# Canyon de Chelly, Painted Desert 2011

Planetary Geology Field Studies – PTYS 594A

September 23-25, 2011

## Note from the Editor

A science fieldtrip becomes a history lesson amid the sediment layers of Canyon de Chelly and the Painted Desert. Here, space and time get all mixed up, and a canyon trail from rim to floor becomes a geological time machine. The Southwest's sediments reveal themselves as the top of a freshly unmade bed, with the covers shoved around and in some places doubled over on themselves, in other places (like the Permian-Triassic unconformity) caught with the duvet lying on the mattress.

Canyon de Chelly time travellers can't help but be distracted from the geology, however, as the canyon takes its visitors back through layers of human history amid its colorful sediments. The Anasazi and Navajo cliff dwellings set back within the canyon walls tell stories of generations of native peoples' ingenuity and persistence, carving out an existence from an environment which most would have called inhospitable to human life. Miles and millenia away, 19th century settlements faced different but similarly difficult conditions, as they strove to mine the Southwest's bedcovers for materials to make human life a bit more comfortable.

Sit back and watch as the Southwest rewinds its home video, then plays it on fast-forward. See the oceans slip slowly westward as the plateau yawns and stretches, and watch the receding waters carve their way through the deepening canyons into the lush lowlands. Trees grow and die and become rocks. On the smaller scales, precipitation pushes mudslides around, and leaves reddish-brown and black drip patterns on canyon walls. Then pause... freeze the frame at September 2011 CE, and explore.

*Melissa Dykhuis, ed.*

Acknowledgements: My thanks to Nathan Dykhuis for his technical support, help with printing, and infinite patience with my stress in pulling all of this together.

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Presentations

# Road log for PTYS 594 – All times are AZ times

**SATURDAY 9/24/2011**

7.30AM Look around area west of the river for petrified wood fragments.

8 AM Leave Camp. Sunrise 6:10AM.

Backtrack on county road to Woodruff (3 miles). Left on woodruff road to 77N (6 miles). Turn right on 77N and go 8 miles to I40. Go east on I40 for 46 miles and take exit 333 to 191N. Go 74 miles north to Chinle. Probably stop for gas here. From Chinle, take Indn route 7 east for ~3 miles.

11AM Enter Canyon De Chelly National Monument.

Continue on Indn route 7 for 11 miles. Turn left and drive 4.5 miles to the Spider Rock overlook. Talks on the Canyon Morphology:

- Sapping and contribution of surface runoff by **Ethan**
- Sapping Morphologies by **Youngmin**
- Sapping on Mars (and Titan?) by **Donna**

12.30 Lunch at Spider Rock Overlook.

Drive back to Indn route 7, turn right and drive 6 miles. Turn right and drive 0.5 miles to the White house overlook.

2PM White House Overlook. Talks on the rim:

- Permian and Triassic geography and their strata by **Kelly**
- Colorado Plateau uplift by **Colin**
- Regional Tectonics of the Plateau by **Pat**
- Sandstone formation by **Michelle**

Hike down the white house trail. Notice the transition from the lower Chinle formation (Shinarump conglomerate) to the De Chelly Sandstone. We'll pass an unconformity that includes the Permian-Triassic boundary, which is the largest mass extinction event in Earth's history... **Gabriel** will tell us more. Talks on Canyon floor:

- Cross-bedding from **Meghan**
- Rock Varnish by **Melissa**
- Anasazi and Najavo inhabitation of Canyon De Chelly by **Dyer**

Hike back up to the rim. Drive back to Indn route 7, turn right and drive 5 miles. Turn left on Indn route 8172 and drive 0.3 miles to the campground entrance.

6.00PM Camp: Cottonwood Campground, Canyon De Chelly.

Elevation 5560'. Sunset 6.14PM AZ time.

# Road log for PTYS 594 – All times are AZ times

**FRIDAY 9/23/2011**

7 AM Arrive at LPL loading dock with all our gear including breakfast, coffee, ice etc...

8 AM Depart LPL
Drive east on University -> north on Campbell -> west on Grant.
Turn north onto Oracle (route 77), drive 79 miles (avoiding the abomination that is Phoenix).

10AM Stop to View the El Capitan Landslide and hear **Beary** talk about the origin of long runout landslides on Earth and Mars.
Continue on the 77N for 19 miles. Switch to 70W for 2 miles, and back on the 77N for another 35 miles.

11.20 Stop at wide pull off that overlooks the Salt River Canyon. It's on the left (and unfortunately right on a bend in the road). This is a classic example of a fluvially incised valley and will make a striking contrast to Canyon De Chelly later in the trip. **Kat** will give us a talk on what sets river profiles and prompts incision such as we see here. There are nearby hieroglyphics whose origins will be expounded upon by **Sky**.

12PM Lunch at Salt River.
Listen to talks on

- Mogollon Rim Volcanism by **James.**
- Ore formation and mining by **Christa**
- 19th century settlement and mining towns by **Erin**

1.15PM Leave Salt River.
Cross the Salt River and continue on 77N/60E for 61 miles (stay on the 60E when the 77N branches off). Turn left onto 61E and drive 19 miles. Turn left (north) onto 180A and drive 11 miles followed by 18 miles on the 180 West. The entrance to the Petrified Forest National Park is on the right; enter and drive 2.3 miles to Giant Logs Trail.

3.30PM Arrive at Giant Logs Trail, Petrified Forest.
Around us we see members of the beautiful Chinle formation. We'll jump back and forth across this formation throughout the trip so **Cecilia** will first tell us how it came to be. We can take a short walk to admire the Chinle and large amounts of petrified wood strewn about. **Corey** will clue us into specifics of the petrifaction process. This time next year the Mars Science Laboratory will investigate Gale crater, a layered sedimentary mound over 5km thick that contains large clay deposits. **Shane** will talk about the comparison with the Chinle.

*Better option, if there's time. Drive further into the park to Blue Mesa, for better views of the Chinle. Round trip drive is an extra 50-60 minutes.*

4.30PM Leave the Park by heading out the way we came in. Turn right (west) onto the 180 and drive 18 miles until route 77. Turn left there and drive 7 miles. Turn left onto Woodruff Road and drive 5.5 miles. After passing through the bustling center of Woodruff we'll turn right on a county road. After 3.2 miles we cross the Little Colorado River and make camp.

5.30PM Camp: Confluence of Little Colorado and Silver Creek.
Elevation 5240'. Sunset 6.18PM AZ time.

# Road log for PTYS 594 – All times are AZ times

**SUNDAY 9/25/2011**

8 AM Leave Camp. Sunrise 6:07AM.

Drive westward back to Chinle and the 191. Drive 30 miles south on the 191, turn right (west) onto the 264 and travel another 30 miles. Turn left (south) onto Navajo Service Route 6 and travel 24 miles to Indn Route 15. Turn right (west) and travel 4 miles.

10AM Stop at Coliseum Maar (on the right). Not sure of the best entrance, but the southern rim is cut by a wash and we should be able to enter there. While we're at the place where we have a cross-section of the rim available we'll hear about Maars from **Sarah** and late stage volcanism on the Colorado Plateau from **Pablo**. Spend a little time exploring the layering in the rim and the Maar interior.

10.45 Depending on available time... Backtrack on Indn Route 15 for 1.5 miles, turn right on an unnamed dirt road and travel south-east for ~1.2 miles ignoring a few turn-offs. Pull up west of the Hoskietso Vents, which are two closely spaced diatremes.

Back to Indn route 15 and go west for 18 miles until you hit the 87. Go south on the 87 for 30 miles until you get to the I40. Take the I40 west to Flagstaff (62 miles) and transfer to I17 south for 3 more miles. Exit the I17 and take the 89A south for ~9 miles until we get to the Oak Creek Canyon overlook.

1.30PM Lunch at the Oak Creek Canyon Overlook.

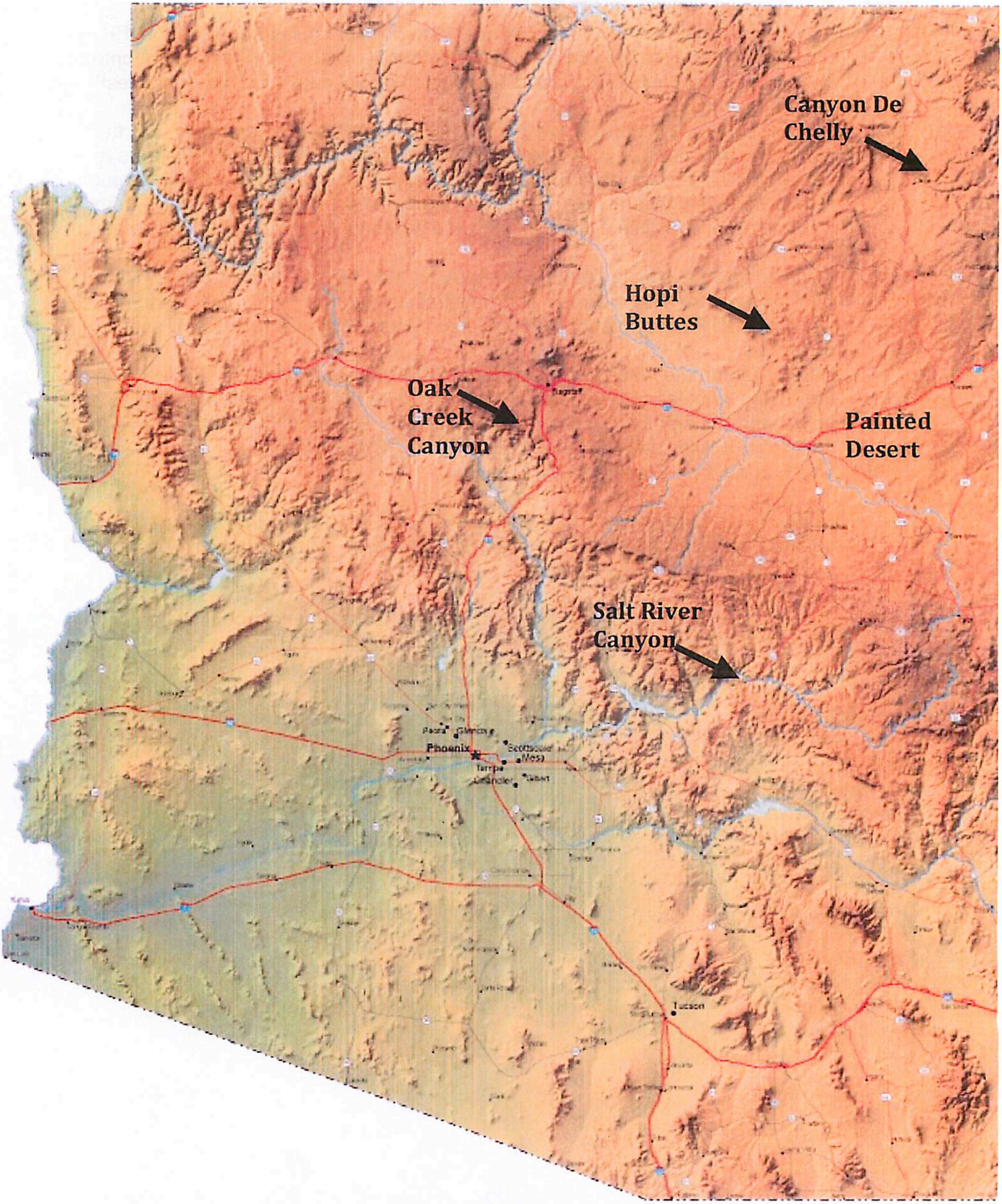
**Shane** will provide the parts of the stratigraphic story here that haven't been covered in other talks and describe the formation of the canyon, perhaps through an interpretative dance.

7PM Return to LPL. Unload the vehicles. Take Shower. Muse about water and sedimentary geology on various planets.

**Participants**

Corwin Atwood-Stone
Vic Baker
Sky Patrick Beard
Patricio Becerra
Shane Byrne
Meghan Cassidy
Youngmin Chung
Colin Dundas
Melissa Dykhuis
Pablo Espinoza
James Keane
Cecilia Leung
Erin Liskiewicz
Dyer Lytle
Kelly Miller
Sarah Morrison
Gabriel Muro
Dave O'Brien
Ethan Schaefer
Joe Spitale
Michelle Thompson
Christa Van Laerhoven
Donna Viola
Kathryn Volk
Zhiyong 'Beary' Xiao

## Road log for PTYS 594 – All times are AZ times



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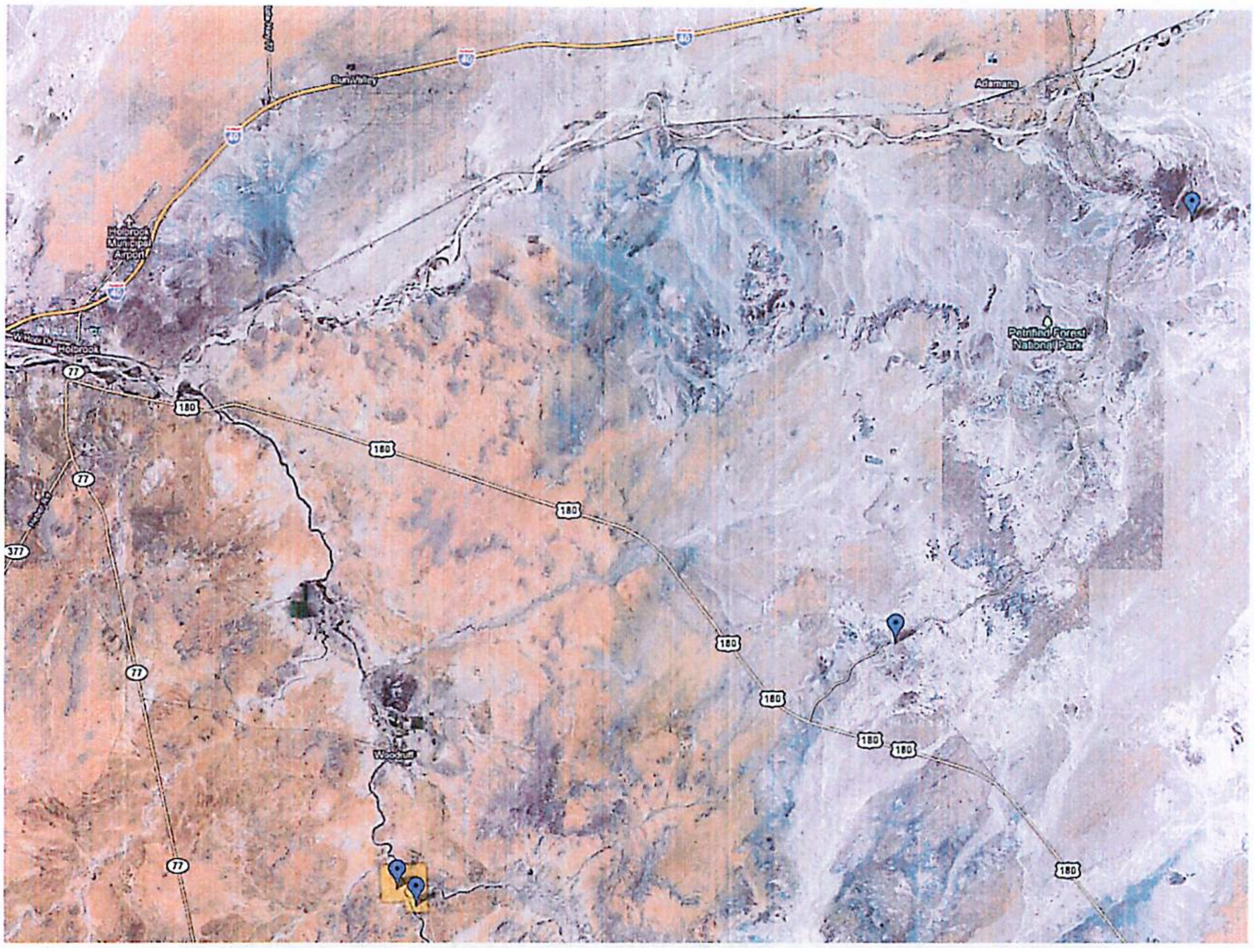
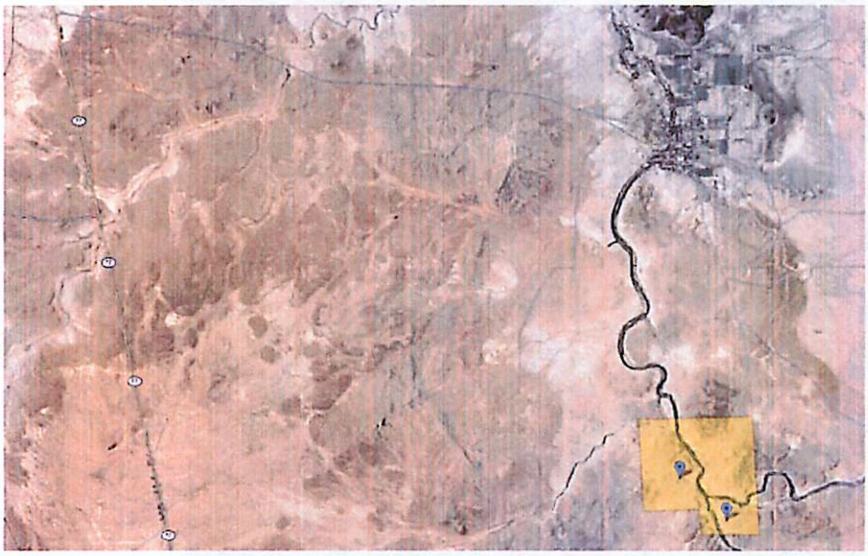
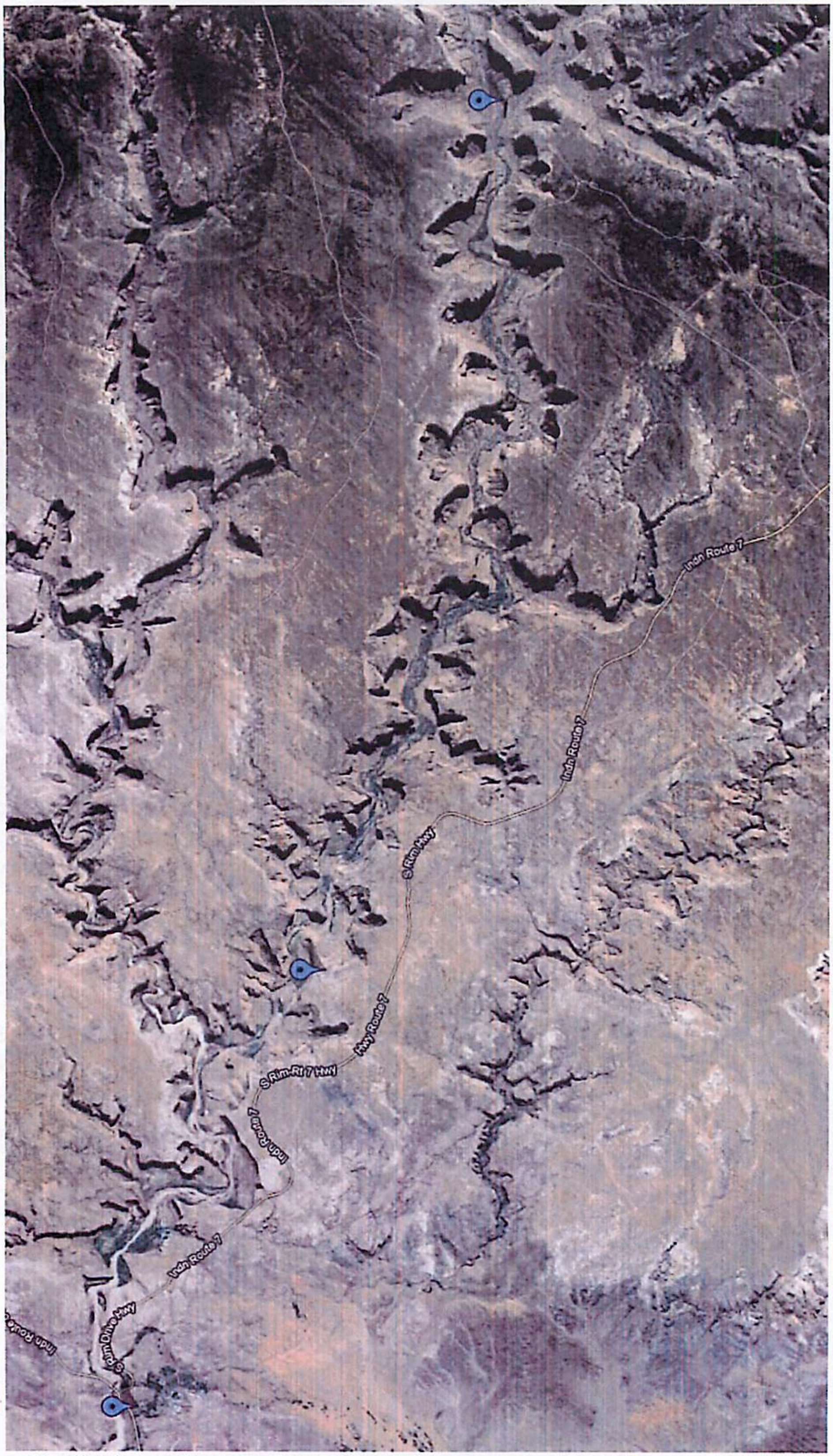


Holbrook and Petrified Forest area (north is up). Stop in the southwest is our campsite. Stops in the east and northeast are Giant Logs Trail and Blue Mesa respectively.



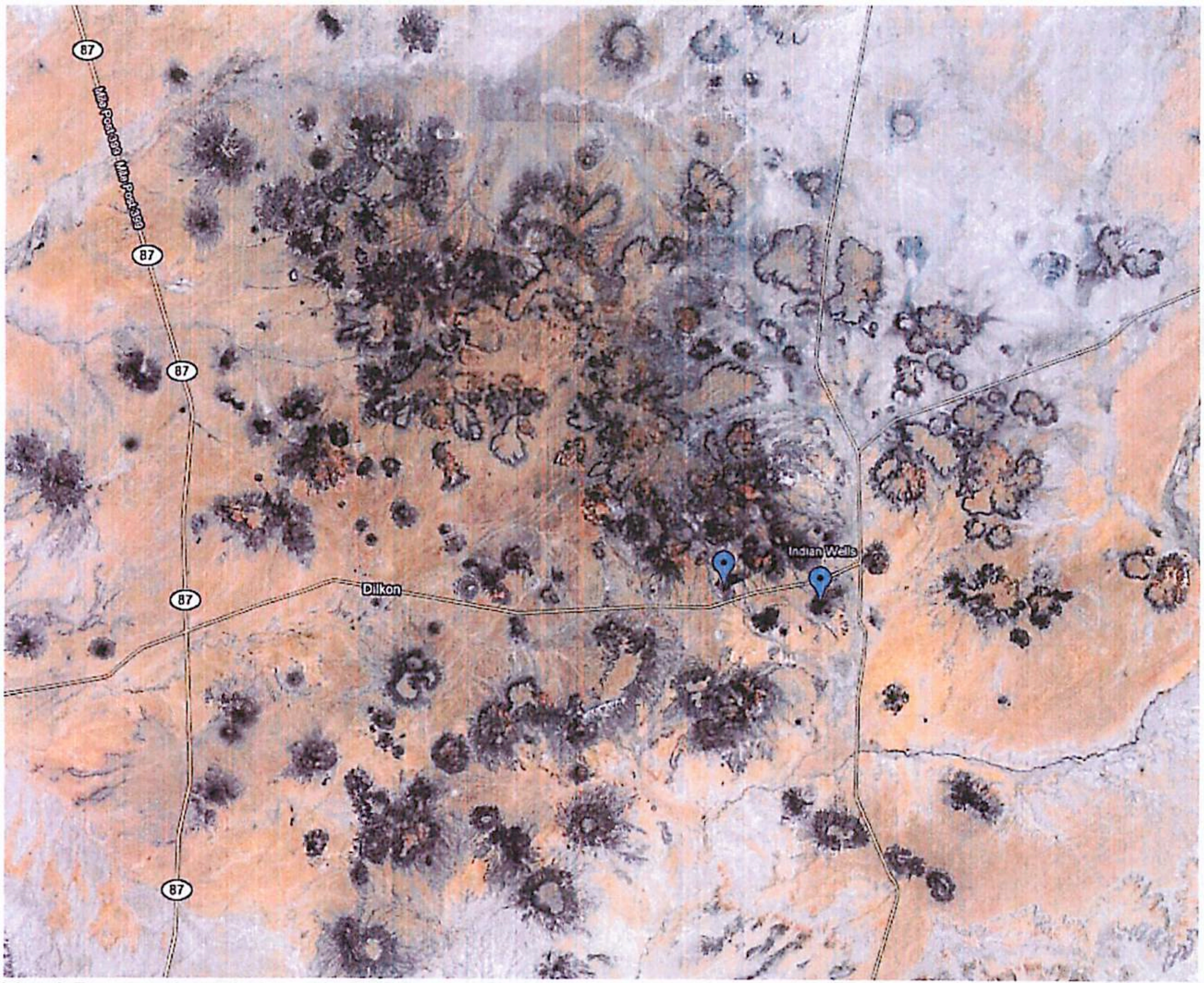
Zoom up of route to Friday nigh camp. The yellow patch is BLM land where we should camp and collect. The town north of the campsite is Woodruff.

## Road log for PTYS 594 – All times are AZ times



Canyon De Chelly (east is up). Stops (west to east) are the campground, White House Overlook and the spider Rock overlook.

## Road log for PTYS 594 – All times are AZ times



Hopi Buttes (north is up). Stops from west to east are Coliseum Maar and the Hoskietso Vents.

Oak Creek Canyon and Sedona (east is up). The northernmost stop is the overlook where we'll have Sunday's lunch. It's very unlikely we'll have time for the other stops on this trip.

## Sunrise/Sunset Times

| Wed 09/23/2011 | Thurs 09/24/2011 | Fri 09/25/2011 | Sat 09/26/2011 |
|---|---|---|---|
| Sunrise: 6:07am | Sunrise: 6:08am | Sunrise: 6:08am | Sunrise: 6:09am |
| Sunset: 6:14pm | Sunset: 6:13pm | Sunset: 6:11pm | Sunset: 6:10pm |
| Moonrise: 2:45am | Moonrise: 3:53am | Moonrise: 5:02am | Moonrise: 6:14am |
| Moonset: 4:41pm | Moonset: 5:18pm | Moonset: 5:53pm | Moonset: 6:28pm |

## This Week's Sky at a Glance

http://www.skyandtelescope.com/observing/ataglance

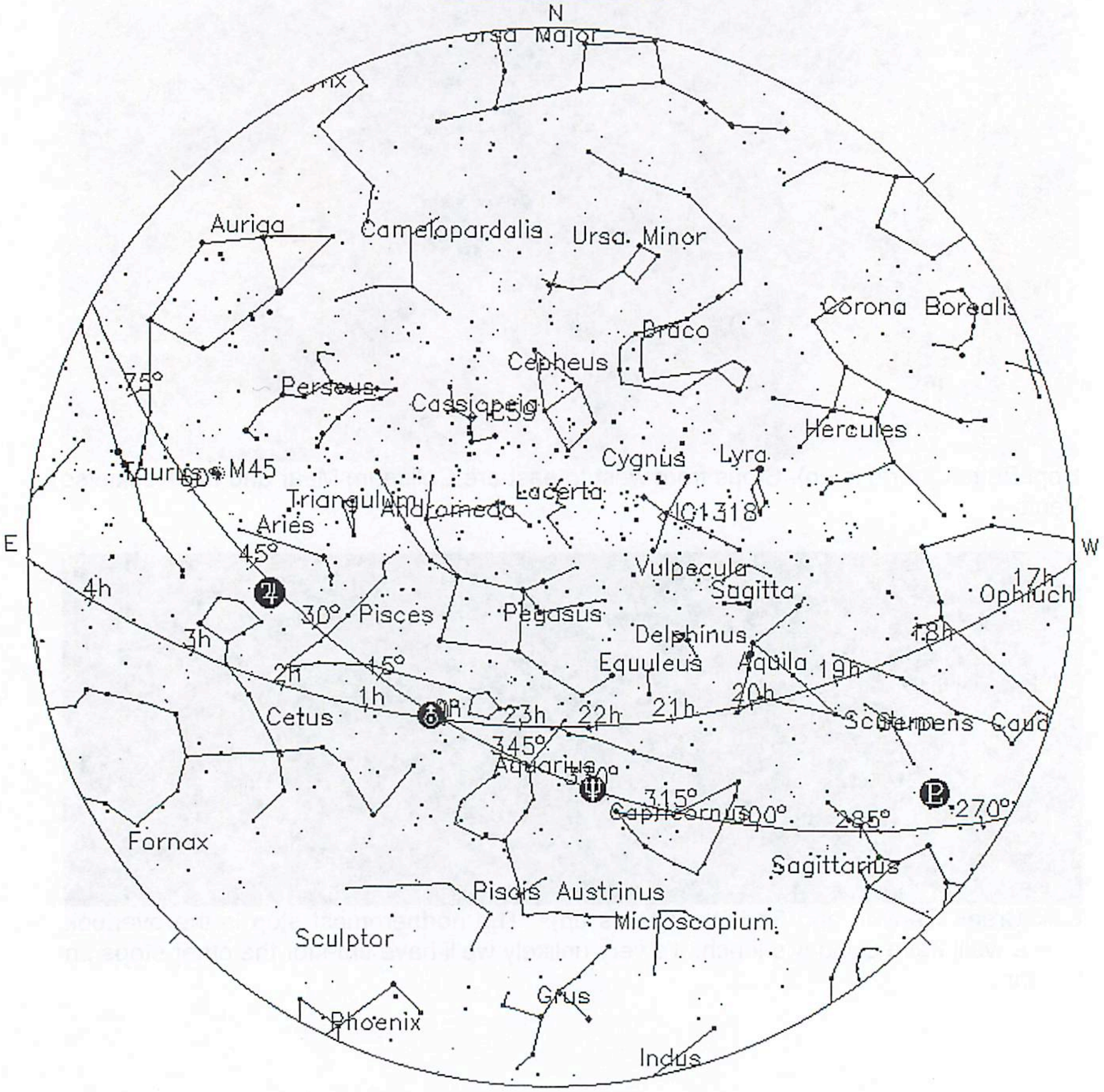
## Sky Map for Sept 24, 2011, 10:27pm MST, Albuquerque, NM

http://www.fourmilab.ch/cgi-bin/Yoursky

Planets (left to right): Jupiter, Uranus, Neptune, Pluto

# Sky above 35°5'N 106°39'3" W at Sun 2011 Sep 25 5:27 UTC

*Explain symbols in the map.*

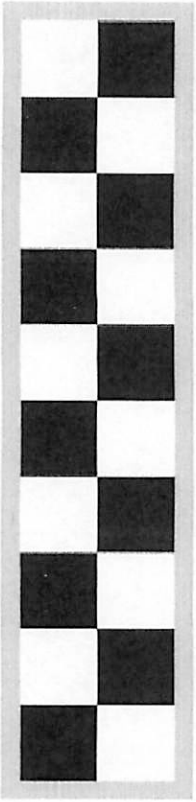


## GEOLOGIC TIME SCALE

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

(From http://sci.waikato.ac.nz/evolution/geological.shtml)

10 cm ruler



## ROCK DENSITIES

| Material type | Density range (Mg/m³) | Approximate average density (Mg/m³) |
|---|---|---|
| *Sedimentary rocks* | | |
| Alluvium | 1.96–2.00 | 1.98 |
| Clay | 1.63–2.60 | 2.21 |
| Gravel | 1.70–2.40 | 2.00 |
| Loess | 1.40–1.93 | 1.64 |
| Silt | 1.80–2.20 | 1.93 |
| Soil | 1.20–2.40 | 1.92 |
| Sand | 1.70–2.30 | 2.00 |
| Sandstone | 1.61–2.76 | 2.35 |
| Shale | 1.77–3.20 | 2.40 |
| Limestone | 1.93–2.90 | 2.55 |
| Dolomite | 2.28–2.90 | 2.70 |
| Chalk | 1.53–2.60 | 2.01 |
| Halite | 2.10–2.60 | 2.22 |
| Glacier ice | 0.88–0.92 | 0.90 |
| *Igneous rocks* | | |
| Rhyolite | 2.35–2.70 | 2.52 |
| Granite | 2.50–2.81 | 2.64 |
| Andesite | 2.40–2.80 | 2.61 |
| Syenite | 2.60–2.95 | 2.77 |
| Basalt | 2.70–3.30 | 2.99 |
| Gabbro | 2.70–3.50 | 3.03 |
| *Metamorphic rocks* | | |
| Schist | 2.39–2.90 | 2.64 |
| Gneiss | 2.59–3.00 | 2.80 |
| Phylite | 2.68–2.80 | 2.74 |
| Slate | 2.70–2.90 | 2.79 |
| Granulite | 2.52–2.73 | 2.65 |
| Amphibolite | 2.90–3.04 | 2.96 |
| Eclogite | 3.20–3.54 | 3.37 |

## Udden-Wentworth Grain Size Scale

| Size Range | Name |
|---|---|
| >256 mm | Boulder |
| 64-256 mm | Cobble |
| 4-64 mm | Pebble (occasionally subdivided) |
| 2-4 mm | Granule |
| 1-2 mm | Very Coarse Sand |
| 0.5-1 mm | Coarse Sand |
| 0.25-0.5 mm | Medium Sand |
| 125-250 µm | Fine Sand |
| 62.5-125 µm | Very Fine Sand |
| 31.25-62.5 µm | Silt |
| 15.75-31.25 µm | Clay |

## MOHS HARDNESS SCALE

| Index Mineral | Scale | Common Objects |
|---|---|---|
| Diamond | 10 | |
| Corundum | 9 | |
| Topaz | 8 | |
| Quartz | 7 | Steel file (6.5) |
| Orthoclase | 6 | |
| Apatite | 5 | Glass (5.5)<br>Knife blade (5.1)<br>Wire Nail (4.5)<br>Penney (3.5)<br>Fingernail (2.5) |
| Fluorite | 4 | |
| Calcite | 3 | |
| Gypsum | 2 | |
| Talc | 1 | |

