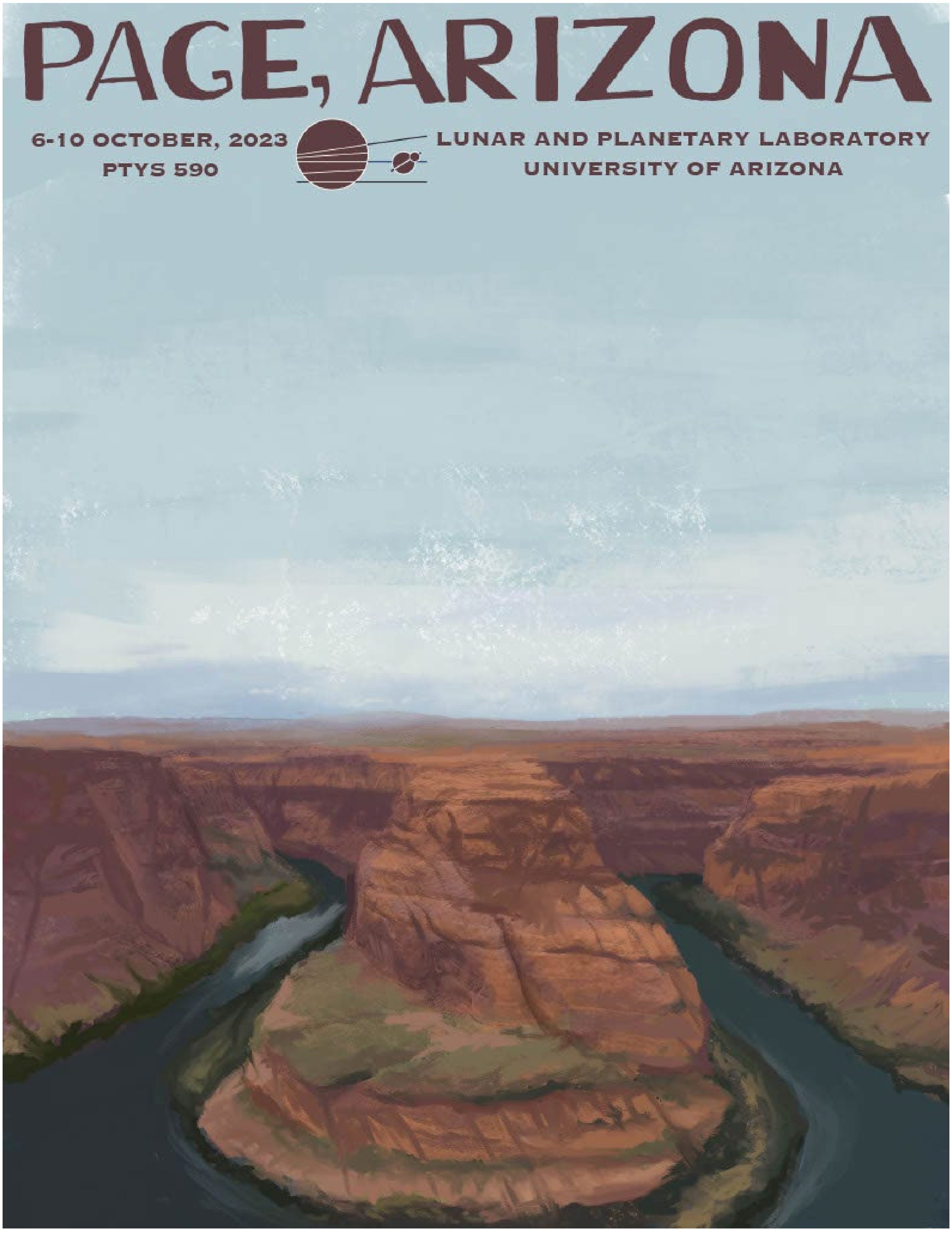

Cover Art by Claire Cook

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Welcome to Pangea!

Exploring the Geology of the Page Area and Navajo Nation

Itinerary

Friday, October 6, 2023 (Sunrise 6:23 am)

6:00 am	Drivers will pick up vehicles at Motor Pool (1597 E. 16th St. Tucson, AZ 85719).
7:00 am	Meet at the LPL loading dock (1629 E University Blvd., Tucson 85721; North of the Planetarium). **Bathroom Facilities Available.**
8:00 am	Depart for Show Low City Park (Show Low City Park, 751 S. Clark Rd., Show Low, AZ 85901). 3 hour 29 minute drive.
11:30 pm	Lunch in the Show Low City Park. **Bathroom Facilities Available.**
12:00 pm	Depart for the Petrified (Petrified Forest National Park, Arizona 86028). 1 hour 17 minute drive.
1:30 pm	1 hour loop hike at the Petrified Forest. **Bathroom Facilities Available.**
3:15 pm	Depart for Page, Shell Station (Shell, 1501 AZ-98, Coppermine Rd., Page, AZ 86040). 3 hour 27 minute drive.
6:15 pm	Shell Station in Page. **Bathroom Facilities Available.**
6:30 pm	Depart for from the Shell for the camp site. <30 minute drive (15 minutes during daylight, at night, expect 30 minutes).
7:00 pm	Set up camp. Sunset: 6:03 pm, Civil Twilight: 6:27 pm. To avoid setting up camp in the dark, we will endeavor to save time during the day, but it is unlikely we will be able to arrive at camp before sunset so be prepared with headlamps, etc.

Saturday, October 7, 2023 (Sunrise 6:25 am)

8:00 am	Suggested wake up time (make your own breakfast and lunch).
9:00 am	Departure for Oljato–Monument Valley (Coordinates: N 37.00414 W 110.09889), via Route via Page. **Bathroom Facilities Available** (in Page). 1 hour 58 minute drive. Note: +1 hour time zone difference. However, all times are presented in Tucson local time.
11:00 am	Arrive in Oljato–Monument Valley. **Bathroom Facilities Available**

4:00 pm	Leave Oljato–Monument Valley. 1 hour 58 minute drive.
6:00 pm	Stop in Page. Note: –1 hour time zone difference. **Bathroom Facilities Available**
6:30 pm	Arrive at camp.

Sunday, October 8, 2023 (Sunrise: 6:27 am)

7:30 am	Suggested wake up time (make your own breakfast and lunch).
8:15 am	Departure for Wilderness River Adventures (199 Kaibab Rd, Page, AZ 86040). 15 minute drive Page with a 15 minute break to use restrooms. **Bathroom Facilities Available**
8:45 am	Depart for Lees Ferry. 1 hour drive.
9:45 am	Arrive at Lees Ferry. 15 minute break to use restrooms. **Bathroom Facilities Available**
10:00 am	Rafting tour.
3:00 pm	Return to Lees Ferry. 15 minute break to use restrooms. **Bathroom Facilities Available**
3:15 pm	Leave Lees Ferry for Horseshoe Bend.
5:15 pm	Return to camp via Page with a 15 minute break to use the restrooms. **Bathroom Facilities Available**
5:45 pm	Leave Page for camp.
6:00 pm	Arrive at camp.

Monday, October 9, 2023 (Sunrise: 6:29 am)

8:00 am	Suggested wake up time (make your own breakfast and lunch).
9:15 am	Leave Camp with a bathroom stop at Paria Contact Station, purchase permits. **Bathroom Facilities Available.**
9:45 am	Leave for Paria Canyon–Vermilion Cliffs Wilderness Area. 1 hour 30 minutes.
11:15 am	Wire Pass trailhead, ~4 miles round trip or White House Trailhead, 8 miles round trip. **Bathroom Facilities Available.**

2:45 pm	Return to camp with a bathroom stop at Paria Contact Station. 1 hour 30 minutes. **Bathroom Facilities Available.**
4:45 pm	Optional additional hike down Stateline Canyon or Lone Rock Beach near Wahweap marina. 15 minute drive.
6:30 pm	Arrive at camp.

Tuesday, October 10, 2023 (Sunrise: 6:31 am)

7:00 am	Suggested wake up time (make your own breakfast and lunch).
8:00 am	Leave Camp for the Painted Desert (Painted Desert Visitor Center, 1 Park Rd., Petrified Forest National Park, AZ 86028) with a stop in Page. Drive time 3 hours 40 minutes. **Bathroom Facilities Available.**
12:00 am	Arrive at the Petrified Forest National Park for lunch. **Bathroom Facilities Available.**
12:30 pm	2 hour hike.
2:30 pm	Leave the Petrified Forest National Park for Tucson. 4 hour 55 minute drive time. With suggested stops in Show Low and/or Globen for bathroom breaks. **Bathroom Facilities Available**.
8:00 pm	Arrive at the University of Arizona (LPL loading dock). **Bathroom Facilities Available**.

Logo Credit: James Keane

Tectonics and Faulting

-Rahul Arora

TECTONICS

The earth's interior is divided into 3 main layers : Core, Mantle and the crust. The crust was formed as a solid slab a few billion years ago. During its evolution the cooler parts of earth's crust were pulled down by the warmer upper mantle, weakening the crust in a few regions. This process continued till the formation of plate boundaries. Presently, the earth's crust is divided into 7 Major plates : Pacific, North American, South America, Antarctica, Eurasian, Indo-Australian and African. Apart from these seven major plates earth has 14 minor plates and some more micro plates as shown in Figure 1. These plates are distinguished on the basis of land area they cover.

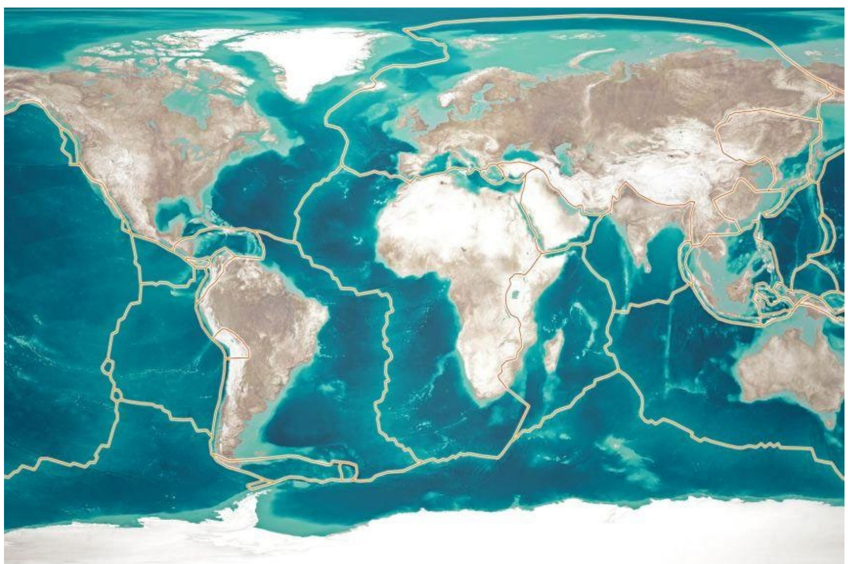

Figure 1 : The image shows the plates and their boundaries on earth.
SOURCE :National Geographic : Education

The upper mantle layer is very hot compared to the crust. As the material being boiled inside the mantle gets hotter and hotter, it becomes less dense and starts a movement upwards towards the crust. This process is known as convection which forms these movements of hot gasses called convection currents. This convection current exerts high amounts of pressure on the plate boundaries leading to the movement of the plates as shown in Figure 2.

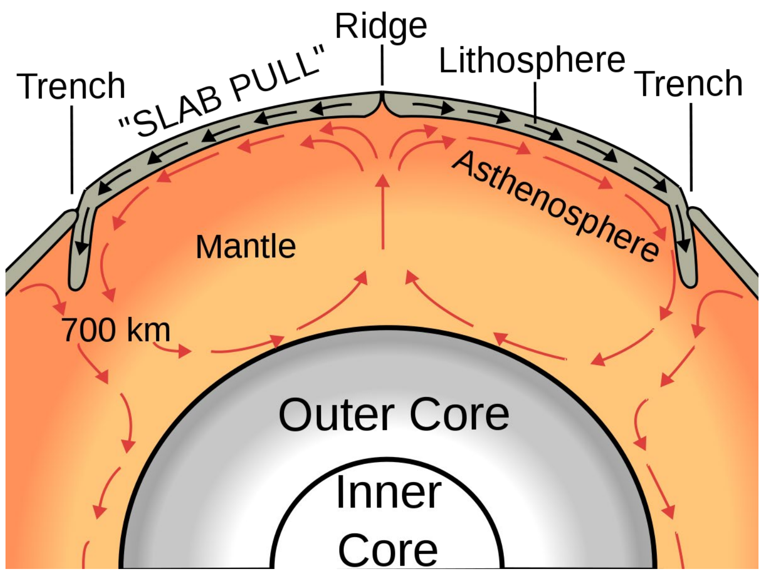

Figure 2 : The movement of tectonic plates due to convection currents
SOURCE : (*Mantle Convection*, n.d.)

Plate movement leads to formation of three types of boundaries as shown in Figure 3. One is the formation of a ridge-like structure in which the two plates drift apart, also known as divergent plate boundaries. Second is the movement of plates towards each other causing one of the plates to move under the other one also known as Subduction/Convergent. Third and the last is lateral movement of two plates known as the transform movement.

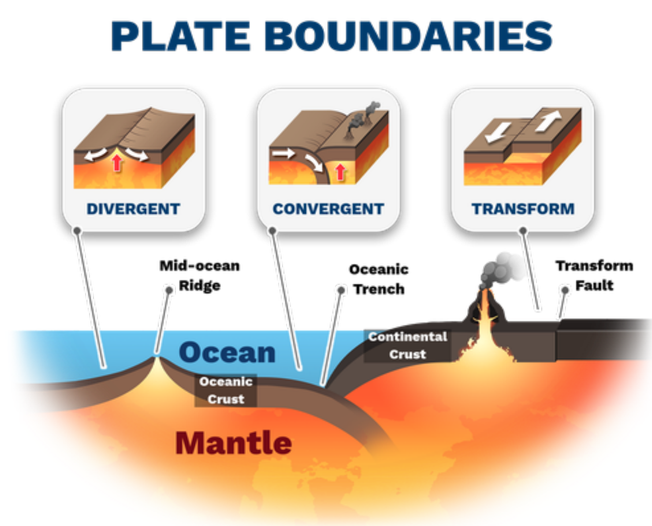

Figure 3 : Three types of plate movements
SOURCE : (*Plate Boundaries*, 2022)

These movements of tectonic plates cause different phenomena such as formation of volcanoes, earthquakes, cyclones etc. The two important results are formation of Volcanoes and generation of earthquakes. Volcanoes can be formed due to either convergent or divergent movement. In case of Divergent movement the two plates spread apart and form a pathway for the magmatic material to move out on the surface forming a volcano. In case of Divergent movement when the crust containing minerals is subducted below another plate. The subducted plate releases the water trapped inside it which reduces the melting temperature in the mantle by 60-100 C . This allows magma formation at depths suitable to feed volcano's (King, n.d.).

Faulting

Over time some rocks form fractures or zones of fractures known as faults as shown in Figure 4. The process of formation of these faults is known as faulting. Due to movement in the plates there develops stress on the earth's crust, as a response to this stress surface breaks and creates faults.

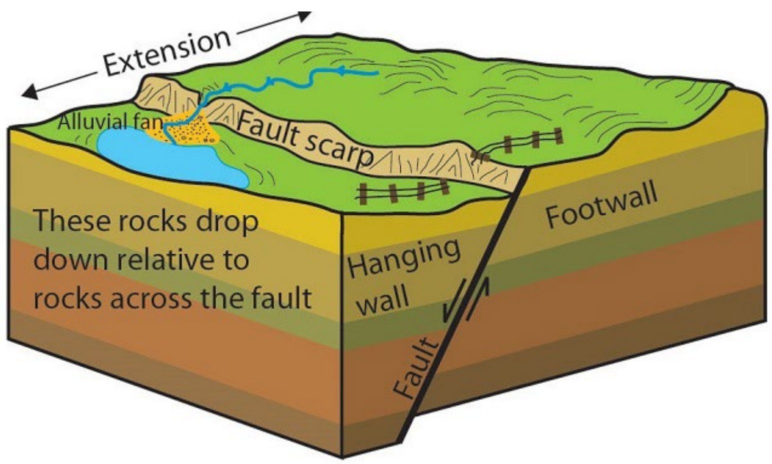

Figure 4 : An example of faulting
SOURCE : National Park Service

There are Three major types of Faults as shown in Figure 5 : Reverse and thrust faulting caused by compressive stress , Normal faulting caused by extension stress and strike slip faulting which is caused by lateral stress.

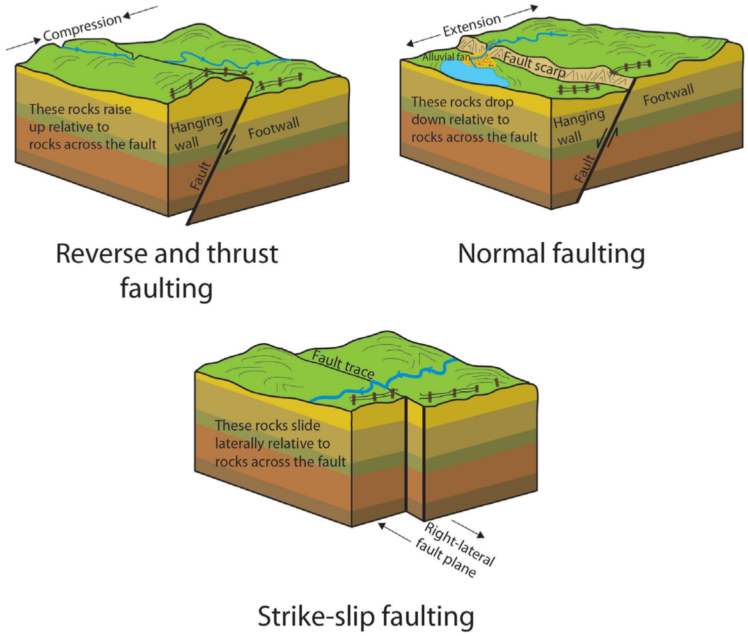

Figure 5 : Types of faults
SOURCE : (Temming, 2022)

There are numerous faults in the grand canyon mostly formed due to earthquakes or plate tectonics . These faults are exposed both in horizontal surfaces and the walls.Faults can be seen through almost all geological layers in the canyon, ranging from the oldest, two-billion-year-old Precambrian rocks to some recent lava flows less than 10,000 years old (*Faults - Grand Canyon National Park (U.S*, 2015).

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Slot Canyons

Claire Cook

What Are Slot Canyons?

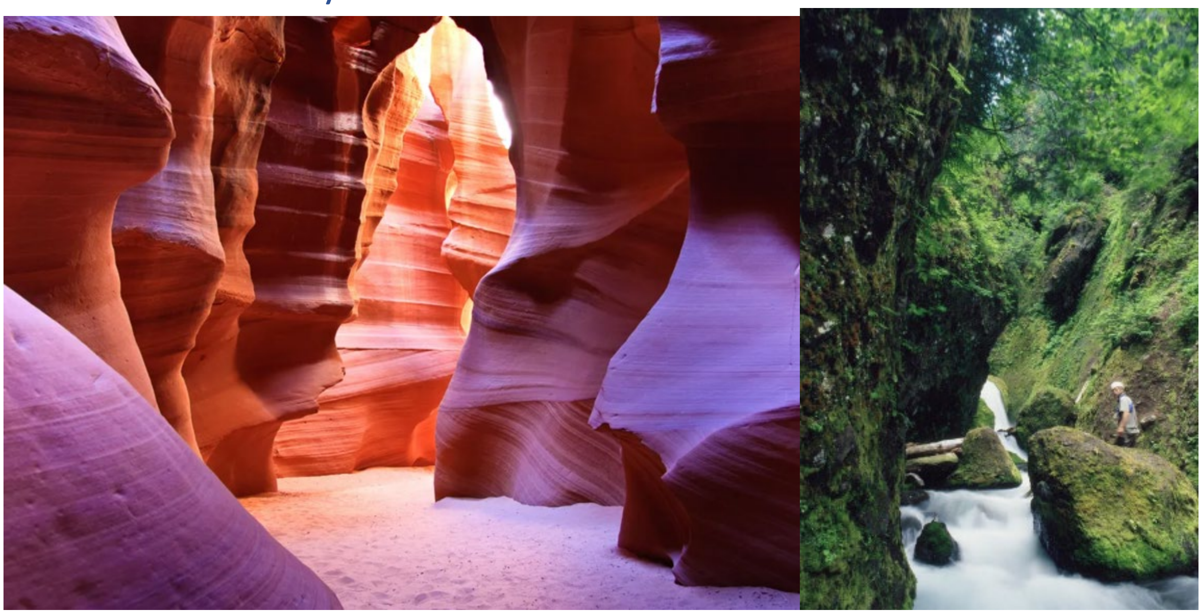

Fig. 1. Left: Upper Antelope Canyon, Arizona [1]. Right: Valhalla Canyon, Oregon [2].

