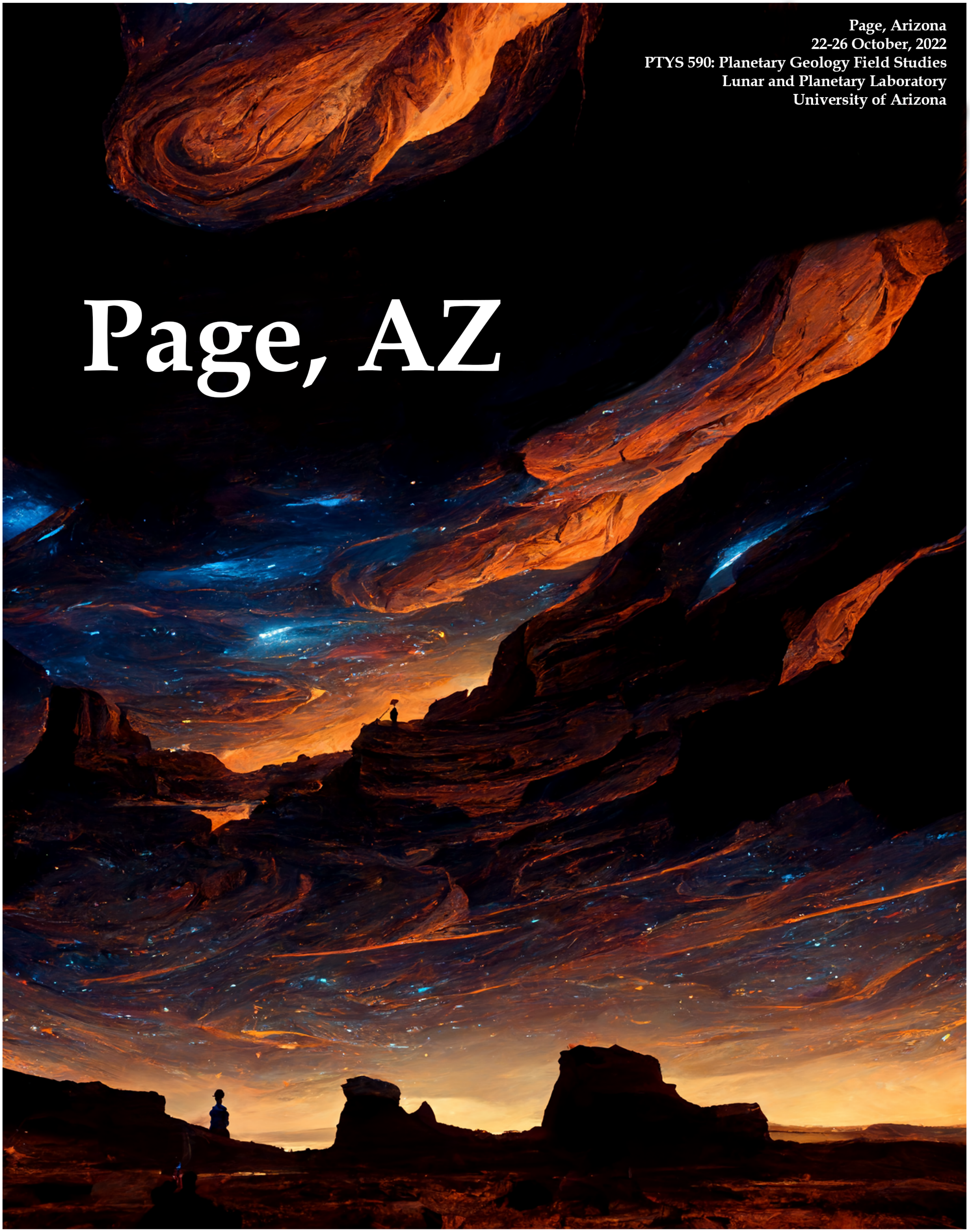


Page, Arizona
22-26 October, 2022
PTYS 590: Planetary Geology Field Studies
Lunar and Planetary Laboratory
University of Arizona

Page, AZ

Welcome to Pangea!

Exploring the Geology of the Page Area and Navajo Nation

Itinerary

Saturday, October 22

7:00 am	Meet at the LPL loading dock (North of the Planetarium). **B: 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. **B**.
11:30 pm	Lunch in the park.
12:00 pm	Depart for the Petrified (Petrified Forest National Park, Arizona 86028). 1 hour 17 minute drive. **B**.
1:30 pm	1 hour 3 minute loop hike at the Petrified Forest. **B**.
3:00 pm	Depart for Page, Shell Station (Shell, 1501 AZ-98, Coppermine Rd, Page, AZ 86040). 3 hour 27 minute drive.
6:30 pm	Depart for Camp Site. **B**. <30 minute drive.
7:00 pm	Set up camp. Sunset: 5:46 pm, Civil Twilight: 6:11 pm.

Sunday, October 23

8:00 am	Suggested wake up time (make your own breakfast and lunch).
9:00 am	Departure for Wilderness River Adventures (199 Kaibab Rd, Page, AZ 86040). <30 minute drive. Drop of people at the River Rafting Headquarters.
9:30 am	Check in at Wilderness River Adventures. **B**.
10:30 am	Begin river rafting tour.
2:10 pm	Arrive at Lees Ferry. **B**.
3:00 pm	Return to Wilderness River Adventures. **B**.
3:15 pm	Depart Wilderness River Adventures for Horseshoe Bend.
3:30 pm	Hike to Horseshoe Bend.
5:00 pm	Return to camp via Page. **B**.
5:30 pm	Arrive at camp.

Monday, October 24

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). 1 hour 58 minute drive. *Note: +1 hour time zone difference; however all times are presented in Tucson local time.* Route via Page. **B**.
11:00 am	Arrive in Oljato-Monument Valley. **B**.

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

Tuesday, October 25

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. **B**. 1 hour 30 minute drive to Paria Canyon-Vermilion Cliffs Wilderness Area.
11:15 am	Wire Pass trailhead, ~4 miles round trip or White House Trailhead, 8 miles round trip. **B**
2:45 pm	Return to camp with a bathroom stop at Paria Contact Station. **B.** 1 hour 30 minute drive.
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.

Wednesday, October 26

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. **B**. Drive time 3 hours 40 minutes
12:00 am	Arrive at the Petrified Forest National Park and have lunch. **B**.
12:30 pm	2 hour hike.
2:30 pm	Leave the Petrified Forest National Park for Tucson. **B**. 4 hour 55 minute drive time. With suggested stops in Show Low and/or Globe for bathroom breaks.
8:00 pm	Arrive at the University of Arizona (LPL loading dock). **B**.

Logo credit: James Keane

Table of Contents

Compiled by Allison McGraw

Arizona in the Paleozoic Era

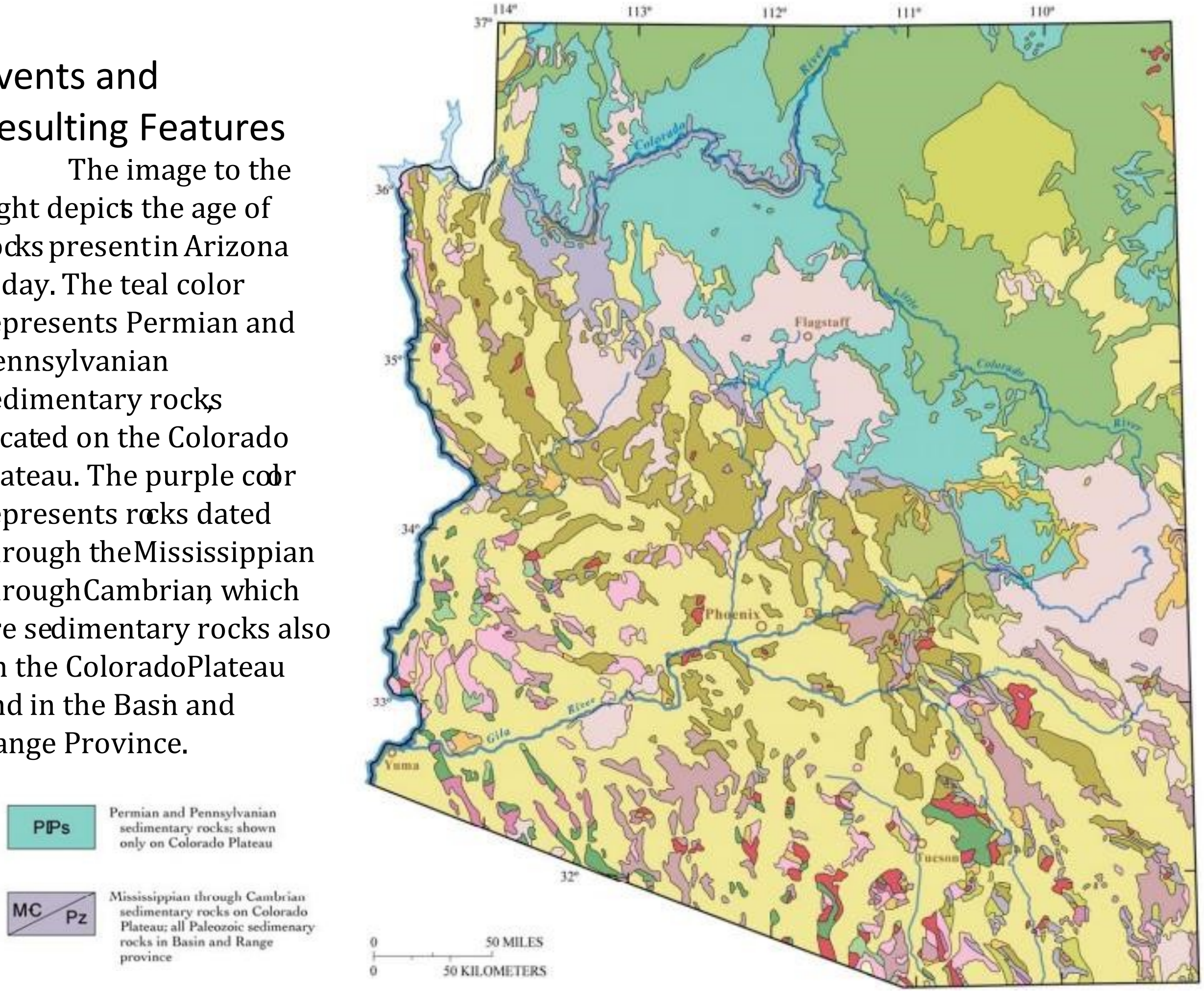
Searra Foote

Arizona and the Geologic Timescale

The geologic time scale is a representation of time based on the rock record of Earth in which geochronological dating techniques are used. The Paleozoic Era occurred in the time range between 538.8 through 251.9 million years ago. Due to such a large scale of time, the Paleozoic Era is divided into six geologic periods as follows, from oldest to youngest: Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian. This time was a landmark era full of the diversification of life, forests of plants, and coal beds of today's North America. As if this was not enough, this era truly went out with a bang – the Permian-Triassic extinction event. This time period will be explored in all its glory, with a special focus on the area known today as Arizona.

Events and Resulting Features

The image to the right depicts the age of rocks present in Arizona today. The teal color represents Permian and Pennsylvanian sedimentary rocks, located on the Colorado Plateau. The purple color represents rocks dated through the Mississippian through Cambrian, which are sedimentary rocks also on the Colorado Plateau and in the Basin and Range Province.



Today's Basin and Range Province.

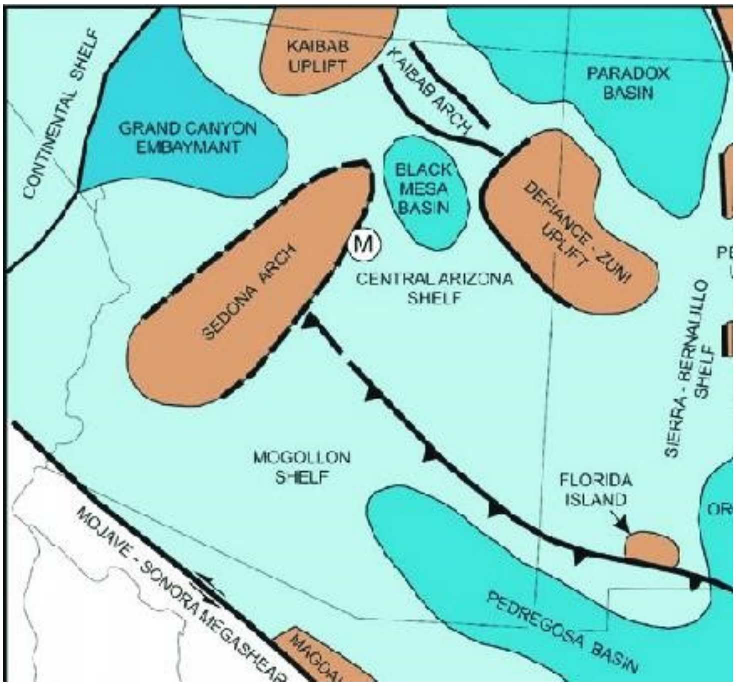
Today's Sunset Crater and the Pueblo Ruins of the Wupatki National Monument, located in the portion of the Colorado Plateau in Arizona.

There were several events throughout the Paleozoic that gave Arizona the special features it has today, namely mountains. At the time of the Paleozoic, these main events occurred:

- North America was on the move eastward towards Europe and Africa ○ Arizona was on the back edge of the continent
- No volcanic eruptions or igneous intrusions occurred
- Oregenic episode ○ Sediments from the continents
- Formation of seaways ○ Resulting in limestone
- Mountain building ○ 1. Taconic mountain building event leads to creation of Appalachian Mountains
    - ■ Led to erosion in Arizona ○ 2. Acadian mountain building event upon the collision of North America with Europe
    - ■ Led to the Late Devonian Martin Formation in Arizona ○ 3. Alleghenian mountain building event upon the formation of Pangea
    - ■ Led to varying sea level in Arizona, leading to layers of deposits seen today in Sedona, Monument Valley, and the Grand Canyon
- Seaways transgress and deposit limestone after Acadian mountain building event seen today in the Grand Canyon
- Caves form as a result, known today as Kartchner Caverns in Cochise County
- More deposition of sediments ○ Invertebrate fossils
- North America separates (Tucson at the equator) ○ Led to formation of volcanoes, which leads to minerals in Arizona
- Subduction zone

Following these events, by the late Paleozoic, Arizona had many features recognized today that are pictured here. This includes:

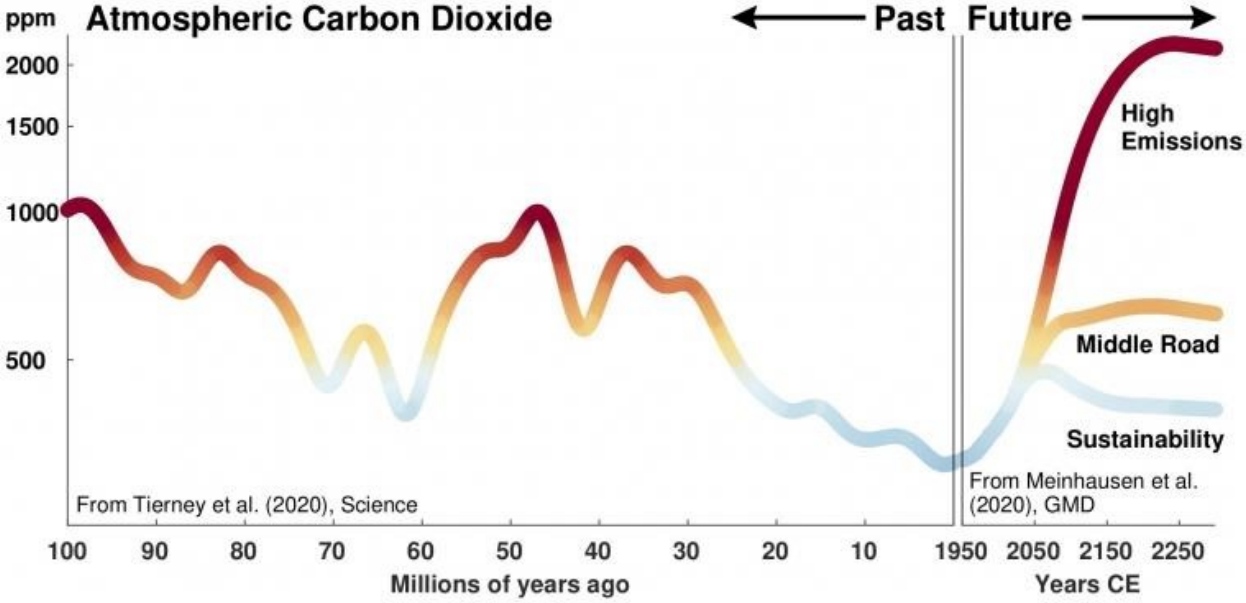
- Kaibab uplift
- Grand Canyon Embayment
- Black Mesa Basin
- Zuni Uplift
- Sedona Arch
- Pedregosa Basin
- Paradox Basin
- Mogollon Shelf
- Central Arizona Shelf



Geology and Climate

The types of rocks from this era can help to explain the climate at this time. Since this era is marked by periods of erosion, specific information about the climate is challenging to gather. However, the presence of certain rocks can help determine what the climate was like at the time. For example, fresh angular feldspars and detrital calcite as well as red clay stones reveal that Arizona had a dry, non-humid climate at this time. During this time of changing sea level, pyrite crystals among clay stones denote stagnant water and even the presence of bacteria.

Arizona Climate Change and Our Future in the Universe



During the Paleozoic Era, Arizona was dry with periods of humidity from the presence of the sea and the changing sea levels. Although climate data is limited during this time, close to this era was characterized by rather high atmospheric carbon dioxide. This is similar to what is seen today. If efforts are not made to curb carbon dioxide emissions, it could be possible to experience an extinction event, just as one ended the Paleozoic Era. In Arizona specifically today, dry and arid is the best way to describe the climate. While Arizona has always seemed to tend towards being dry, the best way to seek improvement for our planet is to be more mindful of our carbon footprints. It is best to remember that geology tells a story through time. Since it is possible to discern the type of climate that area referred to today as Arizona had hundreds of millions of years ago, humans must remember that today will tell a story for millions of years into the future. Geology takes time and geologists are eager to reconstruct the past. What story will Arizona's geology of today tell geologists tomorrow?

References

Dalziel, I. W. (1997). OVERVIEW: Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. *Geological Society of America Bulletin*, *109*(1), 16-42.

Gehrels, G. E., Blakey, R., Karlstrom, K. E., Timmons, J. M., Dickinson, B., & Pecha, M. (2011). Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona. *Lithosphere*, *3*(3), 183-200.

Mckee, E. D. (1947). Paleozoic seaways in western Arizona. *AAPG Bulletin*, *31*(2), 282-292.

Rasmussen, J. (2012). Geologic History of Arizona. *Rocks and Minerals*. 87(1), 56-63.

Ross, C. A., & Ross, J. R. P. (1986). Paleozoic Paleotectonics and Sedimentation in Arizona and New Mexico: Part IV. Southern Rocky Mountains.

Soreghan, G. S. (1997). Walther's Law, climate change, and upper Paleozoic cyclostratigraphy in the Ancestral Rocky Mountains. *Journal of Sedimentary Research*, *67*(6), 1001-1004.

Stoyanow, A. (1942). Paleozoic paleogeography of Arizona. *Bulletin of the Geological Society of America*, *53*(9), 1255-1282.

Basin and Range

Dingshan Deng, October 2022

Introduction

The Basin and Range is a kind of topography characterized by alternating parallel mountain ranges and valleys, as a result of crustal extension due to mantle upwelling, gravitational collapse, crustal thickening, or relaxation of confining stresses. Between these normal faults are blocks of crust (blocks of rocks), which can subside to form basins, be uplifted to form mountain ranges, or be titled to form both valleys and mountain ranges. Besides, as the crust thins, it allows heat from the mantle to melt rock and form magma more easily, resulting in increased volcanic activity.

Figure 1. Satellite Picture from Google Earth at southern-west US. Basin and Range topography can be easily seen as many stripes as mountain ranges or valleys. Ranges identified in the US is presented in the lower left corner [1].

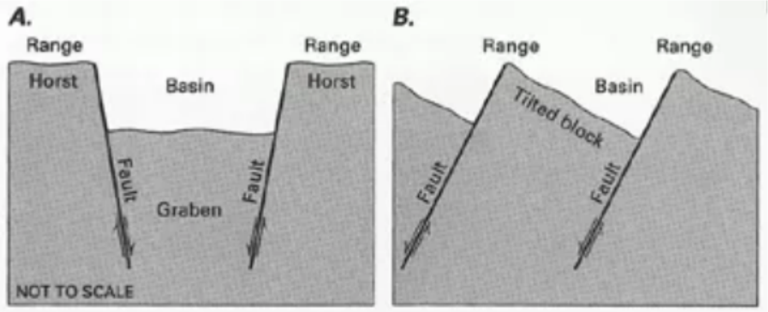


Figure 2. Effects of crustal extension: (A) Uplifting and subsidence, (B) Tilting [2].

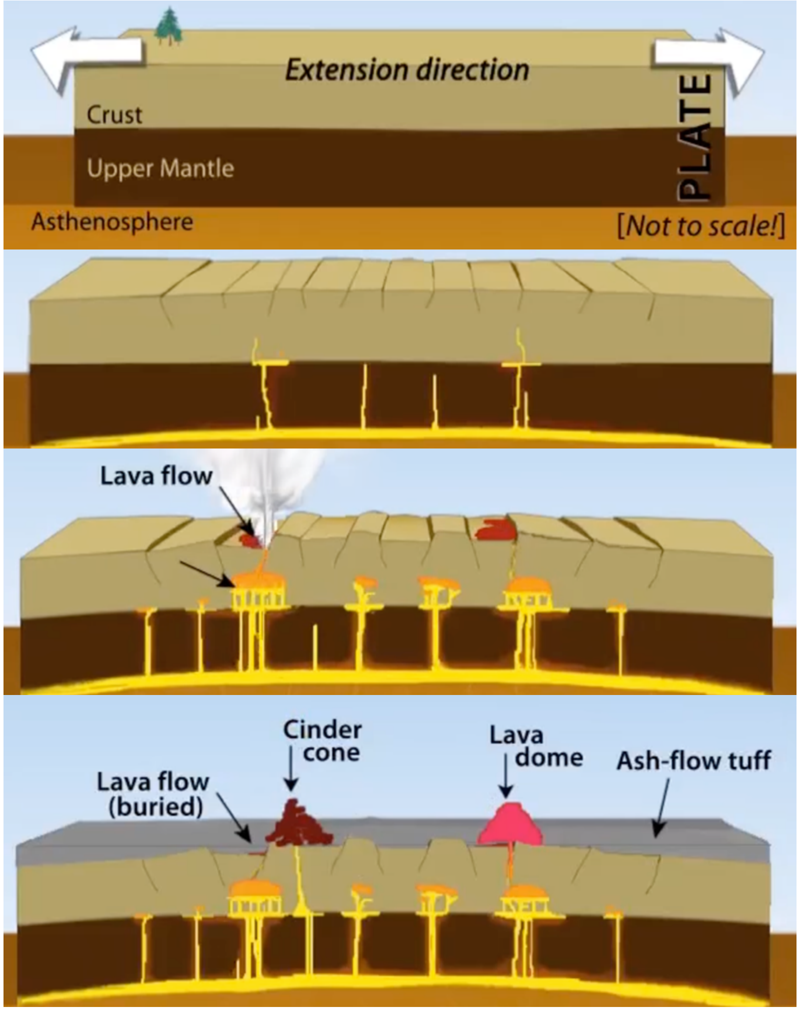


Figure 3. The crust extension and the associated volcanic activities in basin and range topography [3].

The Basin and Range Province

The Basin and Range Province is the most well-known example of basin and range topography. It is an extensive region covering much of the inland Western United States and northwestern Mexico. The Basin and Range Province includes much of western North America. In the United States, it is bordered on the west by the eastern fault scarp of the Sierra Nevada and spans over 500 miles (800 km) to its eastern border marked by the Wasatch Fault, the Colorado Plateau, and the Rio Grande Rift. The province extends north to the Columbia Plateau and south as far as the Trans-Mexican Volcanic Belt in Mexico, though the southern boundaries of the Basin and Range are debated. In Mexico, the Basin and Range Province is dominated by and largely synonymous with the Mexican Plateau. It is characterized by abrupt changes in elevation, alternating between narrow faulted mountain chains and flat arid valleys or basins. The physiography of the province is the result of a tectonic extension that began around 17 million years ago.

Numerous mountain ranges and valleys are located in the Basin and Range Province, they are collectively referred to as the *Great Basin Ranges*. Major ranges include the Snake Range, the Panamint Range, the White Mountains, and the Sandia Mountains. Valleys include Owens Valley, Death Valley, and Snake Valley. The elevation changes are drastic: The highest point fully within the province is White Mountain Peak in California at ~4344m, while the lowest point is the Badwater Basin in Death Valley at ~86 m. The province is semi-desert with arid climate, and most North American deserts are located within it because the high and extending mountain ranges and plateau around are shielding humidity outside.

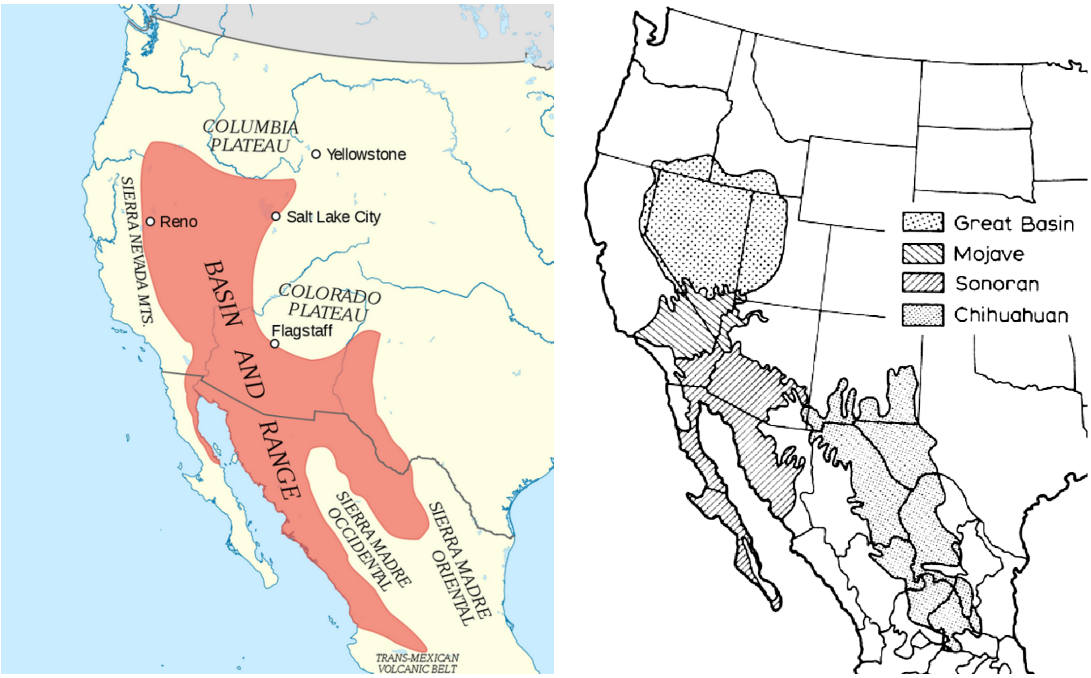


Figure 3. Left: The Basin and Range Province [4].
Right: The North American Deserts [5].

Crustal Extension and Tectonics in Geology History

The total crustal extension in the Basin and Range Province is estimated to be about 100% as the median value, i.e., the crust (and upper parts of its mantle) is now doubled as its original width [6]. The entire region has been subjected to extension that thinned and cracked the crust as it was pulled apart. The average crustal thickness of the Basin and Range region is 30 - 35 km, compared with a worldwide average of around 40 km [7].

The tectonic mechanism driving its development still remains a highly controversial problem [7]. But the general idea converges as after the Laramide Orogeny —the mountain-building event that created the Rockies—ended in the Paleogene, tectonic processes stretched and broke the crust, and the upward movement of magma weakened the lithosphere from underneath. Around 20 million years ago, the crust along the Basin and Range stretched, thinned, and faulted into some 400 mountain blocks. The pressure of the mantle below uplifted some blocks, creating elongated peaks and leaving the lower blocks below to form down-dropped valleys. The boundaries between the mountains and valleys are very sharp, both because of the straight faults between them and because many of those faults are still active.

Reference:

[1].Wallace, R.E. (1975). *United states–basin and range province.* In: World Regional Geology. Encyclopedia of Earth Science. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-31081-1_117

[2].*Stretching of the Basin and Range and Lifting of the Colorado Plateau - Grand Canyon-Parashant National Monument* (U.S. National Park Service). https://www.nps.gov/para/learn/nature/stretching-of-the-basin-and-range-and-lifting-of-the-colorado-plateau.htm

[3].IRIS Earthquake Science *Basin & Range Volcanic Processes*. https://www.iris.edu/hq/programs/education_and_outreach/animations.html

[4].Kathleen Smith*. One definition of Basin and Range Province Boundaries and Landmarks*, https://commons.wikimedia.org/wiki/File:Basin_and_Range_Province_Boundaries_and_Landmarks.svg

[5].Whorley, Joshua & Kenagy, G. J.. (2007). *Variation in Reproductive Patterns of Antelope Ground Squirrels, Ammospermophilus leucurus, from Oregon to Baja California*. Journal of Mammalogy - J MAMMAL. 88. 1404-1411. 10.1644/06-MAMM-A-382R.1.

[6].*USGS, Geologic Provinces of the United States: Basin and Range Province. Archived from the original on 2009-01-25.* https://web.archive.org/web/20090125163038/http://geomaps.wr.usgs.gov/parks/province/basinrange.html

Region 1: The Basin and Range. Retrieved October 11, 2022, from http://geology.teacherfriendlyguide.org/index.php/topography-w/topography-region1-w

Moenkopi and Chinle Formations: Painted Desert

David Cantillo

Introduction

The Painted Desert is a badlands region in northeast Arizona known for its multi-colored terrain and unique geology. Stretching from Cameron-Tuba City past the Petrified Forest National Wilderness Area and Holbrook, the Painted Desert forms a rectangle approximately 190 x 100 km in size (19,420 km^2). The majority of the Painted Desert is located on the Hopi Reservation and Navajo Nation, though the desert is most accessed by visitors in the northern section of the Petrified Forest National Park.

Figure 1. Petrified Forest Member of the Chinle Formation in Painted Desert. Note the variation in color and the badlands terrain.

What Are Badlands?

Badlands such as the Painted Desert are a unique type of terrain composed of softer sedimentary rocks and clay-rich soils. Multiple factors influence the creation of badlands terrain, including

- Soft rock types (often sedimentary rocks or paleosols)
- Lack of vegetation
- Infrequent, but heavy rainfall

Together, these factors result in a highly eroded landscape with little regolith cover and a high drainage density (Thornsbury 1969). Drainage density, (DD), can be defined as DD = L/A, where

- L = length of all channels
- A = total drainage area

Moenkopi Formation

The Moenkopi is the sedimentary basal formation of the Painted Desert and was deposited during the early to middle Triassic (~250 – 240 Ma). Nestled between two highlands regions during the Triassic, the Moenkopi formation represents a broad westward transition from a continental fluvial environment (eastern NM) to a marine environment (SW Utah). The overall environment of deposition is a flat coastal plain reaching the sea, meaning that small changes in sea level could result in large spatial offset in deposits. The Moenkopi Formation is also known for its abundant fossil record of reptiles, sharks, and archosaurs.

<u>Wutpaki Member:</u> Comprised of a thinly bedded, reddish-brown siltstone capped by sandstone. Extensive symmetric ripples and discontinuous lenticular beds illustrate a tidal environment.

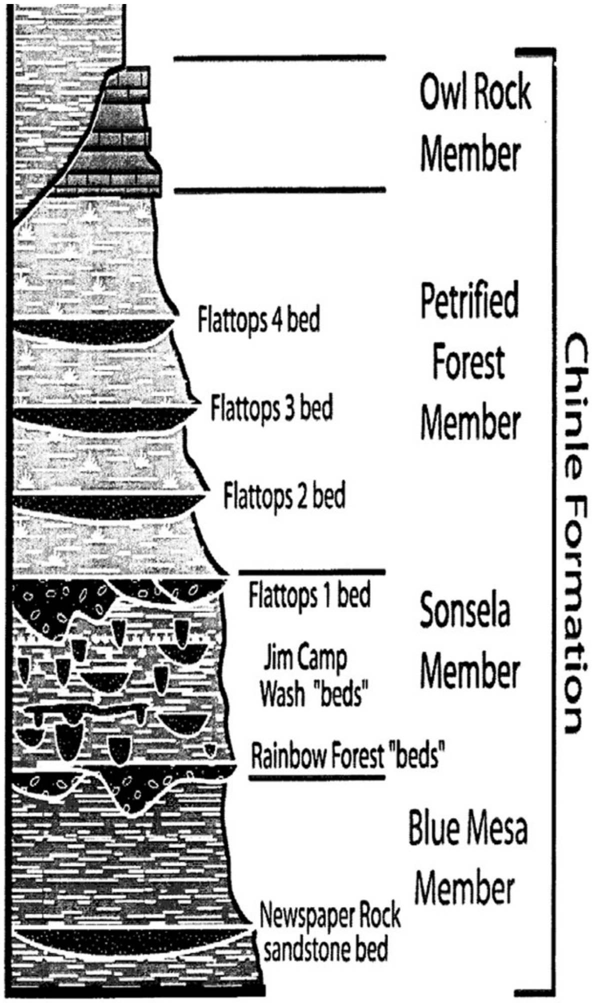
<u>Moqui Member:</u> Pale-brown mudstone and siltstone beds containing high amounts of gypsum nodules. Like the Wutpaki Member, the Moqui Member contains displays lenticular bedding and even sharply defined channels.

<u>Holbrook Member:</u> Largely composed of pale-red sandstone beds varying in thickness. As you travel further to the west, the Holbrook member becomes more siltstone dominant with less crossbedding. Some areas also contain sandy limestone that is thought to have been deposited in brackish-water deposits in shallow coastal lagoons due to the presence of bivalve fossils.

Figure 2. Fossil tracks (left) as well as ripple marks (right) found in the Moenkopi Formation.

Chinle Formation

The Chinle Formation sits on top of the Moenkopi unconformably and is of late Triassic age (~237 – 205 Ma). While both the Moenkopi and Chinle can be found in the Painted Desert, the Chinle formation is the most prevalent and colorful. This variation in color is related to the depositional environment: areas of low, fluctuating water tables led to a highly oxidizing environment resulting in redder minerals like hematite. Areas of high-standing water, on the other hand, led to anoxic environments that preserved the darker blue and green colors of the rocks. The Chinle Formation is thought to mostly be fluvial deposits from a large river system running from present-day western Texas to southern Nevada.



<u>Shinarump Member</u>: Cliff-forming, lenticular beds of red/gray sandstone beds and gray conglomerates. The relatively large size of some of the conglomerate clasts (up to four inches) and their subangular properties indicate some high-energy depositional events. The Shinarump Member is typically about 80 feet in thickness though is absent in some locations, including near the visitor center at Petrified Forest National Park.

<u>Blue Mesa Member:</u> Interstratified lenticular beds of mudstone, sandstone, and conglomerate that have weathered into irregular ledges.

<u>Sonsela Member:</u> Composed of three separate sedimentary beds:

- Rainbow Forest: cross-bedded sandstone/cobble
- Jim Camp Wash: beds of mudstones and sandstone
- Flattops 1: bed made of a cliff-forming, cross-bedded sandstone

Figure 3. Stratigraphic column of the Chinle Formation in Petrified Forest National Park. Note the Shinarump and Rock Point Members are not seen in this location.

Navajo Sandstones

Harry Tang

Fig. 1 - The Wave Navajo sandstone formation in AZ (The Geological Society)

Navajo sandstones are a part of the Glen Canyon formation that is widely prominent across Utah, Nevada, Arizona, and Colorado. They form some of the main attractions in a number of destinations, such as Zion National Park and the Glen Canyon area. They form much of the cliffs, buffs, and other prominent landmarks, and are often capped by a limestone or other marine related rock layer. They are theorized to have formed from the giant sand dunes that existed in this region during the early Jurassic period (~180 mya), and exhibit strong cross bedding as a result.

Cross bedding here preserves the characteristics of the sand dunes that formed the Navajo sandstones. As wind pushes and deposits the mostly quartz sand grains on the lee (down-wind) side of the dune, the sediments build up in layers (Fig. 3) to form the patterns seen in Fig. 2.

Fig. 2 - Cross bedding seen in Zion National Park (The Geological Society)

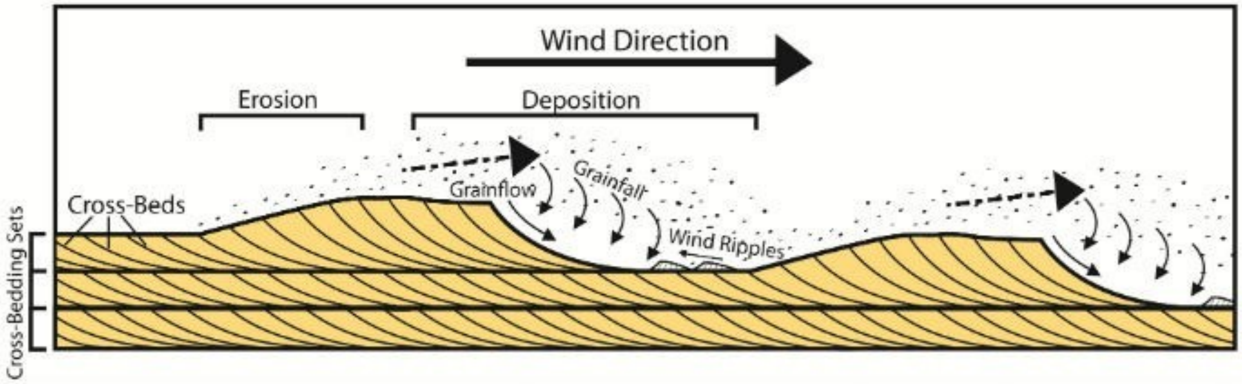


Fig. 3 - Diagram of the deposition of aeolian sediments and the formation of cross bedding patterns. (NPS Zion)

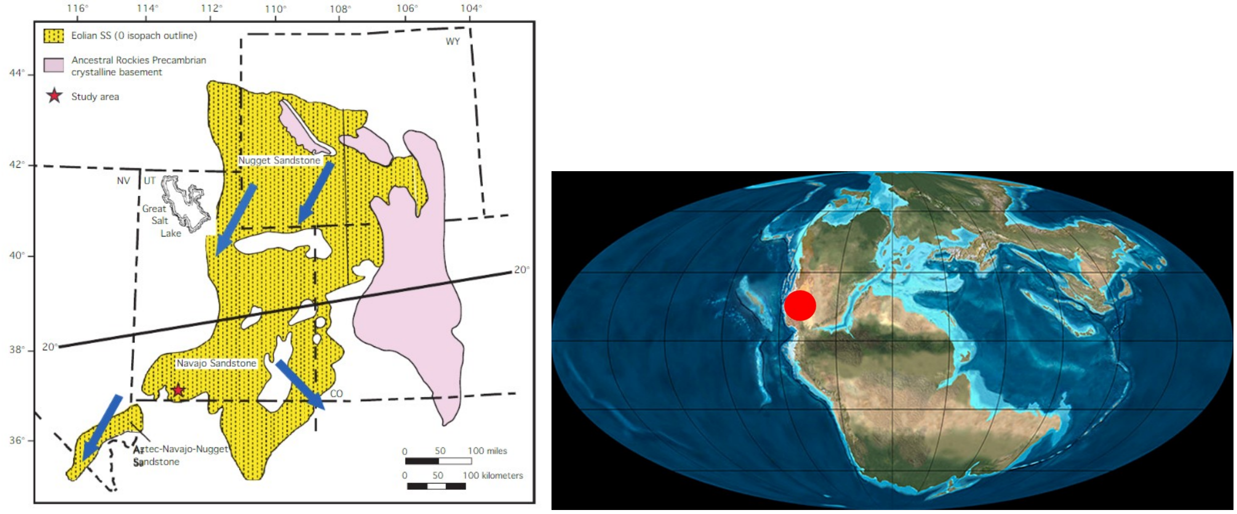


Fig. 4 - Approximate extent of Navajo sandstones, along with its location on Pangea (Chan and Archer 2000, impossible2possible.com)

Radioisotopic dating indicates that some of the sand may have come from as far as the Appalachians, transported by rivers before being blown into sand dunes. As the giant dunes form in the vast desert of this region in the Jurassic, the bottom layers become compacted, and eventually mineral laden ground water helps cement the sand into sandstone. Not many fossils are found in these, indicating possibly a hostile environment to life at the time, though some tracks can be found.

