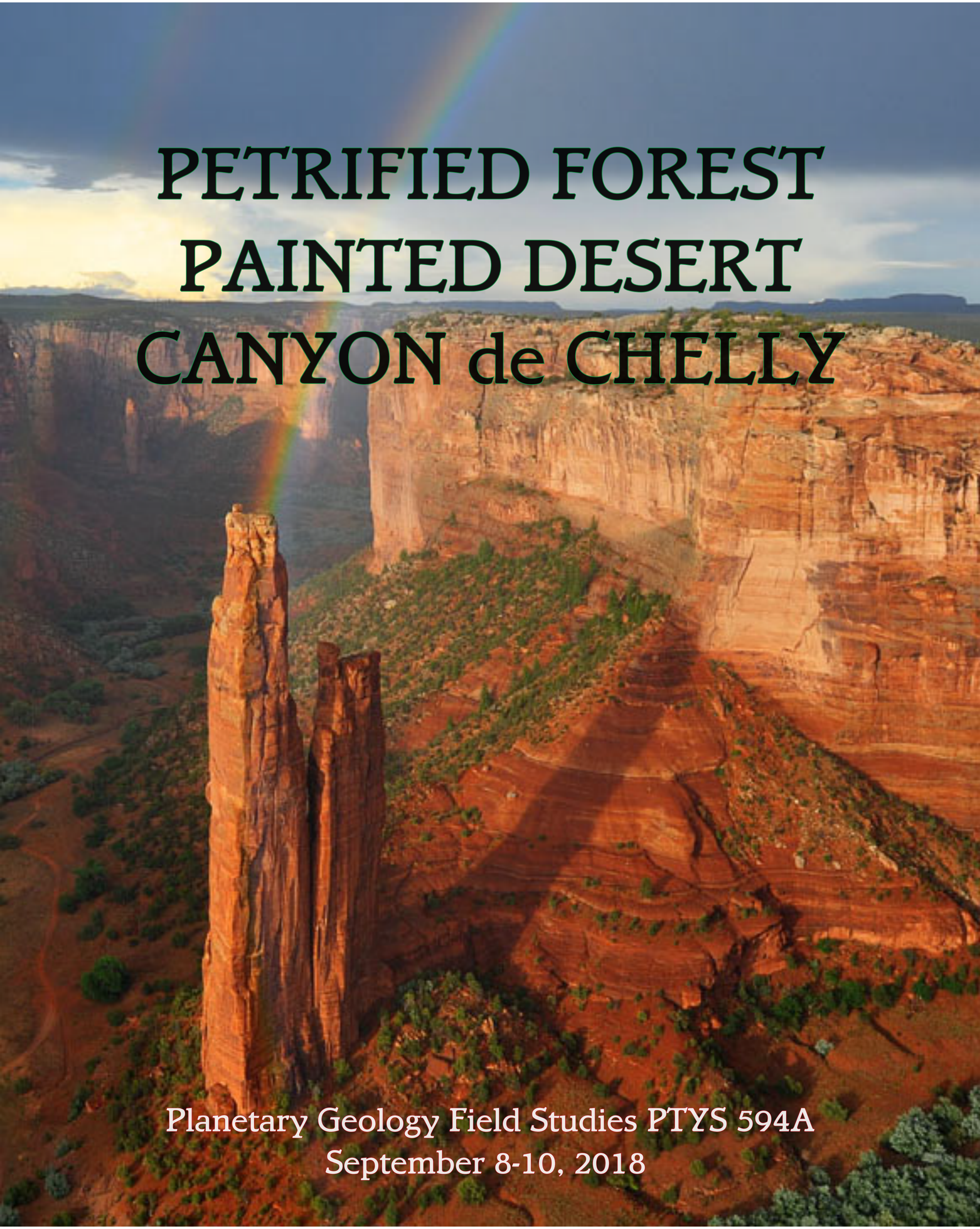
PETRIFIED FOREST
PAINTED DESERT
CANYON de CHELLY



Planetary Geology Field Studies PTYS 594A
September 8-10, 2018

Letter from the Editor

Perhaps we should call this field trip “Triassic Parks”, as we’re visiting three parks with significant geology from the Triassic period and earlier (particularly Permian-period De Chelly sandstone). As we drive and walk over modern “cold” deserts, recall the climate during the Permian was similar to what the Sahara Desert is like now, and that formations from the Triassic period represented a wetter climate. This trip provides opportunities to understand the processes responsible for forming the different rocks of these periods.

While the primary focus of this trip is sedimentary geology and the history of aeolian/fluvial processes in the area, there are also some interesting tectonic and volcanic processes responsible for shaping the region. From the northern overlooks of the Painted Desert look for the Hopi Butte Volcanic Field, one of the largest concentrations of maar landforms in the world.

Since the end of the last major ice age 13,000 years ago, these regions been home to significant human history. Farming began in the Painted Desert around 150 BCE. Ancestral Puebloans (or Hisatsinom, to the Hopi) lived in these areas from the 700s until the late 1200s CE. The Ancestral Puebloans eventually moved onward, but their descendents, including the Hopi and Zuni, still live in the region, along with the Navajo, whose ancestors arrived in the area around 1400 CE.

Hopefully on this trip we’ll learn some natural and human history, and also develop some intuition for geological processes along the way.

Rock on!

Sondy

PS: Same as for the Mojave/Death Valley field trip, **ALL TIMES IN THIS FIELD GUIDE ARE IN MOUNTAIN STANDARD TIME (MST)**, the same timezone as Tucson. DO NOT CHANGE CLOCKS TO MOUNTAIN DAYLIGHT TIME (MDT), the same timezone as the Navajo Nation. If your phone automatically changes timezones, turn that feature off for the trip.

Field trip logo by James Tuttle Keane

Cover photo by flickr.com/tsaiproject

Table of Contents

This page intentionally left blank

Saturday, September 8 (all times in MST)

7:00 am:	Meet at the LPL loading dock
8:00 am:	Depart for the Petrified Forest
1:00 pm:	Arrive at the Petrified Forest (South Entrance) and have lunch
2:00 pm–4:00 pm:	Hiking with park rangers and delivering three presentations
4:00 pm:	Depart for Chinle
6:00 pm:	Arrive at the Cottonwood Campground in Chinle, dinner, and three presentations

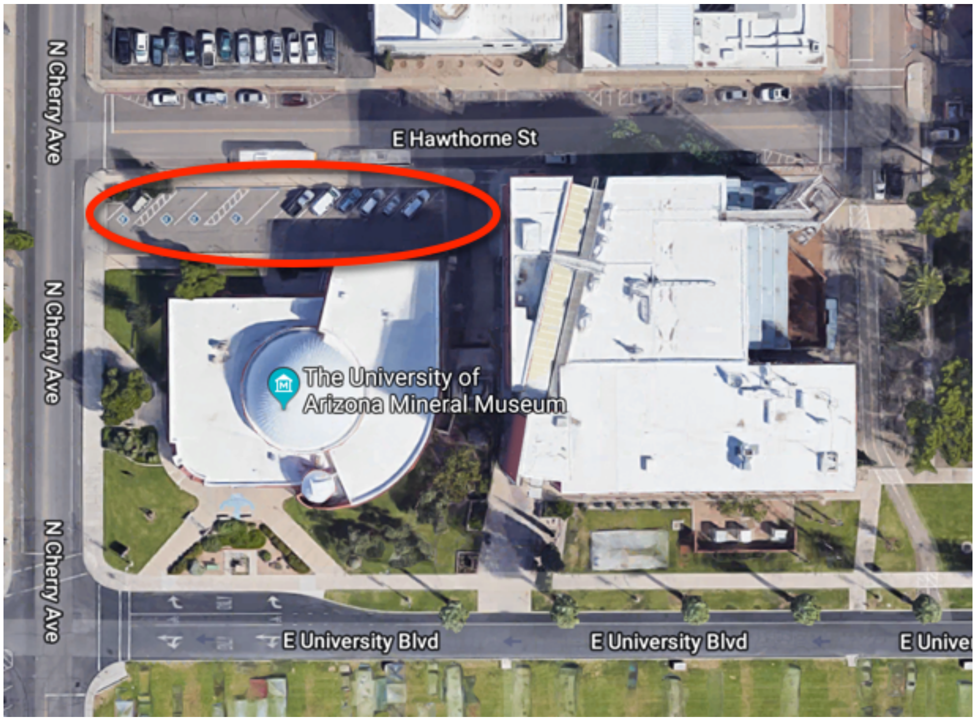
Sunday, September 9

6:00 am:	Wake up
7:00 am:	Meet at the visitor's center
8:00 am–5:00 pm:	Hiking with park rangers, delivering six presentations, and helping with maintenance
5:00 pm:	Return to camp, prepare dinner, and three presentations

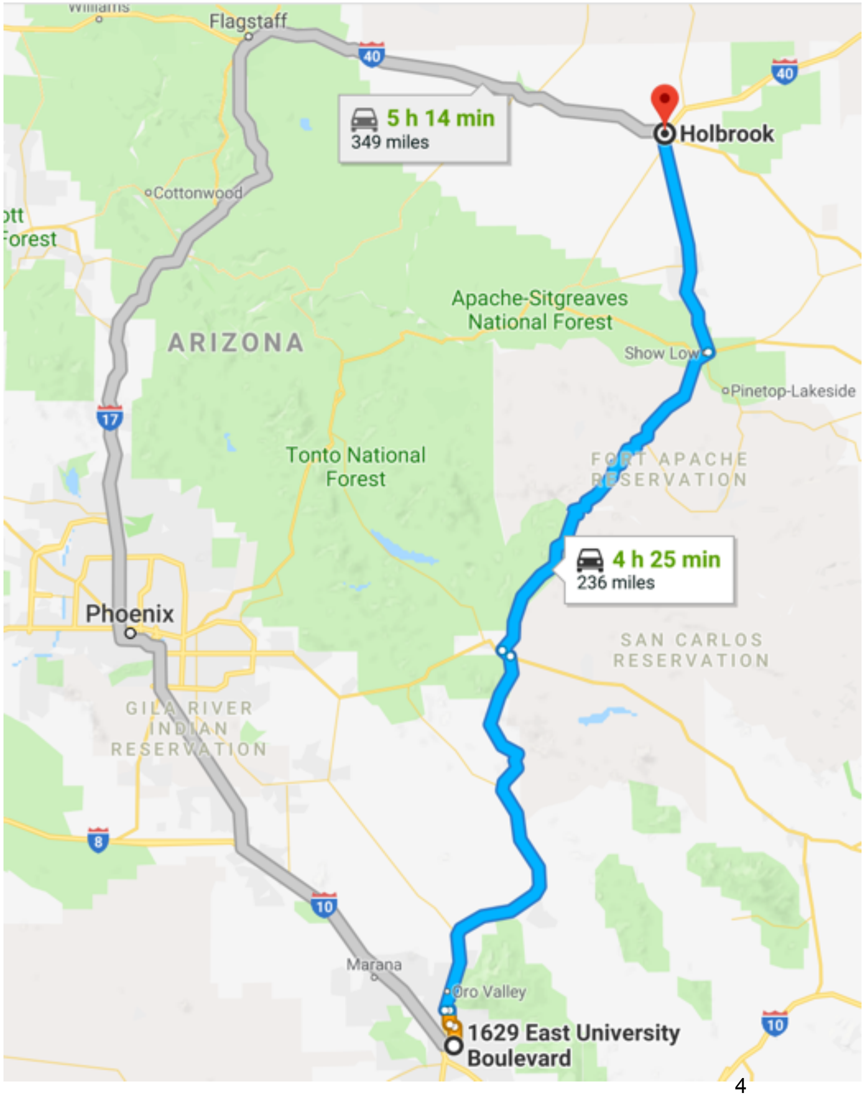
Monday, September 10

6:00 am:	Wake up and decamp
7:30 am	Departure for overlooks
8:00 am–12:00 pm:	Four presentations at overlooks
12:00 pm:	Depart for Tucson

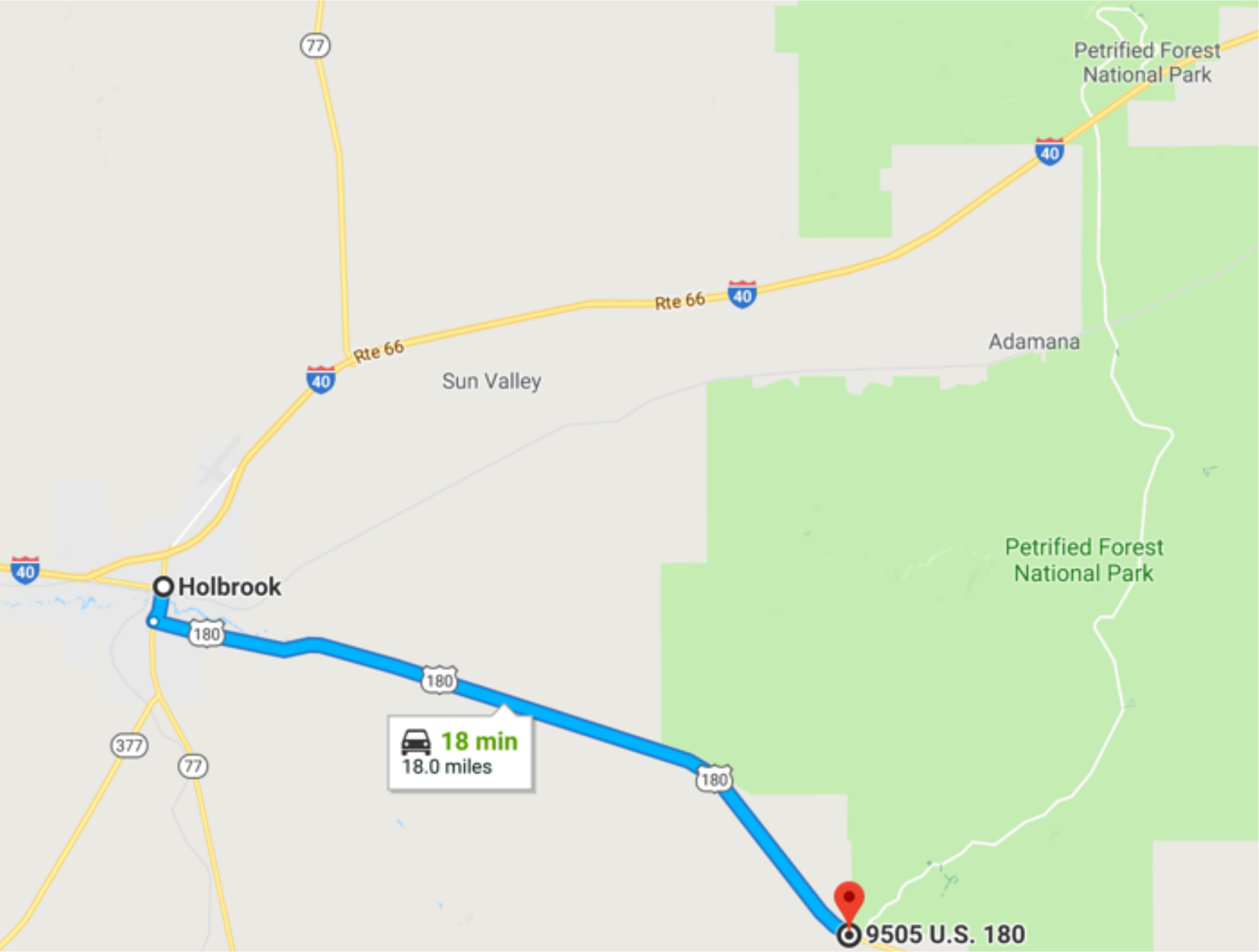
Saturday, September 8, 7:00 am: Meeting Location at LPL (Loading Dock, Departure at 8:00 am)



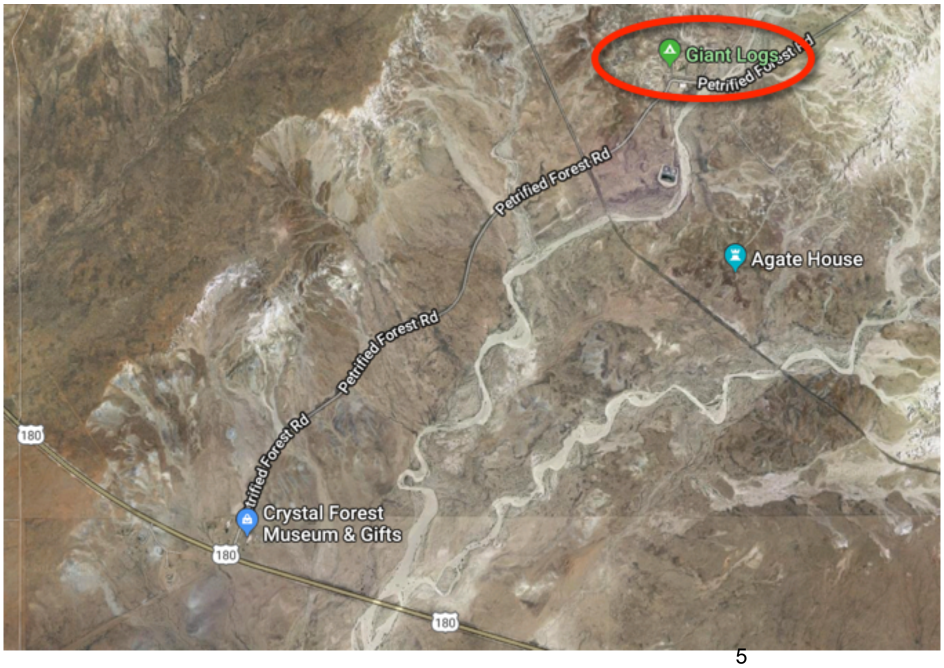
Initial Destination: Holbrook, Arizona (Estimated Arrival: 12:30 pm)



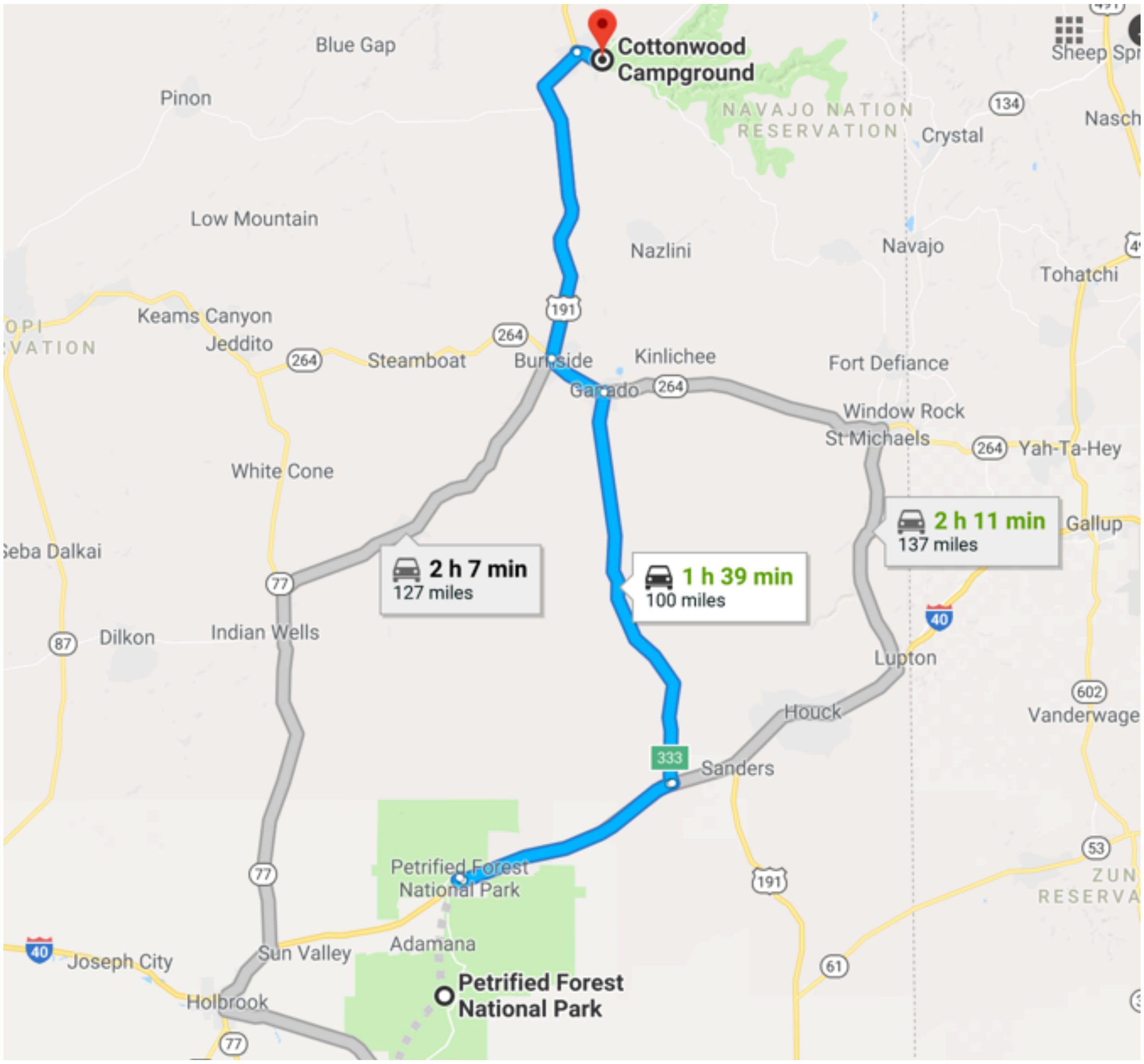
Petrified Forest National Park, South Entrance (Estimated Arrival: 1:00 pm)



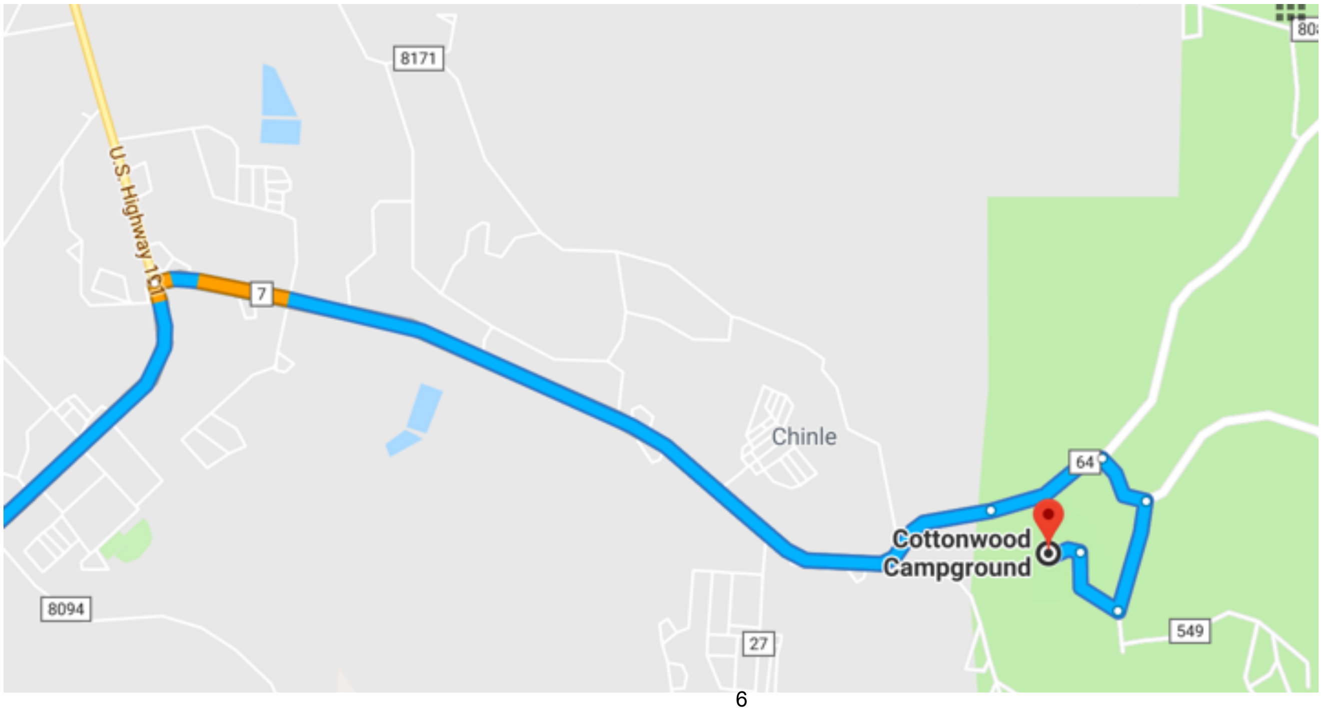
Lunch Stop at Giant Logs.



Depart Petrified Forest, North Entrance, at 4:00 pm and travel to the Cottonwood Campground, Chinle. (Estimated Arrival 6:00 pm)

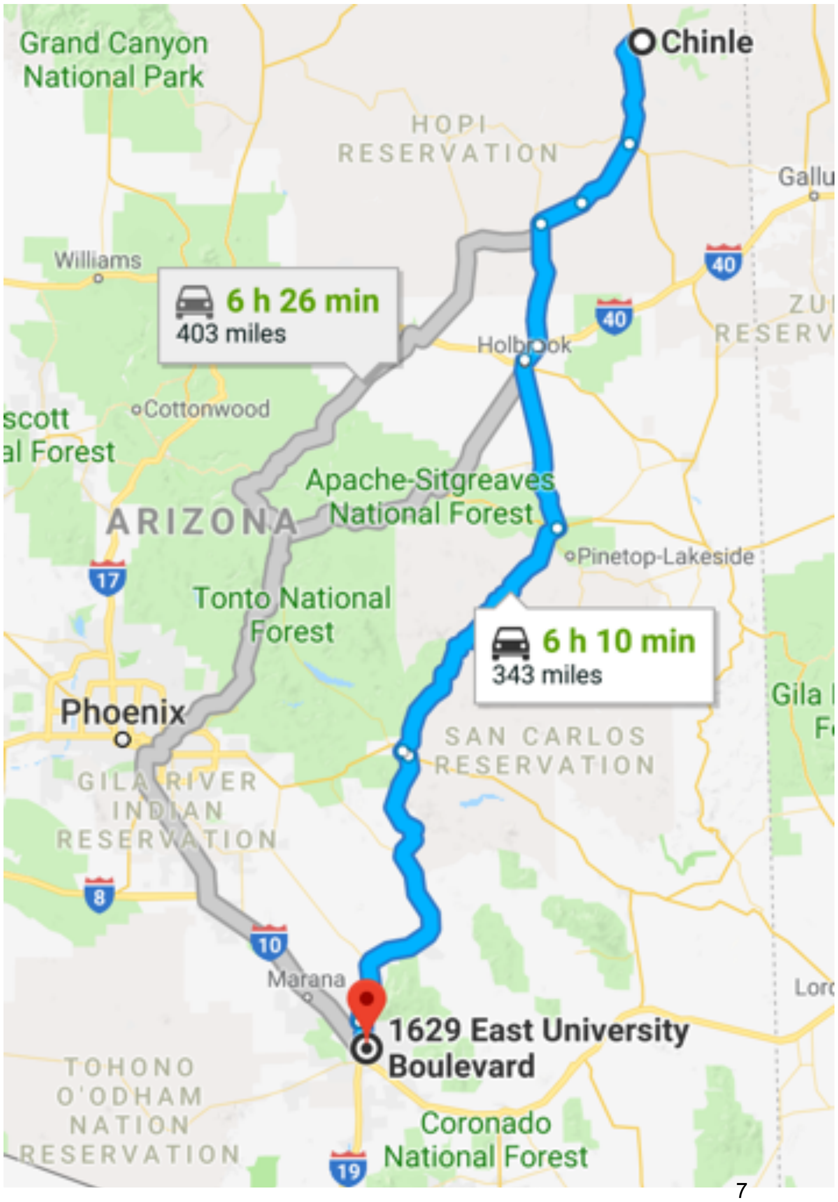


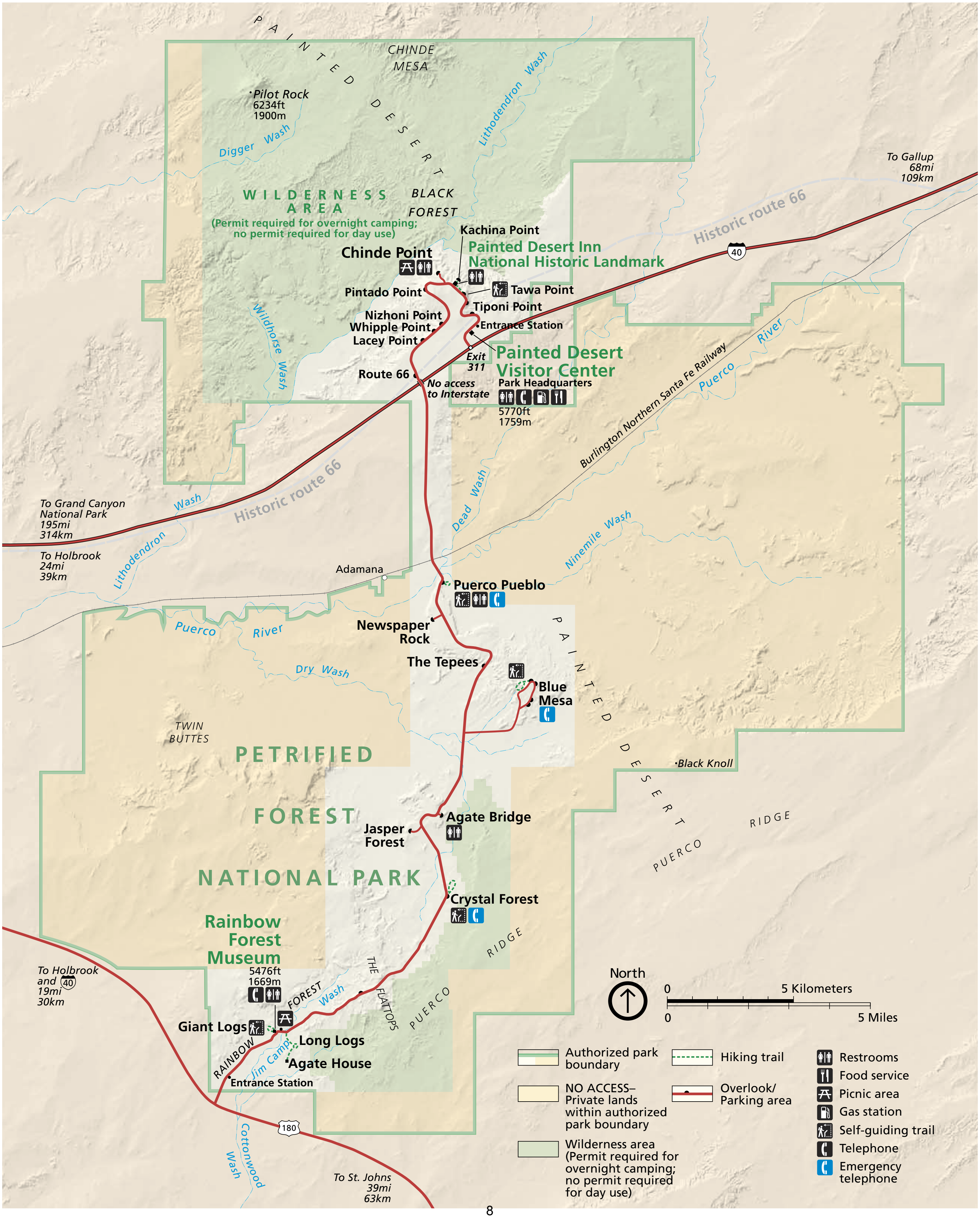
Campsite Location.

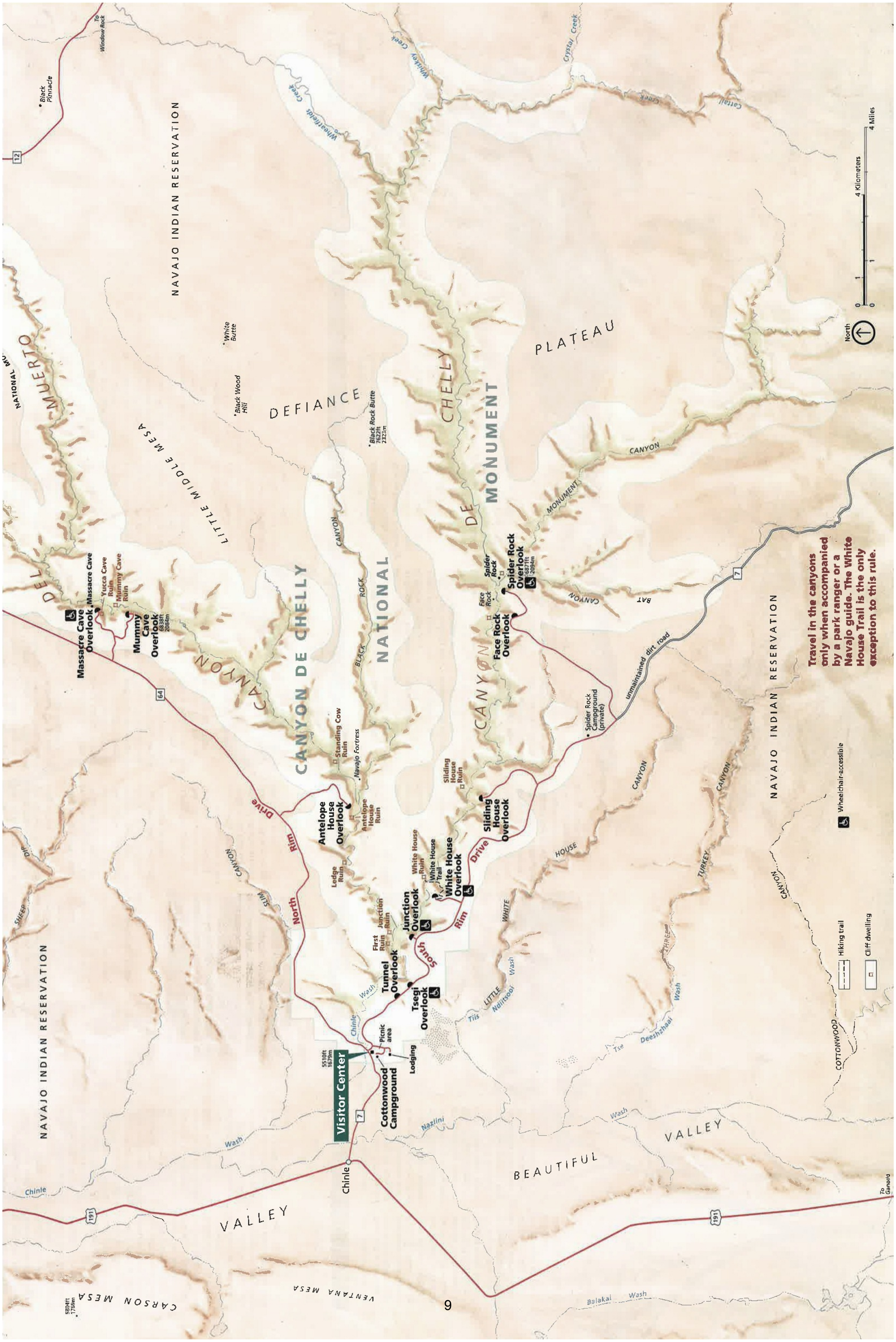


Campsite Location.

Return route from Chinle to Tucson. (Depart Chinle at 12:00 pm, arrive in Tucson before 8:00 pm).

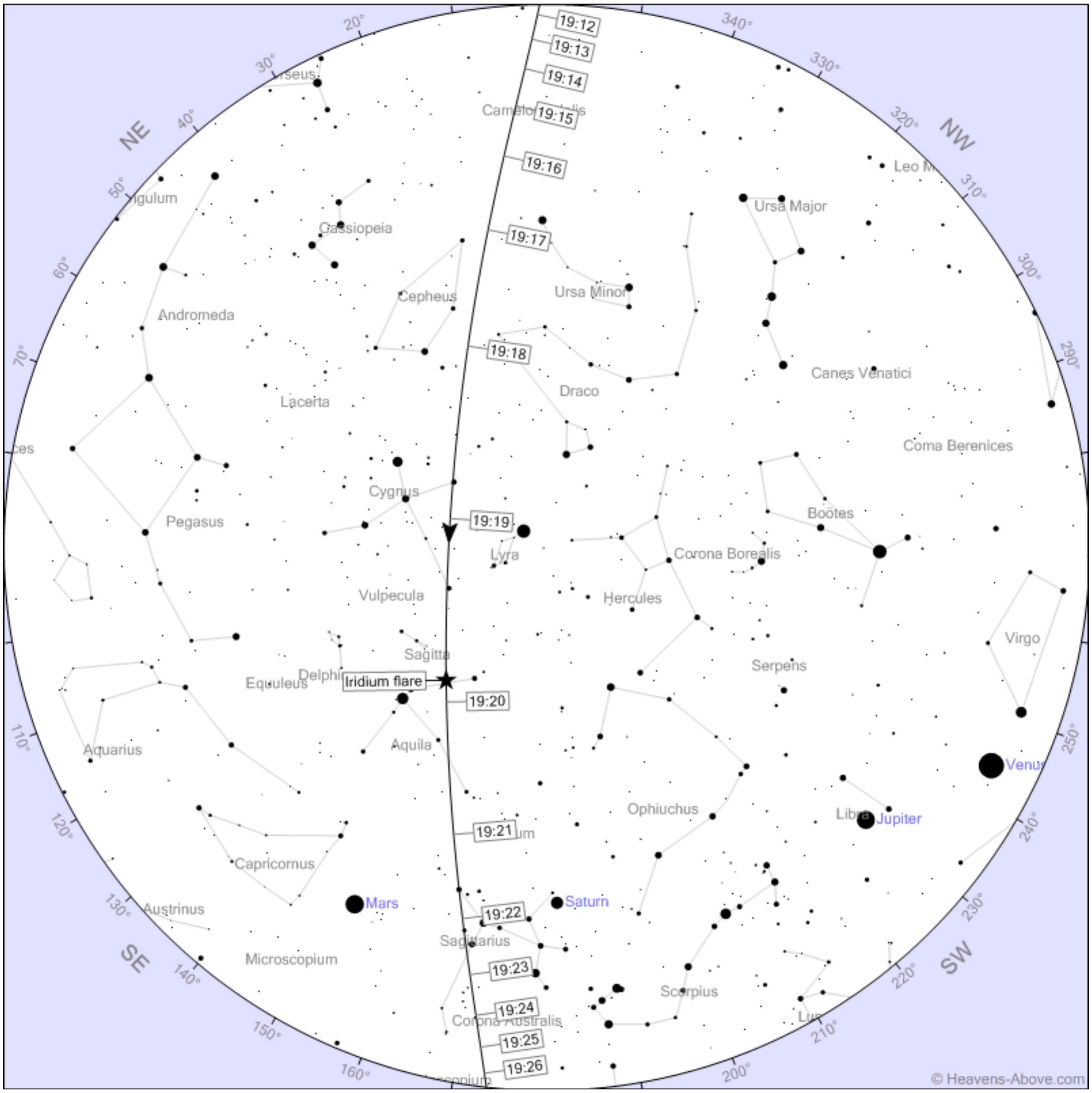



PAINTED DESERT
CHINDE MESA
Pilot Rock
6234ft
1900m
Digger Wash
Lithodendron Wash
WILDERNESS AREA
(Permit required for overnight camping; no permit required for day use)
BLACK FOREST
Kachina Point
Painted Desert Inn
National Historic Landmark
Chinde Point
Pintado Point
Tawa Point
Tiponi Point
Nizhoni Point
Whipple Point
Lacey Point
Entrance Station
Painted Desert Visitor Center
Park Headquarters
5770ft
1759m
Exit 311
No access to Interstate
Route 66
Wildhorse Wash
To Gallup
68mi
109km
Historic route 66
40
Burlington Northern Santa Fe Railway
Puerco River
To Grand Canyon National Park
195mi
314km
Wash
Historic route 66
Dead Wash
To Holbrook
24mi
39km
Lithodendron Wash
Adamana
Ninemile Wash
Puerco Pueblo
Puerco River
Newspaper Rock
Dry Wash
The Tepees
PAINTED DESERT
Blue Mesa
TWIN BUTTES
PETRIFIED FOREST NATIONAL PARK
Black Knoll
Agate Bridge
Jasper Forest
PUERCO RIDGE
Crystal Forest
RIDGE
Rainbow Forest Museum
5476ft
1669m
To Holbrook and 40
19mi
30km
FOREST Wash
THE FLATTOPS
PUERCO
Giant Logs
Long Logs
RAINBOW
Jim Camp Wash
Agate House
Entrance Station
180
Cottonwood Wash
To St. Johns
39mi
63km
North
0
5 Kilometers
0
5 Miles
Authorized park boundary
NO ACCESS–Private lands within authorized park boundary
Wilderness area (Permit required for overnight camping; no permit required for day use)
Hiking trail
Overlook/Parking area
Restrooms
Food service
Picnic area
Gas station
Self-guiding trail
Telephone
Emergency telephone



Travel in the canyons only when accompanied by a park ranger or a Navajo guide. The White House Trail is the only exception to this rule.

Iridium Flare September 9, around 19:19 MST (20:19 MDT)



Flare Details			
Date:	09 September 2018	Distance to satellite:	867 km
Time:	19:19:52	Angle off flare centre-line:	1.2°
Brightness:	-2	Distance to flare centre:	20 km
Altitude:	62°	Flare producing antenna:	right
Azimuth:	143°	Sun altitude:	-9.9°
Satellite:	Iridium 45	Angular separation from Sun:	120.3°

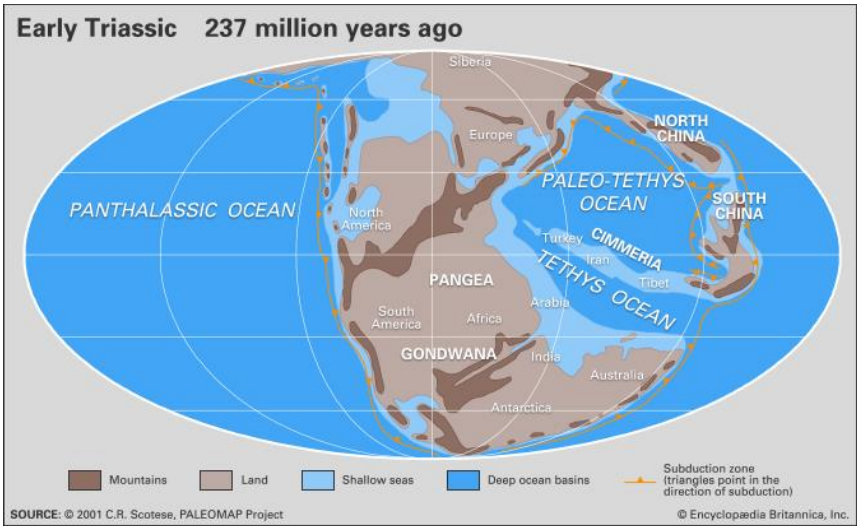
(Source: Heavens-Above.com; Location: Cottonwood Campground, Chinle)

Triassic Climate, Flora, and Fauna: Petrified Forest

Laci Brock

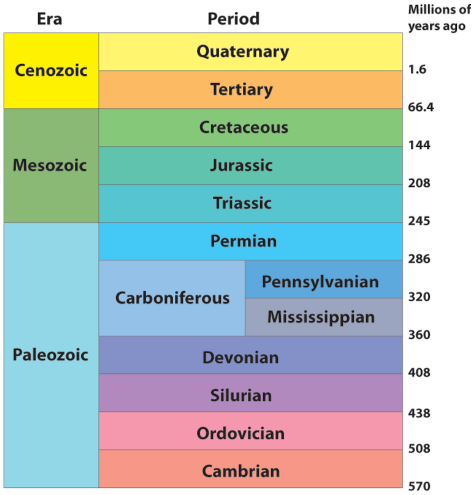
PTYS 594A Fall 2018

Triassic Period (251.9-201.3 Mya)



SOURCE: © 2001 C.R. Scotese, PALEOMAP Project

© Encyclopædia Britannica, Inc.



Era	Period		Millions of years ago
Cenozoic	Quaternary		1.6
	Tertiary		66.4
Mesozoic	Cretaceous		144
	Jurassic		208
	Triassic		245
Paleozoic	Permian		286
	Carboniferous	Pennsylvanian	320
		Mississippian	360
	Devonian		408
	Silurian		438
	Ordovician		508
	Cambrian		570

Quick Facts

- Spanned 50.6 million years from end of Permian to beginning of Jurassic Period
- Flora and fauna are recovering from a mass extinction
- Tectonic plates arranged into supercontinent Pangea
- First dinosaurs appeared during this period
- Period generally hot and dry; no polar ice
- Maximum intensity of Pangean megamonsoon

Climate

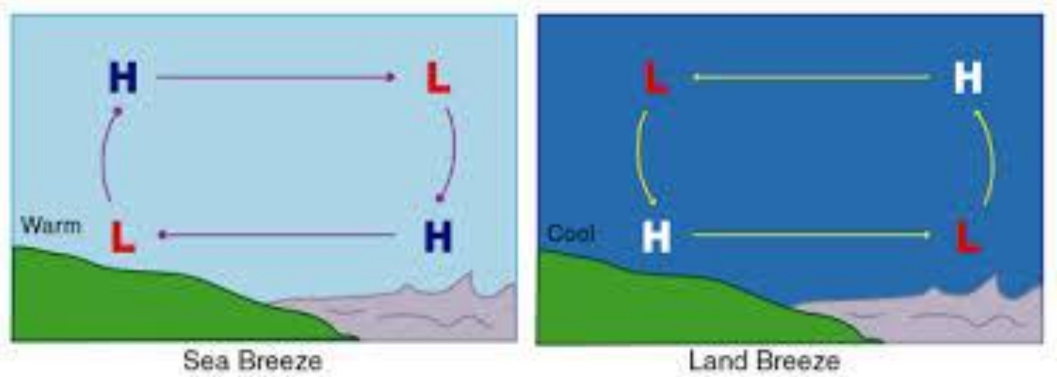
Generally, the climate during the Triassic was hot and dry in interior Pangea. The coastal regions were more tropical in nature with increased rainfall. The poles were moister and more temperate. The large contrast between these climate patterns was partially induced by the structure of the supercontinent and global ocean. This limited the regulating nature of the thermohaline circulation. These large-scale sea breezes form when the temperature on land is different in temperature (warmer or cooler) than the ocean temperature.

Pangean Megamonsoon

Aeolian sand dunes are direct proxies for paleowinds on Earth's surface. As dunes form and migrate, this provides insight to the atmospheric circulation at the time. Most aeolian-deposited sand occurred on the Colorado Plateau during the Triassic. Deposited sediments reflected strong monsoonal wind patterns in the region.

Monsoons are created by thermal differences between continental and oceanic temperatures. Continents heat up more quickly than ocean waters in the summer. This causes convection of warm air above land. Humid, dense air over the cooler ocean waters flows toward the areas of lower pressure over land. Latent heat release powers these convection cells. These localized changing land-sea breeze circulations can cause a reversal of the winds on larger, even global, scales. The Coriolis force near the equator is weaker and permits the reversal of wind direction to occur.

Example of Land-Sea Breezes



The geologic record suggests during the Early Permian as well as the Pennsylvanian-Middle Jurassic that winds blew towards the southeast, southwest, south, or southeast. During the Triassic, however, winds shifted toward the northeast (all present day coordinates). This counterclockwise shift suggests evidence of a monsoonal climate pattern during the Triassic. It is to be noted there is still some debate in the literature whether the monsoon was truly a "megamonsoon" stretching across the globe or a localized phenomenon.

Flora and Fauna

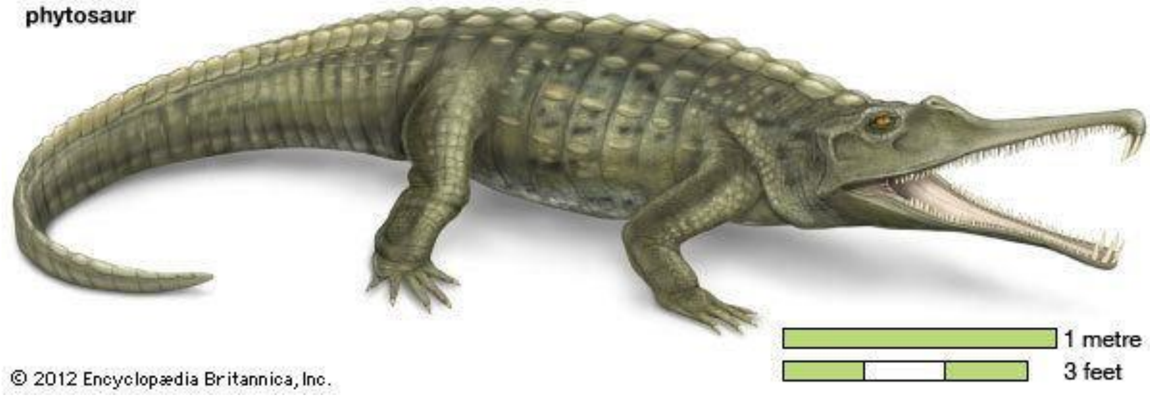
252 million years ago the Permian-Triassic Extinction destroyed 96% of marine species and 70% of terrestrial vertebrates. It is the only known mass extinction of insects. This event significantly altered both the plant and animal dominant species of the time. The cause has been most likely attributed to a series of events rather than a cataclysmic event (e.g., impact).

Though the exact cause is still debated, possible explanations include increased volcanism (Siberian Traps), sea level change, anoxia of the oceans, and climate change.

Petrified Wood and Plants

Arizona was a forest during the Triassic and its remains are preserved now as the Petrified Forest. The forest is mainly the species ***Araucarioxylon arizonicum.*** This is an extinct species of conifer (and state fossil of Arizona) with massive tree trunks and could reach heights of 60 meters. The petrified wood often called “rainbow wood” due to its colors. Nine different species of fossilized tree have been discovered, but all are extinct. Over 40 different forms of fossil plants have been collected within the Petrified Forest such as cones, seeds, leaf impressions, ferns, cycads, and horsetails.

Triassic animals found in the area include several reptilian and amphibian-like species (next page), early dinosaurs, and freshwater snails and clams. The dinosaurs in the area were some of the first dinosaur species, so they were mostly small and bipedal creatures like Coelophysis (below).



References

Blumberg, D. G., and Greeley, R. (1996). A comparison of general circulation model predictions to sand drift and dune orientations. J. Clim 9: 3248.