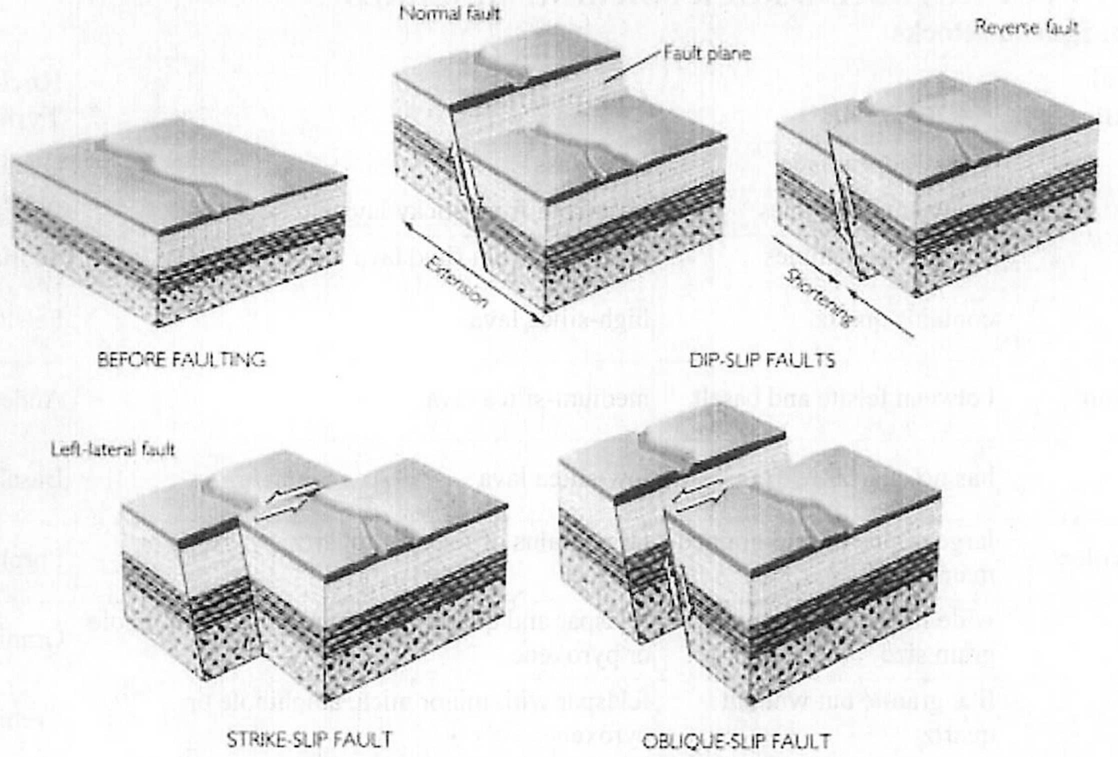
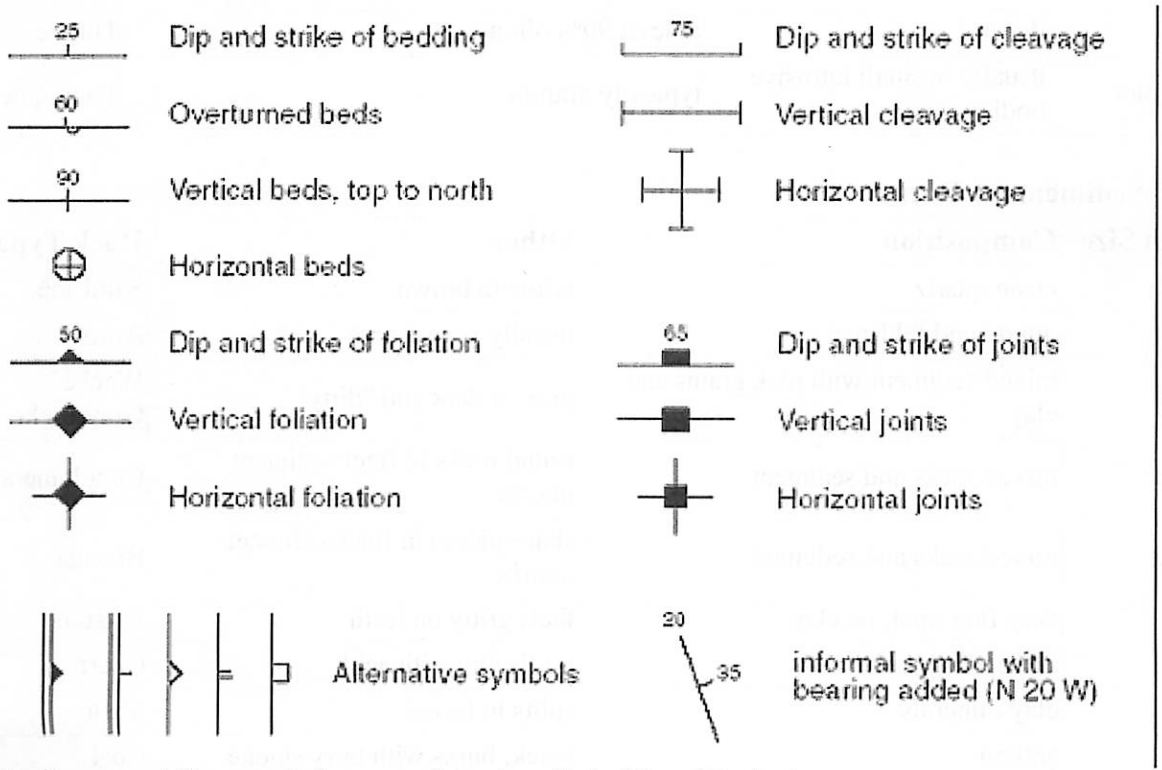


**Figure 10.22**
Press and Siever: *Understanding Earth*

OHT 34

FAULT TYPES
http://www.geo.wvu.edu/~jtoro/Petroleum/Review%202.html



http://www.public.asu.edu/~arrows/structure/Labs/Geo_Blocks/

# IDENTIFICATION OF ROCKS AND ROCK FORMING MINERALS

## Identification of Igneous Rocks

| Grain Size | Usual Color | Other | Composition | Rock Type |
|---|---|---|---|---|
| fine | dark | glassy appearance | lava glass | Obsidian |
| fine | light | many small bubbles | lava froth from sticky lava | Pumice |
| fine | dark | many large bubbles | lava froth from fluid lava | Scoria |
| fine or mixed | light | contains quartz | high-silica lava | Felsite |
| fine or mixed | medium | between felsite and basalt | medium-silica lava | Andesite |
| fine or mixed | dark | has no quartz | low-silica lava | Basalt |
| mixed | any color | large grains in fine-grained matrix | large grains of feldspar, quartz, pyroxene or olivine | Porphyry |
| coarse | light | wide range of color and grain size | feldspar and quartz with minor mica, amphibole or pyroxene | Granite |
| coarse | light | like granite but without quartz | feldspar with minor mica, amphibole or pyroxene | Syenite |
| coarse | medium to dark | little or no quartz | low-calcium plagioclase and dark minerals | Diorite |
| coarse | medium to dark | no quartz; may have olivine | high-calcium plagioclase and dark minerals | Gabbro |
| coarse | dark | dense; always has olivine | olivine with amphibole and/or pyroxene | Peridotite |
| coarse | dark | dense | mostly pyroxene with olivine and amphibole | Pyroxenite |
| coarse | green | dense | at least 90% olivine | Dunite |
| very coarse | any color | usually in small intrusive bodies | typically granitic | Pegmatite |

## Identification of Sedimentary Rocks

| Hardness | Grain Size | Composition | Other | Rock Type |
|---|---|---|---|---|
| hard | coarse | clean quartz | white to brown | Sandstone |
| hard | coarse | quartz and feldspar | usually very coarse | Arkose |
| hard or soft | mixed | mixed sediment with rock grains and clay | gray or dark and "dirty" | Wacke/ Graywacke |
| hard or soft | mixed | mixed rocks and sediment | round rocks in finer sediment matrix | Conglomerate |
| hard or soft | mixed | mixed rocks and sediment | sharp pieces in finer sediment matrix | Breccia |
| hard | fine | very fine sand; no clay | feels gritty on teeth | Siltstone |
| hard | fine | chalcedony | no fizzing with acid | Chert |
| soft | fine | clay minerals | splits in layers | Shale |
| soft | fine | carbon | black; burns with tarry smoke | Coal |
| soft | fine | calcite | fizzes with acid | Limestone |
| soft | coarse or fine | dolomite | no fizzing with acid unless powdered | Dolomite rock |

| | | | | |
|---|---|---|---|---|
| soft | coarse | fossil shells | mostly pieces | Coquina |
| very soft | coarse | halite | salt taste | Rock Salt |
| very soft | coarse | gypsum | white, tan or pink | Rock Gypsum |

### Identification of Metamorphic Rocks

| Foliation | Grain Size | Hardness | Usual Color | Other | Rock Type |
|---|---|---|---|---|---|
| foliated | fine | soft | dark | "tink" when struck | Slate |
| foliated | fine | soft | dark | shiny; crinkly foliation | Phyllite |
| foliated | coarse | hard | mixed dark and light | wrinkled foliation; often has large crystals | Schist |
| foliated | coarse | hard | mixed | banded | Gneiss |
| foliated | coarse | hard | mixed | distorted "melted" layers | Migmatite |
| foliated | coarse | hard | dark | mostly hornblende | Amphibolite |
| nonfoliated | fine | soft | greenish | shiny, mottled surface | Serpentinite |
| nonfoliated | fine or coarse | hard | dark | dull and opaque colors, found near intrusions | Hornfels |
| nonfoliated | coarse | hard | red and green | dense; garnet and pyroxene | Eclogite |
| nonfoliated | coarse | soft | light | calcite or dolomite by the acid test | Marble |
| nonfoliated | coarse | hard | light | quartz (no fizzing with acid) | Quartzite |

http://geology.about.com/library/bl/blrockident_tables.htm

**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<br>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** |

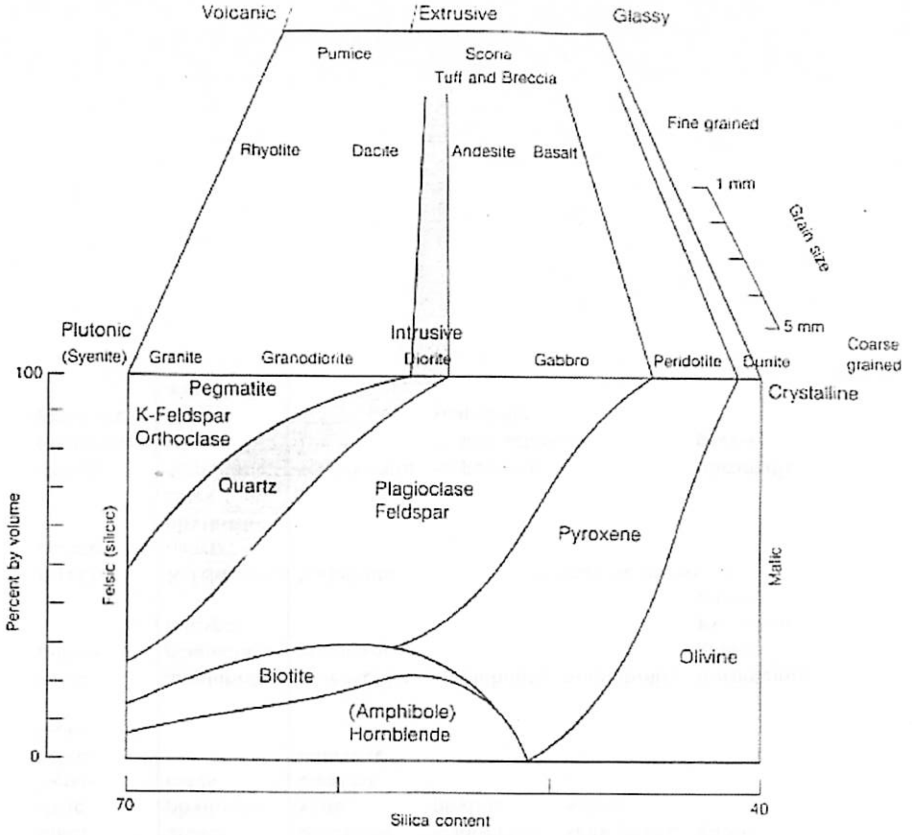
**Light-colored minerals**

| 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<br>White-Milky,<br>Yellow-Citrine,<br>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** |
| | Brown | Silvery black to black tarnishes gray | **Chromite** |
| Harness < 5 | 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** |

http://www.thisoldearth.net/This_Old_Earth/Home.html

## IGNEOUS ROCK TYPES



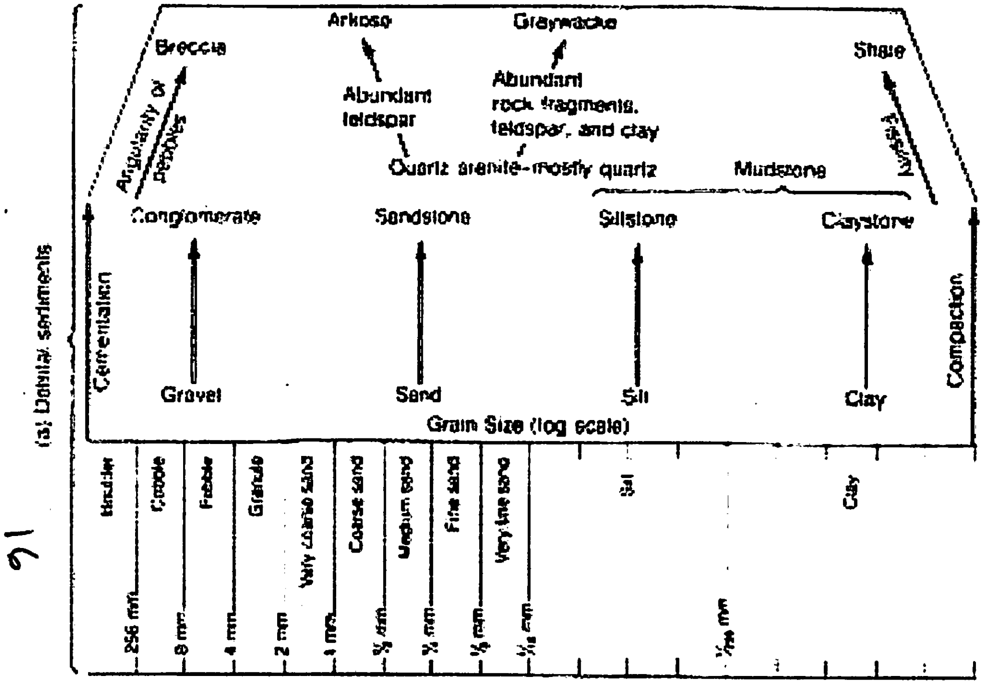
http://www2.ocean.washington.edu

## MINERAL CHEMICAL CLASSIFICATIONS

http://www.appstate.edu/~abbottrn/mnrl-id/

| **CHEMICAL GROUP** | | **ANIONIC SPECIES** | **EXAMPLES** |
|---|---|---|---|
| **OXIDES** minerals | | Oxygen, $O^{-2}$ | Hematite, $Fe_2O_3$; Magnetite: $Fe_3O_4$ |
| **SULFIDE** minerals | | Sulfur, $S^{-2}$ | Pyrite, $FeS_2$ |
| **CARBONATE** minerals | | Carbonate, $CO_3^{-2}$ | Calcite, $CaCO_3$; Dolomite, $CaMg(CO_3)_2$ |
| **SILICATE** minerals | | Silicate, $SiO_4^{-4}$, "Tetrahedron" | |
| | **STRUCTURAL SUBGROUPS OF THE SILICATES** | Isolated $SiO_4^{-4}$ Tetrahedra | Olivine, $(Mg,Fe)_2SiO_4$; Garnet, $(Fe,Mg,Ca)_3Al_2Si_3O_{12}$ |
| | | Single Chains of Tetrahedra, $Si_2O_6^{-4}$ | Pyroxene, e.g., Augite, $Ca(Mg,Fe)Si_2O_6$ |
| | | Double Chains of Tetrahedra, $(Si,Al)_8O_{22}^{-12 \text{ to } -14}$ | Amphibole, e.g.,<br>Hornblende, $NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$ |
| | | Sheets, $(Si,Al)_4O_{10}^{-4 \text{ to } -6}$ | Micas (phyllosilicates), e.g.,<br>Muscovite, $KAl_2(AlSi_3)O_{10}(OH)_2$,<br>Biotite, $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$,<br>Chlorite, $(Mg,Fe)_6Si_4O_{10}(OH)_8$ |
| | | Framework, $SiO_2$ or $(Al,Si)O_2^{-.25 \text{ to } -0.5}$ | Quartz, $SiO_2$<br>Feldspars<br>K-Feldspar, $K(AlSi_3)O_8$<br>Plagioclase, $(Na,Ca)(Al,Si)_4O_8$ |

## SEDIMENTARY ROCK TYPES
http://www2.ocean.washington.edu



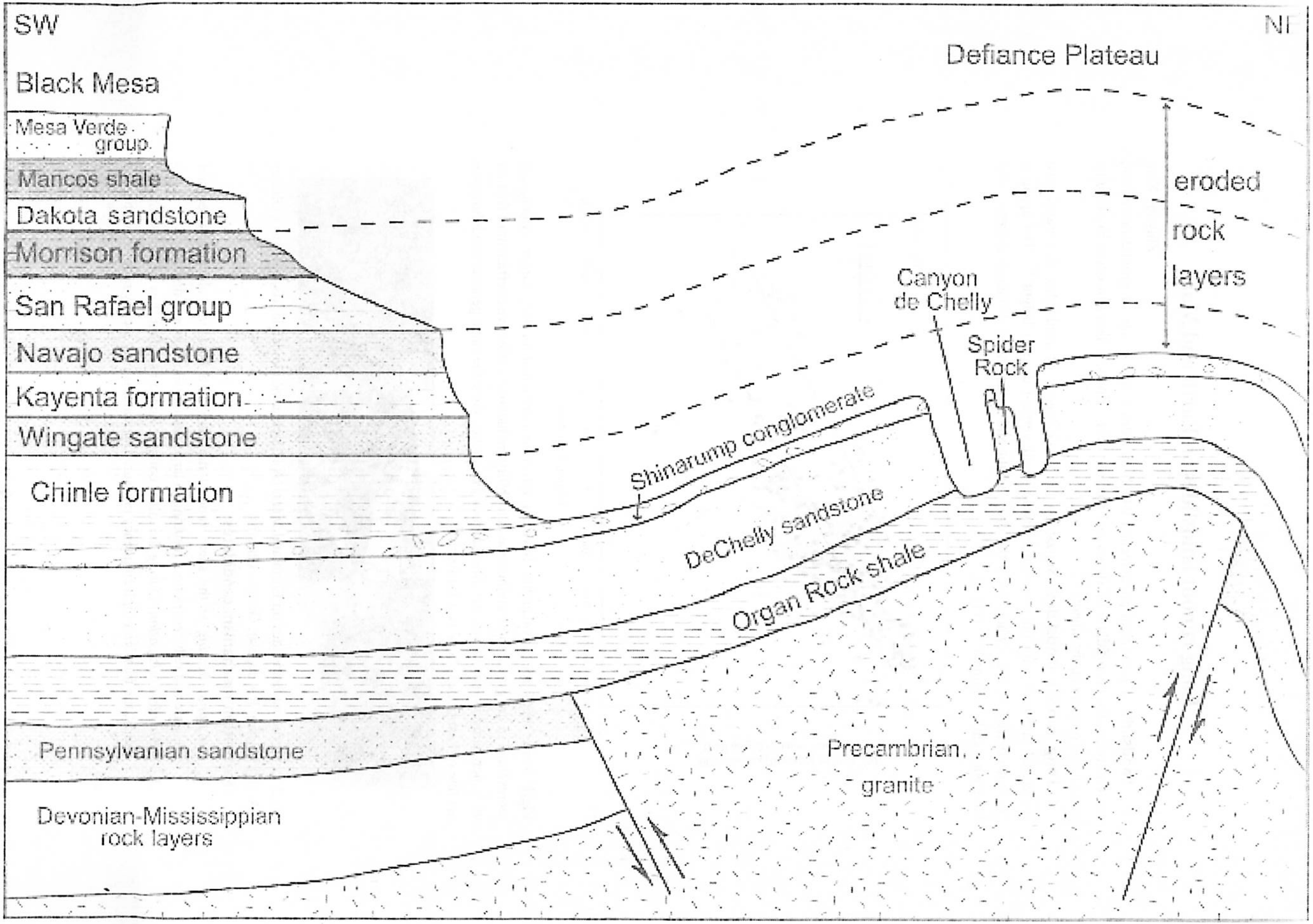
(b) Chemical sediments

| Rock | Limestone | Dolomite | Iron formation | Evaporite | Chert | Organics | Phosphate |
|---|---|---|---|---|---|---|---|
| Chemical composition | $CaCO_3$ | $CaMg(CO_3)_2$ | Fe-silicate<br>-oxide<br>carbonate | NaCl<br>$CaSO_4$ | $SiO_2$ | Carbon | $Ca_3(PO_4)_2$ |
| Minerals | Calcite<br>(Aragonite) | Dolomite | Hematite<br>Limonite<br>Siderite | Gypsum<br>Anhydrite<br>Halite<br>Other salts | Opal<br>Chalcedony<br>Quartz | Coal<br>Oil<br>Gas | Apatite |

**Figure 3-22**
Sedimentary rock classification. (a) Detrital sediments, (b) Chemical sediments.

## METAMORPHIC ROCK TYPES
http://www.dmtcalaska.org/course_dev/explogeo/class09/notes09.html

| *Primary igneous or sedimentary rock composition* | *Main mineral groups present* | *Fine-grained < 0·1 mm* | *Medium-grained 0·1 mm – 1·0 mm* | *Coarse-grained > 1·0 mm homogeneous* | *banded* |
|---|---|---|---|---|---|
| shale 'pelitic rocks' | phyllosilicates, quartz | slate | phyllite | schist | gneiss |
| sandstone 'psammitic rocks' | quartz | | ← quartzite → | | banded quartzite<br>quartzitic gneiss |
| limestone | calcite, dolomite | | ← marble → | | banded marble |
| marl | phyllosilicates, calcite, dolomite | calcareous slate | calc-phyllite | calc-schist | calcareous gneiss |
| sandy shale 'semi-pelitic rocks' | quartz, phyllosilicates | quartzose slate, cleaved quartzite | semi-pelitic phyllite | semi-pelitic schist | gneiss |
| basalt, gabbro | amphiboles, plagioclase feldspar | greenschist<br>greenstone | amphibolite | amphibolite | hornblende gneiss<br>pyroxene gneiss |
| rhyolite, granite | K-feldspar, quartz, phyllosilicates | halleflinta | | ← granitic gneiss → | |
| dunite, pyroxenite, peridotite | serpentine, talc, Mg amphiboles | serpentinite | serpentinite<br>← talc schist →<br>soapstone | | ultramafic gneiss |


SW
NE
Black Mesa
Defiance Plateau
Mesa Verde group
Mancos shale
Dakota sandstone
Morrison formation
San Rafael group
Navajo sandstone
Kayenta formation
Wingate sandstone
Chinle formation
eroded rock layers
Canyon de Chelly
Spider Rock
Shinarump conglomerate
DeChelly sandstone
Organ Rock shale
Pennsylvanian sandstone
Precambrian granite
Devonian-Mississippian rock layers

# Long runout landslides on Earth and Mars

Zhiyong Xiao

**Landslide:** a geological phenomenon which includes a wide range of ground movement, such as rockfalls, deep failure of slopes and shallow debris flows, which can occur in offshore, coastal and onshore environments [1].

**Long runout landslides:** Sturzstrom: a rare category of landslides that travel vast horizontal distances with only a comparatively small vertical drop in height [2]. The apparent friction coefficient H/L (where H is the drop height and L the travel distance) decrease with increasing slide volume V [3] (Fig.1).

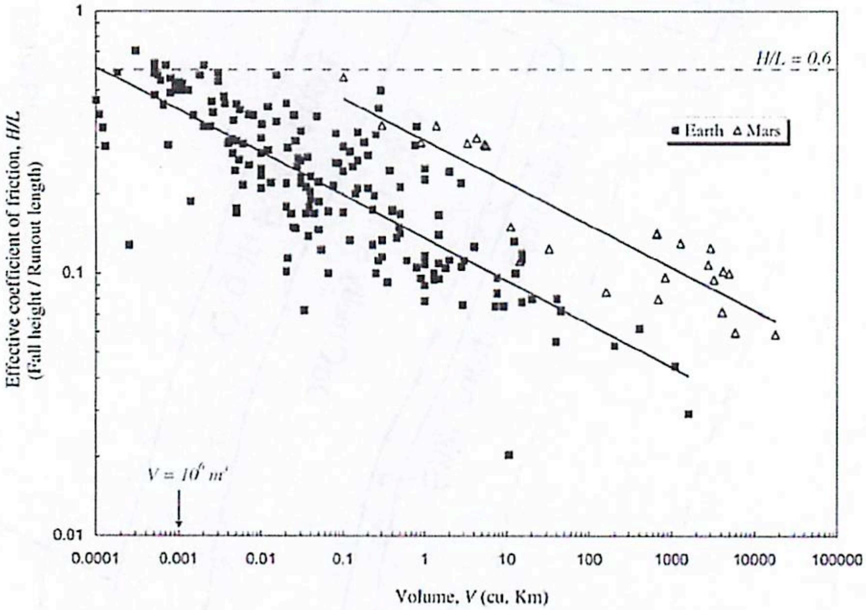


**Fig.1** Most small rock avalanches have an effective coefficient of 0.6; larger avalanches, represented in the graph, show an increase in mobility (reduction in effective coefficient of friction) with increasing avalanche volume. Martian rock avalanches show the same general trend; however, the line of best fit lies above that for Earth [2].

**Fig.2** Long runout landslides on Earth and Mars. (A) Blackhawk Landslide, (B) Sherman Glacier RA, (C) Martian RA deposit, Ganges Chasma.

**Formation mechanism candidates:**

1. ***Frictional heating*** at the shear zone at the base of a landslide, elevates pore fluid pressure and reduces friction, resulting in large sliding velocities and distances [3].
2. ***Acoustic Fluidization***: During the initial collapse and subsequent flow of a mass of rock debris, the transient, high-frequency pressure fluctuations may locally relieve overburden

stresses in the rock mass and thus reduce the frictional resistance to slip between fragments [2, 4].

3. Sliding on an ***air cushion*** which is trapped by the landslides [5].
4. ***Fluidization*** due to effects of low amounts of water in unsaturated landslides or, presence of a basal layer of melted ice [5].
5. The thin Martian atmosphere is unlikely to be dense enough to provide lubrication, but ***outgassing of carbon dioxide*** from the soil on failure could play an important role [6].

**Triggering mechanisms:** Although the action of gravity is the primary driving force for an Earth/Mars landslide to occur, there are other contributing factors affecting the original slope stability.

On the Earth, the triggering mechanisms include [7]: volumetric expansion of fractures in rocks by freeze or thaw processes, increases in soil pore pressure, removal of less-resistant material below a stronger material layer, strong vibrational forces produced from above (e.g., meteorite impact) or below ground (e.g., volcanic eruption, earthquake).

On Mars, the probable triggering mechanisms include: disappearance of carbon dioxide frost, dislodging rocks; expansion and contraction of ice due to seasonal temperature differences; small Mars-quakes; a nearby meteorite impact; vibrations from other avalanches causing other avalanches along the scarp.

**Other examples:**

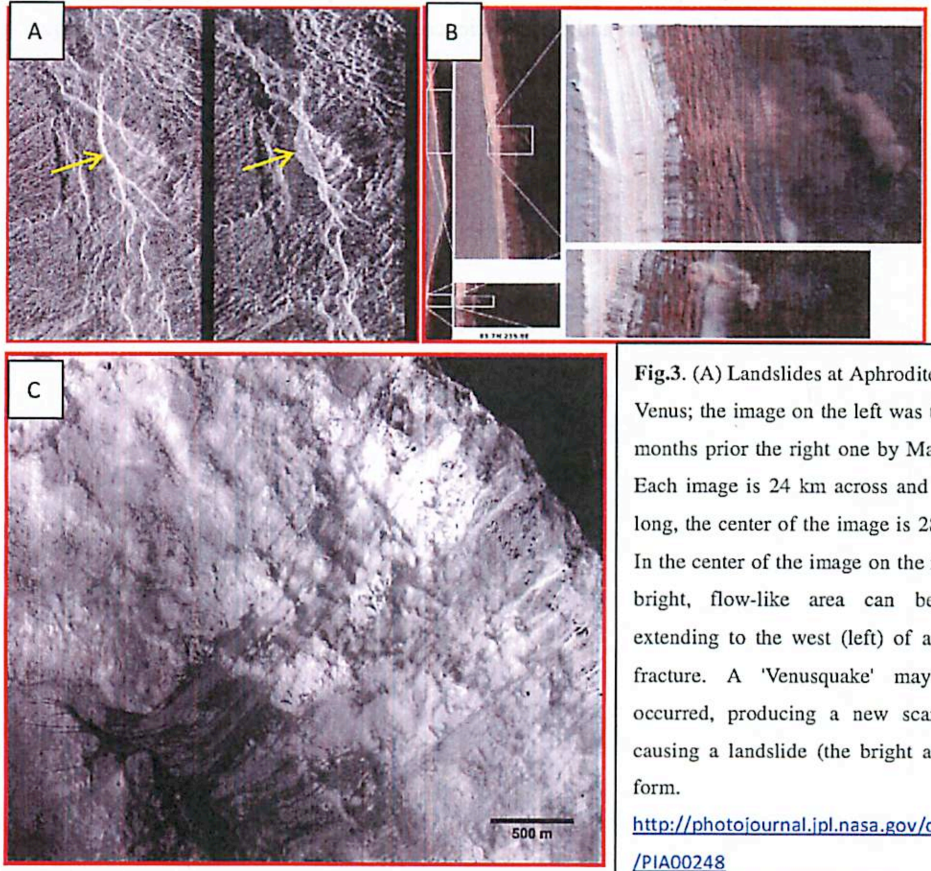


**Fig.3.** (A) Landslides at Aphrodite Terra, Venus; the image on the left was taken 8 months prior the right one by Magellan. Each image is 24 km across and 38 km long, the center of the image is 2S, 74E. In the center of the image on the right, a bright, flow-like area can be seen extending to the west (left) of a bright fracture. A 'Venusquake' may have occurred, producing a new scarp and causing a landslide (the bright area) to form. http://photojournal.jpl.nasa.gov/catalog/PIA00248

(B) This event occurred along a scarp (a distinct cliff, with a steep runoff) around the North Polar Region where surface ice can be found in large quantities. This particular scarp is a high cliff over 700 m tall and slopes at over

60 degrees. A mixture of ice, rock and dust can be seen, frozen in time, as it is plummeting down the slope, ejecting a plume of dust as the debris begins to settle on the gentle slope at the bottom of the cliff. The ejected cloud is approximately 180 meters across and extends about 190 meters beyond the base of the cliff. It is worth noting that the clouds are large 3D structures reaching into the Martian atmosphere and not 2D patterns on the surface. (C) A granular flow at the north crater wall of Kepler. The flows are over 4 km in lengths and can be only 4 m in widths (LROC M104755664LE).

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[1] http://en.wikipedia.org/wiki/Landslide

[2] Collins, G. S., and H. J. Melosh, Acoustic fluidization and the extraordinary mobility of sturzstroms, J. Geophys. Res., 108(B10), 2473, doi:10.1029/2003JB002465, 2003.

[3] Goren, L. and E. Aharonov, 2007. Long runout landslides: The role of frictional heating and hydraulic diffusivity. Geophys. Res. Lett., VOL. 34, L07301.

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[6] Harrison, K.P., and Grimm, R.E. Rheological constraints on martian landslides. Icarus, 163, 347–362, 2003.

[7] Lindsay, J., 1976., Energy at the lunar surfaces, in: Kopal, Z., Cameron, A.G.W. (eds), Developments in Solar System- and Space Science, 3, Lunar Stratigraphy and Sedimentology. Elsevier, pp. 45-55.

# River Profiles and Fluvial Incision

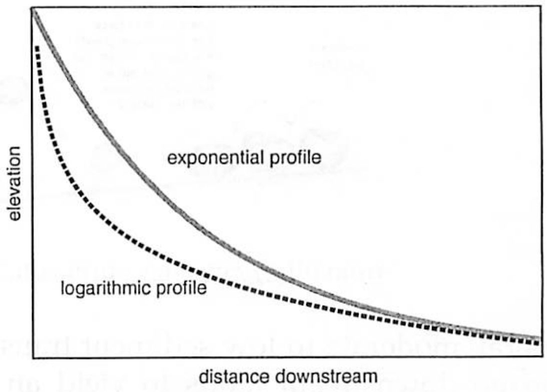
Kat Volk

A river's **longitudinal profile is the elevation of the river as a function of distance downstream**. The steepness of the profile generally decreases as you go downstream, but the overall shape of the profile (exponential, logarithmic, etc) and the small scale variations depend on many factors.

At any given point in the river, the **slope of the profile depends on the sediment load, the size of the material in the sediment load, and the river's discharge** (volume flow rate):

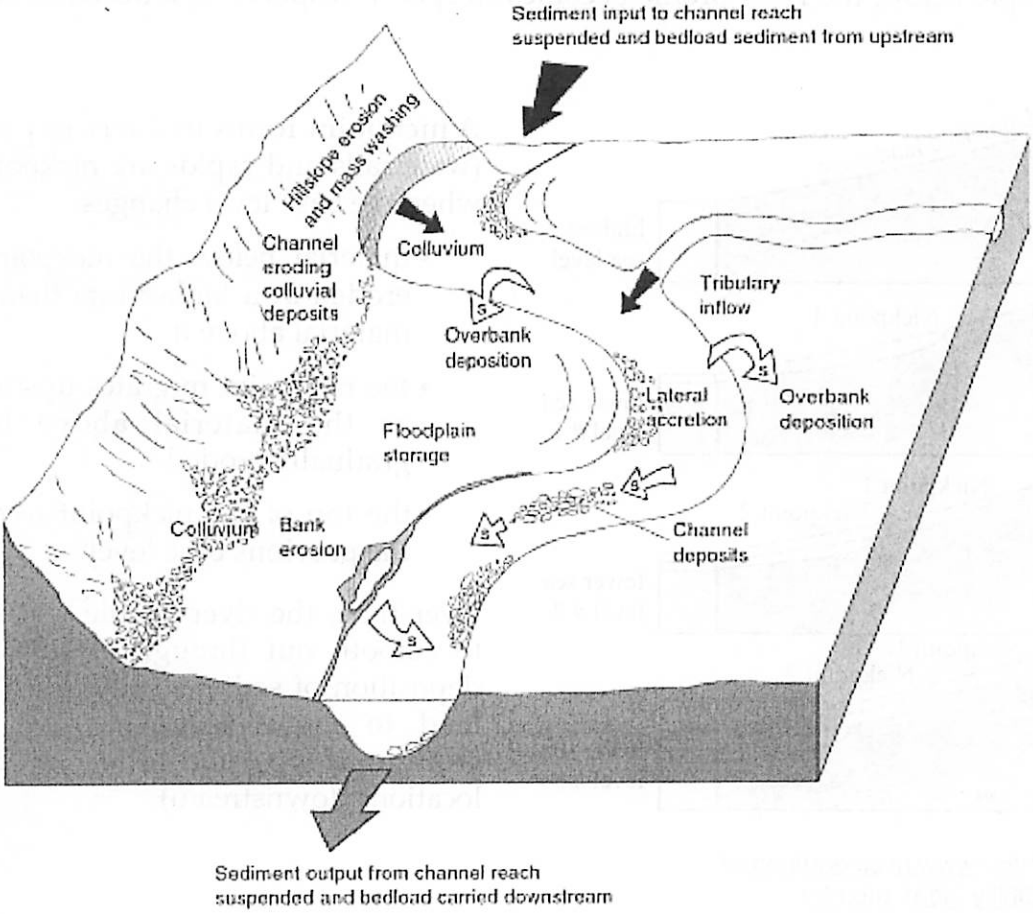
slope ↑ as sediment load, sediment size ↑

slope ↓ as river discharge ↑



Highly idealized river profiles

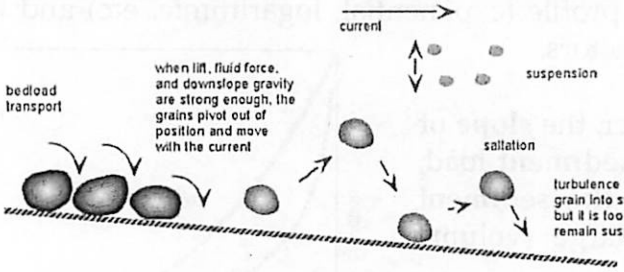
The **sediment load depends on erosion and deposition rates along the river profile**. These rates depend on the rock type that the river flows through/over, the erosion of the surrounding area due to rainfall and mass wasting, what the tributaries of the river are contributing to the sediment budget, etc:



from *Fundamentals of Fluvial Geomorphology*

The **size of the transported material tends to decrease as you go downstream** (large particles travel shorter distances and particles are abraded during transport, resulting in size sorting along the river bed). The **discharge will generally increase downstream** (because the total drainage area of the river increases as you go downstream).

sediment transport modes



from http://geology.uprm.edu/Morelock/4_image/trans.jpg

In general, moderate to low sediment transport coupled with decreasing sediment size as you go downstream tends to yield an exponential profile. If the sediment size decreases very rapidly as you go downstream, then the profile tends to be more logarithmic.

**Fluvial incision occurs when there is a base level change in the river system** (this can come in the form of tectonic uplift/subsidence or changes in the sea level).

In the example below, the river profile becomes steeper in response to a decrease in the sea level.

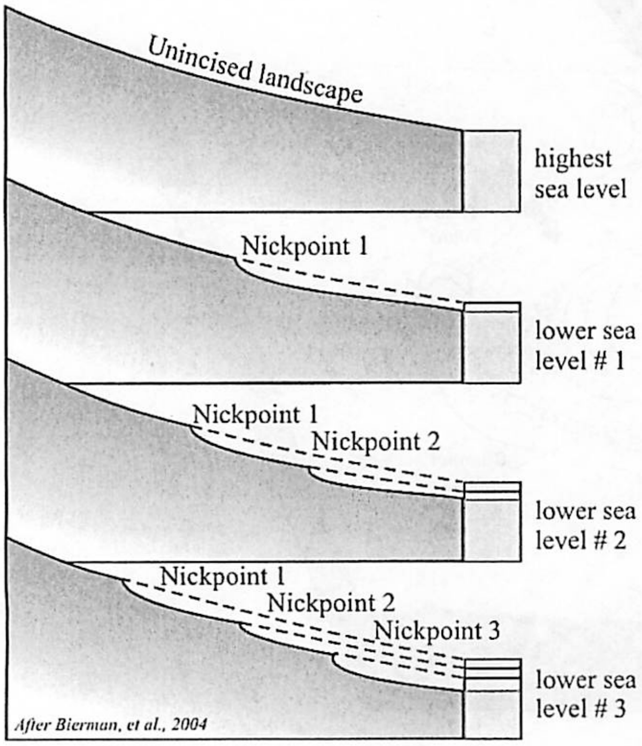


figure from http://www.nvcc.edu/home/cbentley/105/billy_goat_trip.htm

A **nickpoint** forms in the river profile (waterfalls and rapids are nickpoints) when the base level changes:

- material below the nickpoint is eroded at a higher rate than the material above it
- the nickpoint migrates upstream as the material above it is gradually eroded
- the top of the nickpoint records the previous base level

Over time, the river profile will start to smooth out through erosion and deposition of sediment (the river will tend to move sediment from old storage/deposition sties to new locations downstream).