- Slot canyons are very narrow (usually <5 m) and deep (up to 100 m) [3].
- Smooth, often near-vertical walls [3].
- The walls undulate in “wallforms” [3,4].
    - These may be somewhat analogous to bedforms in channel floors [3,4].
    - In some locations, the wallforms on either side of the canyon are in phase and in others are out of phase, so in some places the walls have a pinch-swell shape, and in others appear more like a meander [3,4] (Fig. 2).

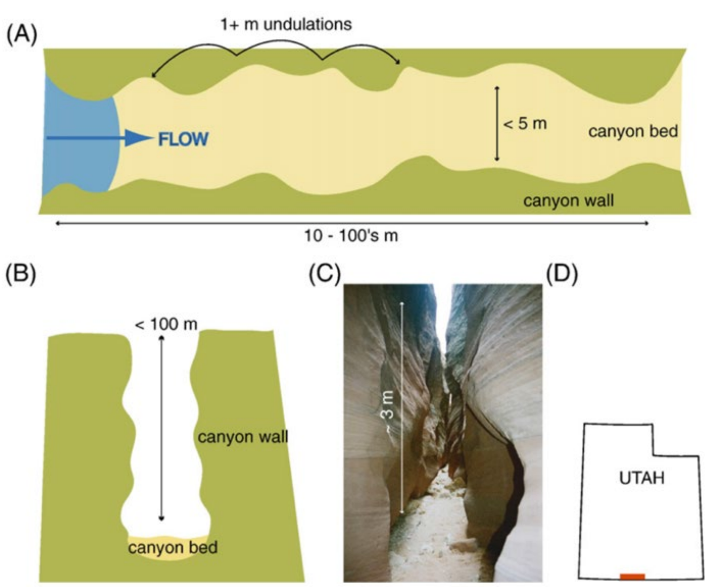

Fig. 2. a) Mapview sketch of a slot canyon, showing typical dimensions and in and out of phase wall undulations. b) Cross section of a slot canyon, showing typical dimensions. c) Photo of Wire Pass slot canyon. d) Location of Wire Pass slot canyon. From [3].

- Slot canyons are a type of bedrock channel [3].
    - In general, bedrock channels form through processes including abrasion, quarrying, and dissolution [3].
    - Slot canyon erosion is abrasion dominated [3].
- Mostly form in relatively soft rock like sandstone, but can also form in basalt and other types of rock [1,3].
- Mostly eroded by less frequent high-flow events (flash floods) and many fill only during flash floods [3].
    - Flash floods are more common in dry, rocky terrain with less soil and vegetation, which leads to less infiltration and more overland flow from rainfall [5].
- Slot canyons are found throughout the world, but are particularly common in the southwest US and Australia. This is due to the combination of soft rocks and flash flood events that are more common in those locations [1].

How Do Slot Canyons Form?

- They start with an initial crack opening, which then is eroded by water, along with rocks/sediment/other debris brought with it [1].
- They are mostly eroded by flash floods, which incise the narrow channels further without widening them significantly [3].
- Lab experiments have attempted to physically model slot canyon erosion [3].
    - Experiments showed that deep, narrow flows tended to widen the artificial channels, possibly because there was more shear stress on the channel walls than the bed [3].
    - This is opposite the case for real slot canyons, which tend to incise more deeply rather than widen [3].
    - This discrepancy may be explained by features present in the field but lacking in the experiment.
        - The experiment did not include a constant supply of sediment so most erosion was due to the impact of water turbulence on the substrate and, downstream, abrasion from particles eroded from the substrate [3].
        - However, flash floods can have very high sediment flux [6] and additional sediment may lead to greater downward incision [3].
        - The experimental channels initially had flat beds [3].
        - An initial bed slope, which would be more reasonable for a natural system, may lead to higher velocity and higher stress on the bed [3].
- Other work suggests that the wall undulations lead to a zone of faster flow in the center of the canyon, contributing to more vertical incision and less channel widening [4].
- In experiments, the style of wallforms controlled discharge, with higher discharge for a meander type channel than a pinch-swell type channel, but incision rates were similar for both [3].
- The cause of the wallforms was unclear in experiments. Small scale hummocks formed along the walls of channels, but experiments weren't run long enough for larger wallforms to develop [3].
- The wavelength, amplitude, and type of wallforms doesn't correlate to substrate characteristics like rock strength [4].

    - Wallform characteristics may be instead controlled by hydraulic processes (such as turbulence) [4].
- Slot canyon wallforms often have cuspate shapes. Experiments showed that the highest erosion rates (in channels with originally smooth, sinusoidal wallforms) were on the lee side of wall bumps, so this may contribute to forming the cuspate wallforms in slot canyons [3] (Fig. 3).

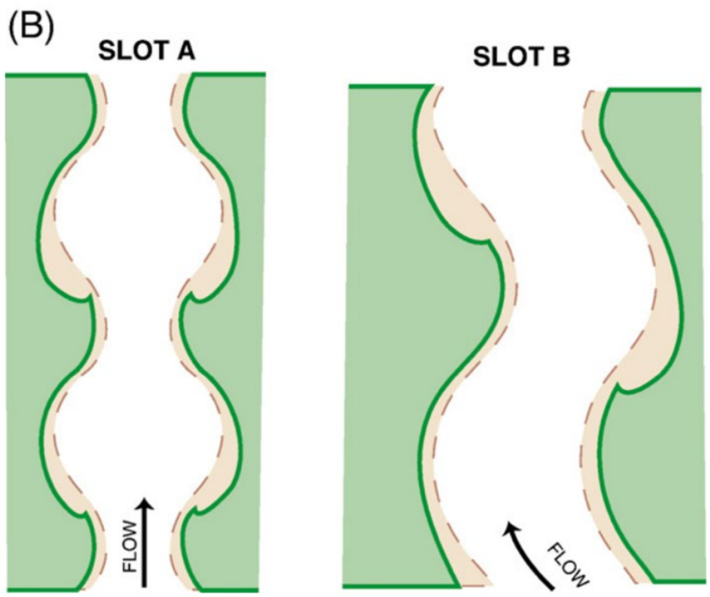

Fig. 3. Left: Diagram of a pinch-swell type channel, with the original sinusoidal wall morphology shown by the dashed lines, and the cuspate morphology after erosion shown in green. Right: Analogous diagram for a meander type channel. From [3].

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Gabe Gowman
PTYS 590 - FA 2023

The Grand Canyon

Geology/Stratigraphy

The Grand Canyon is part of the much broader Colorado Plateau. This plateau covers substantial portions of Utah, Colorado, Arizona, and New Mexico, and was uplifted approximately 30-70 million years ago. It has experienced minimal faulting or folding, and so any exposed rock reveals very clear rock strata that record the region's long history.

Fig. 1: Aerial view of the Grand Canyon over Cardenas Creek (GCNP Website, NPS)

Starting around 5-6 million years ago, the Colorado River began to erode through the surface layers of rock, creating the beginnings of a channel. Over time, the high flow rate of the river combined with the somewhat arid climate of the region to bring relatively quick erosion through nearly 2 billion years of sedimentary rock and create the modern Grand Canyon. The incredible floods that followed melting glaciers in spring would carry rocks and boulders at high speed, accelerating the erosion beyond what would be possible with water alone, and emptying into the Gulf of California allowed for deep incision through the rock. In its current state, the Grand Canyon is one of the largest above-water canyons on Earth; however, there are numerous canyons elsewhere in the solar system of comparable or larger scale.

Rock ages within the Grand Canyon range from around 200 million years old in the uppermost layers, the Kaibab Limestone, to 1.66-1.84 billion years old in the very bottom of the canyon, the Vishnu Schists. Nearly 40 layers have been identified within the canyon, allowing for study of those nearly 2 billion years of history and environmental evolution. Volcanism likely briefly dammed the Colorado River multiple times in the past; however, erosion quickly removed the volcanic dams. These dam-breakings led to significant floods into the western end of the canyon.

Ecology

Thanks in part to its significant elevation range, the Grand Canyon offers a large variety of habitats for animals to reside in. Forested areas give way to the deserts Arizona is best known for, and the river flowing through the bottom of the canyon offers additional ecological niches. Because of these factors, the Grand Canyon is home to an incredible diversity of plants and animals. The mammal population in particular is notably diverse, with a greater number of species than the perhaps friendlier environment of Yellowstone National Park, at 91 known mammalian species. This includes many of the same species that the Rocky Mountain region's national parks are known for, such as bison, elk, and mule deer, as well as some of the highest bat species diversity in the U.S. Photographs of a selection of these species are shown in Figure 2 below.

Fig. 2: The Grand Canyon is home to a broad range of animals due to its variety of habitats. Shown are a ground squirrel, a desert spiny lizard, an elk, and two desert bighorn sheep. Photos from GCNP Website, by A. Sprutta, Michael Quinn, and Mark Lellouch

Human History

Several Native American groups have cultural connections to the Grand Canyon and the surrounding region. In several of these cultures, the Grand Canyon features prominently in their mythology. In modern times, the 11 tribes shown in Figure 3 are involved in the conservation efforts of Grand Canyon National Park and share their stories and cultures with visitors through partnerships, demonstrations, and heritage celebrations with the park, where "first-voice interpretation" is featured prominently.

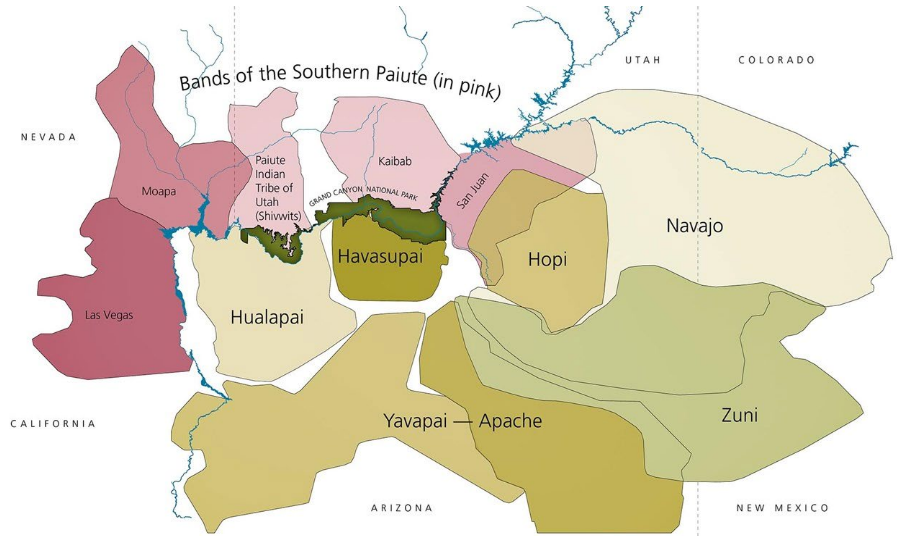


Fig. 3: Approximate locations of the 11 tribes with cultural connections to the Grand Canyon (GCNP Website, NPS)

In 1540, a portion of the Spanish army under Francisco Vásquez de Coronado became the first Europeans to see the Grand Canyon when their Hopi guides led them to a “great river” they hoped could carry them to the Gulf of California. The Hopi guides offered no information of value and the Colorado River was found to be too wide and too intense to travel, so the Spanish headed eastward to Texas and the region was left unexplored. It was not until 1857-58 that an American explorer would attempt once again to explore the Colorado River through the Grand Canyon.

The Grand Canyon gained tourist attention in the 1880s as American tourism began to spread westward, with President Theodore Roosevelt visiting in 1903. The region then became protected land during his administration, first as a “Game Preserve” in 1906, and then as a National Monument in 1908.

“The Grand Canyon fills me with awe. It is beyond comparison—beyond description; absolutely unparalleled throughout the wide world… Let this great wonder of nature remain as it now is. Do nothing to mar its grandeur, sublimity and loveliness.”

- President Theodore Roosevelt, 1903

Following Arizona’s statehood in 1912, and only a few years after the National Park Service’s founding in 1916, the Grand Canyon and the region surrounding it were established as the 15th U.S. National Park on Feb. 26, 1919. This park status prevented damming of the Colorado River within the park’s boundary, but it is still affected by the Glen Canyon Dam upstream, and flooding in the spring has been dramatically reduced. This generally means that erosion has slowed somewhat, but overall just a more regular flow of water through the canyon.

After a few expansions that merged Grand Canyon National Park with neighboring protected areas, GCNP is now the 11th-largest national park in the U.S., and received the 2nd-most visitors in 2022 (behind Great Smoky Mountains National Park), at 4.7 million people.

Sources

Grand Canyon Conservancy,
https://www.grandcanyon.org/our-work/current-priorities/desert-view/desert-view-heritage/

Grand Canyon National Park website,
https://www.nps.gov/grca/index.htm

Library of Congress,
http://loc.gov/pictures/resource/ppmsca.13397/

Fig. 4: Grand Canyon National Park print (Library of Congress)

Fig. 5: Rafts preparing to launch in the Colorado River (GCNP Website, photo by Michael Quinn)

LAKE POWELL AND HYDROELECTRIC POWER

Lori Huseby

Background

The authorization of the Colorado River Storage Project Act by Congress on April 11, 1956 initiated the construction of Glen Canyon Dam, the key unit of one of the most extensive and complex river resource developments in the world. Glen Canyon Dam and the subsequent Lake Powell will provide water storage that will allow the Upper Colorado River Basin states of Utah, Colorado, Wyoming, and New Mexico to utilize their share of the Colorado River while providing the required delivery of water to the Lower Basin states of California, Nevada, and Arizona. Glen Canyon proved to be the perfect location, although because it was such a remote site, it presented some unique construction challenges.

Aerial view of the Glen Canyon Dam and Lake Powell

Construction

There were no rail facilities near the construction site of the proposed project, so a bridge was built to allow trucks to deliver material and equipment across the canyon. Construction of the 1,271 foot-long steel-arch bridge 700 feet above the river was completed in January 1959, reducing a 200-mile trip to cross the river to less than a quarter mile. The bridge was transferred to the state of Arizona. In 1957, Glen Canyon Reclamation constructed a government camp close to the dam site in northeastern Arizona to house construction workers and their families and to provide community services. This community was called Page in honor of Glen Canyon Reclamation Commissioner John C. Page. Glen Canyon Reclamation managed the community of Page during and after construction of the dam until the town was transferred to private ownership, where Page became an incorporated town on March 1, 1975.

Glen Canyon Dam Spillway Construction - 1963

In order to construct the dam, the Colorado River had to be channeled around the site. A temporary dam was constructed upstream of the dam site to redirect the river through two, 3000 foot-long, 45 foot diameter diversion tunnels dug through the walls on each side of the canyon. The material excavated from the tunnels was used to make the temporary dam. With the river diverted, construction began:

- **Early 1960** - Crews began work to excavate down for the dam's foundation
- **June 1960** - Concrete Placement Starts. Construction continued 24 hours a day
- **March 1963** - Water started to build up when the diversion tunnels were closed and Lake Powell was born.
- **September 1963** - The last of over 400,000 buckets of concrete was placed. Power Plant equipment installment begins.
- **September 1964** - First hydroelectric power was generated
- **1966** - All eight generators were installed and working at full capacity.
- **June 1980** - Lake Powell reached elevation 3,700 feet, with a total capacity of over 25 million acre-feet of water being held.

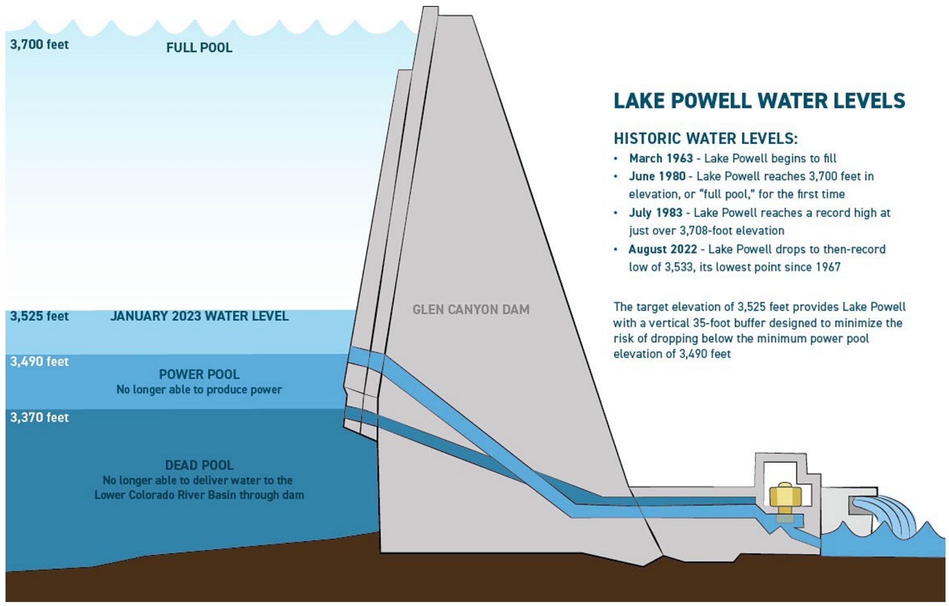
Lake Powell

Formed by the waters of the Colorado River behind Glen Canyon Dam, Lake Powell's 1,960 miles of winding shoreline (when full) and 186 mile-length make it the second-largest reservoir in the United States. In addition to its significant recreation value, Lake Powell functions as a 'bank account' of water that can be drawn on during droughts. As drought conditions persist in the Southwest, the water storage in Lake Powell becomes especially critical. It's natural for the elevation of the lake to fluctuate depending on the amount of spring runoff from the mountains, deliveries to the Lower Basin, and the amount of water carried over from the previous year. Each year, the lake level increases between May and July from snow runoff from many different surrounding mountain ranges followed by a decrease in lake level throughout the remainder of the year, leaving a visible ring along the shoreline. The amount of fluctuation varies each year but during extended periods of drought, Lake Powell's elevation could drop by more than 200 feet below its maximum elevation. As the Colorado River Basin continues to experience its worst drought in recorded history and water stored in Lake Powell has reached its lowest volumes since the reservoirs started filling. Glen Canyon Reclamation continues to closely monitor hydrologic conditions and projections, and foster productive discussions and collaborative decision-making about the future of Lake Powell.

Lake Powell's overall water levels since being filled. 2021 was the lowest recorded elevation.

Hydroelectric Power

Hydroelectric power is a clean, renewable form of energy that does not pollute the air, land, or water. Hydroelectric power plants have low failure rates, low operating costs and are very reliable. As of 2018, hydroelectric power made up 17% of the world's total electricity production and 78% of the world's renewable electricity generation in 2015. In addition, the use of hydropower reduces our dependence on other more environmentally polluting energy sources. The hydropower plant provides system reliability for the overall regional power grid and is the primary unit to assist in a "black start" of the power system following a blackout failure. One drawback to electricity is that it cannot be stored for future use. Consequently, a utility company must have the capacity to provide power instantly to meet public needs. But since power demand varies greatly during the day and night, this job becomes quite complex. Since hydroelectric generators can be started and stopped almost instantly, hydropower is more responsive than other energy sources in meeting changing power needs. Approximately 4.5 billion kilowatt-hours. It would take 2.5 million tons of coal or 11 million barrels of oil each year to generate the same amount of power



Droughts and the Future

Climate change and hydropower are closely related to each other. While hydropower is a great alternative to fossil fuel energy sources, changes to the hydrologic cycle that result from climate change can largely impact its efficiency by reducing river discharge rate, lowering reservoir water levels, and reducing overall hydropower energy generation. Hydropower within the Colorado River Basin is largely dependent on reservoir storage and streamflow. Streamflow primarily affects the turning of turbines within the dam, which turn a generator, generating electricity that is distributed across the energy grid to surrounding communities. Climate change is causing the amount of hydropower generated by the dam to vary seasonally. Changes to streamflow caused by infrequent precipitation and reduced recharge, alongside significantly lower water levels caused by changes in temperature, are currently putting Lake Powell in a crisis where it may be unable to continue generating power. Stricter measures to ensure Glen Canyon can adequately produce enough power to Upper Basin states have been taken. This prompted the Secretary of the Interior to request the seven Colorado River Basin states and Reclamation to establish guidelines and coordinated management strategies for the operation of

Lake Powell under low reservoir conditions. On December 13, 2007, the Secretary signed new interim operational guidelines that established rules for shortages, surpluses, and coordination of operations between Lake Powell and Lake Mead, and encouraged new initiatives for water conservation. With ongoing climate issues, concerns about whether or not the dam will be able to provide enough power while also releasing enough water to supply the Lower River Basin dominate news headlines each year in the affected areas. Current projections state Glen Canyon is around 25% likely to hit its minimum power point within the next 5 years, and with the effects of climate change ramping up every year, stricter means of water flow regulation and power usage are likely to be necessary to ensure the viability of the entire Colorado River System in the long term.

