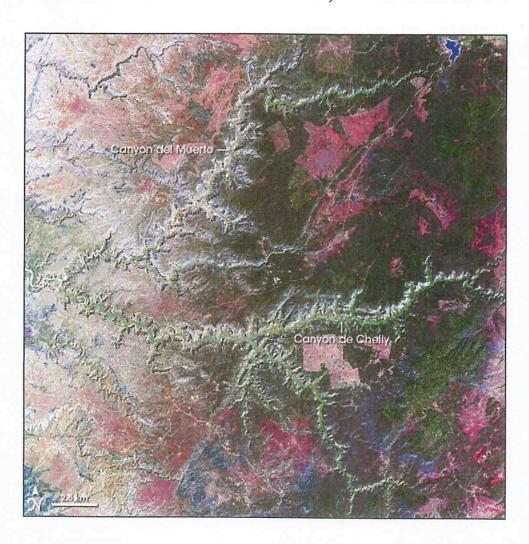




PTYS 594A: Planetary Geology Field Practicum

Canyon De Chelly: Fluvial Processes – Earth, Mars and Titan



20 - 22 April 2007

PTYS 594A: Planetary Geology Field Practicum

Canyon De Chelly:

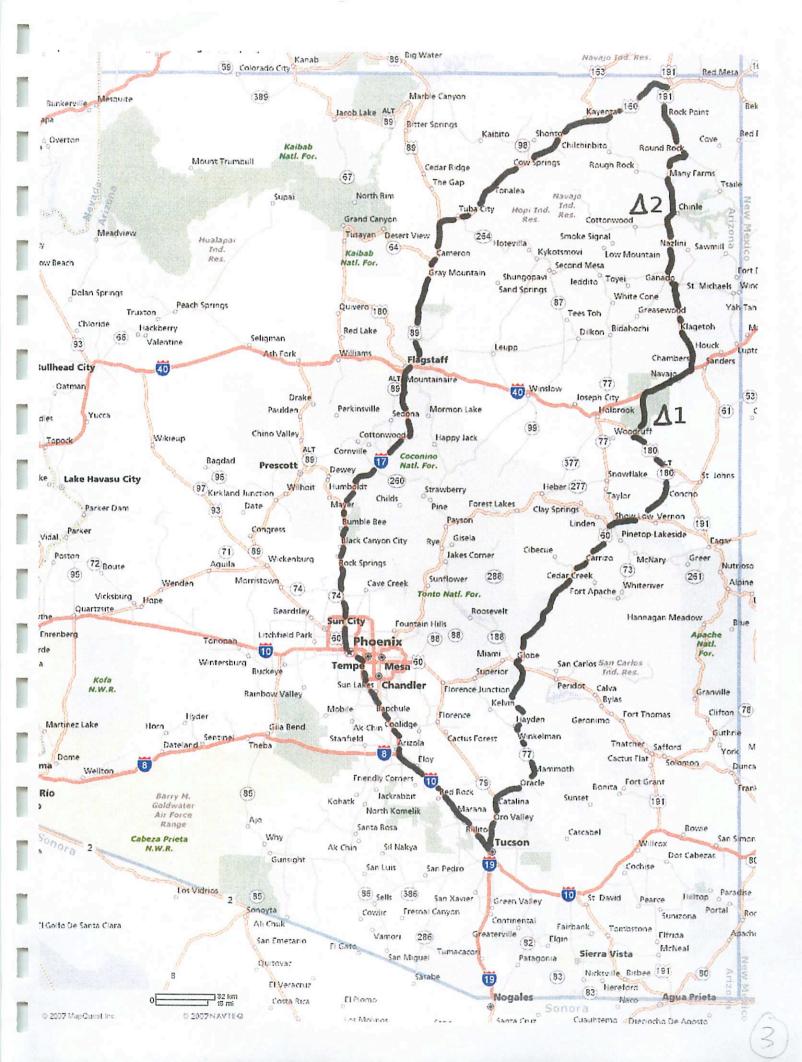
Fluvial Processes – Earth, Mars and Titan Handbook Table of Contents

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Photo: False color Landsat 7 image with green and pink as vegetation, blue as water http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=172	
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PtyS 594a, PLANETARY FIELD GEOLOGY PRACTICUM

Spring 2007 Fluvial Processes—Earth, Mars and Titan

Approximate Itinerary

Friday,	20	April
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- 8:00 AM Depart LPL loading dock. Travel West on Speedway to Oracle Road, North on Oracle. North of Catalina, bear right to take Rte 77 to Mammoth. Just past Mammoth (right after bridge over the San Pedro River) take a right on a small paved road.
- 9:00 AM Stop near an outcrop of the San Pedro gravels (if desired, this could be as far as 3 miles, at the defunct Whitecliff diatomaceous earth mine, but a shorter distance would be desireable). **Mike Bland** will describe the stream terraces of the San Pedro River and their importance for paleontology and archeology.
- 9:30 AM Continue North on Rte 77 through Winkleman to its intersection with Rte 70 in Globe. Turn left, drive about 2 miles, then turn right at the stoplight and continue North on Rte 77 in the direction of Show Low.
- Stop at the overlook South of Salt River Canyon. **Catherine Niesh** has volunteered to give an extemporaneous discussion of the spheroidal weathering exposed here. This is a good lunch stop, if the timing is appropriate.
- 12:15 PM Continue North on Rte 77 through the Salt River Canyon. Stop a few miles short of Carrizzo at an outcrop of the rim gravels of the Colorado Plateau. At this location **Colin Dundas** will acquaint us with the history of the uplift of the Colorado Plateau.
- 12:45 PM Continue on Rte 77 to Show Low. Just after the main shopping area, bear right onto Rte 60 East, traveling in the direction of Springerville. 11 miles after Show Low, bear left onto Rte 61 to Concho and St. Johns. In Concho bear left onto 180A toward Holbrook. This road becomes Rte 180 near the small town of Hunt. Continue North on 180. About 2 miles beyond Hunt, Rte 180 crosses the bed of the Little Colorado River. The map shows a small dirt road that leaves Rte 180 and tends West just before the crossing of the Little Colorado.
- 3:00 PM At the Little Colorado crossing, we will attempt to park and walk down to the bed of the Little Colorado, searching for a site that bears some

resemblance to the Huygens landing site on Titan. Tamara Goldin will describe the Little Colorado River system here and acquaint us with the concepts of river equilibrium and the Graded River. Kelly Kolb will talk about the mechanics of sediment transport by streams, and, aided by the sharp-eyed perceptions of the rest of the class, the evidence for that process that we can see at this site.

- 4:00 PM Continue North along Rte 180 and enter the Southern end of Petrified Forest National Park. If there is time this evening (this may be moved to tomorrow morning if it is too late), tour the visitor center and view the hillsides of petrified wood. Julia Greissl will described how wood attains this strange condition.
- 5:30 PM Camp South of the Park (there are no campsites in the Park itself).

 According to the ranger, the best camping is at the end of Old Woodruff Road. About 3 miles South of Rte 180 is a small waterfall where Silver Creek joins the Little Colorado, and good camping is said to be available there.

Saturday, April 21

- 8:00 AM Break Camp, drive North through Petrified Forest National Park.
- 9:00 AM Stop at Jasper Forest. **Diana Smith** will tell us about the Chinle Formation, which forms most of the terrain in the Park, and describe the ancient river system of which it was part.
- 9:45 AM Continue North through Park. At the North end, join I-40 and drive East 23 miles to Rte 63. Drive North on Rte 63 to the Navajo town of Ganado. There, join Rte 264 and drive 5 miles West, to reach Rte 63 again and continue North to the town of Chinle and Canyon de Chelly. Lunch stop will probably be somewhere near Ganado.
- 2:00 PM Arrive at Canyon de Chelly. The Cottonwood campground near the Visitor Center is free, but on a first-come, first-serve basis, so first stake out a campsite for the evening. Then drive along the North Rim Drive toward Greasewood Springs.
- 3:30 PM Stop at the Massacre Cave overlook. This stop affords a fine view of the canyon system and the river channel within it. At this location **Brian**Jackson will explain our understanding of Stream Orders and Networks, as well as giving a general discussion of the fluvial system on Earth.

 Catherine Neish will talk about sapping features and how they relate to fluvial systems on Earth, Mars and Titan. Mandy Proctor will describe how the lovely meanders we can see in the river channel are formed.

 Doug Archer will tell us about the age of Marian valley networks.

5:30 PM Return to the Cottonwood campground, camp.

Sunday, 22 April

Break Camp. Drive to the head of the White House Ruin trail, proceed into the canyon. The well-graded trail is about 2.5 miles long and winds down about 800 vertical feet through steep cliffs of the Permian age de Chelly Sandstone. At the river, **Prianka Sharma** will discuss how rivers erode their beds and alter the rocks that fall into them. **Nicole Baugh** will discuss similarities and differences between fluvial erosion on Earth and Titan. This is also a good spot for anyone who can to discuss a bit about the history of the Anasazi and the Navajo people who now inhabit the region.

11:00 AM Depart Canyon de Chelly and continue North on Rte 63. Depending on road conditions, we may be able to take the secondary roads between Many Farms and Kayenta. At Kayenta pick up Rte 160 and head West.

12:30 PM Stop for lunch West of Kayenta. This stop affords a good opportunity for **Joe Spitale** to talk about the small block landslides, many of which you should have observed by now. **Dave O'Brien** may such off his mantle as leader briefly to talk about coal mining on Black Mesa and the power plants that it feeds.

1:30 PM Continue West on Rte 160. At Tuba City stop at the dinosaur footprint site where **Maria Banks** and **David Minton** will talk about the defunct lizards of Northern Arizona and their tracks. Note that a Navajo guide **must** be followed here on reservation land.

2:45 PM Depart Tuba City. Continue West on Rte 160 to its intersection with Rte 89. Bear left (South) toward Flagstaff. Stop in Flagstaff for a quick snack, then continue South on Rte 17 through Phoenix to I-10 and a return to Tucson.

9:00 PM Arrive Tucson, unload vehicles, go home.

==Finis==



Drivers:

Primary: Dundas, Proctor, Minton, Neish, Baugh

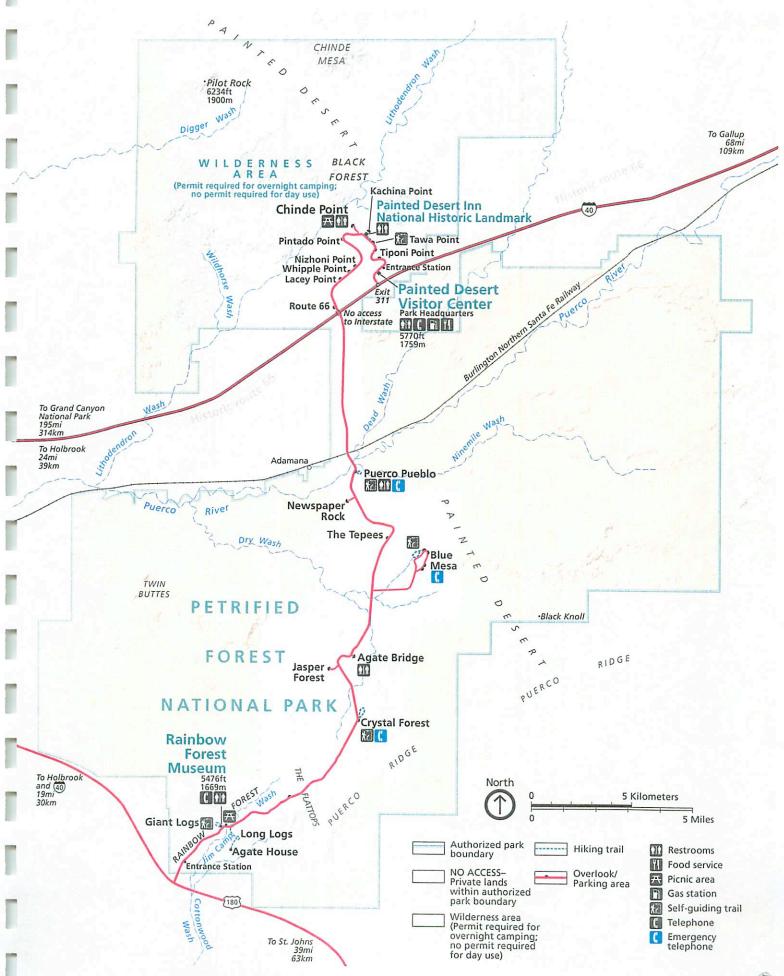
Backups: Bland, Dundas, Jackson, Smith

Leader: Dave O'Brien

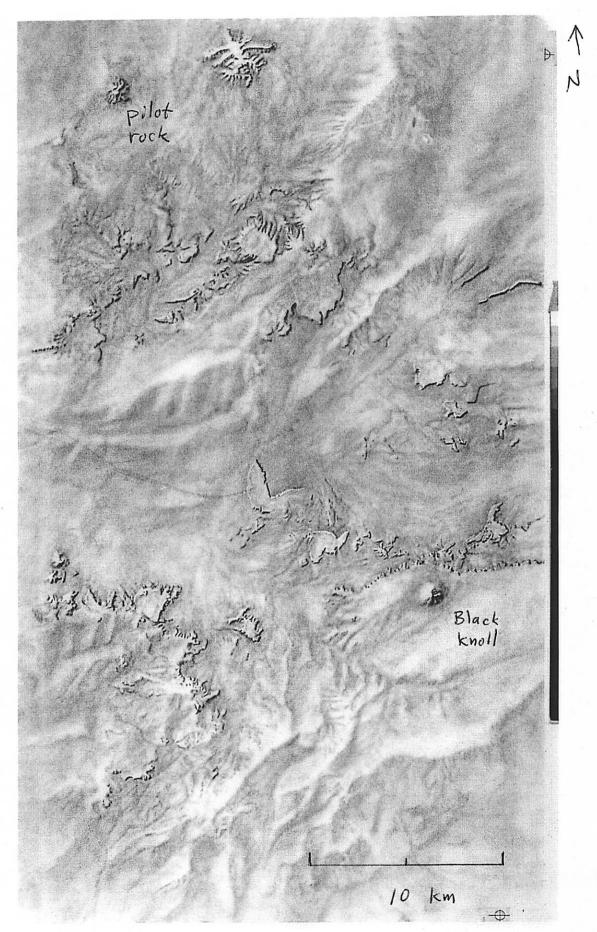
Participants:

Archer, Doug Banks, Maria Baugh, Nicole Bland, Mike Dundas, Colin Goldin, Tamara Greissl, Julia Jackson, Brian Kolb, Kelly Mindon, David Neish, Catherine O'Brien, Dave Proctor, Mandy Sharma, Priyanka Smith, Diana Spitale, Joe

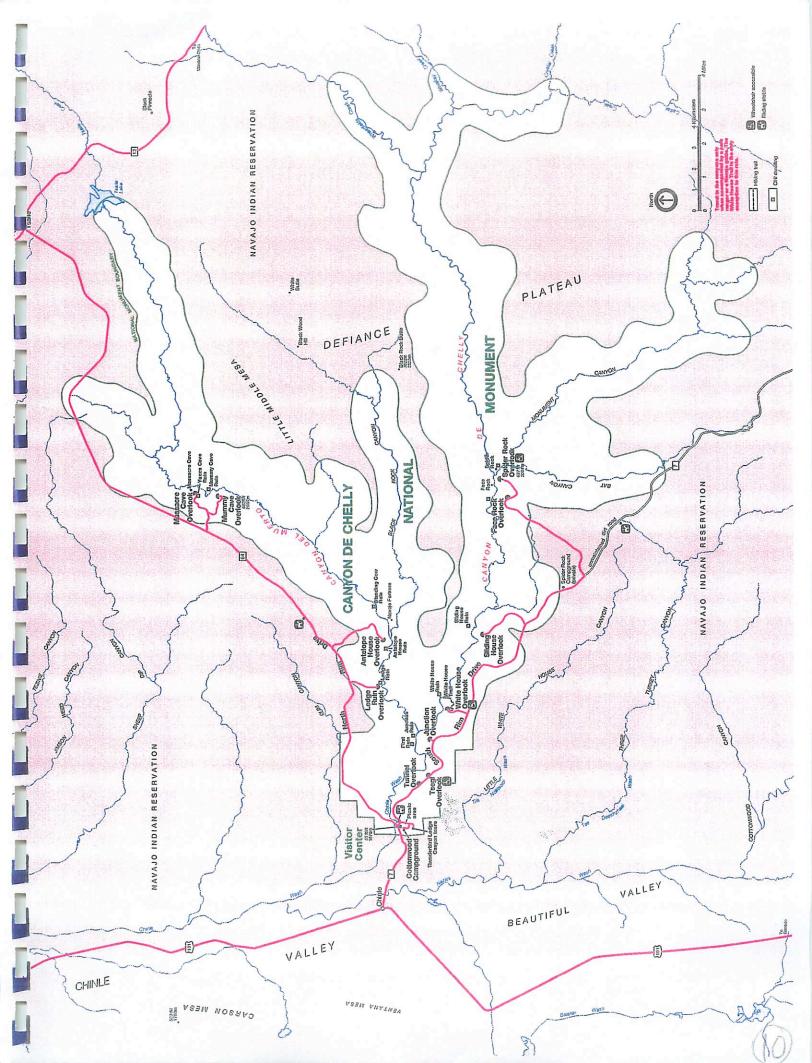
Field Guide Editor: Brian Jackson



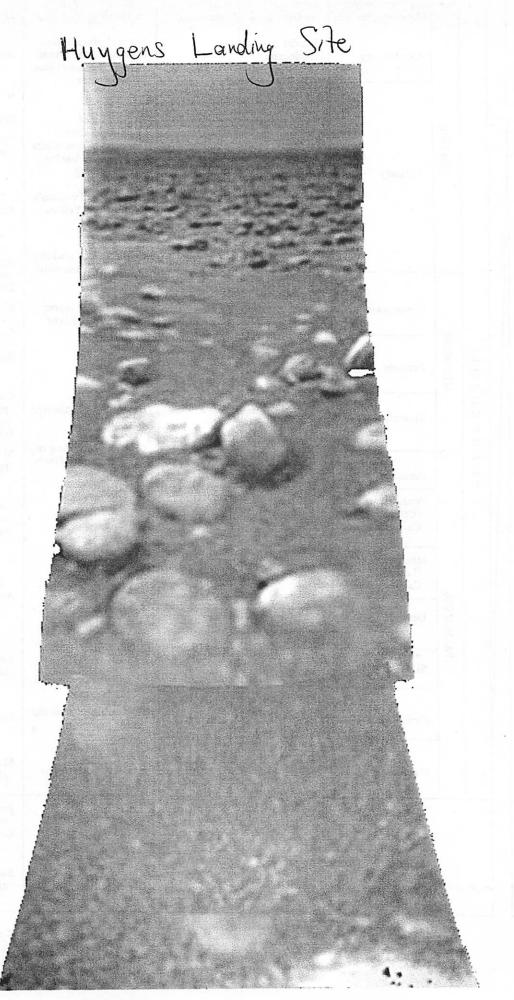




Petrified Forest Shaded Relief



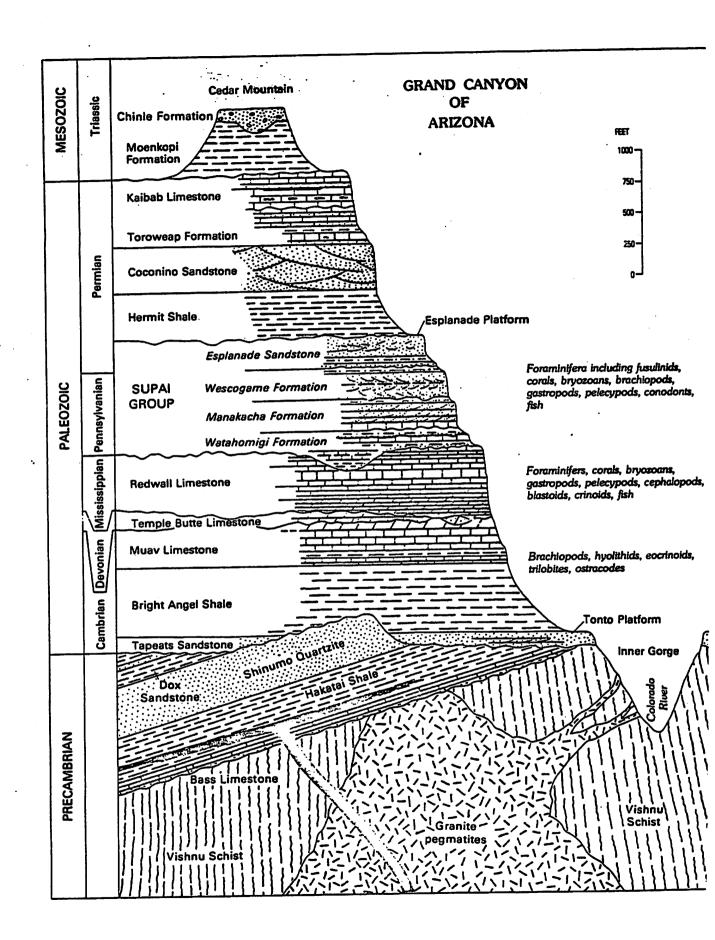
Canyon de Chelly Shaded Relief

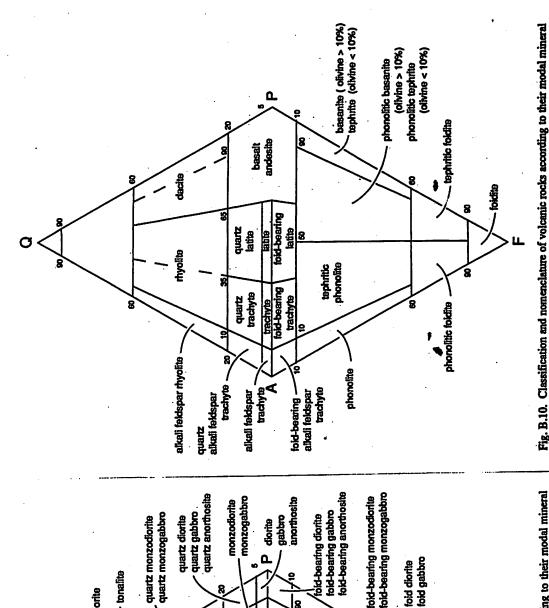


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Uniform		bdivi: ata/1	sions Based on ime		Dates Outstanding Street				
Time Scale			Systems/Periods	Series/Epochs	(millions of years ago)	In Physical History	In Evolution of Living Things		
PHANEROZOIC o	STOTE.		Quaternary	Recent or Holocene Pleistocene	2?	Several glacial ages Making of the Great Lakes; Missouri and Ohio Rivers	Homo sapiens		
NER				Pliocene			Later hominids		
575		CENZOIC		Miocene	6	Beginning of Colorado River Creation of mountain	Primitive hominids Grasses; grazing mammals		
5/3		CEN	Tertiary	Oligocene	36	ranges and basins in Nevada			
				Eocene	58	Beginning of volcanic activity at Yellow- stone Park	Primitive horses		
				Paleocene	65 —	Beginning of making of Rocky Mountains	Spreading of mammals		
	- 3		Cretaceous			Beginning of lower Mississippi River	Dinosaurs extinct Flowering plants		
	0 I C	MESOZOIC	Jurassic		145	Beginning of Atlantic Ocean Climax of making of Appalachian Moun- tains	Climax of dinosaurs Birds		
	EROZ	W	Triassic		210		Conifers, cycads, primitive mammals Dinosaurs		
I A N	P H A N		Permian	Many	250		Mammal-like reptiles		
A M B R			Pennsylvanian (Upper Carboniferous)				Coal forests, insects, amphibians, reptiles		
PREC			Mississippian (Lower Carboniferous)		340	Earliest economic coal deposits			
		PALEOZOIC	Devonian		—— 365 ——		Amphibians		
			Silurian		415		Land plants and land animals		
			Ordovician		510	Beginning of making of Appalachian Mountains	Primitive fishes		
			Cambrian			Earliest oil and gas fields	Marine animals abundant		
				N	575		Primitive marine animals Green algae		
			PRECAMBRIA (Mainly igneous	and	— 1,000 —— — 2,000 ——		Green argae		
			metamorphic rocks; no worldwide subdivisions.) Birth of Planet Earth		— 3,000 ——		Bacteria, blue-green		
1450	m	~			—4,650 ——	Oldest dated rocks	algae		
~4,650					.,550				

Flint and Skinner, 1977 "Physical Geology", 2nd ed.





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fold syenite

fold-bearing diorite

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monzogabb 효 뎿

monzosyenite

syenite

foid-bearing alkali feldspar

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quartz gabbro

(syeno- / (monzo-granite) / granite)

quartz alikali feldspar eyenite -

granite

alkali feldspar

granite

quartz diorita

quartz monzogabbro

quartz monzodiorite

tonalite

granodiorite

quartz-rich granitoids

quartzolite (sllexite)

contents using the QAPF diagram (based on Streckeisen, 1976, Fig. 1a). The corners of the double triangle are Q=quartz, A=alkali feldspar, P=plagioclase and F=feldspathoid. However, for more detailed definitions refer to section B.2. This diagram must not be used for rocks in which the mafic Fig. B.4. Classification and nomenclature of plutonic rocks according to their modal mineral mineral content, M, is greater than 90%.

contents using the QAPP diagram (based on Streckeisen, 1978, Fig. 1). The corners of the double

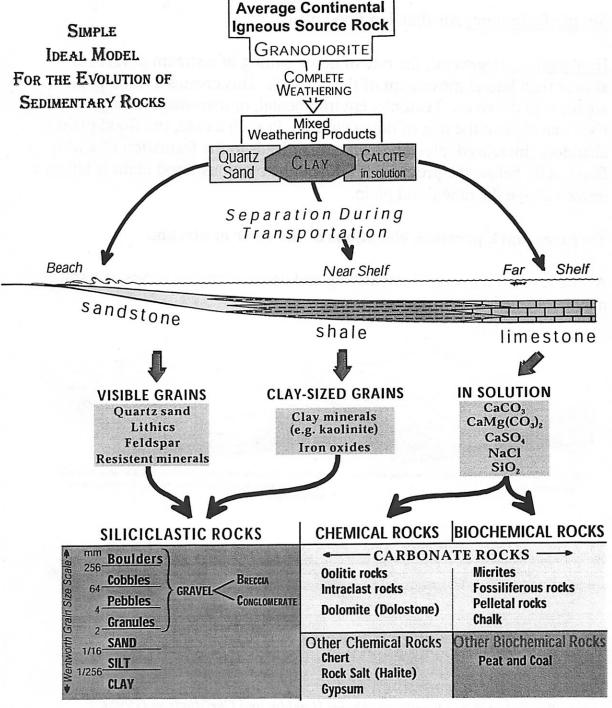
triangle are Q=quartz, A=alkali feldspar, P=plagioclase and P=feldspathoid. However, for more

detailed definitions refer to section B.2

"Classification of Igner's Rocks and Glossary at Terms Le Mairie, ed. Blackwell, 1989

3

SEDIMENTARY ROCK MODELS



L.S. Fichter, 1993, 2000 http://geollab.jmu.edu/Fichter/SedRx/sedclass.html

Stream Terraces

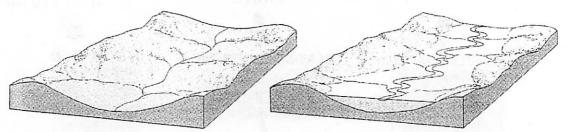
(with emphasis on the San Pedro River Valley)

Simple Definition: An abandon flood plain.