The incision of the river is accompanied by a change in the floodplain of the river. The old floodplains form **river terraces** (relatively flat, step-like features with steep scarps separating them) which are seen in the river cross-section below:

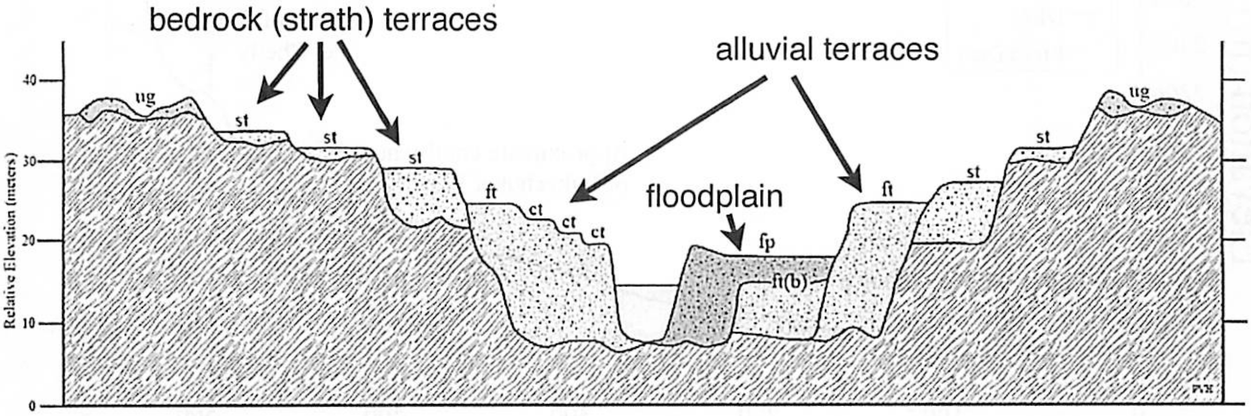


image from http://en.wikipedia.org/wiki/File:FluvialTerraces.jpg

Rapid incision (occurring faster than the river migrates laterally across its floodplain) leads to paired terraces on either side of the river. Slow incision leads to unpaired terraces (because the river is migrating laterally as it is downcutting). Terraces can by cut into previously deposited alluvial sediment, or into bedrock (in the latter case, they usually still have a thin layer of alluvial sediment on top of the bedrock).

A diagram illustrating some of the length scales of typical river features as well as typical timescales for changes to these features:

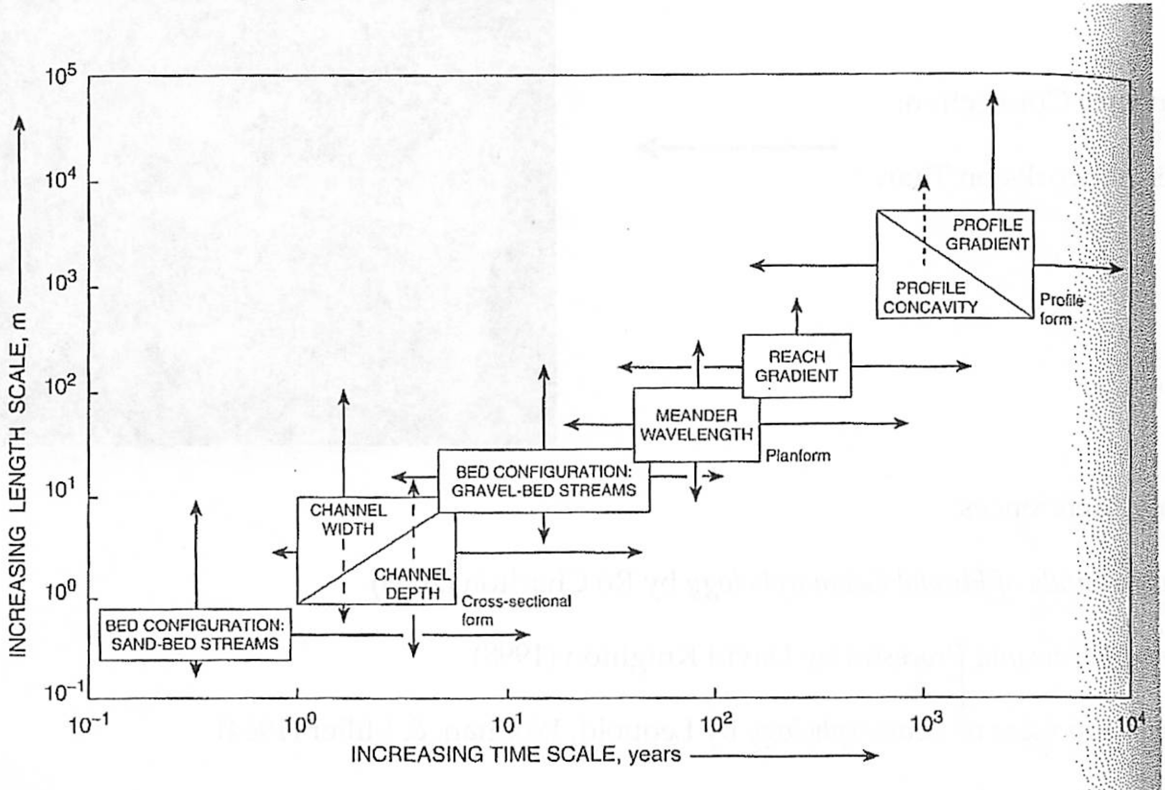
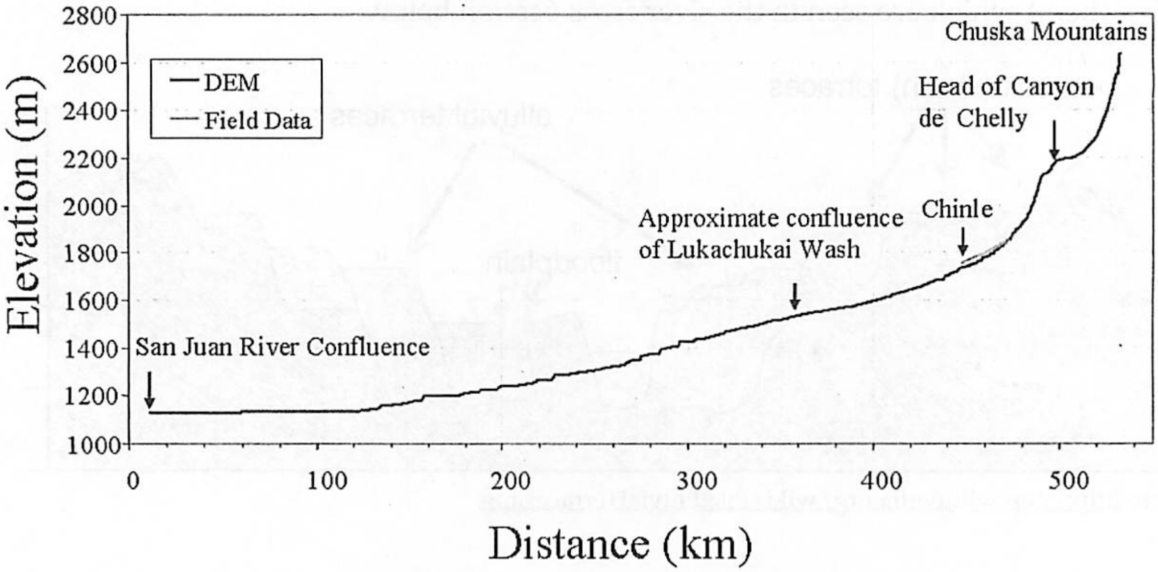


*Figure 8.5* Schematic diagram of the time scales of adjustment of various channel form components with given length dimensions in a hypothetical basin of intermediate size. After Knighton (1998).

from *Fundamentals of Fluvial Geomorphology*

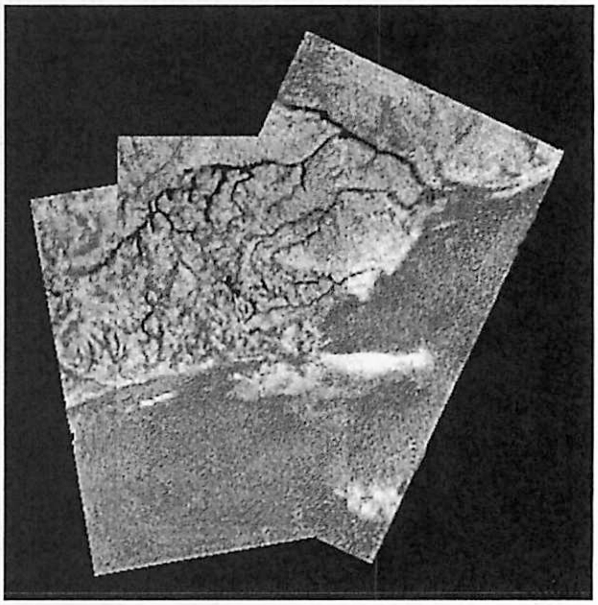
The longitudinal profile of the Chinle wash area (including Canyon de Chelly):



from Jaeger 2009 http://gradworks.umi.com/33/85/3385131.html

Planetary Connection:

river networks on Titan



Useful References:

*Fundamentals of Fluvial Geomorphology* by Ro Charlton (2008)

*Fluvial Forms and Processes* by David Knighton (1998)

*Fluvial Processes in Geomorphology* by Leopold, Wolman, & Miller (1964)

# Salt River Petroglyphs
## Sky Beard
## Geologic Field Studies 2011

### Background:

The word petroglyph is Greek for “rock carving” or “engraving”. They are found throughout the world but are mainly in desert environments and are made by the chiseling away of pieces of rock or scraping off the top layer of desert varnish; usually exposing a lighter color underneath. Desert varnish is a build up of and the chemical and biological weathering of minerals on the rock surface ( Fig.1). Varnish bacteria thrive in arid climates and on smooth rocks. Chiseling through the varnish and top parts of the rock was done by using a sharp pointed rock and a hammer stone. Some petroglyphs show evidence of being colored with various pigments such as blood, berries, charcoal, and others; however, it is rare to see the pigments today as they are more easily weathered away [1].

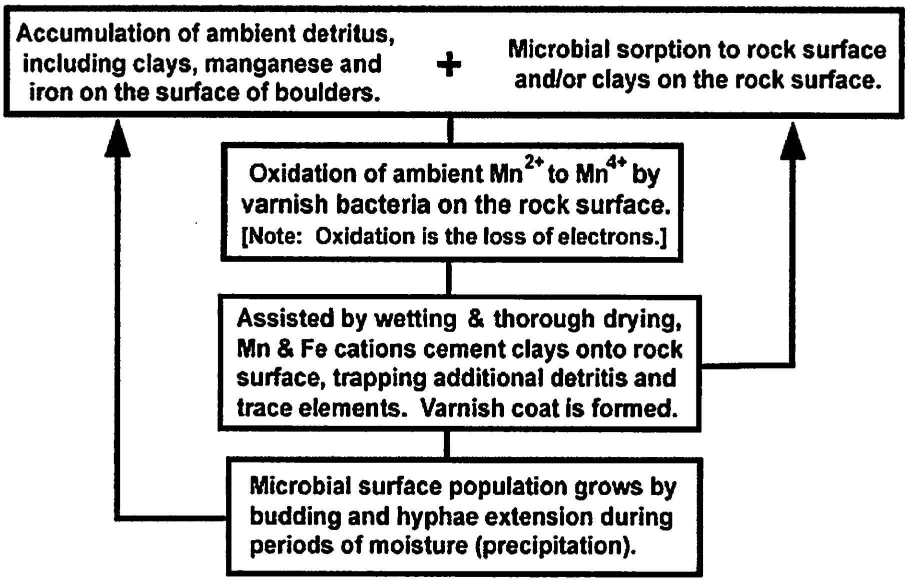


Figure 1: Process of the formation of Manganese Varnish as an example. Different regions have different elements that are oxidized into a varnish. Iron is another example. Modified from Don and Oberlander, 1982.

### Dating:

Petroglyphs are very difficult to date. Some techniques that have been developed including stylistic analysis, relative patination, and chronometric techniques. The most common method is to use the rate of desert varnish formation as a dating method. It is estimated that in the Salt River area, it would take 10,000 years for a full coating of varnish to develop [3]. Another dating method involves looking at the markings themselves to constrain an age. This is called microerosional dating, and looks at the alteration of the rock crystals themselves[4].

**Salt River Petroglyphs:**

There are different styles of petroglyphs attributed to different groups of people. The Hohokam Style is found in the Salt River area. The petroglyphs from these people are believed to have been made between 300-1300 AD. The Hohokam, meaning 'Those who have gone" inhabited the Sonoran Desert of central Arizona, and may have extended down as far as Mexico ( Fig.2). Most evidence suggest they were centered around the Gila and Salt Rivers, becoming masters of irrigation and farming [1].

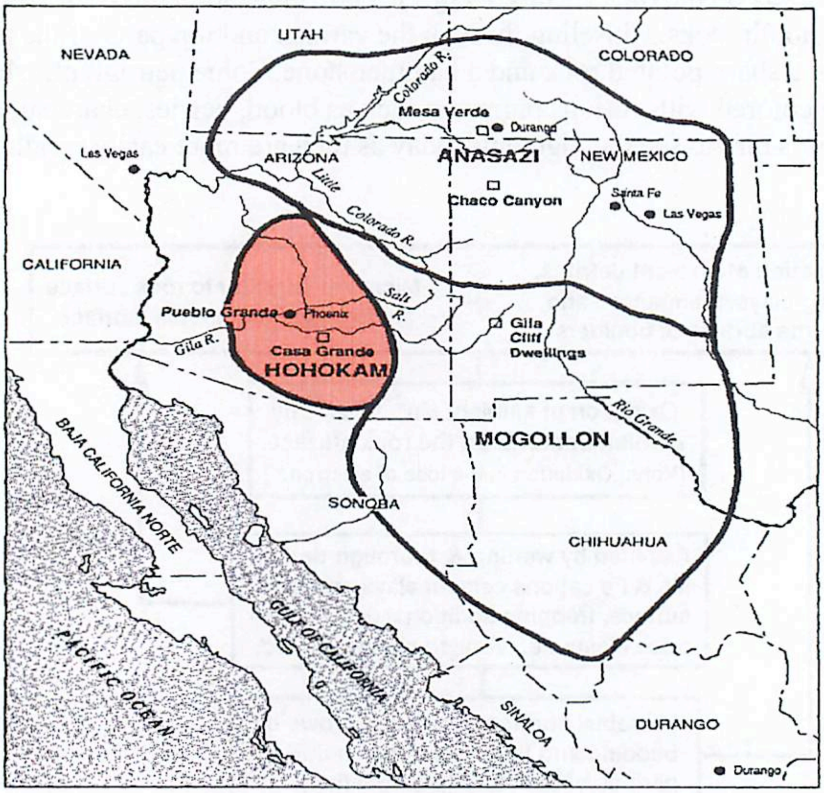


Figure 2: Approximate extent of Hohokam land (shaded/orange area). Centered around the Gila and Salt Rivers.

Hohokam petroglyphs can be found in all the mountain ranges surrounding the Salt River (including the South Mountains, Superstition Mountians, Whte Tank Mountains, and Phoenix Mountains). Hohokam Style includes geometric designs (circles, spirals, wandering lines, crosses, and others) and representational images of what they saw and did in daily life. Many carvings are of birds, snakes, mamals, and humans. Humans are sometimes shown involved in activities, wearing headdresses, and holding objects. Activities shown include hunting, flute playing, and dancing. Some petroglyphs are a combination of geometric and representation and form abstract figures. There are also some cases that show anthropomorphic animals, that is, figures with a mixture of human and animal characteristics. See figures 3-6 and photographs on page 5.

136. Hunters, acrobats, and flute-player, 7th Street Locality. Anthropomorph on right, holding a "string" on which animals are walking, is 20 cm in height. Four anthropomorphs in upper left are holding large objects and may be acrobats.

Figure 3 [1].

134. Hunter (legs together in a single line) with bow and arrow pointed at several quadrupeds, 32n Street Locality. Anthropomorph is 16 cm in height.

Figure 4 [1].

135. Hunter and anthropomorph holding a flute or blowgun, Upper 12th Street Locality.

Figure 5 [1].

It is unknown what the purpose or meaning of the petroglyphs in the Salt River area, or any other for that matter, really was. Some believe that they may have been purely used as a method of recording events. Others suggest they served as territorial signals for different clans, or were for ceremonial or other religious purposes such as marking of sacred locations, created by priests in a shamanistic ritual such as vision quests, curing ceremonies, or other. It has been determined that the Hohokam made solar and lunar observations and may have incorporated these rituals with seasonal cycles. No one really knows. Not only were these petroglyphs important to the Hohokam people at that time, but some also became important in the Pima Indian mythology later on.

Figure 6 [1].

246. Concentric circles, 27th Street Locality. Large concentric circle is 22 cm in diameter. Panel faces southwest.

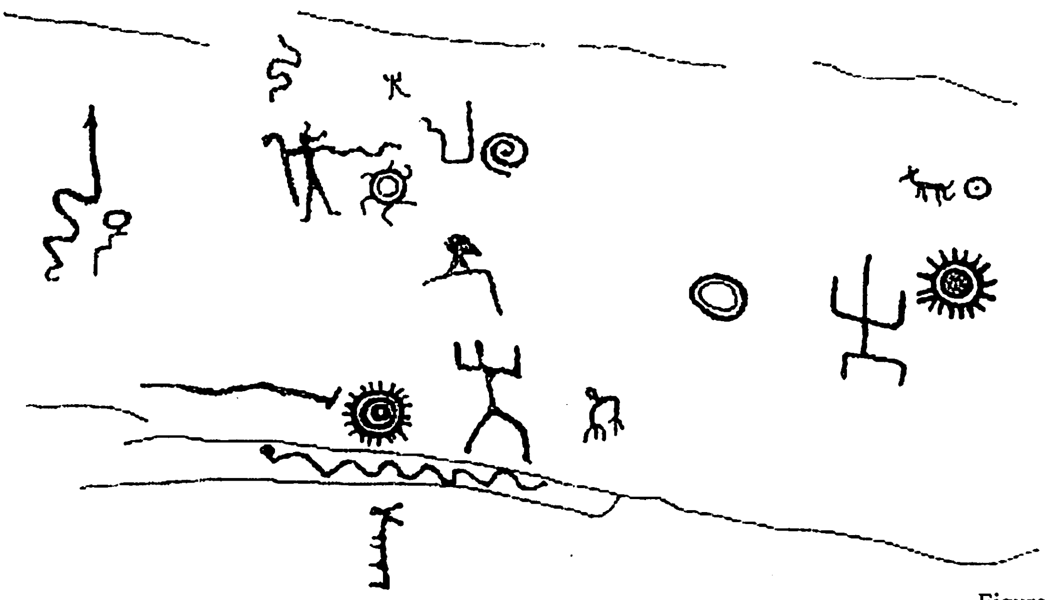


Figure 7 [1].

247. Sun disks, Hieroglyphic Canyon. Sun disk on right is 32 x 36 cm. Panel faces northeast.

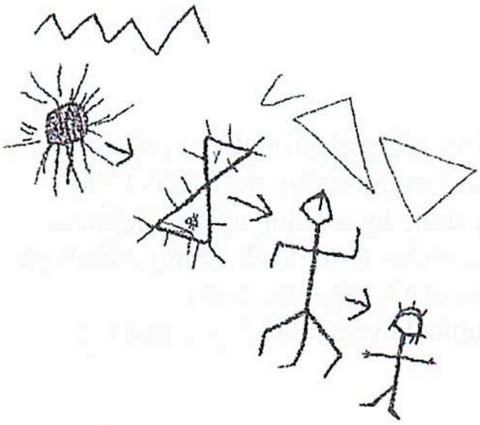


Figure 8 [1]. Transformation from Sun to through hour glass to human form.

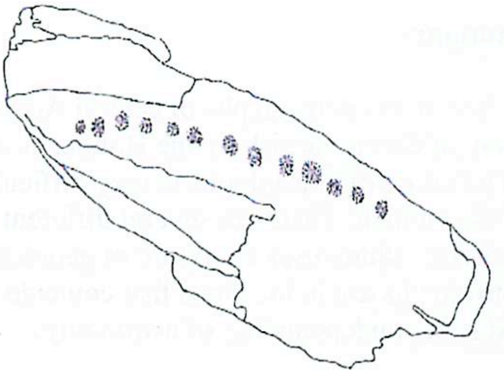


Figure 9[1]. Thirteen dots that may represent full moon cycles.

Hunter with a bow and arrow in the 12th Street Locality. The other anthropomorph in the panel may be playing a flute or shooting a blowgun

Figure 10 [1].

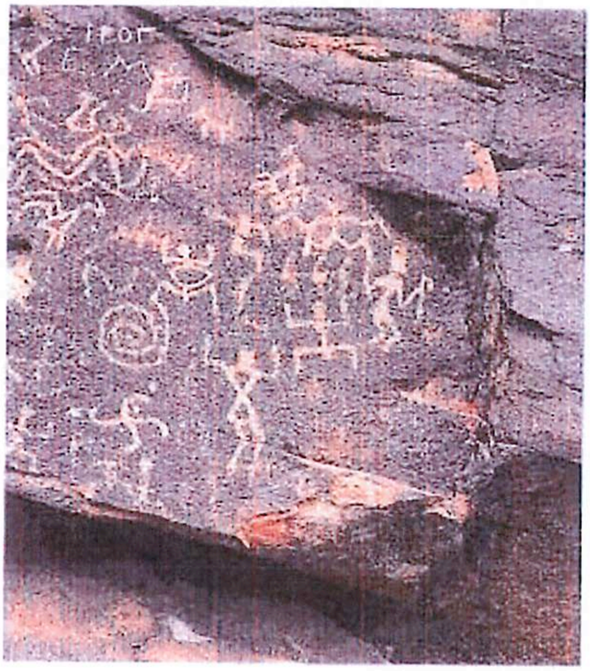


Figure 11 [1].

Rock art panel containing two anthropomorphs with unusual hourglass shaped bodies. Box Canyon.

## Summary

Salt River petroglyphs of central Arizona were mainly formed through the chiseling away of desert varnish by the Hohokam people that lived in the valley from 300-1300 AD. Dating of petroglyphs is very difficult and mainly done by looking at the thickness of the varnish. There are several different characteristic styles to the Hohokam petroglyph tradition, which uses a mixture of geometric and representative figures. Some petroglyphs are in locations that coincide with astronomical events which suggest they had some understanding of astronomy.

## References

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[2.] Dorn, R.I. and T.M. Oberlander. 1982. "Rock Varnish." Progress In Physical Geography 6: 317-367.
[3.] Dorn, R.I. 1982. "Enigma of the Desert." Environment Southwest Number 497: 3-5.
[4.] Bednarik, R. G. (1992). A new method to date petroglyphs. *Archaeometry* 34, 279 – 291.

# *MOGOLLON RIM VOLCANISM*

*PTYS549, Fall 2011 – Canyon de Chelly and Painted Desert*

*James T. Keane*

## 1. *The Mogollon Rim:*

(a) **The Mogollon Rim is an escarpment** that spans across central Arizona and is the physiographic boundary between the Colorado Plateau (associated with a higher elevation, and thicker crust, ~40 km thick) and the Basin and Range province (associated with lower elevation, horst-graben extensional features, and a thinner crust, ~20 km thick), as shown in Figure 1.

(b) **The geophysical origin and formation time** of the Mogollon Rim is not well understood. The age of the formation ranges from early Paleocene (65.5-56.0 Ma) to Pliocene (5.3-2.6 Ma), though most theories have the Rim established before ~15 Ma. There are a number of hypotheses for the formation of the Rim, and they primarily use a combination of faulting and erosion (as shown in Figure 2).

  i. **Faulting:** late Cenozoic (65-0 Ma) uplift and block faulting, or reactivation of earlier faults associated with the earlier Laramide orogeny (which occurred about 80-35 Ma) could explain the escarpment, although no faults that span the entire length of the Mogollon Rim have been found (though there are smaller faults associated with segments of the Rim, such as the Diamond Rim fault, Cataract Creek fault, and Oak Creek Canyon fault system, etc.).

  ii. **Erosion:** the rim could also be an erosional scarp cause by the continual erosion of the uplift from the earlier Laramide orogeny (which occurred about 80-35 Ma). Erosional rates are on order of ~1 cm/yr.

## 2. *The Cause and Style of the Mogollon Rim Volcanism:*

(a) **Subduction of the Farallon Plate:** During the mid-Cenozoic (65-0 Ma), the Farallon and Pacific Plates (separated by the East Pacific rise) were subducting under the western edge of the American Plate. This subduction was occurring at a a very shallow angle (~20 degrees), causing calc-alkaline volcanism nearly 1000 km interior of the subduction zone. This subduction and associated compression had caused the Laramide Orogeny. This is illustrated in Figure 3a.

(b) **Transition to the San Andreas transform fault:** between 30-24 Ma, the East Pacific Rise intersected the subduction zone, which resulted in a change in plate dynamics, and forming the San Andreas transform fault. This shearing caused extension in the Southwest, and the formation of the Basin and Range province (notable by horst and graben style normal faulting). As the Farallon slab subducted, it detached from the Pacific plate, which opened up the mantle wedge. This exposed warmer asthenospheric material to the crust, which caused an intense period of explosive basaltic and siliciclastic volcanism (perhaps as much as > 120,000 cubic miles of igneous rock – which is ~200,000 times as voluminous as the Mt. St. Helens eruption). This event is called the **Mid-Tertiary Ignimbrite Flare Up**. This is illustrated in Figure 3b.

  A. **Ignimbrites** are depositional sediments of pyroclastic flows (composed of poorly sorted volcanic ash, tuff, pumice, and glass).

  B. The "flat-slab" subduction scheme illustrated in Figure 3 cannot completely explain the Mid-Tertiary ignimbrite flare up, since volcanic outflows further north and south are older than those in Arizona/Nevada/Colorado. Proposed solutions involve the warping of the subducting slab in order to accommodate this time-migration of volcanism.

  C. The increase magmatic activity may have weakened the crust and allowed for easier extension and the formation of observed metamorphic core complexes.

(c) **Importance of the Mogollon Rim Volcanism:**

  i. The large temporal and spatial extent of the Mogollon Rim volcanism allows for the detailed study of the paleogeography of the region, as lava flows can be accurately dated (via radiogenic isotope dating), and can give information about the slope direction, shape, steepness, and relative altitude of paleosurfaces over which they flowed (as long as flow structures preserved).

  ii. Volcanic rocks are resistant to erosion and can act as cap rocks to weaker sedimentary rocks, causing the formation of elaborate mesas, canyons and gullies due to differential erosion.

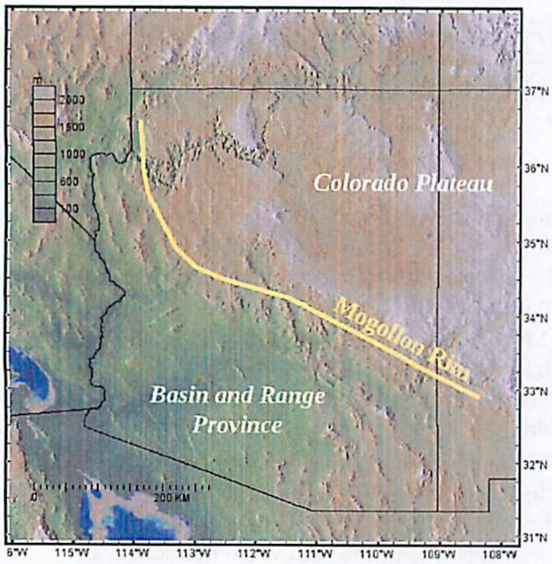

**Figure 1.** Topographic map of Arizona, highlighting the Mogollon Rim – which separates the Basin and Range Province to the south from the Colorado Plateau to the North. (Created by J. T. Keane in GeoMapApp)

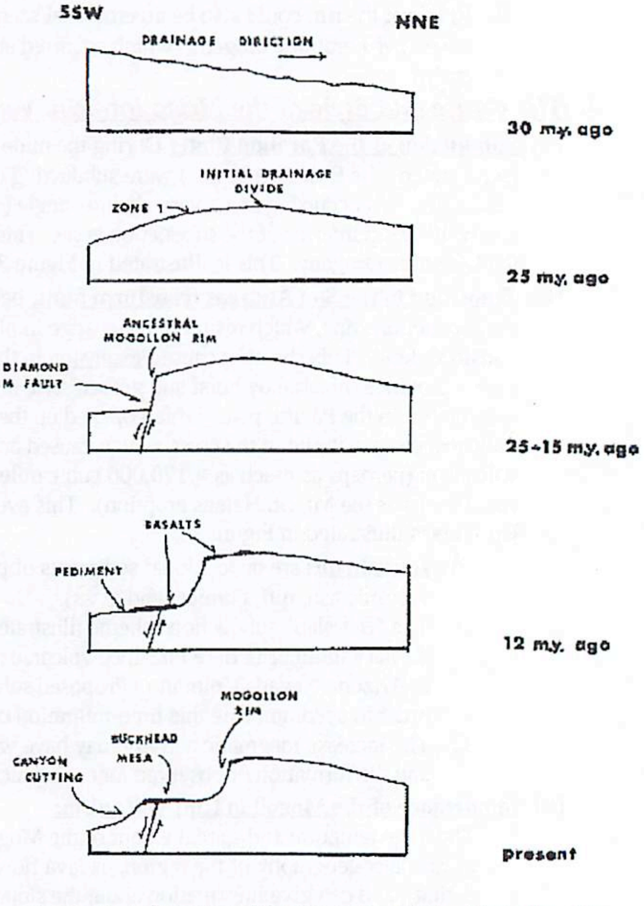

**Figure 2.** Schematic of the formation of the Mogollon Rim over time. The initial high results from the Laramide orogeny, and later normal faulting, and/or erosion carve out the topographic scarp. (from Mayer, 1979)

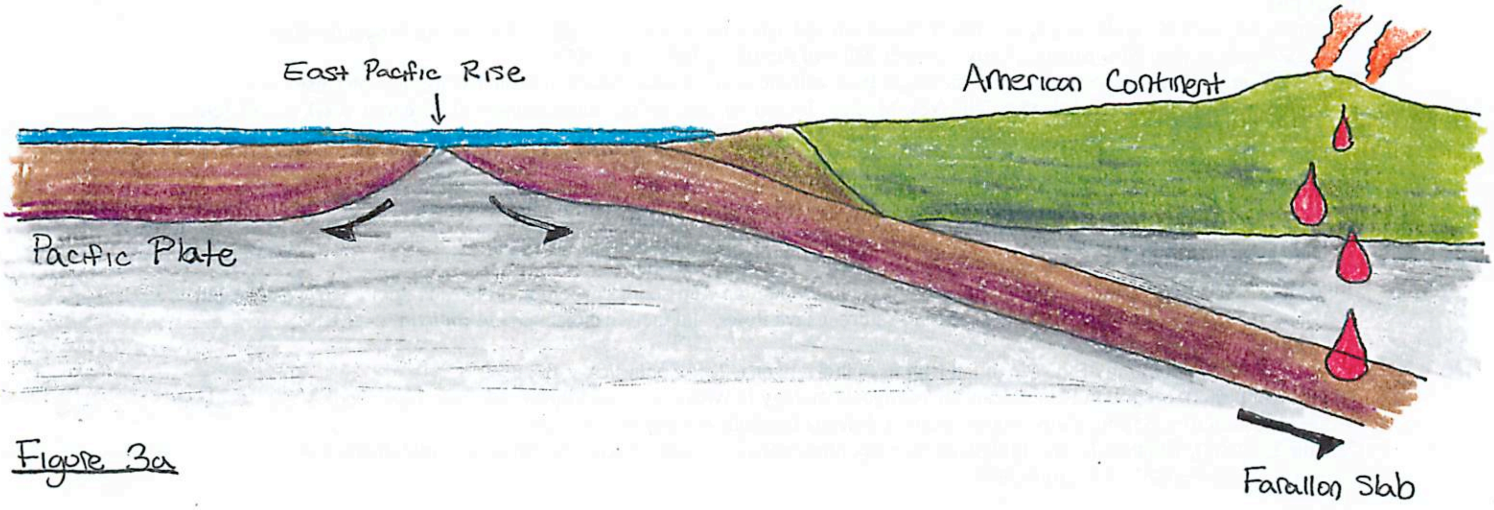

Figure 3a

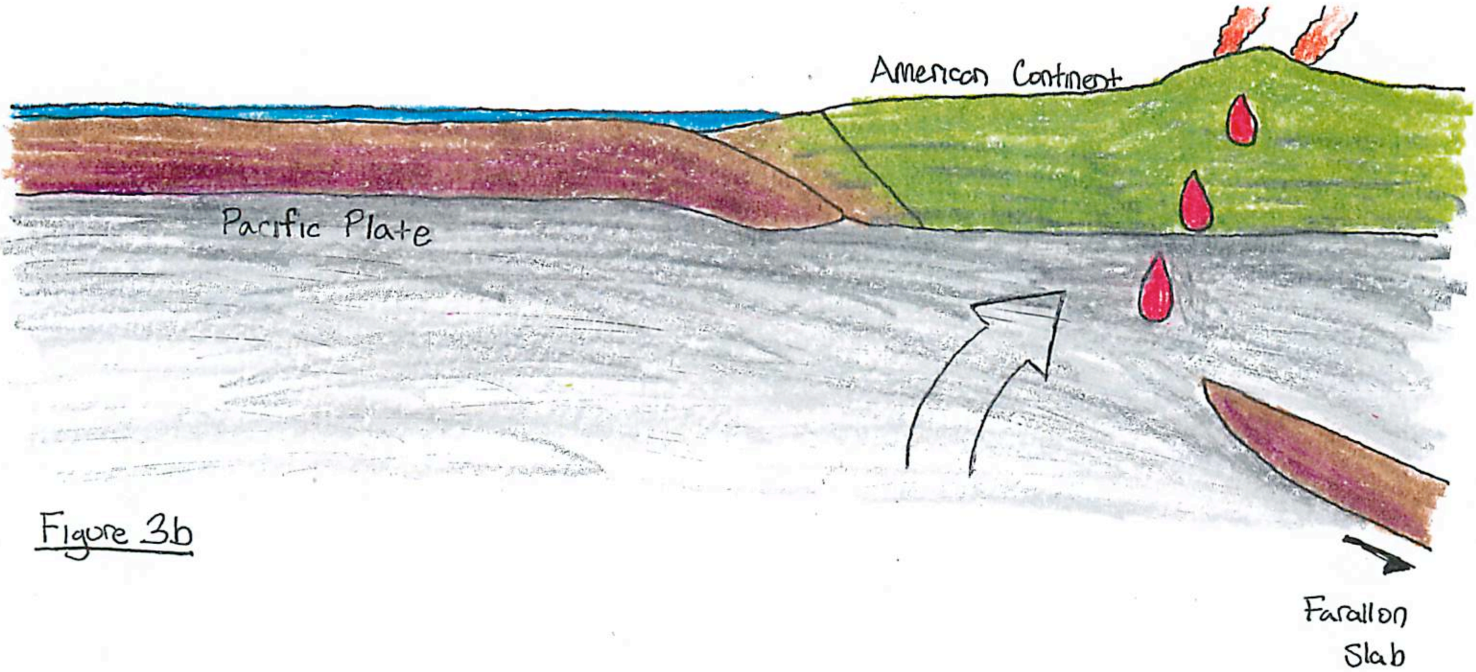

Figure 3b

– J.T. Keane

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# Ore Formation and Mining: Porphyry Copper Deposits

Christa Van Laerhoven

## Formation of Porphyry Copper Deposits

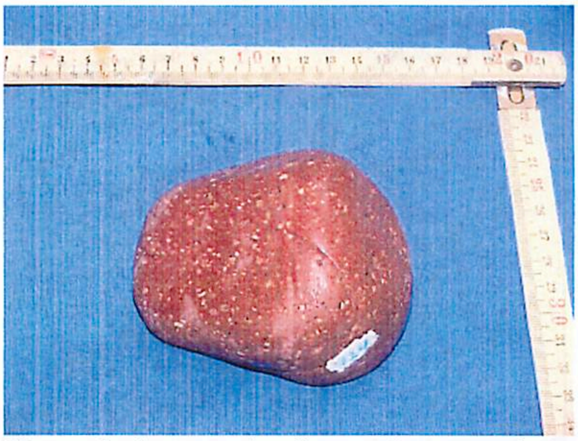

*Figure 1: An example of a porphyritic rock. Image from Wikipedia.*

The large copper deposits found in Arizona are "porphyry copper deposits" (PCDs). PCDs also commonly contain molybdenum, gold, and silver.