Dubiel, R. et al. (1991). The Pangaean Megamonsoon-Evidence from the Upper Triassic Chinle Formation, Colorado Plateau. USGS Staff.

Wikipedia, USGS, and various other websites

Petrification

Daniel Lo

Introduction

A fossil is any preserved remains, impression or trace of any once-living thing from a past geological age. Also called petrifaction, petrification is one of the four modes of fossil preservation, and preserves the most amount of paleobiological information. Petrification involves the permeation of cells and interstices (permineralization) or the replacement of the original organic matter by minerals in typically anoxic environments. The lack of oxygen prevents decomposition, and petrification can create replicas of the original specimen that are similar down to the microscopic level. The high degree of resemblance of petrified samples to the original specimens has been a source of fascination over human history, and has inspired many myths and legends across cultures around the world.

Permineralization


Petrified log at Petrified Forest National Park (credit: pdphoto.org)

One of the earliest scientific explanations for permineralization was advanced by Charles A. White in 1893, who coined the word “histometabasis” to describe “that condition of fossilization in which an entire exchange of the original substance for another has occurred in such a manner as to retain or reproduce the minute and even the microscopic texture of the original”. He suggested that petrified plant matter was formed through “destructive decomposition, molecule by molecule, of the woody tissues and their immediate replacement by precipitated molecules of the silex held in solution in the water in which the wood was immersed”. This hypothesis, however, becomes questionable considering that inorganic molecules are generally much smaller than the organic molecules they were supposed to replace and their geometry is entirely different. Even the commonly observed “substitution” of calcite or aragonite in mineral skeletons of animals by silica is stoichiometrically impossible. Later, improved analysis techniques such as etch and peel demonstrated that much of the original organic material still remains in permineralized samples, but it has been permeated and embedded in a finely crystalline mineral matrix. The most common minerals for permineralization are quartz SiO_4 (silicification), calcite $CaCO_3$, pyrite FeS_2, siderite $FeCO_3$ and apatite $Ca_{10}(PO_4)_6(OH,F,Cl)_2$. Silica is often sourced from chemical weathering of volcanic material.

Pyrite is formed from the reaction of sulfides released from the organic matter with dissolved iron. Carbonates and apatite originate primarily from the mineralization of marine organic matter. The occurrence and type of permineralization thus depends strongly on the availability of various ions and the pH. Cryogenic preservation of fossils can be regarded as a special case of permineralization with H_2O being the mineral, although the H_2O would have been in the organism before its death rather than permeating in from the surroundings after. The environmental conditions for cryogenic preservation are also obviously very different from those for more common forms of permineralization.

Replacement

Replacement, the second process involved in petrification, occurs when water containing dissolved minerals dissolves the original solid material of an organism, which is then replaced by minerals. No direct substitution at the molecular level occurs, and the process has to take place slowly to preserve the original morphology of the organism. The minerals commonly involved in replacement are calcite, quartz, pyrite, and hematite Fe_2O_3. It is rare to find organisms preserved by replacement alone, and replacement often occurs in combination with permineralization.

Types of Petrified Fossils

The most abundant and extensively studied fossils preserved by cellular permineralization are those obtained from coal balls. Coal balls are calcareous concretions, commonly somewhat pyritic, that were formed within unconsolidated peat deposits that led to formation of Carboniferous age coal. Although they occur within the coal, the high amount of carbonate prevents the peat from being turned into coal. The name “coal ball” is thus somewhat misleading since coal balls are not composed of coal and may not actually be spheroidal.

Coal ball (credit: Wikipedia)

Soft tissues have also been found to be preserved through petrification. Examples include muscular tissue of Devonian fish and pyritic plant fossils. Particularly spectacular are mastodon and rhino carcasses preserved by freezing in Pleistocene deposits in Arctic northland.

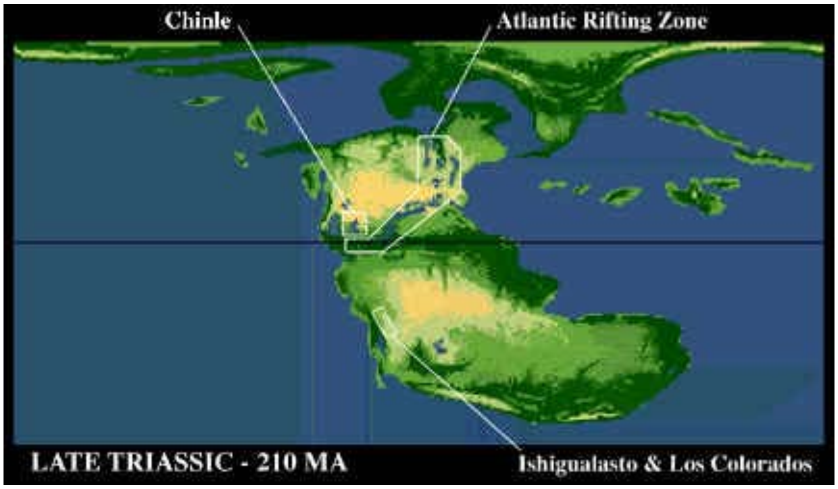
In exceptional circumstances, preservation of even the very delicate subcellular protoplasmic structure does occur in some of the very ancient fossils. Starch gains in permineralized gametophytic tissue of Pennsylvanian age have also been reported. This implies that in the petrification process, protoplasmic organelles have to be fixed and retain their physical relations with respect to other cell contents. Timing is also important. A too rapid interchange from an aqueous to a solid medium probably would destroy the protoplasmic detail, but physical distortion and deterioration would also be expected to occur if permineralization required a period of many months.

Other Modes of Fossilization

Other than petrification, fossils can also be formed through

2. Coalified compression: Softening, collapse and consolidation of nonmineralized tissue in an anoxic environment, with organics eventually becoming coal. Examples include plant megafossils above coal beds and plant microfossils in shale.
3. Authigenic preservation: Formation of surface replicas at time of deposition or during very early (soft-sediment) diagenesis. Molds are often formed, commonly with interstitial cementation. Examples include ironstone concretions, molds in travertine or limestone, and soft-sediment trace fossils.
4. Duripartic preservation: Original parts resistant to oxidation and physical change are preserved, such as the skeletal material of animals and some plants or durable trace indications.

Petrified Forest National Park



Location of Chinle formation during the late Triassic
(credit: http://palaeo.gly.bris.ac.uk/palaeofiles/triassic/setting.htm)

Petrified Forest National Park is known for its fossils, especially of fallen trees that lived in the Late Triassic period of the Mesozoic era, about 213 million years ago. The large amount of petrified wood defines the Petrified Forest member of the Chinle formation. The Chinle formation was a sedimentary unit deposited in present southwestern United States as the supercontinent Pangea started to break up into Laurasia and Gondwana. This results in the formation of shallow seas between the two new continents, and associated rivers and swamps. The shallowness of the seas also gave rise to multiple sets of transgressive and regressive deposits as sea levels rose and fell.

References

Schopf, J. M. (1975). Modes of fossil preservation. Review of Palaeobotany and Palynology, 20(1-2), 27-53.

Wikipedia contributors. "Fossil." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 25 Aug. 2018. Web. 29 Aug. 2018.

Wikipedia contributors. "Petrifaction." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 13 Aug. 2018. Web. 29 Aug. 2018.

Wikipedia contributors. "Petrified Forest National Park." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 8 Aug. 2018. Web. 29 Aug. 2018.

Moenkopi and Chinle Formations: Painted Desert

Emileigh Shoemaker

Introduction

The Painted Desert extends from the eastern portion of Grand Canyon National Park through Petrified Forest National Park as well as the Navajo Nation. The Painted Desert covers an area of ~19.400 km^2. Lieutenant Joseph C. Ives, an explorer in the employ of the Federal Government, gave the official name to this region in 1858 [1]. The colorful stratified layers of the desert are composed of the Upper Triassic Chinle Formation that rests on the Lower-Middle Triassic Moenkopi Formation. The Chinle Formation is visible within the confines of Petrified Forest National Park while the Moenkopi Formation is not. Moenkopi Formation exposures can be found to the west and south in the Little Colorado River Valley (Martz et al., 2012).

Figure 1. A typical exposure in the Painted Desert (image from [1]).

Origin of the Moenkopi and Chinle Formations

Moenkopi Formation

The Moenkopi Formation is the oldest Triassic deposit in the Colorado Plateaus. It is interpreted to be a series of deposits formed in both marine and continental environments. Sandstone and siltstone are cross-stratified indicating a fluvial origin while limestone, dolomite and horizontally stratified siltstone indicate formation in a shallow marine environment (Stewart et al., 1972). In Arizona, the Moenkopi Formation consists of three members. The bottommost is the Wupatki Member that is described as a pale red/brown siltstone with a thin unit of sandstone. Next is the Moqui Member that is predominantly a pale red/brown siltstone with a smaller amount of white gypsum. The topmost member is the Holbrook Member comprised of a mixture of sandstone and siltstone. In addition, various portions of the Moenkopi Formation are host to a variety of fossils. (Stewart et al., 1972).

Chinle Formation

The Chinle Formation is an Upper Triassic deposit that overlies the Moenkopi Formation. The deposition of the Chinle formation likely ended before ~201.3 Ma. These sedimentary deposits have been interpreted to be the result of a major river system that may have originated in west Texas (Riggs et al., 1996). This river was most likely joined by other tributaries in and around Petrified Forest. These rocks indicate that there was likely a subtropical climate that progressed into a more arid climate (Martz et al., 2012). See Figure 2 below for a stratigraphic column of the Chinle formation and its constituent members.

Further deposition continued throughout the Mesozoic Era. The Glen Canyon Group (uppermost layer in Figure 3, panel A) rests on the Chinle Formation and was deposited during the Early-Middle Jurassic. This was followed by uplift and subsequent erosion during the Cenozoic Era (Figure 3, panels B and C). Later, a lake formed on top of these eroded portions of the Chinle Formation in the Late Miocene and Early Pliocene (termed the Bidahochi Formation). Deposition of this lake, referred to as Lake Hopi, was between 16 Ma and 4 Ma (Martz et al., 2012). The Bidahochi Formation creates an unconformity with the Chinle Formation (Figure 3, panel C), the difference of which is ~192 million years [2]. There is evidence of basaltic rocks in this area which could indicate phreatomagmatic volcanism (magma encountering groundwater or lakewater which can produce explosive eruptions [2]). A remnant vent from one maar (a volcanic crater created through a phreatomagmatic eruption) can be found east of Pintado Point on the Painted Desert Rim [2]. Further erosion has erased much of Bidahochi Formation leaving the Painted Desert in the current state we see today (Figure 3, panel D).

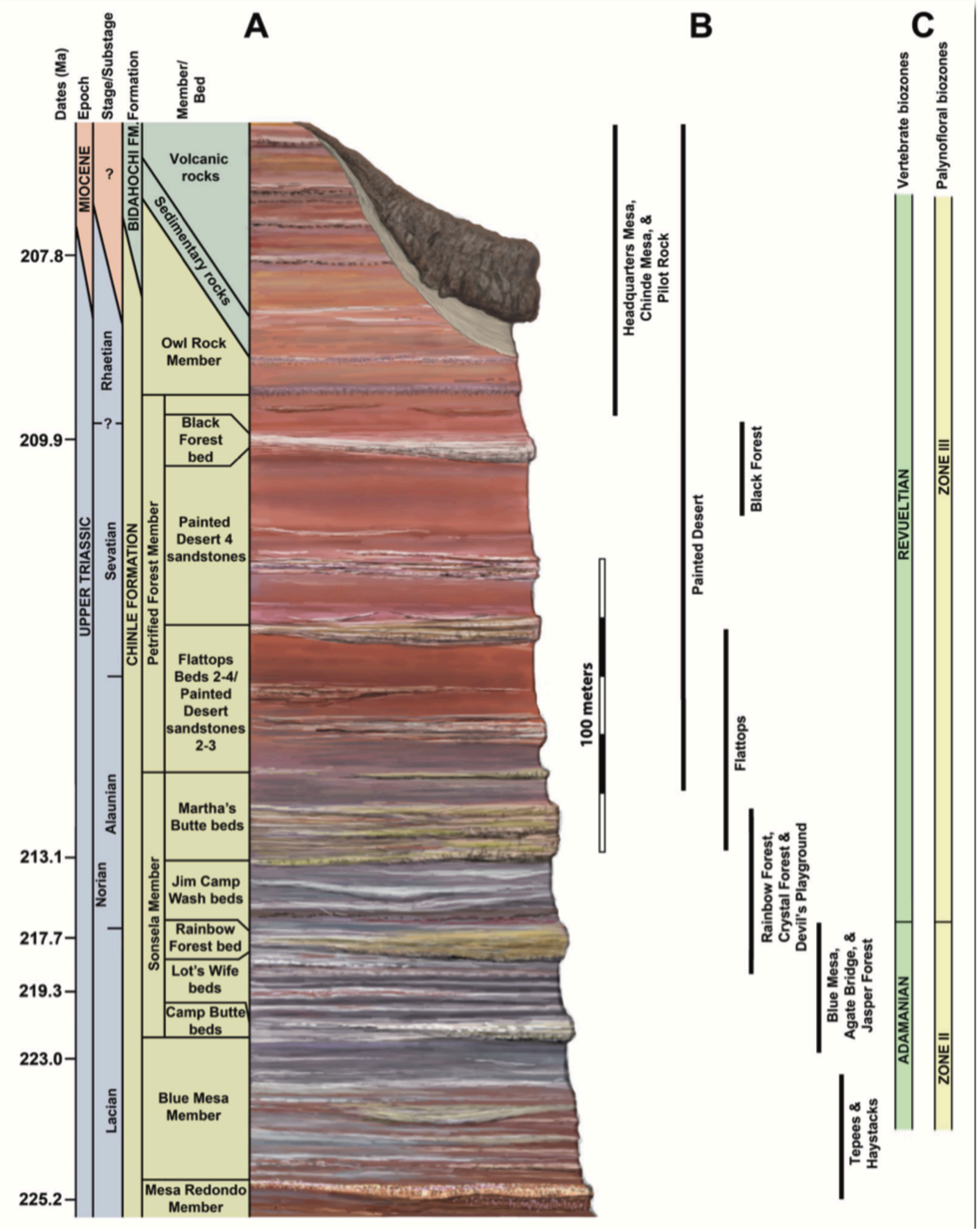


Figure 2. Figure 3 from Martz et al. (2012). This is a stratigraphic column of the Chinle Formation within the Petrified Forest National Park. The ages are determined by radioisotopic dating.

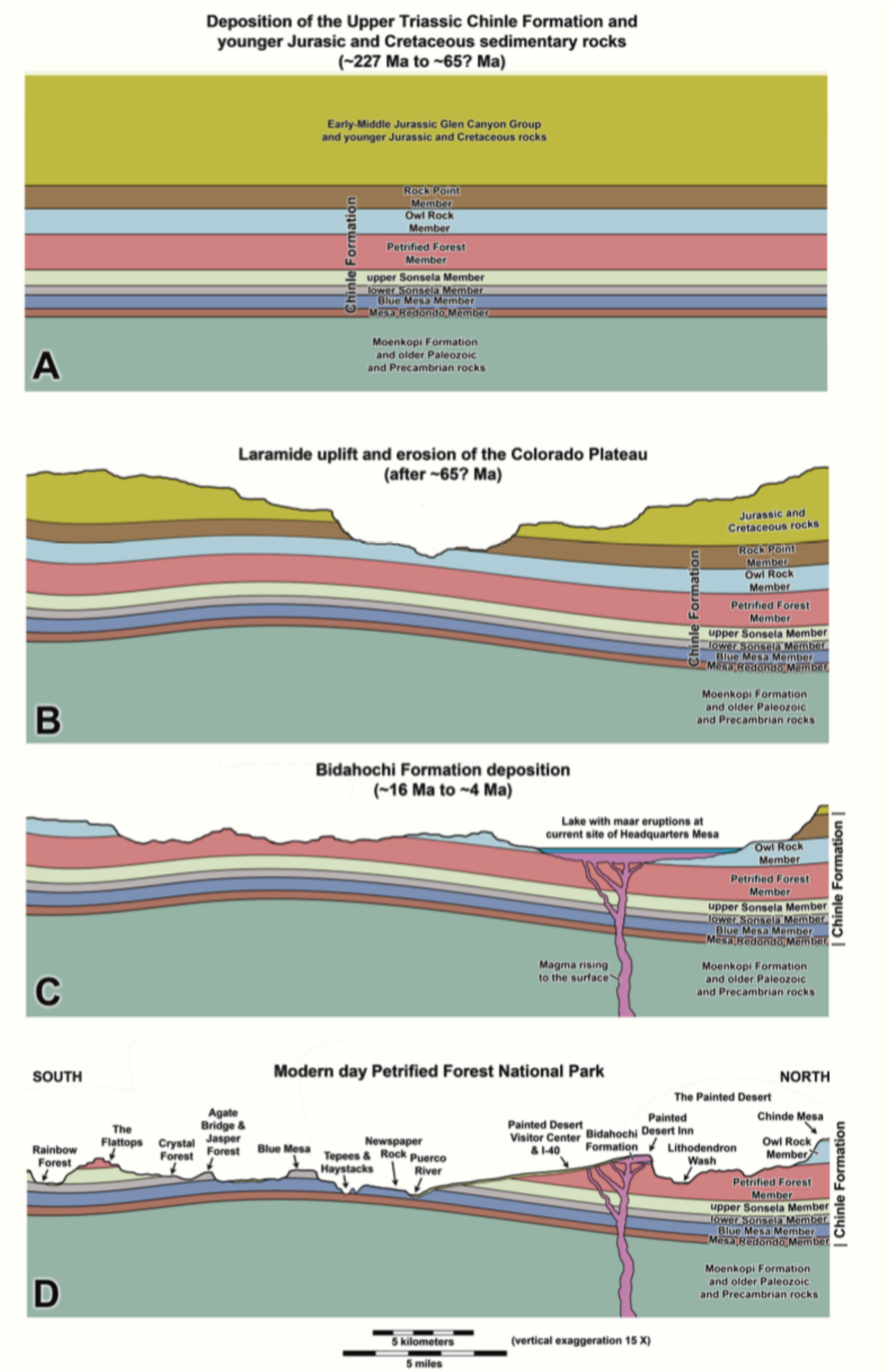


Figure 3. Figure 4 from Martz et al. (2012). The four panels above provide a depositional and erosional history of the Moenkopi and Chinle formations in Petrified Forest National Park. Panel C shows the deposition of the Bidahochi Formation. The right portion of Panel D shows the present state of the Painted Desert.

References

Stewart, J. H., Poole, F. G., and Wilson, R. F., 1972, Stratigraphy and Origin of the Triassic Moenkopi Formation and Related Strata in the Colorado Plateau Region. Geological Survey Professional Paper 691. United States Department of the Interior. 195 p.

Martz, J.W., Parker, W.G., Skinner, L. and Raucci, J.J., Umhoefer, P. and Blakey, R.C., 2012, Geologic Map of Petrified Forest National Park, Arizona. Arizona Geological Survey Contributed Map CR-12-A, 1 map sheet, 1:50,000 map scale, 18 p.

Websites

[1] Image: https://www.britannica.com/place/Painted-Desert-Arizona
[2] https://www.nps.gov/pefo/learn/nature/geologicformations.htm

The Grand Staircase

Rachel Fernandes

Overview:

The term “Grand Staircase” was first coined by Charles Keyes in 1924 to highlight the immense sequence of sedimentary rocks that stretch from the Kaibab plateau, which forms the north rim of the Grand Canyon, northward to the Pink Cliffs of Bryce Canyon National Park. The Grand Staircase is made up of five tilted, southward facing escarpments called stairsteps. Starting with the oldest layer first, the stairsteps are named after their general color: chocolate, vermillion, white, gray and pink (See figures 1 and 2).

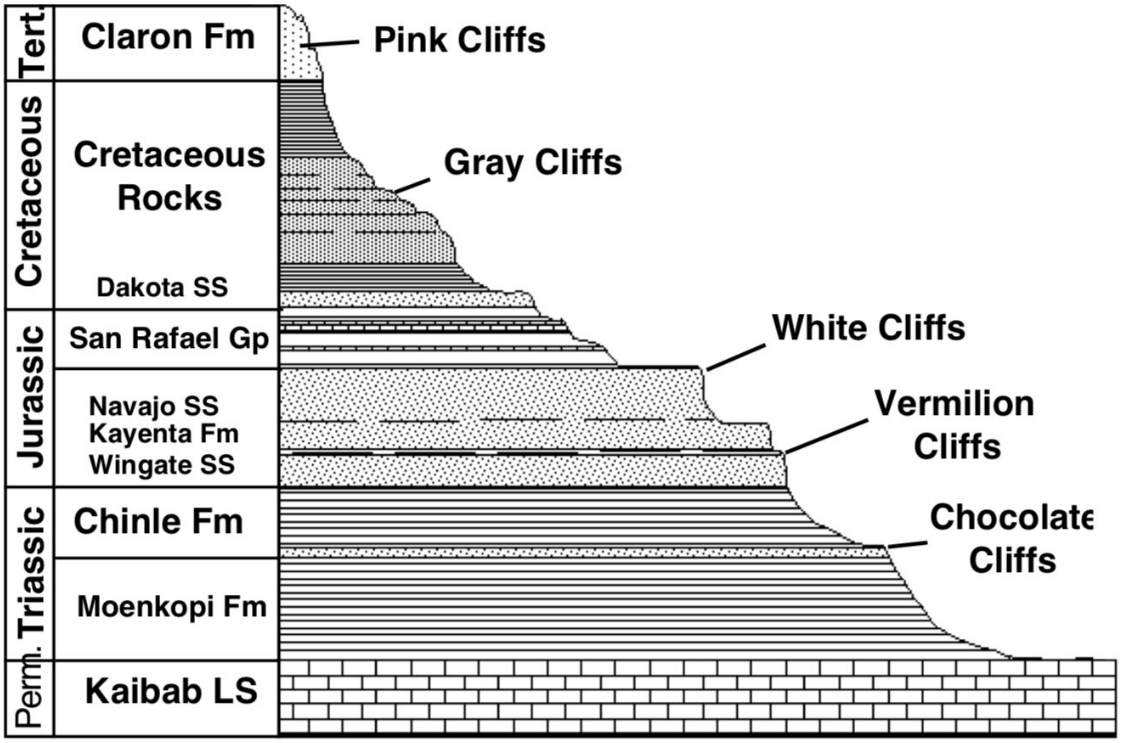


Figure 1. Stratigraphic units of the Grand Staircase

Step Zero: Kaibab Limestone

This step serves as a foyer, with stairs both above and below. The stairs below depict about 2 billion years of Earth's history and 5000 vertical feet down to the Colorado River and its Grand Canyon. The top step of this staircase is the North Rim of the Grand Canyon and the Kaibab Limestone, a Permian formation packed with marine fossils that serves as the hard, protective layer of the Kaibab Plateau and the soft sandstones and shales that make up the red and orange walls.

Step One: The Chocolate Cliffs

The first official step in the Grand Staircase is the Chocolate Cliffs, located near the town of Fredonia, AZ and seen prominently on US highway 89 near the Arizona/Utah Border. This is the oldest or bottom layer of the Grand Staircase, which makes up the North Rim of the Grand Canyon. The Chocolate Cliffs were formed around 200 million to 225 million years ago. This layer defines most of the Kaibab plateau, and is made of Kaibab limestone. Aptly named, these velvet brown cliffs of the Moenave Formation, a variably sandy and silty sandstone/shale that represents a proximal marine fluvial (river) system of early Jurassic age, are part of the greater Glen Canyon Group that includes all the Jurassic-aged units of the Grand Staircase (Wingate, Moenave, Kayenta, Navajo). The Chocolate Cliffs are also home to thousands of dinosaur fossil fragments, though no full specimens have been recovered.

Shinarump Flats - This makes up the upper portion of the Shinarump Member. Above these flats are slopes of bright red, pink, brown, purple, white, yellow, and gray-green mudstones and sandstones of the Chinle Formation.

Step Two: The Vermillion Cliffs

The Vermillion Cliffs are a rich reddish-brown color, made up of silt and ancient desert sand dunes. This layer makes up the red rock cliffs near Kanab. The Vermillion Cliffs date back between 165 million and 200 million years old. Laid down during the mid Jurassic, Vermillion is composed of two distinct rock units that are married to one another across the Colorado Plateau. The Kayenta Formation, which is sandwiched between the older Wingate and younger Navajo Sandstones, is a terrifically diverse and interesting unit that represents a wetter transition period with a howling and vast desert on each chronological side. A veritable melange of lithology, Kayenta has just about everything from thin lenses of limestone and muddy shales to cross-bedded sandstones similar to its stratigraphic neighbors. It records almost seasonal changes with its mud cracks, as well as large scale climatic changes indicated by sand dunes, river beds, and even the occasional shallow lake bed. Kayenta and Navajo are almost always found together, and oftentimes form dramatic cliffs and canyons together as seen in the Vermillion Cliffs and Zion National Park.

Wygaret Terrace - This feature is a narrow tread dotted with sandstone buttes and monuments that includes the soft upper part of the Kayenta and the lower part of the Lower Jurassic Navajo Sandstone.

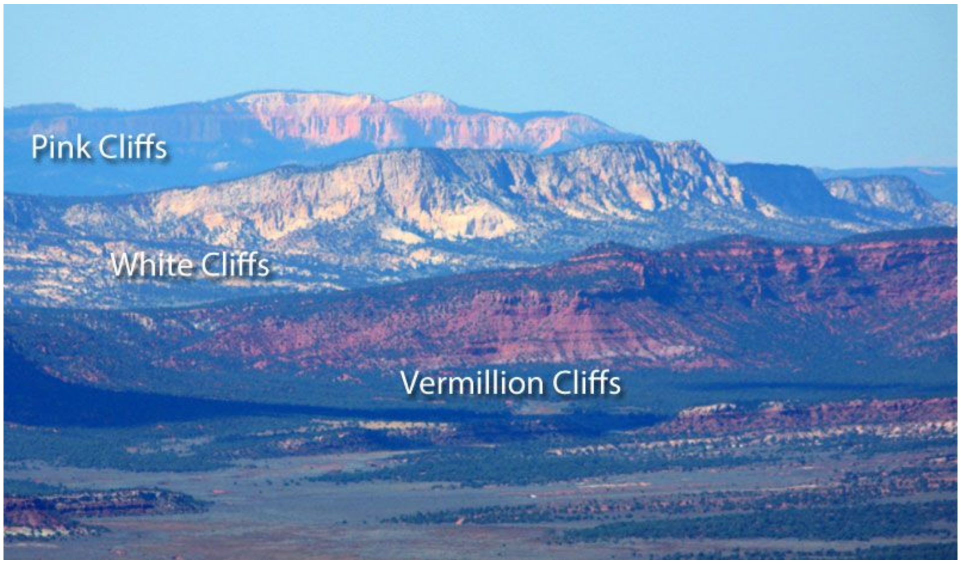


Figure 2. Visual comparison of the Pink, White and Vermillion Cliffs

Step Three: The White Cliffs
The massive white cliffs are made of white, pink, and brown Navajo Sandstone. The Navajo Sandstone consists of thick layers of cross-bedded sandstone formed by windblown sand dunes in a vast ancient desert. In the early Jurassic, the climate of the Colorado Plateau dried significantly, creating desert conditions over a broad region. The Navajo Sandstone is the result of the largest known sand desert in the history of our planet, which covered the area of today's Colorado Plateau and beyond. This white capped thin layer was deposited about 150 million years ago on top of the temple cap formation during the time when streams moved over the Navajo Desert and was later covered by great dunes of sand.

Skutumpah Terrace - The Skutumpah Terrace is located between Zion National Park and Bryce Canyon inside the Grand Staircase-Escalante National Monument. It's made up of carmel formation which consist of limestone containing marine fossils, along with mudstone, sandstone, and gypsum deposited in a shallow interior seaway. The Carmel Formation was deposited in a shallow sea environment, with rock types ranging from marine mudstone and limestone to gypsum layers deposited in evaporative coastal lakes. This ancient interior body of water, called the Sundance Sea by geologists, was warm, surrounded by an arid coastline, and bounded by sandy deserts to the south and the east. Only the lower portion of the Carmel Formation remains in Zion; the rest of the unit has eroded away in this area.

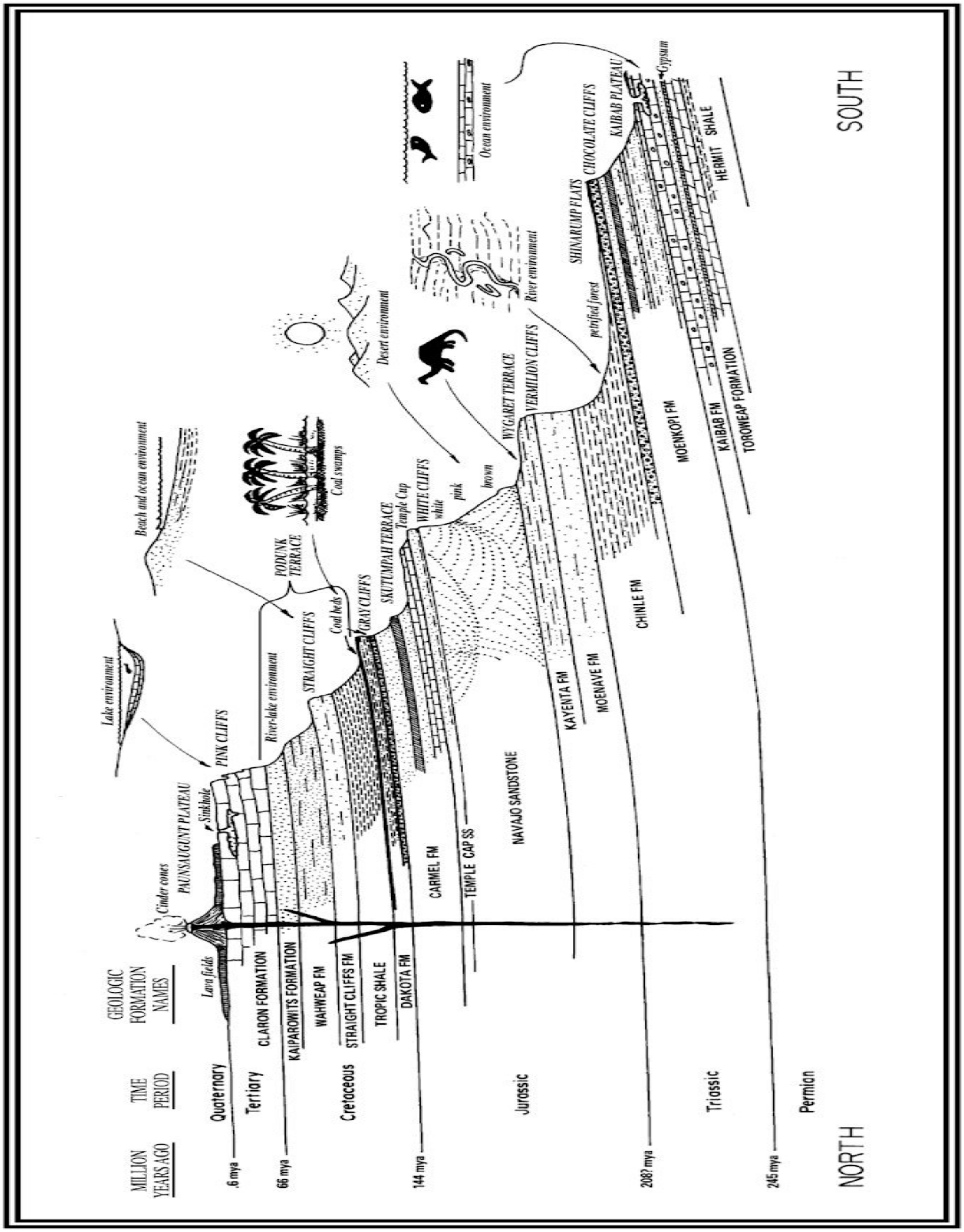
Step 4: The Gray Cliffs
The Gray Cliffs are the second youngest layer of the Grand Staircase, made up of soft Cretaceous shale and Dakotah formation sandstone that was deposited around 130 million years ago. It is seen in Mount Carmel Junction and north of Kanab.
Podunk Terrace - This terrace consists of slopes and cliffs of sandstones, siltstones, and shales of the Tropic Shale and Straight Cliffs, Wahweap, and Kaiparowits Formations.

Step 5: The Pink Cliffs
Bryce Canyon National Parks famous hoodoos are sculpted from the youngest layer of the Grand Staircase. The Pink Cliffs of the Claron Formation are 50 to 60 million years old. The Pink Cliffs also define Red Canyon and Cedar Breaks. Bryce Canyon balances on the edge of the Paunsaugunt Plateau, which rises 7,000 to over 9,000 feet above sea level.
The Paunsaugunt and Aquarius Plateaus - The Paunsaugunt Plateau was created approximately 10-20 million years ago by a tectonic uplift on the Colorado Plateau, which is the highest plateau in North America). Further uplift and erosional forces along the Paunsaugunt Plateau created Bryce Canyon's intriguing hoodoos.
The Aquarius Plateau is another tectonic uplift along the Colorado Plateau, encompassing more than 50,000 forested acres above 11,000 feet. It is the highest timbered plateau in North America. Boulder Mountain's Bluebell Knoll (peaks at 11,328 feet) is the highest point in Bryce Canyon Country and on the Aquarius Plateau.

References:

William Blondeau-Stephan Kochaver-James Kreft-Martin Wernimont-Andrew Yan-Mary Bucknell - https://pubs.usgs.gov/
The Real Grand Staircase - First Three Steps
https://www.brycecanyoncountry.com/the-grand-staircase-first-three-steps/
Geology Of the Grand Staircase-escalante National Monument, Utah
Zion Com - http://www.zionnational-park.com/gsgeology.htm

Figure 3. A profile of a portion of the Grand Staircase in southern Utah and northern Arizona



Supai Group: Canyon de Chelly

Joana Voigt

1. Rock Units in Lithostratigraphy

Lithology is the description of the macroscopic observations of the physical parameters of a rock, e.g., grain size, bedding, color, and fossil content. Thus, lithostratigraphy describes a rock based on its lithology and stratigraphic relationship [1]. The hierarchy of the terms/units is normally structured from the smallest scale to largest scale as followed:

Small scale to large scale

Bed:	smallest distinctive layer in a member or formation [1, 2]; normally not named
Member:	named and distinct part of a formation
Formation:	primary unit of lithostratigraphic classification [2] which can be used as a mapping unit and thus need to be sufficient extended; name includes geographic area and the dominant lithology [2] e.g., Hermit Shale
Group:	set of at least two formations with the same lithological properties [2]; e.g., Supai Group
Supergroup:	composed of two or more groups and/or formations having lithologic characteristics in common [2]

Cross section Grand Canyon

The black numbers are showing the groups, whereas the white numbers represent the different formations.

Number 5 is the Supai Group:

- Esplanade Formation
- Wescogame Formation
- Manakacha Formation
- Watahomigi Formation

Fun fact!
Number 1 is the Vishnu Group

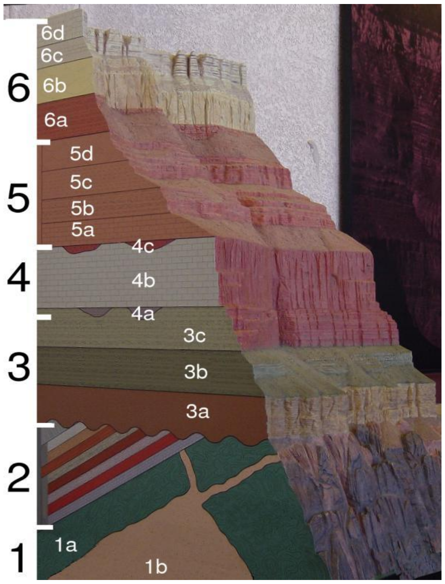


Figure 1 geological cross section of the Grand Canyon, Arizona, from [4].

2. Supai Group in the Canyon de Chelly Area

2.1 Description

The Supai group in general represents the Pennsylvanian series to Lower Permian period (315 – 285 Ma) [5]. The sedimentary deposits of the Supai group are generally dominated by reddish-brown sandstones and reddish-orange limestones. Erosion and weathering of these series produced the steep walls resulting in canyons and valleys formation, like Grand Canyon and Canyon de Chelly. The different members of the formations can be divided into slope forming units and cliff forming units depending on their lithological properties.

The Supai group is composed of four different geological formations which are listed in Figure 2 from its topmost and youngest to lowermost and oldest unit.

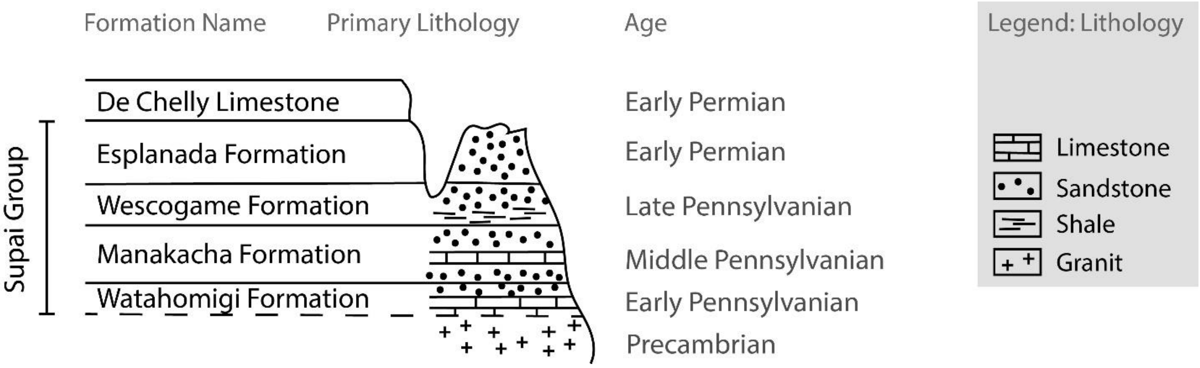


Figure 2 Sketch illustrates the lithostratigraphic formations making up the Supai Group with overlying De Chelly Limestone and an unconformity to the underlying Precambrian rocks in Canyon de Chelly.

The Esplanade Sandstone has a light-red and pinkish-gray color with fine to medium grain sizes and is well sorted. It further contains thin dark-red siltstones [5]. The Wescogame Formation is dominated by light-red coarse grained calcareous sandstone with pale-yellow dolomitic sandstone, siltstone, mudstone, and conglomerates [5]. The Manakacha Formation is mainly composed of a light-red, white, gray sandstone and gray limestone [5]. The major lithologies of the oldest Watahomigi Formation are a gray and purplish-red limestone, less sandstone, and conglomerates [5].

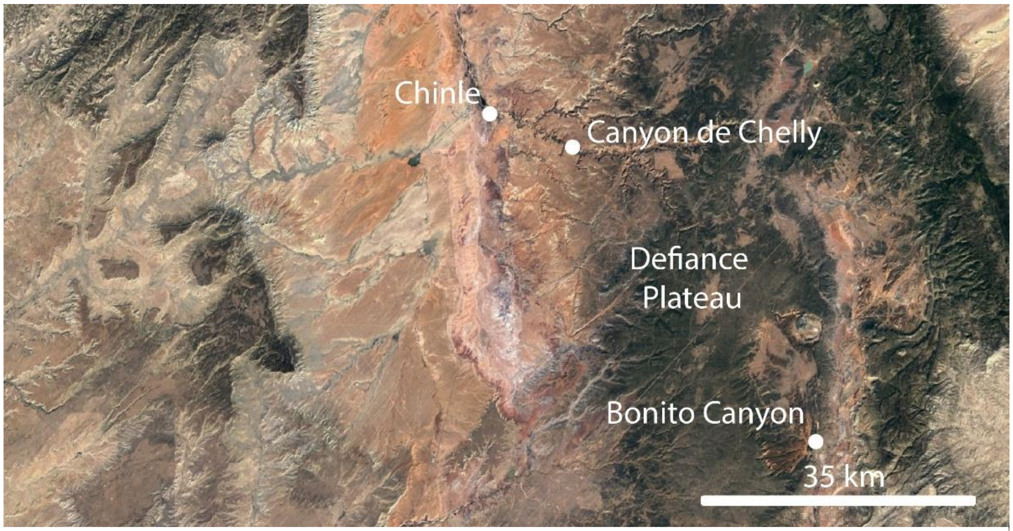


Figure 3 Overview map of the Defiance Plateau region, including the Canyon de Chelly, and Bonito Canyon, as well as the city Chinle. The locations are overlain on a Google Earth satellite image.

In Canyon de Chelly the section is not completely exposed, only in Bonito Canyon (see Figure 3 for location) and close to Hunters point the whole group is exposed to the surface [6].

2.2. Interpretation

In general, the transition from facies can indicate environment changes. For example, coarser grains normally indicate a nearshore deposition, due to the high energy that is required to transport them far away from their source region. Whereas fine grains imply a low-energy transportation and longer travel time and thus indicate an off-shore deposition. The alternating in grain sizes ranging from siltstone to conglomerates in the Supai Group thus present marine transgressions and regressions.

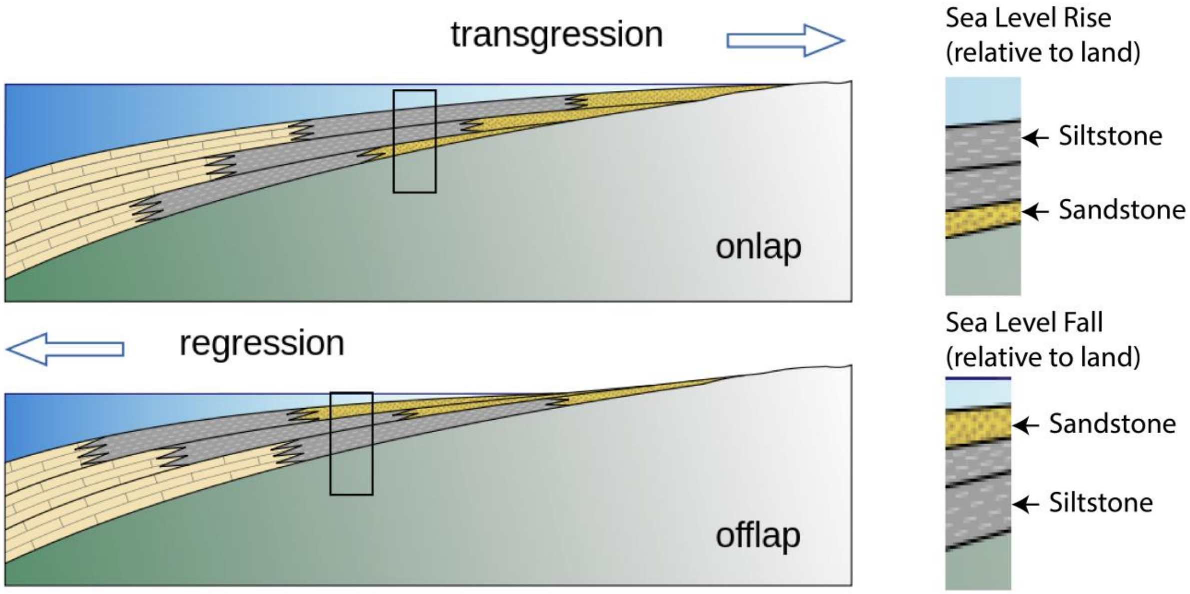


Figure 4 illustrates the model of marine transgression in the upper part and regression in the lower part. The black boxes are a close-up to the different facies. Modified from [7].

3. Planetary Analog

Stratigraphic columns on Mars are also used to infer the energy needed to transport the sediment and thus implications for the historical environment can be made, especially addressing the question whether Mars was warm and wet or cold and dry with episodic warm periods. NASA's Curiosity rover, part of the Mars Science Laboratory (MSL) mission, was landed in August 2012 in Gale impact crater to investigate the climate, the geology, and the role of water in the Kimberly region [8]. Figure 5 gives an overview of Mount Sharp and Figure 6 is a stratigraphic column at the Gale crater with a detailed column for the Kimberley area. The Kimberly sandstones are interpreted to mainly present a fluvial environment with minor eolian reworked sediments [8], where the cross-stratified sandstone most likely represents deltaic depositions [8]. However, these sandstones can also result from meltwater related erosion [10] which would be consistent with the breccia-conglomerates facies interpretation [10].

Figure 5 shows Mount Sharp in Gale crater on Mars. The image was taken on September 2015 [11].

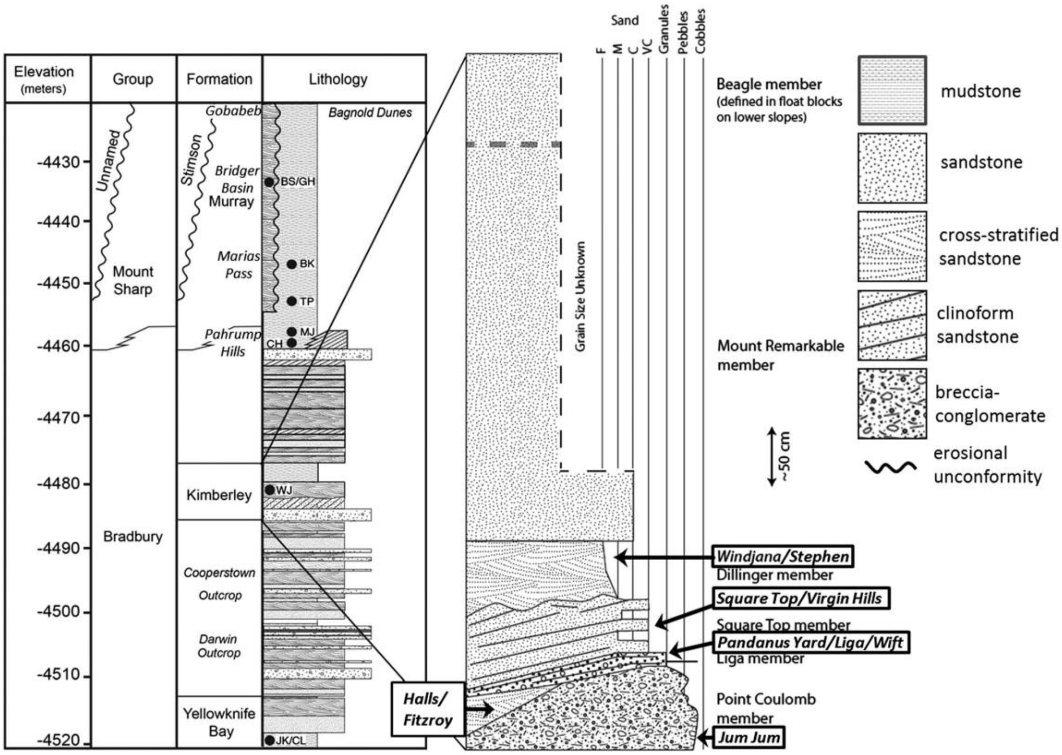


Figure 6 from Thompson et al., 2016 [10] show the stratigraphic column at Gale crater (left) and the Kimberley region (right) on the Curiosity rover landing site to sol 1200, Mars.

4. References

[1] "Chapter 5. Lithostratigraphic Units". International Commission on Stratigraphy. 2013–2014. Retrieved 4 June 2014; [2] Mathur S.M. (2008). Elements of Geology. pp. 129–130. ISBN 9788120335158; [3] Brookfield M.E. (2008). Principles of Stratigraphy. John Wiley & Sons. p. 200. ISBN 9780470693223; [4] https://en.wikipedia.org/wiki/Geological_formation#/media/File:GrandCanyon_geologic_column.jpg; [5] https://3dparks.wr.usgs.gov/coloradoplateau/lexicon/supai_group.htm; [6] Irwin, J. H., et al., (1971): Geology of the Paleozoic Rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utha. Geological Survey Professional Paper 521 – c; [7] http://www.wikiwand.com/en/Sedimentary_rock; [8] https://mars.jpl.nasa.gov/msl/mission/science/goals/; [9] Grotzinger, J. P., et al. (2015), Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars, Science, 350(6257); [10] Thompson, L. M., et al. (2016), Potassium-rich sandstones within the Gale impact crater, Mars: The APXS perspective, J. Geophys. Res. Planets, 121, 1981–2003, doi:10.1002/2016JE005055; [11] https://photojournal.jpl.nasa.gov/jpeg/PIA19912.jpg

Canyon de Chelly carves into the northwest slopes of the Defiance Plateau in northeastern Arizona and runs approximately 42 km eastward. Erosional downcutting of sediments is thought to have initiated between 5 – 10 Ma, predominantly exposing the De Chelly Sandstone. This unit is well known for its large cross-bedding, which resulted from the deposition of windblown sands during the Early Permian between ~250 – 230 Ma. The iconic Spider Rock exposes the entire De Chelly Formation, measuring ~250 m (Baars, 1998).

Figure 1. Canyon De Chelly Map. Source: USGS

Geologic formations exposed in Canyon de Chelly National Monument range in age from ~280 Ma during the Permian, to ~200 Ma during the Late Triassic and include the Supai, De Chelly Sandstone, and Chinle Formations. The oldest of these, the Supai Sandstone, consists of red-brown, fine-grained blocks which are observed at the base of Spider Rock. The main geologic formation exposed at Canyon de Chelly is the De Chelly Sandstone, with its apparent cross-bedding planes. The youngest geologic unit consists of the Shinarump Conglomerate, a member of the Chinle Formation. This Late Triassic (~200 Ma) unit makes up the cap rock of Canyon de Chelly.