Lake Powell's water levels taken by a Landsat Satellite between March-May of each respective year.

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Native American History: Navajo

Kana Ishimaru

“Navajo” is a spanish adaptation of the word navahu’u, meaning “farm fields in the valley” in the Tewa pueblo language. The Navajo call themselves Diné, which means “the people”, and their traditional homeland as Dinétah, which means “among/ in the area of the people”.

History

Settlements of the First Human Inhabitants in the Southwest

The first human inhabitants of the southwest arrived from northern Asia 30,000 - 12,000 years ago. At this time, much of northern North America and northern Europe were covered by continental glaciers (the Last Glacial Period) and the sea level was as much as 90 m lower than present. Siberia and Alaska were connected by a broad strip of dry land, several hundred kilometers wide (figure 1).

Figure 1. Left: the route that first migrants took to inhabit North America [1]. Right: diorama of Arizona 13,000 years ago. There was much greater rainfall and many animal species lived. They include now extinct ground sloth, dire wolf, mammoth, camel, and horse, and still living tapir (similar in shape to a pig with a short nose trunk), jaguar, deer, peccary, bison, and antelope [2].

They were nomadic hunter-gatherers, following wandering herds of animals such as bison. They kept on coming to North America in small bands for thousands of years, and slowly spread southward throughout all of North and South America. Over the course of thousands of years, some peoples began to adopt more settled lifestyles by learning domestication of certain seeds including corn. Those who adopted the growing of corn became increasingly sedentary. This new sedentary life with assured food supply provided leisure time for arts and religious ceremonies to develop.

Figure 2. Left: fossils of a mammoth killed by hunters over 13,000 years ago. Spear points are visible. Discovered near Naco, Arizona (southeast, on the Mexican border) in 1951, excavated by then Director of the Arizona State Museum [2]. Right: restored pithouse [3].

The first houses were partly subterranean and called pit houses (figure 2). Later, houses became above ground structures, and clusters of houses became villages. Some of the villages grew to be large communities and they held great ritualistic events.

The Spanish came to the southwest in around A.D. 1500 and they called the indigenous centers as pueblos, which means villages in Spanish, and the people in the pueblos as Pueblo Indians (e.g. Hopi and Zuni). The ancestors of the Pueblo Indians are sometimes called Anasazi, but Pueblo Indians object to using this term because it means “ancient enemy” in Navajo and some view it as derogatory.

Arrival of the Navajo People in the Southwest

Large areas of Alaska and northern Canada were occupied by the Athabascan Indians, some of whom decided to move southward. They became the Navajo and the Apache. Linguistic studies suggest that the Navajo and the Apache separated from the Athabascans sometime between A.D. 900 and 1300. The migrants moved along the eastern front of the Rocky Mountains, and at the southern end of the range, they turned westward (figure 3). It is unclear exactly when the Navajo entered the southwest, but by the end of the 1500s they were spread throughout northern New Mexico, southern Utah, and northern Arizona, where the Pueblo Indians had occupied.

This Navajo homeland Dinétah is inside four sacred mountains with colors associated, Blanca peak (white) in the east, Mt. Taylor (turquoise) in the south, San Francisco peaks (yellow) in the west, and Hesperus peak (black) in the north (figure 4).

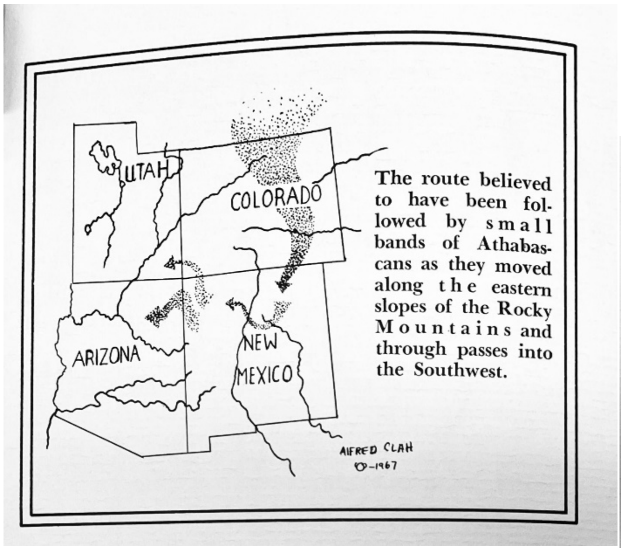
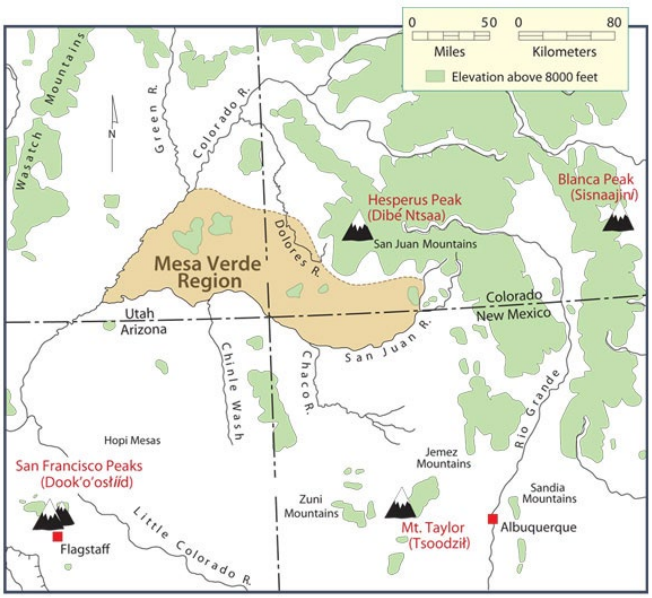


Figure 3. Left: the route that some Atabathican Indians took to migrate to the southwest [1]. Right: illustration of early Athabatican hunters. They were skilled spear throwers [1].



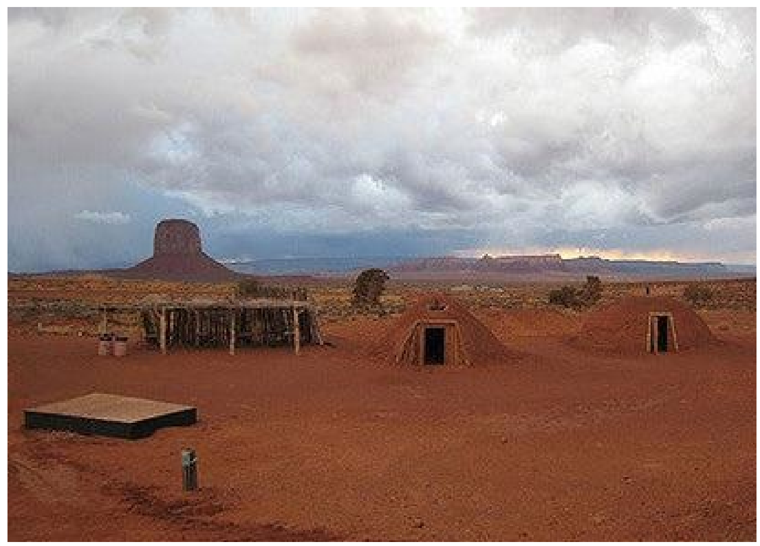


Figure 4. Left: the sacred four mountains that mark Dinétah [4]. Right: traditional Navajo hogans. Today, modern houses are common on the reservation, but families still construct a hogan nearby to conduct their native religion and ceremonies [5].

The Navajo were nomadic hunter-gatherers. They saw the permanent dwellings of the Pueblo Indians and they adopted the sedentary, farming practices. The Navajo houses are called the hogan, which is constructed of wooden poles covered with logs and mud (figure 4). The door was placed in the east so they could get the morning sun and good blessings.

Interactions with the Spanish

The Spanish came to the southwest searching for gold in the mid 1500s, and oppressed the Pueblo Indians for over 100 years. The Navajo and Apache groups helped the Pueblo Indians with the Pueblo Revolt in 1680 against the spanish colonizers. 400 spanish people were killed and the remaining 2000 were forced out of New Mexico. In 1693 the Spanish reconquered the area, and some pueblo Indians fled to the Navajo. The Navajo welcomed the Pueblo Indian refugees and adopted some of their cultural values.

The Spanish introduced sheep, goats, and horses to the Navajo. The Navajo flourished and migrated to northern Arizona and southeastern Utah. Around 1700, they moved into the San Juan River area in Utah (figure 5) and used the land for their sheep and goat herds, and planted fields of corn, beans, and squash.

In the late 1700s, the Navajos became involved in conflict with the Spanish forces. The Spanish formed alliances with the Comanche people and the Ute people against the Navajo. They repeated peace making, raiding, and trading with one another until the Americans arrived.

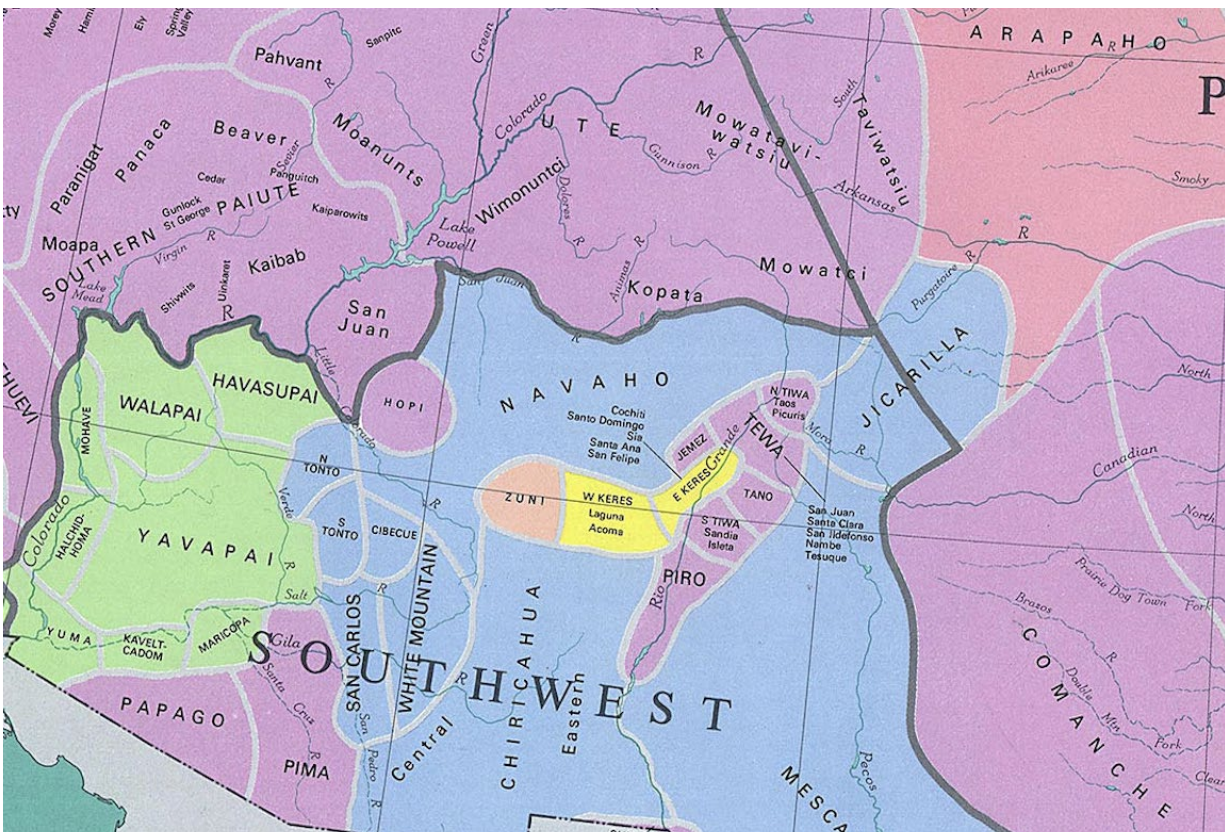


Figure 5: map of early Indian tribes in the southwest [6].

Navajo Wars with the US Army

In 1846, the US Army started invading the Navajo territory. The situation escalated over time and there were battles and treaties between them. In January 1864, the US Army led by Kit Carson conducted a scorched-earth campaign to the Navajo lands, where they burned villages, slaughtered livestock, and destroyed water sources. Carson's policy was to capture the Navajo, instead of killing them. Carson and the Navajo met at the Battle of Canyon de Chelly, where many Navajo people decided to turn themselves in because they were isolated and didn't have enough supplies to survive the coming winter. Those who didn't surrender were killed.

Between 1863 and 1866, Carson forced the surrendered Navajo men, women, and children (more than 10,000 people) to walk from eastern Arizona to Bosque Redondo Reservation, Fort Sumner in western New Mexico (figure 6). This is called the "Long Walk" and it took 18 days for about 500 km. The Army's plan was to force the Navajo to adopt white American culture such as Christianity in the internment camp at the reservation. The Navajo people were not prepared for this long journey, and treated cruelly by the American soldiers. They were never informed where they were going, how long it would take, or why they were relocating. At least 200 people died of cold and starvation during the walk.

Figure 6. Left: the routes of the Long Walk [7]. Right: Navajo captives under US Army guard at Bosque Redondo [8].

The reservation turned out to be a failure due to the poor planning, disease, crop infestation, and generally poor conditions for agriculture. Thousands of people died of starvation and disease. Maintaining this reservation was very expensive ($1.5 million /year) to the U.S. government. They abandoned the reservation and signed the Treaty of Bosque Redondo with the Navajo leaders on June 1, 1868 to allow the Navajo to return to their land. This treaty effectively established the Navajo as a sovereign nation. They were granted 14,000 km^2 of land inside their four sacred mountains. On June 18, 1868, the Navajo people gathered to start their return journey, the Long Walk home. The Navajo became a rare example in the US history of native people successfully returning to their lands after being forcibly removed.

After the Navajo Wars

1920s: Oil was discovered on Navajo land in the early 1920s. The Navajo tribal government was established in 1923 to help meet the increasing needs of American oil companies to lease Navajo land for exploration.

1924: Native Americans were granted citizenship.

1933 - 1950s: The federal government imposed the Navajo Livestock Reduction to reduce the number of sheep, goats, cattle, and horses that the Navajo could support in their land because they believed that the Navajo Nation's livestock was worsening the land erosion in the area. Many Navajo lost their income.

1942 - 1945: During the World War II, 400 Navajo code talkers used their Navajo language to relay radio messages, preventing the Japanese from decoding it.
1968: The Navajo Tribal Council declared the reservation as Navajo Nation, and adopted a flag. The Navajo Nation Flag was designed by Jay R. Degroat, a Navajo from New Mexico (figure 7). It shows the outline of the present Nation in copper color, and the land allocated by the 1868 treaty in dark brown. The four sacred mountains are depicted in theri colors. The rainbow over the Nation and the sacred mountains symbolizes Navajo sovereignty. In the center of the Nation, there are the sun above two green stalks of corn, which surround an animal to represent the Navajo livestock economy, and a traditional hogan on the left, and a modern home on the right. In the middle of the white circle is an oil derrick symbolizing the recourse potential of the tribe, and below the sun are modern sawmill symbolizing the progress and industry characteristic of the economic development.

Figure 7. Navajo Nation Flag [9].

Current state

The Navajo Nation extends in Utah, Arizona, and New Mexico (figure 7), covering over 70,000 km^2 with the population of 165,158 [10]. The Navajo tribe is the largest American Indian tribe in the US. The capital is Window Rock, Arizona (figure 7), and they have their own government with three branches of executive, legislative, and judicial.

Laws and Rules in the Nation

Navajo laws strictly prohibit consumption and/or possession of alcoholic beverages on the Navajo Nation. In the Navajo Tribal Parks, due to their beliefs and religion, cremation scattering, climbing, and base jumping are strictly prohibited.

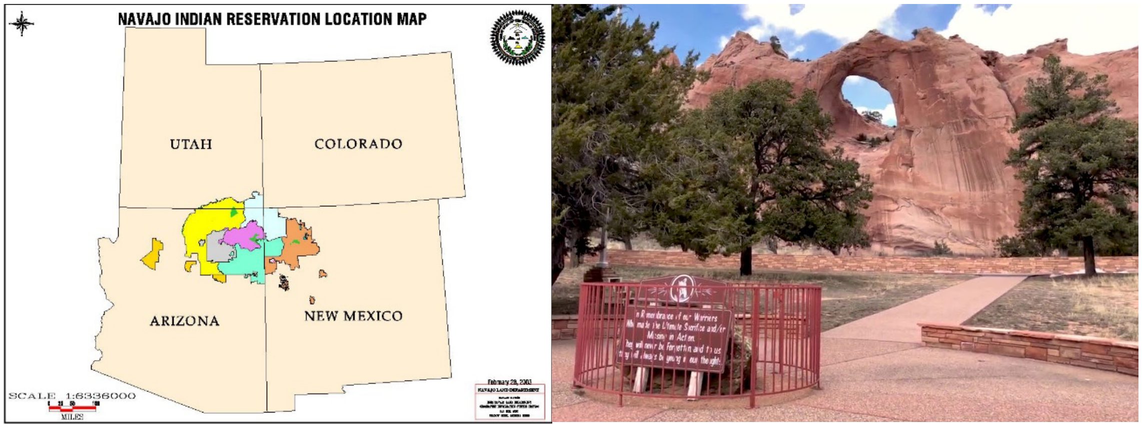


Figure 7. Left: map of the Navajo Nation [11]. Right: Window Rock Tribal Park [12].

Arts

The Navajo arts include sand painting, weaving, pottery, and silversmith (figure 8). They were used for trading and rituals. Sand paintings are symbolic representations of a Navajo mythology and used in ceremonies. They may have learned weaving and pottery from the Pueblo Indians. In the late 1800s, they learned silversmith from a Mexican blacksmith living in the New Mexico territory.

Figure 8. Left to right: Sand painting [13], weaved baskets [2], pottery [2], silver necklace with turquoise [2].

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Basin and Range Province.

Rocío Jacobo. PTYS 590 Fall 2023.

1. Introduction

The Basing and Range is a geologic province extending from Southwestern Canada, western of the United States, and Northwestern Mexico. Its name comes from its geomorphology of basins and ranges alternating across the province as a result of extensional deformation. This deformation started at the end of the Paleocene, and it is still active (total extension from 100 to 300 %) as indicated by seismicity, high heat flow, and recent basaltic volcanism. The deformation occurred in stages varying the stress field orientation due to plate interactions along the western plate boundary of North America (Eaton, 1982; Parsons, 2006; Zoback et al., 1991).

