formed fissures and polygons in a cone shape around the stock watering wells at the south end of the playa. While there is no definitive proof that pumping the regional ground water creates new fissures, the evidence strongly suggests that this theory is valid.

Red Lake playa shows two geometrically distinct systems of cracks (see figure 1). The first system is the orthogonal cracking described above. This type of cracking produces a "Y" pattern that radiates in from the center of an extinct pluvial lake in the south-central portion of the playa. The Y structure has branches that extend northeast, northwest, and south-southeast to the flood plain of the Truxton Wash. The second type of cracking is characterized by curvilinear features located just south of the center of the playa. These curvilinear features form a concentric ring structure that is nearly circular. Perhaps not coincidentally, these rings are centered on the same extinct pluvial lake!

One possible explanation for the two systems of cracks is the underlying salt bed. The curvilinear features are coincident with a low in the topography of the salt caused by salt flowage and differential structure movements (possibly in response to normal faulting on the east side of Hualapai Valley and/or sediment loading). Evidence of salt flow has been observed in drill cores from the Detrital Valley and Phoenix area. The salt appears to have flowed from the valley and formed a ridge that corresponds to the northeastern branch of the Y-structure.

The formation of the giant polygons of the Utopia Planitia and Acidalia plains on Mars (see figure 2) may be related to the formation of features observed on Red Lake Playa. They exhibit a Y-shaped pattern, (circular) concentric structures, and sub-surface topography that correlates well with the spacing of the polygonal troughs.

With all these similarities, the Martian polygons seem to be a perfect match, however, they are 1-2 orders of magnitude larger than their terrestrial counterparts. This presents problems for desiccation models, as Pechmann (1980) convincingly argues that mechanical considerations cannot allow terrestrial mechanisms to be scaled up by orders of magnitude. Pechmann instead proposes that the polygons are grabens or tension cracks, although he acknowledges that the polygons do not resemble tectonic structures. In a paper entitled "Origin of Giant Martian Polygons," published by McGill and Hills in 1992, the authors try to reconcile mechanical principles with geologic observations. They conclude that the polygonal terrane material is sedimentary in origin and that the rough topography underneath the sediments causes differential compaction as the terrane is desiccated. The differential compaction in turn creates bending stresses at the surface capable of fracturing the overlying sedimentary material without affecting the underlying topography. The large size of the polygons is then determined by the spacing of topographic "highs," since the initiation of fractures is favored on the portions of the surface overlying these regions. Thus, according to McGill and Hills (1992), desiccation may indeed play a key role in forming the Martian polygons, but not in the spacing.

The giant desiccation polygons of Mars have yet to yield all of their secrets; but, to use an analogy, they may be the "big brothers" of terrestrial polygons. If the analogy holds, then there is some link between the Martian polygons and their terrestrial equivalents. By studying the polygonal cracking at Red Lake playa and other sites, some fundamental relationship may reveal at least some of these secrets.

Acknowledgment : Special thanks to Jon Pedicino for allowing us the use of his Evolution of Planetary Surfaces paper, for directing us to other helpful references, and for answering our questions.

References :

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McGill, George E., 1986, The Giant Polygons of Utopia, Northern Martian Plains, *Geophys. Res. Let.*, Vol. 13, No. 8, pp. 705-708.

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Pechmann, James C., 1980, The Origin of Polygonal Troughs on the Northern Plains of Mars, *Icarus* **42**, pp. 185-210.

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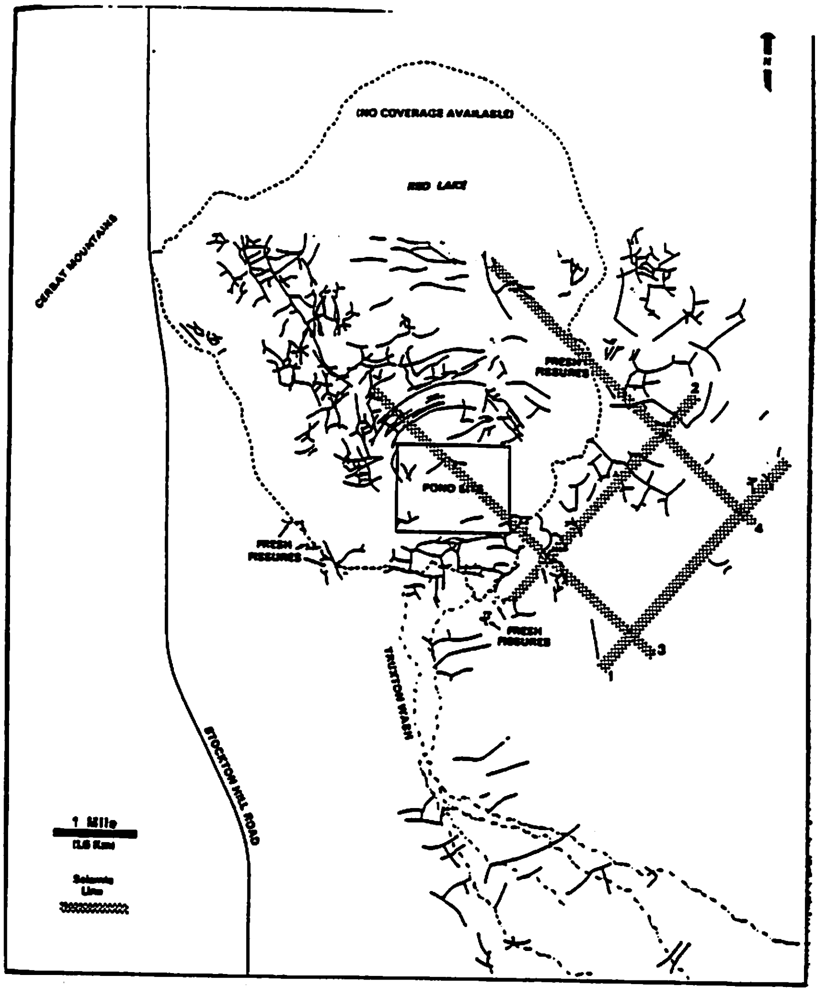

Figure 1: This is a sketch of Red Lake Playa showing the general structure and locations of the desiccation polygons and curvilinear cracks.

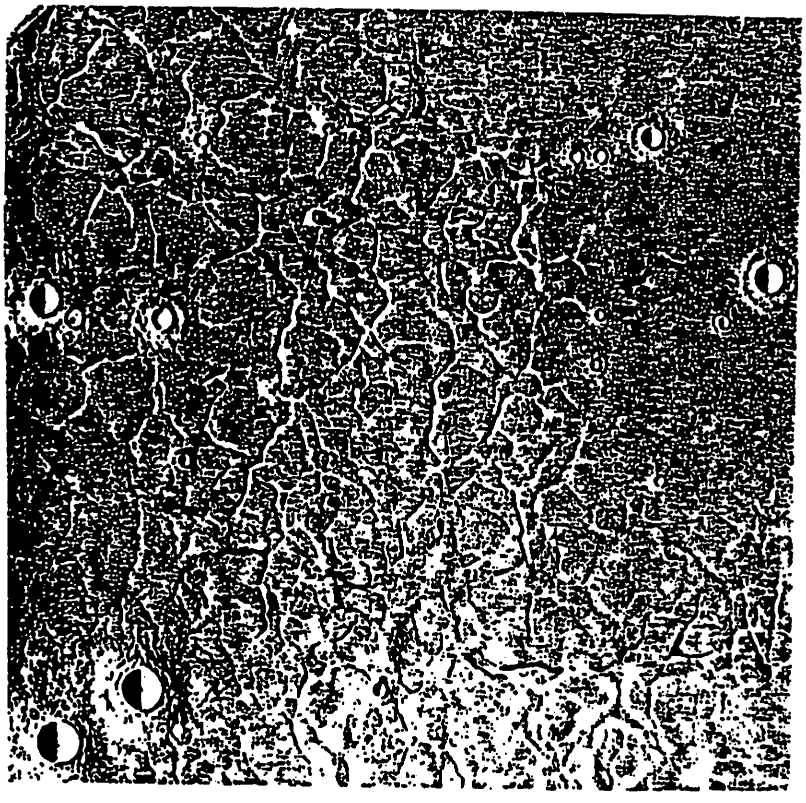

Figure 2: This is a photograph of the giant desiccation polygons found on the northern plains of Utopia Planitia, Mars.

JJ1

LATE CENOZOIC LAVA FLOWS AND TEMPORARY DAMS ALONG THE COLORADO RIVER

Jeff Johnson, PtySci 594a, Spring 1994

Over 150 basaltic lava flows entered the Grand Canyon over the last 1.5 Ma. Some were extruded on the Uinkaret Plateau on the western edge of the Canyon and entered on the north rim near Topoweap Valley and Whitmore Wash. Others were extruded within the Canyon borders, like the lava falls that spill over the Esplanade Platform near Vulcan's Throne (Figs. 0,1). These cap older flows that formed dams up to 2000 feet high and 84 miles long. At least 12 major lava dams formed temporary (< 20,000 y) lakes that extended upstream past the present extent of Lake Powell (e.g,. Fig. 5)

DAM	Elevation (ft)	Height Above River (ft)	Radio-metric Date (Ma)	Volume of Lava (mi^3)	Lake Length (miles)	Water Fill Time	Sediment Fill Time
Prospect	4000	2330		4.0		23 y.	3018 y.
Ponderosa	2800	1130		2.5		1.5 y.	163 y.
Toroweap	3093	1443	1.2	3.7		2.6 y.	345 y.
Esplanade	2600	960		1.8		287 d.	92 y.
Buried Cy.	2480	850	0.89	1.7		231 d.	87 y.
Whitmore	2500	900		3.0	100	240 d.	88 y.
D Flows	2295	635	0.57	1.1	74	87 d.	31 y.
Lava Falls	2260	600		1.2		86 d.	30 y.
Black Ldg.	2033	373		2.1	53	17 d.	7 y.
Grey Ldg.	1813	203		0.3	37	2 d.	10.3 mos.
Layered D	1938	298	0.64	0.3	42	8 d .	3 y.
Massive D	1826	226	0.14	0.2		5 d.	1.4 y.

- Present discharge rates of the Colorado River were used to calculate that a lake formed behind a lava dam 100 feet high would overflow in 17 days (Water Fill Time). The highest dam, 2330 feet, would overflow in 23 years.

- The sediment volume of the Colorado can be used to calculate how quickly the reservoir formed behind a dam would fill with sediment. A 150-foot high dam would fill with sediment in less than a year. The 2330-foot high dam would have taken over 3000 years to fill with sediment.

- Erosion rates of the dams can be estimated using current studies of waterfall migration/downcutting (Fig. 3), e.g., Niagra Falls migrates headward (upstream) at about 3 feet/yr (> 11 miles in last 8,000 years). Lava dams in Canyon (< 20 miles long) probably took up to 20,000 years to erode, mainly from erosion by sediment-laiden Colorado River waters (once the lake had filled with sediment), hydraulic plucking of columnar-jointed basalt flows, and high waterfalls forming large scour holes.

Prospect Dam (Fig. 5). Three to four major flow units, each > 800 feet thick (some of the thickest in Canyon). Some show elliptical structures similar to pillow basalt textures (Fig. 4). Lack of complete submergence of lavas in river prevented classic pillow structures here. Extensive delta/lake deposits in Lake Powell area from the Prospect Lake, whose shoreline reached up to the Redwall Formation near the park headquarters.

Toroweap Dam. Exhibit pillow structures along with "pseudo-pillow" and elliptical textures. Dam was at least 1440 feet high, one of largest in Canyon. Formed by five major periods of extrusion, each followed by short periods of backwater overflow/erosion. Toroweap Lake left deposits at Lees Ferry at an elevation of 3600 feet, as well as silt deposits at Havasu Canyon near Supai. Dam probably lasted only 10,000 years.

Buried Canyon Dam (mile 183). Older basaltic flows filled Canyon gorge, but river shifted outside of a slight meander and overflowed, downcutting to form a completely new river canyon, and leaving the basalt flow in the old dam without eroding them.

⇒ Lava Cascades and Intrusions. The lava falls are just west of Vulcan's Throne at mouth of Toroweap Valley; they originated from volcanic centers on southern tip of Uinkaret Plateau. They are probably only 10,000-20,000 years old (younger than Vulcan's Throne). Vulcan's Forge is supposed to be part of the intrusive dike system in the region. Also see the dike on west side of Prospect Canyon.

⇒ Rates. Hamblin et al. have noted that after erosion of the dam(s), the river returned to its original profile and didn't cut down any further. The river apparently returns to an equilibrium state after each dam destruction. In fact, the hundreds of feet of vertical offset on the Toroweap Fault zone are not expressed on the river surface (e.g., by falls, rapids), suggesting that one million years was enough time to erode the displaced strata. Thus the river can apparently downcut much faster than tectonic forces can uplift the Plateau.

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1) Hamblin, W.K., 1989, Chapter 23. Pleistocene volcanic rocks of the western Grand Canyon, Arizona, in *Geology of Grand Canyon, Northern Arizona (with Colorado River Guides)*, Elston, D.P., G.H. Billingsley, R.A. Young, eds., Amer. Geophys. Union.
2) Hamblin, W.K., 1990, Chaper 17, Late Cenozoic lava dams in the western Grand Canyon, in *Grand Canyon Geology*, eds. S. S. Beus and M. Morales, Oxford Univ. Press, 518 pp.
3) Hamblin, W.K., 1972, Late Cenozoic lava flows in the Grand Canyon of the Colorado River, Arizona, in *Geology and Natural History of the Fifth Field Conference Powell Centennial River Expedition*, Four Corners Geological Society, 41-60.
4) Hamblin, W.K., and J.R. Murphy, 1969, Grand Canyon Perspectives: A guide to the Canyon scenery by means of interpretive panoramas, Brigham Young University Geology Studies, Spec. Pub. No. 1, 48 pp.

JJ3

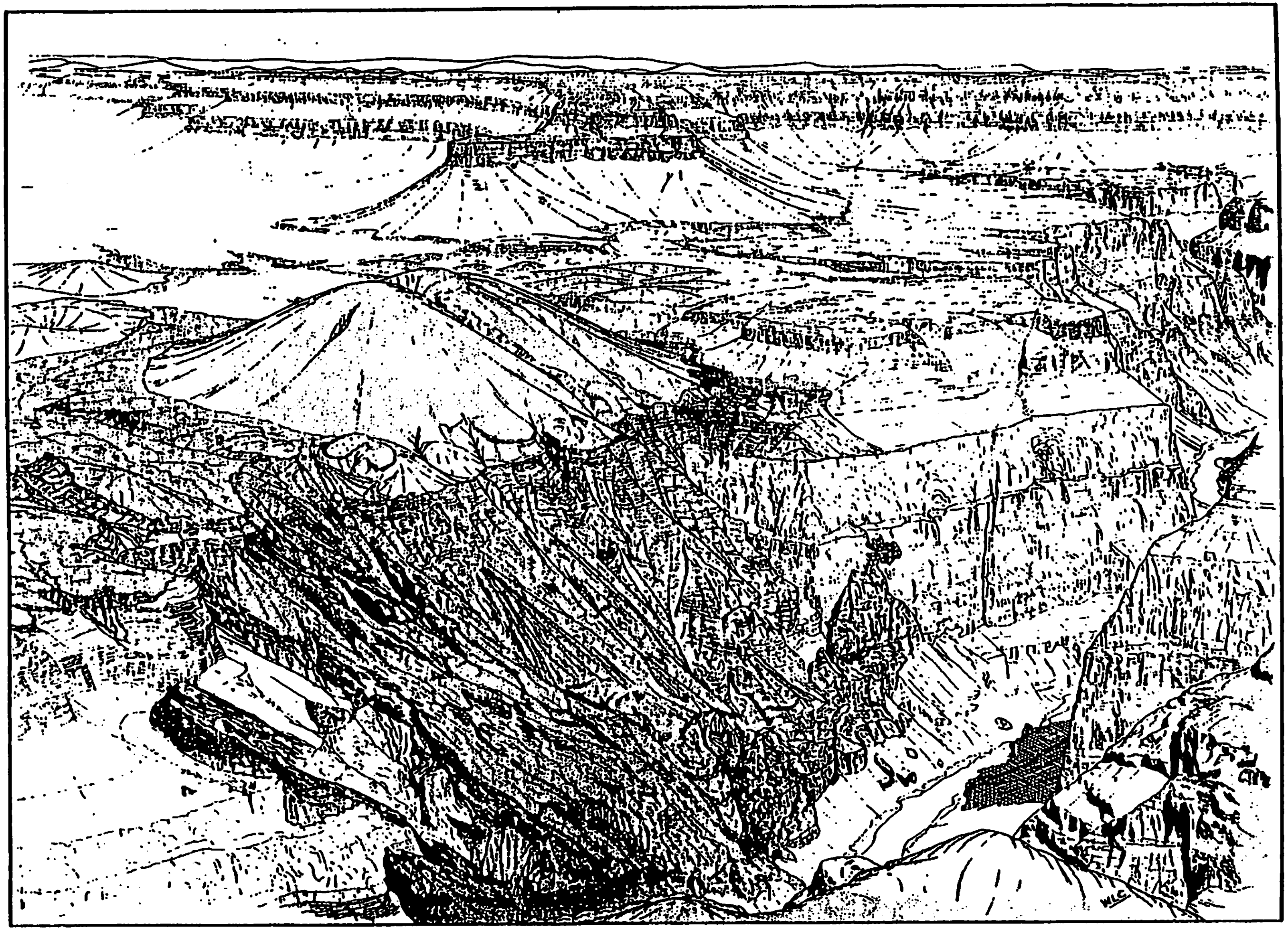


FIGURE O Sketch showing the volcanic features in Toroweap Valley. View looking northeast. Toroweap Valley is filled to the level of the Esplanade platform with thin-bedded basalt and intraflow sediments. Vulcan's Throne is perched above the valley fill on the rim of the inner gorge. Remnants of the Toroweap dam can be seen adhering to the canyon wall 1,400 feet (427 m) above the river.

JJ4

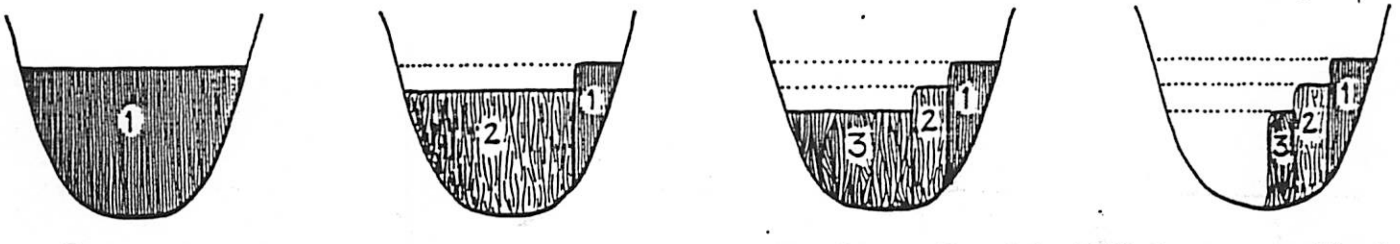


FIG.2—Diagrams showing development of juxtaposed flows in theGrand Canyon. Flow 1 partly fills the canyon and is subsequently eroded leaving only remnants adhering to the canyon wall. Flow 2 refills the canyon and is juxtaposed against flow 1. This process is repeated with flow 3 so that remnants of the flows appear to be stacked side by side against the canyon wall.