Explanation: In general, the rate of down cutting of a stream or river is slower than lateral movement of the channel. This creates a flood plain adjacent to the river. Tectonic, environmental, or man-made changes to the river can change the rate of down cutting. In such a case, the flood plain is abandon. Increased rates of down cutting leads to the formation of a new flood plain below the previous level, and the previous flood plain is left as a terrace above the new flood plain.

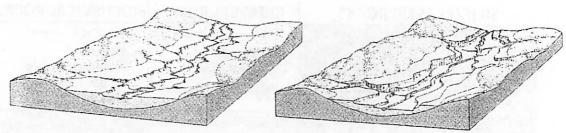
Terraces mark previous elevations of the river or stream.

As the level of the river fluctuates up and down, complex series of terraces may be formed.



(A) A stream cuts a valley by normal downcutting and headward erosion processes.

(B) Changes in climate, base level, or other factors that reduce flow energy cause the stream to partially fill its valley with sediments, forming a broad, flat floor.



(C) An increase in flow energy causes the stream to erode through the previously deposited alluvium. A pair of terraces is left as a remnant of the former floodplain.

(D) The stream shifts laterally and forms lower terraces as subsequent changes cause it to erode through the older valley fill.

Stages in terrace formation. From: Hamblin and Christianson (1998).

Controls on Terrace Formation:

Terrace formation is ultimately controlled by the amount of discharge, stream gradient, and sediment load. In turn these factors are influenced by many factors.

Tectonic:

- Faulting, folding, warping, tilting, etc. can change the channel slope, affecting the rate of down cutting.
- Uplift or subsidence can lead to a change in base level.
- Change in sediment load.

Environmental:

- Water delivery changes in precipitation.
- Sediment delivery changes in vegetation and precipitation.
- Change in base level lake/sea level change.
- Glacial melt

Human induced:

- Change in base level dams, etc
- Change in sediment load

Many of these controls can work simultaneously to change the "grade" of a river or stream.



Stream terraces along the Pahsimerio River, Idaho, were formed by recent recurrent uplift. More than seven well defined terraces can be seen.

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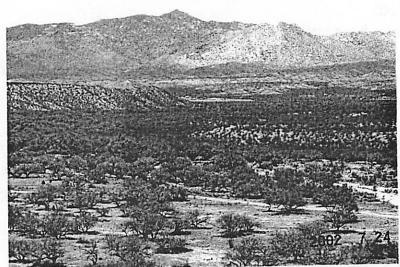
The Graded River:

While a river is an open system, there is an inherent tendency towards self regulation:

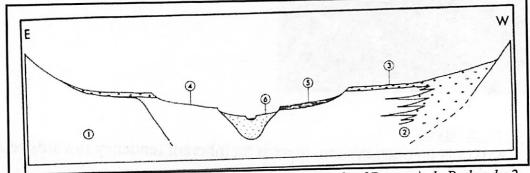
"A graded river is one in which, over a period of years, slope and channel characteristics are [naturally] adjusted to provide, with available discharge, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium..." Leopold and Maddock, 1953 from Bloom, 1998.

The San Pedro:

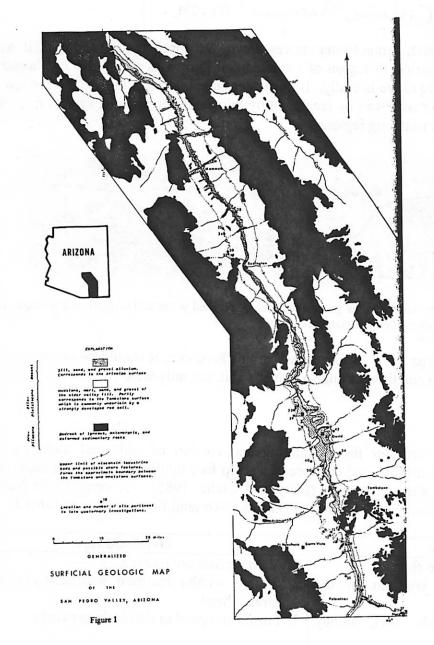
The San Pedro Valley is an extensional rift valley through which the San Pedro River flows. The headwaters are in Northern Sonora, Mexico, and the river flows 140 miles to the Gila River at Winkleman. The valley is famous for both its Pleistocene (think Saber Tooth Tigers) fossils and its early American archeological sites. Many of these fossil and archeological finds are from the river's extensive terrace deposits. Terraces along the San Pedro river are Pliocene aged or younger (5.3 Mya to present). Terraces can be as high as ~30 m.



Terraces near Tres Alamos Wash (north of Benson) along the San Pedro River. From: http://www.saguaro-juniper.com/i_and_i/san_pedro/sanpedro_tributaries.html



Generalized cross-section of San Pedro Valley (south of Benson). 1. Bedrock; 2. old valley fill; 3. Tombstone Surface; 4. Whetstone surface; 5. Late Quaternary fill; 6. Recent Alluvium. Haynes, 1968.



Localities of fossil or archeological sites along the San Pedro River valley. Fossils Pleistocene include "Megafauna" including tiger, sabertooth Mammoth, Camels, Giant Wolves. Bison, Short Ground Sloth, Faced Bear, Tapir, and Archeological Deer. cites include those of Clovis people (earliest inhabitants of North America), the Hohokum Culture (in the form of ball courts and platform mounds), Sobaipuri and the (present day Tohono O'odham) and Apache. Frome Haynes, 1968.

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Haynes, C. V. 1968. Preliminary report on the late quaternary geology of the San Pedro Valley, Arizona. In: Southern Arizona Guidebook III, Titley, S. R. (ed). Arizona Geological Society, p. 79-96.

Leopold, L. B., Wolman, M. G., and Miller, J. P. 1964. <u>Fluvial Processes in Geomorphology.</u> W. H. Freeman and Company, San Francisco, pp.458-485.

Website: http://www.saguaro-juniper.com/i and i/i and i.html (info on the San Pedro)

Groundwater and springs

Sapping features on Earth, Mars, and Titan
Catherine "Anonymons" Neish

In surfaces with permeable rock layers, groundwater moves downward through the rock until it reaches an impermeable layer of rock (the aquitard). A region of saturated soil known as an aquifer or a water table is then formed, and the water is forced to move laterally. If this water table intersects the ground surface, a spring will be formed (Figure 1). The water table can be recharged by rainwater entering the system from above, or from groundwater flowing in from surrounding regions.

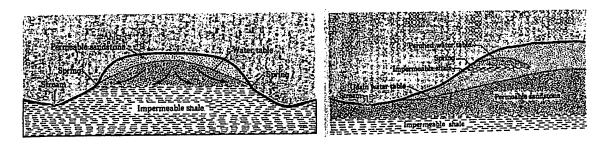


Figure 1: Springs form when the water table intersects the ground surface. A perched water table (right) results when groundwater collects over an impermeable zone separated from the main water table.

NOTE: Though I refer to "groundwater" and "water tables" in this hand-out, it should be noted that this same process would occur for any fluid that can flow through a planet's soil, not only water.

Groundwater Sapping

Groundwater sapping is a generic term for the weathering and erosion of soils and rocks by emerging groundwater. It results from the undermining and collapse of a scarp face by the weakening of basal support as a result of enhanced erosion at a site of seepage (Laity and Malin 1985). A comparison between the morphological features caused by drainage of groundwater flow and overland flow is given in Table 1.

Groundwater flow	Overland flow			
1. Valley fleads are steep mass in 1	1. Valley heads are tapered.			
2. Valley widths remain nearly constant in the	stream head.			
3. Forms long main valleys with short, stubby tributaries.				
4. Valleys generally grow in the direction of the regional joint pattern (Figure 2a). Since valleys follow large-scale joint angles, channel junctions	4. May be joint controlled when fractures are exposed on the surface, but show no control when joints are covered in soil or debris.			
display only two or three orientations. 5. Valleys grow in the up-dip direction with respects to the aquifer layer (Figure 2b).	5. Drainage patterns follow surface topopgraphy			
6. Side profiles of canyons are roughly linear.	6. Side profiles of canyons are usually concave.			
7. Hanging tributary channels commonly occur.	7. No hanging tributaries.			

Large volumes of water are required to produce a well-developed sapping network. The most efficient process of sapping erosion occurs in unconsolidated sediments, where the limiting factor is the transporting capacity of the spring-fed flows. In unconsolidated materials, sediment makes up about 1-10% of the overall flow, whereas in consolidated materials, sediment makes up only 0.1-1% of the overall flow. Thus, at least 10X (and more likely 100 - 1000X) more water than rock volume must be discharged to create a sapping network.



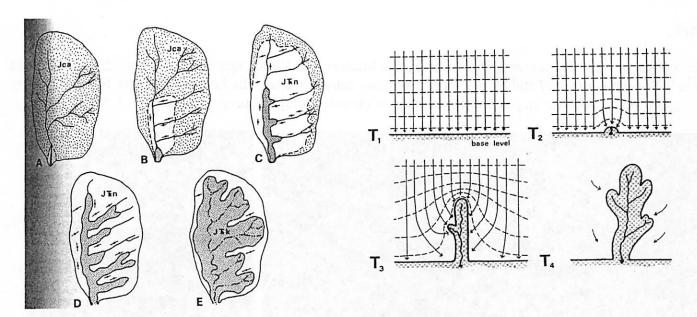


Figure 2: Illustration of canyon development by groundwater sapping. Runoff is concentrated along joints (left) that enlarge to form canyons as groundwater converges at the valley head (right). Note the strong structural control of the valley alignment, leading to only two or three valley orientations.

Planetary connections

a. Earth

Groundwater sapping is an important valley forming process in the sandstones of the Colorado Plateau.

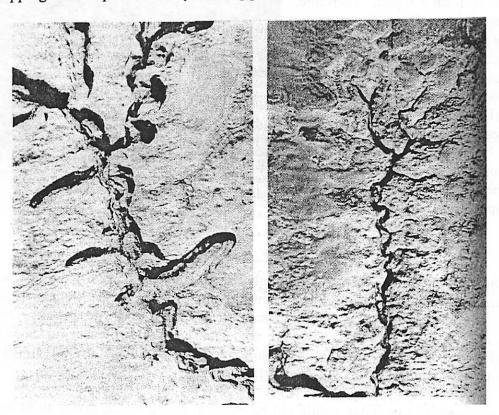
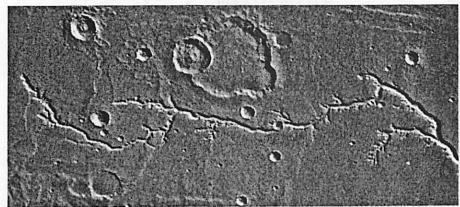


Figure 3: Two morphologically distinct valley types in the Navajo Sandstone of the Glen Canyon region of the Colorado Plateau. Iceberg Canyon (on the left) shows the theatre-headed terminations characteristic of sapping processes. The canyon was developed in a gently dipping syncline, so groundwater is focused toward the canyon walls. A tributary to the lower Escalante River (to the right) shows the tapered terminations characteristic of overland flow.

b. Mars

Channel networks were first observed on Mars by the Mariner and Viking spacecrafts. These features include dendritic valley networks, and stubby networks dissecting canyon walls. The latter are thought to be caused by groundwater sapping because they demonstrate many of the morphological properties listed in Table 1.



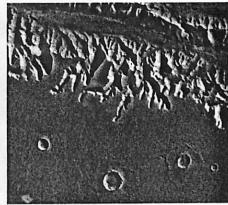


Figure 4: Upper reach of Nirgal Valles, showing stubby tributaries with theatre heads (left). A portion of the southern wall of Valles Marineris showing stubby, theatre-headed valley networks and two rampart craters (right). Viking image mosaics.