Figure 2. Canyon de Chelly, highlighting Spider Rock. Source: Arizona Highways

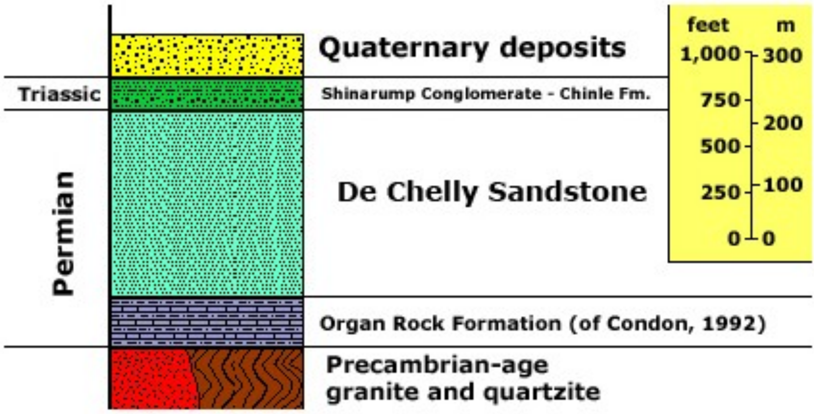


Figure 3. Canyon de Chelly Stratigraphic Column. Source: USGS

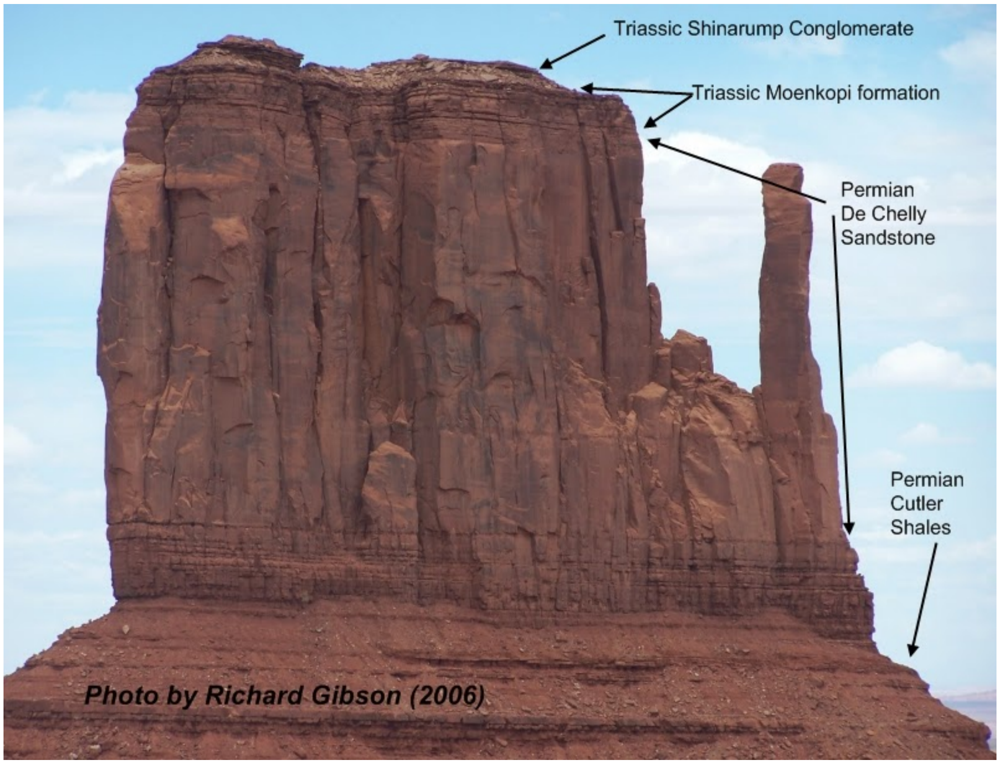


Figure 4. Exposure of De Chelly Sandstone, Moenkopi, and Chinle Formations; Monument Valley, AZ.

De Chelly Sandstone

The De Chelly Sandstone Formation is a geologic unit observed throughout much of the Colorado Plateau. Within Canyon De Chelly, it is the main unit exposed, measuring up to ~250 m (Baars, 1998). Large cross-bedding is observed throughout the formation. Cross-beds represent the bedding surface on the sheltered slopes along the lee side of dunes throughout this Permian-aged depositional environment. Sets have been measured between 3 – 15 m tall, suggesting large, mature dunes. (Baars, 1998). Alcoves formed by the dissolution of calcium-carbonate along these cross-beds have historically served as shelter to the Anasazi.

Moenkopi Formation

This Triassic formation consists of brown, red, and grey sandstone, with alternating red shales. Named after a Hopi town in Arizona, Moenkopi means “place of flowing water.” This unit was likely deposited in broad mud flats or river flood plains along the ocean margin. Ripple marks, mud cracks, and salt casts are evident throughout the formation, supporting a tidal, near-shore, or riverbank depositional environment. While the Moenkopi was deposited on top of the De Chelly Sandstone, it is not present within Canyon De Chelly. This unit appears in the southern portion of the Defiance Uplift, yet thins out southeast of the canyon, leaving a ~50 Myr unconformity between the Permian aged deposits of the De Chelly Sandstone and the Late Triassic aged deposits of the Chinle Formation. Interestingly, while the Moenkopi is not present within Canyon de Chelly, it is preserved in places such as Monument Valley, where it is overlain by the same resistant units found in Canyon de Chelly.

Chinle Formation

The Chinle Formation is a late Triassic unit prominent throughout the Colorado Plateau consists of various colored shales, marls, thin sandstones, and conglomerates. This unit is thought to be non-marine in nature, deposited by streams within shallow bodies of water. The color variations seen in localities such as Beautiful Valley are due to the presence of ash deposits from nearby volcanic activity concurrent with Chinle deposition. Fossil vertebrates, fresh-water invertebrates, and silicified wood are found throughout this formation, supporting a non-marine origin. The name Chinle has the Navajo meaning “place where water flows out of the canyon,” and is named for the Chinle Valley, where this unit has been measured at ~360 m.

Within Canyon de Chelly the Shinarump Conglomerate, a member of the Chinle Formation, exists as an unconformable layer forming the cap rock atop the De Chelly Sandstone. The Shinarump Conglomerate includes coarse grey sandstone and conglomerate. This unit is found throughout the northern portion of the Defiance Uplift. Thin alluvium, gravels, and aeolian sediments of the Quaternary are observed throughout the monument.

References

Baars, D.L., 1998. The rocks and time of Canyon de Chelly National Monument - a visitor’s introduction: Grand Junction, Colorado, Cañon Publishers Ltd.

Keller-Lynn, K., 2007. Geologic Resource Evaluation Scoping Summary, Canyon de Chelly National Monument, Arizona. United States Geological Survey.

Vandiver, V.W., 1937. Southwestern Monuments Special Report. No. 20 Geologic Report Canyon de Chelly National Monument. National Park Service.

https://3dparks.wr.usgs.gov/coloradoplateau/canyondechelly_strat.htm

http://historyoftheearthcalendar.blogspot.com/2014/09/september-7-moenkopi-formation.html

Weigang Liang

Aeolian Processes: Morphology

Aeolian processes are ways in which the wind interacts with the surface. The results of those interactions take the shape of many forms, which include ripples, yardangs, dunes, and other formations. On Earth, an additional element which influences Aeolian processes are vegetation. They are able to help form Aeolian landforms, indicate the level of erosion, or even prevent them. Wind is not a phenomenon exclusive to the Earth, and Aeolian landforms are present in other solid bodies in the solar system with non-negligible atmospheres such as Venus, Mars, Titan, and even perhaps Pluto.

Sediments are transported by wind through primarily four different modes: creep, reptation, saltation, and suspension. Saltation is the primary mode that maintains the others, including suspension, as saltation dictates whether particles can escape into suspension. **Saltation** describes the "leaping" behavior of sediments in the presence of wind. During saltation, sediments are typically launched at angles of around thirty to fifty degrees, with bounce lengths of about 12-15 times the height launched. **Creep** is the near-ground movement of typically coarser particles, which typically roll along the surface due to impacts from saltating particles or gravity-induced forces. **Reptating** particles are defined as those that switch between the saltation and creep modes, as well as having with a velocity distribution distinct from saltation. Finally, particles in **suspension** are in turbulent motion, or otherwise defined as when the speed of the particle is higher than the fall velocity (combination of buoyancy and gravitational forces).

A basic Aeolian landform is the ripple, which typically occurs in great numbers. Their physical appearances are similar to those of sand dunes, but their sizes are distinct from dunes as they are much smaller (wavelength from centimeters to tens of meters). In addition, their formation is closely related to the four modes described previously, while dunes are thought to form due to aerial instability. One theory on the formation of ripples is that particles undergoing creep and reptation are driven by saltation up to the crest, and they settle and accumulate on the other side. An image of ripples is shown below (Fig. 1).

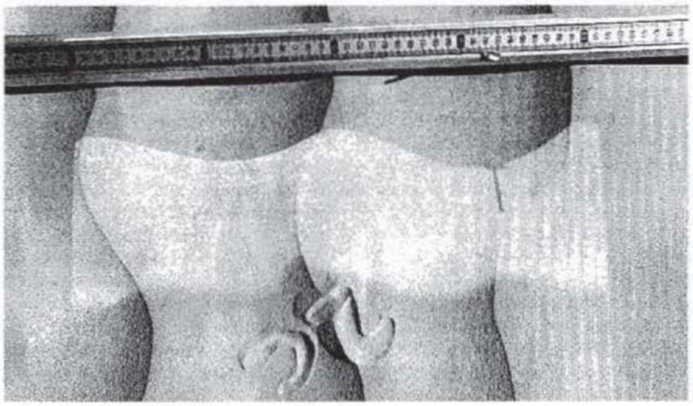


Fig. 1 A ripple along with a ruler for scale

In addition to water, the wind is capable of erosion that leaves visible landforms. The two primary processes of Aeolian erosion are deflation and abrasion. Deflation is the net removal of material due to wind, while abrasion is the fracture of material due to physical impact between wind-driven particles and sedentary material. Landforms due to Aeolian erosion include ventifacts (Fig. 2a), yardangs (Fig. 2b), pans (Fig. 2c), and stone pavements (Fig. 2d).

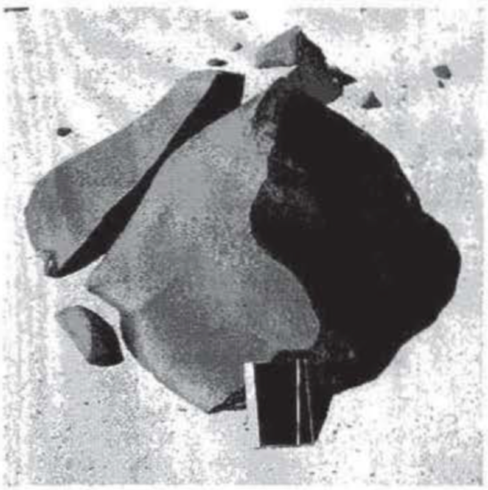


Fig 2a. Ventifact in Namib Desert

Fig. 2b. Yardangs in southern Tunisia

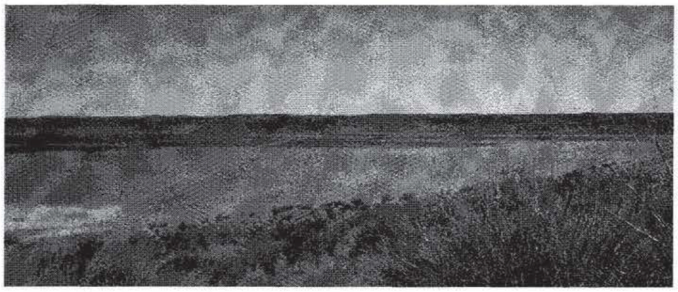


Fig 2c. Pan in Kalahari desert, southern Africa

Fig 2d. stone pavements in Algeria

Ventifacts and yardangs are both primarily caused by aeolian abrasion. One of the differences between them is that ventifacts are produced from individual clasts of rock while yardangs are formed from bedrock. Pans describe depressions or basins that result from aeolian deflation. They are more commonly found on locations with softer sediments. Stone pavements are areas which are covered by polished rocks, normally one or two-stone thick. They occur near locations with less vegetation, and especially in hot deserts.

In addition to sand, dust is also involved in aeolian processes on Earth. Since it's normally difficult to carry sand for long distances, the major component of aeolian activities that disturb human lives is dust. Dust can be composed of material from organic soils to inorganic minerals. Dust phenomena occur in the form of mainly depositional events such as dust storms and dust fallouts. A special form of dust, the loess (Fig. 3), is thought to be the material covering about a few percent of terrain on Earth. Loesses are defined as aeolian dust that has undergone diagenesis. Loesses are useful as they may contain sedimentary information on past fluvial and lacustrine activities.

Fig 3. Loess Hills in Iowa

Dunes are one of the most prominent signatures of aeolian activity. They are considered different from ripples due to their size and theory of formation, and from yardangs as dunes are based on loose material. The theories behind the formation of dunes are still debated, but one of the ways in which dunes could begin to form is as accumulations around slight indentations on the surface such as vegetation or inherent surface roughness. Only a few of these accumulations would eventually become a dune.

Dunes can form either with (anchored dunes) or without (free dunes) obstruction from surface terrain. The free dunes can be separated into transverse, linear, and star dunes. When forming transverse dunes, the wind direction is perpendicular to their crests, while their slip faces (lee sides) all face roughly the same direction (Fig. 4a). A type of transverse dunes is the barchan dune (Fig. 4b), which is a crescent-shaped transverse dune capable of propagating along with the wind. As for linear dunes, the wind direction is parallel to the crest (Fig. 4c). Finally, star dunes result from multi-directional winds (Fig. 4d). Anchor dunes are dunes that form at or around natural obstacles, such as cliffs or significant vegetation.

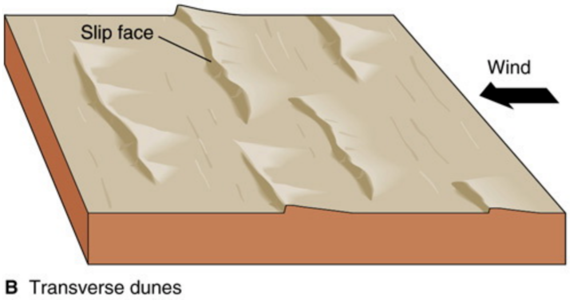


Fig. 4a. wind direction of transverse dunes

Fig 4b. barchan dunes in the Namibian Desert

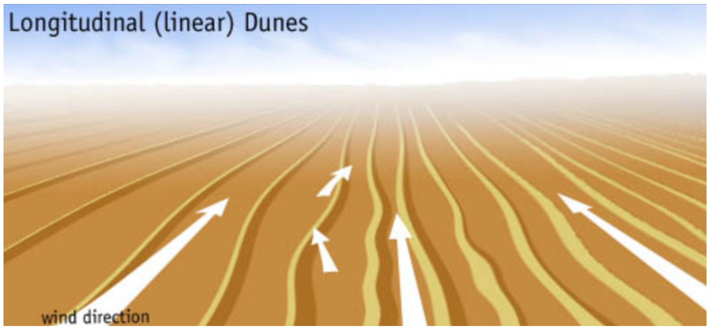


Fig 4c. wind direction of linear dunes

Fig 4d. Star dunes in the Namibian Desert

References:

Livingstone, I and Warren, A (1996) *Aeolian Geomorphology: An Introduction.* Longman Singpore Publications Ltd.

Aeolian Processes: Physics

Maria Steinrueck

Transport processes

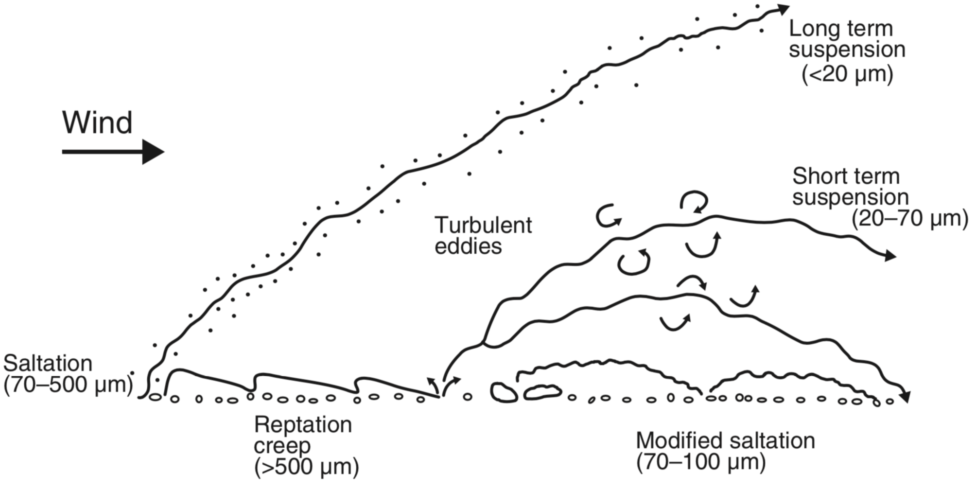


Figure 1 Modes of aeolian transport (Nickling and McKenna Neuman, 2009)

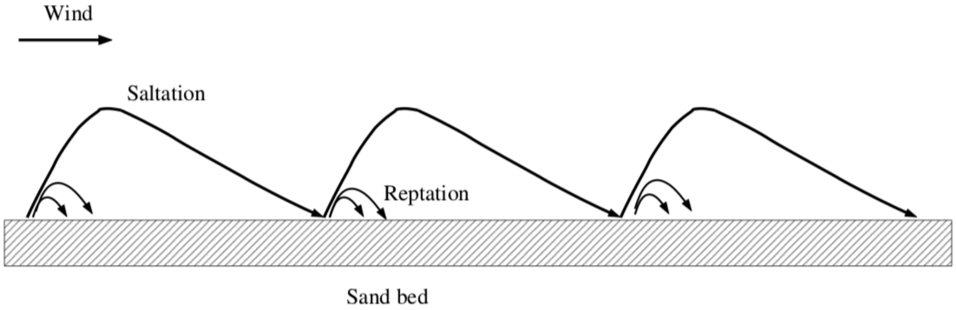


Figure 2 Saltation vs reptation (Valance et al., 2015)

Saltation

Saltation is perhaps the most important aeolian process. **In addition to typically being the most efficient transportation mode, the impact of saltating grains on the ground will also mobilize other all sorts of other grains**. This includes smaller dust grains for which the cohesive forces are too large to be overcome by friction alone, as well as larger grains which are bounced off the surface (reptation) or pushed along on the ground (creep).

Static threshold: When does saltation start?

For grains larger than ~100 μm, cohesive forces are relatively unimportant. **The relevant force balance is then between friction and drag.** The friction can be written as $F_{friction} = \mu g \left(\rho_p - \rho\right) \pi d^3/6$, where μ is the friction coefficient, g the gravitational acceleration, ρ_p and ρ the densities of the particle and the air, respectively, and d the particle size. The drag force can be parametrized as $F_{drag} = \alpha\pi\frac{d^2}{4}\tau$, where α is a constant dimensionless parameter and τ is the shear stress at the surface.

The flow over a sediment layer can be characterized by the **Shields number** $\tau_* = \frac{\tau}{g(\rho_p - \rho)d}$, which is proportional to the **ratio of drag to the effective weight of the particle**.

Setting both forces equal, one obtains the threshold Shields number for the onset of saltation, called the static threshold:

$$\tau_{*,static} = \frac{2\mu}{3\alpha}$$

This static threshold Shields number depends on the material and grain size. For grains with a diameter >100μm, $\tau_{*,static}$ is of the order of $\tau_{*,static} \approx 0.01$.

The threshold shear stress can be related to the shear velocity via $\tau = \rho u_*^2$. The shear velocity is the characteristic velocity near the surface and is related to the actual mean velocity through the law of the wall:

$$u = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right),$$

where $\kappa \approx 0.4$ is the von Kármán constant and z_0 is the surface roughness length.

Dynamic threshold: What is required to maintain saltation?

Once saltation has started, saltating sand grains are very efficient at knocking other grains off the surface. Therefore, a lower wind speed, or equivalently a lower shear stress, is sufficient to maintain saltation. This second threshold is called the dynamic threshold. A typical dynamic threshold Shields number is would be $\tau_{*,dynamic} \approx 0.006$.

Suspension

Dust emission: How does dust get into the air?

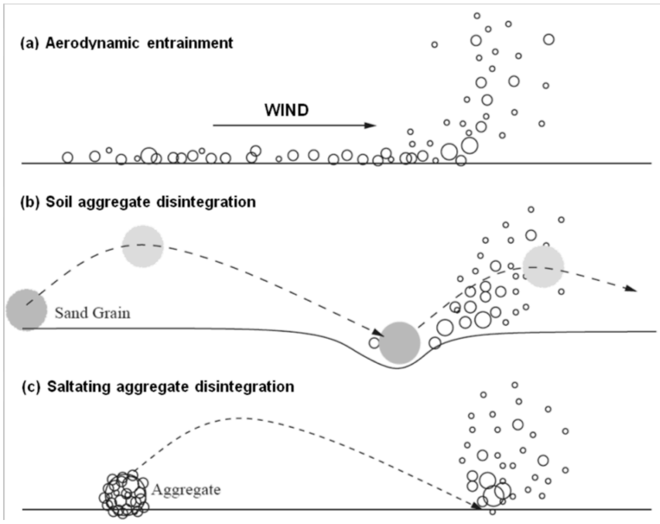


Figure 3 Mechanisms for dust emission (adapted from Shao et al., 2008 by Kok et al,. 2012)

Typically, (b) and (c) are the dominant processes, as for (a) strong interparticle cohesive forces have to be overcome.

Significance of Aeolian Processes on Earth

- Shaping the landscape
    - Erosion/Abrasion
    - Deposition
- Weather and Climate
    - Dust storms (from small scale events such as dust devils and haboobs to synoptic dust storms)
    - Suspended dust can inhibit hurricane formation
    - Suspended dust affects cloud formation and precipitation
    - Deposited material can lower albedo of snow and ice surfaces
- Ecology
    - Distribution of nutrients, effect on soils

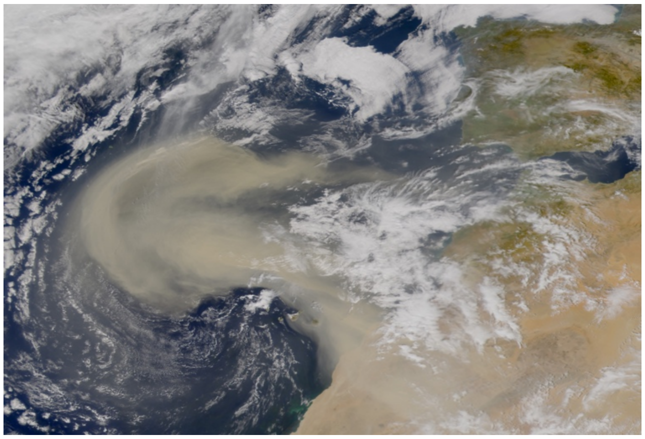


Figure 4 Synoptic scale dust storm over the Western Sahara (NASA/Goddard Space Flight Center, The SeaWiFS Project and GeoEye, Scientific Visualization Studio)

Aeolian Processes on Other Planets

Table 1 Characteristics of saltation on different planets (Table 2.3 in Kok et al., 2012)

Planetary body	Gravitational constant (g)	Air density (kg/m^3)	Dynamic viscosity (kg/m/s)	Particle composition	Particle density (kg/m^3)	Typical particle size (μm)	Threshold shear velocity (m/s)[a]	Ratio of impact to fluid threshold[b]	Typical saltation height (cm)[c]	Typical saltation length (cm)[c]
Earth	1	1.2	1.8×10^{-5}	Quartz	2650	150 – 250	~0.2	~0.8	~3	~30
Mars	0.378	0.02	1.2×10^{-5}	Basalt	3000	100 – 600	~1.5	~0.1	~10	~100
Venus	0.904	66	3.2×10^{-5}	Basalt	3000	Unknown	~0.02	>1	~0.2[d]	~1[d]
Titan	0.138	5.1	6.3×10^{-6}	Tholin/ice	~1000	Unknown	~0.04[e]	>1	~0.8	~8

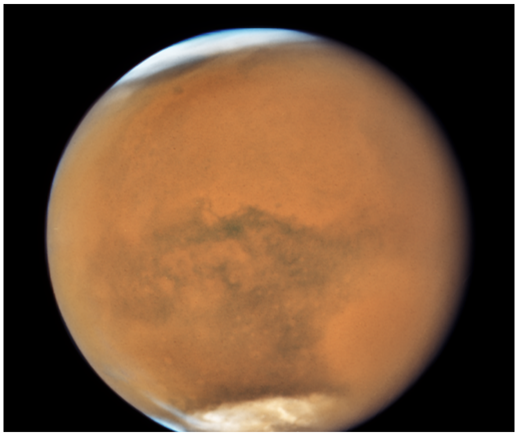


Figure 5 View of the 2018 global dust storm on Mars, taken with the Hubble Space Telescope (NASA/ESA/STScI)

Mars

Dunes observed in many locations on Mars as well as dust devils and global dust storms serve as evidence for aeolian processes on Mars. Because of the lower air density, the static threshold shear velocity is much larger than on Earth. In fact, the threshold is larger than typical wind speeds expected on Mars based on climate models and lander measurements, raising the question of why we still observe active aeolian transport on Mars. A possible solution is that there could be stronger winds in very localized regions due to local topography. Once saltation is initiated, it should be easy to maintain, as the dynamic threshold velocity is only 1/10 of the static threshold velocity.

Figure 6 Dunes on Titan (NASA/Cassini)

Titan and Venus

On Titan and Venus, dunes have been observed as well. However, due to the denser atmospheres and, in case of Titan, the lower density of the particles being transported, it turns out that the static threshold is lower than the dynamic threshold. In other words, it is easier to lift particles than to maintain saltation through impacts! This means that aeolian processes on these planets are fundamentally different from Earth, as direct lifting of particles plays a much larger role.

Sources

Kok, J.F., Parteli, E.J.R., Michaels, T.I., Karam, D.B. (2012) *The physics of wind-blown sand and dust.* Reports on Progress in Physics, Volume 75, Issue 10, id. 106901.

Nickling W.G., Neuman C.M. (2009) *Aeolian Sediment Transport*. In: Parsons A.J., Abrahams A.D. (eds) Geomorphology of Desert Environments. Springer, Dordrecht

Valance, A., Rasmussen, K.R., Ould El Moctar, A., Dupont, Pascal (2015) *The Physics of Aeolian Sand Transport*. Comptes rendus - Physique, Volume 16, Issue 1, p. 105-117.

Fluvial Processes: Morphology

Harry Tang

Fluvial processes involve changes in the landscape resulting from flowing water, such as river or stream. The water can performs three major kinds of work: erosion, transportation, and deposition, all of which depend heavily on the gradient of the stream. A combination of these three can produce a variety of different landforms.

River channels:

Bedload can play a key role in river channel formation. High bedload, along with easily erodible banks, can form a braided channel as opposed to common meandering channels. In braided channels, sediments often deposit into islands that separate the channel, and are favored by variable flow rates, where large floods can form and alter these islands.

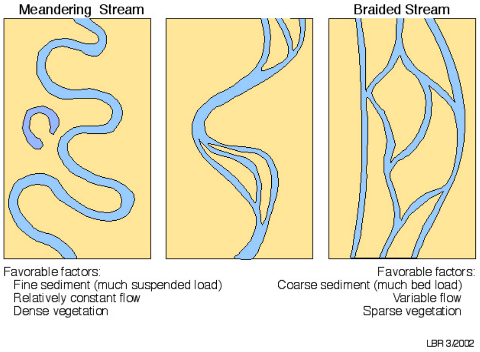


Fig. 1 - Meandering vs braided streams (http://www.gly.uga.edu/railsback/1121RiversB&M.jpeg

Erosional morphologies:

The dominant erosional morphology are V-shaped erosional valleys, carved by downcutting, or removal of stream bed material, by a stream. The size and shape depend on flow rate and the bedrock, among other things. Usually, the downcutting continues down to a base level or a layer of erosion resistant bedrock, and the valley will starting to to expand laterally. Yet sometimes, other geological processes will restart the downcutting by increasing the gradient, such as the case in the Grand Canyon.

Gorges are valleys where a combination of water flow and rock properties are able to keep steep slopes are both sides.

Canyon are just like gorges, but bigger and (sometimes) more gorgeous. Slot canyons are often associated with flash floods, where a deep but narrow cut is made.

Fig. 2 - *Left*: Cascadilla Gorge, NY (http://the-earth-story.com/image/150772995931)
Right: Grand Canyon, AZ (https://savingplaces.org/places/grand-canyon)

Depositional Morphologies:

Floodplains are flatlands on the sides of rivers and streams where unconsolidated sediments are deposited when frequent floods occur. Within a floodplain are often swamps, oxbow lakes, and remains of older river channels. Floodplains are also often rich in nutrient, supporting many of the worlds world's civilizations.

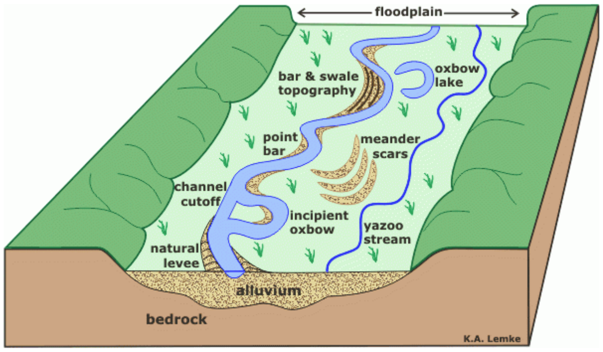


Fig. 2 - View of a floodplain (https://www.revision.co.zw/floodplains-and-levees/)

Alluvial fans are result of deposition by a river or stream after it exits a steep, narrow channel and enter into a more open area. They are usually associated with ephemeral streams in arid locations (Death Valley, Tarim Basin), but can appear elsewhere as well, including Mars and possibly Titan.

Deltas are similar to alluvial fans, but exist at sites where rivers or stream empties into bodies of standing water. The sudden reduction in flow causes particles to be deposited, first the largest particles, then smaller one further downstream, with some even entering the ocean to form subaqueous deltas. Due to the small gradient and low velocity, the river would develop into smaller channels, which can often shift and change. The exact shape and form of the delta depend on factors such as tide, wave, sediment properties, and the river itself.

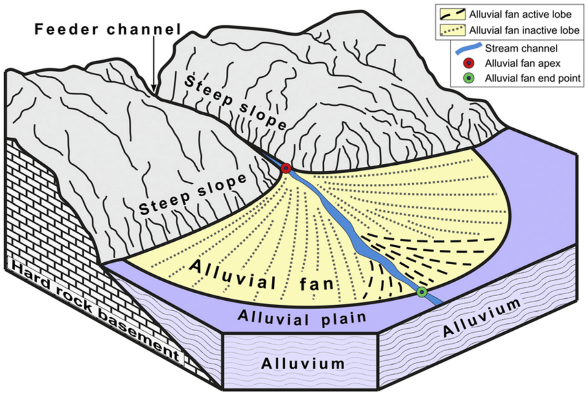


Fig. 3 - Illustration of a fluvial fan (https://www.researchgate.net/figure/Schematic-representation-of-a-typical-active-alluvial-fan-at-a-mountain-front_fig1_305953421)

Fig. 4 -*Left*: Image of channels in a delta, note the sediments in the sea that form the subaqueous delta (https://www.worldatlas.com/articles/what-is-a-river-delta.html)
Right: View of the Nile Delta from ISS, noting the urbanization and economic importance of the area (https://en.wikipedia.org/wiki/Nile_Delta#/media/File:Nile_delta_landsat_false_color.jpg)

Deltas are often host to a diverse number of life forms, and are important wetland environments. They are valuable farmland, and combined with their inland and seaward connections, deltas also often heavily settle, such as at the Nile, Yangtze, and Rhine, among many others. This process has often vastly changed morphology of the deltas, including prevention of natural processes that could endanger the human occupants.

Drainage Systems:

Streams are organized into drainage systems, which removed water and sediments in its drainage basin. They exhibit certain features depending on the surrounding landscape, bedrock, and gradient.

Dendritic pattern - the most common drainage pattern, developed on gentle slopes forming many tributaries.

Parallel patterns develop from steep slopes that allow few tributaries and cause channels to travel in same direction.

Trellis patterns - characteristic of folded mountains, where streams flow parallel to rides, and smaller tributaries coming down from the ridge flanks enter at right angles.

Rectangular pattern - form from intersecting fault and fracture systems, creating right angles in the channels.

Angular/radial patterns - streams flow in all directions from a central peak and are often found near volcanic peaks.

Degranged/contorted systems - irregular due to other geological features in the area.

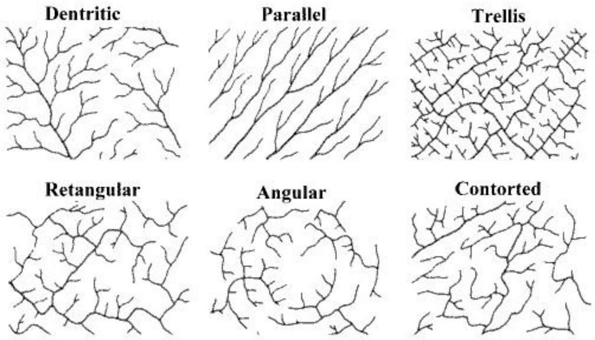


Fig. 5 - Illustration of several different drainage patterns (http://www.latestgkgs.com/drainage-pattern-3617-a)

References (lots of websites):

https://www.nationalgeographic.org/encyclopedia/alluvial-fan/
https://www.nationalgeographic.org/encyclopedia/delta/
http://ion.uwinnipeg.ca/~wbuhay/July%2011.htm
https://www.nps.gov/subjects/geology/fluvial-landforms.htm
https://en.wikipedia.org/wiki/Downcutting
http://www.earthonlinemedia.com/ebooks/tpe_3e/fluvial_systems/drainage_patterns.html

Physics of Fluvial Processes

Claire Cook

Primary Erosion

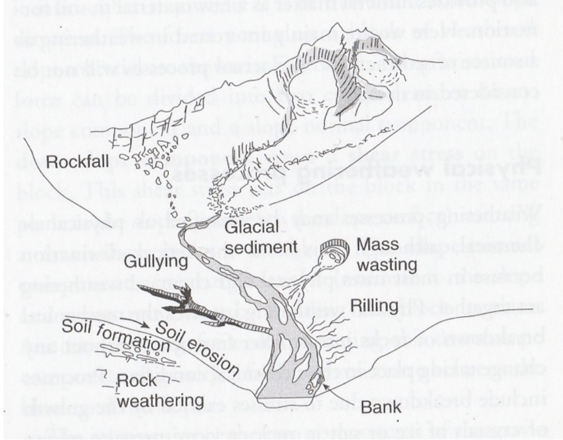


Figure 1: Sources of Sediment (from Charlton 2008)

Primary erosion refers to the erosion of material that has not been previously eroded or transported [1]. Fluids are one way to cause this type of erosion (see Figure 1 for others), either by impact of rain drops or by sheet flow. Rain drops impart kinetic energy which can detach material [1]. Rainfall that doesn't evaporate or infiltrate into the surface will form sheet flows over it [1]. These impart a shear stress on the surface, which is given by

$$\tau = \rho g z \, sin(\alpha)$$

where ρ is the density of the fluid, z is the depth of the fluid, and α is the slope of the surface (see Figure 2) [2].

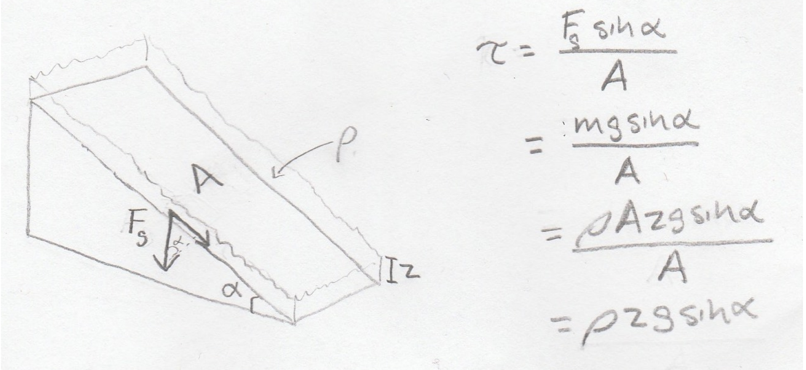


Figure 2: Diagram and derivation of shear stress imparted on a surface by a flow

For the fluid to entrain material, a critical shear stress must be exceeded, which is given by

$$\tau_c = (\sigma - \rho) g d \theta_c$$

where σ is the density of the entrained material, *d* is the particle diameter, and θ_c is called the Shields parameter [2]. The Shields parameter in turn depends on the boundary Reynolds number (a measure of fluid turbulence near the bed, related to near-bed velocity, grain size, and viscosity) [1].

Random variations in topography cause concentration of fluid into low areas, which then erode more because of the greater shear stress caused by increased fluid depth, forming small channels called rills which can transport sediment [2].

Channel Erosion

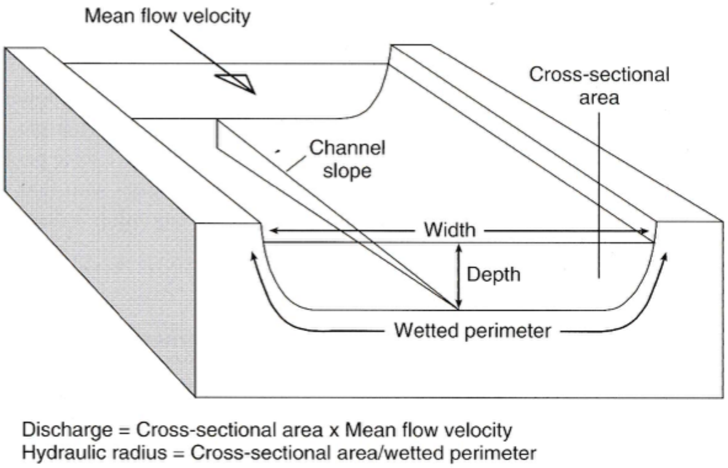


Figure 3: diagram depicting channel parameters (from Charlton 2008)

Channel erosion can be related to the flow velocity. The most general equation for this, the Darcy-Weisbach equation, comes from considering the gravitational force driving the fluid downstream versus the fluid resistance, and is given by:

$$v = \sqrt{\frac{8gR\ sin\alpha}{f}}$$

where v is the mean flow velocity, R is the hydraulic radius (see caption of Figure 3), and f is a friction coefficient, which is a function of the Reynolds number for the flow [2].

Bedrock Channels [3]

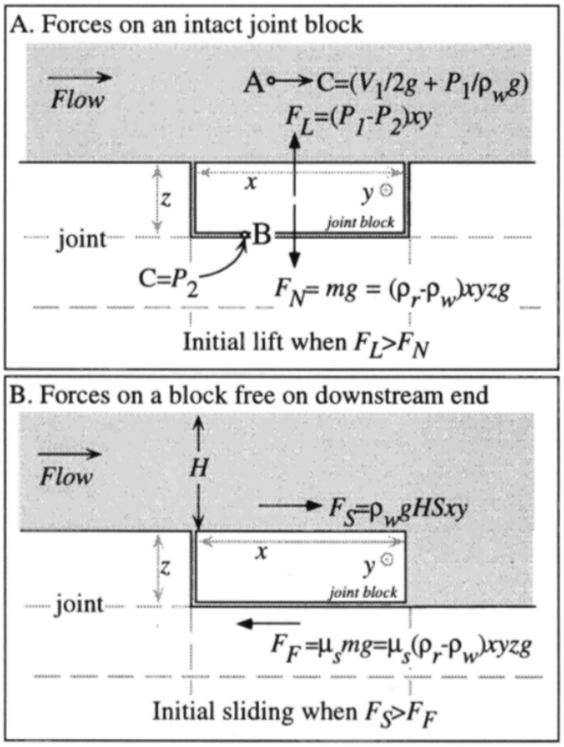


Figure 4: diagram depicting forces on a block in a channel (from Hancock et al. 1998)

There are two main types of erosion in bedrock channels. Block quarrying occurs either through lifting generated by pressure differences or by sliding in response to shear stress on the block's upper surface. Abrasion is the removal of material from a rock surface through impacts by entrained sediment. Cavitation, the formation and subsequent implosion of bubbles, creating high powered jets of fluid, can also be relevant at high flow velocities.

In the case of block quarrying by lifting, the force caused by the pressure on the bottom of the block from fluid in the joint along with the buoyancy must exceed the pressure exerted on the top face of the block and the gravitational force (see Figure 4). The pressures above and below the block can be related to the fluid velocity through the Bernoulli equation:

$$P_1 + \frac{1}{2}\rho_f {v_1}^2 + \rho_f g h_1 = P_2 + \frac{1}{2}\rho_f {v_2}^2 + \rho_f g h_2$$

where (in this context), P_1 and P_2 are the pressures below and above the block, v_1 and v_2 are the fluid velocities below and above the block (the velocity below is assumed zero), and h_1 and h_2 are the heights above the assumed ground level (assumed to be the same).

Setting the forces equal and solving for the threshold velocity gives

$$v = [\frac{2gz}{\rho_f}(\rho_r - \rho_f)]^{1/2}$$

where z is the thickness of the block, and ρ_f and ρ_r are the fluid and bedrock densities respectively.

In the case of sliding, the shear stress due to the gravitational force of the fluid acting at the top of the block ($\rho_f gSHxy$) has to exceed the frictional force, proportional to the normal force acting at the bottom of the block ($\mu_s g(\rho_r - \rho_f)xyz$). Rearranging to solve for HS gives

$$HS = \frac{z\mu_s}{\rho_f}(\rho_r - \rho_f)$$

where H is the depth of water above the block, S is the channel slope (note: $\sin\alpha$~$\tan\alpha$~S for small α), and μ_s is the coefficient of static friction. H~R for wide, shallow streams; in this case using the equation for velocity above, we can say that $v \sim (HS)^{1/2}$ and that means

$$v \sim [\frac{z\mu_s}{\rho_w}(\rho_r - \rho_w)]^{1/2}$$

meaning that the water velocity needed to quarry a block is proportional to $z^{1/2}$ or the block thickness that can be quarried is proportional to v^2 in both the lifting and sliding cases.

The material removed by abrasion is proportional to the kinetic energy delivered by impacts and on how susceptible the rock is to them. The abrasion erosion rate can be written as

$$\frac{dz}{dt} \sim \frac{S_a C_{sed} {v_g}^2 v_f}{2\rho_r}$$

where S_a is the susceptibility of the rock (related to properties like density and hardness), C_{sed} is the mass concentration of a particular size of grain, and v_g and v_f are the grain and fluid flow velocities respectively.

Other complications are involved that aren't discussed here, such as that for block quarrying to occur, the joint spacing must be large enough and more massive rocks require prior cutting by abrasion, and that for abrasion to occur the sediment must be able to decouple from the flow and be flung against the bed.

Alluvial Channels [1]

Alluvial channels are those cut into sediment previously laid down by fluvial processes. Fluids erode these channels by detaching and entraining grains. Smaller particles are entrained more readily and their removal leads to an overall weakening of the structure. Mass wasting and other processes are also involved in the erosion of these channels.

Sediment Transport and Deposition

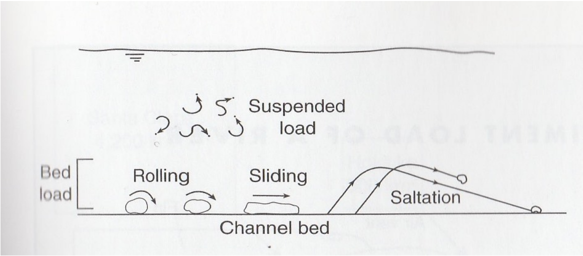


Figure 5: Diagram depicting modes of sediment transport (from Charlton 2008)

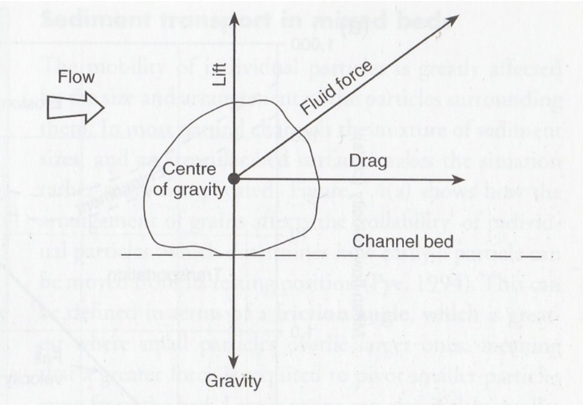


Figure 6: Diagram depicting forces on a sediment in a fluid (from Charlton 2008)

Water flows faster over particles than under them. The Bernoulli equation then dictates that the pressure above the particles must be lower to compensate. The lift generated by this, if larger than the gravitational force, will theoretically lift and entrain the particle (at least if you ignore complications like other particles) [1]. There's also a drag force related to the shear stress.

Larger particles, called bedload, may not actually be lifted; instead, the drag force may cause them to roll or slide along the bed. Some of these particles may be lifted then dropped again (saltated) if the lift doesn't continue to be large enough to overcome gravity [1]. Smaller particles, the suspended load, are carried by advection and turbulent diffusion. In their case, staying aloft requires that the upward velocity in the turbulent eddies exceeds their "fall velocity" [4], which depends on gravity and drag [5].

Deposition occurs when the forces lifting particles no longer exceed those pulling them down. Decreases in velocity are one cause, which in turn might be caused by, among other things, a decrease in channel slope or an increase in the cross-sectional area of the channel (flow continuity requires that A*v be constant) [1].

Implications for fluvial processes on other bodies

Most of the quantities discussed (like shear stress and flow velocity) are dependent on the local gravitational acceleration and fluid density, so they would be decreased by the lower g on bodies like Mars and Titan and the lower fluid density for methane on Titan. This could potentially impact the fluvial processes on these bodies, although the thresholds for entrainment/erosion also depend on g and ρ, which could offset the impact.

References

[1] Charlton, R., 2008. Fundamentals of fluvial geomorphology. Routledge, New York. [2] Melosh, H. J., 2011. Planetary Surface Processes. Cambridge University Press, New York. [3] Hancock, G.S., Anderson, R. S., Whipple, K. X., 1998. Beyond Power: Bedrock River Incision Process and Form. In: Tinkler, K. J., Wohl, E. E. (Eds.), Rivers Over Rock: Fluvial Processes in Bedrock Channels. American Geophysical Union, Washington, D. C., 38-46. [4] Bagnold, R. A., 1966. An Approach to the Sediment Transport Problem from General Physics. Geological Survey Professional Paper 422-I. [5] Chanson, H., 2004. Sediment transport and sediment properties. In: Hydraulics of Open Channel Flow. Elsevier Butterworth-Heinemann, Burlington, 151-168.

Native American History: The Navajo

Indujaa Ganesh

The United States of America (the U.S.) has over 300 Native American tribes within its present-day borders. The largest of these tribes is the Navajo Nation. The Navajo Nation comprises ~71,000 sq. km., mostly in northeastern Arizona, but including portions of northwestern New Mexico and southeastern Utah. (Figure (1)). The people of the Navajo tribe refer to themselves as 'Dine' which means 'the People' in their native Athabascan language. They migrated from regions in the North, which are now parts of Canada and Alaska. The exact details of when they reached the Colorado Plateau are still unclear, but they were by no means the first inhabitants of this region. The American Southwest was already populated by the Pueblos who referred to the Navajo as the Apache which means 'the enemy'. The Navajo were originally hunters and gatherers before their interaction with the very first European settlers in the country.

Early history

The Spaniards first came to the Southwest in the 16th century with three main objectives: to (1) resettle (2) convert the Indians to Catholicism and (3) teach the Indians a 'better way of life'. They brought with them domesticated animals, guns and tools. There was exchange of cultural practices between the two groups. The Indians learned to build Adobe houses, to grind wheat to make bread, to ride horses and to care for domestic animals. The Spaniards, in turn, learned about cooking with corn and corn meal. Though the Native Americans were friendly to the Spanish settlers at first, things quickly turned sour when the Spanish started to invade the Native American territory, capture their best farmlands, and take their women and children as slaves. The Spanish occupation of the Southwest U.S. lasted from 1598 to 1821 with a story cycle that involved enslavement of the Native Americans by the Spanish and retaliation by the natives in the form of frequent raids. The Navajo, being the largest and the most dominant of the tribes, got the major share of the blame for the rebellious activities.

Canyon de Chelly Navajos and the Long Walk

Mexico became sovereign from Spain in 1821; but was invaded by the U.S. troops in 1846. the U.S. government took over the lands in New Mexico after the signing of the Treaty of Guadalupe Hidalgo. Neither the Spanish nor the Mexicans had succeeded in gaining complete control over the Navajo territory; and nor did the U.S. during the 1st 17 years.

There were various attempts to make peace with the Native Americans during this period. An example of relevance here was when Col. Washington signed a peace treaty with three Navajo leaders at the mouth of Canyon de Chelly in 1849. Though the treaty was ratified by the U.S government, the Native American raids continued as before because they were a diverse group of tribes with several different leaders. Both sides failed in honoring the terms of the many treaties that were signed, the custom has been to blame the Native Americans for breaches in the terms of the treaty. Another event of importance that happened during this period was the establishment of Fort Defiance, the first major military post in Navajo country. The U.S. government made a radical decision in the early 1860s to relocate all the Native American tribes to a designated land where they could be held in captivity and taught to live a ‘civilized’ form of life. The campaign, which started in spring of 1863, was led by Col. Kit Carson. He was able to negotiate with a few of the Navajo tribes but not those of Canyon de Chelly. His decisive move was the invasion of Canyon de Chelly in 1864. The American troops under Col. Carson killed Navajo livestock, destroyed their cornfields, burned down their hogans and by doing so, laid waste to the country and destroyed the Navajo economy. To escape the enemy troops, many of the Navajo people retreated to the high mountains and deep canyons in the West that was uncharted water to the U.S. troops at that time. Others, too weak to resist, surrendered and were forced to partake in the ‘Long Walk’ to Fort Sumner on the Pescos river in Eastern New Mexico.