FIG. 1

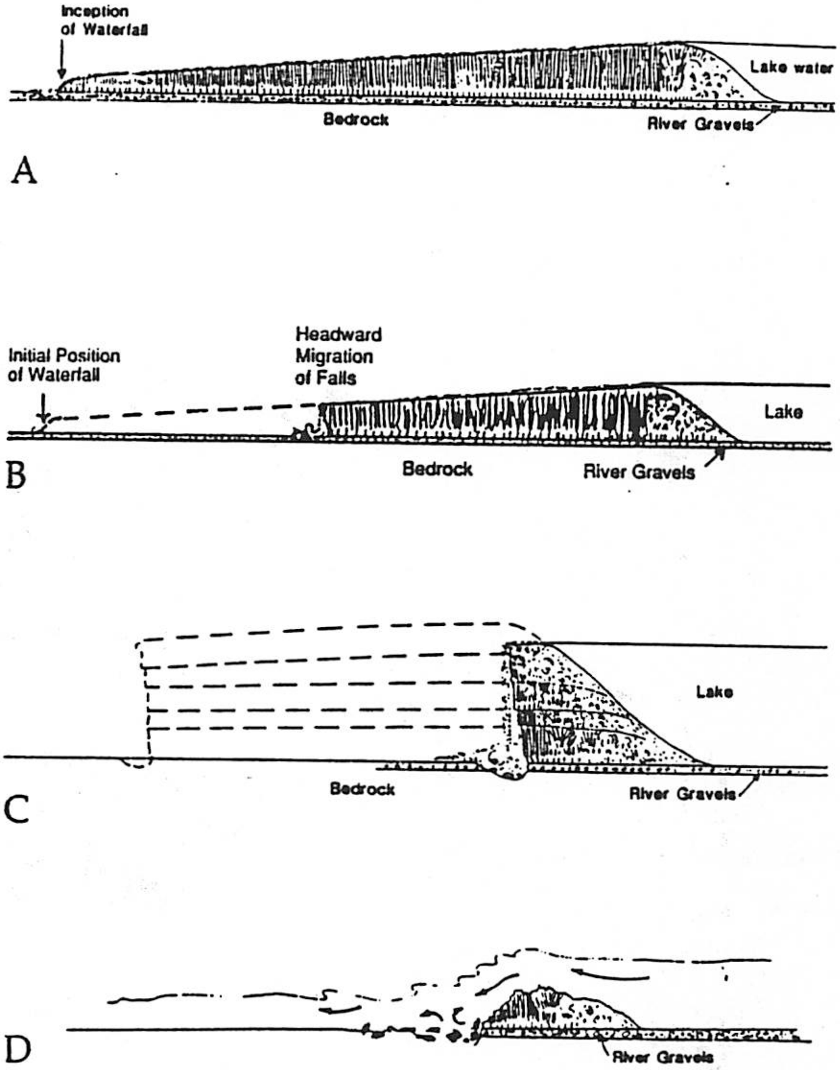
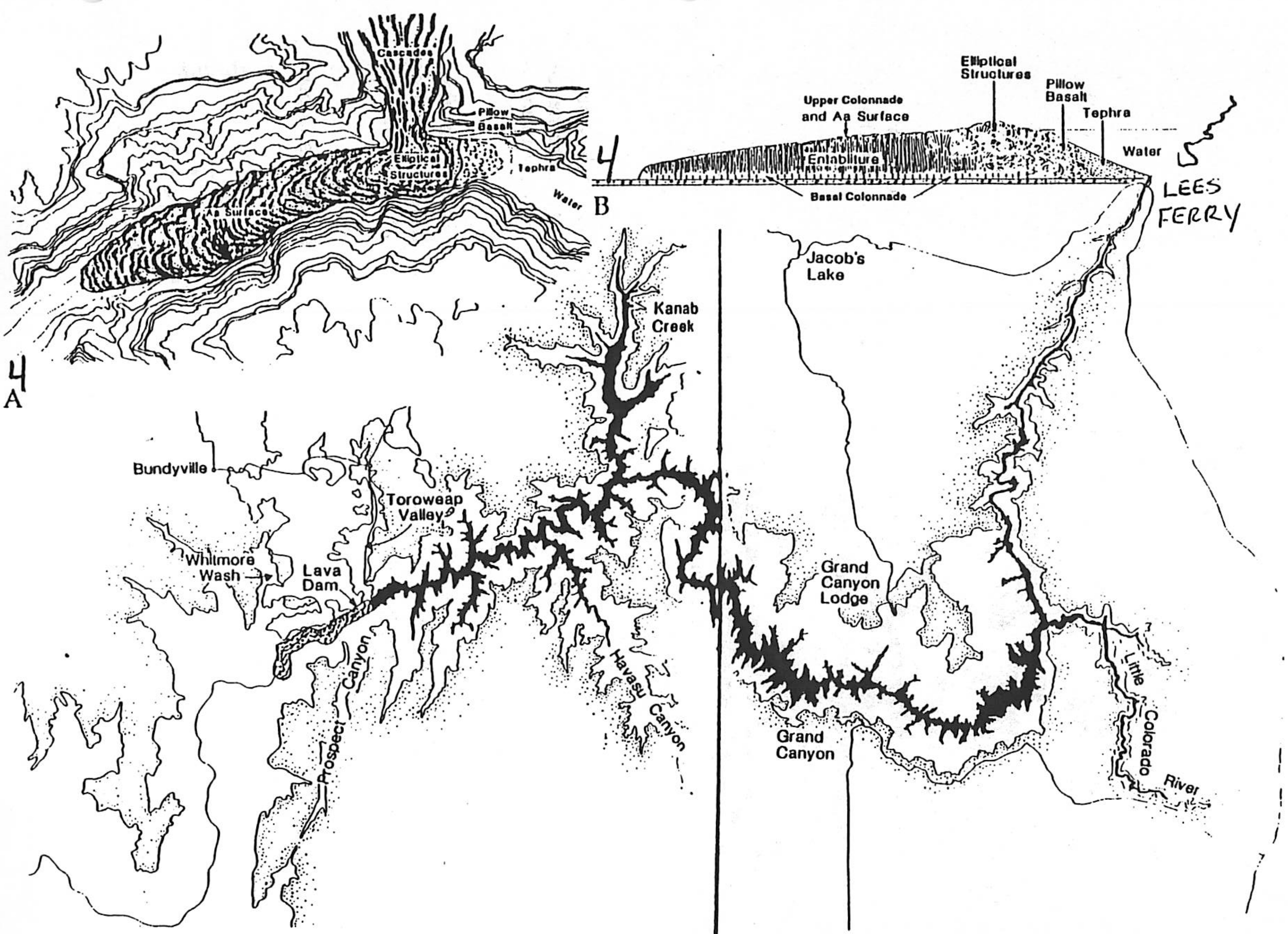


Figure3 Diagrams showing erosion of a lava dam by headward migration of waterfalls. (A) As soon as the backwater overflowed the lava dam, a small waterfall would form at the downstream end of the lava flow. (B) Upstream migration of the falls would be accelerated by undercutting of the unconsolidated river sediments beneath the flow and by the weakness of the rock resulting from vertical columnar jointing. (C) As the waterfalls migrated headward, the stability of the dam could be jeopardized by the pore pressure in the columnar jointing. (D) Some dams may have failed catastrophically. This event could have been minimized if contemporaneous downcutting lowered the level of the overflow before the falls migrated to the head of the dam.



4
A

4
B

Figure 5 The Prospect Lake. The Prospect Dam was the highest lava dam formed across the Colorado River. The lake formed behind the dam that extended all the way through the Grand Canyon and up into Utah. It formed more than 1.2 million years ago.

JJ5

River Hydraulics and Rapids

Mark T. Lemmon

Introduction to rapids

The Colorado River falls over 1900' between Lees Ferry at the upstream end of the Grand Canyon and Lake Mead 235 miles downstream. This drop does not occur as a uniform gradient—most of the drop occurs in short intervals, the "white-water" rapids, that punctuate the relatively tranquil river. Outside of rapids, the flow of the river is slow, and the river is even pond-like in areas. Within the rapids, the flow is fast and violent.

Some physics

The Reynolds number (Re = velocity × depth / viscosity, e.g. $Re = 10\ cm\ s^{-1} \times 100\ cm / 0.01\ cm^2\ s^{-1}$ for a slow shallow river) is in general $\gg 10^4$ in rivers, so the flow is turbulent whether in rapids or not.

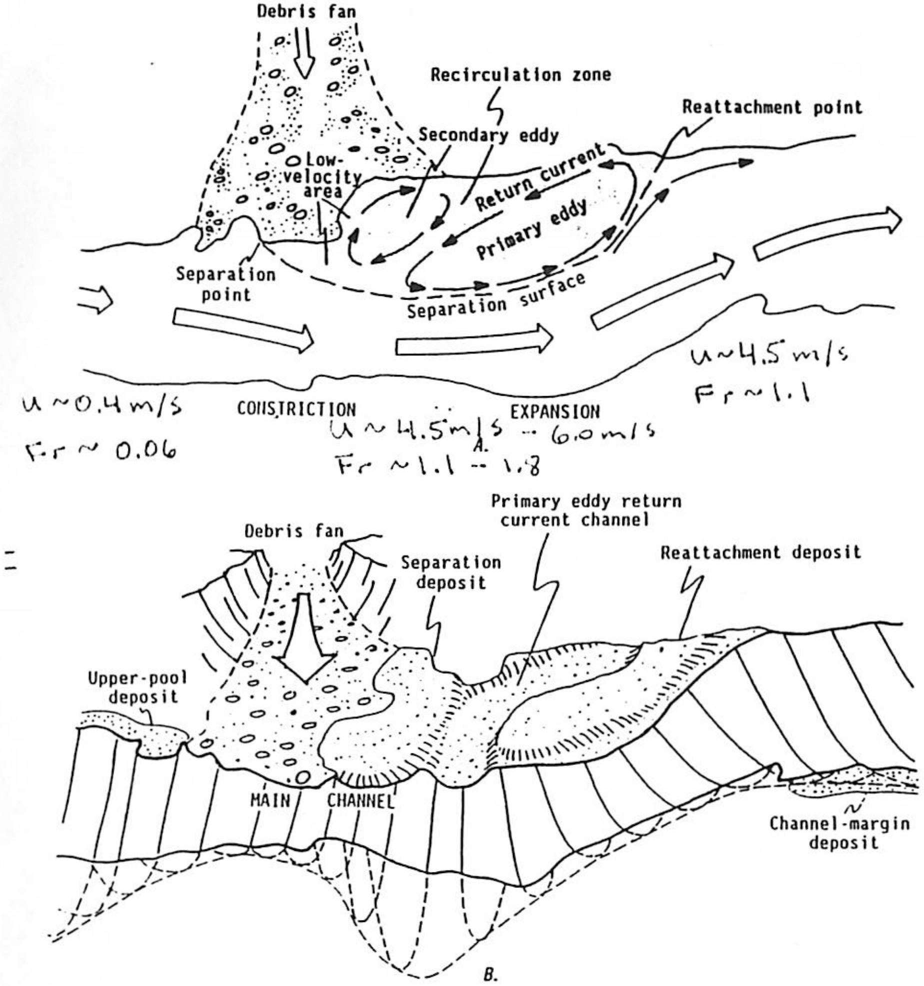
The Froude number ($Fr = \text{velocity} / (\text{gravity} \times \text{depth})^{1/2} = u / (g\ D)^{1/2}$) is the ratio of potential energy to kinetic energy, and is more important. For $Fr < 1$ ($u < c$), the flow is sub-critical, dominated by gravity. This is tranquil flow typical of most of the river. As the river narrows, velocity must increase; typically, the depth of the river decreases, causing c to decrease. For $Fr = 1$, the flow is critical; for $Fr > 1$, the flow is super-critical, dominated by kinetic energy.

Sub-critical flow is characterized by traveling waves and "tranquil" behavior. A disturbance placed in the flow will cause waves to spread from the disturbance. In equilibrium, the flow yields to the disturbance—river bottom topography is not reflected in river surface topography.

Super-critical flow is characterized by standing waves. A disturbance in the flow will leave a "wake" on the surface. Objects on the river bottom leave standing waves at the river surface. Standing waves are also seen at the transition between super-critical and sub-critical flow.

Stay tuned for cool kitchen sink experiment (unless we have real rapids to play with).

Rapids morphology



u ~ 0.4 m/s
Fr ~ 0.06

u ~ 4.5 m/s – 6.0 m/s
Fr ~ 1.1 – 1.8

u ~ 4.5 m/s
Fr ~ 1.1

FIGURE 3.6 a,b. Flow patterns and configuration of bed deposits in a typical recirculation zone. (a) Flow patterns in the recirculation zone downstream from a debris fan. The large open arrows indicate the main current direction; smaller dark arrows indicate flow directions within the recirculating zone. The separation and reattachment points, primary and secondary eddies, and return current channels are discussed in the text. The separation surface between the primary eddy and the main current is indicated schematically; this separation surface seems to correspond directly with the outer break in slope of the edge of the bar crest (fig. 3.6b, and 2.7 c, d, e. (b) Three-dimensional view of the configuration of bed deposits in a recirculating zone and their relation to flow characteristics shown in part (a). Note the small channel-margin deposit indicated downstream in the main current where the channel has returned to full width. The solid and dashed lines indicate schematically the elevation of the bed of the river in the vicinity of a constriction caused by a debris fan.

Obligatory Nth generation photo

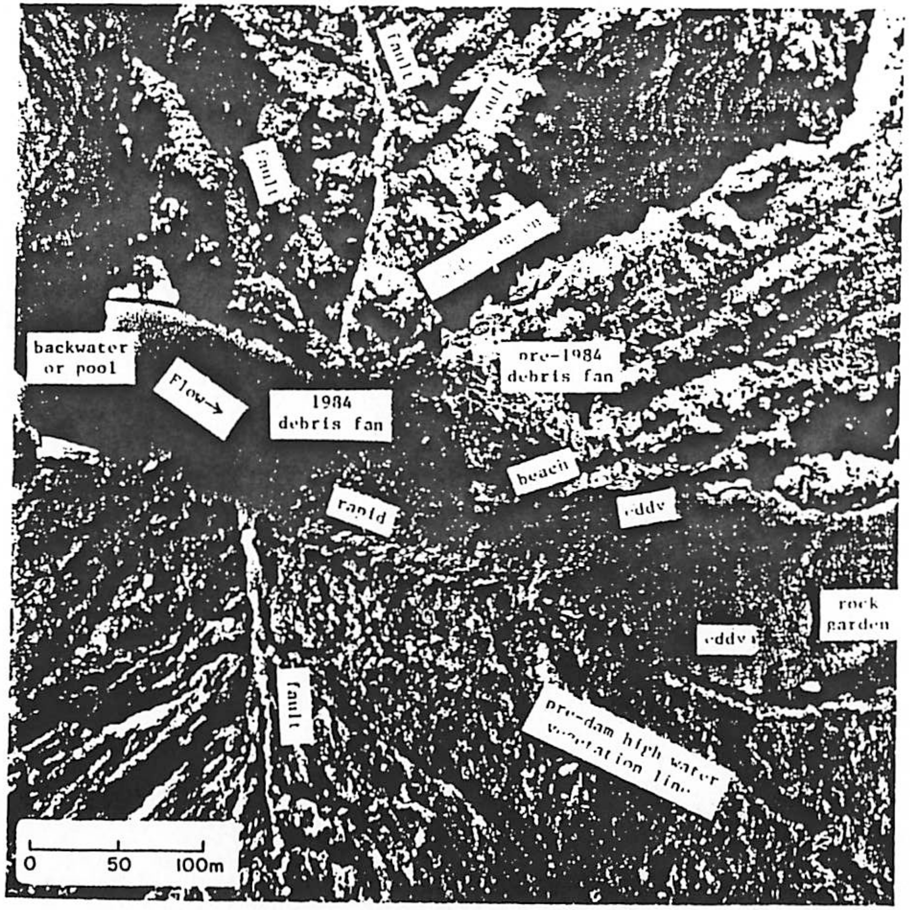


FIGURE 3.1 a. Aerial photo of Granite Rapids at a discharge of 141 cms (5,000 cfs), showing the geomorphic features common to many rapids. Photograph by U.S. Bureau of Reclamation, 1984. Regional faults from Dolan et al. (1978).

Evolution of rapids

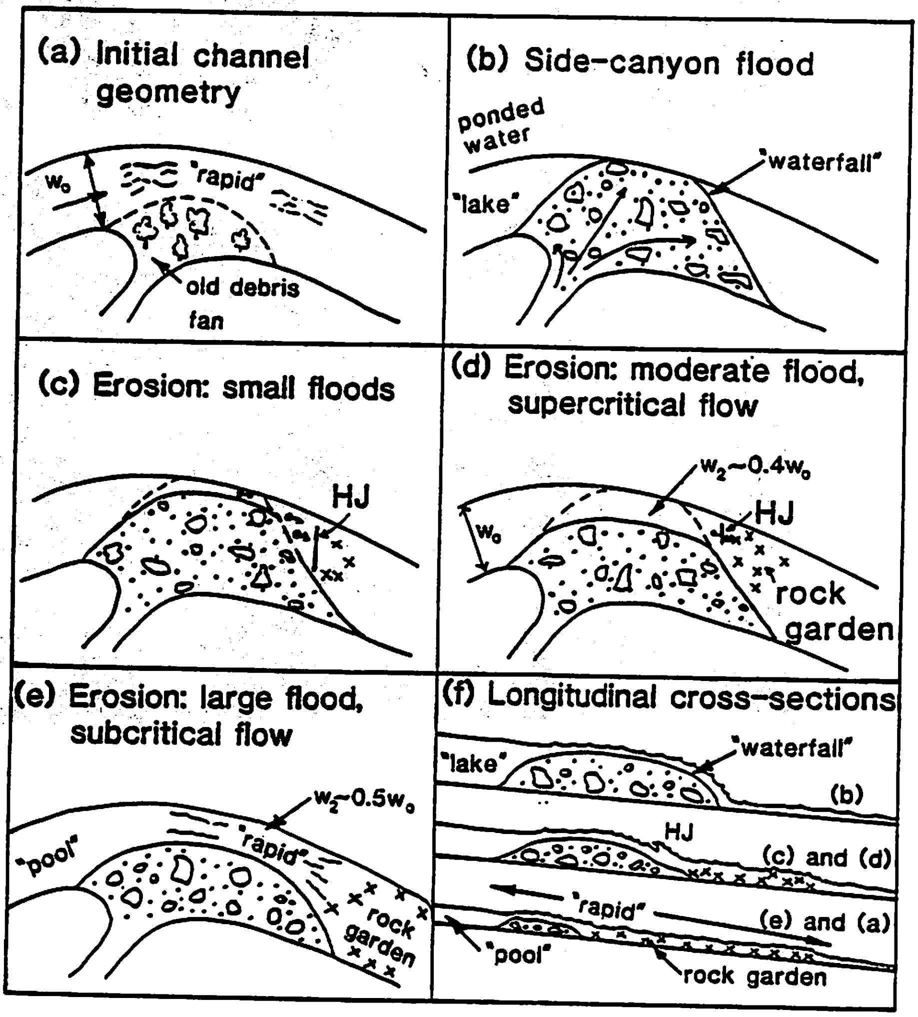


FIGURE 3.10. Schematic illustration of the emplacement and modification of debris fans and channel morphology, the formation and evolution of rapids, and the formation of rock gardens. (a)-(e) Map views. (f) Cross sections corresponding to (a) - (e). See text for details.

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The Uplifts of Colorado Plateau

Shunbin Zhang and Mike Nolan

The Colorado Plateau is a geologic province that is ringed by zones of intense deformation including the extending Rio Grande rift on the east, the compressional Uinta uplift to the north, and a drastically extended Basin-Range to the south and west. The Grand Canyon occupies a position on the southwest corner of the Colorado Plateau (figure 1). The uplifting of the Colorado Plateau is related to the geologic events over hundreds of millions of years.

Since the close of Precambrian time, the Paleozoic rocks in the Grand Canyon region were deposited in equatorial regions of the earth as platform sediments on the southwestern part of a growing continent. At that time the Colorado Plateau was an integral part of the larger land mass. Subsequently, the continent was rafted through plate tectonic processes some 2000 miles northward across the face of the earth. Between the beginning of Cambrian and the end of Cretaceous time, a period dominated by uplift , the Precambrian surface has risen in pulses a total of approximately 2 miles. Clearly the cratonic block upon which the Grand Canyon occurs has moved great lateral distances and has both lost and gained considerable elevation. The best evidence for precambrian faulting in the western Grand Canyon occurs along the Hurricane fault.

The huge interval of Paleozoic time, spanning 325 million years, was characterized in the Grand Canyon region by gradual net subsidence and net accumulation of sediments that now thicken westward from 3500 to 5000 feet. As the crust was thickening through sedimentation , North America was growing rapidly in a westerly and southerly direction through the vastly different process of lateral continental accretion. During Paleozoic and Mesozoic time, the area that was to become the Colorado Plateau was ensconced within the North America craton. The forces operating in the Grand Canyon region were attenuated that deformation occured only as broad-scale but gentle warping of the crust and variable rates of subsidence or uplift. We can best categorize the uplifts associated with erosional disconformities as epeirogenic in nature.

The Laramide orogeny (upper Cretaceous to early Tertiary) had a profound impact on the Colorado Plateau structures. The major uplifts known as the Defiance and Zuni were formed in their present configuration in Laramide time. Other major uplifts such as the Kaibab, Monument and San Rafael Swell took on their present form during the Laramide orogeny. At any rate, virtually every fold and fault on the Colorado Plateau was activited during Upper Cretaceous and Early Tertiary times. The Laramide orogeny was the single most prominent event in the molding of the geologic structure of Colorado Plateau as is is seen today. As the uplifts actively rose, the basins actively subsided in Laramide time. The result was that the positive areas were attacted by erosion to form vast quantities of sediments, which were in turn transported to and deposited in the sinking basins. The San Juan Basin is the best example (figure 2).

The folding and faulting of the Colorado Plateau strata in Laramide time were accompanied by an outbreak of volcanic activity. A general rise of the continental interior began in Late Tertiary time that greatly accentuated the erosive mechanism. The result of erosion is that all areas were bodily uplifted to the tune of several thousand feet.

Reference 1. **Grand Canyon Geology**, S. S. Beus and M. Morales, 1990. 2. **The Colorado Plateau**. D. L. Baars, 1983.