How would groundwater sapping occur on Mars? Currently, the pressure at the surface of Mars is too low for liquid water to be stable there. If heated, surface ice would sublime directly to a gas without melting to form a liquid. Therefore, subsurface deposits of ice and/or water must be responsible for any current fluvial erosion. Large deposits of just this sort were discovered by the Gamma Ray Spectrometer (GRS) on the Mars Odyssey spacecraft in the polar and sub-polar regions on Mars (Boynton et al. 2002). These subsurface ice reserves, under pressure and potentially heated by geothermal activity, could form liquid water on the present day Mars. This water could then be released from its subsurface aquifer to create sapping channels (Figure 5).

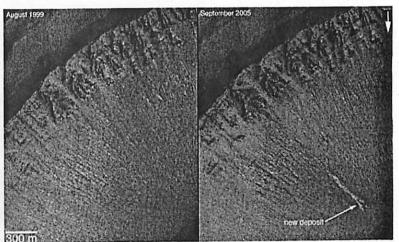


Figure 5: A new gully deposit in the Centauri Montes Region. Image credit: NASA/JPL/Malin Space Science Systems.

c. Titan

In January 2005, the Huygens probe descended through Titan's atmosphere, returning high resolution views of the surface (Tomasko et al. 2005). These images revealed the presence of dark channels cutting into bright terrain, with patterns both dendritic and stubby in nature. Tomasko et al. describe the stubby channels as "...shorter, wider, and relatively straight. They are associated with and often begin or end in dark circular areas." (Figure 6) They go on to say that "the morphology of rectilinear networks with stubby heads is consistent with spring-fed channels or arroyos."

Unlike Earth and Mars, springs on Titan would not be made of liquid water, given its surface temperature of 95K. Springs, if they exist, would likely be made of liquid alkanes (such as methane or ethane) flowing through a soil of water ice or solid organics. Upcoming experiments at JPL will study the wetting properties of liquid methane on solid water ice to help better understand these flows.

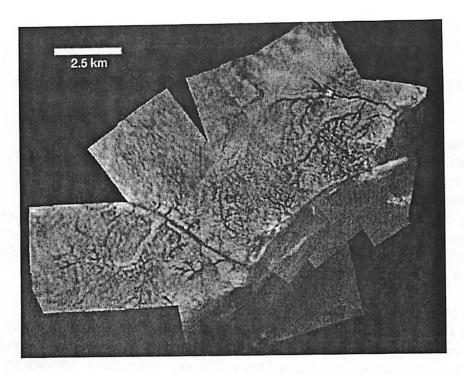


Figure 6: Huygens panorama showing both stubby (left) and dendritic (right) channels along a 'shoreline'. Huygens/DISR image.

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The Colorado Plateau: History, Stratigraphy and Uplift Colin Dundas

Introduction

The Colorado Plateau is a broad, high-standing region of the southwestern United States characterized by a thick sequence of layers representing a long history of sedimentation relatively unaffected by tectonism. The Plateau is surrounded by tectonically altered terrains, including the Basin and Range province, but has been uplifted approximately 2 km without substantial deformation. This is unusual because topographically high and uplifted areas are often associated with significant amounts of deformation (for instance, the Himalayas).

History of Deposition

The rock units of the Plateau (Fig. 1) record a long history of sedimentary deposition in varying environments. This entire column is not fully exposed anywhere, and in places some units are missing or have a different composition and thickness. The layer-cake of formations records a varying environment, from shallow marine to fluvial to desert sandstone deposition. I will spare you the detailed history of each unit.

Within Canyon de Chelly National Monument or Petrified Forest National Park, only a small part of the regional stratigraphy is exposed. In Petrified Forest NP, the exposed rocks are members of the Chinle Formation, unconformably overlain by the Bidahochi Formation from the last 4-8 Myr. The Chinle here is a mix of sandstones and mudstones largely deposited by a major fluvial system. In Canyon de Chelly, the most important units are the Triassic-age Shinarump Conglomerate, the Permian de Chelly Sandstone and "red beds" of the Cutler Group. The Shinarump Conglomerate is a fluvial deposit from the base of the Chinle Formation, the de Chelly Sandstone is cross-bedded eolian sandstone, and the red beds are fluvial sandstone.

Uplift

Colorado Plateau crust is ~45 km thick, in Airy isostatic equilibrium (McQuarrie and Chase, 2000). The heat flow is moderate, and seismic velocities in the upper mantle are normal (Lastowka et al., 2001), indicating that the mantle is not particularly hot.

The timing and mechanism of uplift of the Colorado Plateau are still subjects of active discussion. Morgan and Swanberg (1985) summarized three major classes of explanation for the uplift: thermal expansion, crustal thickening, and phase changes. They argue for thermal expansion due to thinning of the lithosphere and addition of new crust via magmatism. Spencer (1996) proposes uplift driven by partial removal of old mantle lithosphere, due to shallow-angle subduction of the Farallon Plate. McQuarrie and Chase (2000) argue for crustal thickening due to intracrustal flow. Seismic evidence presented by Lastowka et al. (2001) supports the Spencer model over the others.

A critical component in settling this issue is the timing of uplift. Uplift must postdate deposition of late Cretaceous marine sediments (Spencer, 1996); Spencer proposes early to middle Cenozoic uplift, consistent with the shallow angle subduction model. Sahagian et al. (2002) argued for recent uplift, starting at about 25 Ma but accelerating in the last 5 Ma, based on elevations derived from basalt vesicularity;

Libarkin and Chase suggested that the Sahagian et al. estimate had systematic errors and that the data was better fit by rapid uplift 17-20 Ma.

Similar issues are relevant for understanding the origin and tectonic evolution of crustal provinces on other planets, such as Mars. The source (and evolution) of large-scale elevation differences like the Tharsis bulge or the Martian hemispheric dichotomy may involve similar processes.

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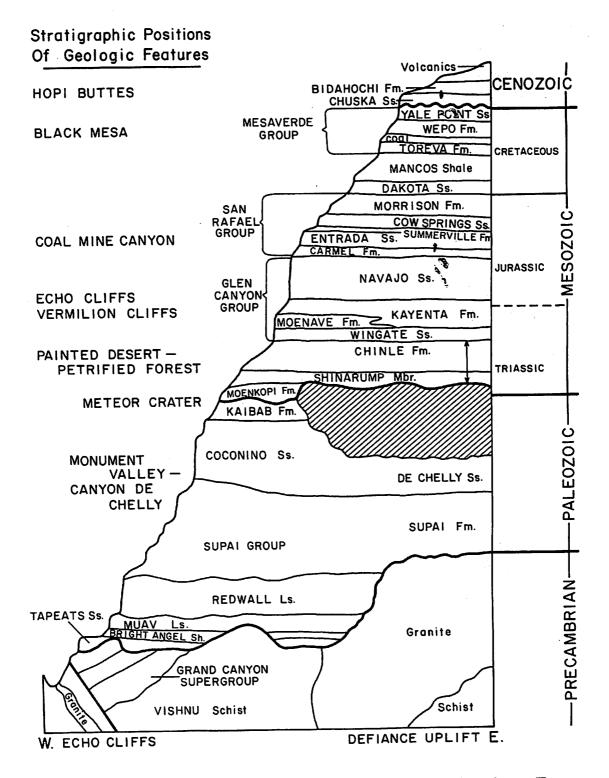


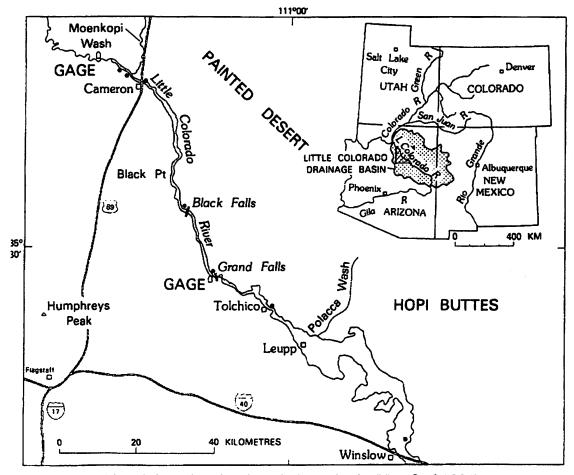
Figure 1: Generalized stratigraphic section of the Colorado Plateau in Arizona (From Landscapes of Arizona: The Geologic Story)

THE LITTLE COLORADO RIVER

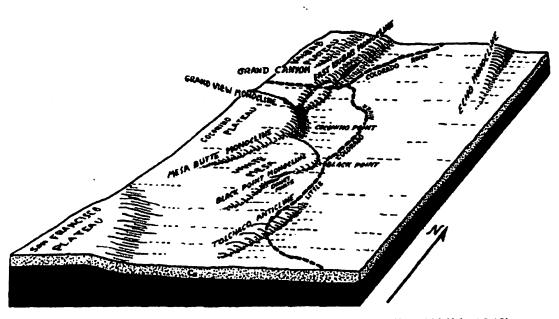
By Tamara Goldin

FUN FACTS:

- -Tributary of the Colorado River
- -Ephemeral stream
- -44,000 km² drainage area on Colorado Plateau
- -507 km long
- -Carries up to 150 m³/s (although highly irregular flow)
- -Average relief is low, sedimentary rocks in region permeable → low runoff
- -Arid to semi-arid climate (winter and summer precipitation maxima)
- -80% of basin receives less than 300 mm precipitation annually
- -Vegetation dominated by pinyon-jupiper woodlands and plains & desert grasslands
- -Main economic activity is livestock production



The Little Colorado River drainage basin (Hereford 1984)



Regional structural features of Little Colorado River valley (Childs 1948)

GEOMORPHOLOGY:

- 1) 1990- early 1940s

 Erosion dominant geomorphic process → River incising older deposits
- 2) 1940s-1980

 Erosive phase ends and aggradation occurs → Flood plain development via vertical accretion
- 3) post 1980
 Flood plain ceases to accrete (has attained a 'critical height'?), erosion of floodplain

The transition from erosion \rightarrow aggradation linked to shift from higher \rightarrow lower mean annual precipitation

-This decrease in precipitation is linked to a change in climate (increased mean annual temperatures)

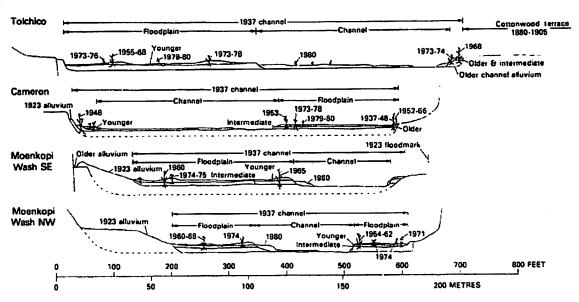


Figure 12. Cross sections, constructed from maps made by plane table and alidade at the scales listed in Table A, illustrating the surface morphology and stratigraphy of the flood plain and older deposits. Extent of the 1937 channel was determined by its morphologic expression and by reference to the November 1936 aerial photographs. "Older," "intermediate," and "younger" refer to salt-cedar germination horizons. Dated trees on flood plain indicate approximate age of salt-cedar groves. The stratigraphic position of buried root collars was inferred from position of trees of similar age exposed in cutbanks (Table 1). Surveyed in January 1981; last flow, September 1980.

(Hereford 1984)

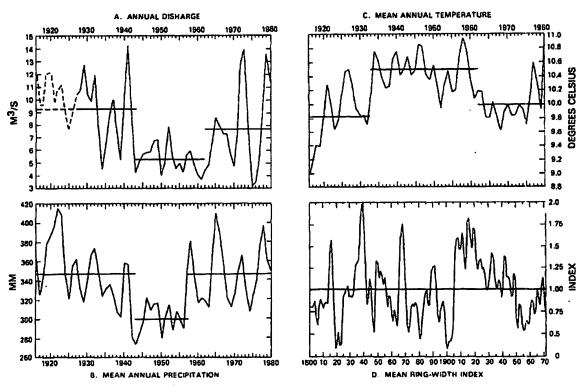


Figure 15. Time series of climatic variables in the Little Colorado River drainage basin. Filter (described in the text) results in loss of first and last years of data set. Horizontal lines in A, B, and C are the averages of the subseries in Table 3. A. Annual discharge, 1916 to 1980; dashed line was estimated from the precipitation and ring-width regression. B. Mean annual precipitation, 1916 to 1980. C. Mean annual temperature. 1916 to 1980. D. Mean ring-width indices, 1801 to 1971; horizontal line is the average.

(Hereford 1984)



THE GRADED RIVER CONCEPT:

A graded river is a river whose slope or other characteristics is adjusted to provide just the velocity required to transport the supplied load from the drainage basin. Basically a graded river transports it's load without net deposition or erosion. So, it's an equilibrium system—tweaking the system will cause the river to readjust to a new equilibrium. Whether a truly graded river can exist in nature is a subject of debate.