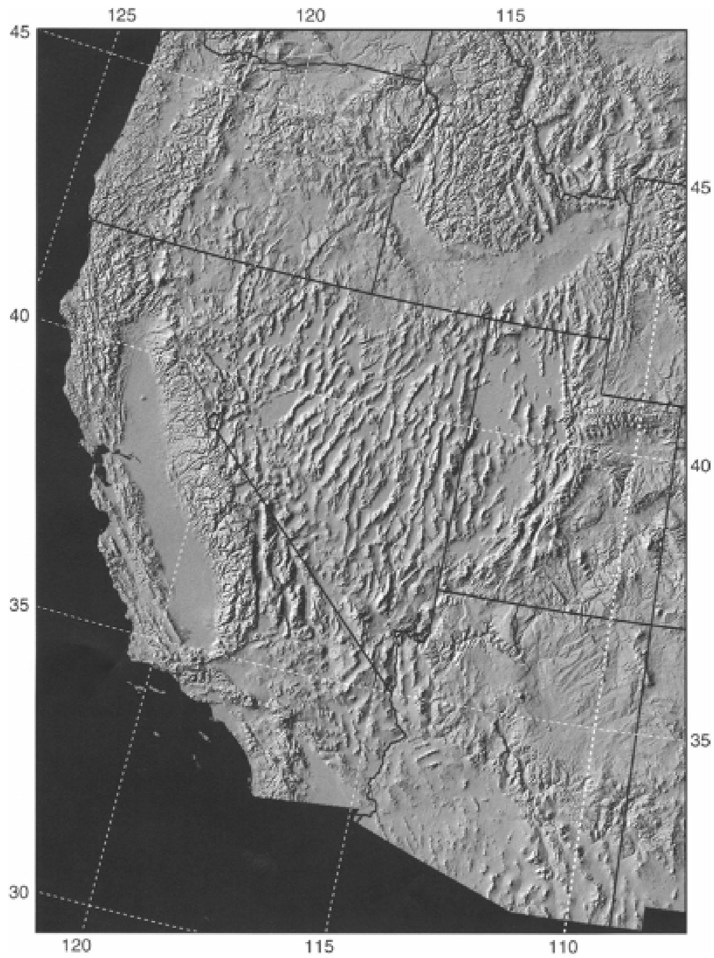

Figure 1. Western United States topography (Parsons, 2006).

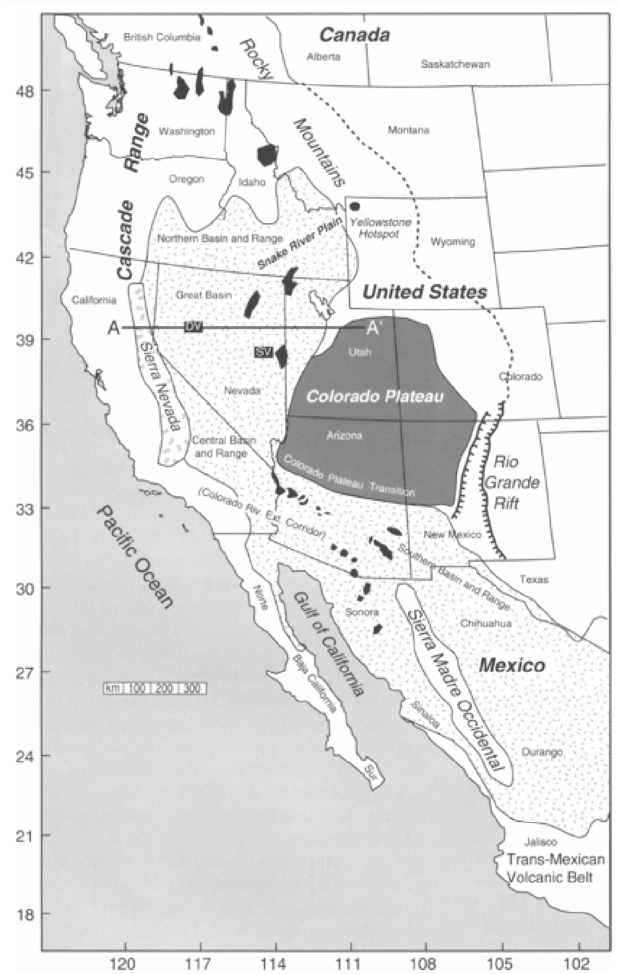

Figure 2. Basin and Range Province location with other geological provinces in North America (Parsons, 2006).

2. Distinctive extensional features within the Basin and Range Province

2.1 Faulting

The Basin and Range Province is characterized by a specific type of geological extensional process known as normal faulting. This type of faulting is responsible for the formation of the distinctive mountain ranges and basins in the region.

Models suggested to explain the cross-sectional subsurface geometry of basin-range faults:

Figure 3a: **Horst and graben model**. Needs a zone of extension beneath the grabens (where the faults intersect) maybe by a zone of dyke intrusion.

Figure 3b: **Tilted block model** and Figure 3c: **Listric fault model**. Faults merge with a region of continuous or quasi-continuous strain at depth (ductile zone below the seismogenic layer 10-15 km thick).

The available geophysical and drill-hole cannot confirm any of those models, for that reason the nature of the Basing and Range faulting can include many types of faults and can be accommodated by uniform stretching or by dyke intrusion or a combination of both (Zoback et al., 1991).

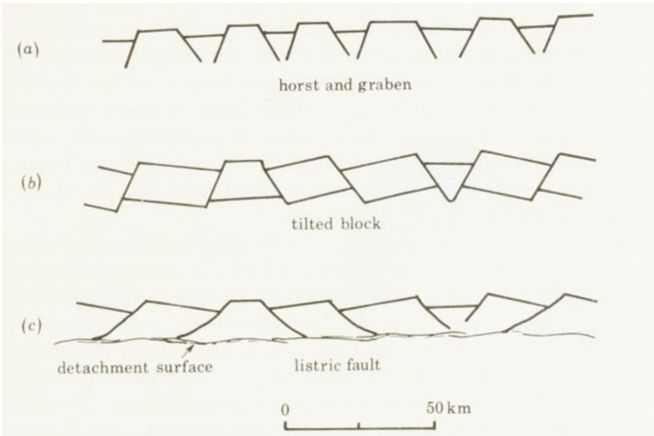

Figure 3. Generalized models of basin-range structure (Zoback et al., 1991).

2.2 Metamorphic core complexes

The Metamorphic core complexes are other typical extensional geological features in the Basing and Range Province. These complexes are characterized by a central core of high-grade metamorphic rocks that have been exhumed to the Earth's surface by low-angle detachment faults. Metamorphic core complexes are a discontinuous belt of uplifted metamorphic rocks. These ranges primarily originated during the mid-Tertiary period (Eocene to Miocene). They reveal metamorphic rocks from the mid-crust situated below low-angle extensional detachment faults. These faults separate the metamorphic core from the upper crust, which contains rocks that have not undergone metamorphism and have been brittlely deformed. Many of these ranges were separated by moderate to high-angle normal faults (Miocene and later) from the Basin and Range extensional tectonics (Wagner & Johnson, 2006).

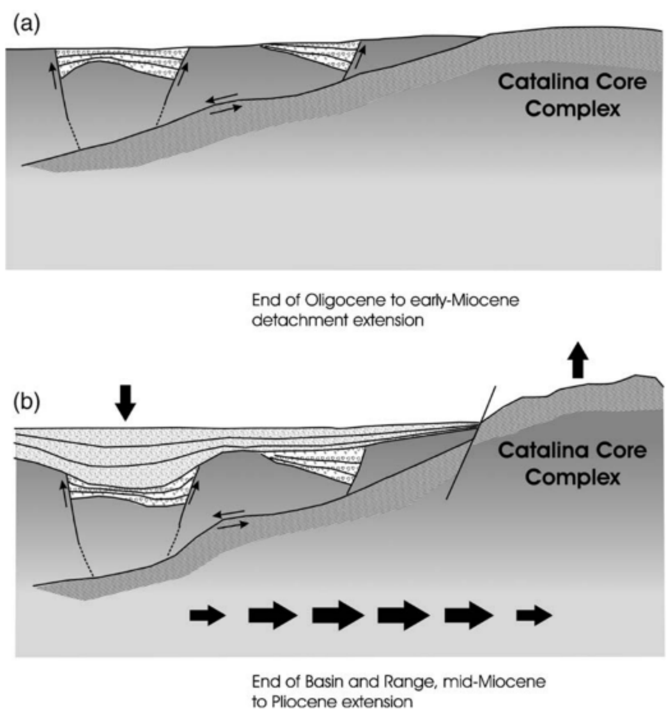

Figure 4. Basin evolution diagram for the Tucson Basin (Wagner & Johnson, 2006).

3. Western North America tectonic evolution

· Late Paleocene to Middle Miocene: The deformation started with the migration of Intra-arc extension due to slab rollback during the Subduction of the Farallon plate (or micro-plates that derived from it). This phenomenon occurred before the formation of the San Andreas transform boundary between the Pacific and the North American plates. Deformation characterized by tectonic denudation of Metamorphic core complexes also happened in this period.

· Eocene: In this period regions of the Pacific Northwest experimented rotation and extension due to the displacement of the Oregon-Washington Coast Range and the Blue Mountains block. These two elements rotated clockwise individually but concurrently moved past each other. The area that eventually became the Southeast Oregon Plateau was later included in the Basin and Range province due to additional block faulting, which followed the Middle Miocene flood basalt eruptions.

· Early Miocene: There was a continuation of extensional tectonic activity in the Great Basing. This extension was influenced by the Mendocino triple junction's oblique northward movement. As the Pacific and North American plates progressively coupled along the evolving San Andreas transform fault, the crustal extension began to affect inland regions. The transfer of this oblique shear stress from the transform boundary triggered the extensional breakup of the continental block.

· Middle Miocene: There was an extensional tectonic activity that affected both coastal and inland regions within the Piman subtaphrogen. This extensional activity occurred in parallel belts, impacting the Gulf extensional province along the coast and the Meseta Central province inland. This geological phenomenon was triggered by the sudden southward movement of the Rivera triple junction past Baja California, coinciding with the consumption of the oceanic Guadalupe plate (Dickinson, 2002).

4. Planetary Analogs

Examples of systems of subparallel grabens similar to the geomorphology of the Basin and Range can be found on other Solar System bodies. **On Venus**, many tesserae present this characteristic. A tessera is a distinctive geological feature found on the surface of Venus. It is characterized by the presence of highly deformed terrain, typically with two or more intersecting tectonic elements. Tesserae are notable for their elevated topography and exhibit a high radar backscatter (Magellan radar images). These formations are often indicative of the oldest geological materials in a given area and are among the most severely tectonically deformed terrains found on Venus's surface (Nikishin, 1990).

On Mars, Karasözen et al., 2016 attributed that The South Tharsis Ridge Belt (STRB) was originated by extensional deformation. This interpretation of the STRB as an extensional tectonic region is supported by several factors, including evidence of crustal thinning and the presence of elongated craters in the vicinity. The relatively wide spacing between the ridges in the STRB, when compared to those in the Basin and Range and other instances of distributed extension, can be attributed to the thicker lithosphere on Mars.

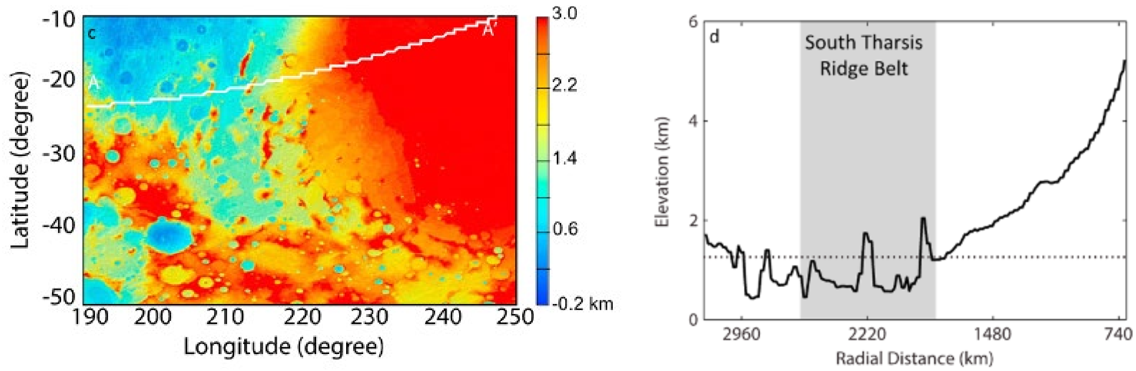

Figure 5. c. Topographic map of the STRB. d. representative topographic profile. The location of the representative profile is shown in Figure 5c with a white line (Karasözen et al., 2016).

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Petrified Forest: Triassic Climate, Flora & Fauna

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By Miriam Keppler

Image source: https://thebotanicaljourney.com/blogs/the-botanical-journey/the-petrified-forest-a-library-in-stone

The Triassic period

The Triassic period is defined as an era between the Permian and the Jurassic periods. It is dated to last between ~252 Myr and ~201 Myr ago. Both, start and end times are marked by major extinction events. The mass extinction event at the transition of the Permian to the Triassic period is considered as Earth's most severe known extinction event (also referred to as 'The Great Dying'), with the disappearance of more than 80% of marine species. A fraction of ecosystems took up to 30 million years to recover. It is thought that the main contribution to the mass extinction event were enormous volcanic eruptions in a region that is now part of Siberia ('Siberian Traps'), releasing large amounts of carbon dioxide and aerosols impacting the global climate and Earth systems. Also the Triassic-Jurassic extinction event was probably caused by massive volcanic eruptions in a region known as the 'Central Atlantic Magmatic Province'.

Geographical context

During the Triassic, almost all landmass was concentrated within the supercontinent Pangea, stretching over the equator and extending into high latitudes. It enclosed the Tethys Sea and was itself encircled by the ocean Panthalassa. Pangea had started to form through the assembly of earlier continental units during the Carboniferous period (about 335 Myr ago), and reached the peak of its continental surface in the Triassic. While it experienced increasing fractures due to faulting and rift basins especially during the late Triassic, it only started to break apart in the early Jurassic.

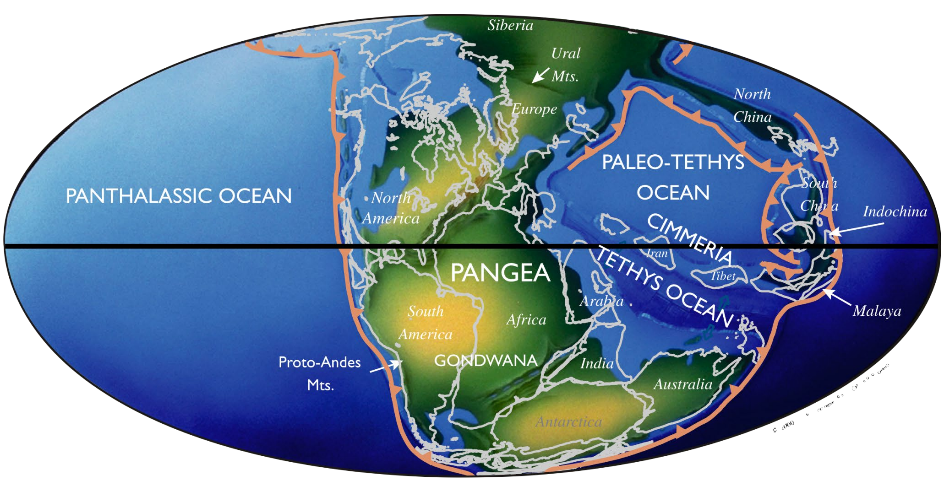

Fig. 1: Shape of Pangea during the Triassic period. Figure taken from [1].

Triassic climate

The Triassic climate was strongly influenced by the unique configuration of Pangea. With its huge concentrated landmass, including large regions located at low latitudes, the inland experienced an extremely dry and hot climate. Further, elevated CO_2 levels (~2200 p.p.m) in particular in the Late Triassic and the lack of ice at the poles indicate that the planet was globally in a greenhouse climate state [2].

In addition, climate models have shown that the large area of exposed land of Pangea, its symmetric distribution about the equator and its respective position with respect to the Tethys Ocean caused favorable conditions for the formation of a megamonsoon – conditions which were optimally expressed during the Triassic period [3]. Due to the Earth axis tilt, during summer in the Northern hemisphere, this part of Pangea would strongly heat up and cause a significant pressure gradient between the Southern and Northern parts of Pangea. The resulting strong northward airflow, moistened from crossing the Tethys sea, would bring strong seasonal precipitation to the Northern hemisphere's coastal regions at lower latitudes. The same would occur in reverse direction during Northern hemisphere winter.

Climate in the Petrified Forest National Park

In the Triassic period, what later became the Petrified Forest National Park was situated near the western coast of Pangea and close to the equator. The climate was thus of warm-tropical, humid and seasonal nature.

Triassic Flora

With the beginning of the Triassic period being marked by a massive mass extinction event, the diversity of life in the Early Triassic was strongly reduced. This period is marked by an important change in flora while plants recovered with time or were replaced by new species, and they had finally developed into a complex vegetation by the Late Triassic.

The understory plants in the Triassic period mostly consisted of ferns, while the middlestory plants were composed of gymnosperms, i.e., plants with exposed seeds, such as the extinct cycadeoids, cycads, and gingkoes. [add Wikipedia drawing]. The upperstory was dominated by conifer forests which began to recover from the Permian Extinction.

Fig. 2: Drawing of Triassic flora.
Source: Wikipedia

Flora in the Petrified Forest National Park

The fossilized forest of Petrified Forest National Park originates from the late Triassic period. The majority of tree fossils found there are *Araucarioxylon arizonicum*, which is an extinct conifer tree [4]. According to research on individual petrified logs, this was a tall monopodial tree with branches growing in a disordered manner on the trunk from the base to the crown with a height of up to 60 m and a diameter of about 1-3 m (see Fig. 3). It is suggested that the branches grew from the trunk at steep upward angles. Since growing in a tropical region, the branches would then have likely swept downward when reaching larger distances from the trunk in order to increase the exposed area of foliate to the solar irradiation, which for most of the day directly came from above.

Other extinct tree species found at the Petrified Forest National Park include *Schilderia adamanica* and *Woodworthia arizonica* [5]. They are thought to have been only half in size as *Araucarioxylon arizonicum*. Their remnants are found very rarely at the Petrified Forest National Park, and it has been suggested that the living trees actually originated from the south-eastern edge of the Chinle Basin, from where their trunks were washed into the Chinle Basin to their finding location by a short-term fluvial event [5].

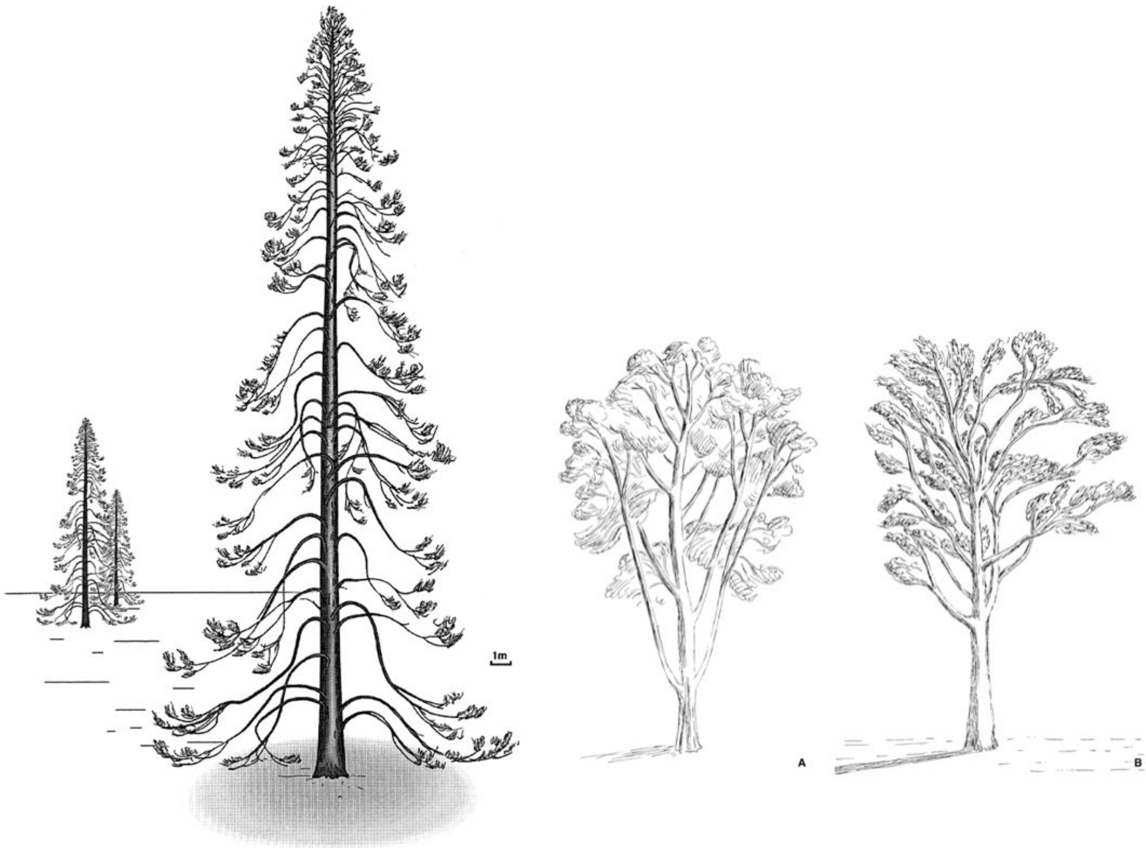

Fig. 3: Schematic drawings of *Araucarioxylon arizonicum* (left), *Schilderia adamanica* (center) and *Woodworthia arizonica* (right), from [4] and [5].