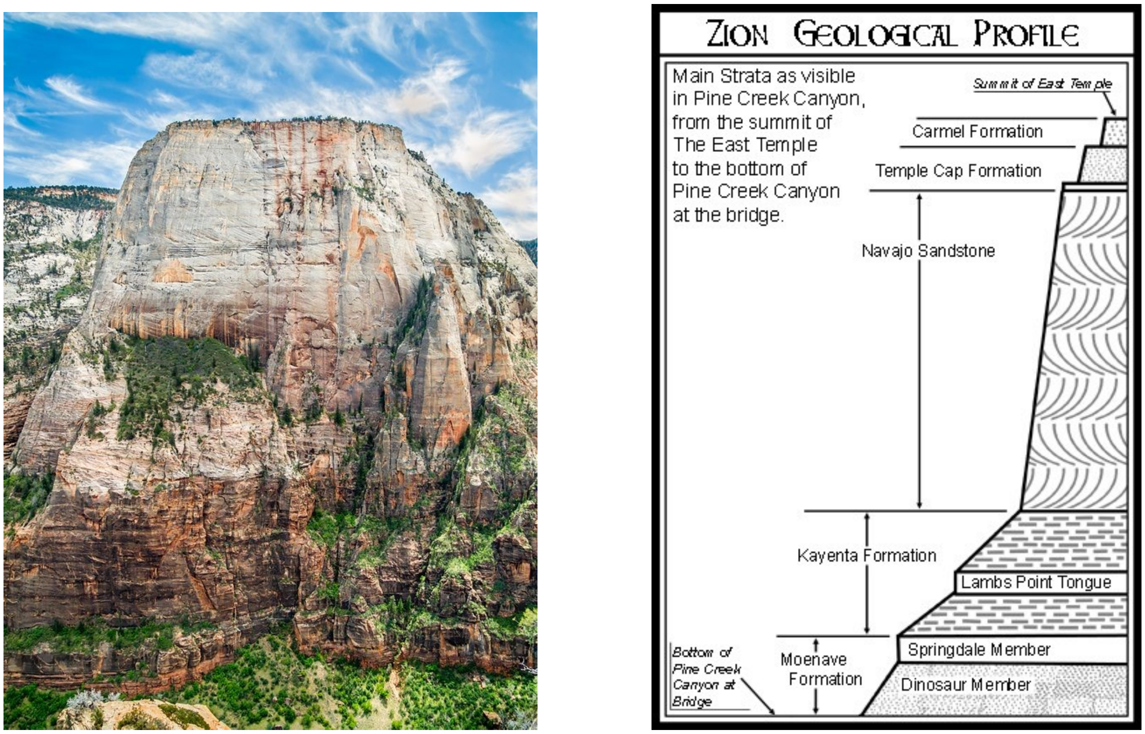


Fig. 5 - The Great White Throne at Zion National Park, and the stratigraphy at Zion National Park (Google Images, Canyoneering USA)

The colors of the sandstones are greatly affected by the presence of iron oxide, and stones range from lightish red to white, depending on the iron oxide and other impurities that are present. These impurities help hold the sandstone together, but in some upper layers these have since been dissolved away, leaving behind a prominent white color such as seen at the Great White Throne at Zion National Park. This also means that these sandstones are particularly susceptible to fluvial erosion, helping create impressive cliff faces and slot canyons.

Iron oxide in the rocks could form iron concretions known as Moqui Marbles, and possibly associated with Hopi ancestor worship ("morqui" translates to "the dead"). These formed from interactions between water that had reduced the iron in the sandstone and oxidizing groundwater, thus causing the iron oxide to precipitate out and form concretions of various shapes and sizes.

These concretions which indicate past water movement have also been found on Mars, known as Martian spherules or blueberries, and are used as indication of water presence on Mars. Features of cross bedding and other characteristics also indicate similarities between Martian landscapes and Navajo sandstones.

Fig. 6 - Moqui marbles found in Navajo sandstones on Earth, and their interior. (Wikipedia)

Fig. 7 - “Blueberries” on Mars, from the Opportunity rover (Wikipedia)

Citations

NPS - Zion https://www.nps.gov/zion/learn/nature/navajo.htm

NPS - Zion https://www.nps.gov/zion/learn/nature/sand-dunes-sandstone.htm

Wikipedia - Navajo Sandstone https://en.wikipedia.org/wiki/Navajo_Sandstone

Canyoneering USA - Zion https://www.canyoneeringusa.com/zion/geology

Chan, Marjorie & Archer, Allen. (2000). Cyclic eolian stratification on the Jurassic Navajo Sandstone, Zion National Park: periodicities and implications for paleoclimate. Utah Geological Association Publication. 28. 607-617.

The Geological Society https://www.geolsoc.org.uk/Policy-and-Media/Outreach/Plate-Tectonic-Stories/Alderley-Edge/Nav ajo-Sandstone

UtahGeology.com https://utahgeology.com/navajo-sandstone/

Impossible2possible.com https://www.impossible2possible.com/utah/includes/education/curriculum-day3.php

The Navajo Nation

Figure 1: Current territories included in the Navajo Nation with important locations for our field trip overlaid.

- The Navajo People, called the *Diné* in Navajo, are the largest Native American tribe in the United States by land and population, with 330,000 tribal members and with a land area larger than West Virginia.
- The Navajo Nation was created in 1868 and kept expanding their territory until the current form was finally reached in 1934.
- The reservation has its own government, with a President, Vice President, Legislature, and judicial system. The capital of the reservation is located in Window Rock, on the Arizona/New Mexico border.

The Ancient History of Monument Valley and the Four Corners Region

- Even if you don’t know it, you have most likely seen Monument Valley growing up. The scenes of Monument Valley have been a staple of Western culture and cinema in the early 20th century, featured in John Ford and John Wayne movies.
- However, these movies neglect to tell the rich culture of the Navajo that have inhabited these lands long before movie producers arrived.

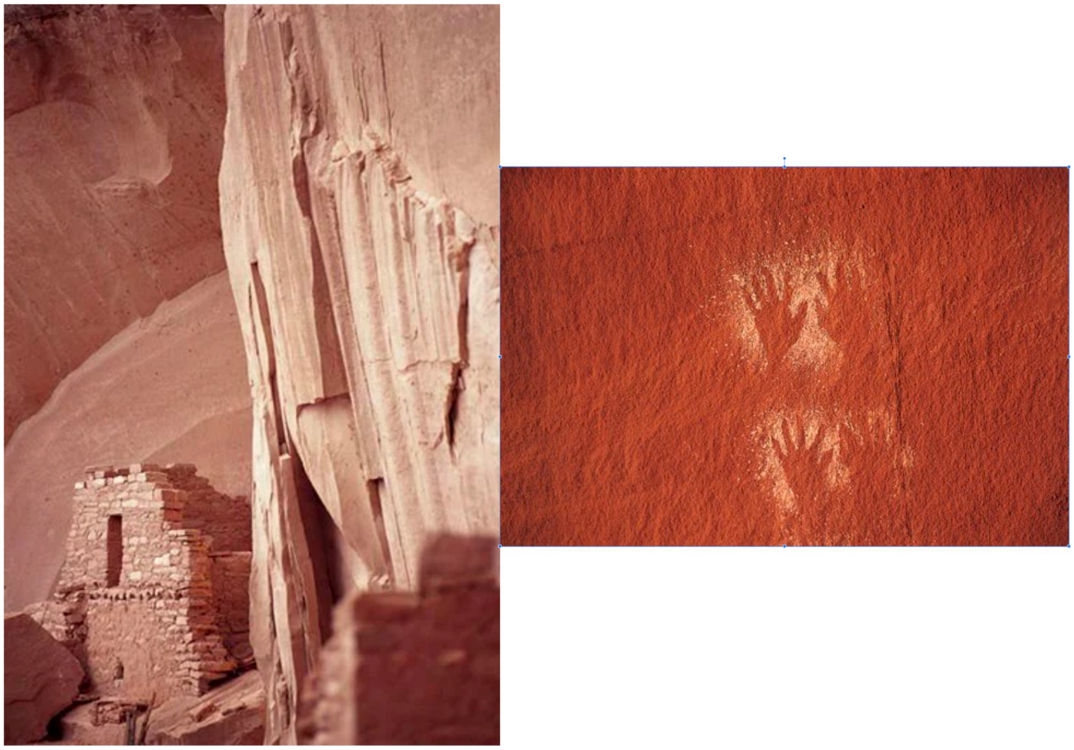


Figure 2: Anasazi artwork and ruins located in Monument Valley. The structures pictured on the left date back to around 1250 CE

- The Navajo people have been inhabiting these lands before the arrival of European settlers, and other Native American groups, called the Anasazi (‘Ancient Enemies’ in Navajo) are thought to have settled the area dating back to at least 1500 BC.
- Archaeologists have found that starting in the 1200’s, the Anasazi people started moving from their traditional dwellings to making homes and settlements in higher elevations and again cliffs, appearing to have been running away from something.
- It is unclear what the reason was for the sudden retreat of the Anasazi into the cliffs of the region, but the current most widely accepted explanation is that a major drought starting in the 12th century caused intertribal conflict. This conflict caused many tribe members to build the structures we see today

- This time period coincided with the settlement of the area by the Navajo, which is thought to have been the reason for the name, Anasazi, being given to this ancient tribe
- It is still unclear how the Anasazi were able to actually build these structures on the sides of cliffs

Hogans

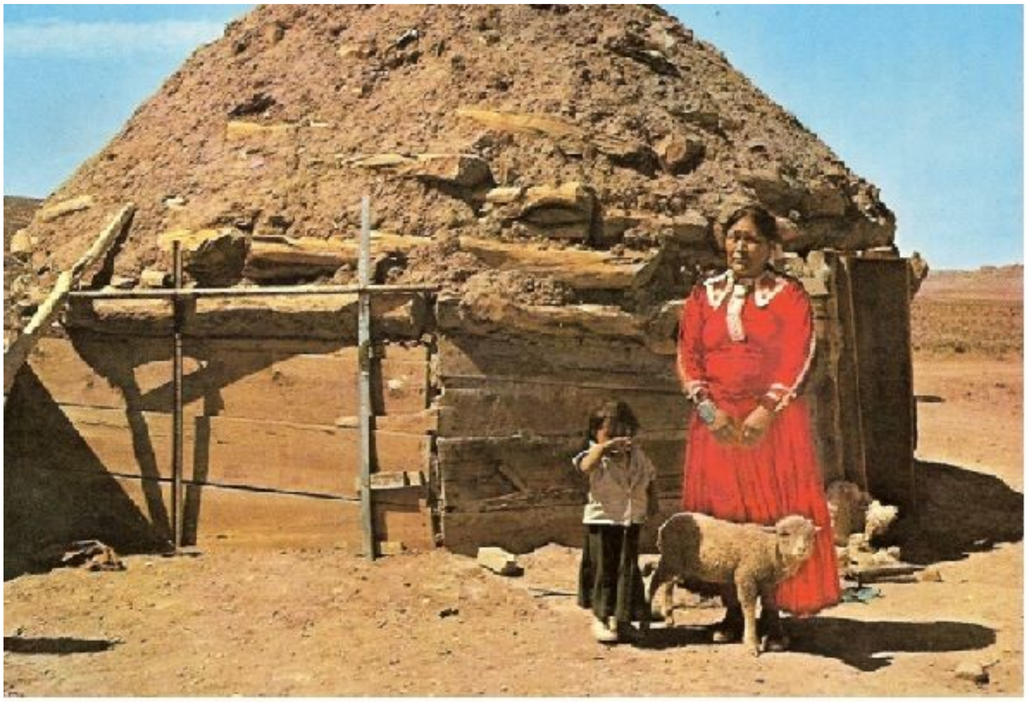


Figure 3: Navajo woman and child standing next to traditional Navajo style home, called a Hogan.

- Monument Valley and its surrounding areas are sacred to the Navajo. Monument Valley is present in Navajo oral traditions and is referred to in the clan migration narratives. It is said to be the torso of the Navajo whose head rests on Navajo Mountain to the West.
- Hogans, pronounced Hohrahn in Navajo, are a traditional form of home made by the Navajo in this region, and are wooden poles, tree bark and mud.
- They are used to practice the Navajo's traditional religion, and the doorways always face East to allow sunlight to shine into their home every morning.
- A handful of families still live traditional lifestyles in and around the Monument Valley region, but most of the Navajo people have begun to make and live in Modern Hogans.

Figure 3: Modern Hogan in Sheep Springs, New Mexico

Uranium Mining In Navajo Land and Monument Valley

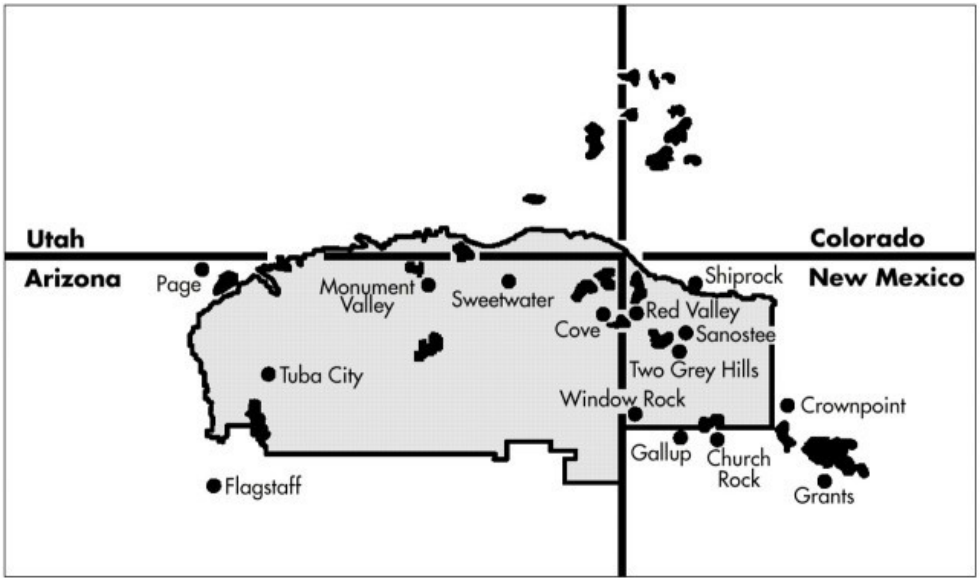


Figure 4: Map of regions of major Uranium mining within the Navajo Nation from 1948 to 1971

- After the development of the atomic bomb, major uranium deposits were found in and around the Navajo Nation, and the federal government opened up those lands to excavation
- Most of the mine workers were Navajo men, working for wages as low as $0.80 an hour, with regular neglect for their safety by White bosses

- Mining diseases like black lung disease and lung cancer, specifically caused by Uranium mining, began to be seen in large numbers among Navajo men
- The federal government tried to brush off these concerns by saying that this was caused by smoking, but studies then showed that Navajo men consumed 6 times less tobacco than their white counterparts.
- In 1998, the federal government passed RECA, the Radiation Exposure Compensation Act, which acknowledged the wrongdoing on the part of the federal government and paid reparations to the families that were affected by the mining
- It is thought that over 600 Navajo men died as a result of lung cancer after working in the Uranium mines on their own territory

References

1. https://www.smithsonianmag.com/history/riddles-of-the-anasazi-85274508/

2. Brugge D, Goble R. The history of uranium mining and the Navajo people. Am J Public Health.

2002 Sep;92(9):1410-9. doi: 10.2105/ajph.92.9.1410. PMID: 12197966; PMCID: PMC3222290

3. Zeman, Scott C. “MONUMENT VALLEY: Shaping the Image of the Southwest’s Cultural Crossroads.” The Journal of Arizona History, vol. 39, no. 3, 1998, pp. 307–24. JSTOR,

4. Watson, Editha “Navajo history: A 3000-year sketch” New Mexico Geological Society 24 th Annual Fall Field Conference Guidebook, 232 pp.

5. https://earthobservatory.nasa.gov/images/92242/monument-valley-an-icon-of-american-west

6. https://discovernavajo.com/navajo-history/

Weathering and Erosion Processes

Chengyan Xie

1.Introduction

Weathering and erosion are both processes that could shape the landform. Weathering is the deterioration of rocks, soils and minerals as well as wood and artificial materials through contact with water, atmospheric gases, and biological organisms. Erosion often follows weathering, removing the deteriorated rocks and minerals and transport them from one location to another. These processes make the landform on our earth change continuously, sculpting many amazing sites of view for people to enjoy.

2. Weathering processes

First let's take a look at how weathering occurs. There're several categories of weathering, physical, chemical and biological. Physical weathering includes frost weathering, thermal stress, pressure release and so on. These processes come from the squeezing and fraction due to pressure changes. For example, when water freezes, its volume increases and the expansion generates pressure. It's similar when temperature goes up and rocks expand.

As for chemical weathering, when rainfalls drop to rocks, they may be able to interact with the rock. For example, rainwater can dissolve halite and gypsum. Given enough time, it can even dissolve quartz, as the following shows:

$$SiO_2 + 2H_2O \rightarrow H_4SiO_4$$

And if CO_2 is dissolved in the rainwater, it can also dissolve calcium carbonate as follows:

$$CO_2 + 2H_2O \rightarrow H_2CO_3$$
$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2$$

Biological factors such as soil microorganisms can also contribute to weathering processes.

3. Weathering landforms

As we mentioned above, weathering and erosion can shape the landform and sculpt it to amazing shapes. In this section I'll show some different weathering landforms.

3.1 Tafoni and Alveoli

A natural arch produced by the wind erosion of differentially weathered rock. By Etan J. Tal - Own work, CC BY 3.0.

From https://www.flickr.com/photos/sharman/3833816139/

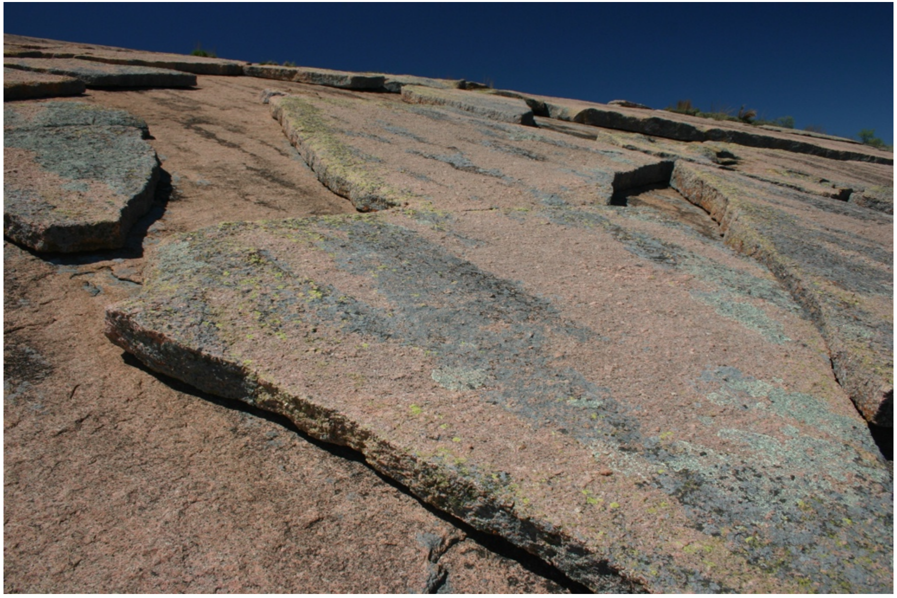
The formation of Tafoni and Alveoli mainly involves the differential recession of the rock faces are granular disintegration and flaking, which may be related to a combination of weathering processes (e.g., salt weathering, chemical alteration, wetting and drying, frost action). Salt weathering related to stresses induced by the crystallisation and hydration of salts in intergranular spaces and cracks is considered one of the main weathering processes.

3.2 Panholes

Circular panhole in Capitol Reef National Park. By Geo310Rose, CC BY-SA 3.0.

Panholes, also known as weathering pits, are depressions or basins eroded into flat or gently sloping cohesive rocks. Like tafoni and alveoli, they develop in a wide range of lithologies and morphoclimatic environments. The physical, chemical and biological weathering processes are also similar.

3.3 Spalling and Flaking



Granite dome exfoliation. By Wing-Chi Poon (talk · contribs) - Own work, CC BY-SA 2.5.

Spall are fragments of a material that are broken off a larger solid body. The outward separation of a continuous shell or discontinuous flakes in rock surfaces is mainly related to differential stresses associated with weathering-related volume changes.

3.4 Sheeting

Steep slope with a sheet fracture cross-cutting bedding planes in the fine-grained conglomerates of Ayers Rock, central Australia. From Francisco Gutiérrez 2015.

Sheeting refers to the development of subparallel joints in rock massifs concordant with the topographic surface. According to the most widely accepted interpretation, sheeting is related to near-surface stress release.

Reference:

[1] Wikipedia page, https://en.wikipedia.org/wiki/Weathering
[2] Wikipedia page, https://en.wikipedia.org/wiki/Erosion
[3] Gutiérrez, F., Gutiérrez, M. (2016). Weathering Landforms. In: Landforms of the Earth. Springer, Cham. https://doi.org/10.1007/978-3-319-26947-4_7
[4] Wikipedia page, https://en.wikipedia.org/wiki/Panhole

Fluvial processes: Geomorphology

As fluvial geomorphology grew as a science, the focus was studying Earth's landforms having as principal goals to study river landform history, understand formative processes and predict changes using a combination of field observation, models, and numerical simulations.

Exploring different planetary surfaces in the Solar System has discovered new fluvial landforms on the surfaces of planets and moons.

-Classic Earth-based fluvial geomorphology fundaments

Fluvial geomorphology studies the interactions between the physical shapes of rivers, their water and sediment transport processes, and the landforms they create.

River systems are influenced by climate, geology, vegetation cover, and topography.

The channel substrate is the material in which the channel is formed. It can be divided between bedrock and alluvial substrates. Bedrock channels are sections of the channel that are cut directly into the underlying bedrock, and alluvial channels are formed in alluvium (sediments deposited on the valley floor by rivers).

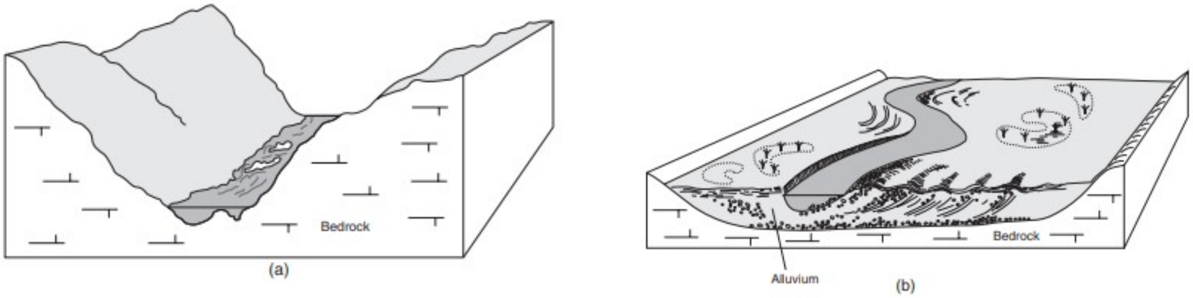


Figure 1. a. Bedrock channel. b. Alluvial channel. [4]

Most rivers flow to the oceans, some drain to inland seas and lakes, and others dry up before reaching the ocean. Each river drains an area of land called its **drainage basin** (supplying water and sediment to the channel).

Fluvial systems are dominated by rivers and streams. Stream erosion is the most significant geomorphic agent. Fluvial processes shape the landscape by eroding landforms, transporting sediment, and depositing it to produce new landforms.

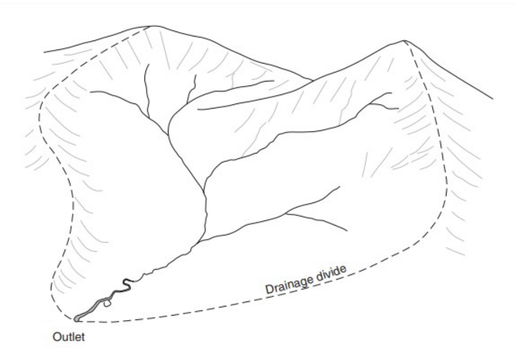


Figure 2. Drainage basin. [4]

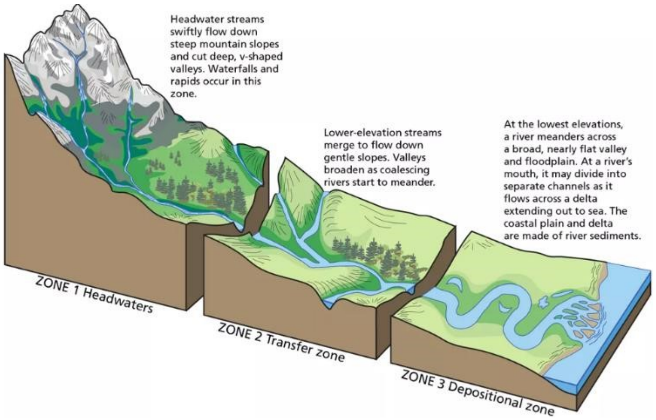
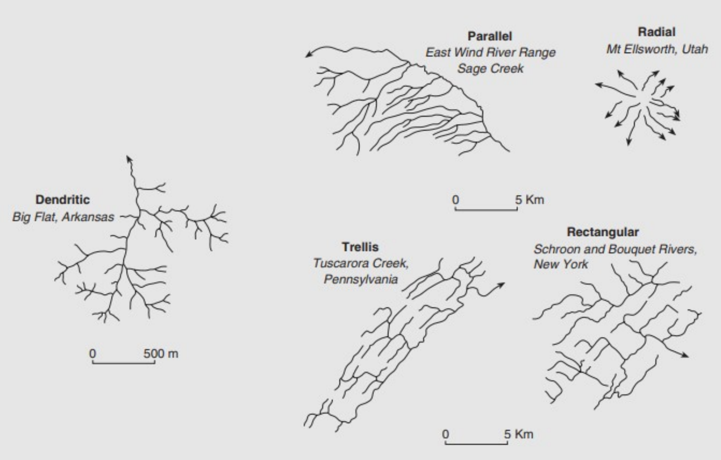


Figure 3. Fluvial system. [15]

A drainage basin is a branching network of channels. Numerous small tributaries feed the main channel. Drainage pattern varies considerably between basins and is influenced by different elements (geology, climate, and long-term drainage basin history).



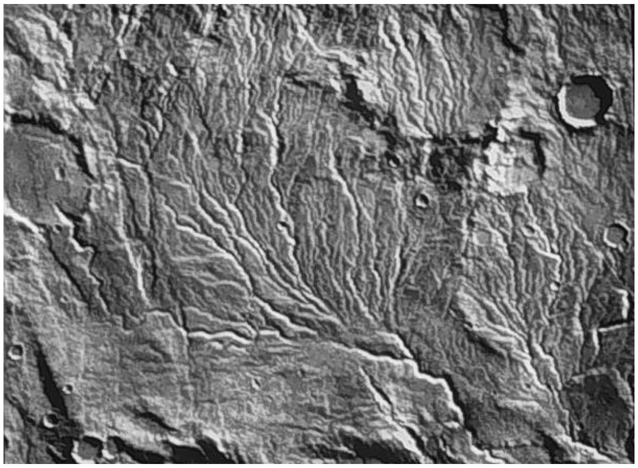


Figure 4. Drainage patterns. [4]

Figure 5. Dendritic drainage pattern on Mars. [12]

Rivers have a **three-dimensional shape**. They present channel planform patterns and vary in cross-sectional shape and channel slop.

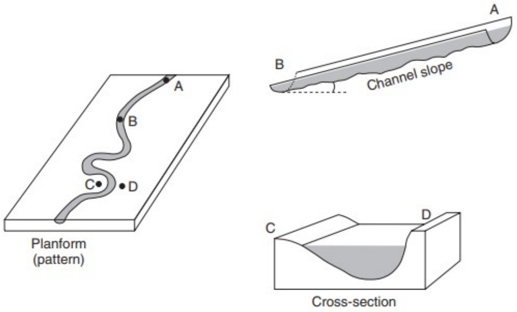
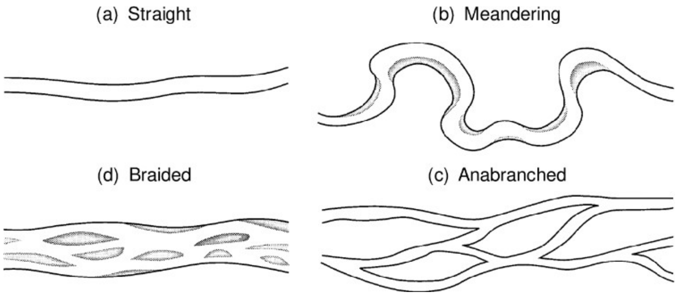
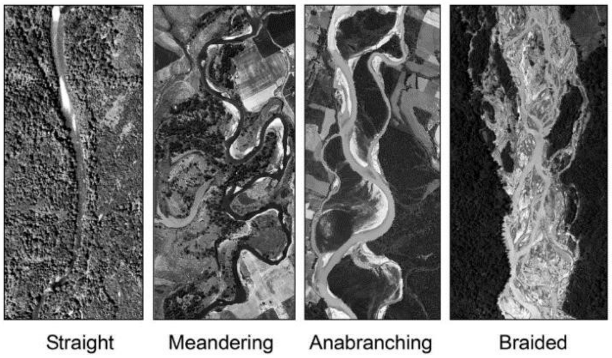


Figure 6. The three-dimensional shape of a river. [4]

Classification of river channel patterns: Four main types of alluvial channel form can be identified: straight, meandering, braided, and anabranching.





Figures 7 and 8. Classification of river channel patterns.

-Solar System fluvial geomorphology tour

Volcanic landforms

Moon. Lunar sinuous rilles are created by thermal erosion or the collapse of lava tubes.

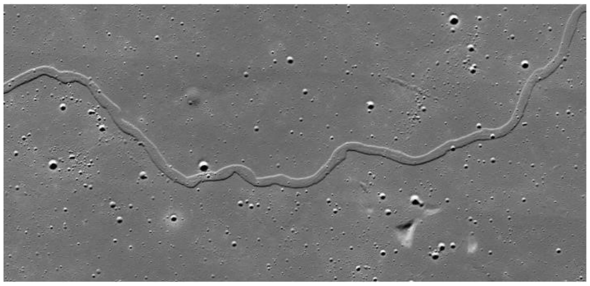


Figure 9. Lunar sinuous rille. [16]

Mercury. The MESSENGER mission (2008) revealed lava flow channels (northern hemisphere) probably formed by thermal and mechanical erosion.

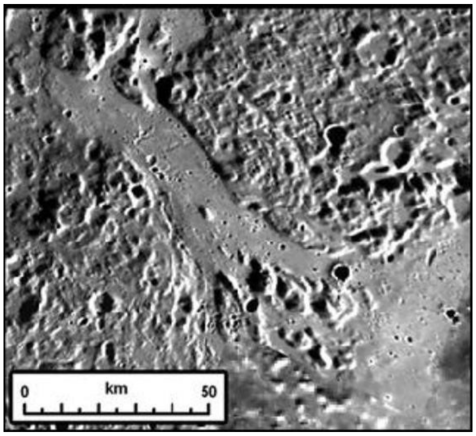


Figure 10. Lava flow channel on Mercury. [13]

Venus. From images generated by the Synthetic Aperture Radar (SAR) (Magellan spacecraft), lava channels have been identified on Venus. There are two types of lava channels on Venus's surface: **Simple channels** consist of a single, sinuous main channel (with flow margins, sinuous rilles, and canali). And **complex channels** that form anastomosing, braided, or distributary patterns.

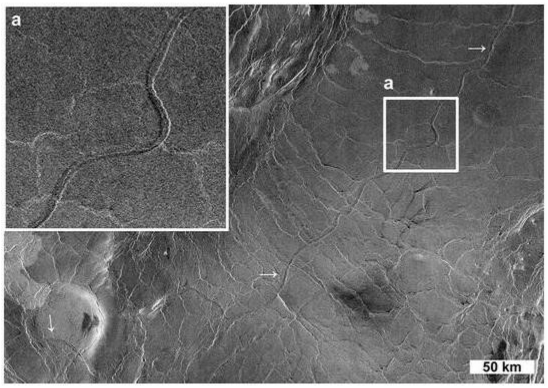


Figure 11. Lava channels on Venus. [7]

Mars. Lava channels on Mars are created by thermal and/or mechanical erosion from lava. It is difficult to differentiate between fluvial and lava channels because there is a possible overprinting where lava flows may have resurfaced fluvial outflow channels.

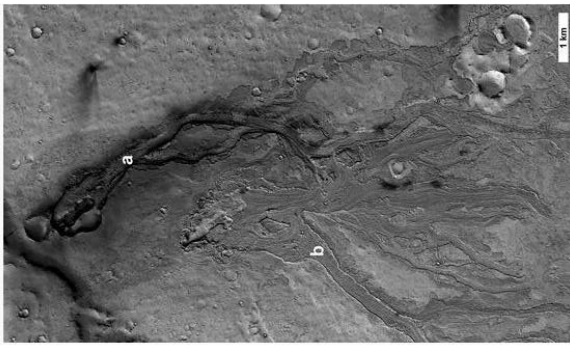


Figure 11. Lava channels on Mars. [7]

Earth. Braided lava channels from Kilauea Volcano.

Figure 12. Lava channels from Kilauea Volcano. [11]

Io. Lava channels were observed on the surface of Io (Jupiter's moon) (Galileo mission). Volcanism on Io is generated by the tidal interaction between Jupiter and Io. The lava channel may present either an ultramafic or a sulfur lava composition. The channel is probably formed into plains with a sulfur composition.

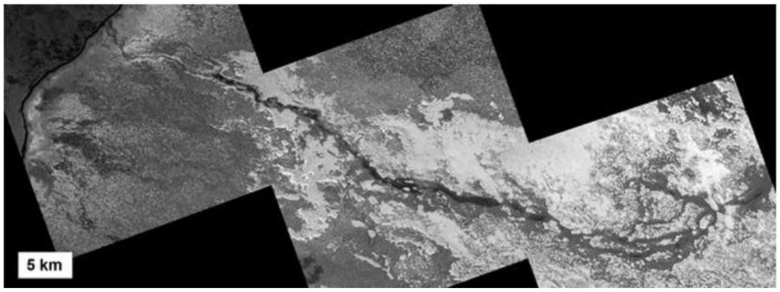


Figure 13. Lava channel on Io. [7]

Water-related landforms

Mars. Alluvial paleochannels have been identified on Mars. In this particular region (Figure 14), the channel sediments present a positive relief because of the erosional removal of adjacent materials.

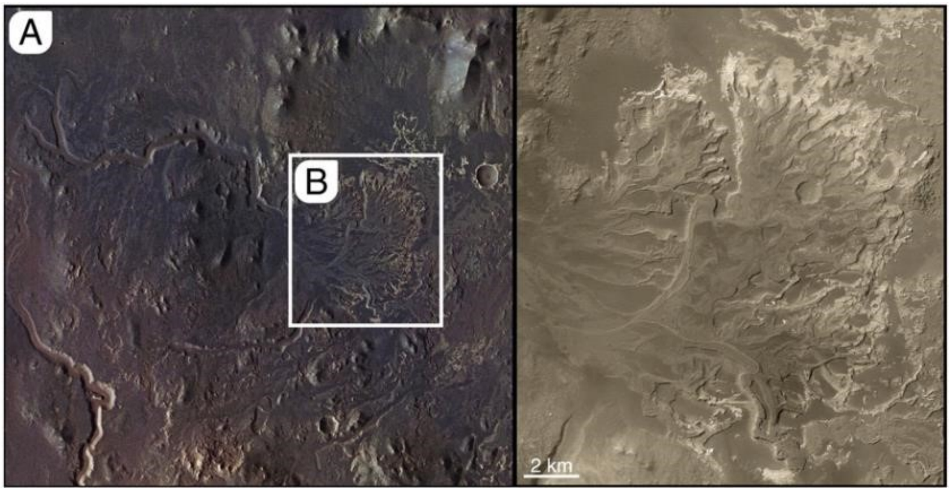


Figure 14. Alluvial channel on Mars. [2]

***Titan**. Titan (the largest satellite of Saturn) presents an N2-rich atmosphere with ~5% methane (CH4). The methane cycle (like the water cycle) on Titan generates clouds, fluvial features, and near-polar lakes.

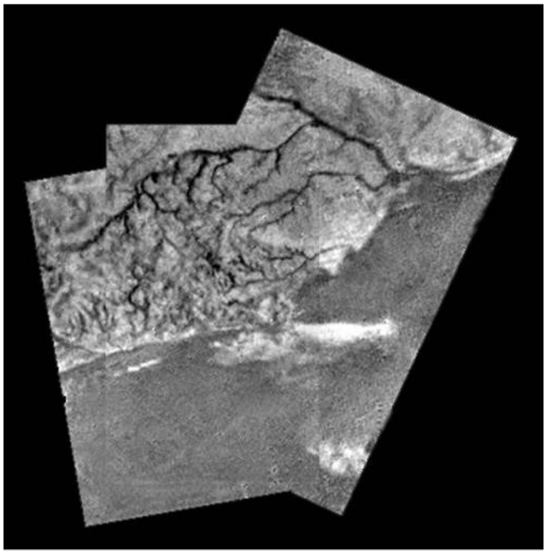


Figure 15. Methane channel on Titan. [9]

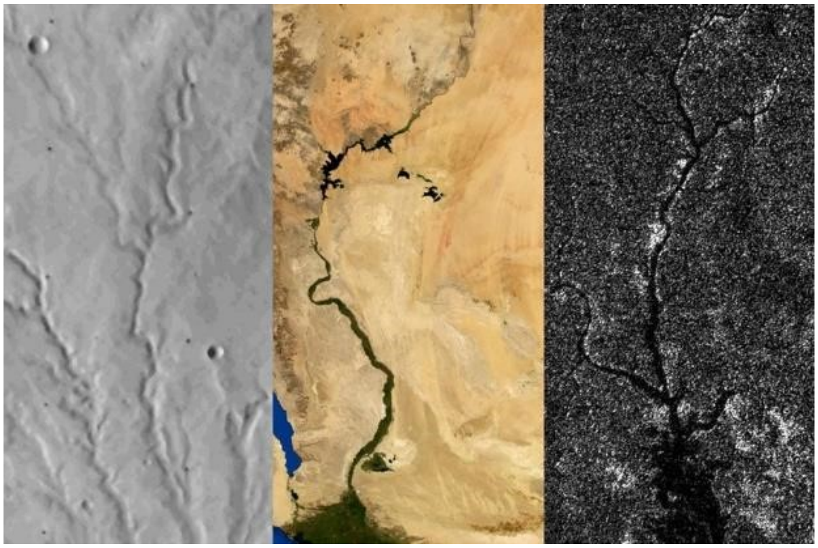


Figure 16. Alluvial channels on Mars and Earth, and Methane channel on Titan (not at scale). [14]

References

[1] Banda, M.S. (2018). Morphological Development of Meandering Rivers Due to Changing Discharge Regimes.

[2] Baker, V. R., Hamilton, C. W., Burr, D. M., Gulick, V. C., Komatsu, G., Luo, W., ... & Rodriguez, J. A. P. (2015). Fluvial geomorphology on Earth-like planetary surfaces: A review. Geomorphology, 245, 149-182.

[3] Beechie, T., & Imaki, H. (2014). Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research, 50(1), 39-57.

[4] Charlton, R. (2007). Fundamentals of fluvial geomorphology. Routledge.

[5] Grant, G. E., O'Connor, J. E., & Wolman, M. G. (2013). A river runs through it: conceptual models in fluvial geomorphology.

[6] Hardy, R. J. (2005). Fluvial geomorphology. Progress in Physical Geography, 29(3), 411-425.

[7] Hargitai, H., & Kereszturi, Á. (Eds.). (2015). Encyclopedia of planetary landforms. New York, NY, USA: Springer.

[8] Lewin, J., Brewer, P. A., & Wohl, E. (2018). Fluvial geomorphology.

Websites:

[9] Does Titan's methane originate from underground? (s. f.). Recuperado 11 de octubre de 2022, de https://www.esa.int/Science_Exploration/Space_Science/CassiniHuygens/Does_Titan_s_methane_originate_from_underground

[10] Evidence of Ancient Martian Rivers. (s. f.). NASA. Recuperado 11 de octubre de 2022, de https://www.nasa.gov/multimedia/imagegallery/image_feature_98.html

[11] Kīlauea Volcano — Braided Lava Channels | U.S. Geological Survey. (2018, 27 junio). Recuperado 11 de octubre de 2022, de https://www.usgs.gov/media/images/k-lauea-volcano-braided-lava-channels-0

[12] 5. Mars: Drainage Channels. (s. f.). Recuperado 11 de octubre de 2022, de https://www.lpi.usra.edu/publications/slidesets/marslife/slide_5.html

[13] NASA - Spectacular Volcanic Features on Mercury. (s. f.). Recuperado 11 de octubre de 2022, de https://www.nasa.gov/mission_pages/messenger/multimedia/messenger_orbit_image20110929_5.html

[14] Rivers on three worlds tell different tales. (2017, 18 mayo). MIT News | Massachusetts Institute of Technology. Recuperado 11 de octubre de 2022, de https://news.mit.edu/2017/rivers-titan-landscaperesembles-mars-not-earth-0518

[15] River Systems and Fluvial Landforms - Geology (U.S. National Park Service). (s. f.). Recuperado 11 de octubre de 2022, de https://www.nps.gov/subjects/geology/fluvial-landforms.htm

[16] Society, T. P. (2020, 22 noviembre). Lunar Rille. The Planetary Society. Recuperado 13 de octubre de 2022, de https://www.planetary.org/space-images/lunar-rille

[17] What is Fluvial Geomorphology (FGM)? (2016, 19 diciembre). River Smart Communities. Recuperado 11 de octubre de 2022, de https://extension.umass.edu/riversmart/resources/what-fluvial-geomorphology-fgm

Aeolian Processes: Physics

Movement of Grains

Initiating Movement

The ability of particles to be mobilized by the wind depends on the velocity provided by the wind and the threshold velocity required for the particles to be lifted. The velocity of wind above a surface at height z depends on whether it is in the laminar regime or the turbulent regime. A height-independent parameter related to the effect of wind at the surface is the friction velocity (v_*) (Fig. 1).