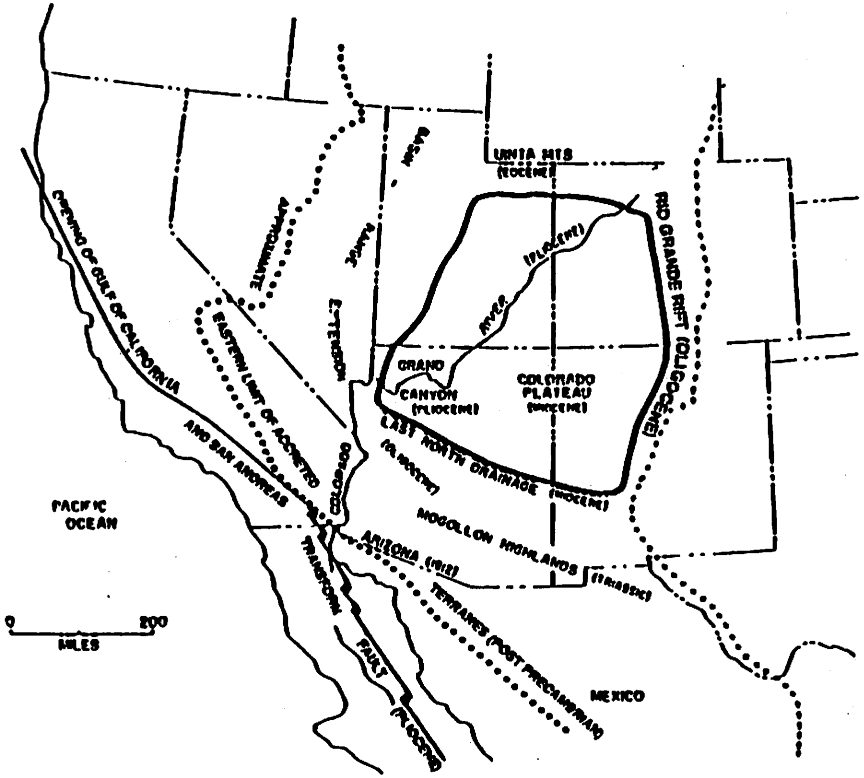


Figure 1. Selected tectonic elements in the western North American cordillera and the timing of their inception

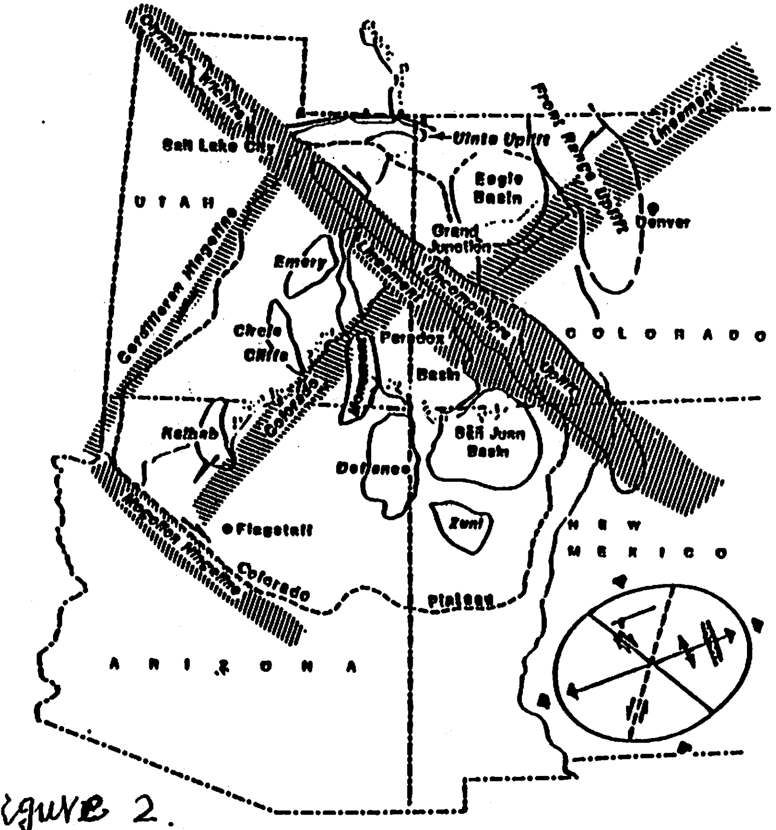
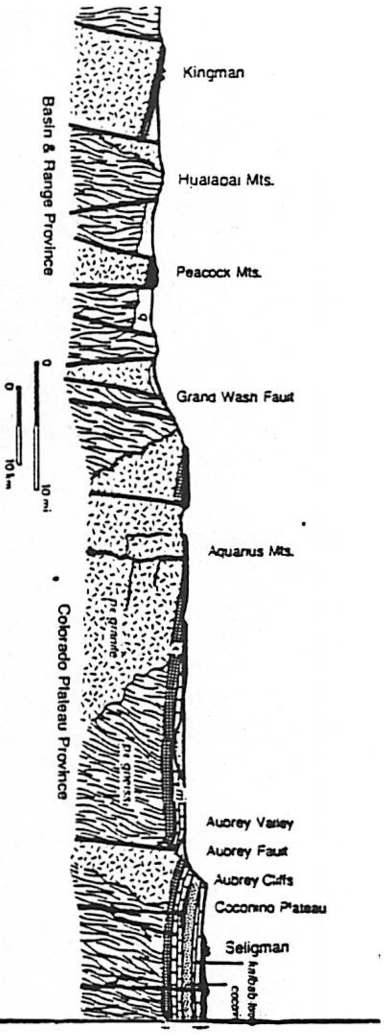


Figure 2.

Index map showing relationship of prominent surface structural features to basement wrench fault systems, shown generalized as shaded lineaments. Strain ellipsoid in lower right corner indicates expected orientations of shears, faults and folds in the Precambrian stress field. (Baars and Stevenson, 1981) p.194, Roadside Geology of Arizona.



Section along I-40 Kingman to Seligman.

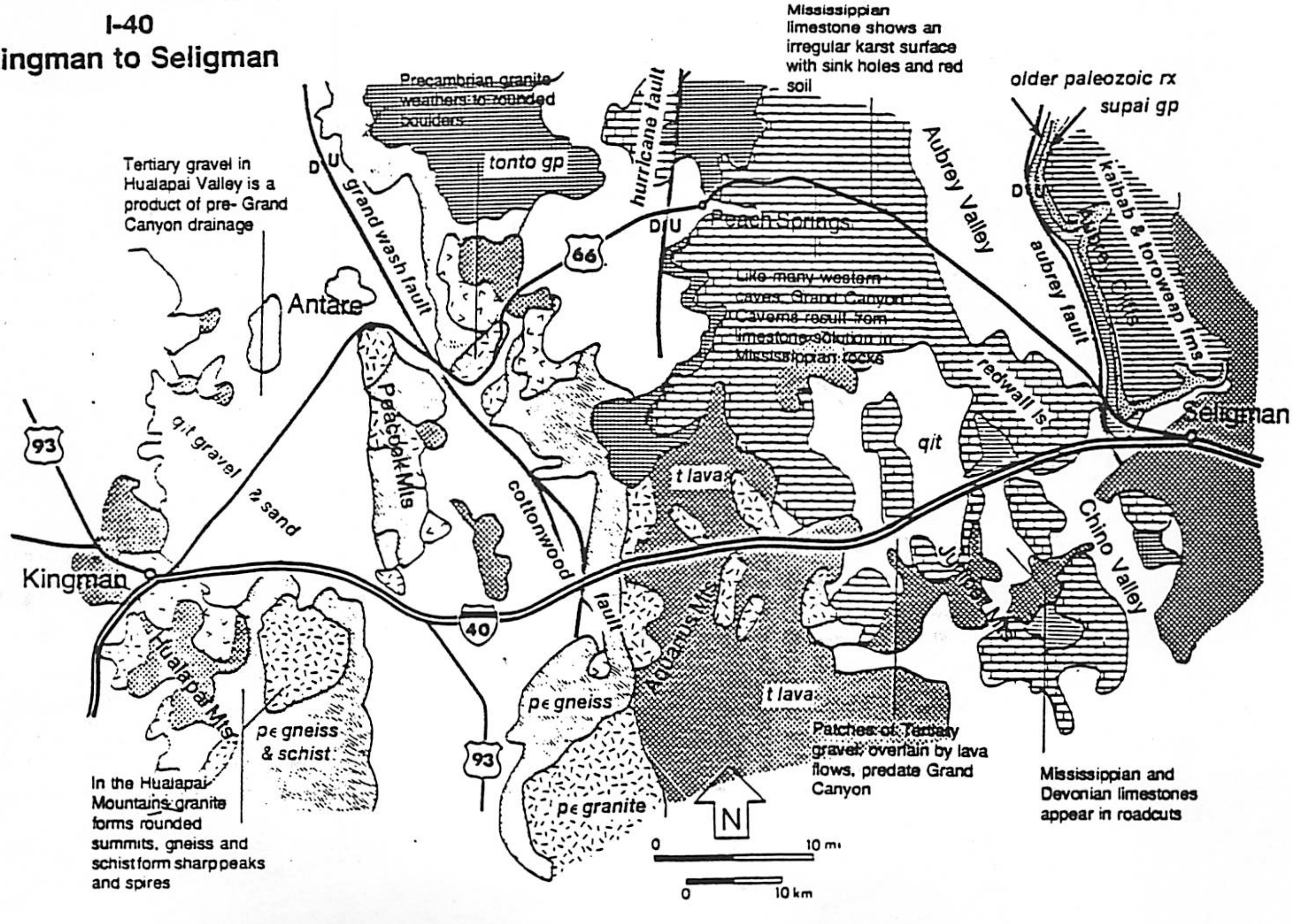
Peach Springs & surrounding geology.

- Jon Pedicino

(The quest for peach cavern, an adventure in geology.)

--- ---- ---

I-40
Kingman to Seligman



from, "Geology of Central + Northern Arizona", P. 161

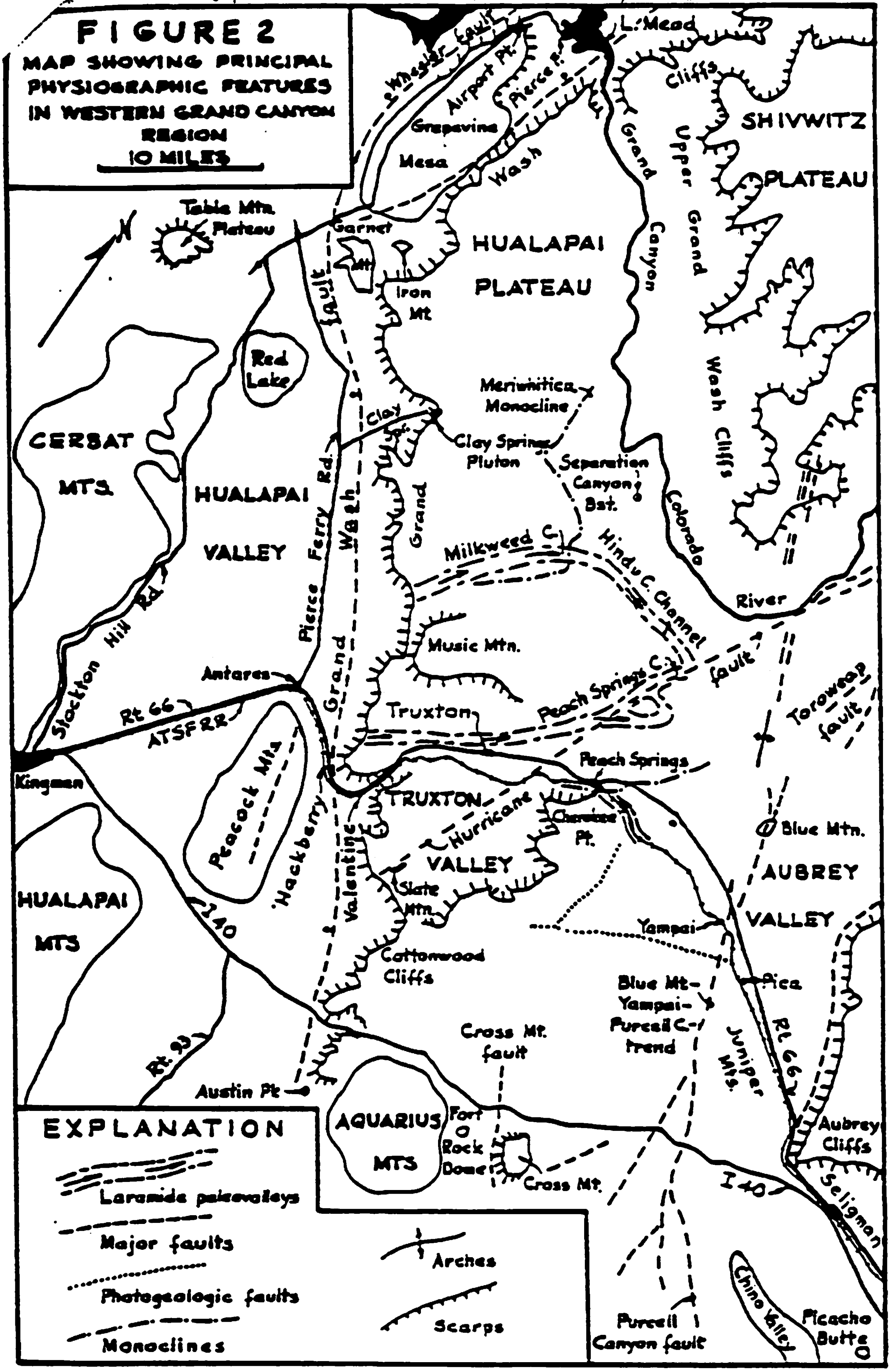


Figure 2. Map showing principal physiographic features in western Grand Canyon region.

Paleozoic History of the Grand Canyon, Part I

or Tequila and Limestone, on the rocks

with your epeirogenic guides, Bårbara Cøhen and Andy̆̈ Riṽkin

When was the Paleozoic?

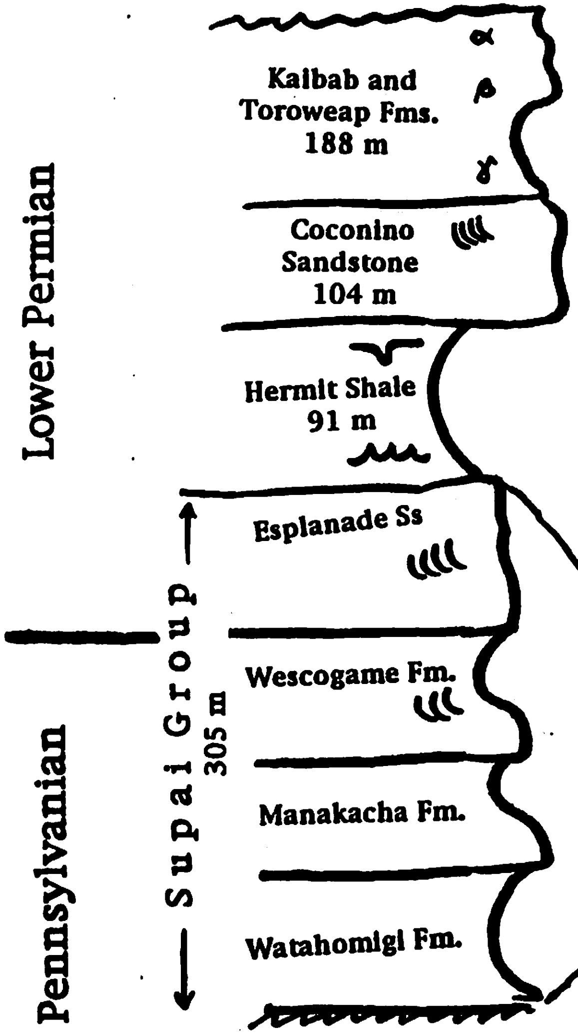
Period	**Dates (My Ago)**	**Distinctive Features**
Permian	230-280	Extinction of Trilobites, many marine animals
Pennsylvanian	280-310	Coal forests; first reptiles; Eagles last win Super Bowl
Mississippian	310-345	Sharks and amphibians; large primitive trees
Devonian	345-405	First Amphibians; Devo's first album released
Silurian	405-425	First land plants and animals
Ordovician	425-500	First fish, commemorated in LPL Atrium
Cambrian	500-570	First abundant record of marine invertebrates

Table 1: Subdivisions of Paleozoic, from *Dictonary of Geological Terms*, Bates and Jackson eds.

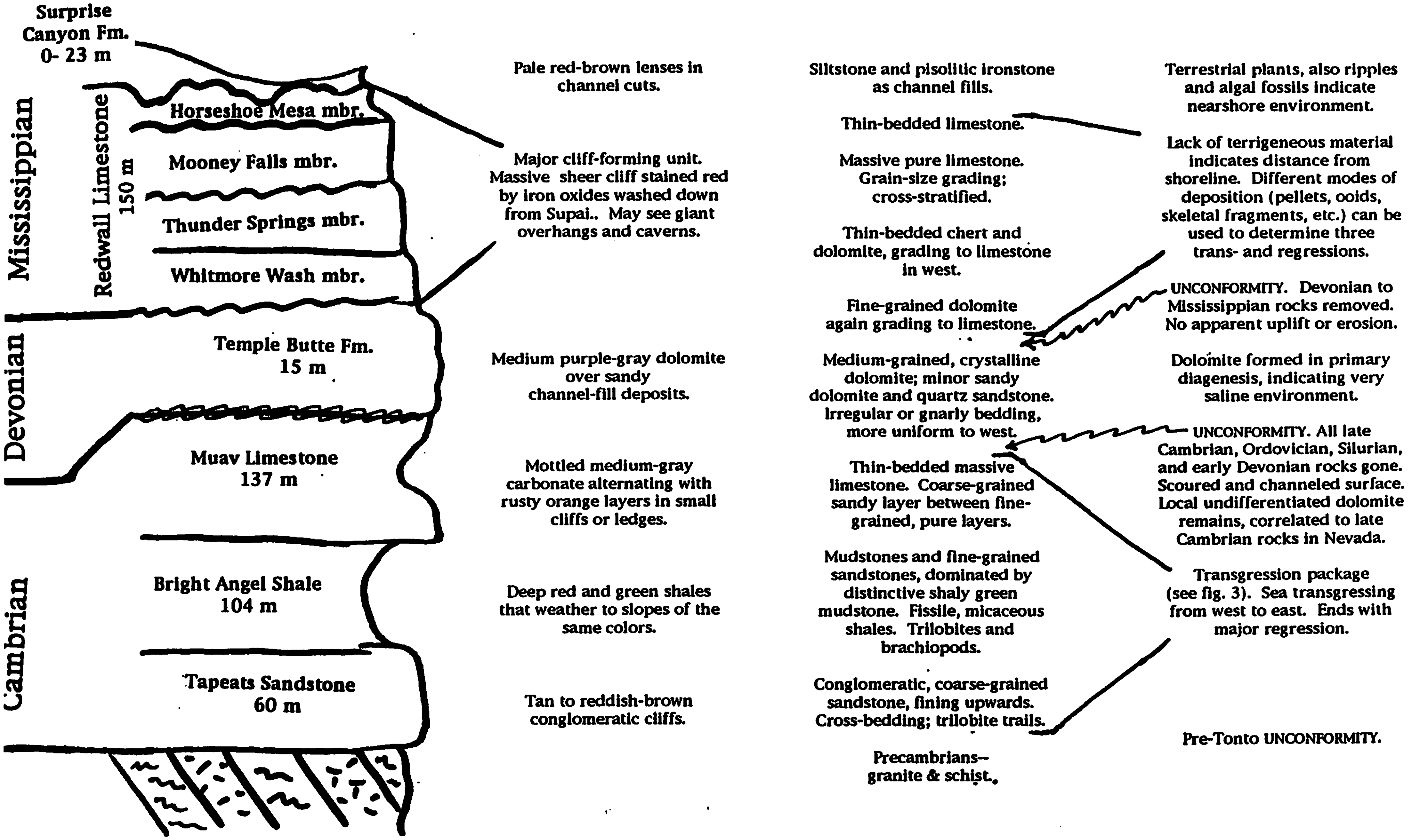
You don't really expect me to memorize the Grand Canyon Sequence (featured on the next page), do you?

Kill	Kaibab Limestone
The	Toroweap Formation
Cockroach!	Coconino Sandstone
He'll	Hermit Shale
Slink	Supai Group
Rascally	Redwall Limestone
To **B**eneath	Temple Butte Formation
My	Muav Limestone
Bed **A**nd	Bright Angel Shale
Taunt!	Tapeats Sandstone

Table 2: Foolproof Mnemonic for remembering the Paleozoic Grand Canyon Sequence.



Highly stylized strat section:	How to tell at what you're looking:	Geologically speaking:	What was going on?
			Current erosional surface.
Kaibab and Toroweap Fms. 188 m	Light-red to pale-gray cliff-forming limestones with thin receding siltstone beds. Base of Toroweap is a recessive yellowish sandstone.	Mostly sandy carbonate sediments. α: Redbeds, thin residual limestones, local gypsum. β: massive limestone. γ: thin limestone; reworked sediments.	Two marine transgressions separated by brief unconformity.
Coconino Sandstone 104 m	Tan to white massive, cross-bedded sandstone; forms huge cliff. Also, look for seeps and springs.	Clean, well-sorted quartz sand. Large-scale cross-stratification; long parallel ripple marks; lizard and worm tracks.	Aeolian deposit. Angle of cross-strata indicates transport from north; ripples form in crosswinds.
Hermit Shale 91 m	Reddish-brown slope-forming siltstones, commonly covered by talus.	Thin-bedded silty sandstone and sandy mudstone; almost no true fissile shale. Local limestone concretions, ripples, conglomerates. Plant fossils.	Many erosion surfaces, channeled and conglomerated; land plants and reptile tracks indicate a near-shore environment. Cross-bedding indicates transport from north; grain sizes in both formations fine to the south. Grades laterally into marine limestones to west and southeast.
Esplanade Ss	Thick reddish cliffs separated by gray ledges and recessive slopes.	Sandstone, grading into thin-bedded siltstone. Cross-bedding. Basal conglomerate (ls and ss fragments) marks unconformity.	
Wescogame Fm.		Alternating mudstones and cross-bedded sandstones. Basal conglomerate fills channels.	
Manakacha Fm.		Limestone-mudstone sequence; grades into sandstone to the west. Local conglomerate.	
Watahomigi Fm.		Alternating silt- and mudstone with limestone thinning downward. Chert-pebble congloms. Marine inverts.	
			UNCONFORMITY. Removal of late Mississippian rocks. Stream channels and solution-caused karst topography.



Pale red-brown lenses in channel cuts.

Siltstone and pisolitic ironstone as channel fills.

Terrestrial plants, also ripples and algal fossils indicate nearshore environment.

Thin-bedded limestone.

Major cliff-forming unit. Massive sheer cliff stained red by iron oxides washed down from Supai.. May see giant overhangs and caverns.

Massive pure limestone. Grain-size grading; cross-stratified.

Lack of terrigeneous material indicates distance from shoreline. Different modes of deposition (pellets, ooids, skeletal fragments, etc.) can be used to determine three trans- and regressions.

Thin-bedded chert and dolomite, grading to limestone in west.

Fine-grained dolomite again grading to limestone.

UNCONFORMITY. Devonian to Mississippian rocks removed. No apparent uplift or erosion.

Medium purple-gray dolomite over sandy channel-fill deposits.

Medium-grained, crystalline dolomite; minor sandy dolomite and quartz sandstone. Irregular or gnarly bedding, more uniform to west.

Dolomite formed in primary diagenesis, indicating very saline environment.

UNCONFORMITY. All late Cambrian, Ordovician, Silurian, and early Devonian rocks gone. Scoured and channeled surface. Local undifferentiated dolomite remains, correlated to late Cambrian rocks in Nevada.

Mottled medium-gray carbonate alternating with rusty orange layers in small cliffs or ledges.

Thin-bedded massive limestone. Coarse-grained sandy layer between fine-grained, pure layers.

Deep red and green shales that weather to slopes of the same colors.

Mudstones and fine-grained sandstones, dominated by distinctive shaly green mudstone. Fissile, micaceous shales. Trilobites and brachiopods.

Transgression package (see fig. 3). Sea transgressing from west to east. Ends with major regression.

Tan to reddish-brown conglomeratic cliffs.

Conglomeratic, coarse-grained sandstone, fining upwards. Cross-bedding; trilobite trails.