HUMAN HISTORY:

- -Occupied by Native Americans, including Navajo and Hopi groups, for hundreds of years
- -Settlement of region by Mormons in late 1800s
 - -The environmental variability of area made life difficult for the Mormon pioneers
- -Non-Mormon immigration and economic development in 1960s
- -Today the area is mostly Hopi and Navajo Reservation land

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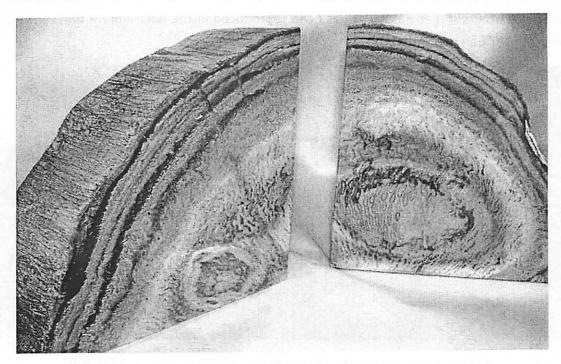
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The Formation of Petrified Wood

Julia Greissi

Petrifaction of wood is the process by which some or all of the organic materials in wood are replaced by inorganic molecules. (Most often silicates, but also carbonates, sulfides, sulfates, oxides and phosphates. [1], [2]) Petrified wood can be found in many different hues, but in the Arizona Petrified Forest it is most often red, with yellow, black or white inclusions. [3]



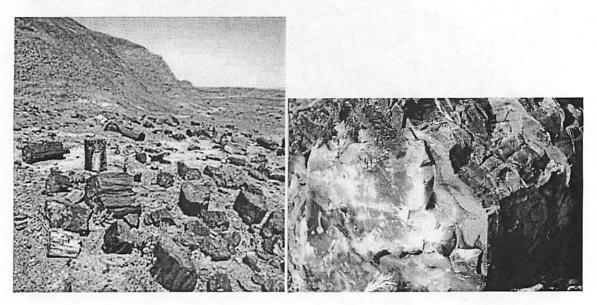
Petrified wood sample including tree rings as well as substructure of the original log. [4]

The mechanism for petrifaction is as follows:

- A tree dies and is submerged in water or often volcanic ash quickly enough to prevent aerobic decay.
- Water rich in minerals or volcanic ash which is naturally rich in silicates, seeps through the cells it will deposit the mineral, which crystallizes and replaces the cell structure of the tree. In the case of silicates this process is thought to occur through hydrogen bonding of monomeric silicic acid (Si(OH)₄) with functional groups (most often OH⁻) in the wood. [2]
- The water evaporates, the silicate crystals slowly turn to higher-ordered forms of opal and quartz. Trace materials in the water (see table below) determine the final color of the petrified wood. [2]

Often this process works so well that the entire structure of the wood is preserved down to the details of the cell structure. Petrified wood can also form more rapidly in an environment where the wood decays and is replaced by the crystalline structures. In this case very little of the original tree structure, excepting the tree rings, is preserved. In nature the petrified wood we see was often formed through a combination of the two processes. [1]

While the first process is thought to take millions of years in nature, the second process can sometimes occurs rather quickly. It has been reproduced in the laboratory in days by soaking wood in a solution rich with SiO_2 . [1]



Petrified Wood in Petrified Forest National Park (courtesy of [3], [5])

In the Arizona Petrified National Forest most of the petrified wood comes from the Triassic Period (approx. 200 Myr) and most of the specific trees one finds are an extinct type of conifer. [6]

Petrified Wood Color Index:

Red	Orange	Yellow	Green	Blue	Violet	Purple	Brown	Black	White	Gray
Fe+3	Fe+3	Fe+3, U	Fe+2, Co, Cu, Cr, U, Ni		Mn, Fe+3	Fe+3, Mn	Fe+3, U	Mn, C, Fe+3	SiO ₂	SiO ₂

See [4].

Some random facts:

- The Paiute tribe thought the petrified logs were spent arrows and spears dispatched by the God Shinauav. The Navajo thought they were the bones of a giant monster. [5]

- The rapid 'petrifaction' of wood in the laboratory has been cited by proponents of Intelligent Design as evidence for a young Earth. [7]

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Mechanics of Sediment Transport by Fluids Kelly Kolb

Entrainment

Definition¹:

the point at which the force or stress from a flowing fluid is sufficiently great as to move stationary sediment from the bed into transport

Threshold of sediment motion depends on 1:

sediment properties- size, shape, orientation, sorting, packing fluid properties- density, viscosity flow conditions- velocity, power, bed roughness

Lift forces arise from²:

- 1. differences in flow velocity between top and bottom of grain (pressure gradient)
- 2. turbulent eddies that can produce local velocity components

If > ~40% sediment is entrained, a fluvial flow will become hyperconcentrated¹. This will reduce the settling velocity of coarser grains because it:

- 1. increases the effective viscosity of the fluid
- 2. increases effective buoyancy of the particle

Critical Stress

Drag Force Moment, Fd:

$$(1) F_d = F_D * \frac{D}{2} \cos \phi$$

$$(2) F_D = \frac{C_D \pi D^2 \rho v_s^2}{8}$$

$$(3) F_d = \frac{\tau}{n} * \frac{D}{2} \cos \phi$$

Submerged Weight Moment, Fw:

$$(4) F_w = F_b * \frac{D}{2} \sin \phi$$

(5)
$$F_b = g(\rho_s - \rho) \frac{\pi}{6} D^3$$

(6)
$$F_w = g(\rho_s - \rho) \frac{\pi}{6} D^3 * \frac{D}{2} \sin \phi$$

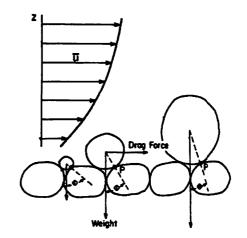


Figure 1. Diagram showing forces on particles in a flow with velocity \vec{u} .

From [3], Fig. 6.

Critical Stress, $\tau = \tau_{cr}$:

(7)
$$\tau_{cr} = Ng(\rho_s - \rho)\frac{\pi}{6}D\tan\phi$$

$$(8) N = nD^2$$

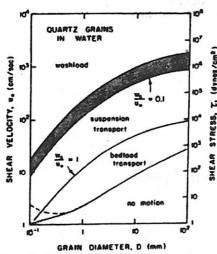


Figure 2. Shear velocity and shear stress required to transport a particle. From [3], Fig. 9.

Variable	Definition				
F _d	drag force moment				
$F_{\mathbf{w}}$	submerged weight moment drag force				
F _D					
F _b	buoyant force				
ρ _s	particle density				
ρ	fluid density				
D	particle diameter				
ф	pivoting angle				
g	gravitational acceleration				
Vs	settling velocity				
τ	shear stress				
η	fluid dynamic viscosity				
C _D	drag coefficient				
N	measure of grain packing				
n	number density / area				
u•	frictional shear velocity				
h flow depth					
S bed slope					

Distinguishing Types of Transport

After being entrained, a particle will experience a particular type of transport.

Ratio of settling velocity to frictional shear velocity:

$$k = \frac{v_s}{u_{\bullet}}$$

 $k > 1.0-1.79$ bedload¹

 $k < 1.0-1.79$ suspended load¹

 $k = 0.05 - 0.13$ [1], 0.05-0.10 [3] washload

k values aren't exact because the classes are really a continuum¹
 example: saltating grains will make longer and longer jumps then in suspension
 division between washload and suspended load is not well-studied

Settling velocity (v_s): rate of fall of a particle under quiescent conditions¹
Stoke's law of settling:

Non-Stokes:

(9)
$$v_s = \frac{D^2 g(\rho_s - \rho)}{18\eta}$$

(10)
$$v_s = \sqrt{\frac{4(\rho_s - \rho)gD}{3C_D\rho}}$$

- applicable for laminar flow

- inertial forces dominate

- viscous resistance dominates¹

Frictional shear velocity (u*): proxy for the turbulence acting to suspend particles 1

$$(11) u_* = \sqrt{ghS}$$

- uniform flow

- use to calculate minimum channel depth required to obtain shear velocities required to transport sediment

Sediment sizes that fall in each mode depend on the flow strength of river: velocity, stress, or power³.

Types of Sediment Transport

Dissolved Load

- soluble material
- results from chemical weathering
- negligible effects on channel shape

Washload

- finest material in the fluid (smallest particles a flow can transport)
- evenly distributed throughout the fluid
- travel approximately the same velocity as the flow
- quantity in flow is based only on availability

Suspended Load

- finer than bedload, coarser than washload
- concentrated near the bed, but found throughout the fluid
- supported by turbulence in the flow (turbulence counters settling velocity)
- drag and lift forces are stronger than submerged weight of particle
- -~70% of the load carried to Earth's oceans²

Bedload

- coarsest particles, coarser than 0.062 mm [2]
- includes saltation, rolling, sliding, and bouncing
 - larger particles will remain in contact with the stream bed almost always (i.e. rolling, sliding)
 - saltation: particles move in a hopping motion
- availability depends on flow strength
- least significant in terms of quantity of stream loads, but most significant in terms of bed morphology
- transport velocities are 2-15% stream velocity²

Together suspended load and bedload make up ~10% of total load².

Sediment Transport on Mars, Earth, and Titan¹

Extraterrestrial Observations

Mars

Titan

- outflow channels
- valley networks
- meanders

- dendritic fluvial-like networks¹



Figure 3. Developed Meander on Mars (HiRISE PSP_001336_1560, 24S, 326E)

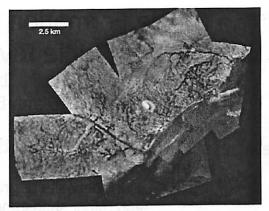


Figure 5 | View of 'shoreline' and channels. Panoramic mosaic projected from 6.5 km. showing expanded view of the highlands and bright-dark interface. As in previous figures, north is up; scale indicated. Branching and rectilinear channel networks of dark lanes are shown along an albedo boundary approximately 12 km long.

Figure 4. Channels on Titan. From [4], Fig. 5.

Silicate sediment is or was moved by flowing water on Earth and Mars.

Organic sediment and ice-rich sediment could be or could have been transported by flowing methane-nitrogen on Titan.

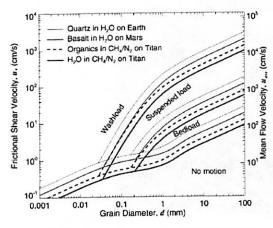


Fig. 3. Fields of transport categories for quartz on Earth, basalt on Mars, and organic material and water ice on Titan. The threshold k value used here for the bedload-suspended load transition is 1.25; the threshold k value used here for the suspended-washload transition is 0.075. Mean flow velocity, $u_{\rm ave}$, is for a gravel bed river with a $D_{\rm E4}$ of 256 mm.

Figure 3. Fields of Transport for Earth, Mars, and Titan. From [1], Fig. 3.

Plot Implications

- sediment is increasingly more likely to be moved (i.e. lower flow velocity or depth) on: Earth, Mars, Titan (easiest)
- water-ice sediment on Titan is more likely to move than organic sediment (density)
- actual transport is limited by availability of transport and amount of liquid flow
- less liquid is required to transport material of a given size on Titan than on Earth or Mars

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³ Komar, P.D. "Sediment Transport by Floods," *in* Baker, V. R., Kochel, R. C., and Patton, P. C., eds., Flood Geomorphology: New York, Wiley, p. 97-111.

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The Chinle Formation and the (now defunct) Chinle River System

by Diana E. Smith

Members of the Chinle Formation:

> Blue Mesa:

- Thick deposits of grey, blue, purple, and green mudstones and minor sandstone beds.
- Newspaper Rock Sandstone is the most prominent unit and is best exposed in the Tepees area of the park.
- Approximately 234 million years old.



Sonsela:

- o Three parts:
 - Lower Rainbow Forest Bed white cross-bedded sandstone and cobbles and logs of the Rainbow Forest
 - Middle Jim Camp Wash Beds blue, grey, and purple mudstones and numerous small grey and white sandstone beds
 - 3) Upper Flattops One Bed thick cliff-forming brown, cross-bedded sandstone. This sandstone caps Blue

Mesa, Agate Mesa, and the mesa north of the Rainbow Forest.

o Approximately 227 million years old.

> Petrified Forest:

- Thick sequences of reddish mudstones and brown sandstone layers
- o Exposed in the Flattops and the red part of the Painted Desert.
- o Black Forest Bed (north of Kachina Point) has been determined to be 214 million years old.

> Owl Rock:

- o Consists of pinkish-orange mudstones mixed with hard, thin layers of limestone.
- o Exposed on Chinde Mesa at the northernmost border of the park.
- o 205 million years old.

Setting

Imagine the super-continent Pangaea during the late Triassic. The Chinle region would have been on the southwestern edge and north of the equator. The climate was humid and sub-tropical during this time, as evidenced from ancient fossil plants and animals as well as paleosols (ancient soils). The sandstones, mudstones, and conglomerates of the Chinle indicate a large river system with periods of droughts and floods.

The Painted Desert is named for its colorful stripes, which correspond to the ancient soil horizons. The red and green layers have the same amount of iron present, but the color corresponds to whether or not the iron has been oxidized. When the water table was high, the environment was non-oxidizing, which gives the greenish/bluish hue (ferrous iron). When the water table fluctuated, this allowed oxidation of the iron minerals to produce the red color (ferric iron). Other color differences are due to differences in the minerals present.

Paleomagnetism

Bazard and Butler took many samples from the Chinle Formation over a wide range of places in Arizona and New Mexico. They used paleomagnetic measurements to show that there was a change from counterclockwise to clockwise in the rotation of Pangaea.