Triassic Fauna

Marine life was massively impacted by the extinction event at the Permian-Triassic boundary, with more than 90% of marine genera disappearing. Only few families of fish survived the extinction, which is reflected by the fact that fossil fish from the Triassic are very uniform.

The marine habitat is increasingly conquered by Ichthysauria. This now extinct form of large marine reptiles resembling a mixture of modern fish and dolphins, emerged from a group of land reptiles that returned to the ocean in the early Triassic, and became dominant in the oceans by mid-Triassic times.

The Triassic is also a time where the first lissamphibians (i.e., modern amphibians) appear, including the progenitors of the first frogs.

Two groups of reptiles survived the Permian-Triassic extinctions: therapsids and archosaurs. Therapsids, i.e., mammal-like reptiles, were the dominant large land animals during the Early Triassic, but declined and most of them became extinct by the mid-Triassic. However, those who survived gave rise to the first mammals near the end of the Triassic period.
In contrast to that, archosaurs became the dominant land vertebrates in the early Triassic. Archosaurs are split into two branches: *Pseudosuchians*, the ancestors to crocodilians and alligators, and *Avemetatarsalia*, the ancestors to birds, which eventually emerged the earliest pterosaurs and dinosaurs in the late Triassic. While dinosaurs were still small predators in the late Triassic, they would become the dominant terrestrial vertebrates after the Triassic–Jurassic extinction event.

Fauna in the Petrified Forest

Phytosaurs are one of the most common vertebrate fossil animal found in the park. While they look very similar to modern crocodiles, they are distinct in several aspects. The most obvious difference is that phytosaurs have their nostrils located high up on the skull, almost between the eyes, while crocodiles have their nostrils at the ends of their snouts. Phytosaurs are thought to be closely related to Pseudosuchians, the

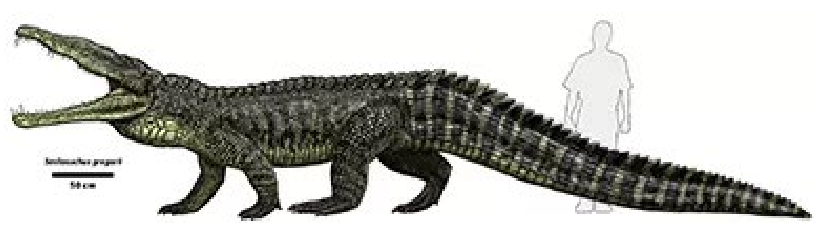
Fig. 4: Schematic drawing of phytosaur. Source: NPS [6]

ancestors to crocodilians.

Another archosaur type found in the park are Rauisuchians [6]. They were characterized by a large skull comprising a powerful biting jaw and long serrated teeth - Rauisuchians represented the dominant terrestrial predator of the Late Triassic.

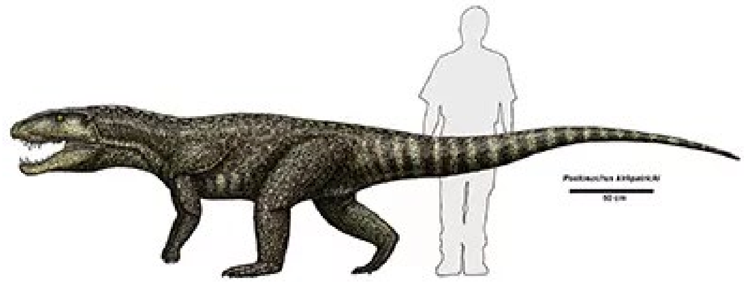

Fig. 4: Schematic drawing of Rauisuchian. Source: NPS [6]

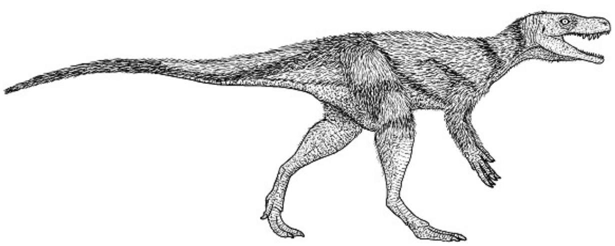

Fig. 5: Schematic drawing of a Chindesaurus. Source: NPS [6]

Even rare dinosaur remnants are found at the Petrified Forest National Park. Among them is a partial skeleton of a Chindesaurus specimen, a bipedal carnivore, approximately as large as a wolf. It was discovered in the park in 1984 and considered at the time as the oldest dinosaur ever found on the planet.

At a site just south east of the Petrified Forest National Park, close to St Johns, the fossils of forty *Placerias* specimen were found in 1930. This site is now known as 'Placerias Querry', and is one of the most diverse Triassic vertebrate fossil localities in the world. Placerias were large planet-eating reptiles with a short neck and a barrel-shaped body. They grew up to about 2.7 m in size and might have weighed as much as two tons.

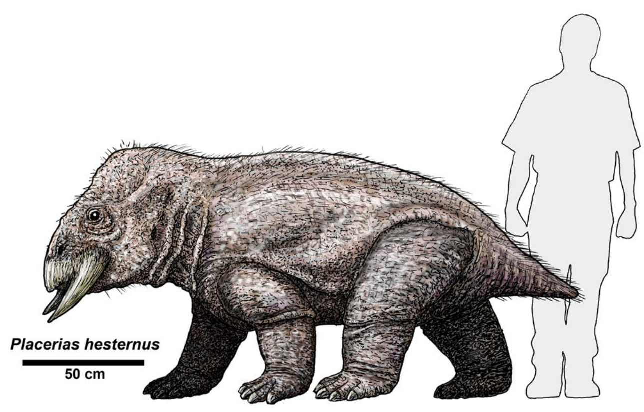

Fig. 6: Schematic drawing of a Placerias. Source: Wikipedia

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The Grand Staircase

Ricardo Maciel

Introduction

The Grand Staircase is a vast series of exposed sedimentary rock layers in the southwestern United States. It spans over 100 miles across from Bryce Canyon National Park in the north to the Grand Canyon in the south, with Grand Staircase-Escalante National Monument and Zion National Park sitting in between. It was first characterized as a staircase in 1870 by geologist Clarence Dutton, who described the most prominent escarpments in the chain as "steps" that ascended from the Grand Canyon's northern rim. Each of the five steps have come to be known by the general color of their respective cliff faces. Starting at the bottom and "climbing" the stairs, they are called the Chocolate Cliffs, the Vermilion Cliffs, the White Cliffs, the Grey Cliffs, and finally the Pink Cliffs (Figure 1).

The exposed layers of the Grand Staircase reveal a combined total of almost 270 million years of geological history. These steps provide a chronicle of numerous geological epochs, preserving evidence of Jurassic river sediments and sand dunes, Cretaceous seaways, and Eocene lake sediments, each telling a story of shifting environments and climates. The cliffs that we see today are formed by harder rock such as sandstone or limestone which resisted erosion throughout this vast period of time.

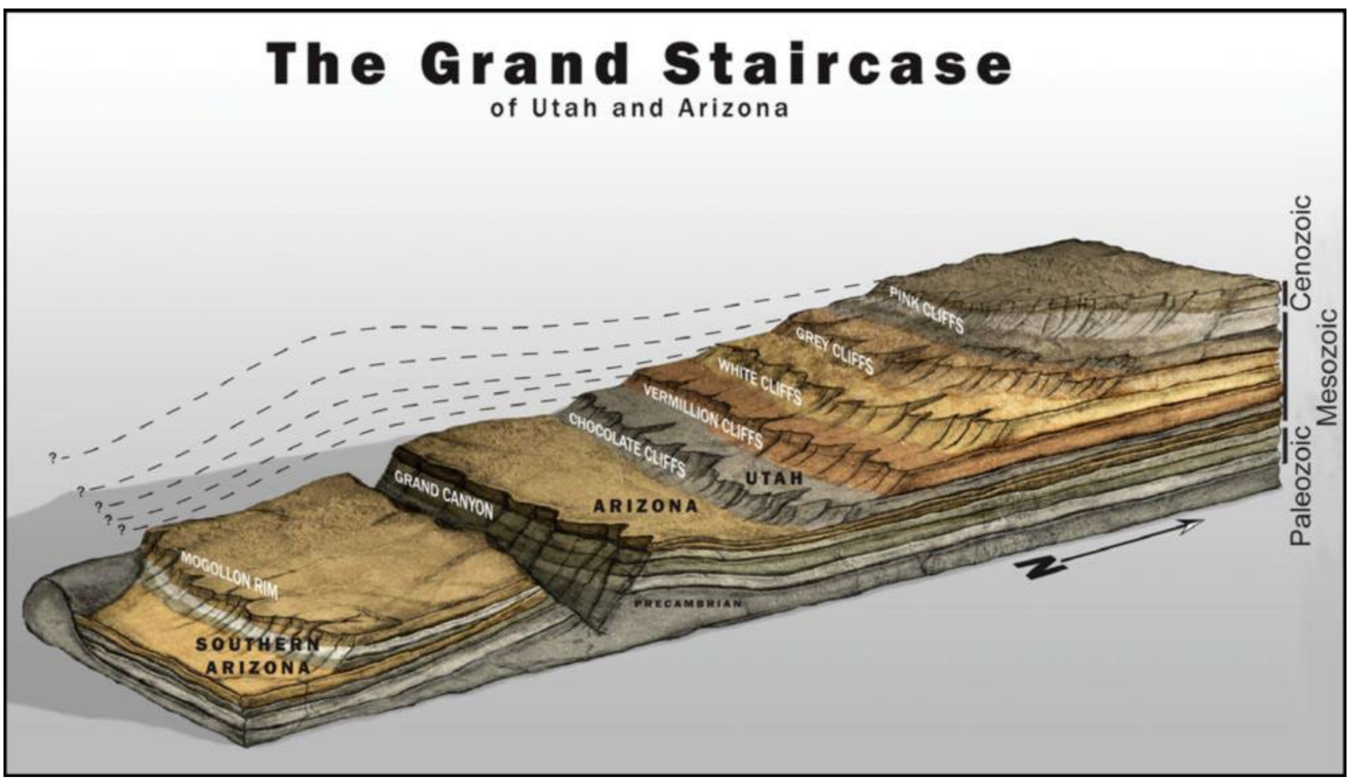

Figure 1: Illustration of the Grand Staircase, compressed to emphasize the prominent steps and colored to highlight the various strata.

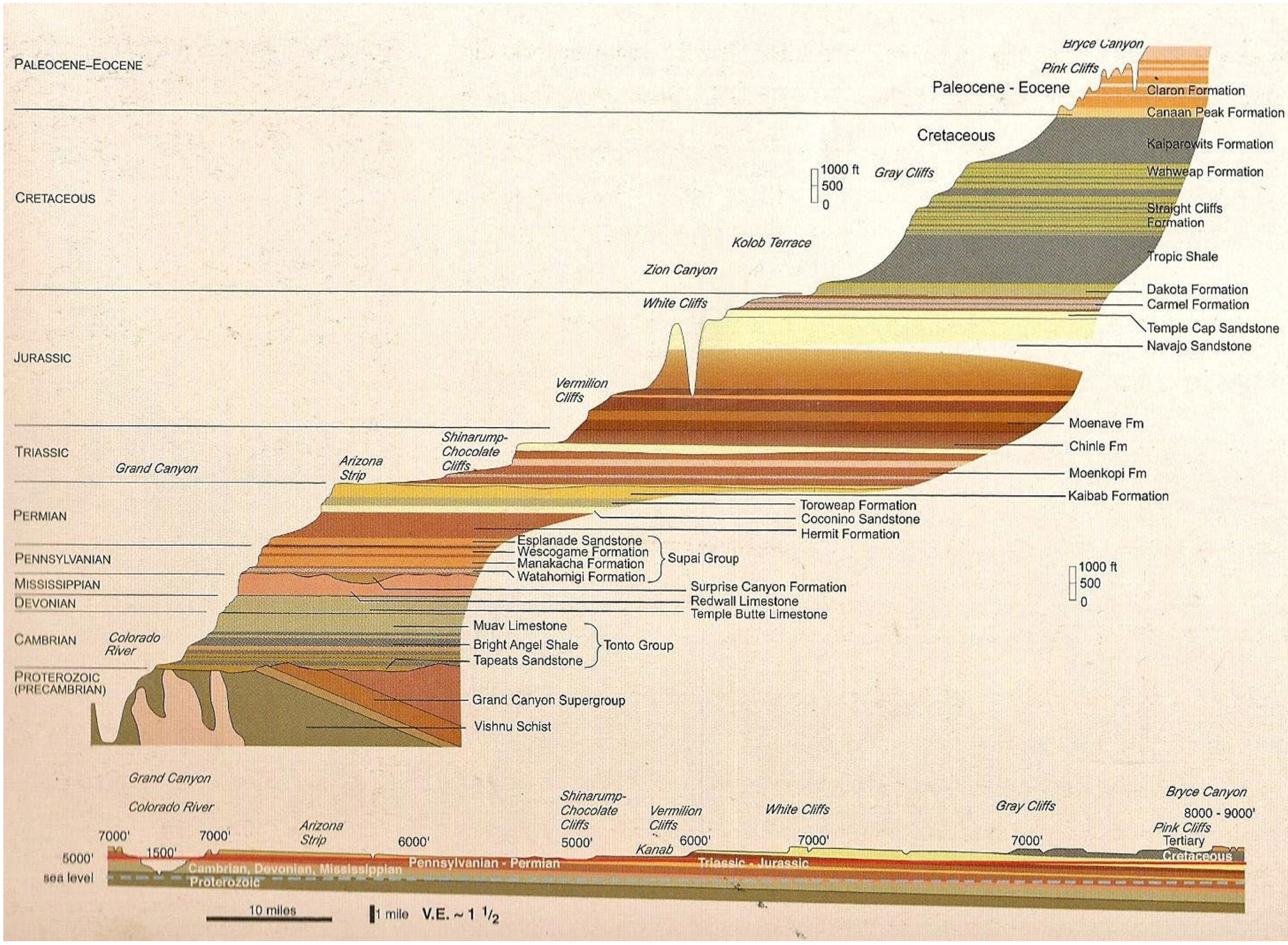

Figure 2: Compressed cross-section of the Grand Staircase showing the strata and geological epochs in finer detail, with a scale illustration below showing spatial extent and vertical climb.

Earthen Layer Cake: The Five Steps

Layer 1 – Chocolate

The oldest of the steps, the Chocolate Cliffs are composed of Moenkopi Formation sandstones, mudstones, and siltstones that were deposited roughly 240 million years ago in the Triassic. These cliffs zig-zag through the Arizona-Utah border and date back to a period of time when the surrounding area was a marine lowland of streams, flood plains, and tidal flats. It is common to find ancient mineralized driftwood in the form of petrified wood in this region.

Layer 2 – Vermilion

Located in the High Plateaus and Canyon Lands sections of the Colorado Plateau Province. The sandstone is stained by minerals such as iron oxide deposited by streams that once flowed from desert environments into the floodplains, about 190 million years ago. The abundance of iron oxide in the sediment as well as the presence of manganese is what gives rise to the rich color observed in these cliffs.

Layer 3 – White

The bleached-white Navajo Sandstone which comprises the White Cliffs rests above the Vermilion Cliffs, having formed some 180 million years ago, and stands out in stark contrast to their vibrant red hues. The Navajo Sandstone is a remnant of a vast prehistoric sand desert – the largest to have ever existed – and is therefore often said to be a fossilized desert. The most spectacular cliffs can be found in this region, with some reaching over 500 feet in height.

Layer 4 – Gray

The Gray Cliffs are an outcropping of the Dakota Formation, which is a mixture of dark mudstone, coal, and shale that was deposited roughly 140 million years ago. Once an ancient coastline, the region has proved to be a rich source of significantly preserved marine fossils: turtles, mollusks, lizards, crocodilians, dinosaurs, and various fish have all been recovered from this layer.

Layer 5 – Pink

The uppermost step and youngest layer at an age of 30-60 million years. It is formed by pink and pale-orange limestone. The dinosaur extinction occurred during the deposition of this layer, so unlike the Gray Cliffs there are sparse dinosaur fossils to be recovered. While the Pink Cliffs extend over a large area of southern Utah, they are most famous for their high concentration of spires and hoodoos in and around Bryce Canyon National Park.

Figure 3: Photographs of the five steps, ordered from youngest in the top left to oldest in the bottom right.

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Moenkopi and Chinle Formations: The Painted Desert

Mackenzie Mills

General Information:

1. The Moenkopi (moe-en-koh-pee) and the Chinle (chin-lee) formations are exposed over large areas of northeastern Arizona
2. General regional stratigraphy (of AZ Canyonlands) is shown in the figure to the right (courtesy of the USGS[1])

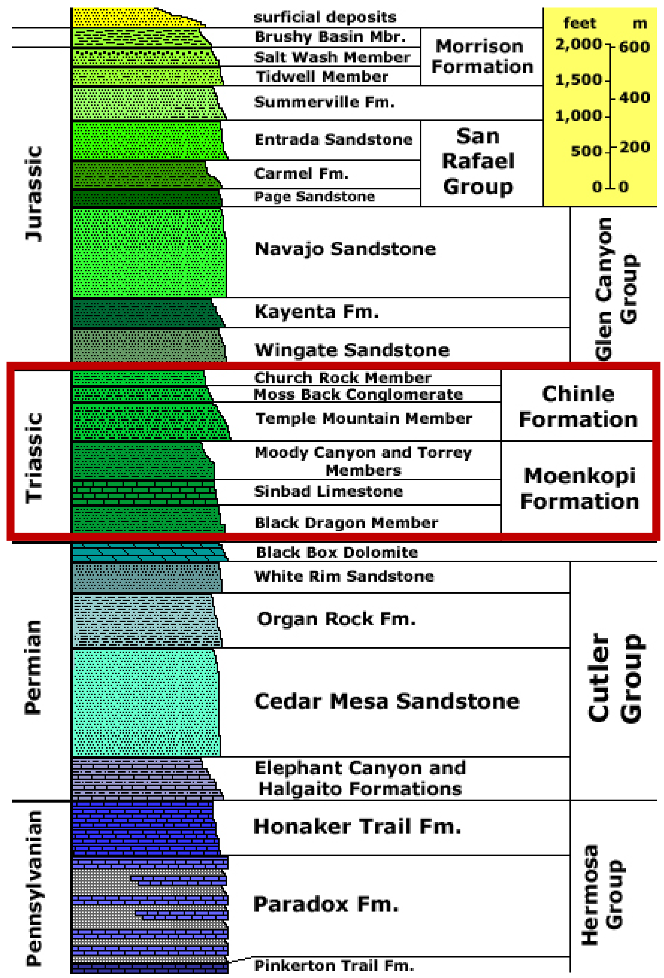
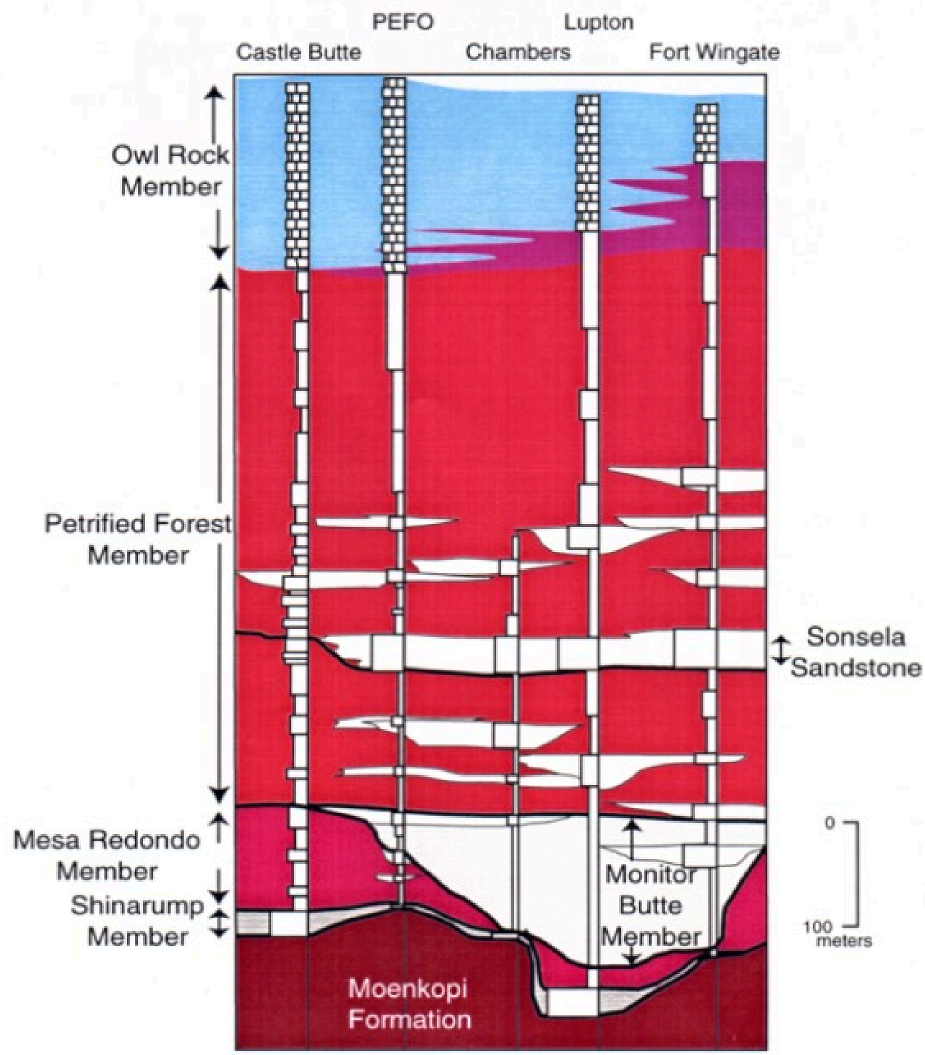


Figure 1: General stratigraphy of the region[1]. Both formations have varying names for their members based on the unconformities preserved in stratigraphy across the region. This makes identifying the same members over space difficult because unconformities can vanish between outcrops.