Pre-Tonto UNCONFORMITY.

Precambrians-- granite & schist.

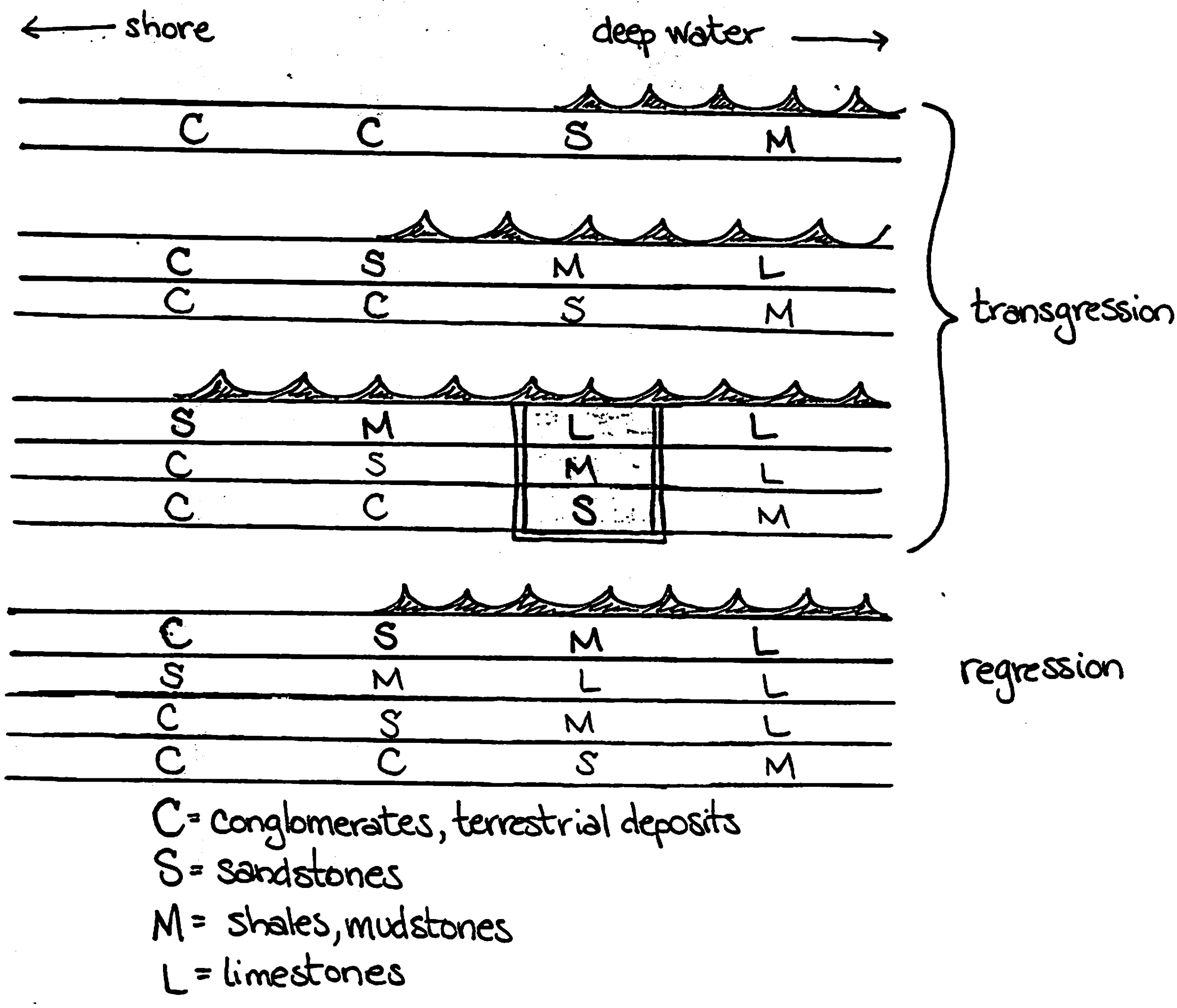


Figure 1: How a ocean trangression-regression sequence manifests itself in the geologic record

Geologic History of the Colorado River

Bill Bottke, Moderator

Questions

1. When and how did the Colorado River come into being?
2. How do rivers like the Colorado evolve?
3. When did canyon cutting and correlative uplift occur?
4. How and why has the Colorado cut across the many belts of high ground astride its course?
5. How quickly was the Grand Canyon cut?

Periods of Tectonism

1. Pre-rifting: (beginning and middle of Tertiary):
   (a) Basin-Range got underway along present course of Colorado River. Colorado Plateau became distinct structurally and morphologically from the adjacent Basin and Range Province.
2. Rifting: (5-8 Myr ago)
   (a) Time of basin-range extension; widespread interior drainage in Basin and Range Province
3. Post-rifting: (5-8 Myr ago to now).
   (a) Rifting ceased, Gulf of California opened, and through-drainage became established.

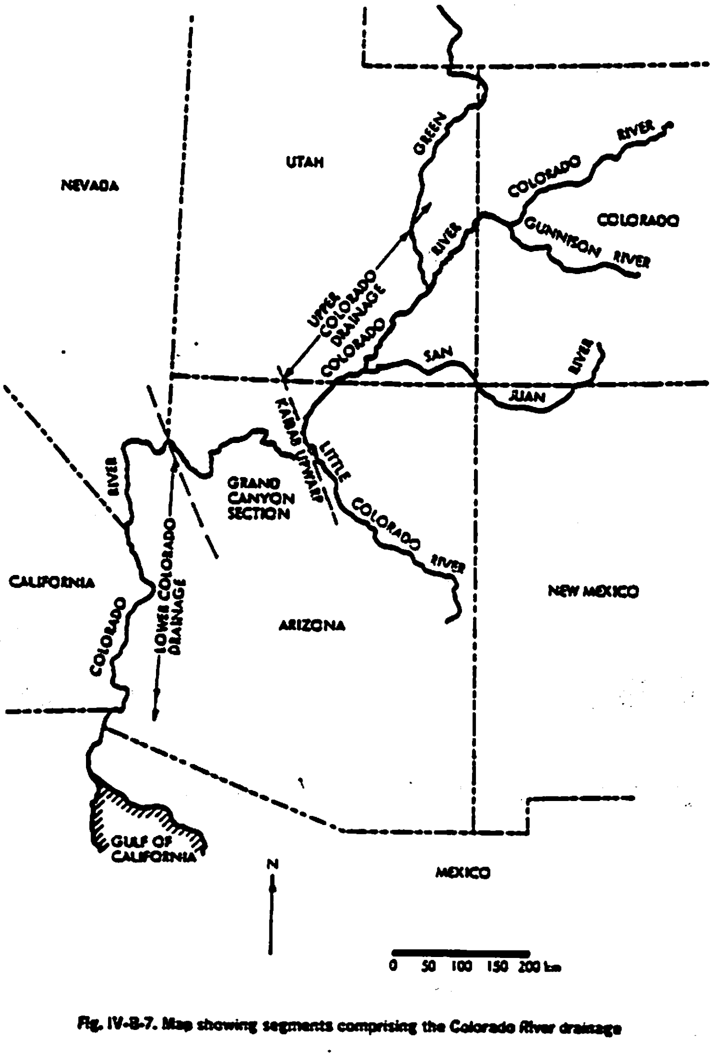
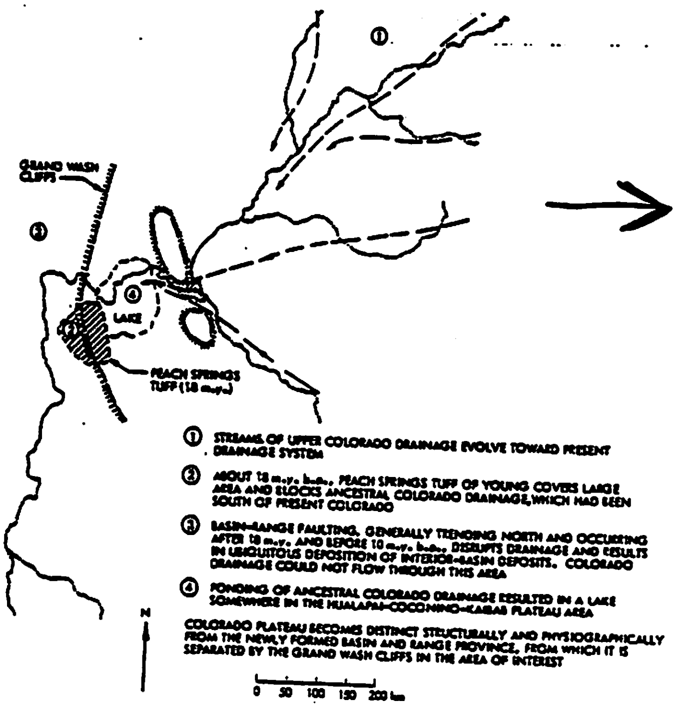


Fig. IV-B-7. Map showing segments comprising the Colorado River drainage

A History of Ideas

- **1860 (Powell)-1930's: ("Clearly, the Colorado River is old and it hasn't changed much.")**
  (a) Assumption that the Colorado River was in place in its present configuration during the Colorado Plateau uplift. Thus, the uplift allowed the river to cut the Grand Canyon during the Tertiary.
- **1930's-1940's: ("Oops! What I meant to say is that the Colorado River is young!")**
  (a) Work in the Basin and Range Province downstream showed the basins are filled with deposits produced by internal drainage. Where was the lower Colorado River at this time?
  (b) The sediments are as young as late Miocene. Thus, the Colorado River and Grand Canyon must be < 10 Myr old.
- **1940's-1960's: ("Well, the upper drainage is old, so it must all be old.")**
  (a) Ancestral drainage systems found in plateau country (Arizona, Utah, Colorado) which existed in Miocene or Oligocene.
- **1966 (Hunt): ("You say the lower drainage is young, now? I'm confused. Beer me!")**
  (a) No stratigraphic or morphological evidence found near mouth of Grand Canyon for through-flowing drainage system depositing interior basin material during Basin-Range deformation.
  (b) Deposits older than Basin-Range suggest drainage to the NE, rather than today's W to SW directions (i.e. from the Basin-Range region to Colorado Plateau).
- **Paradox: The river seemes as old as Miocene-Oligocene in its upper reaches, yet no older than latest Miocene or Pliocene in its lower reaches.**



① STREAMS OF UPPER COLORADO DRAINAGE EVOLVE TOWARD PRESENT DRAINAGE SYSTEM

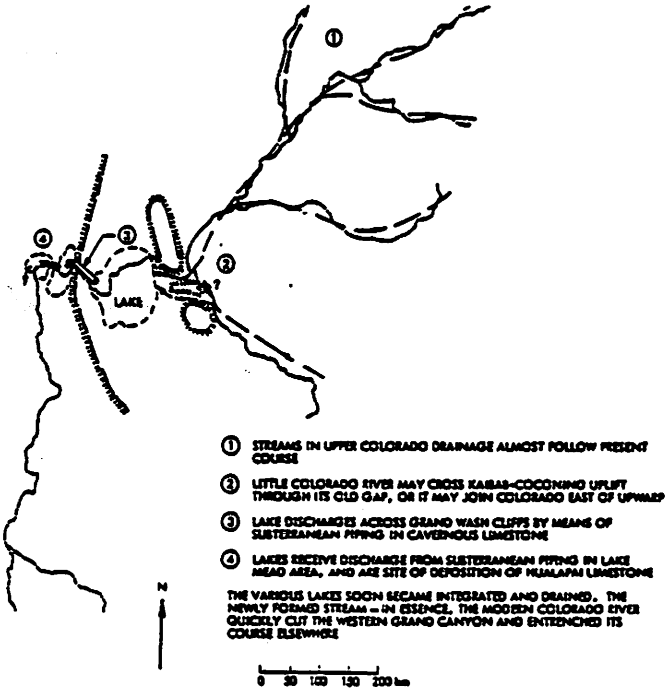
② ABOUT 18 m.y. b.p., PEACH SPRINGS TUFF OF YOUNG COVERS LARGE AREA AND BLOCKS ANCESTRAL COLORADO DRAINAGE, WHICH HAD BEEN SOUTH OF PRESENT COLORADO

③ BASIN-RANGE FAULTING, GENERALLY TRENDING NORTH AND OCCURRING AFTER 18 m.y. AND BEFORE 10 m.y. b.p., DISRUPTS DRAINAGE AND RESULTS IN UBIQUITOUS DEPOSITION OF INTERIOR-BASIN DEPOSITS. COLORADO DRAINAGE COULD NOT FLOW THROUGH THIS AREA

④ PONDING OF ANCESTRAL COLORADO DRAINAGE RESULTED IN A LAKE SOMEWHERE IN THE HUALAPAI-COCONINO-KAIBAB PLATEAU AREA

COLORADO PLATEAU BECOMES DISTINCT STRUCTURALLY AND PHYSIOGRAPHICALLY FROM THE NEWLY FORMED BASIN AND RANGE PROVINCE, FROM WHICH IT IS SEPARATED BY THE GRAND WASH CLIFFS IN THE AREA OF INTEREST

Fig. IV-8-8b. Hunt's hypothesis. Ancestral Colorado Drainage after effusion of Peach Springs Tuff and basin-range faulting (after 18 m.y., before 10 m.y.b.p.)



① STREAMS IN UPPER COLORADO DRAINAGE ALMOST FOLLOW PRESENT COURSE

② LITTLE COLORADO RIVER MAY CROSS KAIBAB-COCONINO UPLIFT THROUGH ITS OLD GAP, OR IT MAY JOIN COLORADO EAST OF UPWARP

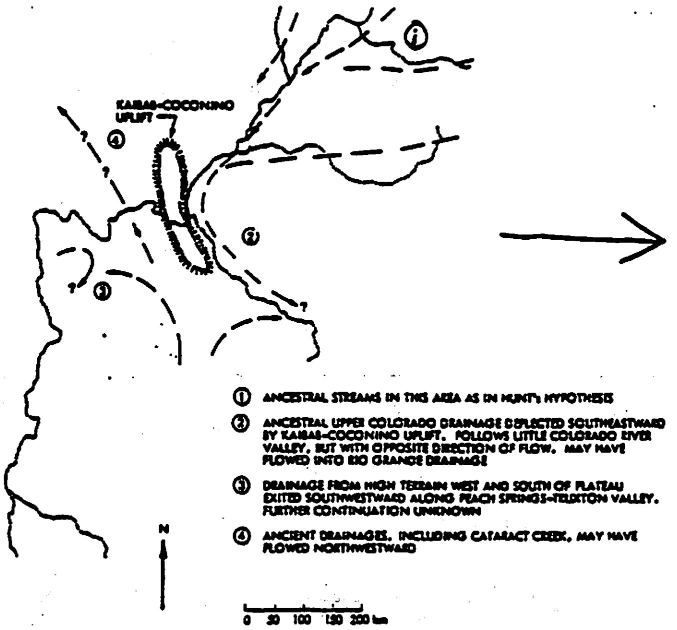
③ LAKE DISCHARGES ACROSS GRAND WASH CLIFFS BY MEANS OF SUBTERRANEAN PIPING IN CAVERNOUS LIMESTONE

④ LAKES RECEIVE DISCHARGE FROM SUBTERRANEAN PIPING IN LAKE MEAD AREA, AND ARE SITE OF DEPOSITION OF HUALAPAI LIMESTONE

THE VARIOUS LAKES SOON BECAME INTEGRATED AND DRAINED. THE NEWLY FORMED STREAM – IN ESSENCE, THE MODERN COLORADO RIVER QUICKLY CUT THE WESTERN GRAND CANYON AND ENTRENCHED ITS COURSE ELSEWHERE

Fig. IV-8-8c. Hunt's hypothesis. Ancestral Colorado Drainage shortly before integration into modern course

- **1969 (McKee): ("The upper drainage is old, the lower drainage is new, and I feel fine!")**
  - (a) Proposed polyphase history for the Colorado River. The ancient upper Colorado followed its present course as far as the East end of the Colorado River, then went SE along the course of the little Colorado and Rio Grande rivers into the Gulf of Mexico.
  - (b) In Pliocene, a youthful stream emptying into the Gulf of California with a steep gradient eroded headward and captured the sluggish ancestral river somewhere in the eastern Grand Canyon area.
  - (c) Once captured, the Colorado River established its present course.
  - (d) This concept shows that drainage systems evolve continually-through headwater erosion and capture in response to tectonic movements. In doing this, the configuration and course of the drainage system can change a lot.



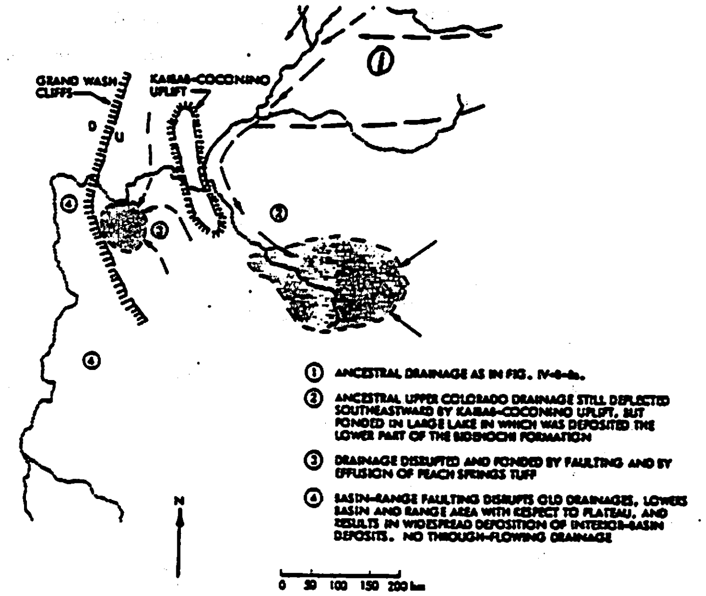
① ANCESTRAL STREAMS IN THIS AREA AS IN HUNT's HYPOTHESIS

② ANCESTRAL UPPER COLORADO DRAINAGE DEFLECTED SOUTHEASTWARD BY KAIBAB-COCONINO UPLIFT. FOLLOWS LITTLE COLORADO RIVER VALLEY, BUT WITH OPPOSITE DIRECTION OF FLOW. MAY HAVE FLOWED INTO RIO GRANDE DRAINAGE

③ DRAINAGE FROM HIGH TERRAIN WEST AND SOUTH OF PLATEAU EXITED SOUTHWESTWARD ALONG PEACH SPRINGS-TRUXTON VALLEY. FURTHER CONTINUATION UNKNOWN

④ ANCIENT DRAINAGES, INCLUDING CATARACT CREEK, MAY HAVE FLOWED NORTHWESTWARD

Fig. IV-8-9a. Hypothesis of McKee et al. Ancestral Colorado Drainage before major basin-range faulting (approximately >18 m.y.b.p.)



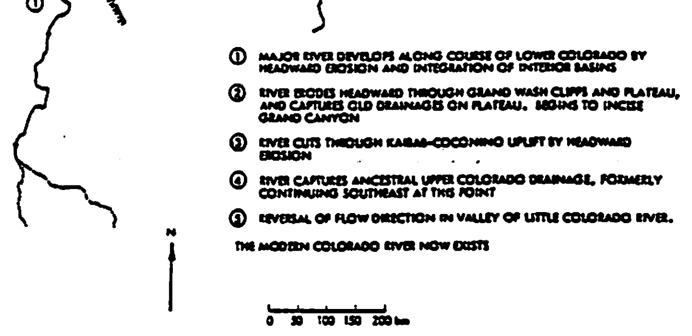
① ANCESTRAL DRAINAGE AS IN FIG. IV-8-9a.

② ANCESTRAL UPPER COLORADO DRAINAGE STILL DEFLECTED SOUTHEASTWARD BY KAIBAB-COCONINO UPLIFT, BUT PONDED IN LARGE LAKE IN WHICH WAS DEPOSITED THE LOWER PART OF THE BIDAHOCHI FORMATION

③ DRAINAGE DISRUPTED AND PONDED BY FAULTING AND BY EFFUSION OF PEACH SPRINGS TUFF

④ BASIN-RANGE FAULTING DISRUPTS OLD DRAINAGES, LOWERS BASIN AND RANGE AREA WITH RESPECT TO PLATEAU, AND RESULTS IN WIDESPREAD DEPOSITION OF INTERIOR-BASIN DEPOSITS. NO THROUGH-FLOWING DRAINAGE

Fig. IV-8-9b. Hypothesis of McKee et al. Ancestral Colorado Drainage after basin-range faulting and effusion of Peach Springs Tuff (approximately 18 m.y. to 10 m.y.b.p.)



① MAJOR RIVER DEVELOPS ALONG COURSE OF LOWER COLORADO BY HEADWARD EROSION AND INTEGRATION OF INTERIOR BASINS

② RIVER ERODES HEADWARD THROUGH GRAND WASH CLIFFS AND PLATEAU, AND CAPTURES OLD DRAINAGES ON PLATEAU. BEGINS TO INCISE GRAND CANYON

③ RIVER CUTS THROUGH KAIBAB-COCONINO UPLIFT BY HEADWARD EROSION

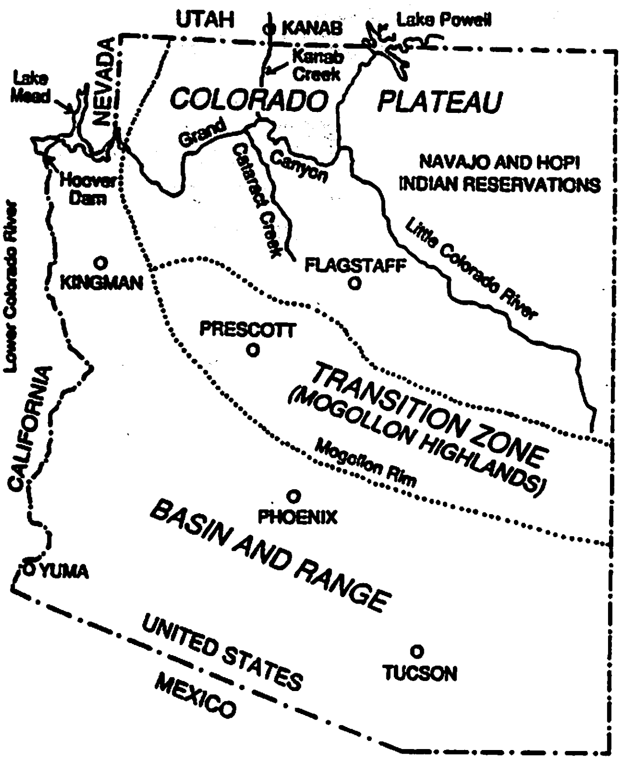
④ RIVER CAPTURES ANCESTRAL UPPER COLORADO DRAINAGE, FORMERLY CONTINUING SOUTHEAST AT THIS POINT

⑤ REVERSAL OF FLOW DIRECTION IN VALLEY OF LITTLE COLORADO RIVER.