"Porphyry" refers to the texture of the rock: large crystals embedded in a fine grained matrix. Originally these rocks were named after the greek word for "purple" due to the common purple-red color (Figure 1). Porphyries are igneous rocks that cooled in two stages: 1) slow cooling (which happens at large depths) that forms the large crystals, 2) rapid cooling (which happens at shallow depths) that forms the fine grained matrix.

PCDs are most commonly associated with subduction zones and can be found all along western North and South America as well as east Asia and Australia (Figure 2). Morenci, Arizona is one of the largest PCDs in the world.

The wedge of mantle between the subducting oceanic crust and overlying continental crust is increased in water content which lowers its melting point. It partially melts and this melt intrudes on the continental crust (Figure 3A, other situations that can lead to a similar process are also shown in Figure 3). When the magma reaches a depth at which it is neutrally buoyant it stops rising and starts crystallizing. The magmatic fluids (water, etc) don't get incorporated into the forming crystals and become concentrated in the magmatic chamber. When the pressure from these fluids is great enough it causes the surrounding rock to fracture. The magmatic fluids, which contain dissolved metals, flow through these fractures and under the right conditions the metals will be deposited (see the next section). The formation of PCDs seems to be enhanced when the subduction is shallow or when buoyant features are subducted (for example, oceanic ridges, plateaus, or seamount chains). Thickened crust may also enhance formation of PCDs since this suppresses volcanism.

### Deposition

Copper deposition is controlled by temperature, acidity, and the availability of sulphur; It is largely independent of pressure. The availability of sulphur (as $H_2S$) is set by

$$4SO_2 + 4H_2O = 2H_2SO_4 + H_2S$$

which favors $SO_2$ at high temperatures (700°C) and $H_2S$ at lower temperatures (400°C). Copper is most commonly deposited as copper-iron sulphide ($CuFeS_2$).

Gold is commonly carried in the water as a gold-sulphur complex. It tends to precipitate at the same time at the same time as the copper because the copper precipitation process decreases the sulphur content the water. Molybdenum probably travels as a molybdenum hydroxide complex. Increased $H_2S$ in the fluid will reduce the hydroxide components and deposit $MoS_2$.

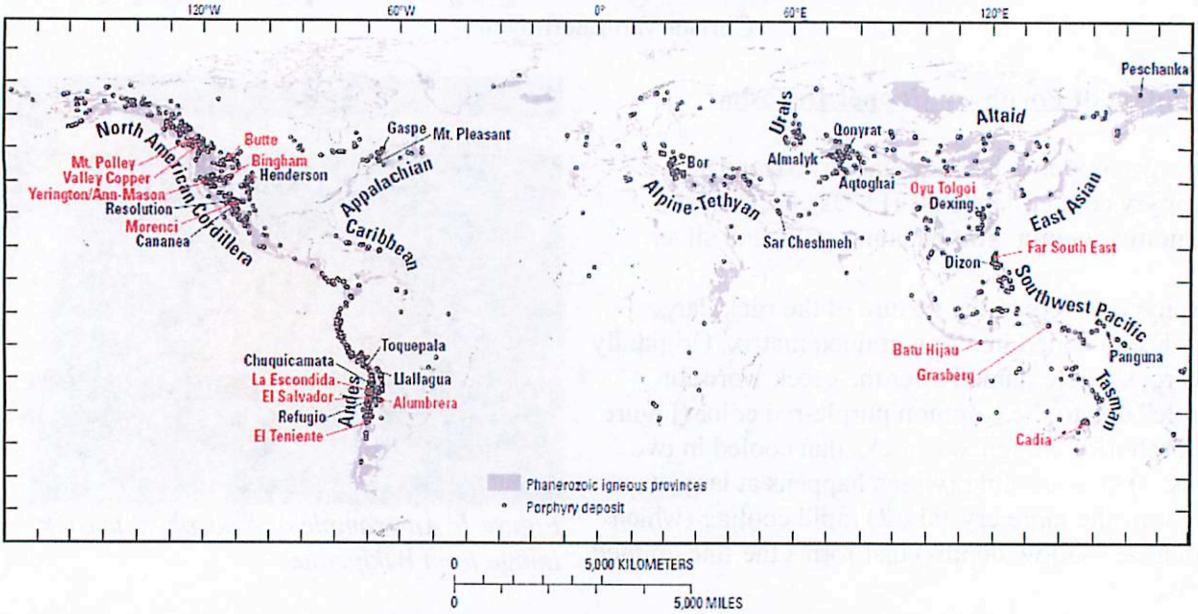

*Figure 2: Porphyry copper deposits of the world. These deposits are most commonly found along the Pacific Ring of Fire. Image from U.S.G.S. Scientific Investigations Report 2010-5070-B.*

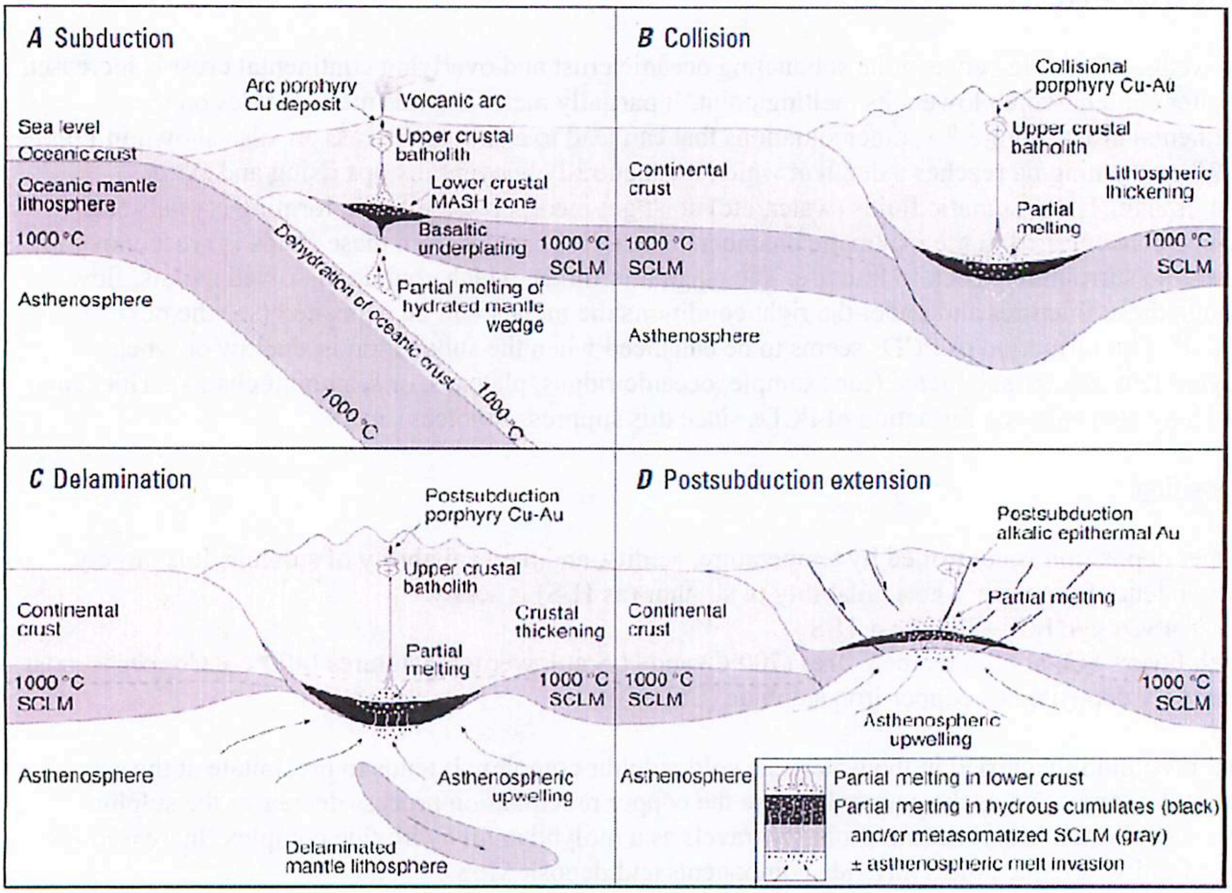

*Figure 3: Various geologic situations that are conducive to the formation of PCDs. Image from U.S.G.S. Scientific Investigations Report 2010-5070-B.*

## Supergene Enrichment

Percolating ground water weathers the rocks and the resulting (sulphuric) acidic water leaches copper (and other similar metals) from the primary deposits. The water enriched in leached metals descends to the water table where the metals again precipitate. For such enrichment to happen the drawdown of water and the suphiric acid content must be great enough for the copper to stay in solution until it reaches the water table. This process oxidizes the upper rock layer.

Supergene enrichment can result in grades up to 8 times the grade of the original deposits.

## Mining Porphyry Copper Deposits

Because PCDs generally form in upper crust (5-10km) in regions prone to uplift (inland of subduction zones) they are commonly exposed due to erosion. PCDs may also be associated with magnetic anomalies.

Most PCDs are mined using open pits, though a few mines use underground tunnels.

Metal-bearing minerals are separated from the non-metal-bearing rock using floatation methods. The concentrated copper-bearing minerals are treated using solvent-extraction electrowinning: The ore is treated with acid to leach the copper into solution. This solution is put through a device that imposes an electrical potential difference and collects the copper ions on the cathode.

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# 19th Century Mining Settlements: Globe, Arizona

By Erin Liskiewicz

## Mining Exploration:

1864- Rumors of mineral deposits sparked interest in the territory causing treasure seekers to explore the area. The future site of Globe and Miami was explored by King S. Woolsey.

1872- The Mining Act of 1872 was adopted as the governing law of the district:

> "District by laws provided that each claim be recorded within 30 days of discovery, that twenty-five dollars worth of location work be performed within a three months of the date of location and failure to perform the work would be deemed abandonment of the claim" (Bigando).

**Initial Rich Mining Sites**

- Apache Mountain:
  - Richmond Basin
  - the Champion
  - the Little Mack
  - the Stonewall Jackson
  - Hannibal
- Pinal Creek:
  - Pioneer Mines

## The Beginning of Globe

1875- Ben Reagen, Isaac Copeland, William Long, and Charles Mason set out to assess a load of ore, which turned out to be very rich. Word spread and prospectors swarmed in.

*At this time, most of the mining district was within the Apache reservation boundaries. Miners invaded the reservation territory looking for ore deposits, creating tension with the Apaches.*

*Petitions were made to restore mineral regions as public lands, and sent to Washington, D.C. for approval. Miners then organized and formed the "Globe Mining District."*

*Early mining settlements called "camps" were also started in order to provide security and companionship for the miners. Makeshift dwellings were built near a spring or a promising mining claim.*

## Ramboz Camp

Summer 1875-The earliest mining settlement in the Globe Mining District, Ramboz Camp, was started by Henry Ramboz and William Hope. The camp was located four miles north of Globe Ledge.

*Soon the trail that formed between Ramboz Camp and the San Carlos Agency became a wagon road.*

Oct. 22, 1875- A post office was formed at the San Carlos Agency. Letters were carried between the San Carlos Agency and Ramboz Camp by Apache couriers for 25 cents a letter.

**McMillenville Camp**

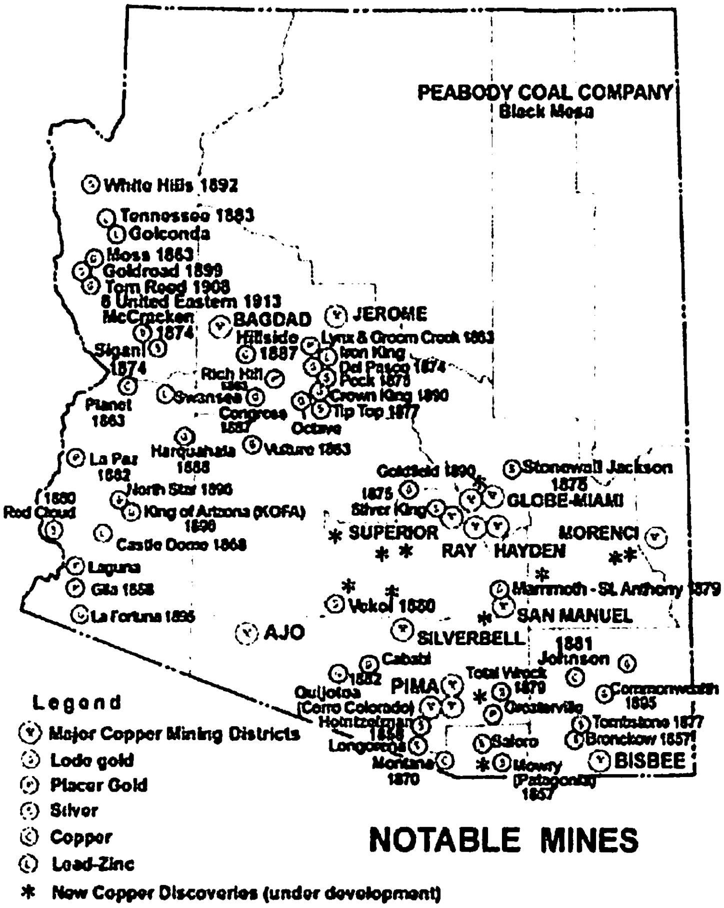
The rich loads of ore found in the Stonewall Jackson and Hannibal mines lead to the formation of the McMillenville Camp, which like the Ramboz Camp, grew to substantial size.

Dec. 12, 1877- The opening of the first post office in the Globe Mining District.

Early 1880's-The miners "lost the lead" and the Stonewall Jackson mine was abandoned. Subsequently, the post office closed in 1882.

**Miami City**

1877-1878-Near Miami Mill, Miami City was built, complete with a hotel, saloon, stores, miners' cabins, and a reduction works.



May 1878-Miami Mill was destroyed in a fire, but rebuilt in 1880.

*The production of silver declined steadily after 1883. The mill continued on and off for the rest of the decade.*

**Hammond Camp, The Future City of Globe**

Andrew A. "Doc" Hammond along with his partner John W. Reed set up permanent camp on the bank of Pinal Creek near the mouth of Alice Gulch. Hammond's Camp was a natural jumping off point for new arrivals to the Globe Mining District.

1875-The first families arrived in the Globe Mining District, which was referred to as Globe City by the close of 1875.

1876-The first appointed saloon in Globe appears.

**1880's**

1881- The price of sliver dropped while the price of copper rose to nearly 20 cents a pound. Old Globe Copper worked on two Globe claims as well as nine other adjacent claims.

1882- Old Dominion Mining Co. bought out Old Globe Copper and moved their furnace from Bloody Tanks to Pinal Creek.

*The year of 1882 was a violent year in Globe: the July 6th Apache Rampage left several people dead when Apaches raided travelers on the trails. The tension between the Apaches and the settlement continued to increase, and the Apaches started disturbing freight shipments and mail deliveries on the trails.*

1883- The price of copper fell. Old Dominion Mine struggled to operate.

1885- Copper prices continued to drop, resulting in a reduction of the workforce and wages at Old Dominion Mines.

1888- The copper market stabilized.

1889- Eight Apaches convicted of various crimes in transport to Territorial Prison in Yuma overpowered the two police escorting them and killed them.

**1890's**

*In this decade the miners faced many obstacles: flood rains, fires, and increasing tension with the Apache Indians. But with these challenges, they also had the promise of Rail Road construction which would run through the city of Globe.*

1894- Old Dominion Mines was sold to new management.

1897- Due to wetness, Old Dominion Mines shut down.

Dec. 9, 1898- Railroad construction reached Globe, Arizona.

Late 1890's-Future significant producers, Black Warrior Mines and Continental Mines, began to develop.

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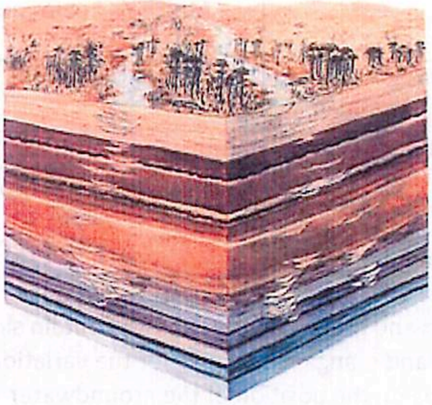
# Chinle Formation:

## In the Petrified Forest Region

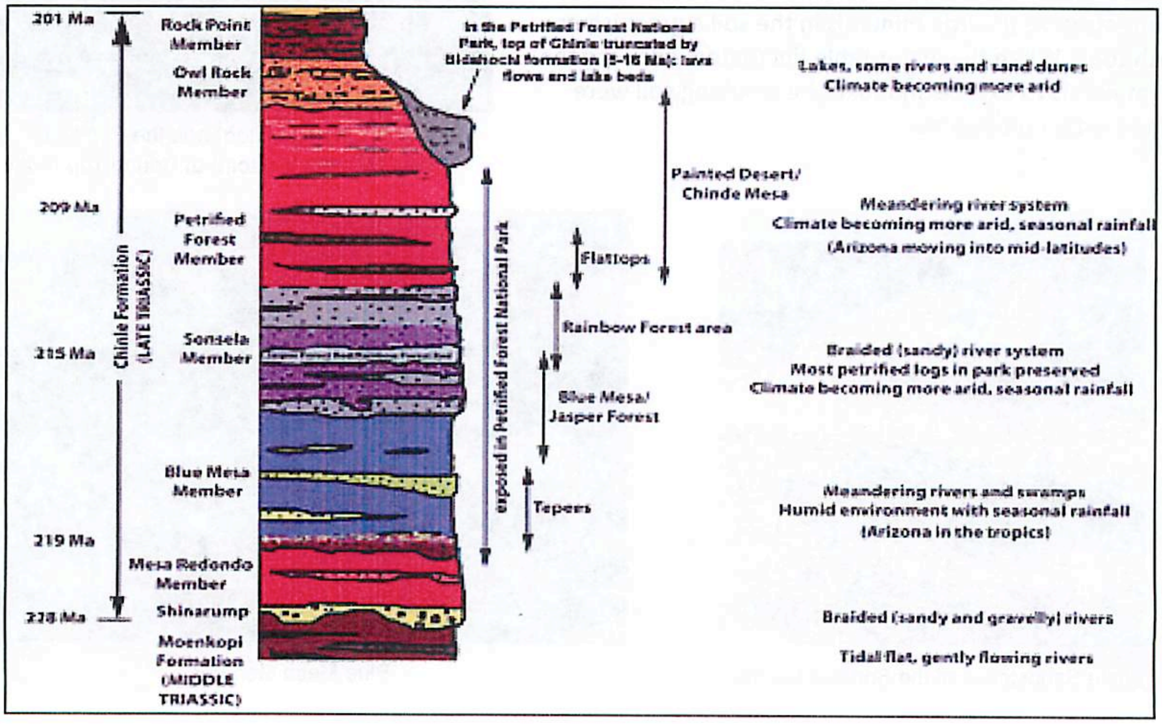
Cecilia Leung

The colorful bands in the Chinle Formation, which gives the Painted Desert its name, represent ancient soil horizons deposited by ancient fluvial systems. During the Late Triassic, this region was located on the southwestern edge of the supercontinent Pangaea, where the climate was humid and sub-tropical. The large river system undergone cycles of incisions and depositions, similar to processes observed in modern river systems. The Chinle rock layers formed from these fluvial deposits chronicle the ever changing conditions of the ancient past. Over the years, erosion has shaped the Chinle Formation into intriguing landforms such as the badland hills, flat-topped mesas, and sculptured buttes.

Chinle Bandlands



Block diagram of Late Triassic deposition



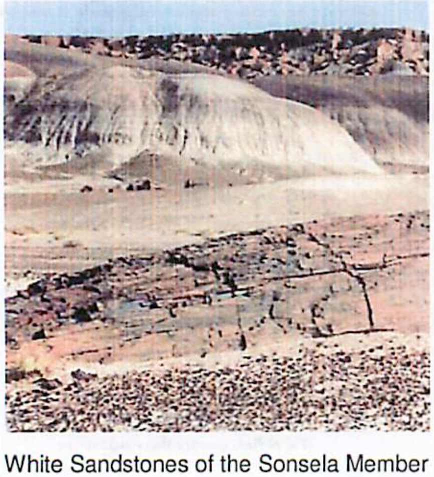
**Within the Petrified Forest National Park, the layers of the Chinle Formation are divided into five individual members:**

| Bidahochi Formation | |
|---|---|
| Rock Point | Lowest member of overlying upper Triassic Wingate sandstone |
| 5. Owl Rock | Pinkish orange mudstones mixed with hard, thin layers of limestone; contains carbonate lenses |
| 4. Petrified Forest | Thick sequences of reddish mudstones and brown sandstone layers |
| 3. Sonsela | Subdivided into five beds<br>i. lower Camp Butte- white sandstone and conglomerates<br>ii. Lot's Wife- purple mudstones and gray sandstones<br>iii. Jasper Forest/Rainbow Forest- thick gravelly sandstone (contain the majority of the colorful petrified wood)<br>iv. Jim Camp Wash- mudstone, sandstone, calcareous lenses<br>v. Martha's Butte- purple mudstones and massive brown Flattops One Sandstones |
| 2. Blue Mesa | Thick deposits of grey, blue, purple, and green mudstones and minor sandstone beds |
| 1. Mesa Redondo | Mainly of reddish sandstone with some mudstones |
| Moenkopi Formation | |

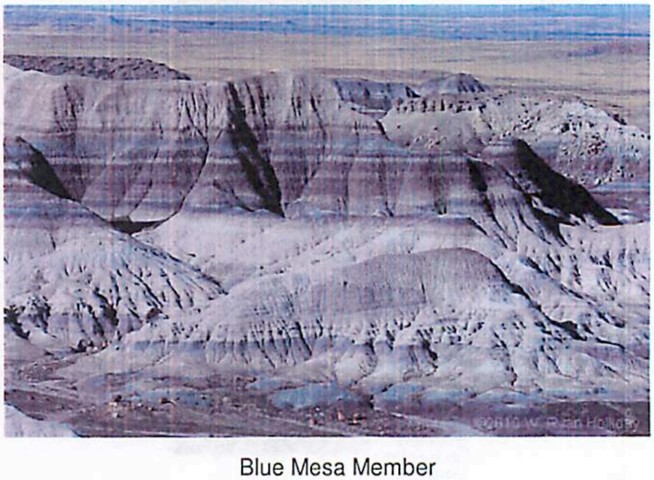
**Coloured Bands:**

The red and green layers generally contain similar amounts of iron and manganese, however the variation in colour depends on the position of the groundwater table when the ancient soils were formed. In soils where the water table was near the surface, a reduced amount of oxygen in the sediments gave the iron minerals in the soil a greenish or bluish tone. When the water table fluctuated, allowing the iron minerals to oxidize and rust, the resulting soil were formed with a reddish hue.

Owl Rock Member (top) and the Petrified Forest Member (bottom) at Round Top Ridge.



White Sandstones of the Sonsela Member



Blue Mesa Member

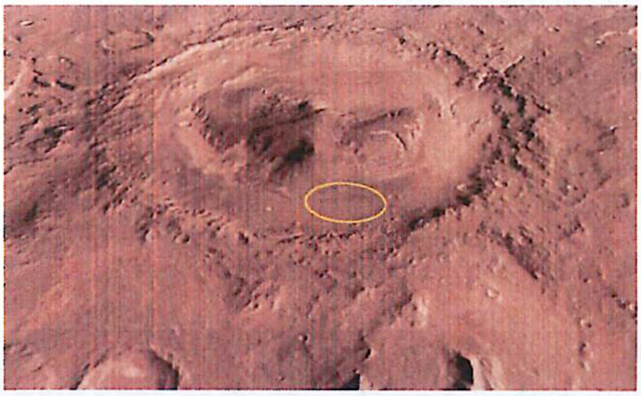
**Unconformity:**

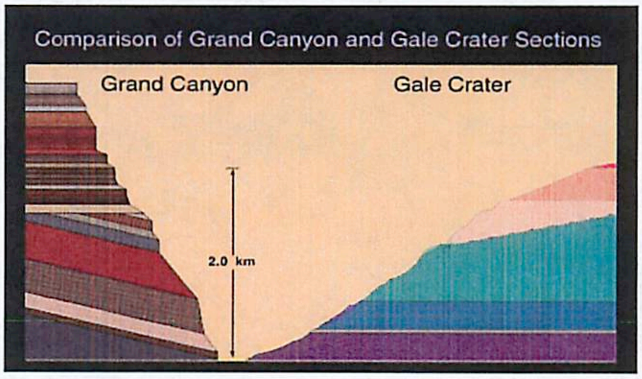
While the Chinle Formation was deposited over 200 million years ago, the overlying Bidahochi Formation is only 8 million years old. The contact between the Bidahochi and Chinle Formations represents a major break in the sedimentary geologic record. This unconformity indicates the older Chinle layer was exposed to major erosional events which obliterated 192 million years of erosional and depositional history.


At Nizhoni Point, the unconformity is between the black Bidahochi basalt on top and the white and red sedimentary Chinle below.

**Mars Science Laboratory Landing Site: Gale Crater**


Layered rock formation containing clays and sulfates, & exhibiting variations in thickness and tones. The Curiosity rover will land at the foot of a similar layered mound.


Oblique view of Gale Crater showing MSL landing site



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# Petrifaction & Fossils: Remains of Late Triassic Life in the Chinle

Corwin Atwood-Stone

## Petrifaction

-Preservation process wherein wood is turned to stone (other life can also be petrified)
-Infiltration of minerals in water into the pore spaces of the cells
-Crystals grow and fill cells from the inside, replacing their original contents
-Sometimes cells are filled without being destroyed
  -microscopic structure preserved
-Other times cell walls are dissolved and detail is not preserved
-Large cavities in log where growth is not restricted frequently form large crystals (Quartz Varieties, Amethyst)
-Minerals in this process
-Silica is the main mineral and the crystals in cells are all quartz
-Other incorporated minerals give the variety of colors
  -Iron: reds, yellows, and browns
  -Copper: blues and blue-greens
  -Carbon & Manganese: blacks
  -Other minerals less common but produce variety of colors
-Cubic foot of petrified wood is 168 pounds

Fig 2: Keystone Arch - A fractured petified log in Petrified Forest NP - Photo from NPS website

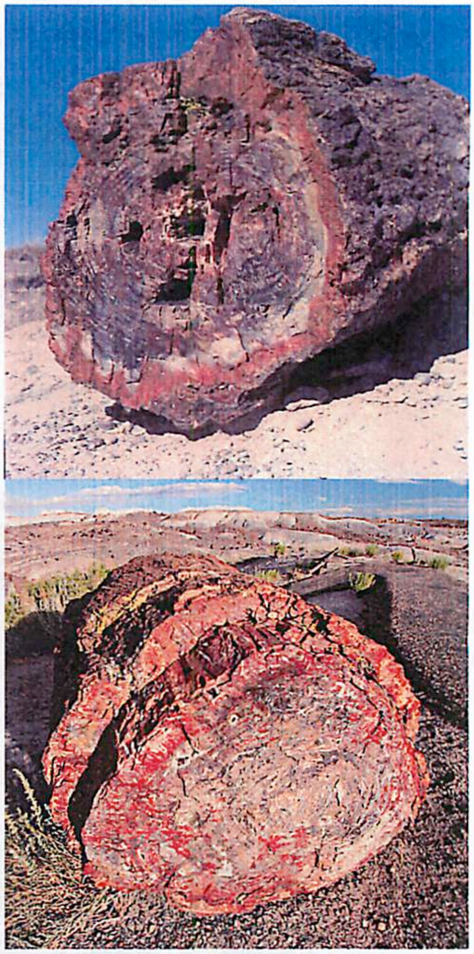


Fig 1: Petrified Logs from Petified Forest NP - (Top Pic by Philip Greenspan) (Bottom Pic from wikipedia)

## Why the Chinle

-In the late Triassic area is marsh, swamp and jungle, with streams running through
-Most logs carried to the area by streams from far away
-They get caught in log jams and mire down in a swampy area
  -Buried in mineral rich muck, water in mud mostly anoxic
  -Thus silica can infiltrate the log in an environment where the log is not decaying
-These conditions are favorable for other types of fossilization as well

## Preserved Trees of the Late Triassic

-Three major types of trees account for the logs in the Petrified Forest

-All are conifers and all are extinct
(there are several other very uncommon types)

-Most are from the group *Araucarioxylon arizonicum* a primative pine

-Living distant relatives in the "Monkey Puzzle Tree" and "Norfolk Island Pine"

-*Woodworthia arizonica* a cone bearing pine

-*Schilderia adamanica* This tree has strange radial rays in the wood, hard to put into plant classification schema


Fig 3: Norfolk Island Pine Trees a relative of *Araucarioxylon*

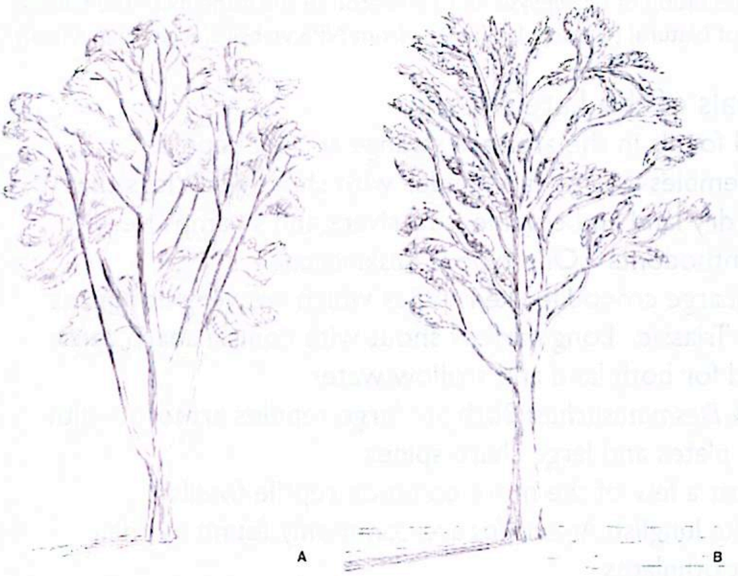


Fig 4: Reconstuctions of - A: *Schilderia adamanica* and B: *Woodworthia arizonica.* Image from Creber & Ash, 2004

## Other Plants

-There are many other types of plants preserved as fossils in the Chinle at Petrified Forest NP

-Small scale petrifaction and other fossilization types (replacement, leaf impressions)

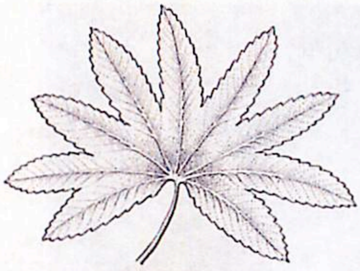
-Ferns: *Clathropteris walkeri* & *Phlebopteris smithii*

-Tree Ferns: *Itopsidema vancleavei* resembles miniature palm but is unrelated

-Seed Plants: Bennettites – trunk and branching stems

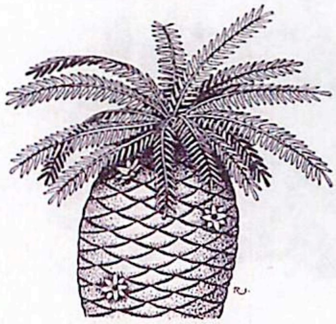

Fig 6: Fern leaf fossil impressions from Petrifed Forest. Image from Ash & May, 1969


Fig 5: The rayed pattern of *Schilderia adamanica.* Image from Creber & Ash, *2004*



*The leaf of the fern* Clathropteris walkeri. *Slightly under natural size.*

*The leaf of the fern* Phlebopteris smithii. *About natural size.*



*Sketch of the trunk and leaves of a Bennettite or "fossil cycad." One eighth natural size.*

Fig 7: Reconstructed plants found as fossils in the Chinle. Image from Ash &May, 1969

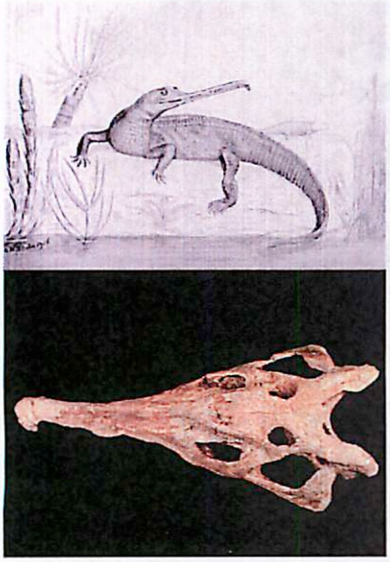


Fig 9: Phytosaur reconstruction and skull. Images from wikipedia (above)
Fig 11: Artistic rendition of *Typothorax* Rendition by Matt Celeskey (right)

## Dinosaur Fossils

- -Dinosaurs: Actually quite rare in the fossil record here as early dinsaurs from this time and area have hollow small bones and thus do not preserve well
- -Two types found here: *Chindesaurus bryansmalii*
  - -*Coelophysis* - Two legged carivore that is 8ft long and 50 lbs

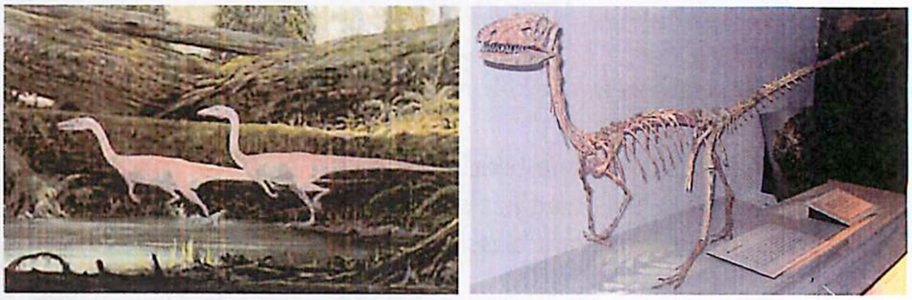


Fig 8: Artists rendition of *Coelophysis* and a Skeleton of the same from the Cleveland Museum of Natural History. Left Image from NPS website, Right image from Wikipedia

## Other Animals of the Late Triassic

- -Most animal fossils in the area are strange ancient reptiles
- -*Eupelor*: Resembles a large salamander with short weak legs that keep it off dry land and confine it to rivers and swamps, very late Labyrinthodonts - One type is *Koskinonodon*
- -Phytosaurs: Large crocodile like reptiles which are very dominant in the Late Triassic. Long narrow snout with conical sharp teeth and adaped for both land and shallow water
- -*Typothorax* & *Desmatosuchus*: Both are large reptiles armored with thick bony plates and large sharp spines
- -These are just a few of the more common reptile fossils
- -Some fish, like lungfish *Arganodus* are commonly found by their fossilized toothplates
- -Other types of animals such as small mammals and insects almost certainly exsisted but they are not preserved in the fossil record

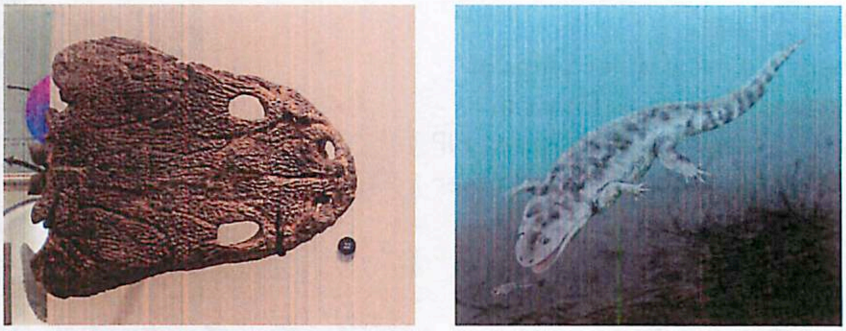


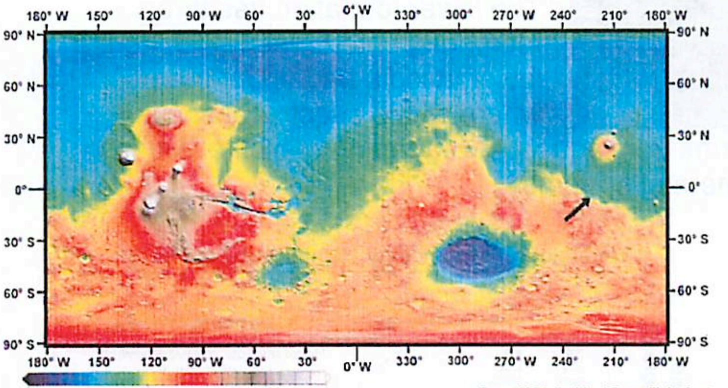
Fig 10: Skull and reconstruction of *Koskinonodon*. Images from wikipedia

References:
1 - Ash, S. & May, D. (1969) Petrified Forest: The Story Behind the Scenery
2 - Brodrick, H. (1951) Agatized Rainbows: A Story of the Petrified Forest
3 - Creber, G. & Ash, S. (2004) The Late Triassic *Schilderia Adamanica* and *Woodworthia Arizonica* Trees of the Petrified Forest National Park, Arizona, USA

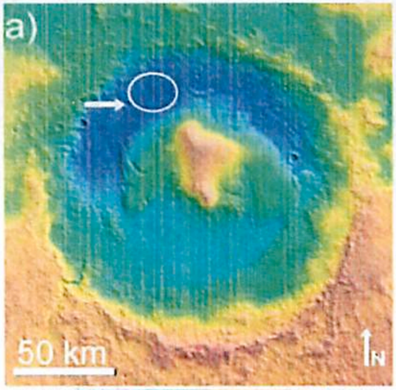
## Extraterrestrial Clay

Shane Byrne

- Mars Science Lab will launch 11/2011 and visit Gale crater near the end of 2012.
- Gale crater is Noachian aged (more on that later) and ~150km in diameter.
- It contains a layered mound of sedimentary material 5.2km high
    - That's higher than the crater rim in places
    - i.e. the entire crater was entombed in sedimentary rock and later exhumed

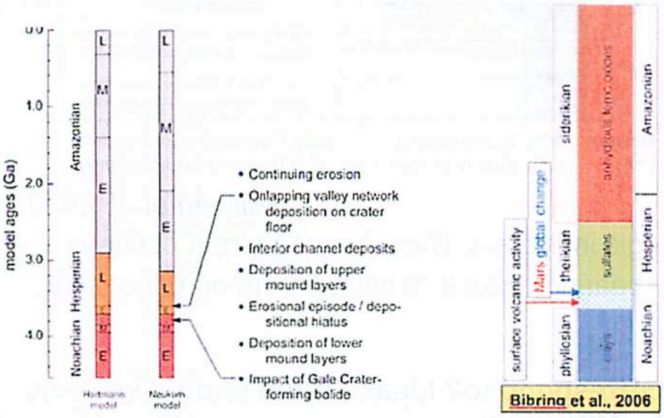


From NASA Goddard Spaceflight Center



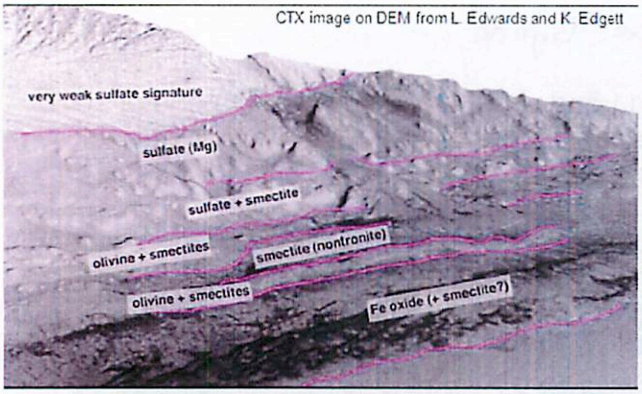
HiRISE PSP_008121_1780 – 1km high – Small canyon within the Gale crater mound

Gale crater is on the edge of the southern highlands. This is the site of vigorous drainage of liquid water into the northern lowlands early in martian history. Sediments accumulated in many craters in these locations and like the Colorado Plateau they record changing environmental conditions.