3. Both formations have ~3 primary members (though some records differ[1,2])
4. The Chinle formation is late Triassic in age (~200—~220 ma), and are mainly fluvial and lacustrine deposits[2]
5. The Moenkopi formation spans from ~235–~252 ma[3], and has small unconformities with the Chinle that vary over the region
6. There is also an unconformity *above* the Chinle formation representing ~192 ma
7. The Chinle is best known for the different colored layers that outcrop in the Painted Desert: reds, yellows, greens, blues, whites, etc.
8. Formation environment causes this. If the soil layer was in a high water table, a reducing environments gives a green or blue hue. If the soil instead was in a low water table, or one that fluctuated a lot, reddish hues formed (oxidized iron!). Figure 3 is an example.
9. Much of the layers we'll see are predominantly sandstones interbedded with mudstones (e.g. Blue Mesa while driving through the Petrified Forest).
10. Other stratigraphy splits the Chinle formation into 5 members (young to old)[2]:
    a. Owl Rock Member: pinkish-orange mudstones interbedded with limestone
    b. Petrified Forest Member: red and brown mudstones and sandstones, petrified wood
    c. Sonsela Member: interbedded, multicolored sandstones and mudstones, some conglomerates
    d. Blue Mesa Member: thick layers of grey-blue mudstones with some sandstones
    e. Mesa Redondo Member: interbedded siltstones and sandy conglomerates

11. Other stratigraphy splits the Moenkopi formation into 3 members[5,6] (young to old):
    a. Holbrook Member: Sandstone beds, usually capping the formation due to durability
    b. Moqui Member: thinly-bedded siltstones and mudstones interspersed with gypsum deposits
    c. Wupatki Member: interbedded siltstones, silty sandstones, and sandstones
12. The Chinle is the majority of the rock record in the Painted Desert. The Moenkopi is exposed in the Petrified Forest where *paleovalleys* have incised[4] (see Figure 2).

Figure 2: Stratigraphic cross section of measured sections of the Chinle Formation in and near Petrified Forest National Park[4]. Systems of paleovalleys incising older layers are shown in white. General formations with relative thicknesses are colored and labeled.



13. These paleovalleys appear in the rock record to be incised and then infilled (like a current wash in the desert today)[4]

<u>Observations:</u>

- Sedimentary layers consisting of: sandstones, siltstones, mudstones, limestones, gypsum deposits, cobbles, etc.
- Lithology is often thinly interbedded and intermixed, making it difficult to distinguish different units across areas
- Multiple unconformities exist across the region, making it difficult to match identified members together across space
- Layers show different colors that indicate a fluctuating groundwater table
- Some members display thick deposits of sandstones usually characteristic of beach deposits
- Incising valleys which have then been infilled

Interpretation[2-6]:

These formations were created over a coastal floodplain. The thin interbedding and variety in lithology shows that this was a dynamic environment, prone to changes. Meandering rivers over this floodplain could have deposited sandstones and siltstones, along with silty sandstones and mudstones when they overflowed their banks. Lakes in the region could have formed when rivers overflowed or were blocked. Lakes could then conceivably preserve mudstones and other fine-grained lithologies. Thick layers of sandstones (e.g. the Holbrook member of the Moenkopi) indicate a high energy beach environment. This coastal floodplain likely had an advancing and retreating shoreline that affected the deposited lithology. Limestone in these formations can be explained by a deeper marine environment after a shoreline prograded. Rivers also act as incisors, and could have formed the paleovalleys identified[4] along with the multiple unconformities that make the members of these formations more difficult to connect between local regions. Finally, the vibrant colors in the various layers, and their abrupt changes indicate that the groundwater level was fluctuating, which also supports this dynamic floodplain/migrating shoreline formation environment.

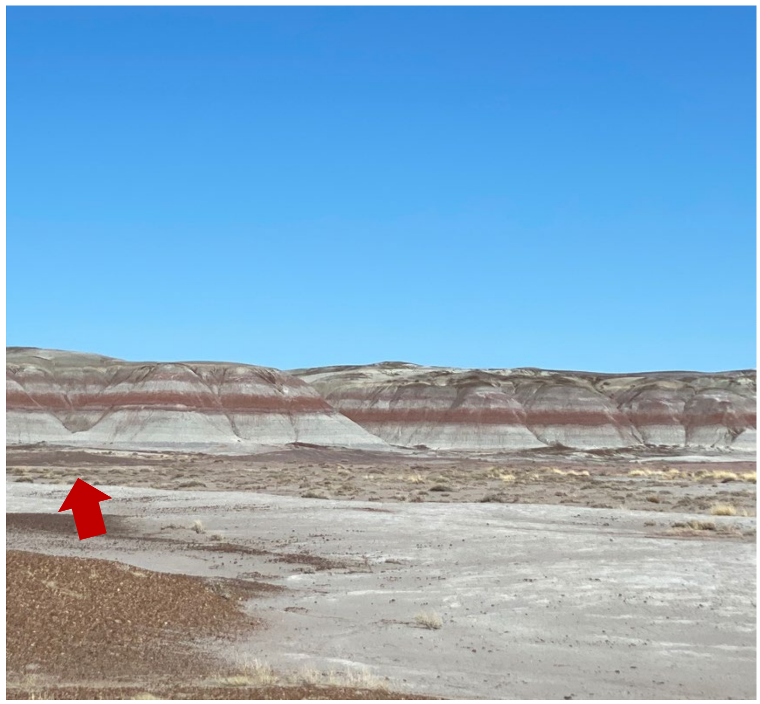


Figure 3: This is a photo I took in the Painted Desert while on a camping trip with family in April 2023. It shows the Blue Mesa group, and the layer are incredibly visible! The brown midlayer (red arrow) here would indicate a soil horizon that had a lower water table, allowing more oxygen to interact with the sediment as it was deposited. Above and below that layer are blueish grey layers. These would indicate soil horizons that were in a higher water table. The changes in deposition environment can be clearly seen in this photo of the rock layers.

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Planetary Geology Field Studies

Weathering and Erosion Processes

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By Martin Schlecker

Introduction

Sedimentary rock and the processes responsible for its formation like weathering, erosion, and lithification, constitute a fundamental aspect of comprehending planetary science. This significance arises from the fact that a substantial portion of Earth's (and possibly other rocky planets') surface consists of sedimentary rocks and their prevalent precursor, sediments. Despite the diverse methods through which sedimentary rocks may develop, they all share a common factor in their origin and formation: the presence of water.

Weathering

Weathering is a process that transforms *bedrock* – the solid rock that makes up Earth's outer crust – into smaller particles, the *sediment*. We may distinguish different types of weathering. *Mechanical weathering* encompasses processes like pressure expansion, wedging through frost or roots, and salt expansion. *Chemical weathering* involves carbonic acid, hydrolysis, dissolution, and oxidation.[1]

Mechanical weathering

Mechanical weathering is the physical fragmentation of bedrock into smaller fragments. Typical agents responsible for mechanical weathering include fluctuations of temperature and pressure, the freezing/thawing cycles of water, salt evaporation, but also activities of plants or animals.

Bedrock located deep within Earth's crust experiences high levels of both pressure and temperature. When uplift and erosion processes bring this bedrock to the surface, its temperature gradually decreases, whereas its pressure decreases abruptly. This abrupt reduction in pressure leads to the rapid expansion and subsequent cracking of the rock, a phenomenon known as pressure expansion. The peeling off of the rock surface in layers is called sheeting or exfoliation. Spheroidal weathering, a subtype of exfoliation, results in the formation of rounded geological features. It is induced when chemical weathering progresses along the joints within the bedrock.

Frost wedging harnesses the expansive force of freezing ice to fracture rocks. Water infiltrates cracks and fissures and when it freezes, it expands substantially. This exerts significant pressure to the rock. Once the ice melts back into liquid water, it moves deeper into the now widened gaps. Cycles of freezing and thawing gradually separate the rocks. If the temperature fluctuates across the freezing point, these cycles can occur on a daily basis.

Similar to frost wedging, plants can pry bedrock apart when their roots work themselves into cracks. The roots may become preserved as fossils called Rhizolith. In a similar manner, tunneling organisms like earthworms can initiate weathering processes.

[1] Adapted from https://opengeology.org/textbook/5-weathering-erosion-and-sedimentary-rocks/ Sep 19, 2023

Another process akin to frost wedging is salt expansion, which takes place in regions characterized by high evaporation rates (typically in proximity to marine environments). As evaporation leaves behind salts, the latter grow and expand into crevices. Salt expansion is contributing to the formation of tafoni (see image), which represent areas more susceptible to weathering.

Tafoni at Pebble Beach, San Mateo Coast, California. CC-by-sa-2.0 Dawn Endico

Chemical weathering

In warm, humid environments, chemical weathering is the primary weathering process. It occurs when water, along with oxygen and various other reactive agents, chemically deteriorates the mineral constituents of bedrock, transforming them into water-soluble ions that can subsequently be carried away by water. Higher temperatures generally increase the rate of chemical weathering.

Because water and the involved reactants cannot penetrate solid rock, chemical weathering occurs only on surfaces. As mechanical weathering breaks up the material, new surfaces emerge that are susceptible to chemical weathering. This also leads to the general rule that higher surface-to-volume ratios lead to higher overall weathering rates.

A prime agent of chemical weathering is *Carbonic acid*, (H_2CO_3), which forms when carbon dioxide dissolves in water. Carbonic acid molecules may directly react with minerals to form molecules of clay minerals. This is one variety of *hydrolysis*, the prime process to break down silicate rock and from clays. Another one is *dissolution*, which leaves the ions of minerals in the bedrock in water. More acidic pH of the water leads to higher dissolution rates. Organisms like lichen and bacteria can enhance the process by releasing organic acids.

Oxidation, the chemical process responsible for the formation of rust in metallic iron, also occurs in geological contexts when iron atoms within minerals bond with oxygen. All minerals containing iron are susceptible to oxidation. The resulting iron oxides can infiltrate a rock if it is rich in iron-bearing minerals, and they may also develop a coating that envelops rocks and individual sediment grains or lines cavities and fractures within the rock. In cases where the oxides are more prone to weathering compared to the original bedrock, they can create empty spaces within the rock mass or depressions on exposed surfaces.

Iron-oxidation reactions yield three frequently encountered minerals: red or gray *hematite*, brown *goethite*, and yellow *limonite*. These iron oxides play a crucial role in coating and binding mineral grains together, a process known as *cementation*, and impart a predominant color to the resulting sedimentary rocks. These minerals are responsible for coloring the rock layers found in the Colorado Plateau region, including prominent national parks such as Zion, Arches, and the Grand Canyon.

Sandstones in Canyon de Chelly, Arizona, USA. The reddish-brown coloration is from hematite. CC BY 2.0 James St. John

Erosion

Erosion, typically driven by forces like water, wind, gravity, or ice, is a mechanical process responsible for transporting sediment (as well as soil) away from the site of weathering. Liquid water acts as the primary agent of erosion, while gravity and mass wasting processes relocate rocks and sediment. Gravity and ice, in the form of glaciers, are capable of moving both large rock fragments and fine sediment.

Physical erosion

Physical erosion refers to the process by which rocks undergo changes in their physical characteristics without undergoing any fundamental alterations in their basic chemical composition. Typically, physical erosion results in the reduction in size or the smoothing of rocks. Rocks that undergo physical erosion often give rise to clastic sediments, which are comprised of fragments from older rocks that have been transported away from their original location. Processes such as landslides and various forms of mass wasting are closely associated with physical weathering, causing rocks to become dislodged from hillsides and break apart as they descend slopes.

Additionally, vegetation can contribute to physical erosion through a process known as *bioerosion*. As plants establish roots, they break apart soil and can create cracks and crevices in rocks they encounter. Furthermore, the movement of ice and liquid water can also play a role in physical erosion by exerting forces that cause rocks to collide or fracture. Some rocks may shatter and crumble, while others gradually wear away. For example, river rocks often exhibit a smoother texture compared to rocks found elsewhere because they have experienced erosion through constant contact with other river rocks.

Water as an erosion agent

Liquid water stands as Earth's principal erosional force. Rain, rivers, floods, lakes, and the ocean all participate in the removal of soil and sand, slowly eroding sediment over time. Rainfall gives rise to four primary forms of soil erosion: splash erosion, sheet erosion, rill erosion, and gully erosion.

1. Splash erosion is the result of raindrop impact, scattering tiny soil particles up to 0.6 meters (two feet) away.

2. Sheet erosion arises from runoff, where water flows over a broad surface.

3. Rill erosion occurs as runoff evolves into distinct streams known as rills.

4. Gully erosion is characterized by the transportation of soil particles through substantial channels.

Gullies intermittently carry water during rainfall or snowmelt but appear as minor valleys during dry periods. Valley erosion is a process where swift streams and rivers erode their banks, forming larger valleys.

Oceans are a significant agent of erosion, causing coastal erosion, which alters entire coastlines. Coastal erosion involves waves breaking rocks into pebbles and pebbles into sand. Waves and currents can also relocate sand, shifting coastlines inland.

Coastal Erosion near Fraisthorpe, East Riding of Yorkshire, England. CC BY-SA 2.0 JThomas

Erosion through ice

Ice erosion, typically in the form of glaciers, can give rise to striking geological features. In icy regions and atop certain mountain peaks, glaciers gradually traverse downhill and across the terrain. During their movement, glaciers transport an array of materials, ranging from minuscule sand grains to substantial boulders. Rocks carried by glaciers interact with the underlying ground, resulting in erosion of both the ground itself and the rocks. Consequently, glaciers function as agents that grind rocks into smaller fragments and strip away the surrounding soil. As glaciers advance, they carve out depressions and create steep-sided mountain valleys. The eroded sediment, known as moraine, is often observable in and around glacier areas.

Vatnajökull, Iceland. CC BY-NC-ND 3.0 Eric Montfort

Wind-induced erosion

Wind, a formidable agent of erosion, continually engages in aeolian (wind-driven) processes that transport dust, sand, and ash from one location to another. On occasion, wind can accumulate sand into imposing dunes, such as those found in the Badain Jaran region of China's Gobi Desert, where some dunes soar to heights exceeding 400 meters. In arid regions, wind-blown sand can exert substantial force against soft rock, gradually wearing it away and imparting a smooth finish, a phenomenon referred to as "desert varnish."

Wind can also erode material to the point of almost complete removal. Ventifacts are rocks meticulously sculpted by the relentless force of wind erosion. In the expansive chalk formations of Egypt's White Desert, these ventifacts have been painstakingly carved over thousands of years by the relentless winds that sweep through the flat terrain.

Some of the most devastating instances of wind erosion are exemplified by the dust storms that marked the "Dust Bowl" era of the 1930s in North America. Prolonged drought and inadequate agricultural practices rendered the soil brittle, and strong winds led to the erosion of millions of tons of precious topsoil, triggering what became known as "black blizzards." These severe dust storms wrought havoc on local economies, compelling thousands of individuals reliant on agriculture for their livelihoods to embark on migration as a result.

Other forces of erosion include thermal erosion, which describes the process of ice-rich permafrost breaking off coastlines or riverbanks, or mass wasting processes like landslides or avalanches.

Erosion resistance

A big role in shaping the impressive geological features that are for instance common in the southwestern US plays *erosion resistance*. Formations like the Grand Canyon or the hoodoos in Bryce Canyon National Park are unique examples of rock that remains standing after less resistant materials have undergone weathering and erosion.

Hoodoos in the Goblin Valley State Park. CC-BY-SA-3.0 Enrico Stirl

Factors influencing erosion

Climate stands out as a particularly influential force in shaping erosion's impact on a landscape, as it encompasses precipitation and wind, along with seasonal variations that influence the likelihood of sediment transport during events like snowmelt, breezes, or hurricanes.

Topography, defined as the surface features of an area, also plays a role in how erosion affects the landscape. For instance, earthen floodplains in river valleys are more susceptible to erosion than rocky flood channels, which may take centuries to erode. The rate of erosion can vary significantly between soft rocks like chalk and harder varieties like granite.

Vegetation can mitigate the impact of erosion by anchoring soil and rock particles with their roots, preventing their displacement during rainfall or wind events. Trees, shrubs, and other plants can even reduce the impact of mass wasting events such as landslides and natural hazards like hurricanes. Conversely, deserts, often lacking dense vegetation, tend to be highly eroded landscapes.

Lastly, tectonic activity shapes the landscape itself, influencing how erosion affects an area. For example, tectonic uplift can elevate one part of the landscape over another. Over approximately 5 million years, tectonic uplift caused the Colorado River to progressively carve deeper into the Colorado Plateau, forming the Grand Canyon.[2]

Disclaimer

The generation of this text was assisted by an AI model. The model was used only to help with formulating concepts. The structure and content of the essay are original to the author or references in the tex

[2] Adapted from National Geographic Society, "Erosion" Sep 19, 2023

Mining in Northern Arizona

Reed Spurling

Background

Mining underpins civilization. We planned this field trip on electronic devices made of mined materials (e.g., copper, silicon, and tin) and powered by energy produced from/with mined materials (e.g., methane, uranium, coal, and silicon). We then drove here in vehicles made of mined materials (e.g., iron and aluminum), propelled by yet more mined materials (petroleum). If the University of Arizona Motor Pool switches to electric vehicles, the batteries in those will be made of mined materials (e.g., nickel, cobalt, and lithium). Today's weather forecast was informed by data from balloons lifted by mining-derived gas (hydrogen or helium).

Overview of Mining in Arizona

Arizona has a long history of mining. Humans have mined this land since Paleo-Indians arrived over 10,000 years ago and started cutting stones into projectile points (Antevs, 1959). Subsequent cultures, including the Hohokam, Mogollon, and Ancestral Puebloans, mined stone, clays, salt, turquoise, and other materials, mainly from surface outcrops (AZGS, n.d.).

Spanish colonizers began industrial mining for gold and silver when they arrived. This continued as the land became part of Mexico (Officer, 1991), and then the United States. The area's mining industry expanded in the mid 1800s, and by 1912, around two billion present-day dollars' worth of mining operations were ongoing in the state (AZGS, n.d.).