THE MODERN COLORADO RIVER NOW EXISTS

Fig. IV-8-9c. Hypothesis of McKee et al. Ancestral Colorado Drainage becoming modern Colorado River through headward erosion, capture, and integration after opening of the Gulf of California

- **1970's: ("Well, I am not so fine anymore. Beer me again!")**
  - (a) Evidence against SE drainage along Little Colorado River.
  - (b) Evidence against ancient river flowing W through western Grand Canyon
  - (c) Lower Colorado deposits in the Basin-range region confirm that part of the river is no older than Miocene. Also, river deposits show that the ancestral river was captured.
- **1980's-Now (Lucchitta): ("Never let the lack of data spoil perfectly good theory!")**
  - (a) Ancient Colorado did not flow SE along the Little Colorado. Instead, the river crossed the Kaibab Plateau along the present course of the Grand Canyon, then continued NW along a strike valley in the area of the Kanab, Uinkaret, and Shivwits plateaus to an (as yet) unknown destination.
  - (b) After the opening of the Gulf of California, this ancestral drainage was captured W of Kaibab plateau by the lower Colorado drainage.
  - (c) Thus, the upper Grand Canyon in the Kaibab plateau is old and related to the ancestral river, whereas the lower part of the canyon in this area and the W Grand Canyon postdates the capture and was carved in a few million years (aided by 0.6 miles of regional uplift).



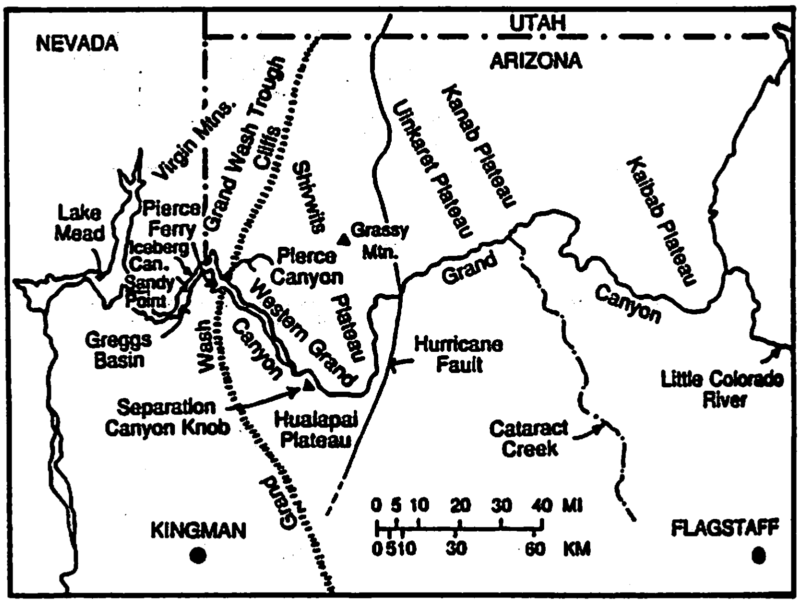


Figure 2. Map showing selected geologic and geographic features in northern Arizona

Figure 1. Location map, Arizona

HOW THE CANYON GOT WIDE & OTHER COOL STUFF:
MASS WASTING IN THE GRAND CANYON

- with your able guides -

Mark Fischer, Will Grundy & Erich Karkoschka

Slope Stability:

F = (shear strength)/(shear stress)

F > 1 ==> stable

F = 1 ==> imminent failure (i.e. get out 'da way)

Table 4.4 Factors that influence stress and resistance in slope materials.

Factors That Increase Shear Stress

- Removal of lateral support
  - Erosion (rivers, ice, wave)
  - Human activity (quarries, road cuts, etc.)
- Addition of mass
  - Natural (rain, talus, etc.)
  - Human (fills, ore stockpiles, buildings, etc.)
- Earthquakes
- Regional tilting
- Removal of underlying support
  - Natural (undercutting, solution, weathering, etc.)
  - Human activity (mining)
- Lateral pressure
  - Natural (swelling, expansion by freezing, water addition)

Factors That Decrease Shear Strength

- Weathering and other physicochemical reactions
  - Disintegration (lowers cohesion)
  - Hydration (lowers cohesion)
  - Base exchange
  - Solution
  - Drying
- Pore water
  - Buoyancy
  - Capillary tension
- Structural changes
  - Remolding
  - Fracturing

After Varnes 1958, with permission of the Transportation Research Board.

RITTER

Types of Mass Movements:

1. Slide - movement of a cohesive block of material along a well-defined surface.
2. Flow - movement by differential shearing w/in transported mass; velocities tend to decrease from the surface downward.
3. Heave - disrupting forces act perpendicular to a surface by expansion of material (e.g. freezing, release of compressive stress).

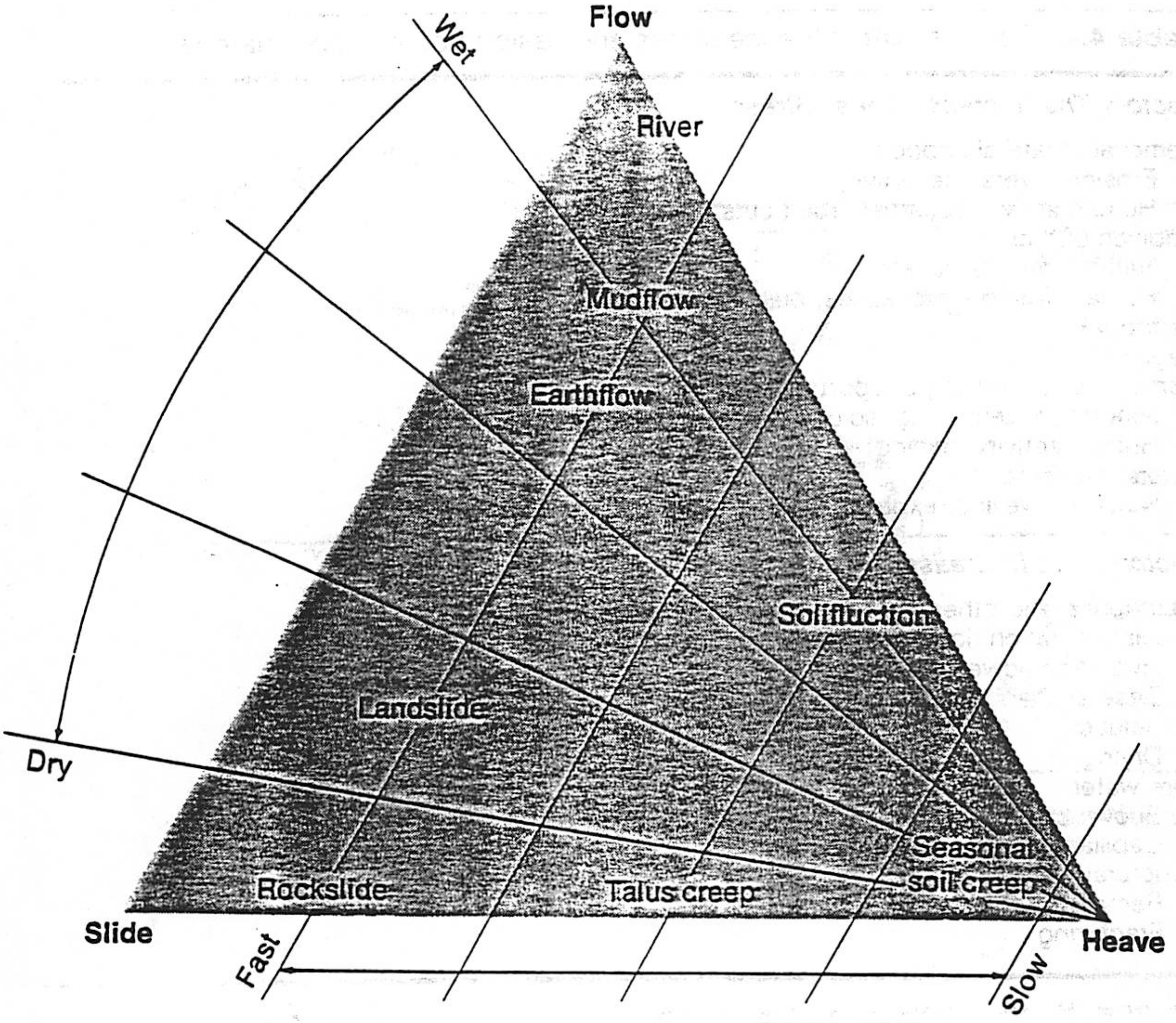


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Figure 4.15.
Classification of mass movement processes.

Slope Profiles & Evolution:

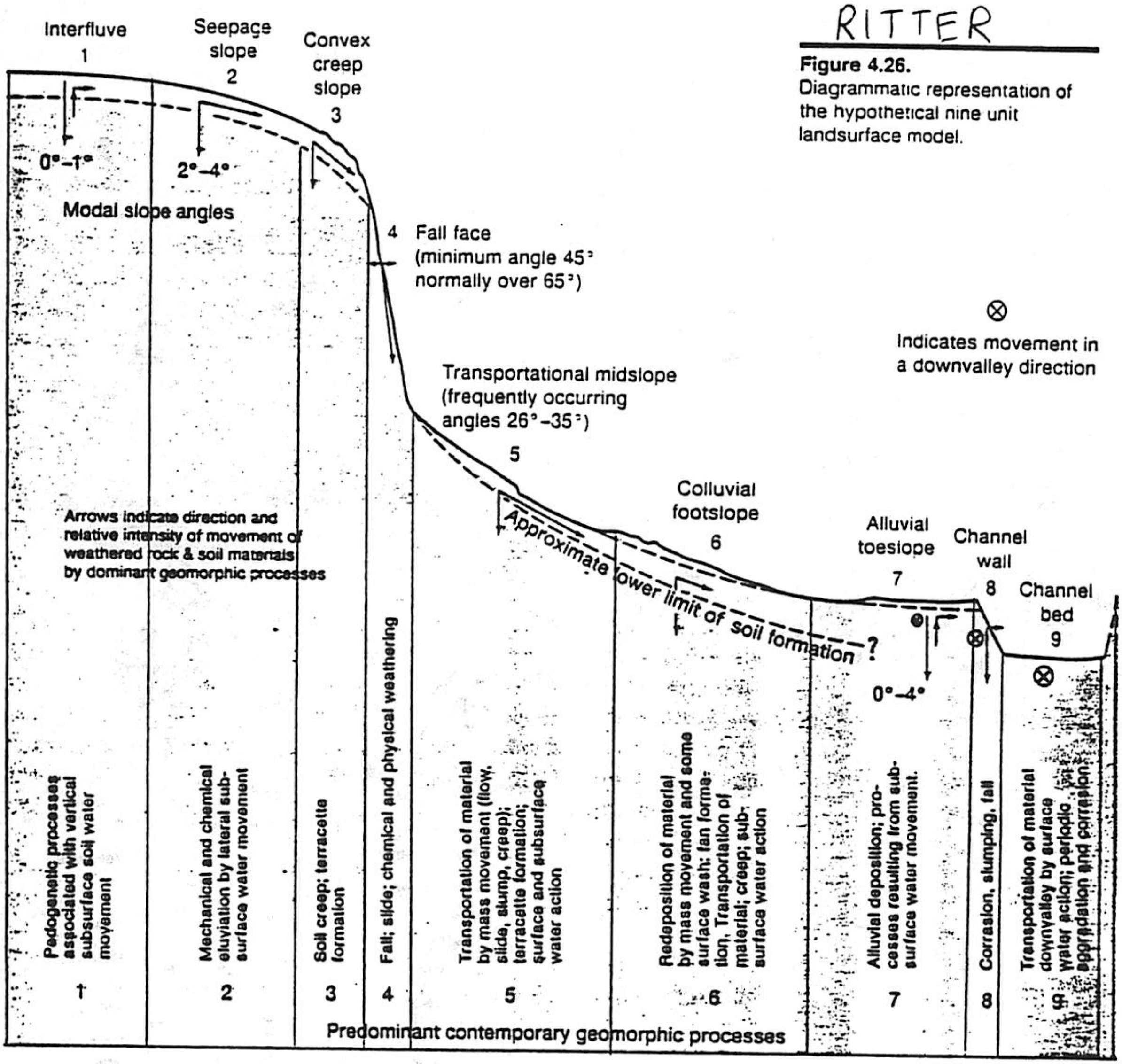

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Figure 4.26.
Diagrammatic representation of the hypothetical nine unit landsurface model.

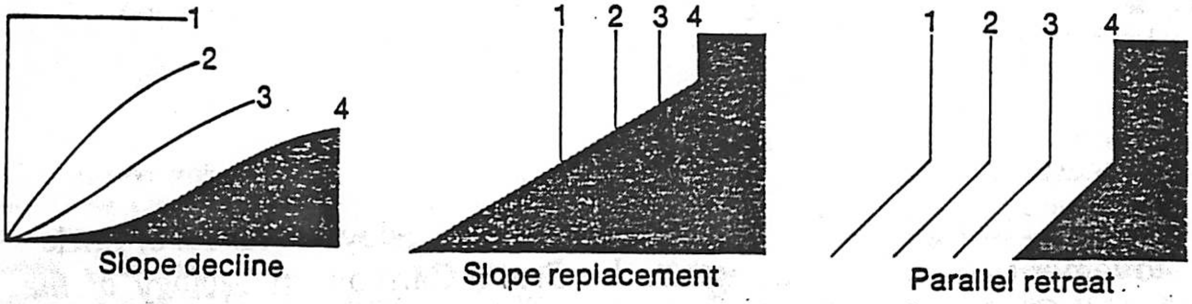

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Figure 4.30.
Three hypotheses of slope evolution. Higher numbers indicate increasing age of the slope. (Adapted from Young, 1972, fig. 14, in *Slopes*. With permission of A. Young.)

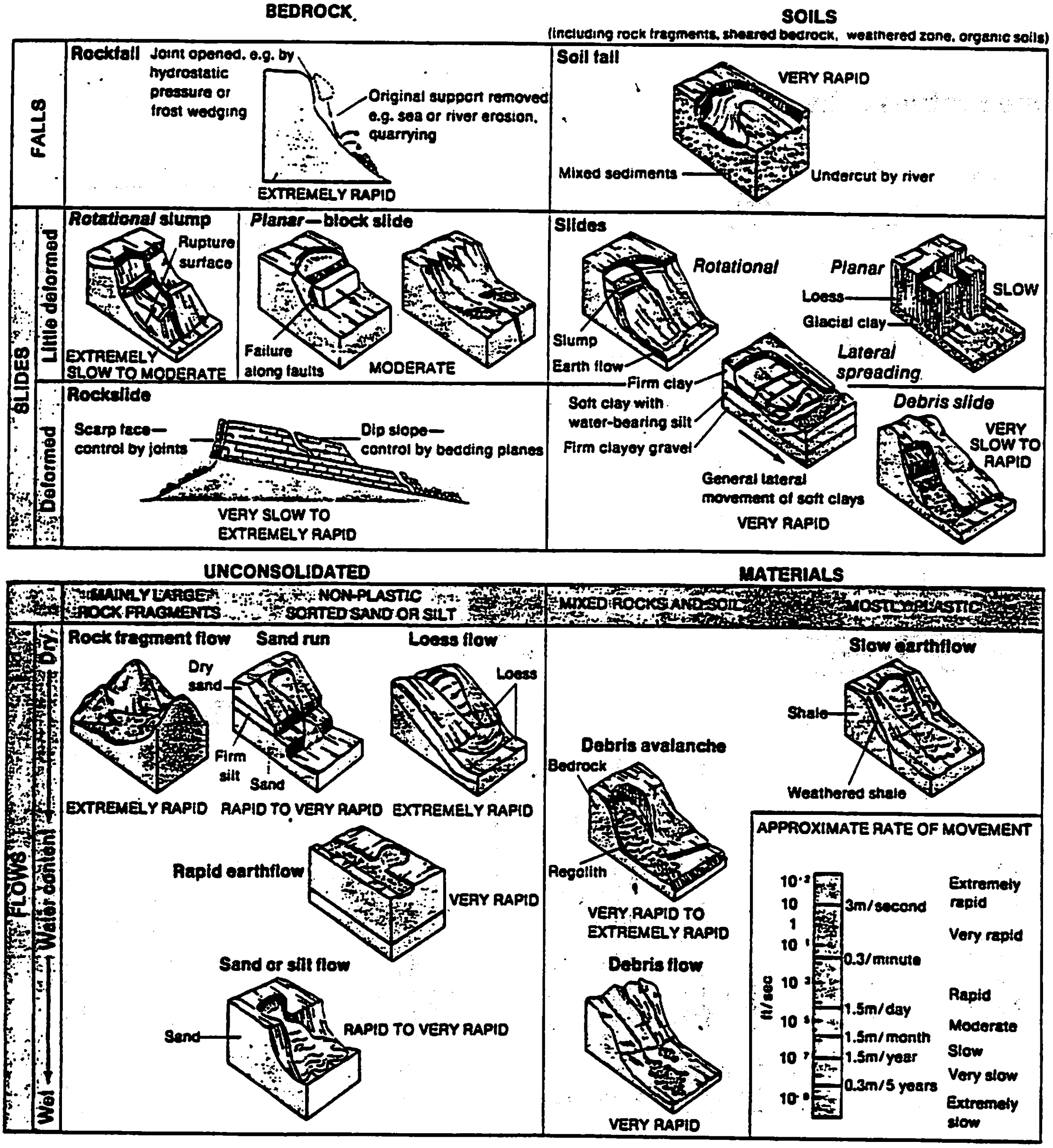

Figure 4.20.
Classification of landslides.

RITTER

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Catastrophism versus Gradualism

Comments on a Comparative Photogeologic Study of the Grand Canyon

Your guide - Jennifer A. Grier

The Grand Canyon:

J.W. Powell executed two trips down the Green and Colorado rivers. The first expedition in 1869 was limited by lack of funds and lack of food, and thus geology was not the main concern. The second expedition in 1871-72 produced a series of 225 pictures of scenes along the two rivers. The process used to obtain these pictures (wet-collodian) was originally developed for astronomical photography, and required that a ton of equipment including glass plates, chemicals, cameras, and a darkroom tent be transported to each camera station. In 1969, the USGS, the Smithsonian, and Natl. Geographic Soc. arranged to commemorate Powell's journeys by retraversing the entire length of Powell's second expedition and rephotographing all the scenes from the original camera stations. H.G. Stephens and E.M. Shoemaker headed up this endeavor.

Extreme care was taken to reoccupy the old camera stations to the best of their ability. Usually, they were successful to within a foot of the old site. *In almost all cases, the scene from 1871-72 is geologically identical to that from 1969.* Flooding from the construction of the Glen Canyon dam, and changes in vegetation are almost the only noticeable differences between the sets of pictures. *In a few instances, dramatic changes can be seen in the photographs.* These have all been ascribed to *catastrophic flooding* of the Green and Colorado rivers. One example of this is a flood witnessed in 1965 on Yampa River Canyon, Utah. This flood deposited a line of boulders which forced the river against its left bank. In three years the river cut away part of the line of boulders (some very large) and scoured out the river's left bank.

This comparative geologic study indicates that gradual change in the Colorado river over the last 100 years has been almost unnoticeable. Whenever change has occurred, it has been dramatic. In each case of dramatic change along the river, catastrophic flooding was offered as the most likely explanation for the change.

Surface Runoff and Erosion:

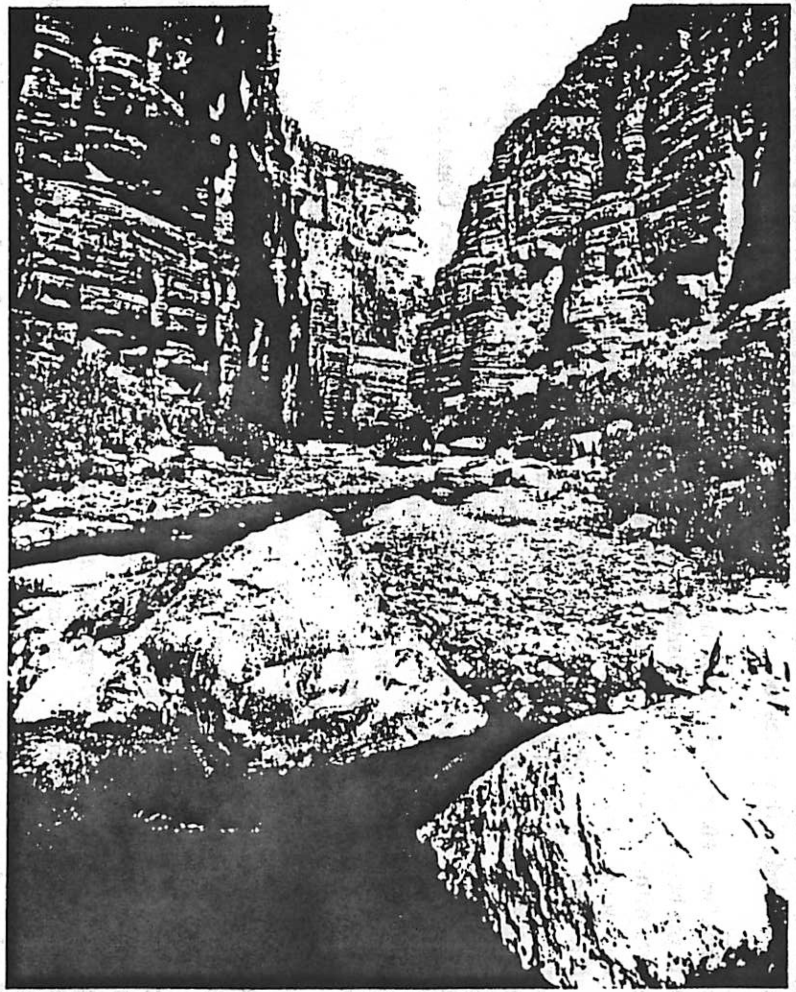
In order for features such as fluvial valleys to develop from surface runoff processes, water runoff must concentrate and flow with enough force to erode the land surface. In order for water to be available at the surface, the rate of runoff must exceed the rate of water infiltration. After this, water from a wide source area migrates across the surface and collects in topographic lows which thereby concentrates the flow of water moving downslope. An increased downslope flow of water has an increased ability to erode the surface and establish or deepen a fluvial valley.