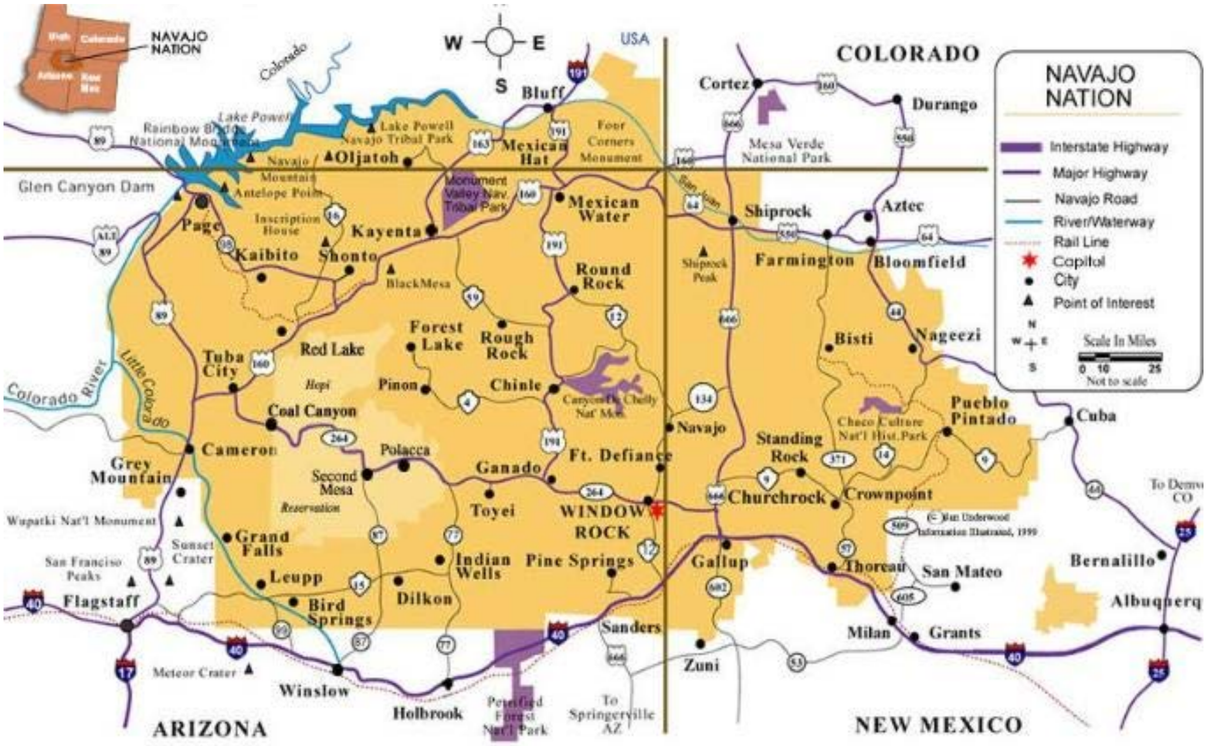


Figure – 1: Map of the Navajo Nation

Gradually, 8000 Navajos were ‘captured’ in this manner and forced to make the 300-mile walk to Fort Sumner which was proclaimed as a reservation by the U.S. government in 1864. Soon enough, the Navajo way of life was changed from raiding and herding to that of closely supervised, sedentary prisoners. While being held captives, Americans tried to enforce upon the Navajos the American way of life, which is the only one they believed to be right. In addition, the Navajo were constantly plagued by raids from other Indian tribes, pest infestation of crops, lack of adequate food and water, sickness and disease.

After 4 long years of suffering, the Navajo people started making petitions to return to their homelands. After several negotiations, the 8th and final treaty between the U.S. and the Navajo was signed in 1868. The Navajo people could finally return to their homeland. The Navajo reservation, as created by this treaty in 1868, encompassed only about 10% of the ancestral Navajo homeland.

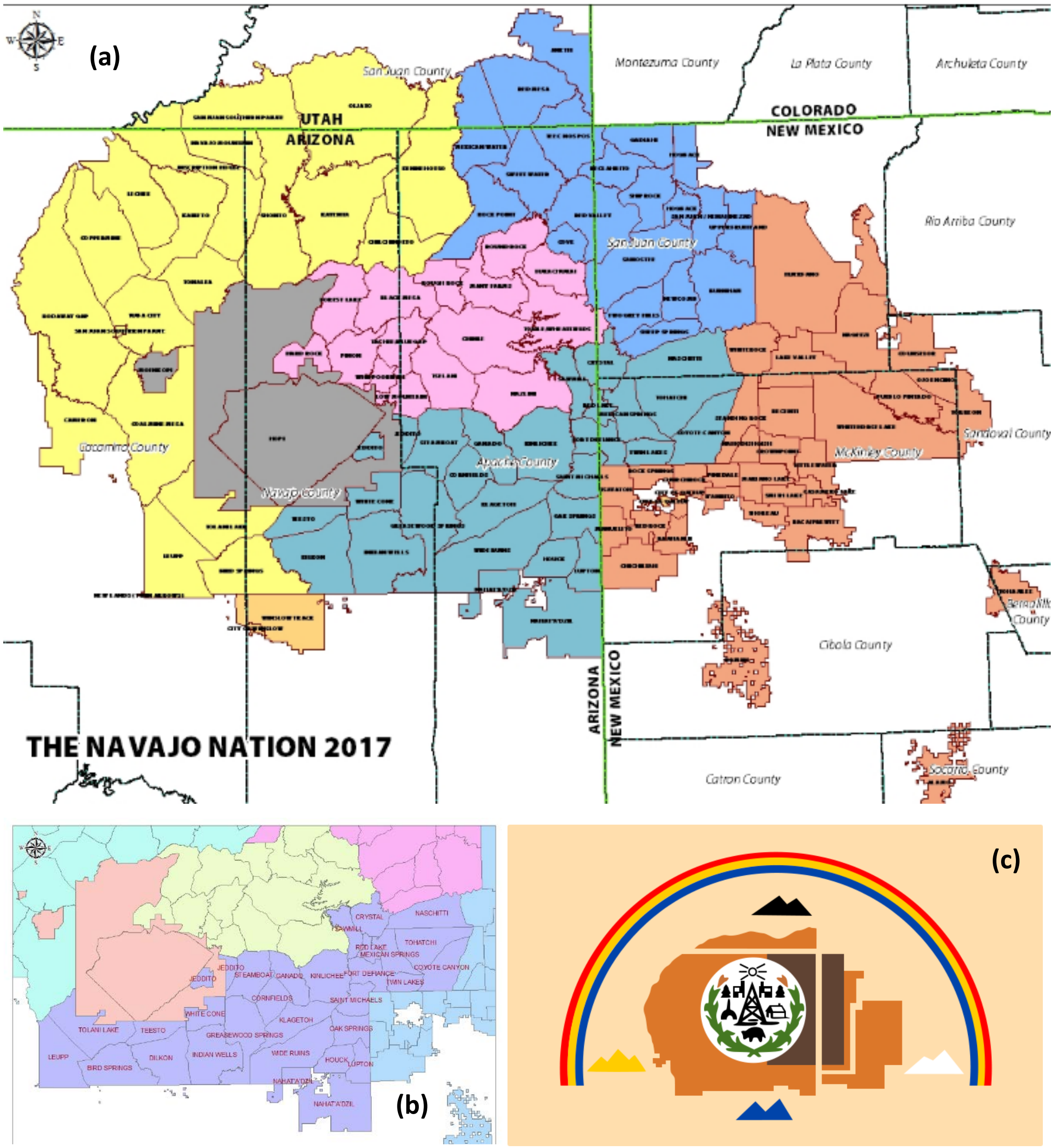


Figure 2: (a) Political map of the Navajo Nation. (b) Political map of Ft. Defiance agency. (c) The Navajo Nation flag.

Government structure

The seat of the Navajo Nation government is Window Rock, Arizona. Native Americans have significant rights of self-governments under the U.S. Constitution. Tribal governments have the power to tax, to pass their own laws and to have their own courts. State governments usually do not interfere with this. Congress, however, has the power to pass laws that govern Indian tribes and their members. Only federal and tribal laws apply to tribe members (unless Congress decides otherwise). Many American Indian tribes have adopted constitutions similar to the U.S. Constitution.

Local government

At a local scale, the Navajo Nation is divided into Chapters. The Nation is broken into 5 agencies and each agency has its own Chapters (Figure 2(a) & (b)). There currently 110 Chapter Houses throughout the nation, which serve as local administrative centers for geographical regions. Before the 1990 tribal elections, the tribal council system of government was reorganized into executive, legislative, and judicial branches. In 1990 Navajos elected a tribal president for the first time, rather than a tribal chairman.

Tribal government

The Navajo Nation government is structured around a 3-branch system.

1. The Executive branch is headed by the President and the Vice-President. They are elected by the popular vote of the Navajo people.
2. The Judicial branch has the Chief Justice at the top of the hierarchy. The appointment of a Chief Justice is made by the President and is confirmed by the Navajo Nation council.
3. The Legislative branch comprises 88 council delegates of the Navajo Nation Council. The councilmen are elected by the registered voters of the 110 Navajo chapters.

The Navajo Nation flag (Figure 2(c)) was adapted in 1968.

Navajo land today

Most of the Navajo Nation land is high-altitude desert. However, the area has ~ 50,000 acres of forest. Uranium, oil, gas and coal are found underground. Over the last century, the Navajo people mostly used their land for grazing livestock. Over the years, the land resources have dwindled down due to overgrazing and misuse of groundwater by oil and gas companies.

The living conditions in the reservation were quoted to be ‘four to five decades behind majority of the Americans’ by Rocky Mountain News. Many areas do not have telephone service and electricity. The people of the Reservation suffer from unemployment and lack of job opportunities. The isolation and limited resources within the Nation makes it hard for the inhabitants to have adequate housing, public health infrastructure and services. Great Falls

Tribune reported that the Federal Government spends half as much on health programs per tribal member as it does on health program for Americans.

The people of Navajo tribe have come a long way since signing the treaty of 1868 which identified them as a sovereign territory. Despite the troubles that have plagued them over the years, the people of the tribe have shown great resilience. While most of the Navajo people speak English and participate in the larger U.S. economy, they have held on to their language, culture and customs. It is common to see traditional hogans standing next to modern houses and sheepherders on horse backs. The Navajo also remain renowned for their crafts that include handmade jewelry and handwoven rugs.

References

1. *The Navajo Way of Life: A Resource Unit* – Cordova Dahlia
2. www.navajo-nsn.gov/govt.html
3. <u>Map courtesy:</u> Navajo Nation Land department (www.dinehbikeyah.org/Home/Maps)
4. navajochapters.org/
5. www.everyculture.com
6. www.nativepartnership.org/site/

Hopi & Zuni Pueblo People of the Southwest

Alessondra Springmann - PTYS 594A - Planetary Geology Field Studies - September 2018

Both the Hopi and Zuni tribes are sovereign nations, descended from the Ancestral Puebloan people who arrived in this region around 800 CE. Pueblo is a Spanish word for “town” or “village”, and is used to describe communities of Indigenous people in the North American Southwest who live in multi-storied apartment structures of adobe and stone.

Pueblo communities center around agriculture (corn), pottery, and religion of deities, spirits, and nature. Prayer includes use of materials such as cornmeal, prayer sticks; religious ceremonies include dancing with singing and drumming. Communities are organized around matrilineal clans and ceremonies, and value pottery, jewelry, painting, and weaving as ways to express their cultural values.

Presently, 21 federally recognized Pueblo communities inhabit Pueblo structures and maintain their traditional cultures, despite efforts by Spanish and US federal forces to colonize, convert, enslave, forcibly relocate, and otherwise commit genocide against Pueblo peoples. In 1680, Pueblo peoples organized an uprising to expel Spanish colonists and the Catholic Church from their lands.

Hopi

The Hopi Tribe is a sovereign agricultural nation located in northeastern Arizona, entirely surrounded by the Navajo Nation. The reservation occupies part of Coconino and Navajo counties, encompasses more than 1.5 million acres, and is made up of 12 villages on three mesas. The present villages were settled around 700 CE. Hopi call their land Hopitutskwa, and live in sacred covenant with Maasaw, the ancient caretaker of the Earth. Descended from the Ancestral Puebloans, or Hisatsinom, the Hopi name is short for Hopituh Shi-nu-mu ("The Peaceful People", or "behaving ones, ones who are mannered, civilized, peaceable, polite, who adhere to the Hopi way.")

Hopi are known as accomplished pottery makers. Pottery was made of wet clay then buried in sand until dry. Pieces were used for bathing and cooking, as well as telling stories with their designs. The design at right is by Rainy Naha.

Katsinas or katsinam are the immortal beings that bring rain, control other aspects of the natural world and society, and act as messengers between humans and the spirit world. In Hopi cosmology, the majority of katsinas reside on the Humphreys Peak. Each year from winter solstice to mid-July these spirits, in the form of katsinas, come down to the villages to dance and sing, to bring rain for the upcoming harvest, and to give gifts to the children. Hopi katsina

figures (tithu or katsintithu), also known as kachina dolls, are figures carved, typically from cottonwood root, to instruct young girls and new brides about katsinas. The katsina pictured is circa 1960.

The Hopi traditional "squash blossom" hairstyle appeared in popular culture in the 1970's with Princess Leia's two twisted hair buns in *Star Wars: A New Hope*. The Hopi hairstyle for unmarried women, a symbol of fertility, is two loops of hair, wrapped around a U-shaped wooden "hair bow", wrapped in a figure-eight pattern, then tied in the middle and spread to create the distinctive shape. This hairstyle later inspired Bjork's hair on her Homogenic album cover.

Zuni

The Zuni Pueblo is a sovereign tribe in western New Mexico, approximately 450,000 acres in size (a percentage of its size prior to the 1840's). The main reservation, is located in the McKinley and Cibola counties in the western part of New Mexico. The tribe has land holdings in Catron County, NM and Apache County, AZ, not adjoining to the main reservation. The Zuni call themselves A:shiwi, and their land Halona:wa or Halona Idiwan'a, "Middle Place". Zuni is perhaps the most remote Pueblo, and its unique language reflects the isolation from other Pueblo communities.

Zuni have been farmers in their present location for up to 4,000 years, cultivating corn with irrigation systems. Recently, Zuni have moved from farming to cattle and sheep herding, and maintain success at ranching due to resource management and community support. Additionally, Zuni are known for their traditional arts and crafts, including pottery and jewelry. Prior to digging clay for pottery, women give thanks to the Earth Mother Awidelin Tsitda. Clay is coiled and shaped into pots, then fired in kilns. Pottery is a community effort, and the process is treated with reverence for the purpose of the clay. The pictured Zuni pottery piece here is an owl with two owlettes.

The Zuni learned Mexican silversmithing techniques and use them to create a variety of jewelry pieces, refining Navajo techniques and using stone inlays, including turquoise. Zuni jewelry is a work of art and an expression of interconnectedness. Fetishes, or small animal carvings worn for ceremonial or religious purposes, are rarely signed by the artist, because traditional jewelry is believed to belong to the entire community.

Similar to the Hopi, Zuni also revere deities, including Earth Mother, Sun Father, and Moonlight-Giving Mother, and their religion is kachina-based, with ceremonies occuring during the growing season.

Ancestral Puebloans: a note about terms

Throughout the Southwest there are references to Ancestral Puebloan culture. About 1,400 years ago a group of people living in the Four Corners region chose Mesa Verde for their home. For more than 700 years they and their descendants lived and flourished here, eventually building elaborate stone communities in the sheltered alcoves of canyon walls. Then, in the late 1200s CE, in the span of a generation or two, they left their homes and moved away. Though the Ancestral Puebloans survived previous changes in climate, the Great Drought (1276–99) probably caused massive crop failure, or could have combined with other factors; however, rainfall continued to be sparse and unpredictable until approximately 1450.

The descendents of the Ancestral Pueblo comprise the modern Pueblo tribes, including the Hopi, Zuni, Acoma, and Laguna. As farmers, Ancestral Pueblo peoples and their nomadic neighbours were often mutually hostile: this is the source of the term “Anasazi”, a Navajo word meaning “ancestors of the enemy,” which once served as the customary scientific name for this group. Many current Pueblo people find the term offensive; hence, a switch in recent decades to using “Ancestral Puebloans”. However, is “Anasazi” sufficiently accurate to describe the modern Pueblo tribes? Modern Pueblo tribes trace their ancestry to nearly all of Arizona, and as far away as the Mexico City region — far beyond the Colorado Plateau where the Anasazi once lived.

Using any single, overarching name, politically correct or not, is simply misleading, because it reinforces the notion that the Anasazi were one distinct group of people. And that is just not true: the archaeological record and reports from living Puebloans reveal myriad ethnicities occupying the Four Corners a thousand or so years ago.

Bears Ears

In 2015, leaders from five tribes–Hopi Tribe, Navajo Nation, Ute Mountain Ute Tribe, Pueblo of Zuni, and Ute Indian Tribe–founded the Bears Ears Inter-Tribal Coalition to conserve the cultural landscape of Bears Ears, a national monument in southern Utah. This area contains sacred lands for these five tribes, including 100,000 archeological sites. The unprecedented coalition represents the first unified modern effort of these groups to work together, including groups with long-standing animosity toward one another. Bears Ears is where tribal traditional leaders and medicine people go to conduct ceremonies, collect herbs for medicinal purposes, and practice healing rituals stemming from time immemorial, as demonstrated through tribal creation stories. In 2016, President Obama proclaimed Bears Ears a national monument; however, the current administration has made efforts to shrink the monument, resulting in a lawsuit from the tribal coalition as well as outdoor/conservation advocacy groups.

References

“About Hopi.” *Hopi Education Endowment Fund*, 2018, www.hopieducationfund.org/about-hopi/.

“Ancestral Pueblo.” *Archaeology Southwest*, 2018, www.archaeologysouthwest.org/ancient-cultures/ancestral-pueblo/

“Native American Tribes of New Mexico.” *Traditional Indian Stories*, www.native-languages.org/nmexico.htm. Accessed 4 Sept. 2018.

“Proposal Overview.” *Protect Bears Ears*, 2015, bearsearscoalition.org/proposal-overview/

“Zuni Jewelry History.” *Native American Jewelry*, 2018, www.silvertribe.com/zuni-jewelry-information.

Anthony, Alexander E., Jr. “Hopi Harvester (Corn Dancer) Katsina Doll.” *Adobe Gallery Art of the Southwest Indian*, 2018, www.adobegallery.com/art/hopi-harvester-corn-dancer-katsina-doll

Anthony, Alexander E., Jr. “Zuni Pueblo Large Pottery Owl with Two Owlets.” *Adobe Gallery Art of the Southwest Indian Alexander E Anthony Jr*, 2018, www.adobegallery.com/art/zuni-pueblo-large-pottery-owl-with-two-owlets

Childs, Craig. “Anasazi: What's in a Name?” *Interior Overhauls Sage Grouse Conservation* -, 3 Oct. 2005, www.hcn.org/issues/307/15815

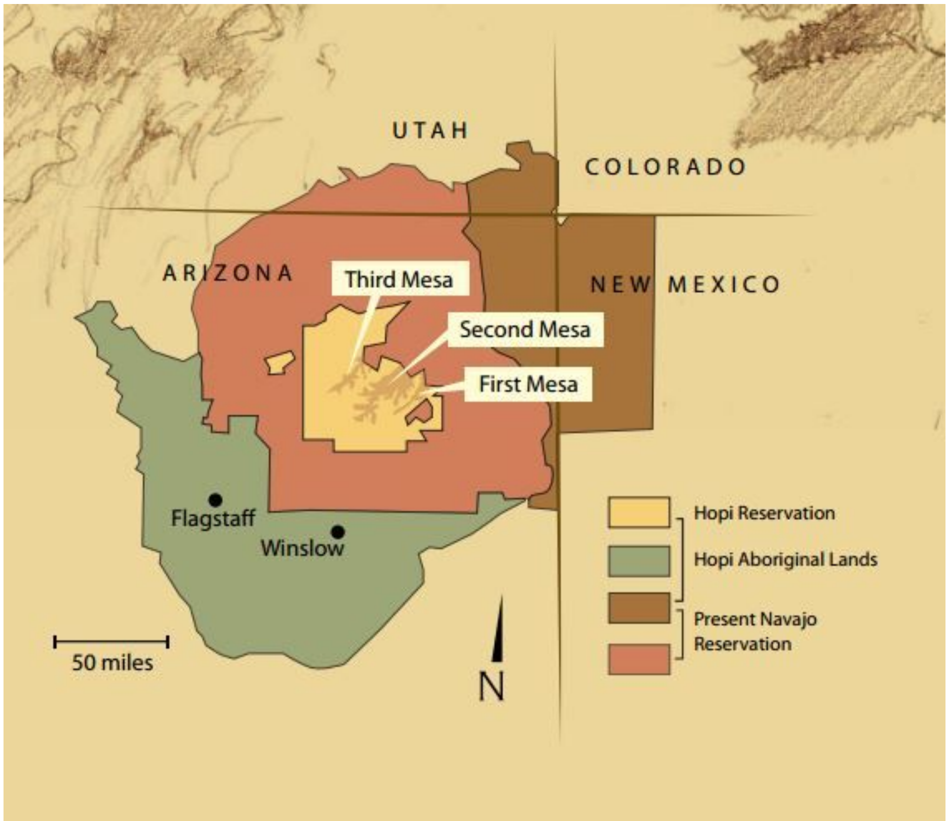
Drury, Flora. “The Story behind Princess Leia's Hairstyle.” *BBC News*, BBC, 28 Dec. 2016, www.bbc.com/news/world-us-canada-38452953

Morell, Virginia. “The Zuni Way.” *Smithsonian.com*, Smithsonian Institution, 1 Apr. 2007, www.smithsonianmag.com/history/the-zuni-way-150866547/

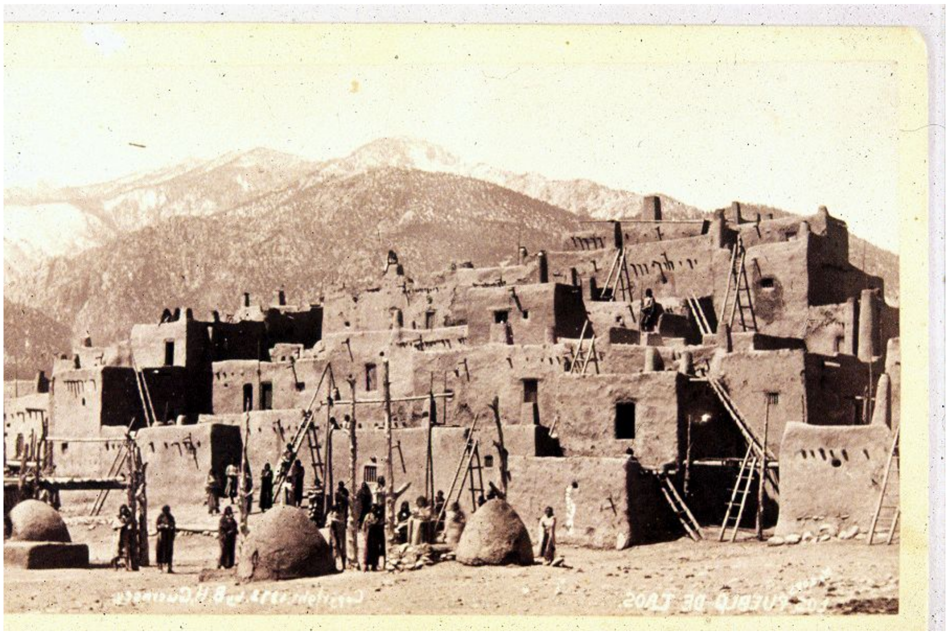
Naha, Rainy. “Hopi Pottery Bowl by Rainy Naha - Hopi Indian Pottery - Rainy Naha.” *Two Grey Hills*, 2018, www.fineindianart.com/product/hopi-pottery-rainy-naha

Native American Netroots, nativeamericannetroots.net/diary/tag/Pueblo%20Indians. Accessed 4 Sept. 2018.

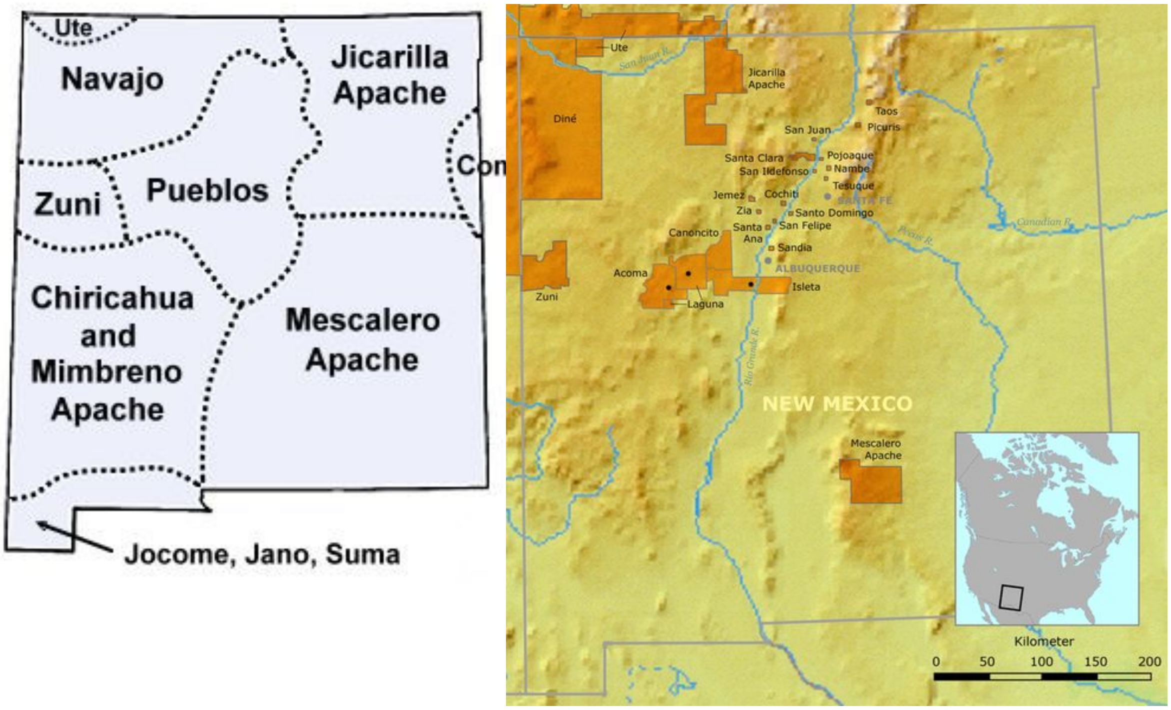
Thorne, Tanis. “Southwest Pueblos.” *Southwest Pueblos*, faculty.humanities.uci.edu/tcthorne/socec15/cosmicharmony.htm



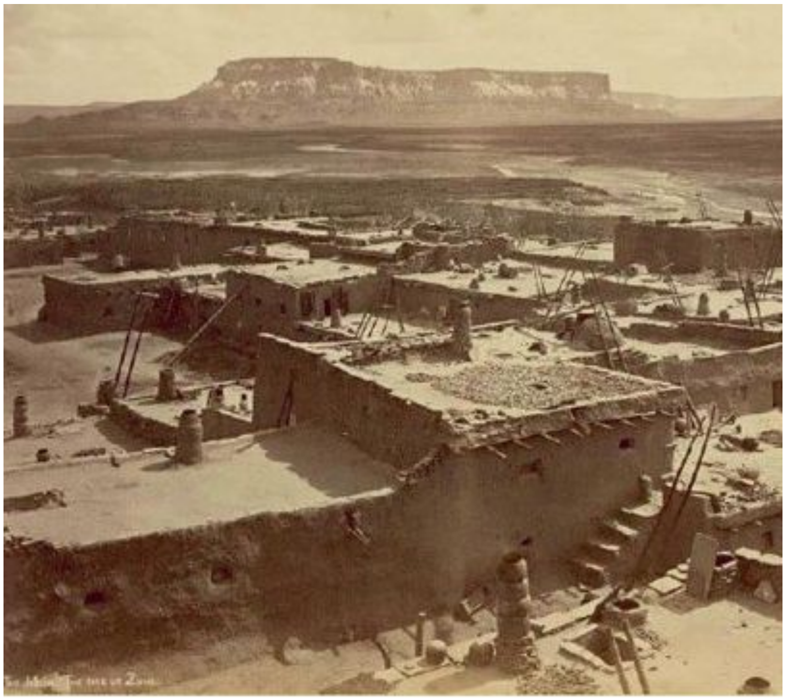
Hopi Reservation and Aboriginal Lands



Hopi Pueblo



Zuni Aboriginal Lands and present location of the Zuni Pueblo



Zuni Pueblo 1879 (Photo: John Hillers, Smithsonian)

The Colorado Plateau Province

Introduction

The Colorado Plateau Province serves as one of the largest Earth story books for humans to read and explore, and is often referred to as a Geological Wonderland. Running rivers incise deep canyons into the large crustal block known as the Colorado Plateau Province (CPP), and expose the ancient Precambrian rocks that comprise the bottom-most structure, revealing extremely metamorphosed mastiffs that are complex. Some of the deepest exposures in the Wind River Range, Wyoming are Archean, and are older than 2.5 Ga (Sims et al, 2001). Still considerably ancient, the rocks dating to the Proterozoic (2.5 Ga to 0.8 Ga) are more abundant throughout the plateau serving as the top portion of the crystalline basement rock. Ancient granites derived from mid-crustal depths that were marine sediments shoved down from paleo-tectonism show extensive volcanic intrusions and ultimately describe ancient volcanism. Such examples expose themselves in the Canyon de Chelly area as well as Colorado National Monument (USGS, 2017). Proterozoic sedimentary deposits co-exist with the ancient volcanism along the margins, revealing insight towards paleo-shorelines. The overlain crustal block of sedimentary formations tells the story of waxing and waning of shallow seas and deposition of marine life as well as terrestrial life. With erosion and uplift combined these sedimentary exposures pose scenic views and textbook deformation processes when the stratified units are faulted and shoved around. Young volcanism sprinkles the top of the CPP and some of the largest volcanic fields in the continental United States reside here.

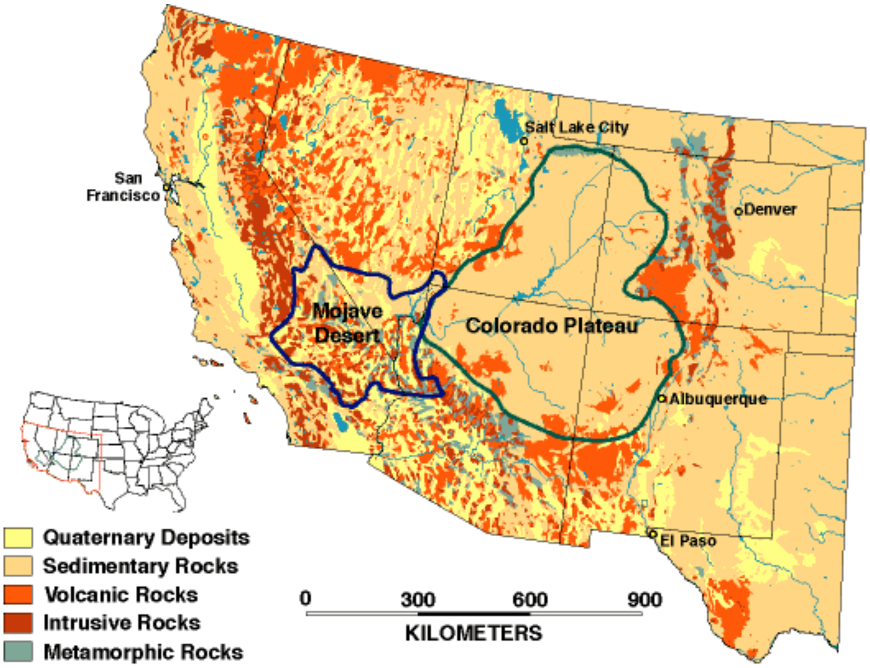


Figure: The Colorado Plateau Province. Credit: The Golden State

Colorado Plateau Province Now-ish

- Large standing crustal block of material, most of the rocks that make up the crustal block are relatively undeformed material. Uplifted by sub-crustal processes.

- Total area of 240,000 square miles and borders up between and extreme range of climates and state boundaries.

- The southern boundary is defined by the Mollogon Rim in Arizona, the eastern portion by the Rio Grande Rift in New Mexico, the west by the eroded portion of the edge of the Basin and Range, and the north by the great Rocky Mountains and the Uintas.

- Avg. elevation of CPP: 5,200 ft., ranges from 3,000 to 14,000 ft.

- The CPP experiences climates from the edges of the Sonoran desert, Mojave Desert, Alpine and huge amounts of grasslands and riparian biomes.

- Largely affected by a rain shadow effect from the high Sierra Nevada range.

- The CPP receives less than 10 inches/Earth year of rain.

- CPP has distinct gravity signatures, also thought to have a relatively thick crust below. There is also a very low heat flow associated with it.

- Colorado Plateau Province is divided into 6 sections (Rigby, 1977):

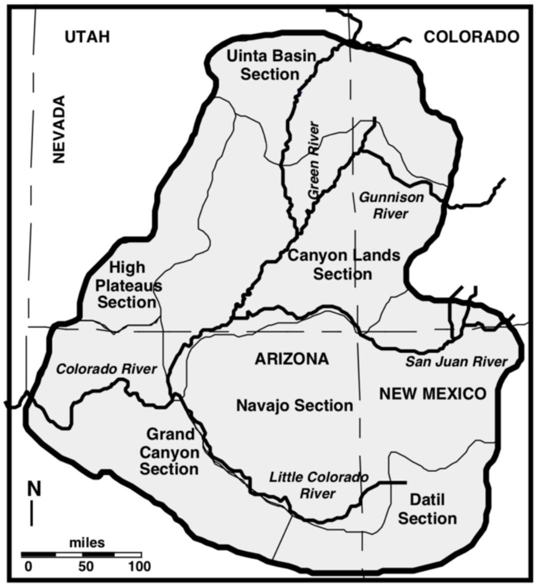


Figure: Sectional breakdown of the Colorado Plateau Province from Rigby, 1977.

1. <u>Grand Canyon section:</u>
    a. Highest elevation on CPP

Image: Grand Canyon looking north. Credit: NPS

2. <u>High Plateaus section:</u>
    a. Dominated by high, north-trending plateaus separated from each other by faults, examples are Bryce and Zion Canyon

Image: Bryce Canyon. Credit: Our Amazing Planet

3. Uinta Basin section:
    a. Structurally lowest part of CPP

Image: Oil mining in the Uinta Basin. Credit: Utah-Oil

4. Canyonlands section:
    a. Deeply incised canyons, contains large monoclines and laccolithic mountains

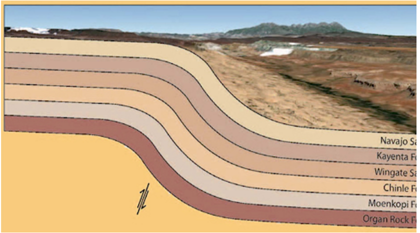


Figure: Monocline. Credit: Plants and Rocks

Image: Double Arch, Arches National Park.
Credit: Our Amazing Planet

5. Navajo section:
    a. Scarped by plateaus, less eroded than Canyonlands

Image: Monument Valley.
Credit: Our Amazing Planet

    b. This is where Canyon de Chelly sits within!

Image: Canyon de Chelly. Credit: NPS

A. M. McGraw

6. <u>Datil section:</u>
    a. Mostly volcanics

Image: Springerville Volcanic Field, 1,160 square miles over 400 dormant volcanic vents. 3rd largest volcanic field in the continental United States. Credit: Our Amazing Planet

Volcanic Igneous Features:

- Intrusive Laccoliths:
    - Injections of magma at shallow depths that create a continuous laccolith that runs along with the present sedimentary rock planes → makes the overlying strata to dome upwards
    - Oligocene to Miocene in age
    - Intermediate composition

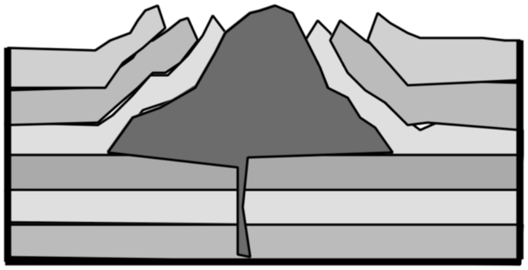


Figure: Laccolith

- Extrusive Volcanics:
    - Deposited less than 6 Ma, as young as 1,200 years
    - Older: andesitic
    - Younger: basaltic and occur as lava flows and cinder cones
    - Some lava flows went down slopes, the underlying sandstone has been eroded away and the lava flows have been left behind as strong ridges and inverted topography
    - Closest mapped volcanic feature to Canyon de Chelly is Black Rock Mesa

REFERENCES:

Foos, Annabelle, Geology of the Colorado Plateau, National Park Service.

Geological Resources Division, National Park Service, US Department of the Interior, (2007). Geologic Resource Evaluation Scoping Summary Canyon de Chelly National Monument, Arizona.

National Park Service, Colorado Plateau Province, *Series: Physiographic Provinces*.

Sims, P.K., Bankey, V., and Finn, C.A., 2001, Preliminary Precambrian basement map of Colorado-A geologic interpretation of an aeromagnetic anomaly map: U.S. Geological Survey Open-File Report 01-0364

United States Geological Survey, 2017, Precambrian Basement Rocks of the Colorado Plateau. *Geology of National Park*

The Natural Vegetation of Canyon de Chelly

By Kyle A. Pearson

The vegetation of Canyon de Chelly includes about 520 known species (Halse 1973). The vegetation within Canyon de Chelly is almost entirely within the transition zone (see Figure 1). The canyon ranges from desert grassland in the Chinle Wash to the woodlands in the Chuska Range (mountain range just east of Canyon de Chelly National Monument). The flora of Canyon de Chelly is divided into seven plant resource groups with each group briefly characterizing in terms of size, area, elevational extent and prominent vegetational cover. However, a depreciated classification system once simplified these seven groups into forest (pinyon-juniper), grasslands (short grass) and desert (sage brush) (Nichol 1952).

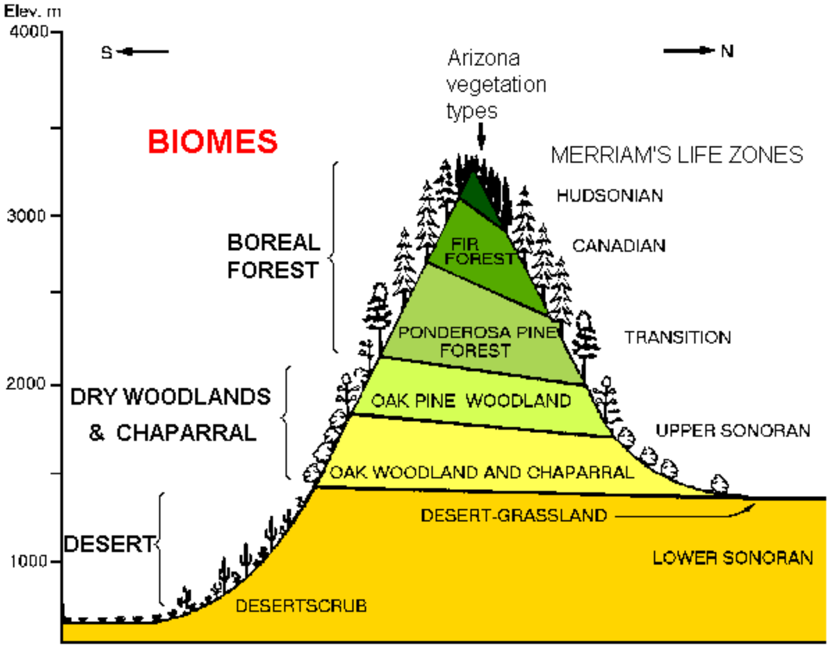


Figure 1. Arizona biomes adapted from Merriam 1890. The elevation range of Canyon de Chelly is roughly 1500 – 2000 meters above sea level. (geo.arizona.edu)

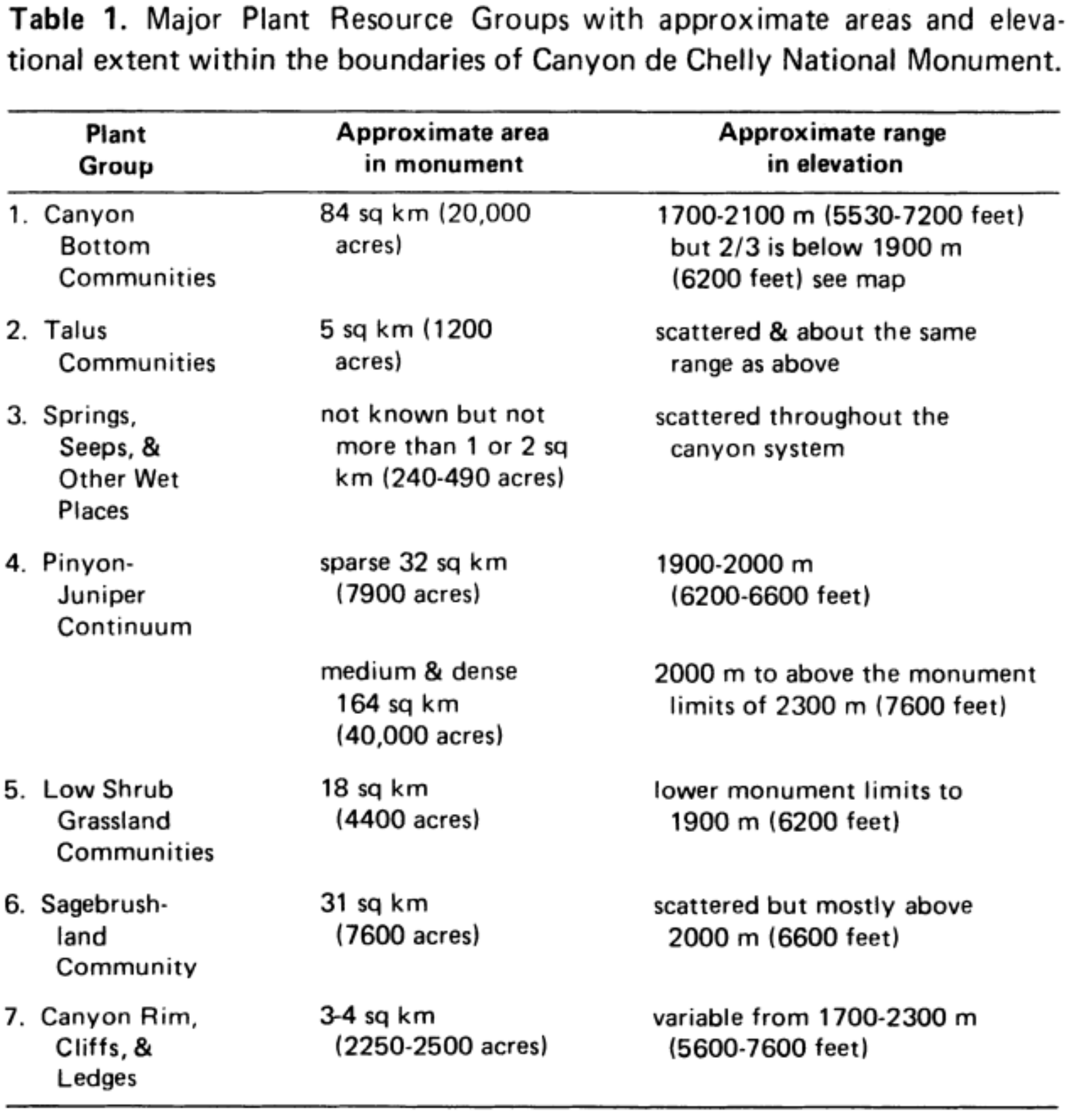


Table 1. Major Plant Resource Groups with approximate areas and elevational extent within the boundaries of Canyon de Chelly National Monument.

Plant Group	Approximate area in monument	Approximate range in elevation
1. Canyon Bottom Communities	84 sq km (20,000 acres)	1700-2100 m (5530-7200 feet) but 2/3 is below 1900 m (6200 feet) see map
2. Talus Communities	5 sq km (1200 acres)	scattered & about the same range as above
3. Springs, Seeps, & Other Wet Places	not known but not more than 1 or 2 sq km (240-490 acres)	scattered throughout the canyon system
4. Pinyon-Juniper Continuum	sparse 32 sq km (7900 acres)	1900-2000 m (6200-6600 feet)
	medium & dense 164 sq km (40,000 acres)	2000 m to above the monument limits of 2300 m (7600 feet)
5. Low Shrub Grassland Communities	18 sq km (4400 acres)	lower monument limits to 1900 m (6200 feet)
6. Sagebrush-land Community	31 sq km (7600 acres)	scattered but mostly above 2000 m (6600 feet)
7. Canyon Rim, Cliffs, & Ledges	3-4 sq km (2250-2500 acres)	variable from 1700-2300 m (5600-7600 feet)

Plant Groups

Table 1 shows the 7 plant resource groups as defined by Dennis 1975. Each group is not a strict ecological community but rather a resource area which contains one or more planet communities, and which would require distinctive methods of exploitation by canyon dwellers. Groups 4, 5 and 6 correspond to the three types in the Nichol's classification system while the other groups describe part of the canyon system.

The ancient inhabitants of the area, the Anasazi, could collect useful plants from the Canyon Bottom Communities. As the population grew, the plants were depleted, and the inhabitants had to range over increasingly greater distances to gather plant resources. The extent of the resulting reduction in native flora can only be inferred. However, as made evident from photographs in the late 1800s and early 1900s, the lower portion of the canyon system were devoid of the now common streamside trees and shrubs. Some of the common streamside trees in plant group 1 include *Populus wislizenii* (cottonwood), *Salix amygdaloides* (peach leaf willow), *Elaeagnus angustifolia* (Russian olive), and *Tamarix ramosissima* (saltcedar). Some of these trees were introduced for channel stabilization and erosion control in the 1930s and 1940s (Burgess 1973; Halse 1973). The Russian olive and saltcedar are native to Eurasia and could not have been present prior to 1500 A.D. Other useful plants found in the lower canyon include *Cleome serrulata* (bee plant), *Equisetum laevigatum* (horsetail), *Opuntia phaeacantha* (prickly-pear), and *Yucca angustissima* (narrow leaf yucca). The willow, carrizo and horsetail are restricted to the Canyon Bottom Communities.

The second largest area is low shrub and grassland on the drier terraces (Figure 2), with scattered trees of *Juniperus osteosperma* (Utah juniper), *Quercus gambelii* (Gambel oak), and *Acer negundo* (box elder). In general, the communities common to the bottom of the canyon system contain a diverse group of plants. About 61 percent of all native plants occur within the low shrub and grass land area.

The Talus Communities typically support as *Pseudotsuga menziesii* (Douglas-fir), *Amelanchier utahensis* (Utah serviceberry), and *Juniperus osteosperma* (Utah juniper). *Oryzopsis hymenoides* (Indian rice grass) is a prominent plant in the Talus Communities and it also provided food for the Anasazi. This area contains several useful shrubs including including *Ephedra viridis* (Mormon tea plant), *Fendlera rupicola* (Fendler bush), *Philadelphus microphyllus* (mock orange), and *Quercus turbinella* (shrub oak).

The fourth, and by far the largest resource group is the Pinyon-Juniper Continuum (Figure 2), which covers almost 60 percent of the monument. Despite the large area covered, only about 15 percent of the plants known in the monument occur here. This area contains mostly *Juniperus osteosperma* (Utah juniper) and *Pinus edulis* (Pinyon pine).

The fifth group, Low Shrub-Grassland, is located along the western edge of the monument, generally at or below 1900 m (6200 feet) in elevation (Table 1). The composition of this area has been changed by overgrazing in the past 200 plus years. It most likely contained palatable grasses and less of the unpalatable low shrubs. One grass, *Hilaria jamesii*, has managed to remain the dominant plant (14 percent cover) in the area sampled (just north of the Ledge Ruin Overlook road), but rabbitbrush and snakeweed appear more prominent, although their combined cover is only 10 percent. Of all native plants known to occur in the moment, about 18 percent occur in Low Shrub- Grassland Communities (Dennis 1975).

The Sagebrushland Community, the sixth plant resource group (Table 1), is the most homogenous group of the seven. One species, *Artemisia tridentata* (big sagebrush), accounts for over 90 percent of the total perennial vegetative cover (30 percent) in the area. Sagebrushland occurs primarily on the broad, flat areas along drainages above 2000 m (6600 feet) mixed with the Pinyon-Juniper which caps the hills and rocky areas. The herbs *Calochortus nuttallii* (segolily), *Delphinium scaposum* (larkspur), along with the grasses *Hordeum jubatum* (foxtail barley) and *Stipa comata* (needle and thread grass), are scattered throughout the Sagebrushland Community, but are not restricted to it. About 30 percent of the approximately 470 known native plants of the monument occur in the Sagebrushland Community (Dennis 1975).