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- http://www.nps.gov/pefo/naturescience/geologicformations.htm

Figures from Riggs:

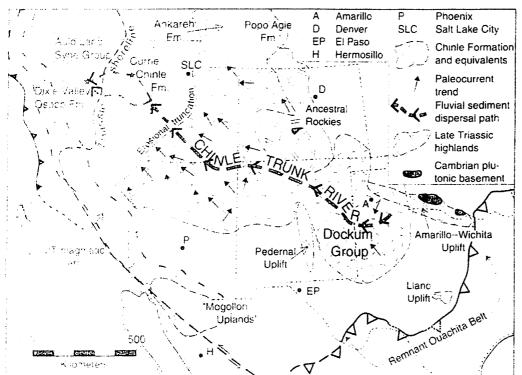


Fig. 1. Late Triassic paleogeographic map showing the proposed location of the Chinle-Dockum trunk river.

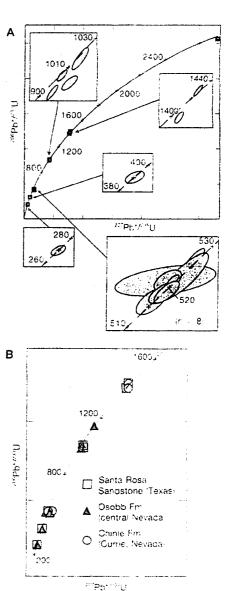


Fig. 2. (A) Concordia diagram showing zircon populations in the Santa Rosa Sandstone. Error ellipses are shown at the 95% confidence level. (B). Concordia diagram comparing congruent zircon populations of the Santa Rosa Sandstone (Dockum Group, Texas), Chinle Formation (Currie, Nevada), and Osobb Formation (Auld Lang Syne Group, Dixie Valley, Nevada).

Ai)

Steam Order

Is that a 10th order stream, or are you just happy to see me?

Brian Jackson

Stream order is a classification system for fluvial network systems which assigns a number to a particular channel based upon its topologic relationship to the stream network. Figure 1 illustrates the three main stream ordering systems (taken from Scheidigger 1970).

The actual evolution of a stream network is very complicated and involves a complex interplay between sediment transport and deposition and local geologic controls, leading to an essentially random process. However, this randomness allows us to formulate relationships between stream parameters which apply on average to all streams.

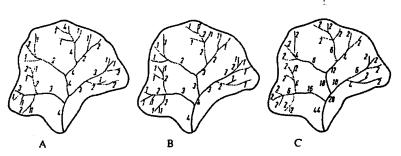


Figure 1: Illustration of stream order methods. (A) is Horton's, (B) is Strahler's (most commonly used), and (C) is Scheidigger's.

Law of Stream Numbers

Let n_i be the number of stream segments of order i in a stream network (using either of the last two ordering systems). Then, empirically:

$$n_{i+1} = \alpha n_i$$

where $1/\alpha$ is called the bifurcation ratio and is about 3.5 for stream networks in the USA (Scheidigger 1970).

Of course, the order assigned to a particular stream depends sensitively on the resolution of your stream map. Low resolution maps may be unable to resolve small, low-order streams, and so the assigned order for the largest streams will be underestimated. However, any systematic offset in stream ordering will not affect the resultant bifurcation ratio.

To get a sense of the range of stream orders, note that the Amazon River, the world's largest river, is a 12^{th} order stream (Kreger 2004), and the Mississippi River is a 10^{th} order stream. However, the majority of terrestrial streams are 1^{st} or 2^{nd} order (Wikipedia). A closely related stream parameter is drainage density, d, which is defined as the average length of stream segments per unit area. Typically mature drainage basins on Earth have stream order > 5 and d > 6×10^{-2} km⁻¹ (Hynek 2003).

The regularity of streams in this classification system seems to be a robust feature of the self-similar, random nature of stream formation. (As an aside, most streams have

components which do not obey the above fractal laws. These streams are called "adventitious streams" and are often attributed simply to statistical variability (Beer and Borgas 1993).) Stream formation is apparently an allometric process, which means that the rate of growth of a stream scales as the size of the stream (Scheidigger 1970). Ideally, some relationship between stream order and stream origin exists (e.g. ground sapping stream networks could always be low order), but studies which attempt to relate stream order to stream origin or evolution have thus far been unsuccessful (Carr 1995). These limitations have not stopped scientists from applying stream order analysis to streams on Earth and other planets in an attempt to trace a stream's origin.

Planetary Connection

The figures below are maps of the simplified stream network of Salt River Canyon on Earth (Davis 1981), of a posited drainage basin on Titan as observed by the Huygens probe (Perron 2006), and of a drainage network on Mars as observed by the MOC spacecraft (Hynek 2003). The stream ordering law given above is surprisingly robust, even on other planets.

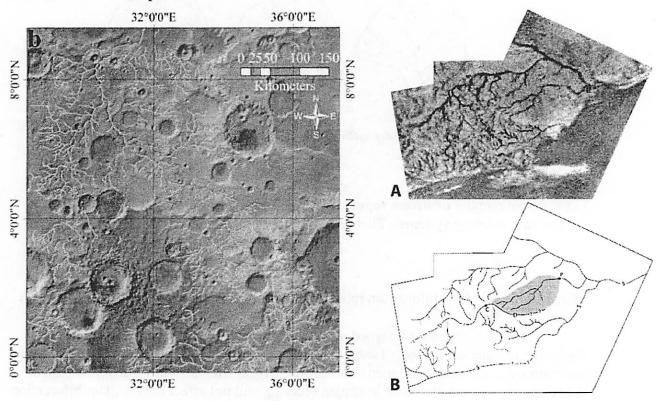


Figure 2: (Left) Martian drainage network in Arabia Terra region. The high stream order (6) suggests a mature drainage basin, indicative of sustained stream flow and possible of long term precipitation. (Right) Titanian drainage basin. Stream order is 4, but low resolution probably induces an underestimate.

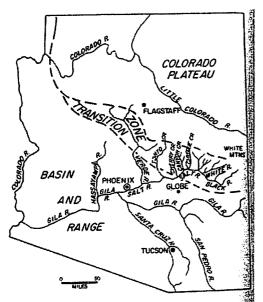


Figure 3: Salt River Canyon (SRC). Simplified map gives stream order 4 for Gila River System of which SRC is a tributary.

Table 1: Stream Order statistics for systems in figures above.

Stream Order	Titan (#)	n(i+1)/n(i)	SRC (#)	n(i+1)/n(i)	Mars (#)	n(i+1)/n(i)
1	105		22		61	
2	34	0.32381	9	0.409090909	17	0.278689
3	12	0.352941	4	0.44444444	7	0.411765
4	1	0.333333	1	0.25	2	0.285714
	avg. bif ratio	2.97005		2.718535469		3.073243

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Why do Rivers Meander? MANDY PR©CT©R

What is a meander?

- A meander is a bend in the river. The morphology of the meanders in a river evolve over time.
- A meander usually has a radius of curvature that is \sim 2-3 times the width of the channel.



Figure 1: Example of a meandering river.

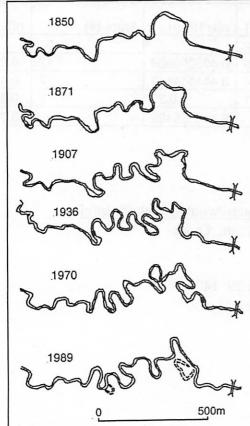


Figure 2: The evolution of the River Bollin. (from Hooke 2003)

How do meanders form?

Any irregularity in the river will result in a deflection of the flow to the opposite bank. This initiated the meander.

Meanders form as a result of erosion and deposition across the river.

- The water on the outer parts of the river flows faster. These fast flows cause erosion on the outer bank.
- The water on the inner part is traveling slower. This slow water cannot carry the same large load. Some of the material drops out of the water and you have deposition in those areas.

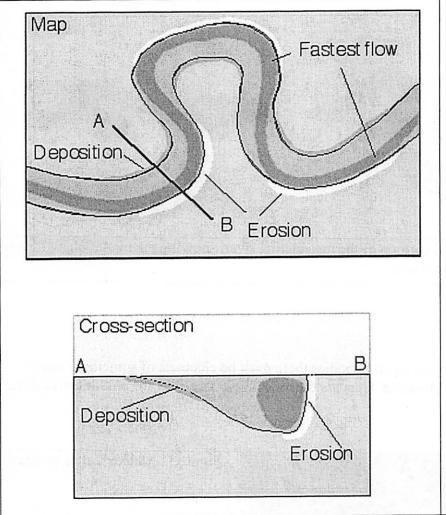


Figure 3: The darker parts of the river show the location of the fastest flow. The lighter water is slower.

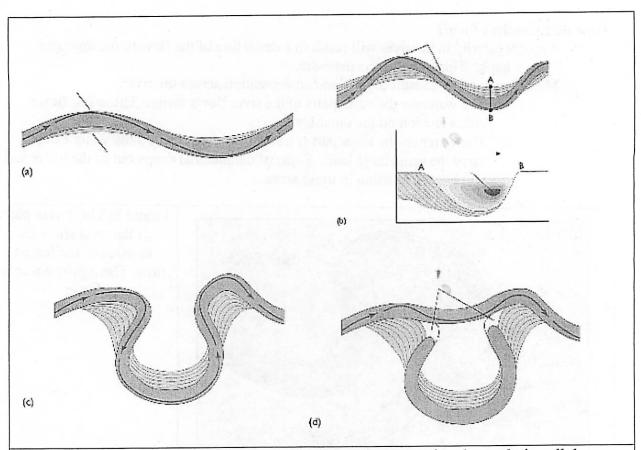
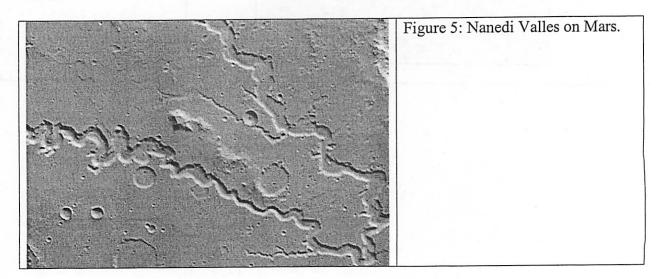


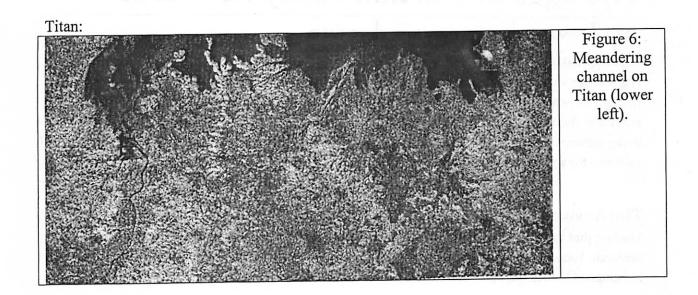
Figure 4: A more detailed cartoon of the meandering river, showing the evolution all the way to the creation of an oxbow lake.

Planetary Connection:

Obviously to have meanders on other bodies there must be channels of something liquid flowing on the surface. Mars and Titan are the most likely locations for possible meanders.

Mars:





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The ages of Martian valley networks

by Dong "Anonymous" Areher. Background

The Martian valley networks are a serious of features that have been assumed to be fluvial in origin (though there are some other theories out there, some more crackpottish than others). They are found entirely in the ancient, heavily-cratered terrain of the southern highlands and not in the Northern plains. Valley networks are important in the grand scheme of Mars research because they provide the strongest evidence for a warm and wet early Mars.

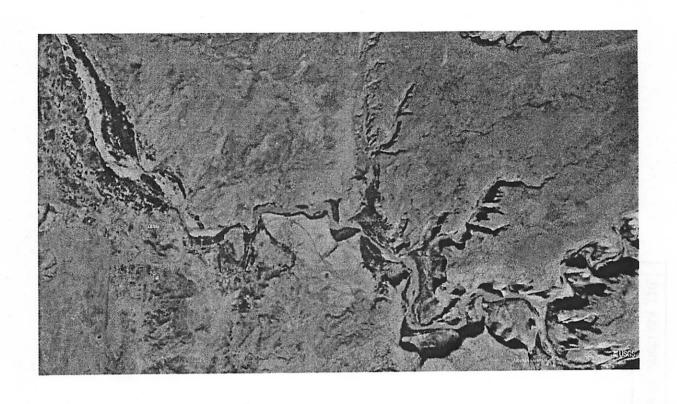
The Answer

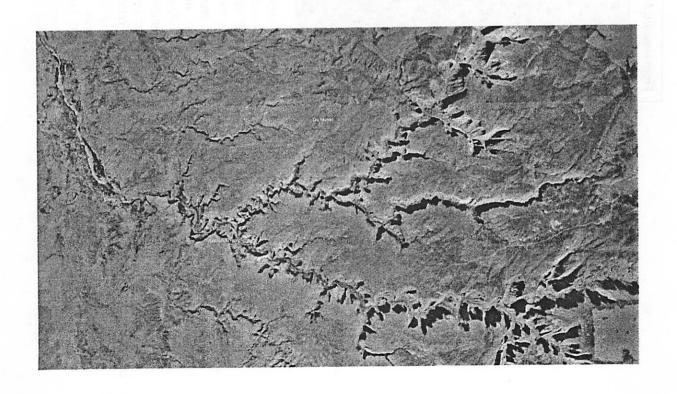
The fact that the valley networks are present in the southern highlands and not in the northern lowlands, superposition relationships, and crater counting place the age of these valley networks in the Noachian (4.5 - 3.5 Ga) up to as late as the mid-Hesperian $(\sim 2.5 \text{ Ga})$

Significance

I think that the age of the Martian valley networks is important primarily because it puts some constraints on the climate of early Mars. It seems absolutely necessary that Martian climate was significantly different during the formation of these channels than it is today. If the channels were formed by liquid water erosion, that has profound implications for Mars early cliamate.

Most people simply say that early Mars had a more massive CO2 atmosphere and would have had a correspondingly greater greenhouse effect. However, due to the faint early sun, the saturation vapor pressure of CO2 in the Martian atmosphere is lower than that required to maintain a global mean surface temperature much higher than 230 K (the present value is 210 K).





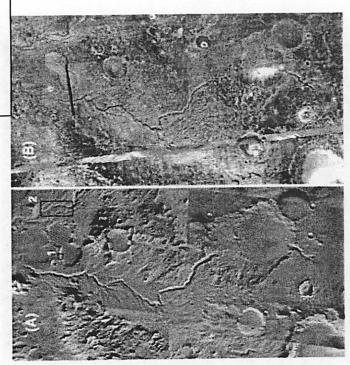


Figure 4. Incised channels and paleolake. (a) THEMIS daytime IR images overlain on MDIM 2.1 mosaic. Located at box 1 in Figure 2a. Image width 97.3 km. (b) THEMIS IR nighttime images of the same location. The valleys in the north end of the figure are interpreted to be incised into earlier alluvial basin deposits deposited at the foot of highlands bordering the basin (Figure 3b). Incised valley floors have low TI (dark in right image) due to eolian infilling, but upper rims and the dissected basin deposits are relatively bright, suggesting coarse sediment or indurated deposits. A double crater in the lower right has both entrance and exit breaches, suggesting that it was a paleolake. The valley system continues about 450 km upstream from the paleolake (Figure 9b). Box 1 shows location of Figure 6, and box 2 shows location of Figure 8.

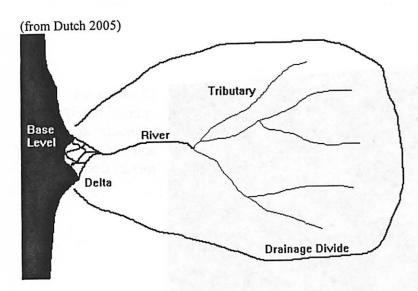


Figure 8. Inner channel within incised valley. Located at box 2 in Figure 4. A portion of THEMIS VIS image V03442003. Image width about 8.96 km.

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Fluvial Systems on Earth and Titan—Nicole Baugh

At its most basic description, a fluvial system, or drainage basin, consists of three parts: a collecting system, a main channel and a dispersing system:

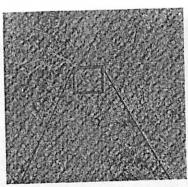


Drainage Divide: A topographical high that separates systems

Base Level: Lake, ocean or dry basin into which the system empties

The collecting system consists of tributaries that direct the flow of fluid and sediment into the main channel. Each tributary typically has its own, smaller set of feeders (Jackson, this work). Images of Earth reveal that most of the land surface is on some scale part of a drainage basin.

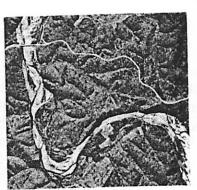
(from Hamblin and Christiansen 1998)



(A) A Landsat image of an area in Ohio shows the regional patterns of a river system and its valleys.



tributary regions of the large streams.



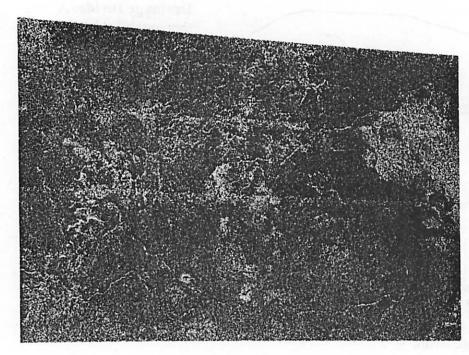
(B) A high-altitude photograph of a portion (C) A low-altitude aerial photograph of part of the area shown in (A) reveals an intricate of the area shown in (B) reveals many smaller network of streams and valleys within the streams and valleys in the drainage system.

The main channel's primary function is of transportation, although collection and deposition (Bland, Proctor, this work) of fluid and sediment do occur.

The dispersing system produces different landforms depending on where the river empties, but common features are deltas, with their distributary networks, and alluvial fans.

Fluvial Features on Titan

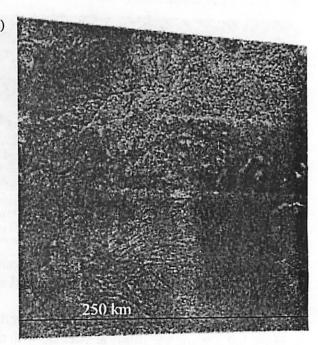
Cassini RADAR images show what appear to be fluvial features on the surface: (NASA/JPL)

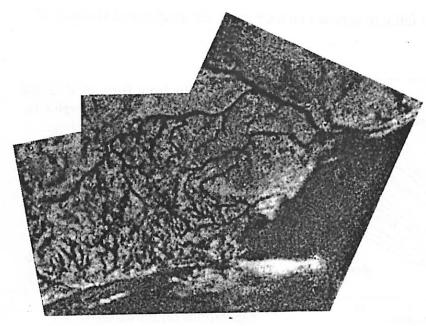


Channels are approximately one kilometer across, and perhaps 200 meters deep

(NASA/JPL)

These channels vary in width and form both branching and radial networks, perhaps suggesting formation by rainfall.





Huygens probe images show what appear to be fluvial systems, with evidence of smaller-scale channels than can be seen in RADAR data.

Fluvial systems on Earth carry water and silicate sediments. The same is more or less true for systems on Mars, with the sediments being more basaltic and less granitic. On Titan, however, the apparent fluvial system must consist of something radically different: Solid ice sediments carried by liquid methane.

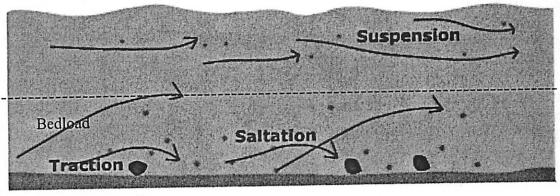
Relevant Parameters for Earth

Quartz, ρ =2650 kg/m³ Water, ρ =1000 kg/m³ Water, ν =1 x 10³ Pa s g=9.8 m/s

Relevant Parameters for Titan

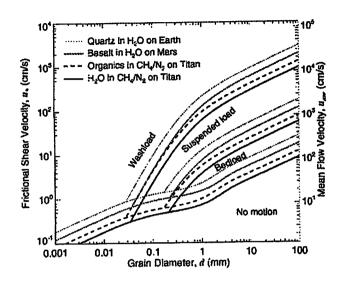
Ice, ρ =992 kg/m³ Methane, ρ =450 kg/m³ Methane, ν =2 x 10⁴ Pa s g=1.35m/s

Sediment transport is discussed in more detail elsewhere in this work (Kolb), but I'll summarize the relevant points here. In order for a particle to be moved by a fluid, a threshold shear stress, dependent on gravity, the relative densities of the materials and the flow velocity, must be reached. Once this condition is met, material may move as bedload or suspended load.



(from Ritter 2006)

Which category particulates fall into depends on their mass, the density and viscosity of the fluid and gravity.



These results from Burr, et al (2005) show that, for a given flow velocity, methane on Titan can carry larger sediments in each regime.

Results from the Huygens landing site images suggest a median particle size of 5 cm (Perron 2006)

Water interacts chemically with the material it flows over, substantially contributing to its erosive capabilities on Earth. Given ice's low solubility in liquid methane,

substantial chemical weathering is unlikely to occur on Titan. However, abrasion by bedload or suspended particles and mechanical erosion by surface runoff are both reasonable and have been proposed as mechanisms to form the features seen on Titan's surface.

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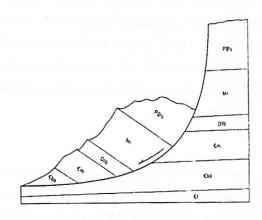
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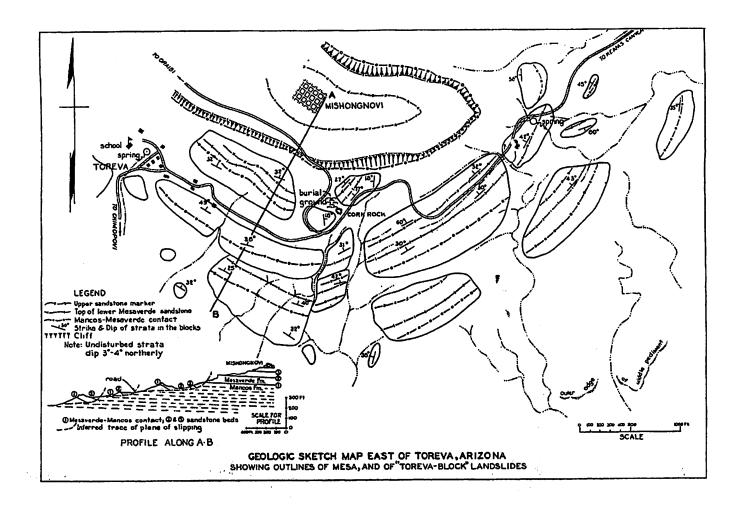
Toreva Blocks

J. Spitale



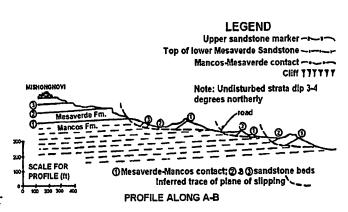
Toreva blocks, first studied by Reiche (1937) near the town of Toreva, AZ, typically occur in thick sedmentary sequences that sit atop weaker materials like shale. The weak layer, aided by pore pressure, may fail plastically, shearing along a log-spiral shaped rupture. The block remains intact, rotating backwards as it descends. Toreva blocks may be several hundred meters long and tens of meters thick. The failures at Toreva are attributed to the Mancos shale. Toreva blocks have been documented in many locales, including the grand canyon, the vermilion cliffs, and Antarctica. Toreva blocks also occur in calderas, where the plasticity is due to heat instead of water.





Large rotational landslides are observed throughout the solar system in complex craters. Because the yield strength of an ideal plastic material does not depend on the overburden pressure, crater depths on a particular body tend to be largely independent of crater diameter. A weak increase of depth with size may be due to a small coefficient of friction.

Toreva-like slumping is ubiquitous in the solar system, occuring in many settings where liquid water and volcanism cannot account for the plasticity of the underlying rock. Their cause in those cases is not understood.



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Coal Mining on the Black Mesa, and the Navajo and Mohave Generating Stations

Dave O'Brien

Coal Mining on the Black Mesa

In the early 1960s, Peabody Energy signed agreements with the Navajo and Hopi tribes to explore for coal on the Black Mesa in northeastern Arizona. Large deposits of coal were found, and commercial mining operations began several years later. Large-scale mining began in the 1970s, once two major power plants, using almost exclusively Black Mesa coal, came into operation. Coal lies near the surface of Black Mesa, and is extracted by strip mining.

There are two main mines on the Black Mesa, both operated by Peabody Energy—the Black Mesa Mine and the Kayenta Mine. The Kayenta Mine supplies coal via railroad to the Navajo Generating Station in Page, AZ. The Black Mesa Mine supplied coal via slurry pipeline to the Mohave Generating Station near Laughlin, NV. Both the Black Mesa mine and the Mohave power plant were closed at the end of 2005.

Mining provides many good-paying jobs for Navajo and Hopi, as well as revenue for the tribes, which is a significant boost to the economy of the reservations. At the same time, many Navajo and Hopi feel that mining is disrespectful to a sacred area (the Black Mesa), and/or that the tribes are not getting their fair share of the revenues from the mining operations. In addition, there are significant environmental problems resulting from the mining operations and associated power generation, which led to the indefinite suspension of operations at the Black Mesa mine and the Mohave Generating Station, as described below.

Power Generation from Black Mesa Coal

The Mohave Generating Station near Laughlin, NV, operated by Southern California Edison, is a 1580 MW plant primarily serving southern California, and also Arizona and Nevada. It was in operation from 1971 until the end of 2005. The Navajo Generating Station near Page, AZ is a 2250 MW plant operated by the Salt River Project. It came into operation in 1974 and is still running. Its largest customer is the U.S. Bureau of Reclamation, with a 24% share, and it also serves Arizona, Nevada and southern California. Tucson Electric Power Company purchases 7.5% of its power.

Environmental Issues

The Mohave Generating Station had the dubious distinction of being one of the most polluting power plants in the United States, and was blamed for a significant reduction in visibility and air quality in the Grand Canyon and throughout the Colorado Plateau region. In addition, the Black Mesa mine used a substantial amount of groundwater from the Navajo aquifer in order to convert coal to a slurry for transport by pipeline to the plant, enough to raise concerns that it was dropping the level of the aquifer. Lawsuits over these issues led to a suspension of operation of the mine and power plant at the end of 2005. In late 2006, the Salt River Project, a co-owner of the plant, announced plans to assemble a new ownership group and attempt restart the plant, but then gave up in February 2007. The future of the plant, and the Black Mesa mine, is unclear.

Coal from the Kayenta mine is transported via railroad to the Navajo Generating Station, and thus it is not as much of a drain on the Navajo aquifer as the Black Mesa Mine. However, it was not always one of the cleanest plants, and was the subject of lawsuits over air quality. In the 1990s, an agreement was reached to install new scrubbers that remove SO₂ as well as fly ash. The cost of this upgrade was \$420 million, nearly half of the original cost of construction. The Kayenta Mine and the Navajo Generating Station are currently still in operation.

Peabody Energy takes measures to reclaim the land that is disrupted by its strip mining operations, such that it can be used for grazing and farming, or as wildlife habitat. Peabody has received awards for it reclamation efforts, although tribal and environmental groups don't always agree that they are sufficient, especially since the mining and reclamation often transforms the original pinyon-juniper woodlands of the Black Mesa into grassland.

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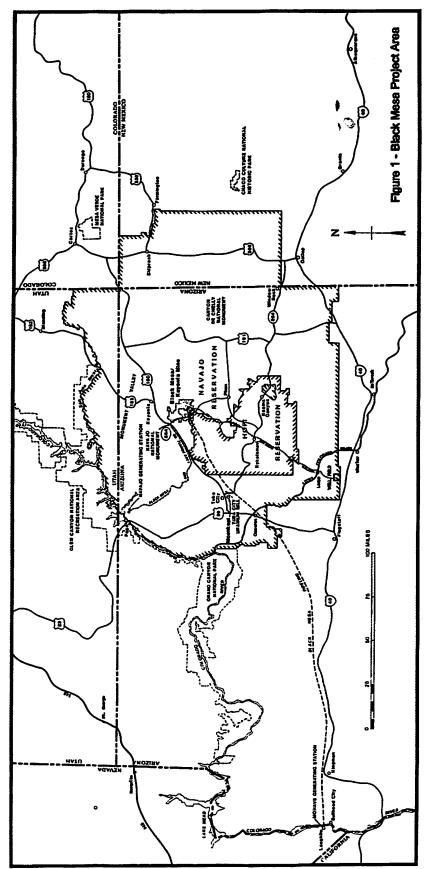
http://www.nps.gov/archive/nava/adhi/adhi8.htm

http://www.srpnet.com/about/stations/navajo.aspx

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http://www.wrcc.osmre.gov/WR/BlackMesaEIS.htm





From http://www.wrcc.osmre.gov/WR/BlackMesaElS.htm

Dinosaur Tracks!

Maria Banks

Dinosaur tracks are surprisingly abundant and provide rich sourcestof scientific information on dinosaur behavior, locomotion, foot anatomy, ecology, chronology, and geographic distributions.

Footprint Morphology:

The size, shape, and depth of the footprint tell us:

- -The size and shape of the dinosaur larger animals generally produce larger and deeper prints.
- -The nature of the dinosaur's locomotion increasing speed alters the angle of the print and the depth.
- -The nature of the substrate substrate particle size, moisture saturation
- -Within tracks of a herd, the number of large and small prints can tells us about age structures and size frequencies within populations.

Footprint Preservation: (See figure 1A and 1B)

- -Tells us about the environment in which the print was formed:
 - -The best preserved tracks were generally formed in wet ground along lake shorelines, in wetlands and swamps associated with coastal plains, in floodplain environments adjacent to rivers, and around ephemeral or playa lakes in arid or desert environments.
 - -Are generally formed in sandy, silty, or muddy sediments.
 - -Are formed during a period of deposition in which the print was quickly covered and protected from erosional processes.

Behavior:

- -herding or other social groupings
- -predator-prey relationships (hunting styles)
- -stampedeing
- -limping

Trackways (multiple tracks):

- -Can reconstruct the stance and posture of the animal as it moved: sprawling, semi-erect, fully erect.
- -Tells us if the dinosaur was bipedal or quadrupedal.

-Ex. Theropod trackways indicate that these animals walked on two legs with both feet passing under the middle of the body (fully erect and bipedal). See figure 2.

- -Trackways indicate the stride and pace of the dinosaur (see Figure 1C)
 - -The size and shape of the footprint can be used to estimate the hip height of the dinosaur (h) and, when combined with the stride length (l), can be used to estimate the speed at which the dinosaur was traveling:

l/h = relative stride

l/h < 2.0 = walking

l / h = 2.0 = trot

l/h > 2.9 = running

To estimate speed:

 $v = 0.25g^{-0.5} l^{1.67} h^{-1.17}$

where v=velocity, and g=gravity (*Alexander*, 1976). Top speeds estimated for large theropods: 10 - 15 m/s!!!!!

Describing Tracks (dinosaur identification):

-Number of toes

-Size of footprint

-Shape of footprint and toeprints

-relative arrangement of digits

- -Claw marks
- -Heel marks
- -Interdigital webbing
 - -Skin impressions



Brontopodus birdi Sauropod Trail Lower Cretaceous Glen Rose, Texas



Carirchnum sp. Omithopod Trail Lower Cretaceous. Grapevine, TX



Grallator
Theropod track
Lower Jurassic
Connecticut Valley, Mass.



Anchisauripus sp. theropod track Lower Jurassic, Connecticut Valley, Mass,



Eubrontes sp. camosaur track Lower Cretaceous Glen Rose, Texas

Dinosaurs tracks found in Northern Arizona were most likely formed by: Late Triassic:

Chinle Formation (e. g. Jacobs, 1980):

Saurischia

Theropoda

Ceratosauria

Prosauropoda

Ornithischia

Early Jurassic:

Moenave Formation (e. g. Morales, 1986):

Theropoda

Ornithischia

Kayenta Formation (e. g. Colbert, 1981):

Theropoda

Ceratosauria

Prosauropoda

Ornithischia

Ornithopoda

Thyreophora

Wingate Sandstone (e. g. Morales, 1996):

Theropoda

Navajo Sandstone (e. g. Camp, 1936):

Theropoda

Prosauropoda

Ornithopoda

Where you can see and learn more about dinosaur tracks in Arizona:

- -Glen Canyon National Recreation Area 520-645-6404
- -Museum of Northern Arizona 602-774-5211
- -Petrified Forest National Park 602-524-6228
- -Dinosaur Tracksite Mile Marker 316 Highway 160, Navajo Reservation Tuba City, AZ
- -Wuparki National Monument 602-556-7042.



Northern Arizona Theropod prints.

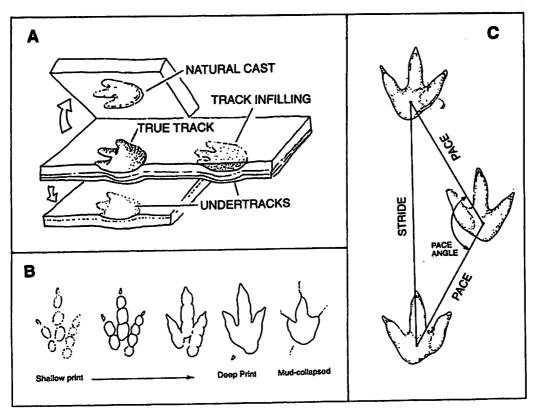


Figure 1.

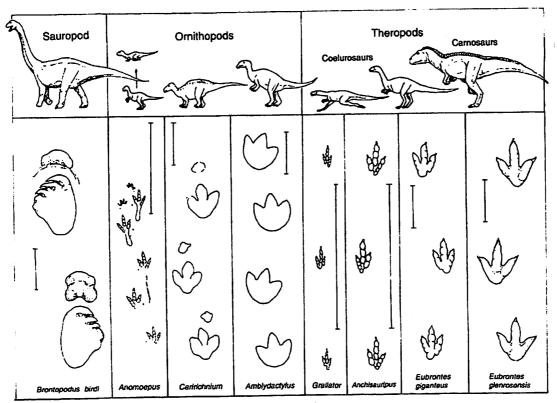


Figure 2. Common types of tracks and trackmaker groups.

Dinosaurs!

David A. Minton

Know your dinosaur

Dinosaurs are animals that evolved from the archosaurs in the mid Triassic period, and by the beginning of the Jurassic would become the dominant land animals on Earth [1]. The fossil record indicates that dinosaurs filled a wide variety of ecological niches throughout the Mesozoic, and their wide variety of sizes, shapes, and habits reflects this. There are two main dinosaur types, or clades, the Saurischia (meaning "lizard-hipped") and the Ornithischia (meaning "bird-hipped"). Within the Saurischia are two of the most recognizable dinosaur clades, the Theropoda and the Sauropodomorpha.

Modern computer-aided cladistic analysis has allowed paleontologists to construct a more-or-less complete family tree of dinosaurs, as shown in Fig. 4, but due to the incompleteness of the fossil record many phylogenetic relationships are unclear. Coelophysis is an early member of the clade Theropoda, and is one of the earliest dinosaur genera known in the fossil record [3]. It appeared in the Mid Triassic period (Late Carnian) roughly 225 million years ago [10], and may either be a member of the Ceratosauria clade or a member of an unknown basal therapod clade [3].

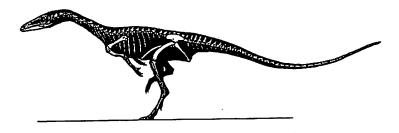


Figure 1: Coelophysis bauri, a Triassic theropod commonly found in the Chinle formation (approx 3 m in length) [9]

One of the most exciting areas of dinosaur research involves the relationship between birds and dinosaurs. The origin of birds has long been a controversy, and for many years it was unclear whether birds were part of the clade Therapoda or descended from an entirely separate reptilian lineage [6]. Based on several fossils that have been uncovered in Liaoning Province, China, in recent years of numerous feathered dromaeosaurids (the clade that includes *Velociraptor*) has lent support to the hypothesis that birds (Aves) are highly derived theropods (see Figs. 2 and 3) [4,5,12].

All non-avian dinosaur lineages went extinct when a carbonaceous asteroid impacted what is now the Yucatán Peninsula [2,8]. The atmospheric thermal pulse due to the impact would have broiled anything on land that could not shelter underground or under shallow water [7].



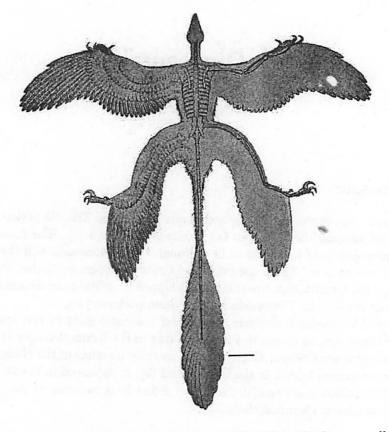


Figure 2: Microraptor gui, a Jurrasic dromaeosaurid with flight feathers on all four limbs [12]

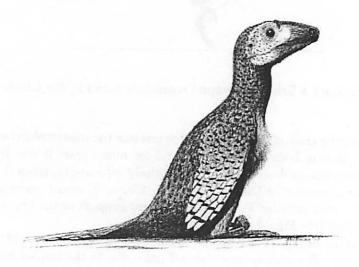


Figure 3: Deinonychus antirrhopus with feathers [9]. Recognize this dinosaur?



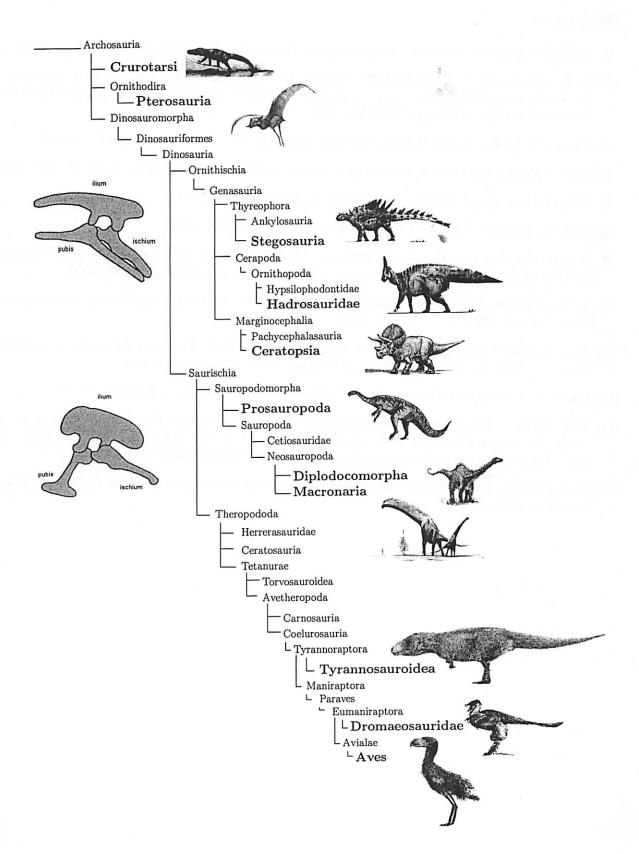


Figure 4: A simplified Archosaur cladogram [11]. Bolded clades have a life-restoration drawing as an example of a typical specimen [9].

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