If surface runoff does not have adequate downslope flow, it will not be capable of significant erosion. In the example from the comparison of the Grand Canyon photographs, it is clear that for most of the time, the gradual flow of the Colorado does not generate significant erosion. The episodes when the Colorado does erode its banks significantly are during catastrophic flood times, when the increased flow of water downslope allows for increased erosion. It appears that the Grand Canyon was cut, not by the gradual flow of the Colorado, but by catastrophic flooding events which had the ability to make significant changes on the surface.

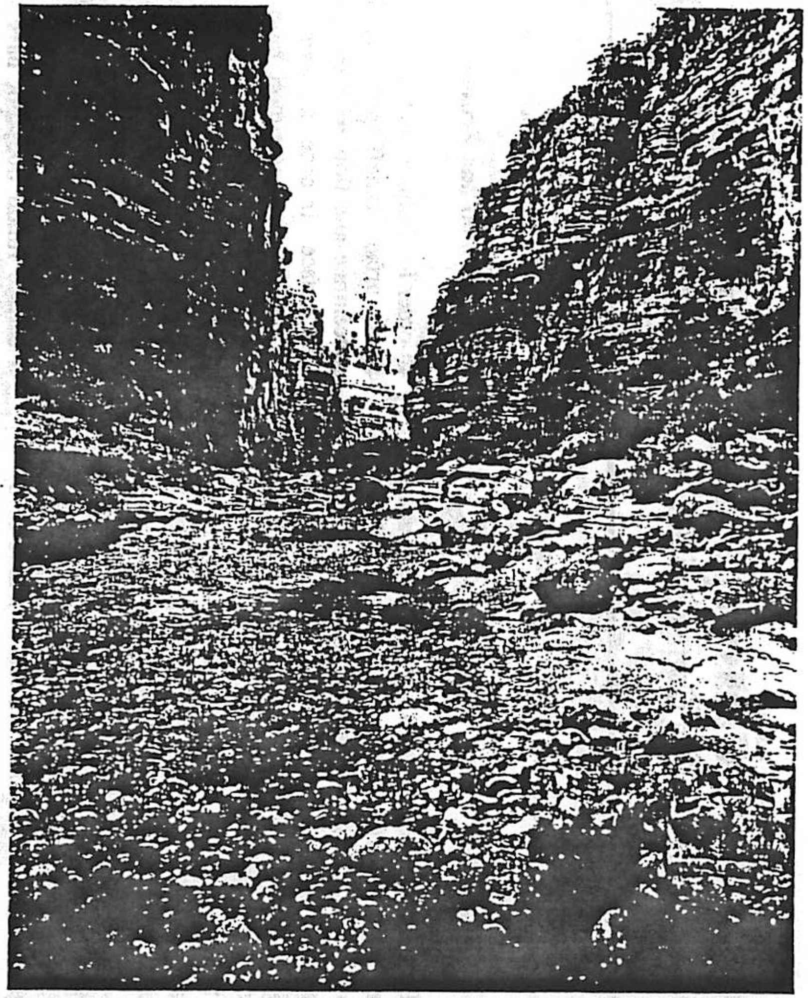
The Planetary Connection:

Is catastrophic flooding an important process in shaping the surface of other planetary bodies? The outflow channels on Mars appear to be a likely candidate. The morphology and scale of these features clearly suggests that they were formed by some fluid flow of immense magnitude. The hypothesis which most completely accounts for the entire range of features associated with outflow channels is cataclysmic flooding. Highly turbulent, catastrophic flows are extremely effective erosion agents, and explain well the magnitude of erosion necessary to create the outflow channels and their related features. A gradual fluid flow would not have possessed the erosive ability necessary to carve these features.

Kanab Creek

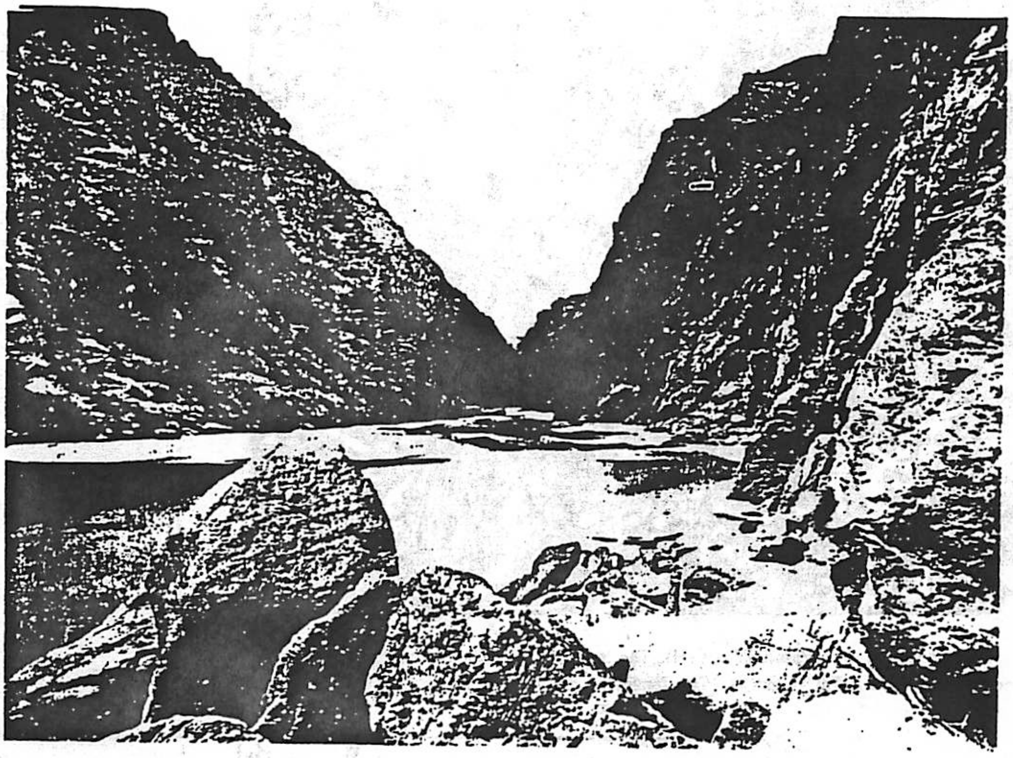


Mid-September 1872, about noon

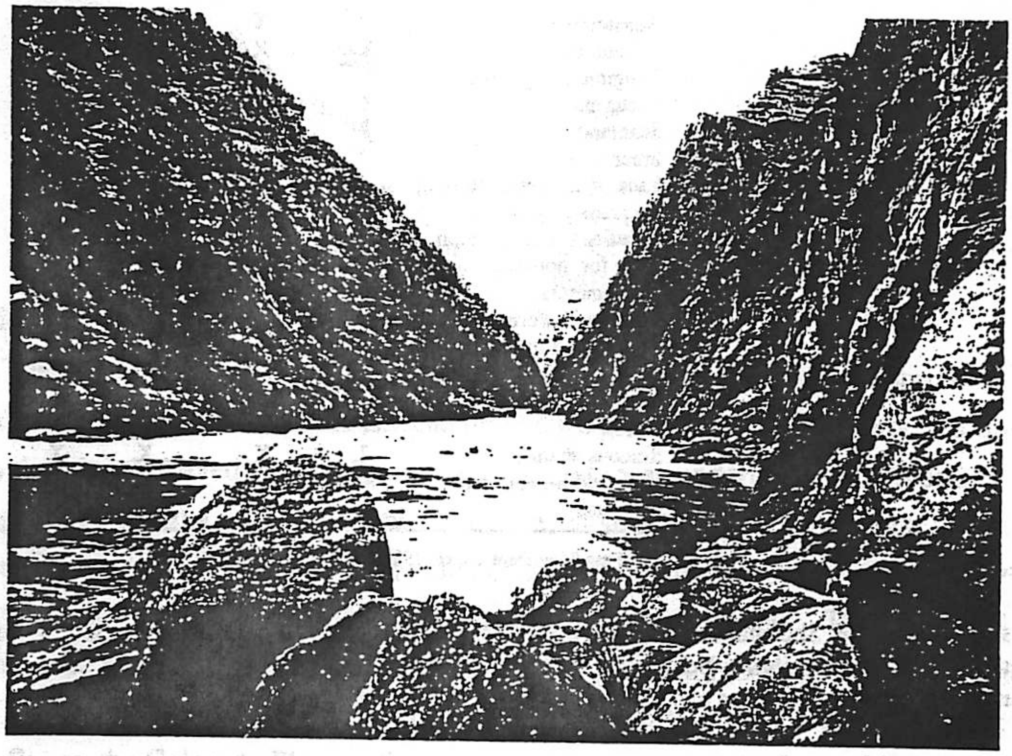


September 23, 1968

Grand Canyon
Camera Station 449



August 29, 1872, about noon



September 11, 1968

Fig. 1. Chaotic terrain at Hydaspis Chaos (H). The large outflow channel extending northward from the chaos zone is Tiu Vallis (T). (The images are a portion of JPL Viking Orbiter Mosaic 211–5556.)

Morphological Features	Wind	Mud Flow	Glacier	Lava	Catastrophic Flood
Anastomosis	?	X	X	X	X
Streamlined uplands	X	X	X	?	X
Longitudinal grooves	X	X	X	?	X
Scour marks	X	?	?	?	X
Scabland	?	—	?	—	X
Inner channels	?	X	?	X	X
Lack of solidified fluid at channel mouth	X	—	X	—	X
Localized source region	?	X	X	X	X
Flow for thousands of kilometers	X	—	X	X	X
Bar-like bedforms	?	?	?	?	X
Pronounced upper limit to fluid erosion	—	X	X	X	X
Consistent downhill fluid flow	?	X	X	X	X
Sinuous channels	?	X	X	X	X
High width-depth ratio	X	X	X	—	X
Headcuts	—	?	X	—	X

*Table modified from Baker (1982).

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Baker, et. al. Channels and Valley Networks. 1992. Mars. University of Arizona Press.
Knighton, D. 1984. Fluvial Forms and Processes. (London: E. Arnold).

Monoclines on the Colorado Plateau

Elizabeth P. Turtle

Ptys 594a, Spring 1994

Characteristics:

- >30 fracture zones
- trend generally northwards, ranging between N55°W and N55°E
- 100-650km long (average = 350km)
- spaced ~45km apart

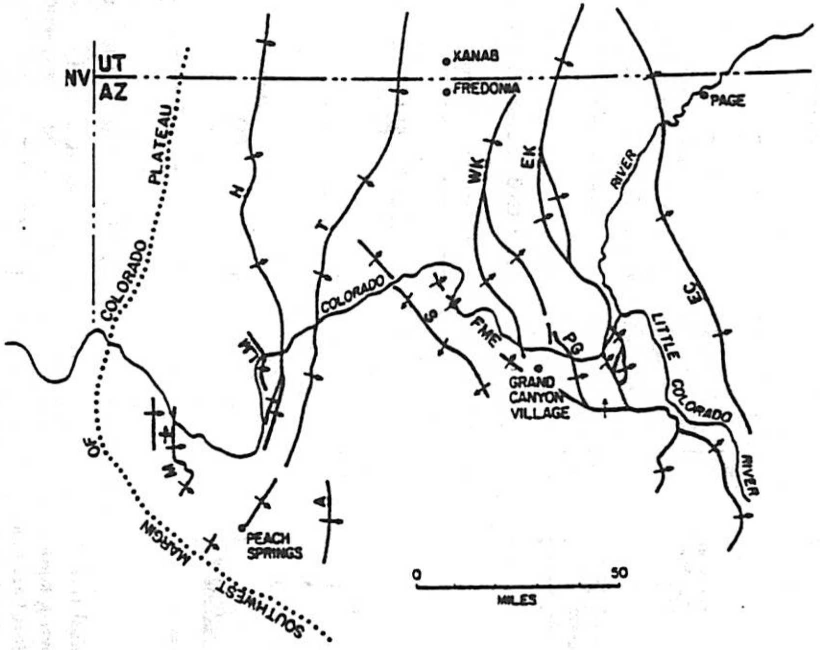


Figure 3. Locations of the Laramide monoclines in the Grand Canyon region, Arizona. From west to east: M - Meriwhitica; LM - Lone Mountain; H - Hurricane; T - Toroweap; A - Aubrey; S - Supai; FME - Fossil-Monument-Ermita; WK - West Kaibab; PG - Phantom-Grandview; EK - East Kaibab; EC - Echo Cliffs

(Huntoon, 1990)

Formation:

The monoclines are thought to have formed due to E/NE horizontal compressive stresses from the late Cretaceous to Eocene time, during the Laramide orogeny. At this point in time it is believed that the Pacific oceanic plate was underplating the North American plate due to a very rapid subduction rate causing uplift and horizontal compressive stresses. Despite the orientation of the maximum compressive stress, the faults over which the monoclines developed have very high dips, ~60°. This is possible if the faults were normal faults which predated the Laramide compression. Other evidence that the monoclines formed by reactivating pre-existing faults is their branching, sinuous nature. So, on the Colorado Plateau, the compressive stresses of the Laramide orogeny resulted in the formation of monoclines by reverse motion along older, normal faults.

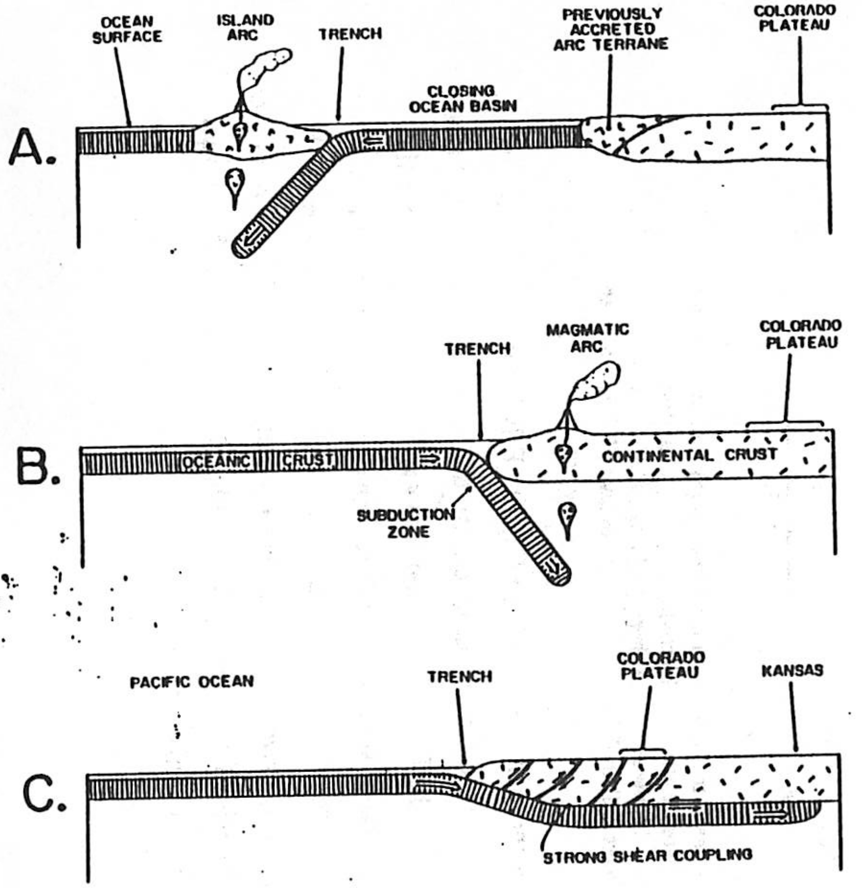
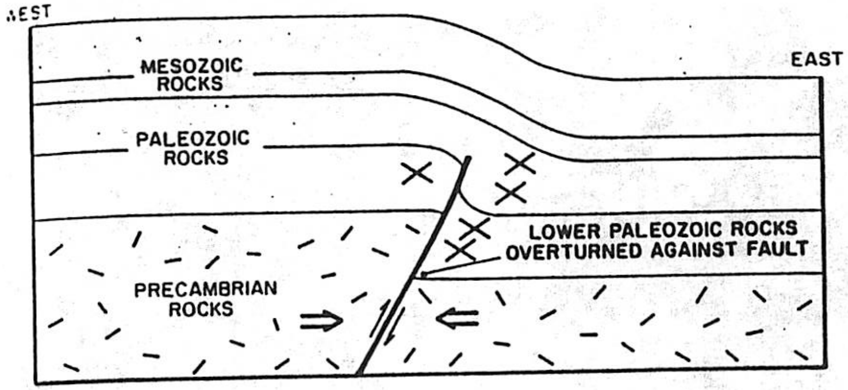
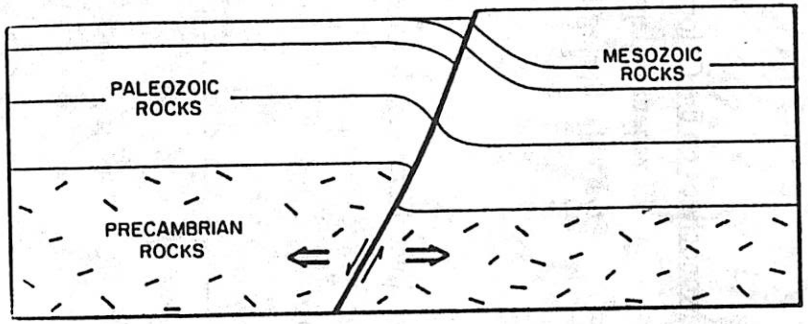


Figure 2. Convergent margin orogens along western North America. (A) Intraoceanic arc-trench orogen active periodically in post-Precambrian through Late Triassic time. Notice that the ocean basin closes, allowing island arc to accrete to continent, then another subduction zone and its island arc can form offshore and likewise eventually accrete to continent. (B) Slow landward subduction causing development of magmatic arc inboard on continent above steeply descending slab active from Late Triassic to Late Cretaceous time. (C) Rapid subduction resulting in shallow slab descent and slab underplating of continent to produce buoyant uplift and strong shear coupling with eastward telescoping of continental crust during Laramide time. Vertical scales are greatly exaggerated. (Huntoon, 1990)