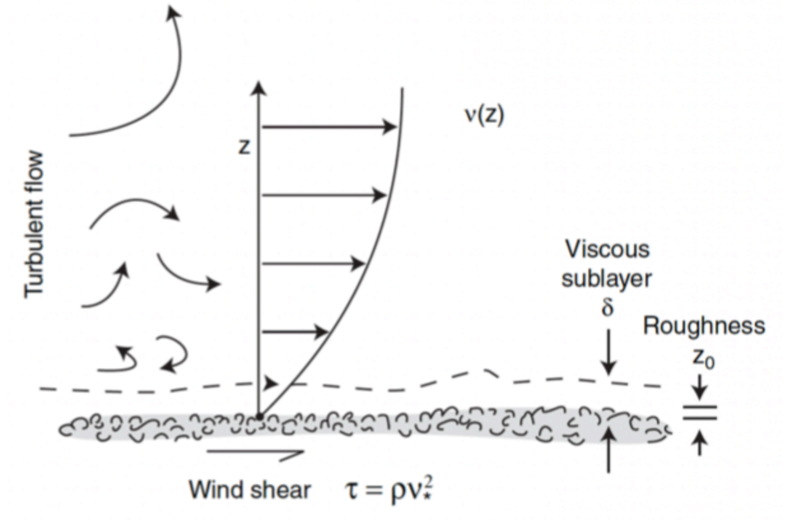
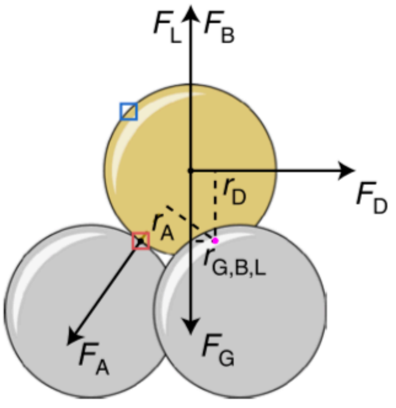


Figure 1: Diagram of wind velocity profile above the surface and definitions of various parameters. From Melosh 2011.

In the viscous sublayer, the velocity depends linearly on height (Melosh, 2011). $\frac{v}{v_*} \propto \frac{z}{\delta}$ (Eqn. 1) where $\delta \sim \frac{5\eta}{\rho v_*}$ (Eqn. 2) and η is the viscosity of the air and ρ is the density.

In the turbulent layer, the velocity has a nonlinear dependence on height (Melosh, 2011). It also depends on the roughness factor z_0. $v(z) = \frac{v_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$ (Eqn. 3) where κ~0.4 is von Karman's constant (Barnes et al., 2017).

The threshold velocity needed to pick up grains that are resting on the surface is called the fluid threshold. The fluid threshold depends on the balance of forces acting on the grain (Fig. 2) (Gunn and Jerolmack, 2022).



Forces that act to keep a grain in place:

- Gravitational force
- Friction/adhesion between grains
- Electrostatic forces (for very small grains)

Forces that act to move a grain:

- Buoyancy
- Drag (from the surface wind)
- Lift (from deflected wind)

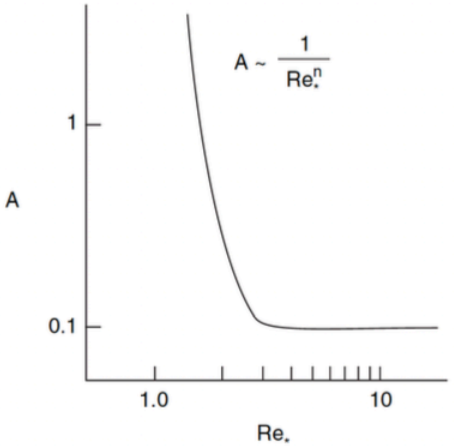
Figure 2: Diagram of the forces acting on a grain. From Gunn and Jerolmack 2022.

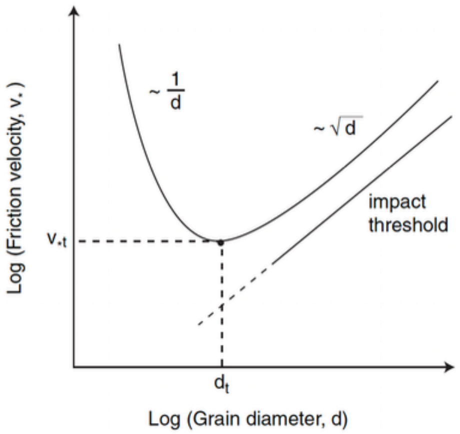
Balancing weight with some component of the drag (depending on various factors like the geometry of the grain, combined in the parameter A) gives an equation for the fluid threshold (Melosh, 2011):

$v_{*t} = A\sqrt{\left(\frac{\rho_s-\rho_a}{\rho_a}\right)gd}$ (Eqn. 4) where ρ_s is the grain density, ρ_a is the air density, and d is the grain diameter.

The factor A depends on the frictional Reynolds number, which is defined as (Melosh, 2011): $Re_* = \frac{\rho_a v_* d}{\eta}$ (Eqn. 5).

The dependence of A on Re* (Fig. 3) and the corresponding relationship between friction velocity and grain size (Fig. 4) shows that there is a grain size where the threshold friction velocity is at a minimum, making particles of that size the easiest to move (Melosh, 2011).

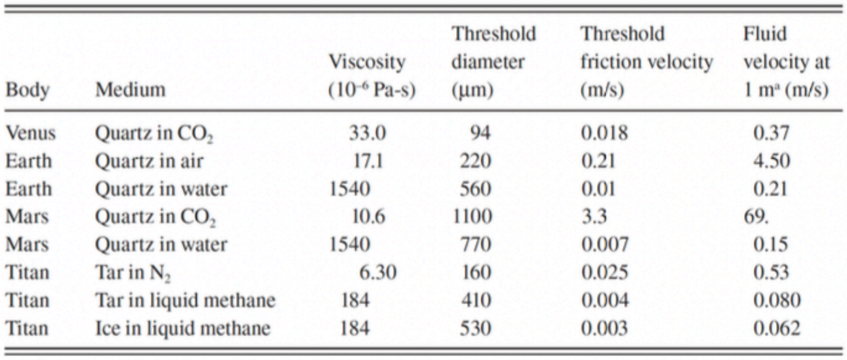




Left: Figure 3: Dependence of A on frictional Reynolds number. From Melosh 2011.
Right: Figure 4: Dependence of threshold friction velocity on grain diameter. From Melosh 2011.

The threshold diameter and corresponding threshold friction velocity are lowest on Venus, followed by Titan, Earth, and Mars (Table 1). This holds for more sophisticated models that explicitly account for lift and adhesion (Fig. 5) (Gunn and Jerolmack, 2022).

Table 1: Threshold diameters, threshold friction velocities (Fig. 4), and the corresponding fluid threshold velocities (Eqn. 3) for Venus, Earth, Mars, and Titan. From Melosh 2011.



Body	Medium	Viscosity (10^{-6} Pa-s)	Threshold diameter (μm)	Threshold friction velocity (m/s)	Fluid velocity at 1 m^a (m/s)
Venus	Quartz in CO_2	33.0	94	0.018	0.37
Earth	Quartz in air	17.1	220	0.21	4.50
Earth	Quartz in water	1540	560	0.01	0.21
Mars	Quartz in CO_2	10.6	1100	3.3	69.
Mars	Quartz in water	1540	770	0.007	0.15
Titan	Tar in N_2	6.30	160	0.025	0.53
Titan	Tar in liquid methane	184	410	0.004	0.080
Titan	Ice in liquid methane	184	530	0.003	0.062

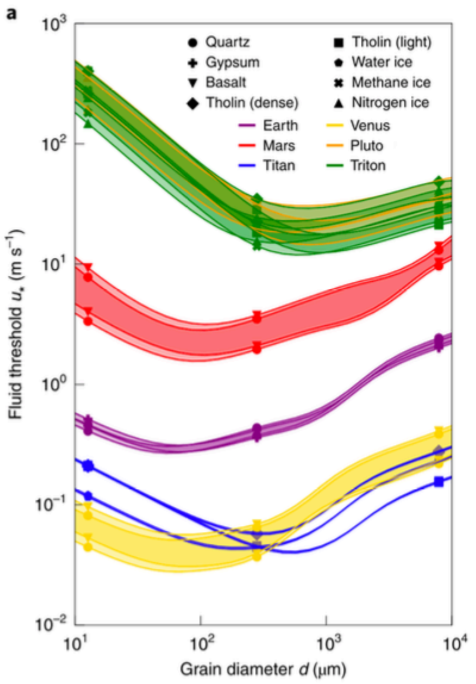


Figure 5: Fluid threshold for a range of grain diameters for various bodies for relevant granular materials. The ranges shown are based on temperature and pressure variability. Based on Gunn and Jerolmack 2022.

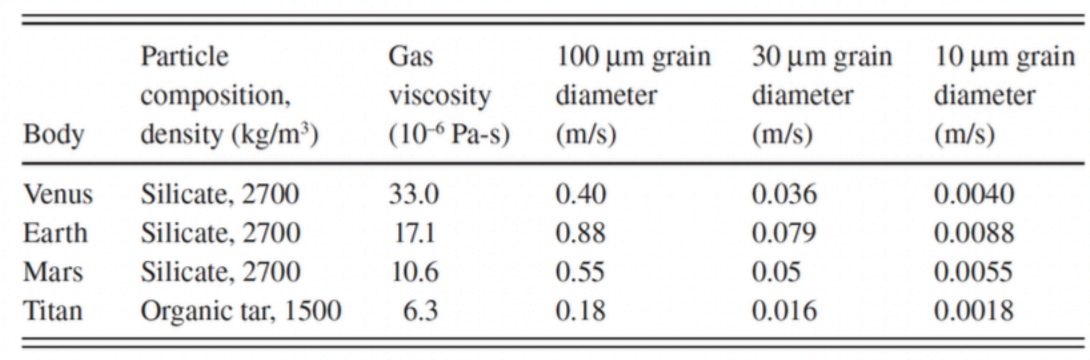
Sustaining Movement

Particles can remain suspended if their terminal (or settling) velocity is low relative to the wind velocity. For both turbulent and laminar flow, the terminal velocity depends on the balance between weight and drag (viscous drag in the laminar case) (Eqns. 6 and 7) (Melosh, 2011). For turbulent flow:

$v = \sqrt{\frac{4(\rho_s - \rho_a)dg}{3C_D\rho_a}}$ (Eqn. 6) where C_D is an empirical drag coefficient. For laminar flow $v = \frac{(\rho_s - \rho_a)d^2 g}{18\eta}$ (Eqn. 7).

The terminal velocities of particles are relatively similar on different planets for a given grain size (Table 2).

Table 2: Terminal velocities of particles of several grain sizes on several different bodies. From Melosh 2011.



Body	Particle composition, density (kg/m^3)	Gas viscosity (10^{-6} Pa-s)	100 μm grain diameter (m/s)	30 μm grain diameter (m/s)	10 μm grain diameter (m/s)
Venus	Silicate, 2700	33.0	0.40	0.036	0.0040
Earth	Silicate, 2700	17.1	0.88	0.079	0.0088
Mars	Silicate, 2700	10.6	0.55	0.05	0.0055
Titan	Organic tar, 1500	6.3	0.18	0.016	0.0018

Particles may be launched off the surface only to reimpact a short time later, causing more particles to be launched off the surface—this is saltation. The minimum velocity needed to sustain saltation is the impact threshold, and it is usually smaller than the fluid threshold, so it is easier to maintain saltation than start it (Melosh, 2011). Relevant forces are the same as for the fluid threshold, except for adhesion (Gunn and Jerolmack, 2022) and the threshold may be approximated with the same equation, with a smaller value of A (Melosh, 2011).

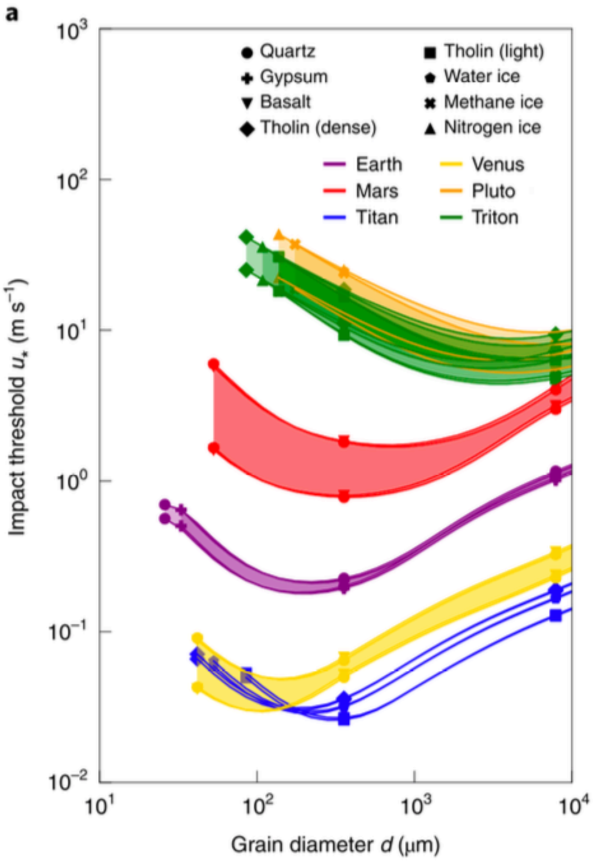


Figure 6: Impact threshold for a range of grain diameters for various bodies for relevant granular materials. The ranges shown are based on temperature and pressure variability. Based on Gunn and Jerolmack 2022.

Movement of Dunes

Sand Flux

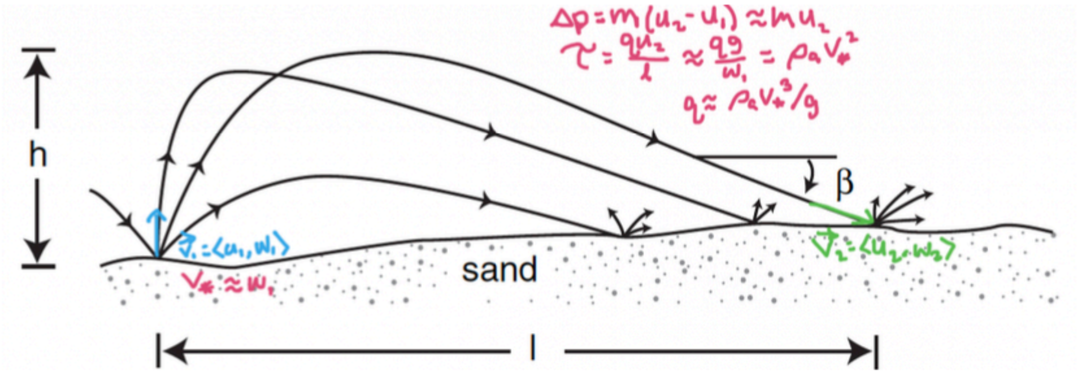


Figure 7: Diagram of saltation showing initial and final velocity vectors of the grains and the main points of the derivation for sand flux based on momentum change of the grains. Modified from Melosh 2011.

The mass flux of sand resulting from saltation can be derived considering the momentum change of grains as they travel over the distance of one saltation hop (Fig. 7). (Melosh, 2011). Experiments have found a wide range of forms for the constant C, which in some cases depends on other parameters such as the particle size (Greeley and Iversen, 1985). $q = C(\frac{\rho_a v_*{}^3}{g})$ (Eqn. 8).

Takeaways from this equation: sand flux depends on the wind velocity cubed → less frequent but stronger than average winds may lead to more sand transport than more typical but gentler winds. This equation predicts sand fluxes from highest to lowest on: Venus, Titan, Earth, and Mars. This doesn't hold up to observations, due to other differences between the planets (for instance, availability of particulates).

Dune Formation

Saltating particles impacting a sandy surface lose energy and slow down, while particles impacting a rocky surface rebound with more energy and higher velocity → positive feedback effect with sand accumulating in areas with more sand (Melosh, 2011). Low hills experience asymmetric shear stress: higher on the upwind/stoss side, leading to mass loss, and lower on the downwind/lee side, leading to mass gain (Pelletier, 2009). Particles that accumulate on the lee side approach the angle of repose and avalanche down, advancing the dune.

Dune Velocity

Balancing the volume of sand blown over to the lee side in a given period of time (mass flux of sand/density of sand * time * unit width) to the volume added to the lee side (length * height * unit width) gives an expression for dune velocity (Fig. 8) (Melosh, 2011):

$\frac{\Delta x}{\Delta t} = \frac{q}{\rho_s h}$ (Eqn. 9).

Takeaways: higher sand flux → dune velocity increases, higher dune height → dune velocity decreases. Small dunes move more quickly than large ones, but when they catch up to large dunes, may merge with the larger one and lead to additional growth of the larger dune.

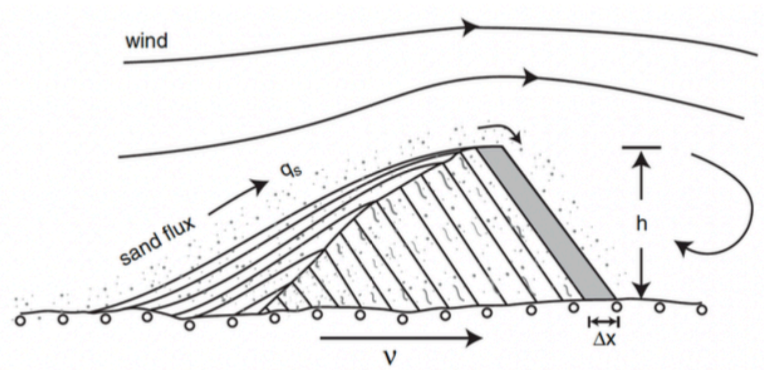


Figure 8: Diagram of a sand dune with parameters used to derive dune velocity. From Melosh 2011.

References

Barnes, J.R., Haberle, Robert M., Wilson, R.J., Lewis, S.R., Murphy, J.R., Read, P.L., 2017. The global circulation, in: Haberle, R.M., Clancy, R.T., Forget, F., Smith, M.D., Zurek, R.W. (Eds.), The Atmosphere and Climate of Mars. Cambridge University Press, pp. 229–294. https://doi.org/10.1017/9781139060172.009

Greeley, R., Iversen, J.D., 1985. Physics of Particle Motion, in: Wind as a Geological Process on Earth, Mars, Venus, and Titan. Cambridge University Press, pp. 67–107.

Gunn, A., Jerolmack, D.J., 2022. Conditions for aeolian transport in the Solar System. Nat. Astron. 6, 923–929. https://doi.org/10.1038/s41550-022-01669-0

Melosh, H.J., 2011. Wind, in: Planetary Surface Processes. Cambridge University Press, pp. 348–379.

Pelletier, J.D., 2009. Controls on the height and spacing of eolian ripples and transverse dunes: A numerical modeling investigation. Geomorphology 105, 322–333. https://doi.org/10.1016/J.GEOMORPH.2008.10.010

Report: Modern Flora at the Glen Canyon

Fuda Nguyen for PTYS 590 FA2022

Yucca in Hites. National Park Service.

Hanging gardens.

Hanging garden along trail to Rainbow Bridge. *NPS/Stephanie Metzler*

Flora in the Glen Canyon National Park.

Glen Canyon National Recreation Area and Rainbow Bridge National Monument have highly diverse vegetations typical of the Colorado Plateau region. Vegetation communities are affected by variations in soil, water availability, substrate type, and elevation. In the Glen Canyon area, low growing shrubs on clay badlands contrast sharply with lush hanging gardens fed by springs which grow on cliff walls. Green strips of riparian zones wind through desert slopes and past sheer cliffs. Vegetation communities create habitat for wildlife by providing important water and food sources.

What grows in the Glen Canyon Park? Vascular plants

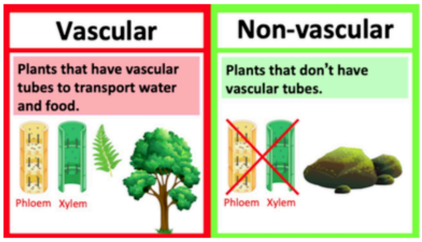
What grows in the Glen Canyon Park?

Hanging gardens

> **Hanging gardens and springs comprise less than 1% of the area, but contribute a disproportionate number of species to the flora of Glen Canyon NRA.**

Water sources in the desert are rare and often critically important for wildlife. Streams and springs support lush, green vegetation, creating a stark contrast to the dry surrounding desert landscape. Perhaps the most unusual form of spring-supported plant community on the Colorado Plateau is the hanging garden. Hanging gardens are spring-fed colonies of plants clinging to the vertical wall of a cliff.

They often form in alcoves or “glens” where conditions are cooler and moister than in the surrounding desert. Hanging gardens support an amazing diversity of water



Vascular vs non-vascular plants

Vascular plants have systems of veins that conduct water and nutrient fluids throughout the plant. Trees, shrubs, grasses, flowering plants, and ferns; just about everything that is not a moss, algae, lichen, or fungus (nonvascular plants) is vascular.

Glen Canyon National Recreation Area (NRA) has one of the largest floras on the Colorado Plateau. This high diversity can be attributed to the variety of habitats that span the area's 1.2 million acres, including slickrock expanses, clay barrens, mesas, river corridors and hanging gardens and springs.

> **With 856 reported vascular species and 900-920 probable species, Glen Canyon National Recreation Area (NRA) has one of the largest floras on the Colorado Plateau.**

Lupine in the Glen Canyon. *NPS*

Evening Primrose (Oenothera caespitosa). *NPS/John Spence*

Herbaceous plants (herbs) have soft rather than woody tissue, and are the most common vascular plants in Glen Canyon NRA. In a study documenting the vascular plant flora of Glen Canyon NRA, the statistics are:

- 53% were perennial herbs ***(lifespan > 2 years)***
- 26% were annual herbs
- 3% biennial herbs ***(lifespan ≤ years)***
- Shrubs (perennial ***woody plants***): 13% of species.
- Succulent shrubs and trees accounted for just 2.5% of species reported.
- Large cacti like saguaro (*Carnegiea gigantea*) do not grow in this area because it is typically too

loving plant species, such as ferns, lilies, sedges, and orchids. These gardens are also "hot spots" of biodiversity, with many species aquatic invertebrates, as well as birds, mammals, and amphibians.

> **HANDLE WITH CARE!** Many hanging gardens were lost in Glen Canyon when the waters of Lake Powell rose behind Glen Canyon Dam. Hanging gardens are very fragile and must be enjoyed with care. Foot traffic causes erosion and increase risks of introduction of invasive exotic plant species.

What grows in the Glen Canyon Park? Rare Plants

Of the more than 3,000 **vascular plants** that have been documented in the region, about 10% are endemic, or found only in the Colorado Plateau.

Jones cycladenia (*Cycladenia humilis* var. *jonesii*) is only found in Southeastern Utah and Northern Arizona on Chinle, Cutler, and Summerville Formations. It was federally listed as a threatened species in 1986 and is monitored by the National Park Service.

Alcove primrose (Primula specuicola). *NPS/John Spence.*

Some plants will grow only on certain geologic formations. *Jones cycladenia* was probably present during the Pleistocene ice age and it has been suggested that its original pollinator is no longer around, which may limit its reproduction. The most pressing threats to *Jones cycladenia* are climate change, which affects the fragile and small habitat it exists on, the potential for mineral and gas exploration, off-road vehicles in some areas, and consumption by herbivores.

References:

1. **National Park Service, Glen Canyon National Park:** https://www.nps.gov/
2. **NPS, Vascular Plants:** https://www.nps.gov/glca/learn/nature/vascularplants.htm
3. **NPS, Hanging Gardens:** https://www.nps.gov/glca/learn/nature/hanginggardens.htm
4. **NPS, Rare Plants:** https://www.nps.gov/glca/learn/nature/rareplants.htm
5. **iNaturalist, Glen Canyon National Recreation Area Plants:** https://www.inaturalist.org/guides/9442

Gallery

Palmer's penstemon one of the few scented perennial penstemons.

Longbeak streptanthella, Western native.

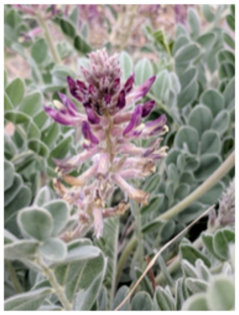
***Atriplex confertifolia* (shadscale)**, evergreen shrub native to the western US & northern Mexico

Isocoma rusbyi, the Rusby's goldenbush.

Tumbleweed, a diehard plant (CPGGrey reference!). **Kali tragus** is the most common & conspicuous species of tumbleweed.

Utah juniper.

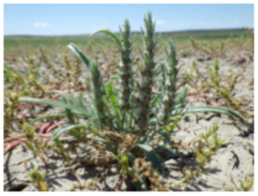
Black maidenhair fern or venus hair fern.



Woolly locoweed, a perennial plant found in the Colorado Plateau and Canyonlands.

Green Mormon tea/ephedra

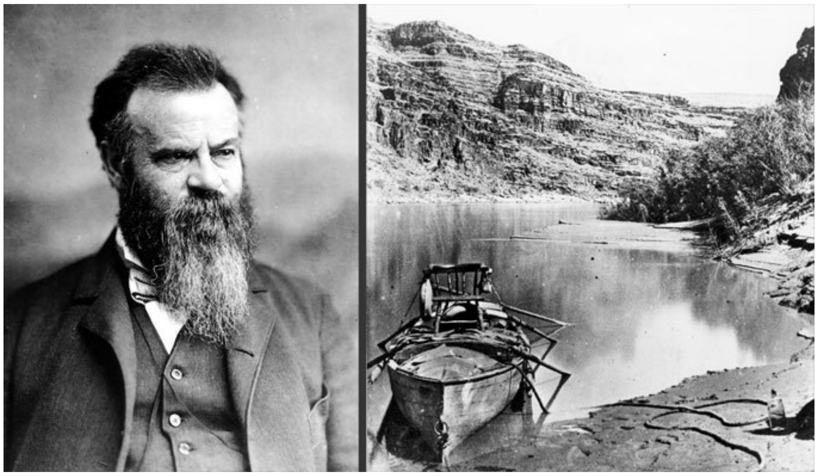
Velvet mesquite, medium-sized perennial legume tree adapted to the Sonoran desert.



Woolly plantain, hairy annual herb.

American Exploration of the Colorado River

Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality.– Joseph Ives, 1857



A man described by one of his biographers as "a stick of beef jerky adorned with whiskers," Powell's (left) greatest achievement left a lasting mark on the American West by launching wooden boats down the Colorado with arm chairs strapped to the deck (right).

The Grand Old Man:

When white explorers advanced into the American West for the first time, they were almost never pioneering a new route. Men like Jebediah Smith, Lewis and Clark, and Daniel Boone were mostly following the ancient trails and routes used by Native Americans for thousands of years for hunting, trade, and war. John Wesley Powell is the rare exception. Although parts of the Grand Canyon were known intimately by Native Americans, many sections had never been touched because of impassable cliffs. In Powell's day, Native Americans and homesteaders alike believed that no one who ventured down the Colorado River would emerge from the canyon alive.

> *"We are three quarters of a mile in the depths of the earth, and the great river shrinks into insignificance, as it dashes its angry waves against the walls and cliffs...We have an unknown distance yet to run; an unknown river yet to explore. What falls there are, we know not; what rocks beset the channel, we know not; what walls rise over the river, we know not.*" John Wesley Powell, August 1869

Powell had a modest career in academia that was abruptly ended in 1861 when he enlisted in the Union Army where he lost his arm while signaling to gunners. After the war, Powell corralled together a ragged band of mountain men, fugitives, and Civil War veterans and convinced them to join him in launching a small fleet of wooden boats down the most untamable river in the entire West, starting at the Green River in Wyoming before it flowed into the Colorado. None of them had ever run a rapid or knew the first thing about white water –the only one equipped with a life jacket was missing an arm. When they started on May 24, 1969, they were so weighed down with cargo they had to dump five hundred pounds of bacon on the first night. Two weeks into the expedition, the boat *No Name* struck a boulder to throw out its three-man crew,

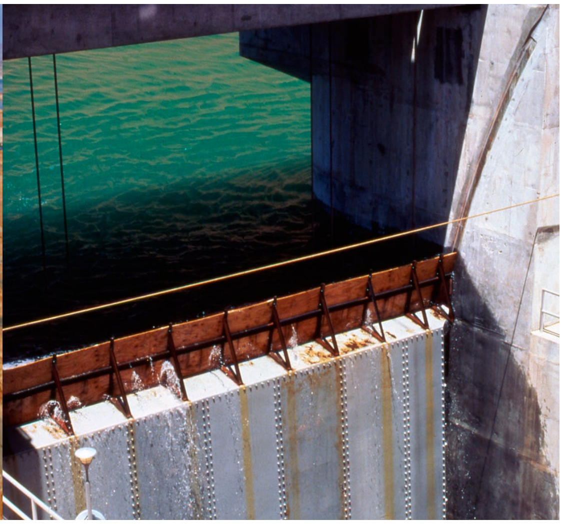
broke in half and sank. What followed was weeks of hardship. The portages grew increasingly frequent once they entered the Grand Canyon, which exacerbated the despair and anger, much of which was directed at Powell himself. One crewmember wrote: "If we succeed, it will be *dumb luck*, not good judgment that will do it." On August 27, they reached the worst rapid they had seen, described as a "perfect hell of foam" and they were unable to portage. The rapid prompted three men to abandon the expedition and climb out of the canyon. The remaining men attempted to run the rapid – the boats scraped against rocks, plunged over a ledge, and were swamped by the waves but after a few seconds were safely through. Although it was not easy going the remaining miles, just over 24 hours after they parted company with the other group, they passed through the gates of the Grand Wash Cliffs which is where the Grand Canyon gives way to the Mojave.

America's Pyramids

"*Damn the expense, just stop that river!*" – Union Pacific Railroad Company

As the United States expanded westward in the late 1800s and early 1900s, attempts to harness the power of the Colorado got bolder. Downstream, flash floods in 1906 caused the river to divert course and start pouring into Imperial Valley and the Salton Sea. Significant investments in housing, farmland, and other developments were washed away. Over several months, crews built a series of rock dams, each larger and more expensive than the last, only to watch the floods obliterate them.

After the failures of Imperial Valley, the newly formed Bureau of Reclamation needed a way of not only taming the Colorado, but also harness its power to generate electricity through hydropower. The site they proposed was where the southern shard of Nevada jutted into the side of Arizona at a place called Black Canyon. After diverting the river by blasting four massive tunnels



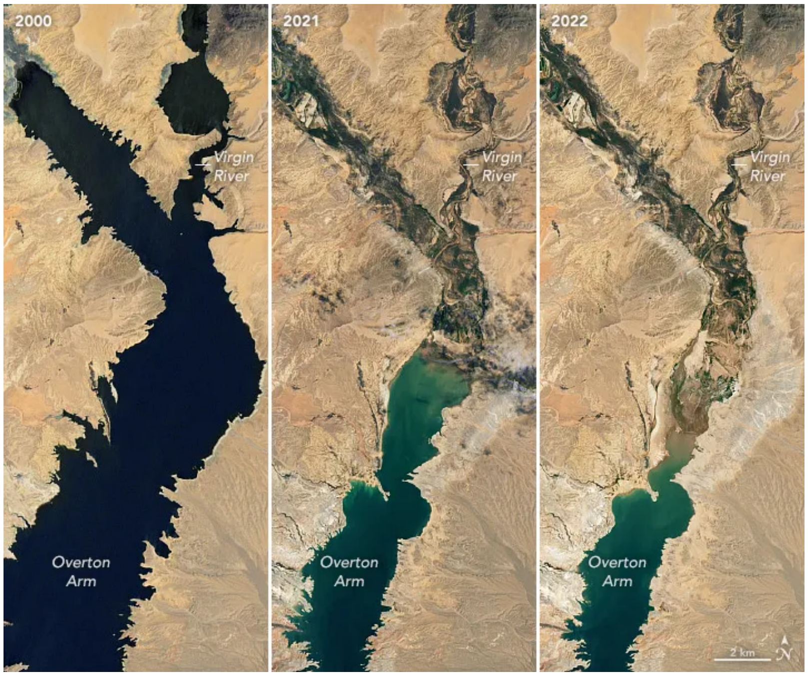
through the canyon walls, an army of five thousand men spent two years pouring concrete that arrived at the bottom of the canyon in giant steel buckets. On February 1st, 1935, just 66 years after Powell completed his expedition, the diversion tunnels were blocked, and the newly formed Lake Mead began lapping at the foot of the Hoover Dam. Over the next two decades, Congress would approve a series of massive appropriation bills that would construct 19 large dams along the Colorado which would complete the river's transformation from the savage beast of the West to a tightly controlled waterworks system.

In 1953, the Bureau of Reclamation reported that they had located two new sites in Dinosaur National Monument in Utah (it was of no concern to the Bureau that the law required the area to preserved to leave it "unimpaired for the enjoyment of future generations"). The Sierra Club and other conservation groups pooled their resources to launch a publicity campaign to build opposition. By 1955, the project died, but it was a bittersweet victory. The compromise was that a dam was to be built 15 miles upstream of Lees Ferry and would be the second largest dam on the Colorado. The lake would flood the little-known Glen Canyon and after David Brower of the Sierra Club did a series of river trips down this canyon, he realized the mistake

they had made. Brower would declare that Glen's side canyons alone boasted "the equivalent of several Dinosaur National Monuments." After these trips, Brower flew to Washington to make a last-ditch effort to save Glen. But there, he learned of plans to flood another canyon – the greatest canyon in the world. The water and power would be used to feed the growing cities of Phoenix and Tucson. What followed over the next five years was a series of court battles, publicity campaigns, and lobbying efforts to convince the Bureau of Reclamation that America's foremost natural wonder should be left alone. By 1968, the appropriation bill removed the dams in the Grand Canyon from the plan.

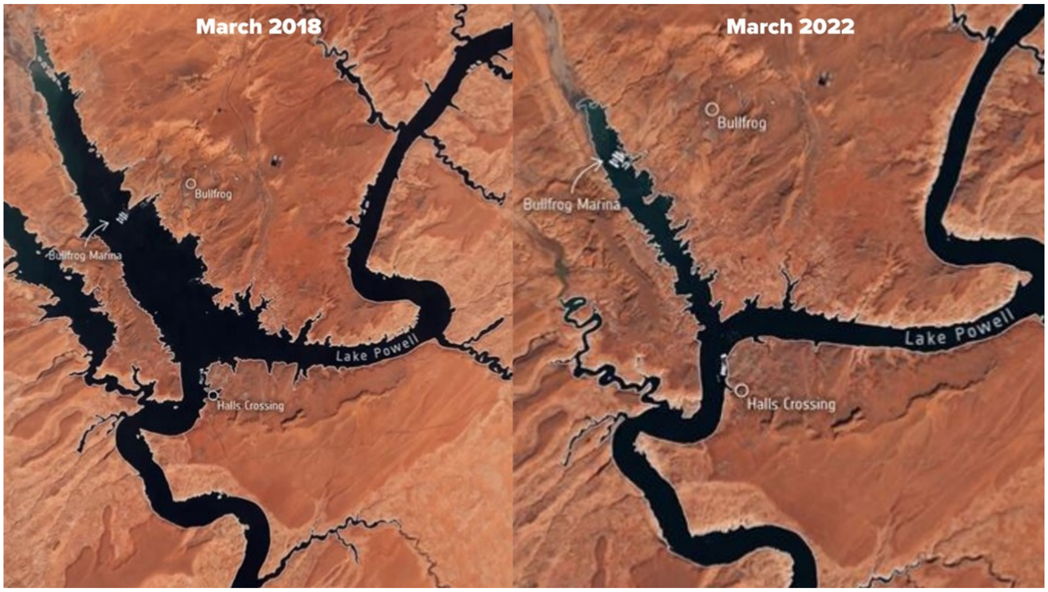
The Nile of the West

The Colorado is neither the longest nor the biggest river in the American West. The drop from thirteen thousand feet is unparalled in North America. The flash floods, before the river was dammed, could have flipped a freighter. However, it also has more people relying on it than any comparable river in the world. If the river stopped flowing, you would have four years of carryover capacity before you had to evacuate the entire southwest. Managing a reservoir as massive as Lake Powell is a balancing act to



satisfy three objectives: (1) keep water in the lake; (2) maximize electricity generation revenue; and (3) leave enough room in the reservoir to accommodate spring runoff. In the 80s, these calculations were made based on measurements of snowfall in Salt Lake City. In 1983, the Bureau's wager on runoff backfired. From March through the first week of April the reservoir ascended at roughly an inch a day. By June 1st, the surface of the lake was less than three inches from the top of the spillway gates. On June 2nd, the spillways were opened. Later that night, strange noises inside the spillway were heard by operators. Upon inspection, the plume of water coming out of the spillways was coming out in a spitting series of coughs and was full of debris – somewhere in spillway, the water was excavating into the bedrock and getting dangerously close to the concrete that plugged the diversion tunnel. They were forced to reduce the flow and a barrier of plywood was constructed at the top of the dam. By July 15, the level of the lake was 8 inches from the top of the plywood but held steady and slowly declined. The flood nearly caused a catastrophic disaster –had the diversion plug broke completely, Lake Powell would have been drained and caused downstream dams to break.

The negotiation of the Colorado River Compact took place in 1922 and is the West's equivalent of the Constitution. Using the Bureau's estimated average flow of 17.5 million annual acre-feet, the delegates divided the river at Lee's Ferry into two artificial basins (California, Arizona, Nevada in the lower and Colorado, Wyoming, New Mexico, and Utah in the upper). Each basin is supposed to receive 7.5 million acre-feet, with Mexico getting 1.5 million. This agreement is still used today and settled several disputes except for one small matter: the average annual flow of the Colorado River has never been anywhere near 17.5 million acre-feet. In 2022, the American West faces the opposite problem that it faced in 1983 – Lake Powell is at significant risk of reach "dead pool" status, meaning the dam can no longer generate power and meet downstream demands. The level of Lake Powell has been steadily dropping, sitting at just above 24%, even with the upper basin taking far less than its share. This summer, the Bureau announced dramatic new steps to prevent both Lake Powell and Lake Mead from reaching dead pool including reducing total water usage by 4 million acre feet. States have until January to propose new measures to meet these goals, otherwise the federal government will impose new rules unilaterally.



References: Reisner, Marc. (1993). Cadillac desert : the American West and its disappearing water. New York, N.Y., U.S.A. :Penguin Books; Fedarko, K. (2013). The Emerald Mile : The epic story of the fastest ride in history through the heart of the Grand Canyon (First Scribner); U.S. Department of the Interior (2022). Interior Department Announces Actions to Protect Colorado River System.

Horseshoe Bend

Kana Ishimaru

Overview

Horseshoe Bend is a part of Colorado Plateau that is shaped by an incised meander of Colorado river. Located in the west of Glen Canyon, it is composed of Navajo sandstone. Most of the Colorado River's water originates in melting snow in the Rocky Mountains, and flows into the Gulf of California.

300 – 240 Ma (the Late Pennsylvanian to the mid Triassic)

Sediments deposited in shallow water, and southeastern Utah became part of the supercontinent Pangea.

200 – 60 Ma (the Jurassic to the Late Cretaceous)

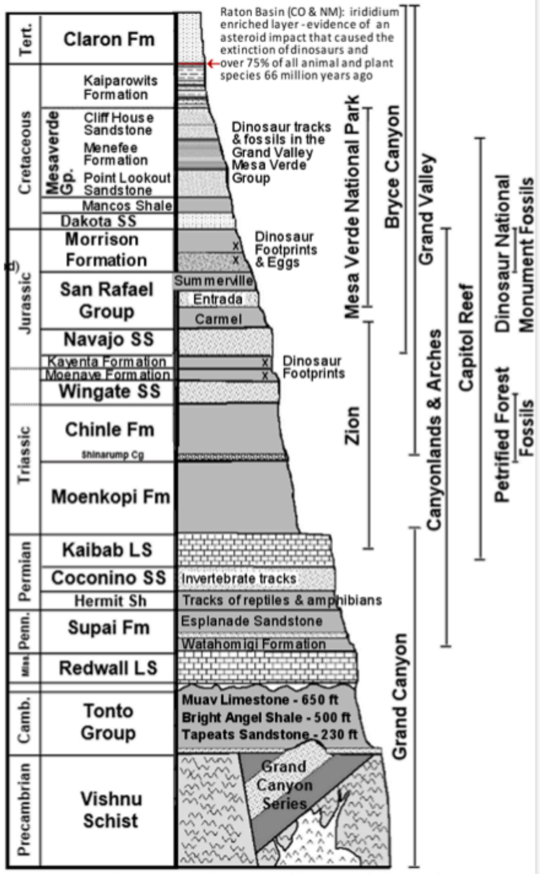
Expansive sand deserts (ergs) covered the region. Navajo dunes formed, which later became Navajo sandstone layer. Tracks of dinosaurs can be followed to their abrupt end in late Jurassic.

70 – 40 Ma (the Late Cretaceous to Eocene, Laramide Orogeny)

Mountain building, uplift period caused by an ancient oceanic plate sliding under the North American plate. Running water, wind, and mass wasting removed 1000s m of sedimentary rock.

5.5 Ma -

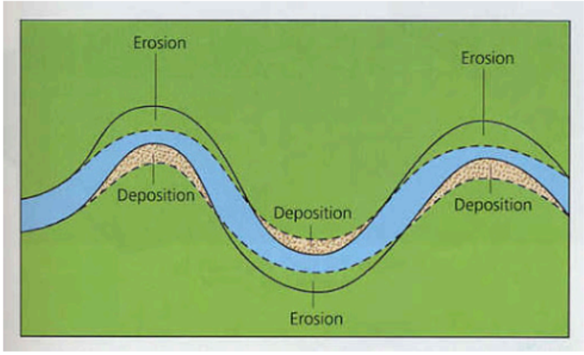
Drainage systems developed and the modern Colorado River began carving the Grand Canyon and Glen Canyon. As the Colorado Plateau continued to rise, the Colorado River incised rapidly into relatively soft Cretaceous, Jurassic, and Triassic strata. Within about the last 1 million years, the river carved the part of Glen Canyon that we see today.

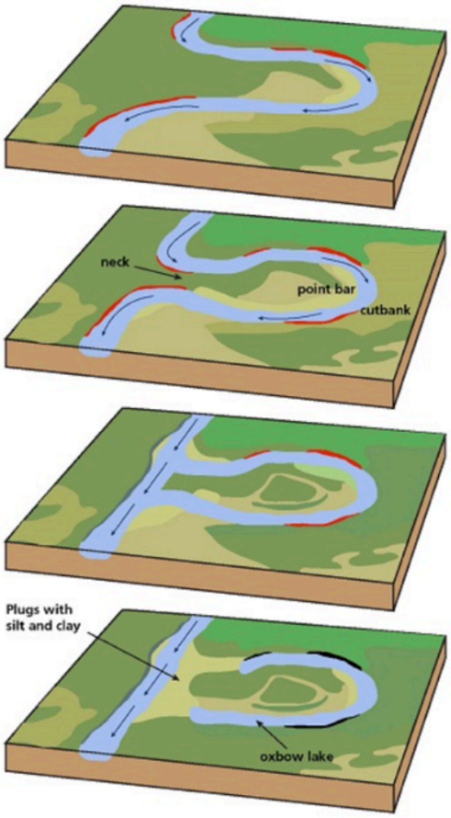


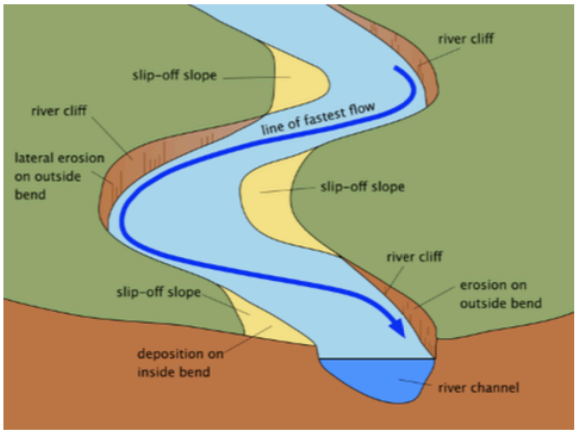
River Meander

A meander is a series of sinuous curves found in rivers or steams. The cause of meandering is not completely known, it is usually associated with the interaction of flow, slope, and streambed resistance. In a meandering river, the velocity of the flow is largest at the outside of the curve. Therefore, the fast flow erodes the outer bank, making the curve deeper. The erosional surface on the outer edge is called a cut bank. At the same time, the flow is slower at the inside of the curve. This results in the deposition of course sediment, such as sand. This depositional surface on the inner edge is called a point bar or a slip off slope.

When the meanders grow and become more curved over time, the flow erodes through the neck and bypasses the meander. Eventually sediments fill the entrance of the old meander and create a U-shaped lake called an oxbow lake.







Incised Meander

When a meander of a river erodes the bedrock downwards, it is an incised meander. An incised meander starts to form when tectonic uplift occurs or the sea level drops. There are two types of incised meanders.

Ingrown meander

Normally develop under slower incision. The incised meander grows horizontally and vertically, with an asymmetric slope on its walls. Steep undercut slope forms on the outside of the meander, and a slip off slope forms on the inside of the meander.

Pease river, Texas

Entrenched meander

Normally develop under rapid incision. The erosion is mainly vertical, making symmetrical, near vertical walls with little horizontal growth.

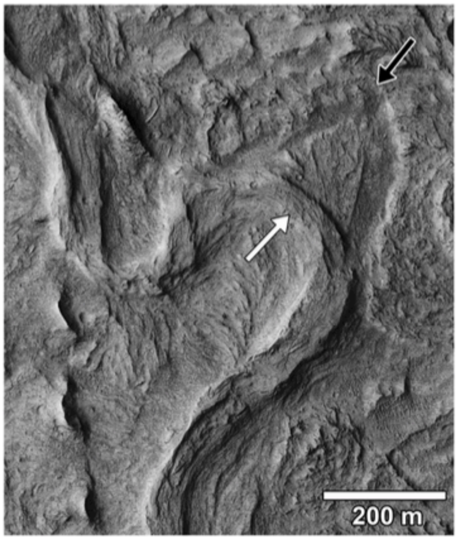
Entrenched meanders are generally rare, but they are common in the low sloped reaches of large plateaus like the Colorado Plateau. They have vertical walls on both sides of the channel, and no slip-off slopes on the inside of bends. This indicates that there was once a rapid downward cutting.

Horseshoe Bend is an example of an entrenched meander. It formed around 5 million years ago, when the Colorado Plateau uplifted. The meandering rivers on the Plateau cut through the uplifted sandstone layers. At Horseshoe Bend, the Colorado River created about 305 m deep, 270° horseshoe-shaped bend in Glen Canyon.

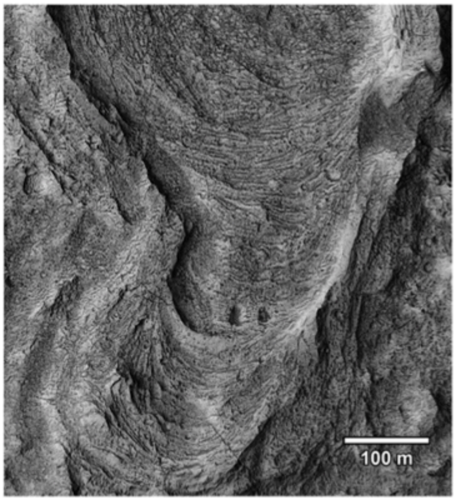
Horseshoe Bend

Meanders on Mars

HiRISE images below show meandering channels in the Aeolis Dorsa region on Mars.



- Highly sinuous meanders
- Black arrow points to an abandoned meander loop.
- White arrow points to the new channel.



- Shows pattern of meander migration
- Interior benches are earlier channel bed deposits

Meandering channels on Mars can develop by abundant mud in the flow. A study at the Quinn River in Nevada showed that in the absence of vegetation, bank cohesion is provided by mud with salts in the water. Both of these elements are likely present in rivers on Mars. Salts aid mud particles to aggregate into small lumps. This encourages the deposition of fine sediment aggregates at the part of the river where the flow is slower, which leads to meandering.

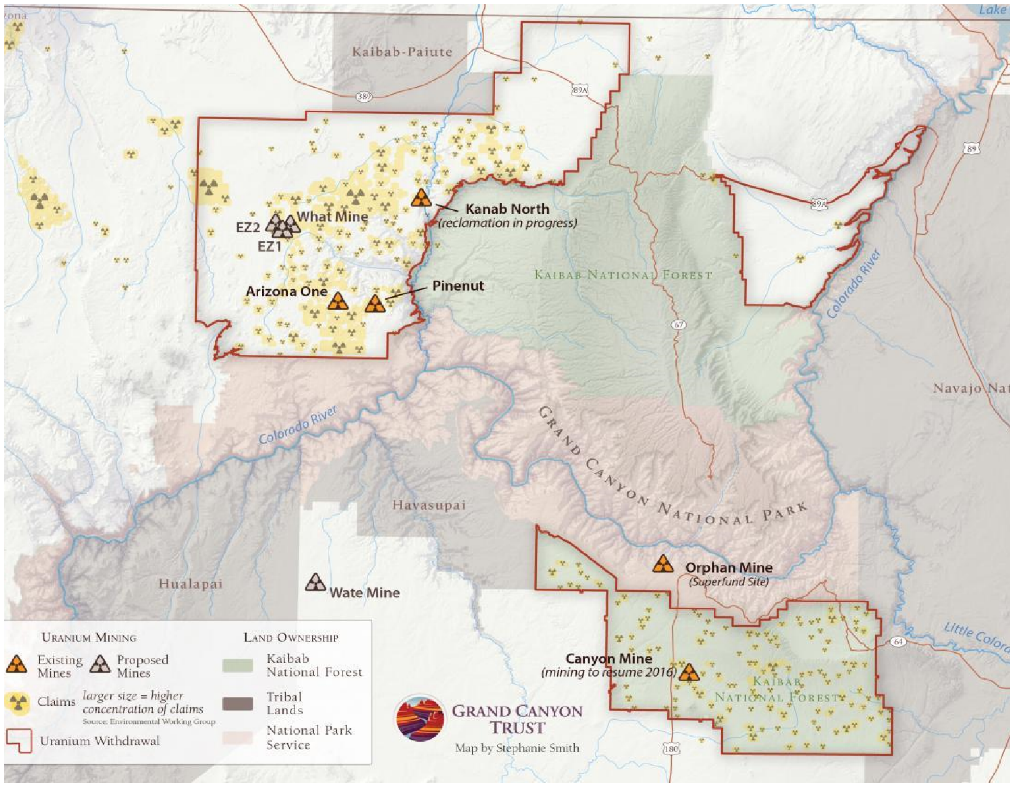
Resources
Glen Canyon National Recreation Area: Geologic Resources Inventory report
"Entrenched Meanders" by Michael Oard
Texas Highways Magazine
National Park Service; Glen Canyon National Recreation Area
Matsubara, Y., et al. (2015). *Geomorphology*, *240*, 102-120.

URANIUM MINING IN NORTHERN ARIZONA

Lori Huseby

Background

The Grand Canyon region of the United States, and specifically northern Arizona, is home to some of the highest grade uranium deposits in the world. The modern history of uranium mining in Arizona is said to have begun in 1948 with the creation of two ore-processing plants. The peak of uranium mining occurred in the 1980's and then has steadily declined. Between 1948 and 1994, a total of 11,650 tons of uranium oxide was mined.



However, there is now new interest in mining as the cost of uranium for power has increased, as well as the need for cleaner energy and energy independence through increases in nuclear power. Currently there are 104 nuclear reactors in the United States that consume approximately 27,500 tons of uranium oxide (UO_2) annually through their fuel rods.

Only 7% of this uranium oxide is mined domestically, and the rest must come from foreign sources. As of 1990, there was over 1.3 million tons of uranium oxide present that had not yet been discovered, which is over three times more than the entire U.S. uranium reserve in 2003. These mines in northern Arizona could provide the extra uranium needed to shift to complete energy independence for the U.S.

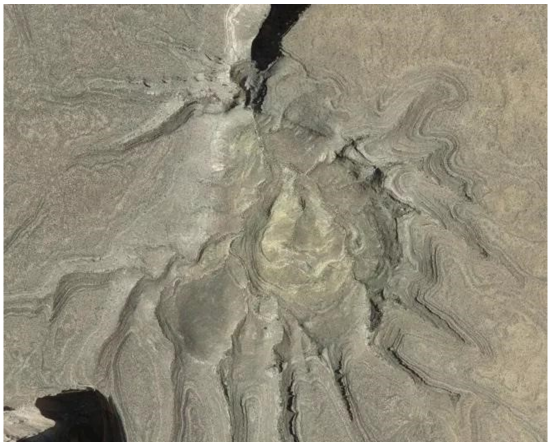
However, due to concerns of contaminated groundwater in the Grand Canyon watershed, over 1 million acres of mineable land was withdrawn in 2009 until 2032. These acres included a national park, two national monuments, a game preserve, and native lands. This involved an estimate of 69% of the total uranium reserves estimated in 1990. This leads us to now, where there are over 100 abandoned mines, and as of 2016 there were three new proposed mines and five existing mines, but there is no active mining in the area.

Geologic Setting

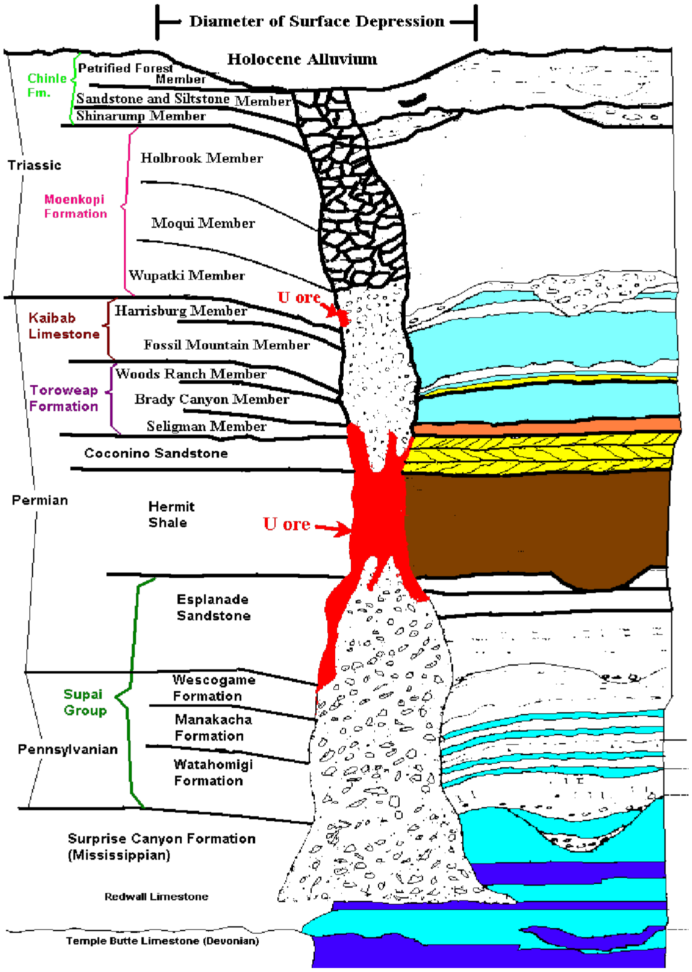
This high quality uranium can be found in breccia pipes.

Breccia pipes are known for:

- Vertical, pipe-like shape
- Broken rock, or breccia fills them
- 300-500ft in diameter at depth
- Forming hundreds of millions of years ago when groundwater dissolved carbonate rock, where these vertical cavities were formed and then the surrounding rock collapsed into the void.
- Highly mineralized groundwater moving vertically through the breccia deposited the ore material, like uranium, into the pipes



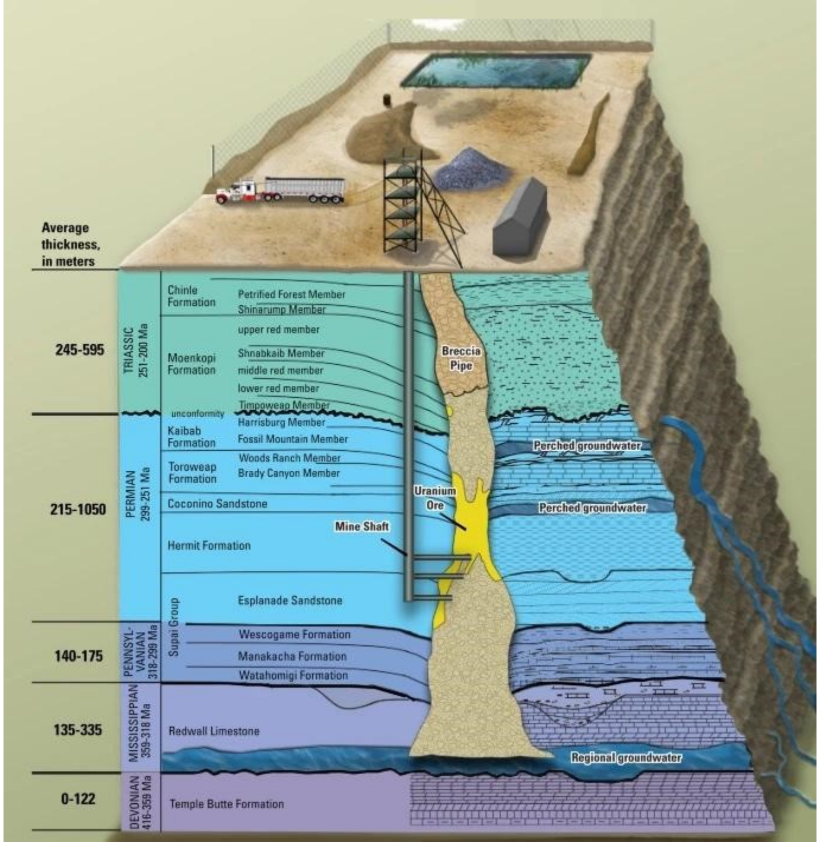
Example of a breccia pipe. A sign of these pipes is the tint of yellow color in the middle of the pipe showing that it is softer than surrounding rock.



Breccia pipes contained not only uranium, but other precious metals such as copper, gold, and silver. These pipes attracted miners many years before uranium mining in 1870 when miners came into the area looking for copper specifically. The copper, gold, and silver were all found at depths less than uranium, the uranium ore was not found until much later. Miners found these close to where rivers and streams were eroding the soft rock, exposing the tops of the pipes. Small pieces of copper were then found and the miners followed the stream until the pipe was found, and mining ensued.

Mining Processes

During the nuclear age, uranium mining was now the focus of these breccia pipes. Uranium ore can look black, a dark yellow/orange, or made of green-brown crystals. A mine shaft would be dug into the rock alongside the breccia pipe, with side shafts being dug into the uranium ore deposits to extract the ore. This ore was then transported to plants where the raw ore was turned into the useful uranium oxide. Many of these mines had very reckless methods to extract the ore, leading to many controversial contaminations in the groundwater and surrounding area, and specifically to the Navajo Nation.



Uraninite, also known as pitchblende, is the Uranium ore found in breccia pipes.

Harmful Effects

In August and October 2009, the USGS conducted field assessments on the groundwater in many abandoned mines on BLM land as well as local rivers and streams north of the Grand Canyon National Park. These samples were then compared to the levels of undisturbed soil with the uranium naturally occurring.

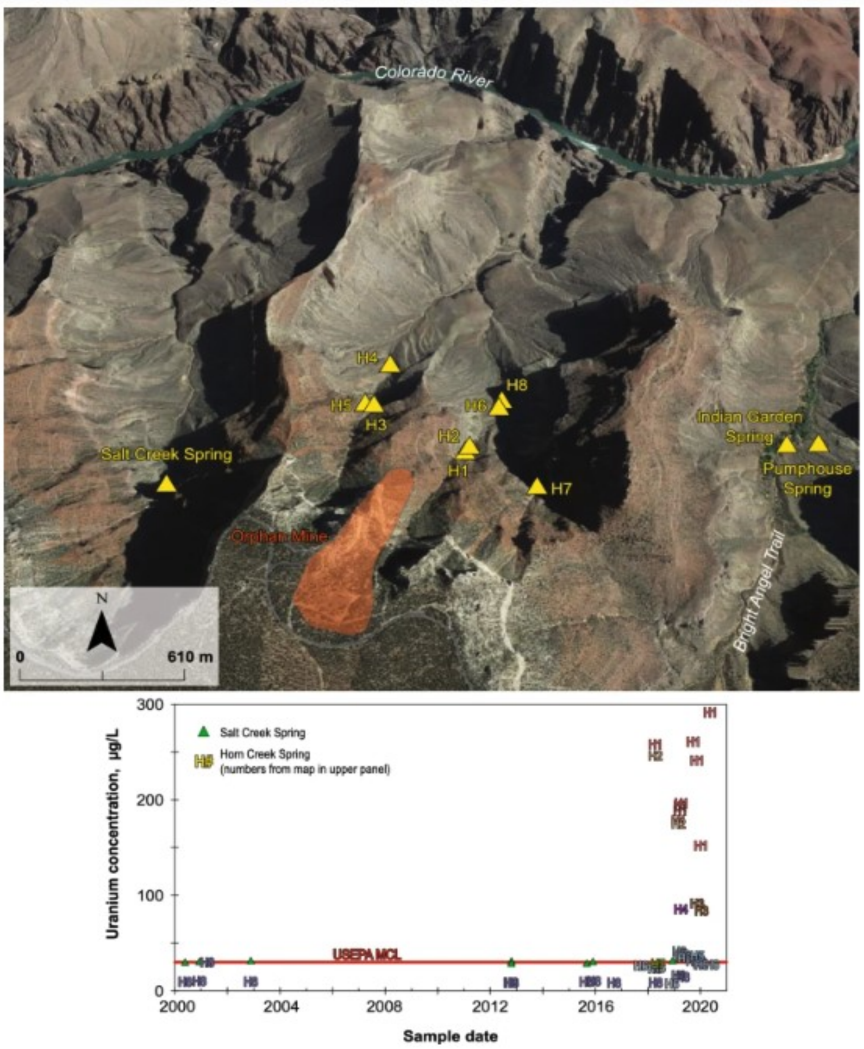
The results are as follows:

- Uranium (9 ppm) and Arsenic (18 ppm) were the largest trace minerals are mined sites and were of the largest concern
- Waste rock and ore have been found downstream by flash floods and mining reclamation efforts
- Wind dispersion of uranium dust was also evident at all sites investigated.

- Further experimentation showed that uranium solubility was proportional to weathering in the area, leaching more contamination
- Elevated but highly variable radioactivity at all mining sites

In a larger analytical study using 573 samples from 180 spring sites and 26 wells from 1981 to 2020, it was found that:

- 95% of samples had a concentration less than the 30 ppm standard for drinking water
- 86% sites being less than the 15 ppm benchmark for Canadian aquatic life.
- There were 8 sites that were over the 30 ppm standard, centering around the Orphan mine.



These sites are ongoing investigations to clarify the link more clearly between the uranium mining and the groundwater chemistry in the area. More groundwater studies must be conducted for years to come as it may take years for the potential effects of the mining to reach groundwater discharge locations.

Planetary Connection

As the availability of these materials declines, or as prices continue to increase, explorations may turn to off-planet mining to mine and process materials like Uranium, Nickel, Cobalt, Titanium, and other metals. It could become a reality of mining on the Moon, Mars, and potential Asteroids within the next 20-30 years. These mining explorations could be done using solar and nuclear processes with no need for human power necessary. This would likely need new methods and technologies in order to mine in little to no gravity, as well as how controlled the drilling process would be.

While this market does exist, there will be a much longer timeline than initially proposed, regarding the processes where uranium can be found, the need for water to be present, and processes to create the source of material, but is a potential for future work, especially regarding Uranium mining. Off-world mining and resource collection would change how collection would continue on Earth as well as the benefits (both economically and resource availability) of opening up an excess of resources available to the human race.

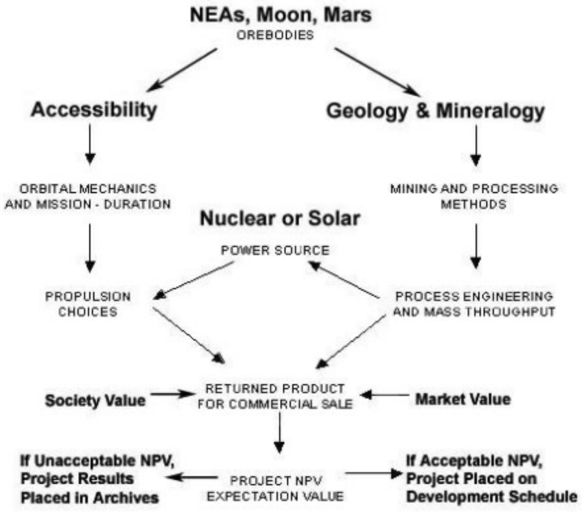


Figure 1 – **Flowchart for Determining Technical and Economic Feasibility of Mining in Space** (After Sonter, 1998).

References:

Bills, D. J., Brown, K. M., Alpine, A. E., Otton, J. K., Van Gosen, B. S., Hinick, J. E., & Tillman, F. D. (2011). Breccia-Pipe Uranium Mining in Northern Arizona—Estimate of Resources and Assessment of Historical Effects. US Geological Survey.

Birdseye, H. S. (1958). Uranium deposits in northern Arizona. In Guidebook of the Black Mesa Basin, northern Arizona: New Mexico Geological Society, 9th Field Conference (pp. 164-168).

Campbell, M. D., Handley, B., Wise, H. M., King, J. D., & Campbell, M. D. (2009, June). Developing Industrial Minerals, Nuclear Minerals and Commodities of Interest via Off-World Exploration and Mining. In Paper/Poster at Conference of the American Association of Petroleum Geologists (AAPG), Energy Minerals Division.

Chenoweth, William L.; Malan, Roger C., 1973, The uranium deposits of northeastern Arizona, in: Monument Valley, James, H. L., New Mexico Geological Society, Guidebook, 24th Field Conference, pp. 139-149. https://doi.org/10.56577/FFC-24.139

Tillman, F. D., Beisner, K. R., Anderson, J. R., & Unema, J. A. (2021). An assessment of uranium in groundwater in the Grand Canyon region. Scientific reports, 11(1), 1-15.

U.S. Department of the Interior. (n.d.). Breccia pipe mining on the Arizona strip and in the Grand Canyon. National Parks Service. Retrieved October 12, 2022, from https://www.nps.gov/para/learn/nature/breccia-pipe-mining-on-the-arizona-strip-and-in-th e-grand-canyon.htm

Oljato Monument Valley

Mackenzie Mills

Overview:

This area shows spectacular erosional remnants—i.e. plains that have undergone significant erosion, separating massive high-standing mesas and buttes that are capped by resistant sandstones, creating the “monuments” in the otherwise rolling valley.

Some spatial sense: (Figure 1)

- Considered part of the Colorado Plateau (sitting between 4500-6500 feet above sea level)[11]
- Located primarily in the Navajo Nation
- Straddles the general intersection of the San Juan and Colorado rivers on the state line between Utah and Arizona
- Popularized in the 1930’s by Hollywood with lots of westerns being filmed here[2]

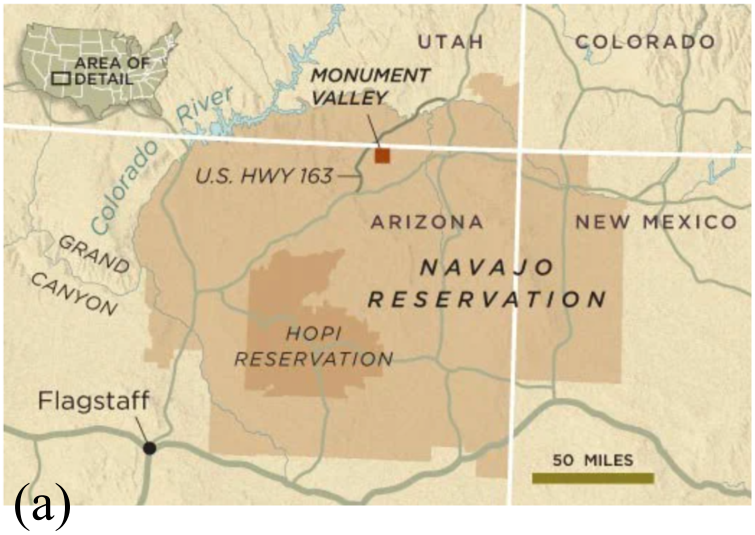


Figure 1: (a) A regional image of where Monument Valley is located regarding the states (and the country)[3]. (b) A Google Maps image of the monuments in Monument Valley, some of which are labeled[4].

Some basic geology:

- In the valley, there are ten primary major formations: Halgaito, Cedar Mesa, Organ Rock, De Shelly, Moenkopi, Owl Rock, Chinle, Wingate, Kayenta and Navajo Formations[2] (see Figure 2)
- The monuments are composed for three primary members: Organ Rock Formation, De Chelly Formation, and the Moenkopi Formation (spanning from Pennsylvanian to Triassic, ~50 Mya)[2]
    - Organ Rock Formation[8,9]:
        - Interbedded sandstones, siltstones, and mudstones (resulting in brown/reddish beds)
        - Late Pennsylvania-Permian in age (~290-272 Mya)
        - ~700 m thick
    - De Chelly Formation[7]:
        - Massive, cross-bedded quartz sandstone, resulting in the resistant layers of the buttes and mesas
        - Mid-Permian in age (~260 Mya)
        - ~300 m thick
    - Moenkopi Formation[5,6]:
        - Interbedded sandstones,

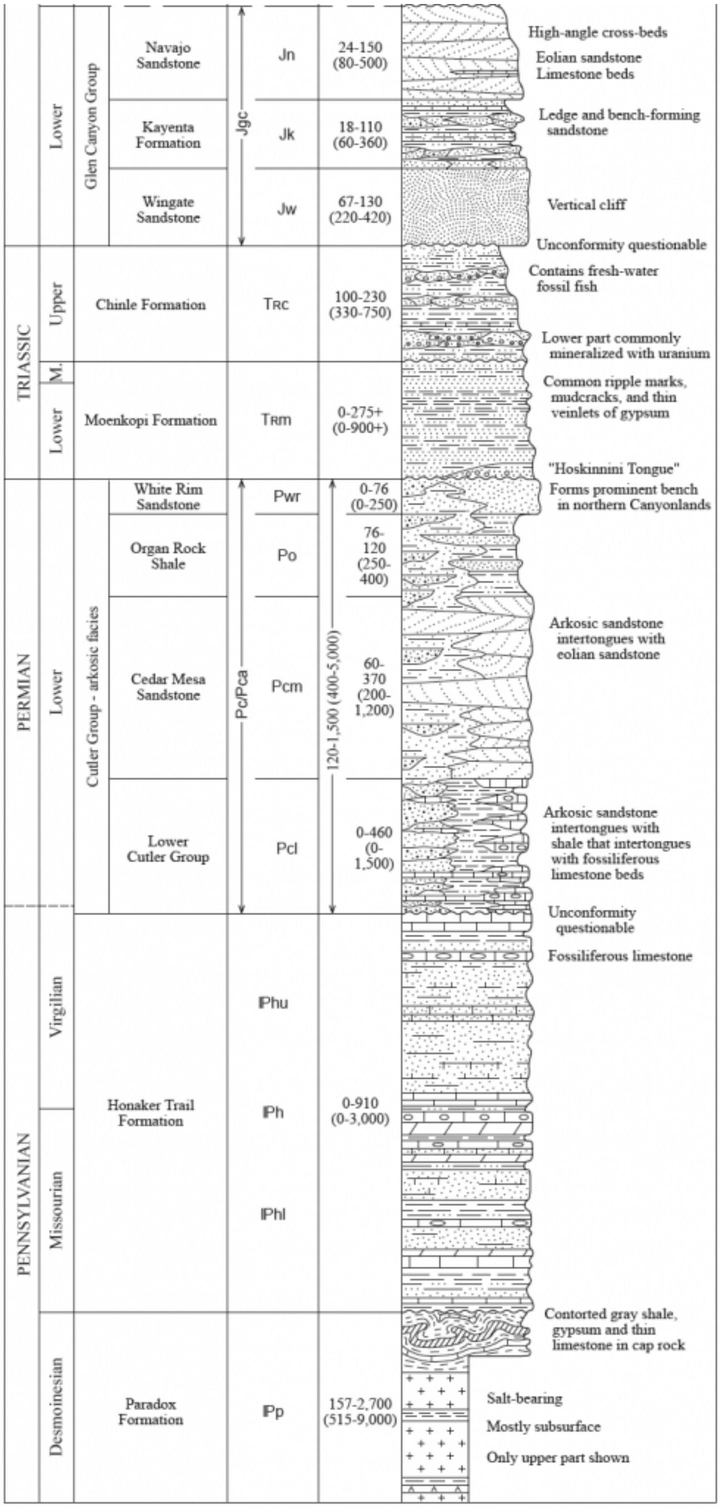


Figure 2: Complete stratigraphy of all units in the region. The primary formations to highlight for Monument Valley are the Organ Rock Shale, the De Challey Formation (labeled here as the White Rim Sandstone), and the Moenkopi Formation[12].

mudstones, and shale, resulting in some "caps" on buttes
    - Characteristic deep red color
    - Younger (relative), so more easily eroded than White Rim—less visible in places
    - Early Triassic to mid-Triassic in age (~240 Mya)
- Some Pliocene volcanics intruded, creating dikes (~2-5 Mya)[10]
- Some regional deformation has generated anti-clines and synclines trending N-S. These are generally asymmetrical and shallow, with 3°W dips and 10-20°E dips[11]

What does the geology tell us about the ancient setting?[2,8]

- First, a fluctuating fluvial environment. Sandstones form along river banks and floodplains, and mudstones and siltstones deposit in middles of river channels. Interbeds have been observed, supporting the idea of meandering river systems covering this locality.
- Then a marine transgression occurs, with rising sea levels (see Figure 3)
- The marine environment then had fluctuations, ranging from deep marine (shales, limestones) to drier times when the area was primarily beaches or river systems and floodplains (sandstones, interbedded with mudstones)
- Some volcanic activity created the dikes
- Now, it is dry and arid, like much of the southwest, undergoing continuous erosion

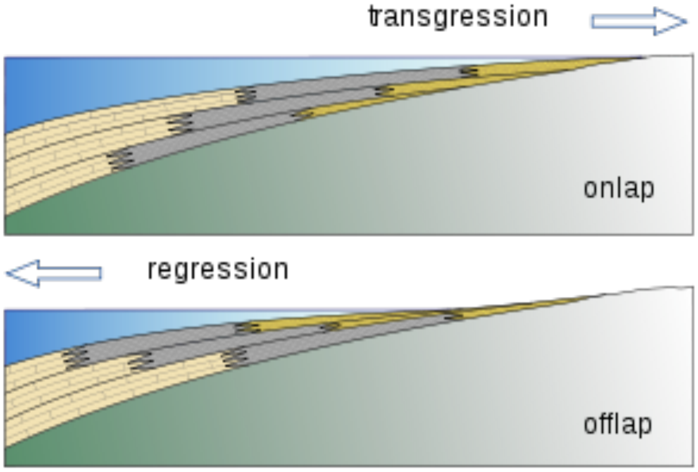


Figure 3: An introductory schematic of marine transgression and regression

Monument Index of Buttes[1,2,13]:
(named by the Navajo people or immigrating settlers)

- Mitchell & Merrick Butte: Named after two silver prospectors
- Three Sisters: Resembles three tall and narrow fingers close together
- Yei'bi'chei: Named after a Navajo god, resembling a dancer
- West and East Mitten: Resembles hands
- Castle Rock: Resembles a castle
- Bear and Rabbit: Resembles a bear and rabbit
- Stage Coach: Resembles a stage coach
- King on his Throne: Resembles a king on his throne
- Saddleback: Resembles a saddle
- Camel Butte: Sort of looks like a camel
- Elephant Butte: Sort of looks like an elephant
- Cly Butte: Named after a well-known Navajo medicine man who is buried at the foot of the formation. "Cly" is Navajo for "left".

Most of these buttes are labeled in Figure 4, along with some nearby mesas.

Figure 4: A labeled diagram of prominent buttes in Monument Valley (Photo from artist James Orndorf[2]).

References:

1. National Park Service, 2014, Navajo National Monument: http://www.nps.gov/nava/index.htm (March 2014).
2. Beauchene, Grenier, and Palmer, Monument Valley, accessed from the University of Rhode Island on 10/12 at https://web.uri.edu/geofieldtrip/monument-valley/#
3. Behind the Scenes in Monument Valley, accessed from the Smithsonian Magazine on 10/12 at https://www.smithsonianmag.com/travel/behind-the-scenes-in-monument-valley-4791660/
4. Monument Valley: An icon of the American West, accessed from the NASA Earth Observatory on 10/12 at https://earthobservatory.nasa.gov/images/92242/monument-valley-an-icon-of-american-west
5. Fillmore, Robert (2011). Geological evolution of the Colorado Plateau of eastern Utah and western Colorado, including the San Juan River, Natural Bridges, Canyonlands, Arches, and the Book Cliffs. University of Utah Press.
6. Lucas, Spencer G. (2017). “Triassic-Jurassic stratigraphy in southwestern Colorado” (PDF). New Mexico Geological Society Field Conference Series. 68: 149–158. Retrieved 26 May 2020.
7. Wood, G.H.; Northrop, S.A. (1946). “Geology of Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico”. U.S. Geological Survey Oil and Gas Investigations. Preliminary Map OM-57.
8. Stanesco, J.D.; Dubiel, R.F.; Huntoon, J.E. (2000). "Depositional Environments and Paleotectonics of the Organ Rock Formation of the Permian Cutler Group, Southeastern Utah". Utah Geological Association Publication. 28: 1–15.
9. Cain, S.A.; Mountney, N.P. (2009). "Spatial and temporal evolution of a terminal fluvial fan system: the Permian Organ Rock Formation, South-east Utah, USA". Sedimentology. 56 (6).

10. Gregory, H. E., 1917, Geology of the Navajo Country, a reconnaissance of parts of Arizona, New Mexico, and Utah: U.S. Geol. Survey Prof. Paper 93.
11. Baker, A. A., 1936, Geology of the Monument Valley-Navajo Mountain region, San Juan County, Utah: U.S. Geol. Survey Bull. 865.
12. Doelling, H. H. and Chidsey Jr., T. C. (2009), Dead Horse Point State Park and vicinity geologic road logs, Utah, The Paradox Basin Revisited, New Developments in Petroleum Systems and Basin Analysis, 635-672.
13. Monument Valley Visitor guide, by Utah's Canyon Country, accessed on 10/12 at https://www.utahscanyoncountry.com/Monument-Valley-Oljato
14. Monroe, James Stewart, and Reed Wicander. Physical Geology: Exploring the Earth. Fifth edition; Thomson Brooks/Cole, 2005; p. 162.

Roberto Aguilar

Droneborne Photogrammetry

Drone photogrammetry involves capturing large volumes of 2D images over a geographical area and compiling them to create 3D topographical models and orthomosaic maps or images created from photographs collections [1]. Orthomosaics and DTMs enable measurements of distances, areas, volumes, and slopes. This methodology has been previously used in geologic studies, including stratigraphic characterization of fluvial deposits [2]

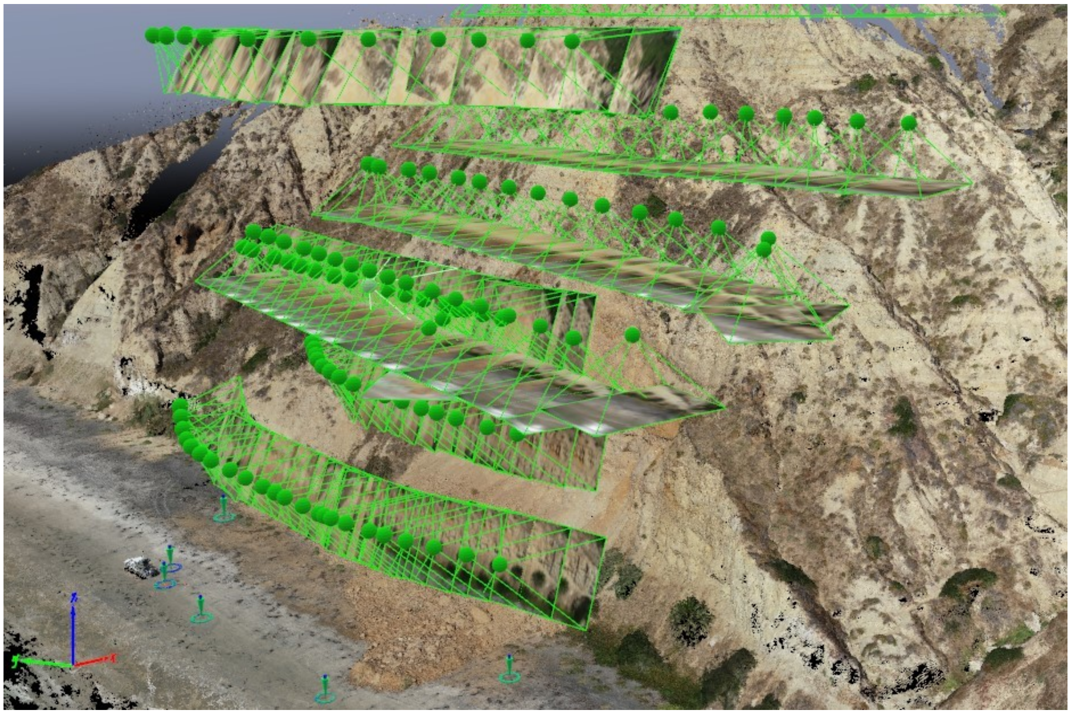


Fig 1. Examples of the cameras obtained with a drone survey. It includes vertical images (nadir) and oblique images with different angles. Source: [3].

Technology:

Equipment for the survey:

- Drone: Phantom 4 RTK
- GNSS receivers: Emlid RS2 (base and rover)

Software for post-processing:

- Emlid Studio
- Agisoft Metashape
- QGIS

Data acquisition and validation

For the survey, we will use post-processing kinematics (PPK) [4]. This means that the GNSS base receiver will be set to read raw data from different GNSS sources (GPS, GLONASS, GALILEO) in RINEX format while the drone is capturing photos and storing the raw GNSS data as well.

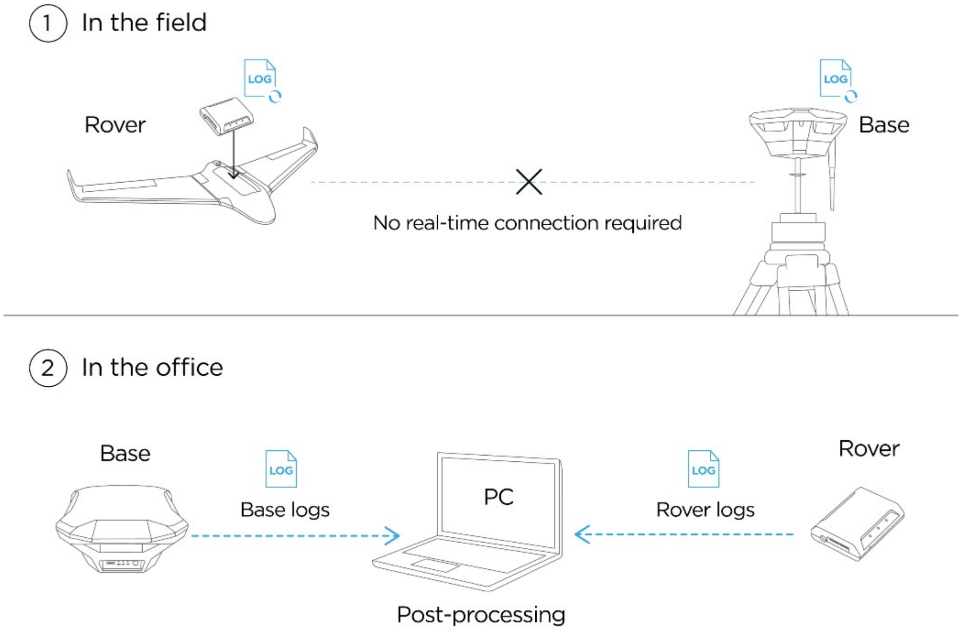


Fig 2. Diagram of the survey and processing of PPK

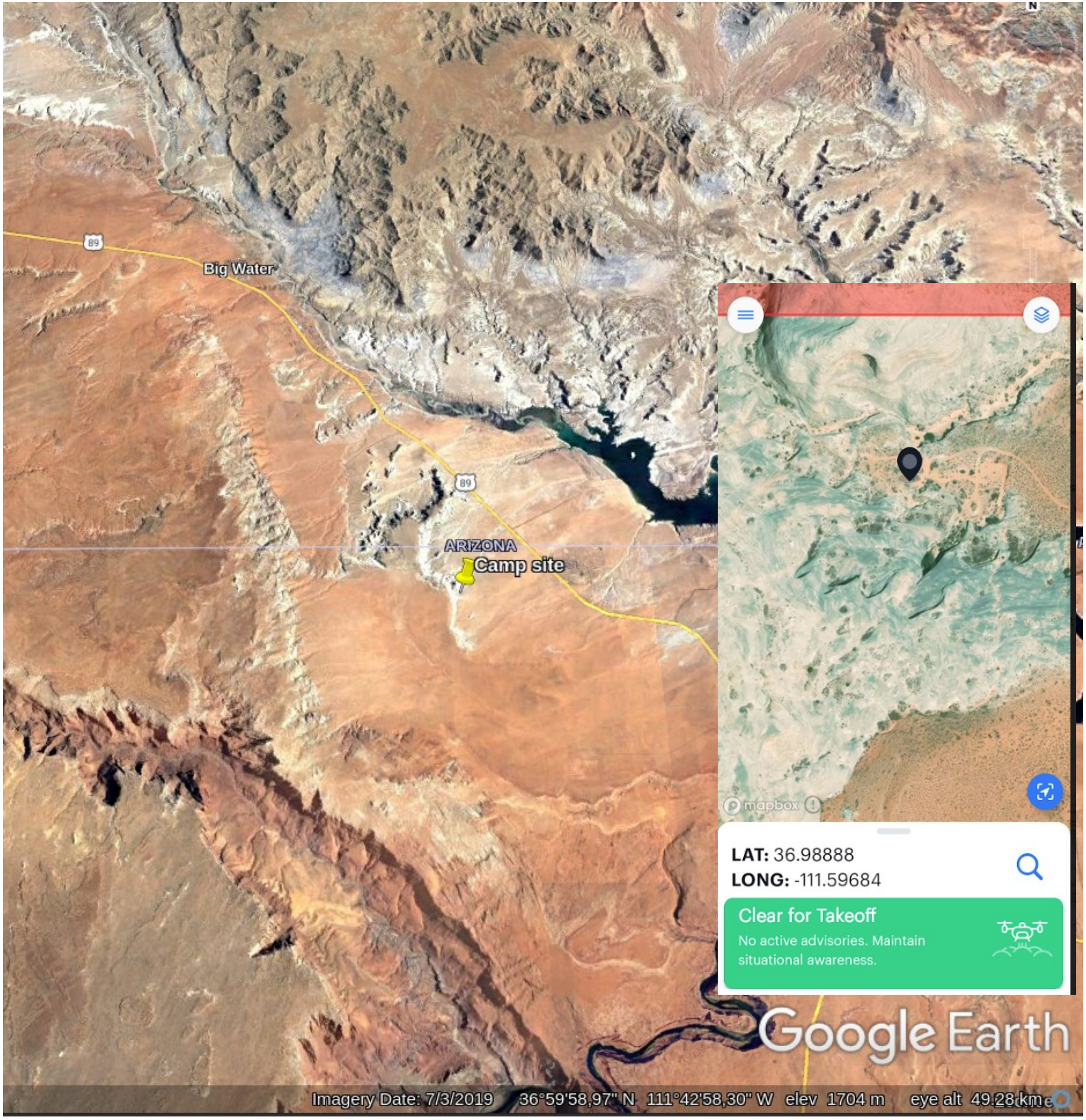
For validation of the accuracy of the measurements, we will include markers and ground control points (GCP) and take measures in situ.

Final products

- Orthomosaic from vertical images (nadir) of the area of study (see Fig 4)
- Orthomosaic from oblique images of a wall (see Fig. 5 and Fig. 6)
- Digital elevation model

Location

Due to the drone flight restrictions in National Parks and Navajo Nation, we decided to make the survey in the area of the campsite (see Fig.)



LAT: 36.98888
LONG: -111.59684

Clear for Takeoff
No active advisories. Maintain situational awareness.

Fig. 3. Study site with clearance for takeoff, source B4UFLY mobile app.

Fig. 5. Views from the study site from Google Earth 3D.

References

[1] https://www.irisonboard.com/what-is-drone-photogrammetry/

[2] Lewis et al., Fluvial Architecture of the Burro Canyon Formation Using UAV-BasedPhotogrammetry and Outcrop-Based Modeling.

[3] https://siocpg.ucsd.edu/technology/photogrammetry-2/

[4] https://docs.emlid.com/reachrs2/ppk-quickstart/ppk-introduction/

Passive Seismic Experiment

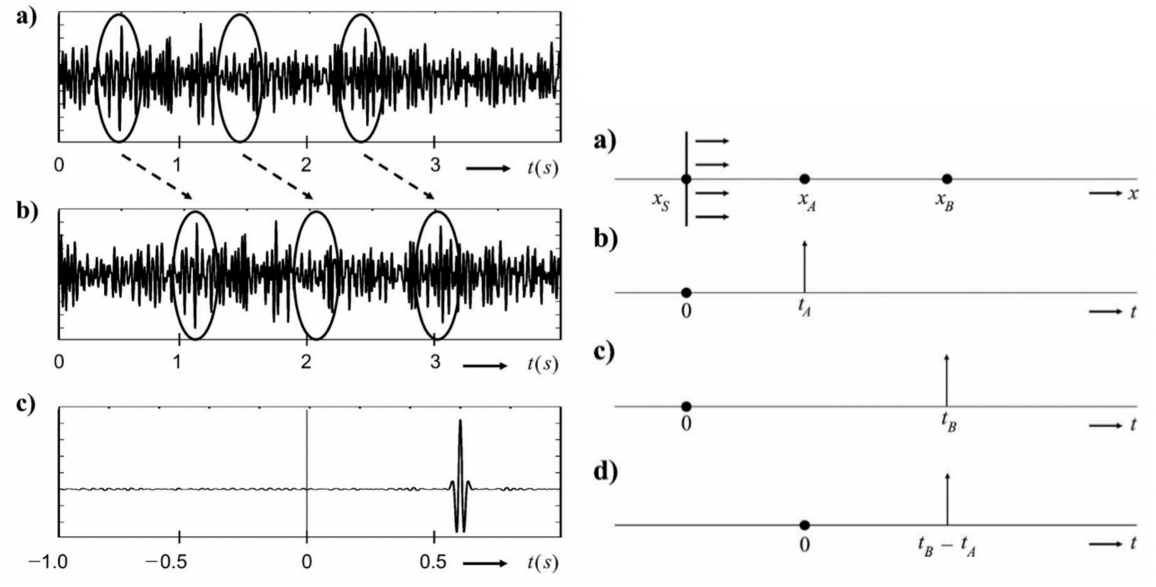
Naman Bajaj, Namya Baijal, Reed Spurling, Rishi Chandra

We're deploying a few Raspberry Shake devices to take seismic measurements of ambient noise at several sites on our field trip. The following is a primer on the context and principles behind what we're doing, a little bit about what we think we might find, and how this relates to planetary science.

Introduction

Among the various methods of imaging the Earth's subsurface, the one most used is *active* seismology, not passive, valued for its use in oil and mineral exploration. This method requires an anthropogenic seismic energy source, such as an explosive source or an active vibroseis. Ambient seismic waves/ micro-earthquakes (naturally occurring) are always present in the data collected for active seismology but are regarded as noise and are generally removed from the data and subsequent analysis. Conventional passive seismology typically uses the seisms of distant earthquakes to permit similar analysis where active source seismology would be cost or labor prohibitive. Recent advances have, however, allowed scientists to extract useful information about the Earth's subsurface from the ambient noise wavefield at low frequencies (<20 Hz).

The basic principles enabling ambient noise seismology have been known for decades; two widely used methods are (i) <u>Interferometry:</u> a seismic signal (on surface or underground) is recorded by adjacent seismometers; the difference between the two recordings provides information about the intervening underlying rock (see the figure below). (ii) <u>Horizontal-toVertical Spectral Ratio (HVSR):</u> Ambient-noise vibrations are recorded in the three spatial components and the processing consists of estimating the ratio between the Fourier amplitude spectra of the horizontal (H) to vertical (V) components. This gives us crucial information about the fundamental resonance frequency of the ground. As can be seen, HVSR is a passive seismology method which can be performed using a single 3-D seismometer and hence, widely applicable. We will discuss HVSR in much more detail in the later sections.



Left figure: (a) shows the propagation of 1-D seismic wave through two seismometers xA and xB. tA and tB are the time intervals at which the wave is recorded at xA and xB respectively. (d) shows the relative time interval between xA and xB. **Right figure:** (a) and (b) show the signal recorded at xA and xB respectively. A cross-correlation is performed between the two and the resulting signal is shown in (c) which can now be used to trace the relevant parameters of the seismic source. Example from [1]

The most widely used source of seismic energy has been micro-earthquakes or low magnitude earthquakes. An example of this can be deformation monitoring for reservoir management. The overall deformation of the rock surrounding the producing reservoir (or zone of injection), as well as spatial variation in pore pressure, can alter the state of stress in the host rock; subsequent changes in either pore pressure or deformation-induced stresses can then cause seismic events, even though these may occur at conditions that would not have originally induced seismicity. The other sources include ambient noise consisting of wind, sea waves, tides, etc. and human-activity generated noise - for example, while trying to map the subsurface rock structure of a city, the traffic, vehicle movement, industry, etc. can be used as the energy source for continuous monitoring. These applications and continuous monitoring possibility using passive noise seismology is nearly impossible through active seismology as the energy source in active seismology remains active only for a limited amount of time, while passive sources can be detected indefinitely.

Citations:

1. Wapenaar, Kees & Draganov, Deyan & Snieder, Roel & Campman, Xander & Verdel, Arie. (2010). Tutorial on seismic interferometry. Part I: Basic principles and applications. Geophysics. 75. 75A195-75209. 10.1190/1.3457445.

Passive Seismic Methods

During the field trip, there are **two** main passive seismic methods we seek to use to better interpret the shallow subsurface structure. There are several difficulties associated with imaging shallow structures in the Earth's crust due to seismic resolution constraints. These techniques allow us to not only resolve the soft sedimentary layer thickness but also image the depth of shallow structures such as the Moho (crust-mantle boundary).

In traditional seismology, receiver function analysis is performed on teleseismic (distant earthquakes) recorded by a seismometer, to model the amplitude and timing of its body wave reflections (Figure 1). This yields important results about the underlying geology of the region by recording reflections from sharp boundary layers. However, the Moho can often be difficult to interpret if this boundary is gradational and/or these crustal reverberations are diffuse. Additionally, we must rely on using earthquake data from an array of seismometers for best results.

Instead, we can make use of the fact that the reflectivity response of the Earth can be extracted from ambient noise data using passive seismic methods and thereby retrieve the body wave reflections (P waves). These methods are known as horizontal to vertical spectral ratio (HVSR) analysis and noise autocorrelation.

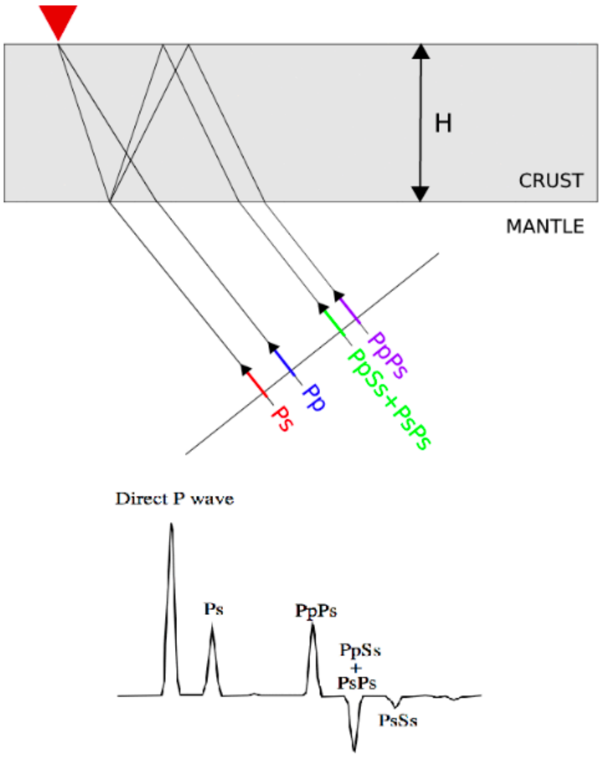


Figure 1: Velocity structure beneath a seismic station (in red) representing the conversion of P waves into various crustal phases. Reflections of these phases from the Moho allow estimation of crustal thickness.

Horizontal to Vertical Spectral Ratio (HVSR) Analysis

The HVSR method analysis involves recording microtremors using a three-component seismometer. This includes three instruments (geophones), two to record horizontal waves in the north-south direction and another to record east-west waves, and finally one to record the vertical ground motions. The device is then left to record passive ground motions for 20-30 minutes. The next step of the analysis involves the conversion of each of the horizontal and vertical directions into a frequency spectra by applying a Fourier transform. Next, the mean of the two horizontal frequency spectra is taken and divided by the vertical spectra to form a horizontal to vertical spectral ratio (Figure 2). For ambient noise that arises due to local sources within the sedimentary layer, H/V ratios exhibit only one strong peak that represents natural resonant frequency of the ground. For sources deeper in the sedimentary layer, H/V ratios exhibit two peaks. One is produced by the local resonant frequency due to a mixture of surface and body waves and the other produced by S waves from the sediment-bedrock interface. For sources within the bedrock, the H/V ratio peaks are dominated by multiple S waves.
In summary, this method allows us to recognise the impedance (density and seismic velocity) contrast between unconsolidated sediment and bedrock thereby allowing for estimates of sedimentary thicknesses. This can then be extended to the construction of a full S wave velocity profile.

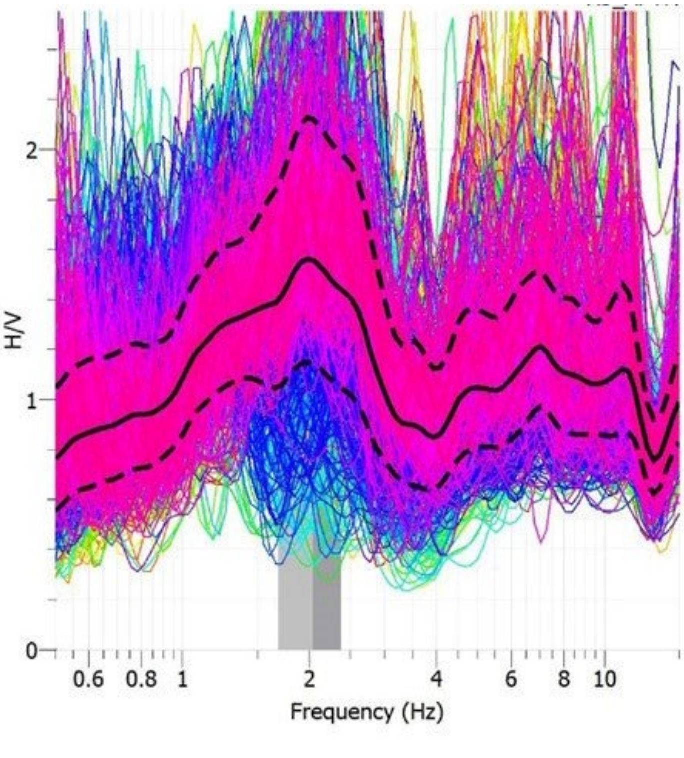


Figure 2: Representation of a H/V frequency spectra. The peak at 2Hz represents the natural resonant frequency of the ground.

Noise Autocorrelation

Ambient noise autocorrelation is a method of particular importance when only a single seismometer is available. It permits the determination of the zero-offset reflection response of the subsurface. Along the vertical component of the seismogram, the autocorrelated wavefield estimates the reflectivity response of the earth as if it were vertically oriented source at the surface with no offset. The next step involves phase-weighted stacking. The waveforms with similar instantaneous phases are stacked to obtain a high signal-to-noiseratio. This produces a 1-D profile of the wave reflectivity of the subsurface at each station where the recording is taken across a range of slowness values (1/velocity). In addition, bandpass filtering of the frequencies needs to be performed across the waveforms to enhance the arrivals.

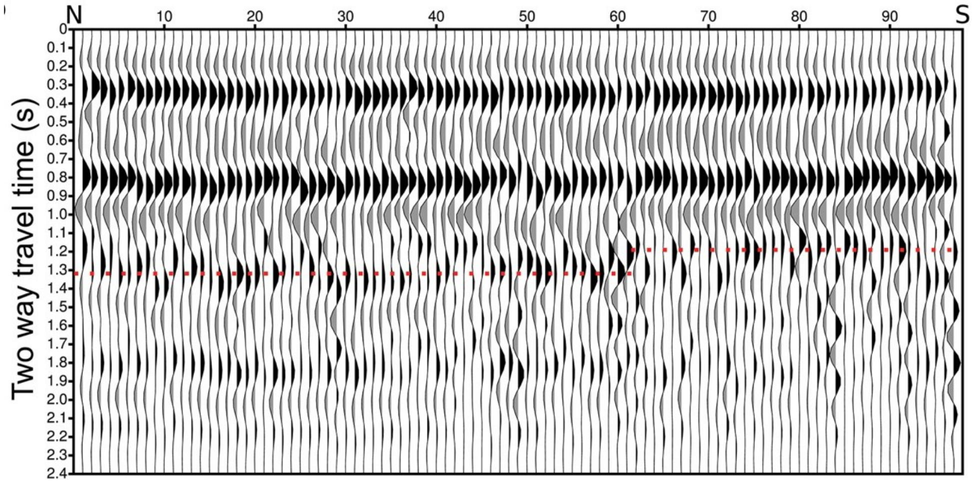


Figure 3: Stacked waveforms sorted from N-S. The red dashed line represents the reflection from the interface between the basin and bedrock obtained from the second autocorrelated arrival.

References

Becker, G. and Knapmeyer-Endrun, B., 2018. Crustal thickness across the Trans-European Suture Zone from ambient noise autocorrelations. *Geophysical Journal International*, *212*(2), pp.1237-1254.

Ground investigation, horizontal to vertical spectral ratio analysis,

https://www.g-i.co.nz/our-services/horizontal-to-vertical-spectral-ratio-analysis-hvsr/

Saygin, E., Cummins, P.R. and Lumley, D., 2017. Retrieval of the P wave reflectivity response from autocorrelation of seismic noise: Jakarta Basin, Indonesia. *Geophysical Research Letters*, *44*(2), pp.792-799.

Schimmel, M., Stutzmann, E., Lognonné, P., Compaire, N., Davis, P., Drilleau, M., Garcia, R., Kim, D., Knapmeyer-Endrun, B., Lekic, V. and Margerin, L., 2021. Seismic noise autocorrelations on Mars. *Earth and Space Science*, *8*(6), p. e2021EA001755

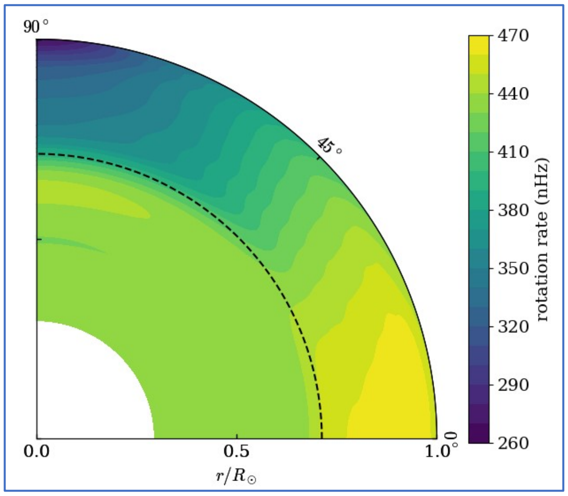
Sylvette, B.C., Cécile, C., Pierre-Yves, B., Fabrice, C., Peter, M., Jozef, K. and Fäh, D., 2006. H/V ratio: a tool for site effects evaluation. Results from 1-D noise simulations. *Geophysical Journal International*, *167*(2), pp.827-837.

Ullah, I. and Prado, R.L., 2017. Soft sediment thickness and shear-wave velocity estimation from the H/V technique up to the bedrock at meteorite impact crater site, Sao Paulo city, Brazil. *Soil Dynamics and Earthquake Engineering*, *94*, pp.215-222.

Xu, R. and Wang, L., 2021. The horizontal-to-vertical spectral ratio and its applications. *EURASIP Journal on Advances in Signal Processing*, *2021*(1), pp.1-10.

Seismology Everywhere!

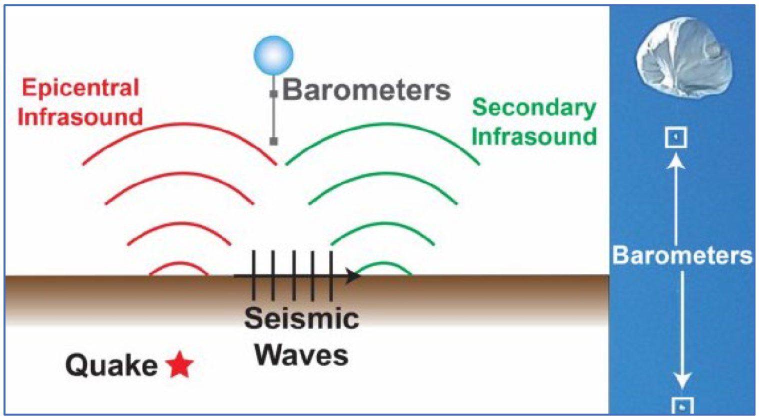
Introduction: Seismology, broadly, is the study of quakes and of the propagation of waves through substances. Because seismology can elucidate the material properties and interior structures of a broad range of objects, it is applicable throughout the solar system and beyond. Seismology has thus far been applied to Earth, the Sun, the Moon, Mars, and comet 67/P Churyumov–Gerasimenko.



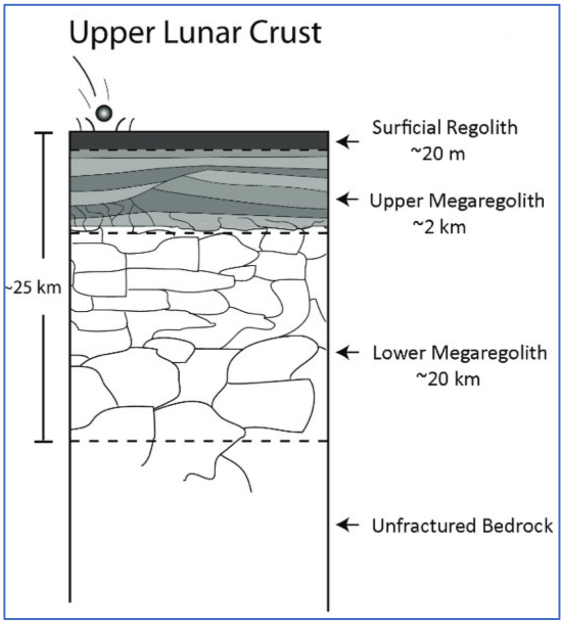
The Sun: The field of helioseismology uses oscillations in the Sun's outer layers to probe its interior structure. We have learned much about the Sun this way [1]. One notable discovery from helioseismology is of the tachocline (dashed line in image), a boundary between the convective outer region and mostly non-convective interior of the Sun [2]. Image (left) by Warrickball on Wikimedia, from Solar Dynamics Observatory (SDO) data.

Mercury: Potential sources of seismic activity include wrinkle ridges (maybe still active), tidal forces, and the sharp temperature difference between Mercury's day and night sides [3]. Seismology could be used to measure Mercury's core, though it would be difficult to get a lander to the planet; Carolyn Ernst led a recent study of such a mission [4].

Venus: The seismicity of Venus is unknown, but potential active volcanism and tectonism could be seismic sources there [3]. It would be difficult to build a seismometer for the surface of Venus, but infrasound detectors (barometers) on balloons could be used instead, as successfully demonstrated on Earth [5]. Image (right) from [6].



Earth's plate tectonics, lunar tidal forces, volcanism, and human activity provide a wealth of seismic sources. Earth's varied geography and interior structure likewise enable a huge variety of uses for seismology, giving us examples of how seismology might be used on other planets.



The Moon was the location of the first extraterrestrial seismic network, deployed by the Apollo missions and tragically deactivated in 1979. Several previous seismic instruments launched in the Ranger program were not successfully landed. The Farside Seismic Suite investigation, led by Mark Panning, has been selected for delivery to Schrödinger basin on a near-future Commercial Lunar Payload Services (CLPS) mission. The Moon's brittle crust—likely similar to Mercury's—has been fractured (by impacts) into large blocks known as megaregolith, which strongly diffract seismic waves, posing a challenge to lunar seismologists [3]. Image (left) from James E. Richardson and Oleg Abramov.

Mars has only recently been seismically investigated, after a string of failed attempts on the

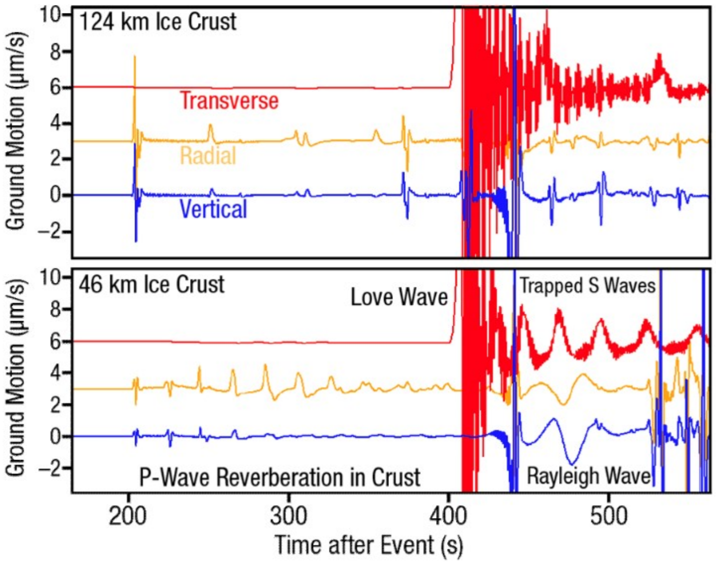
Viking, Mars 96, and Deep Space 2 missions [7]. The InSight mission has now showed that Mars has a moderate level of seismic activity. Much of the activity detected by InSight is centered in the Cerberus region [3], where tectonism may be associated with actively widening cracks (fossae) and very recent volcanic and fluvial activity. Ask Dr. Hamilton about this. InSight's seismometer has also detected and located meteoroid impacts [8].

Phobos and Deimos were the target of seismic investigations on the Phobos 1 and 2 missions, but these missions failed [7]. The upcoming Martian Moons Explorer (MMX) mission may use its inertial measurement unit as a seismometer to study the enigmatic structure of Phobos [3].

Asteroids, Comets, and Interstellar Objects are promising targets for seismology. The Philae lander operated an active seismic experiment on comet 67/P Churyumov–Gerasimenko but returned limited data. Lessons learned from Philae for future missions include 1) the need for direct communication between the electronics of seismometers and of active seismic sources (hammers, etc.) and 2) the need for instruments to have high computer clock speeds to account for the short travel times of seismic waves in small bodies [9].

Ceres is relatively easy to get to, and has a mysterious interior structure, though its seismicity is likely low [3]. I say we might as well try.

The Giant Planets of our solar system very helpfully come pre-outfitted with giant seismometers—the rings of Saturn record periodic normal-mode (compressional) oscillations of material in the interiors their host planet, and similar phenomena may be detectable in the rings of Jupiter, Uranus, and Neptune [3]. Matthew Hedman has some cool papers on this subject [10].



Icy Moons are often strongly affected by tidal forces that cause seismic activity. Ongoing geologic activity on Enceladus and Europa should make them especially valuable places to do seismology. Ask Rishi about special considerations for seismometers on ice sheets.

Titan: The Dragonfly mission to Titan, led by LPL alum Zibi Turtle, plans to include a seismometer that may help us determine whether a subsurface ocean exists on Titan. Image (above) from [11], showing simulated measured waveforms from a Magnitude-4 seismic event on Titan at two possible ice crust thicknesses.

Exoplanets are likely seismically active, "and many exoplanets should exhibit more seismic activity than the Earth" [12]. How might we detect this activity?

References

[1] Gough, D. O., Leibacher, J. W., Scherrer, P. H., Toomre, J. (1996). Perspectives in helioseismology. Science, 272(5266), 1281–1283. https://doi.org/10.1126/science.272.5266.1281

[2] Howe, R. (2009). Solar Interior Rotation and its Variation. Living Reviews in Solar Physics, 6. https://doi.org/10.12942/lrsp-2009-1

[3] Stähler, S. C., & Knapmeyer, M. (2022, June 3). Seismology in the Solar System. arXiv. Retrieved from http://arxiv.org/abs/2206.01785

[4] Ernst, C. M., Kubota, S., Chabot, N., Klima, R., Rogers, G., Byrne, P., et al. (2021, July 14). Mercury Lander: Planetary
Mission Concept Study for the 2023-2032 Decadal Survey. arXiv. https://doi.org/10.48550/arXiv.2107.06795

[5] Brissaud, Q., Krishnamoorthy, S., Jackson, J. M., Bowman, D. C., Komjathy, A., Cutts, J. A., et al. (2021). The First Detection of an Earthquake From a Balloon Using Its Acoustic Signature. *Geophysical Research Letters*, *48*(12), e2021GL093013. https://doi.org/10.1029/2021GL093013

[6] Krishnamoorthy, S., Komjathy, A., Cutts, J., Lognonné, P., Garcia, R., Panning, M., et al. (2021). Seismology on Venus with infrasound observations from balloon and orbit. *Bulletin of the AAS*, *53*.

https://doi.org/10.3847/25c2cfeb.9f0f1917

[7] Lognonné, P., & Johnson, C. L. (2015). Planetary Seismology. In Treatise on Geophysics (pp. 65–120). Elsevier. https://doi.org/10.1016/B978-0-444-53802-4.00167-6

[8] Garcia, R. F., Daubar, I. J., Beucler, É., Posiolova, L. V., Collins, G. S., Lognonné, P., et al. (2022). Newly formed craters on Mars located using seismic and acoustic wave data from InSight. Nature Geoscience, 1–7. https://doi.org/10.1038/s41561-022-01014-0

[9] Knapmeyer, M., Fischer, H.-H., Knollenberg, J., Seidensticker, K. J., Thiel, K., Arnold, W., et al. (2016). The SESAME/CASSE instrument listening to the MUPUS PEN insertion phase on comet 67P/Churyumov–Gerasimenko. Acta Astronautica, 125, 234–249. https://doi.org/10.1016/j.actaastro.2016.02.018

[10] Hedman, M. M., & Nicholson, P. D. (2013). KRONOSEISMOLOGY: USING DENSITY WAVES IN SATURN'S C RING TO PROBE THE PLANET'S INTERIOR. *The Astronomical Journal*, *146*(1), 12. https://doi.org/10.1088/0004-6256/146/1/12

[11] Lorenz, R., Panning, M., Stähler, S. C., Shiraishi, H., Yamada, R., & Turtle, E. P. (2019). Titan Seismology with Dragonfly : Probing the Internal Structure of the Most Accessible Ocean World. Presented at LPSC.

[12] Hurford, T. A., Henning, W. G., Maguire, R., Lekic, V., Schmerr, N., Panning, M., et al. (2020). Seismicity on tidally active solid-surface worlds. *Icarus*, *338*, 113466. https://doi.org/10.1016/j.icarus.2019.113466

Slot Canyons

Allison McGraw

Rapid erosional processes at their finest!

Some crack to kickstart it all. The vertical sheer (Fig. 1) appears near when a small niche opens up. Some depressive topographic low becomes an erosional focal point, sinking below further. A focused point, a disjoint, a structural failure ends up becoming fluvial mechanical success (Fig.2), becoming a conduit for mass movement wasting of considerable proportions. Hundreds to thousands of cubic meters per second of discharge describes a typical flash food rate which carves and creates a slot canyon. An average daily discharge the rate is more like 2-4 cubic meters per second (Fig. 3).

Figure 1. (Left). Sheer vertical cliff in Buckskin Gulch ~1000 meters tall. **Figure 2. (Right)** The Paria River flowing through Paria Canyon. *Credit: The American Southwest*

Differential erosion. Down-cutting. Of geomorphic origins, the streams that encounter steep topography tend to undergo a continual downcutting experience. Ripping both fine and course-grain material off act as a sediment source with no deposition in sight. Big sediment loads are sustained downstream by high gradients of channels imparting sufficient energy for water to maintain particles. Dumping deposition of particles occurs when a stream emerges from steep terrain to that of flat. AKA the gradient of the channel decreases and flows spread out and lose energy. This creates sediment banks and sink and become a floodplain. The fate of a floodplain isn't forever. It may then turn into a sediment source when some hydraulic change locally occurs.

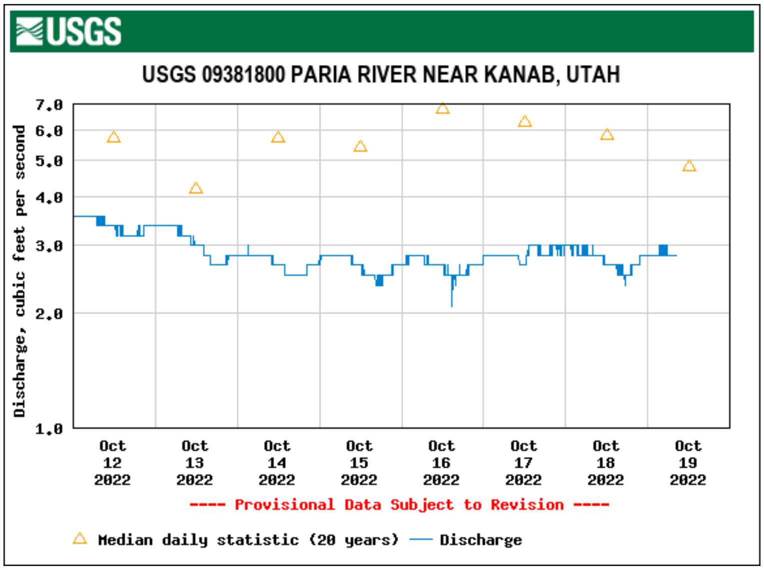


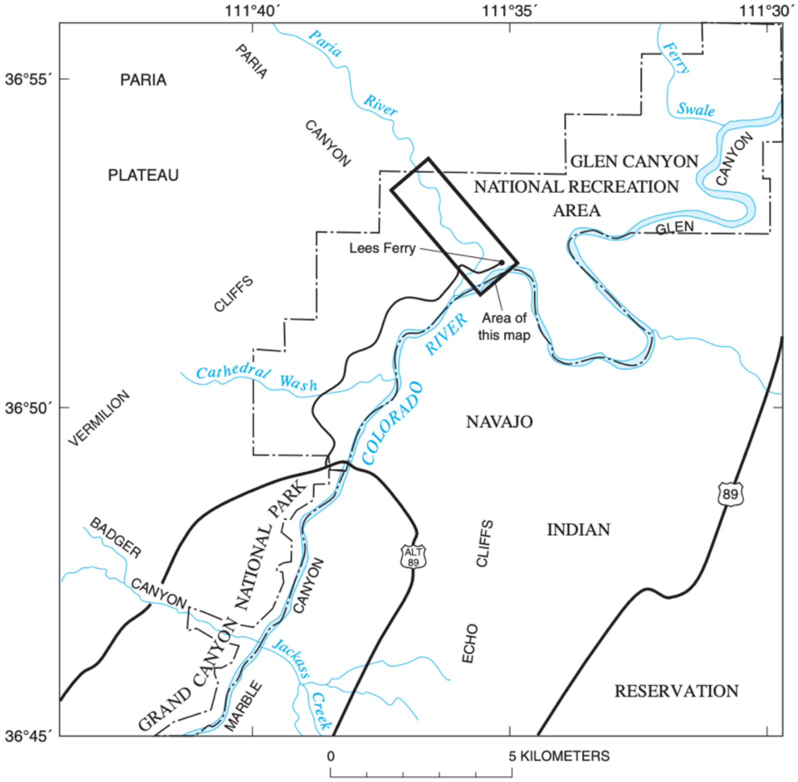
Figure 3: Discharge in cubic feet per second for the Paria River gage station.

Changes to local hydrology are typically due to shifts in climate patterns as well as anthropogenic influences.

Notice the height of deposited materials. If we see any of the alluvial outcrops look for (abrupt) changes in grain sizes. “Walls of knowledge”.

Flash floods in slot canyons make up the most fatalities in Utah for natural disasters. With a September 2015 event killing 20 people, 15 of which were in slot canyons in Zion National Park (Smith et al. 2019). The peak discharge for the event of ~500 kilometers^2 was 266 cubic meters per second.

<u>Paria Canyon & Buckhorn Gulch</u>



This is the longest slot canyon in the world! You can backpack the entire section in a few days (Fig. 4).

The Paria River is a perennial river that joins the Colorado River downstream of Lee’s Ferry.

Figure 4: Map with inset of the Paria slot canyon location and the confluence with the Colorado River after Lee’s Ferry. *Credit: USGS*

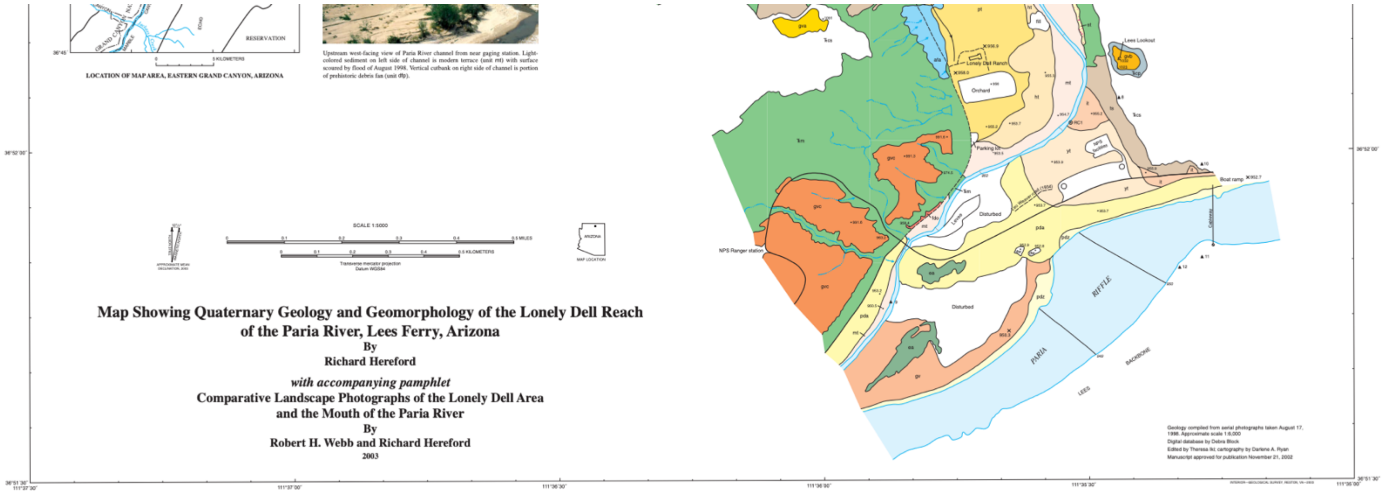
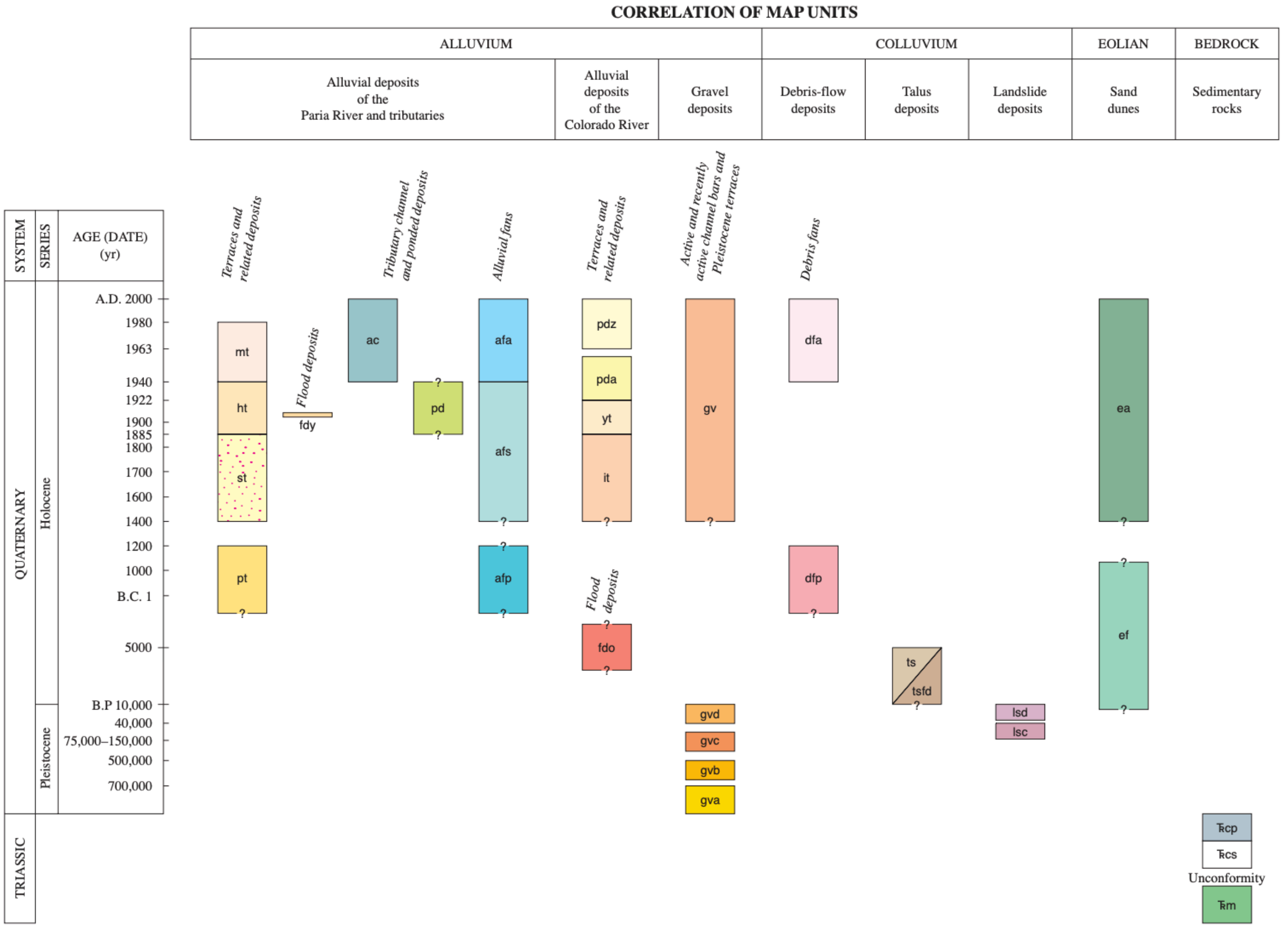


Figure 5 (Above): Map of lower area of the Paria River and Canyon. *Credit: USGS and NPS.*

Figure 6 (Below): Map units. *Credit: USGS and NPS.*



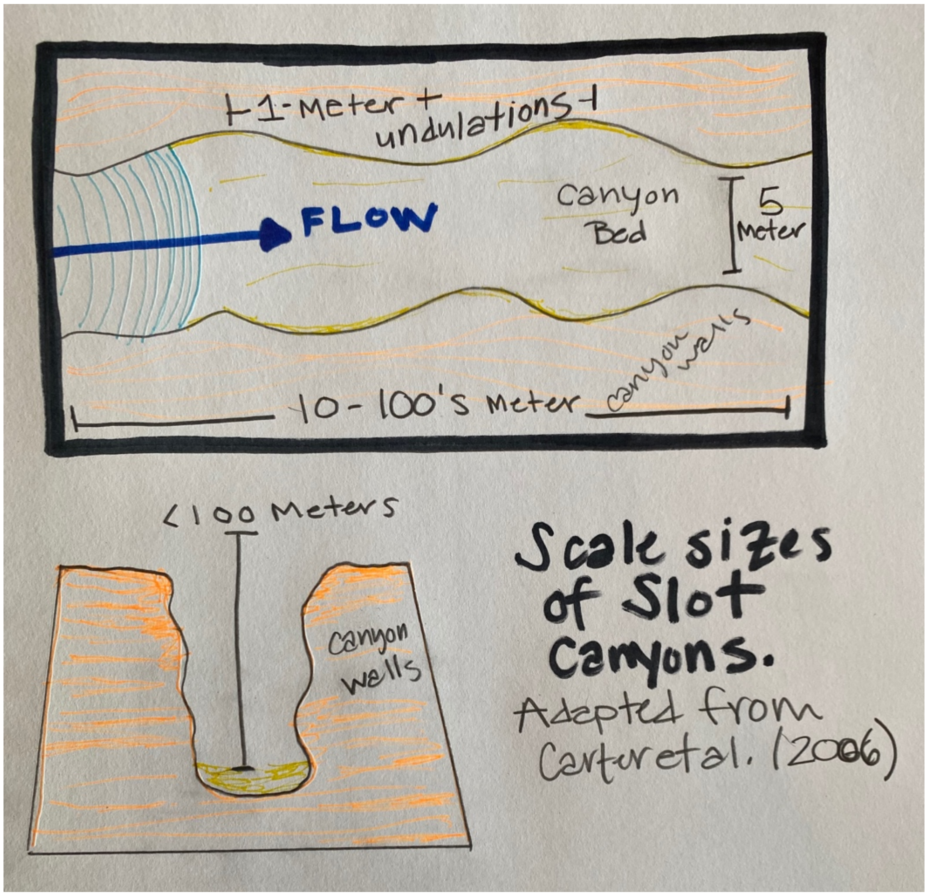


Figure 7: Schematic of scale sizes of slot canyons. Cartoon adapted from Carter et al (2006).

References:

[1] https://www.americansouthwest.net/slot_canyons/paria_river/canyon.html

[2] https://pubs.usgs.gov/imap/i2771/i2771map.pdf

[3] Smith, J. A., Baeck, M. L., Yang, L., Signell, J., Morin, E., & Goodrich, D. C. (2019). The paroxysmal precipitation of the desert: Flash floods in the southwestern United States. *Water Resources Research*, 55, 10218– 10247. https://doi.org/10.1029/2019WR025480

[4] Carissa L. Carter, Robert S. Anderson, Fluvial erosion of physically modeled abrasion dominated slot canyons, Geomorphology, Volume 81, Issues 1–2, 2006, Pages 89-113, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2006.04.006.

[5] Bill Jones image: https://www.alltrails.com/trail/us/arizona/water-holes-canyon/photos

Figure 8: Image of ~meter-scale undulations. *Credit: Bill Jones*

Welcome to Pangea!

Tailgating	First aid kit usage	Bacon smells from the meat food group	Joe buys, eats ice cream	Crossbedding
Boxed in by bigrigs	Sheep jokes	Spherical weathering	Military vehicles	Tumbleweeds
Sunburn	Diving Farallon Plate	FREE SPACE	Rusted truck	Joe kvetchin'
Columnar basalt	Sand in pants	Directions in metric	Lava: it's the bomb	Error on interpretive sign
Flat tire	Rock hugging	Fox	Useless CB radio chatter	Basin & Range

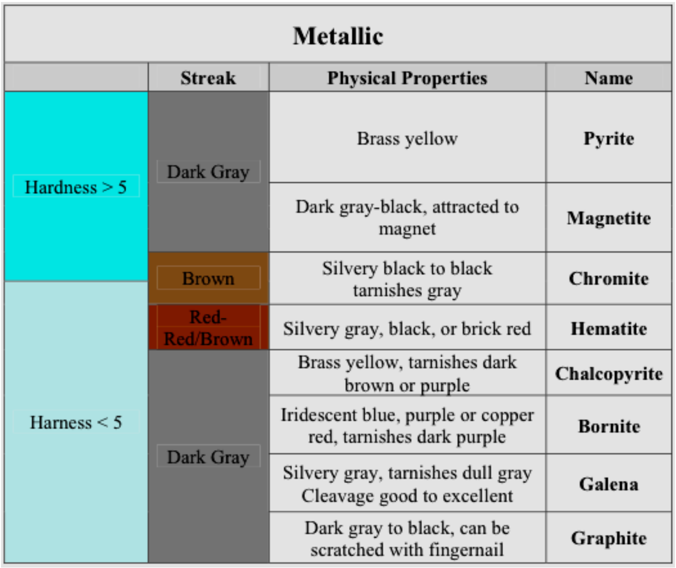
Welcome to Pangea!

Tractor	Directions in metric	Wifi searchin'	Flat tire	Facilities Management at loading dock
Lane change without signalling	Temperature above 80 °F	Lava: it's the bomb	Military vehicles	Joe kvetchin'
Clay dunes	Shane uses a selfie stick	FREE SPACE	Useless CB radio chatter	Sheep jokes
Reading papers in vehicle	Coyote	Pluton	Tumbleweeds	Joe buys, eats ice cream
Snaaake	Someone is late	Impostor vehicles	Friability	Train

Common Rock Forming Minerals

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

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

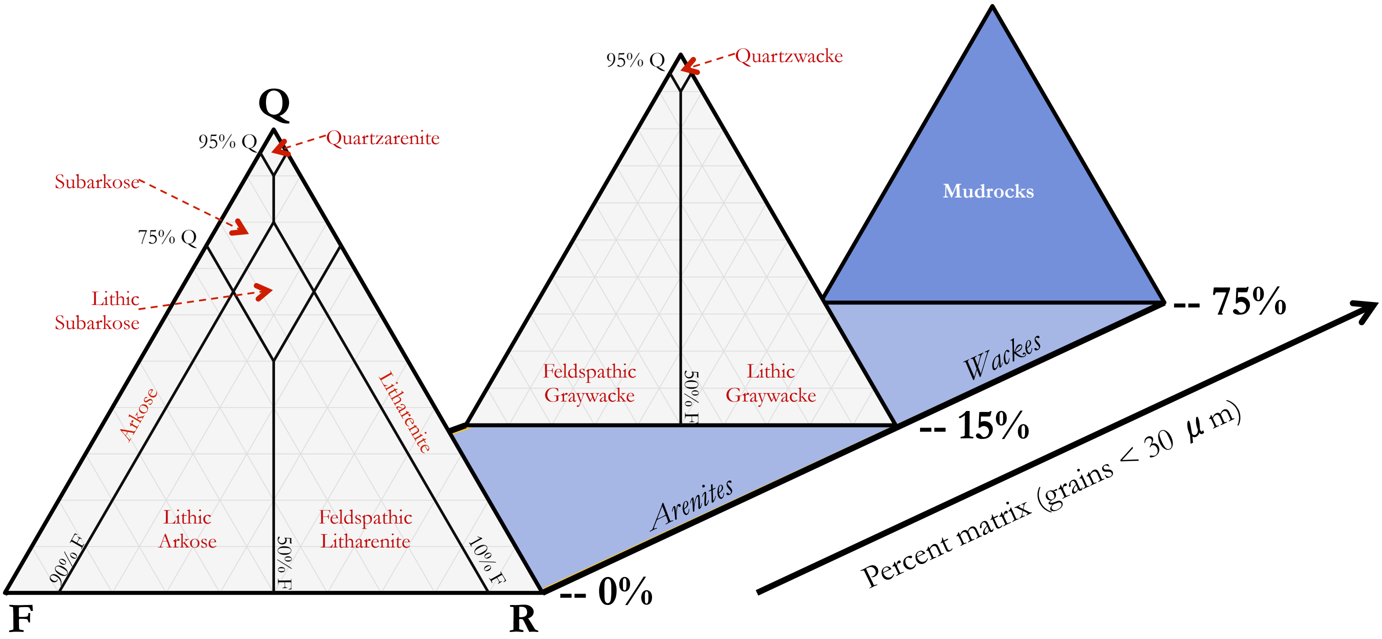


Metallic			
	Streak	**Physical Properties**	**Name**
Hardness > 5	Dark Gray	Brass yellow	**Pyrite**
		Dark gray-black, attracted to magnet	**Magnetite**
Harness < 5	Brown	Silvery black to black tarnishes gray	**Chromite**
	Red-Red/Brown	Silvery gray, black, or brick red	**Hematite**
	Dark Gray	Brass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

Sedimentary Rocks

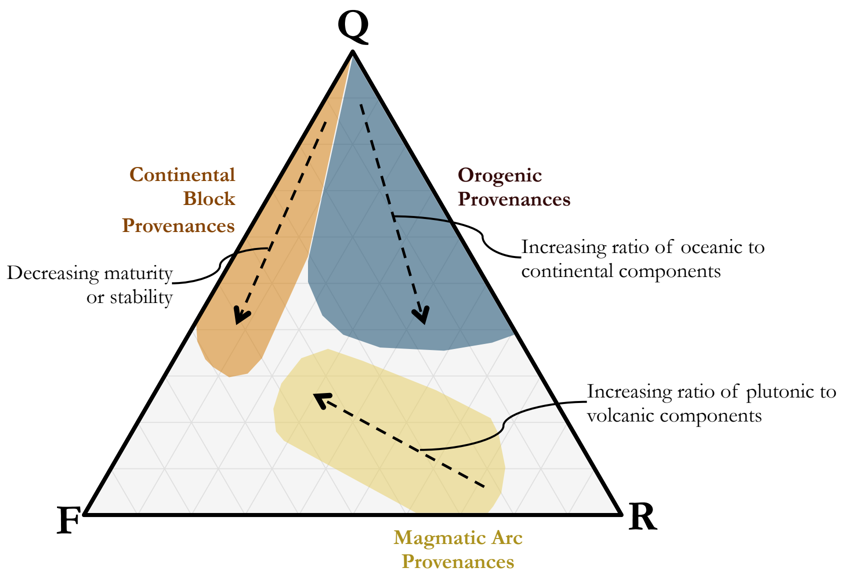
McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

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



Tectonic Setting for Clastic Sedimentary Rocks

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



Sedimentary Rocks

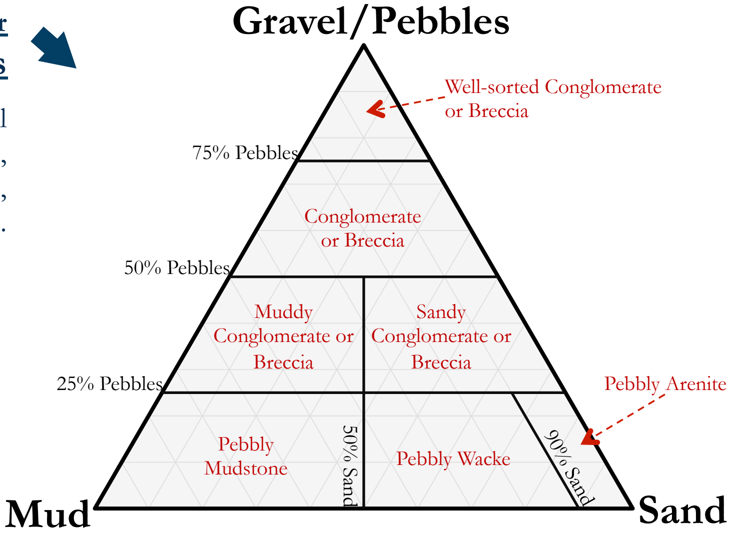
Classification Scheme for Mudrocks

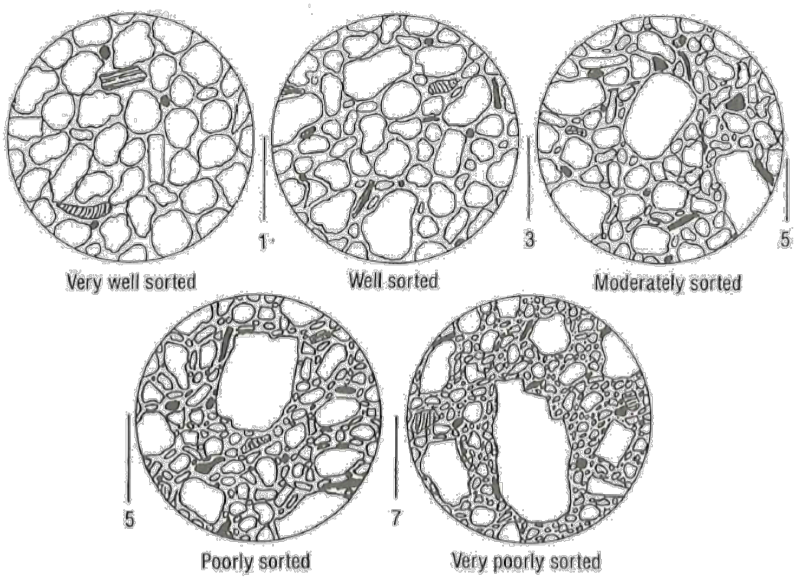
Scheme based on clay/silt content, and whether the rock is laminated (layered) or not.

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

Classification Scheme for Sub-Conglomerates and Sub-Breccias

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





Very well sorted

Well sorted

Moderately sorted

Poorly sorted

Very poorly sorted

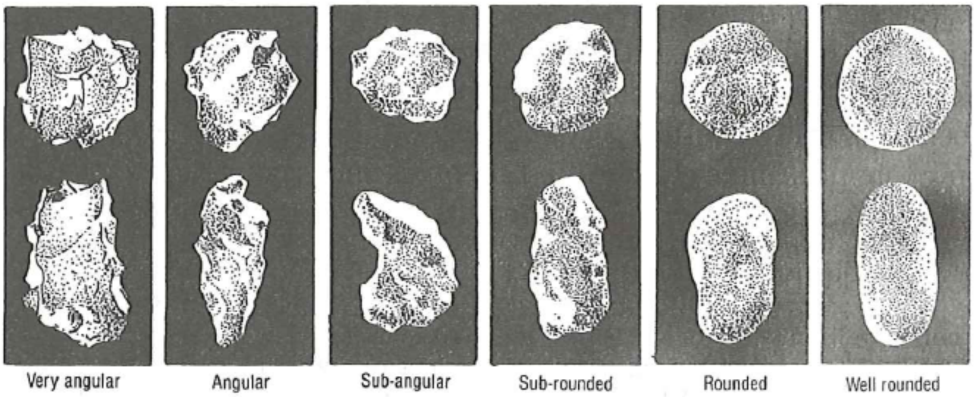
Estimating Sorting

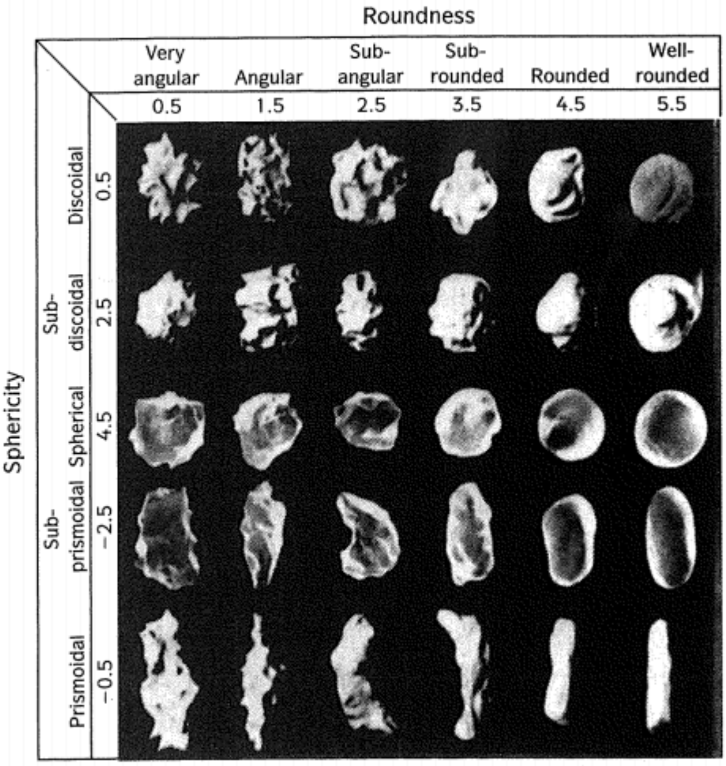
Example hand-lens view of detritus. From Compton, 1985

Sedimentary Rocks

Degrees of Rounding

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

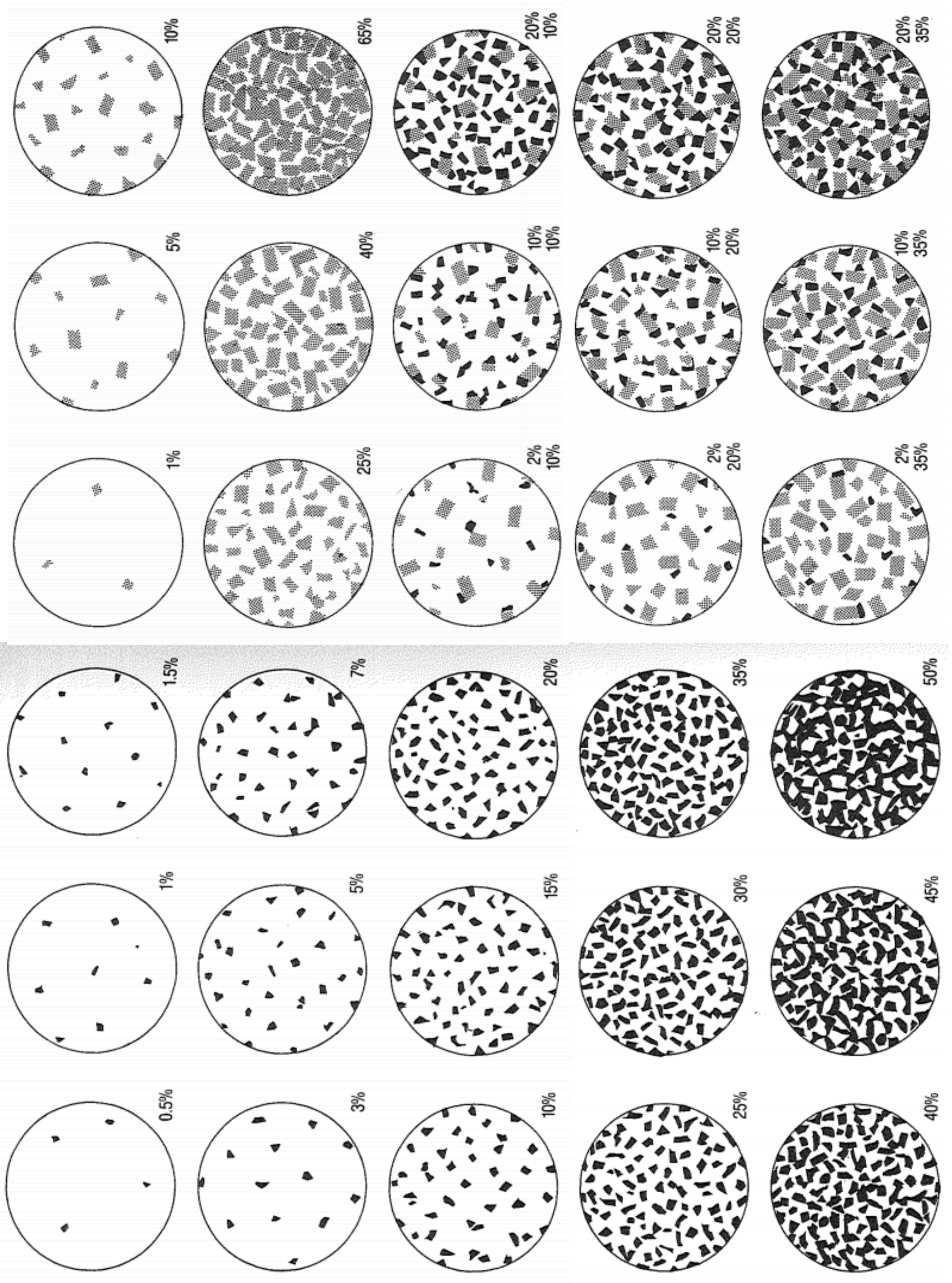




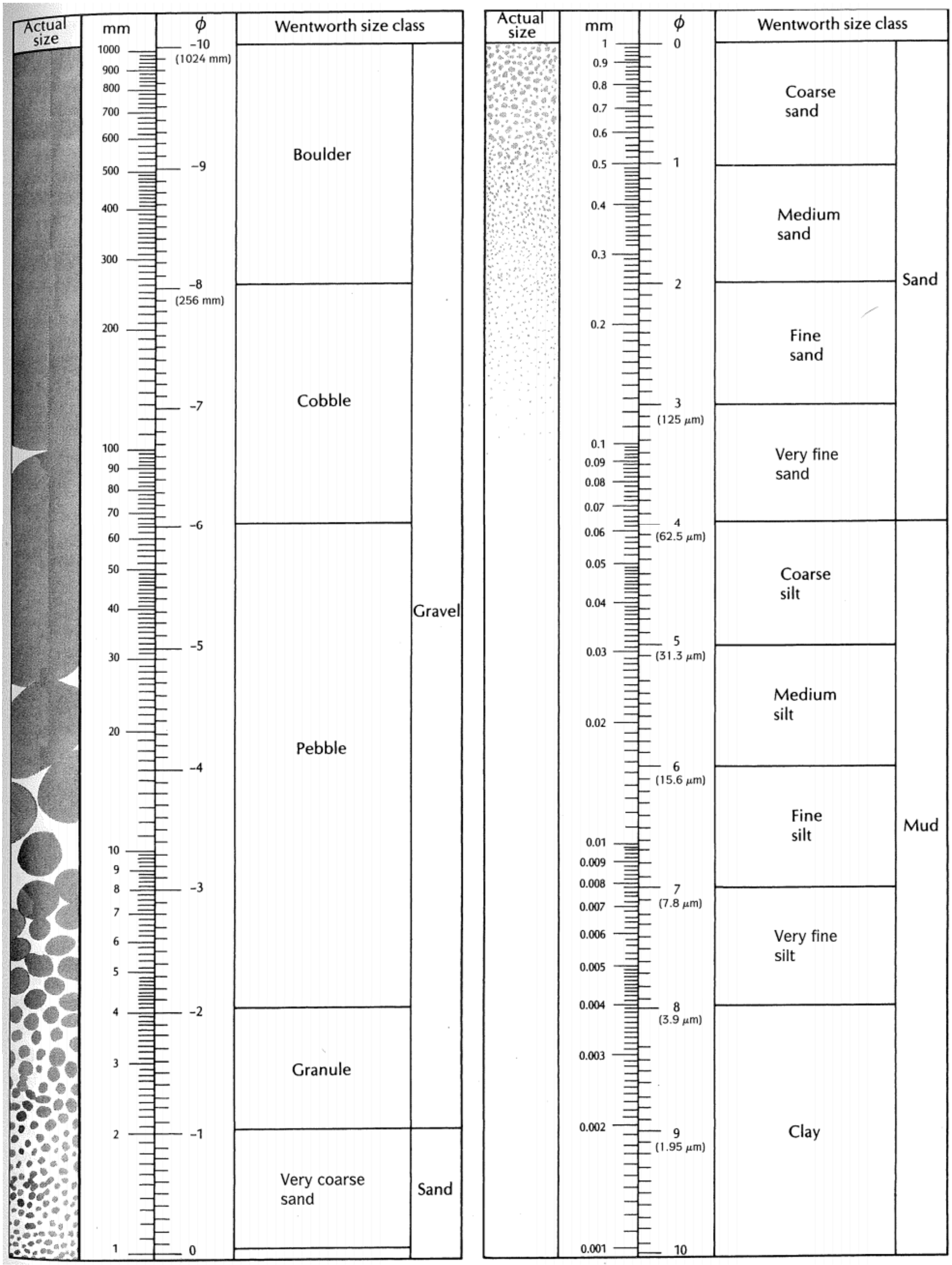
Sedimentary Rocks

Percentage Diagrams for Estimating Composition by Volume

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



Sedimentary Rocks

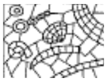
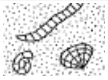
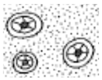
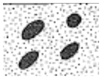
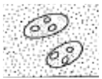
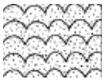
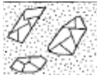


From Prothero and Schwab, 2004

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

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

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

Dunham Classification Scheme for Carbonate Rocks

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

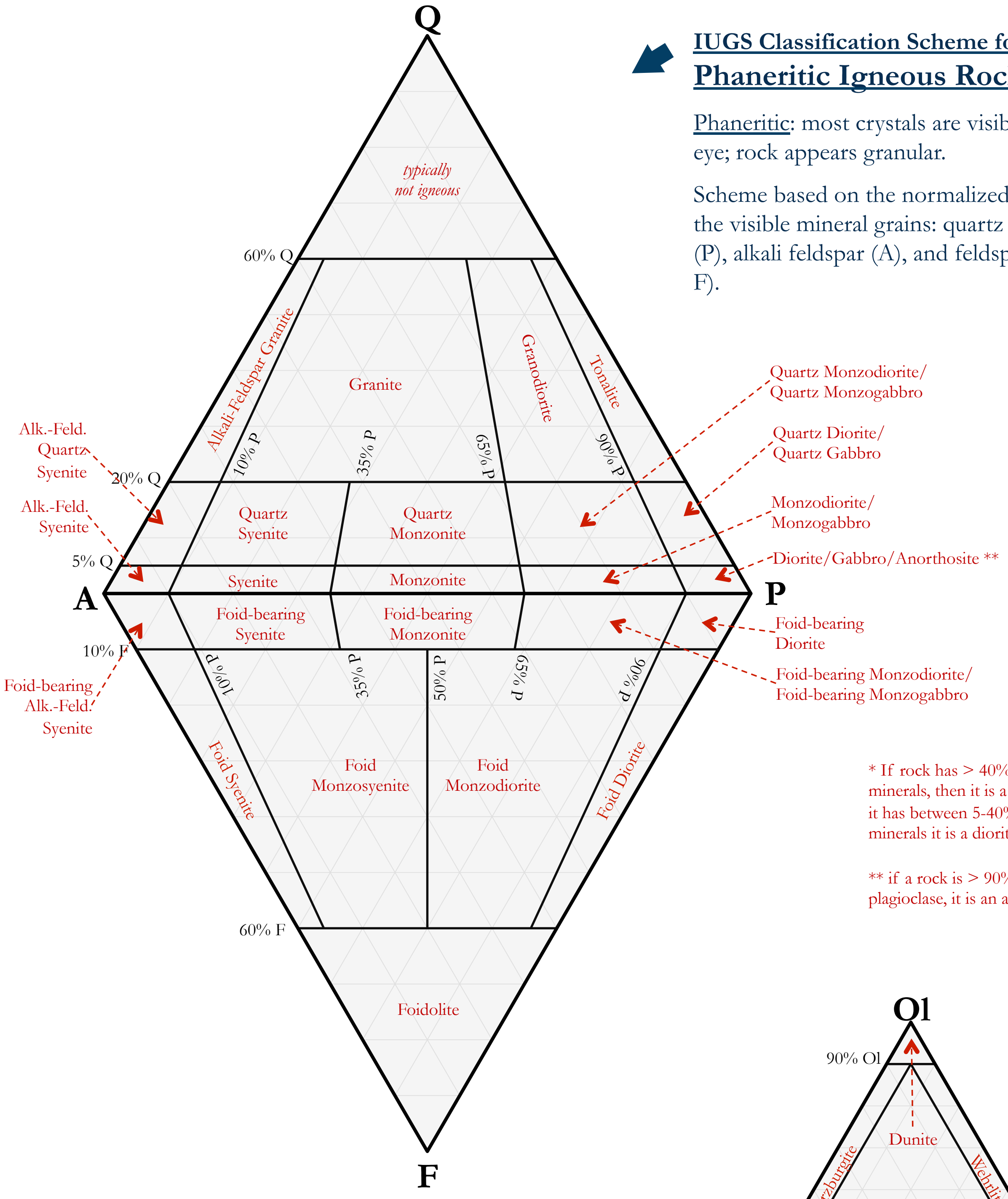
Allochthonous Limestone (original components not organically bound during deposition)						**Autochthonous Limestone** (original components organically bound during deposition; reef rocks)		
Of the allochems, less than 10% are larger than 2 mm				Of the allochems, greater than 10% are larger than 2 mm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

Igneous Rocks

IUGS Classification Scheme for Phaneritic Igneous Rocks

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

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



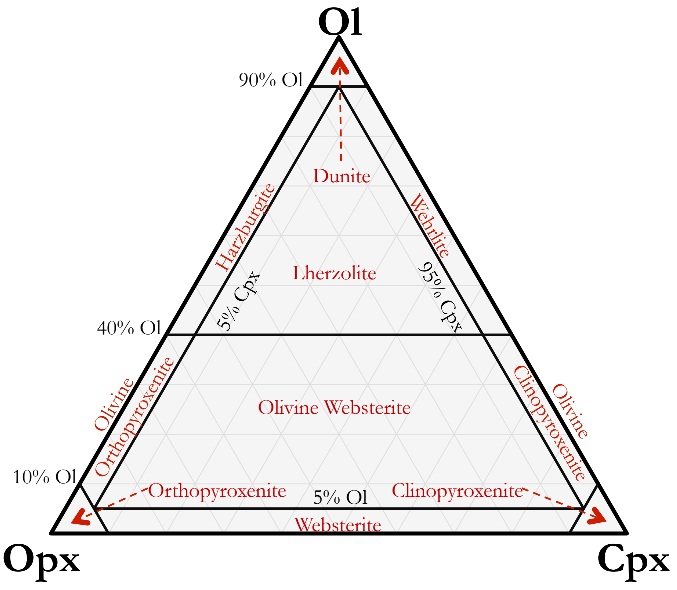
* If rock has > 40% mafic minerals, then it is a gabbro. If it has between 5-40% mafic minerals it is a diorite.

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

IUGS Classification Scheme for Phaneritic Ultramafic Igneous Rocks (1)

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

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

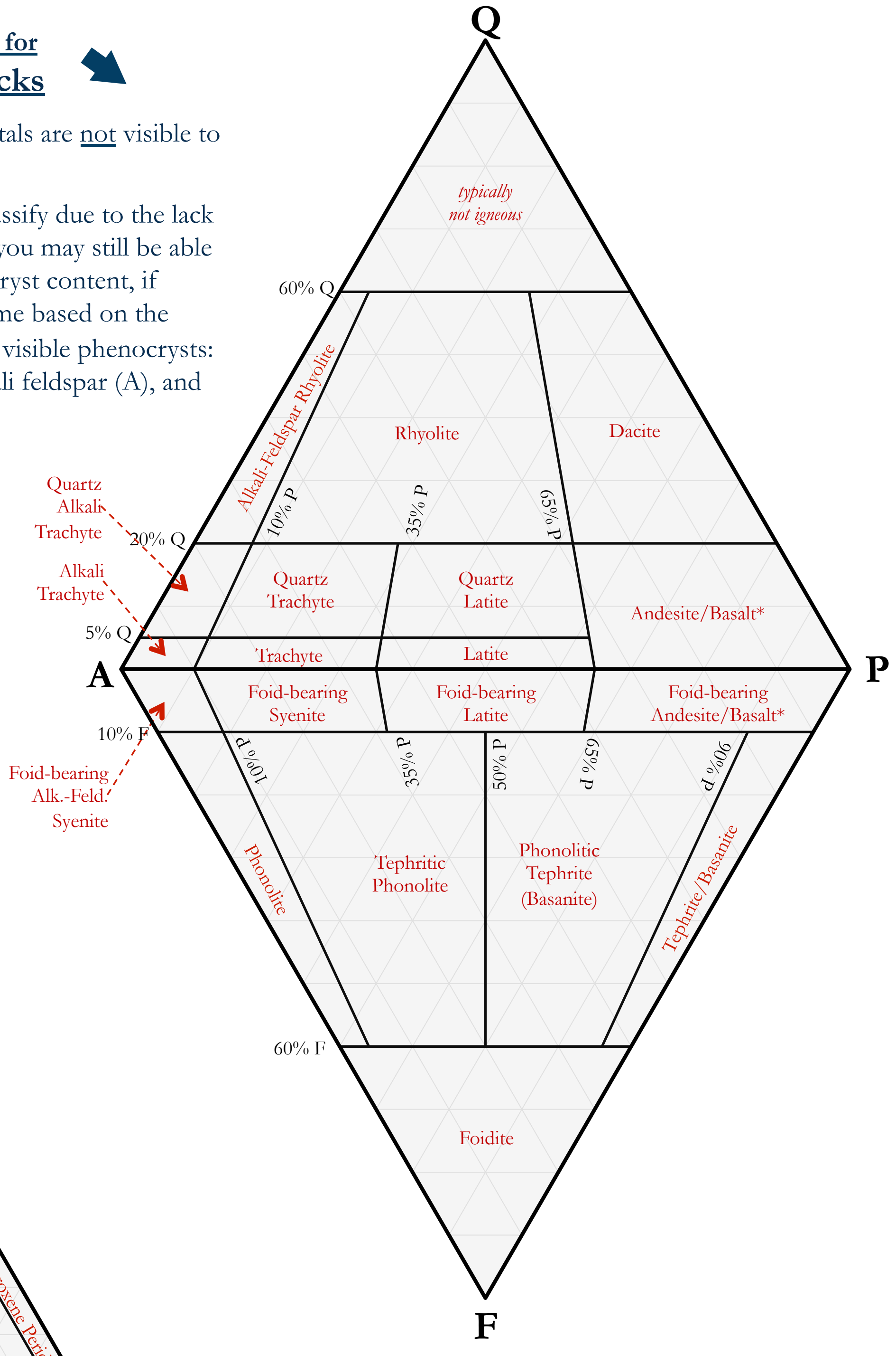


Igneous Rocks

IUGS Classification Scheme for
Aphanitic Igneous Rocks

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

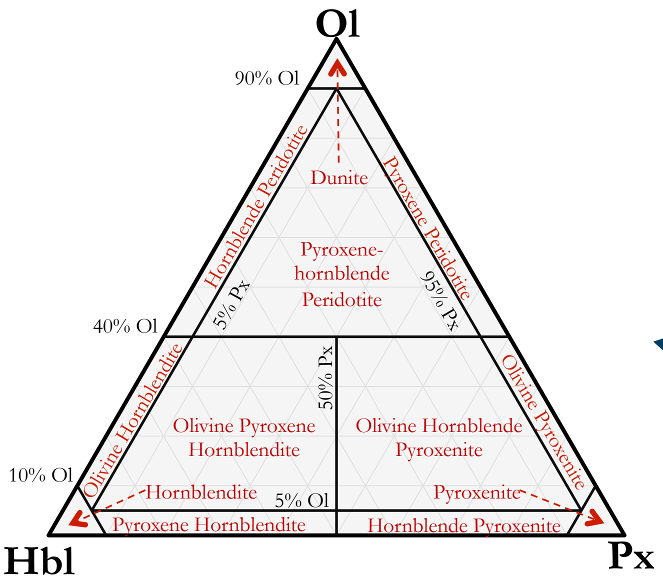
Aphanetic rocks are hard to classify due to the lack of visible minerals. However, you may still be able identify them based on phenocryst content, if phenocrysts are present. Scheme based on the normalized percentages of the visible phenocrysts: quartz (Q), plagioclase (P), alkali feldspar (A), and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



IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (2)

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

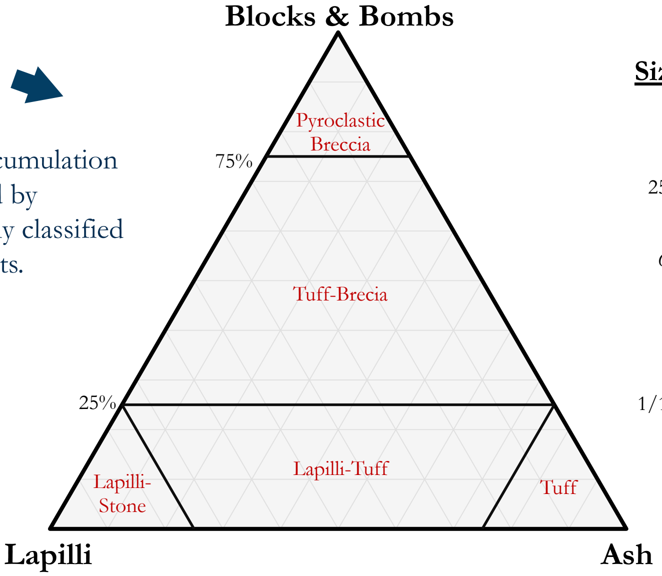
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

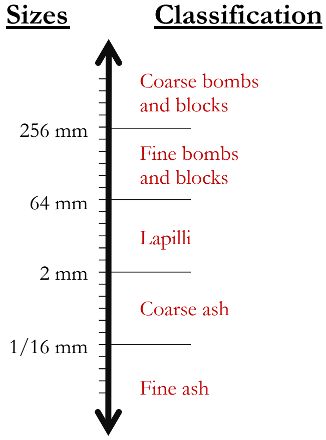


Igneous Rocks

Classification Scheme for Pyroclastic Igneous Rocks

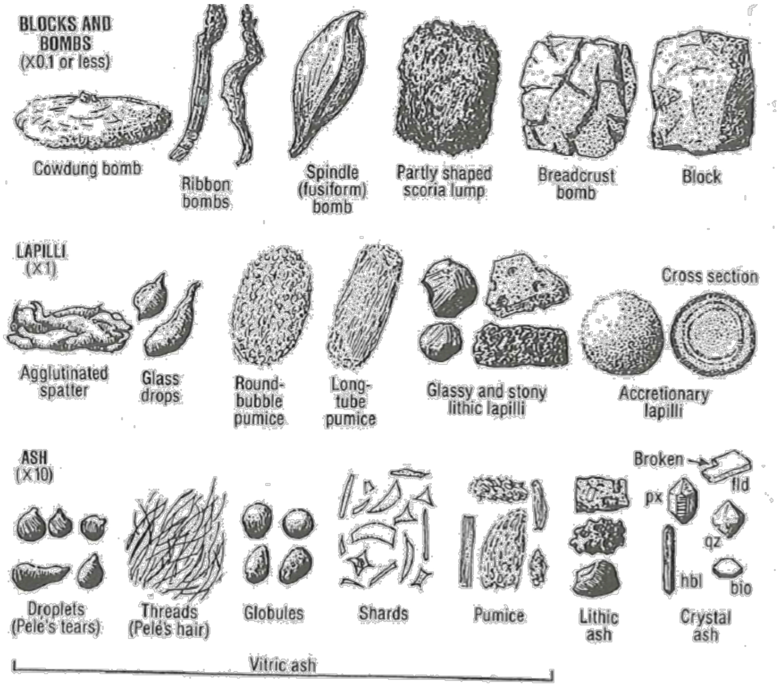
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.





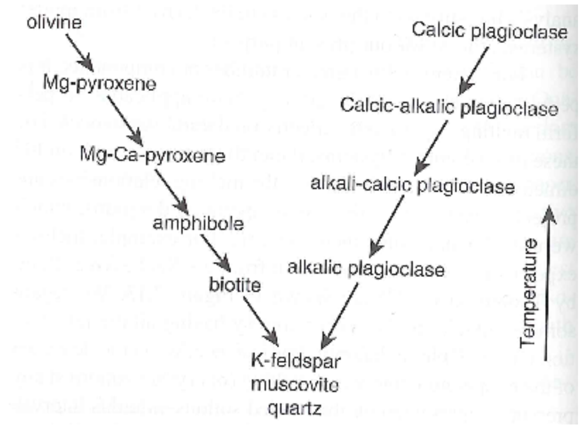
Types of Tephra (Pyroclasts)

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



Bowen's Reaction Series

From Winter, 2010.



Metamorphic Rocks

Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

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

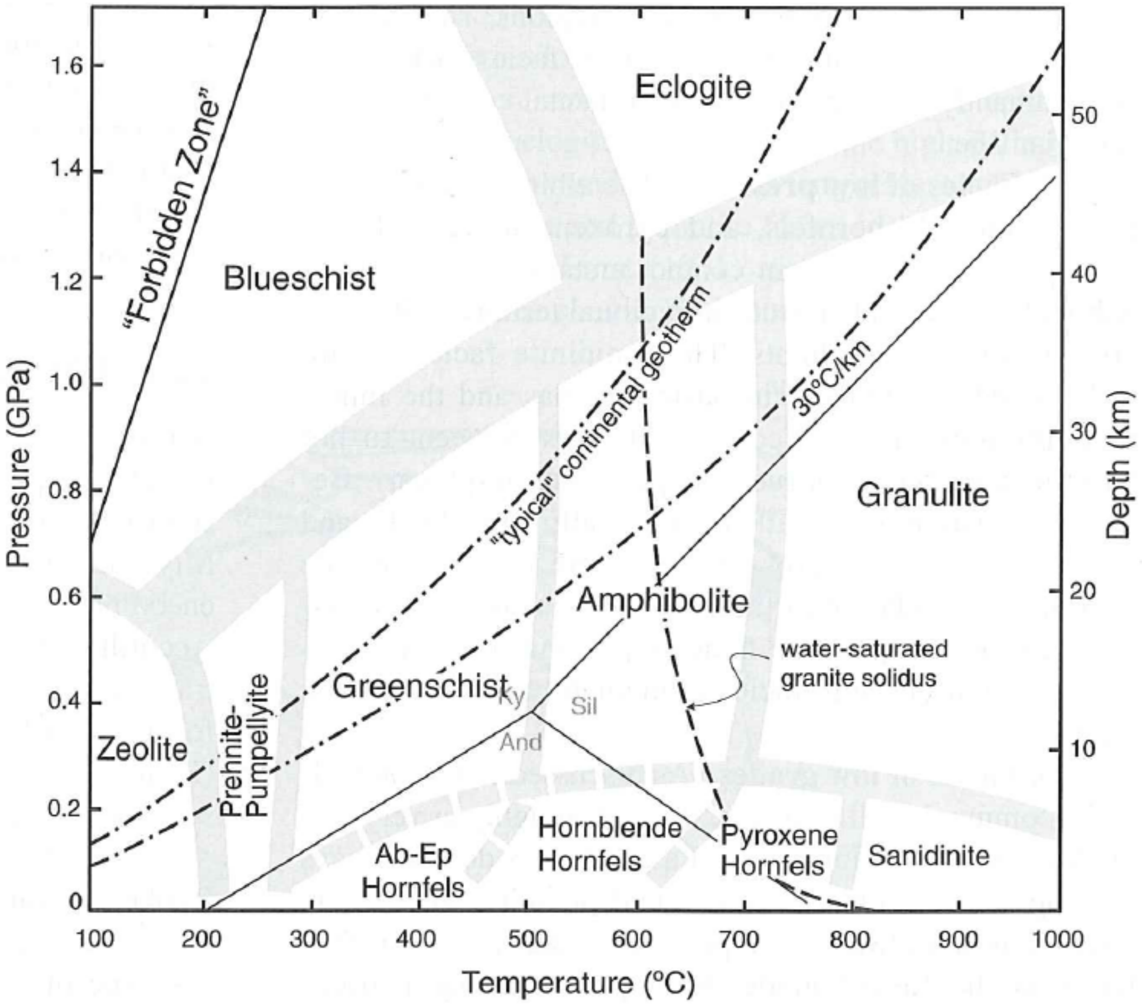
Mineralogy for Metamorphic Rock Facies

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

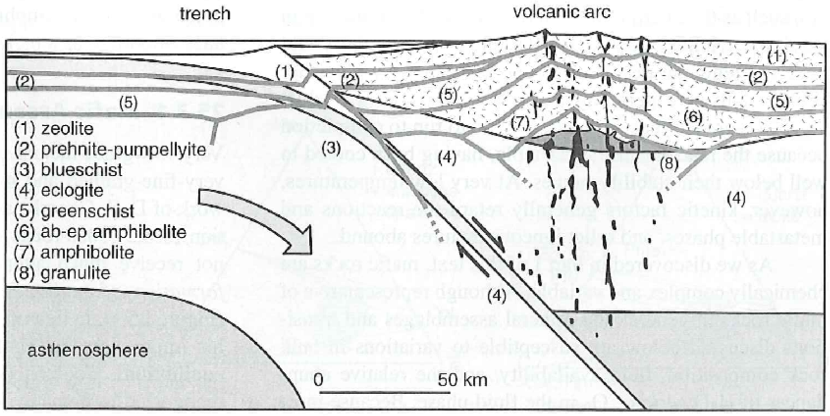
Metamorphic Rocks

Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010



Schematic of Island Arc, and the origins of Metamorphic Facies

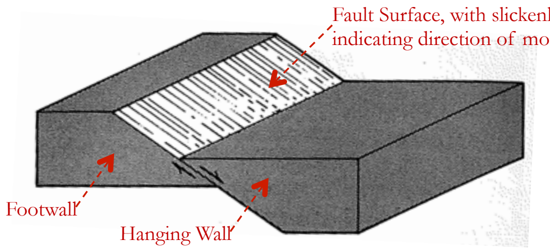


A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010

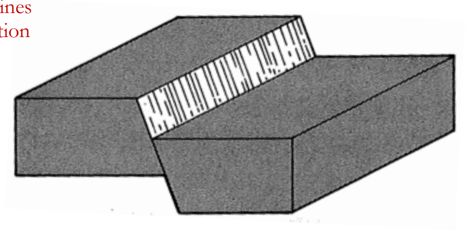
Structural Geology: Normal Faults

Normal Faults

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



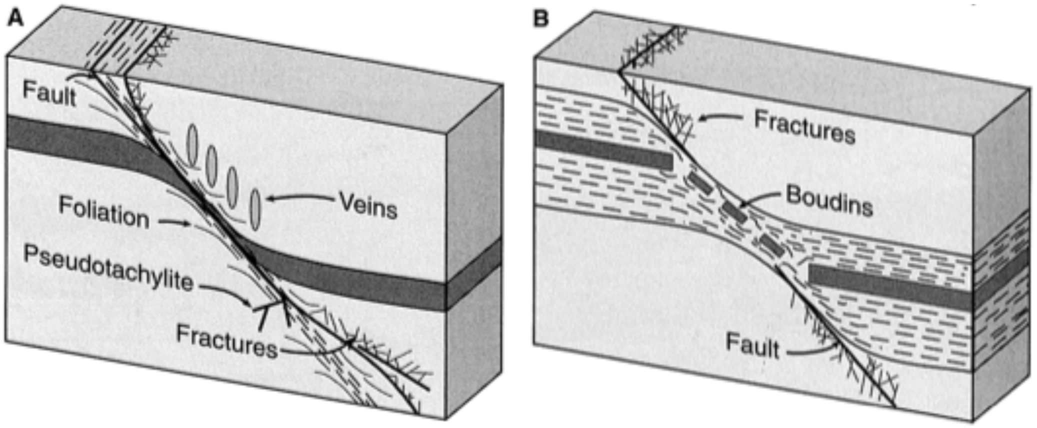
Low-angle Normal Slip Fault



Normal Slip Fault

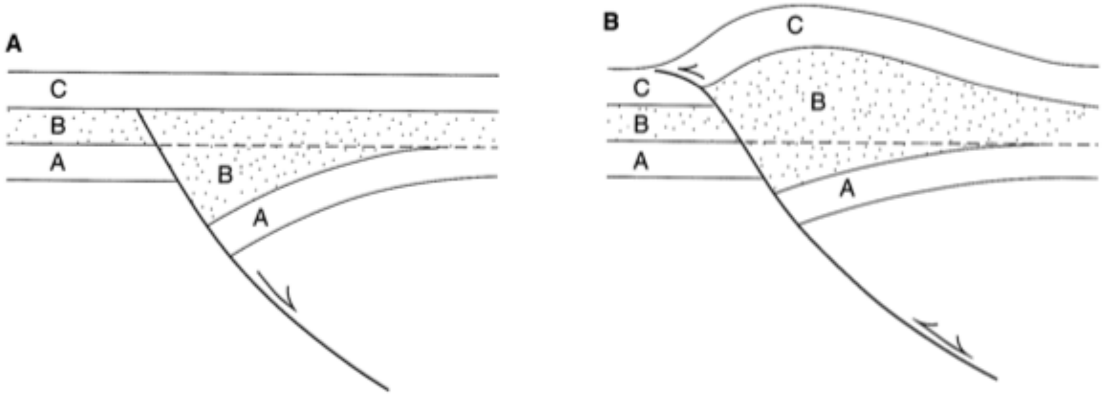
Effects of Brittle or Ductile Shear in Normal Faults

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



Inversion Tectonics

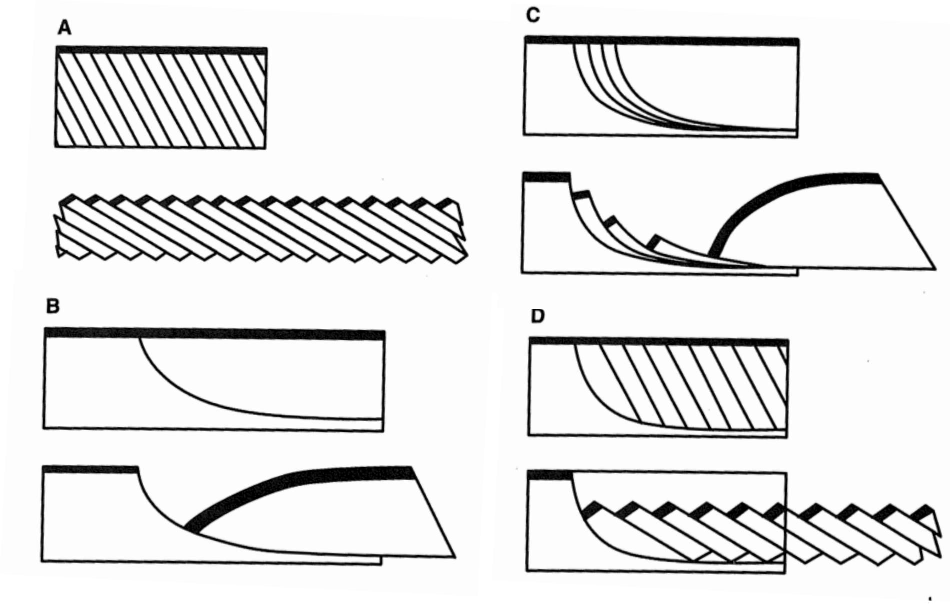
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right,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

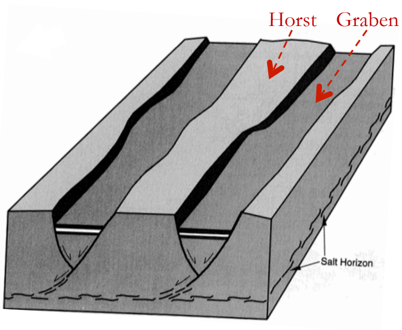


Structural Geology: Normal Faults

Normal Faults Geometries

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



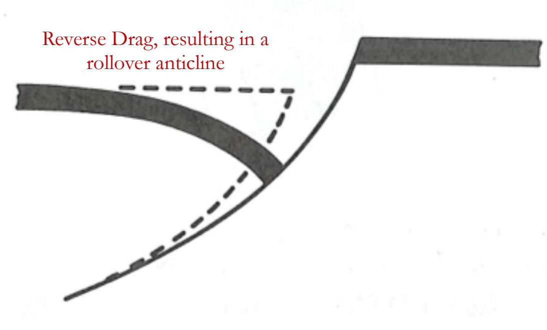


Horsts & Grabens

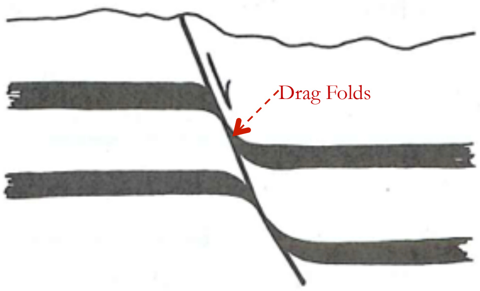
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

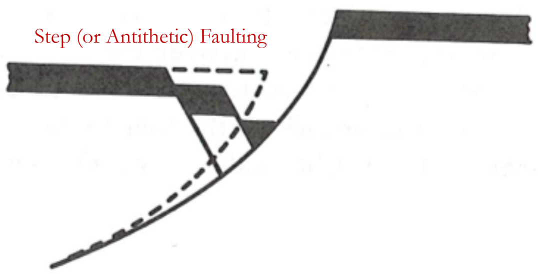
Faulting does not always produce clean displacement along the fault surface. Fault blocks are frequently folded or fractured, and the nature of these deformations are non-trivial. Figures from Davis & Reynolds, 1996.



Reverse Drag, resulting in a rollover anticline



Drag Folds

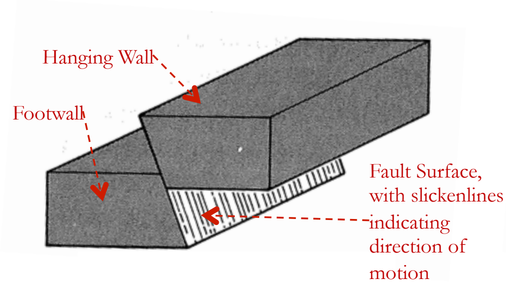


Step (or Antithetic) Faulting

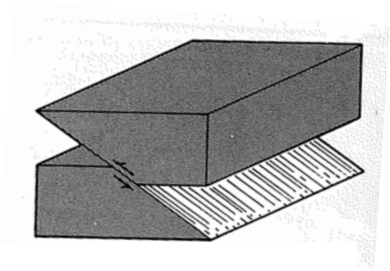
Structural Geology: Reverse & Thrust Faults

Reverse Faults

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



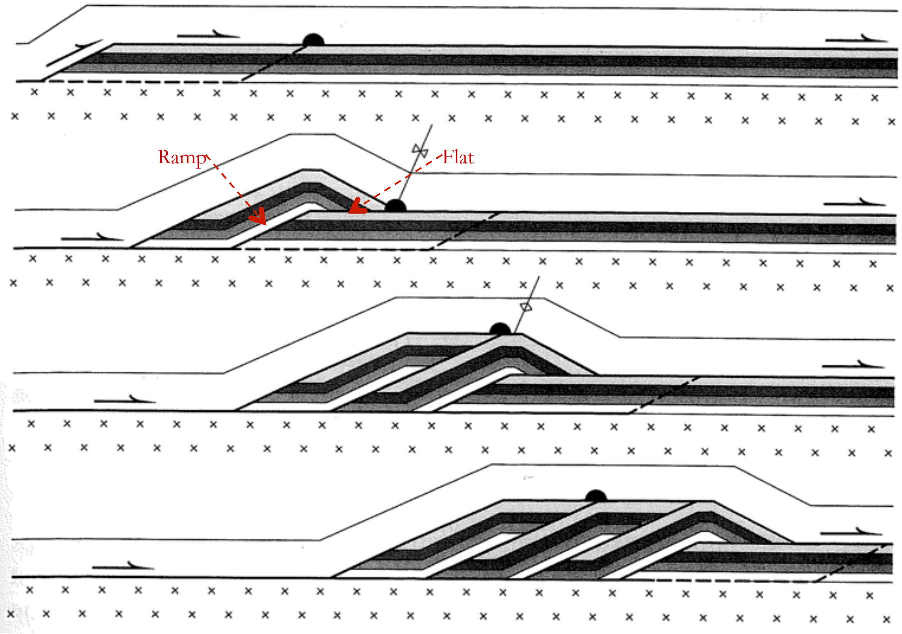
Reverse Slip Fault



Thrust Slip Fault

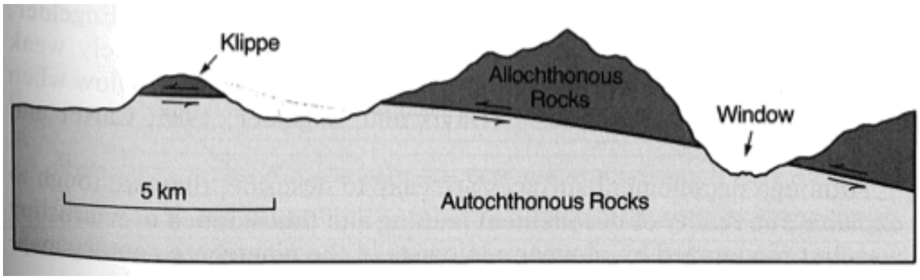
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

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

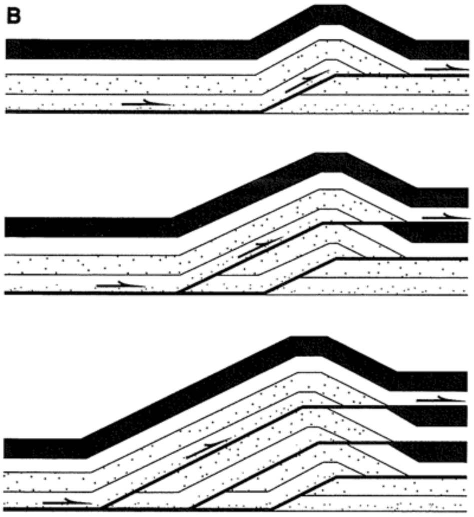


Klippe & Windows

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



Structural Geology: Reverse & Thrust Faults

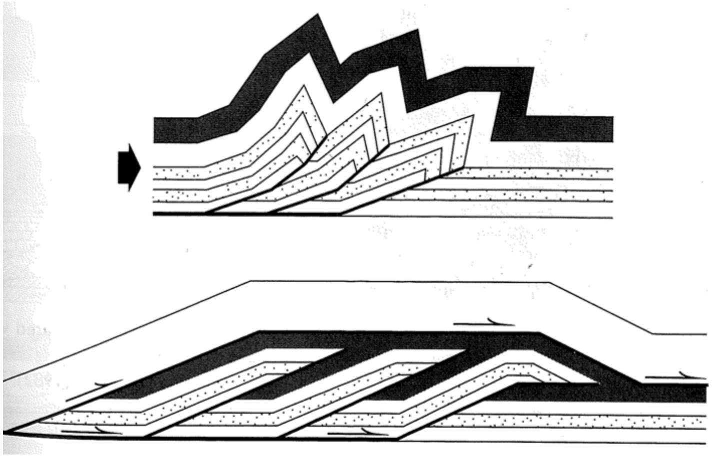


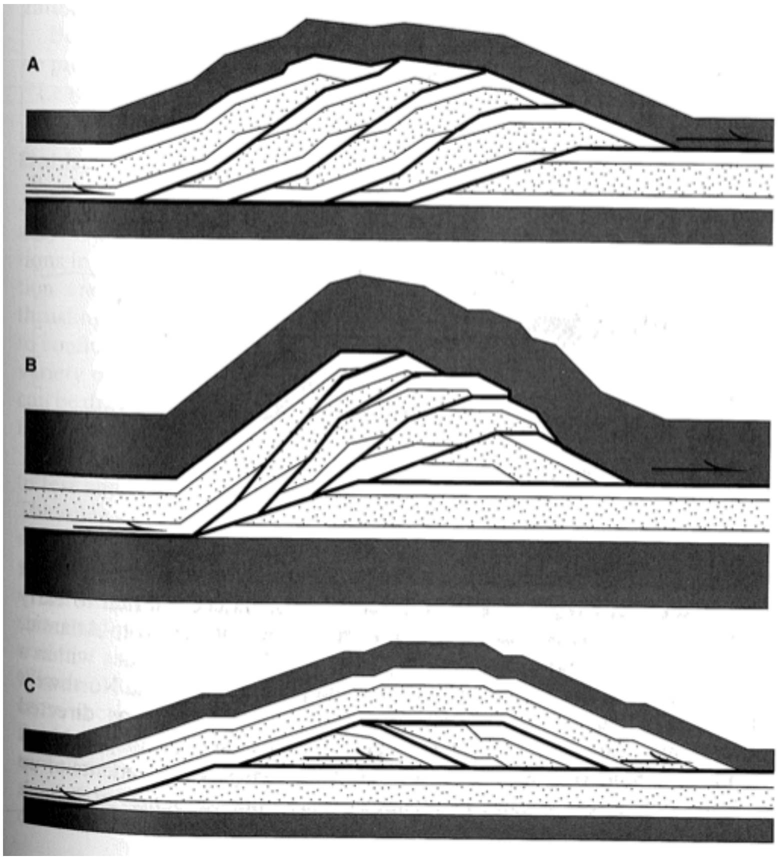
Out-of-Sequence Thrust Fault System

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

Imbricate Fans vs. Duplexes

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





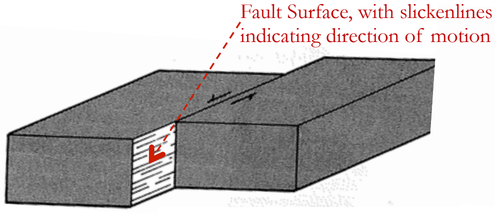
Forms of Duplexes

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

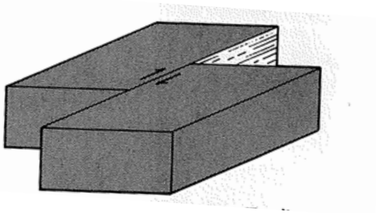
Structural Geology: Strike-Slip or Transform Faults

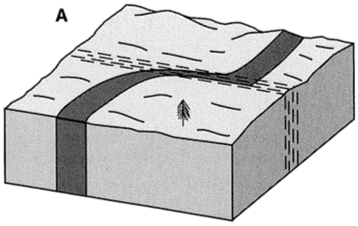
Strike-Slip Faults

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

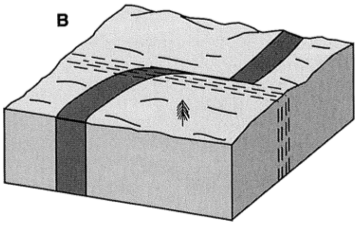

Fault Surface, with slickenlines indicating direction of motion

Left Lateral (Sinistral) Strike-Slip Fault


Right Lateral (Dexteral) Strike-Slip Fault



Continuous Shear Zone



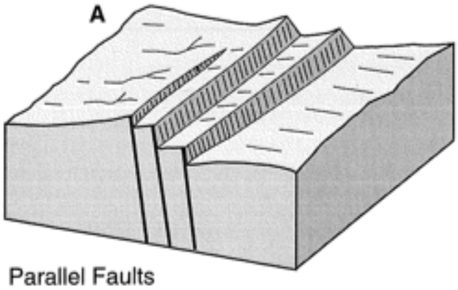
Discontinuous Shear Zone

Ductile Shear Zones

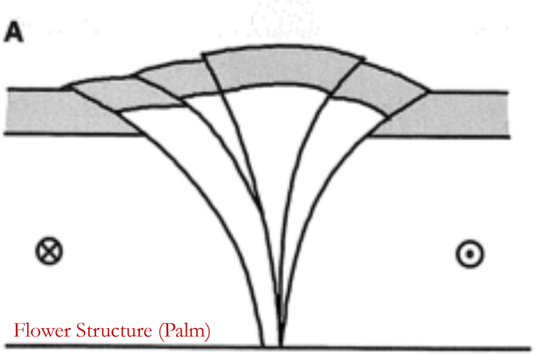
Shear in a strike-slip fault is not always located in a single plane. Sometimes, shear takes place over an extended region. Figures from Davis & Reynolds, 1996.

Brittle Shear Zones

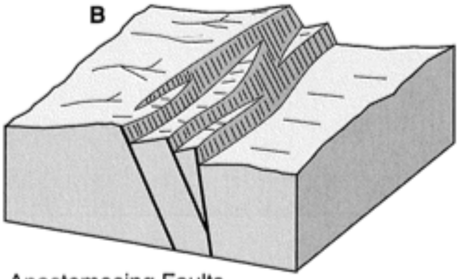
Figures from Davis & Reynolds, 1996.



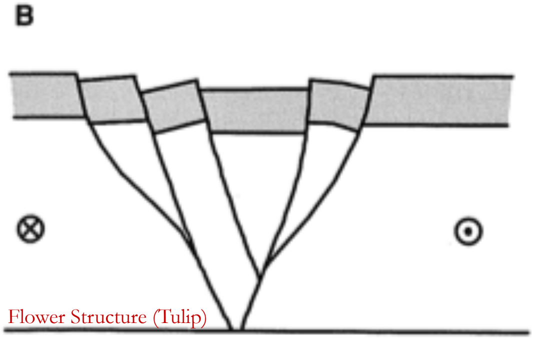
Parallel Faults



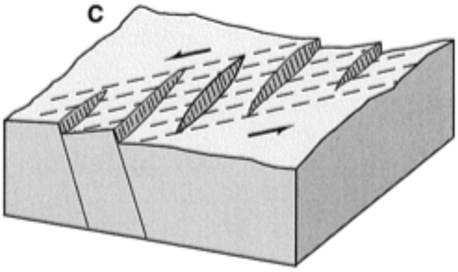
Flower Structure (Palm)



Anastomosing Faults



Flower Structure (Tulip)

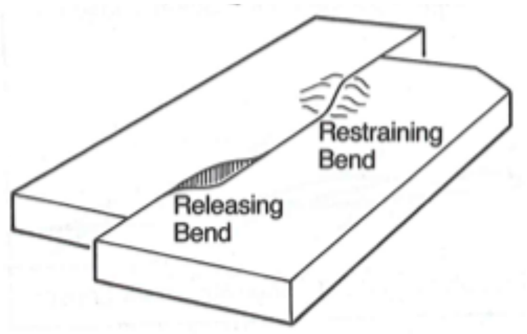


En Echelon Faults

Structural Geology: Strike-Slip or Transform Faults

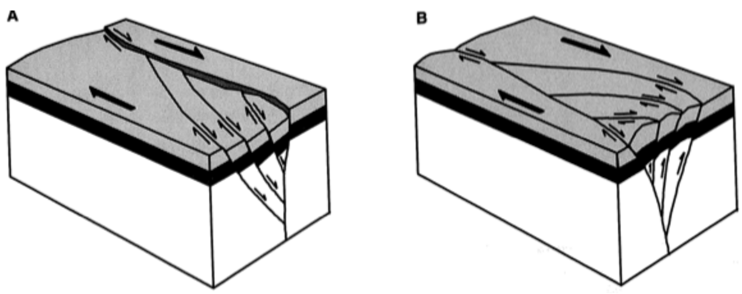
Bends in Strike-Slip Faults

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



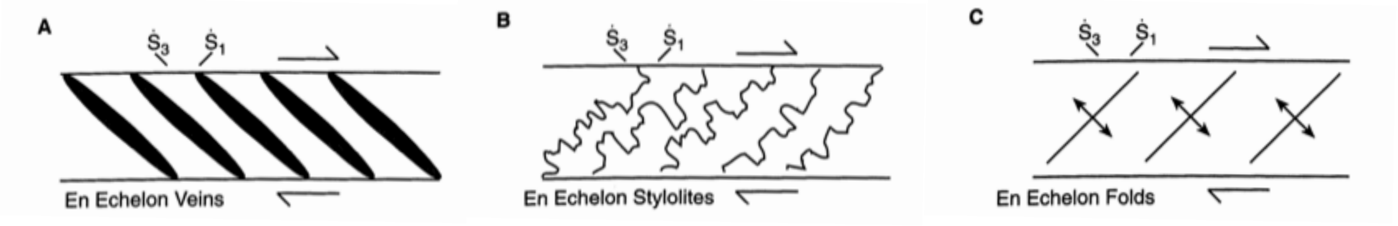
Strike-Slip Duplexes

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



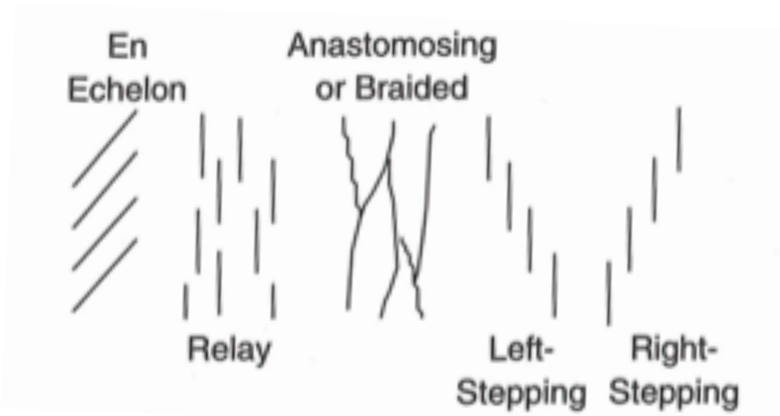
Slip Indicators in Strike-Slip Systems

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



Even more Geometric Arrangements of Strike-Slip Faults

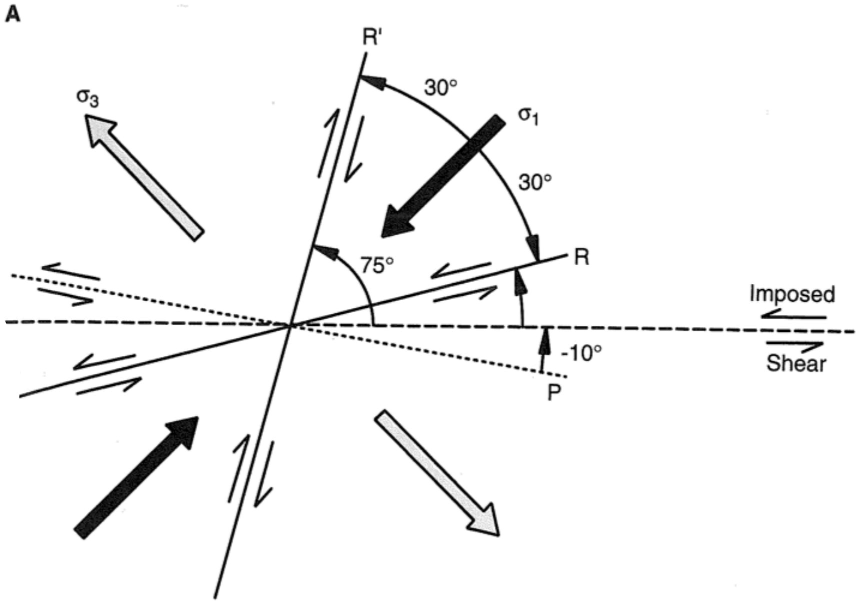
Figures from Davis & Reynolds, 1996.

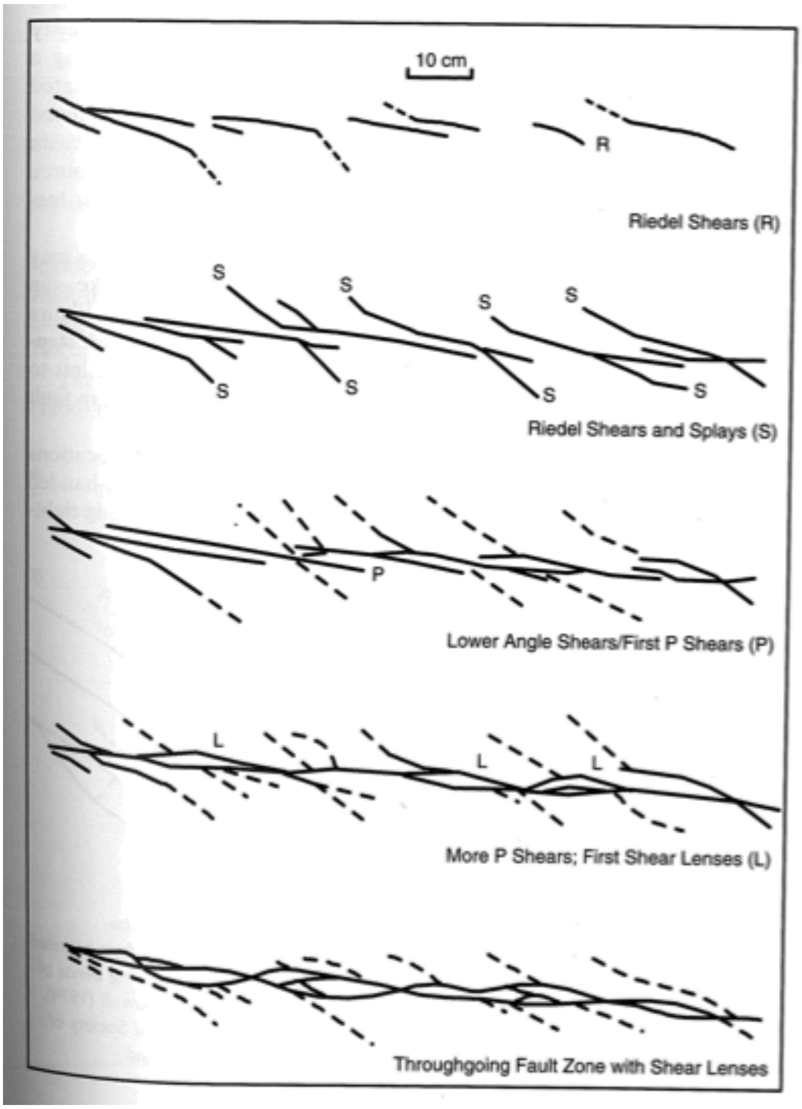


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

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



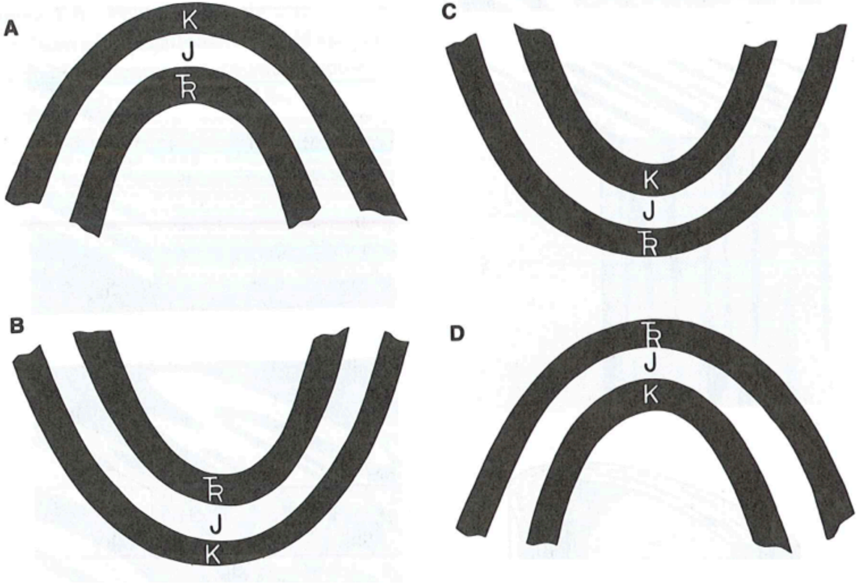


The figure at left illustrate the formation sequence of Riedel shears and other splays and shears in a right-handed strike-slip zone. Figures from Davis & Reynolds, 1996.

Structural Geology: Folds

Anticlines & Antiforms, and Synclines & Synforms

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



Anticline

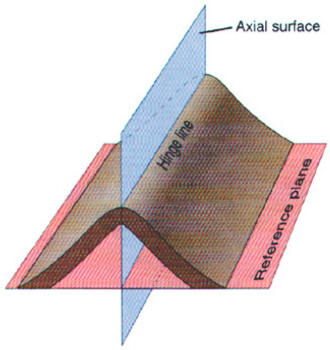
Syncline

Antiform

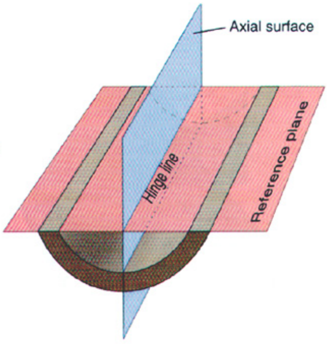
Synform

Plunging Folds

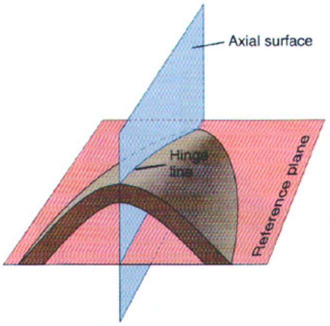
Folds (defined by hinge lines and axial surfaces) are not necessarily perpendicular to the Earth's surface. They can be dipping into or out of the surface. This can create interesting patterns of exposed surface rock, or even topography. Figures from Jones, 2001.



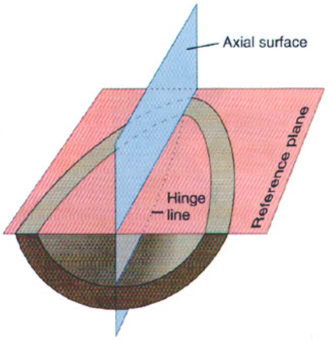
Non-plunging antiform



Non-plunging synform



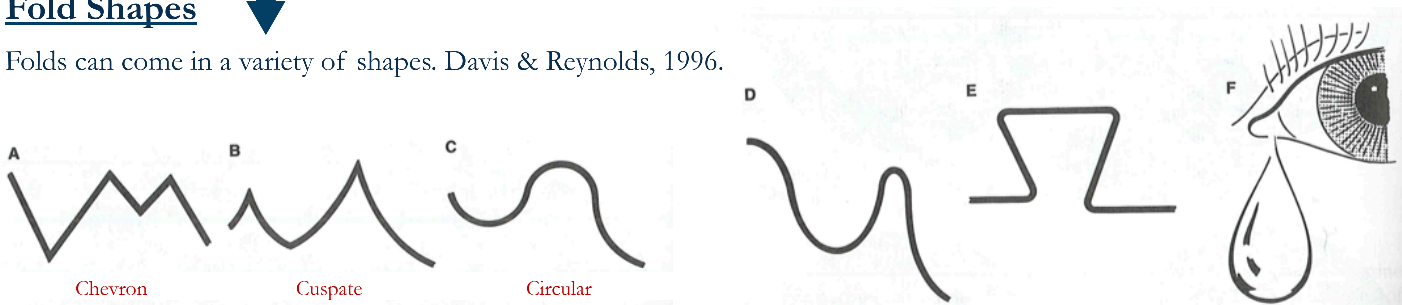
Plunging antiform



Plunging synform

Fold Shapes

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



Chevron

Cuspate

Circular

Elliptical

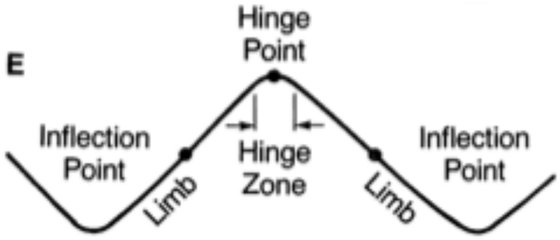
Box (Conjugate)

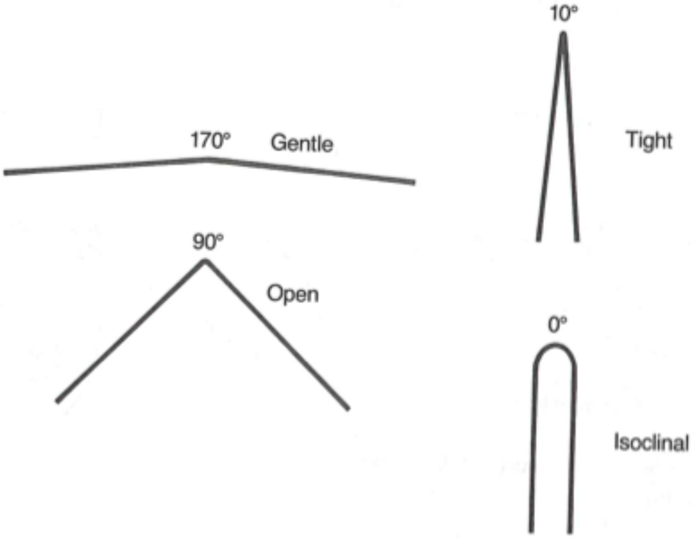
Teardrop

Structural Geology: Folds

Fold Tightness

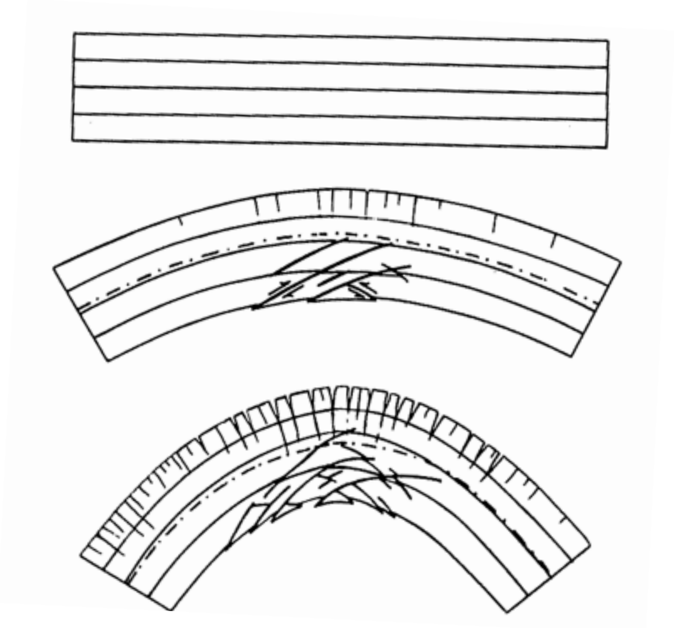
Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.





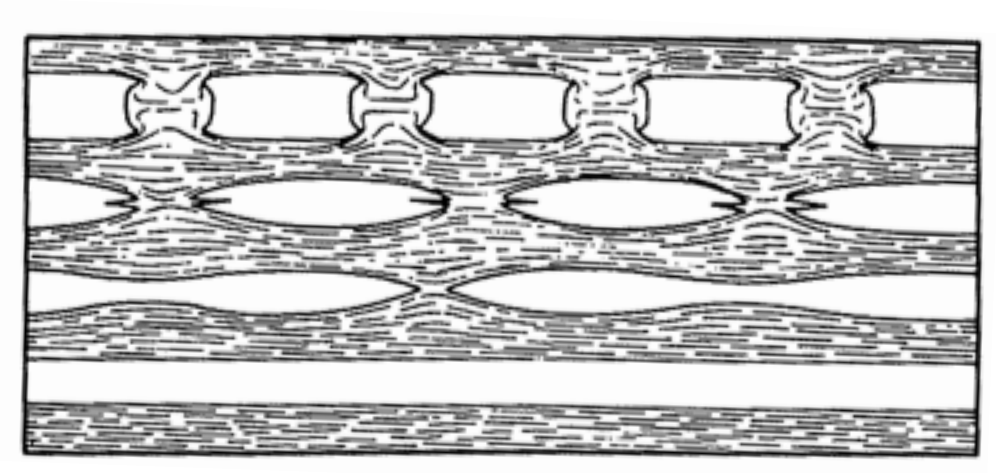
Minor Structures in Folds

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

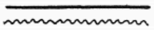
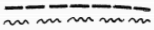
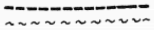
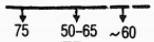
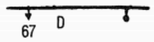
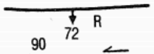
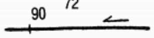
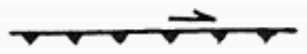
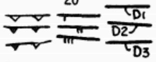
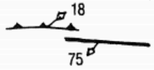
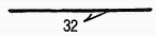
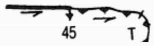
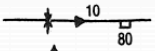
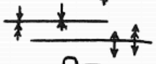
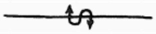
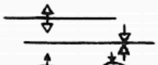
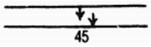
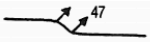
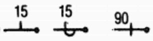
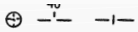
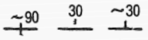
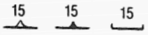
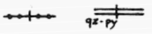
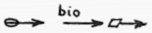
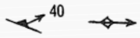
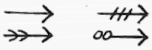


Boudins

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

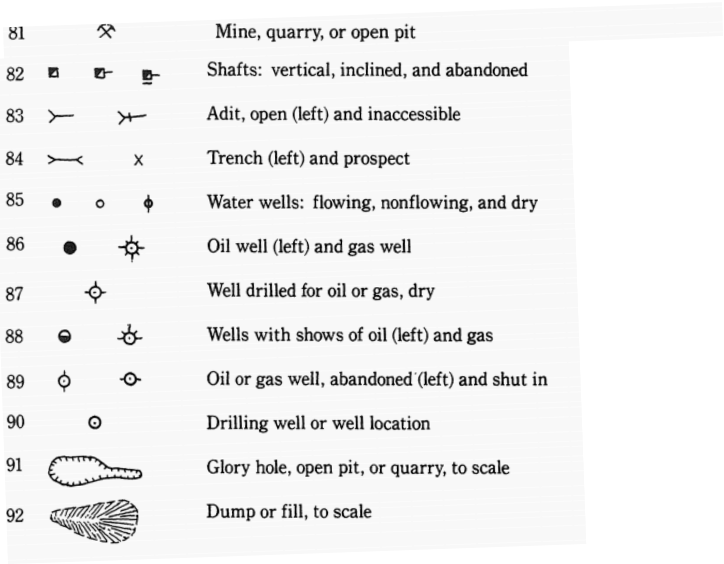


Geologic Map Symbols

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

From Compton, 1985

Geologic Map Symbols

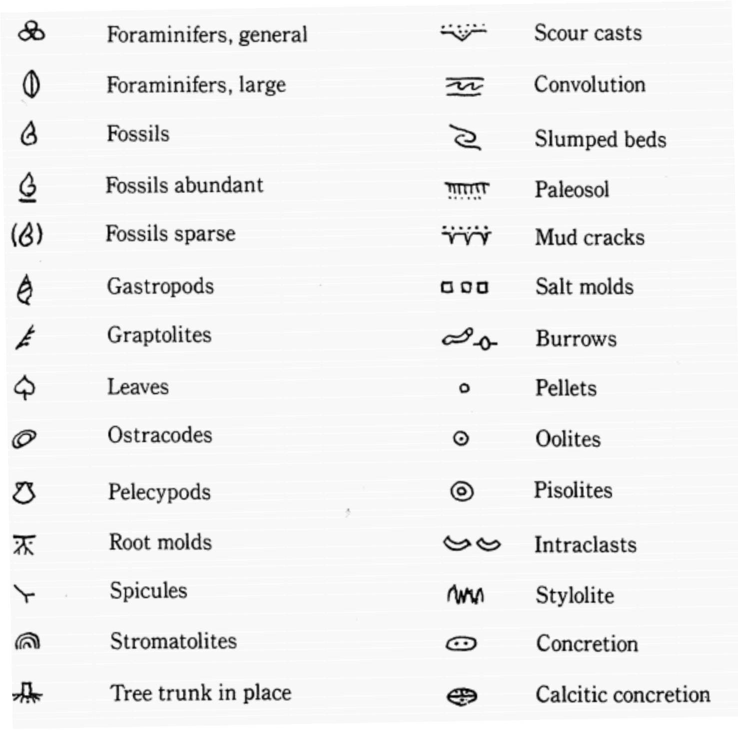


81	Mine, quarry, or open pit
82	Shafts: vertical, inclined, and abandoned
83	Adit, open (left) and inaccessible
84	Trench (left) and prospect
85	Water wells: flowing, nonflowing, and dry
86	Oil well (left) and gas well
87	Well drilled for oil or gas, dry
88	Wells with shows of oil (left) and gas
89	Oil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

Fossil and Structural Symbols for Stratigraphic Columns

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

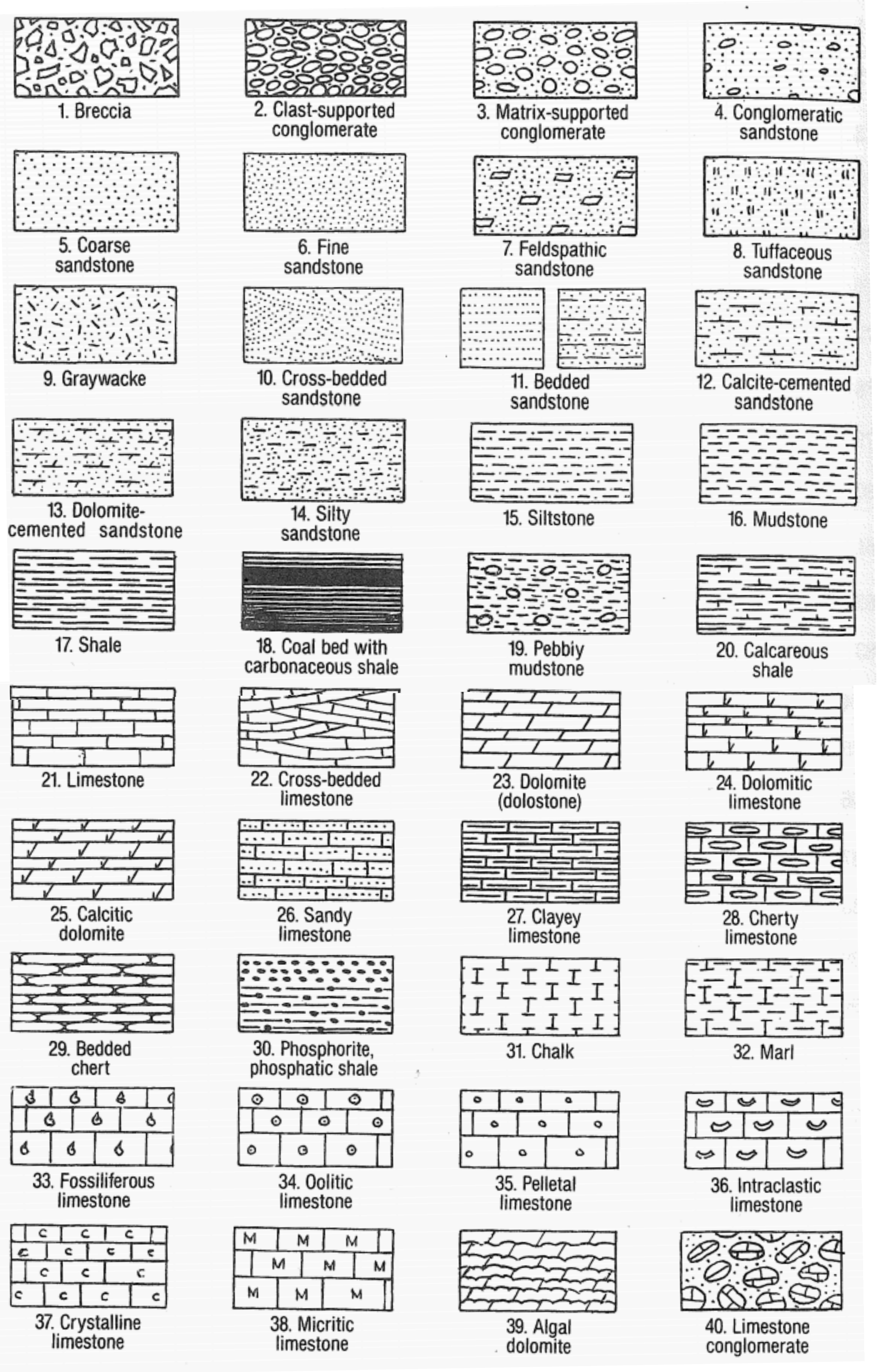
- Tree trunk fallen
- Trilobites
- Vertebrates
- Wood
- Beds distinct
- Beds obscure
- Unbedded
- Graded beds
- Planar cross-bedding
- Trough cross-bedding
- Ripple structures
- Cut and fill
- Load casts



- Foraminifers, general
- Foraminifers, large
- Fossils
- Fossils abundant
- Fossils sparse
- Gastropods
- Graptolites
- Leaves
- Ostracodes
- Pelecypods
- Root molds
- Spicules
- Stromatolites
- Tree trunk in place
- Scour casts
- Convolution
- Slumped beds
- Paleosol
- Mud cracks
- Salt molds
- Burrows
- Pellets
- Oolites
- Pisolites
- Intraclasts
- Stylolite
- Concretion
- Calcitic concretion

From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections



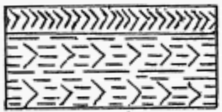
1. Breccia
2. Clast-supported conglomerate
3. Matrix-supported conglomerate
4. Conglomeratic sandstone
5. Coarse sandstone
6. Fine sandstone
7. Feldspathic sandstone
8. Tuffaceous sandstone
9. Graywacke
10. Cross-bedded sandstone
11. Bedded sandstone
12. Calcite-cemented sandstone
13. Dolomite-cemented sandstone
14. Silty sandstone
15. Siltstone
16. Mudstone
17. Shale
18. Coal bed with carbonaceous shale
19. Pebbiy mudstone
20. Calcareous shale
21. Limestone
22. Cross-bedded limestone
23. Dolomite (dolostone)
24. Dolomitic limestone
25. Calcitic dolomite
26. Sandy limestone
27. Clayey limestone
28. Cherty limestone
29. Bedded chert
30. Phosphorite, phosphatic shale
31. Chalk
32. Marl
33. Fossiliferous limestone
34. Oolitic limestone
35. Pelletal limestone
36. Intraclastic limestone
37. Crystalline limestone
38. Micritic limestone
39. Algal dolomite
40. Limestone conglomerate

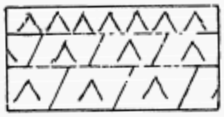
From Compton, 1985

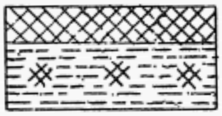
Lithologic Patterns for Stratigraphic Columns & Cross Sections

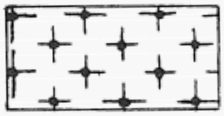

41. Limestone breccia

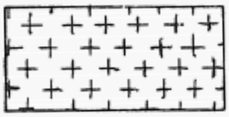

42. Algal dolomite breccia

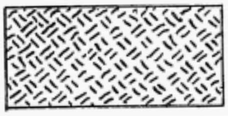

43. Gypsum bed, gypsiferous shale

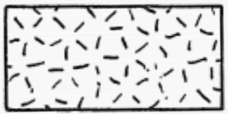

44. Anhydrite, anhydritic dolomite

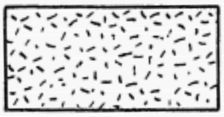

45. Rock salt, salty mudstone

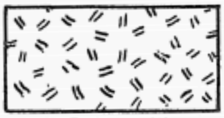

46. Peridotite

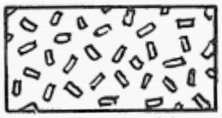

47. Gabbro

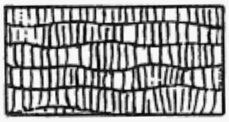

48. Mafic plutonic rock

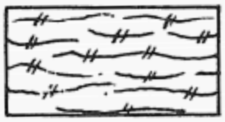

49. Coarse granitic rock

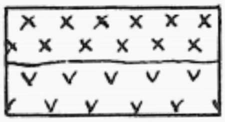

50. Fine granitic rock

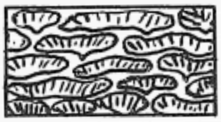

51. Porphyritic plutonic rock

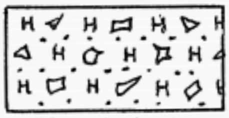

52. Porphyritic plutonic rock


53. Mafic lava

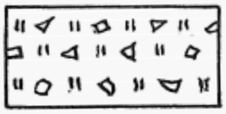

54. Silicic lava

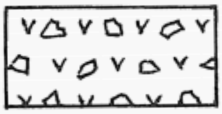

55. Intrusive volcanic rocks

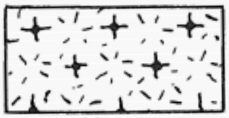

56. Pillow lava


57. Hyaloclastite

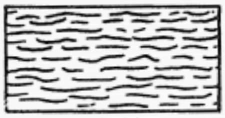

58. Tuff

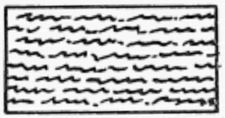

59. Tuff-breccia


60. Volcanic breccia

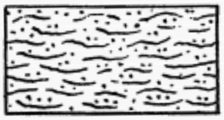

61. Massive serpentinite

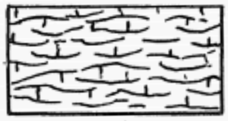

62. Foliated serpentinite

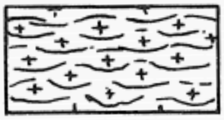

63. Schist


64. Crenulated schist

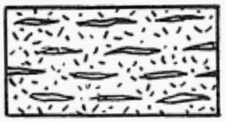

65. Folded schist

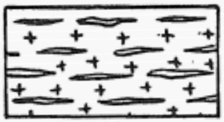

66. Semischistose sandstone

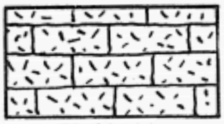

67. Semischistose limestone

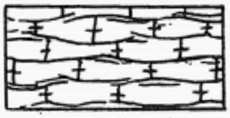

68. Semischistose gabbro

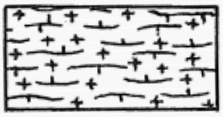

69. Greenstone

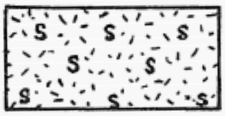

70. Silicic gneiss

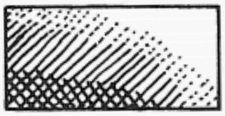

71. Mafic gneiss

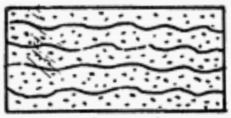

72. Marble

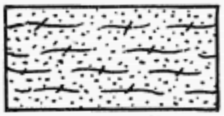

73. Foliated marble

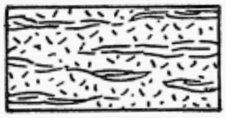

74. Foliated calc-silicate rock

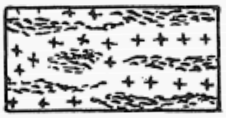

75. Massive skarn


76. Alteration zones


77. Quartzite

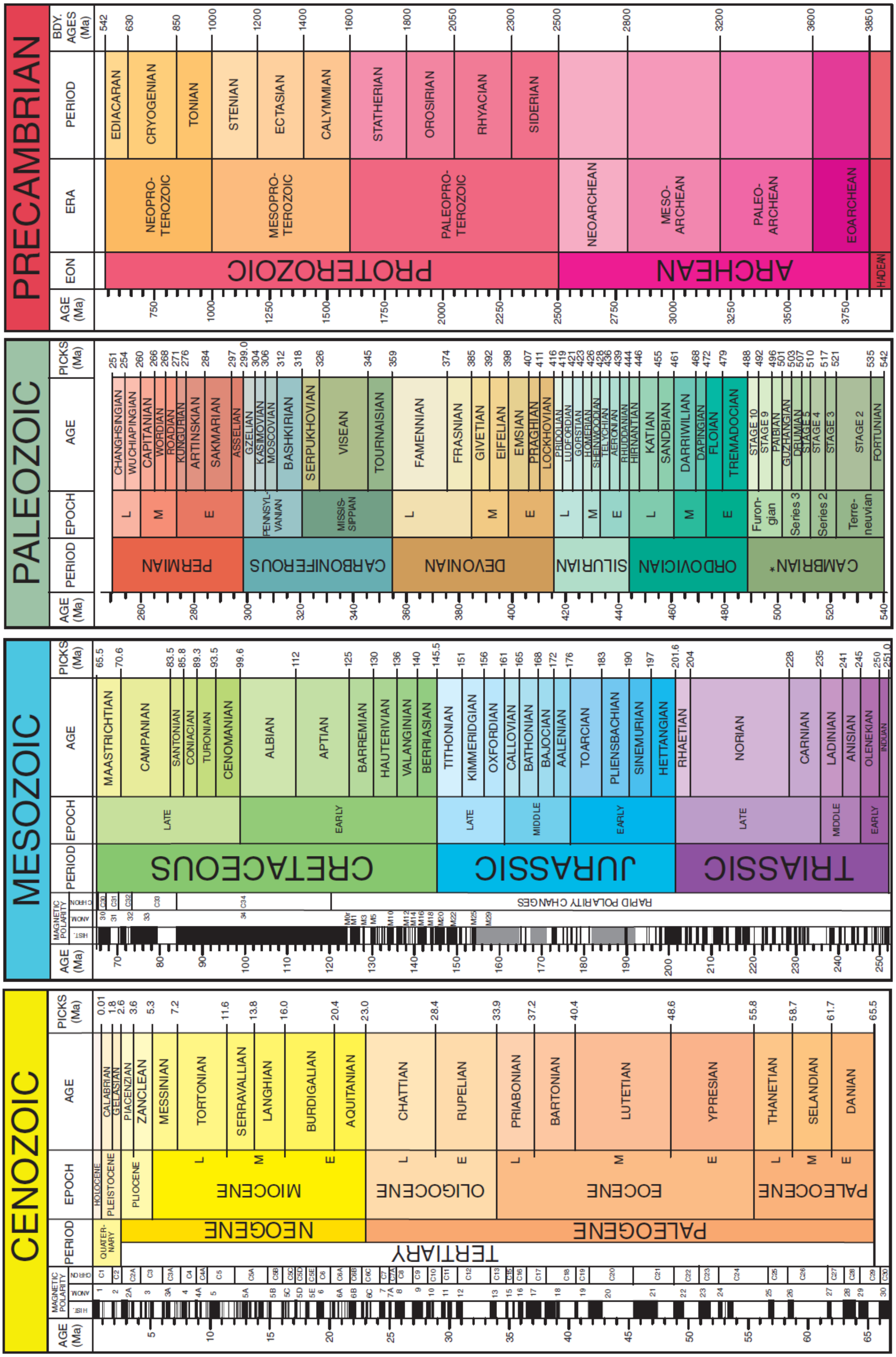

78. Quartzite


79. Silicic migmatite


80. Mafic migmatite

From Compton, 1985

Geologic Timescale



2009 version, from the Geologic Society of A

Aa: A blocky and fragmented form of lava occurring in flows with fissured and angular surfaces.

Alkali metal: A strongly basic metal like potassium or sodium.

Alluvial fan: A low, cone shaped deposit of terrestrial sediment formed where a stream undergoes an abrupt reduction of slope.

Alluvium: Unconsolidated terrestrial sediment composed of sorted or unsorted sand, gravel, and clay that has been deposited by water.

Angle of repose: The steepest slope angle in which particular sediment will lie without cascading down.

Aquifer: A permeable formation that stores and transmits groundwater in sufficient quantity to supply wells.

Arroyo: A steep-sided and flat-bottomed gully in an arid region that is occupied by a stream only intermittently, after rains.

Artesian well: A well that reaches an aquifer containing water under pressure. Thus water in the well rises above the surrounding water table.

Barchan: A crescent-shaped sand dune moving across a clean surface with its convex face upwind and its concave slip face downwind.

Basalt: A fine-grained, dark, mafic igneous rock composed largely of plagioclase feldspar and pyroxene.

Basement: The oldest rocks recognized in a given area, a complex of metamorphic and igneous rocks that underlies all the sedimentary formations.

Basic rock: Any igneous rock containing mafic minerals rich in iron and magnesium, but containing no quartz and little sodium rich plagioclase feldspar.

Basin: In tectonics, a circular, syncline-like depression of strata. In sedimentology, the site of accumulation of a large thickness of sediments.

Batholith: A great irregular mass of coarse-grained igneous rock which has either intruded the country rock or been derived from it through metamorphism.

Bathymetry: The study and mapping of sea-floor topography.

Bedding: A characteristic of sedimentary rocks in which parallel planar surfaces separating different grain sizes or compositions indicate successive depositional surfaces that existed at the time of sedimentation.

Bolson: In arid regions, a basin filled with alluvium and intermittent playa lakes and having no outlet.

Butte: A steep sided and flat topped hill formed by erosion of flat laying strata where remnants of a resistant layer protect the softer rocks underneath.

Caldera: A large, circular depression in a volcanic terrain, typically originating in collapse, explosion, or erosion.

Carbonate rock: A rock composed of carbonate minerals, especially limestone and dolomite.

Cataclastic rock: A breccia of powdered rock formed by crushing and shearing during tectonic movements.

Chemical weathering: The total set of all chemical reactions that act on rock exposed to water and atmosphere and so change it minerals to stable forms.

Chert: A sedimetary form of amorphous or extremely fine-grained silica, partially hydrous, found in concretions and beds.

Cinder cone: A steep, conical hill built up about a volcanic vent and composed of coarse pyroclasts expelled from the vent by escaping gases.

Clastic rock: A sedimentary rock formed from mineral particles (clasts) that were mechanically transported.

Clay: Any of a number of hydrous aluminosilicate minerals formed by weathering and hydration of other silicates.

Composite cone: The volcanic cone of a stratovolcano, composed of both cinders and lava flows.

Deflation: The removal of clay and dust from dry soil by strong winds.

Delta: A body of sediment deposited in an ocean or lake at the mouth of a stream.

Deposition: A general term for the accumulation of sediments by either physical or chemical sedimentation.

Deposition remnant magnetization: Magnetization created in sedimentary rocks by rotation of magnetic crystals into line with the ambient field during settling.

Desert pavement: A deposit produced by continued deflation, which removes the fine grains of a soil and leaves a surface covered with closely packed cobbles.

Detrital sediment: Sediment deposited by a physical process.

Diagenesis: The physical and chemical changes undergone by a sediment during lithification and compaction, excluding erosion and metamorphism.

Diatreme: A volcanic vent filled with breccia by the explosive escape of gases.

Dip: The angle by which a stratum or other planar feature deviates from the horizontal. The angle is measured in a plane perpendicular to the strike.

Drainage basin: A region of land surrounded by divides and crossed by streams that eventually converge to one river or lake.

Drift (glacial): A collective term for all the rock, sand, and clay that is transported and deposited by a glacier either as till or as outwash.

Dune: An elongated mound of sand formed by wind or water.

Eolian: Pertaining to or deposited by wind.

Epicenter: The point on the Earth's surface directly above the focus or hypocenter of an earthquake.

Erosion: The set of all processes by which soil and rock are loosened and moved downhill or downwind.

Evaporite: A chemical sedimentary rock consisting of minerals precipitated by evaporating waters, especially salt and gypsum.

Exfoliation: A physical weathering process in which sheets of rock are fractured and detached from an outcrop.

Fault: A planar or gently curved fracture in the Earth's crust across which there has been relative displacement.

Fault plane: The plane that best approximates the fracture surface of a fault.

Felsic: An adjective used to describe a light-colored igneous rock poor in iron and magnesium content, abundant in feldspars and quartz.

Fissure: An extensive crack, break, or fracture in the rocks.

Flood basalt: A plateau basalt extending many kilometers in flat, layered flows originating in fissure eruptions.

Flow cleavage: In a metamorphic rock, the parallel arrangement of all planar or linear crystals as a result of rock flowage during metamorphism.

Fluid inclusion: A small body of fluid that is entrapped in a crystal and has the same composition as the fluid from which the crystal formed.

Focus (earthquake): The point at which the rupture occurs; synonymous with hypocenter.

Fold: A planar feature, such as a bedding plane, that has been strongly warped, presumably by deformation.

Foliation: Any planar set of minerals or banding of mineral concentrations including cleavage, found in a metamorphic rock.

Forset bed: One of the inclined beds found in crossbedding; also an inclined bed deposited on the outer front of a delta.

Friction breccia: A breccia formed in a fault zone or volcanic pipe by the relative motion of two rock bodies.

Fumarole: A small vent in the ground from which volcanic gases and heated groundwater emerge, but not lava.

Geochronology: The science of absolute dating and relative dating of geologic formations and events, primarily through the measurement of daughter elements produced by radioactive decay in minerals.

Geomorphology: The science of surface landforms and their interpretation on the basis of geology and climate.

Geosyncline: A major downwarp in the Earth's crust, usually more than 1000 kilometers in length, in which sediments accumulate to thicknesses of many kilometers. The sediments may eventually be deformed and metamorphosed during a mountain-building episode.

Geotherm: A curving surface within Earth along which the temperature is constant.

Geyser: A hot spring that throws hot water and steam into the air. The heat is thought to result from the contact of groundwater with magma bodies.

Glacial rebound: Epeirogenic uplift of crust that takes place after the retreat of a continental glacier in response to earlier subsidence under the weight of ice.

Glacial striations: Scratches left on bedrock and boulders by overriding ice, and showing the direction of motion.

Glacial valley: A valley occupied or formerly occupied by a glacier, typically with a U-shaped profile.

Glacier: A mass of ice and surficial snow that persists throughout the year and flows downhill under its own weight, of sizes 100 m–10,000 km.

Glass: A rock formed when magma is too rapidly cooled (quenched) to allow crystal growth.

Graben: A downthrown block between two normal faults of parallel strike but converging dips; hence a tensional feature. See also horst.

Graded bedding: A bed in which the coarsest particles are concentrated at the bottom and grade gradually upward into fine silt.

Granite: A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar, and micas.

Gravity anomaly: The value of gravity left after subtracting the reference value based on latitude, and possibly the free-air and Bouguer corrections. Gravity survey: The measurement of gravity at regularly spaced grid points with repetitions to control instrument drift.

Groundwater: The mass of water in the ground below the phreatic zone occupying the total pore space in the rock.

Horst: An elongate, elevated block of crust forming a ridge or plateau, typically bounded by parallel, outward-dipping normal faults.

Hydration: A chemical reaction, usually in weathering, which adds water or OH to a mineral structure.

Hydraulic conductivity: A measure of the permeability of a rock or soil: the volume of flow through a unit surface in unit time with unit hydraulic pressure difference as the driving force.

Hydrologic cycle: The cyclical movement of water from the ocean to the atmosphere, through rain to the surface, through runoff and groundwater to streams, and back to the sea.

Hydrology: The science of that part of the hydrologic cycle between rain and return to the sea; the study of water on and within the land.

Hydrothermal activity: Any process involving high-temperature groundwaters, especially the alteration and emplacement of minerals and the formation of hot springs and geysers.

Hydrothermal vein: A cluster of minerals precipitated by hydrothermal activity in a rock cavity.

Igneous rock: A rock formed by congealing rapidly or slowly from a molten state.

Inclination: The angle between a line in the Earth's magnetic field and the horizontal plane; also a synonym for dip.

Infiltration: The movement of groundwater or hydrothermal water into rock or soil through joints and pores.

Intrusion: An igneous rock body that has forced its way in a molten state into surrounding country rock.

Intrusive rock: Igneous rock that is interpreted as a former intrusion from its cross-cutting contacts, chilled margins, or other field relations.

Isograd: A line or curved surface connecting rocks that have undergone an equivalent degree of metamorphism.

Isostasy: The mechanism whereby areas of the crust rise or subside until the mass of their topography is buoyantly supported or compensated by the thickness of crust below, which "floats" on the denser mantle. The theory that continents and mountains are supported by low-density crustal "roots."

Isotope: One of several forms of one element, all having the same number of protons in the nucleus but differing in number of neutrons and atomic weight.

Joint: A large and relatively planar fracture in a rock across which there is no relative displacement of the two sides.

Laccolith: A sill-like igneous intrusion that forces apart two strata and forms a round, lens-shaped body many times wider than it is thick.

Lahar: A mudflow of unconsolidated volcanic ash, dust, breccia, and boulders mixed with rain or the water of a lake displaced by a lava flow.

Laminar flow: A flow regime in which particle paths are straight or gently curved and parallel.

Lapilli: A fragment of volcanic rock formed when magma is ejected into the air by expanding gases.

Lava: Magma or molten rock that has reached the surface.

Lava tube: A sinuous, hollow tunnel formed when the outside of a lava flow cools and solidifies and the molten material passing through it is drained away.

Leaching: The removal of elements from a soil by dissolution in water moving downward in the ground.

Left-lateral fault: A strike-slip fault on which the displacement of the far block is to the left when viewed from either side.

Levee: A low ridge along a stream bank, formed by deposits left when floodwater decelerates on leaving the channel.

Limb (fold): The relatively planar part of a fold or of two adjacent folds (for example, the steeply dipping part of a stratum between an anticline and syncline).

Limestone: A sedimentary rock composed principally of calcium carbonate (CaCO2), usually as the mineral calcite.

Lithification: The processes that convert a sediment into a sedimentary rock.

Lithology: The systematic description of rocks, in terms of mineral composition and texture.

Lithosphere: The outer, rigid shell of the Earth, situated above the asthenosphere and containing the crust, continents, and plates.

Lode: An unusually large vein or set of veins containing ore minerals.

Longitudinal dune: A long dune parallel to the direction of the prevailing wind.

Lopolith: A large laccolith that is bowl-shaped and depressed in the center, possibly by subsidence of an emptied magma chamber beneath the intrusion. Maar volcano: A volcanic crater without a cone, believed to have been formed by an explosive eruption of trapped gases.

Mafic mineral: A dark-colored mineral rich in iron and magnesium, especially a pyroxene, amphibole, or olivine.

Magma: Molten rock material that forms igneous rocks upon cooling. Magma that reaches the surface is referred to as lava.

Magma chamber: A magma-filled cavity within the lithosphere.

Magnetic anomaly: The value of the local magnetic field remaining after the subtraction of the dipole portion of the Earth's field.

Magnetic north pole: (1) The point where the Earth's surface intersects the axis of the dipole that best approximates the Earth's field. (2) The point where the Earth's magnetic field dips vertically downward.

Magnetic stratigraphy: The study and correlation of polarity epochs and events in the history of the Earth's magnetic field as contained in magnetic rocks.

Magnetometer: An instrument for measuring either one orthogonal component or the entire intensity of the Earth's magnetic field at various points.

Mantle: The main bulk of the Earth, between the crust and core, ranging from depths of about 40–3,480 km It is composed of dense mafic silicates and divided into concentric layers by phase changes that are caused by the increase in pressure with depth.

Mass spectrometer: An instrument for separating ions of different mass but equal charge (mainly isotopes in geology) and measuring their relative quantities.

Mechanical weathering: The set of all physical processes by which an outcrop is broken up into small particles.

Mesophere: The lower mantle.

Metamorphism: The changes of mineralogy and texture imposed on a rock by pressure and temperature in the Earth's interior.

Meteorite: A stony or metallic object from inter-planetary space that penetrates the atmosphere to impact on the surface.

Micrometeorite: A meteorite less than 1 millimeter in diameter.

Microseism: A weak vibration of the ground that can be detected by seismographs and which is caused by waves, wind, or human activity.

Mineral: A naturally occurring element or non-organic compound with a precise chemical formula and a regular internal lattice structure.

Mohorovic discontinuity ("Moho"): Boundary between crust and mantle, marked by a rapid increase in seismic wave velocity to >8 km/s (depth 5-45 km).

Mohs scale of hardness: An empirical, ascending scale of mineral hardness.

Monocline: The S-shaped fold connecting two horizontal parts of the same stratum at different elevations. Its central limb is usually not overturned.

Moraine: A glacial deposit of till left at the margin of an ice sheet.

Normal fault: A dip-slip fault in which the block above the fault has moved downward relative to the block below.

Oblique-slip fault: A fault that combines some strike slip motion with some dip-slip motion.

Ore: A natural deposit in which a valuable metallic element occurs in high enough concentration to make mining economically feasible.

Orogenic belt: A linear region, often a former geo-syncline, that has been subjected to folding, and other deformation in a mountain-building episode.

Orogeny: The tectonic process in which large areas are folded, thrust-faulted, metamorphosed, and subjected to plutonism. The cycle ends with uplift and the formation of mountains.

Outgassing: The release of juvenile gases to the atmosphere and oceans by volcanism.

Oxidation: A chemical reaction in which electrons are lost from an atom and its charge becomes more positive.

Pahoehoe: A basaltic lava flow with a glassy, smooth, and undulating, or ropy, surface.

Paleoclimate: The average state or typical conditions of climate during some past geologic period.

Paleomagnetism: The science of the reconstruction of the Earth's ancient magnetic field and the positions of the continents from the evidence of remnant magnetization in ancient rocks.

Paleowind: A prevailing wind direction in an area, inferred from dune structure or the distribution of volcanic ash for one particular time in geologic history.

Pangaea: A great proto-continent from which all present continents have broken off by the mechanism of sea-floor spreading and continental drift.

Pediment: A planar, sloping rock surface forming a ramp up to the front of a mountain range in an arid region. It may be covered locally by thin alluvium.

Preferred orientation: Any deviation from randomness in the distribution of the crystallographic or grain shape axes of minerals of a rock produced by deformation and non-uniform stress during crystallization in metamorphic rocks or by depositional currents in sediments.

P-wave: The primary/fastest wave traveling away from a seismic event through the solid rock, consisting of a train of compressions/dilations of the material.

Pyroclastic rock: A rock formed by the accumulation of fragments of volcanic rock scattered by volcanic explosions.

Radiative transfer: One mechanism for the movement of heat, in which it takes the form of long-wavelength infrared radiation.

Recrystallization: The growth of new mineral grains in a rock at the expense of old grains, which supply the material.

Recumbent fold: An overturned fold with both limbs nearly horizontal.

Regolith: Any solid material lying on top of bedrock. Includes soil, alluvium, and rock fragments weathered from the bedrock.

Relief: The maximum regional difference in elevation.

Remote sensing: The study of Earth surface conditions and materials from airplanes and satellites by means of photography, spectroscopy, or radar.

Rhyolite: The fine-grained volcanic or extrusive equivalent of granite, light brown to gray and compact

Ridge (mid-ocean): A major linear elevated landform of the ocean floor, from 200–20,000 km in extent It is not a single ridge, but resembles a mountain range and may have a central rift valley.

Rift valley: A fault trough formed in a divergence zone or other area of tension.

Right-lateral fault: A strike-slip fault on which the displacement of the far block is to the right when viewed from either side.

Ripple: A very small dune of sand or silt whose long dimension is formed at right angles to the current

Saltation: The movement of sand or fine sediment by short jumps above the ground or stream bed under the influence of a current too weak to keep it permanently suspended.

Sandblasting: A physical weathering process in which rock is eroded by the impact of sand grains carried by the wind, frequently leading to ventifact formation of pebbles and cobbles.

Sandstone: A detrital sedimentary rock composed of grains from 1/16–2 mm in diameter, dominated in most sandstones by quartz, feldspar, and rock fragments, bound together by a cement of silica, carbonate, or other minerals or a matrix of clay minerals.

Sea-floor spreading: The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room. This process may continue at 0.5–10 cm/year through many geologic periods.

Secular variation: Slow changes in orientation of the Earth's magnetic field that appear to be long lasting and internal in origin.

Sedimentary rock: A rock formed by the accumulation and cementation of mineral grains transported by wind, water, or ice to the site of deposition or chemically precipitated at the depositional site.

Sedimentary structure: Any structure of a sedimentary or weakly metamorphosed rock that was formed at the time of deposition.

Sedimentation: The process of deposition of mineral grains or precipitates in beds or other accumulations.

Seismic reflection: Mode of seismic prospecting in which a seismic profile is examined for waves that reflected from near-horizontal strata below the surface.

Seismic refraction: Mode of seismic prospecting in which the seismic profile is examined for waves that have been refracted upward from seismic discontinuities below the profile. Greater depths may be reached than through seismic reflection.

Seismic surface wave: A seismic wave that follows the earth's surface only, with a speed less than that of S-waves.

Stratification: A structure of sedimentary rocks, which have recognizable parallel beds of considerable lateral extent

Stratigraphic sequence: A set of beds deposited that reflects the geologic history of a region.

Stratigraphy: The science of the description, correlation, and classification of strata in sedimentary rocks.

Stratovolcano: A volcanic cone consisting of both lava and pyroclastic rocks, often conical.

Stress: A quantity describing the forces acting on each part of a body in units of force per unit area.

Striation: See Glacial striation.

Strike: The angle between true North and the horizontal line contained in any planar feature (inclined bed, dike, fault plane, etc.).

Strike-slip fault: A fault whose relative displacement is purely horizontal.

Subduction zone: A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinkingoceanic plate and an overriding plate.

Sublimation: A phase change from the solid to the gaseous state, without passing through the liquid state.

Subsidence: A gentle epeirogenic movement where a broad area of the crust sinks without appreciable deformation.

Syncline: A large fold whose limbs are higher than its center; a fold with the youngest strata in the center.

Tectonics: The study of the movements and deformation of the crust on a large scale. including epeirogeny. metamorphism, folding, faulting, plate tectonics.

Thermal conductivity: A measure of a rock's capacity for heat conduction.

Thermal expansion: The property of increasing in volume as a result of an increase in internal temperature.

Thermoremnent magnetization: Permanent magnetization acquired by igneous rocks in the Earth's magnetic field as they cool through the Curie point Thrust fault A dip-slip fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.

Tilt: An unconsolidated sediment containing all sizes of fragments from clay to boulders deposited by glacial action, usually unbedded.

Topography: The shape of the Earth's surface, above and below sea level; the set of landforms in a region; the distribution of elevations.

Topset bed: A horizontal sedimentary bed formed at the top of a delta and overlying the foreset beds.

Trace element: An element that appears in minerals in a concentration of less than 1% (often <0.001%).

Transform fault: A strike-slip fault connecting the ends of an offset in a mid-ocean ridge. Some pairs of plates slide past each other along transform faults.

Transverse dune: A dune that has its axis transverse to the prevailing winds or to a current

Trench: A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

Tuff: A consolidated rock composed of pyroclastic fragments and fine ash. If particles are melted slightly together from their own heat, it is a "welded tuff".

Turbulent flow: A high-velocity flow in which streamlines are neither parallel nor straight but curled into small tight eddies (compare Laminar flow).

Ultramafic rock: An igneous rock consisting dominantly of mafic minerals, containing less than 10% feldspar.

Unconformity: A surface that separates two strata

Unconsolidated material: Nonlithified sediment that has no mineral cement or matrix binding its grains.

Uplift: A broad and gentle epeirogenic increase in the elevation of a region without a eustatic change of sea level.

Vadose zone: The region in the ground between the surface and the water table in which pores are not filled with water. Also called the unsaturated zone.

Valley glacier: A glacier that is smaller than a continental glacier or an icecap, and which flows mainly along well-defined valleys, many with tributaries.

Vein: A deposit of foreign minerals within a rock fracture or joint

Ventifact: A rock that exhibits the effects of sandblasting or "snowblasting" on its surfaces. which become flat with sharp edges in between.

Vesicle: A cavity in an igneous rock that was formerly occupied by a bubble of escaping gas.

Viscosity: A measure of resistance to flow in a liquid.

Volcanic ash: A volcanic sediment of rock fragments, usually glass, less than 4 mm in diameter, formed when escaping gases force out a fine spray of magma.

Volcanic bomb: A pyroclastic rock fragment that shows the effects of cooling in flight in its streamlined or "breadcrust" surface.

Volcanic breccia: A pyroclastic rock in which all fragments are more than 2 mm in diameter.

Volcanic cone: The deposit of lava and pyroclastic materials that has settled close to the volcano's central vent

Volcanic dome: A rounded accumulation around a volcanic vent of congealed lava too viscous to flow away quickly; hence usually rhyolite lava.

Volcanic ejecta blanket: A collective term for all the pyroclastic rocks deposited around a volcano, especially by a volcanic explosion.

Volcano: Any opening through the crust that has allowed magma to reach the surface, including the deposits immediately surrounding this vent

Warping: In tectonics, refers to the gentle, regional bending of the crust, which occurs in epeirogenic movements.

Water table: A curved surface below the ground at which the vadose zone ends and the phreatic zone begins; the level to which a well would fill with water.

Weathering: The set of all processes that decay and break up bedrock, by a combination of physically fracturing or chemical decomposition.

Xenolith: A piece of country rock found engulfed in an intrusion.