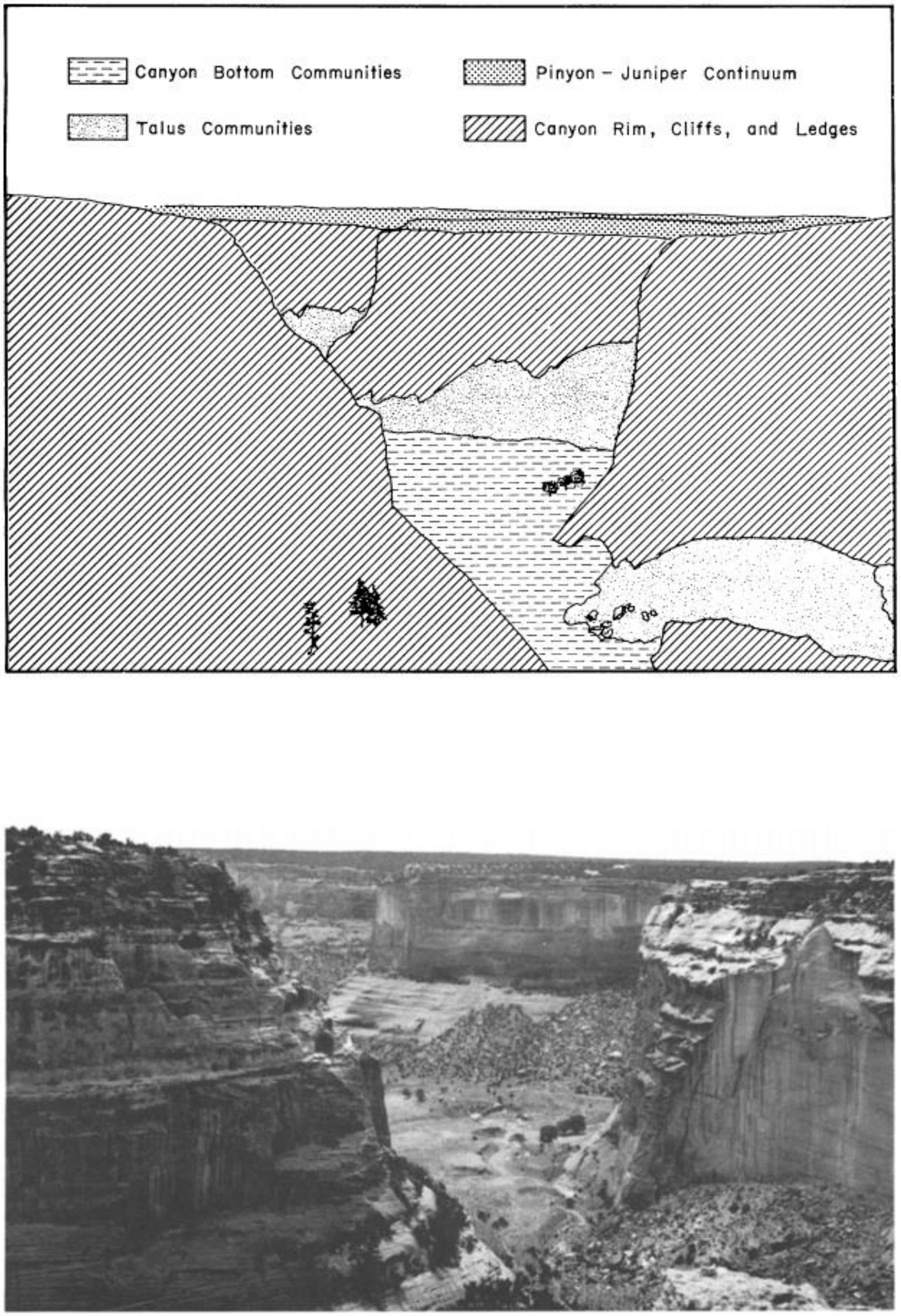
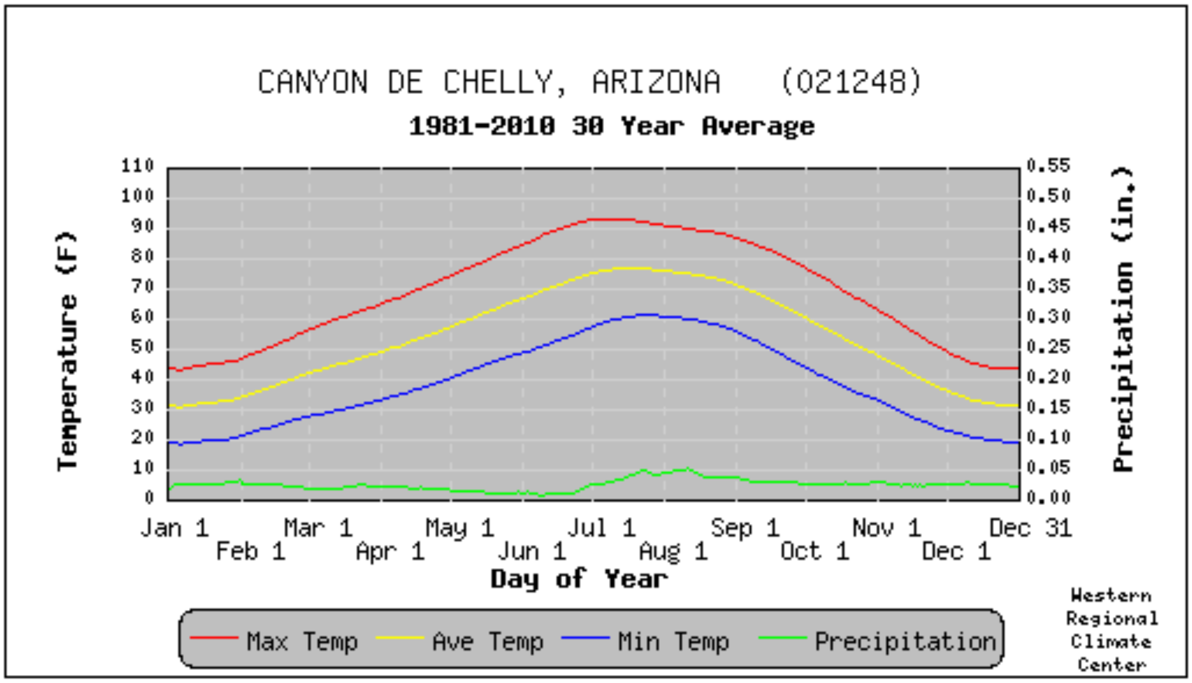


Figure 2. A view of Tseh-Ya-Kin Canyon looking out into Canyon del Muerto near Mummy Cave Ruins, Canyon de Chelly National Monument, Apache Count, Arizona, (May 6, 1974). Four of the seven Planet Groups (See Table 1) are shown. Not seen in this photograph are the following groups: Springs, Seeps & Other Wet places, Low Shrub Grassland and Sagebrush community. (Dennis 1975)

Weather

The average temperature and precipitation of Canyon de Chelly ranging from year 1981 to 2010 is plotted below



Data is smoothed using a 29 day running average.

The average precipitation is a little misleading, but it does show an increase in precipitation during the summer months of July and August indicative of the monsoons. The yearly average precipitation from 1970-2012 is 9.14 inches with the maximum rainfall being 17.95 inches in 1982 and a minimum rainfall of 3.29 inches in 1989.

Resources:

Canyon de Chelly National Monument - https://www.nps.gov/cach/index.htm

Western Regional Climate Center - https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?az1248

Dennis, Arthur. 1975 The Natural Vegetation of Canyon de Chelly National Monument

Halse, Richard R. 1973 The flora of Canyon de Chelly National Monument.

Burgess, T. L. 1973 Mammals of the Canyon de Chelly Region, Apache County, Arizona

Nichol, Alexander A. 1952 The natural vegetation of Arizona.

Populus wislizenii (cottonwood)

Salix amygdaloides
(peach leaf willow)

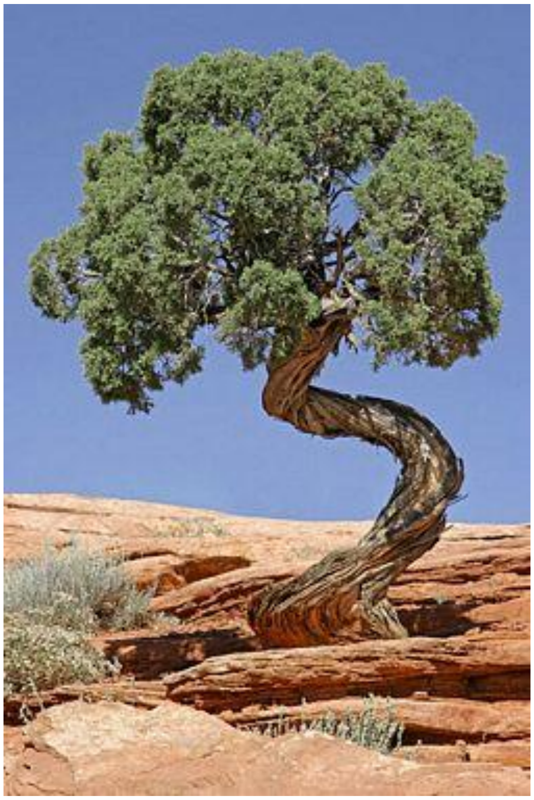
Scientific classification
Kingdom: *Plantae*
(unranked): *Angiosperms*
(unranked): *Eudicots*
(unranked): *Rosids*
Order: *Malpighiales*
Family: *Salicaceae*
Genus: *Salix*
Species: *S. amygdaloides*
Binomial name:
Salix amygdaloides Andersson

Elaeagnus angustifolia (Russian olive)

Tamarix ramosissima (saltcedar)

Yucca angustissima (narrow leaf yucca)

Juniperus osteosperma (Utah juniper)



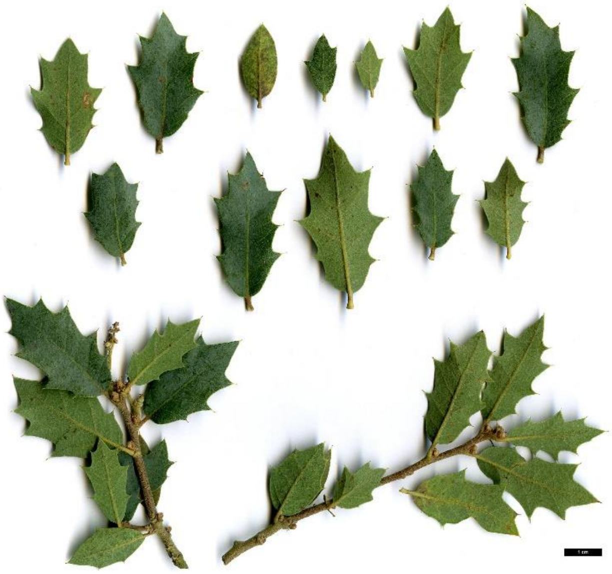
Quercus gambelii (Gambel oak)

Acer negundo (box elder)

Fendlera rupicola (Fendler bush)

Philadelphus microphyllus (mock orange)

Quercus turbinella (shrub oak)



Calochortus nuttallii (segolily)

Delphinium scaposum (larkspur)

Hordeum jubatum (foxtail barley)

Stipa comata (needle and thread grass)

Hilaria jamesii
(James Galleta)

Cleome serrulata (bee plant)

Equisetum laevigatum (horsetail)

Sagebrush

Fauna of Canyon de Chelly and Petrified Forest National Park

Zarah Brown

Petrified Forest National Park (PFNP) and Canyon de Chelly National Monument (CCNM) span the semi-desert grassland / shrub steppe life zones, with Canyon de Chelly also extending into the ponderosa pine life zone at higher altitudes (Figure 1). Park status means that wildlife is protected from various forms of human encroachment. Riparian (relating to wetlands) areas provide access to water and a wide variety of vegetation. CCNM hosts 12 springs, a perennial pond and both persistent and intermittent streams. PFNP's riparian areas include seeps, tinajas (surface depressions in bedrock), intermittent washes and tanks. The water and associated vegetation add to the biodiversity of these parks, which support insects, reptiles, amphibians, mammals and a large variety of birds, which use these regions for migration and breeding. Prior to attaining park status in 1906, the Petrified Forest area had been used by pioneers for the grazing of cattle and sheep. The cessation of this type of land use has allowed for biodiversity to return. This report aims to give a sense of the variety of the various types of animals found in the parks and their strategies for living in the park environment and highlights a few interesting species.

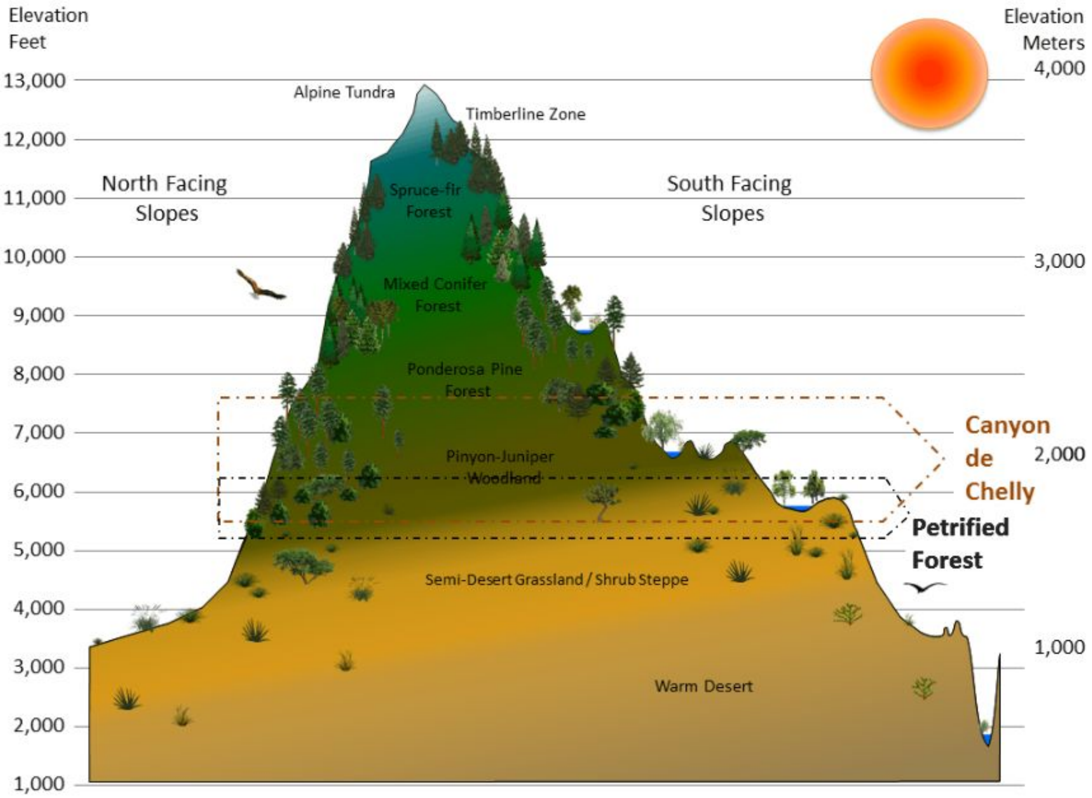


Figure 1. Life zones of Canyon de Chelly National Monument. Petrified Forest ranges from 5,307 to 6,262 feet in elevation and Canyon de Chelly from 5,553 to 7,662 feet. Image Credit: National Park Service

Reptiles

Reptiles are ectothermic vertebrates that lay eggs, or in some cases, give live birth.Fourteen species of reptiles have been identified in CCNM and 16 in PFNP. They feed on many of the insects, arachnids, and scorpions, as well as other other reptiles and small mammals. Their voracious consumption prevents an overrun of any single species and contributes significantly to the health of the overall ecosystem. PNFP is home to 9 species of lizard, 7 species of snake and one plucky species of turtle, the Western box turtle, *Terrapene ornata*.

Collared Lizard, *Crotaphytus collaris*

These handsome lizards grow up to 12 cm in length, have a distinctive black marking on the neck and are greyish-brown to blue-green with additional yellow markings. They are larger than other lizards in the park and are one of the most commonly seen sunning themselves in the mid-mornings. Like some kindergarteners, this lizard can run on its hind legs and will bite. Photo Credit: National Park Service

Snakes! Snakes are shy and all but one of the snake species living in the park are non-venemous:

Gopher snake
Pituophis catenifer
Photo Credit: Matt Jeppson

Glossy snake
Arizona elegans
Photo Credit: Sam Murray

Western Terrestrial Garter Snake
Thamnophis elegans
Photo Credit: J.N. Stuart

Western Rattlesnake, *Crotalus oreganus*
Rattlesnake are pit vipers, distinguishable by their large, triangle-shaped heads, elliptical eyes and thick tail ending in a rattle (Gopher snakes are similar in appearance and are much more common, but lack the rattle). They live mainly in the grassland and shrub areas and are the only species in the park to give live birth). Should you encounter a rattlesnake, you stay back 6-1000 ft. Photo Credit: Art Van Renssalaer

Mammals

Mammals are warm-blooded vertebrates that give live birth, produce milk and have fur or hair. Mammals use migration, burrowing, nocturnalism, and physical characteristics like hollow hairs to survive the challenging temperatures of the desert. The best times to see these animals are early morning and dusk. Mammals contribute to the control of insect species as well. The blond-furred palid bat eat beetles, centipedes, moths, cicadas, praying mantises, grasshoppers, crickets and scorpions. A restoration effort to remove the non-native Russian olive and tamarisk (“saltceder”) trees has encouraged black bears that reside in the park to prefer higher elevations, where they live on other, native species. 44 mammal species have been identified in PFNP and 49 in CCNM.

Pronghorn, *Antilocapra americana*

This unique creature looks like an antelope but is in a separate taxonomic family, of which it is the only member. They have a combination horn/antler that, like horns, have prongs and are made of keratin, not bone, but like antlers, shed yearly. They are usually found in the grasslands alone or in small herds.
Photo Credit: Tad Motoyama

Black-tailed jackrabbit, *Lepus californicus*, a.k.a. American desert hare

Though a fuzzy desert-dweller, this creature maintains an appropriate body temperature by radiative cooling via extensive network of blood vessels in its wide, flat ears. Vasodialation, the process by which blood vessels widen, and greater circulation to the ears, support this process. These reduce the need for evaporative cooling, helping the hare retain water.
Photo Credit: Evan Bornholtz

Amphibians

Amphibians are ectothermic vertebrates that develop from a larval, gilled tadpole stage, and thus, like so many theorized alien life forms, require liquid surface water to live. While adult amphibians have lungs, they can also respire through their skin. Amphibians do not drink water, instead, absorbing it through their skin. Many amphibians in PFNP spend much of their time underground. This prevents evaporative water loss and unwanted cooling and some species, like the New Mexico and Plains Spadefoot, derive their water from the soil. Many amphibious species in the park spend the majority of the time burrowed underground. Seven species of amphibians have been identified living in PFNP and 8 in CCNM.

Tiger Salamander, *Ambytstoma mavortium nebulosum*

Tiger salamanders are 7-18 cm in length and have a gray, olive or black background coloring with lighter colored mottling. They are the only salamander species found in Arizona and are found near major drainages in the the park grassland. They spend the majority of the year underground, breeding in rivers and temporary pools in the spring and early summer. Photo Credit: Gary Nafis

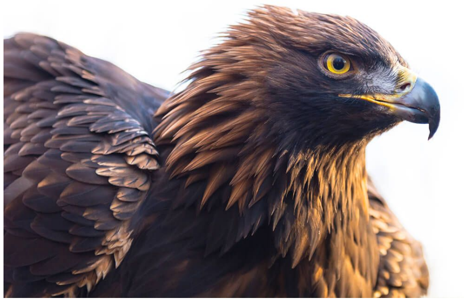
Red-Spotted Toad, *Bufo punctatus*

This toad is 4-8 cm in length with a light grey, olive or reddish background color. Glands in the skin of the toad give it red or orange spots. Tadpoles undergo an accelerated development time of just 6-8 weeks due to the sometimes transient pools available for breeding. These are most active during the rainy season - June through September.
Photo Credit: none, public domain.

Birds

Hundreds of bird species have been identified at PFNP and CCNM. These protected areas provide a sanctuary for migrating species as well as permanent residents and those that visit for breeding. Riparian corridors provide water and unique variety of vegetation and food sources for birds. The greatest diversity in bird species can be found during fall and winter migrations. The most commonly seen birds are the common raven and the Western meadowlark. Near the visitors' center and museum, look for Western tanagers, hermit warblers, and house finches. Classes of birds found in PFNP include ducks and geese, quail, grebes, heros and bitterns, ibises, vultures, hawks and eagles, rails and coots, avocets, plovers, sandpipers, gulls, cuckoos and roadrunners, swifts, owls, hummingbirds, woodpeckers, falcons, flycatchers, shrikes, vireos, jays and crows, larks, swallows, chickadees and titmice, bushtits, nuthatches, creepers, wrens, gnatcatchers, kinglets, thrushes, mockingbirds and thrashers, starlings, pipits, waxwings, longspurs, wood warblers, towhees and sparrows, cardinals and tanagers, blackbirds, and finches. Early morning is the best time to look for birds in the park.

Golden Eagle, *Aquila chrysaetos*



The largest and most majestic bird found in the park, the golden eagle is a member of the hawk family and can have a wingspan up to 2 meters. Its large eyes take up most of the space in it's head, and while they don't move much in their sockets, the bird's head can rotate 270 degrees, like an owl. They use thermal uprafts along mountain ridges to gain elevation and survey for prey.
Photo Credit: San Diego Zoo

Anna's hummingbird, *Calypte anna*

The smallest bird in the park, this medium-sized hummingbird has an iridescent bronze-green back and green flanks and named after Anna Massena, Duchess of Rivoli. These birds breed primarily along the West coast and southern Arizona, only reaching the these parks to winter.
Photo Credit: Robert McMorran

References:

https://science.nature.nps.gov/im/units/scpn/parks/cach.cfm/
https://science.nature.nps.gov/im/units/scpn/parks/pefo.cfm/
https://www.nps.gov/pefo/planyourvisit/upload/Mammals04w.pdf
https://www.nps.gov/pefo/planyourvisit/upload/Reptile.pdf
https://www.nps.gov/pefo/planyourvisit/upload/Amphibians.pdf
http://animals.sandiegozoo.org/animals/pronghorn
http://animals.sandiegozoo.org/animals/golden-eagle
Williamson, S. (2001). A Field Guide to Hummingbirds of North America. New York, NY: Houghton Mifflin Harcourt. p. 199
Tredick, C.A. (2011). "Black bears in Canyon de Chelly National Monument: Life in a changing environment." PhD Dissertation, Virginia Polytechnic Institute and State University.

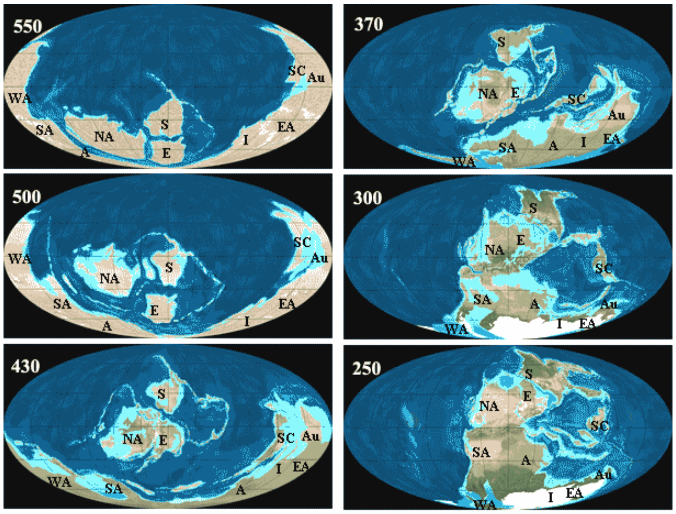
The Paleozoic: Not Just a Fad Era

Patrick O'Brien

The **Paleozoic Era** lasted from 541 to 252 Mya and is subdivided into six periods, from oldest to youngest: Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian. This was a time of significant geological and biological change on the Earth.

The Global Picture

- At the start of the Paleozoic era, most of the Earth's landmass was concentrated in a supercontinent called Pannotia, which was centered on the South Pole.
- The Cambrian began with the breakup of this landmass and over the course of the next five geologic periods, the cratons broke up and reassembled to form Pangaea at the end of the Paleozoic era.
- Biology aside: This era kicks off with the Cambrian explosion, a rapid expansion in the number of phyla seen in the fossil record. This era also ends with the largest extinction event ever recorded, the Permian-Triassic extinction event, where 96% of marine species and 70% of terrestrial vertebrate species were destroyed [1].



A = Africa
Au = Australia
E = Europe (Baltica)
EA = E. Antarctica
I = India
NA = N. America (Laurentia)
S = Siberia
SA = S. America
SC = South China
WA = W Antarctica

Arrangement of major continents at intervals (in Mya) during the Paleozoic. Adapted from Blakey. Apparant changes in size are due to distortion inherent in the map projection.

Figure 1. Continental drift during the Paleozoic (from [2])

The Regional Picture

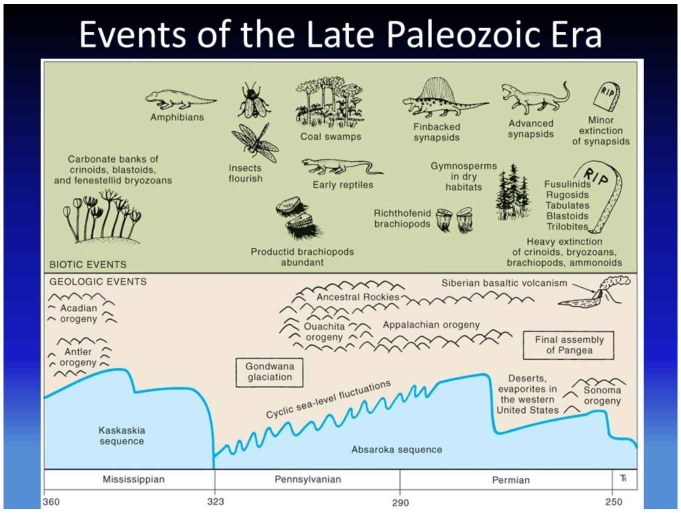


Figure 2. Geologic events during the final two periods of the Paleozoic (from [3])

-Throughout the Paleozoic, shallow seas covered much of North America. Water levels varied due to climate change and glaciation, leading to differences in the rates of sedimentation/erosion.

-Evaporitic deposits formed in the present-day western United States as well as aeolian deposits from large sand seas.

-As Pangaea coalesces at the end of the era, the Appalachian Mountains form when the North American continent collides with Africa and South America (Figure 2).

The Local Picture

Sedimentary deposits from this era are preserved and exposed in the American Southwest, where they have been carved away to from some of the most spectacular formations in the region, including Canyon de Chelly (and also the Grand Canyon). South of approximately Phoenix, Paleozoic beds are predominantly marine carbonate deposits but moving north we find deposits of sandstone and shale.

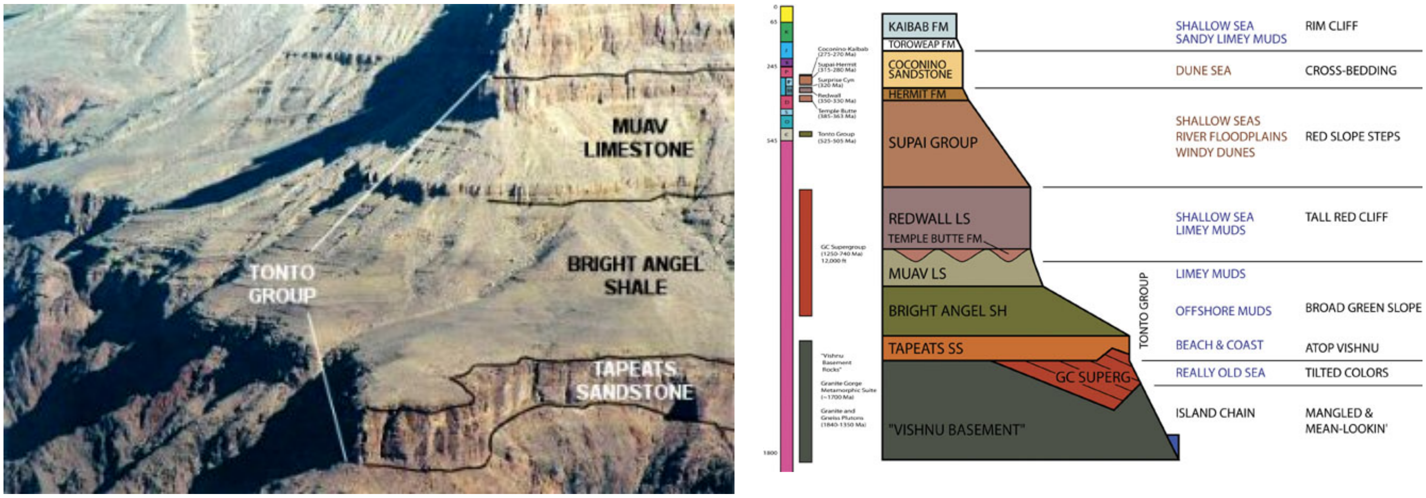


Figure 3. Stratigraphy of the Grand Canyon (from [4] and [5])

General stratigraphy in the area

- There is an unconformity at the base of the oldest Cambrian rocks. An erosional surface separates some unknown amount of pre-Cambrian and Cambrian time
  - The Cambrian rocks in this area are called the Tonto Group (see Figure 3) and are over 1000 feet thick in some places
- No (definite) Ordovician or Silurian rocks are present anywhere on the Navajo reservation Devonian-age deposits are exposed in the Little Colorado River and Monument Canyons in the form of the Temple Butte Limestone
- The Redwall Limestone is an early Carboniferous deposit, overlain by late-Carboniferous and Permian deposits like the Supai Group and the Coconino Sandstone
- The details of this stratigraphy reveal the depositional environments that were present during the Paleozoic

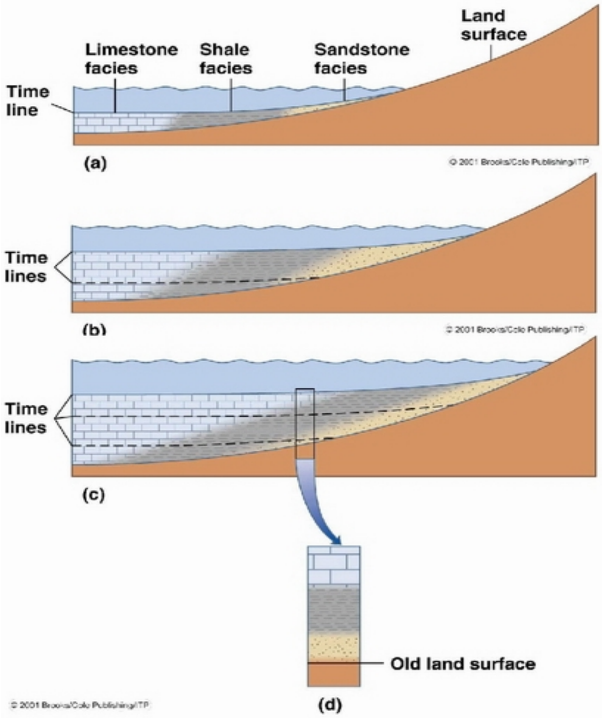


Figure 4. Formation of a transgression sequence due to rising sea levels (from [6])

Paleozoic Stratigraphy of the Defiance Plateau

- Unlike at the Grand Canyon, the only Paleozoic rocks preserved near Canyon de Chelly are from the Permian period as this region lies on the uplifted Defiance Plateau
- Overlaying pre-Cambrian granitic and metamorphic rocks are so-called "early-Permian red beds". These shale deposits are part of the Supai Group and constitute the floor of Spider Rock
- Following the deposition of the de Chelly sandstone, the late Permian period saw intense erosion, as evidenced by the unconformity between the late-Permian sandstone and the Triassic sedimentary deposits above it

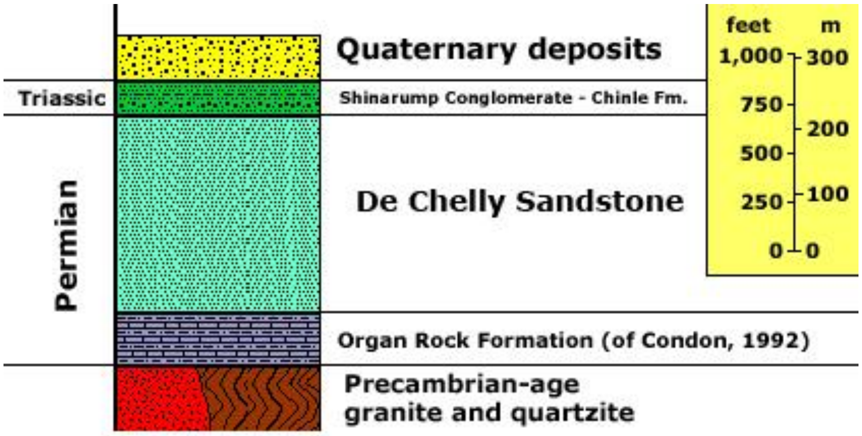


Figure 5. Permian stratigraphy on the Defiance Uplift (from [7])

De Chelly Sandstone

- Red, cross-bedded aeolian deposits that form the walls of Canyon de Chelly and Monument Valley, separated into two distinct layers which are similar in composition but different in depositional character
- Upper de Chelly sandstone is lateral with but <u>different</u> from the Coconino sandstone:
    - Different type of cross-bedding, grain size, mineral composition, cementing
    - This suggests that they formed at the same time but from different sources
    - Dip orientation of the two deposits suggests that the Coconino was sourced from the south and primarily deposited by the wind as dunes. The relatively uniform dip of the de Chelly sandstone suggests it was sourced from the north and in some areas shows evidence of water-deposited sand

Figure 6. Sandstone deposit in Canyon de Chelly (from [8])

Planetary Analog – late-Noachian/Hesperian = Paleozoic?

- No good evidence of plate tectonics anywhere in the Solar System
- On Mars, sedimentary rocks put down in a wide variety of depositional environments
    - Water draining through valley networks collected in low-lying craters forming lakes and subsequently lake deposits (Gale Crater, Jezero Crater, etc.)
    - Uniform sediment beds in Valles Marineris point to numerous periods of deposition in dynamic, energetic environments
    - Cross-bedded sandstone (Mount Sharp)

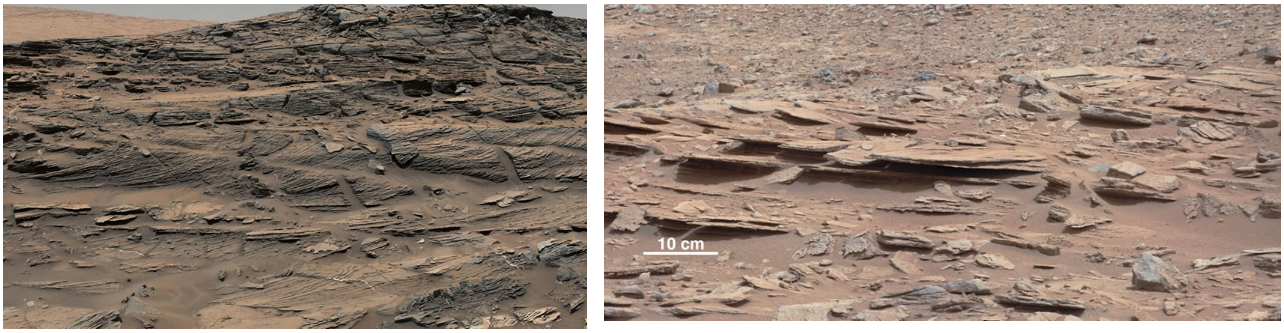


Figure 7. Martian sandstone outcrop (left) and sheet-like shale deposits (right), from [11]

References

[1] Sahney S; Benton M.J (2008). "Recovery from the most profound mass extinction of all time". Proceedings of the Royal Society B. 275 (1636): 759–765. doi:10.1098/rspb.2007.1370.

[2] https://www2.nau.edu/rcb7/

[3] Eustace Joel Porter. The Paleozoic Era Part 5a: Stratigraphy and Tectonics of the Carboniferous and the Permian Periods in North America.

[4] http://www.grandcanyonnaturalhistory.com/pages_nature/geology/tonto-group.html

[5] http://travels-in-time.com/plateau/grcanorim/index.html

[6] http://www.geologyin.com/2015/09/how-to-identify-transgression-and.html

[7] https://3dparks.wr.usgs.gov/coloradoplateau/canyondechelly_strat.htm

[8] https://servicedriven.wordpress.com/2011/10/06/photo-review-canyon-de-chelly/

[9] Irwin et al. (1971). Geology of the Paleozoic Rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah

[10] Vandiver (1937). No. 20 Geologic Report, Canyon de Chelly National Monument

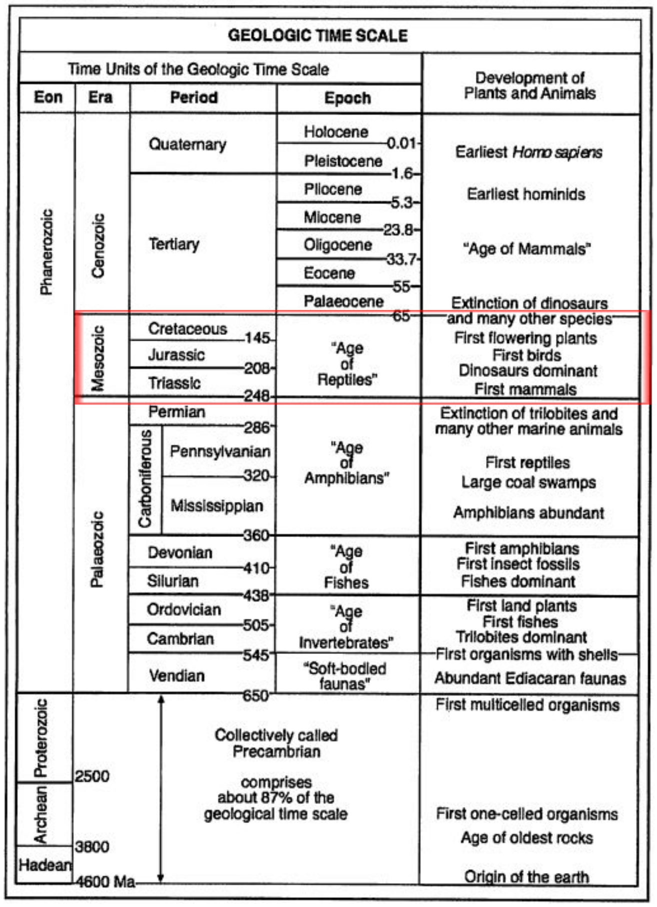
[11] https://geology.com/stories/13/rocks-on-mars/

Mesozoic era - Canyon de Chelly

Saverio Cambioni Field Trip Fall 2018

What does Mesozoic era mean?

- The Mesozoic Era is an interval of geological time from about 252 to 66 million years ago (figure 1).
- The era began in the wake of the **Permian–Triassic extinction event**, the largest well-documented mass extinction in Earth's history, and ended with the **Cretaceous–Paleogene extinction event**, another mass extinction whose victims included the non-avian dinosaurs.
- The Mesozoic was a time of significant **tectonic**, **climate** and **evolutionary activity**. The era witnessed the gradual rifting of the supercontinent Pangaea into separate landmasses that would move into their current positions during the next era.
- The climate of the Mesozoic was varied, alternating between warming and cooling periods. Overall, however, the **Earth was hotter than it is today.**



GEOLOGIC TIME SCALE

Time Units of the Geologic Time Scale					Development of Plants and Animals
Eon	Era	Period	Epoch		
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Earliest *Homo sapiens*
			Pleistocene	1.6	
		Tertiary	Pliocene	5.3	Earliest hominids
			Miocene	23.8	"Age of Mammals"
			Oligocene	33.7	
			Eocene	55	
			Palaeocene	65	Extinction of dinosaurs and many other species
	Mesozoic	Cretaceous	"Age of Reptiles"	145	First flowering plants
		Jurassic		208	First birds Dinosaurs dominant
		Triassic		248	First mammals
	Palaeozoic	Permian	"Age of Amphibians"	286	Extinction of trilobites and many other marine animals
		Carboniferous Pennsylvanian		320	First reptiles Large coal swamps
		Mississippian		360	Amphibians abundant
		Devonian	"Age of Fishes"	410	First amphibians First insect fossils
		Silurian		438	Fishes dominant
		Ordovician	"Age of Invertebrates"	505	First land plants First fishes
		Cambrian		545	Trilobites dominant First organisms with shells
		Vendian	"Soft-bodied faunas"	650	Abundant Ediacaran faunas
Proterozoic		Collectively called Precambrian comprises about 87% of the geological time scale		2500	First multicelled organisms
Archean				3800	First one-celled organisms Age of oldest rocks
Hadean				4600 Ma	Origin of the earth

Tectonics

During the Late Paleozoic to Early Mesozoic (320-200 million years ago), the oceanic plate began to subduct, or move beneath the North American Plate, while Africa collided with the other side of the plate.

- The stress of the subduction and collision resulted in reactivated faulting and uplift in the Grand Canyon Region.
- At the beginning of the Mesozoic era (~265 million years ago), the breakup of the Pangea supercontinent began, separating eastern North America from northwestern Africa and ultimately leading to the initiation of a subduction zone along western North America.
- A series of orogenies (mountain-building events) caused uplift (rocky mountains)
- During the early Cretaceous period (~140 Ma), the Colorado Plateau was once again in a shallow marine/coastal terrestrial depositional setting, this time in the Cretaceous Interior Seaway (figure 2)

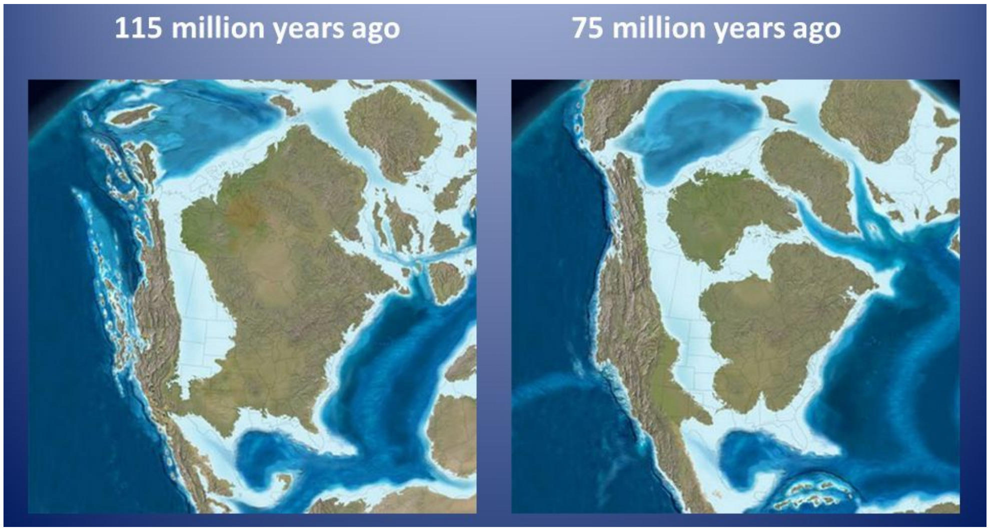


Figure 1.

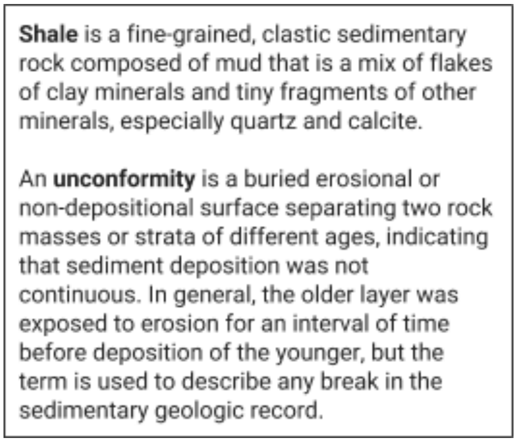
North America during the Mesozoic era.

Geologic features

- Mesozoic rocks were formed mostly by terrestrial deposits and are mainly sandstones with some shale [1].
- The dominant geologic feature in Canyon de Chelly is the Lower Permian De Chelly Sandstone.

Figure 2. The unconformity between Permian De Chelly Sandstone and Upper Triassic Shinarump

- Located above the De Chelly Sandstone is the **Upper Triassic Shinarump Member of the Chinle Formation (Triassic, so formed during the early mesozoic)**.
- The Shinarump is a coarse grained conglomerate that is mostly lenticular *(Craigg, 2001)*.
- A vertical contact between the De Chelly Sandstone and Shinarump Member can be observed on the canyon wall towards the top of the White House Ruins Trail (Figure 3, [3]) The contact is an **unconformity** that represents an erosion surface on the De Chelly Sandstone that was then overlain by the Shinarump Member *(Stanesco, 1991)*.
- **Bonus.** Regarding stratigraphy, Canyon de Chelly is similar to the Grand Canyon, but the mesozoic strata are more accessible at the former, while you should hike many hours to get to substantial remnants at the latter.


Shale is a fine-grained, clastic sedimentary rock composed of mud that is a mix of flakes of clay minerals and tiny fragments of other minerals, especially quartz and calcite.

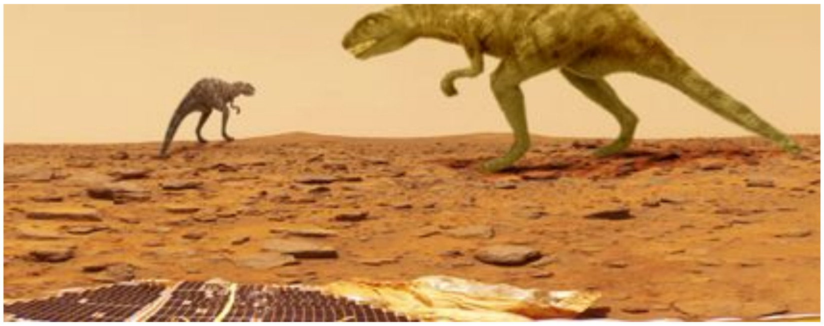
An **unconformity** is a buried erosional or non-depositional surface separating two rock masses or strata of different ages, indicating that sediment deposition was not continuous. In general, the older layer was exposed to erosion for an interval of time before deposition of the younger, but the term is used to describe any break in the sedimentary geologic record.

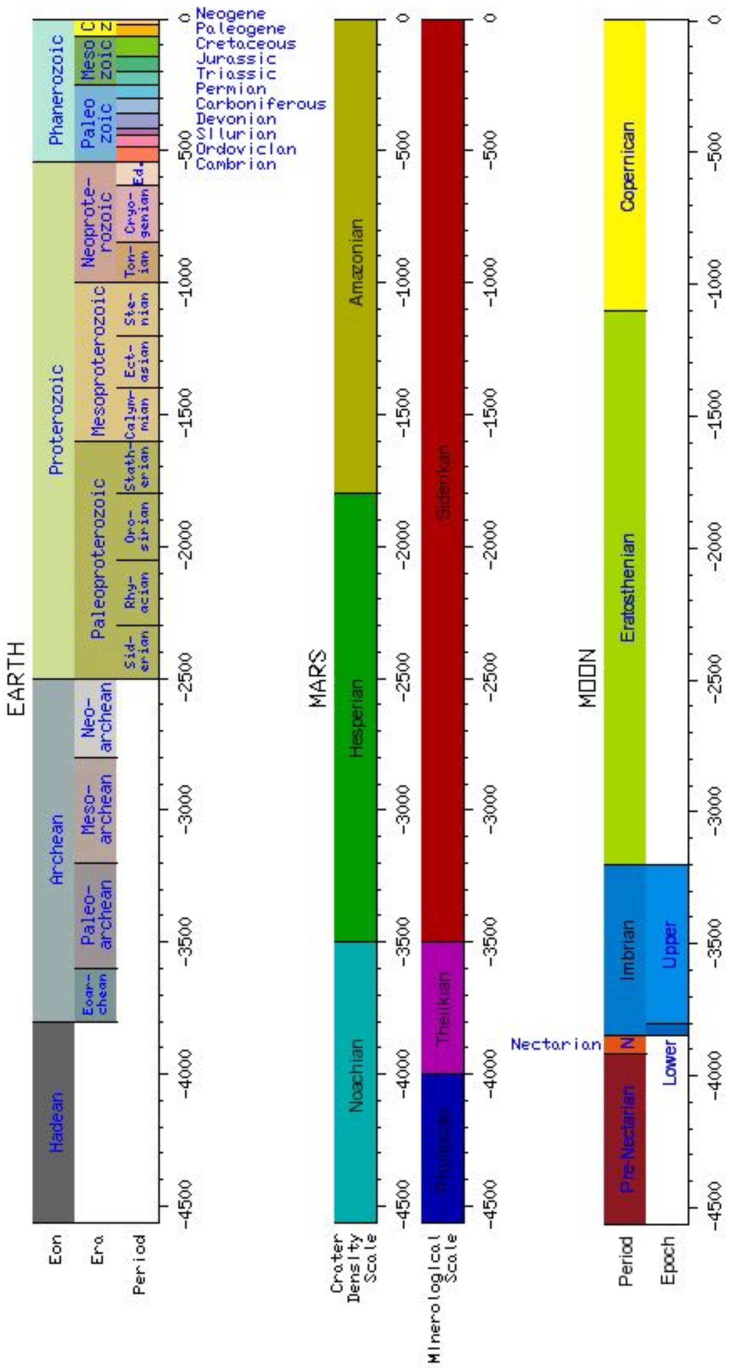
Planetary connections: Mars and the Moon during Mesozoic era. [3]

During the Mesozoic era, Mars and the Moon were in the late Amazonian and late Copernican era respectively.

Amazonian on Mars. The Amazonian is a geologic system and time period on the planet Mars characterized by low rates of meteorite and asteroid impacts and by cold, hyperarid conditions broadly similar to those on Mars today. Because it is the youngest of the Martian periods, the chronology of the Amazonian is comparatively well understood through traditional geological laws of superposition coupled to the relative dating technique of crater counting. The geological feature such as glacial dynamics and brittle tectonics.

Copernican on the Moon. The Copernican Period in the lunar geologic timescale runs from approximately 1.1 billion years ago to the present day. The base of the Copernican period is defined by impact craters that possess bright optically immature ray systems. While animal life bloomed on Earth, the Moon's geologic activity was coming to an end.Copernican age deposits are mostly represented by crater ejecta, but a small area of mare basalt has covered part of (and is thus younger than) some of the rays of the Copernican crater Lichtenberg, and therefore the basalt is mapped as Copernican age.





References

Craigg, S.D., 2001, Geologic framework of the San Juan Structural Basin of New Mexico, Colorado, Arizona, and Utah, with emphasis on Triassic through Tertiary rocks: Reston, VA, U.S. Dept. of the Interior, U.S. Geological Survey: Denver, CO, Branch of Information Services, 70p.

Stanesco, J.D., 1991, Sedimentology and Cyclicity in the Lower Permian De Chelly Sandstone on the Defiance Plateau: Eastern Arizona: The Mountain Geologist, v. 28 (4), p. 1-11.

Websites

[1] https://serc.carleton.edu
[2] https://web.uri.edu
[3] Wikipedia

Tectonic Processes of Petrified Forest and Canyon de Chelly

Tyler Meng

The Petrified Forest National Park (PFNP) and Canyon de Chelly (CDC) are located in northeastern Arizona, approaching the Four Corners region and the southern margin of the Colorado Plateau. These two parks contain various features related to local tectonic processes influence by their regional setting on the plateau.

While the Colorado Plateau is a regionally uplifted area spanning several hundred kilometers, it is interspersed with various minor uplifts and basins on the scale of ten to one hundred kilometers (Kelly, 1967). In the Four Corners region, these structures all exhibit a general E-NE compressive trend. The PFNP, being further southwest than the CDC, lies in the Black Mesa Basin, while the canyon is carved into a region called the Defiance Uplift.

The major E-NE compressive stress likely arises from the subducted Farallon plate which triggered the Laramide orogeny in approximately the late Cretaceous (Davis and Bump, 2009). Additionally, the Rio Grande rift lies to the east, providing a source of opposing forces to the compression from the subducted slab.

In the PFNP, tectonic deformation is relatively minor and does not play a major role in the geomorphology of the park compared to other geologic processes (Figure)2. Since the park is in the Black Mesa Basin, it is crossed by some gently dipping synclinal beds, but there are no exposed faults at the surface (Martz et. Al, 2012). This location within the mostly undeformed basin may have potentially played a role in the lack of erosion of the beds within the park, which could have help to preserve the fossils that the park is known for.

The CDC, on the other hand, is located in a region known as the Defiance Uplift. This uplift is bound by monoclines and is cross-cut by various folds and faults (Woodward et. Al 1997). Due to its location on the uplift, the erosive potential in this area would have been very strong. This helps to explain why there is a canyon in the uplifted region. Additionally, the faults appear to have a strike (43°) that trends approximately perpendicular to the strike of the axes of all of the folds (164°) in the region (calculated from GIS data)(Figure 3). These faults are not thrust faults, but instead minor normal faults with relatively little offset. This indicates that while the bedrock in the region did not experience enough compression to cause thrust faulting, but the combined compression and uplift of the Defiance region led to some relaxation faulting in the direction of maximum extensional stress, which would be perpendicular to maximum compressional stress (Figure 4).

The Defiance region is bound by monoclines, and not thrust faults, although it is hypothesized that this rocks lay on top of a fractured and faulted basement which does not outcrop in the four corners region, as it does in the Rocky Mountains Front Range. Instead, it is hypothesized that the compression led to thrusting of the basement, but this fracture did not exceed the strength of the overlying strata. Instead, these rocks were deformed into monoclines, showing plastic deformation but not brittle failure (Davis and Bump, 2009)(Figure 5).

Tectonic Features of the Four Corners Region, USA

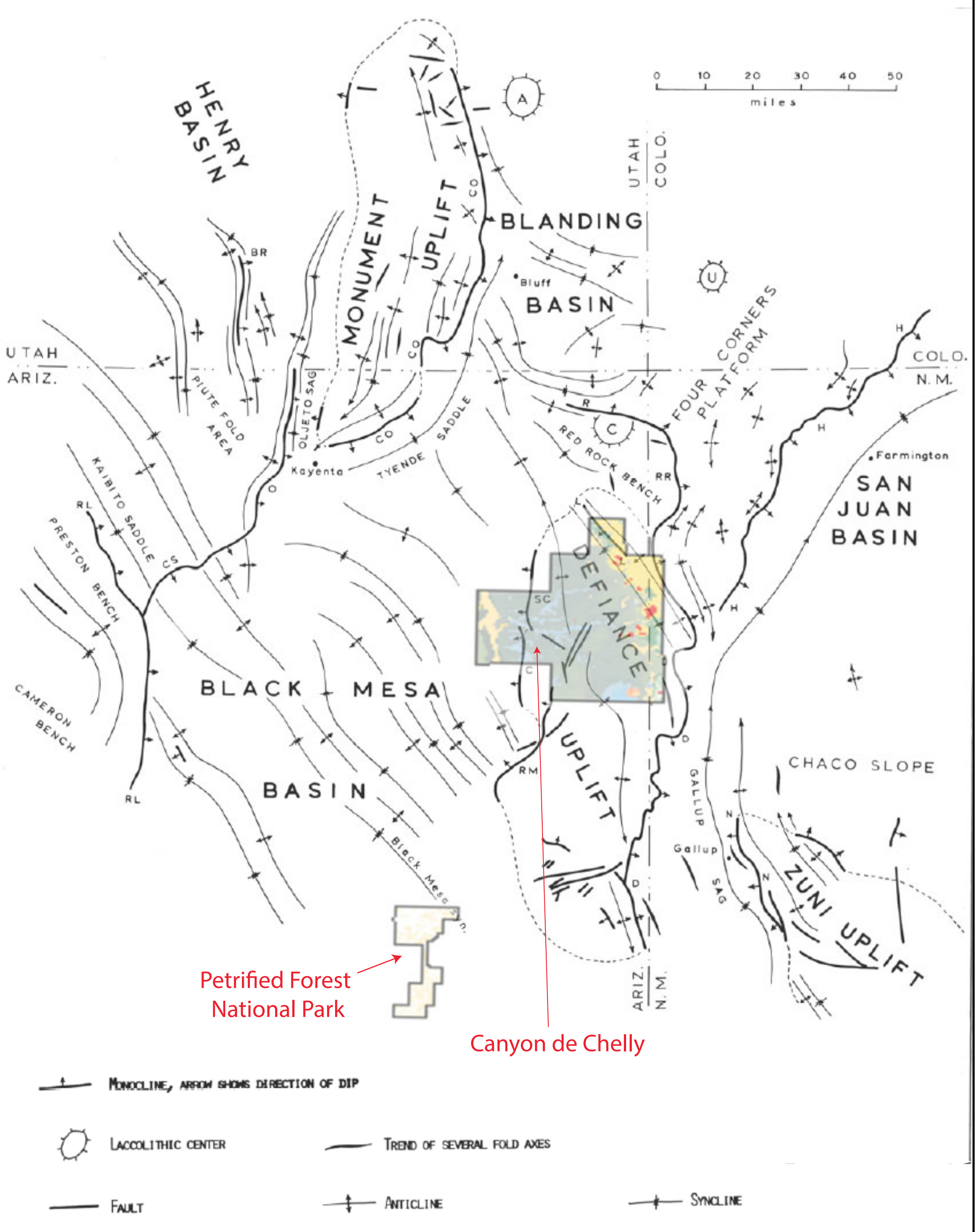


Figure 1: Context map showing the Petrified Forest National Park and Canyon de Chelly area overlain on a map of the regional tectonic features. Geologic units are included in the Canyon de Chelly region to show the location of the actual canyon in relation to the structural features (modified from Woodward et. Al, 1997 using GIS data obtained from data.gov).

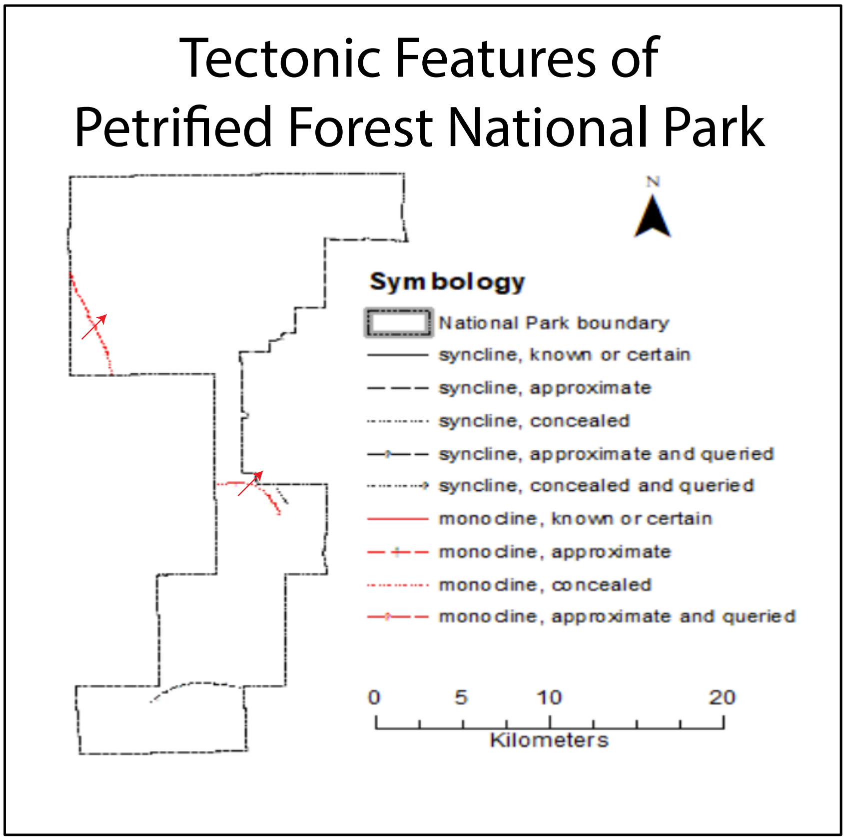


Figure 2: Petrified Forest National Park has a relatively small amount of tectonic features, containing some gently-dipping monoclines and synclines within the Black Mesa Basin.

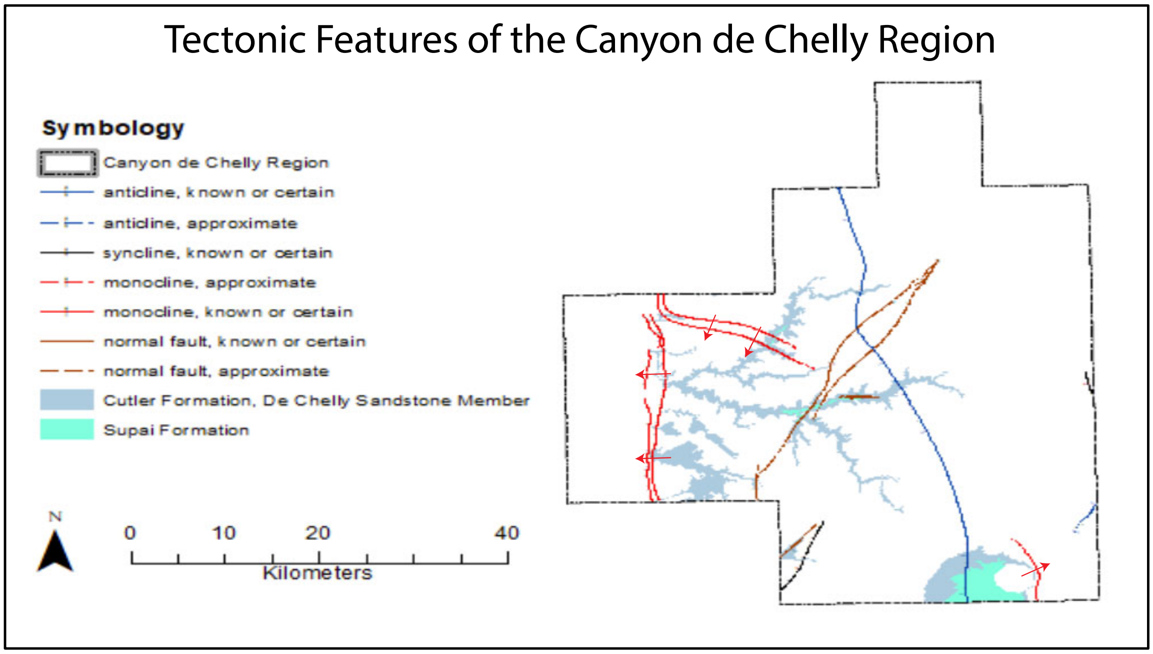


Figure 3: Located on the Defiance Uplift, the Canyon de Chelly area contains several tectonic features. Most of these features are folds, but there is also some normal faulting perpendicular to the direction of maximum compressional stress. Geologic units within the canyon are shown to give context of its proximity in relation to these tectonic features.

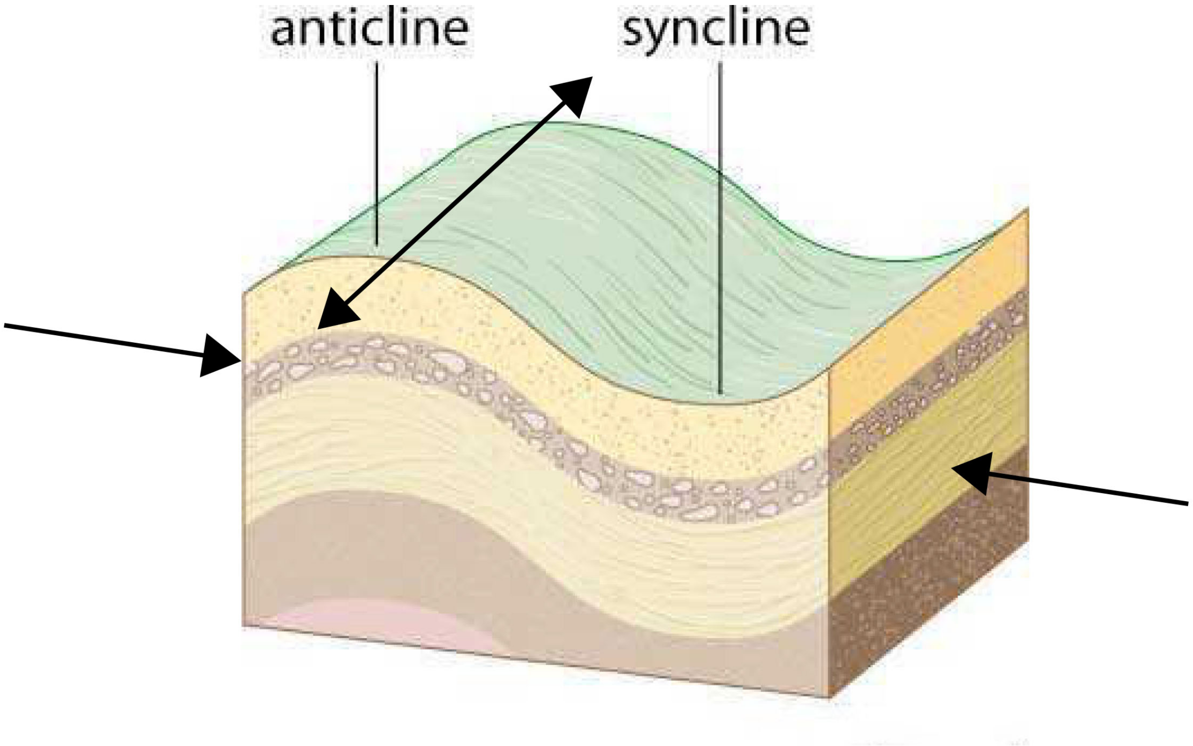
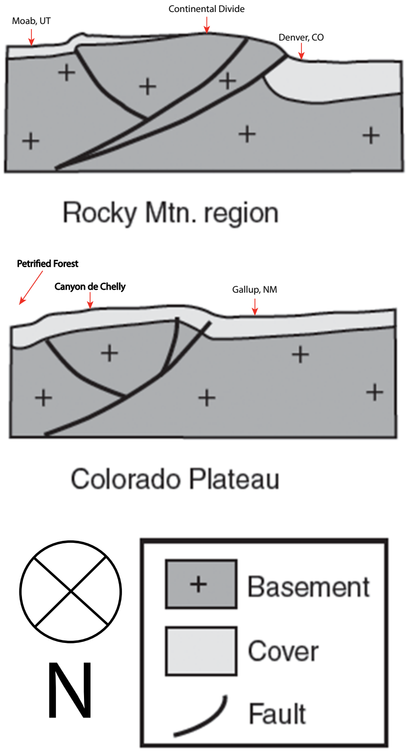


Figure 4: Diagram (modified from yourdictionary.com 2018) showing generalized stress scheme in a compressional environment such as the Four Corners regions. While the compression in the region dominates the stress regime and creates structural folds, some extension also occurs in the perpendicular direction, which could lead to normal faulting.

Figure 5: Diagram showing the differences in the Colorado Plateau, where PFNP and CDC are locate, and the Rocky Mountain Region located to the north (modified from Davis and Bump, 2009). Since the major thrust faulting does not penetrate the strata overlying the basement in the Colorado Plateau, the result is a series of monoclines with no exposed basement rather than thrust faulting surface expressions with exposed basement.



Weathering and Erosion Processes

Jessie J. Brown

September 8 - 10, 2018

1 Introduction

Canyon de Chelly is a deep canyon cut by the action of surface water streams during the uplift of the surrounding region. Millions of years ago, the surrounding Colorado Plateau was uplifted by more than a kilometer. Streams on this newly lofty plateau were high above sea level, so they rapidly cut down through the rock and created dramatic canyons (Figure 1).

Figure 1: Spider Rock at Canyon de Chelly

2 Weathering and Erosion Processes

Weathering

Weathering is the process of breaking rocks down. It may be either mechanical weathering (physically breaking a rock into smaller pieces) or chemical weathering (a chemical change in some of the minerals that make up the rock).

Mechanical weathering

Frost wedging is a weathering mechanism that occurs when water freezes in cracks, pores, joints, etc, splitting and breaking apart the rock. It occurs quickly, and requires regular temperature fluctuations.

Abrasion occurs when rocks bump together, bashing pieces off. For example, abrasion occurs in rivers when material carried along by the water wears away at the streambed, smoothing and polishing the rock. Abrasion may create distinctive landforms such as potholes, bowl shaped or cylindrical depressions carved by sediment swirling in an eddy. Abrasion is the primary mechanism by which rivers and streams deepen their beds, and it is how they can, in time, carve out canyons. Abrasion may also occur when gravity causes rocks to tumble downhill, bashing other rocks; by 'sandblasting' when strong winds carry small particles; or in glacial flow.

Mechanical weathering may also take place due to biological agents. I'm sure we will see plants growing in extremely unlikely places on this trip, and perhaps on paths we'll notice the traces of another weathering agent - people.

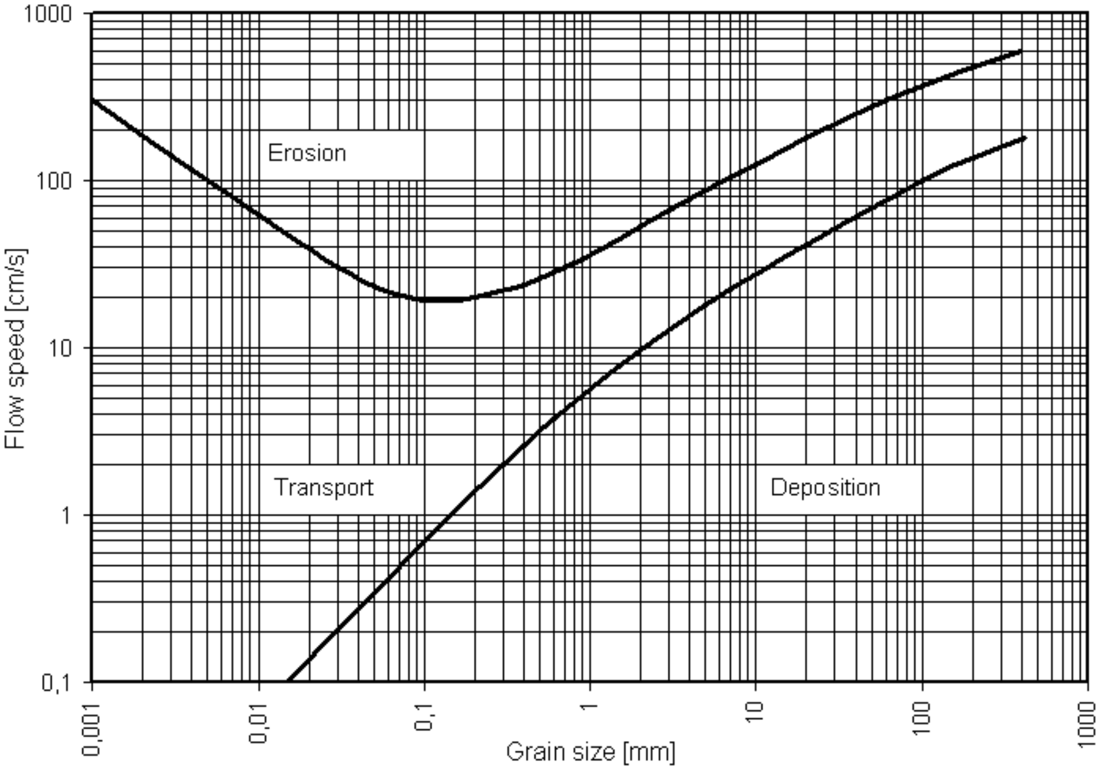


Figure 2: The Hjulström curve, introduced by Hjulström 1935, is used to understand whether a flow will erode, transport or deposit sediment of a given size. The upper curve shows critical erosion velocity and the lower curve shows deposition velocity

Chemical weathering

Chemical weathering occurs when some kind of chemical reaction takes place, causing a change in composition. Most chemical weathering relies on water, although carbon dioxide and oxygen are also agents of chemical weathering. **Hydrolysis** refers to a reaction between water and something else. Olivine, potassium feldspar, and plagioclase are all broken down by hydrolysis. Secondary minerals, often clays, may be formed by this process.

Erosion

Erosion is the process of moving a bit of rock, presumably loosened by weathering, from its original location to some other place. The agents of erosion are water, wind, glaciers, and gravity, as well as plants and animals. In this section I will focus upon the agents of erosion that have played the most part in shaping the landscape in the region of Canyon de Chelly.

Erosion by rivers and streams

Fluvial erosion has removed most of the material that once filled canyons like Canyon de Chelly. The material carried by a stream is termed its **load**. **Hydraulic action** is the ability of moving water to dislodge and transport rock particles. Faster moving, steeper rivers have the greatest capacity for erosion through hydraulic action. The *suspended load* consists of material small enough to be borne aloft by the water, essentially never striking the bottom. The *bedload* is the larger particles that bounce (saltation) or slide and roll (traction) along

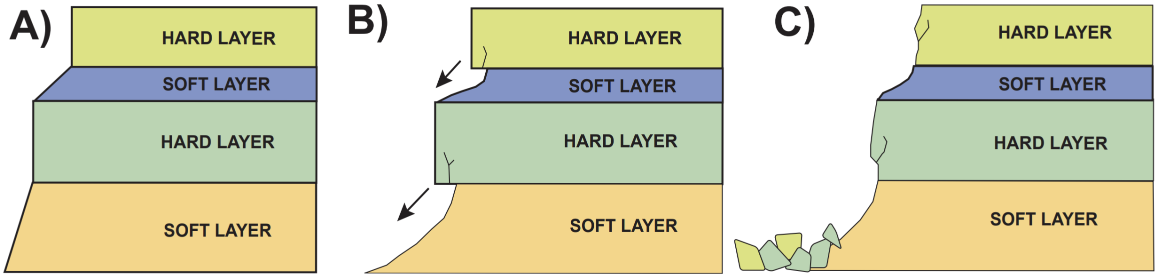


Figure 3: Canyons may be widened by mass wasting. A) A sedimentary sequence with different competences; B) 'Soft' layers erode faster, leaving undercut shelves of 'hard' rock; C) Eventually the hard rock collapses in chunks, restarting the whole process as it re-exposes the softer material to weathering. Image from Timmons 2003.

the bottom. As these particles abrade the streambed, they are abraded in turn and become smaller and rounder the further they have been transported (attrition). Rivers and streams may carry material in **solution**, when part of a rock is dissolved. The *dissolved load* refers to the material carried in solution.

The ability of a river to transport sediment is dependent on the speed of flow. This is commonly described using the Hjulström curve (Figure 2). Referring to the figure, it is clear that the same flow may be simultaneously eroding particles of one size and depositing particles of a different size. There may be temporal changes in capacity as well. Here in the desert streams are often transient; a sudden cloudburst may create a flow that moves boulders but lasts only hours. Afterwards, a slot canyon may be left bone dry but mysteriously full of tumbled boulders and uprooted shrubs – a demonstration of erosion and deposition, and a warning to hikers.

Erosion by gravity

Another important mechanism of erosion in canyon terrains is erosion by gravity, or **mass movement**. Mass movement refers to the bulk movement of sediment down a slope due to the force of gravity. Geologists love to subdivide, so there are many types of mass movement: slow downslope movement of soil and other debris, called *creep*; *landslides*, a term which describes falls, topples, slides, spreads, and flows, and are then further divided by type of geologic material (bedrock, debris, soil); and many more descriptions.

Of particular interest to this field trip: mass movement widens canyons. When a slope is too steep, the force due to gravity overcomes the competence of the rock and material breaks off and travels down slope. How steep is "too steep" is a function of the competence of the rock. A shaley, crumbly rock forms slopes less steep than those formed in a hard, cohesive limestone. In the Colorado Plateau, the alternation of hard and soft units often causes a stair-step shape to develop, as seen in the Grand Canyon. A possible mass movement scenario is shown in Figure 3.

References

Hjulström, Filip (1935). "The Morphological Activity of Rivers as Illustrated by River Fyris". PhD. Geological Institute of Uppsala.

Timmons, Stacy S. (2003). *Grand Canyon Geology Training Manual: Learning to Read the Pages of a Book*.

Battleship

Another fun activity from:

www.funorama.com

Defensive Grid

A										
B										
C										
D										
E										
F										
G										
H										
I										
J										
	1	2	3	4	5	6	7	8	9	10

Put the following ships on your defensive grid by placing the appropriate letters -- horizontally, vertically or diagonally.

1 - Aircraft Carrier

A	A	A	A	A

1 - Battleship

B	B	B	B

1 - Cruiser

C	C	C

2 - Destroyers

D	D		D	D

Offensive Grid

A										
B										
C										
D										
E										
F										
G										
H										
I										
J										
	1	2	3	4	5	6	7	8	9	10

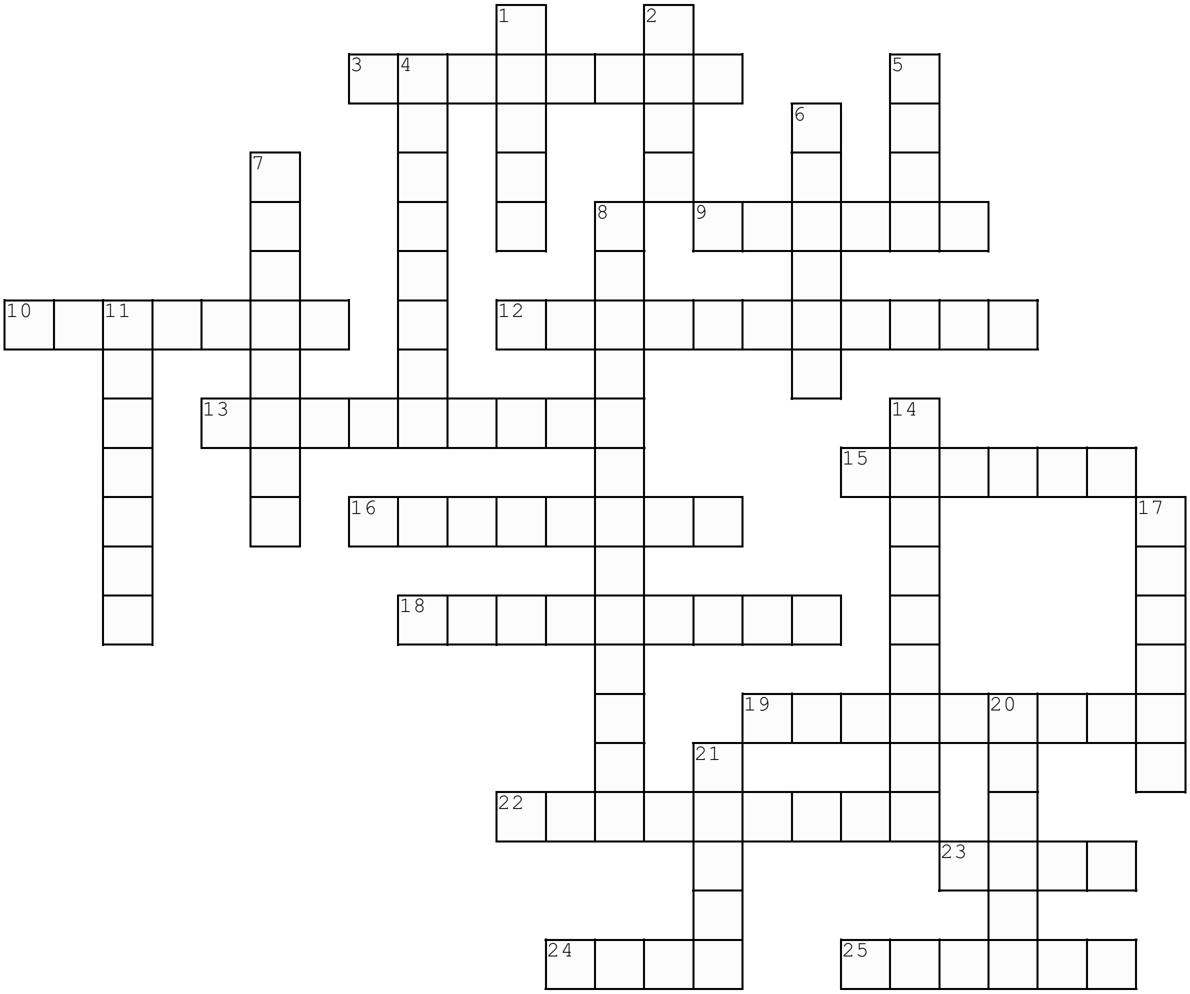
Instructions (2 Players Required):

Both players place their ships on the defensive grid according to the chart above. Whoever goes first calls out a position (i.e. G-6). The other player says either “Hit” or “Miss” depending upon whether one of his ships is in the position called out. The person calling out should mark a hit or a miss on the “offensive grid” to keep track of the shots. The other person should mark the shot on the “defensive grid”. If the shot is a “Hit”, the player goes again--otherwise the other player takes a turn. Once the opposing player has scored a hit on all of the spaces for a particular ship, you must call out “Hit...you sunk my Cruiser“ (or whatever type of ship it was). Once a player has sunk all the opponents ships, he is declared the winner.

Name:________________

Canyon de Chelly Crossword

Complete the crossword below. Remember who put it together if you need help.



Across

3. Time period of Chinle formation
9. Central rock in Canyon de Chelly
10. Regional clay artwork
12. Artwork on rocks
13. Formation containing maar landforms (obscure)
15. Multistoried adobe houses
16. The ability of a substance to yield to viscous flow under large strains
18. Iron and ______ give local rocks their color
19. The Grand _______
22. Common sedimentary rock
23. Separate sovereign nation within the Navajo Nation
24. Isolated Pueblo language
25. 3.8 of these per gallon

Down

1. Fancy word for corn
2. Number of tribes in the Bears Ears Inter-Tribal Coalition
4. Waves with forward and vertical vibrations
5. Navajo word for their people
6. Sediment formation containing fossil logs
7. Arachnid; glows under blacklight
8. When things get scared stiff into minerals
11. A sinuous imaginary line following the deepest part of a stream
14. Blue-green stone used in jewelry
17. Hopi _____ (plural)
20. Local trickster mammal
21. Navajo word for Canyon de Chelly

1

		5			7			
						9		2
7		1	2		9	6		
9	5			8		3		
	2			3	6			
		7			5		1	
			6				5	9
5	3			9				
			1	5		2	6	

2

		2		8				
	1				3	4	9	
		9		7				5
6	4					3		
					4	8		9
		5		2	7			4
	9						1	
			8	9	2			
		7	1	4			2	

3

			6	5				
7				4		9	5	2
3		5	1					4
		3					4	5
2		7					9	
4			5	2	6		7	
	7				8	5		
		4				7	2	
	9				5		6	

4

	4		3					9
		7	6		5			
		2	4			5		1
1		3						2
8					4			
2					6	9	8	
	3	1	7					
	9			2				5
	2					1	9	4

5

					1		8	2
			5	6		1		7
6	3			7	2			
			7			9	1	
		3	4		6	7		
		2					4	
	1				3		7	
	2	5		1				
		6		5		3		

6

			4			8		2
3		7			5			
		2				9		
9		3				1		
		1			7	4	9	8
			6		1			7
	3		8	6		2	4	
	4		3	5				
2	9						3	

7

	3		2		4	5		8
		4	6		7			2
		5			3			4
	2	1					4	
	5		9	3	2			
	6					3		
5			4	7				
6			3	1		7	5	
7							1	6

8

2	5			7				
			5	9		1	3	
				2	3		6	7
							9	6
8	1	4						
			7		5			
4		2	1			6		
		8			6	3	1	
		1		3		8		9

9

		8	2				1	5
2			3	6				
9	5	6					2	
								4
7		5		3	2			
			6	5	7		8	
	6	1				4		
			1	4	3	5		
	2					8	7	

10

1			7	8	4			
8	2					9	3	
	6				2			
			3	2				7
		5		9			8	2
6	1							
					8	5	9	
9		6		5				
7						8	2	3

11

	5	9		8				
						2		7
		7	6	1				
	1	6	5	9			8	
			7					1
	9	8				6	2	
8					9		4	
2							1	8
9	6				5			2

12

					5	4		6
	6	2			9	1		
9				8	4			
	9					6		5
3		8		2				
		5			8	2	1	
8			7	6			2	
							4	7
1		7	4					

SUDOKU

Created by Peter Ritmeester / Presented by Will Shortz

SUDOKU 1

		3			4			
2	9							4
			3	1	9			7
	7				8	6		
3								
						5		8
		9	2					
		6				7		
							3	6

597A

SUDOKU 2

				3				
		2		4		9		
	3		1				6	
						8		7
							2	
	2	5				3	9	
			8	9	5			
			6					

597B

ANSWERS TO SUDOKU 1

7	1	3	5	2	4	8	6	9
2	9	5	6	8	7	3	1	4
6	8	4	3	1	9	2	5	7
5	7	2	1	9	8	6	4	3
3	6	8	4	5	2	9	7	1
9	4	1	7	6	3	5	2	8
1	3	9	2	7	6	4	8	5
4	5	6	8	3	1	7	9	2
8	2	7	9	4	5	1	3	6

ANSWERS TO SUDOKU 2

4	5	1	9	3	6	7	8	2
6	8	2	5	4	7	9	3	1
9	3	7	1	8	2	4	6	5
3	6	9	4	2	1	8	5	7
7	4	8	3	5	9	1	2	6
1	2	5	7	6	8	3	9	4
2	1	4	8	9	5	6	7	3
5	9	3	6	7	4	2	1	8
8	7	6	2	1	3	5	4	9

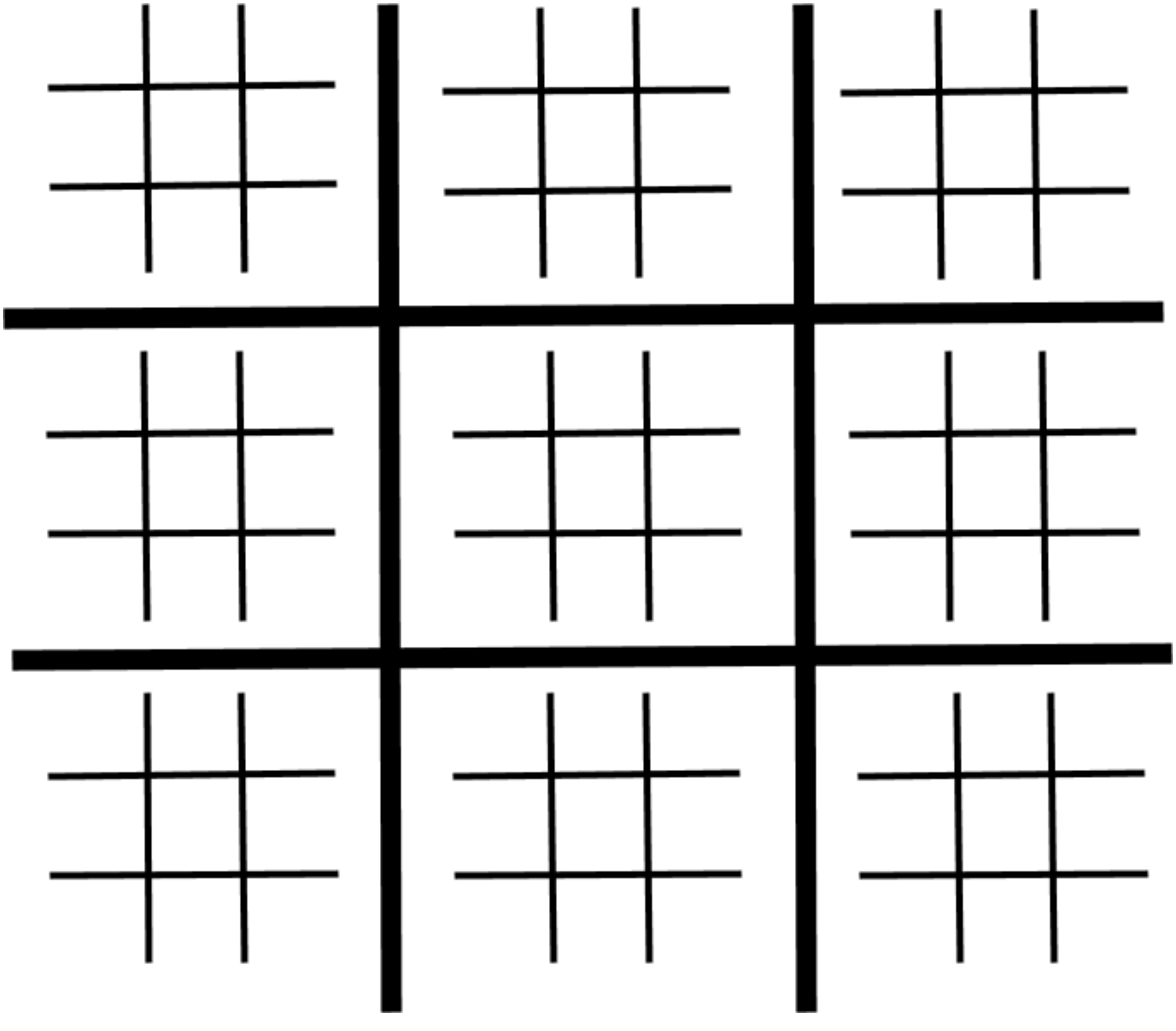
SINGO

Please enjoy this BINGO-styled bird-spotting game of the 24 most commonly found species in the Canyon de Chelly riparian corridors, as reported by the National Park Service in 2015. Don’t forget to do like Lynyrd Skynyrd and play free bird.

Reference:
Holmes, J. A., and M. J. Johnson. 2016. Bird community monitoring for Canyon De Chelly National Monument: 2015 summary report. Natural Resource Data Series NPS/SCPN/NRDS—2016/1067. National Park Service, Fort Collins, Colorado.

SUPER TIC TAC TOE

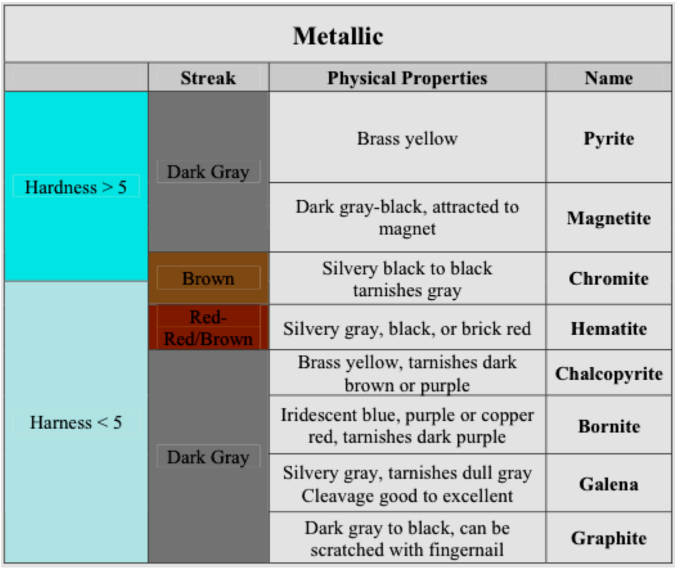
Like the normal version, but more. The board is made up of 9 sub-games within the larger supergame. Player one begins by placing an X inside one of the sub-games. The square chosen within that sub-game determines the next sub-game for player two to make their move, and so on. For example, if player one chooses the middle square in the upper-right sub-game, player two must place their move within the middle sub-game. If you win a sub-game, you win that space in the uber-game. Connect three squares in a row in the super game to win. This game can be broken. There might not be a winner. Maybe you'll have fun. You'll probably get mad at your opponent.



Common Rock Forming Minerals

Dark-Colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	Dark gray, Blue-gray or black. May be iridescent. Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Brown, gray, green or red. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Opaque black. 2 cleavage planes at 60°and 120°. Hardness- 5.5	**Hornblende (Amphibole)**
	Poor or absent	Opaque red, gray, hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Gray, brown or purple. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz Black or brown- Smoky , Purple- Amethyst**
		Opaque red or brown. Waxy luster. Hardness- 7. Conchoidal Fracture	**Jasper**
		Opaque black. Waxy luster. Hardness- 7	**Flint**
		Transparent- translucent dark red to black. Hardness- 7	**Garnet**
Hardness < 5	Excellent or good	Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Green. Splits along 1 excellent cleavage plane. Hardness- 2-3	**Chlorite**
		Black to dark brown. Splits along 1 excellent cleavage plane. Hardness- 2.5-3	**Biotite mica**
	Poor or absent	Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Serpentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy red to light brown. Hardness- 1.5-6	**Hematite**

Light-colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	White or gray, Cleavage in 2 planes at nearly right angles, Striations. Hardness-6	**Plagioclase Feldspar**
		Orange, brown, white, gray, green or pink. Cleavage in 2 planes at nearly right angles. Exsolution Lamellae. Hardness-6	**Potassium Feldspar**
		Pale brown, white or gray. Long slender prisms. Cleavage in 1 plane. Hardness- 6-7	**Sillimanite**
	Poor or absent	Opaque red, gray, white hexagonal prisms with striated flat ends. Hardness- 9	**Corrundum**
		Colorless, white, gray or other colors. Greasy luster. Massive or hexagonal prisms and pyramids. Transparent or translucent. Hardness- 7	**Quartz White-Milky, Yellow-Citrine, Pink- Rose**
		Opaque gray or white. Waxy luster. Hardness- 7. Conchoidal Fracture	**Chert**
		Colorless, white, yellow, light brown. Translucent opaque. Laminated or massive. Cryptocrystalline. Hardness- 7	**Chalcedony**
		Pale olive green. Conchoidal fracture. Transparent or translucent. Hardness- 7	**Olivine**
Hardness < 5	Excellent or good	Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl. Hardness- 3	**Calcite**
		Colorless, white, yellow, blue, green. Excellent cleavage in 3 planes. Breaks into rhombohedrons. Effervesces in HCl only if powdered. Hardness- 3.5-4	**Dolomite**
		White with tints of brown. Short tabular crystals or roses. Very heavy. Hardness- 3-3.5	**Barite**
		Colorless, white or gray. Massive or tabular crystals, blades or needles. Can be scratched by fingernail. Hardness- 2	**Gypsum**
		Colorless, white. Cubic crystals. Salty taste. Hardness- 2.5	**Halite**
		Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	**Flourite**
		Colorless, yellow, brown. Splits along 1 excellent cleavage plane. Hardness- 2-2.5	**Muscovite mica**
	Poor or absent	Yellow crystals or earthy masses. Hardness 1.5-2.5	**Sulfur**
		Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	**Sepentine**
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	**Talc**
		Opaque earthy white to light brown. Hardness- 1-2	**Kaolinite**

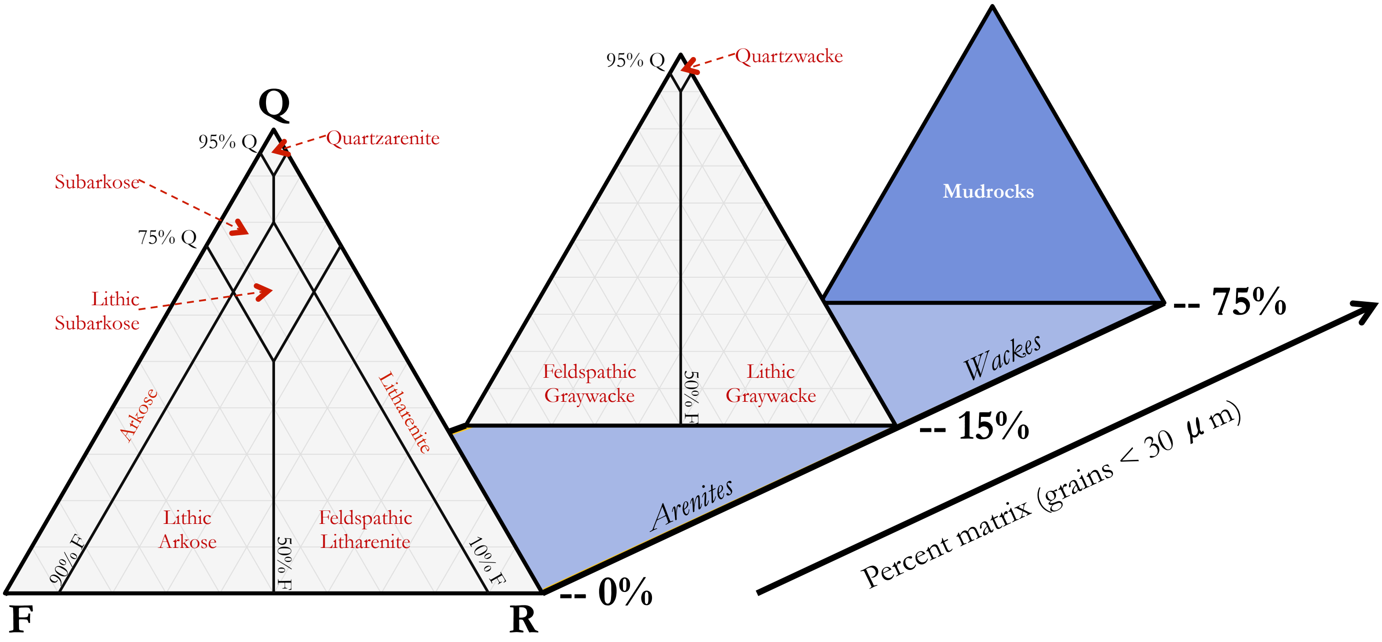


Metallic			
	Streak	**Physical Properties**	**Name**
Hardness > 5	Dark Gray	Brass yellow	**Pyrite**
		Dark gray-black, attracted to magnet	**Magnetite**
Harness < 5	Brown	Silvery black to black tarnishes gray	**Chromite**
	Red-Red/Brown	Silvery gray, black, or brick red	**Hematite**
	Dark Gray	Brass yellow, tarnishes dark brown or purple	**Chalcopyrite**
		Iridescent blue, purple or copper red, tarnishes dark purple	**Bornite**
		Silvery gray, tarnishes dull gray Cleavage good to excellent	**Galena**
		Dark gray to black, can be scratched with fingernail	**Graphite**

Sedimentary Rocks

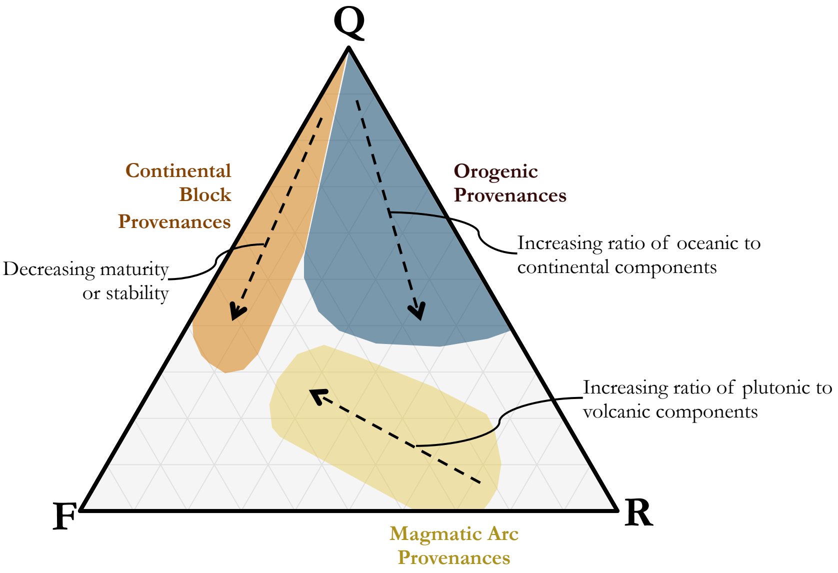
McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert(Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt)



Tectonic Setting for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert(Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt). Regions based upon field data.



Sedimentary Rocks

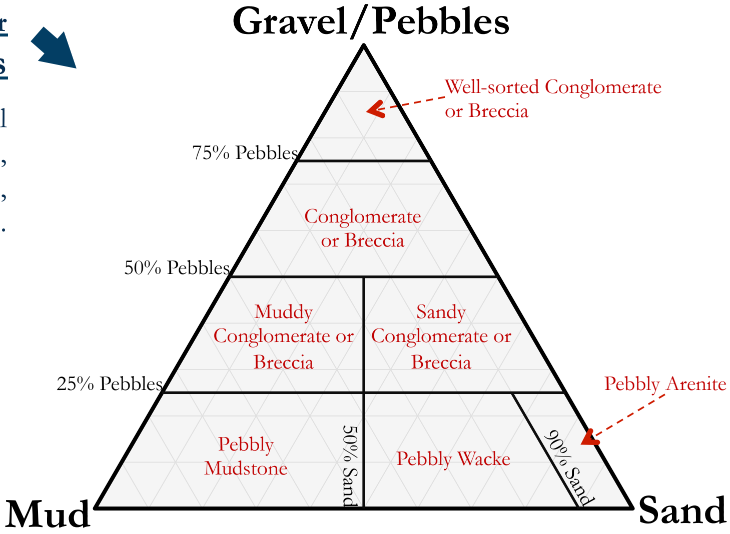
Classification Scheme for Mudrocks

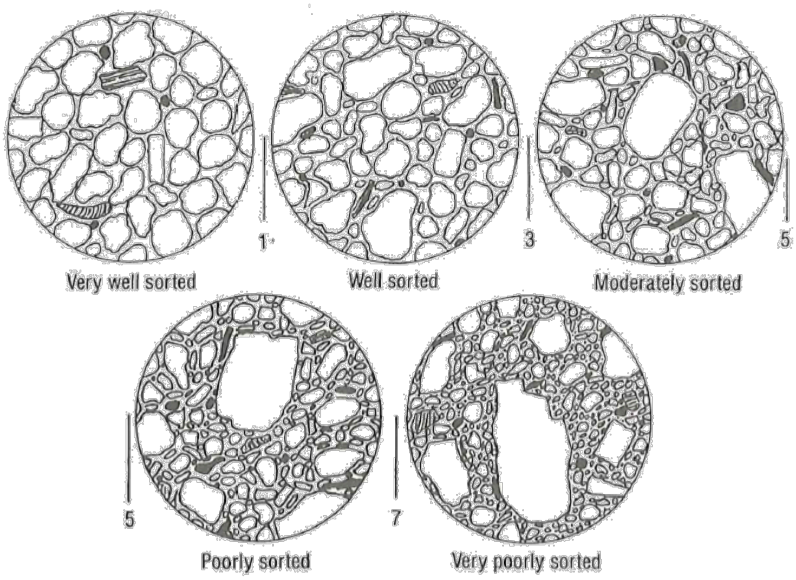
Scheme based on clay/silt content, and whether the rock is laminated (layered) or not.

	Mudrocks (containing > 50% mud)			**Rocks with <50%mud**
	Silt dominant (> 2/3 of rock)	Clay and Silt	Clay dominant (> 2/3 of rock)	Sand-sized or larger grains dominant
Non-laminated	Siltstone	Mudstone	Claystone	Conglomerates, Breccias, Sandstones, etc.
Laminated	Laminated Siltstone	Mudshale	Clayshale	

Classification Scheme for Sub-Conglomerates and Sub-Breccias

Scheme based on percent of a rock composed of: gravel or pebbles (size >2 mm), sand (2 mm > size > 1/16 mm), and mud (size < 1/16 mm).





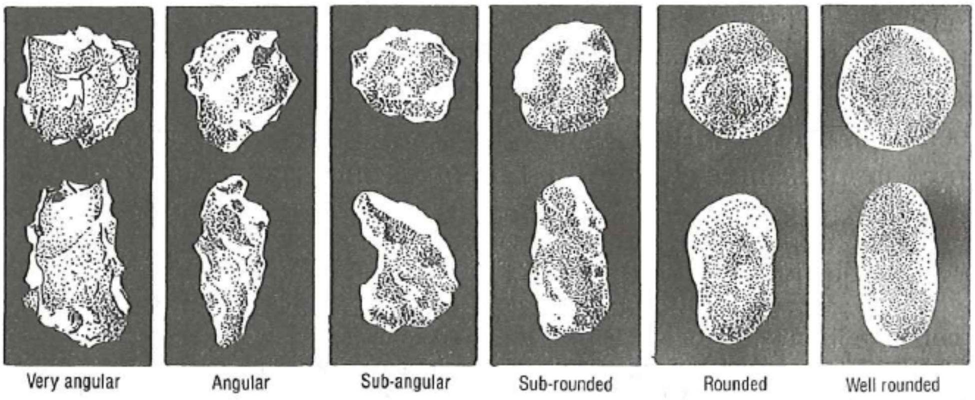
Estimating Sorting

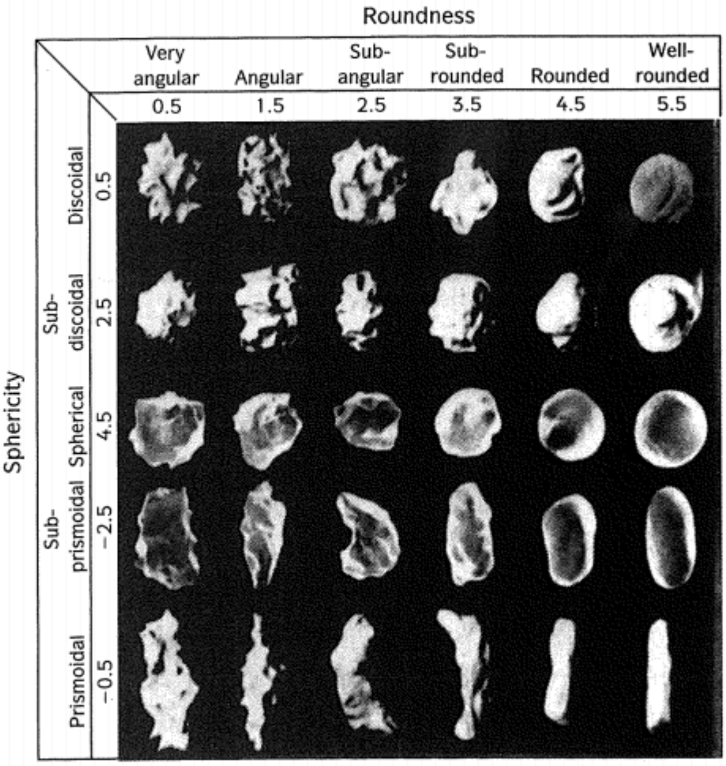
Example hand-lens view of detritus. From Compton, 1985

Sedimentary Rocks

Degrees of Rounding

Example hand-lens view of detritus of varying degrees of roundedness. The top row are equidimensional (spherical) grains, while the lower row are elongated grains. From Compton, 1985 and Davis & Reynolds, 1996, respectively.

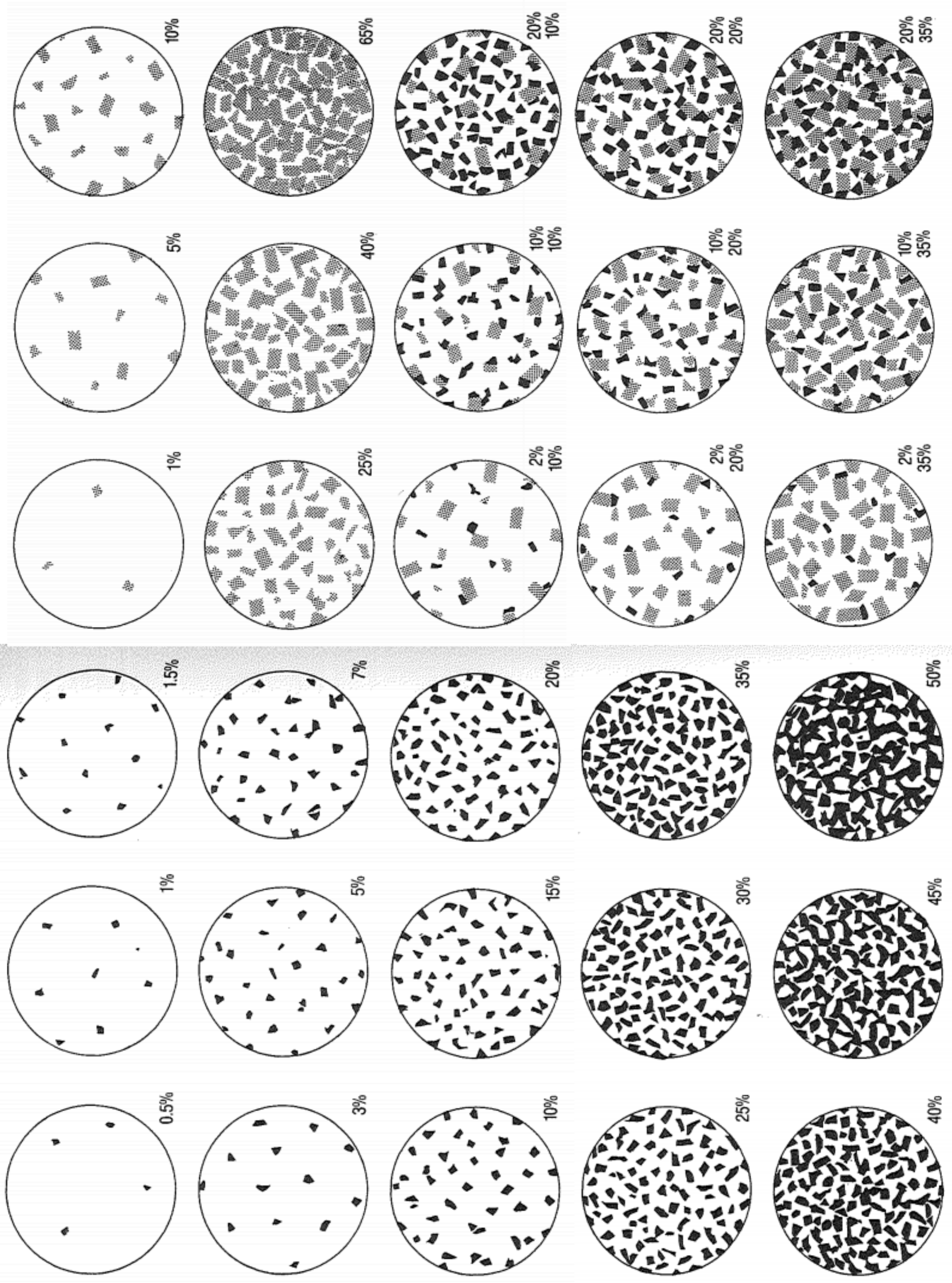




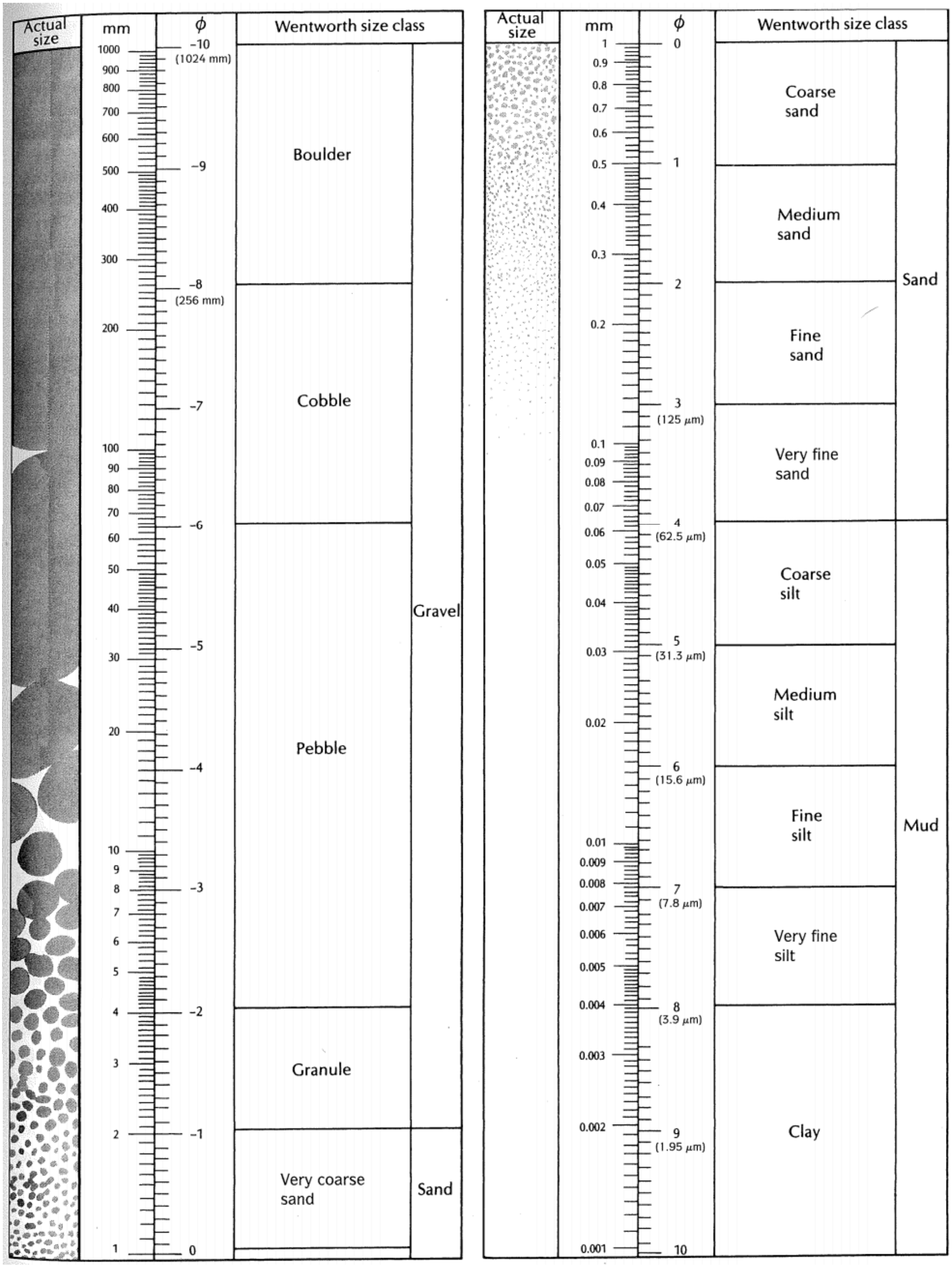
Sedimentary Rocks

Percentage Diagrams for Estimating Composition by Volume

Example hand-lens view of rocks with varying composition. To find weight percents, simply multiply each volume percent by the specific gravity of that mineral, and re-normalize. Compton, 1985



Sedimentary Rocks

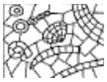
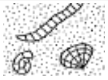
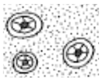
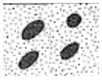
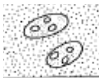
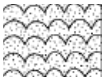
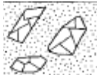


From Prothero and Schwab, 2004

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

Folk's classification scheme is based upon the composition (and type of allochems) within a limestone. Figures from Prothero and Schwab, 2004

Principle Allochems in Limestone	**Limestone Type**			
	Cemented by Sparite		Cemented by Micritic Matrix	
Skeletal Grains (Bioclasts)	Biosparite		Biomicrite	
Ooids	Oosparite		Oomicrite	
Peloids	Pelsparite		Pelmicrite	
Intraclasts	Intrasparite		Intramicrite	
Limestone formed in place	Biolithite		Terrestrial Limestone	

Dunham Classification Scheme for Carbonate Rocks

Dunham's classification scheme is based upon depositional textures within a limestone.

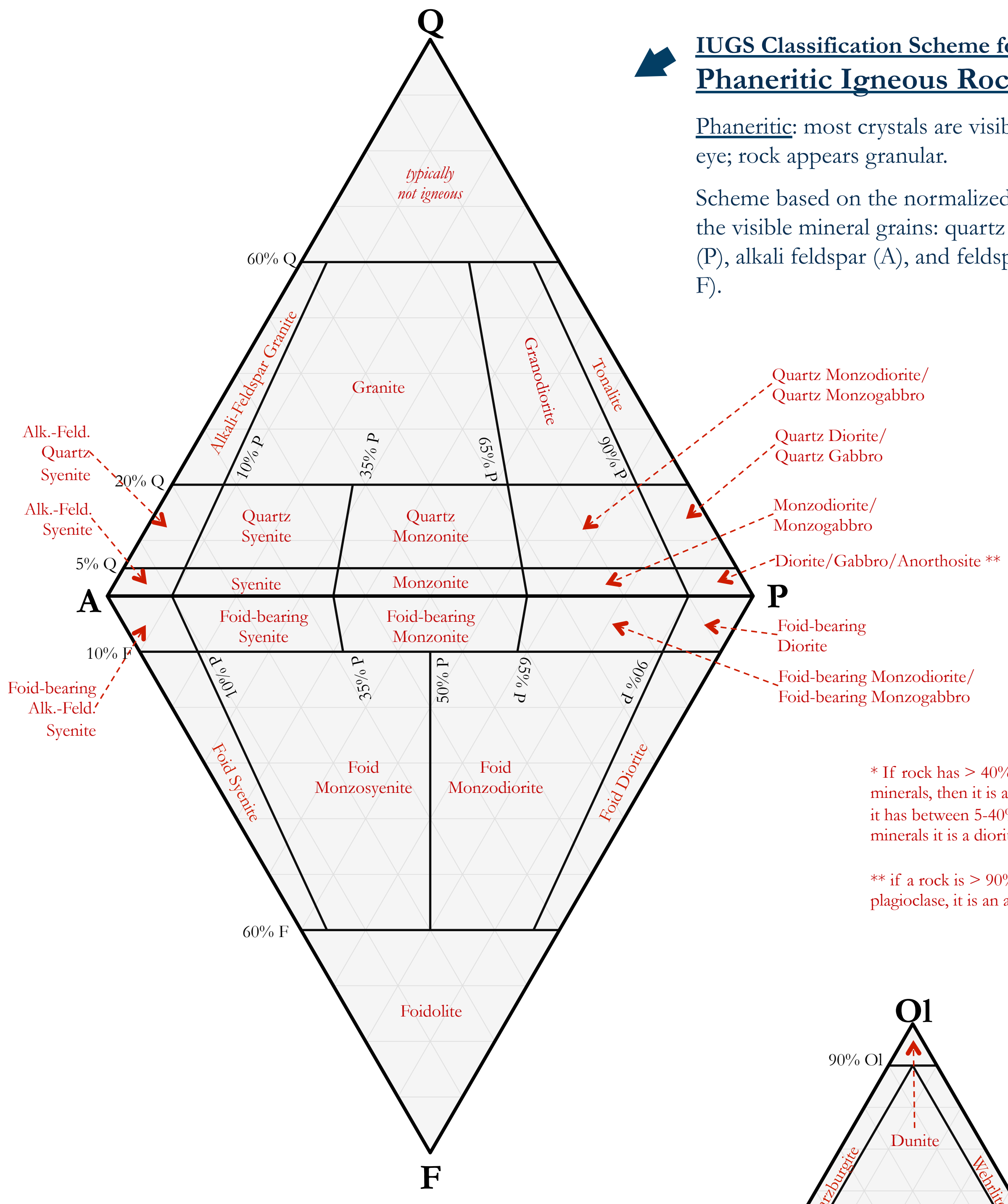
Allochthonous Limestone (original components not organically bound during deposition)						**Autochthonous Limestone** (original components organically bound during deposition; reef rocks)		
Of the allochems, less than 10% are larger than 2 mm				Of the allochems, greater than 10% are larger than 2 mm				
Contains carbonate mud			No mud	Matrix supported	Grain supported	Organisms acted as baffles	Organisms are encrusting and binding	Organisms building a rigid framework
Grain supported		Grain supported						
Less than 10% grains	More than 10% grains							
Mudstone	Wackestone	Packstone	Grainstone	Floatstone	Rudstone	Bafflestone	Bindstone	Framestone

Igneous Rocks

IUGS Classification Scheme for
Phaneritic Igneous Rocks

Phaneritic: most crystals are visible to the naked eye; rock appears granular.

Scheme based on the normalized percentages of the visible mineral grains: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).



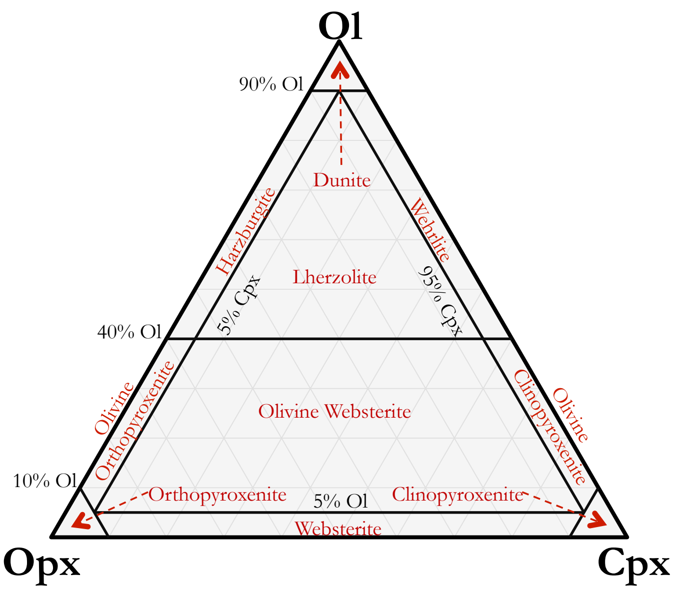
* If rock has > 40% mafic minerals, then it is a gabbo. If it has between 5-40% mafic minerals it is a diorite.

** if a rock is > 90% plagioclase, it is an anorthosite

IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (1)

Ultramafic: more than 90% of the total minerals are mafic.

Scheme based on the normalized percentages of the visible minerals: olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx).

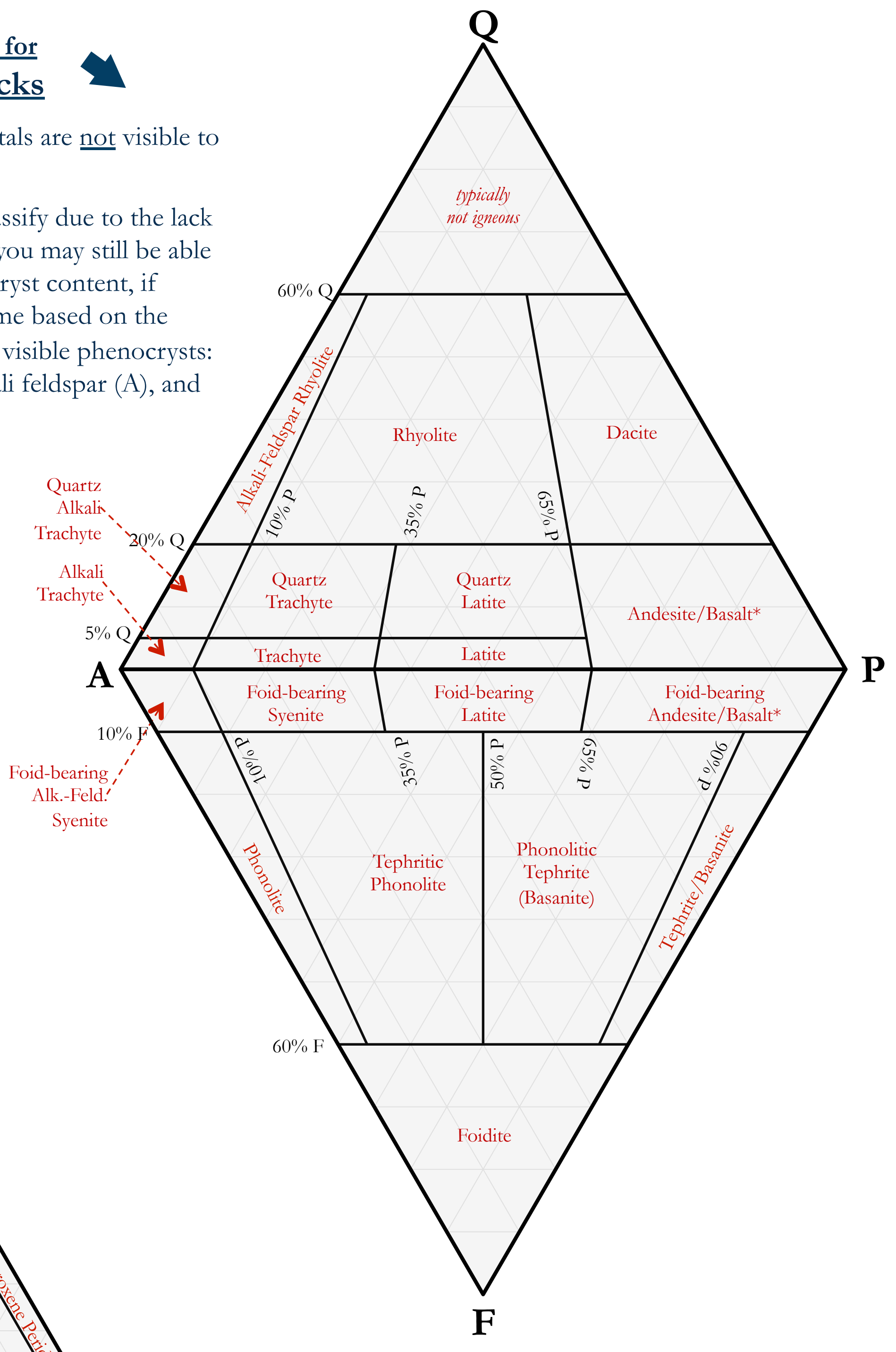


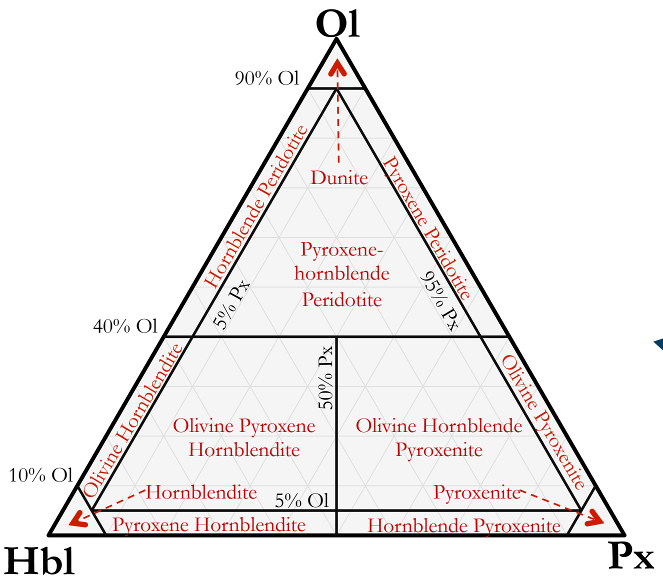
Igneous Rocks

IUGS Classification Scheme for
Aphanitic Igneous Rocks

Aphanitic: the majority of crystals are not visible to the naked eye.

Aphanetic rocks are hard to classify due to the lack of visible minerals. However, you may still be able identify them based on phenocryst content, if phenocrysts are present. Scheme based on the normalized percentages of the visible phenocrysts: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).





IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (2)

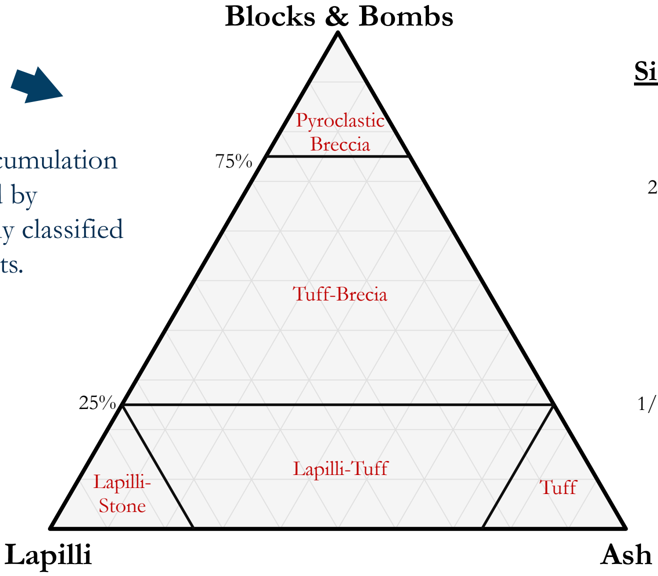
Ultramafic: more than 90% of the total minerals are mafic.

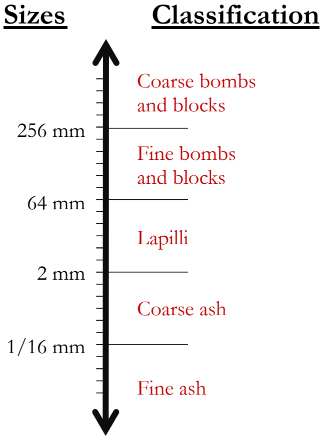
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

Igneous Rocks

Classification Scheme for Pyroclastic Igneous Rocks

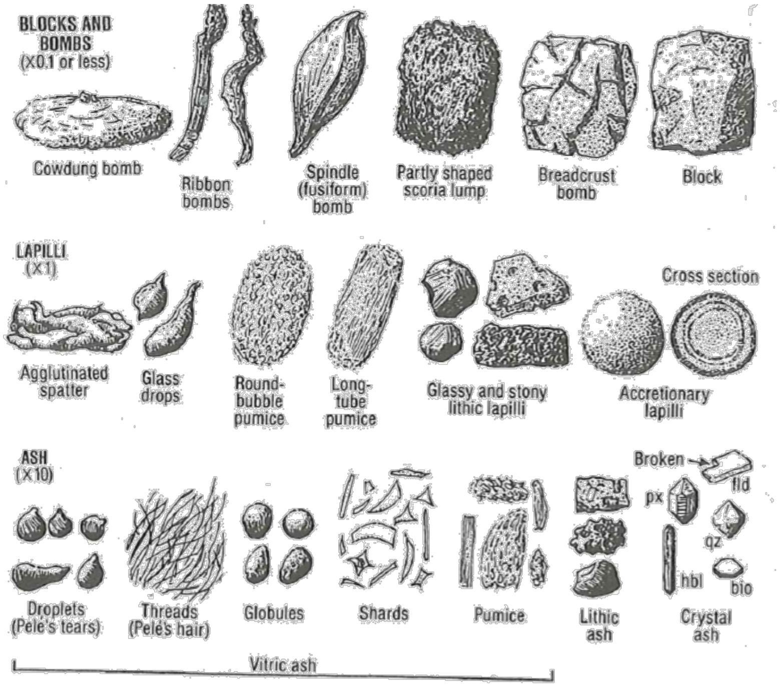
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.

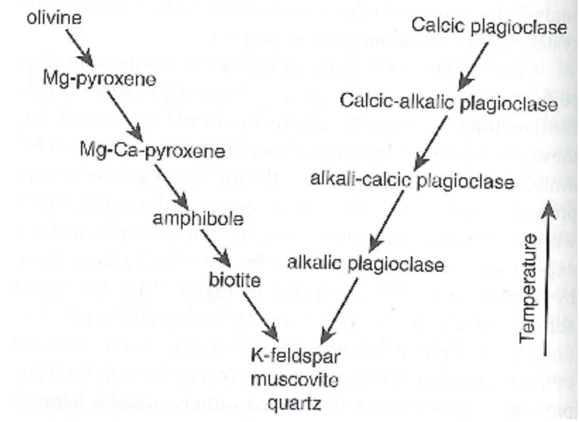




Types of Tephra (Pyroclasts)

In each row, the viscosity of the lava increases to the right. From Compton, 1985.





Bowen's Reaction Series

From Winter, 2010.

Metamorphic Rocks

Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

Structure & Texture	Characteristic Properties	Characteristic Mineralogy	Rock Name
Foliate (layered) Increasing grain size, and degree of metamorphism ↓	Dull luster; very flat fracture surface; grains are too small to readily see; more dense than shale	No visible minerals	Slate
	Silky sheen; Crenulated (wavy) fracture structure; A few grains visible, but most are not	Development of mica and/or hornblende possible	Phyllite
	Sub-parallel orientations of individual mineral grains; wavy-sheet like fracture; often contains porphyroblasts; thinly foliated	Abundant feldspar; Quartz and mica are common; hornblende possible	Schist
	Sub-parallel, alternating bands or layers of light and dark material; coarsely foliated; blocky fracture	Abundant feldspars; Quartz, mica, and hornblende are common	Gneiss
Foliate (layered)	Interlocking crystals; effervesces in dilute HCl; softer than glass	Calcite	Marble
	Nearly equigranular grains; fracture across grains (not around them); sub-vitreous appearance; smooth feel compared to sandstone	Quartz	Quartzite

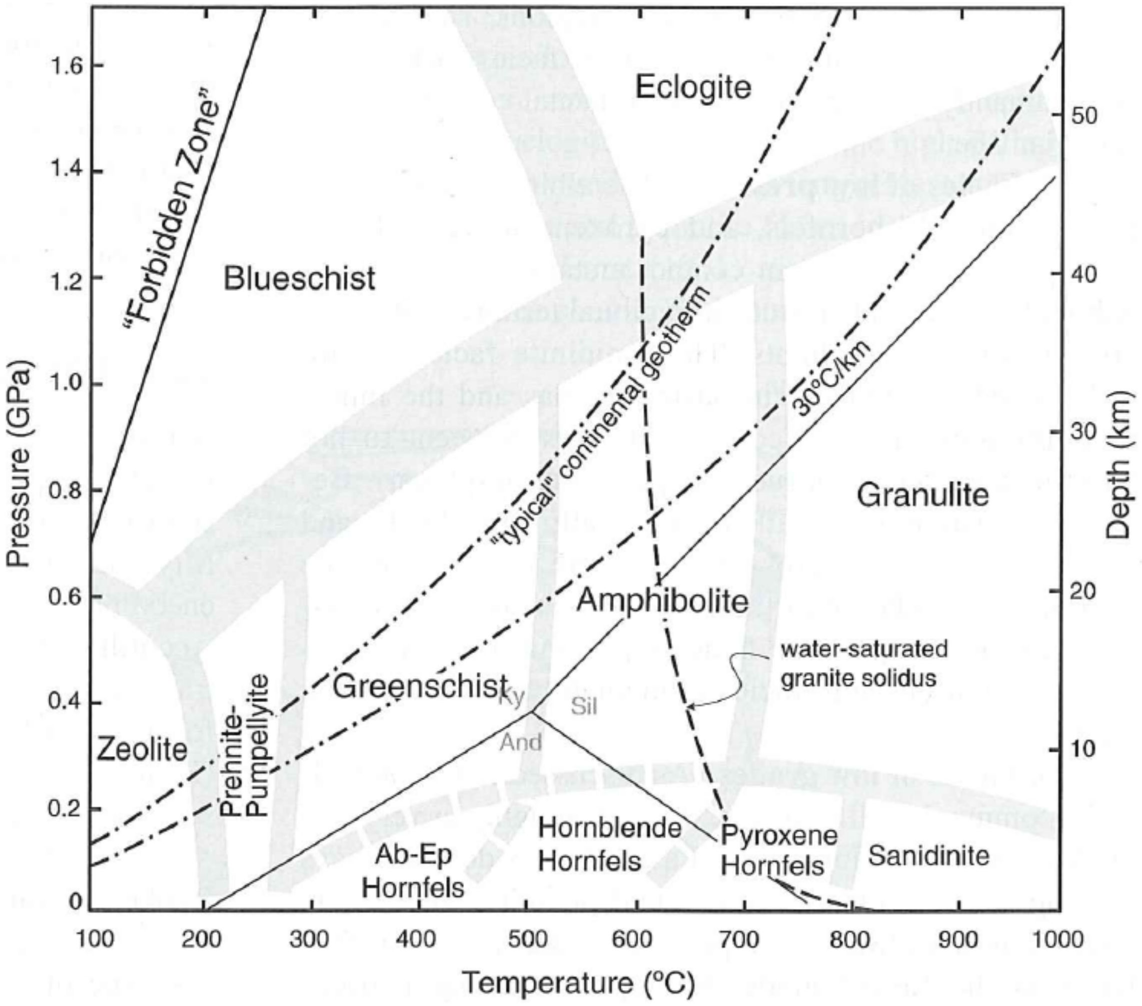
Mineralogy for Metamorphic Rock Facies

Facies	Definitive Mineral Assemblages in Mafic Rocks
Zeolite	zeolites: especially laumontite, wairakite, analcime (in place of other Ca-Al silicates such as prehnite, pumpellyite and epidote)
Prehnite-Pumpellyite	prehnite + pumpellyite (+ chlorite + albite)
Greenschist	chlorite + albite +epidote (or zoisite) + actinolite ± quartz
Amphibolite	hornblende + plagioclase (oligoclase, andesine) ± garnet
Granulite	orthopyroxene + clinopyroxene + plagioclase ± garnet
Blueschist	glaucophane + lawsonite or epidote/zoisite (± albite ± chlorite ± garnet)
Eclogite	pyralspite garnet + omphacitic pyroxene (± kyanite ± quartz), no plagioclase
Contact Facies	mineral assemblages in mafic rocks of the facies of contact metamorphism do not differ substantially from those of the corresponding regional facies at higher pressure

Metamorphic Rocks

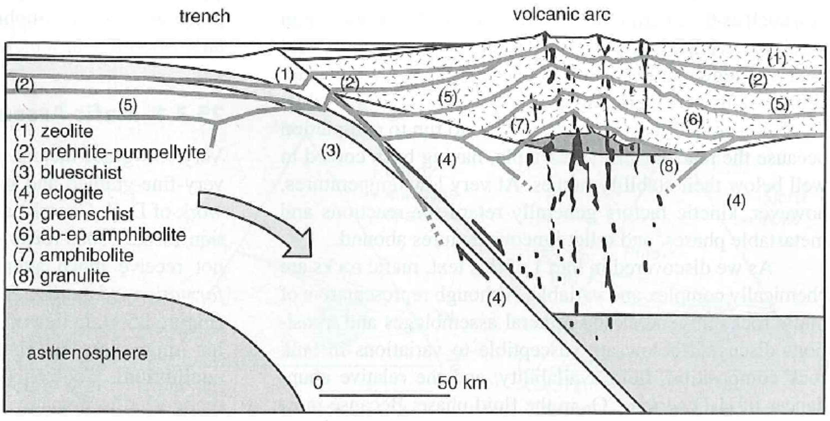
Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010



Schematic of Island Arc, and the origins of Metamorphic Facies

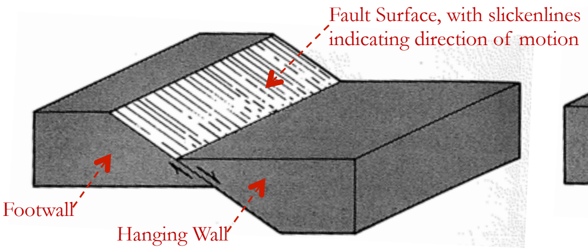
A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010



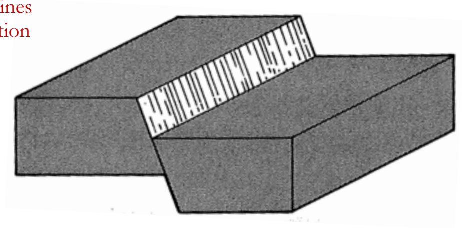
Structural Geology: Normal Faults

Normal Faults

In normal faults, the footwall goes up with respect to the hanging wall. Normal faults are indicative of extension. Figures from Davis & Reynolds, 1996.



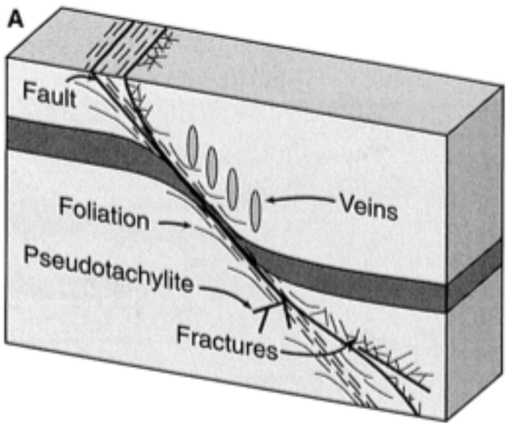
Low-angle Normal Slip Fault

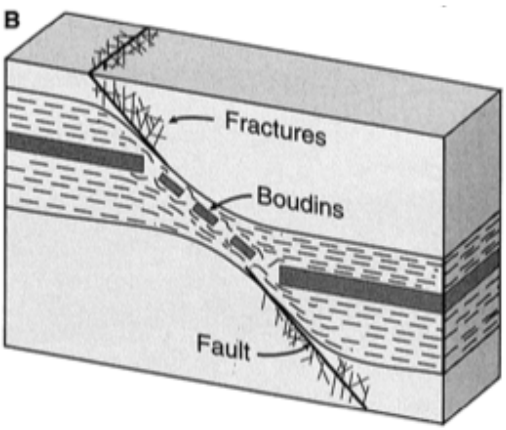


Normal Slip Fault

Effects of Brittle or Ductile Shear in Normal Faults

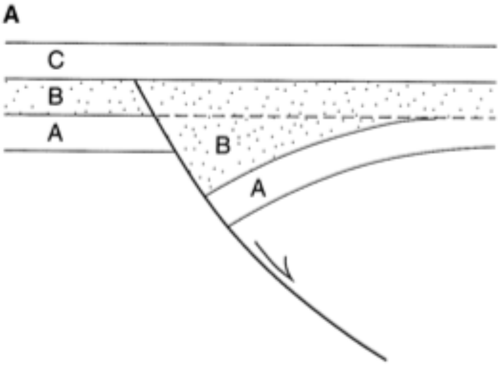
The block diagrams below illustrate the effects of changing the nature of deformation, between brittle deformation (which results in clear fault planes, fractures and fault rocks), ductile deformation (which causes deformation over a larger shear zone). Often, strata of different rheologies will behave differently, as is shown in the figure at right. The dashed layer was weak and deformed ductilely, while the middle grey layer was rigid and formed boudins. Figures from Davis & Reynolds, 1996.

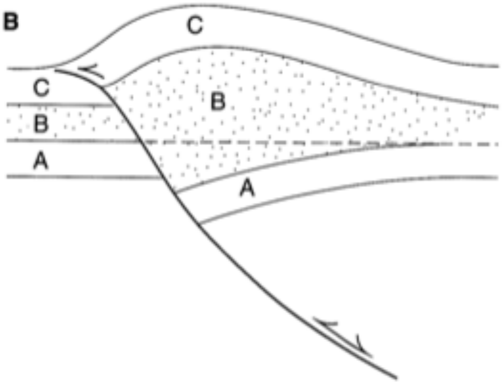




Inversion Tectonics

If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right, the fault has reactivated, though as a reverse fault. The resulting stratigraphic sequence is a combination of effects one would expect from both normal and reverse faults. Figures from Davis & Reynolds, 1996.

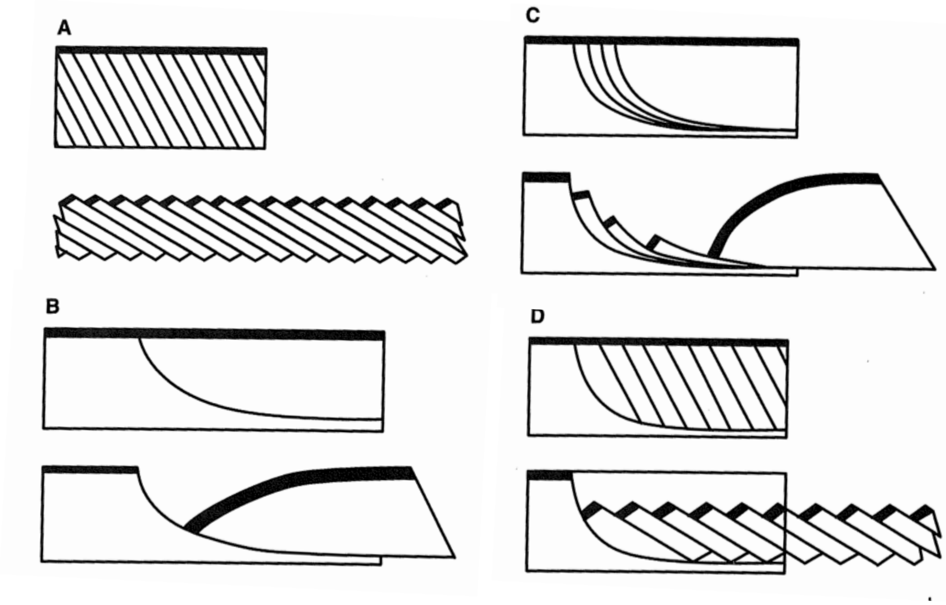


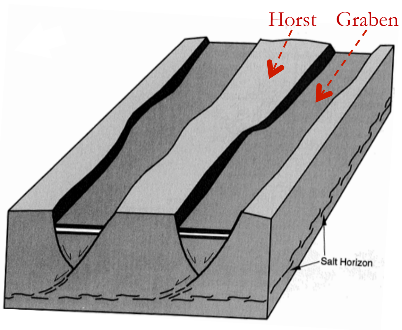


Structural Geology: Normal Faults

Normal Faults Geometries

Various normal fault geometries are possible. They all allow for lithospheric extension. (A) Domino style faulting. (B) Listric normal faulting with reverse drag. (C) Imbricate listric normal faulting. Note that listric faulting can cause extreme rotation of faulted blocks. (D) Listric normal faulting bounding a family of planar normal faults. Figures from Davis & Reynolds, 1996.



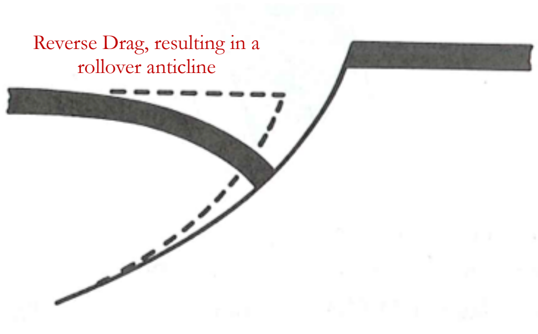


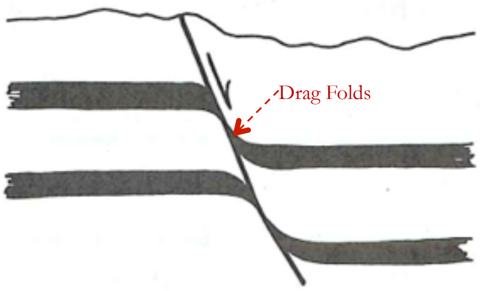
Horsts & Grabens

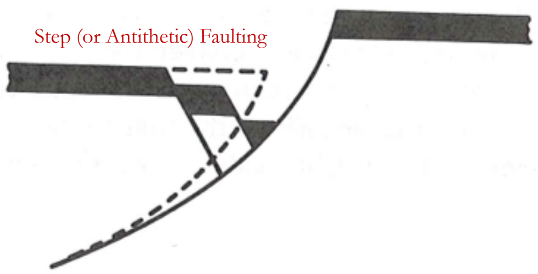
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

Faulting does not always produce clean displacement along the fault surface. Fault blocks are frequently folded or fractured, and the nature of these deformations are non-trivial. Figures from Davis & Reynolds, 1996.



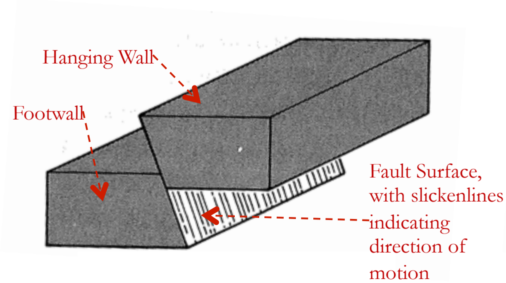




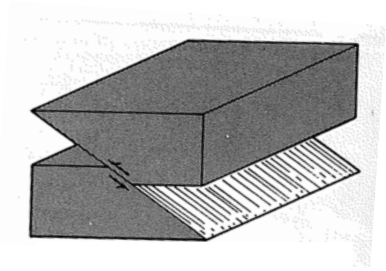
Structural Geology: Reverse & Thrust Faults

Reverse Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.



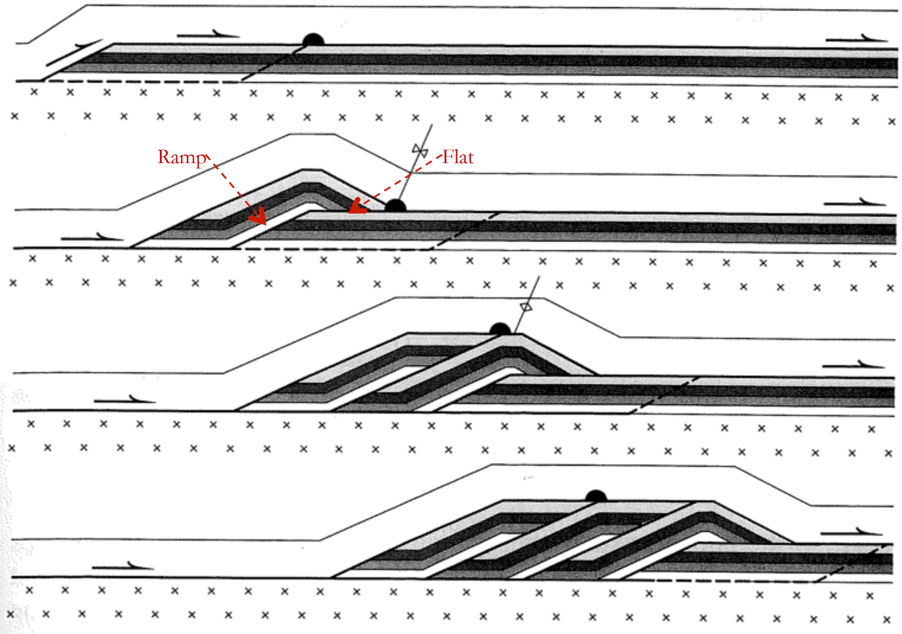
Reverse Slip Fault



Thrust Slip Fault

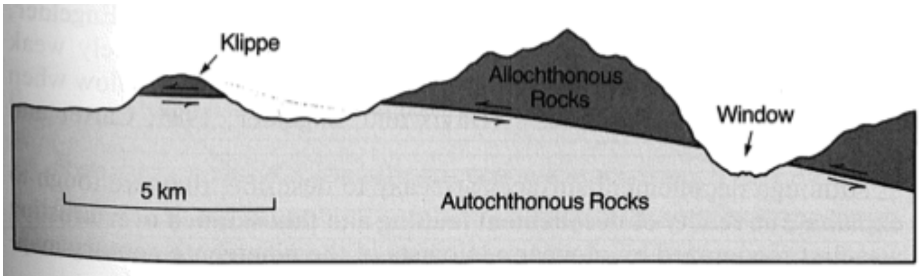
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

In a regional thrust, faulted blocks are "thrust" on top of younger strata. The exact geometry of these thrust systems can vary significantly. Figures from Davis & Reynolds, 1996.

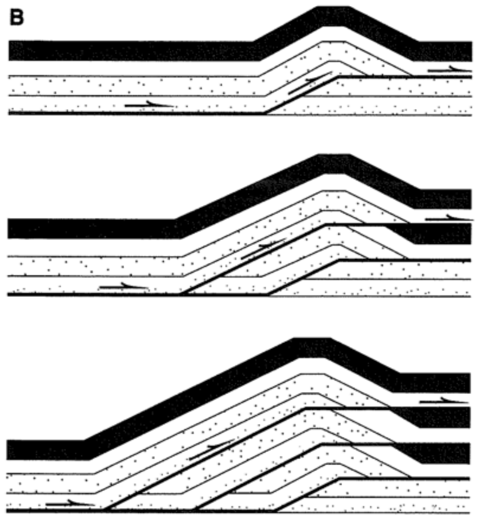


Klippe & Windows

Thrust faults move large blocks of non-indigenous rock (referred to as "allochthonous" rock) over emplaced rock (referred to as "autochthonous" rock). If the overlying allochthonous rock is eroded, it can create windows into the lower underlying autochthonous rock. Erosion can also create islands of isolated allochthonous rock, called klippe. Figures from Davis & Reynolds, 1996.



Structural Geology: Reverse & Thrust Faults

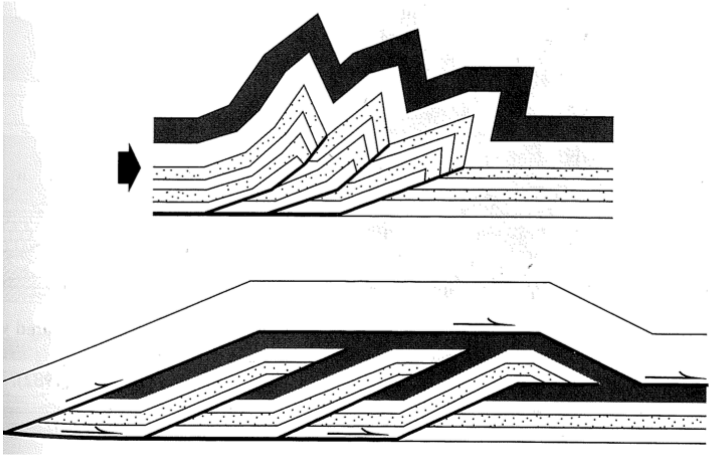


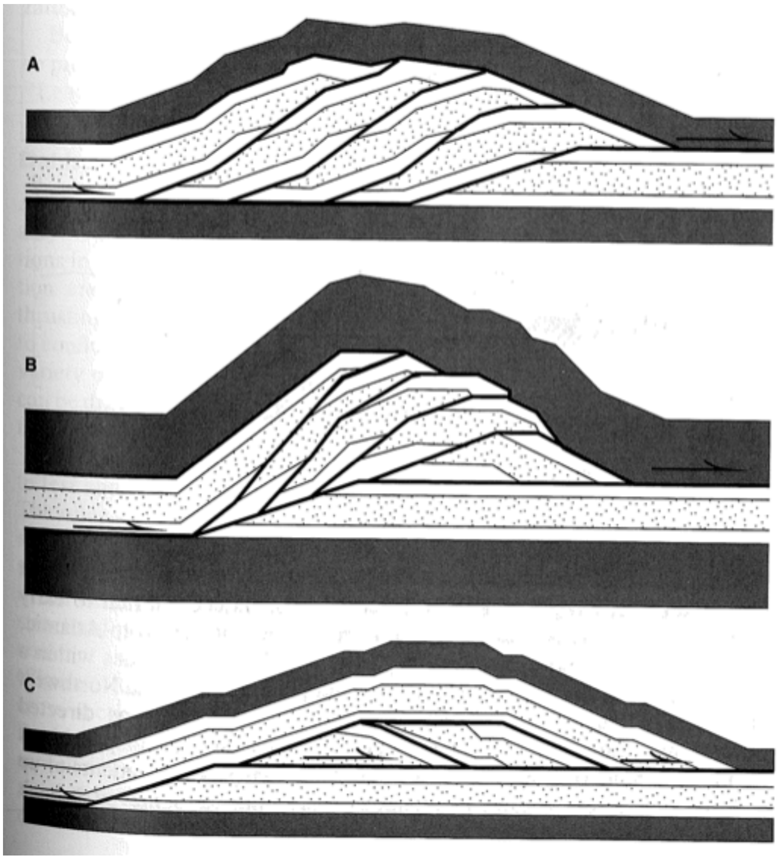
Out-of-Sequence Thrust Fault System

Unlike "in-sequence" thrust fault systems (as shown on the previous page, the "roof" of the thrust block in an out-of-sequence system becomes the "flat" for subsequent fault blocks. Figures from Davis & Reynolds, 1996.

Imbricate Fans vs. Duplexes

Two thrust fault geometries: imbricate fans (top) and duplexes (bottom). Figures from Davis & Reynolds, 1996.





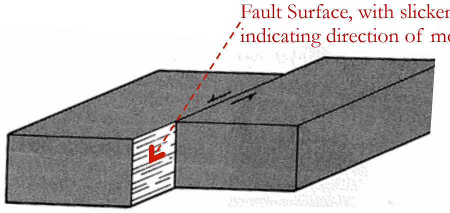
Forms of Duplexes

The exact form of a duplex or imbricate fan depends on the spacing of ramps and the amount of slip. (A) A normal duplex develops when slice length exceeds the fault slip. (B) An antiformal duplex develops when slice length and fault slip are effectively equal. (C) A forward-dipping duplex develops when the fault slip is greater than the slice length. Figures from Davis & Reynolds, 1996.

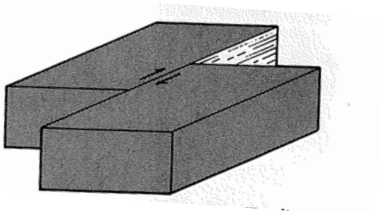
Structural Geology: Strike-Slip or Transform Faults

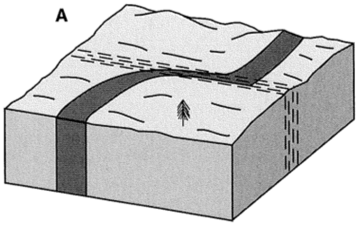
Strike-Slip Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.

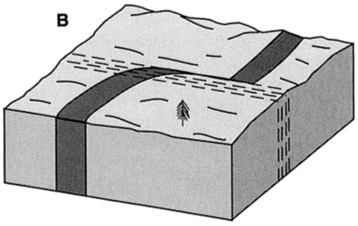

Fault Surface, with slickenlines indicating direction of motion

Left Lateral (Sinistral) Strike-Slip Fault


Right Lateral (Dexteral) Strike-Slip Fault



Continuous Shear Zone



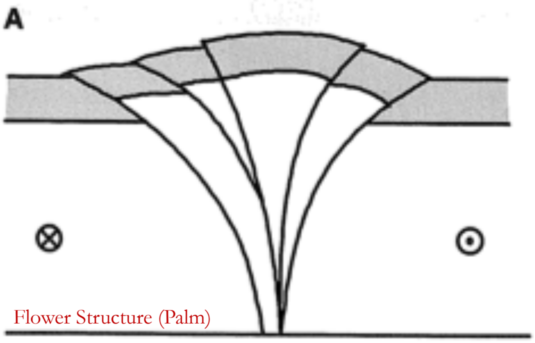
Discontinuous Shear Zone

Ductile Shear Zones

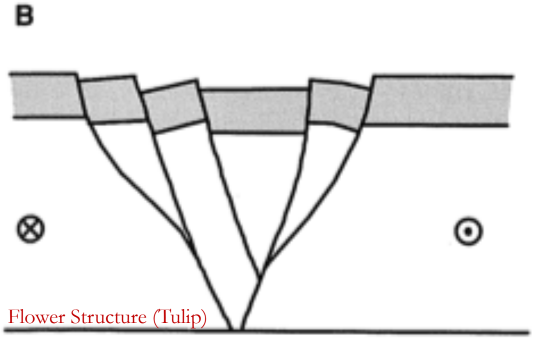
Shear in a strike-slip fault is not always located in a single plane. Sometimes, shear takes place over an extended region. Figures from Davis & Reynolds, 1996.

Brittle Shear Zones

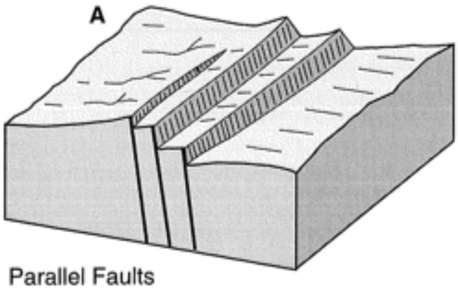
Figures from Davis & Reynolds, 1996.



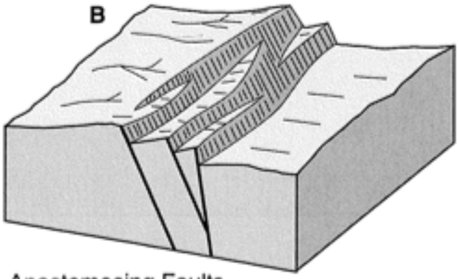
Flower Structure (Palm)



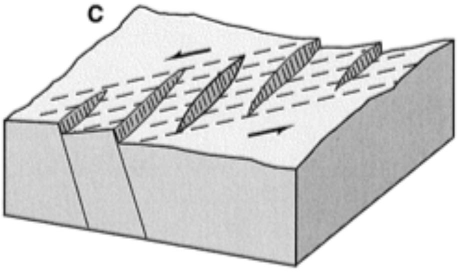
Flower Structure (Tulip)



Parallel Faults



Anastomosing Faults

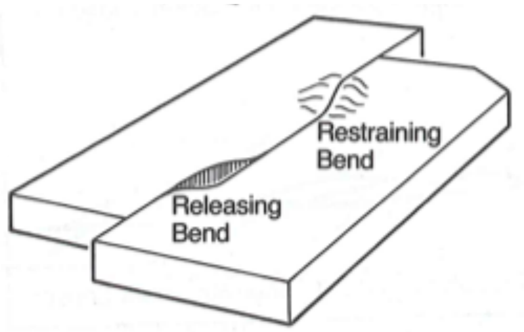


En Echelon Faults

Structural Geology: Strike-Slip or Transform Faults

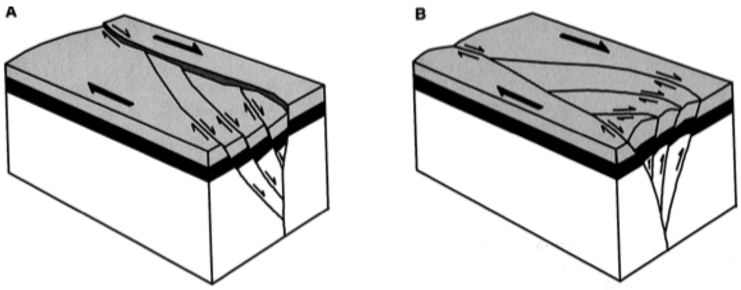
Bends in Strike-Slip Faults

Strike-slip faults along irregularly curved faults creates localized regions of extension and compression. Figures from Davis & Reynolds, 1996.



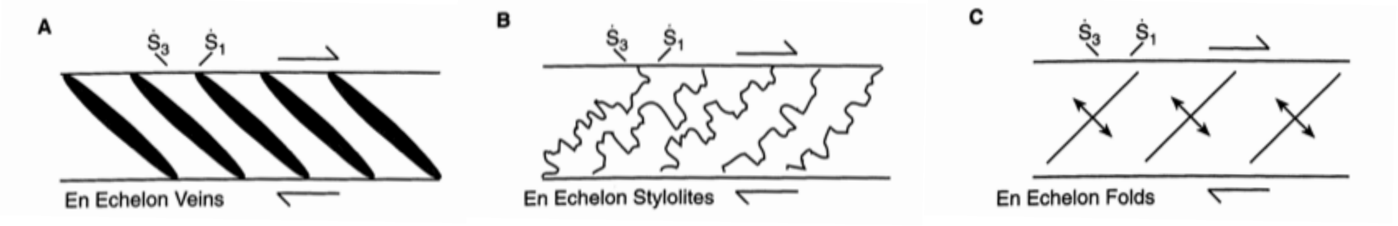
Strike-Slip Duplexes

(A) Extensional duplexes can form at releasing bends. (B) Compressional duplexes can form at restraining bends. Figures from Davis & Reynolds, 1996.



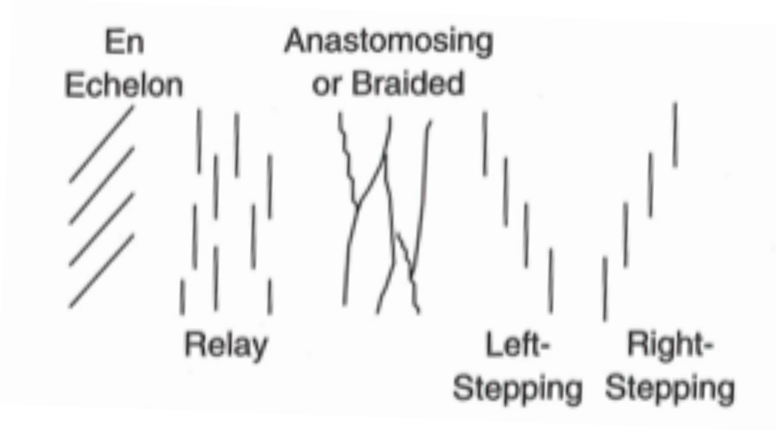
Slip Indicators in Strike-Slip Systems

In strike-slip systems, the maximum (S_1) and minimum compressional stresses (S_3) are at an angle with respect to the sense of shear. This can lead to the formation of both large scale folds and faults, or small scale fractures or veins, which are indicative to the sense of motion. Figures from Davis & Reynolds, 1996.



Even more Geometric Arrangements of Strike-Slip Faults

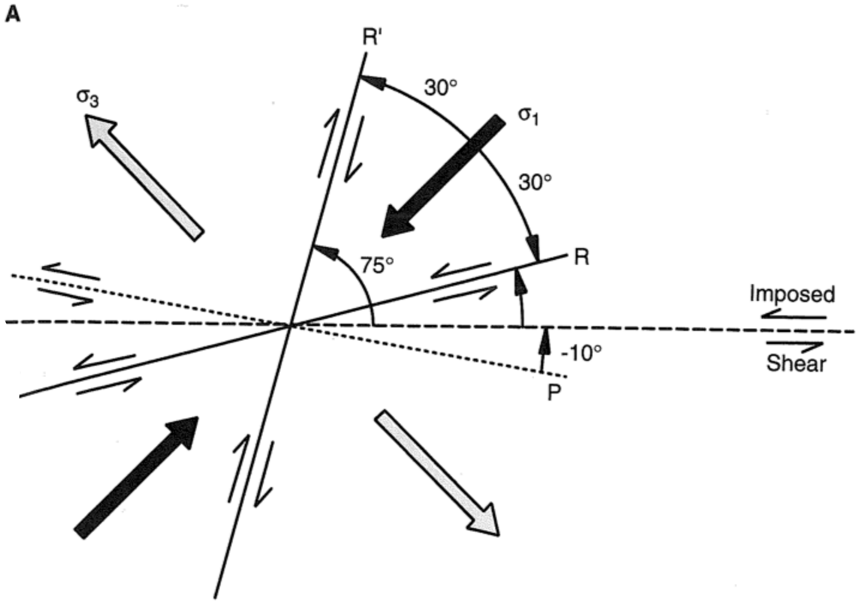
Figures from Davis & Reynolds, 1996.

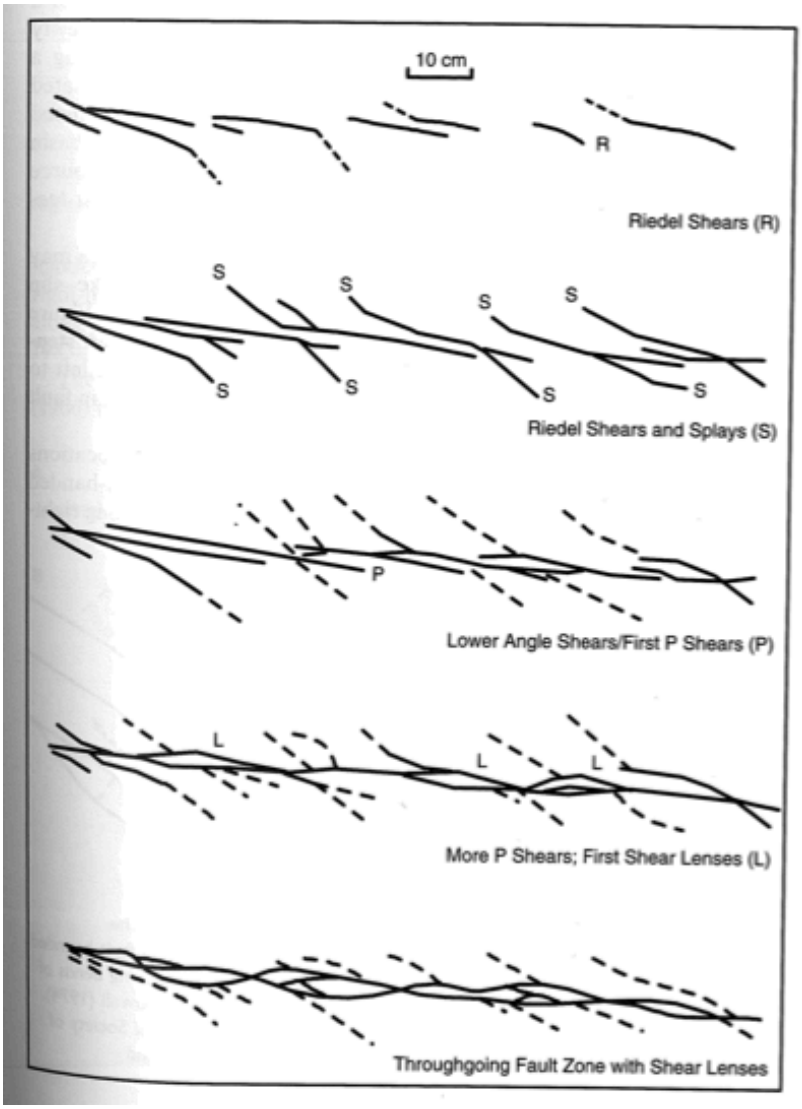


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

When under compression, rocks tend to form fail with faults forming 30° from the primary compressional stress. In a strike-slip fault, the primary compressional stress (σ_1) is 45° away from the plane of strike-slip shearing. The combination of these two facts results in fractures at interesting angles with respect to the motion of shear. These are called Riedel shears. The figure below shows a left-handed strike-slip zone. Figures from Davis & Reynolds, 1996.



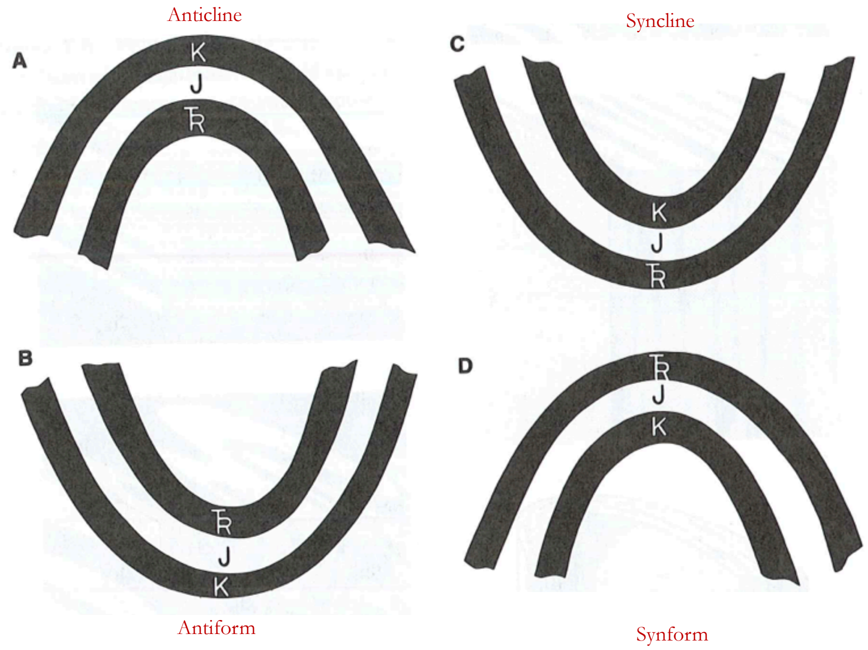


The figure at left illustrate the formation sequence of Riedel shears and other splays and shears in a right-handed strike-slip zone. Figures from Davis & Reynolds, 1996.

Structural Geology: Folds

Anticlines & Antiforms, and Synclines & Synforms

Antiforms are concave-down folds, while Synforms are concave-up folds. Anticlines are antiforms were we know that the younger strata lie on top of older strata. Similarly, Synclines are antiforms where younger strata lie on top of older strata. Figures from Davis & Reynolds, 1996.



Anticline

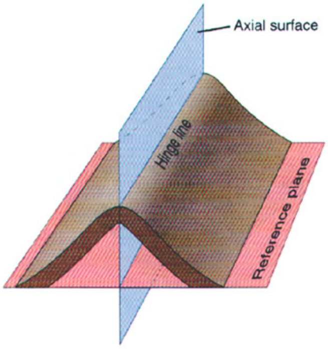
Syncline

Antiform

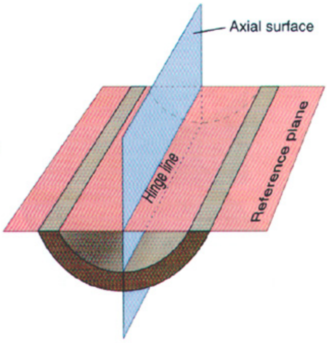
Synform

Plunging Folds

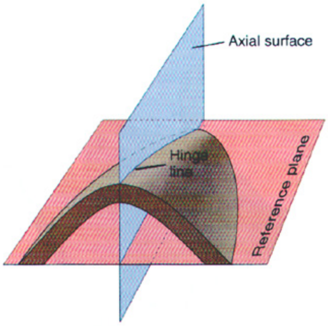
Folds (defined by hinge lines and axial surfaces) are not necessarily perpendicular to the Earth's surface. They can be dipping into or out of the surface. This can create interesting patterns of exposed surface rock, or even topography. Figures from Jones, 2001.



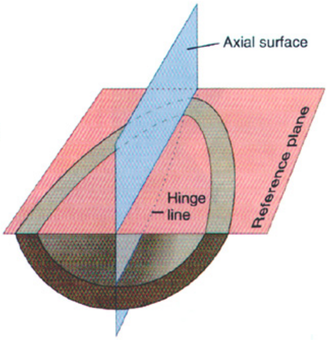
Non-plunging antiform



Non-plunging synform



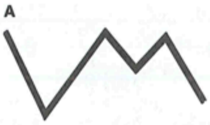
Plunging antiform



Plunging synform

Fold Shapes

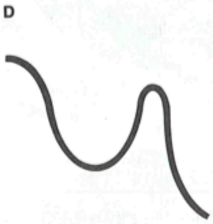
Folds can come in a variety of shapes. Davis & Reynolds, 1996.



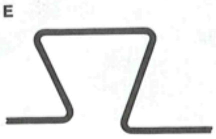
Chevron

Cuspate

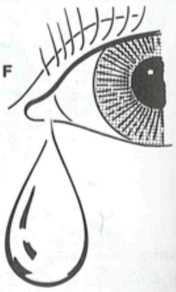
Circular



Elliptical



Box (Conjugate)

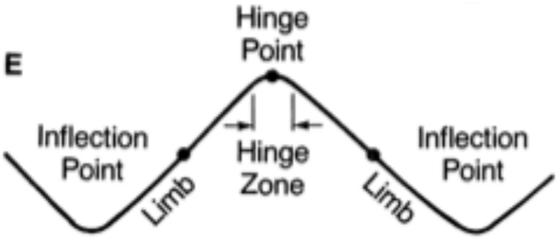


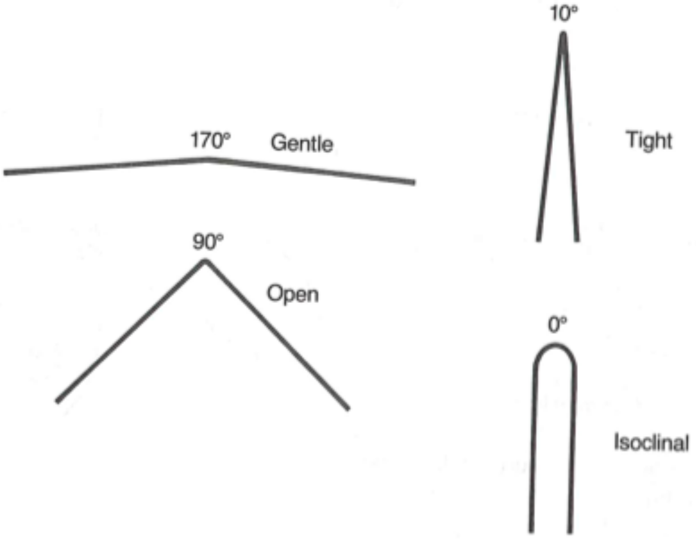
Teardrop

Structural Geology: Folds

Fold Tightness

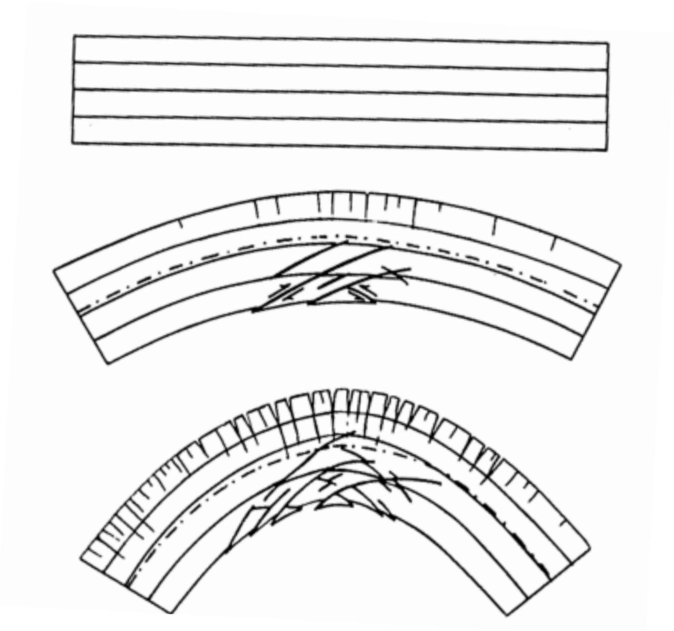
Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.





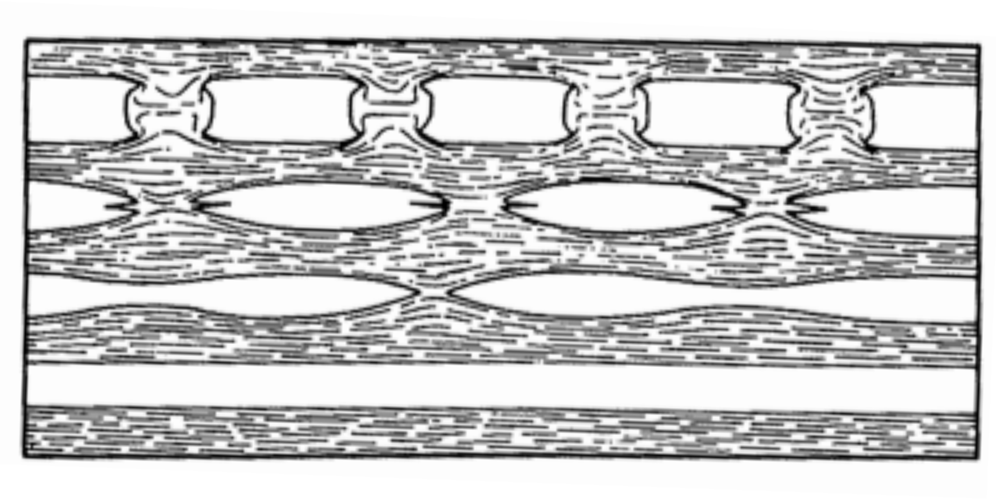
Minor Structures in Folds

When folding layers of strata, layer-parallel stretching occurs in the outer arc of a folded layer, while layer-parallel shortening occurs in the inner arc. Figures from Davis & Reynolds, 1996.

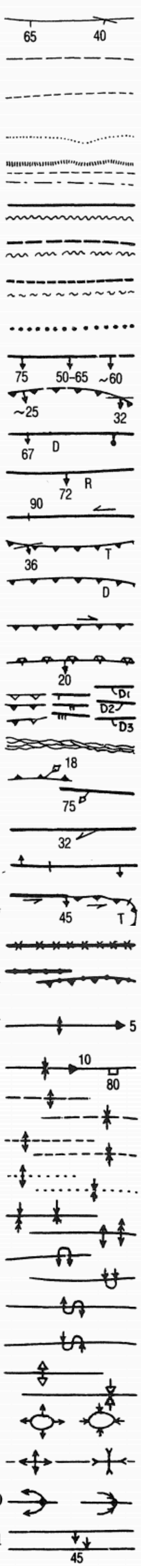
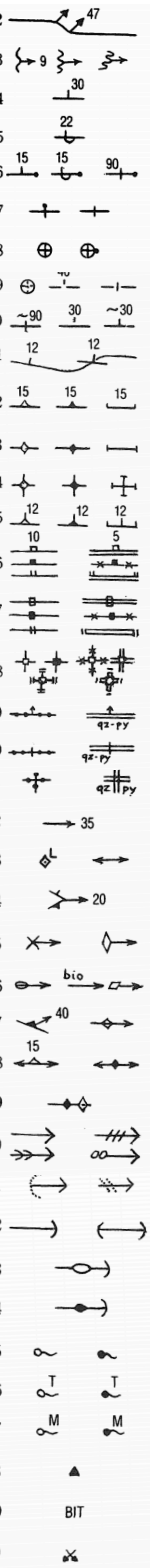


Boudins

Layer-parallel stretching can pinch off layers of strata, depending on the ductility contrast between layers. This can result in pinch-and-swell structures or boudins (where the pinching completely pinches off portions of a given strata). Figures from Davis & Reynolds, 1996.



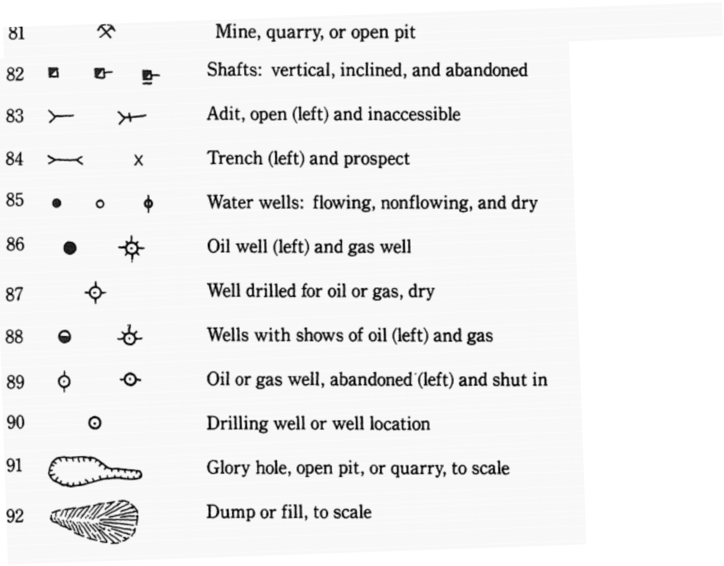
Geologic Map Symbols



1	Contact, showing dip where trace is horizontal, and strike and dip where trace is inclined
2	Contact, located approximately (give limits)
3	Contact, located very approximately, or conjectural
4	Contact, concealed beneath mapped units
5	Contact, gradational (optional symbols)
6	Fault, nonspecific, well located (optional symbols)
7	Fault, nonspecific, located approximately
8	Fault, nonspecific, assumed (existence uncertain)
9	Fault, concealed beneath mapped units
10	Fault, high-angle, showing dip (left) and approximate dips
11	Fault, low-angle, showing approximate dip and strike and dip
12	Fault, high-angle normal (D or ball and bar on downthrown side)
13	Fault, reverse (R on upthrown side)
14	Fault, high-angle strike-slip (example is left lateral)
15	Fault, thrust (T on overthrust side)
16	Fault, low-angle normal or detachment (D on downthrown side)
17	Fault, low-angle strike-slip (example is right lateral)
18	Fault, low-angle, overturned (teeth in direction of dip)
19	Optional sets of symbols for different age-groups of faults
20	Fault zone or shear zone, width to scale (dip and other accessory symbols may be added)
21	Faults with arrows showing plunge of rolls, grooves or slickensides
22	Fault showing bearing and plunge of net slip
23	Point of inflection (bar) on a high-angle fault
24	Points of inflection on a strike-slip fault passing into a thrust
25	Fault intruded by a dike
26	Faults associated with veins
27	Anticline, showing trace and plunge of hinge or crest line (specify)
28	Syncline (as above), showing dip of axial surface or trough surface
29	Folds (as above), located approximately
30	Folds, conjectural
31	Folds beneath mapped units
32	Asymmetric folds with steeper limbs dipping north (optional symbols)
33	Anticline (top) and syncline, overturned
34	Antiformal (inverted) syncline
35	Synformal (inverted) anticline
36	Antiform (top) and synform (stratigraphic sequence unknown)
37	Separate dome (left) and basin
38	Culmination (left) and depression
40	Vertically plunging anticline and syncline
41	Monocline, south-facing, showing traces of axial surfaces
42	Steeply plunging monocline or flexure, showing trace in horizontal section and plunge of hinges
43	Plunge of hinge lines of small folds, showing shapes in horizontal section
44	Strike and dip of beds or bedding
45	Strike and dip of overturned beds
46	Strike and dip of beds where stratigraphic tops are known from primary features
47	Strike and dip of vertical beds or bedding (dot is on side known to be stratigraphically the top)
48	Horizontal beds or bedding (as above)
49	Approximate (typically estimated) strike and dip of beds
50	Strike of beds exact but dip approximate
51	Trace of single bed, showing dip where trace is horizontal and where it is inclined
52	Strike and dip of foliation (optional symbols)
53	Strike of vertical foliation
54	Horizontal foliation
55	Strike and dip of bedding and parallel foliation
56	Strike and dip of joints (left) and dikes (optional symbols)
57	Vertical joints (left) and dikes
58	Horizontal joints (left) and dikes
59	Strike and dip of veins (optional symbols)
60	Vertical veins
61	Horizontal veins
62	Bearing (trend) and plunge of lineation
63	Vertical and horizontal lineations
64	Bearing and plunge of cleavage-bedding intersection
65	Bearing and plunge of cleavage-cleavage intersections
66	Bearings of pebble, mineral, etc. lineations
67	Bearing of lineations in plane of foliation
68	Horizontal lineation in plane of foliation
69	Vertical lineation in plane of vertical foliation
70	Bearing of current from primary features; from upper left: general; from cross-bedding; from flute casts; from imbrication
71	Bearing of wind direction from dune forms (left) and cross-bedding
72	Bearing of ice flow from striations (left) and orientation of striations
73	Bearing of ice flow from drumlins
74	Bearing of ice flow from crag and tail forms
75	Spring
76	Thermal spring
77	Mineral spring
78	Asphaltic deposit
79	Bituminous deposit
80	Sand, gravel, clay, or placer pit

From Compton, 1985

Geologic Map Symbols

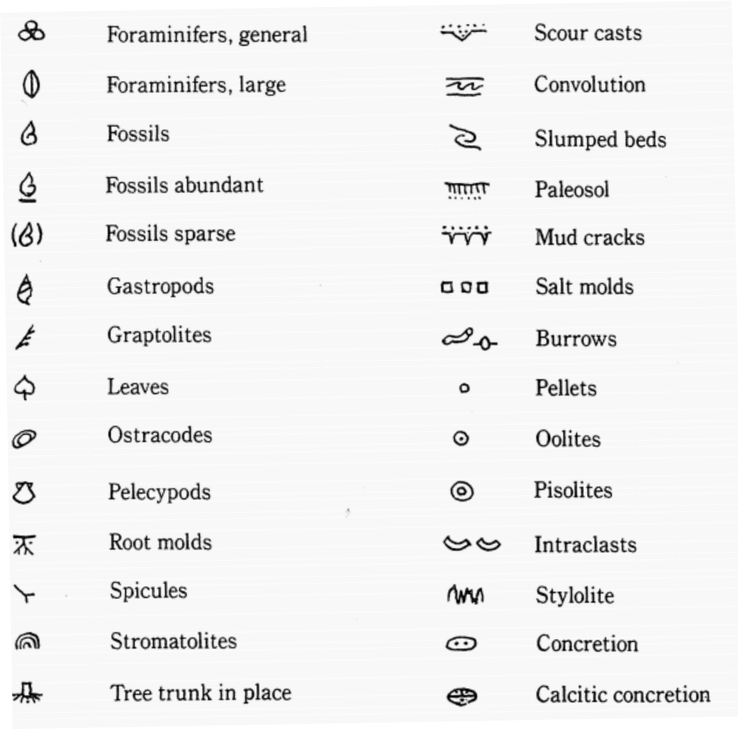


81	Mine, quarry, or open pit
82	Shafts: vertical, inclined, and abandoned
83	Adit, open (left) and inaccessible
84	Trench (left) and prospect
85	Water wells: flowing, nonflowing, and dry
86	Oil well (left) and gas well
87	Well drilled for oil or gas, dry
88	Wells with shows of oil (left) and gas
89	Oil or gas well, abandoned (left) and shut in
90	Drilling well or well location
91	Glory hole, open pit, or quarry, to scale
92	Dump or fill, to scale

Fossil and Structural Symbols for Stratigraphic Columns

Algae
Algal mats
Ammonites
Belemnites
Brachiopods
Bryozoans
Corals, solitary
Corals, colonial
Crinoids
Echinoderms
Echinoids
Fish bones
Fish scales

Tree trunk fallen
Trilobites
Vertebrates
Wood
Beds distinct
Beds obscure
Unbedded
Graded beds
Planar cross-bedding
Trough cross-bedding
Ripple structures
Cut and fill
Load casts



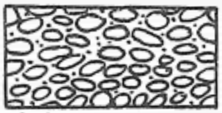
Foraminifers, general
Foraminifers, large
Fossils
Fossils abundant
Fossils sparse
Gastropods
Graptolites
Leaves
Ostracodes
Pelecypods
Root molds
Spicules
Stromatolites
Tree trunk in place

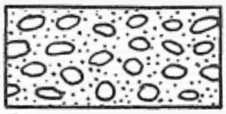
Scour casts
Convolution
Slumped beds
Paleosol
Mud cracks
Salt molds
Burrows
Pellets
Oolites
Pisolites
Intraclasts
Stylolite
Concretion
Calcitic concretion

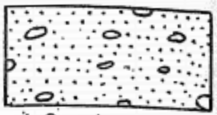
From Compton, 1985

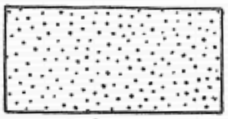
Lithologic Patterns for Stratigraphic Columns & Cross Sections

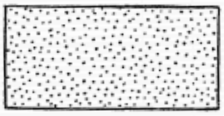

1. Breccia

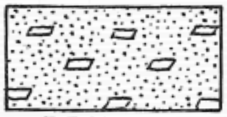

2. Clast-supported conglomerate

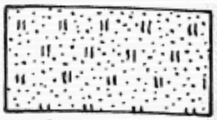

3. Matrix-supported conglomerate

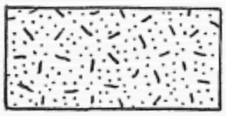

4. Conglomeratic sandstone

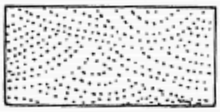

5. Coarse sandstone

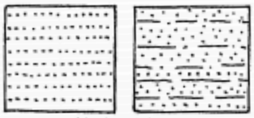

6. Fine sandstone

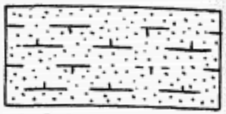

7. Feldspathic sandstone

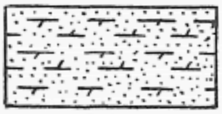

8. Tuffaceous sandstone

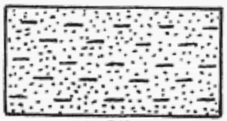

9. Graywacke

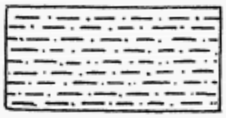

10. Cross-bedded sandstone

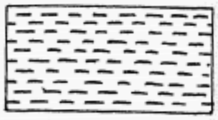

11. Bedded sandstone


12. Calcite-cemented sandstone

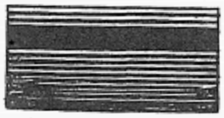

13. Dolomite-cemented sandstone

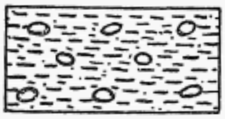

14. Silty sandstone

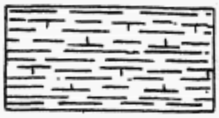

15. Siltstone

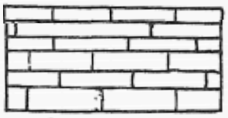

16. Mudstone

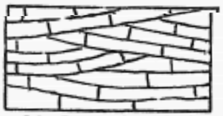

17. Shale

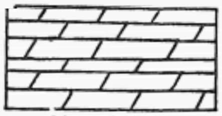

18. Coal bed with carbonaceous shale

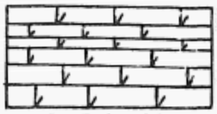

19. Pebbiy mudstone

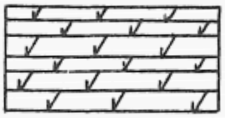

20. Calcareous shale

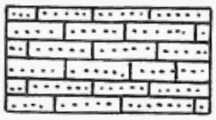

21. Limestone

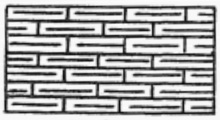

22. Cross-bedded limestone

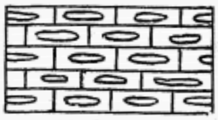

23. Dolomite (dolostone)

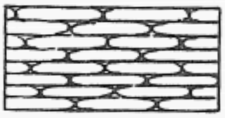

24. Dolomitic limestone

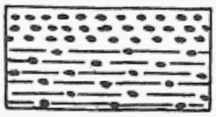

25. Calcitic dolomite

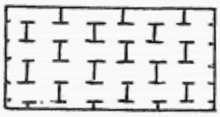

26. Sandy limestone

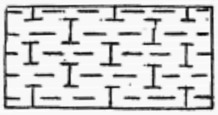

27. Clayey limestone

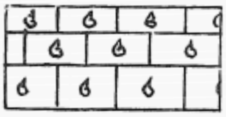

28. Cherty limestone

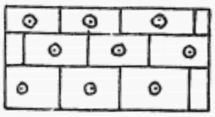

29. Bedded chert

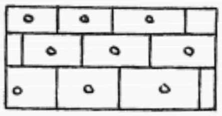

30. Phosphorite, phosphatic shale

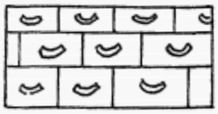

31. Chalk

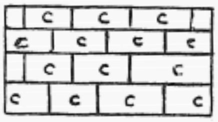

32. Marl

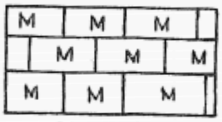

33. Fossiliferous limestone

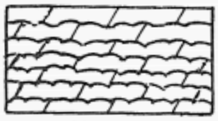

34. Oolitic limestone


35. Pelletal limestone


36. Intraclastic limestone


37. Crystalline limestone


38. Micritic limestone


39. Algal dolomite

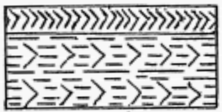

40. Limestone conglomerate

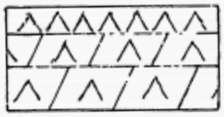
From Compton, 1985

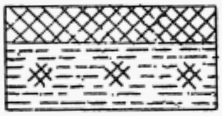
Lithologic Patterns for Stratigraphic Columns & Cross Sections

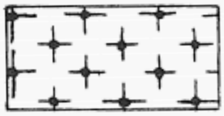

41. Limestone breccia

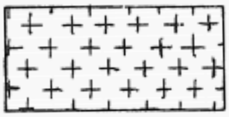

42. Algal dolomite breccia

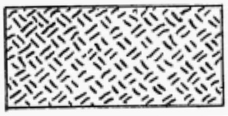

43. Gypsum bed, gypsiferous shale

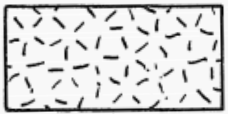

44. Anhydrite, anhydritic dolomite

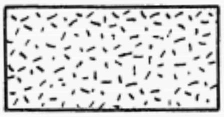

45. Rock salt, salty mudstone

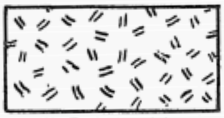

46. Peridotite

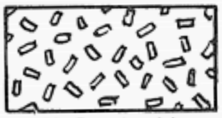

47. Gabbro

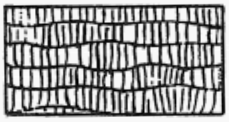

48. Mafic plutonic rock

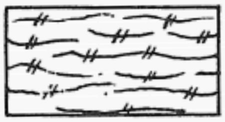

49. Coarse granitic rock

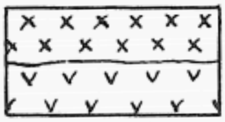

50. Fine granitic rock

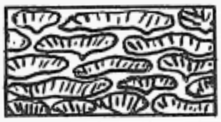

51. Porphyritic plutonic rock

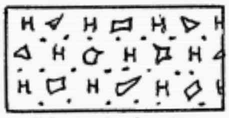

52. Porphyritic plutonic rock


53. Mafic lava

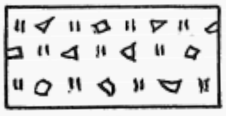

54. Silicic lava

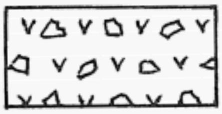

55. Intrusive volcanic rocks

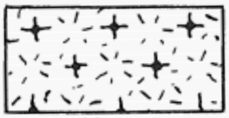

56. Pillow lava


57. Hyaloclastite

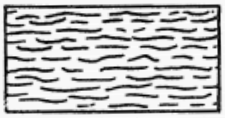

58. Tuff

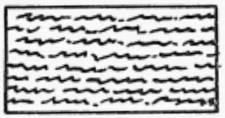

59. Tuff-breccia


60. Volcanic breccia

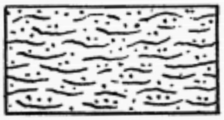

61. Massive serpentinite

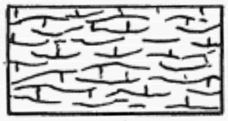

62. Foliated serpentinite

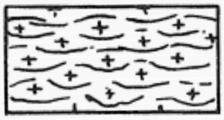

63. Schist


64. Crenulated schist

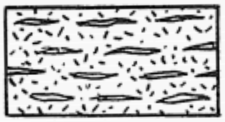

65. Folded schist

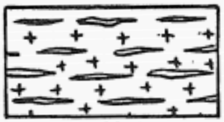

66. Semischistose sandstone

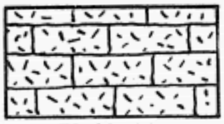

67. Semischistose limestone

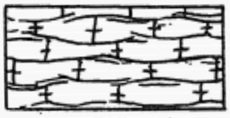

68. Semischistose gabbro

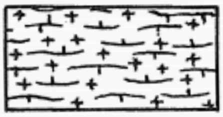

69. Greenstone

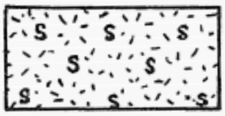

70. Silicic gneiss

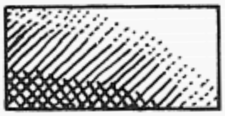

71. Mafic gneiss

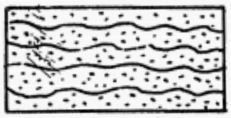

72. Marble

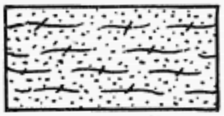

73. Foliated marble

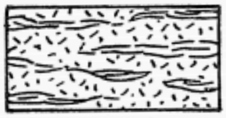

74. Foliated calc-silicate rock

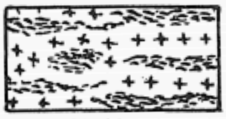

75. Massive skarn


76. Alteration zones


77. Quartzite

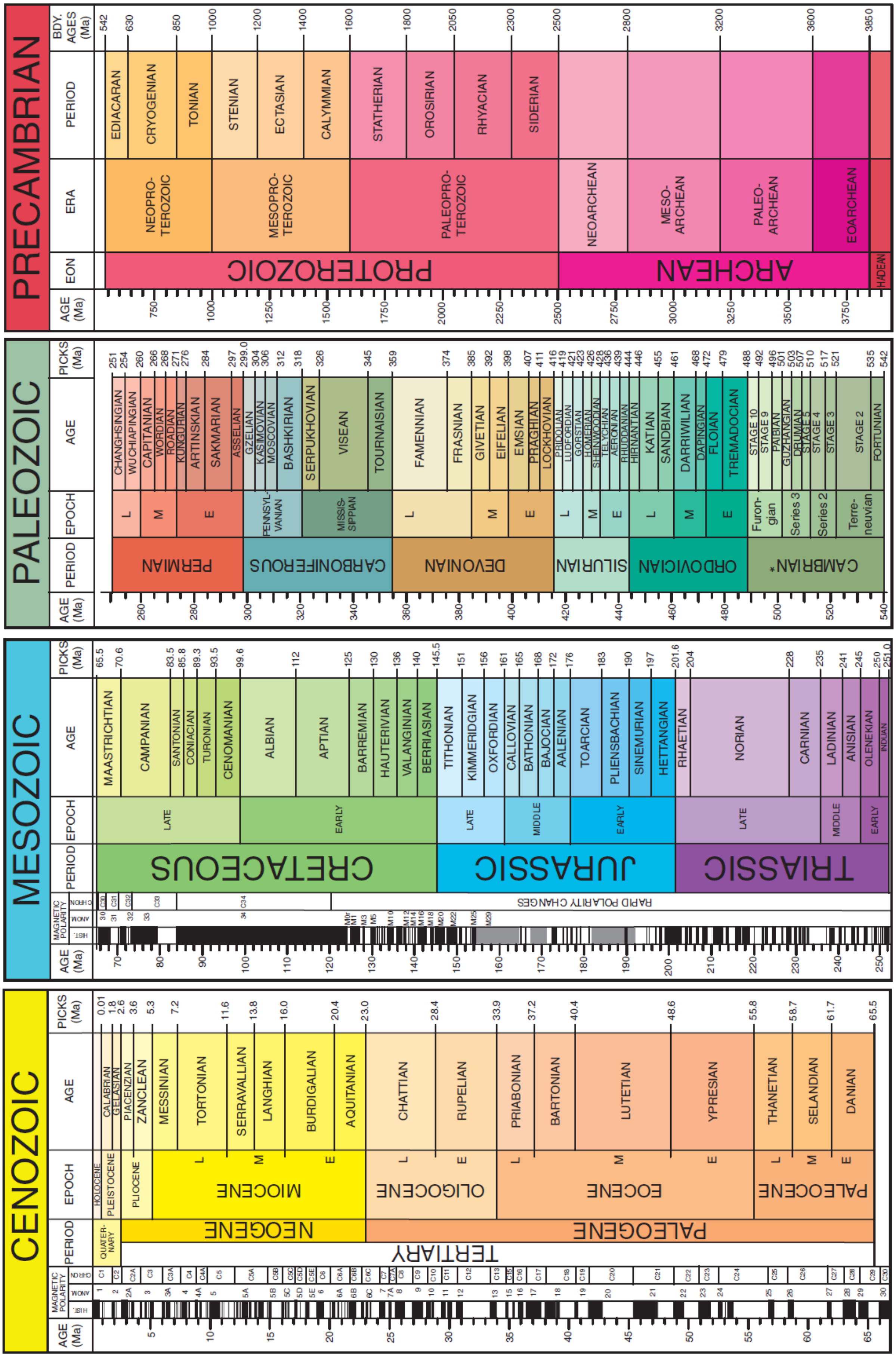

78. Quartzite


79. Silicic migmatite


80. Mafic migmatite

From Compton, 1985

Geologic Timescale



2009 version, from the Geologic Society of A

Canyon de Chelly Bingo

Wildlife encounter	Coyote	Joe buys, eats ice cream	First aid kit usage	Rusted truck
Snaaake	Farallon Plate	Directions in metric	The CB in Christopher's car doesn't work	Campfire songs
Tumbleweeds	Christopher's phone doesn't work	Mogollon Rim	Error on interpretive sign	Racist historical markers
Braking uphill on interstate	Asking around for an AUX cord	Temperature above 80 ºF	Impostor vehicles	Pluton
Train impedes forward movement	Useless CB radio chatter	No Service	Phrase	Scorpion