A. Laramide folding over reactivated Precambrian fault; Precambrian fault was normal.



B. Late Cenozoic normal faulting.



C. Late Cenozoic configuration after continued extension.

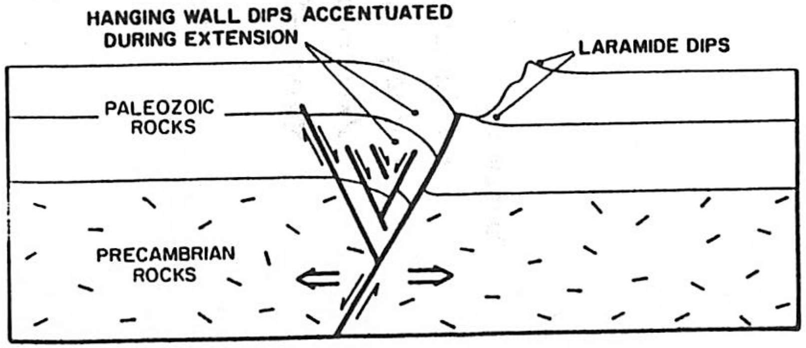
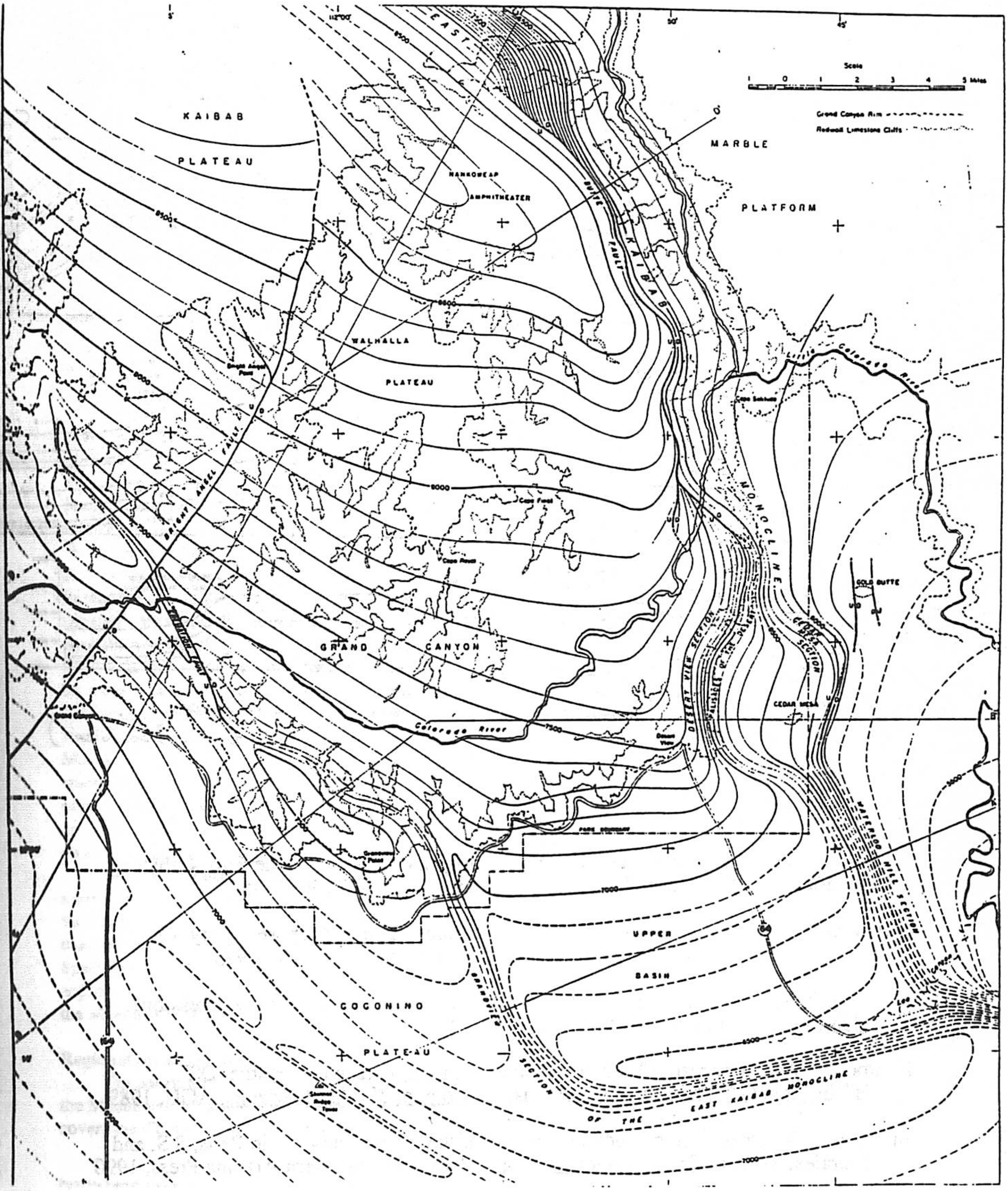
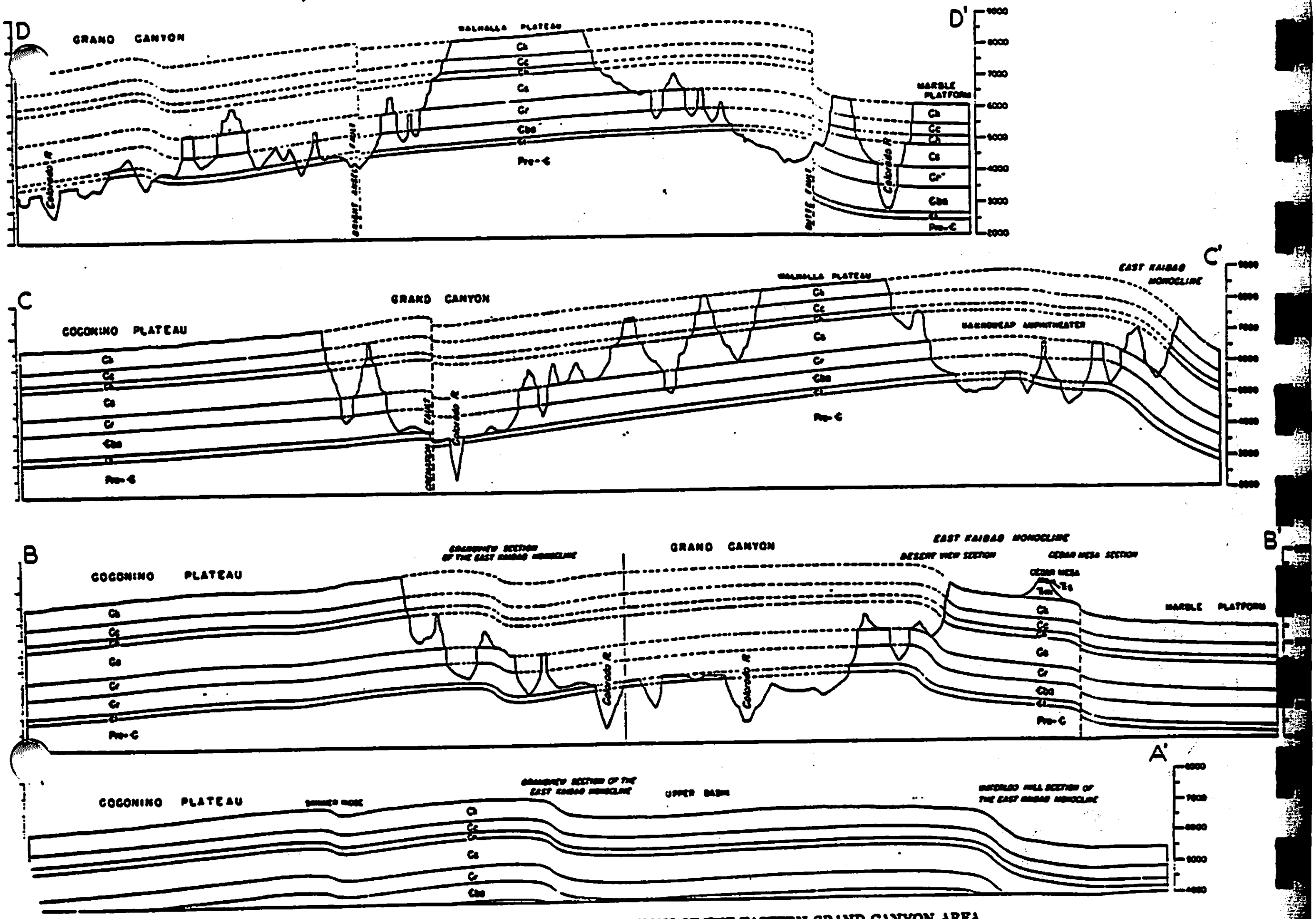


Figure 4. Stages in the development of a typical north-trending monocline-fault zone, Grand Canyon region, Arizona (Huntoon, 1990)



(Babenroth & Strahler)



STRUCTURE MAP AND STRUCTURE SECTIONS OF THE EASTERN GRAND CANYON AREA

Contours approximately on top of Beta member of Kaibab limestone. Contour interval 100 feet. Dashed contours unreliable.

(Babenroth & Strahler)

REFERENCES:

Babenroth, D.L. and Strahler, A.N. Geomorphology and structure of the East Kaibab Monocline, Arizona and Utah. GSA Bulletin, **56**, pp. 107-150, 1945.

David, G.H., Regional fracture system of the Colorado Plateau as expressed by the monoclinal-fold pattern, GSA Abstracts with Programs, **7**, p. 1046, 1975.

Huntoon, P.W., Grand Canyon monoclines: vertical uplift or horizontal compression?, Contributions to Geology, **19**, pp. 127-134, 1981.

Huntoon, P.W., Phanerozoic Tectonism, Grand Canyon, Arizona, in Elston, D.P., Billingsley, G.H., and Young, R.A. eds., Geology of Northern Arizona, AGU, 1989

Huntoon, P.W., Phanerozoic structural geology of the Grand Canyon., in Beus, S.S. and Morales, M. eds., Grand Canyon Geology, Museum of Northern Arizona Press, 1990

Another article which sounds very useful, but which is, unfortunately, currently missing from the Uof A science library:

Kelley, V.C. Monoclines of the Colorado Plateau. GSA Bulletin, **66**, pp 789-803, 1955

DINOSAUR TRACKSITES

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Introduction

Dinosaur tracks, like fossilized dinosaur skeletons, are preserved fragments of Mesozoic life. They are, however, more subtle features than fossilized bones and have, consequently, not been utilized to the same extent as skeletal remains until recently. It is now recognized that tracks provide information about dinosaur mobility and social behavior that is unobtainable from dinosaur bones. In addition, there are some portions of the stratigraphic sequence in which the only record of dinosaur fauna is in the form of tracks. For example, in eastern Utah tracks the only record of dinosaur fauna in the Wingate, Kayenta, Navajo, Dewey Bridge, Slick Rock, or Moab Tongue formations, representing the entire lower and middle Jurassic (Lockley 1991, p. 90).

Tracksites are known throughout the Southwest and Rocky Mountain regions, in formations that range in age from Late Triassic through Late Cretaceous. On this fieldtrip, we will examine the Moenave Road Tracksite near Tuba City. It is one of several Early Jurassic dinosaur tracksites that have been found in northeastern Arizona and studied by the Museum of Northern Arizona (MNA; see Table 1). After seeing the Moenave Road Tracksite, we will visit the museum where Grace Irby will show us some casts from the other Arizona sites and explain how the tracksites are being used to infer the behavior of individual dinosaurs and groups of dinosaurs.

(Please note that most of the tracksites in northeastern Arizona are on reservation land, and thus deserve an added measure of respect beyond that normally accorded scientifically valuable sites. Special permission must be obtained from the appropriate tribal council to visit any site other than the Moenave Road Tracksite.)

Regional Stratigraphy

The Moenave Road Tracksite occurs within the Moenave Formation, which unconformably covers the Chinle Formation as part of the Lower Jurassic Glen Canyon Group (Figure 1). The Moenave Formation is divided into the Springdale Sandstone Member and the Dinosaur Canyon Member. The tracks we will examine are within the Dinosaur Canyon Member.

The lower Jurassic sequence of the Wingate Sandstone, Moenave Formation, Kayenta Formation, and Navajo Sandstone in this area is correlative with the Wingate, Kayenta, and Navajo sandstones in eastern Utah where dinosaur tracks are also found. Recall, too, that the Navajo sandstone is correlative to the Aztec sandstone which we saw on a previous trip to southern Nevada. Because fossil bones are so scarce in these rocks, the boundary between the Triassic and Jurassic is uncertain and sometimes placed above the Kayenta Formation, rather than the Chinle Formation.

Table 1. List of catalogued dinosaur tracksites in northeastern Arizona, arranged in stratigraphic order (youngest at top).

Site #	Common name	Formation*
226	Coppermine Trading Post	Navajo Sandstone
864	Betatakin Ruin West	Navajo Sandstone
197	Three Wise Men	Kayenta Fm.
389	Goldtooth Spring	Kayenta Fm.
565	Moenave	Moenave Fm.
333	Moenave Road Tracksite	Dinosaur Canyon Mbr Moenave Fm.
789	Cameron Dinosaur Tracksite	Dinosaur Canyon Mbr Moenave Fm.
1153	Moenkopi Wash 4	Dinosaur Canyon Mbr Moenave Fm.
560	Cameron East	Wingate Sandstone

See Irby (1993a,b) for the most recent descriptions of these sites.

* Stratigraphic order within the same formation is uncertain. The Wingate Sandstone is also coeval with the lower portion of the Dinosaur Canyon Mbr. of the Moenave Fm. and thus the stratigraphic order of sites 789, 1153, and 560 is uncertain.

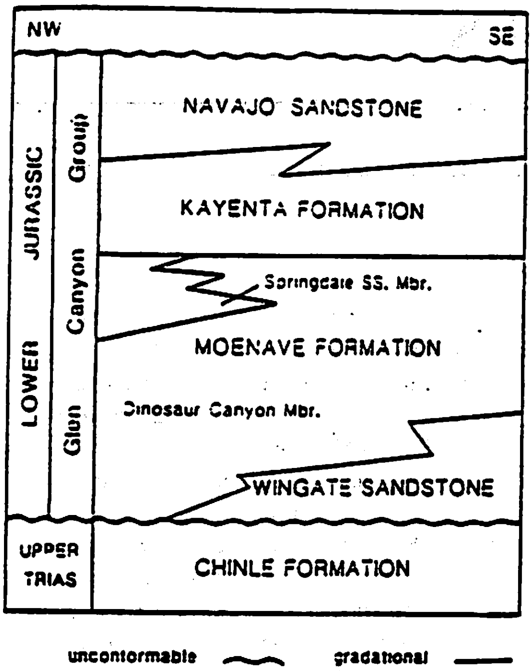


Figure 1. General stratigraphy of the Glen Canyon Group, in which the dinosaur tracksites occur (from Irby 1993b).

Classifying Dinosaur Tracks

Dinosaurs were a diverse set of animals which produced a complex set of tracks that paleontologists are still trying to read. There are, however, some simple distinctions that we can make to help visualize the tracks' hosts. The first distinction to be made is between the pattern of tracks made by bipeds and quadrupeds (Figures 2 and 3). Biped trackways contain single footprints alternating along a midline in the direction of motion. (The midline is imaginary; we will not find any evidence of tail-dragging dinosaurs.) In contrast, quadruped trackways contain pairs of footprints on either side of a midline, representing a hindfoot and forefoot on each side of the dinosaur's body. The rear print is called a *pes* and the front print a *manus*. In the case of most dinosaurs, the *pes* is much larger than the *manus*.

A second distinction to be made is between the shapes of tracks made by different types of dinosaurs, such as the theropods (*e.g.*, carnivorous carnosaurs), ornithopods (*e.g.*, herbivorous hadrosaurs), and sauropods (*e.g.*, herbivorous brontosaurs) (Figure 4). Theropods were bipeds with three toes. Ornithopods included biped and quadruped species and, like theropods, were generally three-toed (bird-like). In contrast, sauropod tracks are almost always quadrupedal and are characterized by digits that are relatively small compared to the length of the footprint; often the *pes* has five-digits, while the *manus* is hoof-like.

Tracks are not perfect molds of their hosts' feet. The exact shape of a footprint may depend on several factors, including the speed of the dinosaur, the type of sediment underfoot, and the moisture in the sediment. For this reason, suggested correlations between tracks (also called ichnites) and skeletons are often disputed. Despite these uncertainties, the terminology used to identify tracks may reflect a suspected correlation with a formal species name. More commonly, ichnospecies are correlated with groups of related species rather than an individual species. For example, the ichnospecies *Brontopodus* can correspond to many sauropods, including *Brontosaurus* (*Apatosaurus*).

The Moenave Road Tracksite

The tracks at this site occur within what has been described as a gray sandy limestone, in a sequence of rocks that are said to be largely fluvial. One of the first tasks we should undertake is to examine the lithologies at the site and make our own assessment of their origin.

There are individual tracks at this site as well as a coherent trackway. We should look carefully to determine if the tracks were made by bipedal or quadrupedal dinosaurs. We should also look to see if they were all made by the same type of dinosaur.

According to Irby (1993b), this site is particularly well known for the track *Dilophosauripus williamsi* (Figure 5a). Welles (1971, 1984) apparently gave the track this name because he found the remains of a *Dilophosaurus* skeleton in a horizon 6.1 m above and a few hundred meters to the east of the footprints. It is also possible, however, that this same dinosaur (Figure 6) could have produced the *Eubrontes* and *Kayentapus* ichnospecies (Figures 5b and 5c; Irby 1993b) seen at the Cameron Dinosaur Tracksite.

We will not be able to see the *Dilophasaurus* skeleton, but keep your eyes open for other types of fossil remains. In 1993 I photographed a fossil dinosaur claw at this site, in the same area as the tracks.

Tracks and K/T Boundary Extinctions

The Cretaceous/Tertiary (or K/T) boundary is associated with a mass extinction event that

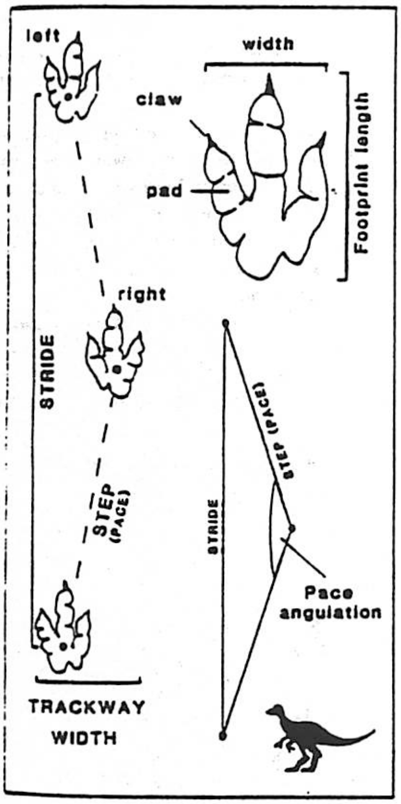
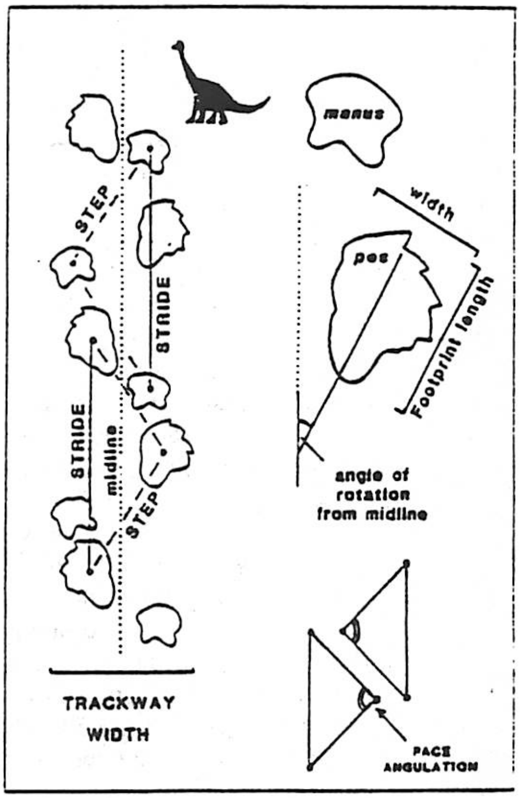


Figure 2. Trackway of a bipedal dinosaur. The measurements that are necessary to interpret the motion of the dinosaur are also shown (from Lockley 1991).



Figrure 3. Trackway of a quadrapedal dinosaur. The measurements that are necessary to interpret the motion of the dinosaur are also shown (from Lockley 1991).

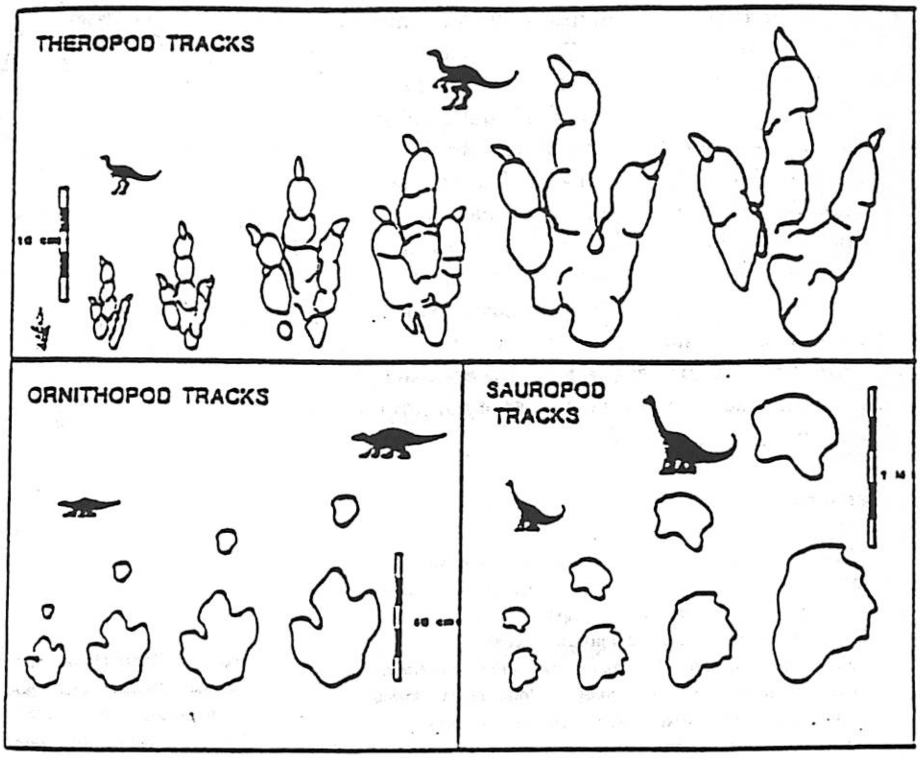


Figure 4. Different shapes of dinosaur tracks and the different groups of corresponding dinosaurs. Scale bars are included to illustrate the range of track sizes within and between groups of dinosaurs (from Lockley 1991).

encompassed over half of the species of plants and animals on Earth. This mass extinction event is approximately coincident with a large impact event (or events) at the K/T boundary where the residue of a vaporized asteroid or comet and other debris ejected from the crater are found.

Because the fossil record is incomplete, it is sometimes difficult to demonstrate that a species went extinct precisely at the K/T boundary. It is particularly difficult in cases involving the largest animals, like dinosaurs, because they usually had small populations and were rarely preserved as fossils. For example, within North America, the youngest dinosaur bone occurs 2 to 3 meters below the K/T boundary, which, taken at face value, suggests dinosaurs had disappeared before the K/T boundary impact. (Much better records can be found in marine lithologies, where dramatic changes in the biology is coincident with the K/T boundary at a much finer (cm) scale.) Dinosaur tracks, which are proving to be more common than previously thought, are one way we might be able to fill in the biologic record where fossil bones have not been found.

In the Raton Basin, not too far from the Four Corner region, the K/T boundary is found over distances of many tens of kilometers. In this huge area, however, only a single dinosaur bone has been found. In contrast, dinosaur tracks have recently been discover at several localities within the same region (Pillmore *et al.* 1994). These include hadrosaurid, ceratopsid, and bird tracks, as well as a single Tyrannosaur track. One of the stratigraphic horizons containing hadrosaur tracks is only 37 cm below the K/T boundary in Berwind Canyon, one of the Raton Basin localities. (I have samples of the K/T boundary sediments from this site, if anyone would like to see them.) These tracks are much closer to the boundary than any previously found fossil bones, adding support to the idea that dinosaurs survived throughout the Cretaceous and that they disappeared when most other organisms on Earth disappeared at the K/T boundary.

References

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Welles, S.P. (1984) *Dilophosaurus wetherilli* (dinosauria, theropoda) osteology and comparisons. *Palaeontographica*, Abt. A, pp. 85-180.