Crater counts on the external rim of Gale and crater floor+mound date the deposition to be around the Noachian Hesperian boundary. Minerologic transitions expected due to changing martian climate at this time.

Nighttime temperatures (a proxy for thermal inertia) indicate the upper parts of the mound are dust covered.



The mound can be divided into an upper and a lower formation.

The upper formation is layered but has the spectral appearance of martian dust.

The lower formation has three members, unfortunately named the lower, middle and upper member. It's where all the spectral action is.

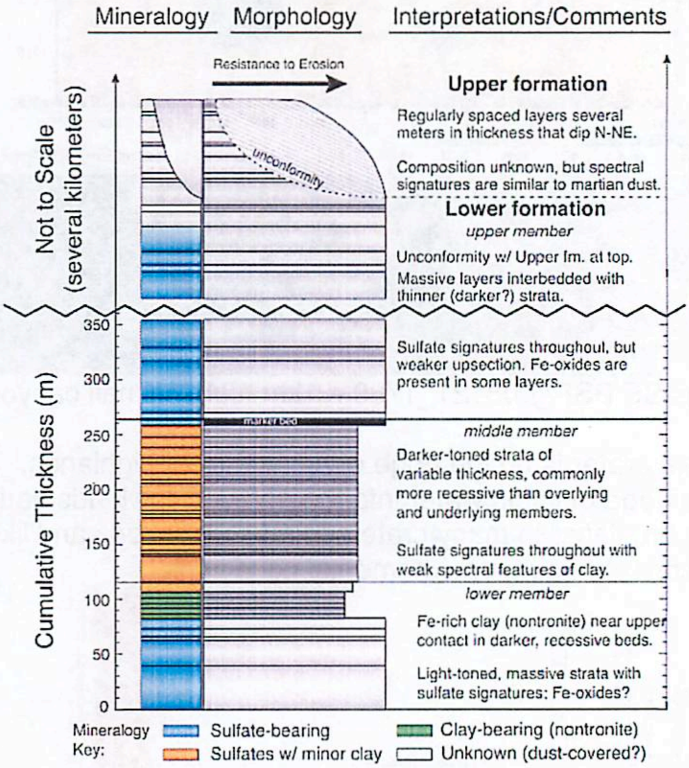
Nontronite (an iron-rich smectite) forms from aqueous weathering of biotite (found in intermediate-silica basalt) or hydrothermal systems.

Upper formation

- Lack of absorptions indicative of hydrated minerals
- Similar to martian dust

Lower formation has abundant hydration signatures

- Sulfates in the lower member
- Transition to clay mineral-bearing rock at the lower-middle member boundary
- Gradation to sulfate-clay mixtures in the middle member
- Progression to sulfate-bearing rocks in the upper member



*Milliken et al. 2010*

These distinctions correlate with morphologic indicators. Clay-bearing strata occur as thin, recessive beds, whereas the sulfate-bearing rocks that bound them on either side erode to form cliffs

**So what do we expect these layers to correspond to? Ideas? What should we look for at the MSL site?**

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# IS MORPHOLOGY DIAGNOSTIC OF GROUNDWATER SAPPING? E. I. Schaefer

**Introduction:** For over 100 years, a multitude of workers have argued that certain valley morphologies result from groundwater sapping (i.e., undermining by groundwater) [e.g., *Russel*, 1902; *Laity and Malin*, 1985; *Howard*, 1988; *Pelletier and Baker*, 2011]. Perhaps the most iconic of these morphologies is the "theater-headed" valley, a valley whose upstream terminus is U-shaped in planform [**Fig. 1a**] as opposed to the V-shape [**Fig. 1b**] of valley heads cut by overland flow.

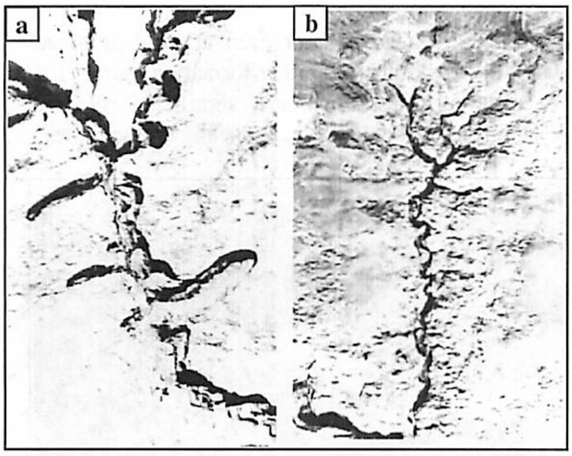

**Fig. 1**: (a) Theater-headed and (b) pointy-headed valleys on the Colorado Plateau of southernmost Utah [*Latiy and Malin*, 1985].

Until very recently, it was generally assumed that theater-headed valleys were nearly diagnostic of groundwater sapping, so that process could be directly inferred from form with few caveats and further, that the theater-headed valleys of the Colorado Plateau were among the best examples of groundwater sapping morphology on Earth [e.g., *Laity and Malin*, 1985; *Howard*, 1988]. These conclusions are significantly challenged in a series of papers by *Lamb et al.* [2006; 2007; 2008] using a combination of field evidence and theoretical considerations but conversely reaffirmed by *Pelletier and Baker* [2011], who quantitatively model groundwater sapping-driven valley formation on Earth for the first time. The ultimate conclusion of this controversy could also significantly influence the interpretation of strikingly similar morphologies on Mars, where the valley-forming processes are extinct, subtler morphologies have been erased, and detailed field analysis is impossible.

**Alternative Mechanisms:** *Lamb et al.* [2006] suggest three mechanisms other than groundwater sapping that may form theater-headed valleys:

- catastrophic flooding
- waterfall erosion
- mass wasting

Since catastrophic flooding would leave abundant evidence that is absent on the Colorado Plateau [*Pelletier and Baker*, 2011], only the latter two mechanisms need be considered.

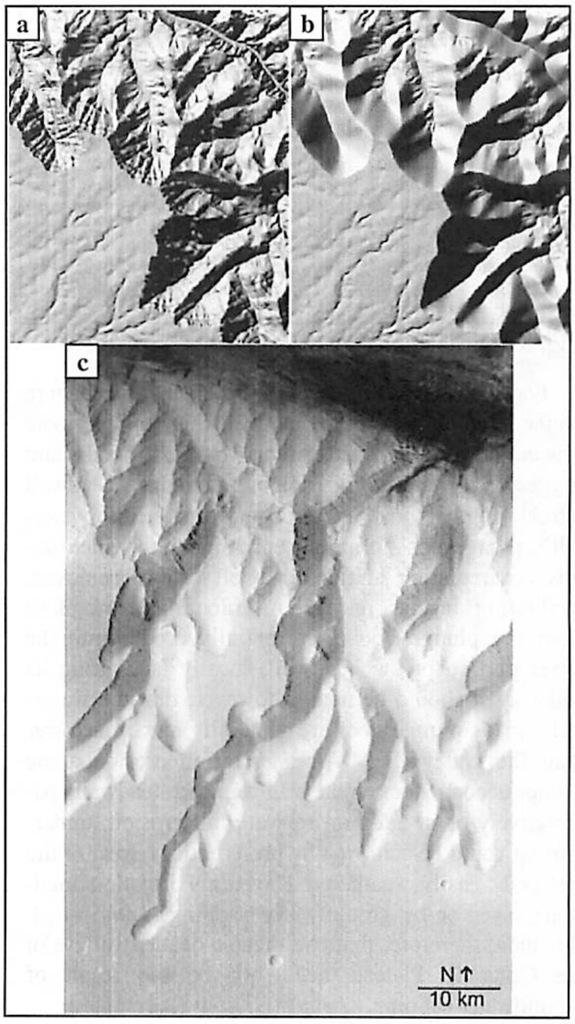

**Fig. 2** Simple iterative simulation in which slopes >20° in a portion of the Grand Canyon (a) are relaxed to 20° while maintaining volume (b), meant to simulate mass-wasting. For comparison, Ius Chasma (c), a theater-headed valley on Mars, is shown. [*Lamb et al.*, 2006]

*Lamb et al.* [2006] cite and re-implement [**Fig. 2**] simulations by *Howard* [1995] which demonstrate that initially V-shaped valley heads can be rounded when weathering and mass wasting (i.e., physical and chemical breakdown of rocks and their gravity-driven transport downslope) cause uniform slope retreat in layered rock. However, this results in substantial unconsolidated material lining the valley, whereas *Laity and Malin* [1985] observe that coarse debris is limited in the theater-headed valleys of the Colorado Plateau.

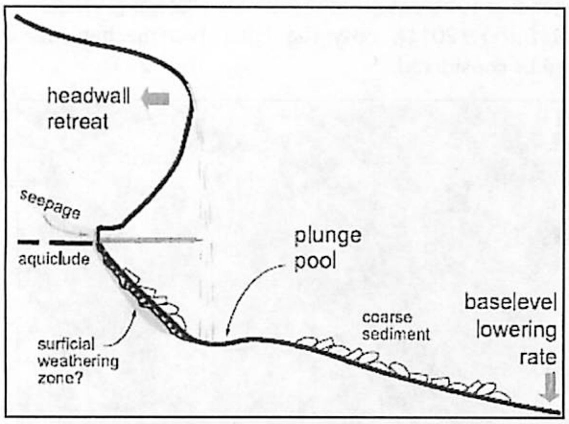

**Fig. 3** Conceptual model of *Lamb et al.* [2006].

For this region, *Lamb et al.* [2006] instead seem to prefer a combination of mass wasting and periodic evacuation of accumulated debris by flash floods, and suggest that waterfall erosion may enhance headwall retreat [**Fig. 3**]. In this conceptual model, the waterfall's plunge pool forms a depression into which debris accumulating at the headwall can be removed, facilitating further retreat. Additionally, backsplash from the plunge pool preferentially erodes into the lower portion of the headwall, locally facilitating its collapse. It should be noted, however, that the waterfall and its plunge pool are generally much narrower than the valley [**Fig. 4**], so waterfall erosion alone cannot account for retreat of a rounded headwall. Alternatively or in addition to waterfall erosion, undermining could be achieved by preferential retreat of the relatively easily weathered Kayenta Formation mudstone layer or by groundwater sapping. *Lamb et al.* conclude, therefore, that the theater-headed valleys of the Colorado Plateau need not be the result of groundwater sapping.

**Groundwater Sapping:** Conversely, *Pelletier and Baker* [2011] describe these same valleys as "particularly compelling examples of sapping" because they only occur where an aquifer/aquiclude contact (e.g., the Navajo Sandstone/Kayenta Formation contact) is exposed at the surface. *Pelletier and Baker*, like *Lamb et al.* [2006], concede that robust overland flow is necessary to evacuate debris, but they also point out that this was recognized by *Laity and Malin* [1985], among others.

Earlier literature [*Laity and Malin*, 1985; *Howard*, 1988] offers additional evidence for the sapping-dependent formation of the theater-headed valleys of the Colorado Plateau:

- other morphologies consistent with sapping
  - relatively constant widths along-valley
  - high and steep valley walls
  - pervasive structural control (e.g., the valley coarse is determined by regional fractures)
  - frequent hanging (perched) valleys
  - tributaries that are stubby in planform
- no clear positive evidence for plunge-pools or significant stream erosion on top of the plateau
- valleys head near or even at local drainage divides, implying either formation by very little overland flow or a significant role for groundwater, which can locally cross divides

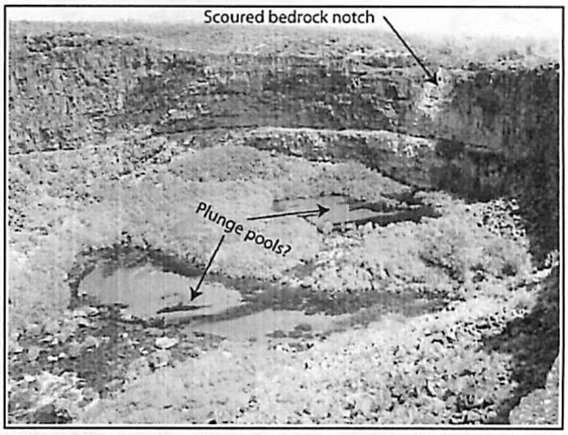

**Fig. 4** Headwall of Box Canyon, Idaho. The scoured bedrock notch reflects channel width, and possible former plunge pools are indicated. [*Lamb et al.*, 2006].

More generally, *Pelletier and Baker* [2011] and *Lamb et al.* [2006] both recognize that sapping alone cannot form theater-headed valleys, but unlike *Lamb et al.*, *Pelletier and Baker* argue that sapping is an essential component to the morphology (where catastrophic flooding can be excluded). This conclusion is supported by their numerical model, which produced pointy-headed valleys in the absence of sapping [**Fig. 5a**] but theater-headed valleys in both a sapping-dominated [**Fig. 5b**] and a hybrid case [**Fig. 5c**].

**Conclusions:** For the Colorado Plateau, the apparent strong stratigraphic control on the occurrence of theater-headed valleys coupled with other associated morphologies, discrepancy between drainage area and formation, and the lack of clear evidence for alternative mechanisms strongly suggest that sapping is essential to formation, as suggested by the model of

Pelletier and Baker. However, where such detailed observations are either inaccessible or potentially obliterated by degradation, as on Mars, it is still unclear whether groundwater sapping may be directly inferred from the theater-headed valley form. More rigorous testing of the mechanisms suggested by *Lamb et al.* [2006; 2007; 2008] is a clear next step in resolving the current controversy. Resolution of this debate could have significant implications for the paleoclimate, hydrology, and astrobiologic potential of Mars.

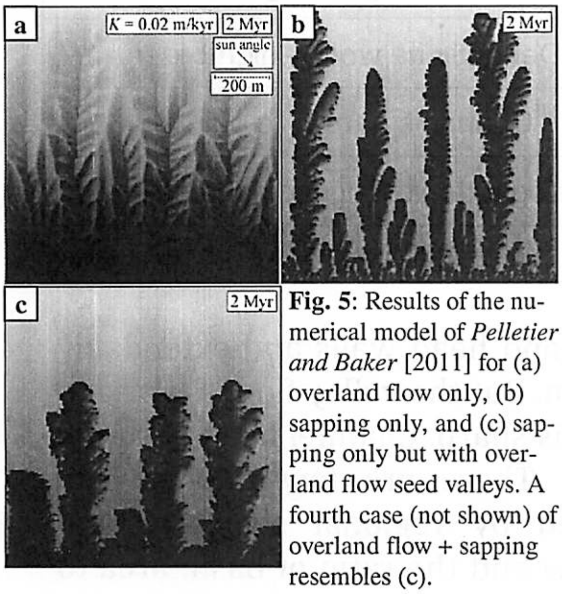

**Fig. 5**: Results of the numerical model of *Pelletier and Baker* [2011] for (a) overland flow only, (b) sapping only, and (c) sapping only but with overland flow seed valleys. A fourth case (not shown) of overland flow + sapping resembles (c).

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Howard, A. D. (1995), *Geomorph., 12*, 187-214.

Laity, J. E., and M. C. Malin (1985), *Geol. Soc. Am. Bull., 96*, 203– 217.

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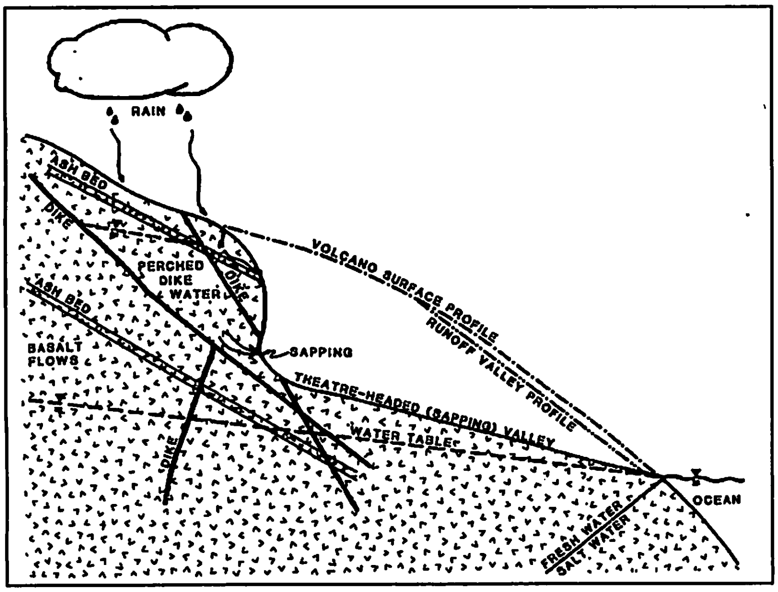
# Sapping Morphology

Youngmin JeongAhn

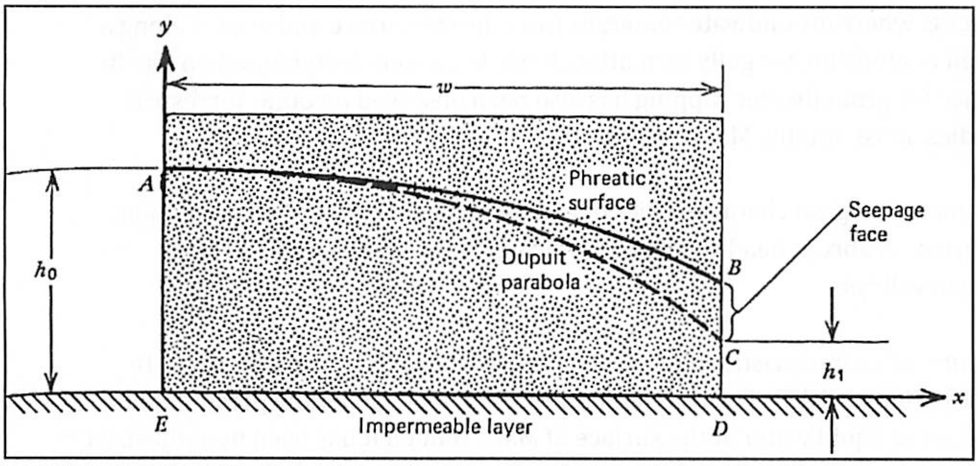
| Sapping | Runoff |
|---|---|
| Head-ward erosion of alcove | Down-cutting through terrain |
| Few tributaries – low order | Dendritic network – high order |
| Channel head is theatre-shaped | Channels narrow to points |
| Flat piecewise segments for floors | Logarithmic longitudinal profile |

**from PTYS594 Lecture**

Sapping channel contains steep valley and head walls and extends by mass wasting related to the basal erosion. But the valley floor is flat and the junction between the floor and wall is sharp. Channel head abruptly terminates with blunt theatre shape. There are few downstream tributaries and patterns are governed by regional structure and stratigraphy. The drainage density is low and the ratio of basin area to canyon area is small.



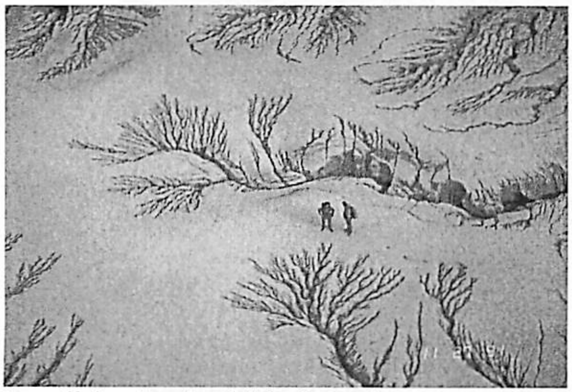
Schematic cross-section of Kohala, Hawaii (Kochel & Piper, 1986)



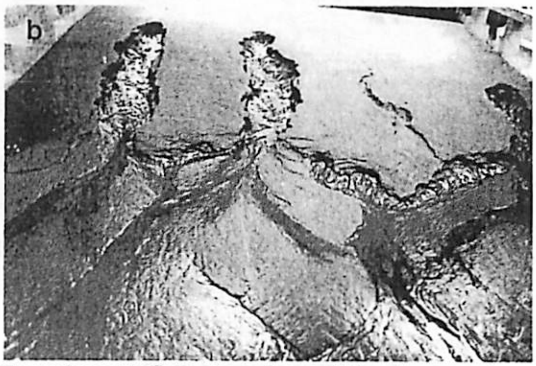
Dupuit-Fuchheimer discharge (from Geodynamics by Turcotte and Schubert)

Head-ward erosion near Mount Tamalpais in CA (USGS)

Sapping channel with short stubby tributaries



Runoff showing dendritic channels



Experiment of sapping channel development (Kochel & Piper, 1986)

# Sapping on Mars and Titan

Donna Viola

Sapping is a process where groundwater emerges from the subsurface and erodes along a slope, and is often responsible for gully formation. It has been well-documented on Earth; however, evidence for groundwater sapping has also been observed on other terrestrial solar system bodies, most notably Mars and Titan.

Some of the key morphological characteristics of gullies formed by groundwater sapping are short tributaries, an abrupt headward point ("theater" termination), and lack of dissection between valleys.

On Mars, these sorts of characteristics have been observed, and have been attributed to sapping processes (Figures 1&2). The cold temperatures on Mars generally preclude the prolonged existence of liquid water at the surface of Mars, though it has been hypothesized that groundwater seepage on Mars may have occurred as a result of geothermal heating (Squyres & Kasting 1994) or impact events which penetrate into subsurface aquifers (Newsom et al, 1996). It is also thought that sapping may have worked in tandem with overland flow in some regions of Mars (Bouley et al, 2009).

**Figure 1: MGS MOC image of gully erosion along the wall of an impact crater, Noachis Terra, Mars. Likely formed due to groundwater sapping. NASA JPL.**

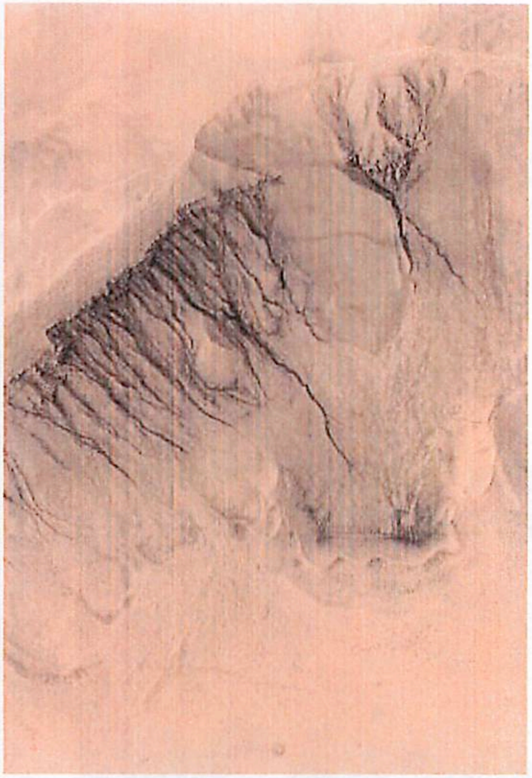


**Figure 2: High-resolution MGS MOC image of recent gullies, possibly formed by groundwater seepage, on the wall of a crater in Newton Basin, Sirenum Terra, Mars. NASA JPL.**

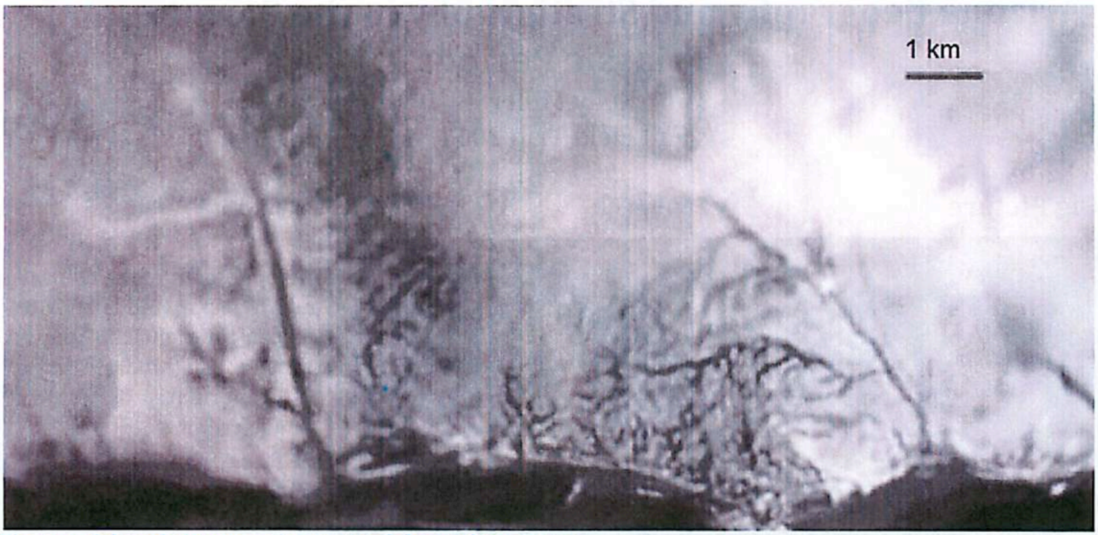


**Figure 3 (above): Huygens imagery of channels on Titan. The network on the left is thought to be the product of methane spring sapping since the tributaries are short and stubby, compared to the network on the right, whose formation was likely driven by precipitation (Soderblom et al. 2007).**

Titan, like Mars and Earth, has a solid surface which shows evidence of fluvial erosion. However, Titan's surface is primarily composed of water ice and solid organic material, and the eroding liquid is methane and ethane. Sapping on Titan could have occurred as methane flowed through the icy bedrock and emerged at the surface. Though we do not have high resolution imagery of Titan, Figure 3 depicts two channel networks – one which appears to have been formed by overland flow, while the other possesses some of the characteristic traits of sapping. Figure 4 also reveals evidence for erosion, which may be partially due to groundmethane sapping.

**References:**

Bouley et al. (2009) *Planetary and Space Sciences* 57: 982
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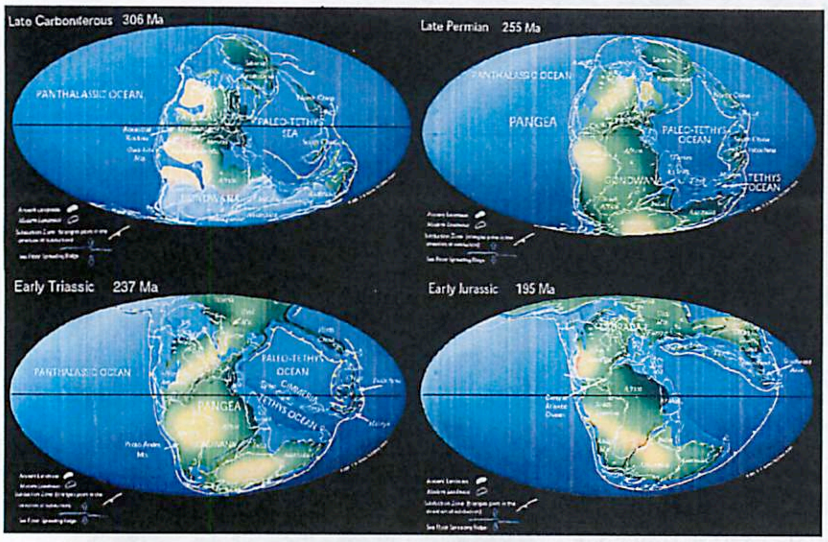
Soderblom et al. (2007) *Planetary and Space Science* 55: 2015
Squyres & Kasting. (1994) *Science* 265: 744

**Figure 4 (right): SAR Radar image from Cassini, near Titan's south pole. Evidence of severe erosion visible, especially in the southern part of the image. Probably the combined result of methane rainfall/runoff and groundmethane sapping. NASA JPL.**

# Arizona Geography and Stratigraphy in the Permian and Triassic Periods

Kelly Miller
Fall Field Trip 2011

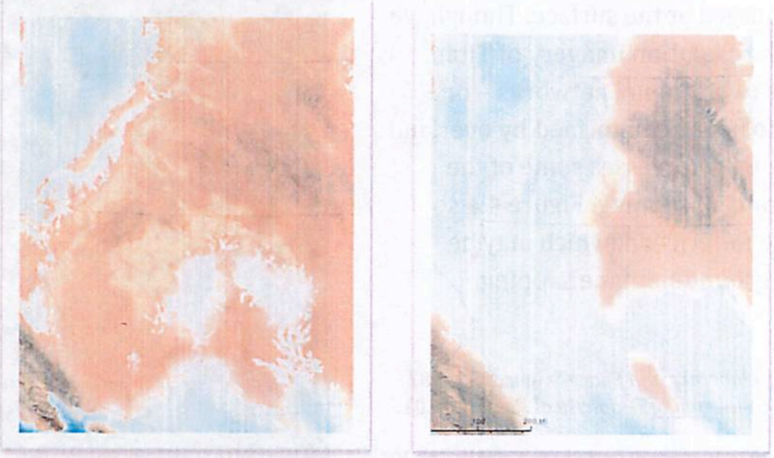
## The Big Picture



Arrangement of the continents at 306 m.y.a. (top left), 255 m.y.a. (top right), 237 m.y.a. (bottom left), and 195 m.y.a. (bottom right)
Image credit: http://www.scotese.com/earth.htm

- The Permian period was from 280-240 m.y.a. and the Triassic was from 230-180 m.y.a.

## Locally – The Permian Period



The Four Corners area in the Early (left) and Middle (right) Permian period
Image credit: Dr. Blakey, http://www2.nau.edu/rcb7/ColoPlatPalgeog.html

- Seas regressed and transgressed repeatedly in the Permian, leaving different layers of sedimentation behind.

- The Ancestral Rockies to the northeast and Uncompahgre Uplift to the northwest were both sources of sediment.
- In the late Permian, erosion became the dominant force shaping the landscape.
    - At Canyon de Chelly, this is evidenced by the uncomformity marking the boundary between Middle Permian and Triassic stratigraphic layers. The absence of rock from the Late Permian indicates either erosion of the layer or no deposition during this time.
- The floor of Spider Rock is an example of the Early Permian red beds; these are the same layer as the Organ Rock Shale.
- The walls of Canyon de Chelly are from the same layer as the high cliffs in Monument Valley.

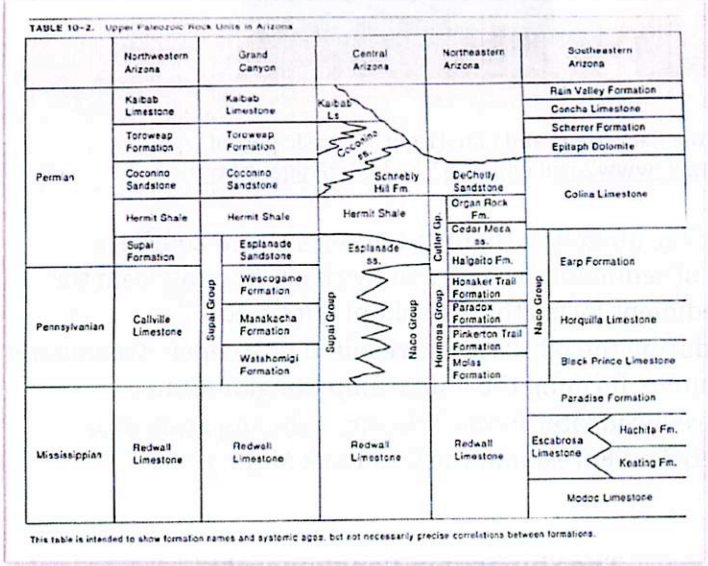


TABLE 10-2. Upper Paleozoic Rock Units in Arizona

| | Northwestern Arizona | Grand Canyon | Central Arizona | Northeastern Arizona | Southeastern Arizona |
|---|---|---|---|---|---|
| Permian | Kaibab Limestone<br>Toroweap Formation<br>Coconino Sandstone<br>Hermit Shale<br>Supai Formation | Kaibab Limestone<br>Toroweap Formation<br>Coconino Sandstone<br>Hermit Shale<br>Supai Group: Esplanade Sandstone | Kaibab Ls<br>Coconino ss.<br>Schnebly Hill Fm<br>Hermit Shale<br>Esplanade ss. | DeChelly Sandstone<br>Cutler Gp.: Organ Rock Fm.<br>Cedar Mesa ss.<br>Halgaito Fm. | Rain Valley Formation<br>Concha Limestone<br>Scherrer Formation<br>Epitaph Dolomite<br>Colina Limestone<br>Naco Group: Earp Formation |
| Pennsylvanian | Callville Limestone | Supai Group: Wescogame Formation<br>Manakacha Formation<br>Watahomigi Formation | Supai Group<br>Naco Group | Hermosa Group: Honaker Trail Formation<br>Paradox Formation<br>Pinkerton Trail Formation<br>Molas Formation | Naco Group: Horquilla Limestone<br>Black Prince Limestone |
| Mississippian | Redwall Limestone | Redwall Limestone | Redwall Limestone | Redwall Limestone | Paradise Formation<br>Escabrosa Limestone: Hachita Fm.<br>Keating Fm.<br>Modoc Limestone |

This table is intended to show formation names and systemic ages, but not necessarily precise correlations between formations.