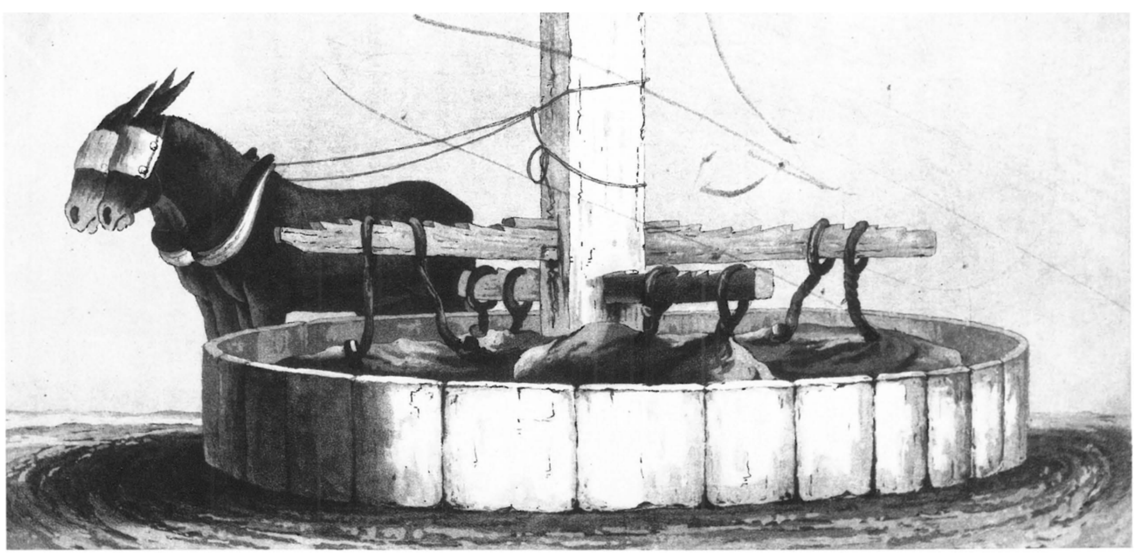
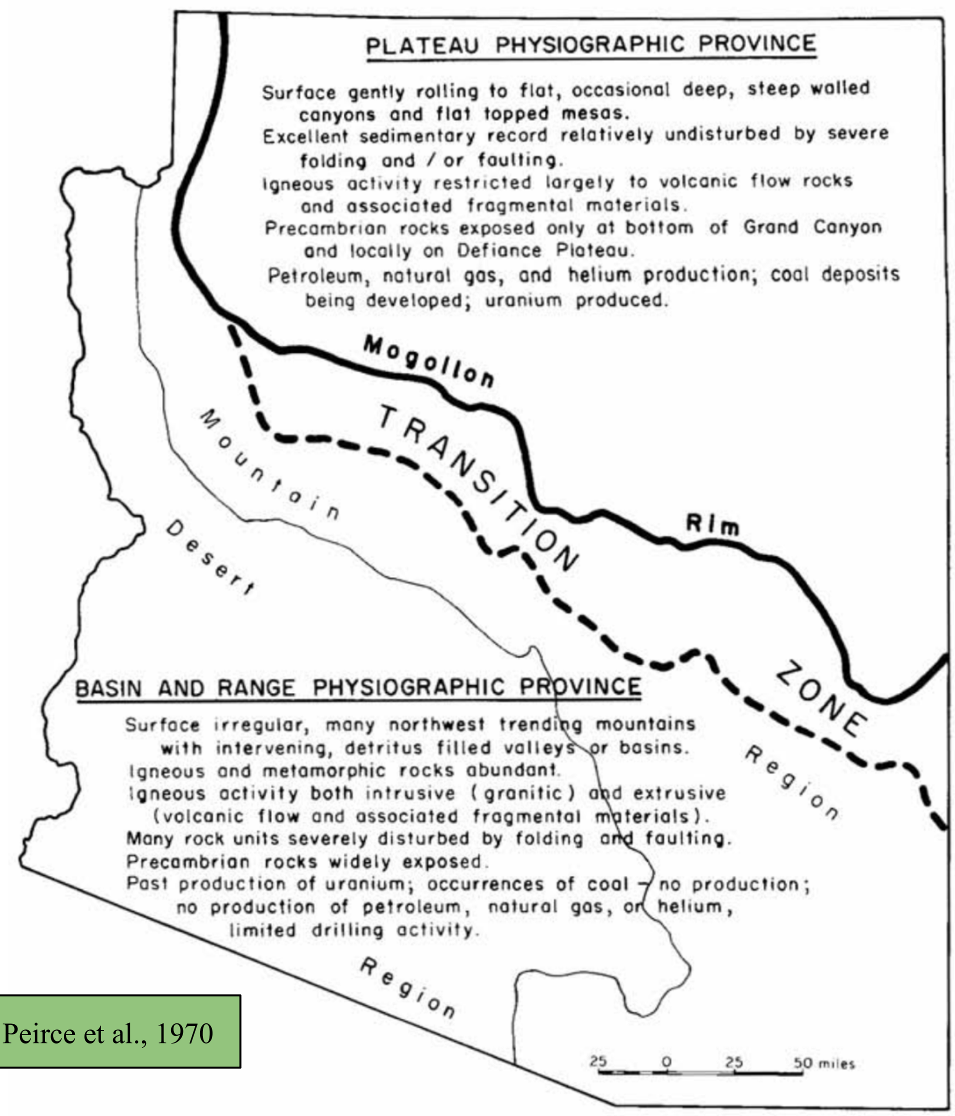


Figure: An arrastra, a mill for refining silver ore, as used in early Mexico. Illustration by Emily Swinburne Ward, in (Ward, 1828).

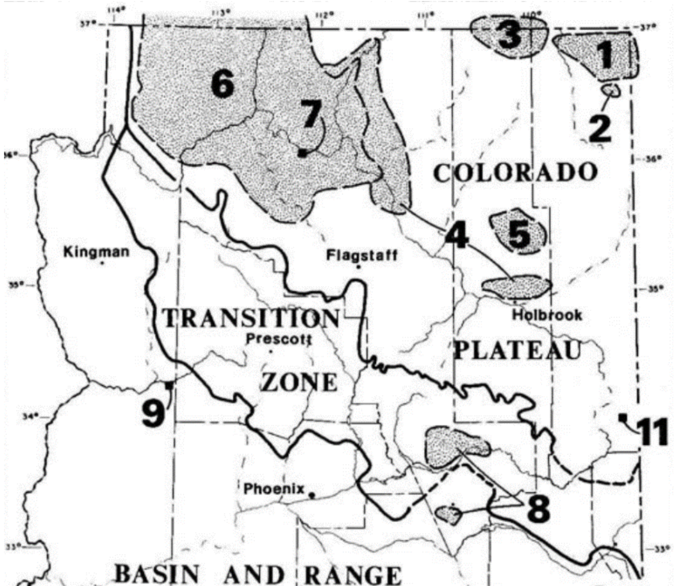
The past and present distribution of mining in Arizona is defined by geology on multiple scales. On a broad scale, the state can be split into two geologic provinces: the **Basin and Range** province in the south, and the **Plateau** province in the north. See map below.

The Basin and Range province has been shaped by faulting and metal-rich intrusive volcanism, creating ideal conditions for the concentration of metallic minerals (e.g., gold, silver, and copper). See the following page for maps of gold and copper occurrences in Arizona.

The Plateau province, which we are visiting on this field trip, has in contrast been shaped mainly by sedimentary and erosional processes, creating conditions ideal for the formation of hydrocarbon deposits (e.g., coal and oil) and the concentration of other materials (e.g., uranium and helium). I will briefly discuss two of these materials in particular: uranium and coal.

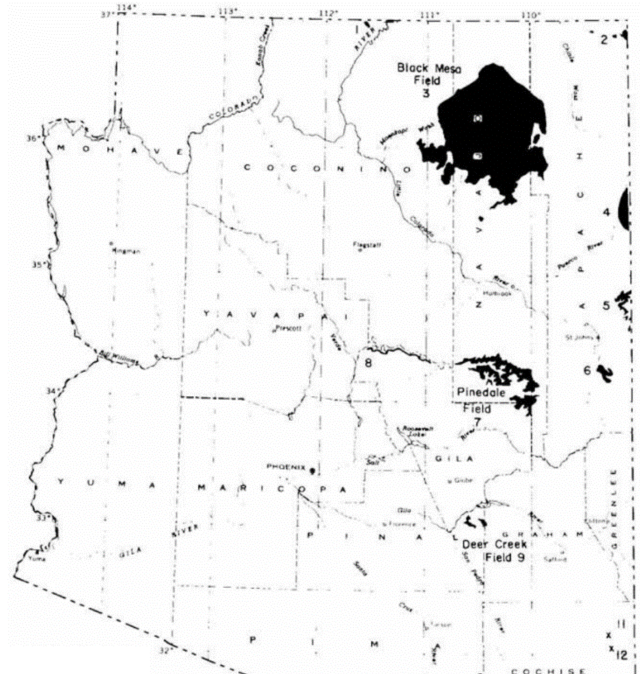


Peirce et al., 1970

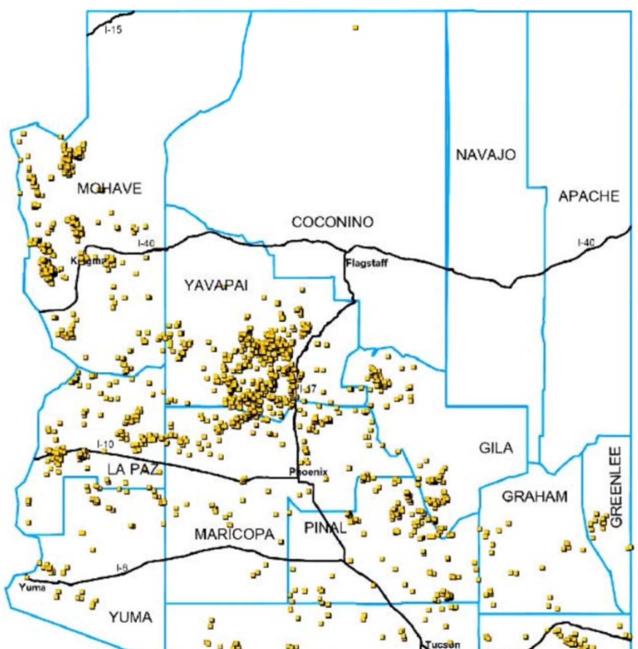


Uranium occurrences in AZ. Niemuth, 2008.

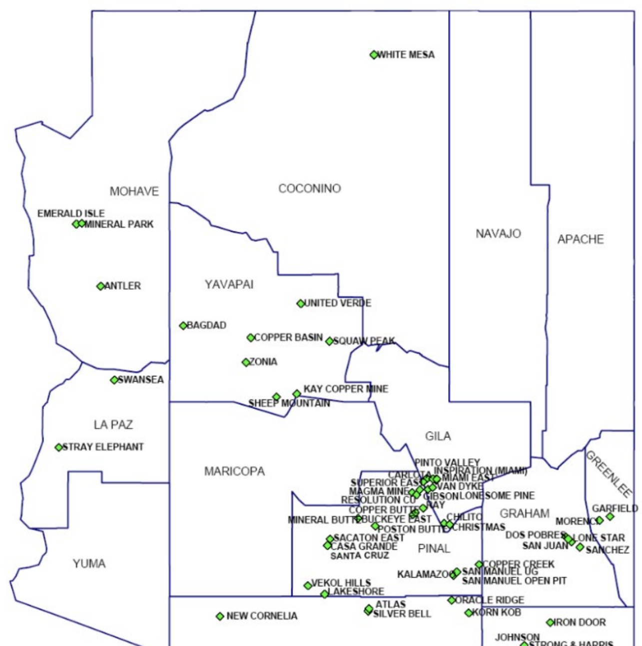
1, 2: Morrison Formation, Salt Wash Member; 3, 4: Chinle Formation; 5: Hopi Buttes volcanic field;



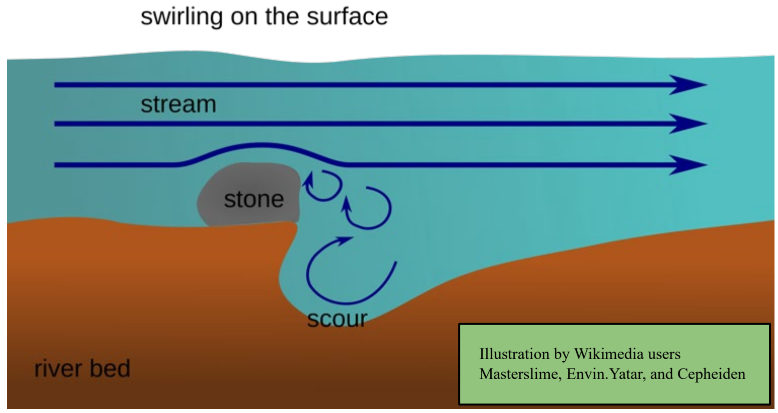
Coal occurrences in AZ. Peirce et al., 1970



Gold occurrences in AZ. AZ Dept. of Mines and Mineral Resources, 2007



Copper occurrences in AZ. AZ Dept. of Mines and Mineral Resources, 2002



Uranium is found in subsurface channels where water can concentrate it and other minerals. In northern Arizona, these include gently sloping fluvial channels in the Chinle and Morrison formations that have been covered by many layers of sedimentary rock since they formed. Pits formed in these ancient channels by <u>scour</u> (see illustration on upper right) are especially good places to look for uranium (Chenoweth, 1993).

In northwestern Arizona, uranium can be found in breccia pipes—collapse-formed, rubble-filled vertical channels through many layers of rock. Much like the ancient fluvial channels in the Chinle and Morrison formations, breccia pipes provide convenient paths for groundwater to flow through. As water flows down, it deposits minerals, including uranium oxide, in the breccia pipes.

Because of historical watershed contamination from unsafe uranium mining in breccia pipes, and the high risk of continued contamination from such mining, much of the land containing breccia pipes has been made off-limits to uranium extraction. This year, the Biden administration established a new national monument to indefinitely extend these protections in certain areas surrounding the Grand Canyon.

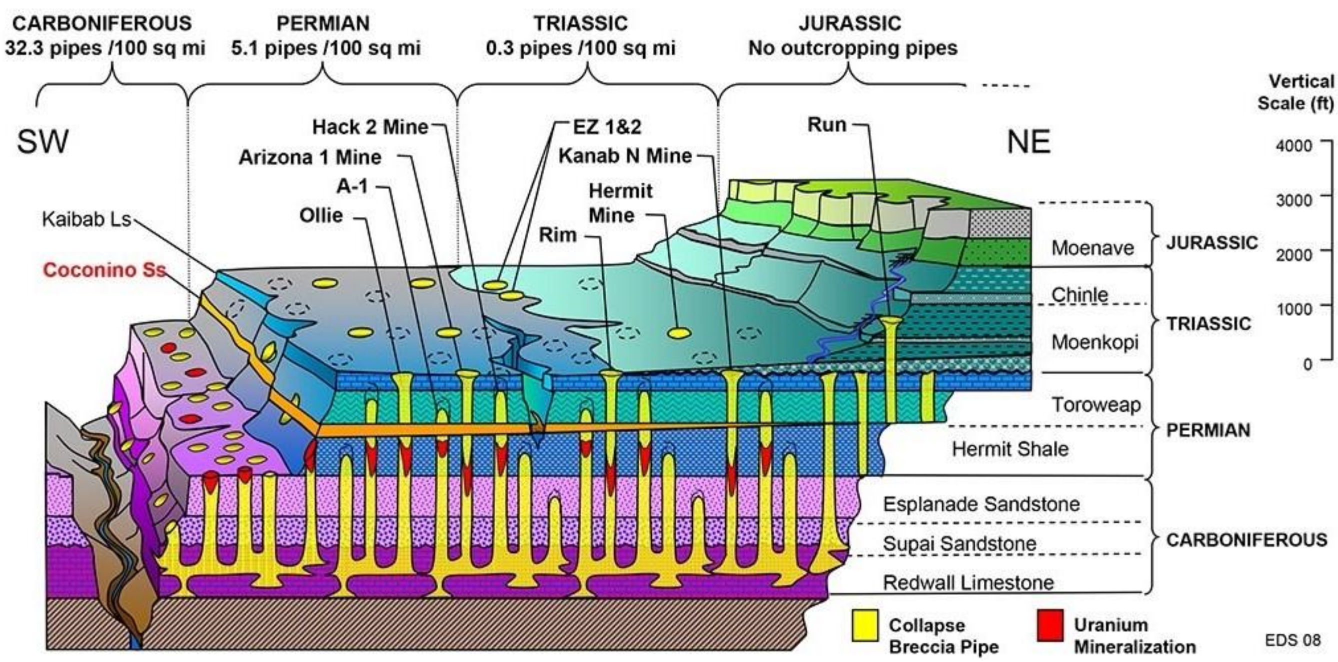


Figure: A cross-section of the Grand Canyon's north rim, showing breccia pipe locations and structure. Source: USGS

Coal in Arizona formed from biomass that grew on the edge of a shallow sea during the Cretaceous (~85 Ma) (Richard et al., 2000), and was then compressed beneath subsequent layers of sedimentary rock, which were later eroded in places to reveal the coal-bearing layers beneath.

Arizona's primary coal deposit is on Black Mesa, on the Hopi and Navajo reservations. This deposit was known as early as 1909, but at the time, the tribes lacked the legal authority to give mining companies access to it (and had no desire to do so). Over the following decades, a series of actions by the federal government formally divided ownership of mineral rights on Black Mesa between the Hopi and Navajo tribes. A variety of political pressures and betrayals ultimately forced the two tribes to lease Black Mesa to coal mining company Peabody Energy in the mid 1960s. The attorney hired by the Hopi to broker their deal with Peabody Energy was also on Peabody's payroll at the time, in a shameful conflict of interest. The resulting deal was egregiously generous towards Peabody, especially in terms of the water rights given to the company (Dougherty, 1997).

Following the signing of the original leases, members of the two tribes worked to negotiate successively stronger positions in their contracts with Peabody Energy and in their relationships with the federal government. Water rights litigation by the Hopi, along with Clean Air Act litigation by environmental groups, and falling demand for coal, eventually caused the closure of the two mines on Black Mesa in 2005 (Holt, 2010) and 2019. These closures, though welcomed by many, had large negative impacts on the tribes' finances (Randazzo & Silversmith, 2019).

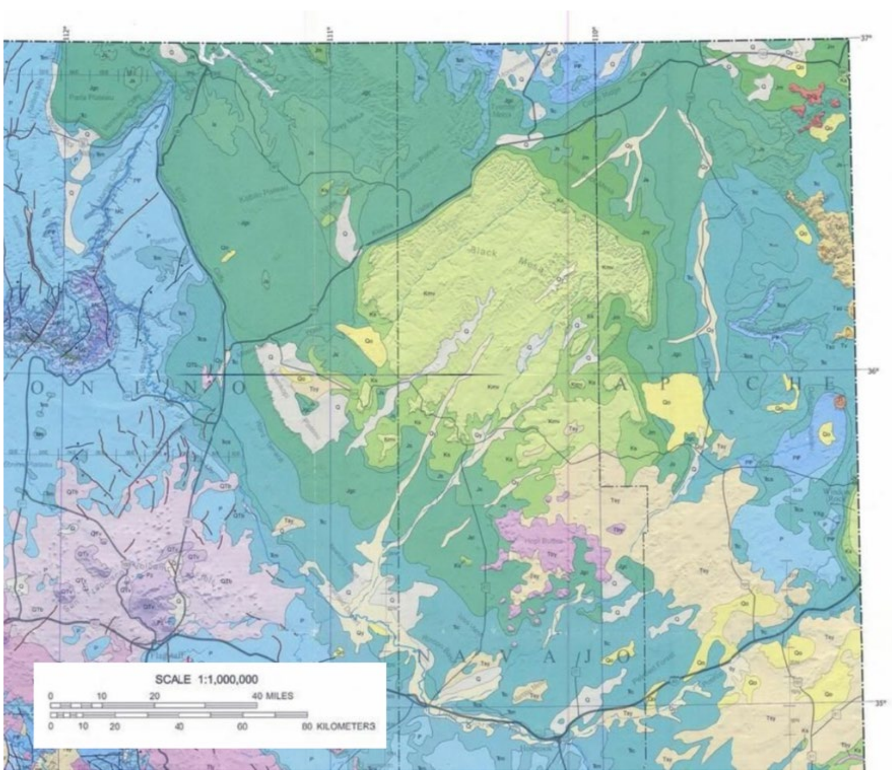


Figure: A section of a geologic map of Arizona, showing the northeastern quarter of the state. The large, light green area in the middle is the Mesaverde Group, which comprises Black Mesa.
Source: Richard et al., 2000.