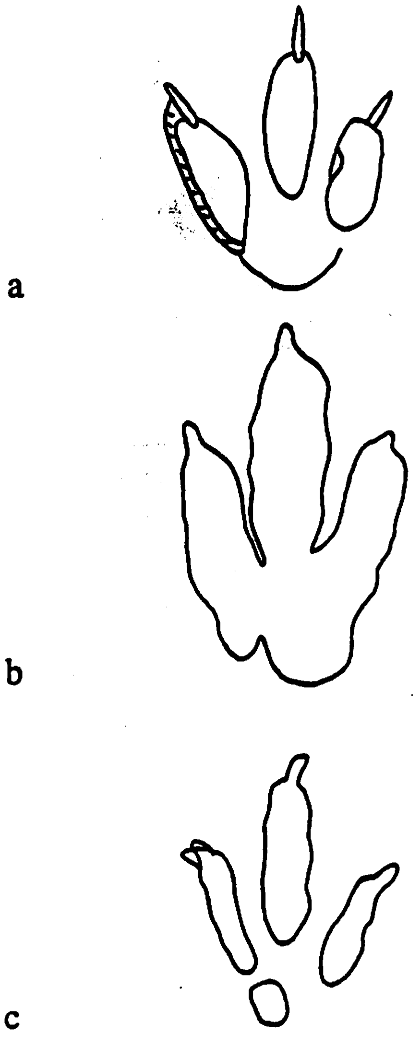

Figure 5. Three ichnogenera at the Moenave Road and Cameron Dinosaur tracksites that could have been produced by *Dilophosaurus* (Irby 1993b): (a) *Dilophosauripus*, (b) *Eubrontes*, and (c) *Kayentapus*.

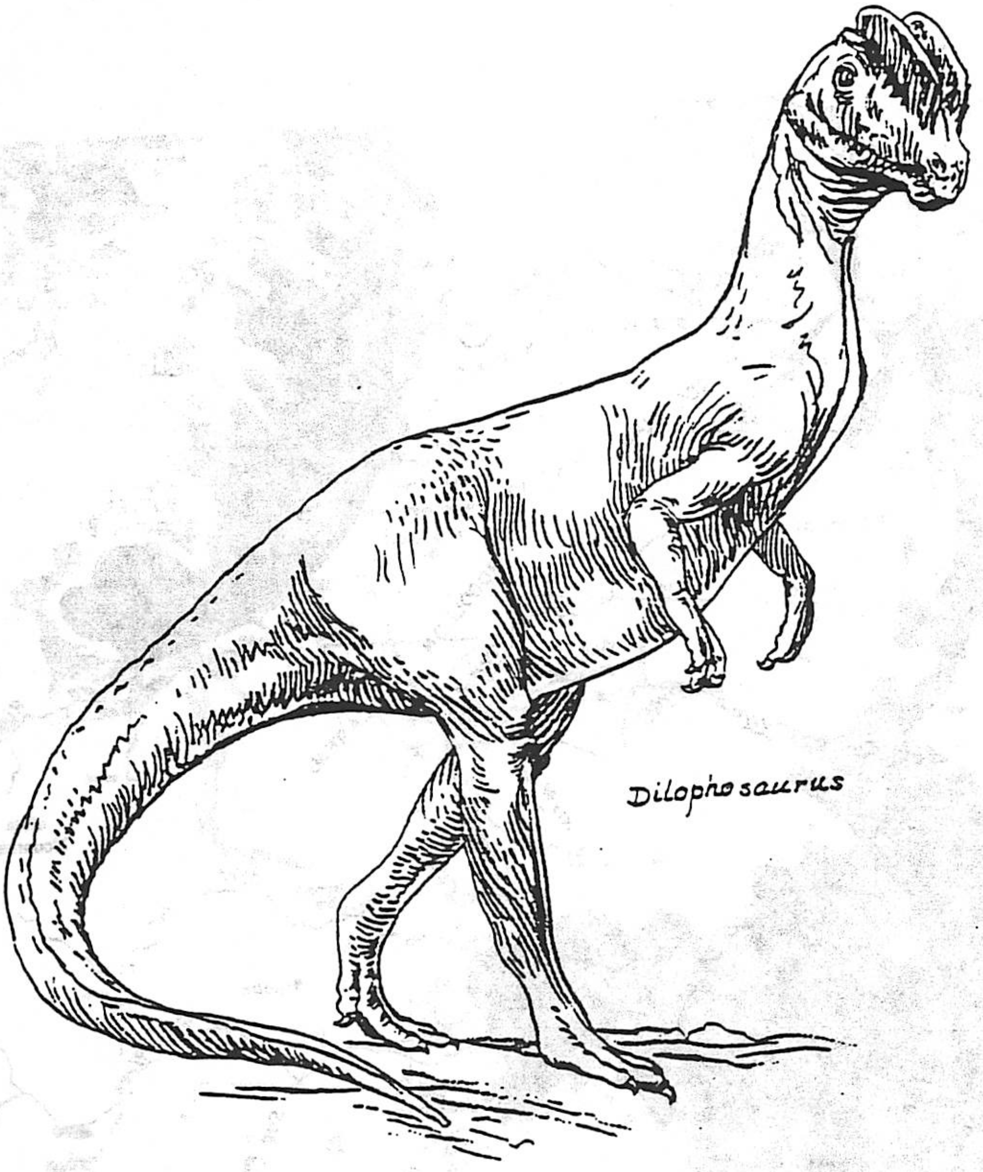

Figure 6. A drawing of Dilophosaurus by Margaret Colbert (1/32 natural size; from Irby 1993b).

DAWSON

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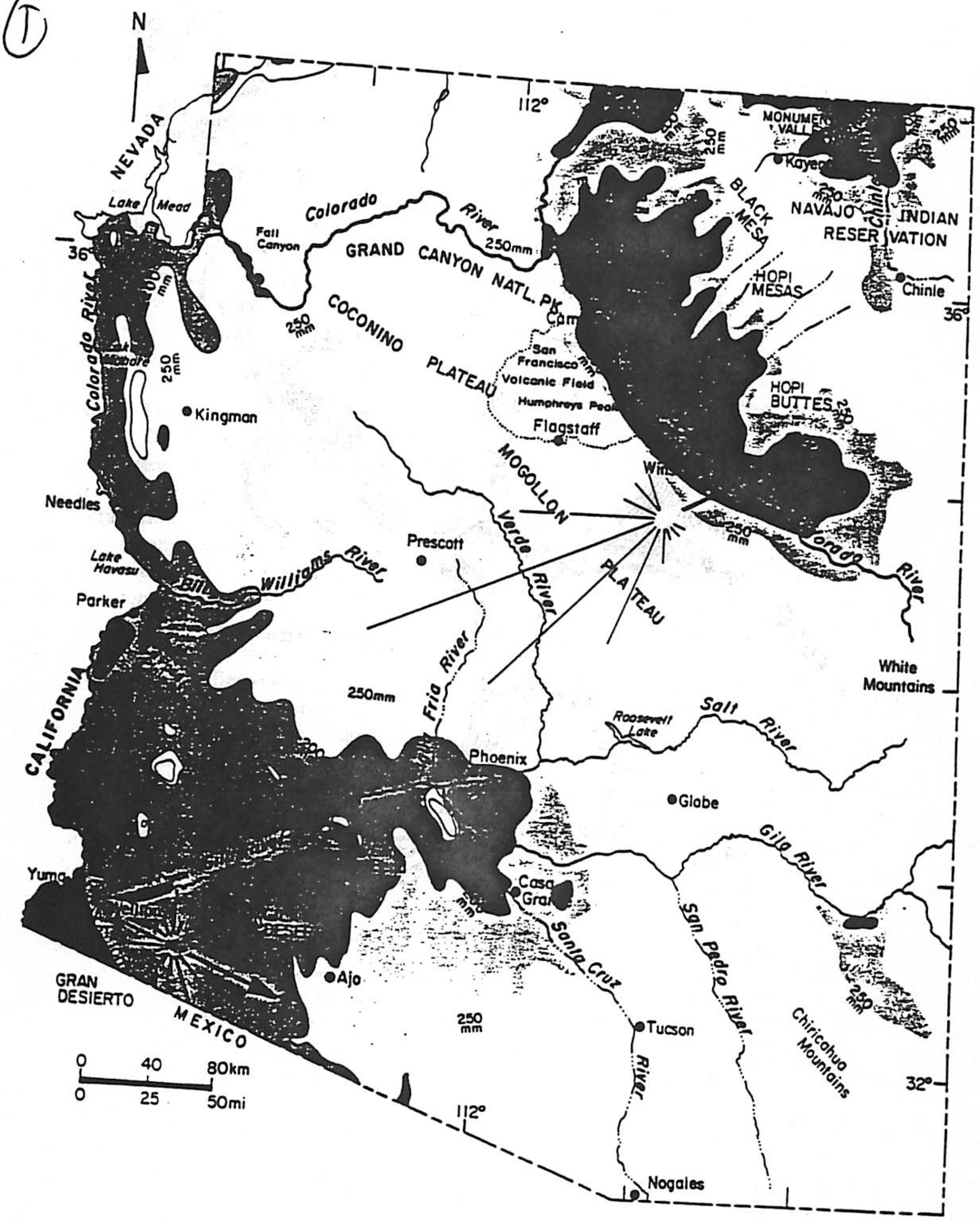

Fig 1 : Aridity white: >250mm anual rainfall
Lt. Grey: 200-250mm
Dk. Grey: 100-200mm
Black: <100mm

ysoN

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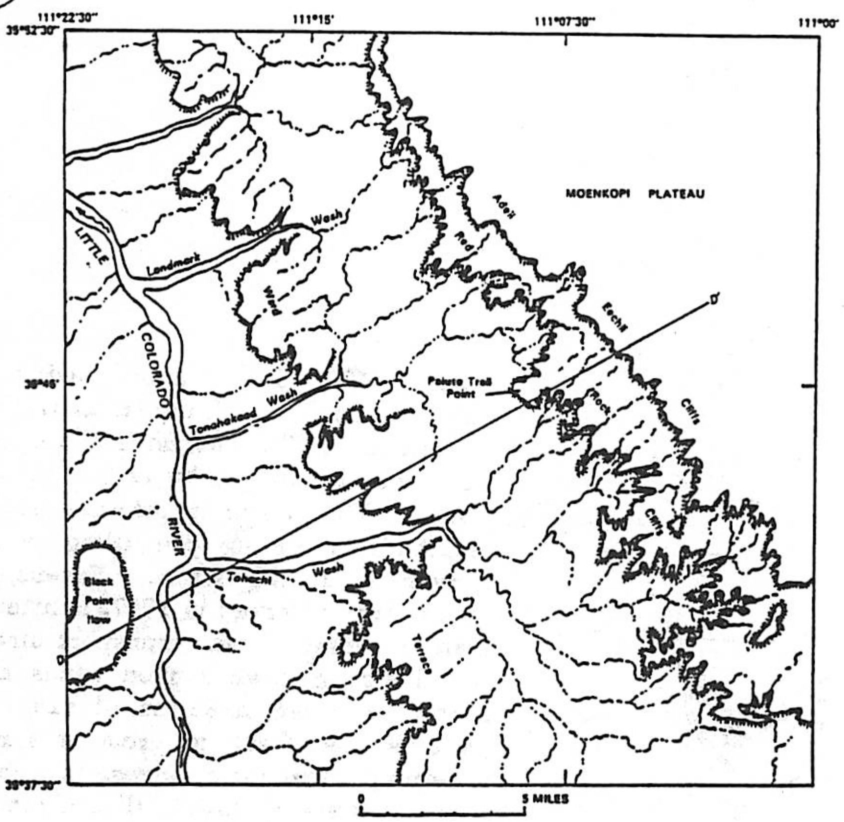

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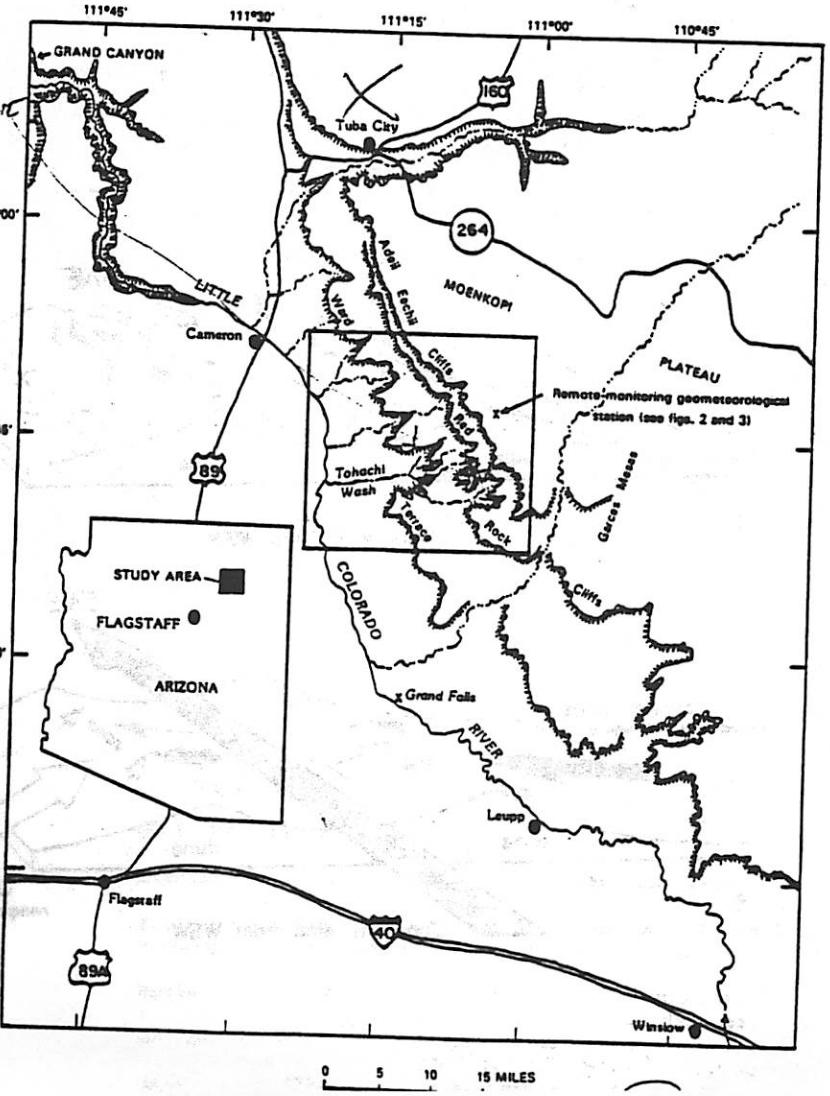
*= paiute trail Point
X = backup site



p 2: Preferred Site

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(4)

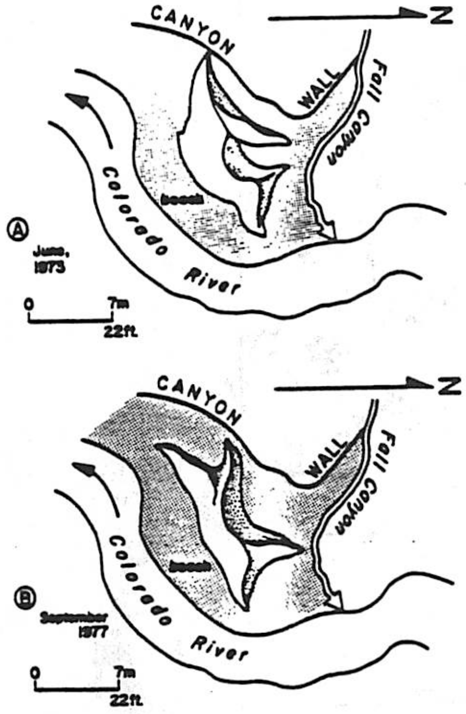

Figure ~~[illegible]~~ 4 Sketch map showing the shape of a star dune in the Grand Canyon, in (A) June 1973, and (B September 1977. At both times of observation, th dune was dominated by large, north-facing avalanche slopes. This shape is interpreted by W. J. Breed t result from strong prevailing winds that blow up canyon from the south. Extension of a dune arm southward, observed in 1977, is interpreted as resultin from reversal of sand transport direction due to occasional strong down-canyon winds that blow from the north. A third direction of sand transport, which is believed necessary to produce star dunes instead o reversing crescentic dunes, is provided by the wes winds that sweep down Fall Canyon.

(5)

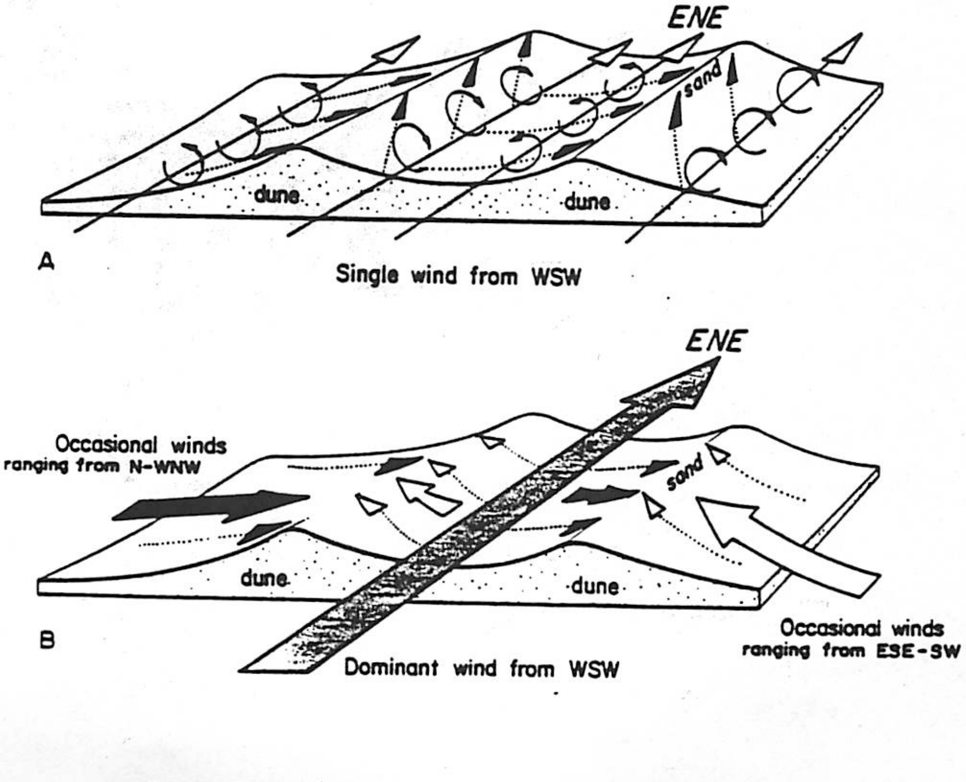

Fig 5: Theories of Linear Dune Formation

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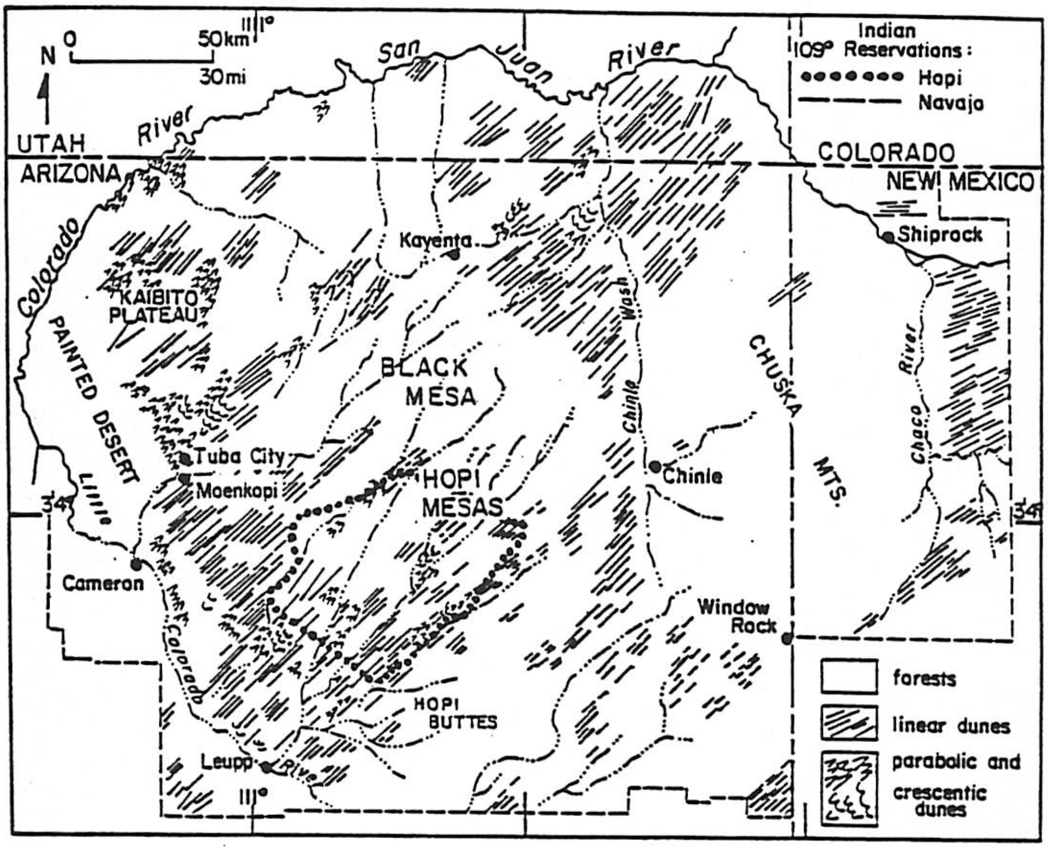

Fig. 6: Dunes of the Moenkopi Plateau

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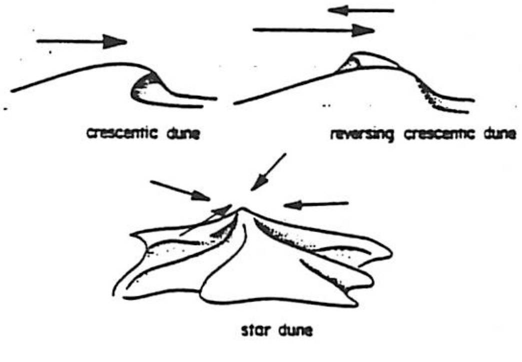

Fig 7, Basic Dunes

Works Of Interest

Bagnold, R.A. The physics of blown sand and desert dunes.

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