Arizona Stratigraphy in the Paleozoic Era
Image credit: Nations and Stump 1981

## DeChelly Sandstone

- In some places, DeChelly Sandstone is 1000 feet thick, and in others it is only 200 feet thick. This is evidence of the Defiance Uplift, a high region that stood where Canyon de Chelly is now. Deposits of sediment were thin on the top of the uplift, and thicker on the low edges.
    - The Defiance Uplift consists of northwest-pointing anticlines and synclines and was a highland from the beginnings of the Paleozoic.
- Cross bedding in the sandstone is evidence of large well-formed dunes that the eolian rock formed from. It indicates winds at the time blew from the northeast in a southerly direction.
- Salt and gypsum deposits in DeChelly Sandstone are due to the Permian salt basin found by drilling underlying the Black Mesa Basin, centered at Holbrook.

An example of anticline(left) and syncline (right) in New Jersey.
Image credit:
http://en.wikipedia.org/wiki/Anticline

## The Triassic Period

The Four Corners area in the Early (left) and Late (right) Triassic period
Image credit: Dr. Blakey, http://www2.nau.edu/rcb7/ColoPlatPalgeog.html

- During the Triassic, uplifting of the Mogollon Highland in central and southern Arizona resulted in deposition of sediment in the north by rivers flowing from the south. The first layer of this sediment forms the Moenkopi Formation.
- Further uplift of the Highland during the late Triassic resulted in steeper streambeds carrying coarser grains of sediment, forming the Shinarump Conglomerate.
- The degree of uplift was again reduced later in the Triassic, reducing grain size during the deposition of the Petrified Forest and the Owl Rock Member.

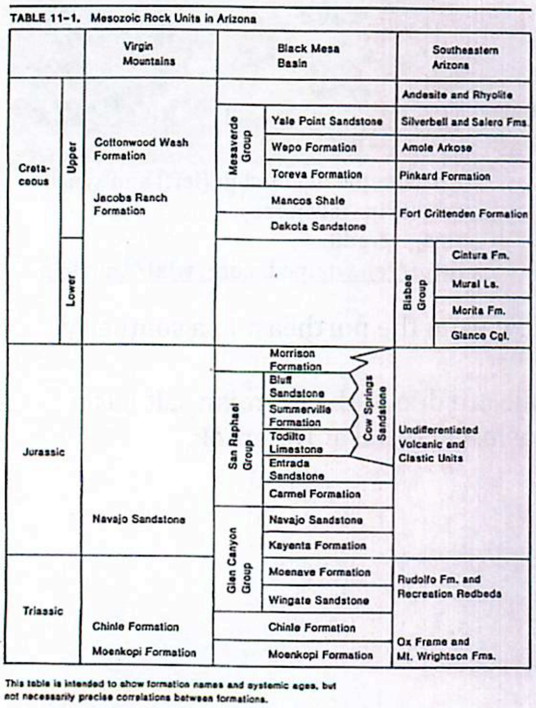


TABLE 11-1. Mesozoic Rock Units in Arizona

| | | Virgin Mountains | Black Mesa Basin | | | Southeastern Arizona | |
|---|---|---|---|---|---|---|---|
| Cretaceous | Upper | Cottonwood Wash Formation | | | | | Andesite and Rhyolite |
| | | | Mesaverde Group | Yale Point Sandstone | | | Silverbell and Salero Fms. |
| | | | | Wepo Formation | | | Amole Arkose |
| | | | | Toreva Formation | | | Pinkard Formation |
| | | Jacobs Ranch Formation | | Mancos Shale | | | Fort Crittenden Formation |
| | | | | Dakota Sandstone | | | |
| | Lower | | | | | Bisbee Group | Cintura Fm. |
| | | | | | | | Mural Ls. |
| | | | | | | | Morita Fm. |
| | | | | | | | Glance Cgl. |
| Jurassic | | | | Morrison Formation | | | Undifferentiated Volcanic and Clastic Units |
| | | | San Raphael Group | Bluff Sandstone | Cow Springs Sandstone | | |
| | | | | Summerville Formation | | | |
| | | | | Todilto Limestone | | | |
| | | | | Entrada Sandstone | | | |
| | | | | Carmel Formation | | | |
| | | Navajo Sandstone | Glen Canyon Group | Navajo Sandstone | | | |
| | | | | Kayenta Formation | | | |
| Triassic | | | | Moenave Formation | | | Rudolfo Fm. and Recreation Redbeds |
| | | | | Wingate Sandstone | | | |
| | | Chinle Formation | | Chinle Formation | | | |
| | | Moenkopi Formation | | Moenkopi Formation | | | Ox Frame and Mt. Wrightson Fms. |

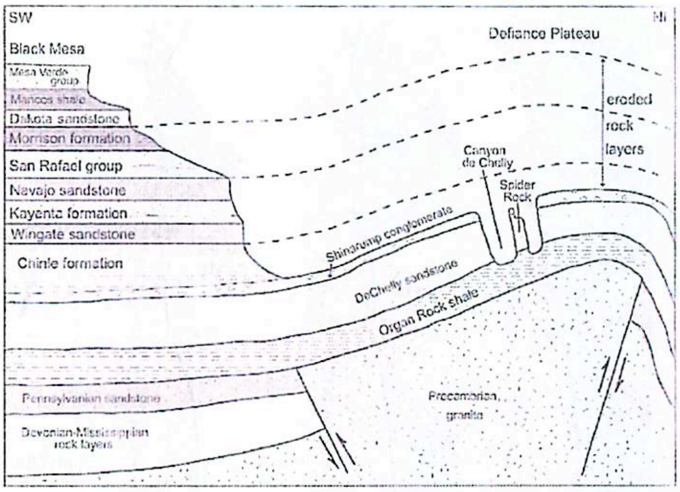
This table is intended to show formation names and systemic ages, but not necessarily precise correlations between formations.

Arizona Stratigraphy in the Mesozoic Era
Image credit: Nations and Stump 1981

### The Shinarump Conglomerate

- The Shinarump is more resistant to erosion than the underlying DeChelly Sandstone, and fills the eroded streambeds in the latter.
- Cross-bedding in the Shinarump is smaller and more lens-like, indicating that instead of dunes, it was deposited by streams that filled with sand.
- Grain size in the Shinarump is coarser than DeChelly Sandstone, and coarsest in the south, indicating steeper run-off from the Mogollon Highland in the south.
- Grains are Paleozoic and Precambrian sand and pebbles that flowed out of central Arizona.
- Sediment layers are between 0 and 345 feet thick and contain stumps from petrified conifers.

The Colorado Plateau
Image credit: http://ngm.nationalgeographic.com/ngm/0505/feature2/map.html



Stratigraphy of Canyon de Chelly
Image credit: Abbott, L. (2007) Geology Underfoot in Northern Arizona

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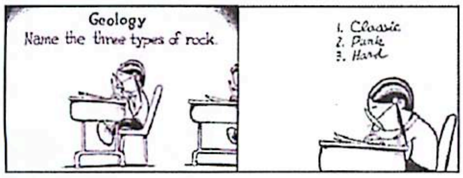


# Regional Tectonics of Western North America and Colorado Plateau Uplift

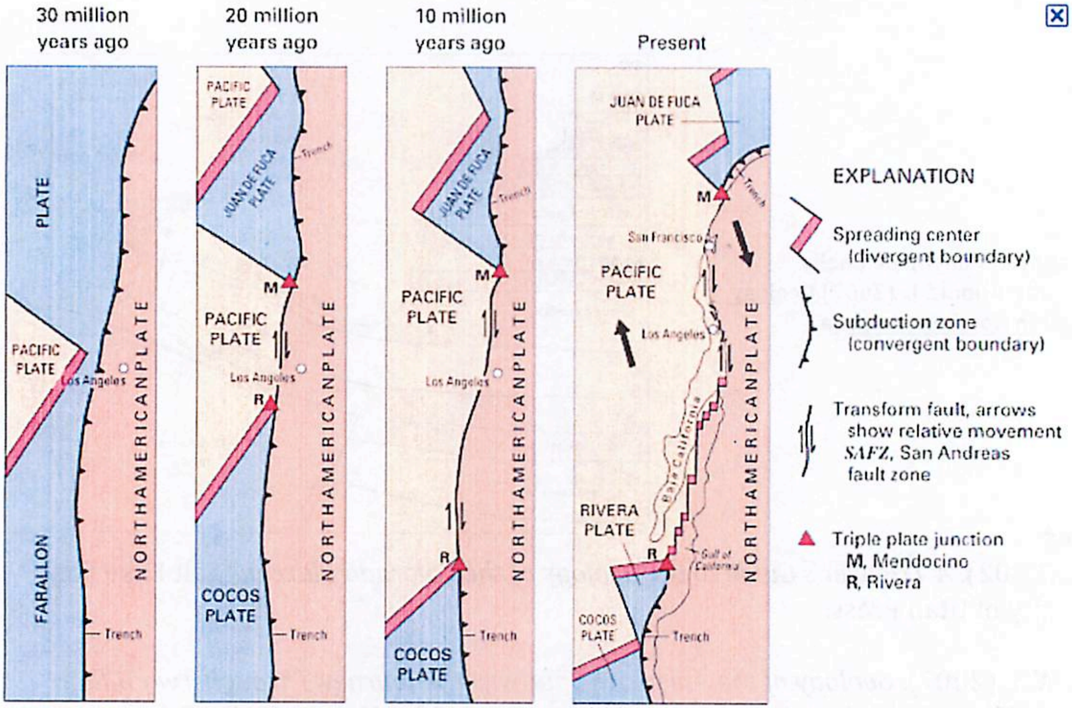
Colin Dundas

Major events:

- Subduction of the Farallon Plate, eventually converting to transform fault movement
- Laramide orogeny: large-scale uplift and mountain building
- Basin and Range extension
- **Uplift of the Colorado Plateau**

### Farallon Plate subduction

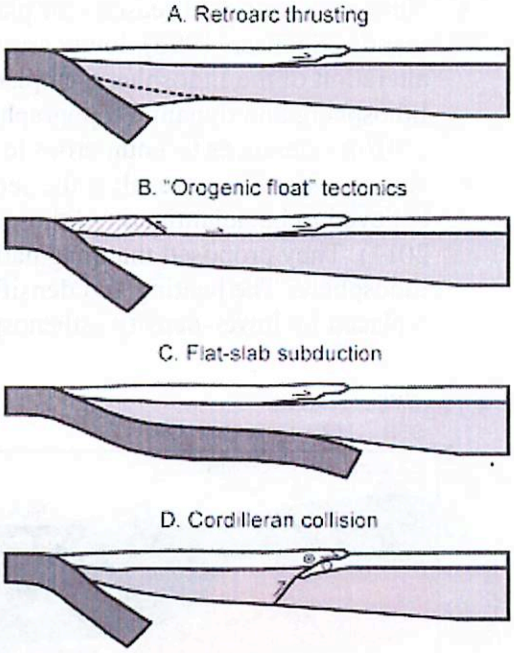
- Unusually shallow subduction, particularly in Late Cretaceous when part of the subducted slab was flat-lying and the subducted slab was near the surface under much of western North America (Liu et al., 2008).
- Subduction later steepened and the plate "rolled back" starting around 45 Ma. This shift may have driven the change from compression and uplift to Basin and Range extension (Schellart et al., 2010).



(http://pubs.usgs.gov/gip/dynamic/Farallon.html)

### Laramide Orogeny

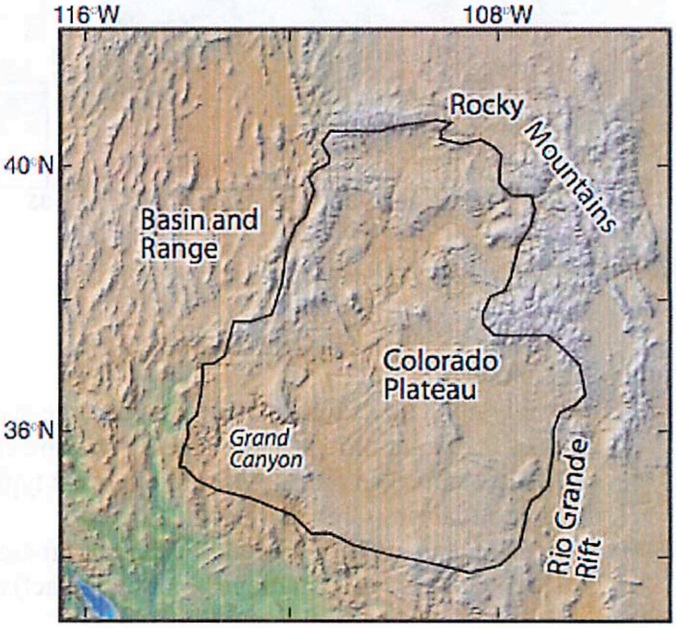
- Major period of uplift and mountain-building around 80-55 Ma.
- Unusually, deformation extended far inland from subduction zone (~1000 km).
- Magmatism along the margin of North America shut down during this period.
- Several models proposed; English and Johnston (2004) argued that none of these work…The most popular model has been that the shallowly subducting Farallon plate drove uplift and transferred deformation inland (reviewed by Jones et al., 2011).
- Jones et al. (2011) propose a variant model in which shallow subduction interacted with thick crust under Wyoming, causing subsidence which led to increased deviatoric stress and uplift.



(Right) Models for Laramide uplift reviewed by English and Johnston (2004).

### Colorado Plateau Uplift

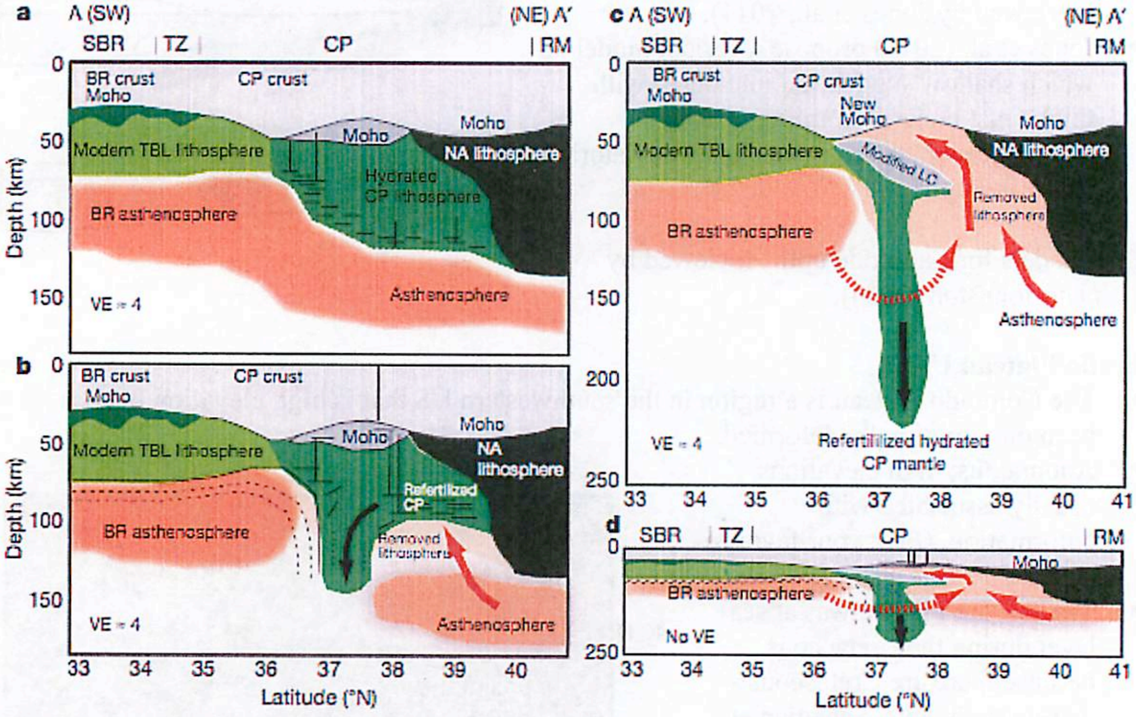
- The Colorado Plateau is a region in the southwestern US that is high elevation but has been only minimally deformed.
- Anomalous; high elevations usually associated with deformation. (Pick your favorite mountain range.)
- Timing: the Plateau was at sea level during the Cretaceous, because there are Cretaceous marine sediments. Sahagian et al. (2002) suggest slow uplift from 25-5 Ma, followed by faster uplift over the last 5 Ma, but this method has been vigorously challenged (Libarkin and Chase, 2003; Bondre, 2003). Libarkin and Chase suggested uplift rates were highest from 17-20 Ma. This brief suggestion shortchanges a much larger literature…



The Colorado Plateau (Flowers, 2010)

**Reasons for Uplift**

- Numerous proposed reasons for plateau uplift: removal of (dense, cold) lithospheric mantle (Spencer, 1996), lower crustal flow (McQuarrie and Chase, 2000), chemical alteration of the lithosphere, emplacement of warm asthenosphere, warming of the lithosphere and dynamic topography due to mantle flow. (See short review by Flowers (2010); references too numerous to lift here.)
- A recent significant result is the seismic imaging of a "drip" underneath the plateau believed to be delaminating lithospheric and lower-crustal material (Levander et al., 2011). They proposed that magmatic intrusion leads to increased density of the lower lithosphere. The heating and densification cause the lithosphere to founder and be replaced by lower-density asthenospheric material, raising the plateau.



(Levander et al., 2011)

**Planetary Connection**

- Probably no plate tectonics on Mars, but large-scale tectonic patterns are observed on most of the larger moons and planets. Some are easier to decipher than others.
- Uplifts are observed on Europa, although at a typical scale much smaller than the Colorado Plateau (Greenberg et al., 2003).
- Some mechanisms for Colorado Plateau uplift are also relevant for topics like the Martian crustal dichotomy—formation (if not by impact) and modification.

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# Tectonics of the Black Mesa Region and the Defiance Uplift

Patricio Becerra

The region lies in the south-west Colorado Plateau Province. It extends from the Kaibab uplift on the west to the Defiance uplift on the east, and from about the Utah state-line on the north to about the Mogollon Slope on the south (see Map 1).

The most important characteristics of a number of tectonics features in the area are outlined here, as well as a summary of the tectonic history of the region. Refer to Map 3 for the location and trending of folds.

## Tectonic Features in the Region

*Black Mesa Basin*

- Nearly circular downwarp ~90 miles in diameter
- Low regional dips and shallow structural relief
- Long, broad, parallel folds cross the basin in NW directions
- Deepest part is formed by the Black Mesa Syncline (BM(S)) → adjoined by the Cow Springs anticline (CS(A))
- Rim syncline (R(S)) and Black Mtn. (BMt(A)) anticline form the northern edge of the basin
- Principal SW deformations: Mount Beautiful anticline (MtB(A)), and Howell Mesa syncline (HM(S))

*Defiance Uplift*

- Borders the black mesa basin on the east
- Broad, north-trending asymmetrical fold. ~30 miles wide and ~100 miles long
- The eastern limb is defined by the defiance monocline (D(M))
- The broad crestal axes of the uplift have a relief of ~7500 ft, with 3000-6000 ft on the monocline
- Notable for its sinuosity
- Overall northerly trend is modified by SE trending anticlines and synclines that make it right-echeloned

*Tynde Saddle*

- Bounds the Black Mesa basin on the northeast
- Irregular outline. About 40 miles across.
- Broad and flat (~1000 ft overall structural relief)

*Piute Fold Belt*

- Consists of several northerly trending folds most of which are steeper to the east
- Principal folds are Organ Rock (OR(A)) and Balanced Rock anticlines
- Largest fold to the west is the Navajo Dome:
  - Possibly of laccolithic origin
  - Radius ~3 miles, and minimum structural relief of ~2000 ft. No obvious elongation

*Echo Cliffs Uplift*

- Long, narrow, north-trending monocline (EC(M))
- 80 miles long, 30 miles wide
- Only the eastern boundary is sharp, all others grade into basins
- Relief: North > 2000 ft, South: < 1000 ft
- Intermediate structural step between the lower Preston Bench, and the Kaibab uplift to the west. East Kaibab syncline intervenes.

*Kaibab Uplift (East Kaibab Monocline) (Map 2)*

- Northerly trending uplift. 125 miles long, 20-30 miles wide
- Relief: South ~ 2000 ft, Center ~ 3000 ft, North ~ 4000 ft
- East Kaibab Monocline is the type for monoclines
- Splits in two places → structural terraces
- Surface generally follows the upper contact of the Kaibab limestone
- Slopes generally parallel the dips of the monoclines and terraces

*Coconino Salient*

- Small protuberance from the south end of the EKM
- Formed by the intersection of the East Kaibab, Grand View, and Coconino Monoclines.

- Northeast section is very abrupt, with max dips on the monocline being vertical or overturned
- Southwest section merges gently with Grand Canyon section of the plateau
- Modified by younger faults: Gray Mtn. Grabens
- Appears to have resulted from the pushing of a deep-seated block northeastward and upward between flanking shear zones beneath Grand View and Coconino Monoclines

Mogollon Slope

- Wide southern border of the Colorado Plateau
- Gentle broad dip to the northeast
- 200 miles long, 65 miles wide
- General northwestern trend
- Atarque fault is exposed along the AZ-NM border: largest fault within the SW Colorado Plateau

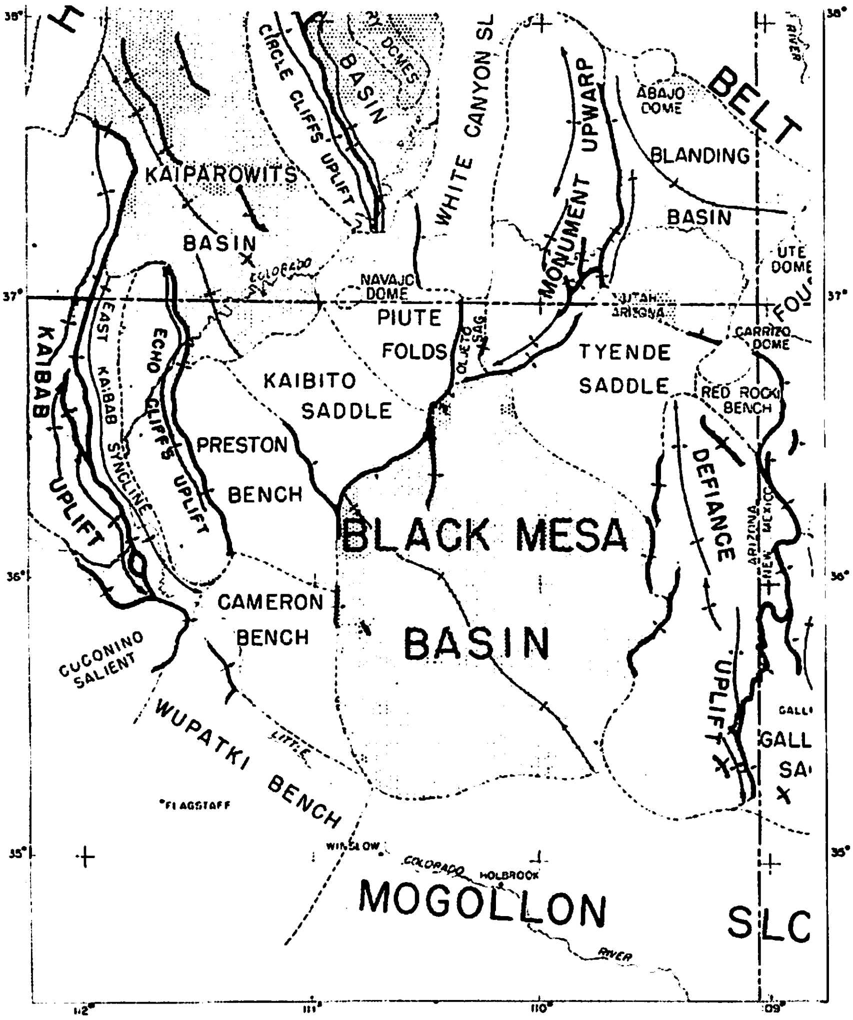
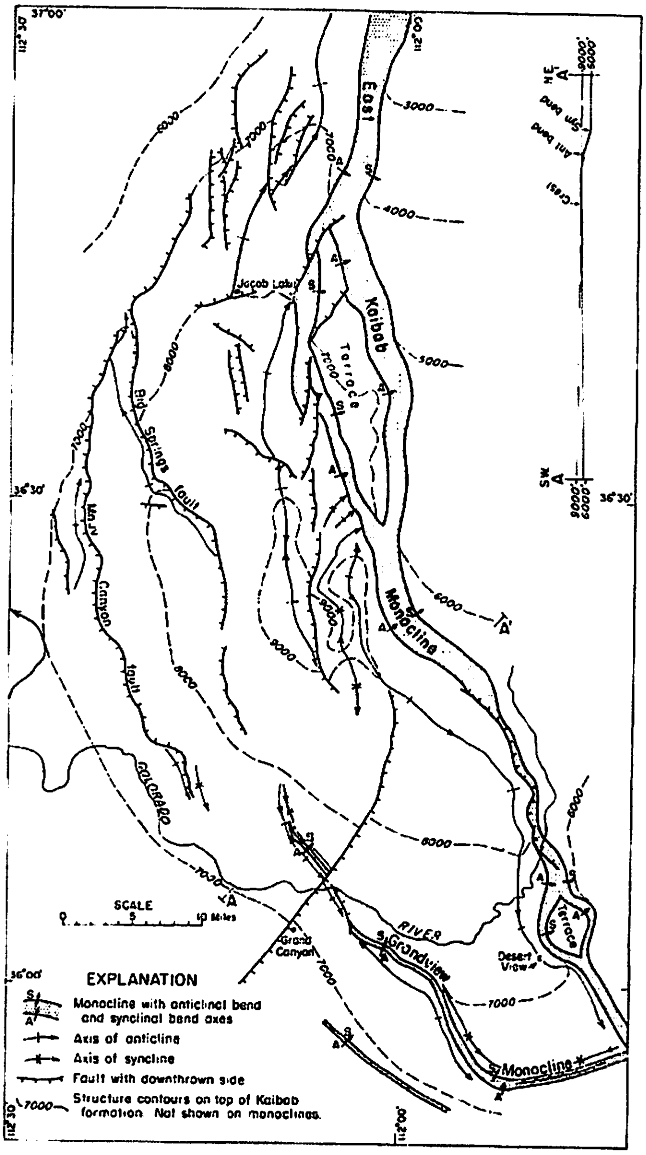


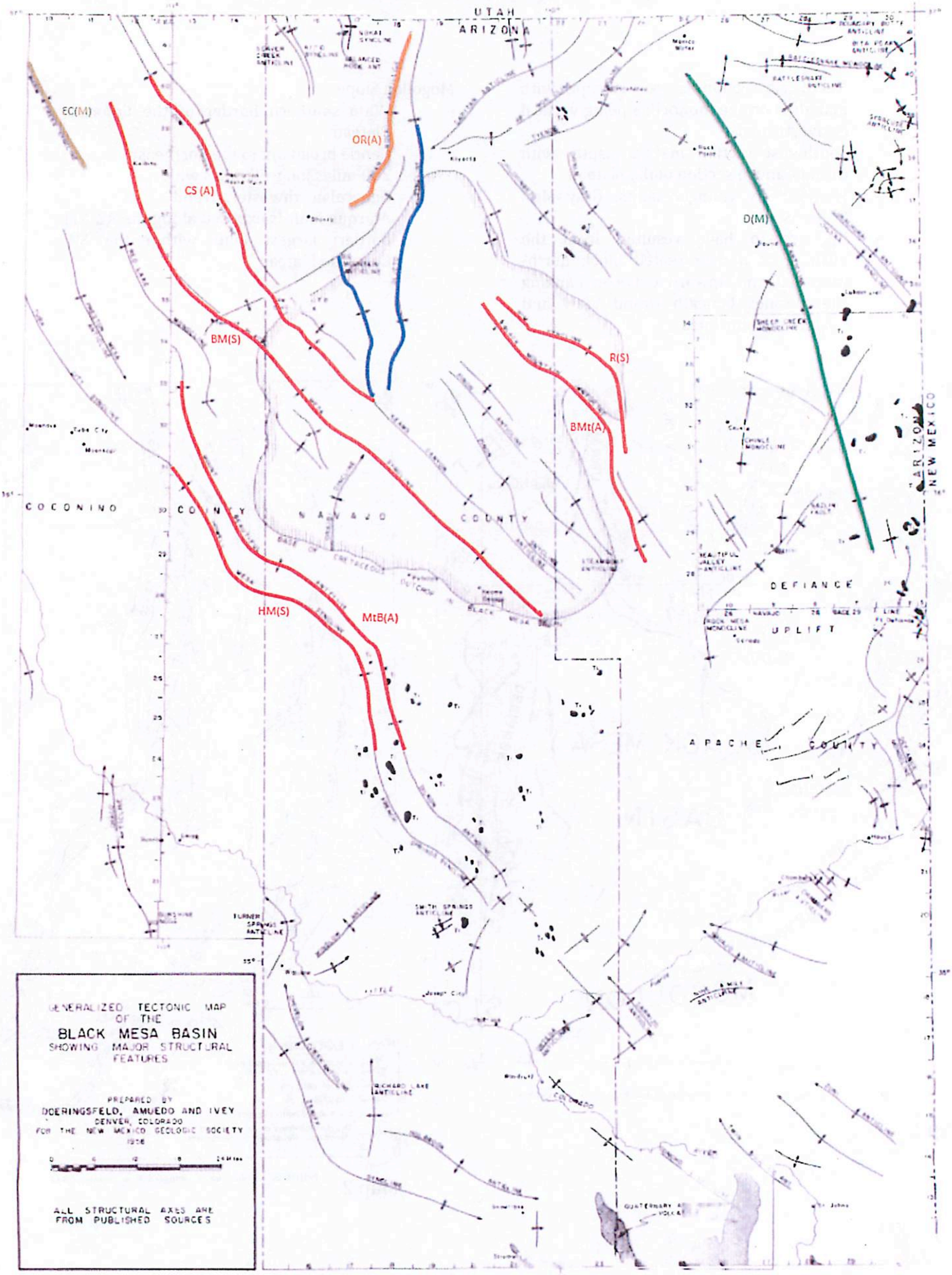
FIGURE 1. Index map of the tectonic divisions of the Black Mesa basin region.

Map 1



Map 2

FIGURE 3. Kaibab uplift; adapted from Strahler, 1948.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ARIZONA
EC(M)
OR(A)
CS (A)
BM(S)
R(S)
BMt(A)
D(M)
HM(S)
MtB(A)
COCONINO COUNTY
NAVAJO COUNTY
APACHE COUNTY
DEFIANCE UPLIFT
ARIZONA
NEW MEXICO
SHEEP CREEK MONOCLINE
CHINLE MONOCLINE
BEAUTIFUL VALLEY ANTICLINE
ROCK MESA MONOCLINE
RATTLESNAKE ANTICLINE
BOUNDARY BUTTE ANTICLINE
SMITH SPRINGS ANTICLINE
TURNER SPRINGS ANTICLINE
RICHARD LAKE ANTICLINE
QUATERNARY VOLCANICS
GENERALIZED TECTONIC MAP OF THE BLACK MESA BASIN SHOWING MAJOR STRUCTURAL FEATURES
PREPARED BY DOERINGSFELD, AMUEDO AND IVEY DENVER, COLORADO FOR THE NEW MEXICO GEOLOGIC SOCIETY 1956
0 6 12 18 24 Miles
ALL STRUCTURAL AXES ARE FROM PUBLISHED SOURCES

Map 3

## Tectonic History

- Nothing is known about the Precambrian history of the region
- Region must have been greatly deformed, uplifted and denuded to a lowland before Cambrian time began
- Mostly positive through Silurian time with a trend E-NE
- Mississippian time: Hinge line between positive and negative tendencies changed to NE as the NW portion of the region tilted toward the Cordilleran geosyncline
- During the Pennsylvanian, a NW positive trend was resumed and continued through Permian.
- Late Permian: Tectonically stable and rising very slowly
- Late Triassic: Region subsided during the accumulation of ~ 2000 ft of floodplain materials
- Subsidence continues through Jurassic as 1000-2000 ft of aeolian and playa deposits are accumulated
- During the Cretaceous the entire region became part of the Rocky Mtn. geosyncline, and subsided gradually until the basal beds of the sequence lay ~ 4000 ft below sea level. This rate of subsidence was 8 times that of the previous one (Permian-Jurassic)
- The region most likely remained relatively high during Paleocene and Eocene times, contributing sediments to northern areas
- Most of the structural/tectonic features of the Black Mesa basin region are probably the result of Laramide disturbances in the late Cretaceous or possibly early Tertiary.
- Main evidence for the age of the folds is the Kaibab uplift and the Kaiparowits basin (Map 1) where late Cretaceous beds are folded and overlain by undeformed early Tertiary beds in southern Utah
- Pronounced folds such as Organ Rock, Echo Cliffs, and Comb monocline have no direct stratigraphic evidence of Laramide formation. They have been assigned this origin because of similarity to, or extension from, the folds where this evidence exists
- The NW trending synclorium belt is the most persistent trend of folds in the Colorado Plateau. It could be regarded as a lineament caused by one of the tectonic spreads of the Sierra Oriental to the SE.
- The two principal tectonic trends in the region, NW, and N, may be the product of two Laramide deformation periods that possibly overlapped.

### Planetary Connection

- Lots of tectonic activity similar to that seen in this region (folds, grabens, contractional and extensional features) can be seen on the surfaces of most terrestrial planets.
- Some of the best examples can be seen on Mercury, Ganymede, and Europa

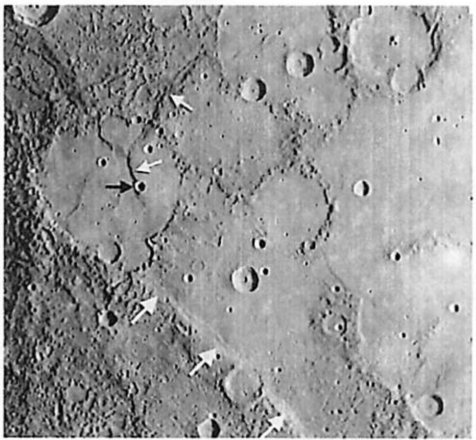

Fig. 1. Mercury wrinkle ridges

Fig. 2. Scalloped ridges on Europa

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PTYS 594A
September 2011

# The Formation of Sandstone

Michelle Thompson

## General Information:

Sandstone is a sedimentary rock that is composed primarily of sand sized mineral grains (0.0625 to 2.0 mm in diameter). These mineral grains are clastic (i.e not organic or chemical in nature) and are termed the 'detrital' or 'framework' material. They are typically quartz or feldspars. Additionally, sandstones have fine grained matrix material that fills in pore spaces between framework grains, as well as cement that bonds all of these phases together into a cohesive rock. The matrix material is present in the interstitial pore spaces between the detrital mineral grains, and is a function of the degree of sorting the sediment underwent before deposition. The cement binds the mineral grains together and is composed of secondary mineral formation. Several different types of cement exist.

## Formation of Sandstone:

The formation of sandstone occurs in several distinct phases. Initially, layers of sand must accumulate in a specific region, through either fluvial or aeolian processes. This sand builds up over time, as material is eroded from other rocks and transported by mechanisms such as rivers or by the wind. As more material accumulates, layers of unconsolidated sediment are buried. This buried material is subjected to several components of diagenesis:

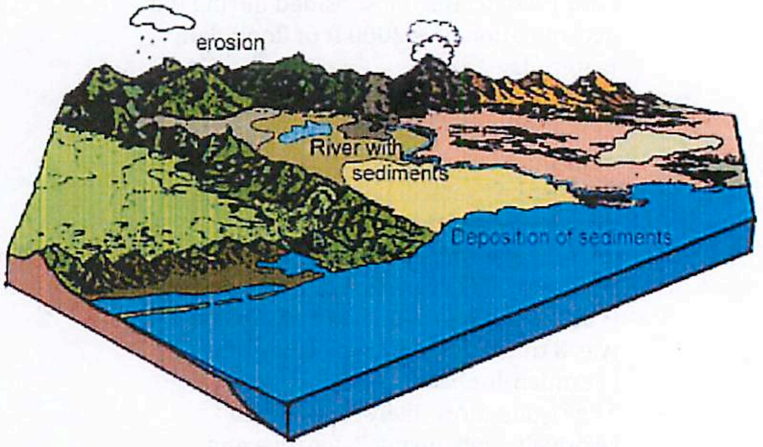

Figure 1: The formation of sandstone requires erosion and transport of sediment through wind or water to the final depositional environment.

### Compaction

- Unconsolidated sediment is buried, begins to compact under the weight of overlying material
- Pressure begins to push the individual grains closer together, expelling any fluid from the spaces between the sediment
- Grains can deform under the pressure, molding themselves to surrounding grains, further reducing pore space

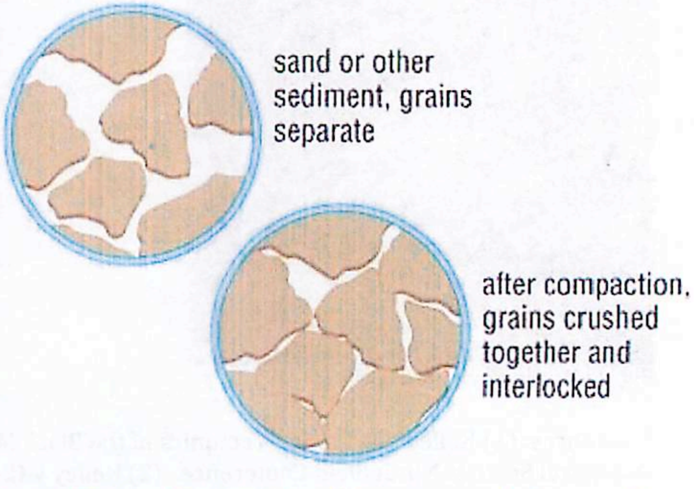

Figure 2: Compaction serves to reduce pore space between grains.

## Recrystallization:

- Change in pressure (contributed by all the overlying sediment) also generates changes in temperature, resulting in the melting/recrystallization of some mineral phases
- This may further reduce open pore space

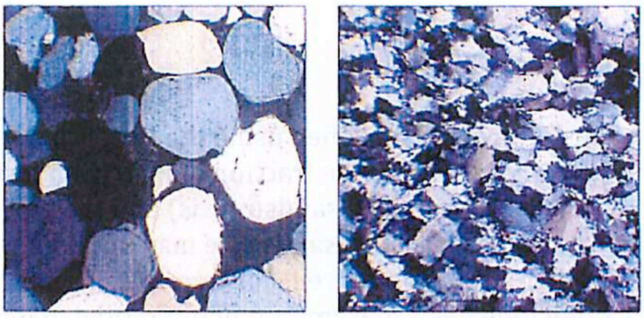

**Figure 3: Image showing initial sediment grains (left) recrystallized due to increased pressure and heat (right).**

## Solution:

- Fluids may percolate through the sediment, dissolving unstable mineral phases
- Major type: at the boundary between two grains, pressure is concentrated
- Fluid containing ions migrates away from this region towards an area of lower pressure to deposit and recrystallize

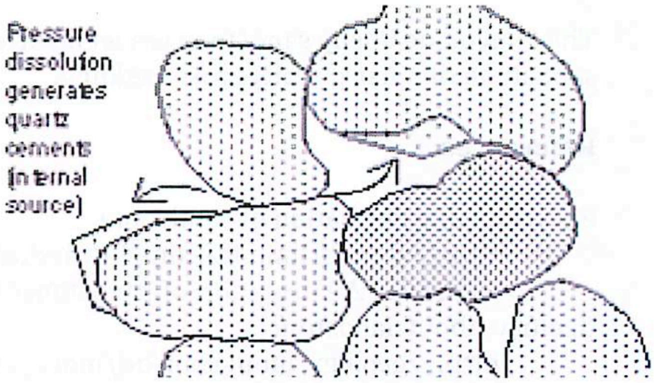

**Figure 4: Pressure dissolution of mineral grains resulting in deposition of new material in pore spaces.**

## Cementation:

- Pore spaces that remain open after compaction host new minerals that crystallize in situ as the result of pore fluid percolation
- Several types of cement exist, including quartz, calcite, hematite and various clay minerals

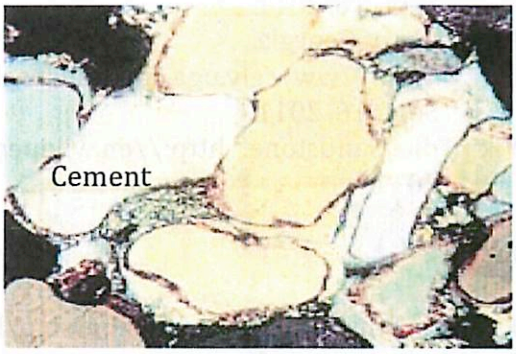

**Figure 5: Notice the grey cement material in between grains as annotated in the image.**

Each of these processes work to take loose unconsolidated sediment and, through pressure and the presence of solution fluids, turn it into a consolidated rock.

## Other Information:

Sandstones are classified using the Dott Scheme, based primarily on the fraction of matrix material (how well sorted the sandstone is) and the type of framework grains. A sandstone may undergo further alteration as well. For example, if a sandstone has a low amount of interstitial matrix material, and a high proportion of quartz forming its framework grains, and it is subjected to intense heat and pressure, these quartz grains may recrystallize and become interlocked to form the metamorphic rock quartzite.

Figure 6: A sandstone with a quartzite vein running through it.

The Canyon de Chelly sandstone is a well-sorted red sandstone that has distinct cross-bedding.

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## Images:

1. http://msnucleus.org/membership/html/jh/earth/sedimentary/jhsedmentary.pdf
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3. http://www.nd.edu/~cneal/PhysicalGeo/Lab-Metamorphic/index.html
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# The Permian-Triassic Extinction

by Gabriel Muro

The Permian period ended 251 million years ago with the most extensive extinction event in history. Researchers have estimated that the event resulted in up to 96% of marine species, and 70% of land species disappeared.[1] In addition to being the only known mass extinction of insects[2], the fossil record shows that the recovery period was exceptionally long.

## Late Permian Life

During the Permian period, the most abundant ocean fauna were ammonoids[3] (1) and brachiopods[4] (2). The mammal-like synapsids (3,4), were the largest land animals. Amphibians (5) remained common, and giant insects (6) such as Meganura were last seen in the Permian.[1,2]

After the extinction event, a small variety of carnivorous reptiles known as archosaurs (7) and the remaining synapsids, Lystrosaurus (8), were abundant across all of Pangaea throughout the early Triassic. Coelophysis (9), the first bipedal dinosaur, appears in the fossil record as well. In the oceans, the surviving invertebrates are a diverse variety of bivalves (10), echinoids (11) and gastropods (12).[5]

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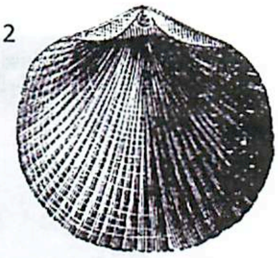

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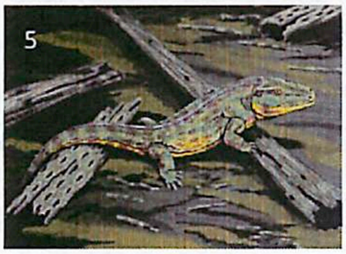

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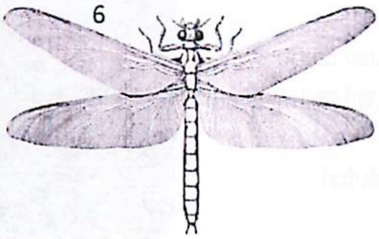

## Early Triassic Life

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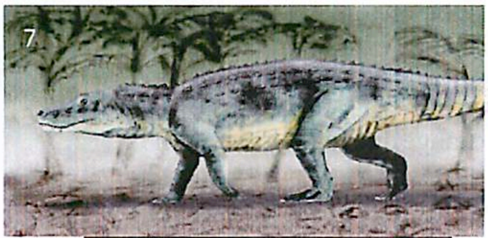

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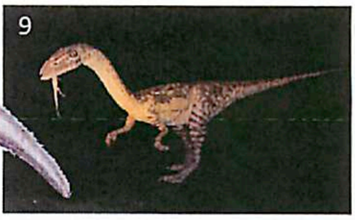

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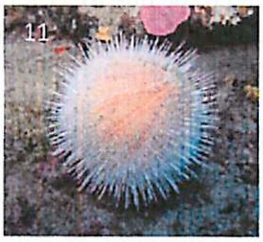

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Image credits: Wikipedia

## Possible causes of extinction:

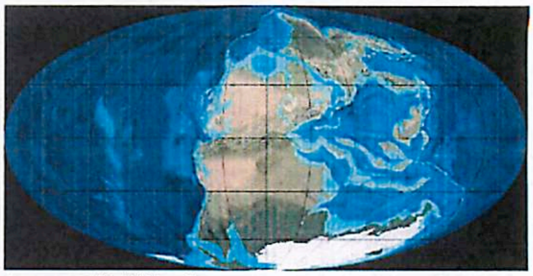

Image credit: Wikipedia

Formation of Pangaea[6]

- Closing of Paleo-Tethys Ocean decreased amount of coastal habitats
- Arid climate throughout interior
- Not a major factor in extinction

DAVID A. HARDY/SCIENCE PHOTO LIBRARY/Science Photo Library

Image credit: BBC

Large meteorite impact…?[1]

- Crater evidence up for debate
  - Ocean crater would be subducted by now
- No KT-like boundary layer of Iridium[7]
- Not consistent with drawn out extinction

CHRIS BUTLER/SCIENCE PHOTO LIBRARY/Science Photo Library

Image credit: BBC

Extreme volcanism

- Antipode of impact?[8]
- Siberian Traps[9]
  - Dated 251.2 ± 0.3 Ma
  - Largest known flood basalt event (2,000,000 $km^2$)
  - 20% of eruption appears pyroclastic
  - Occurred in large coal bed, releasing even more $CO_2$
- Estimated rise in $CO_2$ would raise global temperatures up to 4.5°C[10]

While none of these events are thought to be independently capable of an extinction on the level of the end-Permian, researchers have suggested that three distinct phases of extinction occurred[11]:

- The first phase was likely due to gradual environmental change due to the formation of Pangaea.
- The middle phase has been argued to be due to a catastrophic event, such as a massive meteorite impact, the sudden release of methane clathrate from the sea floor, or increased volcanism from the Siberian Traps.
- The final phase is attributed to long term environmental changes evident in the geologic record. Most likely a combination of the warming of the global climate, sea-level change, ocean anoxia, increased aridity on land, and a shift in ocean circulation driven.

## Sequence of events initiated by the Siberian Traps:

- Methane hydrate released into atmosphere[11]
    - Vast quantities in continental shelves
        - Lava from Siberian Traps extended to shallow sea
    - Deposited in permafrost
        - Likely released gradually due to warming
    - Capable of 6°C increase at equator, more at poles
    - Accounts for decrease in $^{13}C/^{12}C$ ratio[12]

- Ocean Anoxia[13]
    - Occurs due to lack of mixing
        - Low thermal gradient between poles and equator due to global warming
        - Thermohaline circulation stops
    - Oxygen deficient ocean devastates marine life
    - U/Th ratios consistent with severe anoxia[13]

- Increase in hydrogen sulfide emissions[13]
    - Ocean anoxia results in sulfate-reducing bacteria
    - Hydrogen sulfide released into atmosphere
        - Poisons plants and animals on land
        - Weakens ozone layer
            - Increased exposure to UV radiation
    - Anaerobic photosynthetic bacteria (green sulfur bacteria) in abundance through early Triassic[14]

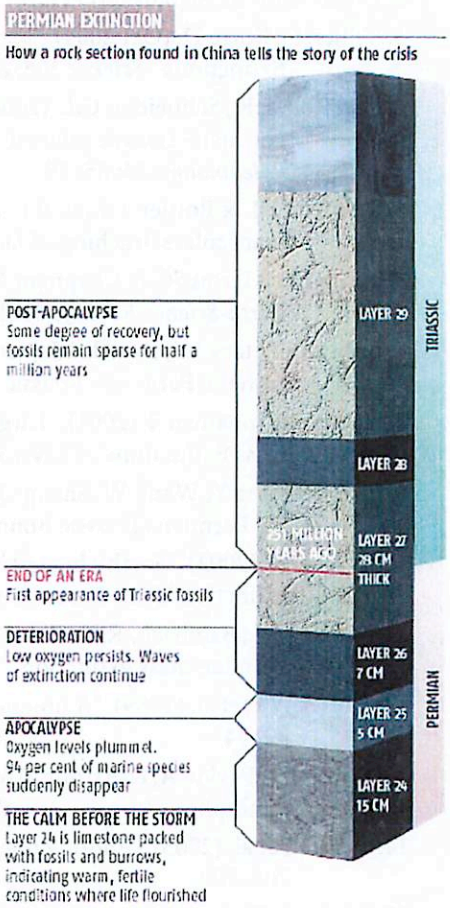

Image credit: Michael Benton, University of Bristol

## Recovery:

During the first 4-6 million years of the Triassic sediments, no coal deposits have been found[15] and river patterns switched from meandering to braided[16], indicating that the overall plant biomass was very low for an extended period. As a result of these harsh conditions, only a small number of genera were distributed worldwide ecosystem for much of the early Triassic. While the disaster taxa experienced a huge population boom in the wake of the Permian-Triassic event, it took nearly 30 million years before complex ecosystems with high biodiversity returned.[17]

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# Cross-Bedding

Meghan Cassidy

**Cross-bedding** forms when sediment are moved by eolian or fluvial processes and eroded along a gentle up-current slope, and deposited on the down-current slope. After several of these beds have migrated over an area, and if there is more sediment deposited than eroded, there will be a buildup of cross-bedded sandstone layers. The inclination of the cross-beds indicates the transport direction and the current flow. The style and size of cross bedding can be used to estimate current velocity, and the orientation of the cross-beds can be used to determine the direction of the paleo-flow.

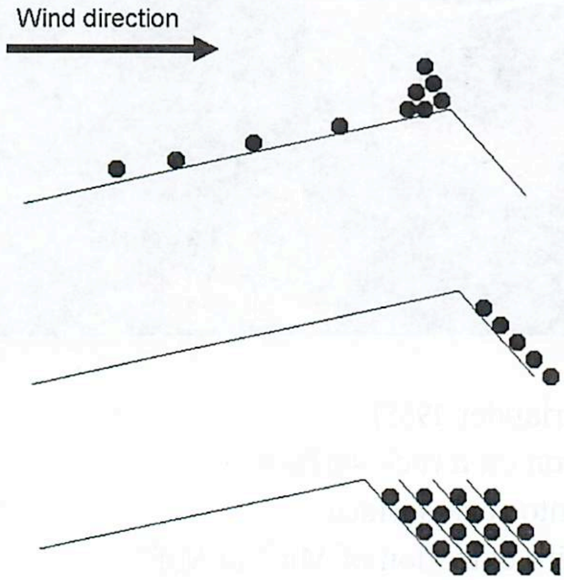


*Figure 1*: Cartoon of cross-bedding formation.

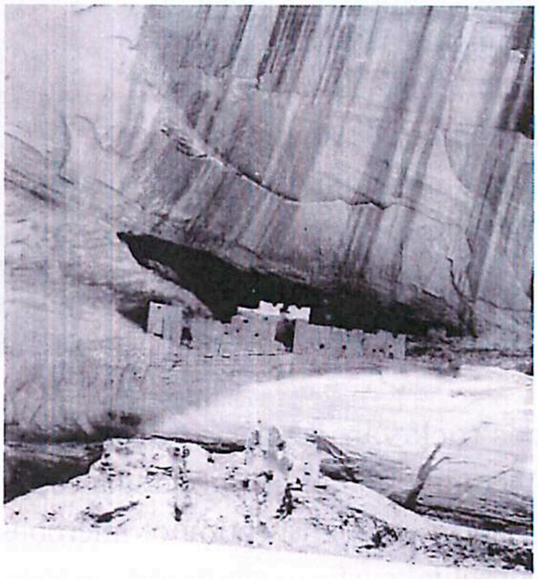


*Figure 2*: Canyon de Chelly National Monument, Arizona. White House cliff dwelling. Cross-bedding of Permian De Chelly Sandstone and alcove occurring at the base of the sandstone unit. July 1924 (USGS)

**Planetary Connection**

*Figure 3*: Rim of Victoria Crater

*Figure 4*: Endurance crater walls (Opportunity)

# Rock Varnish (Desert Varnish)

Melissa Dykhuis

**Rock varnish**: Natural dark coating observed on exposed rocks in arid regions

- *Composition*: clay minerals, oxides and hydroxides of manganese & iron
- *Color*: black, orange, brown
- *Thickness*: ~100 μm
- Drip patterns suggest formation process involves water

Desert varnish in Canyonlands Nat'l Park, UT
Richard Barron (richardbarron.net)

**How does rock varnish form?** (Dorn & Oberlander 1982)

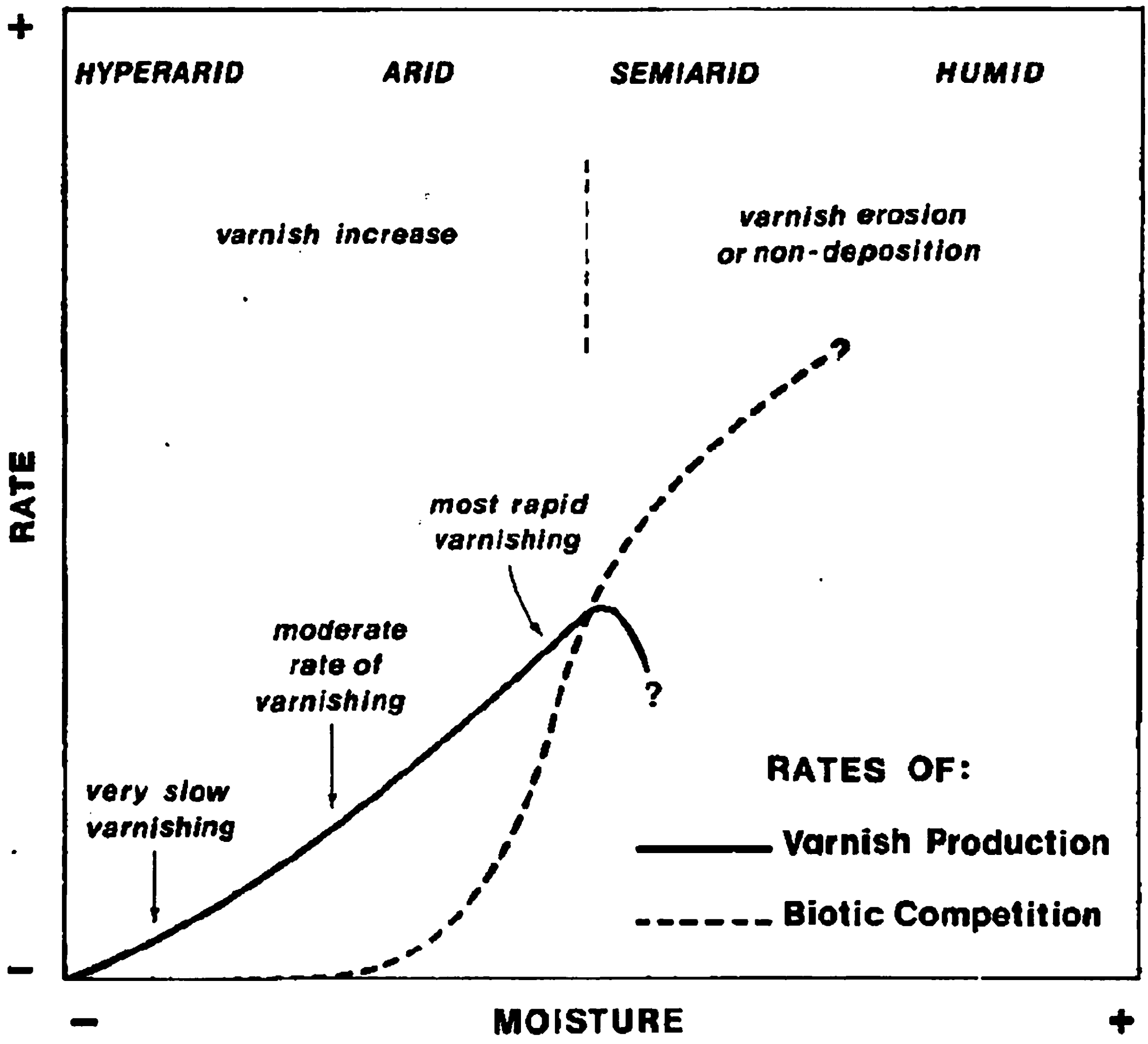
- Accumulation of clays, manganese & iron on a rock surface
- Absorption & adsorption of microbes onto rock surface
- Microbial surface community assists with oxidation of $Mn^{2+}$ to $Mn^{4+}$
- $Mn^{4+}$ cements clays onto rock surface, *requires wetting and thorough drying*
- Periodic rain allows microbial surface community to grow

Petroglyphs carved into rock varnish. Photo by Meghan Cassidy.

**Rates of varnish microlamination (VML)**

- About 1-15 µm per 1000 yr (Liu & Dorn, 1996)
- From <1-40 µm per 1000 yr (Liu & Broecker, 2000)
- *Caution*: rates seem to vary, from place to place, from time to time, even from rock to nearby rock (Dorn & Oberlander, 1981).
- Petroglyphs fade over time. Knowledge of VML rates can constrain dates of habitation of native peoples in desert areas.

**Dependence on moisture**

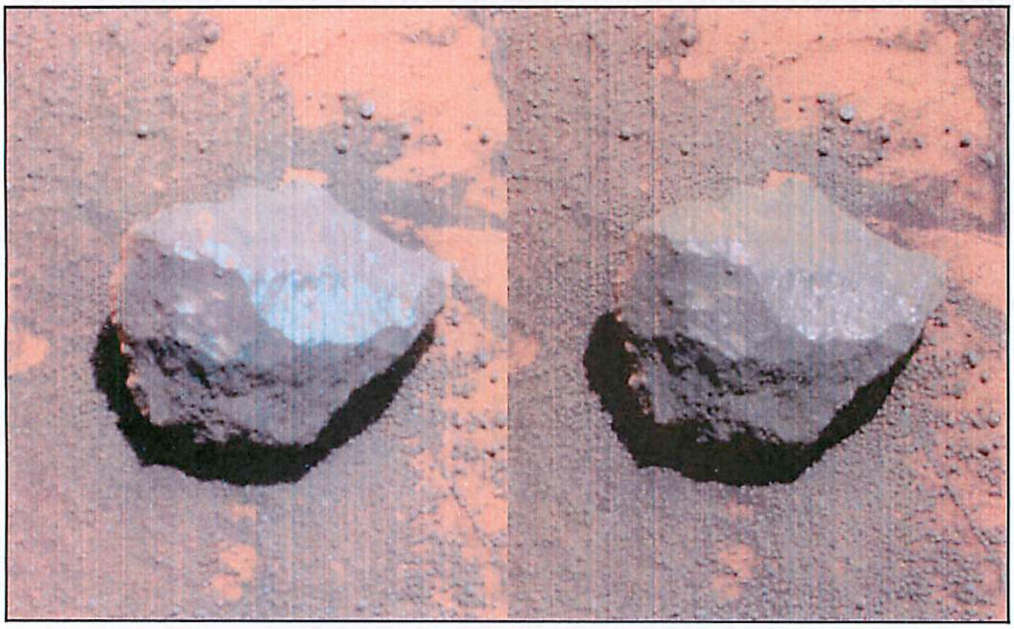


From Dorn & Oberlander 1982: In regions of high humidity, varnish is eroded more quickly; thus there exists an optimum climate for varnish production.

## Planetary connections

### *Mars*

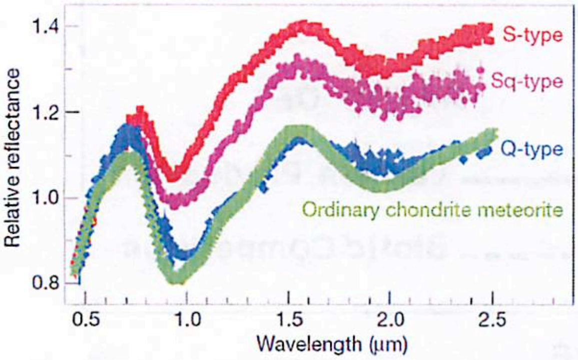
Varnish on Martian rocks might suggest the presence of microbial life! Many rocks on Mars show a shiny exterior, raising questions about rock varnish on the red planet (DiGregorio, 2002).

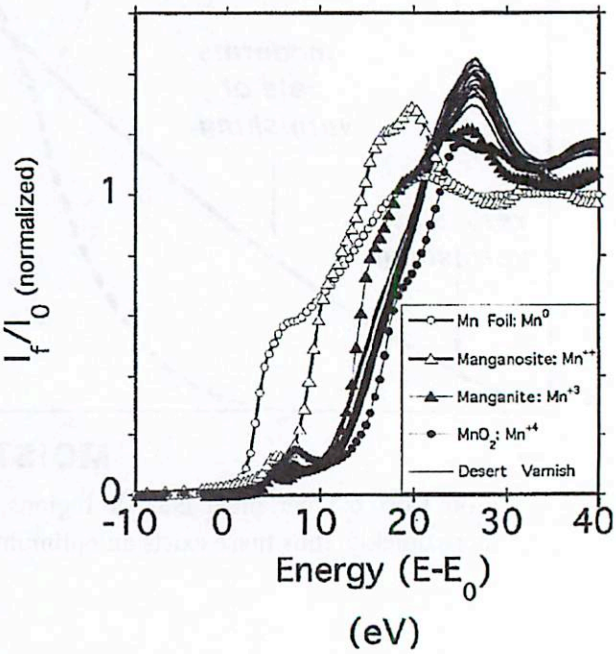


Stereo image from marsroverblog.com

### *Space weathering*

The process of varnish microlamination dating is similar in many ways to astronomers' use of space weathering rates to date surfaces of asteroids and moons. These rates can both be probed using spectroscopy of rock surfaces.





**Left:** From Binzel et al. 2010, space weathering example. The youngest surfaces are in blue and green, oldest are red. **Right:** From McKeown & Post 2001, spectrum of several samples of rock varnish, compared with spectra of various components, to determine mineralogy.

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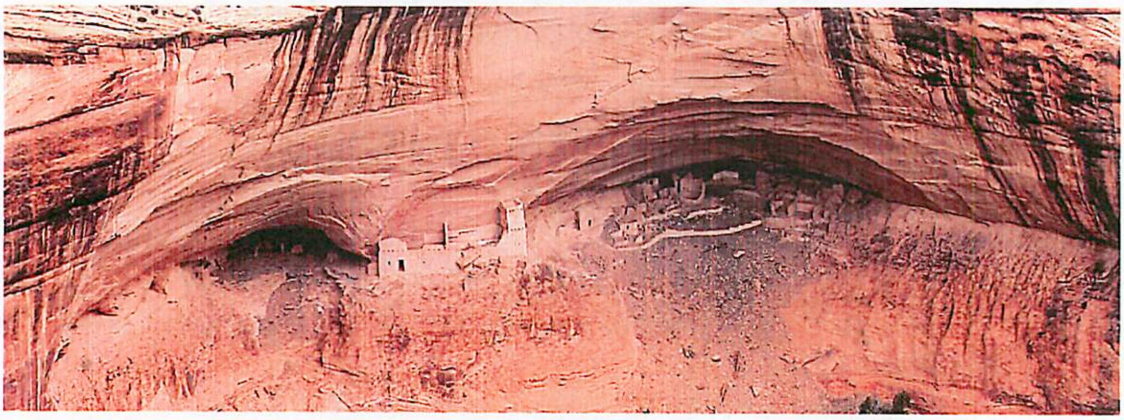
# Anasazi and Navajo Inhabitation of Canyon de Chelly

by Dyer Lytle

for LPL Fall 2011 Fieldtrip

## Anasazi

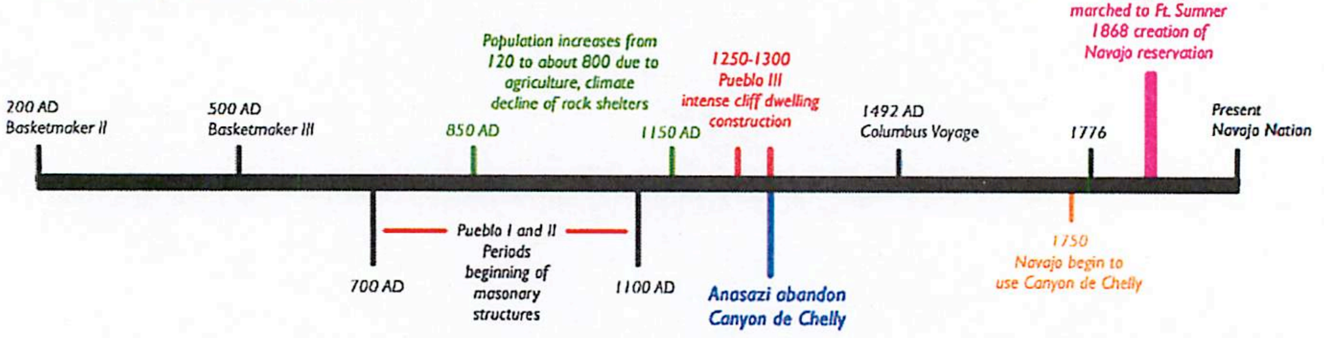
Evidence for inhabitation in Canyon de Chelly begins around 200 AD. Paleo-Indian or Archaic peoples probably used the canyon in earlier times but they left no identifiable remains. Mummy Cave, pictured below, shows evidence for continuous inhabitation from 200 AD until 1300 AD when the Anasazi abandoned the canyon.



*Mummy Cave, in Canyon del Muerto, at Canyon de Chelly National Monument.*

The Basketmaker II (200AD to 500 AD) culture made shelters in the natural caves in the canyon. Basketmaker III (500 AD to 700 AD) people built small pit houses in the canyon bottoms and in canyon wall alcoves. The Basketmakers raised crops of corn and squash using the streams in the canyons for irrigation.

**Timeline for Anazazi and Navajo history in Canyon de Chelly 200 AD to Present**



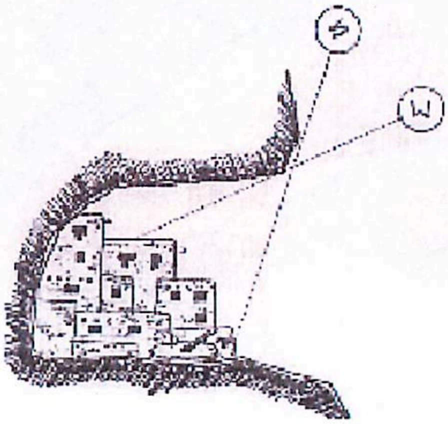
*tséyi' means "canyon" in Navajo*
*This was Hispanicized to de Chelly*

To give a sense of the history of the canyon that has been determined from prehistorical evidence as well as historical records, a timeline is shown above with Anasazi, Navajo, and European events.

**Pit Houses**

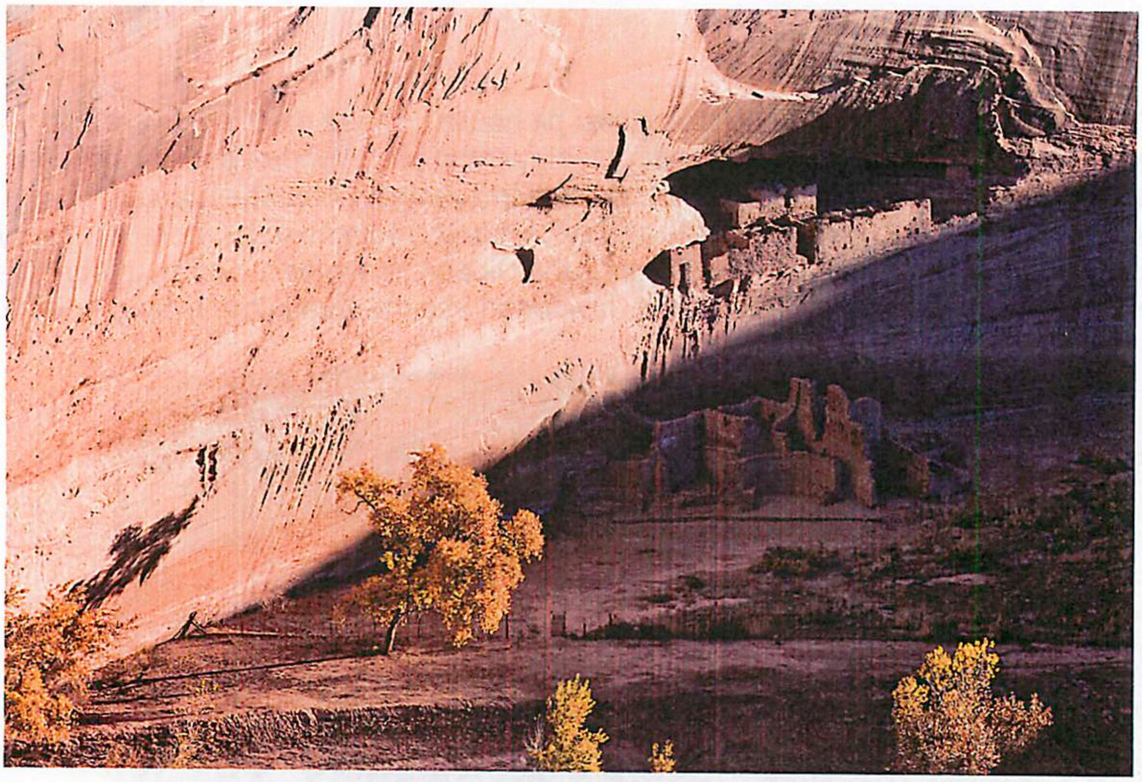
Shown below is a reconstruction of an Anasazi pit house. These dwellings were dug into the ground and then a roof was constructed over the pit. Wooden posts were used to support the roof which was made of wooden beams, smaller branches, and dirt. Many pit houses had two rooms with the second, smaller, room used for storage. Every pit house had a smaller pit in the floor which is the Sipapu, a symbolic entrance from the underworld. The pit-house may have later developed into the kiva in the Pueblo culture.

**Cliff Dwellings**



The later Pueblo I, II, and III cultures used rock to build shelters and later large cliff dwellings and pueblos. During the Pueblo III culture (1250-1300 AD) some of the largest cliff dwellings were constructed. The cliff dwellings were often built on the south wall of the canyon in such a way that they would be shaded from the summer sun but receive the winter sun.

The White House Ruin, to which we'll hike on this fieldtrip, was probably built during the Pueblo II times, around 1200 AD.



*White House Ruin in Canyon de Chelly National Monument*

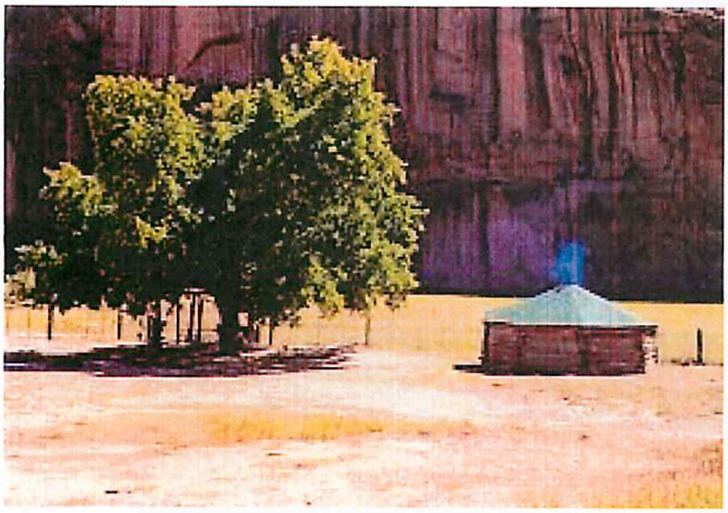
### Rock Art

Petroglyphs and pictographs in Canyon de Chelly record something about the thoughts of the people who lived in the area. Although much of the artwork in the canyon today was done by the Navajo in the last 260 years, there is also earlier work done by the ancestral peoples. The pictographs are painted on the rock, petroglyphs are scratched or chiseled into the rock. Shown on the left is an Anasazi antelope petroglyph.

## Navajo

The Navajo moved into the area of Canyon de Chelly in about 1750 AD. In 1804 a Spanish army troop massacred 150 Navajo men, women, and children at a site now called "Massacre Cave" in Canyon del Muerto. There was warring back and forth between various groups, increasing as the U.S. gained its western territories. Kit Carson and company marched the Navajo off to Fort Sumner in New Mexico in 1863 but they were eventually returned in 1868 when a 3.5 million acre Navajo Reservation was established. The Navajo have remained in the canyons ever since, farming and raising sheep. There are about 40 Navajo families living in the canyon today.

Canyon de Chelly was declared a national monument in 1931 and the arrangement is a particular one. Tribal rights and land ownership are preserved in the monument.

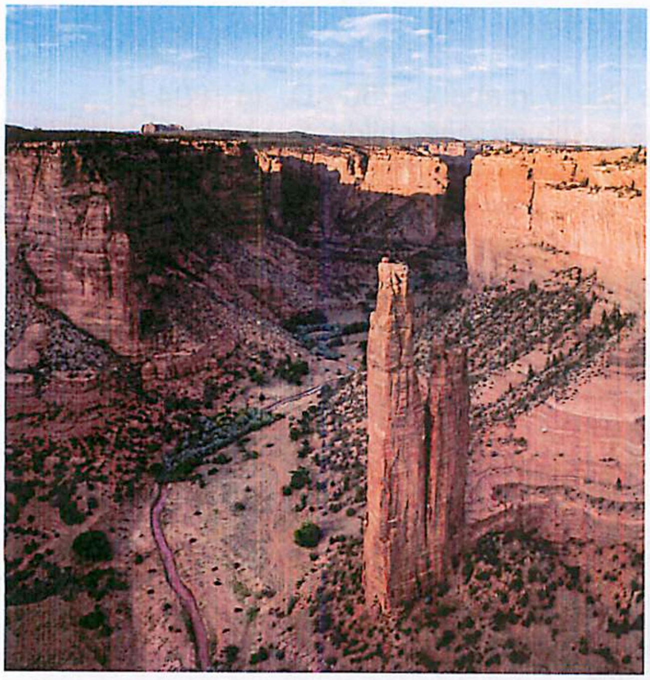


## Hogan

The traditional dwelling used by the Navajo is the Hogan. The religious song "The Blessingway" describes the first hogan as being built by Coyote with help from beavers to be a house for First Man, First Woman, and Talking God. Early hogans were wood and mud cone shaped structures, modern hogans are usually hexagonal with the entrance facing the east to welcome the rising sun.

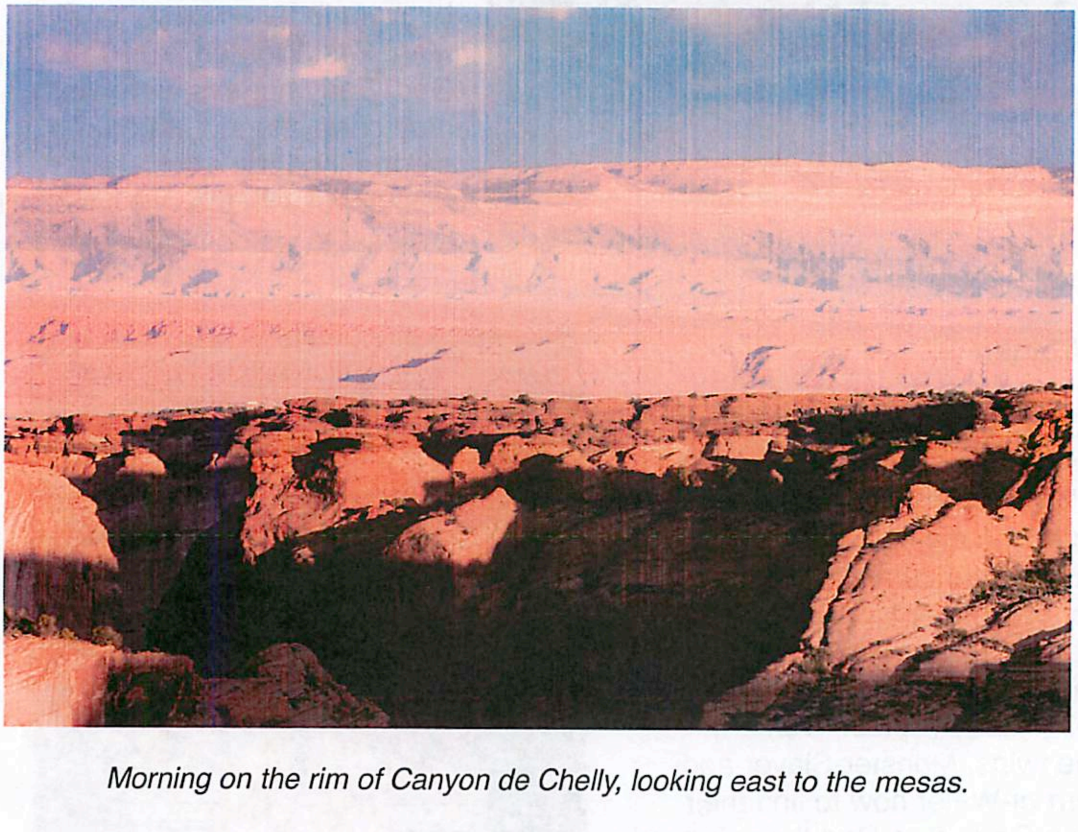
## Spider Woman

One of the overlooks we'll stop at on this fieldtrip is one for Spider Rock on the south side of Canyon de Chelly. In Navajo creation mythology, as in various other Native American tribal mythologies, is the story of Spider Woman and she lives on top of Spider Rock. When the Navajo emerged into the forth world, Na'ashjéii asdzáá (Spider Woman), taught the twins, Monster-Slayer and Child-Born-of-Water how to find their father, Sun-God. Sun-God then showed them how to destroy all the monsters on the land and in the water. For this,



Spider Woman is considered a highly honored deity. Spider Woman chose the top of Spider Rock for her home and she taught the Navajo the art of weaving. Her husband, Spider Man, built the looms. Left: Spider Rock in Canyon de Chelly.

Stories are told by Navajo parents to their children that if they do not behave, Spider Woman will let down her web-ladder and carry them up to her home and devour them. Some of the white rock on top of Spider Rock is said to be these children's bones. On the other hand, Spider Woman sometimes helps peaceful Navajo youths when they are in trouble.



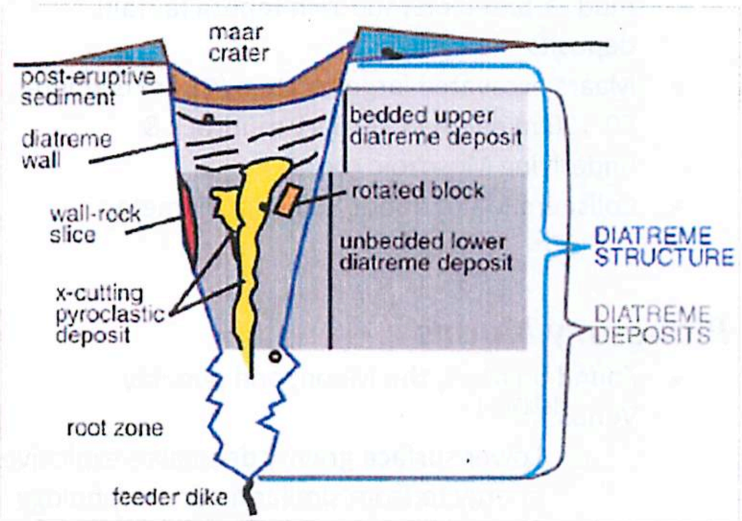
*Morning on the rim of Canyon de Chelly, looking east to the mesas.*

# *Maars*

Sarah Morrison

## *General Characteristics*[1]

- Volcanic explosion crater cut into the country rock
- Typically caused by **phreatic** eruptions—volatiles (water) contacting hot rock/magma=**fluid-coolant interaction (FCI)** & explosion
- Maars (on Earth) often have or had lakes in the crater shortly following the eruption given the nature of the eruption and its interaction with the water table →subsequent modification by aqueous/lacustrine processes
- Because of the association of maars and diatremes, maar deposits are often rich with xenoliths (deep seated rock fragments)—a way to study the Earth's interior



Cross-section of maar-diatreme volcano. From [1].

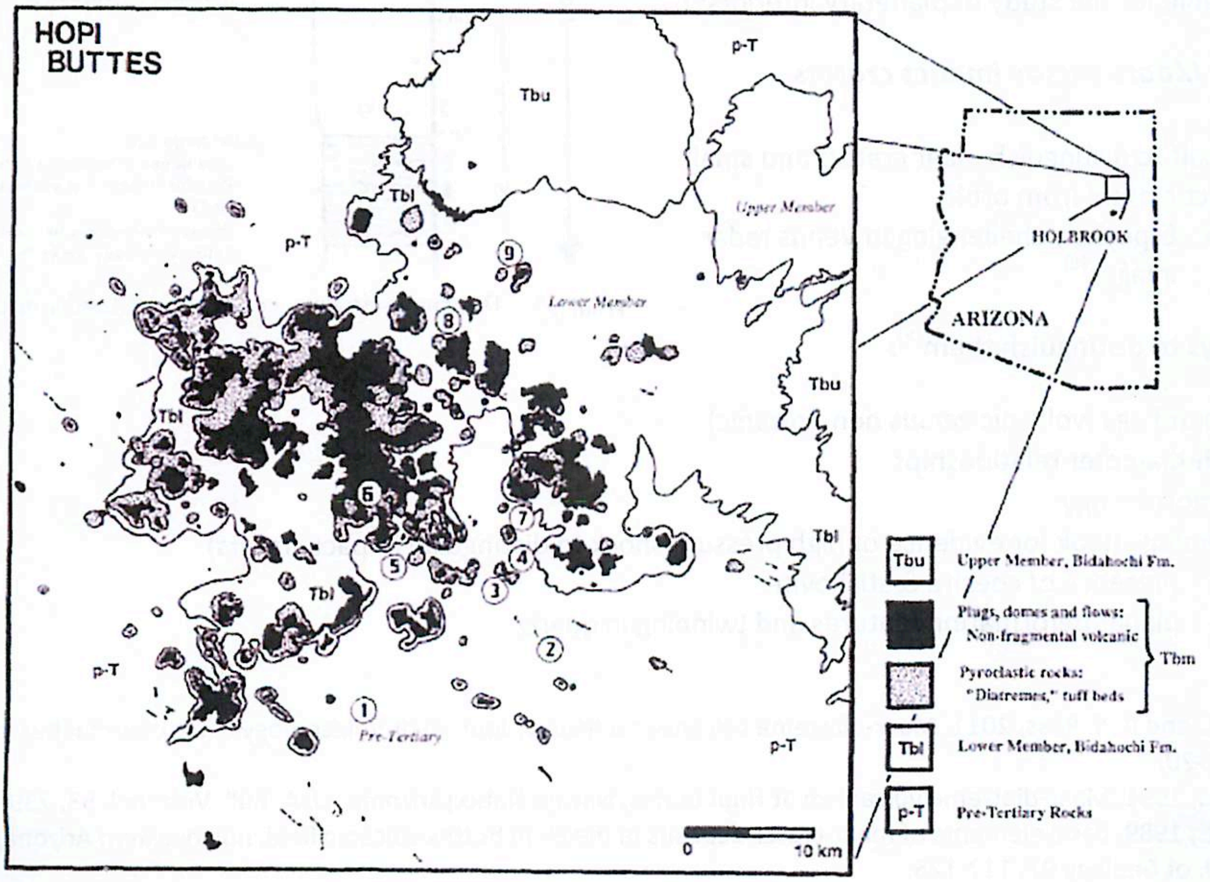
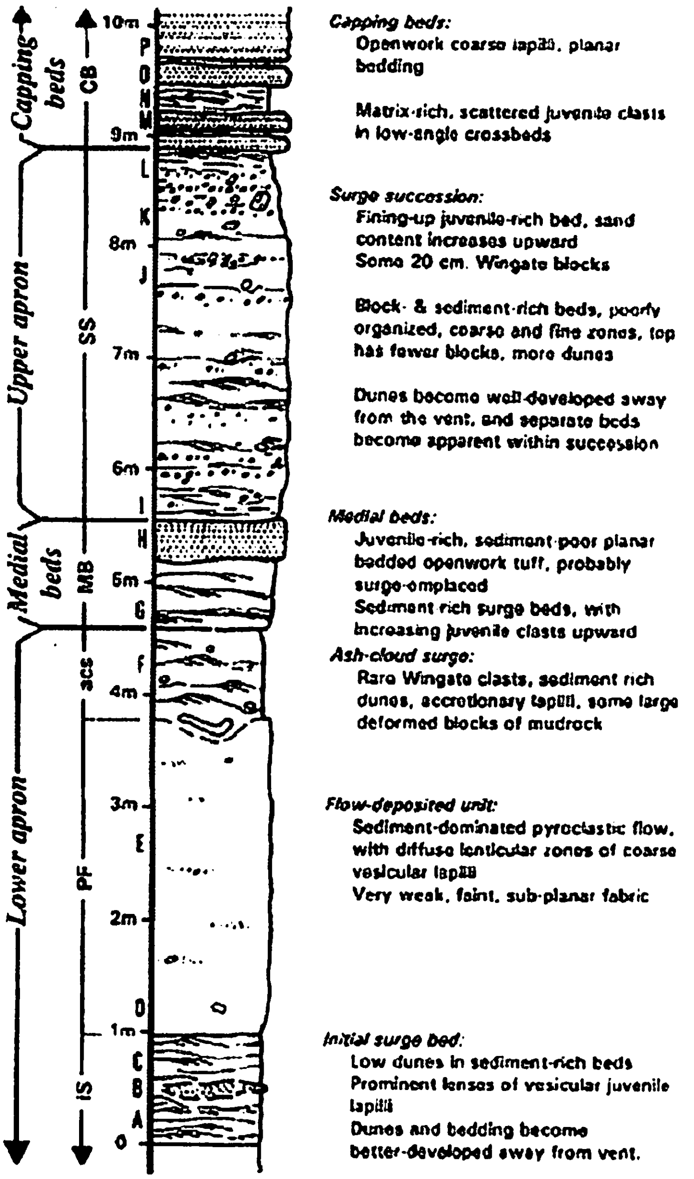


**Fig. 1.** Index map of the Hopi Buttes volcanic field (drawn after Cooley et al. 1969). Marked vents are: (*1*) Standing Rocks vents; (*2*) Round Butte; (*3* and *4*) Hoskietso Claim vents; (*5*) Coliseum vent; (*6*) Crazy Waters vents - Tse Gis Toh, Doh Halian; (*7*) Bidahochi Butte; (*8*) Teshim Butte and Teshim maar; (*9*) White Cone vent From [2].

## *Maars in the Hopi Volcanic Field*[2,3]

- 100s of maars formed here in the Mio-Pliocene (2.6-12 Ma ago)
- Thought to have been formed from phreatomagmatic eruptions involving rising magma interacting with wet, unconsolidated mud → based on mud-rich tephra (airfall) deposits
- Maars excavated larger craters (~1 km diameter, 50-150 m deep) in Tertiary mudrock & underlying Mesozoic rocks
- Coliseum Maar: about 800 m in diameter



From [2]. Diagram illustrating stratigraphy of Teshim maar apron

## *Planetary Maars*

- Found on Mars, the Moon, and possibly Venus[4],[5],[6]
  - Lower surface gravity decreases explosive energy to from similar maar morphology
    - May not necessarily need large amount of volatiles for FCI
- For surface missions: xenoliths would be valuable for the study of planetary interiors[7]

***Caveat: Maars versus impact craters***

- Difficult to distinguish maar craters and small impact craters from orbit
  - Especially challenging in Venus radar images[6]

**Possible ways to distinguish them[8]:**

- Surroundings (volcanic versus non-volcanic)
- Depth-diameter relationships
- Rim morphology
- Mineralogy (look for evidence of high pressure shock to distinguish impact craters)
  - presence of coesite & stishovite
  - planar deformation features and twinning in quartz

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# Late Stage Volcanism on the Colorado Plateau

Pablo Espinoza

## 1. Colorado Plateau

The Colorado Plateau (CP) is a tectonic block of continental crust characterized by a 3-5 km thick section of Phanerozoic sedimentary rocks. These lies above igneous and metamorphic rocks with crystallization ages ranging from 1.69 to 1.79 Gyr. The CP has remained stable during Phanerozoic time, with the exception of a contractional deformation (75-40 Myr) and extensional deformation during Paleogene time along its western and southern perimeters. On the other hand, tectonic regions next to the CP (Basin and Range, central Rocky Mountains) have gone through important orogenic and magmatic activity throughout much of the Cenozoic time [1]. Its extension is shown in Fig.1.

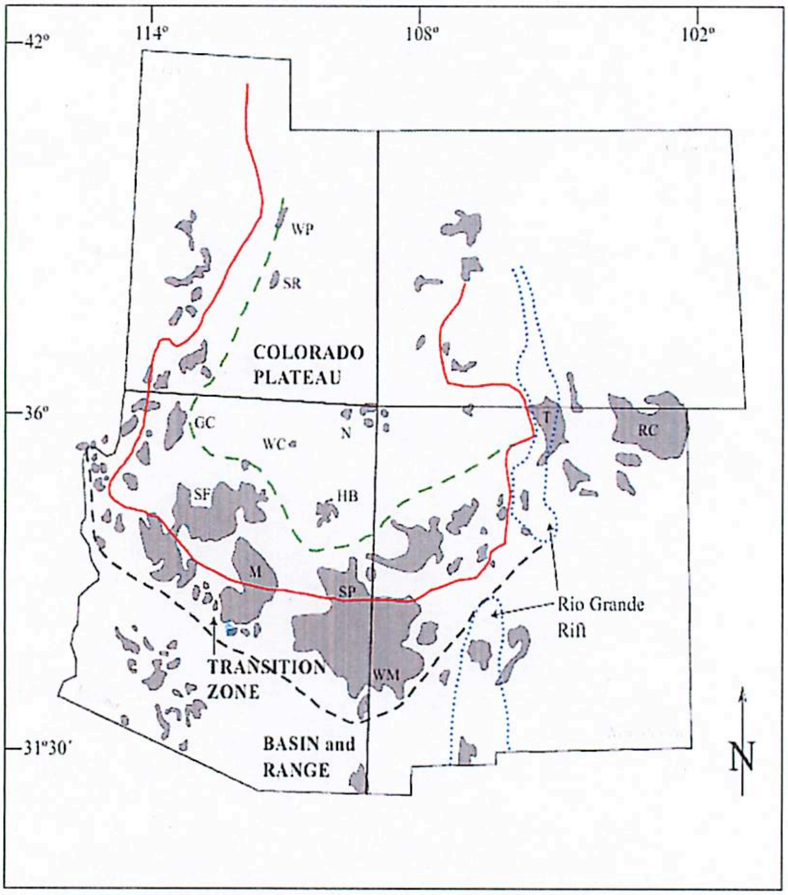

FIG 1. Cenozoic volcanic centers in the Southwest. The CP boundary is given by the red line. Dashed green and black line represent the geophysical boundaries of the CP, and Basin and Range, respectively. [2]

## 2. Recent Volcanism

While the interior of the CP remained quiescent, the situation was quite different in its western boundary. Spatial patterns and ages of volcanoes suggest that magmatism has migrated eastward, following an eastward progression in active faulting. During the last Neogene time (10 Myr), it's been suggested that this faulting is responsible for the elevation of the CP (~2 km above the sea level) [1].

- 17.5 - 5 Myr: Alkaline Magmatic activity at volcanic fields of
  - San Francisco
  - Mormon Mountain
  - White Mountain
  - Springerville
  - Mount Taylor
- 7.8 - 6.8 Myr: (the most volumetrically significant volcanic activity on the geophysical CP during late Neogene time)
  - Hopi Buttes volcanic field [2]

## 3. Hopi Buttes Volcanic Field

Hopi Buttes is a volcanic field located in northeastern Arizona (See Fig. 2). The volcanic field consists of about 300 Miocene maars and diatremes in an area of 965 square miles.

The most successful model proposed to explain the origin of the maars and diatremes suggests that they result from phreatic explosions caused by magma coming in contact with water saturated rock under a lake. Early studies of this area argued for eruption into late Miocene-Pliocene (6-4 million years old) Lake Bidahochi but it's been shown that, at least in some vents, there was no surface water present at the time of eruption and the phreatomagmatic activity resulted from the interaction of melt with mud, rather than with water [2].

Vents in the eastern part of the Hopi field preserve surficial maar deposits while vents in the western part preserve the sub-volcanic plumbing system or diatreme (see Fig. 3). The maars formed through explosive interaction of ground water, liquefied lower Bidahochi sediments, and/or lake water with monchiquitic and nephelinitic magmas. The ratio of water to magma during the eruptions may have controlled the type of landform produced [2].

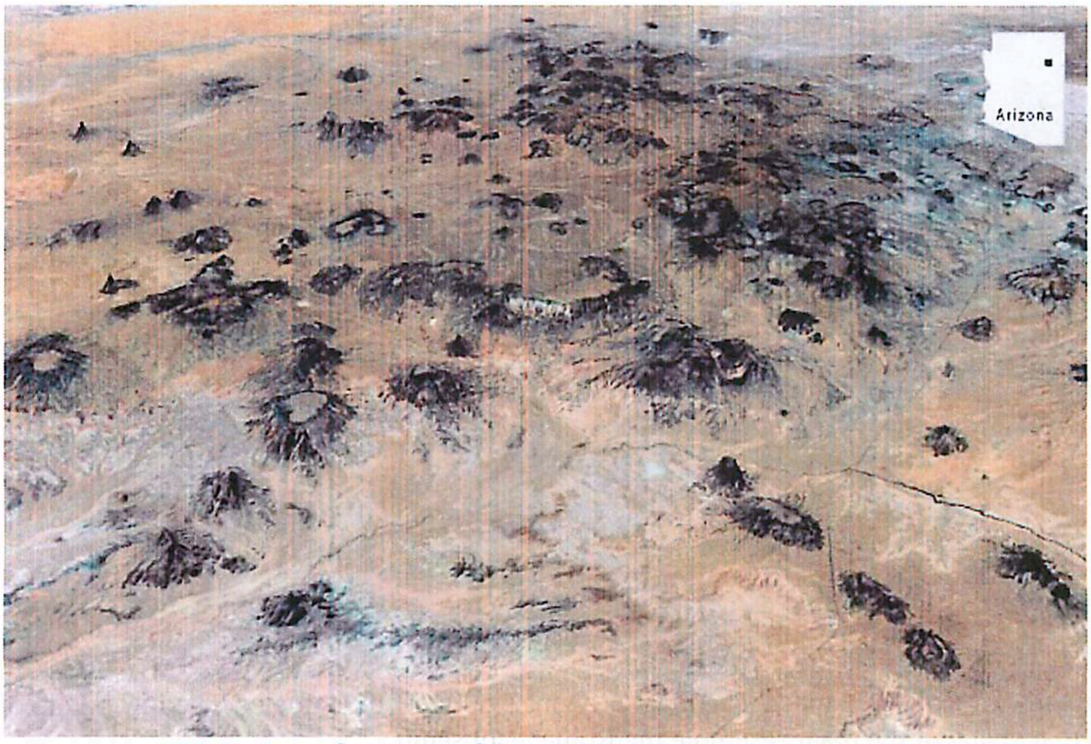

FIG 2. Central portion of the Hopi Buttes Volcanic Field [3]

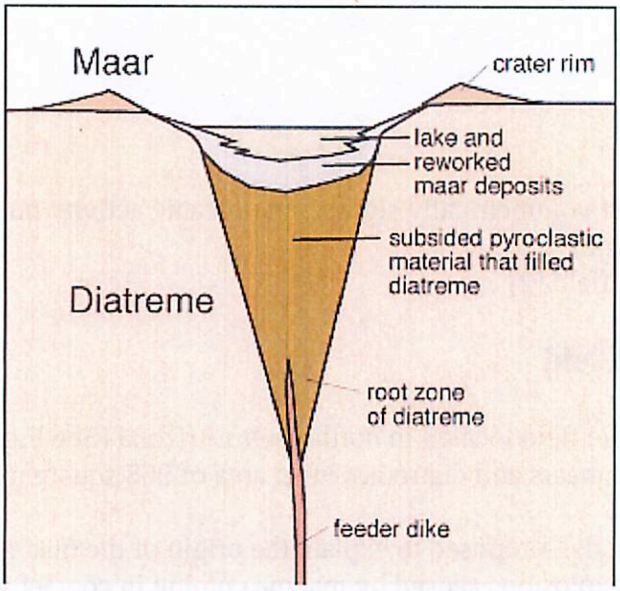

FIG 3. The maars are volcanic cones that form from phreatic explosions. The diatremes are subsurface pipes that fed the maars and were filled by volcanic material at the time of the eruption. They are now exposed because of erosion. Most of the maars and diatremes at Hopi Buttes formed between 8.5 and 6 Myr ago. The youngest volcanoes are 4.2 Myr old [4].

## 4. Phreatomagmatism

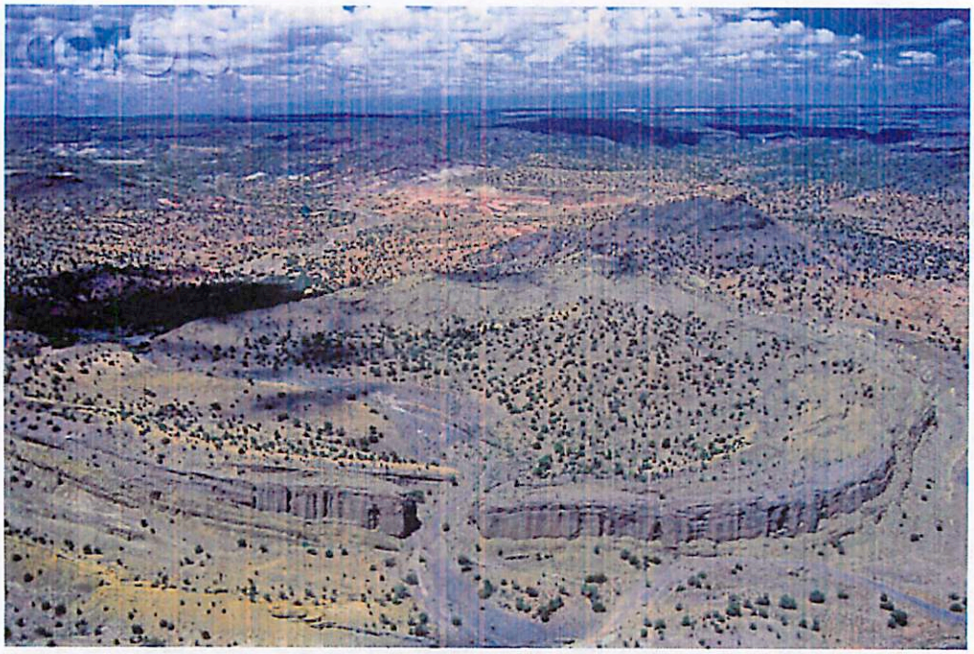

FIG 4. Aerial view of Coliseum maar. The maar is about 2,600 feet in diameter. The inward dip of the beds and circular shape of the maar resemble the Roman Coliseum (http://www.corbisimages.com/stock-photo/rights-managed/42-23930370/).

This reaction occurs during the interaction between molten material (fuel) and external (non-magmatic) water (coolant) in a process known as Molten Fuel-Coolant Interactions, or MFCIs. The process in 4 steps [1]:

- hydrodynamic premixing of water and melt under stable film boiling conditions;
- quasi-coherent quantitative vapor film collapse in the premix leading to direct contact between melt and water;
- fine fragmentation of melt and rapid increase of heat transfer in a positive feedback mechanism;
- system expansion and generation of superheated steam.

The type of maar volcano created is controlled by water/magma ratios during the eruption; maars are produced at low ratios, tuff rings and tuff cones result from high ratios [2].

## References

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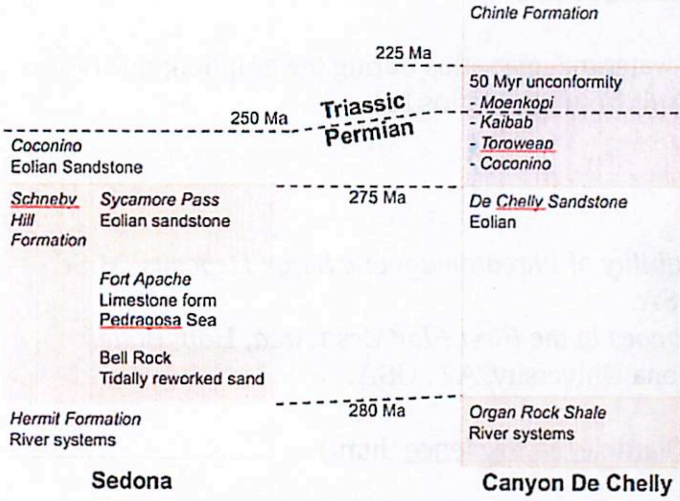
[3] *The Hopi Buttes Volcanic Field,* (http://www.azgs.az.gov/arizona_geology/spring10/article_earthscience .html)
[4] *Coliseum Maar, Hopi Buttes, Arizona,* (http://volcano.oregonstate.edu/vwdocs/volc_images/north_america/coliseum_maar.html)

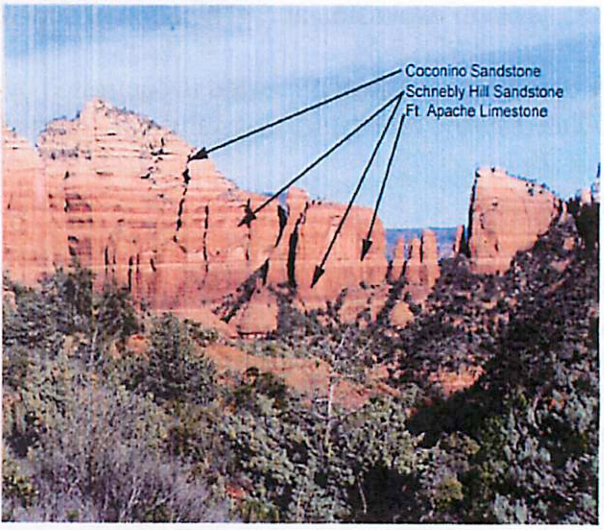
# Oak Creek Canyon and Sedona Stratigraphy

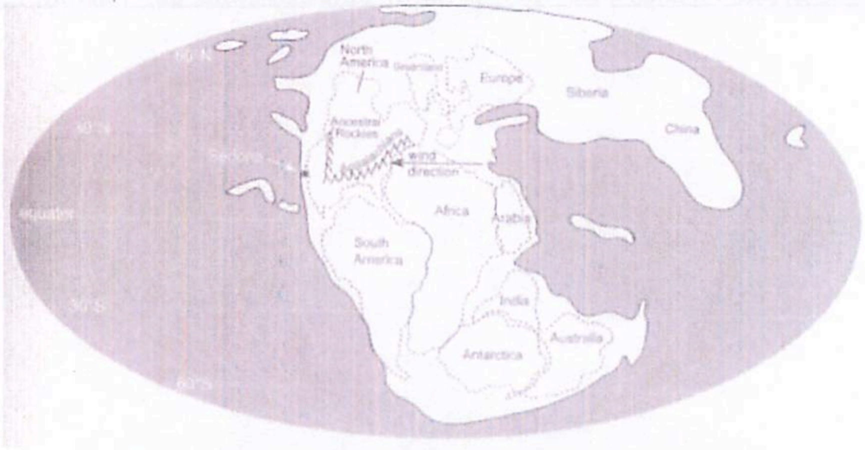
Shane Byrne

Rock units exposed at Sedona are mostly contemporaneous with those at Canyon De Chelly. But…

- The sequence ends at the Coconino Sandstone (late Permian)
- There's no major unconformity
- Materials are similar, but depositional environment differed





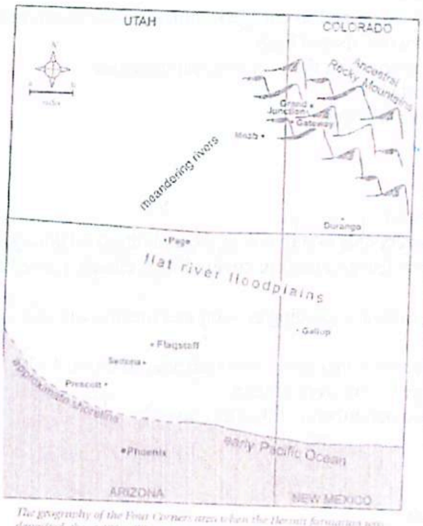


*From 'Geology underfoot in northern Arizona.'*

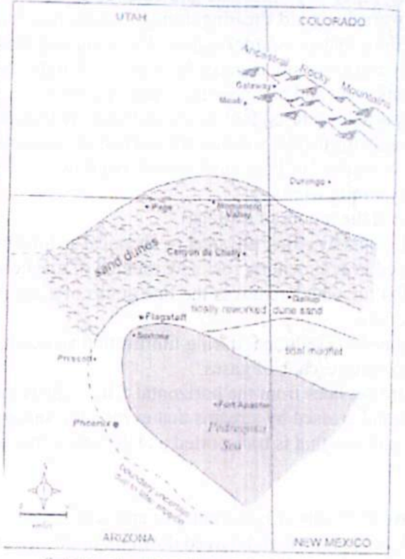
Canyon De Chelly was in the interior of Pangaea whereas Sedona was on the coast. The Ancestral Rockies dominated sediment production in the late Permian. Material was transported from the northeast.

- River plains form both the Organ Rock and Hermit shales.
  - Fine-grained flood plain deposits and coarser riverbed deposits
- Dunes were later mobilized to form the De Chelly sandstone.
  - Containing high-angle cross beds
- At Sedona the dunes were periodically washed flat in a tidal zone (Bell rock member)

    - Tidal swash creates low-angle crossbeds
    - Grains still frosted indicating they were delivered here by the wind
- Sea level rose a little (enough to inundate Sedona, but not Canyon De Chelly) forming the Fort Apache limestone.
    - Highstand of Pedregosa sea barely reached Sedona
- Sea level retreats (apart from occasional excursions) so that Sycamore pass member is deposited as an eolian unit.
    - Interbedded high and low-angle crossbedding
- Coconino Sandstone comes next.
    - Lack of iron oxide staining gives this unit a blond color



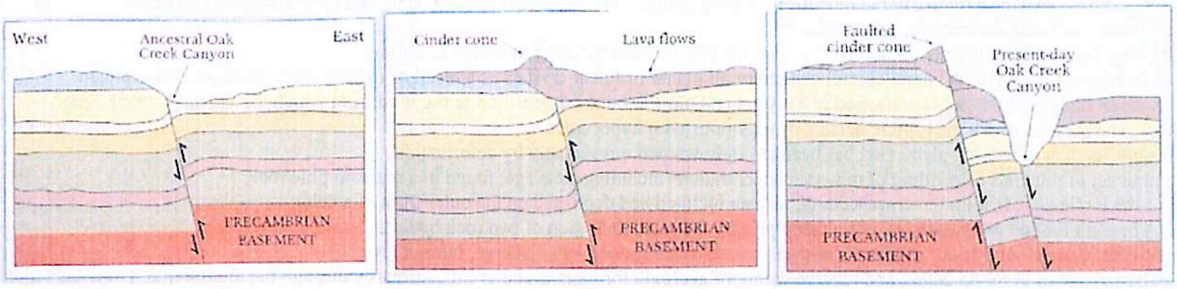
*The geography of the Four Corners area when the Hermit formation was deposited about 280 million years ago. At that time, Sedona lay near the terminus of rivers that drained off the Ancestral Rockies.*



*The Sedona area lay at the edge of the Pedregosa Sea [illegible] million years ago. Sand dunes covered the low-lying land to the north.*

*From 'Geology underfoot in northern Arizona.'*

## Formation of Oak Creek Canyon



*From 'Hiking the Southwest's Geology'*

- Oak creek fault is thrust up during Laramide-era compression (east side moves up)
- Higher east side layers are worn down, ancestral Oak Creek forms
- Ancestral Oak Creek Canyon filled with lava 6-8 Myr ago by at least 5 flows.
- Oak Creek fault reactivated under regional extension (part of the basin and range forming episode). Normal fault drops the east side.
- Mogollon Rim continues to retreat through basin and range extension ~0.5m/Kyr

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 gulley 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 – 10000 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 to 3480 kilometers. 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 to 20,000 kilometers 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 to 2 millimeters 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 to 10 centimeters/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 sinking oceanic 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.
Till: 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 percent (often less than 0.001 percent).
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 percent 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 sand-blasting 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 "bread-crust" surface.
Volcanic breccia: A pyroclastic rock in which all fragments are more than 2 millimeters 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.