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Petrified Forest: Petrification Processes
PTYS 590 - Planetary Geology Field Study - Final Report

Introduction

The Petrified Forest National Park in northeastern Arizona has been a staple in western tourist stops for around 100 years since its declaration as a national monument in 1906. The bright and unexpected colors, as seen in Figure 1, of the fallen trees in this national park have attracted more than 100,000 tourists since 1945 [1]. These awe-inspiring colors form due to a process called petrification, in which organic materials are slowly transformed into stone-like materials by replacing organic materials with minerals [2]. These fossils can be a significant source of knowledge about ancient life forms and environments, as they can preserve intricate details about organisms and minerals that existed millions of years ago. This report will discuss the petrification process and the insights we can gain into the past from petrified objects with specific examples from Arizona's own Petrified Forest National Park.

Figure 1: Colorful crystal patterns are displayed in a cross-section of petrified wood in the Petrified Forest National Park in northeast Arizona. Photo by: Patrick Fuchs

The Process

Figure 2 shows a brief overview of the petrification process for wood. The organic material dies, the tree is buried by sediments, volcanic ash, or another type of porous substance, water containing minerals seeps into the burial site, minerals replace organic material, and the wood is petrified over time.

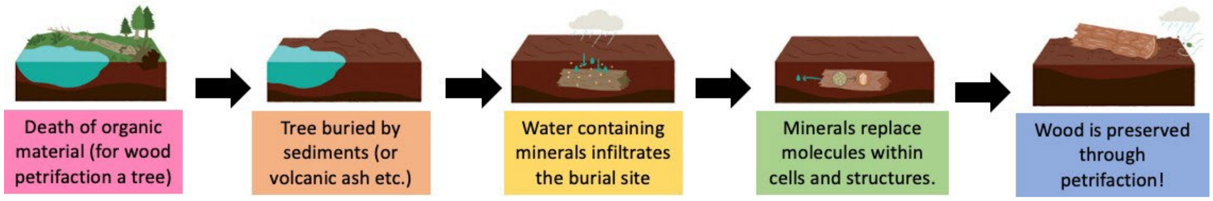

Figure 2: A flowchart showing the overall process of wood petrification. Art by Sara Lynn Cramb.

Death of Organic Material

Wood petrification begins with organic wood, typically derived from ancient trees that existed millions of years ago. This wood, once part of a living tree, may have been buried by sediment, volcanic ash, or other geological events, which protect it from environmental factors that would otherwise lead to decomposition. As the wood is buried, it becomes isolated from the processes of decay and exposure. The burial provides the initial conditions necessary for petrification to occur [3]. The coupling of two processes, permineralization, and replacement, allows dead organic material to become mineral-rich [4].

Permineralization

Over time, groundwater containing dissolved minerals infiltrates the burial site. The mineral-rich water percolates through the porous structure of the organic material, carrying minerals like silica (SiO_2), calcium carbonate ($CaCO_3$), or iron oxides (Fe_2O_3). This crucial step allows for the gradual introduction of mineral components into the organic matter [5]. There are two common types of permineralization. The first type is called silification, where organic material is saturated with silica (SiO_2), and most of the original organic matter is replaced [6]. For this process to occur, the dead organic material must be in a silica-rich environment, including volcanic ash and floodplain sediments. The second common type of permineralization is pyritization. This process is similar to silification, but iron and sulfur are deposited into the dead organic material instead of silica deposits. When organisms die, they release sulfides, which can react with iron. If there is iron in the surrounding environment to form pyrite (FeS_2), organic material is replaced with the newly formed pyrite [7]. In permineralization, organic materials are replaced with minerals by gradually precipitating minerals from groundwater that infiltrate the organic material. Minerals fill the material's pores, cells, and cavities, preserving its original structure. Permineralization typically results in the preservation of the original morphology and structure of the organic material. Delicate details like cell walls can often be seen in the fossil. The fossil retains the internal and external features of the original organism [3].

Replacement

Replacement is a fossilization process in which the original organic components break down over time, creating vacant spaces once occupied by cell walls. Minerals then precipitate and slowly take the place of the original organic molecules within the cells and structures of the organic material [2]. This process maintains the integrity of the material's original shape and microscopic features while transforming it into a stony substance. The slower this process is, the better preserved the original structure of the organic material will be [3]. Replacement involves completely removing the original organic material and replacing it with minerals. Unlike permineralization, where the organic material's structure is preserved, in replacement, the organic material is dissolved or removed, leaving behind an empty space that is then filled with minerals. Replacement typically does not hold the organic material's original structure or fine details. Instead, it results in a fossil composed entirely of minerals and retains the shape of the original organism but lacks the internal structure [2]. Wood petrification involves replacement and permineralization. Most literature claims that permineralization usually dominates, but that has been refuted in recent studies [7, 2].

Solidification

Over time, the organic wood becomes increasingly replaced by minerals, ultimately transforming it into a petrified specimen. Petrified wood retains the overall appearance and structure of the original tree, albeit now composed primarily of minerals. This transformation imparts remarkable durability to the fossil, making it highly decay-resistant. Petrified wood often exhibits beautiful patterns and colors due to the specific minerals in the replacement process.

Analyzing Colors of Petrified Wood

A paper published in 2016 in the MDPI Geosciences Journals entitled "Origin of Petrified Wood Color" explores the colors shown in different petrified wood samples, including samples from various places in Arizona [8]. An example of the samples used in the study from the Petrified Forest National Park can be seen in Figure 3.

Figure 3: Sample used in the Mustoe & Acosta study from the Petrified Forest National Park. Caption: "Longitudinal view of Araucarioxylon wood from Holbrook, Arizona, USA, showing diffuse color transformations developed along wood grain directions [8]."

This study focused on understanding the origins of the vibrant colors in petrified wood in fossil forests worldwide. Through detailed analyses of trace elements using spectral analysis, the researchers found that the most common cause of these colors, primarily pastel and bright hues, is the presence of iron (Fe) in varying amounts and oxidation states, often in the form of tiny mineral particles. Dark green colors may be linked to one form of iron, while bright green colors are associated with elevated levels of chromium. Additionally, remnants of organic matter in the wood can influence its color, particularly in brown specimens. The study revealed that the distribution of these colors within a single sample can result from a combination of factors, producing intricate and complex color patterns. This complexity arises during the wood's transition to a mineralized state, where changes in groundwater chemistry can lead to the precipitation of different colors during successive stages of mineralization. Early in this process, the wood's cellular structure can influence the direction of color development. Later, groundwater infiltration through fractures or openings can introduce additional colors. Surprisingly, the study found that neither the geological age of the specimens nor their taxonomic classification plays a significant role in determining the petrifaction colors. Instead, the availability of dissolved trace metals in percolating groundwater and the step-by-step sequence of mineralization are more critical factors. The study, based on analyzing fossil wood samples from various ages and locations, including samples from our own Petrified Forest National Forest in Arizona, provides valuable insights into the origins of petrified wood coloration [8].

Conclusion

Wood petrification is a testament to the enduring processes of geology, offering a unique perspective on Earth's past. The steps of wood petrification, from organic wood to petrified relic, illustrate the incredible transformation that can occur over geological timescales. These petrified remnants serve as valuable scientific and historical records, enriching our understanding of ancient forests and the life that once inhabited them.

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Aeolian Processes: Geomorphology

Madison Tuohy - PTYS 590

Aeolian processes refer to the movement of sediment through erosion, transportation, and deposition by wind (Tsoar et al., 2004). Types of aeolian systems include yardangs, dunes, and ventifacts, among many others (Fig. 1) Aeolian dune-field systems are present in various environments on planetary bodies, including coastal and arid regions. The movement, or morphology, of these systems are complex due to external environmental factors, autogenic formation, and interaction between dune systems. Despite these complexities, movement patterns have been observed from all scales, including small ripples on Earth, to remotely observed systems on distant planetary bodies (Fig. 2). Aeolian geomorphology is primarily studied based on observed patterns and characterizing these patterns using classification systems (Ewing and Kocurek, 2009). Understanding the interaction between wind and planetary surfaces provides insight into the geologic history of planets and contributes to broader comprehension of planetary systems.

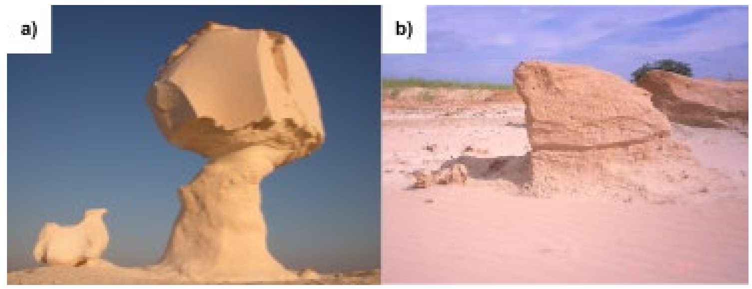

Figure 1. *Ventifacts (a) and Yardangs (b)*

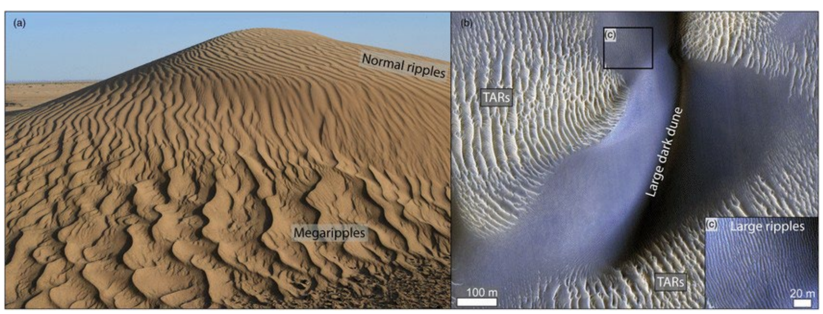

Figure 2: *Aeolian systems present on (a) Earth and (b) Mars* (Silvestro et al., 2020)

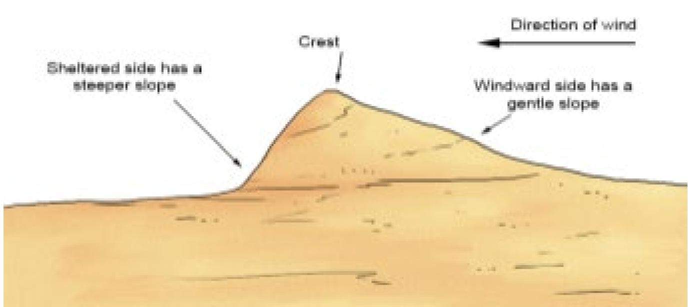

Figure 3. *The basic components of a dune. The windward side has a gentler slope when compared to the leeward side.*

Dune Structure

Basic dune structure consists of the crest, which is the dune's highest point, the slip face, which is the steep slope on the downwind side, the windward side facing the prevailing wind, the crestline, an imaginary line connecting dune crests, interdune areas between dunes, and the dune field, which is a collection of dunes in a given area (Fig. 3). The windward side has a more gentle slope as compared to the leeward side due to deposition of particles. When the wind loses energy on the windward side, its ability to carry the particles decreases, therefore leading to deposition. On the leeward side, the slope is steep when compared to the windward side because the particles are being driven by gravity as accumulation occurs from the windward side (*Sand Dune – Geography - Mammoth Memory Geography*)

Transport Modes

There are four types of particle movement in aeolian systems: creep, reptation, saltation, and suspension, listed in increasing order of velocity required to begin particle movement (Neuman, 2003). The large-scale movement of aeolian dune systems are dependent on the particle movement patterns, therefore grain-size distributions are important to classify.

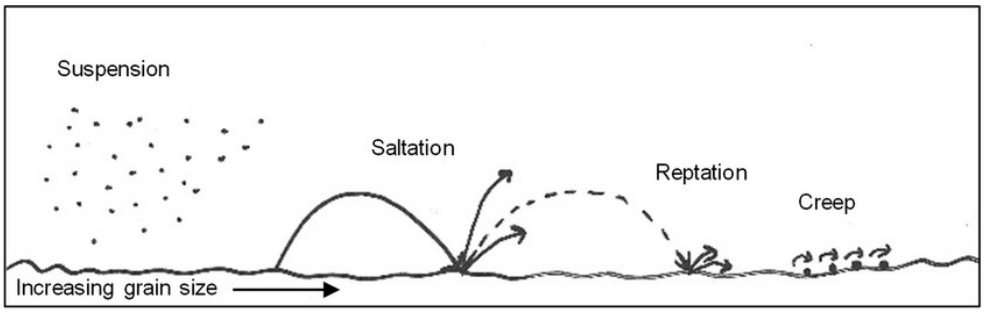

Figure 4: *The four types of particle transportation modes* (Hallin, 2019).

Creep describes the rolling of particles along the surface. The particles do not lose contact with the surface and are generally coarser grained. Reptation occurs when the impact from other saint grains dislodges the particles from the surface and causes them to move. This is the most common form of particle transportation. The process of saltation occurs as a predecessor to reptation. Saltated particles are airborne particles that are transported and deposited at a sufficient enough energy to dislodge particles upon impact. Suspension is the transport mode that requires the most wind velocity and is suspended in the airstream's turbulent motion. Sand grains rarely go into suspension due to their relatively larger size, as compared to clays and silts, which are smaller in size allowing for higher susceptibility to suspension (Neuman, 2003)

Classification

Aeolian system dunes are generally classified into three distinct categories. These categories are primarily based on wind speed and direction.

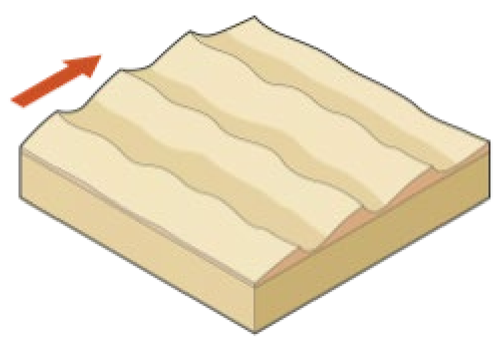

Figure 5. *Transverse dunes*

I. *Migrating Dunes*: Migrating dunes, characterized by their consistent shape and dimension as they advance, are a compelling focus in aeolian geomorphology. Transverse and barchan dunes serve as prime examples of this dune type.

Transverse dunes form perpendicular to prevailing winds, creating continuous ridges, while barchan dunes exhibit crescent shapes with a downwind-pointing horn. (Fig. 5) (Tsoar et al., 2004).

II. *Elongating Dunes*: Elongating dunes, a distinctive dune type exemplified by linear dunes, undergo a transformation over time that results in their significant extension in *length*. This elongation process is fundamentally distinct from the mechanisms that influence migrating dunes. Unlike migrating dunes, which maintain their shape while advancing, elongating dunes gradually stretch and elongate, illustrating the dynamic nature of aeolian landscapes (Fig. 6) (Tsoar et al., 2004).

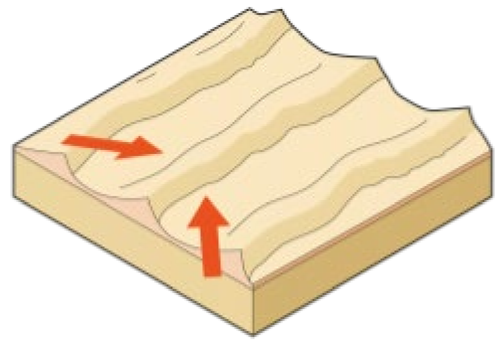

Figure 6. *Linear dunes*

III. *Accumulating Dunes:* Accumulating dunes, a distinctive category of dune formations exemplified by star dunes, exhibit a remarkable stability characterized by minimal net advancement or elongation over time. Unlike migrating or elongating dunes, which experience pronounced shifts in their shape and dimensions, accumulating dunes maintain their core structure and exhibit a relative state of equilibrium in terms of their overall movement (Fig. 7) (Tsoar et al., 2004).

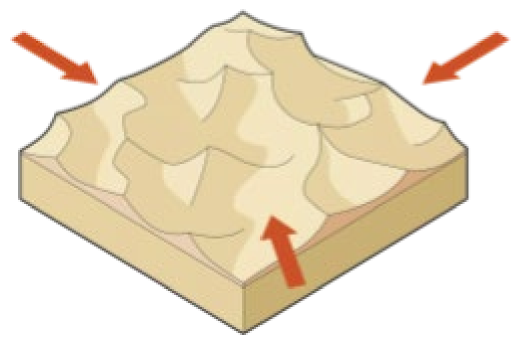

Figure 7. Star dunes

Applications to other terrestrial planetary bodies

Aeolian systems have been observed on terrestrial bodies including Earth, Venus, Mars, and Titan. With these observations, the geomorphology of the imaged systems can reveal important information about the planets' atmospheres and environments.

Venus

Linear features imaged by the Magellan spacecraft radar illumination indicate potential aeolian processes on Venus (Fig. 8). Due to its thick carbon dioxide atmosphere, Venus has a high surface pressure of approximately 90 atm, which is equivalent to the pressure of being approximately 900 meters beneath sea water on Earth (Craddock, 2012). Despite these

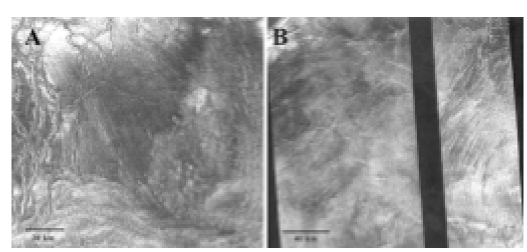

Figure 8. *Linear features imaged on Venus (Magellan spacecraft)*

conditions, it is observed that particles under this pressure can still be driven by wind (Iversen et al., 1976).

Mars

There have been plenty of observations from various spacecrafts and rovers proving the existence of aeolian systems on Mars. Specifically, barchan, transverse, yardangs, star and climbing dunes have been observed, in addition to occasional dust devils (Craddock, 2012). Data from these instruments assist research in determining the current climate on Mars and constructing Mars' geologic history (Fig. 9).

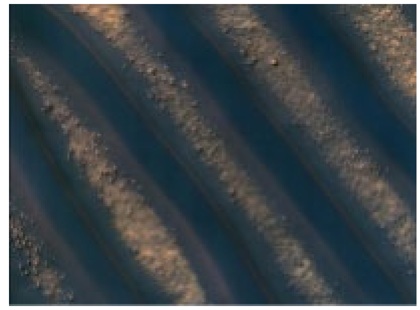

Figure 9. *Linear dunes found in an impact crater in Noachis Terra on Mars (HiRISE)*

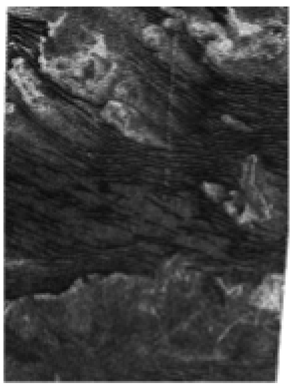

Figure 10. *Dark parallel lines indicates potential aeolian systems (Cassini)*

Titan

Aeolian observations of Titan from Cassini proved the presence of wind on Titan's surface, which previously was thought not possible due to insufficient solar radiation to drive winds (Fig. 10). Dark linear features captured by Cassini have been interpreted as potential aeolian systems, and recent global circulation models of Titan show there may have been periods of turbulent winds that created these systems (Tokano, 2010)

By investigating the aeolian morphologies that shape features such as dunes, yardangs, and ventifacts, we gain invaluable insights into past and present environmental conditions. As we continue to explore

terrestrial like Mars, Venus, and Titan, the study of aeolian processes not only deepens our understanding of these celestial bodies but also sheds light on the broader field of planetary science, unraveling the complex tapestry of planetary evolution and climate dynamics.

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Geologic Time Scale

QR Code to Geologic Resources: