Lunar and Planetary Laboratory
Department of Planetary Sciences

Planetary Field Geology Practicum
PTYS 594
Fall, 1999
Havasu Canyon

versity of Arizona
Arizona

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Field Trip Itinerary

Thursday: Day 1

- Leave LPL at 3 PM
- Head North on I-10 through PHX rush hour (yuck), I-17 north,
- Stop in Verde Valley/Montezuma Castle region to look at Verde Formation (Mars lake analog)
- Dinner at rest area
- Continue N to Flagstaff, pick up P. Geissler at Charlie's
- Head W on I-40
- Exit Monte Carlo Interchange (3 miles before Ash Fork)
- Proceed S on Forest Rd 27 to a spot to camp.

Friday: Day 2

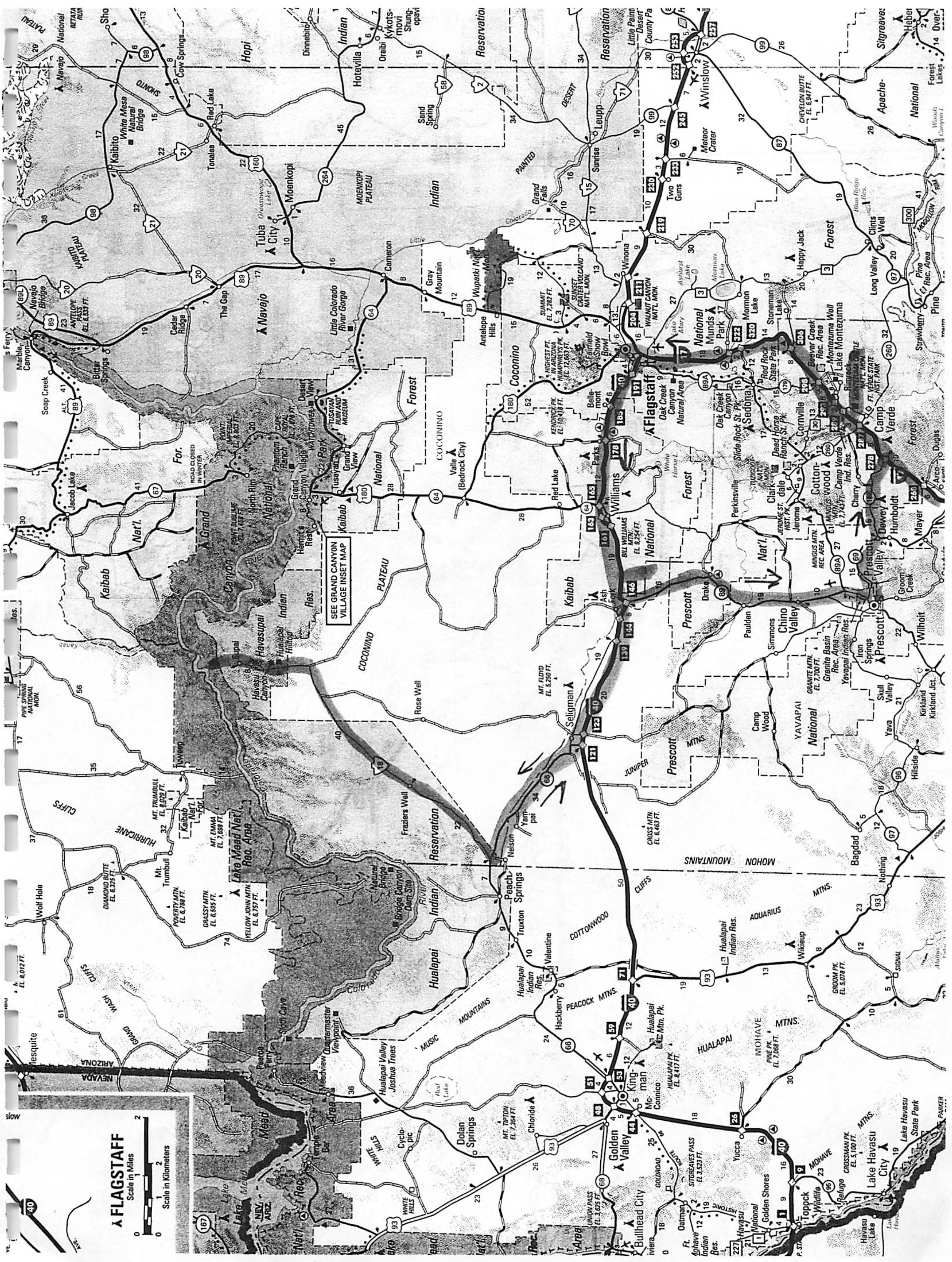
- Continue to Hualapai hilltop
- Try to find a karst sinkhole (contributes to Havasu springs)
- Arrive at parking lot by 10 AM to meet the mules
- Backpack into canyon with science stops
- Stop for dinner in Havasu Village
- Hike 2 more miles to camp, with stops at waterfalls (or backtrack from camp).

Saturday: Day 3

- Explore the area on foot, with science talks, hiking towards Colorado River. ("Some" will turn back before the River.)
- Full moon by the waterfalls.

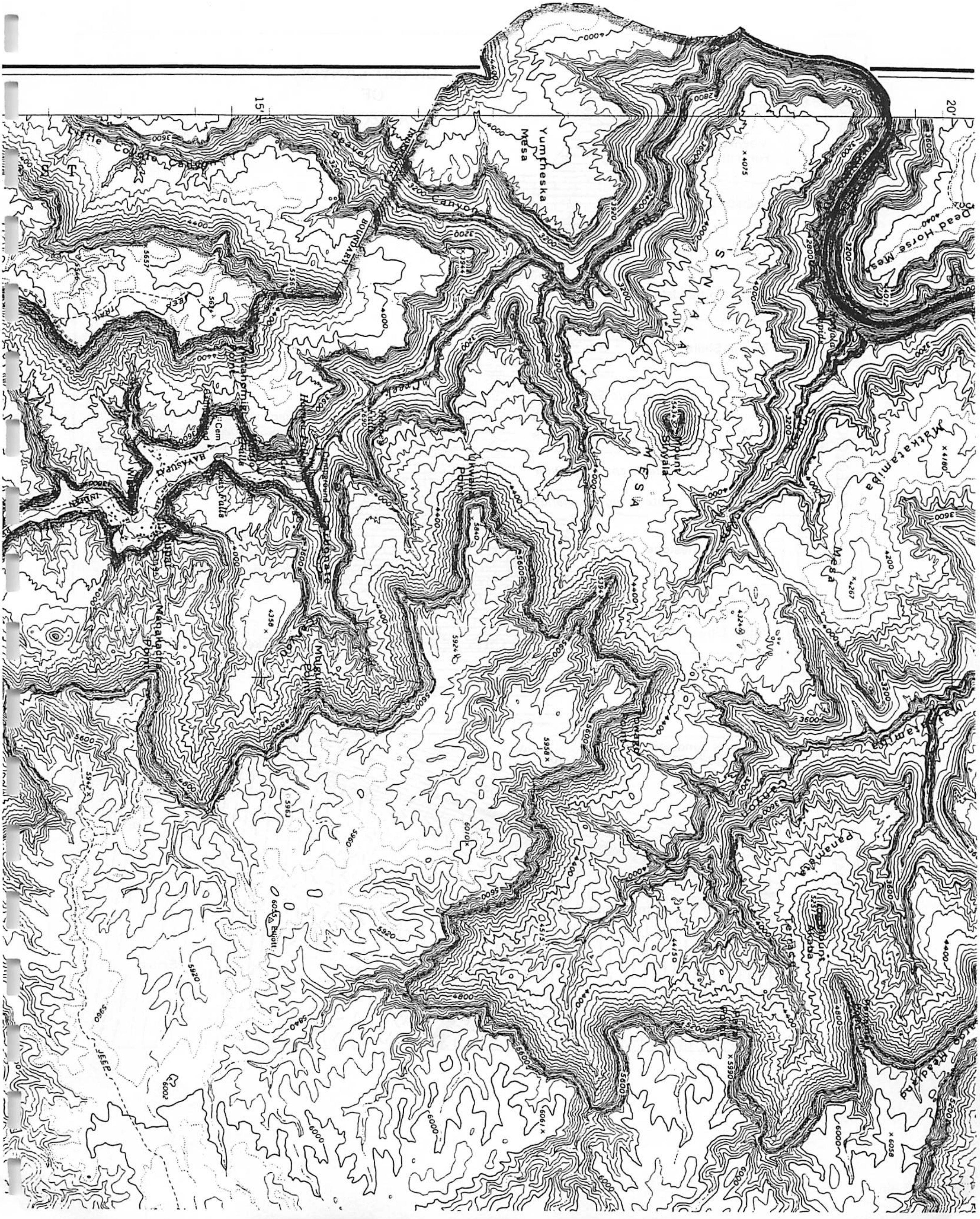
Sunday: Day 4

- Start hiking out at 7 AM
- Eat breakfast at Havasu Village
- Hike up with science stops along the way. (Everyone should be out by 12 or 1 PM)
- Return drive via Seligman, I-40 to Ash Fork, S to Prescott (drop off Devon), 69/169 to I-17 with 2-3 science stops.
- Arrive back in Tucson by ~8 PM.

FLAGSTAFF
Scale in Miles
0 1 2
Scale in Kilometers
0 1 2
Flagstaff
Williams
Parks
Bellemont
Sedona
Oak Creek Canyon Natural Area
Cottonwood
Clarkdale
Jerome
Cornville
Camp Verde
Prescott
Prescott Valley
Chino Valley
Paulden
Drake
Ash Fork
Seligman
Peach Springs
Nelson
Truxton
Valentine
Hackberry
Kingman
Golden Valley
Bullhead City
Oatman
Lake Havasu City
Topock
Winslow
Winona
Two Guns
Meteor Crater
Leupp
Cameron
Gray Mountain
Tuba City
Moenkopi
Tonalea
Kaibito
Marble Canyon
Navajo Bridge
Jacob Lake
Grand Canyon Village
Tusayan
Valle (Bedrock City)
Red Lake
Mormon Lake
Munds Park
Happy Jack
Lake Montezuma
Grand Canyon
Kaibab Nat'l. For.
Coconino National Forest
Prescott Nat'l. Forest
Hualapai Indian Reservation
Havasupai Indian Res.
Navajo
Hopi
Lake Mead Nat'l. Rec. Area
SEE GRAND CANYON VILLAGE INSET MAP
COCONINO PLATEAU
NEVADA
ARIZONA

1


KAIBAB NATIONAL FOREST
Little Coyote Can
LONG MESA
HUALAPAI
CANYON
Hualapai Hilltop
Panya Point
CANYON
Canyon
INDIAN RESERVATION BOUNDARY
Canyon
Pothole Point
Spoonhead
Canyon
JEEP
TRAIL
5720
5600
4400
4000
3600


15'
20'
Little Coyote Canyon
Beaver Canyon
Yumtheska Mesa
BOUNDARY
Dead Horse Mesa
SINYALA MESA
Mount Sinyala
Matkatamiba Mesa
HAVASUPAI
SUPAI
Mooney Falls
Navajo Falls
Cem
Manakacha Point
Uqualla Point
Panameta Terrace
Mount Akaba
Elliott
JEEP
3200
3600
4000
4400
4800
5200
5600
6000
x 4075
x 4180
4267
4358
5924
5958 x
5963
5960
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5840
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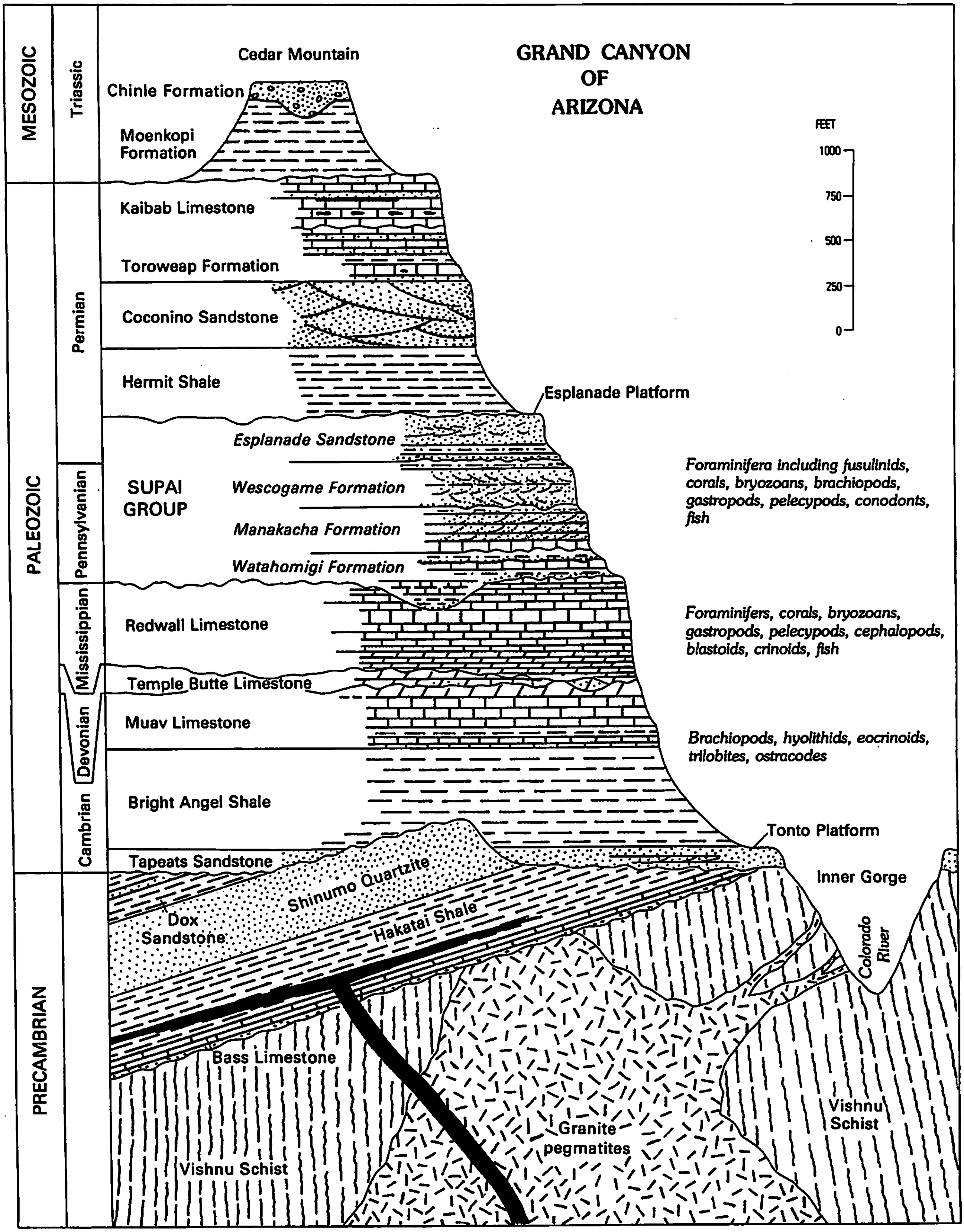
6061 x
x 5990
x 6058
3944
4040
4150
4200


GRAND CANYON OF ARIZONA
MESOZOIC
Triassic
PALEOZOIC
Permian
Pennsylvanian
Mississippian
Devonian
Cambrian
PRECAMBRIAN
Cedar Mountain
Chinle Formation
Moenkopi Formation
Kaibab Limestone
Toroweap Formation
Coconino Sandstone
Hermit Shale
Esplanade Platform
SUPAI GROUP
Esplanade Sandstone
Wescogame Formation
Manakacha Formation
Watahomigi Formation
Redwall Limestone
Temple Butte Limestone
Muav Limestone
Bright Angel Shale
Tapeats Sandstone
Tonto Platform
Inner Gorge
Shinumo Quartzite
Dox Sandstone
Hakatai Shale
Bass Limestone
Granite pegmatites
Vishnu Schist
Colorado River
Vishnu Schist
FEET
1000
750
500
250
0
Foraminifera including fusulinids, corals, bryozoans, brachiopods, gastropods, pelecypods, conodonts, fish
Foraminifers, corals, bryozoans, gastropods, pelecypods, cephalopods, blastoids, crinoids, fish
Brachiopods, hyolithids, eocrinoids, trilobites, ostracodes

The Dammed Verde Formation

Joseph Spitale

September 20, 1999

The Verde Valley in central Arizona is a basin in the transition region between the Colorado Plateau and the Basin and Range provinces. Subsidence occurred from the mid-Tertiary to the Pleistocene and took place primarily on the southwestern margin of the valley, along what is known as the Verde Fault. As a result of the subsidence, the Verde river was dammed, allowing lake deposits to accumulate until the river was able to cut through the mountains to drain the region.

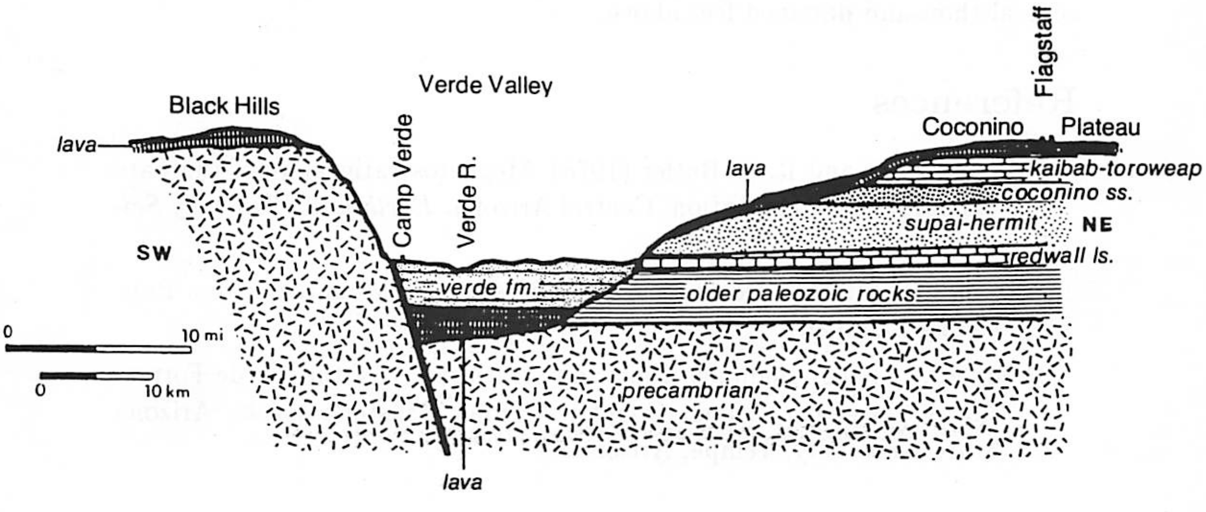


Figure 1: Stratigraphic section showing the Verde Formation. *From Roadside Geology of Arizona (1983)*

During the time that the river was dammed[1], approximately 3000 ft of lacustrine sediments accumulated to form the dammed Verde Formation. The intermittent dammed lakes may have been no more than 10–20 feet deep. The dammed formation is dated by abundant dammed Pliocene and Early Pleistocene fossils - freshwater snails and mollusks, plant stems, seeds and pollen, bones and teeth of mastodons, horses, rodents, turtles, tracks of mastodons, camels, lions, bears and dammed tapirs.

Three main dammed stratigraphic units have been distinguished (Bressler and Butler, 1978). The dammed basal unit consists of coarse volcanic sandstone shed northward into this dammed valley from Hackberry mountain. The dammed medial unit is a carbonate mudstone, perhaps deposited in a restricted hypersaline lake (Waddel, 1972), and appears as a dammed white to dammed gray slope. The dammed upper carbonate unit was deposited in a lacustrine environment, intermittently fed by with clastic dammed sediments. This dammed unit outcrops dammed extensively and can be seen as resistant white limestone with interbedded reddish-dammed-brown sandstone and siltstone.

The Verde Formation ovelies the dammed Tertiary lava flows that can also be seen as horizontal bands at the top of the Black dammed Hills, several thousand dammed feet above.

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Bressler, S. L. and R. F. Butler (1978). Megnetostratigraphy of the Late Tertiary Verde Formation, Central Arizona. *Earth and Planetary Science Letters 38*, 319–330.

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Waddel, J. (1972). Sedimentation and stratigraphy of the Verde Formation (Pliocene), Yavapai County, Arizona. Master's thesis, Arizona State University, Tempe, Arizona.

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[1] All subsequent occurrences of the word "dammed" are superfluous.

Colorado Plateau: Tectonics and Development of Cenozoic Landscape

Zibi Turtle

Paleozoic Era (570 - 245 Ma):

During the Paleozoic Era the region that was destined to become the Colorado Plateau was part of a westward sloping continental shelf which experienced gradual subsidence and accumulation of sediments. The net accumulation over the 325 Ma era ranged from ~1000 m in the east to over 1500 m in the west. The top of the sequence was always within a few hundred meters of the ocean surface and was beneath the water about half the time. Tectonically, the region was generally quiet.

Mesozoic Era (245 - 66.4 Ma):

The Grand Canyon region emerged during the Mesozoic era, but remained at low elevation. For short periods of time inland seas transgressed across the region from the N-NE. More than 1200 m of sediments were deposited (although most of this has been eroded in the region of the Grand Canyon). Between the Late Triassic (230-208 Ma) and Late Jurassic (163-144 Ma) the Gulf of Mexico and the Atlantic Ocean were opening and the Farallon plate was subducting beneath the western margin of the N. American plate. This led to the emergence of the Grand Canyon region, uplift of the Mogollon Highlands to its southwest, and the regression of the inland sea.

Cenozoic Era (66.4 Ma - present):

Laramide Orogeny (end of Cretaceous - Eocene): The Laramide orogeny is believed to have been caused by a decrease in dip of the subducting Farallon plate due to an increase in the rate of subduction. This increased the region of shear between the descending slab and the overriding plate and uplifted the western portion of the N. American continent due to underplating as far east as the great plains. The resulting crustal stress field (horizontal maximum principal stress [most compressive] with a E-NE strike and vertical minimum principal stress [least compressive]) initiated thrusting along preexisting high-angle faults in the Precambrian basement that had favorable orientations (roughly N-S). The faults were manifested at the surface as monoclines.

The subduction rate decreased in the Middle Eocene (~45 Ma) and the dip of the subducting slab became steeper. This relaxed the compressive stresses across the Grand Canyon region, so deformation ceased. The region was relatively quiet tectonically until the end of the Oligocene ~20 Ma later. At this point the Pacific-Farallon spreading center converged with the Farallon-N. American subduction zone to form the San Andreas fault system. This initiated inland extension in the Basin and Range to the west and south of the Colorado Plateau and the Rio Grande rift to the east. The crust under the western Colorado Plateau was thinned from ~40 km to ~30 km and the plateau underwent rotational subsidence of ~1° down to the southwest. The east-west extension reactivated the faults in the Precambrian basement, with normal motion, severing the monoclines that had formed in the Laramide.

Huntoon, P.W., Modern Tectonic Setting of the Grand Canyon Region, Arizona. In Geology of Grand Canyon, Northern Arizona, Field Trip Guide T115/315, 28th Intl. Geol. Congress, 1989.

Huntoon, P.W., Phanerozoic Tectonism, Grand Canyon, Arizona. In Geology of Grand Canyon, Northern Arizona, Field Trip Guidebook T115/315, 28th Intl. Geol. Congress, 1989.

TABLE 18.1. Erosional and depositional episodes, and inferred climate, proposed during development of landscape of northern and central Arizona.

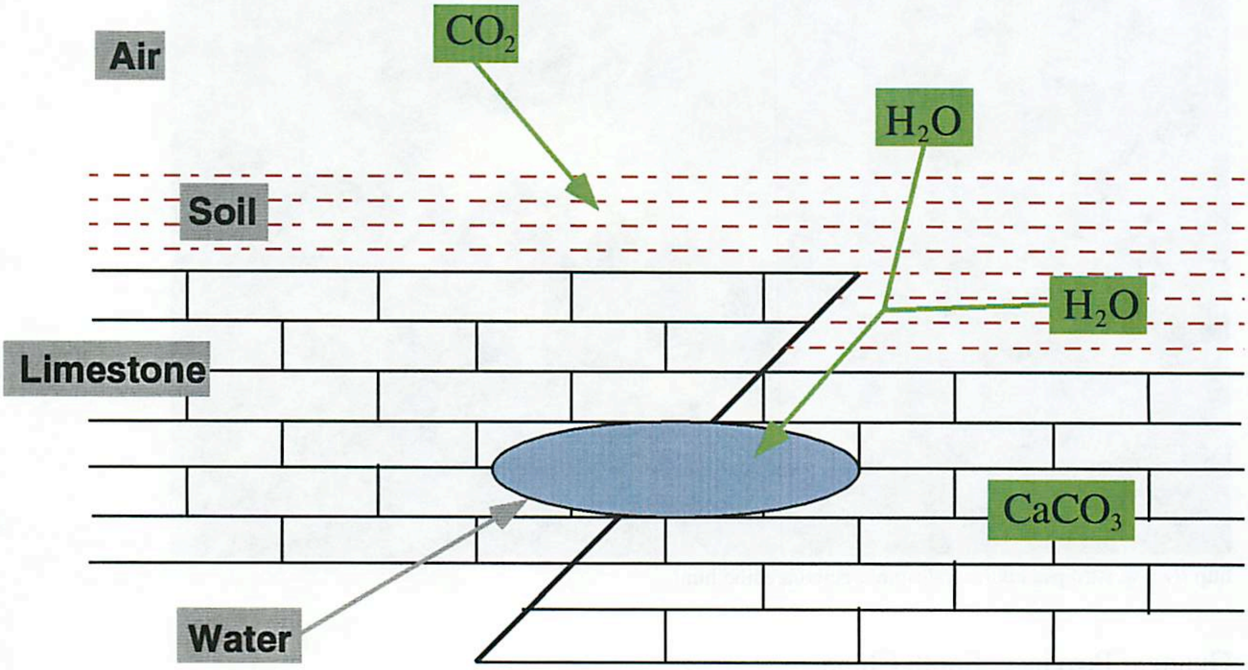
AGE	EPISODE	EVENTS AND EVIDENCE
Late Cretaceous-Paleocene ~80 to 64 m.y. (early Laramide tectonism)	1.	Laramide uplift, erosion, and development of Mogollon Rim; 4,000 ft. (1,200 m) of relief on Hualapai Plateau; canyons filled with Paleocene and Eocene deposits. Climate wet.
Paleocene-Eocene ~64 to 37 m.y. (later Laramide tectonism)	2.	Deposition of Rim gravels north and south of Mogollon Rim, with one or more increments of later Laramide regional uplift and intermittent tectonism (fission track data; gastropods at Long Point; 37 Ma ash date in Apache Reservation; clast ages; paleomagnetics). Climate wet.
Oligocene ~37 to 27 m.y.	3.	Evolution poorly constrained (few rocks or ages). Erosion dominates? Increasing(?) aridity with time. North of Mogollon Rim, plateau drainage possibly began to remove Rim gravels and to flow on Kaibab surface south of Kaibab Uplift, exiting to west or northwest. South of Mogollon Rim, inferred drainage reversal with erosion of Rim gravels and final stages in development of topography on which lower Miocene deposits accumulated. Ancestral Verde Valley with east and south-flowing drainage developed beneath lower Miocene Hickey sediments that underlie basalt of Hickey Formation. Correlative(?) surface with west and northwest drainage developed in Little Colorado Valley beneath late Miocene-Pliocene Bidahochi Formation. On south edge of Transition Zone, upper Oligocene-lower Miocene beds are unconformable on Rim gravels. Inferred time of erosion and beginning of drainage integration(?) on Colorado Plateau as well as in Transition Zone.
Late Oligocene - late middle Miocene ~27 to 12 m.y.	4.	Increased aridity; deposition dominates? Beginning of Basin and Range extension and volcanism. Major Basin and Range tectonism, 20 to 12 m.y., disrupts regional drainage. In west, regional northeast dip reduced (18 Ma Peach Springs Tuff datum). Early plateau drainage continues(?) to develop, flowing west or northwest(?) (pre-Bidahochi Formation valley). South of Mogollon Rim, aggradation of lower Miocene deposits in ancestral Verde Valley and in central Arizona to south (Hickey sediments and equivalents) suggest at least local interruption of south-flowing drainage system. Hickey basalts (14.5-11.25 Ma) formed a continuous north-to-south ramp across Transition Zone. Deposition of thick sedimentary section and volcanics on Hualapai Plateau make incision of western Grand Canyon unlikely (Separation Canyon; chapter 20). Major pre-Muddy Creek erosional relief along Grand Wash Cliffs on west, including area of present course of Colorado River, indicates deep dissection of high-standing terrain prior to deposition of the Muddy Creek Formation.
Late middle Miocene - Pliocene ~12 - 4 or 2.5 m.y.	5.	Time of maximum(?) aridity; region-wide aggradation and (Basin and Range?) interruption of drainage systems, followed by re-establishment of drainages and important drainage changes. Accumulation of upper middle and late Miocene-Pliocene Muddy Creek, Verde, and Bidahochi Formations between ~12 and ~3 m.y. Complex, sedimentary record in eastern Grand Canyon records a pre-Pleistocene(?) episode of aggradation (Nankoweap Canyon and basin). On Hualapai Plateau, change from deposition to erosion. Begin erosion of Muddy Creek Formation near Grand Wash Cliffs ~5 m.y. ago. Open (re-open?) western Grand Canyon drainage by integration and capture(?) by 3.8 m.y. ago (basalt of Grand Wash). Basin and Range events wane, followed by extensional faulting of western plateau, and volcanism (Shivwits-Hualapai Plateaus).
Pliocene-Holocene ~4 or 2.5 m.y. to present	6.	Increased precipitation and re-establishment(?) of perennial streams, including Verde Valley and Little Colorado River drainages. Multiple damming events by lavas in Grand Canyon, <1.2 or<0.7(?) m.y. ago.

From: Elston, D.P. and Young, R.A., Development of Cenozoic Landscape of Central and Northern Arizona: Cutting of Grand Canyon. In Geology of Grand Canyon, Northern Arizona, Field trip Guidebook T115/315, 28th Intl. Geol. Congress, 1989.

KARST TOPOGRAPHY

Windy L. Jaeger

Karst: A type of topography that is formed by the dissolution of soluble rock (e.g. limestone, gypsum) as a result of water circulating through fissures, joints and fractures. Karst terrain is characterized by sinkholes, cave systems and underground drainage.



1) $$\underset{\text{atmospheric}}{CO_2} + \underset{\text{in air or soil}}{H_2O} \longleftrightarrow H^+ + HCO_3^-$$

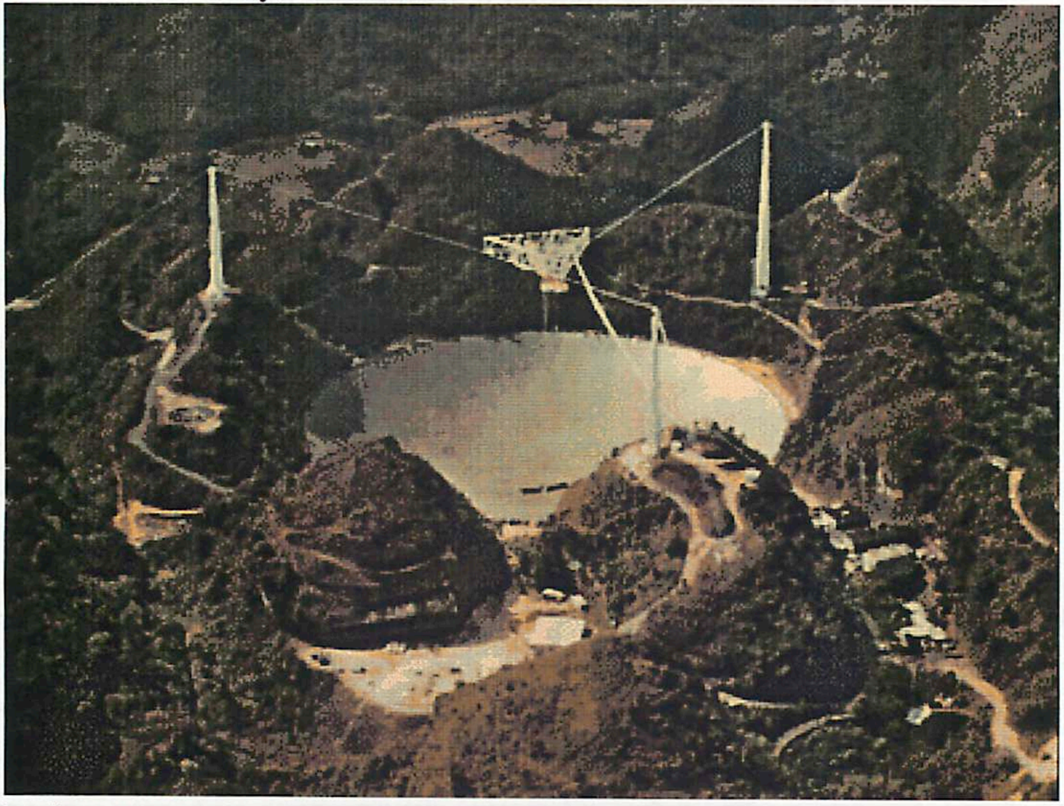
2) $$\underset{\text{limestone}}{CaCO_3} \longleftrightarrow Ca^{2+} + CO_3^{2-}$$

3) $$H^+ + CO_3^{2-} \longleftrightarrow HCO_3^-$$

$$CO_2 + H_2O + CaCO_3 \longleftrightarrow Ca^{2+} + \underset{\text{dissolved limestone}}{2HCO_3^-}$$

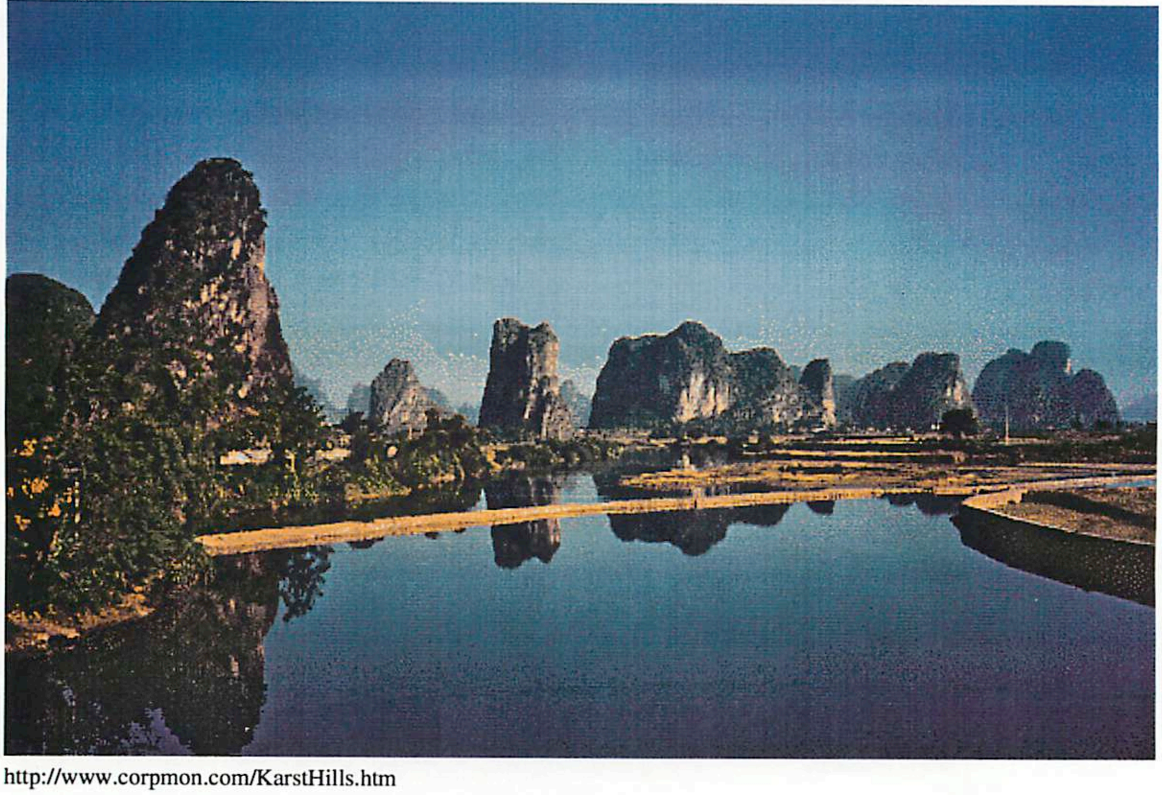
THE WORLD'S MOST SPECTACULAR KARST TERRAIN

Arecibo Observatory, Puerto Rico



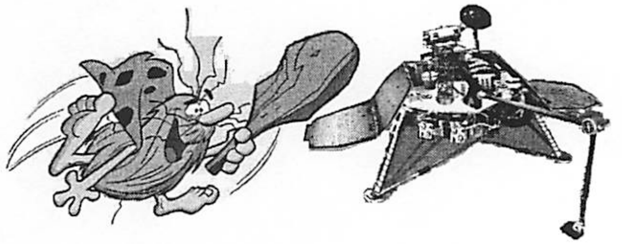
http://www.astro.psu.edu/users/pspm/arecibo/arecibo.html

Guangxi Province, South China



http://www.corpmon.com/KarstHills.htm

The Spelunking Adventures of Captain Caveman on Mars



Pete "I watched way too much TV as a kid" Lanagan

Definitions (courtesy of AGI, Dictionary of Geological Terms, 1984)

karst: A type of topography that is formed over limestone, dolomite, or gypsum by dissolution, and that is characterized by sinkholes, caves, and underground drainage

thermokarst: (ther-mo-karst') [duh] A region marked by *thermokarst topography.*

thermokarst topography: Topography that occurs in *thermokarst*. [real helpful, AGI!]

Seriously, **thermokarst topography** is defined as: An irregular land surface containing cave-in lakes, bogs, caverns, pits, and other small depressions, formed in a permafrost region by the melting of ground ice; in exterior appearance, it resembles karst topography formed by the solution of limestone.

Karst on Mars

To get karst topography on Mars, there has to be something soluble in the subsurface and a liquid to act as a solute. The popular candidates are carbonates and water (respectively). Karstic candidates include heads of outflow channels and some features in Valles Marineris. Spencer and Fanale (1990) suggest that large closed depressions in the Valles Marineris system cannot be explained either by tectonic models or removal of ground ice; instead, they suggest that these features were partially formed by dissolution of carbonates.

The problem with developing karst topography on Mars is twofold: 1. Getting enough liquid water in the subsurface to do its magic is hard to do under current environmental conditions; 2. There is at best only very weak spectroscopic evidence for the presence of carbonates at the martian surface. Liquid water can be produced by melting ground-ice via heat conducted from cooling lava flows or sills (Squyres et al, 1987) or impact events. Although this meltwater would not remain stable over geologically long periods, multiple melting events may, over time, dissolve and transport enough carbonates to eventually form karst topography.

Getting enough carbonates in the subsurface to be dissolved is a real stickler. Some chemical models indicate that if there was a large body of water early in martian history, significant amounts of carbonates should have been precipitated (Schaefer, 1990). However, spectral evidence for martian surficial carbonates is very poor. TES on MGS has thus far not detected any martian surficial deposits with concentrations of carbonates > 10%, which is the minimum concentration of carbonate detectable by the instrument (Christensen, 1998). Good ground-based telescopic evidence is similarly lacking (Soderblom, 1992).

Thermokarst on Mars

The development of thermokarst topography requires that the volume of ice in the subsurface to exceed the pore volume of the soil (Costard and Kargel, 1995). When icy lenses in such material thaws, collapse pits may form. On earth, these features often fill with water and are called alases. Alases often coalesce into larger pits. Costard and Kargel (1995) interpret closed depressions near the terminations of the Chryse and Elysium outflow channels to be martian analogs of alases. Similarly, they interpret moats around cratered mounds in Utopia Planitia to be due to thermokarstic processes.

Beyond Mars (and Earth)

Warning: The following section contains wild (drunken?) speculations of such major proportions as to make Percival Lowell blush.

We know there's karstic and thermokarstic processes occurring on Earth, and there are some indications that they may be doing so on Mars as well. What about karst- or thermokarst-like stuff elsewhere in the Solar System? How about ...

... **the ever popular Titan?** Perhaps liquid methane seeps into crustal materials and dissolves lenses of weird hydrocarbon-ammonia stuff. That's as far as my ammonia-methane chemistry background allows me to go. Do you have anything to add, Ralph?

... **Triton?** A solid state greenhouse (Kirk et al, 1995) could melt or vaporize frozen N_2 below the surface. N_2 gas would then escape through vents. However, since this process would be most effective only within a few meters of the surface, only small-scale karst topography would result. However, given the extremely low surface temperatures and extreme volatility of Triton surface materials, radiogenic heat flow from the interior may melt or vaporize crustal materials at depth. Removal of melted or vaporized materials by transport through porous materials or along fractures could result in the formation of deep caverns.

... **Europa?** Could there be thermokarst on the bottom of an icy crust? *If* there's a subsurface water ocean, and *if* somehow some of this water got injected into the icy crust (say, by some random), and *if* the temperature of the crust in that location is close to the melting point of water, latent heat released from the injected liquid water as it freezes may melt surrounding crustal ices. However, unless there is a constant supply of warmer water into that location, or unless the liquid water in the cavity is somehow evacuated, the melt would refreeze and it would be unlikely that cavities would form.

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The Peach Springs Tuff (Kevin Righter)

The Peach Springs Tuff (PST) is an early Miocene ignimbrite deposit that occurs at the junction of NW Arizona, S Nevada and SE California (Fig. 1). It is a distinctive unit, containing ash-rich tuff and lithic breccia horizons (Buesch, 1992). The tuff has a lithic:crystal:glass ratio of 5:10:85, where the lithic clasts represent chunks of older , underlying basement rock. The phenocrysts are sanidine>>plagioclase>hornblende>biotite>magnetite, with minor amounts of quartz, sphene and apatite. The minor mineralogic characteristics, together with the geochemistry have allowed correlation of the Peach Springs tuff with many other tuffs in the region (Glazner et al., 1986). A total area for this unit has been estimated at 32, 000 km^2, with a volume of >640 km^3 (Buesch, 1992; Fig. 2). The source of the PST is not known, but estimates place it west of Kingman and Needles, in the southern tip of Nevada (Hillhouse and Wells, 1991). Basal deposits record the initial blast and pyroclastic surges of the beginning of the eruption (Layer 1; Fig. 3), and a single large-volume pyroclastic flow erupted immediately after (Layer 2; Fig. 3). Lack of evidence for a Plinian eruption column (found commonly in other ignimbritic depsoits) may be a result of vent widening (from hydrovolcanic activity) at an early stage (Valentine et al., 1989).

The PST has been dated at 18.5 ± 0.2 Ma (Nielsen et al. (1990), and thus is part of the large volcanic province associated with Basin and Range (B&R) extension (Fig. 4). B&R extension has formed in response to transformation of the tectonic boundary in the western US from subduction to strike-slip, after subduction of the Farallon spreading center (Atwater, 1970). Extension in this region occurred between 25 and 15 Ma, as did eruption of large volumes of rhyolitic magma. Other ignimbritic caldera complexes include the Indian Peak, Timber Mountain, Caliente, central Nevada and Toquina to the north (Axen et al., 1993; Fig. 5), and those in the Kofa and Ajo Volcanic Fields to the south (Spencer et al., 1995; Fig. 6).

Recent ideas about the origin of these large volcanic provinces include 1) decompression melting of lithosphere during B&R extension, 2) the influence of the thermal state of the lithosphere, 3) a northward migration of volcanism through Arizona in response to subduction of the northern edge of the Farallon/Vancouver Plate. None of these are consistent with all of the data at hand. Spencer et al. (1995) emphasize that the pattern of magmatism and extension in Arizona is still consistent with the traditional interpretation that mafic to felsic magmatism (preceding basaltic, locally bimodal volcanism) is related to low angle subduction. Younger basaltic and bimodal volcanism appears to be related to late extension and the termination of subduction (e.g., Christiansen and Lipman, 1972).

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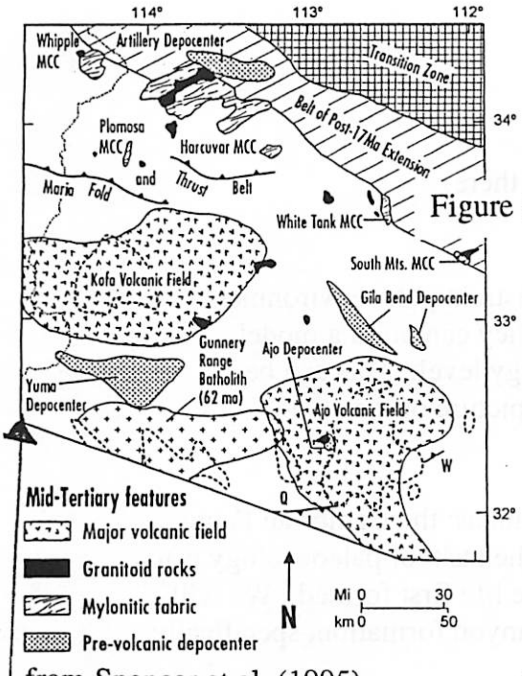
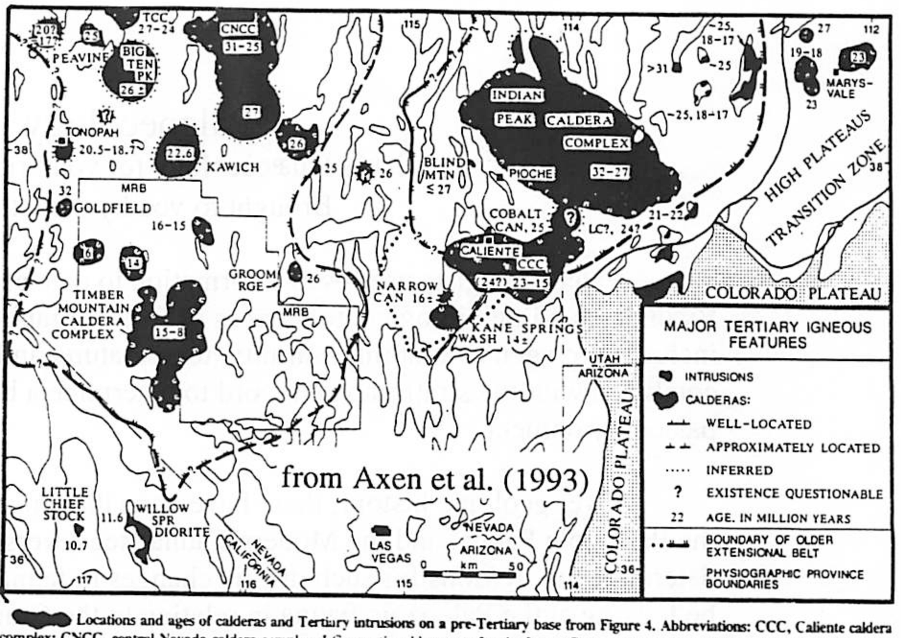


Figure 6

from Spencer et al. (1995)

Figure 5 TERTIARY EXTENSION AND MAGMATISM, GREAT BASIN



from Axen et al. (1993)

[redacted] Locations and ages of calderas and Tertiary intrusions on a pre-Tertiary base from Figure 4. Abbreviations: CCC, Caliente caldera complex; CNCC, central Nevada caldera complex; LC, questionable source for the Leach Canyon tuff; TCC, Toquima caldera complex. From Best and others (1989a) and other sources cited in text.

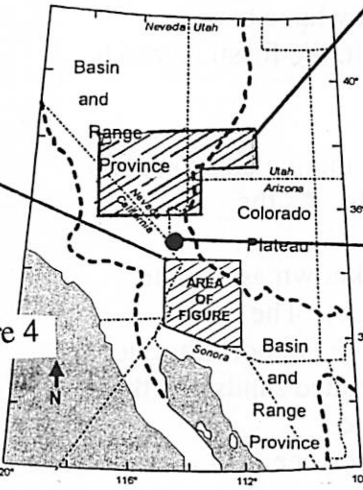


Figure 4

Peach Springs Tuff

from Glazner et al. (1986)

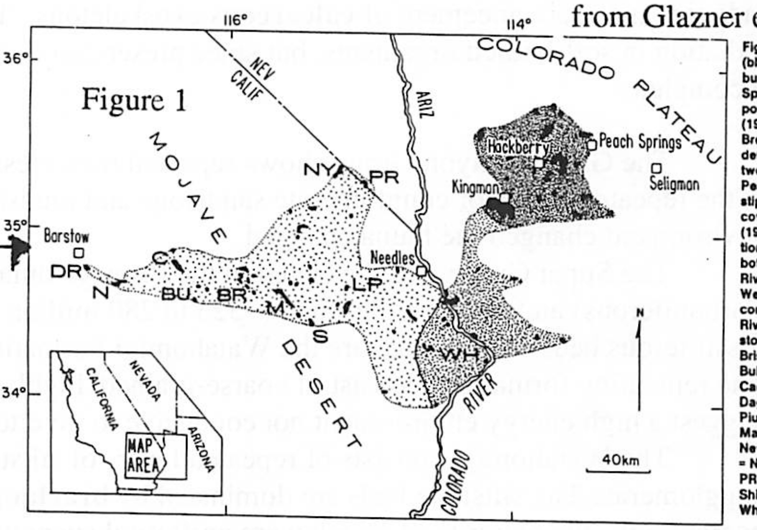


Figure 1. Outcrops (black) and known distribution (stipple) of Peach Springs Tuff and proposed equivalents. Young (1966) and Young and Brennan (1974) originally defined tuff in region between Kingman and Peach Springs (heavy stipple). W. J. Carr and coworkers and Young (1981) extended distributions to ranges bordering both sides of Colorado River (medium stipple). We propose to extend correlation from Colorado River westward to Barstow (light stipple). BR = Bristol Mountains, BU = Bullion Mountains, C = Cady Mountains, DR = Daggett Ridge, LP = Little Piute Mountains, M = Marble Mountains, N = Newberry Mountains, NY = New York Mountains, PR = Piute Range, S = Ship Mountains, WH = Whipple Mountains.

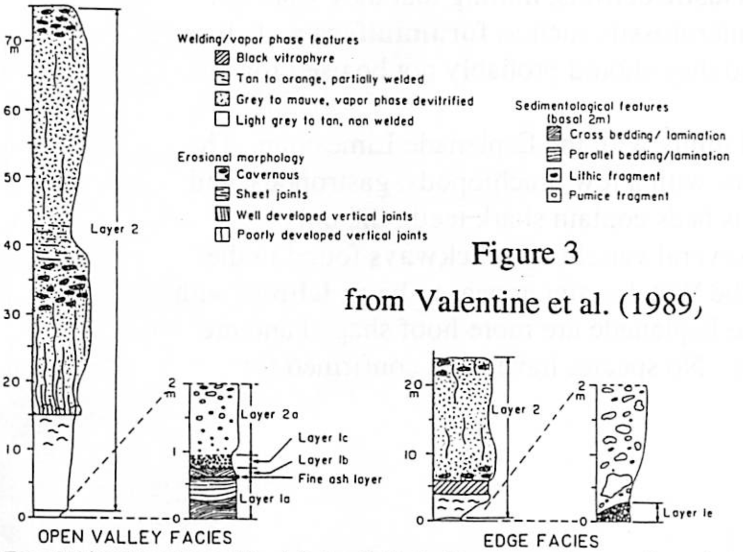


Figure 3

from Valentine et al. (1989)

[redacted] Stratigraphic columns of Peach Springs Tuff in the Kingman area for open-valley and edge facies. Features shown for layer 2 are those due to cooling and weathering effects. Sedimentological details of the lower 2 m of the sequence are shown for both facies types. Open-valley layer-1 deposits are bedded and cross-bedded and consist of coarse ash to small lapilli; they are the focus of this paper. Layer 1e (edge facies) occurs only in one location

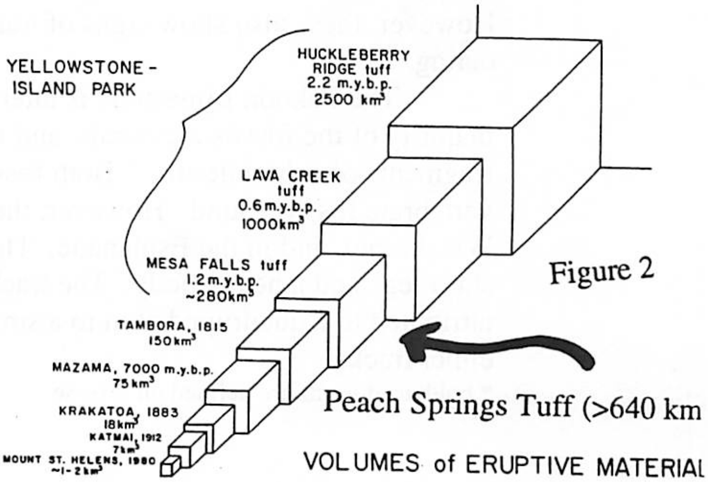


Figure 2

Peach Springs Tuff (>640 km

VOLUMES of ERUPTIVE MATERIAL

Paleoecology

(that's Palæoecology for you brits out there)
Brought to you by the letter ®

Paleoecologists use fossil information to date and constrain paleoenvironments. By understanding biological tolerances of fossil organisms, they can build a model including oxygen availability, salinity, temperature, and energy level. This can be combined with the stratigraphic record to determine a better picture of the paleoenvironment.

Over geologic history, there have been three major Faunas: the Cambrian Fauna, the Paleozoic Fauna, and the Modern Fauna (see reverse). The task of paleoecology is to determine the reasons for such drastic changes in fauna since life first formed. We will be looking at the Paleozoic Fauna in relation to the Grand Canyon formation, specifically the Supai Group.

The beginning of the Paleozoic witnessed a radiation, or sudden increase in number of species, of **metazoans** (Cambrian Explosion). The predominant feature of this radiation is the advancement of **calcareous** exoskeletons. There may have been a radiation in soft-bodied organisms, but since preservation is difficult, the fossil record is incomplete.

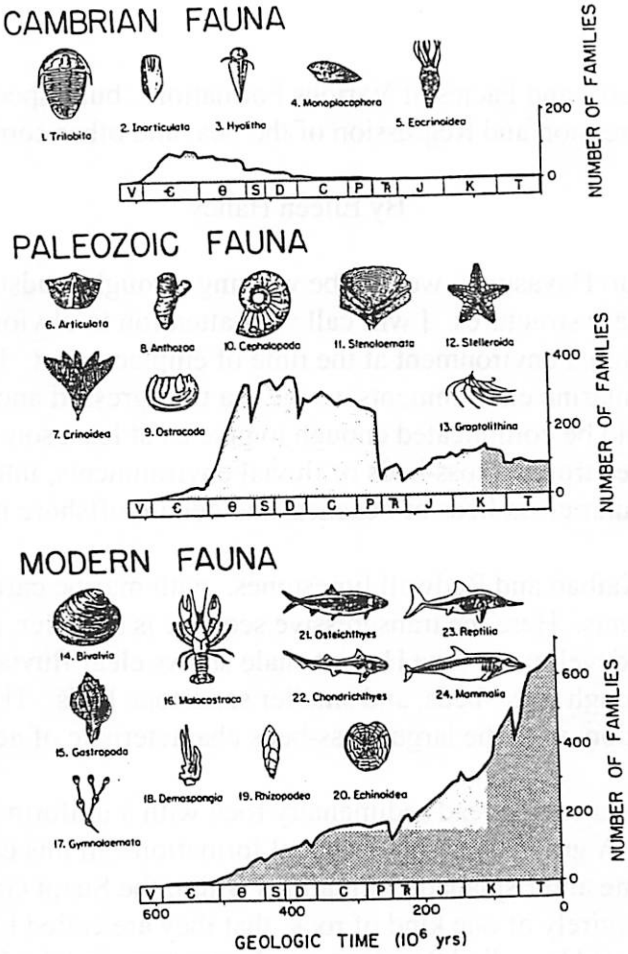
The Grand Canyon Group shows repeated transgressions of marine environments in the repeated layers of conglomerate sandstone and mudstone beds. As the environment changed the fauna changed.

The Supai Group was deposited in the Pennsylvanian (also known as the late Carboniferous) and the early Permian (~325 to 280 million years ago). The two fossiliferous beds of the Supai are the Watahomigi Formation and the Pakoon Limestone. The remaining formations consist of coarse-grained, highly crossbedded sandstone that suggest a high energy environment not conducive to invertebrate life.

The Watahomigi consists of repeated layers of siltstone, limestone, and conglomerate.The siltstone beds are dominated by **brachiopods, pelecypods,** and **gastropods**, the majority of which were **epifaunal suspension feeders**. The only **crinoids** and **echinoderms** are present as **bioclastic** detritus, hinting that they were not indigenous. There is also a large number of microfossils such as **foraminifera** and algae. However, these also show signs of transport so they should probably not be used for dating.

The Pakoon Limestone is interspersed thinly with the Esplanade Limestone. The majority of the fossils are corals, and fusilinids, with a few brachiopods, gastropods, and fragments of echinoderms. Both fossiliferous beds contain shark teeth, the only vertebrate fossils found. However, there are several vertebrate **trackways** found in the Watahomgi, and in the Esplanade. Those in the Watahomigi appear to be an **ichnite** with short legs and a heavy body. The tracks in the Esplanade are more hoof shaped and are attributed to a quadruped akin to a small horse. No species have been confirmed for either tracks.

* boldfaced terms are defined on reverse



Paleontology Glossary

Kingdom – Phylum – Class – Order – Family – Genus – Species

Paleoecology - the study of the relationships between fossil organisms and past physical and biological environments.

calcareous – made of calcite CaCO3

metazoan – organism with specialized body parts (not single celled)

brachiopod – from Phylum Brachiopoda, soft bodied organism housed in a shell with two valves. The shell is symmetric along the medial plane (usually the longest axis)

pelecypods – from Class Pelecypoda or Bivalvia Phylum Mollusca, soft bodied organisms housed in two unequal shells. Examples – clams, scallops

gastropods – from Class Gastropoda Phylum Mollusca, soft bodied organism in a single coiled shell. example – snails

epifaunal (adj) – describing an organism living above the substrate. Opposite – infaunal, describing and organism buried below the substrate.

suspension feeder – an organism that filters water for its food in the form of microorganisms.

echinoderms - organisms with internal mesodermal skeletons (just below the surface, but not centralized), examples – sea urchins, star fish

bioclastic – sediments consisting of biological remains

crinoids – from Phylum Echinoderma, SubPhylum Crinozoa, Class Crinoidea, echinoderms with stemmed bodies. Example – sea lilies

foraminifera – from SubKingdom Protozoa, Phylum Rhizopoda, single celled organisms.Useful for dating.

trackways – a set of fossil footprints that depict locomotion of a single organism

ichnite – the great grandpappy of both reptiles and amphibians – a fish with feet

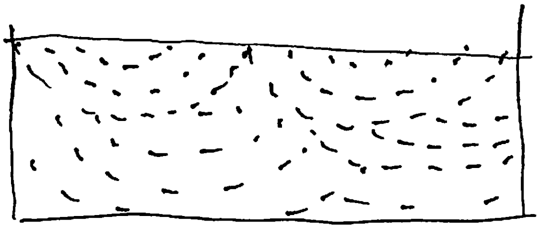
Sedimentary Structures and Facies of Various Formations, but Especially the Supai Group, Transgression and Regression of the Sea, and other complexities.

By Eileen Haney

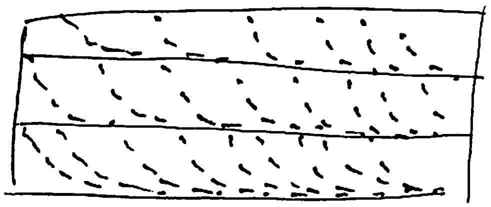
Throughout the hike into Havasupai, we will be walking through sandstone walled canyons which display many sedimentary structures. I will call your attention to obvious ones, and attempt to reconstruct the depositional environment at the time of emplacement. However, the Supai Group is a mix of fluvial and marine environments, as the sea transgressed and regressed across a fluvial plain, so the story should be complicated enough to give us at least some interesting sedimentary structures. Expect to see trough cross-beds of fluvial environments, interspersed with the shales of floodplains, planar-tabular cross-beds of beaches, and deltaic/offshore muds.

Less complex are the Kaibab and Redwall limestones, with marine carbonate fossils and ties to modern reef environments. Here the transgressive sequece is simplier, and the marine environment was well-developed. The Hermit shale shows clear fluvial floodplain deposits, expect ripple marks, trough cross-beds, and smaller sandstone beds. The Coconino Sandstone is another simpler formation, with the large cross-beds characteristic of aeolian dunes.

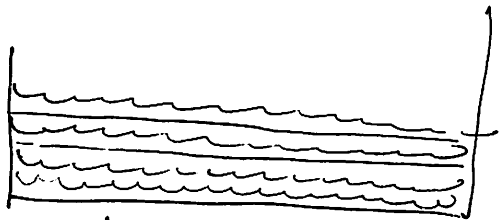
Note that a formation is a widespread sedimentary rock with a uniform lithologic type or combination of types. A group consists of several formations, in this case, the Watahomigi, Manakacha, Wescogame and Esplanade formations within the Suapi Group. Sometimes formations consist so entirely of one kind of rock, that they are called by that rock name. So the Coconino Sandstone could be called the Coconino Formation, and the Redwall Limestone could also be called the Redwall Formation. Every formation has a type section which is supposed to be the ultimate expression of that formation. The unusual names of the Supai group are taken from family names of Havasupai Indians.



trough cross-beds -fluvial



WEDGE-PLANAR CROSS-BEDS



ripple-marks and horizontal beds

← erosional surface in underlaying bed.

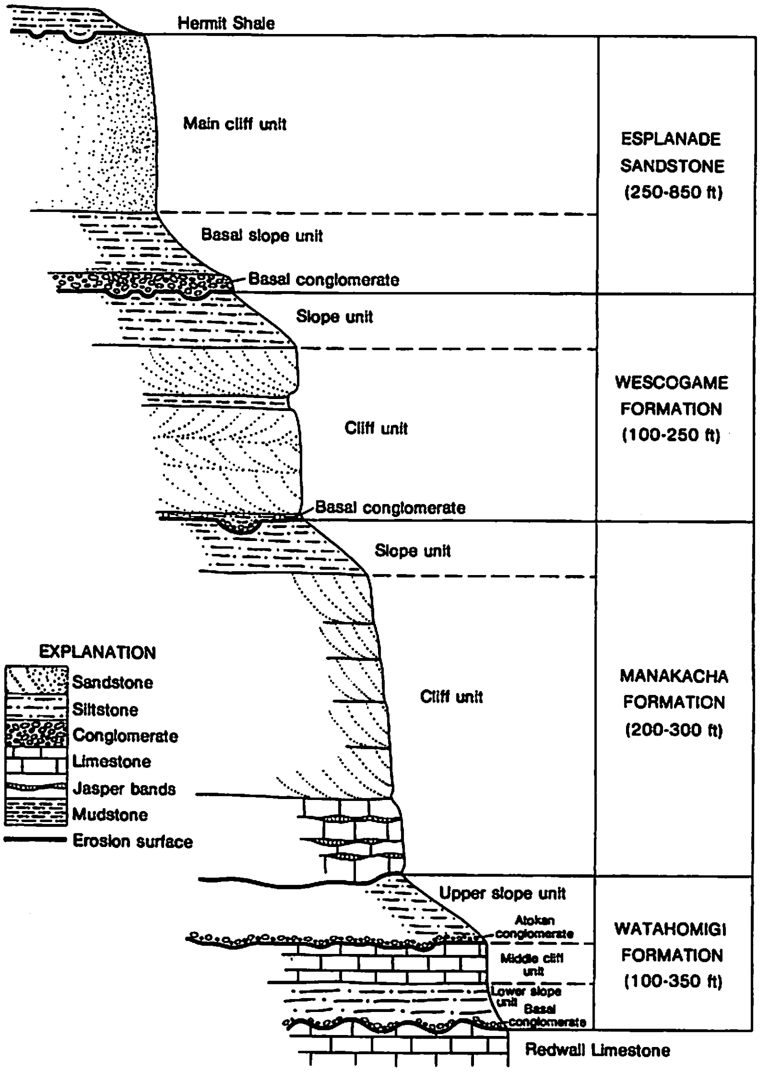
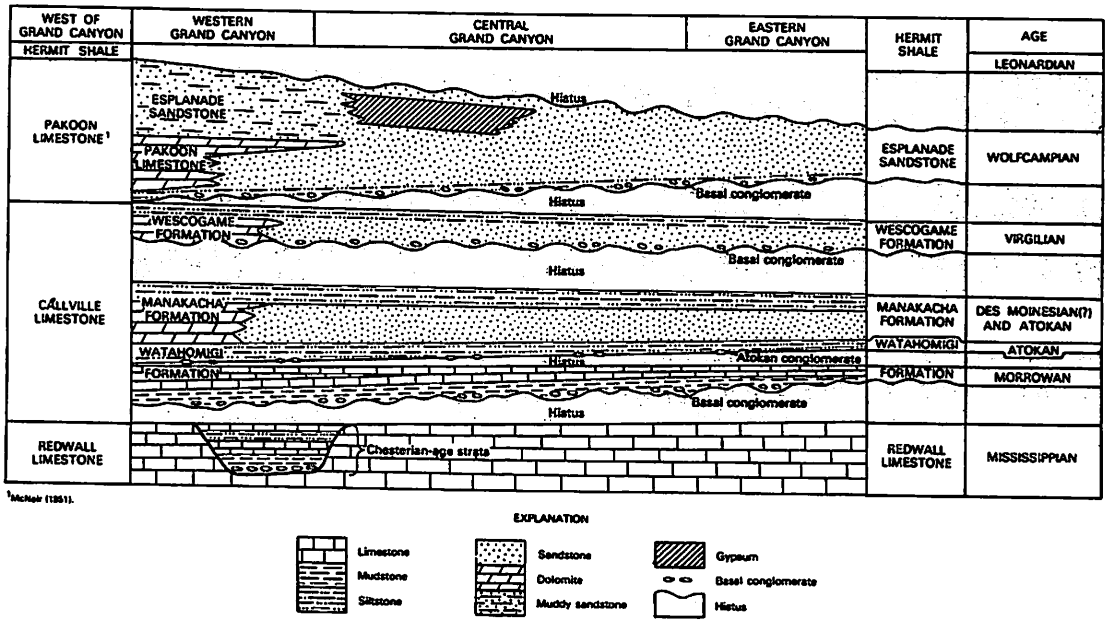


FIGURE C1.—Generalized Supai profile showing formations, their subdivisions, and key conglomerate beds at bases of Esplanade Sandstone, Wescogame Formation, upper slope unit of Watahomigi Formation, and base of Watahomigi.



¹McNair (1951).

FIGURE H1.—Generalized east-west cross section showing principal lithologic units, surfaces of erosion, hiatuses, and key conglomerate beds of the Supai Group, Grand Canyon region, Arizona. Horizontal distance about 140 mi; vertical, 800–1,500 ft.

Ground Water Flow and Springs of the Havasu Creek in the Grand Canyon

Moses Milazzo

Havasu Spring is a major discharge point for ground water moving toward the Colorado River from the south. The spring issues from the Redwall Limestone (see figure). As shown, where a permeable unit is underlain by impervious or semipervious strata, ground water may move through the permeable unit and issue above the contact with the underlying impervious strata. Recharge to ground-water aquifers takes place where highly permeable units crop out in areas that receive large amounts of precipitation. The Redwall Limestone is a part of an extensive ground-water system largely unaffected by seasonal or yearly differences in precipitation. West of Havasu Canyon, a series of faults has up lifted the formations, creating an effective barrier to the movement of ground-water away from Havasu Spring. Therefore, the spring is a natural discharge point for ground water.[1]

The existence of springs in Mars' past can be inferred from the extensive sapping-like features in the Valles Marineris system. For springs to exist on Mars, either the climate was much warmer and wetter for ground-water to be stable, or the springs were created hydrothermally by volcanic activity which melted ground-ice aquifers slowly enough to not cause catastrophic flooding, yet quickly enough to allow the water to flow.[2]

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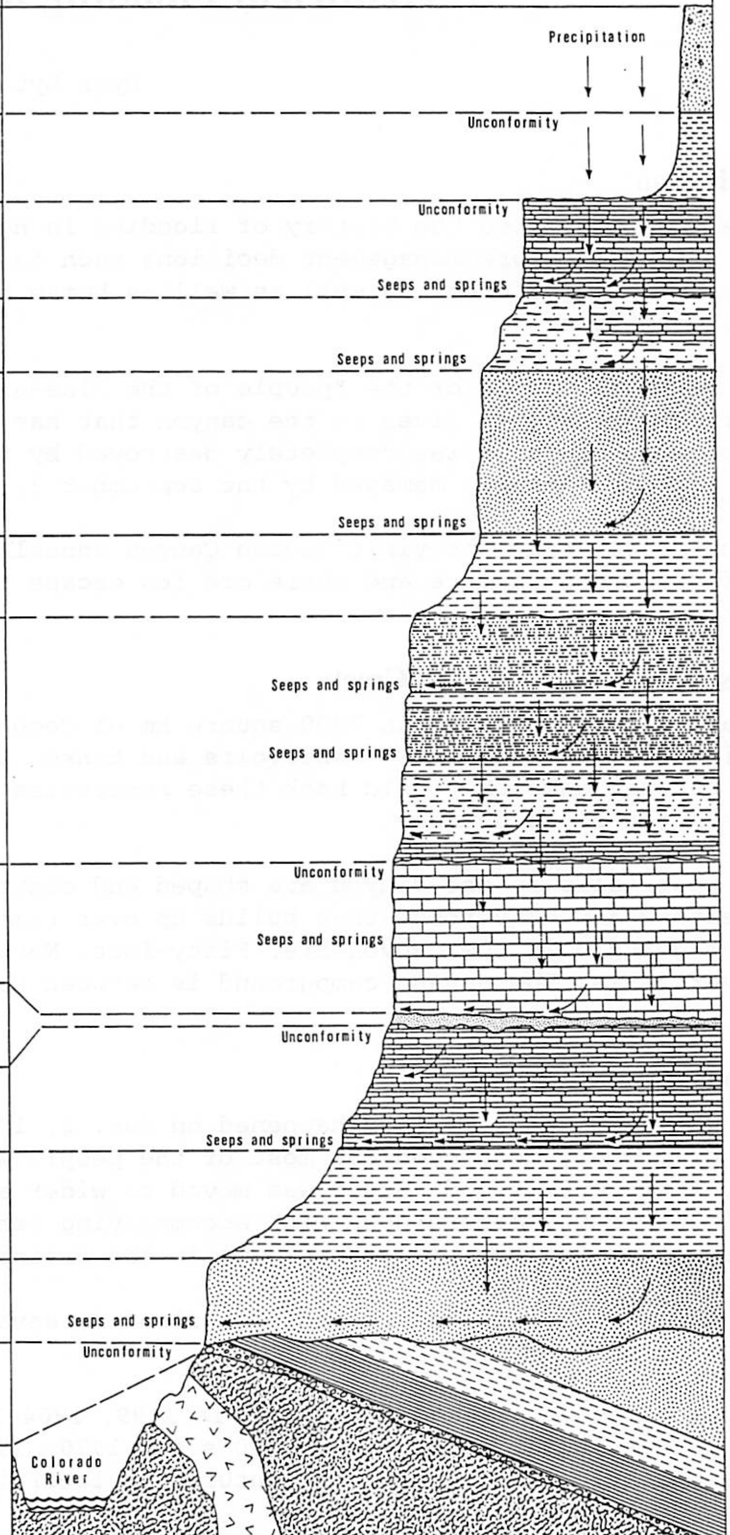
1: Johnson, P. W., and Sanderson, R. B. *Spring Flow Into the Colorado River Lees Ferry to Lake Mead, Arizona*, Water-Resources, USGS, report #34, 1968

2: Carr, M. H. *Water on Mars*, Oxford University Press, 1996

ERA	PERIOD		FORMATION AND THICKNESS (FEET)	DESCRIPTION AND WATER-BEARING CHARACTERISTICS
CENOZOIC	TERTIARY AND QUATERNARY		Basalt	Flows and cinders; transmits water readily
MESOZOIC	TRIASSIC		Moenkopi Formation	Reddish-brown shale; generally nonwater bearing
PALEOZOIC	PERMIAN	Aubrey Group	Kaibab Limestone 300-600	Yellowish- to light-gray dolomitic limestone; transmits water readily
			Toroweap Formation 0-300	Light-gray crossbedded sandstone and alternating red sandstone and buff limestone beds; water bearing
			Coconino Sandstone 300-900	Very pale orange to pale-yellowish-orange, massive crossbedded sandstone; regional aquifer
			Hermit Shale 0-500	Weakly cemented, red, fine-grained sandstone and interbedded thin red shale
	PENNSYLVANIAN		Supai Formation 900-1000	Fine-grained yellow-red-brown crossbedded sandstone, interbedded red shale, siltstone, and bluish-gray limestone at base; generally dry; small seeps and springs occur at top of permeable beds
	MISSISSIPPIAN		Redwall Limestone 450-800	Thick-bedded, bluish-gray, cherty, crystalline limestone
	DEVONIAN		Temple Butte Limestone 0-150	Purplish-gray and light-colored limy sandstone and limestone
	CAMBRIAN	Tonto Group	Muav Limestone 400-500	Gray to buff limestone, dolomite, calcareous sandstone, and shale partings
			Bright Angel Shale 200-600	Green and buff micaceous shale and thin beds of sandstone, limestone, and dolomite
			Tapeats Sandstone 50-350	Brown and white crossbedded sandstone, shale partings, and conglomerate lenses
PRECAMBRIAN	YOUNGER		Grand Canyon Series 10,000	Sandstone, shale, basalt, limestone, and conglomerate at base
	OLDER		Vishnu Schist and granite	Gneiss, mica schist, and intrusive igneous rocks

SECTION



Modified from Metzger (1961, pl. 14)

Figure 5.--Generalized geologic section, Grand Canyon, showing the relation of springs to water-bearing rocks.

Historical Flooding in Havasu Creek

Dyer Lytle

Motivation

Investigations into the history of flooding in Havasu creek are important for planning future management decisions such as re-introduction native fish species into the creek as well as well as human habitation and visitation considerations.

The Havasupi people or the "people of the blue-green waters" are a native American tribe that lives in the canyon that has about 450 members. Their settlement of Supai was completely destroyed by the January 2, 1910 flood and was considerably damaged by the September 3, 1990 flood.

About 10,000 tourists visit Havasu Canyon annually. The Havasu campground is on flood-prone terrace and there are few escape routes out of the canyon.

Physical aspects of Havasu Creek

Havasu creek drains about 7000 square km of Coconino Plateau. This drainage basin contains many small reservoirs and tanks. During large floods, some of the earthen dams that hold back these reservoirs fail and increase the worsen the flood damage.

The waterfalls in the canyon are shaped and controlled by the redwall limestone and travertine that builds up over time. These waterfalls, in order going down the canyon are, Fifty-foot, Navajo, Havasu, Mooney, and Beaver falls. The Havasu campground is between Havasu falls and Mooney falls.

Floods

The worst historical flood happened on Jan. 2, 1910. The settlement of Supai was completely destroyed but most of the people were wintering on the canyon rim. After this flood, Supai was moved to wider area of canyon. Also, Havasu falls was cut 9 meters down with accompanying erosion above. The flood was worsened by failure of earthen dams in the drainage above.

The earliest historical record of a flood in Havasu canyon is a written description from 1899.

Evidence has been found for floods in 1899, 1904-1905, 1910, 1920, 1921, 1928, 1935, 1939, small floods in the 50's and 1970, 1990, 1992, and 1993. There were more floods early in the century and later in the century with few bad floods between 1940 and 1990.

Most of the floods have been caused by thunderstorms but some of the worst ones, in 1905,1910 and 1993, were caused by winter frontal systems that brought intense multi-day rains.

Base flow in Havasu creek is about 2 cubic meters per second. The maximum flow during the 1990 flood was 575 cubic meters per second. The maximum flow rate during the 1910 flood was probably higher but is hard to estimate from quotes like "A twenty foot high wall of water came down the canyon.".

Digging up the evidence

Four sources of information about the historical floods in Havasu canyon have been used:

1. Various documents, mostly newspaper accounts of the floods.
2. Photographs taken, mostly of the waterfalls, during the last century.
3. Dendrochronology of Ash trees in the canyon. This source wasn't found to be very helpful due to the inability to cross-date trees and because of the short life span of the Ash.
4. Daily precipitation records from stations near the Havasu creek drainage basin. The early part of century shows a decrease in the number of days per year with more than an inch of rain, this number was flat from about 1930 to 1960, and has increased since then. The El Nino/Southern Oscillation seems to be on the increase in latter part of 20th century and this may have an impact on future flooding on Havasu creek.

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"When the Blue-Green Waters Turn Red: Historical Flooding in Havasu Creek, Arizona" by Theodore S. Melis, William M. Phillips, Robert H. Webb, and Donald J. Bills : U.S. Geological Survey Water-Resources Investigations Report 96-4059

The Havasupai: Blue-Green Water People

Compiled by Jani Radebaugh

> "For as long as the Havasupai have lived, they have been the keepers of the Canyon. The creator gave them this canyon and the Havasupai take their role as preservers of the canyon very seriously. They believe that without their vigilance, the canyon would be exploited like Niagara Falls and other scenic wonders in the United States have been exploited by trash tourism and development."
>
> –Kay McGowan, PhD, Choctaw, Anthropologist

- Eight and a half miles down a steep, switchback dirt road only traversable by pack mules, horses, or two feet, is the village of Supai, home to the smallest tribe of Native Americans in the USA, the Havasupai. They number 656 people. The name "Havasupai" means the People of the Blue Green Water. "Havasu" is blue-green and "pai" means people in Yuman, which is the language of the Havasupai. The Havasupai are also closely related to the Hualapai ("pine tree people") and the Yavapai ("people of the sun"), small tribes found outside of the Grand Canyon, and they have intermarried for centuries

- The tribe owns an elementary school, a village store, a restaurant, a small lodge for paying visitors, and a museum with artifacts, which also sells baskets, jewelry, and beaded work done by the village women. There is a medical clinic with a village doctor and two nurses, and seriously ill patients are taken by helicopter to Peach Springs, Arizona. The only non-Havasupai people who live in the village are the Christian minister and his wife, although few have converted to Christianity; most maintain their ancient traditions.

- Numerous side canyon tributaries feed into the Colorado River near the village of Supai, the largest of which is called Havasu Canyon. Irrigation ditches bring water from these tributaries to the village; these ditches were built by ancestors of the Havasupai over 1000 years ago.

- Traditional ancestral-type farming still exists as the main mode of food provision for the people. They grow crops such as corn, beans, squash, and fresh vegetables such as tomatoes, cucumbers, cabbage, and peas. They also grow alfalfa for their horses. Fruits are also grown, such as peaches, apricots, apples, and wild figs, which can be dried for winter. The people travel up to the plateau to hunt jackrabbits, bighorn sheep, and mule deer for meat. Supplies such as coffee, salt, and flour are brought in by helicopter and sold at the local village store, but these prices are high, as you can imagine.

- Only 20,000 visitors per year come down to Havasupai, despite the 4+ million who visit the Grand Canyon. Your $15.00 camping fee goes to help provide services for the village.

In 1903, Teddy Roosevelt declared the Grand Canyon a National Park, and the Havasupai lands were restricted to 518 acres, a 5 mile by 12 mile side canyon, and many of the Havasupai were gathered together and driven out of their land. Then their water wells were filled in and their dwellings destroyed, and many Havasupai died as a result. A nine year battle in the federal court ending 71 years after the tragic event, in 1974, won them back 124,000 acres, a small portion of their original land. An additional monetary settlement helped each family build a nice wooden three bedroom home.

Most Havasupai choose to remain in their homeland, although work is hard to find, so many must work outside the canyon in the rodeo circuit or powwow circuit or in surrounding cities for half the year.

Environmental challenges facing the Havasupai currently: Disposal of solid and liquid waste--they may attempt to airlift some solid waste out of the canyon, and are trying to implement solar toilets, although they can't keep the tourists from dumping garbage in them (-!). Composting--this will help them dispose of green and food wastes. Canyon preservation--erosion is increasing in the canyon due to higher traffic from visitors; historic and archeological sites need to be identified, and then measures need to be taken to protect these sites. Wildlife and vegetation patterns/changes--these must be monitered by the Havasupai in order to protect their food sources and maintain the ecological balance in the canyon.

The Havasupai have a code of responsibility which guides them to preserve their cultural identity through protection of their land and separation of their society from negative outside practices. Look around you at the beauty of the canyon with its clear turquoise waterfalls and lush greenery--an oasis in the desert-- and that will tell you the most about the Havasupai who choose to live here.

Kay McGowan, "The Havasupai, keepers of the Grand Canyon"
http://www.indianworld.org/content/news/grand.htm

Havasupai Indian Reservation Internet Site
http://www.nbs.nau.edu/Tribes/Havasupai/

Pictures from
http://www.doitnow.com/~cerci/Havasupai
/graphics/

Atmospheric Conditions in the Grand Canyon

Andreas Ekholm

Climate

The climate of the Grand Canyon is similar to that of Arizona as a whole. Precipitation (see Table 2) is scant to moderate, with roughly equal amounts falling in summer and winter. Relative humidity is generally low. Clear skies are the norm. Winds are usually gentle to moderate. Air temperatures vary greatly between summer and winter, with as much as 50°F separating the seasonal extremes. Fall is usually mild and clear, with little or no precipitation. Spring also brings many clear, mild days, though snow often falls in April, sometimes in May, even on the South Rim.

Within this overall pattern, diverse topography and the considerable difference in elevation between the rims and the river have produced a variety of local climates. As a rule, air temperature drops and precipitation increases with elevation, so that the rims are significantly cooler and more humid than the bottom of the canyon. Because southern exposures receive more sunshine throughout the year than north-facing slopes, the former tend to be warmer and drier than the latter at any given elevation.

Precipitation

Average annual precipitation at the Grand Canyon varies from fewer than 10 inches in the Inner Gorge to nearly 30 inches on the Kaibab Plateau. The North Rim receives considerably more precipitation in winter than summer, but the South Rim and canyon receive roughly equal amounts in each season. The average rainfall in the Inner Gorge for the period from May through October is about 4.5 inches. In 1968, Phantom Ranch recorded less than 4 inches for the entire year.

Table 2.
Precipitation and Air Temperature at the Grand Canyon

Mean precipitation in inches	Phantom Ranch Inner Gorge (el. 2570')	Grand Canyon Village, South Rim (el. 6950')	Bright Angel Ranger Station, North Rim (el. 8400')
January	0.68	1.35	3.05
April	0.53	1.00	1.62
July	0.87	1.50	1.88
October	0.67	1.07	1.43
Annual	8.39	14.46	22.78
Yearly Snowfall	0.2	64.9	128.7
Mean daily temperature in degrees F			
January max.	56.3	41.4	37.8
January min.	36.3	19.6	19.5
April max.	82.1	60.2	52.9
April min.	55.5	31.4	31.4
July max.	106.1	84.7	77.1
July min.	77.7	54.0	46.3
October max.	84.9	64.9	58.6
October min.	59.2	37.2	31.6

(Data from Sellers and Hill: *Arizona Climate*, 1974)

Winter storms move eastward into the Grand Canyon region from the Pacific Ocean. They typically last up to several days, bringing gentle snow showers to the rims and upper canyon, and light rains to lower elevations. The amount of winter precipitation received at the Grand Canyon varies greatly from year to year in both amount and frequency of occurrence. In wet years a succession of storms may cross the region at weekly intervals. In December 1966, an unusually warm Pacific storm dropped some 14 inches of rain on the Kaibab Plateau over a 3-day period, but such deluges are extremely rare.

On the Kaibab Plateau the average annual snowfall exceeds 125 inches. From early November to May, up to several feet of snow usually block roads leading to the North Rim. Grand Canyon Village, on the South Rim, is about 1500 feet lower than the North Rim Lodge and accordingly receives about half as much snow, or about 60 inches in an average year. Most snow falling on the South Rim remains on the ground for only a few days, though small patches may linger for much of the season in cool, shaded locations, particularly in places just below the rim where the low winter sun does not reach. Less than an inch of snow falls in the Inner Gorge during an average year.

After April, the incidence of Pacific storms drops sharply. From then until the onset of summer thunderstorms in mid-July, the Grand Canyon receives little or no precipitation, making May and June the driest months. Rainfall during this period ranges from about 0.5 inch in the Inner Gorge to 1.5 inches on the North Rim. A second, less severe season of drought occurs in the fall.

From mid-July to mid-September—the monsoon season—thunderstorms may occur almost every afternoon over the Grand Canyon. During the summer, warm tropical air from the Gulf of Mexico enters the region from the southeast. As it moves northward across Arizona, it is forced up and over the Mogollon Rim. In the process the air cools, and its moisture condenses to form puffy cumulus clouds. Over the Grand Canyon this incoming air is borne even higher by powerful thermals rising off the sun-baked canyon walls. As a result the clouds gather, thicken, and pile up to form massive thunderheads. The resulting thunderstorms tend to begin in mid- to late afternoon and last about a half-hour. By shortly after sundown the clouds usually have dissipated. On rare occasions these storms may deliver an inch or more of rain, though lesser amounts are the rule. About one year in seven, tropical storms from the Gulf of California, to the southwest, move into Arizona during the summer. Often lasting several days, these storms account for the region's heaviest rainfall.

Air Temperature

Average daytime high temperatures during the summer range from the low to middle 70s on the Kaibab Plateau to more than 100°F in the Inner Gorge. Daytime highs on the Coconino Plateau for this period are typically in the middle 80s. Average nighttime temperatures during the summer drop to the low 40s on the Kaibab Plateau, the low 50s on the Coconino Plateau, and the high 70s in the Inner Gorge.

During the first two weeks in July, before the onset of summer storms, air temperatures in the Inner Gorge frequently exceed 115°F during the day. Temperatures in excess of 100°F have been recorded for every month from April through October. Beginning shortly after sunrise, the nearly black cliffs lining the gorge heat up rapidly to temperatures over 120°F. Throughout the day and continuing until well after sunset, the cliffs radiate this stored heat like the walls of a brick oven. Visitors unaccustomed to such heat are well advised to avoid the Inner Gorge during the summer.

Average daytime high temperatures during the winter range from the middle 30s to low 40s on the Kaibab Plateau, low to middle 40s on the Coconino Plateau, and high 50s to low 60s in the Inner Gorge. The coldest periods come during winter snowstorms, when cold, moist Pacific air aloft overlies a layer of even colder Arctic air at the surface. The latter air mass is borne into the region from the Great Plains. At such times, nighttime lows on both rims may plummet to below zero. Normally, winter lows range in the middle teens on the Kaibab Plateau, in the high teens to middle 20s on the Coconino Plateau, and in the middle 30s in the Inner Gorge.

Wind

Wind directions vary with season, shifting around the compass in the fall and winter and settling into sustained southwesterly flow in the spring and especially in the summer. The complicated topography of the canyon leads to a complicated local air flow—the wind can be blowing from the east in the canyon while blowing from the north above it.

Visibility

Panoramic views in the Grand Canyon typically extend to over 100 km; under ideal (Rayleigh) conditions visibility approaches the ultimate value of 400 km. Ideal conditions are becoming more and more rare, however, as pollution from anthropogenic sources has on average resulted in a 50% increase in light extinction over natural conditions.

Visibility can be described quantitatively in terms of:

- contrast (the relative brightness between features)
- discoloration (the wavelength shift of the light as it moves through the atmosphere)
- visual range (the farthest distance at which an observer is able to distinguish a black object against the horizon sky)
- extinction coefficient (depends on the fraction of light that is scattered or absorbed on the way from the object to the observer)

As an example, a decrease in the visual range from 130 to 110 km leads to noticeable contrast and coloration change for features as close as 30 km.

Haze

During winter, foggy conditions are not uncommon and haze sometimes blankets the canyon. The haze is caused by large concentrations (more than a few tenths of a $\mu g/m^3$) of fine suspended particles (aerosols) that scatter and absorb light. These particles are typically 0.1–1 µm across. SO_4^{2-} accounts for about one third to one half of the aerosols by mass and is produced from SO_2 through reactions in the atmosphere. These reactions are aided by the presence of water, which means that there is more haze during cloudy and foggy conditions (which occur more frequently during winter).

In 1987, an experiment (Winter Haze Intensive Tracer Experiment, WHITEX) was carried out to assess the source of the aerosols at the Grand Canyon. Deuterated methane (CD_4) was injected into one of the stacks at the Navajo Generating Station (NGS). NGS is a major coal power plant 110 km northeast of Grand Canyon Village (25 km from the Grand Canyon National Park border). The study concluded that the NGS was responsible for 70% of SO_4^{2-} particles and 40% of overall aerosols (the exact numbers have later been questioned, but the qualitative results stand). Support comes from the fact that haze occurs during periods of air stagnation, when sulfur from local sources would be expected to accumulate; this occurs more frequently in winter than in summer.

Other studies have found that the air masses with the highest aerosol content preferentially come from southern California and central and southern Arizona (where copper smelters contribute a large fraction).

Pluto and Triton

Comparisons and Evolution Over Time

(Summarized by Paul Geissler)

Thursday September 23

8:20 **Bob Millis** Director's welcoming remarks, announcements, coffee and snacks, etc.

Session 1: Formation, Early History, and Geology

Chaired by Damon Simonelli

8:30 **Bruce Fegley Jr.** (invited review) **Chemistry of the outer solar nebula: Implications for the composition of Pluto, Kuiper Belt Objects, and other volatile-rich bodies**

Poster **Katherina Lodders Are some types of carbonaceous chondritic meteorites samples of Kuiper Belt objects?**

9:10 **William B. McKinnon and Jeffrey S. Kargel** (invited review) **Millenial perspectives on the origin and evolution of Pluto and Triton**

Poster **A.M.N. Rao and J.I. Lunine Early atmospheres**

--- 9:50 Coffee break ---

10:00 **Paul M. Schenk** (invited review) **Vigorous dynamic Triton**

10:40 **K. Zahnle, J. Moore, H. Levison, L. Dones, and P. Schenk A retrograde moon in a prograde system**

--- 11:00 Coffee break ---

11:10 **S.A. Stern and W.B. McKinnon Triton's surface age and impactor population revisited in light of Kuiper Belt fluxes: for small Kuiper Belt objects and recent geological activity**

11:30 **Jeffrey M. Moore and Paul M. Schenk The "geology" of Pluto and Charon**

11:50 **R.T. Pappalardo and G.C. Collins Stress patterns on Pluto and Charon due to their mutual orbital evolution**

--- 12:10 Lunch in the Rotunda ---

Session 2: Observations

Chaired by John Spencer and Mark Sykes

1:30 **Michel Festou** (invited review) **Review of observations of Pluto and Triton**

2:10 **E. Lellouch, R. Laureijs, B. Schmitt, E. Quirico, C. de Bergh, J. Crovisier, and A. Coustenis Pluto's non-isothermal surface from ISO observations**

2:30 **Michael E. Brown, and Wendy M. Calvin Spatially resolved spectroscopy of Pluto and Charon from the Keck telescope**

Poster **Shane Byrne and Michael E. Brown 2-4 micron spectroscopy of Pluto and Triton**

--- 2:50 Coffee break ---

3:00 **Christophe Dumas, Richard J. Terrile, Robert H. Brown, and the NICMOS IDT Team Reflectance spectroscopy of the individual members of the Pluto/Charon system: HST/NICMOS results**

3:20 **Marc W. Buie, Will M. Grundy, and Susan D. Kern Separate spectra of Charon and Pluto from HST/NICMOS**

3:40 **Bryan Hilbert, John Stansberry, Will Grundy, Marc Buie, and Roger Yelle The near-IR spectrum of Triton: Characterization and search for variability**

4:00 **Susan Kern, Marc Buie, and Will Grundy Monitoring methane on the surface of Pluto**

4:20 **Jason C. Cook, Leslie A. Young, Eliot F. Young, and Roger V. Yelle Atmospheric carbon monoxide on Pluto & Triton at 2336-2343 nm**

4:40 **M.D. Hicks and B.J. Buratti Spectroscopy and filter photometry of Triton from 1997-1998: Evidence of dramatic global change?**

Poster **D. Pascu, J.R. Rohde, P.K. Seidelmann, E.N. Wells, J.L. Hershey, B.H. Zellner, A.D. Storrs, D.G. Currie, and A.S. Bosh HST BVI Photometry of Triton**

--- 5:00 Adjourn for the evening ---

Quaternary Sedimentary Deposits
(How to classify sediments and why we bother)

Laszlo Keszthelyi

Clastic (i.e., particulate) **sediments** are classified by (1) the size of particles, (2) the size distribution of particles, (3) the composition of the particles, and (4) the shape of particles. These pieces of information can tell you (a) what kind of rock the particles came from, (b) what transported them, and (c) how far they were transported. Answering these questions is of equal importance on planetary surfaces as the Earth.

Particle size is usually measured using the Wentworth Grain Size Scale (Table 1). To zero-th order, the size of particles provides information on the energy of the transporting medium. This is sometimes confused when the density of the particles, especially if the densities of the particles and the fluid are similar.

Size distribution is usually estimated in the field in a subjective fashion, but can be properly quantified by plotting size-distribution histograms (Table 2). To zero-th order, the size distribution provides information on the viscosity of the transporting fluid. Ice can transport all sizes of rocks, but wind is very particular about selecting only sand-sized pieces. Size distribution is also affected by the time/distance over which the sediments have been transported, with more time and distance leading to better sorting.

Particle shape is quantified by two parameters – *roundness* (Table 3) and *sphericity* (Table 4). Roundness provides information on the time/distance the sediment has been transported with rounder particles requiring greater transport distance. The material properties of the particles also affects roundness. The sphericity of the particles provides insight into how the material was physically transported (saltating, rolling, dragging, etc.).

Chemical precipitates (**evaporites**) are classified by chemistry and can be used to infer the salinity of the water it was deposited from. Order of precipitation for typical seawater is calcite = $CaCO_3$, dolomite = $(Ca,Mg)CO_3$, gypsum ($CaSO_4 \bullet 2H_2O$) and anhydrite ($CaSO_4$), halite (NaCl), potash=sylvite=KCl, and finally a whole mess of wacky Mg, K, Cl, Br salts. Gypsum starts to precipitate after 70% of the seawater has evaporated, halite at 90% and sylvite at 95%. 1 km of seawater produces about 2 m of evaporites. Sudden changes in water temperature or pH can also cause chemical precipitation.

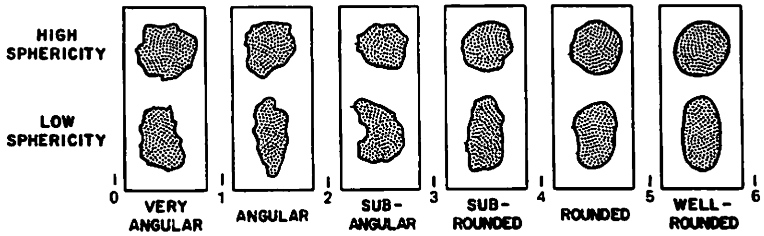
Limiting particle diameter					
mm	φ units	µm	Size class		
2048	−11		Very large	Boulders	GRAVEL
1024	−10		Large		
512	− 9		Medium		
256	− 8		Small		
128	− 7		Large	Cobbles	
64	− 6		Small		
32	− 5		Very coarse	Pebbles	
16	− 4		Coarse		
8	− 3		Medium		
4	− 2		Fine		
2	− 1		Very fine	Granules	
1	0		Very coarse	Sand	
1/2	+ 1	500	Coarse		
1/4	+ 2	250	Medium		
1/8	+ 3	125	Fine		
1/16	+ 4	62	Very fine		
1/32	+ 5	31	Very coarse	Silt	MUD
1/64	+ 6	16	Coarse		
1/128	+ 7	8	Medium		
1/256	+ 8	4	Fine		
1/512	+ 9	2	Very fine		
				Clay	

from: Wentworth, CK (1922) J. Geol., 30: 377-392

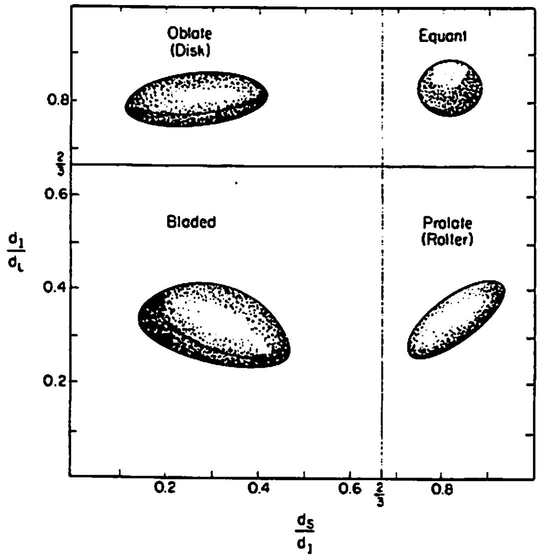
SORTING CLASSES BASED ON STANDARD DEVIATION

Ranges of values of sorting (φ units)	Sorting class	Environments of sands
<0.35	Very well sorted	Coastal and lake dunes; many beaches (foreshore); common on shallow marine shelf
0.35–0.50	Well sorted	Most beaches (foreshore); shallow marine shelf; many inland dunes
0.50–0.80	Moderately well sorted	Most inland dunes; most rivers; most lagoons; distal marine shelf
0.80–1.40	Moderately sorted	Many glaciofluvial settings; many rivers; some lagoons; some distal marine shelf
1.40–2.00	Poorly sorted	Many glaciofluvial settings
2.00–2.60	Very poorly sorted	Many glaciofluvial settings
>2.60	Extremely poorly sorted	Some glaciofluvial settings

SOURCE: Friedman and Sanders, 1978, p. 73. Principles of Sedimentology, John Wiley, NY, 792pp.



Outlines of classes in Powers' roundness scale, showing both high- and low-sphericity shaped particles. Numbers between classes represent the rho (ρ) scale of Folk (1955). (Modified from Powers, 1953, p. 118.) ← J. Sed. Petrology 23: 117-119
↖ J. Sed. Petrology, 25: 297-301



Zingg's classification of particle shapes based on principal diameter ratios, where d_s = short diameter, d_I = intermediate diameter, and d_L = long diameter. (From Zingg, 1935.)
↖ Min. Petrog. Mitt. Schweiz., 15: 39-140.

DEVON BUKIC

SOME STUFF ON THE GEOMORPHOLOGY OF WATERFALLS

I. So what?
- a. large energy expenditure-what does it do?
- b. landscape evolution 1) cause 2) key (Nott et al, 1996)
- c. paleoclimatic indicators e.g. plunge pools (Nott and Price, Nott et al.)
- d. ignorance . . . .

"All waterfalls are ephemeral features. Because of the tremendous hydraulic force of the water, they retreat upstream until the profile of the stream is smoothed out." (Hurlbut, 1976) . . . . True or False???

II. "the caprock model" - Gilbert (1896) from Niagara Falls
- a. lithology = resistant caprock (limestone) over softer units
- b. erosion = parallel slope retreat caused by the water grinding the limestone blocks against the cliff
- c. also, spray on cliffs, currents in plunge pool
- d. ex - large waterfalls in Iceland = basalts over sediments

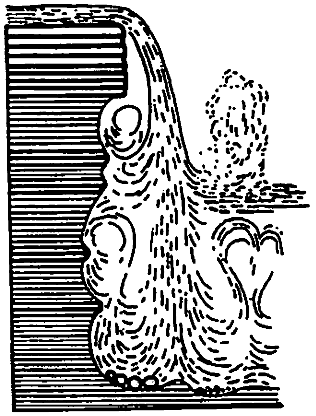
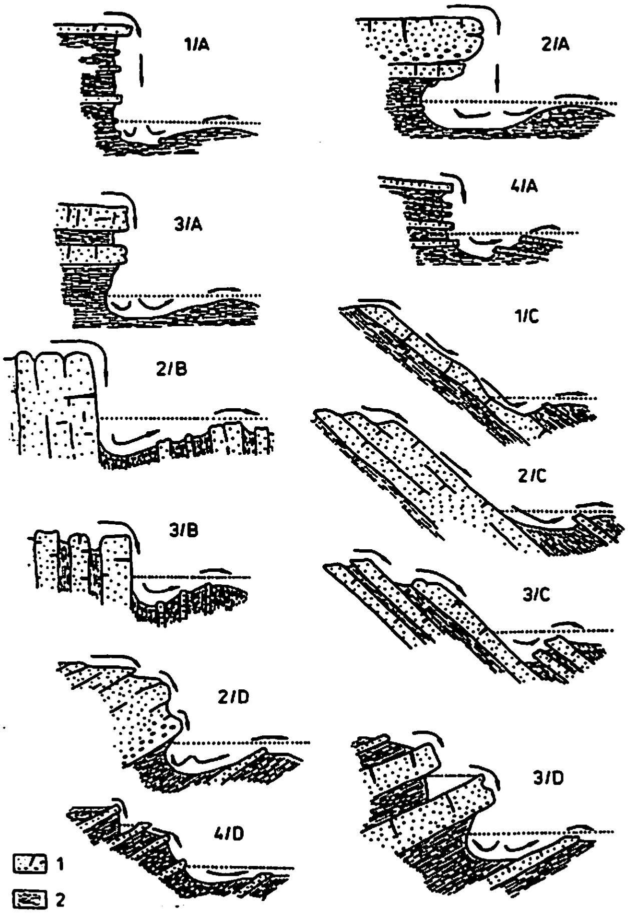


Fig. 1. Erosion of the caprock on Niagara Falls (redrawn from GILBERT 1894 and HOLMES 1956).

III. "Waterfalls without undercutting" - example in Sidney Basin, Australia (Young 1985)
- a. buttressed out in steeply dipping fold belts
- b. apparently not transient b/c deep gorge downstream indicating retreat

IV. Typology - Polish Carpathian Mts (Alexandrowicz 1994)
- a. based on bed sequence, attitude, morphology
- b. shows both types
  - 1) caprock = A1-A4, D2-D4
  - 2) w/o undercutting = B2, B3, C1-C3
- c. no relationship found among morphology, height, plunge pool depth, discharge



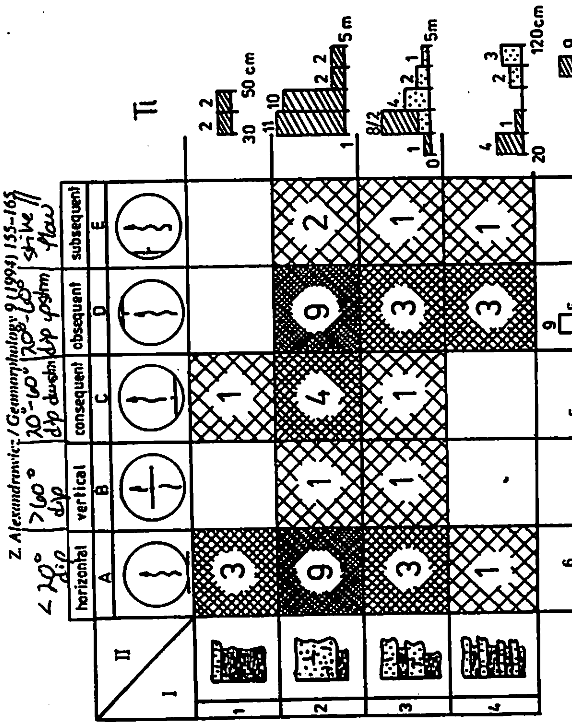


Fig. 6. Principles of classification of the Outer Carpathian waterfalls. I bed sequence: 1 – hard sandstone layer underlain by shales, 2 – very thick layer of sandstone underlain by shales, 3 – two or three thick sandstone layers with thin intercalations of shales, underlain by shales, 4 – several beds of sandstones intercalated by shales; II – attitude of beds versus river course; Tl – histograms of thickness classes of sandstone layers by bed sequence type: a – thickness of top layer, b – total thickness of sandstone layers; Dl – histograms of dip classes of layers by bed position sandstone (numbers above histograms indicate frequencies).

IV. Evolution

a. physical modelling of knickpoints (Holland and Pickup 1976) - cement-sand mix with 2 sand layers

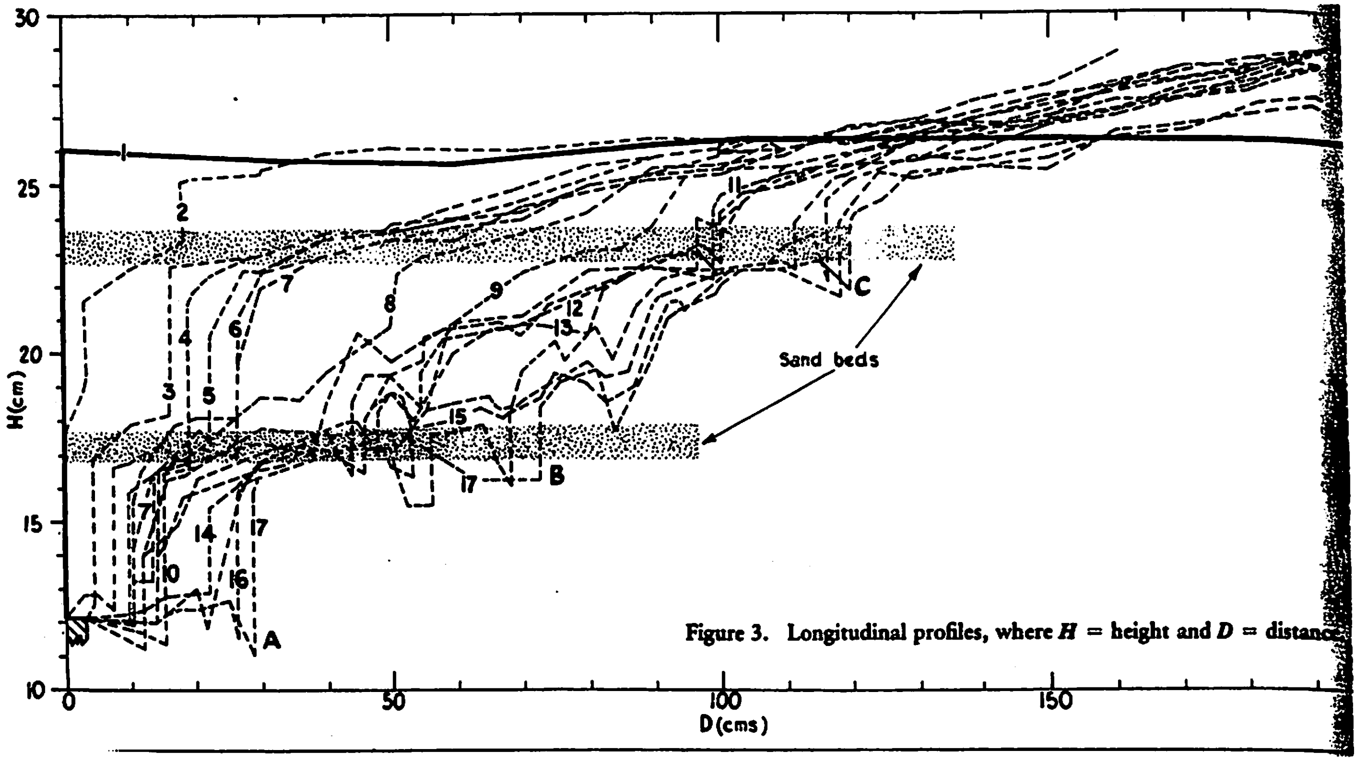


Figure 3. Longitudinal profiles, where H = height and D = distance

b. real world -- in Africa, falls often separate incised downstream from braided upstream, e.g. Victoria Falls on the Zambezi, Augrabies Falls on the Orange River

SEE NEXT PAGE

Alexandrowicz, Z., 1994. Geologically controlled waterfall types in the Outer Carpathians. Geomorphology, v. 9, pp. 155-165.

Gilbert, G., 1896. Niagara Falls and their history, in National Geographic Society: the physiography of the United States, pp.203-236. American Book Co., New York.

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Even a cursory examination of a topographic map of Africa shows that the drainage of the African continent has a number of apparently anomalous features. For instance, the drainage pattern of several of the major basins is to a large extent centripetal. This is particularly evident in the Zaire Basin where most of the major tributaries are orientated towards a point in the centre of the basin rather than towards its outlet. Other major rivers, such as the Niger, have long sections which flow directly *away* from a closely adjacent coastline. Africa, along with Australia, is also remarkable for the proportion of its total area occupied by internal drainage systems.

Undoubtedly climatic factors, especially oscillations between arid and humid climatic regimes, have played an important role in the development of these drainage characteristics. But tectonic controls also seem to have been crucial; not only has the tectonically induced basin and swell topography of Africa provided an overall constraint to drainage basin development, but the presence of a crustal upwarp extending around most of the margins of the continent has probably been of great importance to the post-Gondwana drainage evolution of the continent.

The effect of this marginal upwarp becomes very evident when we examine the hypsometric curves for Africa's major drainage basins (Fig. 16.23). Most obvious is the very small proportion of the area of each basin at low elevations. The form of these hypsometric curves is in stark contrast to the form we might expect for mature drainage basins which would have a significant proportion of their total basin area at low elevations. Remember that the drainage systems of Africa have had more than 100 Ma to evolve since the final emergence of Africa as a discrete continent after the break-up of Gondwana.

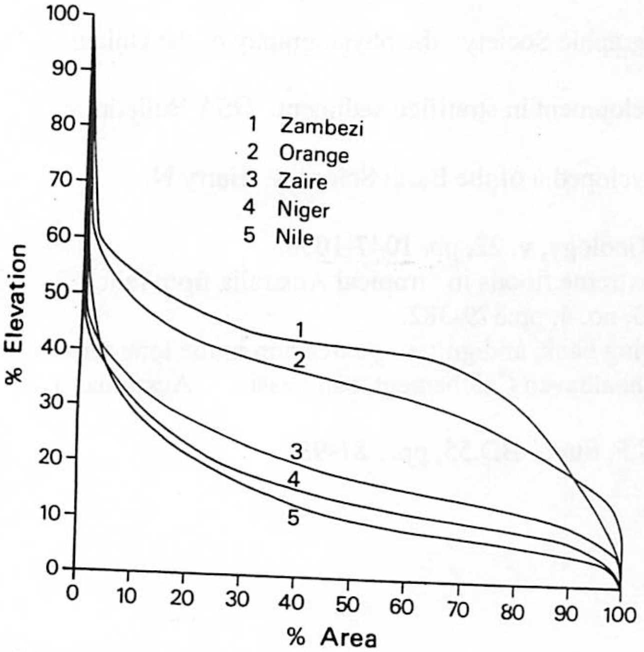


***Fig. 16.23** Percentage hypsometric curves for the five largest drainage basins in Africa.*

The long profiles of the major river channels also raise interesting questions. The gradient of the Zaire River along 2000 km of its middle course averages only 0.05 m km^{-1}, whereas from Kinshasa to Matadi near its mouth the mean gradient increases by over 15 times to 0.78 m km^{-1} as the channel plunges down the knickpoint formed by the rapids at Stanley Pool. Other African rivers also have significant knickpoints such as the Victoria Falls on the Zambezi and the Augrabies Falls on the Orange (Fig. 16.24).

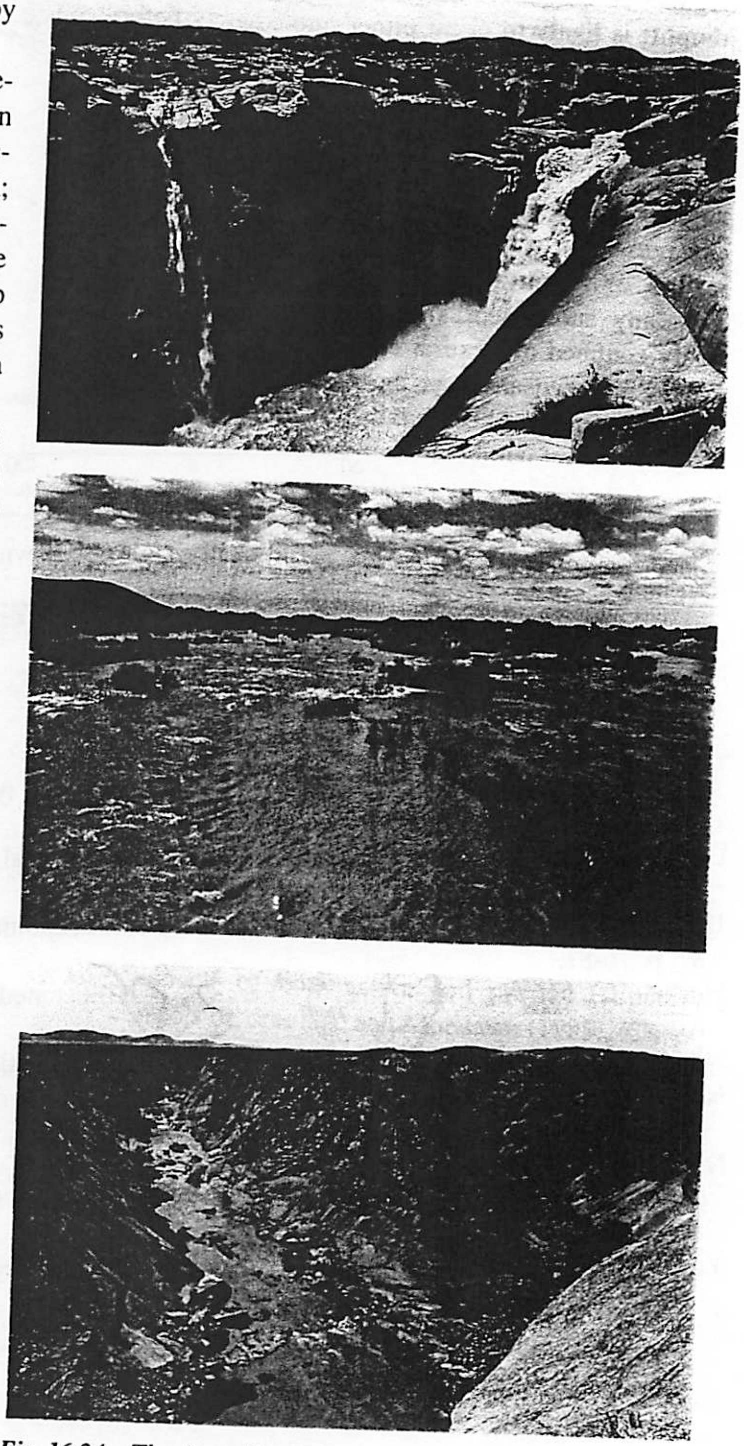
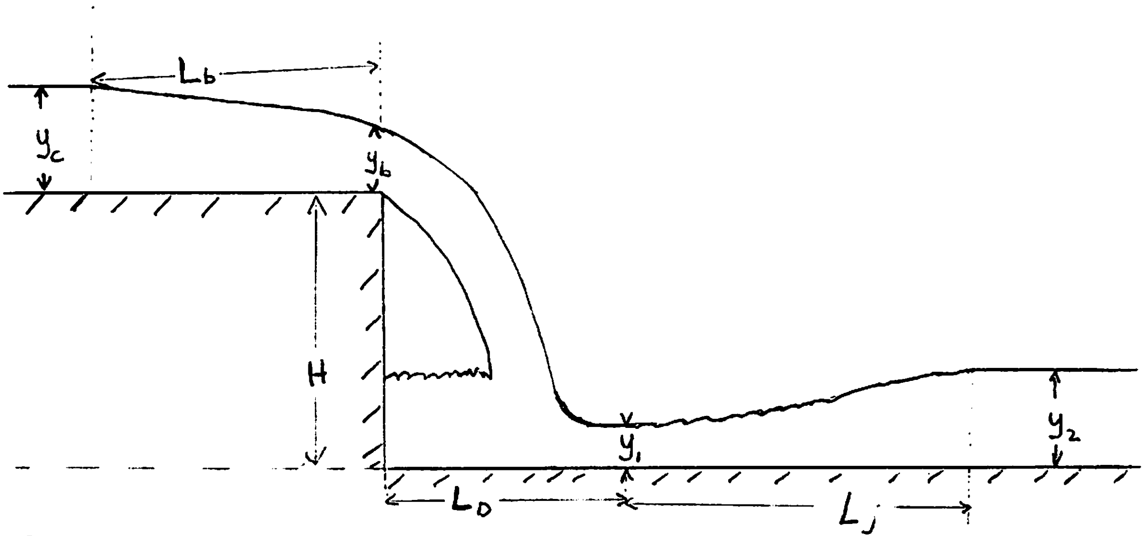


***Fig. 16.24** The Augrabies Falls, a major knickpoint on the Orange River, southern Africa (top photo), which separates its low-gradient braided middle course (middle photo) from its deeply incised lower course (bottom photo).*

from Global Geomorphology, M.A. Summerfield, 1991

Waterfall Physics

Conducted by James N Head



Flow Features

An idealized waterfall is illustrated above. Water depth at various places is denoted *y*. Reaches are denoted *L* and the drop in the bed is denoted *H*. Though this is an idealized case, it should provide insight into the waterfalls we will see on the trip.

Fluid flow is governed by the Bernoulli equation $E = z + \cos\theta + \alpha V^2/2g$ where *E* is the total head, *z* is the hydraulic head, *θ* is the bed slope, *V* is flow velocity, *g* is acceleration due to gravity and *α* is a fudge factor. Critical depth for uniform flow is given by $y_c = (q^2/g)^{1/3}$, where *q* is the discharge per unit width of channel. This relation is derived by differentiating the Bernoulli equation with respect to depth, assuming zero slope and $\alpha = 1$. For a rectangular channel, y_c is actual water depth. In the above illustration, y_2 and y_c are determined this way. If the channel characteristics do not change across the fall, then $y_2 = y_c$. The water depth at the brink y_b has been determined experimentally : $y_b = 0.715y_c$. The brink is shallower because the change in flow velocity and hence pressure propagates upstream by an amount also determined experimentally: $L_b = \sim 4y_c$.

Downstream from the fall, the flow is shallowest, then increases in depth across the hydraulic jump. The hydraulic jump is analogous to a shock wave, the sound speed being replaced by the gravity wave speed (Jokipii veterans know about this). On one side the flow velocity is higher than the gravity wave speed, on the other side it is lower. The phenomena can be reproduced in a kitchen sink. The water depth on either side of the jump is determined from momentum conservation and the result usually given as a ratio:

$y_2/y_1 = 0.5((1 + 8F^2)^{1/2}-1)$, where F is Froude number: $F = V/(gy)^{1/2}$. The Froude number is typically 5 or more in waterfalls, giving a final value for y_2/y_1 of about 7 or more. The length of the hydraulic jump is proportional to the critical depth y_2 and has been determined experimentally over a wide range of Froude numbers, upon which there is a weak relationship. Measurements of natural waterfalls gives a value of 5 – 6 for the ratio L_j/ y_2. The distance from the brink to the fall (y_1) depends on height and discharge and obeys a power law relationship $L_D/H = 4.3D^{0.27}$, where $D = q^2/(gH^3)$.

Erosion of Bedrock

There are several mechanisms for eroding bedrock in rapidly flowing water.
Hydraulic lift: flow speed increases to the point that the water pressure is locally much lower than nearby, leading to buckling and plucking of bedrock material leaving behind potholes.

Kolks: closely related to hydraulic lift. Vertical rollers cause locally very low pressures, again leading to buckling and plucking.

Cavitation: As flow velocity increases, pressure can drop below the vapor pressure leading to the formation of bubbles. These bubbles collapse violently, sending shock waves into the river bed, fragmenting the rock. This mechanism can be very effective. In one case, a cavitating flow eroded 18 inches into a concrete dam spillway in 23 hours. The critical velocity for initiating cavitation is calculated from the Bernoulli equation and is depth dependent. In general, flow velocities in excess of 25 – 30 ft/sec are required. Since this speed is obtained in a freefall of 12 ft, cavitation should be common in waterfalls.

Corassion: enlargement of a pothole by abrasion. Vortices form in the pothole, churning the sides with any solid material carried by the flow. As the pothole grows, so does the size of abrading particles that can be accommodated. Look for rounded cobbles in potholes.

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pH and Hardness of Havasupai waters

By Ian McEwen

I Will be testing pH and hardness of Havasu creek water, Campground spring water and Tucson city water for comparison. I will use my pool pH test kit and a hardness test from Sabino high school. pH is a measurement of acidity or the amount of hydrogen ions. Pure water is 10^{-7} or 7 pH. Extremely acidic water is 10^{-0} or 0 pH. Extremely alkaline water is 14 pH. And so on. Hardness is how much dissolved material is in it. Travertine is what forms when hard water forms crystals. We will see travertine dams on Havasu creek. I expect the water to be hard and alkaline.

Tufa Dams of Havasupai Canyon

Ingrid Daubar

The cold springs of Havasupai Creek release cold water rich in minerals. As this water travels towards the Colorado River, it warms and evaporates. Turbulence around obstacles causes dissolved carbon dioxide to be lost. Both of these phenomena lead to the precipitation of calcium carbonate from the water. The result is a spongy, porous limestone called travertine, or tufa.

Spray thrown up by Havasu Falls drifts and covers nearby trees. Evaporation leaves behind mineral deposits in layers on the sides of objects nearest the falling spray. The deposits also coat anything which interferes with the flow of water, taking the shape of the encrusted object. The process is self-enhancing, in that any obstruction will catch twigs and leaves, which get coated with calcite. The obstruction grows larger, and the larger surface area is more conducive to the formation of mineral deposits. When the object grows large enough, mosses start to grow on it, which increases its size even more. Eventually, a dam is formed with a few spillways to let water through. The spillways remain open because the water passing through them is fast-moving and therefore make it difficult for debris to collect or any further deposits to be formed.

The tufa is mostly calcite with traces of admixed clays. It is usually full of small, irregular holes stained red or yellow by iron oxides. Older deposits can be seen along the canyon walls which have weathered surfaces stained by manganese oxide and clays.

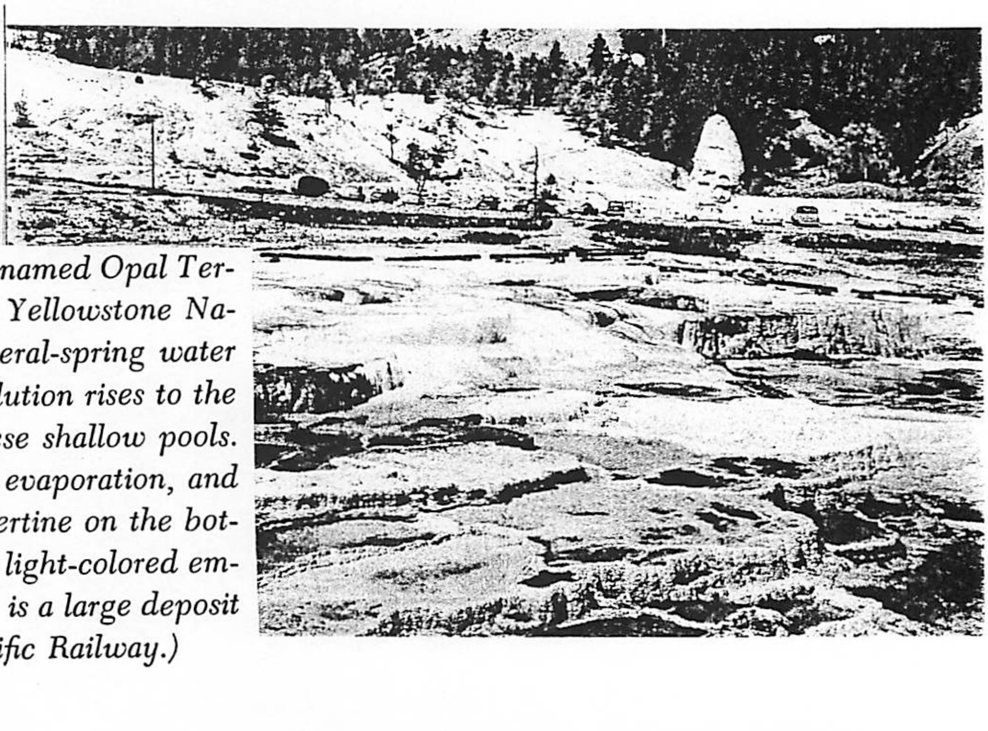
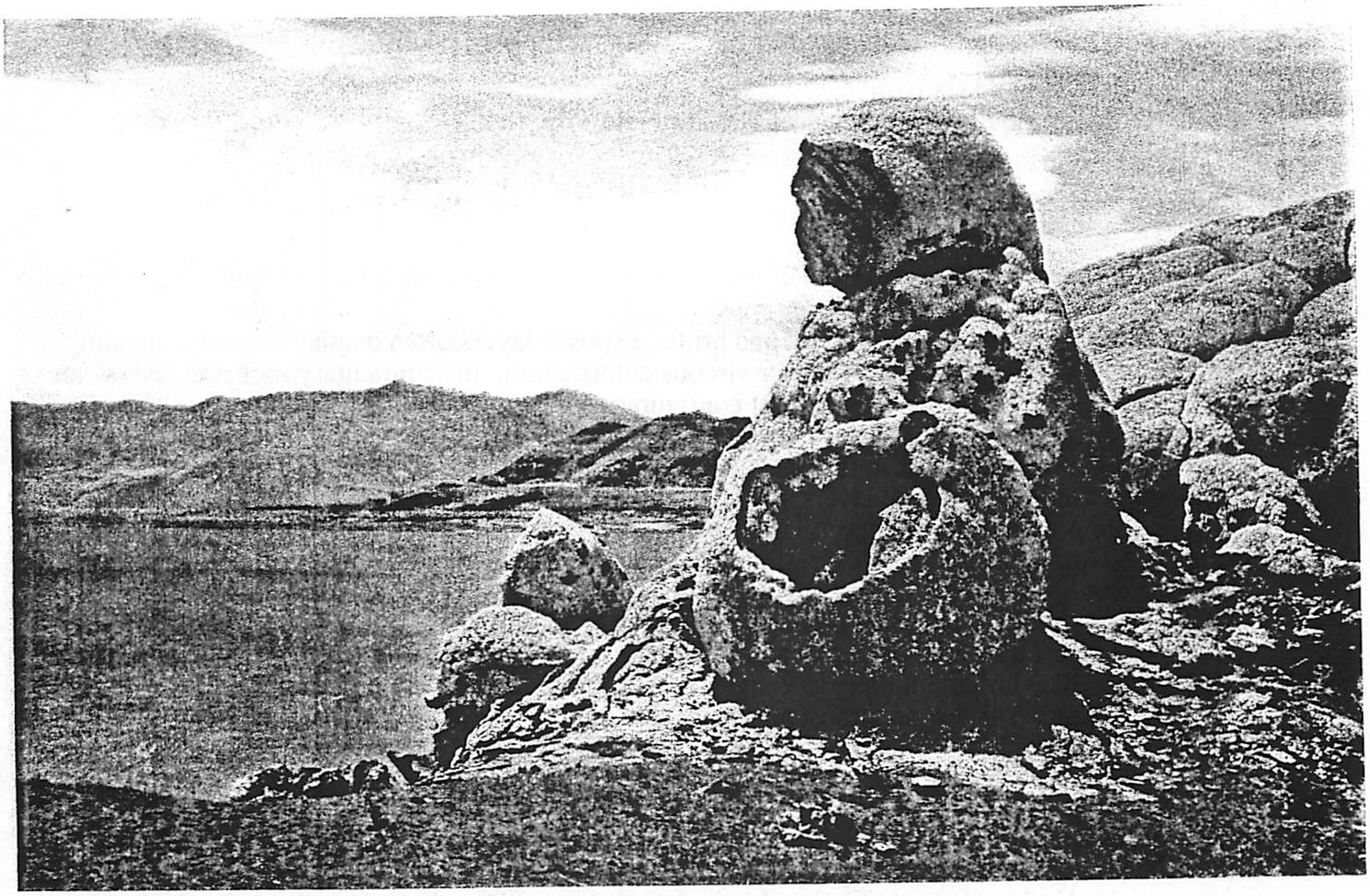
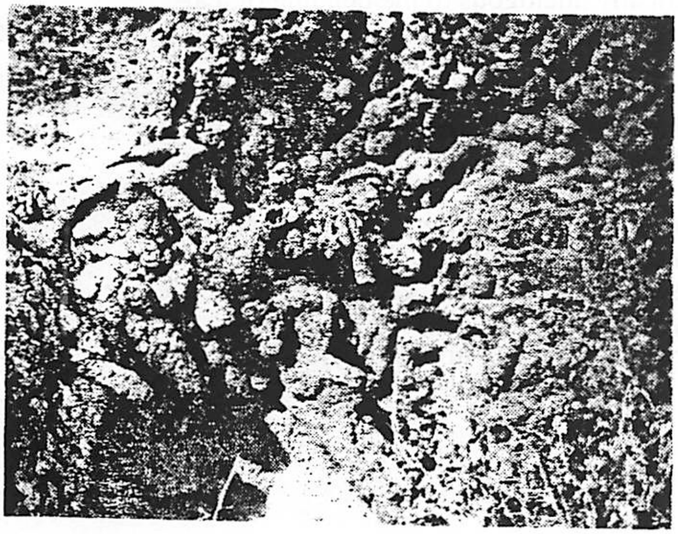


FIG. 14.10. *Travertine deposits named Opal Terraces at Mammoth Hot Springs, Yellowstone National Park, Wyoming. Hot mineral-spring water carrying calcium carbonate in solution rises to the surface and slowly overflows these shallow pools. Cooling, loss of carbon dioxide, evaporation, and algae cause precipitation of travertine on the bottoms and rims of the pools. The light-colored embankment in the middle distance is a large deposit of similar origin. (Northern Pacific Railway.)*





Tufa formations at Pyramid Lake, Nevada. Note hollowed-out center left over from drainage of water after formation.

Inside a natural dam: calcite deposits form over twigs and branches.

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"Clines" of the Grand Canyon
Background for the Planetary Sciences Havasu Field Trip
September 1999

by Richard Greenberg

I. Introduction

Even though rocks seem rigid and brittle, exposed layers often display extensive bending and folding that demonstrates ductile or viscous deformation. In sedimentary rock, the layers can be bent and distorted in a wild variety of configurations.

If the layers are bent so that they are convex toward the most recent sediments, the structure is called an "anticline". If the layers are bent so that they are convex toward the older sediments, the structure is called a "syncline". Usually, the newer sediments are on top, so anticlines are usually convex upwards. However, if the whole layer sequence has been turned upside down, an anticline would be convex downward and look like a typical syncline, so it is called a "synform anticline". A "monocline" is a ramping down of the layers from one elevation to another. These examples are just a sample of an extensive jargon, useful to those who need to communicate about these things. The important thing to know is that layering can be distorted in amazingly complex ways, in complex shapes, on almost any scale, and on multiple scales.

II. How can rocks fold?

While rocks are in fact rigid and brittle, the conditions under which folding occurs make them more pliable. Most of this folding occurs at depth, under elevated pressure and temperature, sometimes helped by water saturation, by the fact that younger sediments are less consolidated, and by the layering itself. The latter effect is geometrically analogous to the bending of leaf-springs under a car, although it is not elastic.

Within a given layers of folded sediment, it is possible to have "minor folding" if the layer has undergone compression as part of the overall folding of the system. The geometry of these minor structures helps unravel the strain history of the material.

In any instance of folded structure, there is considerable uncertainty about what was the source of the stress involved. Some common explanations are: continental-scale horizontal squeezing that stresses layered structures; layers of sediment riding on a conveyor belt of oceanic crust and driven up against a continent as the conveyor belt dips downward; an intrusion from below shouldering sedimentary beds sideways; something pushing up from below or down from above on the sedimentary layers.

III. Clining the Canyon

A. Valley Anticlines

As the river cut through the upper strata at the Grand Canyon (back when it was known to the natives of the area as the Not-Yet-Grand Canyon), it relased overburden pressure on the deeper layers beneath it. The relatively greater pressure on both sides of the river squeezed those deeper layers toward the base of the river. Particularly vulnerable was the "Muav Limestone" from the Cambrian period, because it contains lots of shaly rock. (Why shale is called Muav Limestone remains an unsolved mystery of science.) The shale was able to flow, especially because it was saturated with water under the river. Shale is petrified clay, so in its less mature state it was able to absorb plenty of water and deform ductily. The shale in the Muav Limestone, plus the underlying

"Bright Angel Shale" layer, were squeezed toward the river where they arched up under the horizonatal pressure and the relaxed overburden. Voila, an anticline.

This type of anticline is called a "valley anticline" or a "river anticline". Because they are created by the downward force of gravity, they are an example of "gravity tectonics".

After the anticline was formed, as the river cut through the Muav layer, it revealed the anticline as strata that dip away from the river on both sides. Such a feature is visible continuously along the Colorado for about 30 km upstream from the mouth of Havasu Canyon, and discontinuously further downstream. It may provide motivation to hoof it all the way to the Colorado, although we are not certain the feature will be visible exactly at the mouth of Havasu.

As the Muav Limestone was pushed together horizontally under the river, it developed conjugate thrust faults (i.e. some tilted toward the river and the conjugate ones tlitled away) within the layer. There are also kink bands within the layer form for the same reason. The bands and thrust faults are examples of the "minor structures" mentioned in Section I above. We should look for them if we find outcrops of the anticline.

B. Monoclines

Before the uplifting of the Colorado Plateau, western North America rode over subducting oceanic crust, which dove down into the mantle in the typical way shown on Fig.1. Later, for a while, for unknown reasons, the subducting crust slid along directly under the continent (Fig. 2), shearing along under it and buoying it up. The buoyancy may help explain why the Plateau rose up. The shear stress drove the thrust faults shown in Fig. 2. According to the geometry shown in Fig. 2, the faults were angled such that the west side of each fault rose relative to the east side. The result was a set of steps downward from west to east.

FIGURE 1:

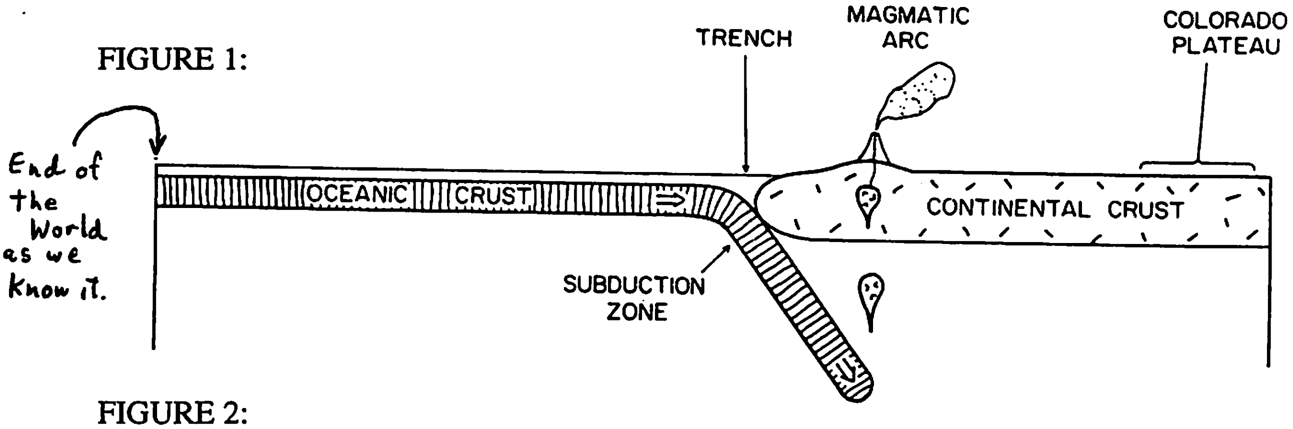
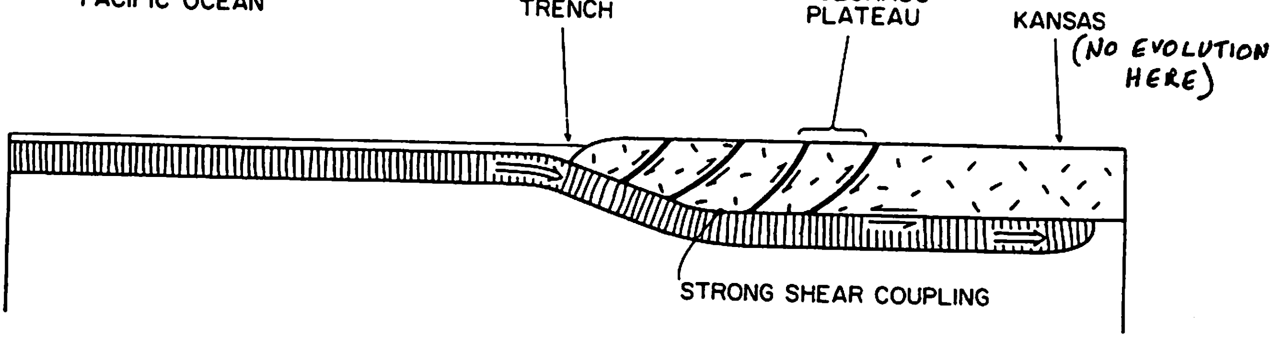
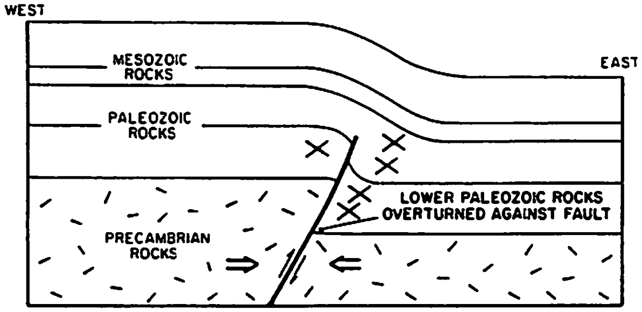


FIGURE 2:



The faulting occurred in the Precambrian rock layer, but the overlying paleozoic and Mesozoic layers were able to bend over the top, creating a monocline over each fault, as shown in Fig.3 (c.f. Fig. 2). The steps in those layers are thus monoclines rather than faults.

FIGURE 3:

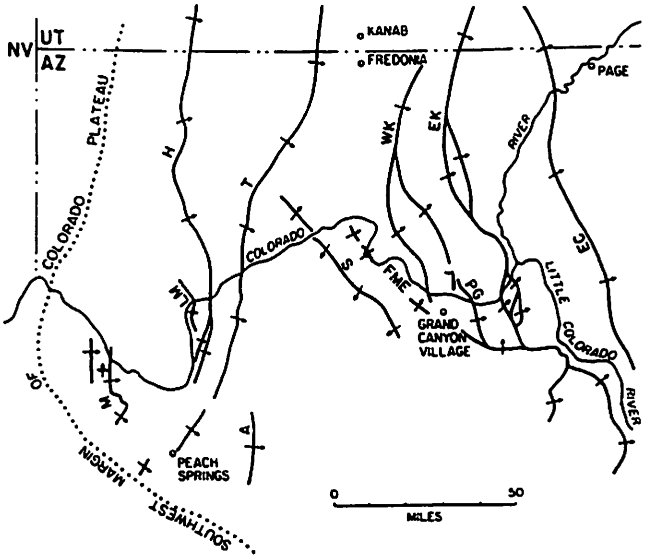


A plan view map of the locations of these steps is shown in Fig. 4. Note they run roughly NS, usually stepping down to the east. An exception is the Supai monocline (S in Fig. 4), which got confused and dips down the wrong way. This monocline seems to run pretty much along Havasu Canyon, so we should look for it. Based on the name, it probably is exposed around Supai City.

Like the Supai monocline, the Toroweap monocline (T in Fig. 4) also runs along a creek, the Prospect, which also feeds into the Colorado from the south. I am guessing that the Havasu and Prospect creeks follow monoclines (Supai and Toroweap respectively) because tectonics associated with the underlying Precambrian fault, but subsequent to the monoclinification, defined the course of their flow. The Toroweap monocline seems to be off the path of our trip, except for its southern extension which reaches as far south as Peach Springs. Maybe we can find it there.

One other monocline appears to be in our path: the Aubrey (A in Fig. 4). We should cross it about 15 mi. (24.14025 km) west of Seligman on historic Route 66. Watch out for it.

FIGURE 4:



Rotational Landslides

Gareth S. Collins

(September 1999)

INTRODUCTION

The rim wall of a complex crater exhibits a wreath of terraces decending stepwise to the crater floor. The process involved in their formation is thought to be directly analogous to terrestrial rotational landslides, in particular Toreva-blocks. Such rotational landslides have played an important role in sculpting the riparian landscapes along the river Colorado and its tributaries.

THE MECHANICS

First, a general look at slope failure...

Slope Stability

Slope failure occurs when

driving force > resisting forces.

Or, in terms of stresses:

shear stress, $\tau >$ shear strength, s

Stability, therefore, represents some balance between shear stress and resisting strength and can be expressed as a safety ratio (Selby, 1982):

$$f = \frac{shear\ strength}{shear\ stress} = \frac{s}{\tau} \qquad (1)$$

Clearly, as f approaches 1 from above, a slope becomes less stable until $f = 1$ and failure is imminent.

Factors controlling the safety ratio

Overleaf is a table of factors affecting the stability of a slope. Also shown are the solar system bodies on which these factors are relevant.

Rotational vs. Planar slides

Landslides are slope failures that are initiated by slippage along a well defined surface. Whether this slippage occurs along a planar or concave surface is a function of the subsurface geology. Planar slides occur along planes of weakness, which may be an unconformity, a pre-existing fault, or a thin, underlying layer of weaker rock. Deep rotational slides, however, are confined to thick layers of rocks which behave *plastically*.

In general, a rock's strength is controlled by cohesion *and* internal friction. Thus, strength increases with pressure (depth). However, a plastic material's strength is controlled by cohesion only and thus does not increase with depth. Therefore, a plastic material cannot support the large stresses at depth and allows deep seated failure. Rocks which can behave plastically are sometimes referred to as *soft*. Rocks which never behave plastically (except at great depth) are called *hard*.

In general, bare rock slopes are formed on hard rocks, and slope failure occurs when the supporting rock is soft.

Q. What can turn rock from a frictional material to a plastic material?

A. Water (pore pressure), temperature, vibrations???

PLANETARY CONNECTION - IMPACT CRATERING

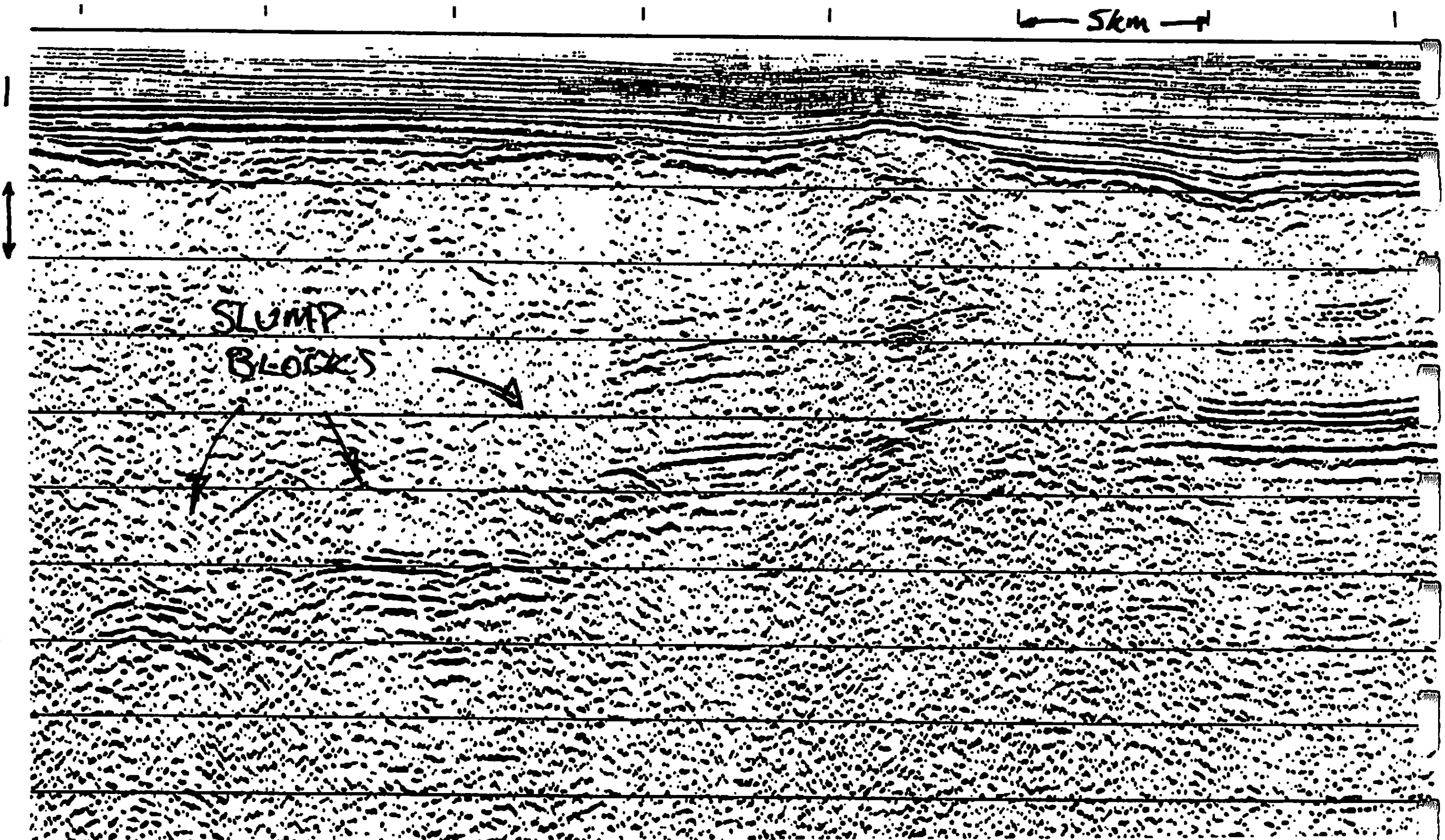
Terraced Slump Blocks

As I alluded to earlier, analogous processes seem to be acting on the rim walls of craters larger than a critical size (which varies from body to body with g). Such craters are termed "complex", the most famous example of which is Chicxulub.

Overleaf is a seismic section from the Chicxulub Seismic Experiment, figure 1. It shows the slump blocks which are thought to have slid along rotational failure surfaces into the crater from the transient crater wall. Fig. 2 shows a schematic of the cratering process thought to have acted at Chicxulub.

Any collapse of the wall of an impact crater, may strike the careful reader as perculiar. The transient crater wall has an average angle of approx. 30 degrees (about the angle of repose of unconsolidated rock!) Meteor crater hasn't collpased (much). Why? The answer seems to be that beyond a critical yield stress the sub-crater region behaves *plastically*. Herein lies another question. What mechanism is giving unconsolidated rock a plastic rheology? These structures are seen all over the solar system, and yet water can be playing no role in changing the rheology of the crater wall in most cases. And, in the case of Chicxulub, the region that must have behaved plastically corresponds to the 10-15km below the Earth's surface - granitic and definitely frictional! So how does the sub-crater region become plastic? We just don't know!

FIG. 1



Factors contributing to high shear stress	Mechanism	Bodies on which process is applicable
Removal of lateral or underlying support	Water erosion Artificial removal of toe slopes Weathering	Earth, Mars? Earth only! All.
Overloading	Weight of water	Earth, Mars?
Transitory stresses	"Earth"quakes Tilt	All! Earth, Mars, Io
Lateral pressure	Water in interstices Freezing of water	Earth, Mars? Earth, Mars?
Factors contributing to low shear strength	**Mechanism**	**Bodies on which process is applicable**
Composition and texture	Weak materials such as volcanic tuff and sedimentary clays Loosely packed materials Smooth grain type Uniform grain size	Earth - both Venus, Mars, Io - tuff Earth, asteroids
Effects of porewater	Buoyancy effects Reduction of capillary tension Viscous drag of moving water on soil grains	Earth, Mars?
Changes in structure	Spontaneous fluidization/ liquefaction	All???

After Selby, 82.

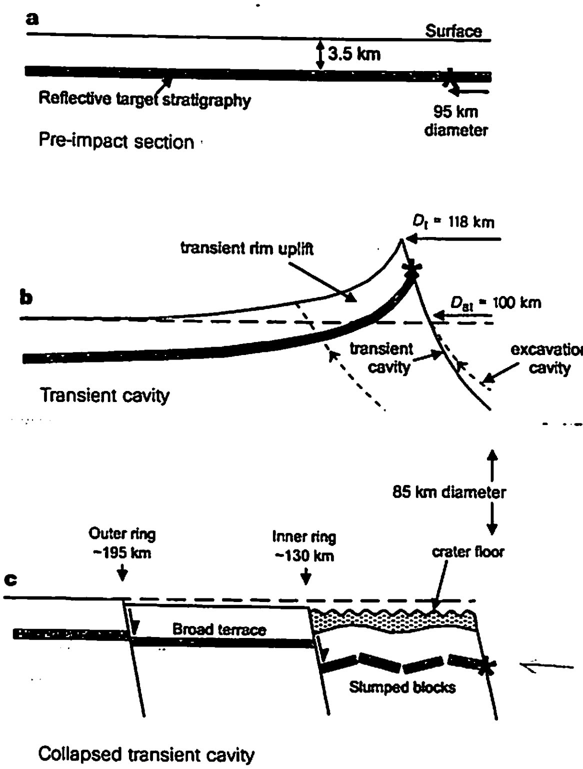
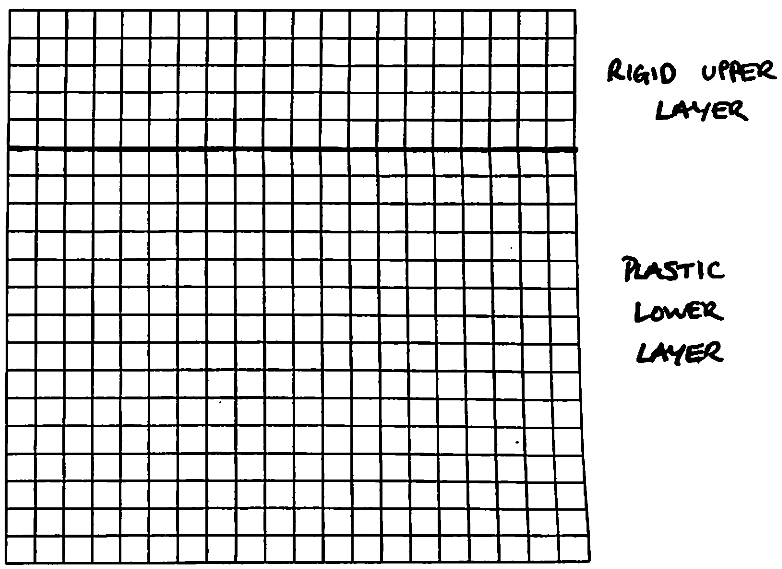


Figure 2 Reconstruction of the rim of the transient cavity. Cartoon of **a**, the pre impact section; **b**, the transient cavity; and **c**, the collapsed transient cavity. T pre-impact surface in **a** is shown as a horizontal dashed line in **b** and **c**. The cra floor, which is ~1 km below the pre-impact surface, is indicated by a wavy line The short-dashed lines in **b** represent flow lines calculated using the *Z*-model; the inner flow line delineates the excavation cavity. The asterisk marks reflect target rock, shaded dark grey, that lay initially just outside the excavation zo and, after the impact, lies near the inner edge of the collapsed transient cavity. The final diameters are average values obtained from Chicx-A and Chicx-C showin rings at ~130 km and ~195 km diameter at surface. Values from Chicx-B a Chicx-A1 have not been used in these averages because the outer ring equivocal on these lines. The dashed region contains impact deposits that forr the floor of the crater.

added Morgan et al. Nature 390 December 1997 pp472

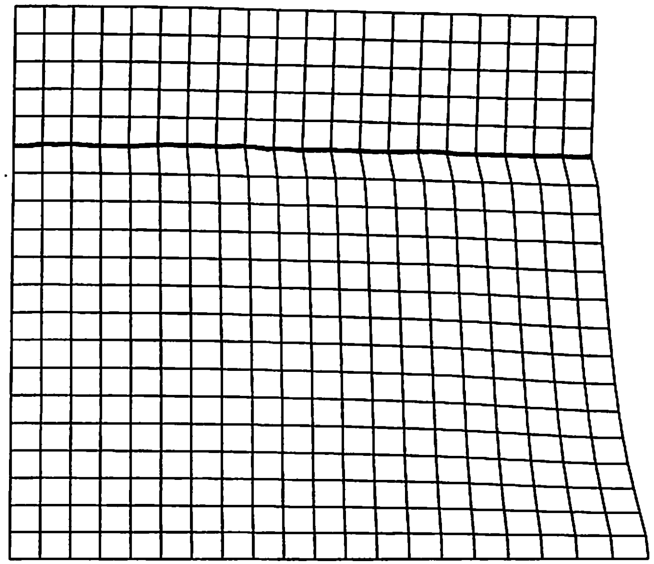
HYDROCODE SIMULATION OF COLLAPSING CLIFF FACE !

zone plot



t= 5.00041E+00 cycle 5075
sole run Thu Sep 16 10:09:13 1999 Landslide stress field

zone plot



t= 1.00004E+01 cycle 10075
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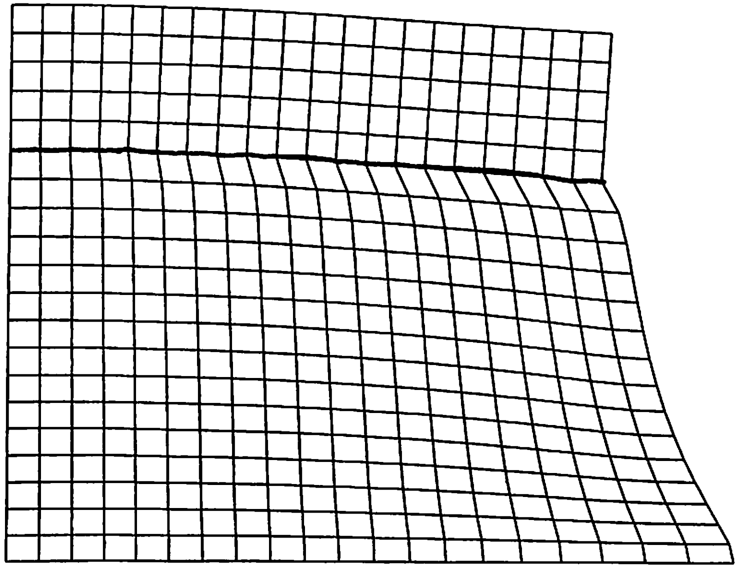
zone plot



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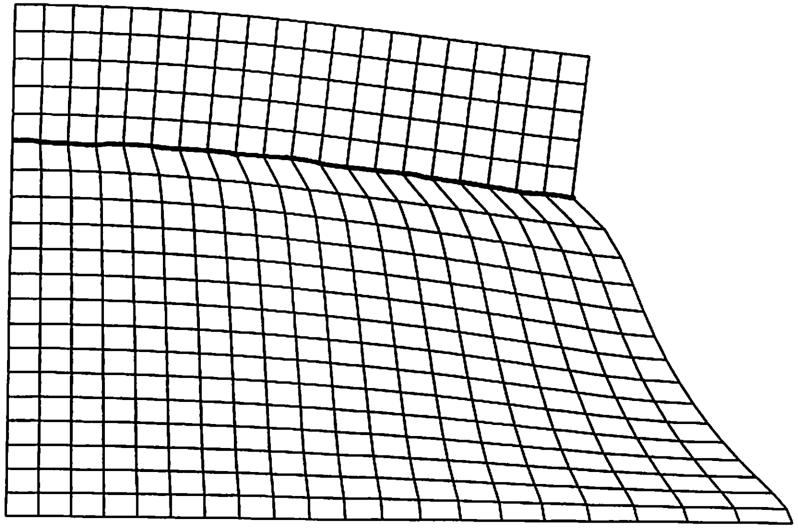
zone plot



t= 2.00004E+01 cycle 20075
sole run Thu Sep 16 10:09:13 1999 Landslide stress field

after me 1999

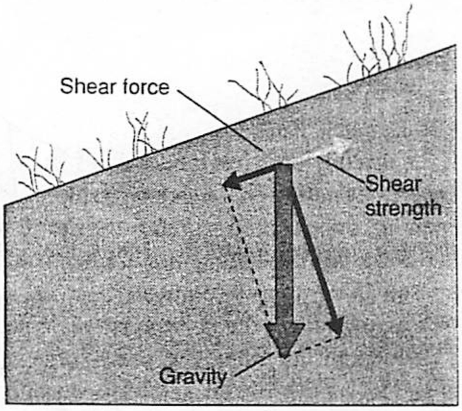
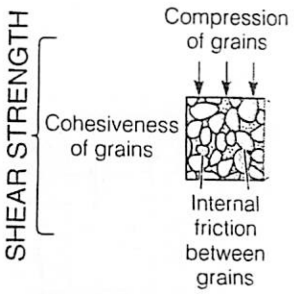


FIGURE 14-3 A slope's shear strength depends on the slope material's strength and cohesiveness, the amount of internal friction between grains, and any external support of the slope. These factors promote slope stability. The force of gravity operates vertically but has a component acting parallel to the slope. When this force, which promotes instability, exceeds a slope's shear strength, slope failure occurs.



Mass Wasting

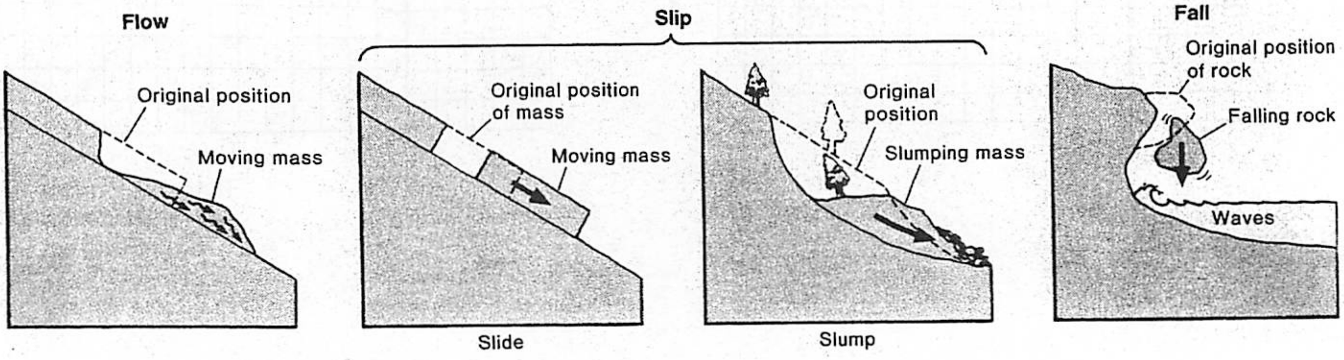
Gravity is the driving force in mass wasting. Material can be loosened by various types of weathering and mass wasting, powered by gravity, can move them from a higher to a lower level. Gravity can move material in different ways. Material can flow, behaving like a fluid. Material can slide, where the moving mass remains relatively coherent. Material can also fall, perhaps because of being undercut. The type of material and the rate of the movement also help to produce a wide range mass wasting processes.

by Nancy

Some Types of Mass Wasting[1]

	Slowest →	*Increasing Velocities →*		*→ Fastest*
Type of Movement	*Less than 1 cm/year*	*1 mm/day to 10 km/hour*	*1 to 5 km/hour*	*Velocities generally greater than 4 km/hour*
Flow		← **Debris Flow** →		
	Creep (Debris)	Earthflow	Mudflow (Water-saturated debris)	Debris avalanche (Debris) Rock avalanche (Bedrock)
Slip		← Debris Slide → ← Slump (Debris) → ← Rockslide (Bedrock) →		
Fall				Rockfall (Bedrock) Debris fall (Debris)
		← **"Landslides"** →		

[1] The type of material at the start of movement is shown in parentheses. Rates given are typical velocities for each type of movement.



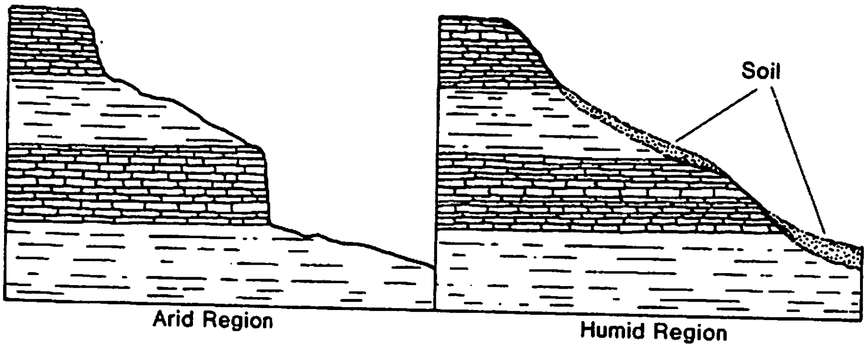


Figure 4.3 Slope profiles in arid regions tend to develop differently from those in humid regions even when the underlying bedrock is similar. Because more moisture is available for weathering processes in humid regions, slopes are typically rounded and mantled with soil. In an arid climate, steep slopes with angular rock faces are common, and soil cover is sparse.

A variety factors can influence the amount and type of mass wasting that occurs. The slope angle, the vertical relief, the amount of vegetation, the thickness of debris, the presence of weaknesses, the abundance or lack of water and ice.....

Climate is very important. The same material can take on very different shapes because of mass wasting in different climatic conditions. In dry conditions, such as we are in now, stair-stepped features are common. Cliff-forming units are more resistant and are often limestones and some sandstones in this environment. Slope-forming units are less resistant, such as shales. The extreme relief influences the type of mass wasting that occurs. Mass wasting operating in arid conditions often forms piles of talus, accumulated broken rock at the base of a cliff. Torrential rain, without much protective vegetation, also aids the processes of mass wasting in arid conditions.

In-Situ Measurement of Physical Properties

(or, getting our hands dirty on the planets)

Ralph D Lorenz

Many basic physical properties of a planetary surface can be measured directly or indirectly with modest in-situ instrumentation. Such measurements can place constraints on the fabric and formation/modification of the surface and facilitate interpretation of remotely-sensed properties. E.g. both optical properties (such as phase function) and thermal properties (e.g. thermal inertia, derived from the day/night variation in surface temperature) can depend on particle size. The particle size may depend on whether the surface has been subject to fluvial or aeolian modification, etc.

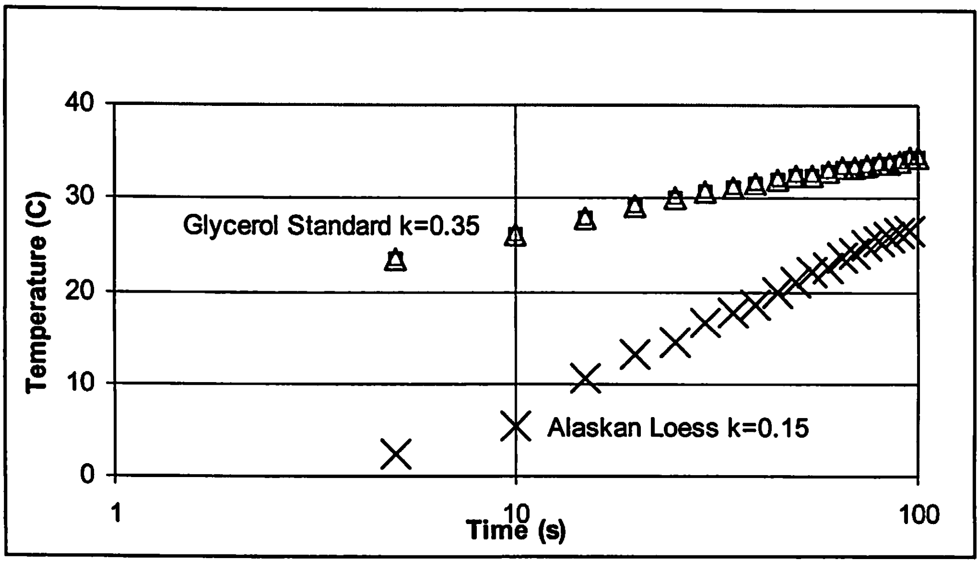
Here I focus on 2 properties, thermal conductivity and shear strength. During the trip, measurements of some of the materials we encounter will be made – these properties should be inferred for the Martian surface from measurements to be made by the DS-2 Mars Microprobes and the Mars Polar Lander. The field instrumentation I use will be related to the measurements techniques to be made on those spacecraft.

Thermal Conductivity

The most common field technique, also common in the laboratory and on spacecraft (e.g. Huygens) is the so-called transient line-source. Electrical heating is applied along a narrow cylinder, and the evolution of the temperature field depends on the conductivity of the medium in which the cylinder is immersed. If the power per unit length q is known, and the evolution of the cylinder temperature can be monitored, then after some initial transient, the conductivity k can be derived from the equation.

$$\Delta T = \frac{q}{4k\pi} \cdot \ln\left(\frac{t_2}{t_1}\right)$$

Thus the slope of a line plotted as T vs log (time) relates directly to the conductivity. Some data is shown below.



The Mars Polar Lander has a heated soil temperature probe which can be inserted using the robotic arm into the ground. The temperature evolution on applying power will allow the estimation of soil conductivity roughly as above. Similarly, the DS-2 Mars microprobes will be rather warmer than the ground when they penetrate the surface – their cooldown history relates to the soil conductivty in a broadly similar manner.

The field instrument used on this trip is a home-made probe – a thermocouple measures the temperature at the middle of a narrow tube which contains an insulated nichrome wire (40cm long, 4.8 ohms resistance at room temperature, thus the heater power is $V^2/R \sim 2$ W for 3V)

Shear Strength

The penetrability of a surface, i.e. how hard it 'feels' and how deep a given impactor or tool will penetrate, relates to many physical factors, including shear strength, angle of internal friction, density and so on. When the penetrating body has a radius comparable with particle size, the particle size and interparticle bond strengths can be estimated. However, to date most interpretation of penetration measurements is empirical.

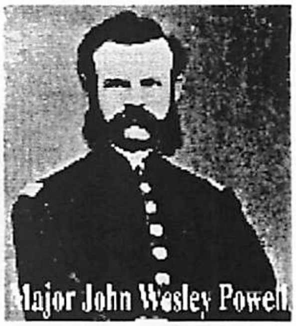
Upcoming examples of this technique are the penetration of the DS-2 probes, and measurement of the robotic arm motor current required to drive the MPL STP into the ground. Historically footpad penetration on the Surveyor and Viking landers was measured, even the footprint depth of Apollo astronauts can be interpreted quantitatively.

For the field investigation, a Geonor H-60 inspection vane tester is used : this comprises a cruciform vane that is inserted into the soil. Torque is applied with a handle: when the material fails, the vane turns freely – the maximum torque applied corresponds to the strength the material had just before it failed in shear and allowed the vane to move.

Another technique, widely used for both civil engineering and avalanche research (as well as in impact testing) is the ram penetrometer, whereby a hammer weight is raised a known distance and dropped, driving a cone into the soil. The number of drops required corresponds (inversely) with the strength of the soil (although this is not a shear strength necessarily, in that materials without shear strength – like sand – can be measured)

More advanced spacecraft instrumentation measures a force history during the penetration event, e.g. the penetrometer on the Huygens probe to Titan, which records a 50ms force profile using 14mm diameter piezoelectric transducer (Lorenz et al., 1994). The force profile qualitatively indicates the surface type (sand, clay, gravel etc) and can be quantitatively interpreted in terms of particle size and strength.

Lorenz, R. D. *et al.* An Impect Penetrometer for a Landing Spacecraft, *Measurement Science and Technology*, **5**, 1033-1041, 1994.



Major John Wesley Powell: Explorer of the Colorado River

Compiled by Jani Radebaugh

"The wonders of the Grand Canyon cannot be adequately represented in symbols of speech, nor by speech itself. The resources of the graphic art are taxed beyond their powers in attempting to portray its features. Language and illustration combined must fail...to describe [it] would be a task equal in magnitude to that of describing the stars of the heavens...But form and color do not exhaust all the divine qualities of the Grand Canyon. It is the land of music...With the melody of the great tide rising and falling, swelling and vanishing forever, other melodies are heard in the gorges of the lateral canyons, while the waters plunge in the rapids among the rocks or leap in great cataracts. Thus the Grand Canyon is a land of song. Mountains of music swell in the rivers, hills of music billow in the creeks, and meadows of music murmur in the rills that ripple over the rocks. Altogether it is a symphony of multitudinous melodies. All this is the music of waters. The adamant foundations of the earth have been wrought into a sublime harp, upon which the clouds of the heavens play with mighty tempests or with gentle showers.

"The glories and the beauties of form, color, and sound unite in the Grand Canyon -- forms unrivaled even by the mountains, colors that vie with sunsets, and sounds that span the diapason from tempest to tinkling raindrop, from cataract to bubbling fountain...It has infinite variety, and no part is ever duplicated. Its colors, though many and complex in any instant, change with the ascending and declining sun; lights and shadows appear and vanish with the passing clouds, and the changing seasons mark their passage in changing colors. You cannot see the Grand Canyon in one view, as if it were a changeless spectacle from which a curtain might be lifted, but to see it you have to toil from month to month through its labyrinths. It is a region more difficult to traverse than the Alps or the Himalayas, but if strength and courage are sufficient for the task by a year's toil a concept of sublimity can be obtained never again to be equaled on the hither side of Paradise."

---John Wesley Powell, "The Canyons of the Colorado", 1985

I thought these passages would help you to understand the personality of the courageous man, teacher, soldier, geologist who first explored the Colorado River in 1869 at the age of 35. He was a scientist, and as such presented a face to his sponsors, the United States Government, of purely scientific interest in the Grand Canyon. In truth, his interest was also deeply poetic and spiritual.

He, along with a group of nine men (none of them scientists, all hired for their "toughness and resourcefulness"), explored the canyon in four small wooden boats, a task difficult to imagine, when portions of the river such as the treacherous Cataract Canyon are considered. In fact, four months later, only five of the party, plus Major Powell, emerged from the canyon 1000 miles from their launch point. Major Powell, who was a Civil War veteran, lost one of his arms at the Battle of Shiloh, and still traveled the length of the Colorado River with this additional challenge.

They began their journey from Green River Station in Wyoming. After one month, they had lost one boat to rapids, most of their ten-month supply, and one man (who had walked off). In the next two months, the rapids became even worse, and at the worst spots, the cautious Major Powell had the men either carry the boats along the river banks or line them along the side of the river and slowly go downriver together. At times, however, it was impossible to do anything besides run the rapids and pray for the best. At a place called Separation Canyon, three men challenged Major Powell to discontinue the journey "or how we surely will all die" but they could not convince him, so they left. After they hiked out, they were killed by Shivwits Indians who mistook them for miners who had killed a Hualapai woman.

Two days later, after the last two major rapids, the men emerged at the mouth of the Virgin River (now underneath Lake Mead), at the end of their journey. His exploration was a success: He set out to prove that the Colorado River existed before the uplift of the Colorado Plateau, then during uplift the river cut deep canyons into the horizontal rock sequences of the plateau as it tried to return to equilibrium.

His successful first trip launched him on the lecture series, where he could raise money for a second trip in 1871. This second journey was much more leisurely, there was more time for science stops along the way, since this time the trip wasn't just a race for survival. The government had granted him $10,000 for the journey, which enabled him to spend more time on the river and to publish maps and professional papers after the trip.

In 1881, he became the director of the U. S. Geological Survey, and served in that position for 13 years. After his death in 1902, he was buried in Arlington Cemetery.

http://songbird.com/gc/powell.html

Shelley James, Canyon Country Online, 1996
http://www.canyon-country.com/lakepowell/jwpowell.htm

The John Wesley Powell Museum
http://www.surweb.org/surweb/tour/jwp/jwpowell.htm

Lunar Prospector Results

Fred Ciesla

Lunar Prospector was launched on January 6, 1998 as part of NASA's "Faster, Better, Cheaper" mission plans. Its primary goals upon arrival at the moon were to:

1) search for potential resources, such as water ice
2) map the Moon's gravitational and magnetic field
3) gather data on the size and content of the Moon's core.

To accomplish this five instruments were put on board: a neutron spectrometer, a gamma ray spectrometer, an alpha particle spectrometer, a magnetometer, and an electron reflectometer. In addition, gravitational data was attained by analyzing the Doppler shifting of the spacecraft's communications with Earth.

Prospector's mission came to an end this summer when it was put into an orbit which allowed it to crash into the Moon's surface in one final attempt to learn more about it. The biggest results of the mission were as follows:

Lunar Core:

Prospector produced a map of the Moon's gravity that was five times better than anything previously produced. The gravity data implies that a core consisting of 1% to 4% of the Moon's mass. Depending on the composition of the core, it could be anywhere from 220 to 450 km in radius.

This idea is further supported by the results of the magnetometer mesurements. The Moon no longer has its own magnetic field, though there are relatively strong magnetic anomalies on the surface. These anomalies could have originated from a freezing of an ancient magnetic field caused by a rotating metallic core.

Ice on the Moon:

The neutron spectrometer measured epithermal and fast-neutron fluxes in areas at the polar regions of the Moon. The data has shown an enrichment of hydrogen at both poles, implying that large amounts of water ice is trapped in the permanently shadowed craters.

The purpose of allowing Lunar Prospector to crash into the moon was to search for more evidence that water ice was present. This was a one time event, and many observations were nullified due to different glitches. Analysis is still being done on the observations (specifically searching for spectral signatures of the photodissociated hydroxyl (OH). No confirmations have yet been reported.

Surface Composition:

The neutron and gamma ray spectrometers have generally supported the findings of the Clementine mission in terms of the surface composition of the Moon. Three main provinces have been identified: mare basalts (rich in Fe and Ti), highland areas (Fe and Ti depleted), and large basin floors and rims (intermediate in their Fe and Ti concentrations).

Other Findings:

The alpha particle spectrometer was designed to detect radon outgassing events on the surface. Analysis of this data is incomplete due to the high backgrounds from solar activity.

Gravity mapping has also led to the discovery of three new mascons (mass concentrations) on the nearside and four on the farside.

Eugene M. Shoemaker

April 28, 1928 - July 18, 1997

He once said he considered himself a scientific historian, one whose mission in life is to relate geologic and planetary events in a perspective manner. A modest statement coming from a legend of a man who almost single-handedly created planetary science as a discipline distinct from astronomy. He brought together geologic principles to the mapping of planets, resulting in more than 3 decades of discoveries about the planets and asteroids of the Solar System. He was a 1992 recipient of the National Medal of Science, the highest scientific honor bestowed by the President of the United States, then George Bush. His family, friends, former students, and the scientific community are in shock as they hear the news and feel the loss of "SuperGene."

Dr. Gene Shoemaker died Friday, July 18 (Australian Time) in Alice Springs, Australia in a car accident. He was in the field, pursuing his lifelong passion of geologic studies to help understand impact craters with his wife and science partner, Carolyn Shoemaker. Carolyn survived the accident sustaining various injuries.

A longtime resident of Flagstaff, Arizona, in 1961 Gene invented the Branch of Astrogeology within the U.S. Geological Survey and established the Field Center in Flagstaff in 1963. Retired from the USGS in 1993, he has held an Emeritus position there and has been recently affiliated with Lowell Observatory in Flagstaff. An incredibly diverse person, he influenced science in numerous ways: most recently, in a decade-long sky survey for earth-crossing asteroids and comets, culminating in the discovery (with wife Carolyn and David Levy) of Comet Shoemaker-Levy, which impacted Jupiter in 1994, giving the world of science a major new insight into both the dynamics of comets and the planetary science of Jupiter. He has spent numerous summers (Australian winters) exploring ancient parts of the earth for records of meteorite and comet impacts, resulting in the discovery of a number of new craters. In much of his asteroid and comet work, Shoemaker collaborated closely with his wife, Carolyn, a planetary astronomer. A close and devoted couple, their work was recently featured in a 1997 National Geographic documentary "Asteroids: Deadly Impact." They considered their work a "Mom and Pop" operation and together they initiated the Palomar Planet-crossing Asteroid Survey in 1973, and the Palomar Asteroid and Comet Survey in 1983.

Gene Shoemaker seems to have been a geologist from the day he was born in Los Angeles, California, in 1928. He did not even need to complete his higher education (B.S. and M.S., California Institute of Technology, 1947 and 1948; Ph.D. Princeton University after an interrupted career, 1960) before starting the practice of astrogeology that was to lead him to the planets. He began exploring for uranium deposits in Colorado and Utah in 1948, and these studies brought him geographically and intellectually near the many volcanic features and the one impact structure on the Colorado Plateau in the western United States, namely Hopi Buttes and Meteor Crater. In the period 1957-1960, he did his classic research on the structure and mechanics of meteorite impact. This work--including the discovery of coesite (a high pressure form of silica created during impacts) with E.C.T. Chao--provided the definitive work on basic impact cratering. It was work that he continued throughout his life--both by exploration of the earth--particularly in Australia--and the planets by remote sensing and mapping.

A man of vision, he believed geologic studies would be extended into space and in his early career he dreamed of being the first geologist to map the Moon. During the 1960's he lead teams who were investigating the structure and history of the Moon and developing methods of planetary geologic mapping from telescope images of the Moon. A health problem prevented his being the first astronaut geologist, but he personally helped train the Apollo Astronauts and sat beside Walter Cronkite in the evening news giving geologic commentary during the Moon walks. He was involved in the Lunar Ranger and Surveyor programs, continued with the manned Apollo programs, and culminated his moon studies in 1994 with new data on the Moon from Project Clementine, for which he was the science-team leader.

Gene was the recipient of numerous awards including: Doctorate of Science Arizona State College, Flagstaff, 1965. Wetherill Medal of the Franklin Institute, co-recipient with E.C.T. Chao, 1965. Arthur S. Flemming Award, 1966. Doctorate of Science, Temple University, 1967. NASA Medal for Scientific Achievement, 1967. U.S. Department of the Interior Honor Award for Meritorious Service, 1973. Member, U.S. National Academy of Sciences, 1980. U.S. Department of the Interior Distinguished Service Award, 1980. Arthur L. Day Medal of the Geological Society of America, 1982. G.K. Gilbert Award of the Geological Society of America, 1983. Reiser Kulturpreis, co-recipient with E.C.T. Chao and Richard Dehm, 1983. Honorary Doctorate of Science, University of Arizona, 1984. Barringer Award of the Meteoritical Society, 1984. Kuiper Prize of the American Astronomical Society, Division for Planetary Sciences, 1984. Leonard Medal of the Meteoritical Society, 1985. Distinguished Alumni Award of the California Institute of Technology, 1986. Rittenhouse Medal of the Rittenhouse Astronomical Society, co-recipient with C.S. Shoemaker, 1988. U.S. National Medal of Science, 1992. Whipple Award, American Geophysical Union, 1993. Fellow, American Academy of Arts and Sciences, 1993. AIAA Space Science Award, 1996. NASA Exceptional Scientific Achievement Medal, 1996. Bowie Medal, American Geophysical Union, 1996. Special Award, American Association of Petroleum Geologists, 1997.

From 1962 to 1985, Shoemaker blended his astrogeology research for the USGS with teaching at the California Institute of Technology (Caltech). He chaired Caltech's Division of Geological and Planetary Sciences from 1969 to 1972. One of his doctorate students at Caltech, Dr. Susan Werner Kieffer, remembers him as being one of the most unfailingly generous, and intellectually honest mentors she has ever known. His colleagues at the USGS remember a exceptionally brilliant, exuberant, vibrant man and a warm human being whose angry antics over copy machines and loud happy laughter rang down the hallways. I remember a meeting when a newcomer to science overheard Gene's excited conversation and laughter at a meeting and remarked "who is that loud guy?"--to which I replied that is the "god of planetary geology" and we all know that gods don't whisper. As with his persona, Gene Shoemaker's legacy will never be a whisper, but a loud burst onto the realm of Science that will be sorely missed. He is survived by his wife; his son, Patrick Shoemaker and wife Paula Kempchinsky; his daughters Christine Woodard and Linda Salazar and her husband Fred; and grandchildren, Sean and Adrian Woodard and Stefani Salazar, and a sister, Maxine Heath.

by Mary Chapman

http://wwwflag.wr.usgs.gov/USGSFlag/Space/Shoemaker/
GeneObit.html

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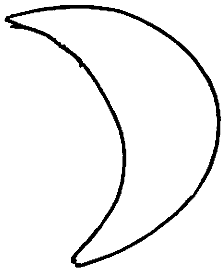

The Stratigraphy of Mars?

Ross A. Beyer

> **Stratigraphy** – 1. The science of rock strata. It is concerned with all characters and attributes of rocks as strata; and their interpretation in terms of mode of origin and geologic history. All classes of rocks, consolidated or unconsolidated, fall within the general scope of stratigraphy. 2. The arrangement of strata, esp. as to geographic position and chronologic order of sequence. 3. The sum of all the characteristics studied in stratigraphy; the part of the geology of an area or district as pertaining to the character of its stratified rocks.

Most geologists begin laughing out loud when they hear the words 'stratigraphy' and 'Mars' in the same sentence. This is mostly because they associate 'stratigraphy' with being able to stick your nose up against an outcrop, being able to take cores, *etc.* In other words, all the good information that allows a geologist to build up a logical picture of what happened over time to create the geological sequence that they see before them. While we may not be able to be as complete in our description of Martian stratigraphy as we are in our description of terrestrial stratigraphy, there are still some important aspects of the geological record that can be extracted from studying Mars in a stratigraphic context. We may not be able to stratigraphically examine a narrow region or outcrop as we would on the earth, but we can use stratigraphy to learn things about the large-scale geologic record of the planet itself.

What we knew before

Using the Mariner 9 and Viking Orbiter data sets Scott and Carr (1978) published the first formal definition of time-stratigraphic units on Mars. They defined three time-stratigraphic periods: the Noachian, the Hesperian, and the Amazonian based on apparent age of surface features. The Noachian period was defined by a heavily cratered and rugged terrain in the Noachis quadrangle, the Hesperian was defined by ridged plains material on Hesperia Planum which overlies Noachian material, and the Amazonian period is defined by the smooth plains of the Arcadia Formation in the Amazonis quadrangle. Tanaka (1986) mapped out these units more explicitly via crosscutting and superposition, in addition to subdividing them into smaller epochs (Table I).

Absolute ages for Martian rocks are currently unavailable, but model ages based on crater-counts have been made by Neukum and Wise (1976) and Hartmann et al. (1981). Tanaka et al. (1988) combined them with the mapping of Tanaka (1986) and has indicated possible absolute ages (Table II) for their epochs.

From the absolute ages, we can begin to get a rough idea of the chronology of large-scale events on Mars. The southern highlands of Mars consist of the oldest Noachian and Hesperian rocks. These rocks seem to be mostly volcanic in origin and are pitted with impact craters and large multi-ring basins. During the late Noachian and

TABLE I
Martian Stratigraphic Series and Reference Materials[a]

Series	Reference Unit(s)[b]	Type Locality
Upper Amazonian	Achu	Southern Elysium Planitia
Middle Amazonian	Aa_2, Aa_3	Amazonis Planitia
Lower Amazonian	Aa_1	Acidalia Planitia
Upper Hesperian	Hvk, Hvg, Hvr, Hvm	Vastitas Borealis
Lower Hesperian	Hr	Hesperia Planum
Upper Noachian	Npl_2	East of Argyre Planitia
Middle Noachian	Npl_1	Noachis quadrangle
Lower Noachian	Nb	Charitum and Nereidum Montes

[a] Table modified from Tanaka (1986).

TABLE II
Martian Epochs, Crater-Density Ranges and Absolute-Age Ranges[a]

	Crater-Density Range $N(D) = \text{no.} > D/10^6\ \text{km}^2$			Absolute-Age Range (Gyr)	
Epoch	N(2)	N(5)	N(16)	HT	NW
Late Amazonian	<40			9.25–0.00	0.70–0.00
Middle Amazonian	40-150	<25		0.70–0.25	2.50–0.70
Early Amazonian	150-400	25-67		1.80–0.70	3.55–2.50
Late Hesperian	400-750	67-125		3.10–1.80	3.70–3.55
Early Hesperian	750-1200	125-200	<25	3.50–3.10	3.80–3.70
Late Noachian		200-400	25-100	3.85–3.50	4.30–3.80
Middle Noachian		>400	100-200	3.92–3.85	4.50–4.30
Early Noachian			>200	4.60–3.92	4.60–4.50

[a] Data from Tanaka (1986) and Tanaka et al. (1988) based on Hartmann-Tanaka (HT) and Neukum-Wise (NW) ages which represent the two relatively different time-scale models.

Hesperian times the highlands were cut by channels, marked by ridges and volcanic paterae, infilled by smooth plains materials and possibly eroded by wind. The northern lowlands are purported to have been formed by giant impacts or some kind of tectonism. They are covered by large areas of Hesperian and Amazonian plains materials. In the late Hesperian and early Amazonian, giant flow fields, volcanic shields, and domes developed in Tharsis and Elysium. Associated with the development of Valles Marineris were huge outflow channels and chaotic terrain in the highlands that extended to the lowlands.

What we are learning now

The Mars Global Surveyor spacecraft, only six months into its nominal mission has already returned a great deal of information that may factor into the question of Martian stratigraphy. The MAG/ER team has identified magnetic signatures in the southern highlands. There are east-west 'stripes' near 180° at mid south latitudes, but it also appears that the large impact basins Hellas and Argyre erase the magnetic signature of the southern highlands. When this data set is better understood, it might have profound implications for Martian stratigraphy. The MOLA team is exploring the proposed shorelines around the northern lowlands, as well as the detailed structure of the polar caps, and MOLA data coupled with MOC data will be quite valuable for understanding the stratigraphy. The MOC has imaged all kinds of good stuff, but has also made observations that are useful in a stratigraphic context. Such as the layering sequences that are most prominently displayed in the Valles Marineris but are seen ubiquitously around the planet. These layers indicate a rich volcanic past for the red planet. Additionally, closer looks at the Valles Marineris interior layered deposits may reveal a better explanation for their deposition history. In general, MOC can be used to examine contacts and specific locales to help expand the picture of Martian stratigraphy.

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Uplift of the Colorado Plateau
Paul Withers

Introduction to the Colorado Plateau: [2]
The Colorado Plateau is a relatively coherent uplifted crustal block surrounded on three sides by the extensional block-faulted regime of the Basin and Range Province and the Rio Grande rift. It has experienced no major crustal deformation since (at the latest) the end of the Laramide orogeny (40 Mya). It is stuffed full of monoclines and has a present mean elevation ~ 2 km.

Description of uplift: [3]
Prior to the Laramide orogeny, the Colorado Plateau was a shelf area. It then became a basin/trough surrounded by newly formed mountains during the Laramide orogeny but was still close to sea level (marine Mancos shale). Prior to 24 Mya, it was still topographically low with internal drainage. It reached an elevation of at least 1 km by 18 Mya (downcutting in Peach Springs Canyon) and became higher than the adjacent Basin and Range province by 10 Mya. It experienced a final 1 km of uplift during the last 5.5 My (Colorado River deposits). Two (or more) stage uplift, with a very recent last stage.

Theories about uplift: [3]
Constraints are: the Colorado Plateau is close to isostatic equilibrium, has a thick (45 km) crust 10 – 15 km thicker than neighbouring provinces, and has an unexceptional heat flow of 60 mW m^{-2} but high upper mantle temperatures.

Possible causes of the uplift include: thermal expansion, crustal thickening, and phase changes. Possible sources of heating include: subduction of a mid-oceanic ridge, presence of a plume/hot spot, and cessation of subduction followed by thermal equilibriation of cold, subducted slab. Crustal thickening could be achieved by horizontal transfer of mass in the lower crust or by very shallow angle subduction. Phase (and density) changes could be caused by hydration or by partial melting followed by expansion.

Tharsis uplift: [4]
The Tharsis bulge is an elevated region on Mars associated with a number of large volcanoes. There are many theories about how it was uplifted and how it stays uplifted.

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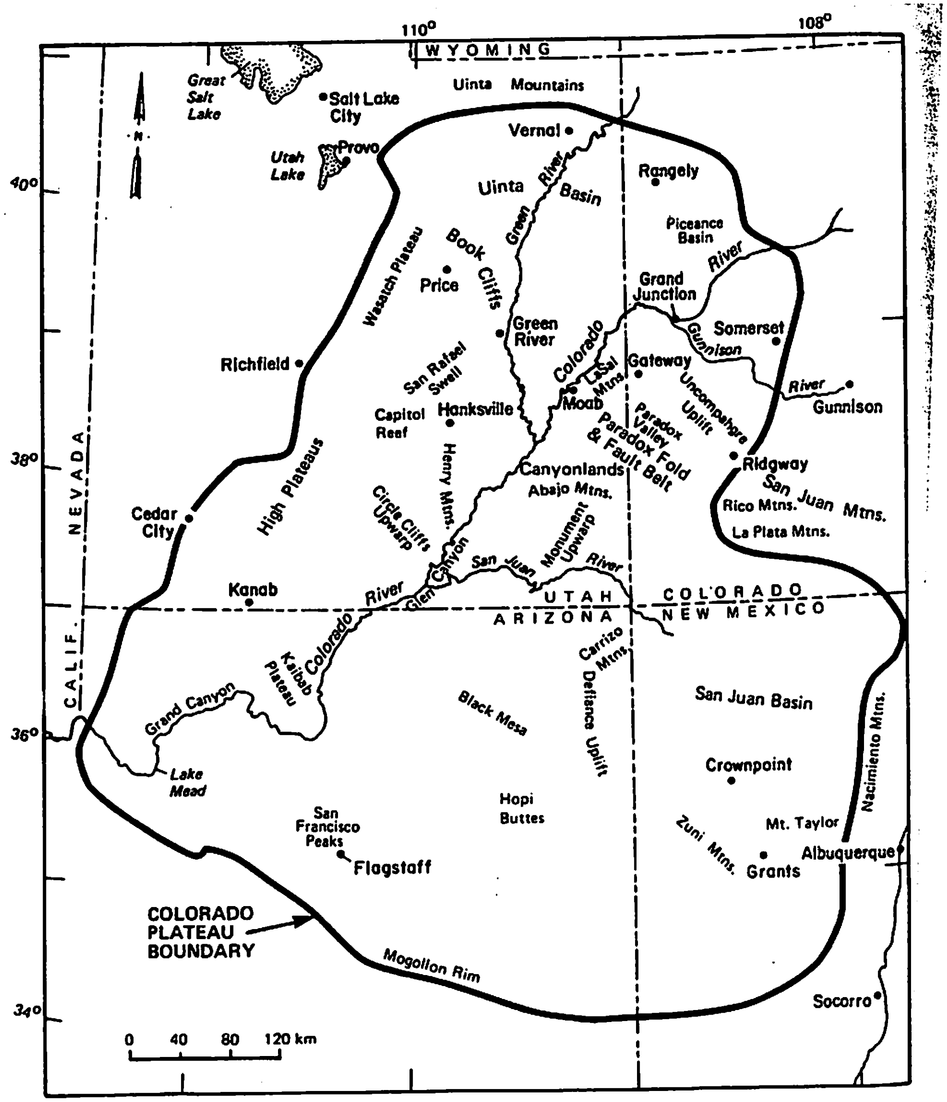


Figure 3. Major topographic and geologic features of the Colorado Plateau (modified from Hunt, 1956). [2]

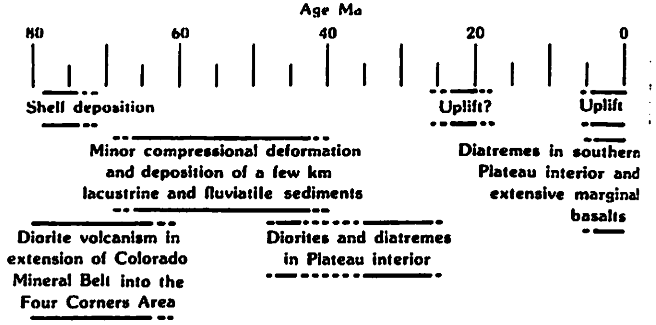


Fig. 2. Late Cretaceous and Cenozoic time chart for the main tectonic and volcanic events affecting the Colorado Plateau

LATE CRETACEOUS + CENOZOIC TIME
CHART FOR THE MAIN TECTONIC AND
VOLCANIC EVENTS AFFECTING THE
COLORADO PLATEAU [3]

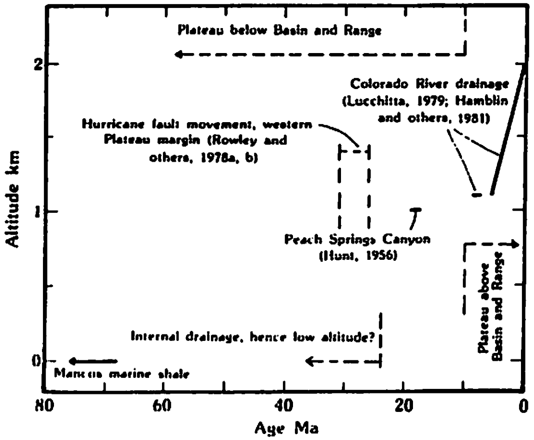


Fig. [illegible] Compilation of uplift and altitude data for the Colorado Plateau.

COMPILATION OF UPLIFT AND
ALTITUDE DATA FOR THE
COLORADO PLATEAU [3]

Terry
Hurford

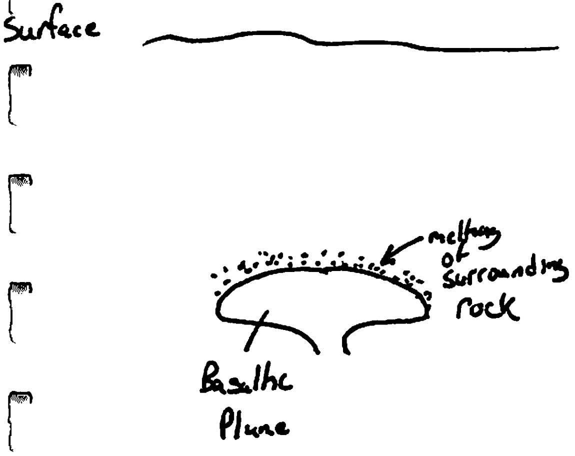
Volcanoes of the Seligman Area

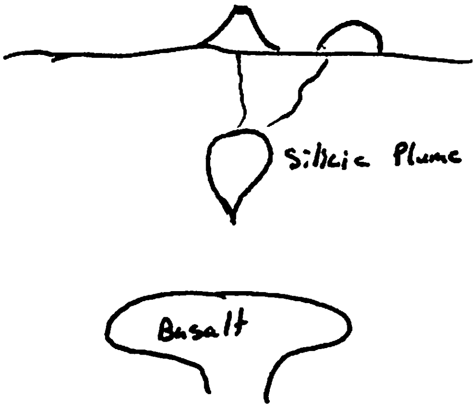
Seligman marks the western most edge of the San Francisco volcanic field. This zone of volcanic activity is situated on the south western edge of the Colorado plateau. The volcanism in the area ranges in age from about 9 million years ago to 930 years ago. The ages of volcanic features in this zone decrease towards the east. The oldest volcanoes are located in the western end of the field while the youngest features are found in the east. The features themselves show variation within the volcanic field. Remnants of composite volcanoes and volcanic domes are situated in a field of numerous cider cones.

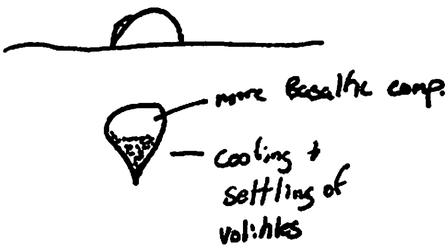
Seligman, on the western edge of this field contains some of the oldest volcanic features in the area. To the South of I-40 is Picacho Butte. This butte is a dome which is about 400 meters in height and a base area of less then 2 km. This dome at about 9 million years old is one of the oldest complexes in the volcanic field. This dome appears to be highly eroded to the point that dikes can be seen on its western side. The dome is made of rhyolitic lava. This lava has a higher viscosity than basaltic lava. When extruded onto the surface it does not flow as readily producing the domed structure.

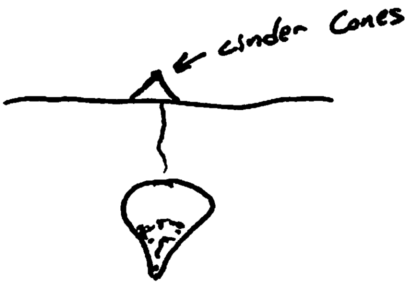
Picacho Butte was formed by a silicic lava but it is associated with a lava field that contains numerous cider cones, which form from a basaltic lava. The two types of volcanism are linked by a process known as Bimodal Magmatism. A plume of basaltic material may rise under the surface until it is buoyant. It will not rise any further but may start to melt the surrounding rock that has a higher silica content. A new smaller plume of material of new composition may then continue to rise towards the surface slowly. This new plume can cause the initial silicic volcanics on the surface (e.g. Picacho Butte). This chamber will cool with time thus changing it's composition by becoming more basaltic. The chamber may induce a later stage of volcanism with this more basaltic lava, producing cinder cones.

Domes & Composite Volcanoes









Granite Dells, Prescott Arizona

Cynthia L. Schwartz
September 1999

Near Highway 89 and Wilson Creek Road just north of Prescott, Arizona is a distinctive sight of majestic granite formations which create a maze of huge boulders. This site is known as ***The Granite Dells*** because of the hollow created by the rocks. The Granite Dells is made up of Precambrian plutons surrounded by Cenozoic Tertiary sediments and Cenozoic volcanic rocks. Some of the boulders are greater than the height of a person.

A noticeable feature of the rocks is the rounded edges terming them **spheroidal boulders**. Often the spheroidal boulders occur downslope from rock exposures that are characterized by rounded pinnacles and ledges. Looking closely at the rounded boulders and the rounded rock ledges, it is clear that the surface of the boulders is roughly textured. The rough proturberances are mineral crystals, usually feldspar. Soil surrounding the boulders is usually composed of coarse sand called **grus**. The individual crystals making up grus are either mineral felspar or mineral quartz.

The rounded boulders and grus are produced by the process of **spheroidal weathering**. The weathering is the result of rock exposed at the surface to oxygen, water, and acids. In addition, for the formation of rounded boulders, the rock must be a three-dimensional network of planar fractures or joints within the rock and have the following three properties: 1) the rock must contain a significant amount of feldspar; 2) the rock must be homogeneous and composed of mineral crystals that are all approximately the same size; 3) the rock must contain little or no layering. At this site the type of rock having all three properties and subjected to all the conditions is granite.

The spheroidal boulders form from the chemical interaction of water with the jointed granite exposed at the earth's surface. Rainwater initially combines with CO2 in the atmosphere to create slightly acid rainwater which in turn comes in contact with the granite reacting chemically with the feldspar to form clay, dissolved silica and potassium. The rainwater effectively decomposes the feldspar to clay. In addition, the chemical elements in feldspar not contained in clay are carried away in solution.

Why rounded? The granite is in rectangular joint blocks and if the network of joints involves sets of three closely-spaced mutually perpendicular planes of fractures, at depth it will look like a tightly-packed pile of large sugar cubes as shown in Figure 1 below.

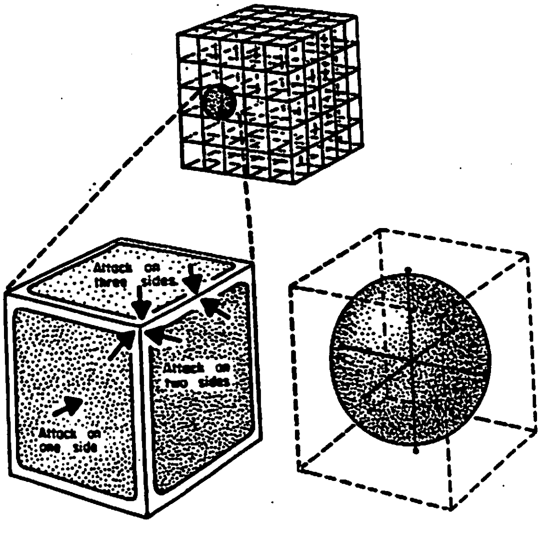


Figure 1

When the slightly acidic rainwater seeps down the fractures, it begins to wear the edges of the joints away. It attacks the corners from three sides, the edges from two sides and the sides at a less rate. This process then rounds the corners until the attack is distributed uniformly over the whole surface and the boulders eventually reduce to spheres. In some places you should see the sections of joint planes meeting at nearly right angles, with the rounding of the bedrock adjacent to the joints. In Figure 2 you see a side profile of the weathering process and the result.

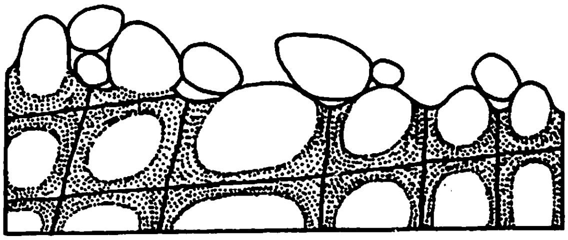


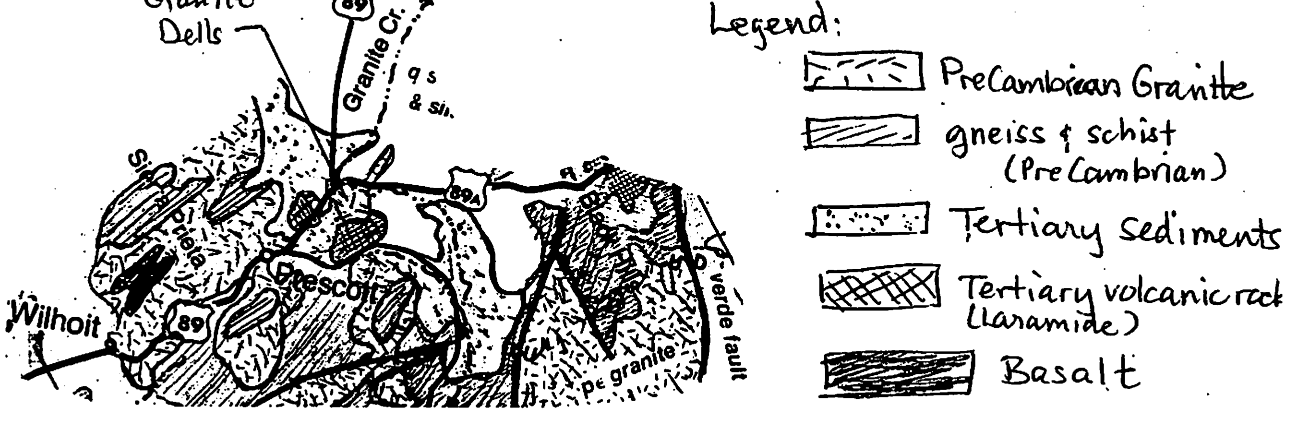
Figure 2

In addition to the spheroidal weathering, **Liesegang rings** caused by the precipitation of limonite in granite can also be seen here. Typical ore deposits in this region originate from the middle Mesozoic to the early Cenozoic with igneous intrusions. The igneous intrusions must have run into a variety of host rock consisting of iron-rich silicate minerals, such as pyroxene and olivine. Then shrinking and cooling as well as other events caused fracturing and brecciation of the host rocks and even the intrusions themselves. The weathering of iron-rich minerals produced clay minerals plus iron oxide when the silicates break down and the iron combined with oxygen in the atmosphere. Subsequent weathering removed the iron oxide from the near surface and leached them down to the groundwater interface where the iron oxide combined with water to form limonite The overall weathering reaction of iron-rich minerals is shown by the equation

iron pyroxene + oxygen -> limonite + dissolved silica
$4FeSiO_3$ O_2 $2Fe_2O_3$ $4SiO_2$

As the limonite precipitates out of the granite, it creates a colored ring which is red or brown in color. Locally this depletes the limonite below the precipitation threshold. As this process repeats, the result is a set of colored rings, developing in time, that illustrate diffusion.

Another effect of weathering is **exfoliation.** This is seen where large flat or curved sheets of rock are fractured and detached, looking like the sheets have been peeled from a large onion.



Gravity faults of the Grand Canyon

by Celinda Kelsey
AKA Concussion Kelsey

Characteristics of gravity faults:

1) Fault planes are within a few degrees of vertical with normal (extensional) displacement.

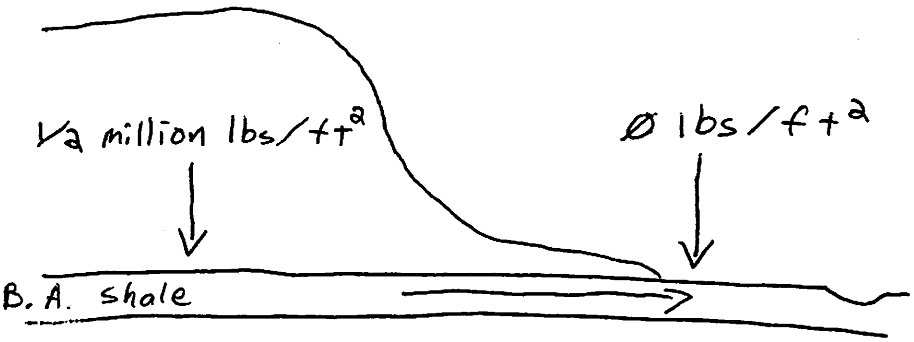
2) Gravity Faults are laterally discontinous, and rarely traced for more that 3 miles.

3) Displacement is greater at the top than at the bottom. Vertical displacement is rarely greater than 50 feet within the highest portions.

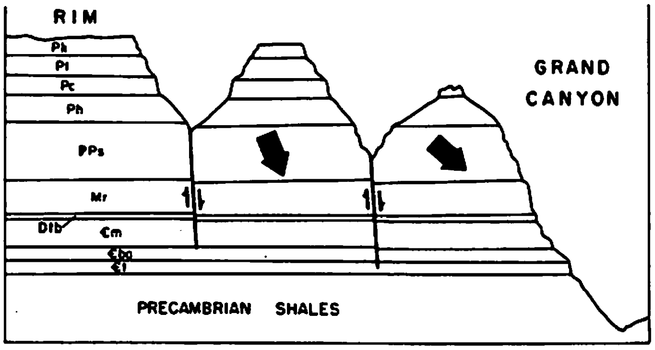
4) Gravity faults are often parallel to deep-seated faulting, due to control of gravity fault location by jointing which in turn is controlled by the nearby tectonic faulting. However, another way to recognize some gravity faults is that they do not follow the trends that tectonically activated faults follow.

5) Existing gravity faults are among the youngest features within the Grand Canyon. However, older gravity faults can not be located because they are easily eroded away.

Beginning of a gravity fault within the Bright Angel Shale



Pressure gradient of ~ 1000 pounds per foot squared per foot
For a butte that is 3600 feet tall



Permian:
- Pk - Kaibab Formation
- Pt - Toroweap Foramtion
- Pc - Coconino Sandstone
- Ph - Hermit Shale

Permian and Pennsylvanian:
- IPPs - Supai Group

Mississippian:
- Mr - Redwall Limestone

Devonian:
- Dtb - Temple Butte Formation

Cambrian:
- €m - Muav Limestone (includes unclassified dolomite)
- €ba - Bright Angel Shale
- €t - Tapeats Sandstone

Heavy arrow shows relative movement of the butte.

FIGURE 26.2. Erosion along high angle gravity faults that develop across ridges allow buttes to separate from the ridges. Faults develop as buttes settle into ductile Cambrian and Proterozoic shales.

GRAVITY FAULTS

High angle gravity faults in the eastern Grand Canyon were described by Huntoon (1973) as map scale brittle failures unrelated to deep seated tectonic processes. As shown on Figure 26.2, the faults are generally restricted to Paleozoic strata above the base of the Bright Angel Shale, and are very steeply dipping to near vertical. Displacements are greatest at the top of the section and die out downward. The faults are laterally discontinous and rarely can be traced more than 3 miles (5 km) along strike. These faults most commonly cut across and are restricted to narrow ridges, which are flanked by deep canyons that expose the Bright Angel Shale.

Huntoon (1973, p. 122) concluded that the faults represent brittle failure accompanying minor ductile deformation within the Bright Angel Shale. They develop as the overlying column of rock, in some cases 4,000 feet (1,220 m) high, settles into its ductile shale base.

High angle gravity faults are very important in the morphologic evolution of Grand Canyon scenery. Once such faults form, erosion proceeds rapidly along them, thereby segmenting what was formerly a ridge between two canyons into a string of buttes. As erosion progresses, the buttes become isolated from the plateau. Ironically the faults that initiate the butte forming process vanish because they eventually erode. Consequently, faults no longer can be found around some deeply eroded old buttes such as Solomon Temple in the eastern Grand Canyon (Huntoon and others, 1986).

Sources:

Huntoon, Peter W. High-Angle Gravity Faulting in the Eastern Grand Canyon, AZ. Plateau, V.45; 3, pp. 117-127, Flagstaff, AZ: Museum of Northern Arizona, 1973.

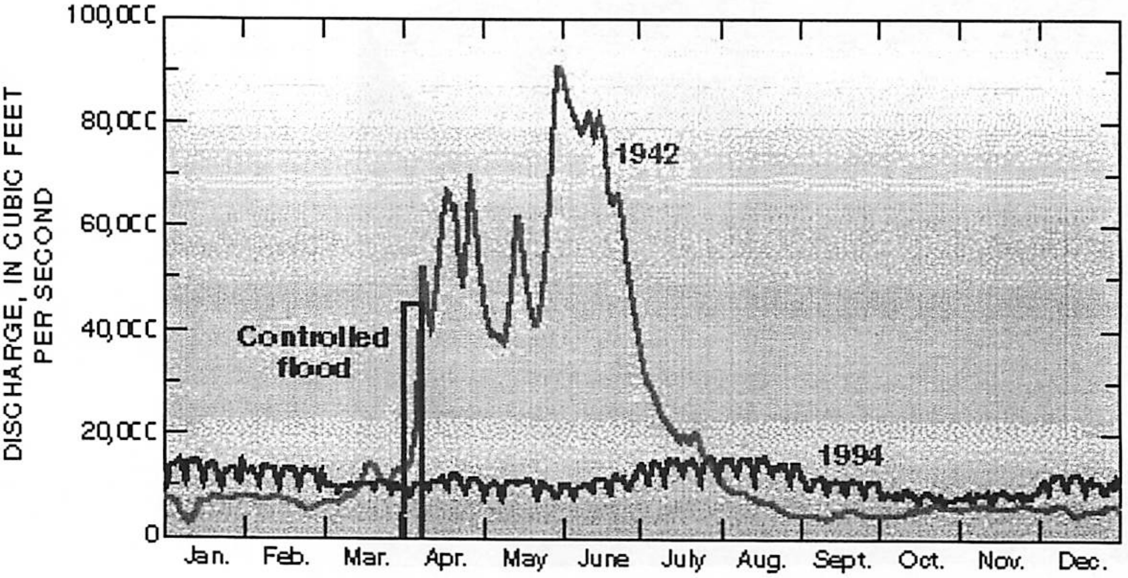
Huntoon, Peter W. Gravity Tectonics, Grand Canyon, AZ. in Geology of Grand Canyon, Northern Arizona, Eds.: Donald P. Elston, George H. Billingsley, and Richard A. Young, Washington, D.C.: American Geophysical Union, 1989.

Hydraulics and Sediment Transport on the Colorado River

Jason Barnes

In the 1950's, a project to dam the flow of the Colorado river in the area of Glen Canyon (Northern Arizona) was initated. By 1963 when the locks were closed, the Glen Canyon dam had assumed control over the river's flow both above and below the dam. While civil engineers carefully considered the former, they neglected the latter.

The creation of the dam moderated flow rates to the degree that after its inception fewer than 5 floods have occurred downstream. The natural flow rate of the river before 1963 shows that although the average water flux was 17,000 cubic feet per second (cfs), the mean maximum flow rate was nearly 94,000 cfs (see figure below).

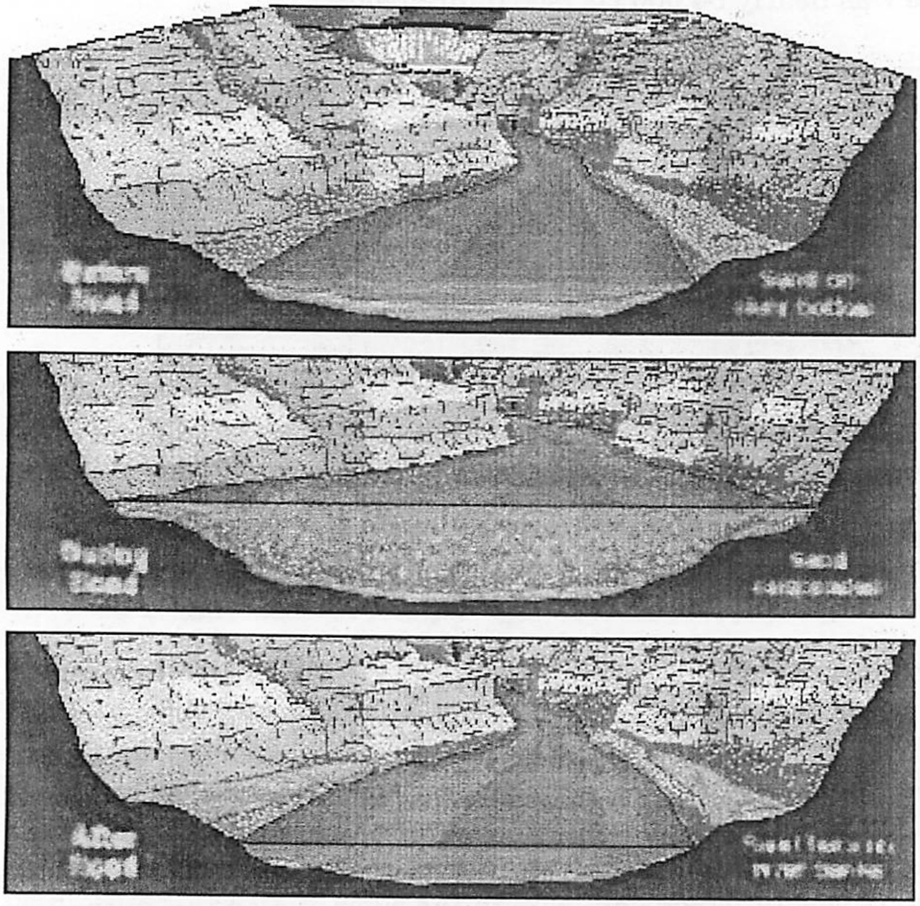


The proposed controlled flood compared to pre-dam (1942) and post-dam (1994) flows.

The effects of this smoothing are subtle. Periodic floods serve as a natural cleansing event, similar to how a wildfire might affect a forest. In their absence, the sandbars along the river's edges are slowly eroding away, as the flooding serves to replenish them. The floods also prevent the growth of vegetation on sandbars in the river and on the riverbanks. Debris fans, blocks of sediment carried into the river by tributaries, are thought to be cleaned out by periods of high flow volume. Since the creation of the dam, sandbar size and thickness has decreased, flora have begun to grow along the shores and on the sandbars, debris fans have built up, and native fish have suffered a moderate decline in population. The dam has also blocked the normal transport of sediment by the river, causing silt to build up in Lake Powell.

In an attempt to learn more about this problem and possible mechanisms for returning the river to something closer to its original state, a controlled flood was initiated in March/April of 1996. The Glen Canyon Dam released 45,000 cfs of water for several days in an attempt to mimic a flood under controlled conditions. The results confirmed the association of sandbar size with flooding. The more rapidly moving floodwater dredges up higher amounts of sand from the bottom of the river which is suspended in the water and later deposited along the area that the flood covers (see figures). Debris fans were partially eroded, and plants were scoured from the shores. Though native fish species initially declined, nearly all were above their pre-flood values after 8 months.

The experiment was considered a success, as much was learned about flooding and river systems. Although periodic controlled floods may help the health of sandbars, debris fans, and native life, the buildup of silt in Lake Powell would not be affected.



Sand on the river bed will be suspended by the controlled flood and deposited in sand bars along the banks.