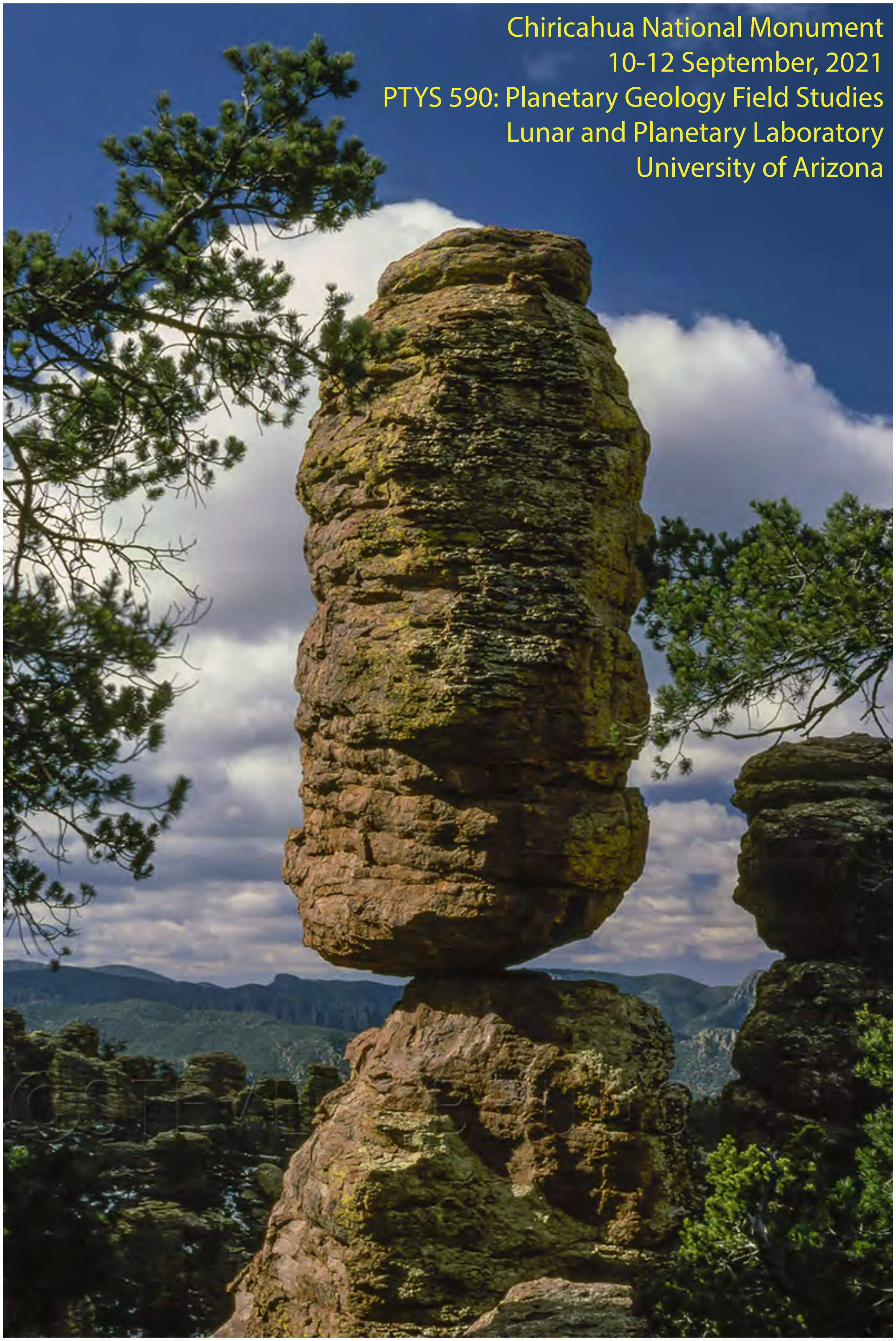
Chiricahua National Monument



Chiricahua Mountains, San Bernardino Volcanic Field, and Willcox Playa

Table of Contents

Fall 2021 Field Trip itinerary

Day 1 (Friday, September 10). Meet at the LPL loading dock at 7:00 am and depart at 8:00 am

Stop 1: Triangle Ranch, Texas Canyon. We will arrive at the ranch around 10:00 am and will take time to explore the natural rock formations and Native American rock carvings. Hiking Difficulty: Easy.

Stop 2: Willcox Playa. After having lunch at the ranch, will drive to Wilcox Playa around 12:30 pm, and arrive at our second stop at 1:00 pm. To avoid the most intense heat of the day, the stop will be short (around 30 minutes). Hiking Difficulty: Easy.

Stop 3. Fort Bowie. We will arrive at the trail head to Fort Bowie around 3:00 pm. It is a short (1.5 mile) hike on flat ground to site and in the afternoon, it will be warm, but not too hot. The walk itself will take about an hour, but we should plan to be back at the vehicles no later than 5:00 pm. Hiking Difficulty: Moderate.

Camping.

Day 2 (Saturday, September 11). To avoid hiking during peak sun hours. We will leave the camp site at 7:30 am. It is up to each student to gauge how much time they will need in the morning.

Stop 1. Chiricuhua National Monument–"Massai Point". We will stop at the overlook in the morning, and time permitting, walk the 30-minute loop trail. Hiking Difficulty: Easy.

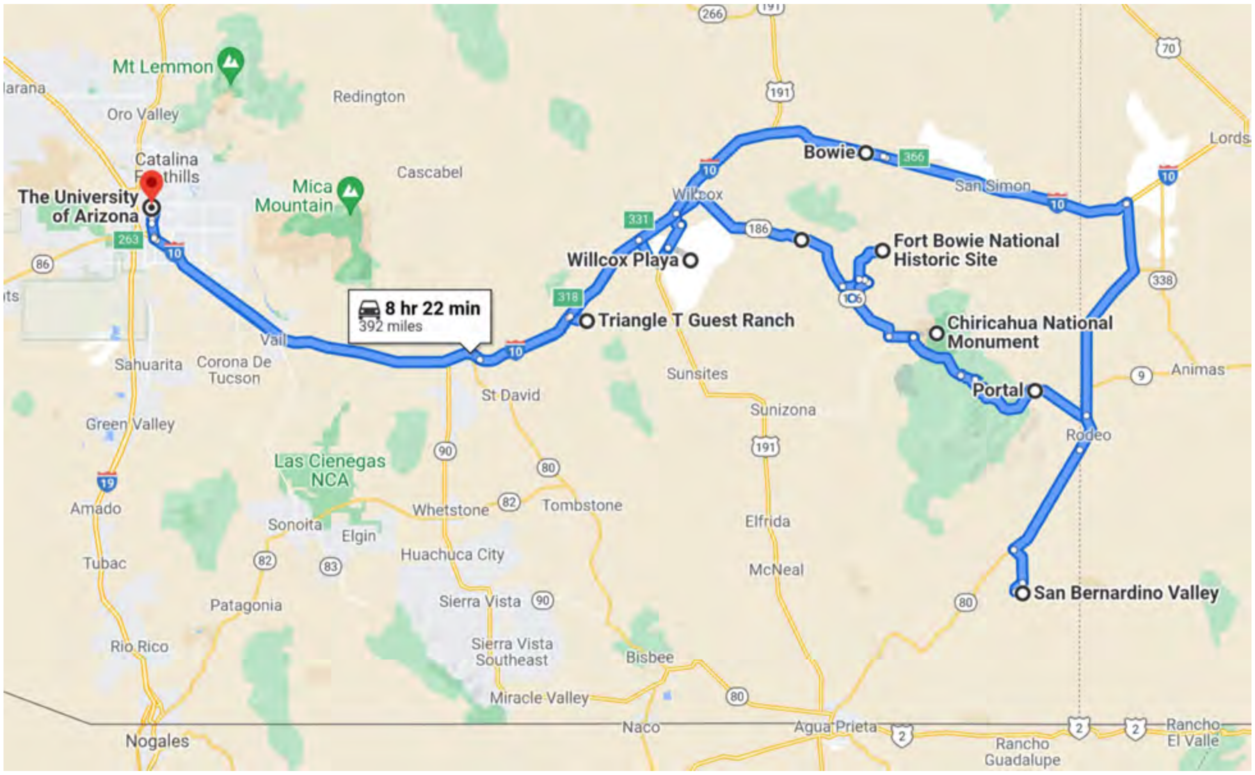
Stop 2. Chiricuhua National Monument–"Echo Canyon Trail". We will embark, no later than 9:00 am on the Echo Canyon loop trail. The hike includes 1000” of elevation change and a length of 2 miles. The first and final thirds of the trail are protected from the sun, but the middle third is exposed. We will aim to be back at the vehicles by 12:30 pm and have lunch in a shady area, but bring lunch with you just incase you get Hungary given the early start in the morning. Hiking Difficulty: Moderate

Stop 3. Chiricuhua National Monument–"Sugarloaf". At around 2:30 pm we will begin the hike to Sugarloaf. This hike has 500” of elevation gain and a length of 1.5 miles. We will aim to be back to the vehicles by about 4:30 pm. Hiking Difficulty: Moderate.

Camping

Day 3 (Sunday, September 12). To avoid hiking during peak sun hours. We will leave the camp site at 7:30 am. It is up to each student to gauge how much time they will need in the morning.

Stops 1 and 2. The San Bernadeno Volcanic Field. We will make two stops in the San Bernadeno Volcanic field to example scoria cones and maar craters. Then depart back to Tucson around 2:00 pm with the goal of returning to the University of Arizona by 6:00 pm.



Route Plan.

Documents. Operating in Southern Arizona, it is possible that our group may be stopped by Border Patrol. Please consider the following guidelines:

"No documentation is required at a Border Patrol checkpoint for US citizens; however, lawful permanent residents (LPRs) are required to carry their registration cards (green cards) "at all times" according to federal law. People in a non-immigrant status should carry proper documentation. If you are an international student, You are not required to request a travel signature if you are traveling within the U.S. (including Alaska and Hawaii), however, you must carry your original immigration documents (I-20/DS-2019, passport and I-94) at all times. A driver's license, state ID and CatCard do not verify your lawful immigration status within the U.S. All students should also carry a copy of their UAccess class schedule showing full-time enrollment, including at least one in-person or flex in-person class.

Weather. Weather conditions are highly variable, but are currently predicted to be as follows:

Fri 10	87°/61°	Sunny	11%	E 7 mph
Sat 11	87°/61°	Mostly Sunny	0%	N 7 mph
Sun 12	87°/60°	Mostly Sunny	3%	ENE 7 mph

General driving directions

Kuiper → Triangle Ranch at Texas Canyon

Exit the campus and drive south on Campbell/Kino for 4.7 miles, enter I-10 E. Drive ~50 miles east and take exit 318 to Dragoon Road. Turn left onto Triangle T Road.

Triangle Ranch at Texas Canyon → Willcox Playa

I-10 route: Get back on I-10 E. Take exit 331 to US-191 S.

Dragoon Road route: Keep driving East on Dragoon Road. Turn left onto US-191 N.

Willcox Playa → Fort Bowie

I-10 route: Get back on I-10 E and drive for ~32 miles. Take exit 362 and drive south on S Apache Road / Apache Pass Road for ~15 miles.

Fort Bowie → Portal (general campsite area)

Keep driving east on I-10. Take exit 5 to NM-80 S. Turn right onto NM-533 / Portal Road. Turn left onto 42 Forest Road (turns into Pinery Canyon Road).

Portal (general campsite area) → Chiricahua National Monument visitor center

Drive West Pinery Canyon Road. Turn right onto E Bonita Canyon Road. Follow this road to the visitor center.

general campsite area → San Bernardino valley

Get back on Portal Road. Drive east on Portal Road towards highway 80. Turn right onto NM-80 S (turns into AZ-80 W). Turn left after ~20 miles towards the San Bernardino valley.

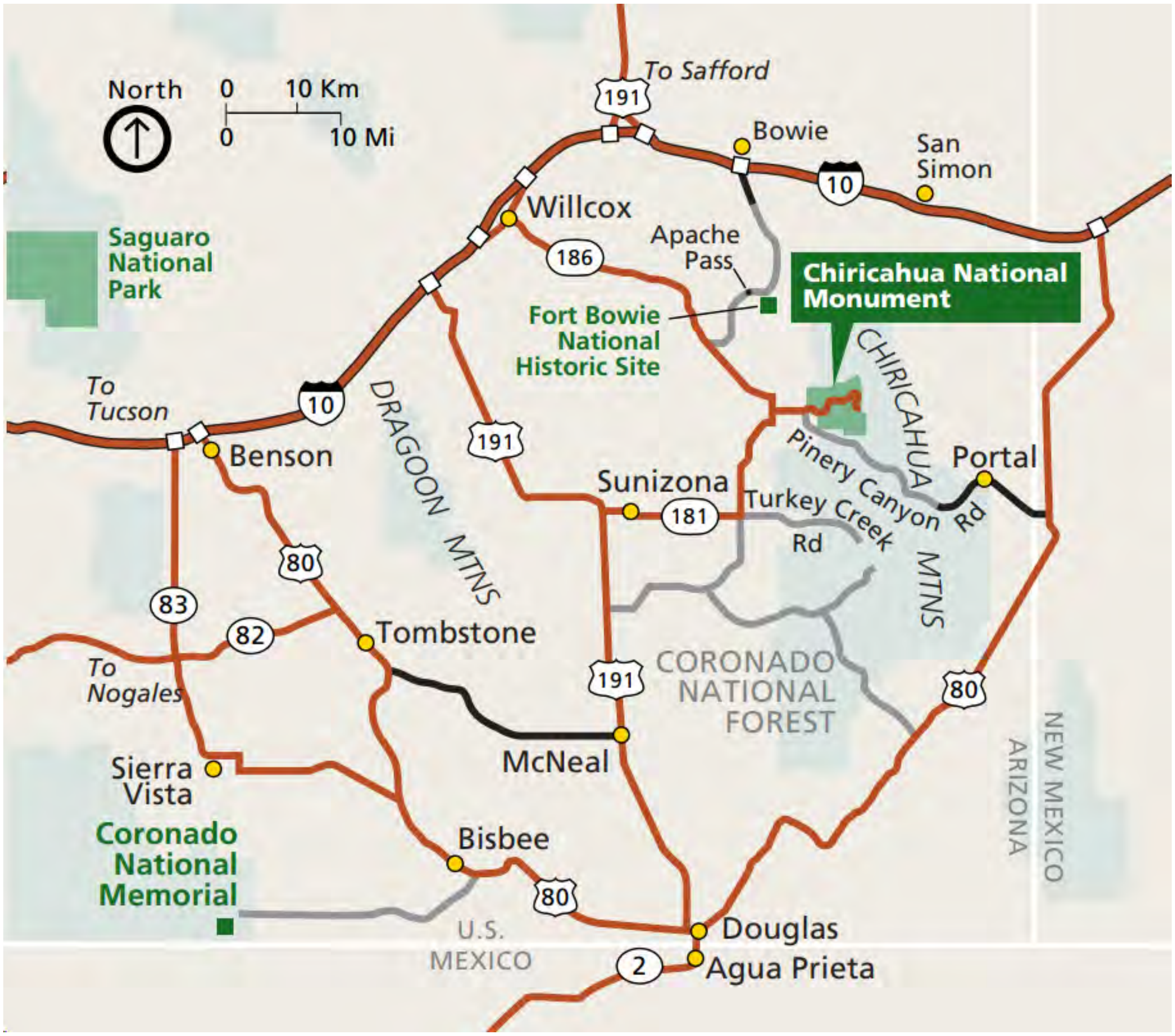
San Bernardino valley → Kuiper

Take AZ-80 E and NM-80 N to I-10 W. Drive towards Tucson on I-10 W. Take exit 263 to Campbell/ Kino.

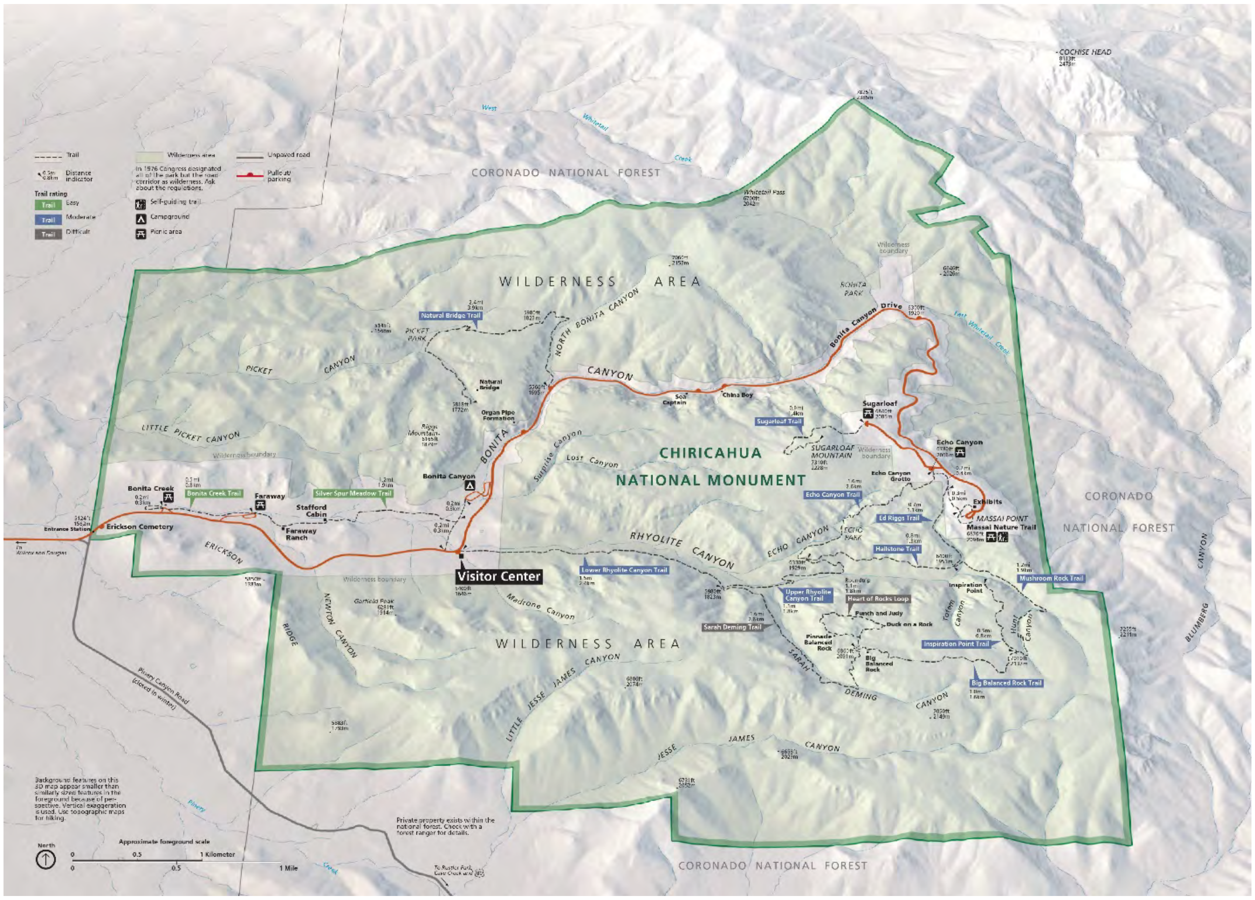
List of talks (tentative)

Texas canyon, Willcox Playa, and Fort Bowie	
Native people: Apache nation	Robert Melikyan
Spheroidal Weathering	Sam Moruzzi
Playas and Southwestern Climate History	Michael Daniel
Desiccation Polygons	Indujaa Ganesh
Flora and Fauna	Reed Spurling
Chiricahua National Monument	
Southern Arizona geologic overview	Tyler Meng
Turkey Creek & Portal Caldera Eruptions & Tuff	Michael Christoffersen
Joints and Hoodoos	Harry Tang
Arizona's Copper Deposits	Weigang Liang
Climate Change and Environmental Instability in the Chiricahuas	Nathan Hadland
San Bernardino Volcanic Field	
History of San Bernardino Volcanism	Joana Voigt
Maar Volcanoes	Mackenzie Mills
Mantle Xenoliths	Rishi Chandra
Alluvial fans	Rowan Huang
The 1887 Sonora Earthquake	Patrick O'Brien

Maps

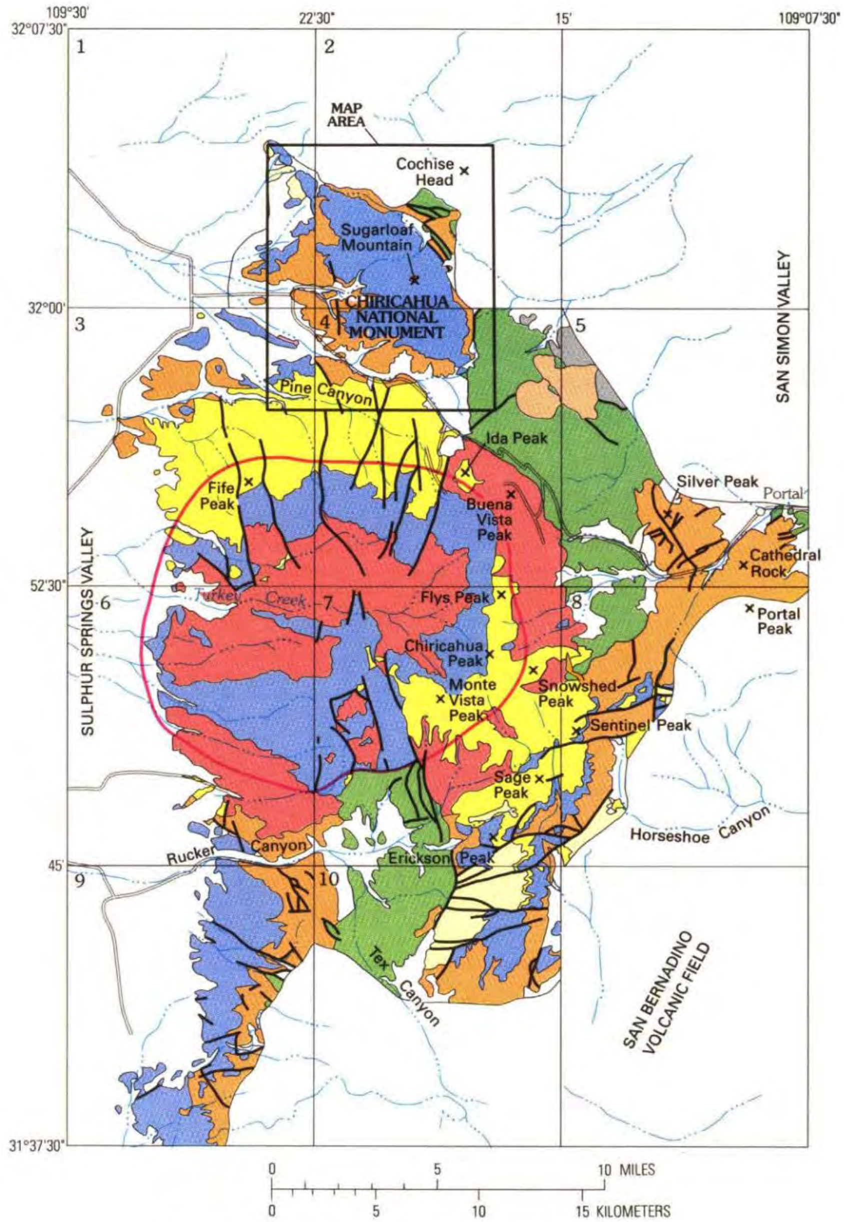


Source: National Park Service (https://www.nps.gov/chir/planyourvisit/maps.htm)



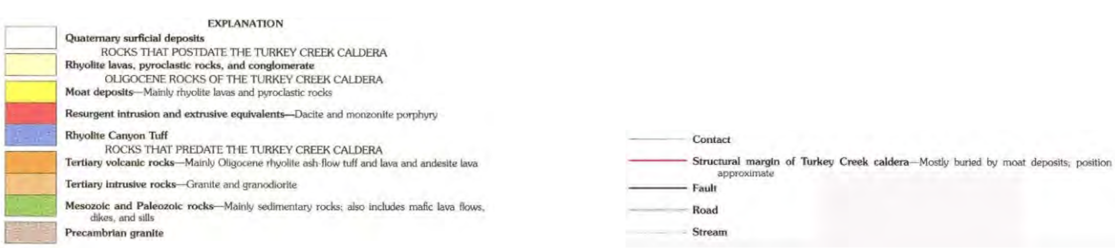
Source: National Park Service (https://www.nps.gov/chir/planyourvisit/maps.htm)

Geologic Maps of the Chiricahua Mountains

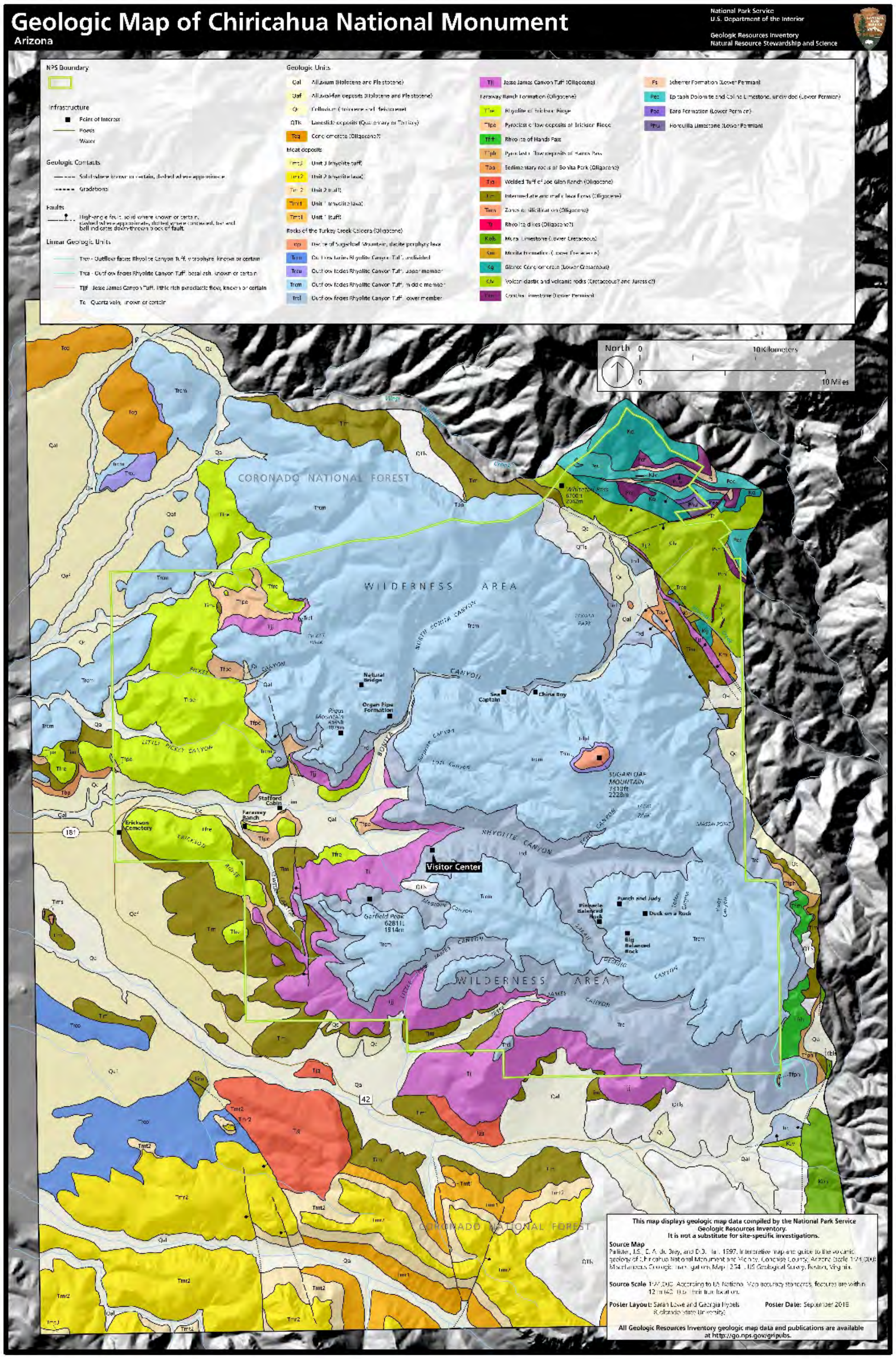


GEOLOGIC INDEX MAP OF THE CHIRICAHUA MOUNTAINS

[(Simplified from *Geologic map of the Turkey Creek caldera* (du Bray and others, in press)]



Source: USGS (https://doi.org/10.3133/i2541)



Source: National Park Service

ftcreature

Children, this is dirt.

dirt?dirt? dirt?dirt? dirt?dirt? dirt? dirt? dirt? dirt? dirt?

wild-west-wind

A geology field trip

Flora and Fauna

Most important concept: **sky islands**

Sky islands are ecologically isolated mountainous areas typically surrounded by desert. They are generally cooler and wetter than the land that surrounds them, and they are home to many endemic species.

A fine example of a sky island (in fact the first mountain range to be called such) is the Chiricahua Mountains:

Photo credit: BAlvarius

A Sandhill Crane (*Antigone canadensis*) above Willcox Playa:

Photo credit: Glenn Seplak

A Chiricahua Leopard Frog (*Rana chiricahuensis*):

Photo credit: Gary Nafis

A Banded Rock Rattlesnake (*Crotalus lepidus klauberi*), one of many rattlesnake species in the area:

Photo credit: Michael Price

An Arizona Striped Whiptail (*Aspidoscelis arizonae)*
in Willcox Playa:

Photo credit: Larry Jones

A Yaqui Chub (*Gila purpurea*), one of numerous vulnerable/endangered species of minnow formerly abundant in the San Bernardino watershed:

Photo credit: inthecurrent.org

A Phoenix Talussnail (*Maricopella allynsmithi*):

Photo credit: Nick D. Waters

A pallid bat (*Antrozous pallidus*):

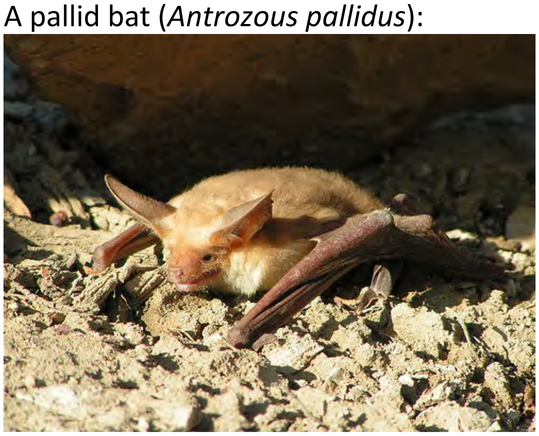


Photo credit: Keaton Wilson

Further reading on the Sky Islands:

(Many of the authors here are from the University of Arizona. Laura Marshall and Greg Barron-Gafford are especially good people to talk to about the Sky Islands)

Barton, A. M., & Poulos, H. M. (2018). Pine vs. oaks revisited: Conversion of Madrean pine-oak forest to oak shrubland after high-severity wildfire in the Sky Islands of Arizona. *Forest Ecology and Management*, *414*, 28–40.

Coe, S. J., Finch, D. M., & Friggens, M. M. (2012). *An assessment of climate change and the vulnerability of wildlife in the Sky Islands of the Southwest* (RMRS-GTR-273; p. RMRS-GTR-273). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Iniguez, J. M., Swetnam, T. W., & Baisan, C. H. (2016). Fire history and moisture influences on historical forest age structure in the sky islands of southern Arizona, USA. *Journal of Biogeography*, *43*(1), 85–95.

Margolis, E. Q., Swetnam, T. W., & Allen, C. D. (2011). Historical Stand-Replacing Fire in Upper Montane Forests of the Madrean Sky Islands and Mogollon Plateau, Southwestern USA. *Fire Ecology*, *7*(3), 88–107.

Pelletier, J. D., Barron-Gafford, G. A., Breshears, D. D., Brooks, P. D., Chorover, J., Durcik, M., Harman, C. J., Huxman, T. E., Lohse, K. A., Lybrand, R., Meixner, T., McIntosh, J. C., Papuga, S. A., Rasmussen, C., Schaap, M., Swetnam, T. L., & Troch, P. A. (2013). Coevolution of nonlinear trends in vegetation, soils, and topography with elevation and slope aspect: A case study in the sky islands of southern Arizona: COEVOLUTION IN SKY ISLANDS. *Journal of Geophysical Research: Earth Surface*, *118*(2), 741–758.

References for flora/fauna information:

Arizona Game and Fish Department Website. (Archived 2015). *Plant and Animal Abstracts.* (Including subpages)

Arizona Game and Fish Department Website. (Archived 2015). *Willcox Playa Wildlife Area*.

In the Current. (2017, May 8). Native Species of the Month—Yaqui Chub. *www.inthecurrent.org.*

Price, M. (n.d.). Meet the Banded Rock Rattlesnake: One of the smallest rattlesnakes in Texas. *San Angelo Standard-Times.*

Price, M. (n.d.). WILD ABOUT TEXAS: New Mexico milksnake; a glossy beauty. *San Angelo Standard-Times.*

U.S. National Park Service Website (n.d.). Animals—Chiricahua National Monument.

U.S. National Park Service Website (n.d.). Plants—Chiricahua National Monument.

Spheroidal Weathering

Samantha Moruzzi

Overview:

Mechanical and chemical weathering often result in the alteration of a rock's composition, size, and shape. Spheroidal weathering is a type of both chemical and mechanical weathering through which water weathers hard, uniform rocks with well-developed joint systems. Weathering occurs at the jointed surfaces, leaving behind spherical or concentric layers of weathered rock that typically surround a corestone [1]. Depending on the composition, the concentric layers are formed from a chemical alteration along the rock joints, often resulting in the formation of secondary minerals such as kaolinite [2,3]. The corestone is usually comprised of the original bedrock. Granite, diabase and basalt are common examples [1]. Due to the deep extent of jointing in these rocks, spheroidal weathering can also occur in the subsurface. Additional surface weathering can expose the corestones and concentric layers to the surface, leaving both free-standing rounded boulders and rounded boulders still bound to the weathered matrix at the surface (Figure 1). The spherical shapes of the corestones and the concentric layers surrounding them account for other names for spheroidal weathering such as onion skin weathering and concentric weathering [4].

Figure 1: Spheroidal weathering in diabase rocks in Salt River Canyon, Arizona. Rounded corestone are visible. Credit: [6]

Process:

i.Mechanical component

The original large rock mass is subjected to some form of stress, resulting in well-developed joint systems. The joints are usually oriented perpendicular to each other, which divides the original rock mass into smaller cubes. When groundwater infiltrates the joints, the cubes are weathered on at least three sides (Figure 2) [1,4]. The corners of the cubes weather the fastest because of their position between the weathering faces. The faster weathering in these areas causes rounding of the rock as it weathers, resulting in the inner shells being more spherical than the outer shells [1]. The interior of the block, or the corestone, remains, usually in a spherical or rounded boulder shape, with a distinct boundary between itself and the weathered rock around it (often termed the weathering front) [1].

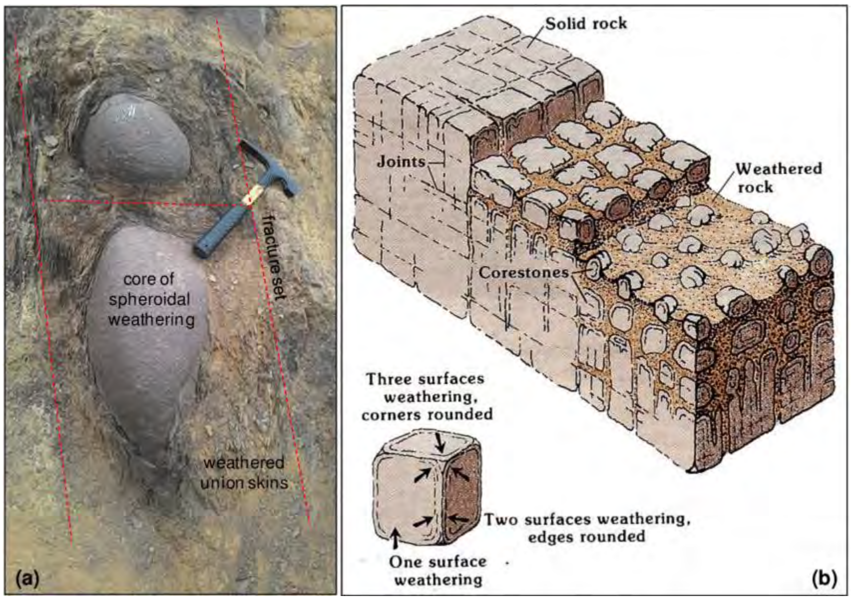


Figure 2: a) Corestone shown surrounded by the concentric layers resulting from spheroidal weathering. b) A schematic diagram of the spheroidal weathering process. Credit: [2]

The resultant structure of the weathered mass varies depending on composition of the original rock mass and the shape of the original rock mass. On average, the concentric shells are a few millimeters to centimeters thick, and the thickness is typically locally uniform. Basalt tends to have many thinner shells while granite tends to have fewer, thicker shells [1]. Sometimes the corestones are surrounded by clearly visible shells (like in Figure 3) and other times the shells have decomposed so the corestones are only identifiable (like in Figure 1). Additionally, if the original rock mass contains cubic shapes, the concentric layers will be spherical, while if the original rock mass contains elongated rectangular shapes, then triaxial ellipsoid layers will form [1].

Figure 3: Spheroidal weathering of basalt from Bacchus Marsh Australia. The concentric shells are clearly visible. Credit:[1]

ii.Chemical component

Chemical weathering usually accompanies the mechanical weathering in this process [2]. As the groundwater infiltrates the joints, chemical weathering occurs along the joint and cube faces, causing the eventual concentric shell structure. The chemical breakdown of the rock structure depends on the composition of the original rock mass. For example, a study on spheroidal weathering of Miocene age granite porphyry showed that the weathering resulted in the oxidation of pyrite and chlorite as well as the precipitation of iron hydroxides along the weathering front near the corestone [2]. A separate study on the weathering of basalt showed weathering trends between the corestones and outer shells where certain

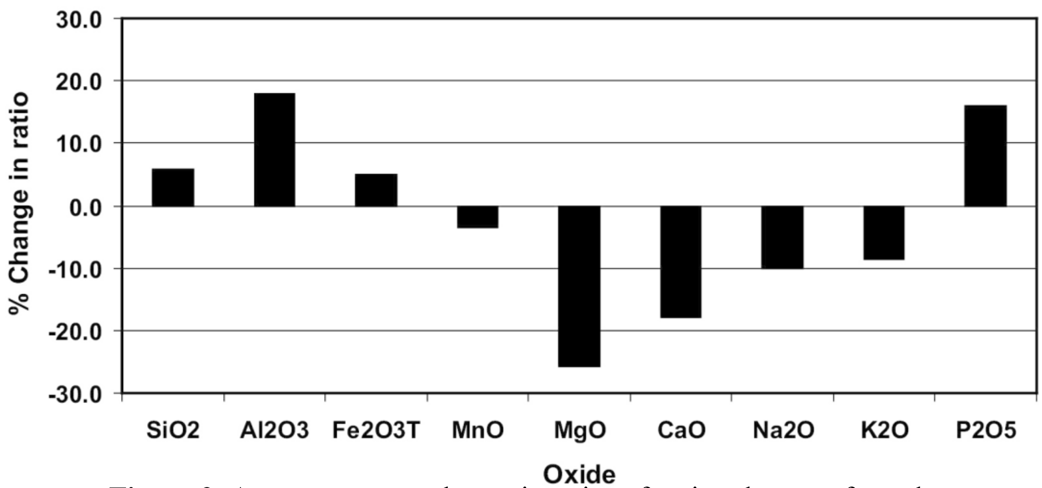
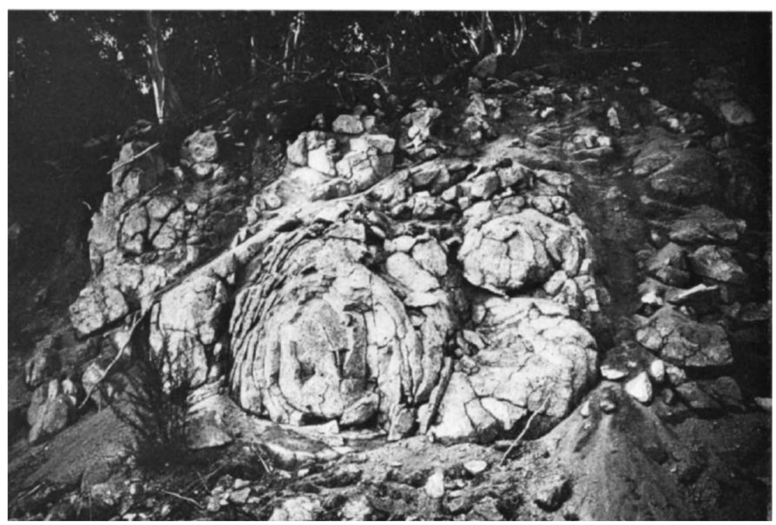


Figure 3: Average percent change in ratios of major elements from the layers/shells and inner corestone of basalt spheroids. Credit: [5]

elements were depleted from the corestones to the outer shells due to the weathering of minerals such as olivine and pyroxene in the outer shells. The changes in composition and degree of weathering also gave clues to the original climate conditions under which the weathering occurred [5]. The original rock mass can also sometimes be weathered to kaolinite that is found to surround some corestones [3].

<u>Examples:</u>



Top left: Rounded granite boulders/corestones from spheroidal weathering on Arizona's beeline highway. Credit: [3]

Bottom left: Spheroidal weathering in a basalt outcrop in Turkey. Credit: [7]

Top right: Spheroidal weathering of granite in Kosciusko Area, Australia. Credit: [1]

References:

[1] Ollier, C. D. (1971). Causes of spheroidal weathering. *Earth-Science Reviews*, *7*(3), 127-141.

[2] Hirata, Y., Chigira, M., & Chen, Y. (2017). Spheroidal weathering of granite porphyry with well-developed columnar joints by oxidation, iron precipitation, and rindlet exfoliation. *Earth Surface Processes and Landforms*, *42*(4), 657-669.

[3]https://www.pinalgeologymuseum.org/index.php/learn-play/arizona-rocks/244-arizona-spheroidal-weathering

[4] Husein, S., & Novian, M. I. (2014). GUIDE BOOK.

[5] El-Hinnawi, E., Abayazeed, S.D. & Khalil, A.S. Spheroidal weathering of basalt from Gebel Qatrani, Fayum Depression, Egypt. *Bull Natl Res Cent* **45,** 1 (2021). https://doi.org/10.1186/s42269-020-00453-2

[6] https://epod.usra.edu/blog/2014/05/spheroidal-weathering-in-salt-river-canyon-arizona.html

[7] https://epod.usra.edu/blog/2015/06/spheroidal-weathering-in-a-basalt-outcrop.html

Playas and South-Western Climate History

By: Michael Daniel

Willcox Playa:

- Playas are:
  - Flat expanse
  - Deposited from lakes
  - Located in interior draining basins (no water reaches an ocean above ground)
- After heavy rains, Willcox Playa can be up to 30 cm deep (Waters, 1988)
- White silt and clay floor (Stevens, 2011)
- Sparse vegetation dominated by alkalai sacaton and Saltgrass (Stevens, 2011)
- Saltbushes, mesquite, and non-native tamarisk around the edges (Stevens, 2011)
- Wintering grounds for sandhill cranes (Stevens, 2011)

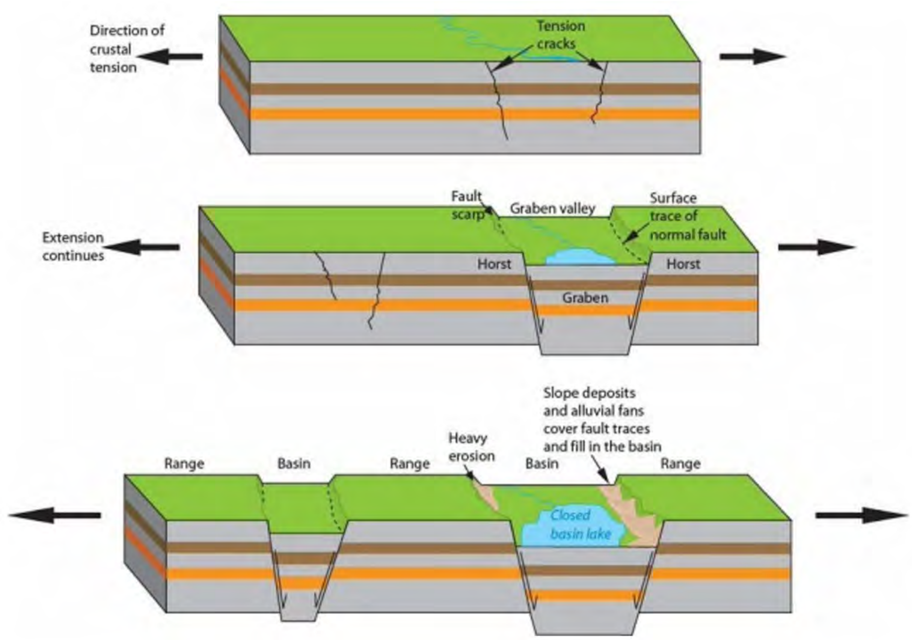


Figure 1: Schematic of graben and horst features becoming basin and range features from NPS.

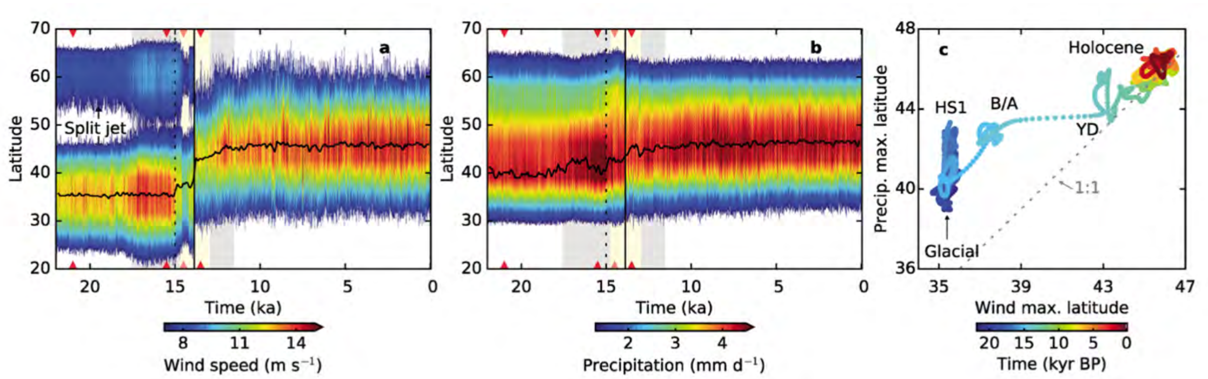


Figure 2: Tropospheric (700 mbar) wind speed averaged over 25 degrees longitude along west cost of N. America (Left), Winter precipitation over same region as left (Middle), evolution of relative positions of the jet stream and maximum precipitation (Right) from Lora (2016).

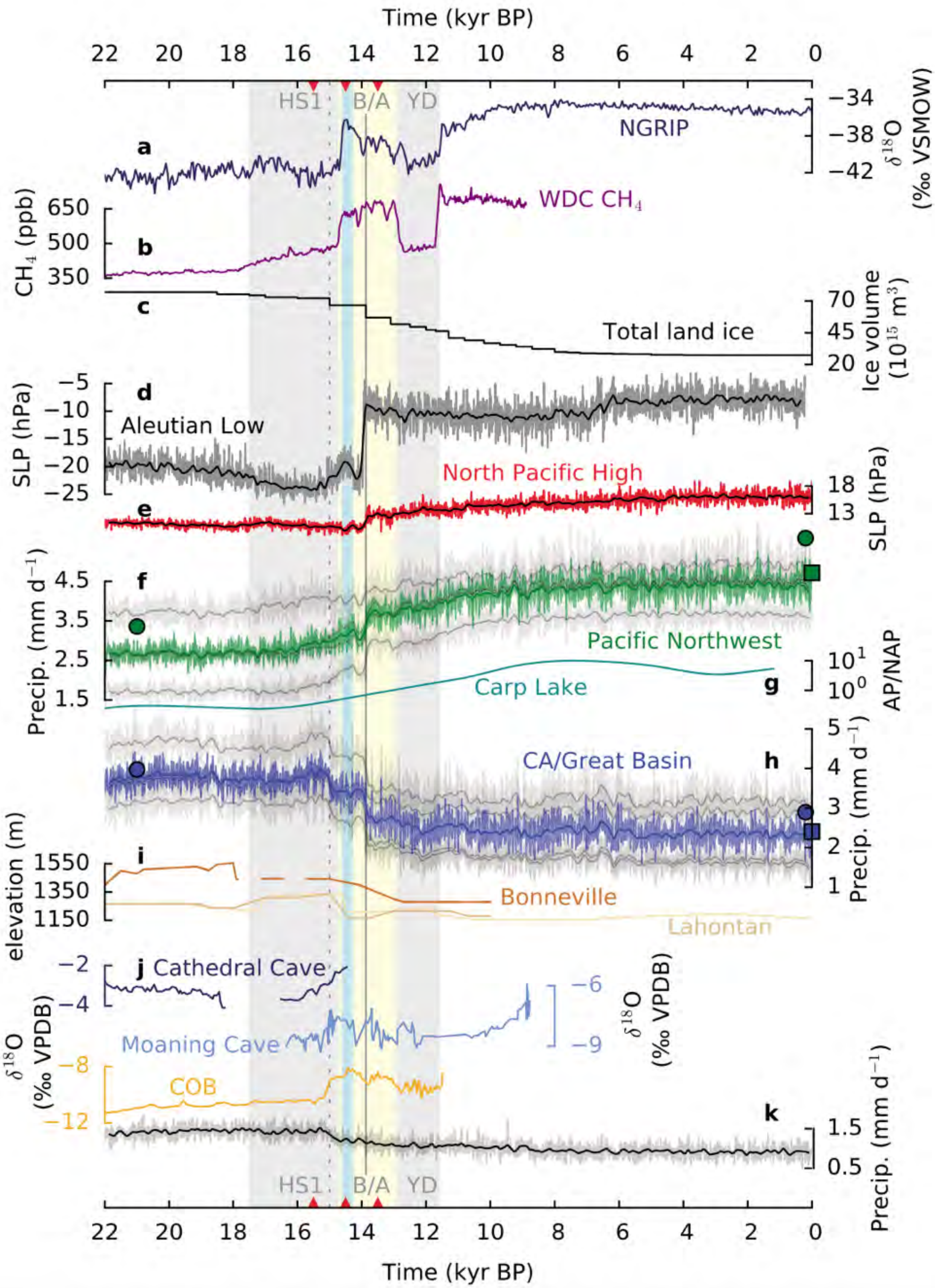


Figure 3: *Showing the sudden changes to climate in the Western north America around 14,000 yr. B.P. Lora (2016). Key parts of this graphic are the precipitation and Aleutian Low plots.*

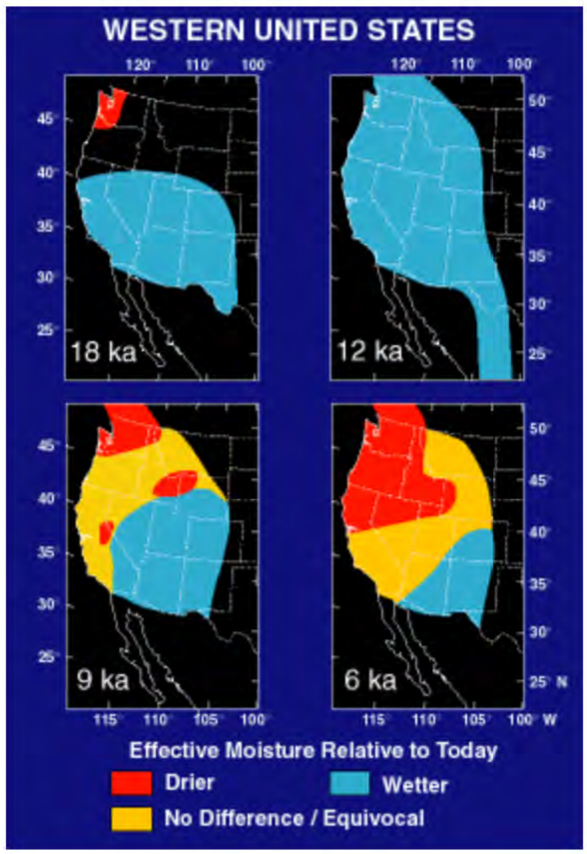


Figure 4: (Left) Precipitation trends in the Western US at four different points in the last 18,000 years Thompson (2016).

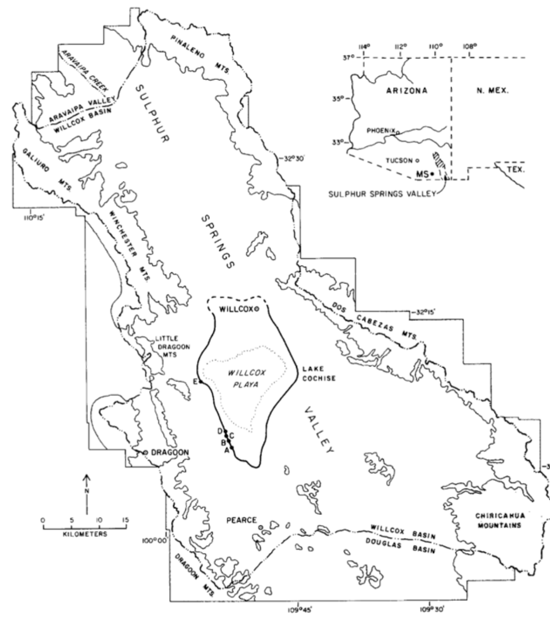


Figure 5: Comparing the scale of prehistoric Lake Cochise to present day Willcox Playa from Waters (1998). Willcox Playa in dotted line, Lake Cochise is the solid/dotted line.

Climate:

- 20,000 years ago -> wetter and cooler
- ~18,000 years ago -> Last glacial maximum
- ~15,000 years ago -> Willcox Playa/Lake Cochise had a maximum depth of 46 ft (Stevens, 2011)
- Up to 10,000 years ago -> Westerlies far south of current location -> more precipitation in southwest = wetter and cooler than today (Thompson, 2016)
- ~9,000 years ago -> human occupation of area began + last ‘high lake level’ (Stevens, 2011)
- ~8,000-10,000 years ago -> monsoons were much stronger than today, summer temps likely warmer than today but wetter (Thompson, 2016)
- ~6,000 years ago -> climate warms and dries, most species established in current ranges (Thompson, 2016)

Bibliography

"Horst and Graben." *National Park Service*. Last Modified April 22, 2020. https://www.nps.gov/articles/horst-and-graben.htm.

Lora, J. M., J. L. Mitchell, and A. E. Tripati (2016), Abrupt reorganization of North Pacific and western North American climate during the last deglaciation, *Geophys. Res. Lett.,* 42, 11, 796-11, 804, doi:10.1002/2016GL071244

Stevens, L. E., and Jeri Ledbetter. "Willcox Playa". *Northern Arizona University*. Last Modified 2011. http://www.azheritagewaters.nau.edu/loc_wilcox_playa.html.

Thompson, R. S. and Katherine H. Anderson. "Past Climate and Vegetation Changes in the Southwestern United States". *Geochange, USGS*. Last Modified Dec 9, 2016. https://geochange.er.usgs.gov/sw/impacts/biology/pastclim/.

Waters, M. R. (1988), Late Quaternary Lacustrine History and Paleoclimatic Significance of Pluvial Lake Cochise, Southeastern Arizona, *Quaternary Research*, 32, 1-11

Desiccation Polygons in the Willcox playa

Indujaa Ganesh

Mud cracks (or desiccation cracks) typically form due to loss of moisture and subsequent shrinkage in clay-rich environments. This is a common occurrence in ancient (horizontal to sub-horizontal) depositional environments that were regularly subjected to subaerial exposure, like tidal flats, lake shorelines, and playas. Mud cracks that develop this way often intersect to form desiccation polygons. The final morphology and dimensions of the desiccation polygons depend on various factors such as sediment composition, bed thickness, rate of drying, and depth of ground water table.

- Thick beds of sediment, homogeneous compositions, high salinity and/or high temperature → large desiccation polygons. *Example:* the giant desiccation polygons at Willcox playa (see Figure 1). Giant desiccation polygons are particularly common in the Basin and Range Province (Figure 1). Some of these polygons are as large as 300 m (Neal, 1968).

- Low salinity and/or lower temperatures, thinner beds, and inhomogeneous sediment compositions → smaller desiccation polygons.

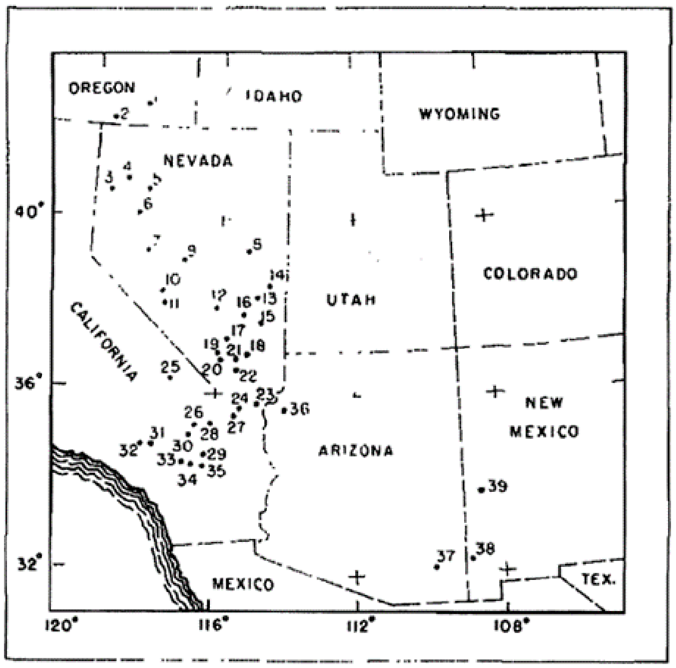


Figure 1. Giant polygon desiccation locations (Neal et al., 1968); Willcox playa is marked as number 37 in the SE corner of Arizona.

Giant desiccation polygons can develop either in an orthogonal system, or a non-orthogonal system. It has been suggested that homogeneity and plasticity of the clay bed play a major role in determining the morphology of the polygon system.

Thick homogenous beds with relatively higher plasticity (more free water) lead to orthogonal polygons. Non-orthogonal polygons develop in heterogenous, and extremely dry beds. Two distinct styles of polygons are seen in the Willcox playa: “oriented orthogonal” and “irregular random orthogonal” polygon networks in the eastern part of the playa and more anisotropic pattern in the western part (see Figure 2).

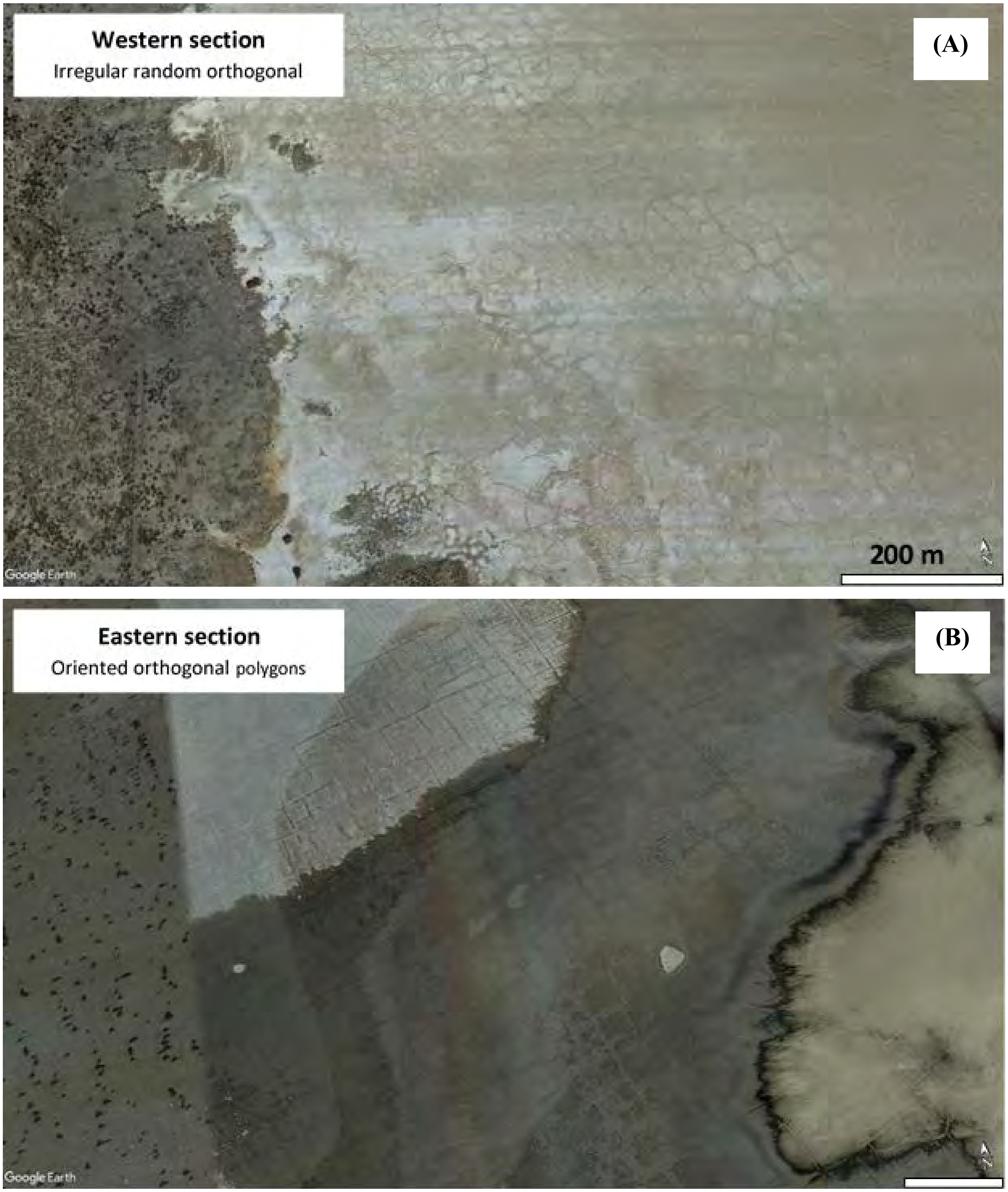


Figure 2. Giant desiccation polygons in the Willcox playa. (A) irregular, random polygons in the west and (B) oriented orthogonal polygons in the east.

Closer look into formation. Desiccation cracks form when a (clayey) unit rich in volatiles dries up, loses volume, and creates stresses through changes in surface tension between the grains. The loss of volume can result from one or more of the following factors: 1) intense evaporation from the surface downward, 2) lowering of water table, and 3) natural variations following pluvial or other cyclic events. In arid regions where there is very little rainfall, or the evaporation potential is significantly larger than precipitation, or the water table is unusually low, a hard dry clay crust exists between the surface and the water table conducive to the formation of fissures. Within this region, at some point in the subsurface above the water table where the clay is no longer plastic, loss of moisture may result in a significant reduction of volume. This leads to fissure development in the subsurface, which then propagate both downward and upward, eventually reaching the surface. This is shown in the left panel in Figure 3.

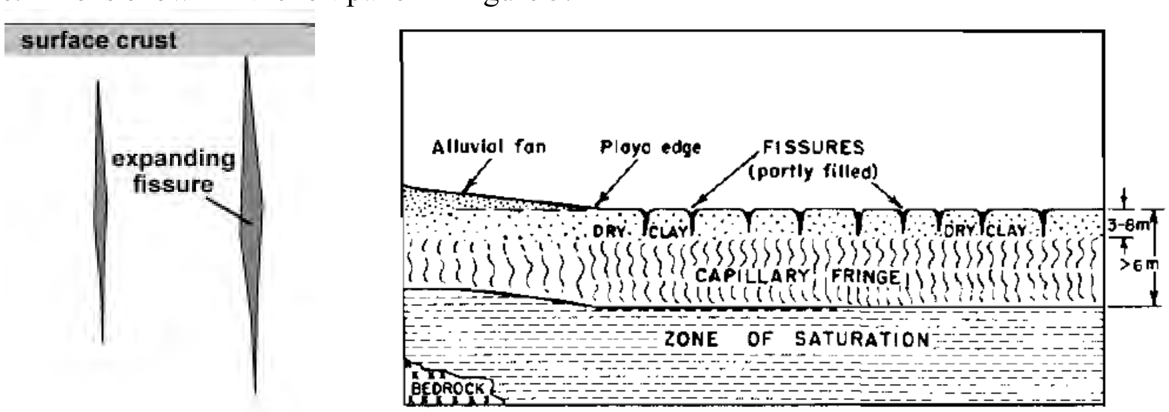


Figure 3. Left: Cross-section of inferred fissure development. Desiccation at depth causes buried sediments to shrink, forming subsurface joints (Messina et al. 2005). Right: Hypothetical cross section of a fissure environment. (Neal et al., 1968)

Minimum crust thickness. Formation of fissures requires hard, dehydrated bed in the subsurface that is below the rainfall infiltration depth, and above the reach of capillary fringes, as shown by the schematic in the right-hand side panel in Figure 3. This bed must be thick enough for substantial stresses to develop, and the water table must have receded fast enough for the stresses to not be relieved by creep. The clay bed thickness plays an important role in determining the crack depth and widths. Minimum bed thickness of 8 m has been cited in the literature for Rogers playa (Neal, 1968). This is expected to differ between different playas.

Mineral content of fissured playas. Studies of bulk mineral assemblages in fissured and non-fissured playa have shown that desiccation cracks develop in very hard, clay crusts enriched in sheet silicates and carbonates, and low in soluble salts. The clays found are generally illite, montmorillonite, vermiculite, and chlorite with little to no kaolinite. Well-crystallized clays are plastic when wet and undergo shrinkage when dehydrating. This leads to volume change that is directly proportional to the absolute particle size composition. The clays noted here, however, are specifically sensitive to environmental changes and undergo intramineral contraction when dehydrating. Lowering of ground water table and evaporation from the surface would then result in both interparticle AND internal shrinkage leading to large changes in volume.

Miscellaneous. *How long do mud cracks take to form?* No one has reported seeing a desiccation crack form. It has been suggested that these cracks form rapidly, sometimes even within the course of day. Observations have shown new cracks or extensions to existing ones develop within the course of a year. *Do all dry, clayey playas have desiccation cracks or polygons?* There are playas in the American SW with hard clayey crusts and deep water tables that do not have desiccation polygons. Some of these playas have desiccation “stripes” indicating previous fissuring episode.

Polygonal terrain on Mars: not related to desiccation. Polygonal ground patterns are common on Mars. Giant polygons, at larger than scales than any polygonal ground found on earth, have been observed in the northern plains (Pechmann, 1980). They were proposed to be tectonic in origin, formed by isotropic extension, due to their large scale and extent (see Figure 4, left panel). Latitude dependent periglacial polygons formed by thermal contraction cracking of ice-rich mantle, shown in the right panel of Figure 4) have been observed in both northern and southern hemispheres on Mars (Levy et al., 2009).

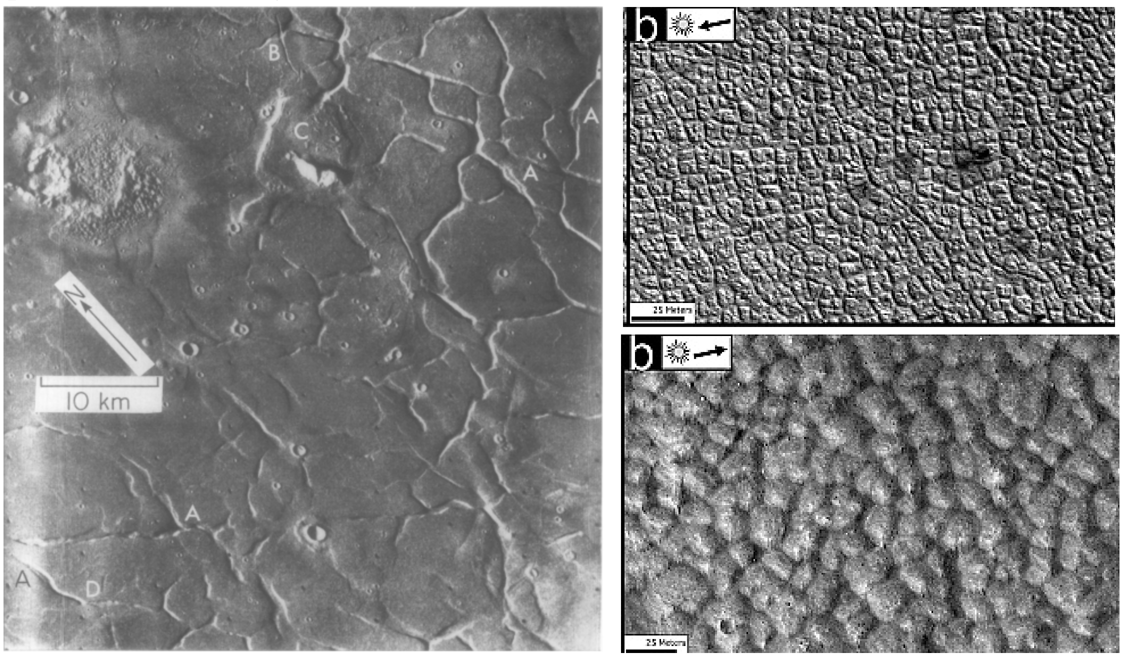


Figure 4: Non-desiccation cracks on Mars. Left: Polygonal troughs in southeastern Acidalia Planitia attributed to tectonic forces (Pechmann, 1980). Periglacial polygons on Mars. High-relief polygons and subdued polygons (levy et al., 2009).

Desiccation cracks on Mars. Polygonal cracks formed by desiccation of water-rich soils and sediments on Mars has been the focus of several studies (El-Maarry et al. 2015a and citations within). Desiccation cracks have been identified at several settings on Mars, especially in chloride-rich, and clay-rich deposits, impact crater floors, and the plains of Meridiani Planum (see Figure 5). They range in size range from sub-meter to 10s of meters, as observed in HiRISE images. They are primarily found in deposits that show spectral evidence for the presence of Fe/Mg smectites or vermiculites, and Al-rich smectites, and sometimes also in kaolinites and carbonates.

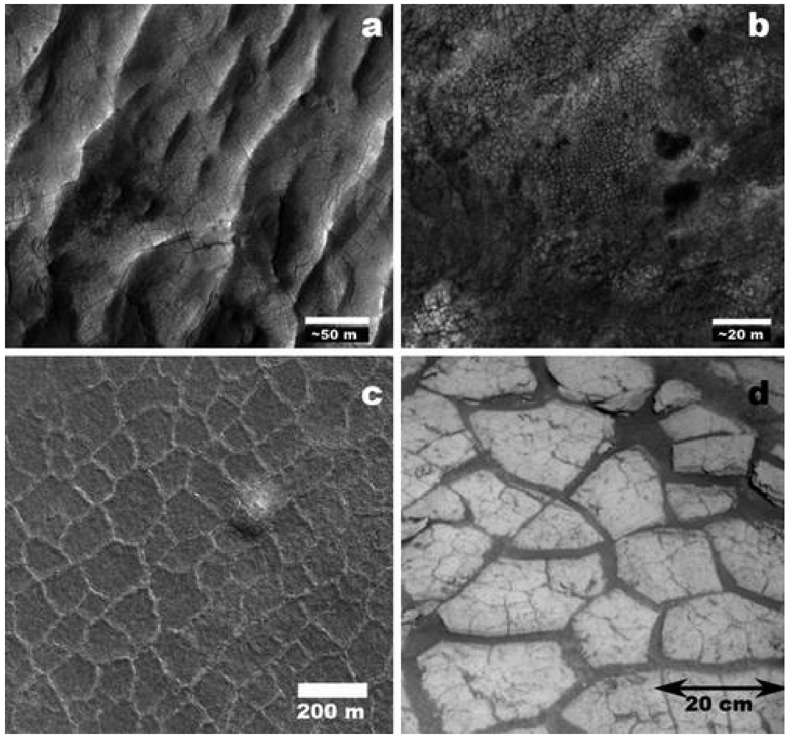


Figure 5: Examples of polygonal cracks on Mars at various scales ranging from centimeters to hundreds of meters that are currently attributed to desiccation in (a) chloride-rich terrains, (b) clay-rich deposits, (c) floors of impact craters, and (d) the plains of Meridiani as seen by the MER Opportunity (El Maarry, 2015b).

References

Neal, J. T., et al. (1968). Giant desiccation polygons of Great Basin playas. *Geological Society of America Bulletin*, *79*(1), 69-90.

Messina, P., et al. (2005). Macropolygon morphology, development, and classification on North Panamint and Eureka playas, Death Valley national park CA. Earth-Science Reviews, 73(1-4), 309-322.

Pechmann, J. C. (1980). The origin of polygonal troughs on the northern plains of Mars. *Icarus*, *42*(2), 185-210.

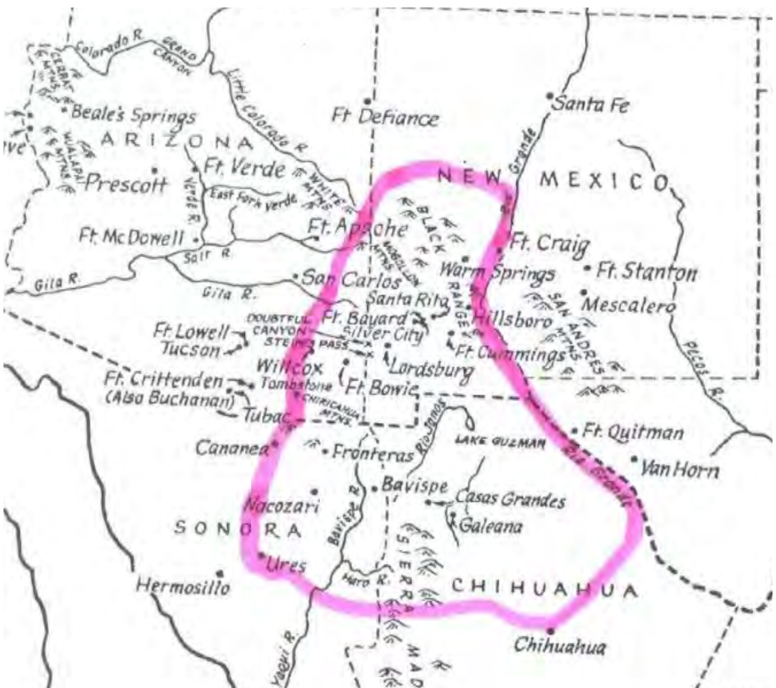
Levy, J., et al. (2009). Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations. Journal of Geophysical Research: Planets, 114(E1).

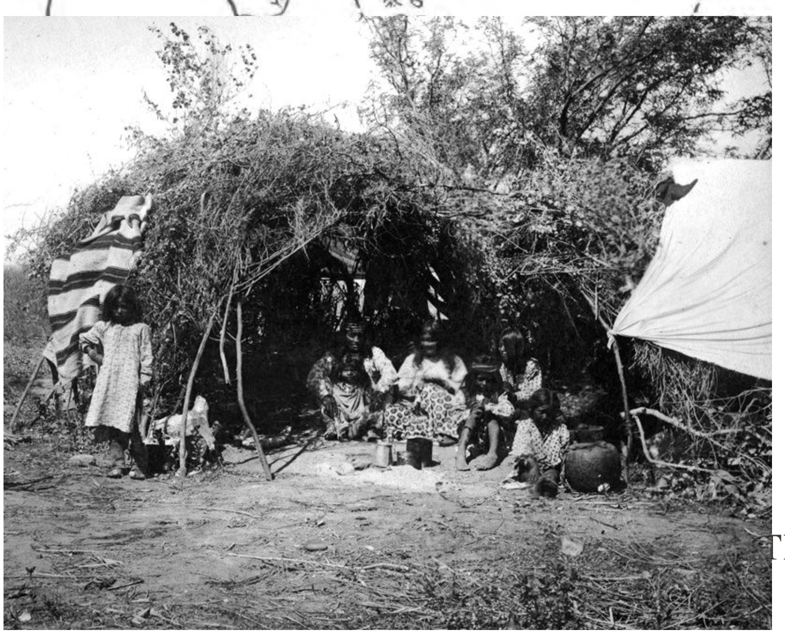
El Maarry, et al. (2015a). Desiccation of phyllosilicate-bearing samples as analog for desiccation cracks on Mars: Experimental setup and initial results. Planetary and Space Science, Volume 111.

El-Maarry M.R. (2015b) Desiccation Crack Polygon. In: Hargitai H., Kereszturi Á. (eds) Encyclopedia of Planetary Landforms. Springer, New York, NY.

The Chiricahua Apache Nation

"The People" and their History





- Apache translates to Enemy
  - Spanish transliteration of Zuñi term
- Knew themselves as the "Nde"
  - Translates to "The People"
- Chiricahua are Eastern Apache
- Athabaskan Language: Origins in Western Canada
- Migrated to present day American Southwest: ~1500
- Culturally Nomadic
  - Winters on the plains
  - Summers in the local mountains
- Hunter gatherers living in quickly constructed structures - "Wickiups"
- The warrior was the most sacred vocation/position
  - Available for both Men and Women
- Leadership of bands (10-30 families) determined by capability in battle
- Trained extensively to toughen their physicality
- Quick learners: Mastering horses and firearms easily
- Raiding was commonly practiced
  - Brought capital and cultural fulfillment

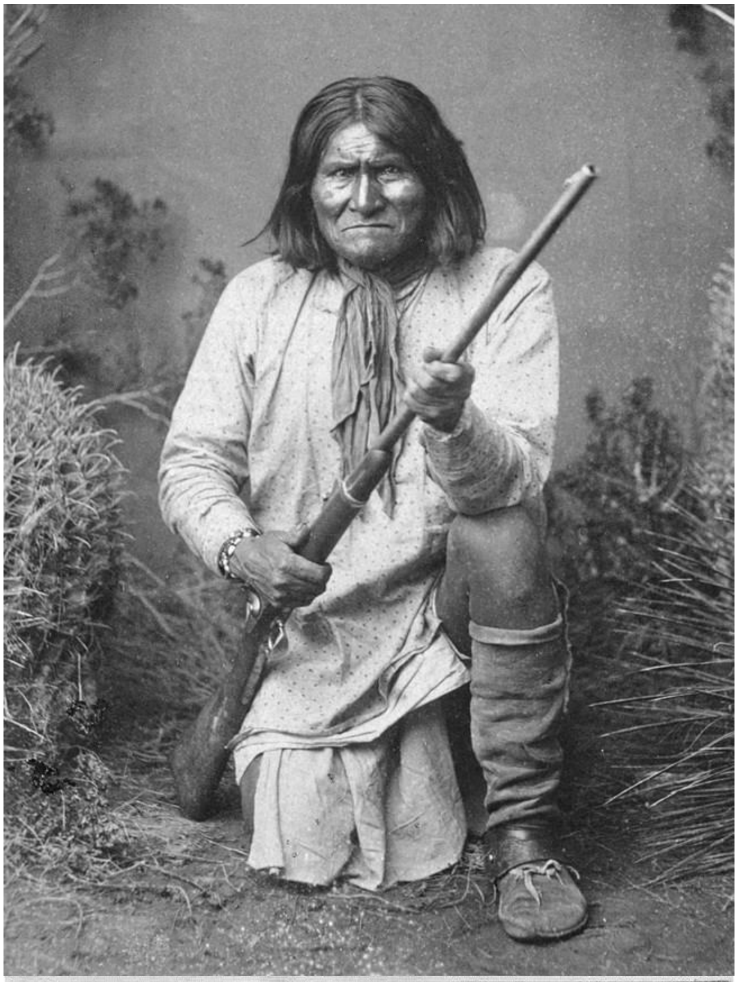
Thus the Chiricahua Apache have been regarded as the archetypal native "savage"

The Apache Wars

The arrival of the Chiricahua Apache to the present day American Southwest coincided with arrival of the Spanish in present day Mexico. By 1700, the Apache raiding of the Spanish was recognized as a problem and resulted in minor skirmishes throughout the century, though relative peace had been found by the 1770s. In 1821, when Mexico gained independence from Spain this peace began to slip, and by 1835 the Mexican government announced a bounty on Apache scalps.

Similar conflict was arising between the Chiricahua Apache and American settlers in the early 1800’s. The American victory in 1848 of the Mexican American War led to the Treaty of Guadalupe-Hidalgo which ceded much of the Chiricahua land to America. As brilliant warriors and tacticians, the Apache were too hard for the American militias to pin down. In 1854, America pursued the Gadsden Purchase of today's Southern Arizona and New Mexico. The major motivation behind this purchase was the tactical advantage these lands held in waging war against the Chiricahua.

Conclusion to the War



No. 176—Council between General Crook and Geronimo.

Capt. Roberts Geronimo Nana Lieut Maus Three Interpreters Capt. Bourke Gen. Crook

The 1861 raid of a farm in the Chiricahua mountains sparked the famous battle now known as The Battle of Apache Pass which took place at around Fort Bowie.

This was one of the few open battles that the Chiricahua took during the "Apache War". Under the strategic leadership of a Chief Cochise, the Apache enacted a highly mobile form of guerrilla warfare. The bands under Cochise's leadership where nearly impossible for the Americans to track. Their tactics exhausted the American General Crook and Howard. A peace deal was struck in 1872 for the procurement of a large reservation for Cochise and his people in what is now Cochise County, Southern Arizona.

After Chochis's death, the war resumed. A new leader, Geronimo emerged. Infamous for multiple captures, escapes, and incredible luck, Geronimo led an ever decreasing number of Chiricahua from the grasps of the American military. Only after 9000 soldiers were gathered to face the remaining 37 Apache with Geronimo, did they finally surrender.

Today, there are over 850 Chiricahua Apache spread across reservations. Their culture and history is continued through the "Practice, advance and celebrat[ion of] the Sacred Spirituality of the Chiricahua Apache Nation"

References and Further Reading

- https://chiricahuaapachenation.org/
- https://www.britannica.com/topic/Apache-people
- https://www.britannica.com/topic/Chiricahua
- https://www.britannica.com/biography/Geronimo
- https://www.nps.gov/fobo/learn/historyculture/the-chiricahua-apache.htm
- https://www.nps.gov/chir/learn/historyculture/pre-apache-wars.htm
- https://www.nps.gov/chir/learn/historyculture/apache-wars-cochise.htm
- https://www.nps.gov/chir/learn/historyculture/apache-wars-geronimo.htm
- https://www.nps.gov/chir/learn/historyculture/post-apache-wars.htm
- Menchaca, Martha. Recovering history, constructing race: The Indian, black, and white roots of Mexican Americans. University of Texas Press, 2001. Pages 224-227

A Vagrant by Kate Beaton

An Overview of the Geology of Southern Arizona – Tyler Meng

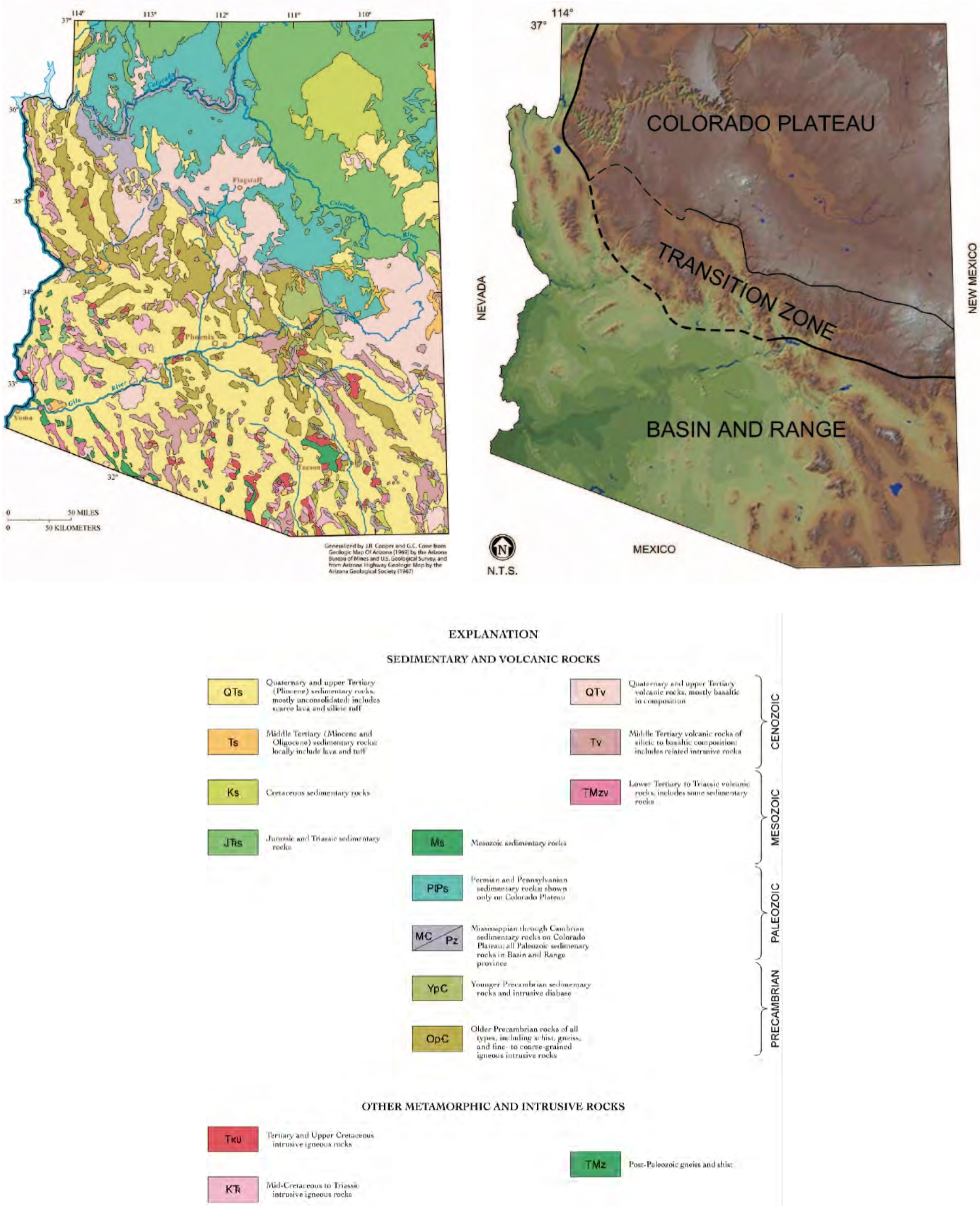


Figure 1: A geologic map of Arizona (top left) and an elevation map depicting the two distinctive physiographic provinces dividing the northern and southern portions of the state (Rasmussen, 2012).

A Rich Geologic History: Arizona's Mineral Wealth

Southern Arizona is a region renowned for its high-grade gem and mineral production, particularly copper along with its associated chemical compounds and crystal structures. The dispersed mountain ranges create "sky islands" which produce unique ecosystems and sweet relief from the toasty lowlands. Still, the dry basins of the Sonoran Desert region are a central feature in this part of the southwest. All of these characteristics stem from a varied geologic history spanning from the Proterozoic to the present.

Precambrian (>540 million years)

- Local mountain building, metamorphism, and granitic intrusion (Oracle Granite, Pinal Schist, Zoroaster Granite) – "exotic" minerals bearing elements such as Be, Li, etc…
- Sedimentary deposition from the Grenville Orogeny in eastern U.S.
- The Great Unconformity: up to 900 million years of erosion at the end of the Proterozoic

Paleozoic (540 – 250 million years)

- Arizona was a passive margin and underwent many transitions between continental and shallow marine environments. These led to a wide range of sedimentary rocks including limestones, siltstones, and sandstones, which are especially apparent in large outcrops such as the Grand Canyon.

Mesozoic (250 – 65 million years)

- Breakup of Pangea and subduction at the western boundary of N. America (Figure 2).
- Significant volcanic activity and mineral emplacement from granitic intrusions.
- The Petrified Forest was created with the help of tephra in the Triassic.
- The subduction zone evolved and the slab flattened, leading to different phases of andesitic and rhyolitic volcanism, along with more mineral deposition (e.g. Cat Mountain Rhyolite in the Tucson Mountains).
- Porphyry copper: deposited during the large eruptions during the Laramide Orogeny in the late Cretaceous/early Paleogene.

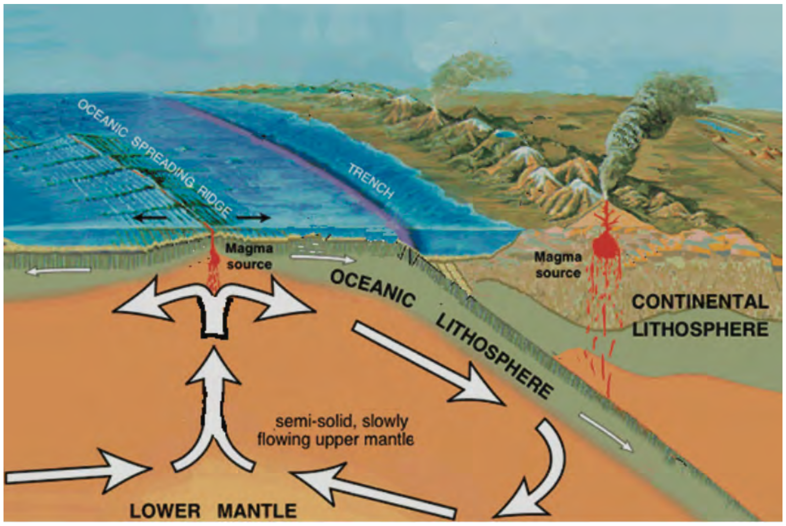


Figure 2: Diagram of a subducting slab with an approaching mid-ocean ridge and associated continental volcanism, similar to western North America in the late Cretaceous (Rasmussen, 2012).

Cenozoic (65 million years – Present)

- Early on: more mountain building due to the subducting slab!
- The Chiricahuas are built from the tuffs of explosive eruptions that occurred around 30 Mya, creating the Turkey Creek and Portal calderas (Figure 3).
- Present day topography: basin and range province began about 14 Mya. The subducting slab was cut off by ridge subduction and the San Andreas Fault, which led to slab foundering and crustal delamination. This led to widespread crustal extension and normal faulting, creating the iconic *horsts* and *grabens* of the region(Figure 4).
- Some more recent volcanism has occurred (such as the San Bernardino field in the Pleistocene), and these more basaltic compositions (Biggs et al., 1999) indicate a change in magma source due to the change in the lithosphere and slab geometry.
- Some basins such as the Willcox Playa filled with rainwater when the climate was wetter and cooler during the Pleistocene, but since has dried into a flat lakebed with evaporite deposits.

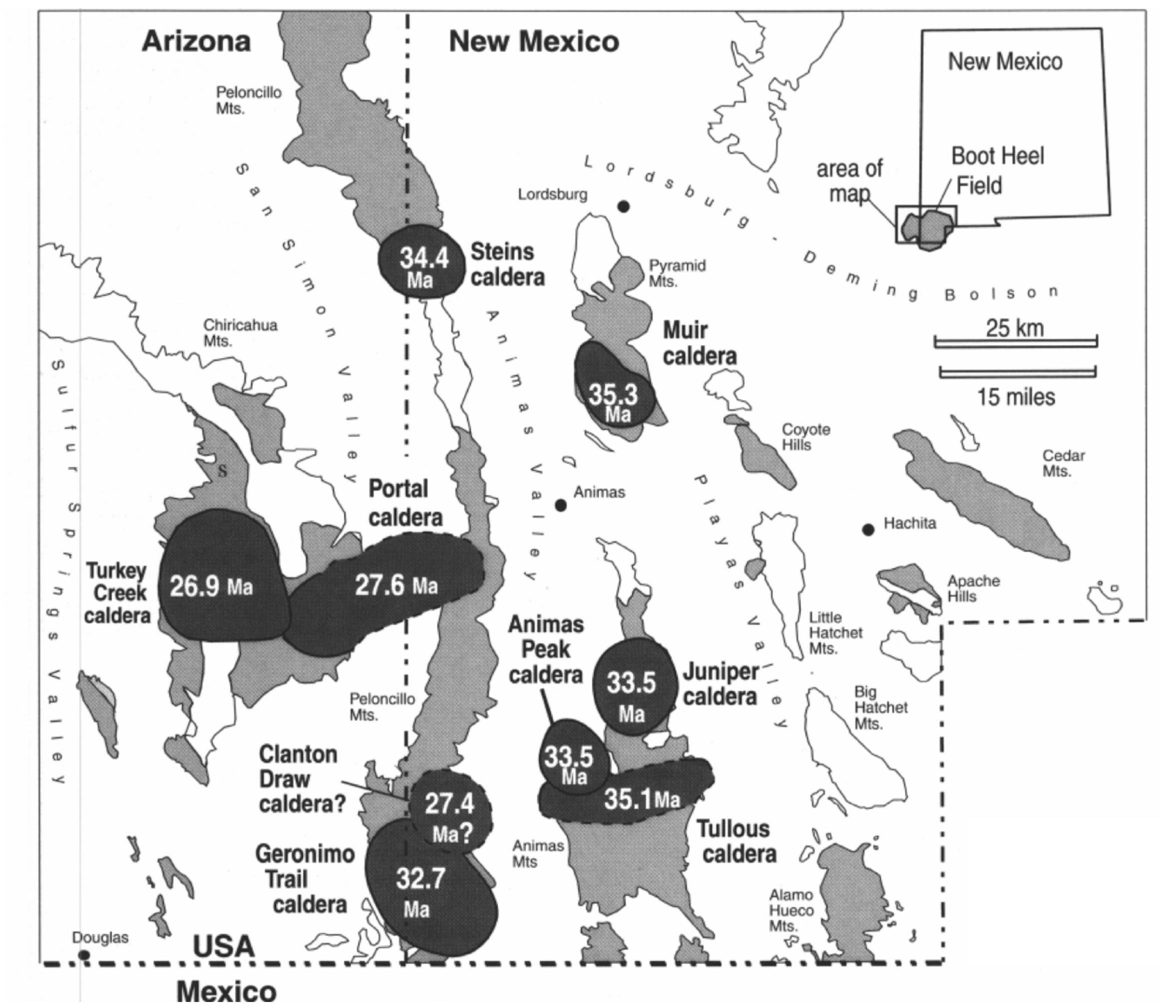


Figure 3: Map showing the Chiricahua Mountains and its calderas in the context of the broader Boot Heel Volcanic Field, which extends into western New Mexico (McIntosh & Bryan, 2000).

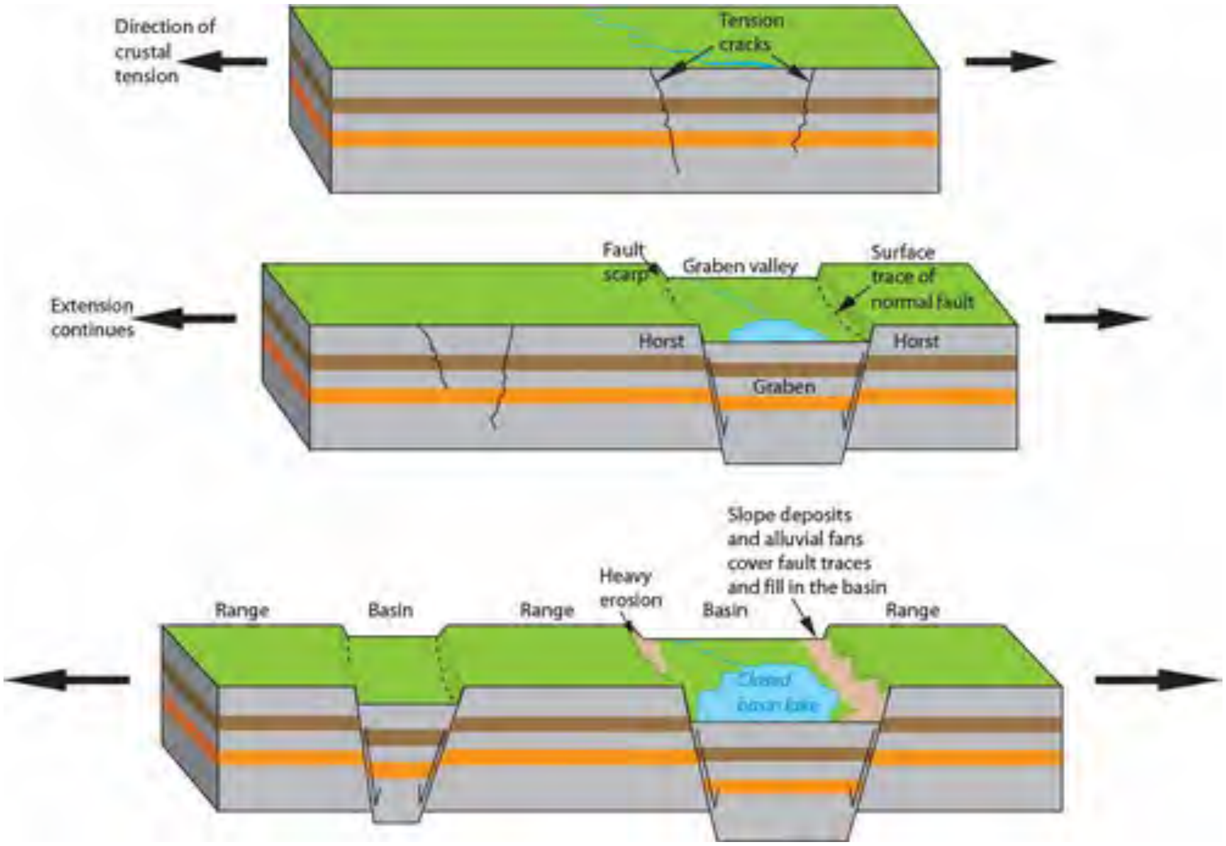


Figure 4: Schematic diagram of the formation of the basin and range province through crustal extension. Note how the faulting is more likely to occur in zones of pre-existing weakness, and lakes may form in the basins (such as Willcox Playa).
Image source: <u>https://opengeology.org/historicalgeology/san-andreas-fault-and-basin-and-range/</u>

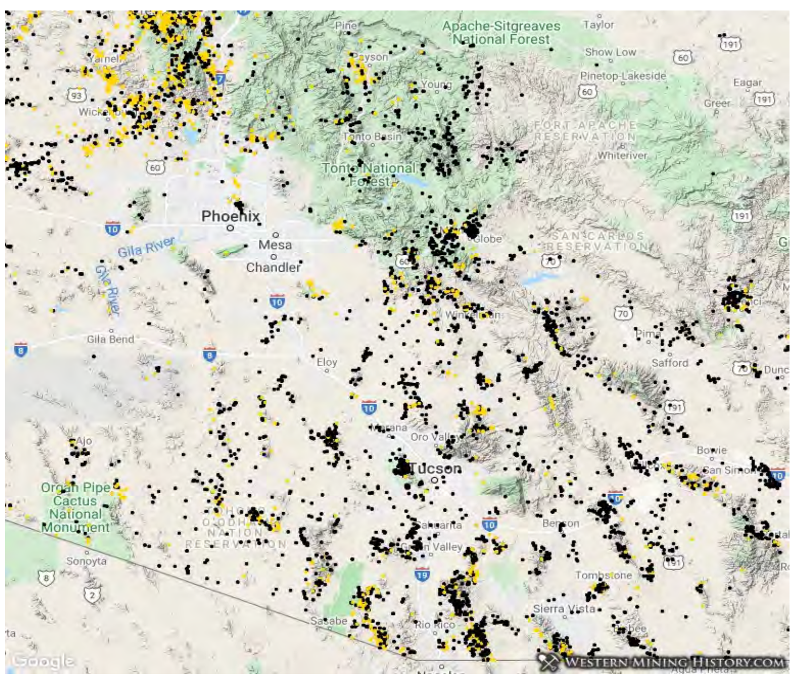


Figure 5: Distribution of mines in southern Arizona, where yellow dots are gold mines and black dots are "other" – most likely copper. Image source: https://westernmininghistory.com/mine_state/arizona/.

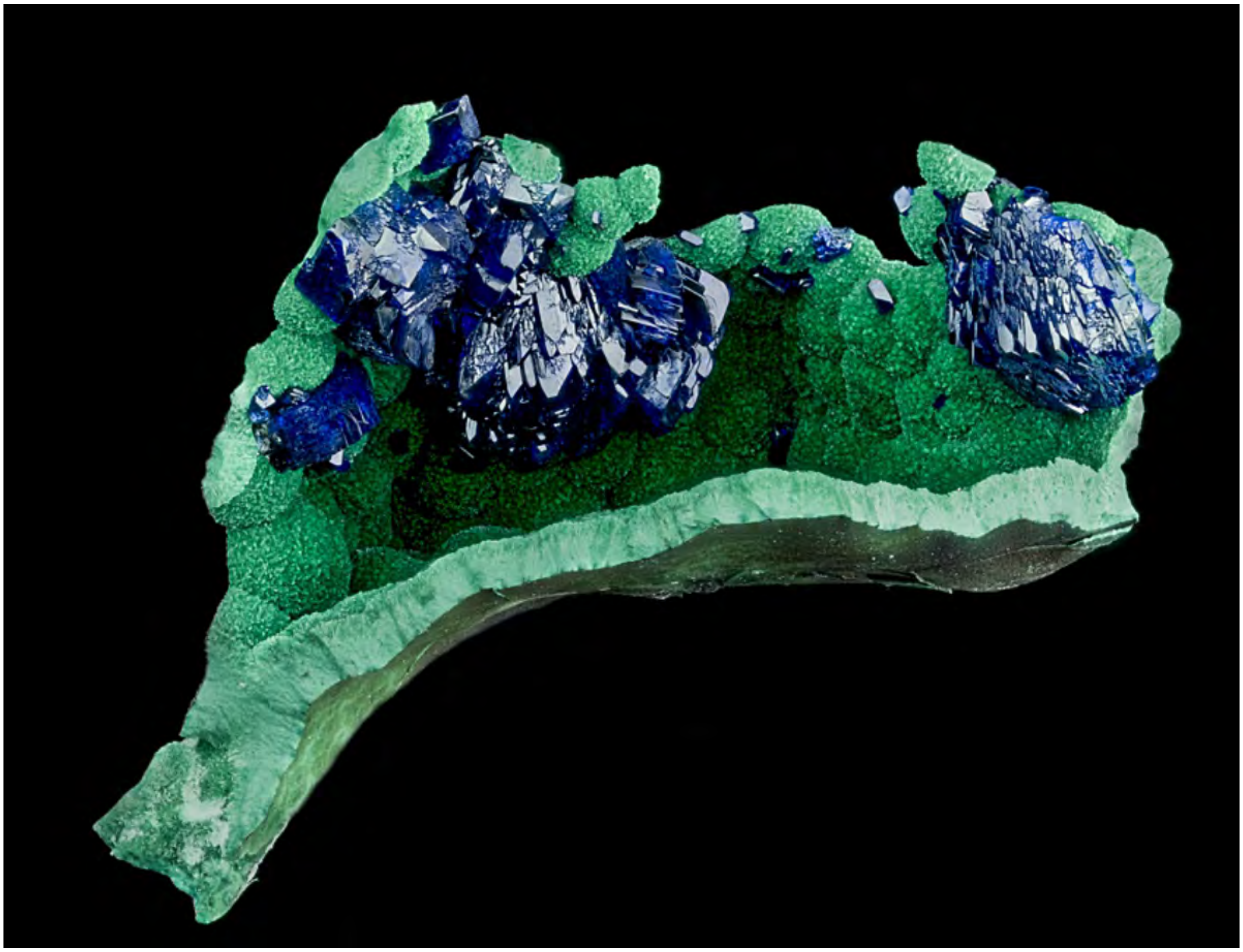


Figure 6: Sample of malachite and azurite, two dramatic copper-bearing minerals, which was found at the Copper Queen Mine in Bisbee, AZ.Image source: https://www.mindat.org/photo-1054534.html, Copyright Matt McGill.

References

Biggs, T.H., Leighty, R.S., Skotnicki, S.J., and Pearthree, P.A. 1999. Geology and Geomorphology of the San Bernardino Valley, Southeastern Arizona. *Arizona Geological Survey Open-File Report 99-19*.

McIntosh, W.C. and Bryan, C. 2000. Chronology and Geochemistry of the Boot Heel Volcanic Field, New Mexico. *New Mexico Geologic Society Guidebook, 51st Field Conference*.

Rasmussen, J.C. 2012. Geologic History of Arizona. *Rocks & Minerals*, 87, 56-63. DOI: 10.1080/00357529.2012.639192.

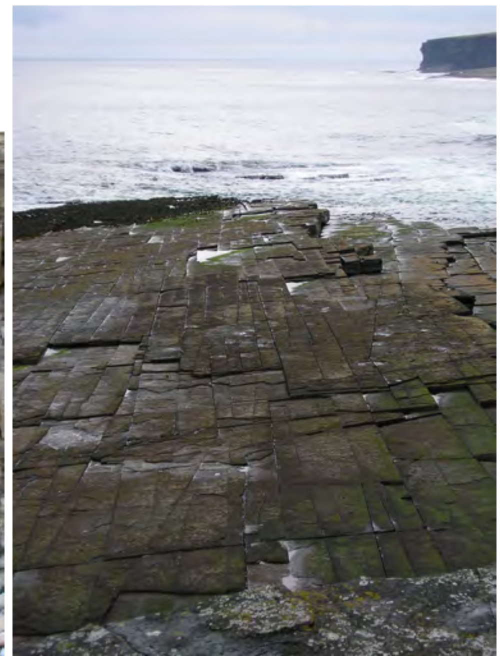
Joints and Hoodoos

Harry Tang

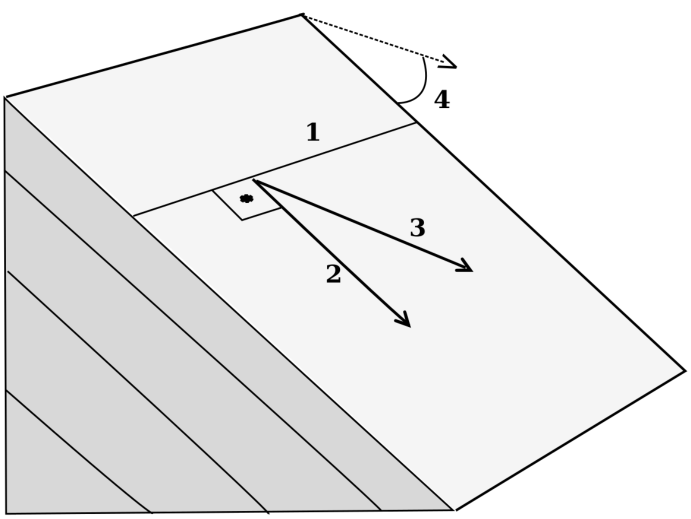
Example of a hoodoo, Thors Hammer in Bryce Canyon National Park (myutahparks.com)

Joints in the Almo Pluton, City of Rocks National Reserve, Idaho (Wikipedia)

Joints are natural breaks or fractures where little or no displacement has occurred [1]. These are often amplified over time through weathering, and are exploited by quarrying operations. Joints differ from faults based on the visibility or measurability of lateral movements, where joints either have movement invisible at the observation scale, or contain movement of rocks perpendicular to the joint [2]. They are a result of tensile stress (stress) on the rock, which in turn could be caused by a variety of factors such as tectonic or hydraulic.

Examples of joints and joint systems



Joints can be singular or form sets, which can intersect to then form joint systems. In sedimentary rocks, joints are often along the strike and dip of the rock, where the strike is the intercept of a sedimentary layer with a horizontal plane, and the dip is the steepest angle of descent of the bed relative to a horizontal plane. [1]

1-Strike, 2-Dip direction, 3-Apparent dip, 4-Angle of dip (Wikipedia)

Hoodoos (Canyon Trail Rides)

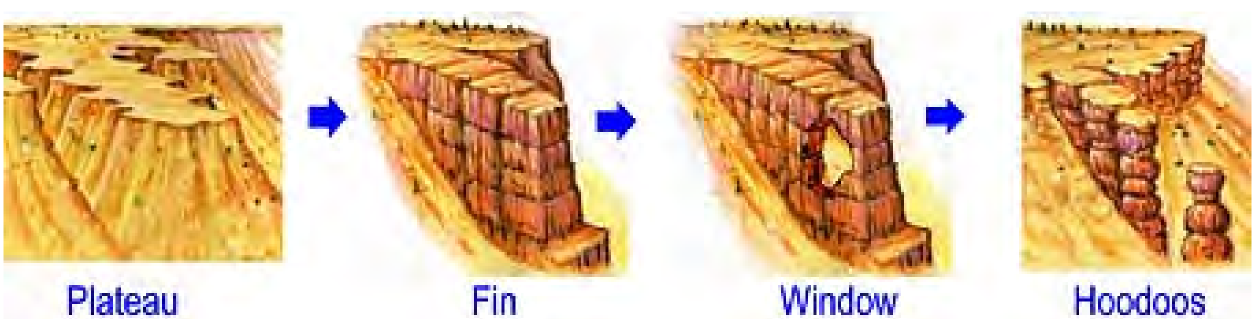
Hoodoos are pillars of rock left over from erosion, usually noted for their spectacular shapes [3]. Water from streams and intense thunderstorms, and sometimes ice, can wear down rocks along joints to create the pillars. Wind then does the final touch ups and polishing [3].

Often these pillars have layers of rocks with varying susceptibility to erosion, typically with harder rocks forming the protective caps, allowing the carvings of fantastic shapes to form. The resulting variable thickness distinguishes them from common spires. [4-5]

(National Geographic)

Hoodoos in Chiricahua (https://www.arizonahighways.com/blog/hoodoo-you-do)

The hoodoos in Chiricahua are formed from erosion of volcanic ash-flow tuff from an eruption ~27 million years ago, and created through frost wedging. Over time, especially the last ice age, water would flow into the joints and cracks of the rocks and freeze, expanding and enlarging the cracks. Overtime, this would break the rocks along the joints to form the hoodoos that we see. [6-7]



Progressive erosion of a plateau into hoodoos (https://en.wikipedia.org/wiki/Hoodoo_(geology))

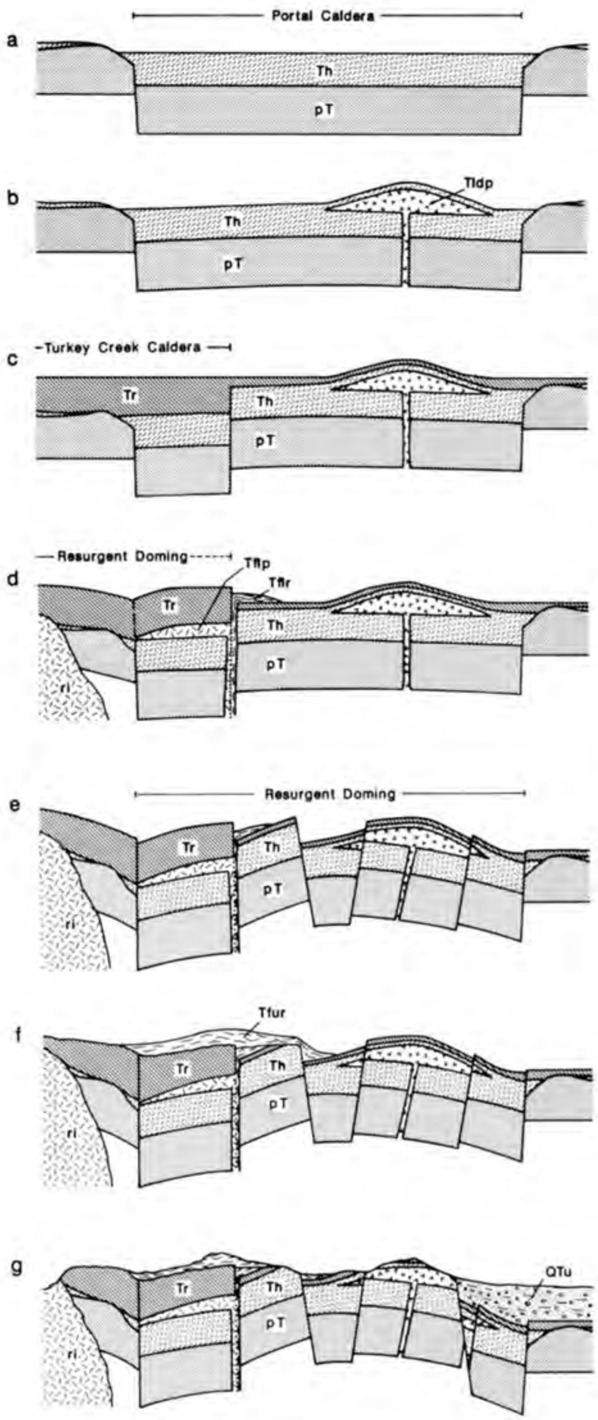
References

[1] https://www.britannica.com/science/joint-geology
[2] https://en.wikipedia.org/wiki/Joint_(geology)
[3] https://www.brycecanyon.com/bryce-canyon-geology/
[4] https://www.nationalgeographic.com/pages/article/131022-hoodoo-goblin-valley-state-park-utah-toppled-boy-scout
[5] https://www.myutahparks.com/things-to-do/natural-wonders/rock-formations-in-zion-park/
[6] https://www.arizonahighways.com/blog/hoodoo-you-do
[7] https://azgs.arizona.edu/photo/rhyolite-hoodoos-chiricahua-mountains

Turkey Creek and Portal Eruptions and Tuff

Michael Christoffersen

The Portal and Turkey Creek caldera-forming eruptions occurred in rapid succession between 25 and 28 million years ago [1, 2]. The Portal eruption occurred first and its caldera is poorly exposed – the western region is overprinted by the Turkey Creek caldera and much of the eastern region is thought to be buried below sediment filling the San Simon Valley [Bryan]. Figure 1 shows the structural development of the two calderas from the Portal eruption through to the present.



Formation of the Portal caldera
Th – tuff of the Horseshoe Canyon
pT – pre-Tertiary rocks

Intrusion of the latite of Darnell Peak
Tldp – latite of Darnell Peak

Formation of the Turkey Creek caldera-eruption
Tr – Rhyolite Canyon Tuff

Beginning of the resurgence of the Turkey Creek caldera and the intrusion of latite porphyry in the zone of overlap that lifts caldera-fill above the outflow sheet of Tr
Tflp – porphyritic latite member, Fife Canyon Volcanics
Tflr – lower rhyolite member, Fife Canyon Volcanics

Resurgent doming of the Portal caldera

Eruption of the upper rhyolite member of the Fife Canyon volcanics
Tfur – upper rhyolite member, Fife Canyon Volcanics

Basin and Range faulting and erosion produces present day topography
QTu – Quaternary deposits, undifferentiated

Figure 1 : Structural development of the Chiricahua landscape, modified from [1]

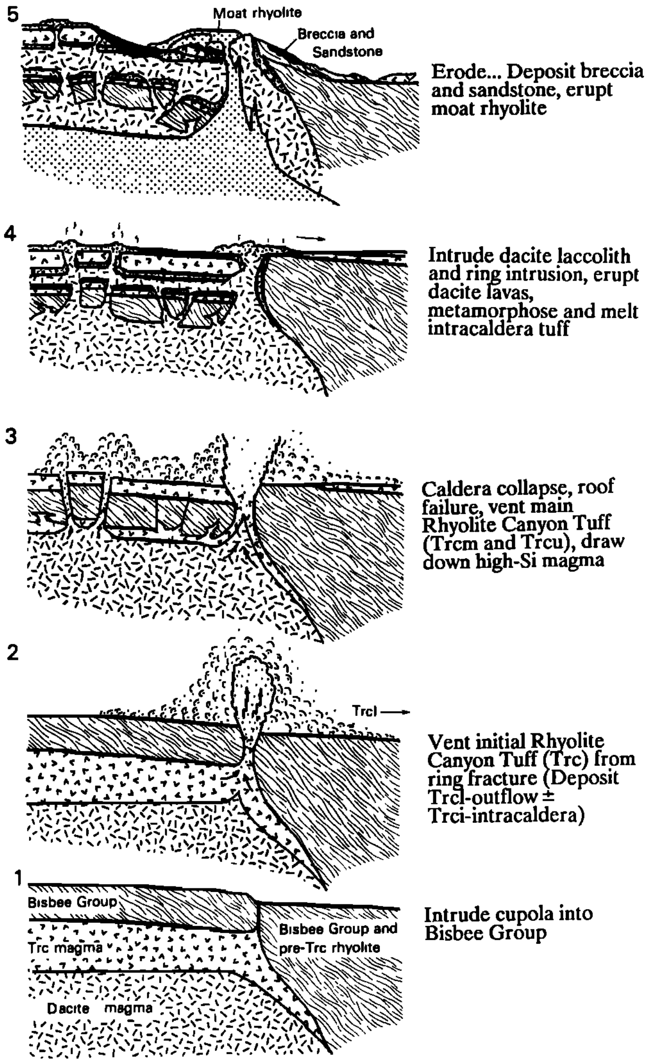
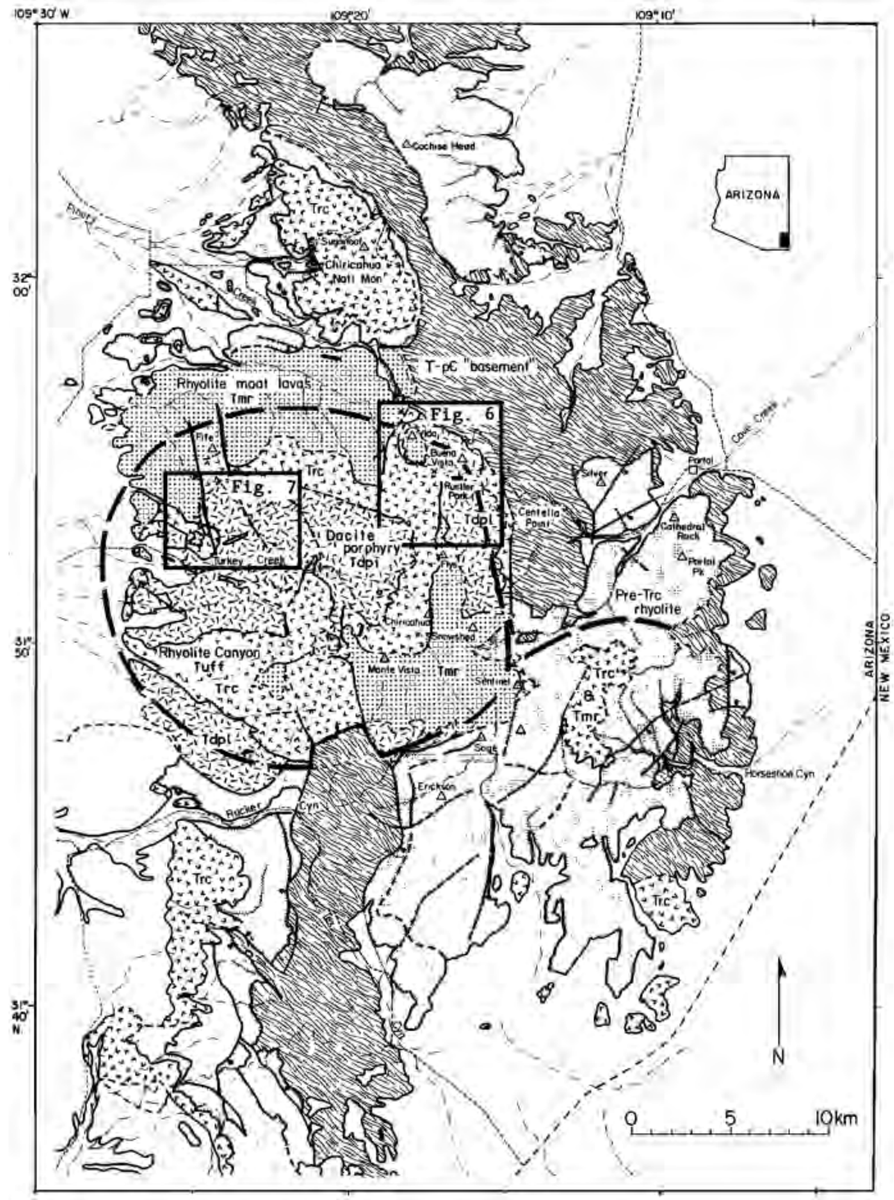
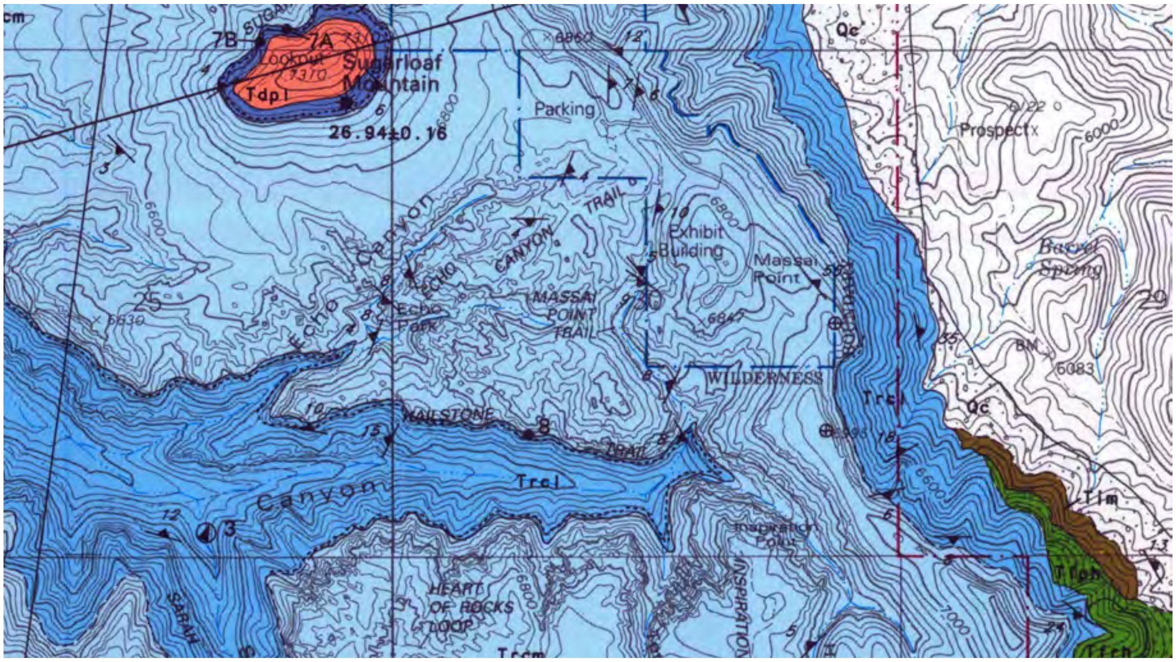


Figure 2 : Proposed structural evolution of the Turkey Creek Caldera, what would have occurred during step c and d of Figure 1. Note that chronology is bottom to top. Trc(l/m/u) are the lower, middle, and upper members of the Rhyolite Canyon Tuff, respectively. From [2].

Figure 3 : Regional geologic map showing relationship of Turkey Creek and Portal calderas (bold dashed lines) to the Chiricahua National Monument. From [2].





Outflow facies Rhyolite Canyon Tuff (Oligocene)

Light-gray, typically pumice-rich and lithic-poor, moderately crystal-rich (15–25 percent) quartz-sanidine rhyolite (76–78 weight-percent SiO_2) ash-flow tuff erupted from the Turkey Creek caldera (Marjaniemi, 1969; Latta, 1983; Pallister and others, 1990; du Bray and Pallister, 1991). Divided into intracaldera and outflow facies; intracaldera facies exposed south of the map area. Outflow facies consists of lower, middle, and upper members, which are separated by ash-cloud and surge deposits (figure 3). Phenocrysts composed almost entirely of sanidine and quartz; sanidine is typically more abundant (ratios vary from 2:1 to about 1:1). Sanidine is chatoyant, yielding a bluish luster in sunlight; cryptoperthitic (approximately Ab_{50}-Or_{50}); and it forms subhedral, lath-shaped phenocrysts, typically 1–4 mm in length. Quartz is rounded and embayed; 1–3 mm in diameter. Also contains accessory opaque oxide minerals and trace amounts of clinopyroxene, biotite, hornblende, zircon, and apatite. Eutaxitic and vitroclastic; locally spherulitic. Most has undergone granophyric vapor-phase recrystallization. Radiometric ($^{40}Ar/^{39}Ar$) ages for sanidine samples from outflow facies are 26.94±0.16 million years and 26.93±0.12 million years for upper and lower members, respectively. Composite thickness of entire outflow facies in Chiricahua National Monument about 1,600 feet

Trco **Outflow facies, undivided**—Most exposures probably equivalent to middle member

Trcu **Outflow facies, upper member**—White, ash-rich surge beds overlain by gray, densely to moderately welded tuff. Surge beds cut by vertical fines-depleted pipes (fossil fumaroles) and overprinted by low-angle secondary Liesegang bands (figure 7). Trace augite, zircon, and biotite tend to be more common than in most samples of lower and middle members. Welded tuff contains both white fiamme and dark-gray to maroon lensoidal masses of sanidine-megacrystic rhyolite, thought to represent poorly vesiculated magma clots. Chemically equivalent to voluminous intracaldera facies Rhyolite Canyon Tuff, which contains similar megacrystic magma clots at high stratigraphic levels. Uppermost 20 feet of member is moderately to poorly welded and poorly exposed. Exposed principally as erosional outlier near top of Sugarloaf Mountain, although ash-rich zone and overlying tuff that contains sparse megacrystic magma blebs also exposed in northwest part of map area. Thickness 80 feet at Sugarloaf Mountain

Top of surge beds

Trcm **Outflow facies, middle member**—Voluminous, gray, densely welded, pumiceous ash-flow tuff. Prominent vertical columns (hoodoos) produced by erosion along joint planes in this member. Jointing attributed primarily to contraction related to cooling (Hall, 1993). Internally homogeneous; however, slight variation in welding and weathering profile suggest member formed from multiple ash flows that were erupted in rapid succession and cooled together. Base locally marked by a 0–3-foot-thick section that consists of pumiceous ash-flow, ash-cloud, and surge deposits that were welded as a result of emplacement of the overlying main body of the middle member (figure 4). The middle member overlies the white, poorly welded, top of lower member. Thickness 1,050 feet at Sugarloaf Mountain where top exposed

Vitrophyre—Black perlitic glass locally exposed at base of the middle member where it directly overlies basement rocks of Faraway Ranch Formation in western part of Monument. Perlitic glass not present at base of middle member in central part of outcrop area where middle member is thick and overlies lower member. Vitrophyre typically less than 10 feet thick

Trcl **Outflow facies, lower member**—Pumiceous and locally lithophysal ash-flow tuff and related ash-cloud deposit. Consists of red-brown densely welded lower zone and gray moderately welded middle zone. Middle zone grades upward into white, pumice-bearing, poorly welded ash-cloud deposit. Thickness 0–600 feet; forms a wedge that thickens to south and east

Our stops on this trip will not take us to the Turkey Creek or Portal calderas. We will visit the outflow facies of the Rhyolite Canyon Tuff, material produced by the Turkey Creek eruption that settled outside of the caldera. Three eruptive phases produced the three members of the Rhyolite Canyon Tuff.

Figure 4 : (Top) Geologic map of the Massai Point and Echo Canyon area along with (left) unit descriptions of the outflow facies of the Rhyolite Canyon Tuff, modified from [3]

References

[1] Bryan, R. C. (1989) *Mid-Tertiary volcanism in the eastern Chiricahuas: The Portal caldera.* New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 153-157.

[2] du Bray, E. A. and Pallister, J. S. (1991) *An Ash Flow Caldera in Cross Section: Ongoing Field and Geochemical Studies of the Mid-Tertiary Turkey Creek Caldera, Chiricahua Mountains, SE Arizona.* Journal of Geophysical Research, vol. 96, no. B8, p. 13,435-13,457.

[3] Pallister, J. S. and du Bray, E. A. (1997) *Guide to the Volcanic Geology of Chiricahua National Monument and Vicinity, Cochise County, Arizona*. Unites States Geological Survey.

Arizona's Copper Deposits

Common copper minerals

Azurite ($Cu_3(CO_3)_2(OH)_2$)

Malachite ($Cu_2CO_3(OH)_2$)

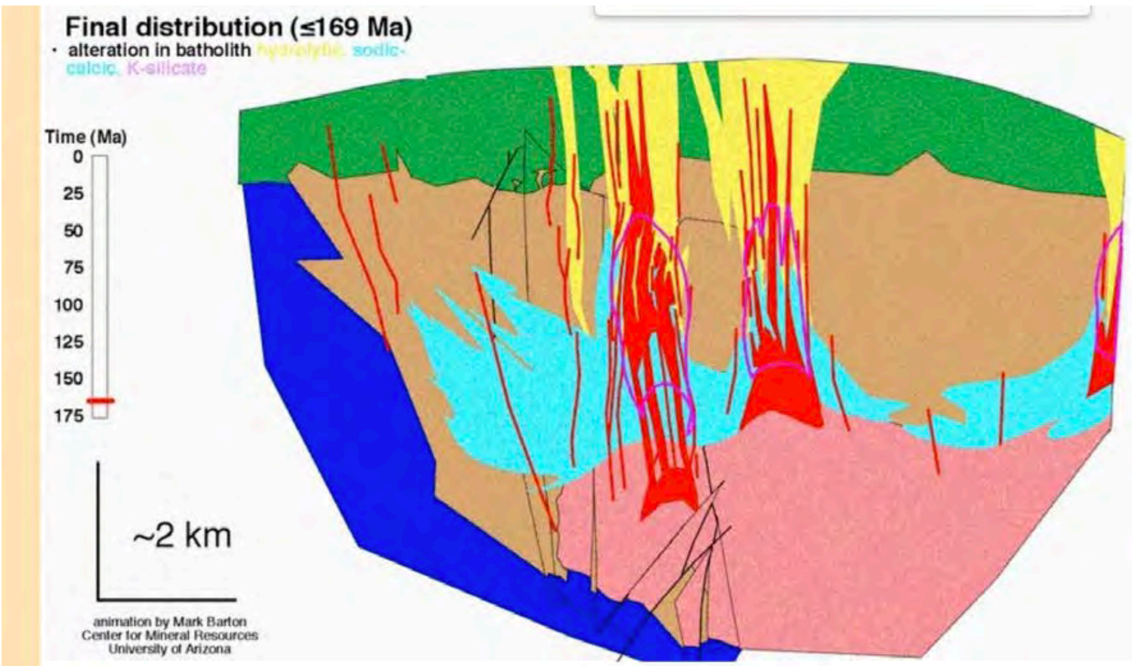
Chalcopyrite ($CuFeS_2$)

Bornite (Cu_5FeS_4)

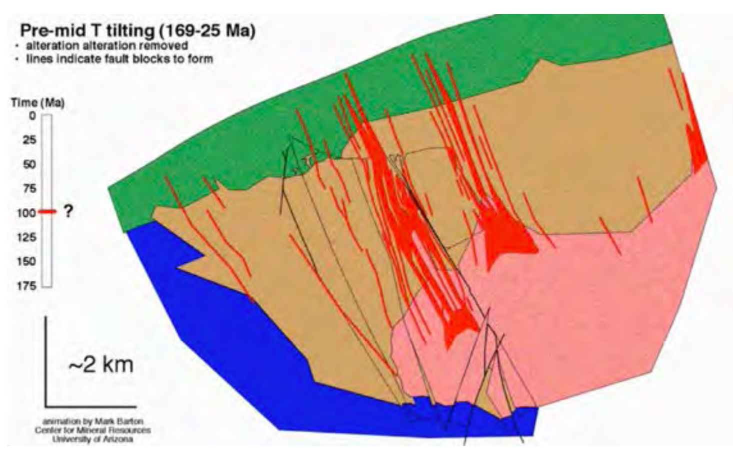
Turquoise ($CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$)

Formation of the deposits

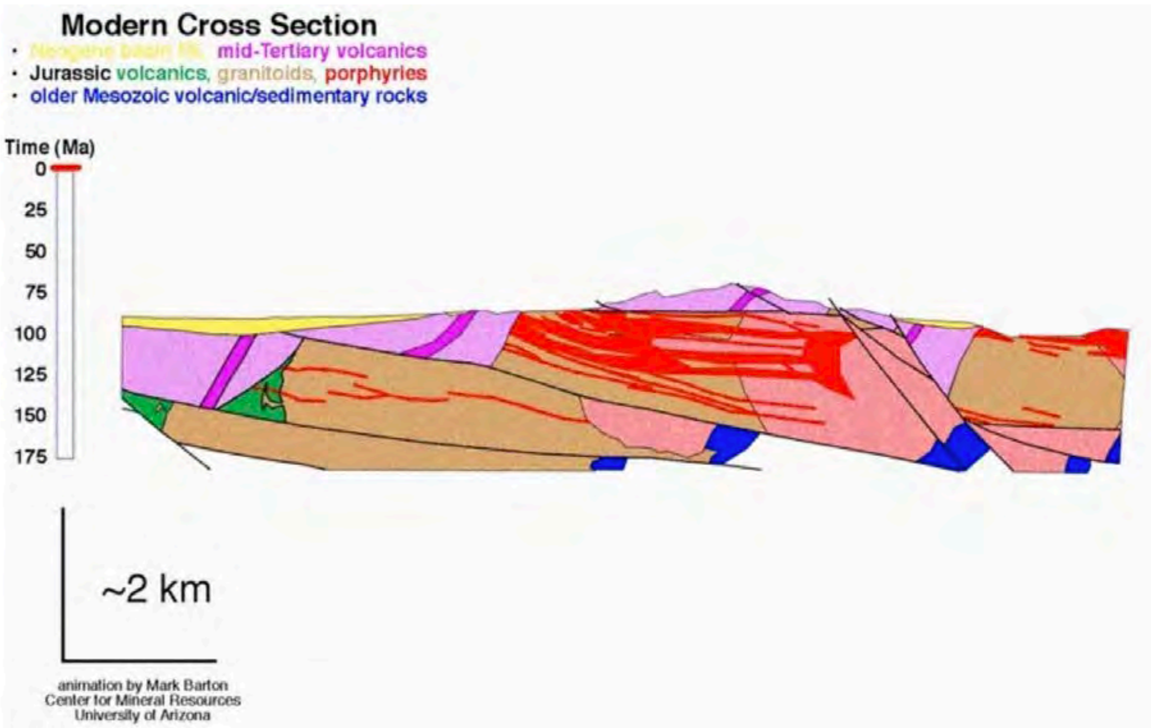
Most of the copper deposits in Arizona are **porphyry** (por-free) deposits, which are normally formed from the precipitation of copper during the cooling of shallow dikes (<~5 km deep) and the interaction between associated hydrothermal fluids. These are usually sourced from larger magmatic reservoirs at ~10-15km depth. The particular magmatic events that resulted in these copper deposits in Arizona are thought to have occurred in the middle Mesozoic era (~70-200 million years ago).



The porphylic copper is typically first formed as sulfides, e.g., chalcopyrite. However, some of these deposits are eventually exposed to the surface elements after years of erosion or tectonic activity, and then weathered and leeched into the subsurface, where they recrystallize into their hyroxide, carbonate, and phosphate forms, e.g. turqoise and

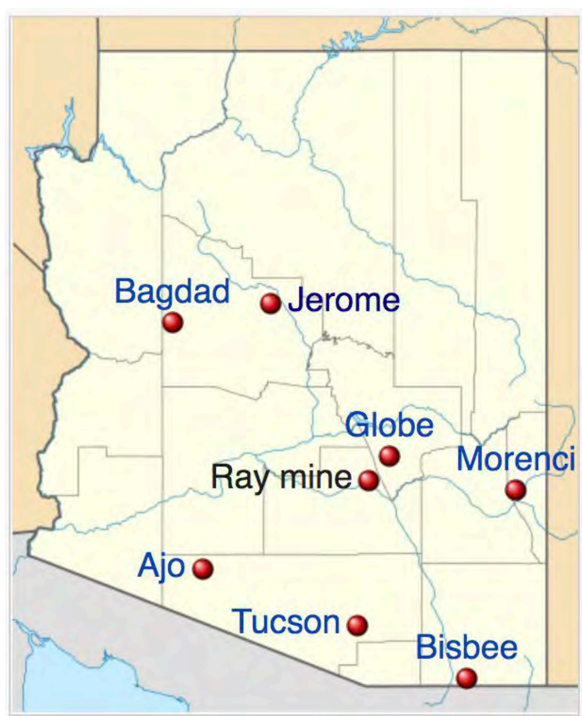


azurite. These are pretty, but are sometimes not as profitable as the sulfide versions below. In Arizona, however, due to the tectonic history of the region as well as the arid climate, copper deposits have been more well exposed and preserved than most locations on the Earth.



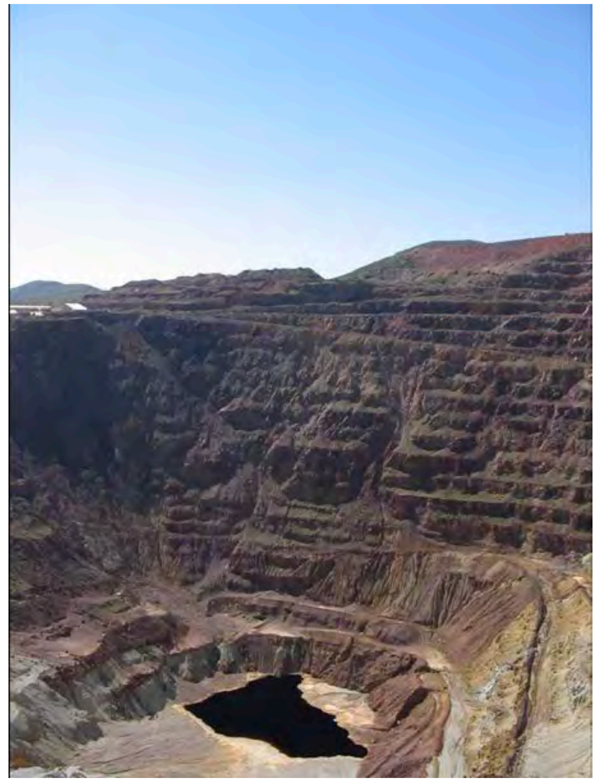
History and Present State:

High purity copper deposits found near the surface have been used by Native Americans since antiquity to decorate skin and textiles. While copper ores were also found by the Spaniards, no major mining operations were conducted due to their preference of gold and silver, as well as the nature of the Arizonan desert preventing economical mining. It wasn't until the influx of prospectors spurred in part by the Gadsden Purchase and the Southern Pacific Railroad in the mid to late 1800s that the region's enormous



Past and Present Mining Centers

potential for copper mining were discovered. Now, Arizona produces ~60% of the total U.S. copper, whose notable byproducts include gold, silver, and molybdenum.



Lavender Pit, Bisbee

Operational (top 3 ranked by 2012 output):

1. Morenci
2. Ray
3. Bagdad

Discontinued:

Ajo (1750-1983)

Bisbee (1880-1975)

Globe (1879-1931)

Jerome (1880-1953)

Climate Change and Environmental Instability in the Chiricahuas

Although there is consensus regarding the broad-scale ecological consequences of global climate change in desert ecosystems and the American Southwest, the impacts on localized spatial and temporal scales are difficult to predict. Climate change and other anthropogenically caused environmental impacts have presented numerous threats to the Chiricahuas including invasive species, habitat fragmentation, drought, and wildfires.

Arizona Sky Islands are some of the most biodiverse ecosystems in Arizona and in the United States largely due to the convergence of several biogeographic regions including the Chihuahuan Desert and Desert Grasslands from the east, the Sonoran Desert from the west, the temperate forests from the Rocky Mountains from the North, and the woodland biome of the Sierra Madres from the south (Dimmitt et al. 2015). Additionally, the topographic variability throughout the Chiricahuas provides a wide mix of microclimates and niches. The drier desert grassland ecosystem at the base of the Chiricahuas transitions to high desert chaparral at mid-elevations. Riparian forests cluster along streambeds and in canyons. The higher elevation areas support cold-adapted, wetter woodland ecosystems including Arizona pine, Douglas-fir, and many other species. Due to these varied biogeographical regions, climate change can have widespread, unpredictable, and detrimental effects on the local ecosystem.

Wildfires

Wildfires are a natural part of many ecosystems and part of a restorative cycle that returns vital nutrients to the soil, clears dead or dense plant life at the surface, and can be a part of many plants' reproductive cycle. However, decreasing precipitation and harsher summers can exacerbate the intensity and scope of wildfires, particularly in desert regions. Recent work has shown that there has been a dramatic decline in tree and overall ecosystem regeneration in different forests in the last century following fires (Stevens-Rumann et al. 2017). Starting in the early 19th century, cattle grazing disrupted the natural process of widespread, but low intensity wildfires in southern Arizona by modifying the landscape. This disruption combined with

Fig. 1: (Left) Satellite image of the Horseshoe 2 fire in May 2011 (NASA) (Right) Aerial view of the Horseshoe 2 fire (NPS).

Fig. 2: Percent of biogeographic regions in the Chiricahuas before and after the 2011 Horseshoe 2 fire (Barton and Poulos 2018)

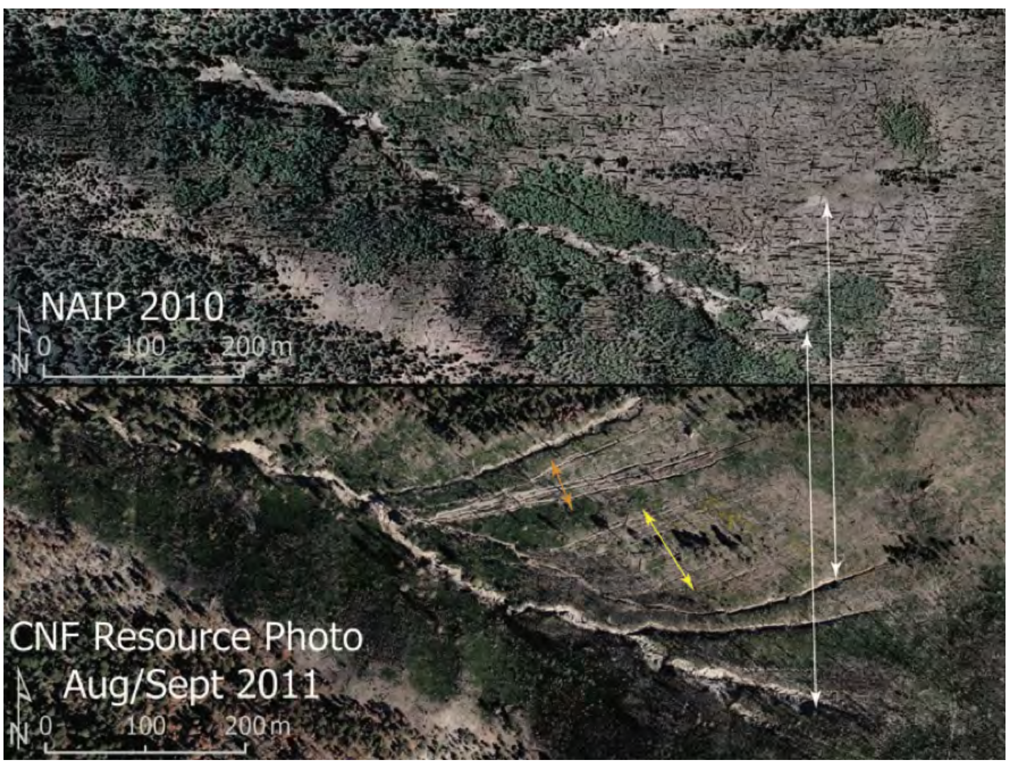


Fig. 3: Example of post fire erosion after the Horseshoe 2 fire including rills (orange), new gullies (yellow), and older gullies from the 1994 fire (white) (Youberg et a. 2013).

aggressive fire suppression by the United States Forest Service (USFS) resulted in fuel accumulation which has led to less frequent, but much more catastrophic fires (Swetnam 2005).

Fire initiation (typically by lightning strikes during monsoon season) and spread are exacerbated by warmer, drier, windier conditions that reduce moisture in fuel and increase flammability (Falk 2013). Consequently, climate change is projected to increase the length and severity of wildfire season in the Arizona Sky Islands and the Chiricahuas.

The Horseshoe 2 fire in 2011 was one of the largest fires in Arizona history, burning 222,954 acres (Fig. 1 and 2). The "Fire Suppression Era" resulted in many layers of shrubs, trees, and grass. The Horseshoe 2 fire dramatically reversed this trend, resulting in closed woodlands to be converted into open chaparral (Fig. 2). The fire also resulted in significant post-fire monsoon erosion which led to reduced nitrogen and other nutrients in the soil (Youberg et al. 2013). Fig. 3 shows partially infilled gullies before and after the fire, and erosion from monsoon storms in August, 2011. These eroded gullies have the potential to create debris flows which can destroy vegetation and infrastructure (Dimmitt et al. 2015).

Drought, Warming and Habitat Fragmentation

Total precipitation in the Chiricahuas is decreasing due to climate change (Fig. 4). On top of wildfires, drought and warming can cause widespread changes to the ecological makeup of an environment. For example, rising temperatures are increasing aridity, so biological communities are shifting higher in elevation and farther north. The National Park Service expects that tropical communities from Mexico (jaguars, parrots, etc.) will migrate into the Chiricahuas. These

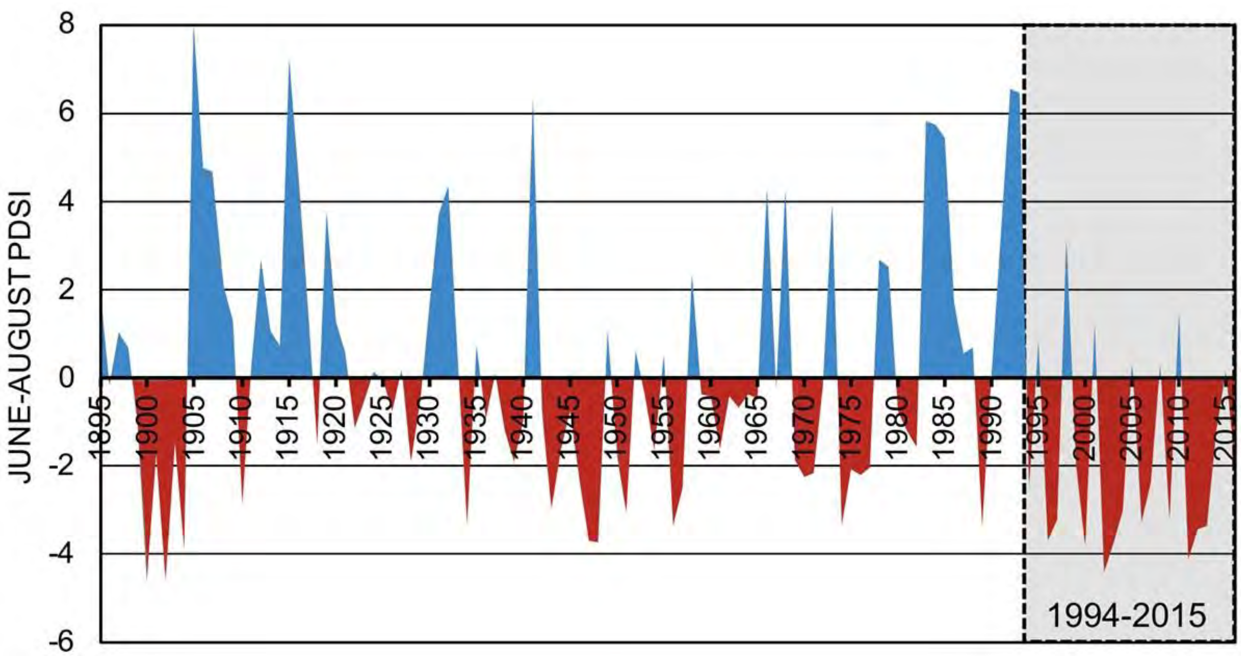


Fig. 4: Palmer Drought Severity Index in the Chiricahuas vs. years starting in 1895. This combines precipitation levels each year with the evaporative effects of temperature, indicating the amount of moisture available for plants. 1994 is the start of the "Fire Intensification Era" in the Arizona Sky Islands, culminating with one of the driest years on record in 2011 and the Horseshoe 2 fire (Barton and Poulos 2018).

shifts may cause regional extinctions of species that are already at their height limits and may cause habitat fragmentation as certain high elevation regions can be cut off from others. (Dimmitt et al. 2015).

Changing temperature can also cause secondary and tertiary ecological effects. For example, there are many dead and dying pines and junipers in the Chiricahuas due to bark beetle infestations (Fig. 5). Bark beetle populations increase when winters are mild and not sufficiently cold to limit growth. Pines and junipers are vulnerable to infestation when under drought stress, which has exacerbated the loss. Changing precipitation patterns and average temperatures may also encourage the introduction of invasive species such as bufflegrass (Fig. 6).

Fig. 6: (Left) The yellowing pines in the Chiricahuas are dying from bark beetle infestation (Dimmit et al. 2015). (Right) Bufflegrass is an invasive species that has spread uncontrollably across southern Arizona. It was originally brought from Africa and the Middle East in the 1930s for cattle grazing due to its drought tolerance (NPS).

References

Barton A, Poulos H. (2018). A Sky Island Fire Ecology Primer, with a Focus on Chiricahua National Monument: A Reference Document for the National Park Service.

Dimmitt, M. A., R. C. Brusca, K. Krebbs, C. L. McIntyre, J. Viers, C. Filippone and A. Berry. (2015). Chiricahua National Monument, Coronado National Memorial, and Fort Bowie National Historic Site: natural resource condition assessment 2015 update. Natural Resource Report NPS/SODN/NRR—2015/1080. NPS, Fort Collins, Colorado.

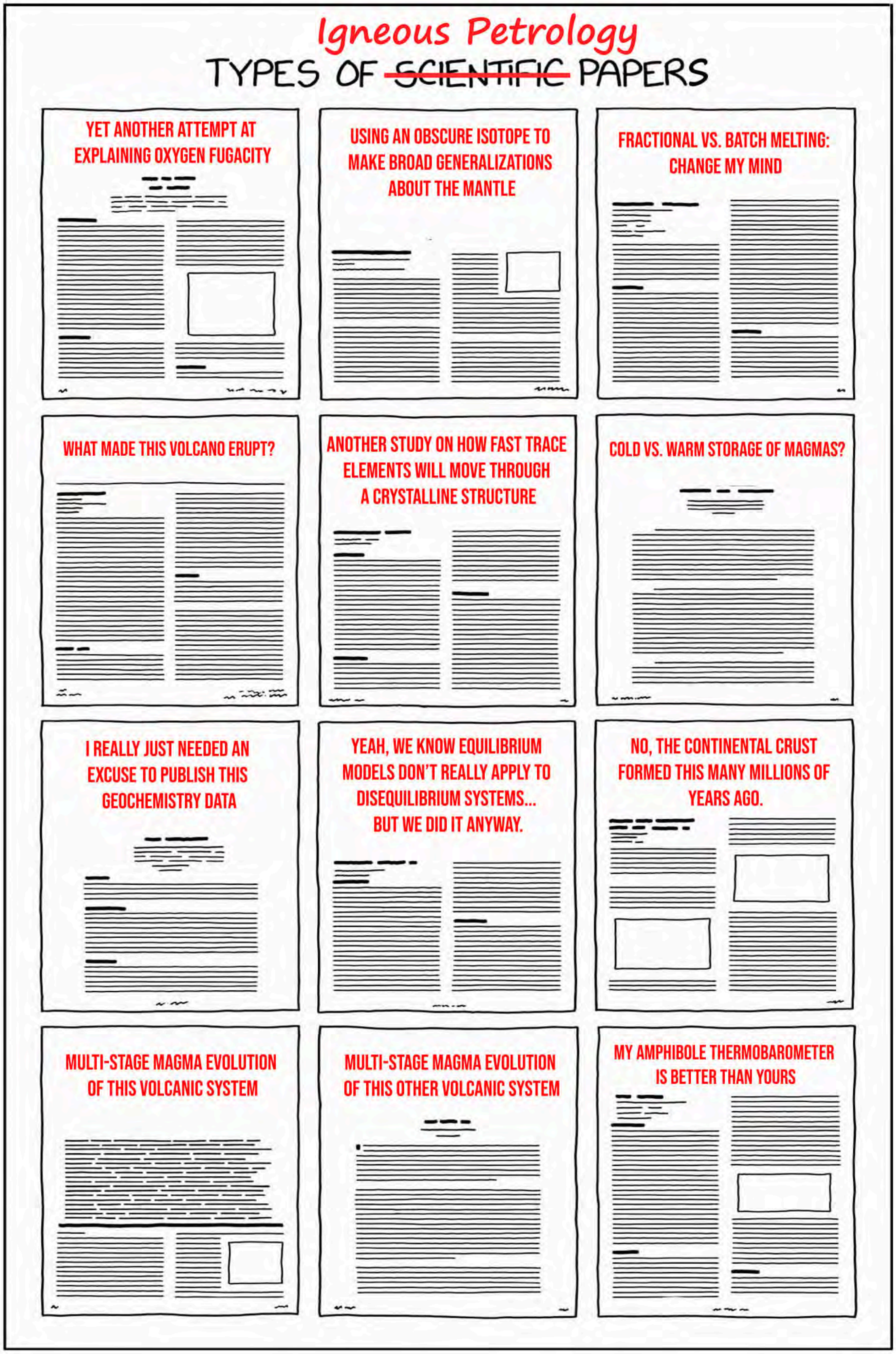
Falk, D.A. (2013) Are Madrean ecosystems approaching tipping points? Anticipating interactions of landscape disturbance and climate change. USDA Forest Service Proceedings RMRS.

Stevens-Rumann CS, Kemp KB, Higuera PE, Harvey BJ, Rother MT, Donato DC, Morgan P, Veblen TT (2018) Evidence for declining forest resilience to wildfires under climate change. Ecol Lett 21(2):243–252

Swetnam, T.W., (2005). Fire histories from pine-dominant forest in the Madrean Archipel- ago. Proceedings RMRS-P-36. USDA Forest Service Proceedings RMRS-P-36, pp. 35–43.

Youberg, Ann; Neary, Daniel G.; Koestner, Karen A.; Koestner, Peter E. (2013). Post-wildfire erosion in the Chiricahua Mountains. USDA Forest Service Proceedings RMRS-P-67.


Janelle Shane @JanelleCShane · 2d
attention, visible on an iceland volcano cam right now is a happy lava frog
youtube.com/watch?v=-A182z...
25
735
2,759
Janelle Shane @JanelleCShane · 2m
someone has upset the lava frog


Igneous Petrology
TYPES OF ~~SCIENTIFIC~~ PAPERS
YET ANOTHER ATTEMPT AT EXPLAINING OXYGEN FUGACITY
USING AN OBSCURE ISOTOPE TO MAKE BROAD GENERALIZATIONS ABOUT THE MANTLE
FRACTIONAL VS. BATCH MELTING: CHANGE MY MIND
WHAT MADE THIS VOLCANO ERUPT?
ANOTHER STUDY ON HOW FAST TRACE ELEMENTS WILL MOVE THROUGH A CRYSTALLINE STRUCTURE
COLD VS. WARM STORAGE OF MAGMAS?
I REALLY JUST NEEDED AN EXCUSE TO PUBLISH THIS GEOCHEMISTRY DATA
YEAH, WE KNOW EQUILIBRIUM MODELS DON'T REALLY APPLY TO DISEQUILIBRIUM SYSTEMS... BUT WE DID IT ANYWAY.
NO, THE CONTINENTAL CRUST FORMED THIS MANY MILLIONS OF YEARS AGO.
MULTI-STAGE MAGMA EVOLUTION OF THIS VOLCANIC SYSTEM
MULTI-STAGE MAGMA EVOLUTION OF THIS OTHER VOLCANIC SYSTEM
MY AMPHIBOLE THERMOBAROMETER IS BETTER THAN YOURS

The San Bernardino volcanic field, Arizona

Joana Voigt

1. San Bernardino Valley

The San Bernardino Valley is located in the southeast of Arizona, southwest of New Mexico, and northern Sonora in Mexico (figure 1 and 2; [1]). The valley is northeast by southwest-trending and has a north-south extension of 34 km and an east-west width of 29 km. It is bounded by four mountain ranges: the Peloncillo mountains towards the east and the Perilla, Pedregosa, and Chihuahua mountains in the west and northwest. Tectonically, the valley sides are bounded by normal faults creating an asymmetric graben (a crustal block that subsided). Geologically, the valley is described as a semi-bolson (a type of sedimentary basins in the desert that drains into a playa; [2]). The valley is mainly made of three geologic units/elements: sedimentary rocks, Mid-Tertiary eruptive features, and Tertiary to Quaternary lava flow-fields and alluvial fans [2]. Associated with the extension of the region (graben forming) volcanic activity started 3 Ma ago [1, 2].

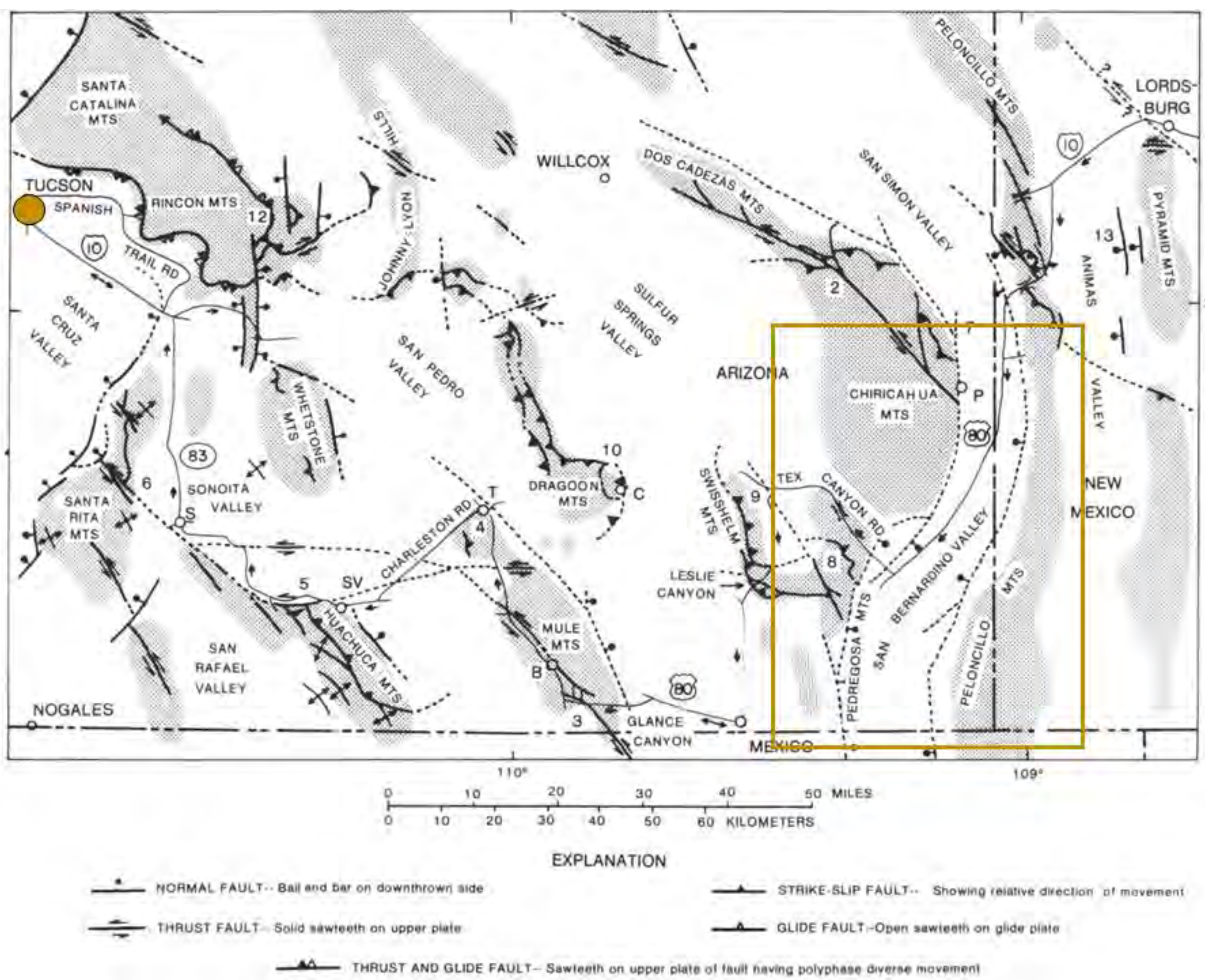


Figure 1 Sketch illustrates the tectonic setting of the southeast of Arizona and southwest of New Mexico. Box roughly outlines the San Bernadino volcanic field and its surrounding shown in

Figure 2 and dot marks Tucson, which is ~180 km to the northwest. Images is modified from Drewes and Thorman, 1978 [3].

2. San Bernardino volcanic field

2.1 Location, overview, and volcanic features

Figure 2 Perspective overview of the San Bernardino volcanic field with the Paramore maar crater and its surrounding mountains: with Chihuahua in the northwest, Peloncillo in the east, Perilla and Pedregosa mountains in the west. Labels are overlain on a Google Earth mosaic.

The San Bernadino volcanic field dominates the northern third of the San Bernadino valley and includes ~130 volcanic vents with basaltic lava flow-fields, cinder cones, and maar volcanoes [2]. The most prominent volcanic features are pyroclastic cones—also referred to as cinder cones or scoria cones.

Cinder cones are steep sided (30–40 degrees) commonly symmetrical hills made up of loose pyroclastic materials including ash, cinder (or scoria), and clinker. The cones are formed by monogenetic explosive eruptions or lava fountaining (gas-rich magma). Towards the end, the eruption often changes its characters and gas-depleted magma quietly gets emplaced as lava flows. Lava flows are often associated with cinder cones but mainly occur on the base of the volcano, it rarely makes it to the summit due to the density differences between the low-density cinders and high-density molten basalt and the loose cinder are also too weak to support the pressure of the rising lava. In the San Bernadino volcanic field, the lava flows are typically a few square kilometers [1].

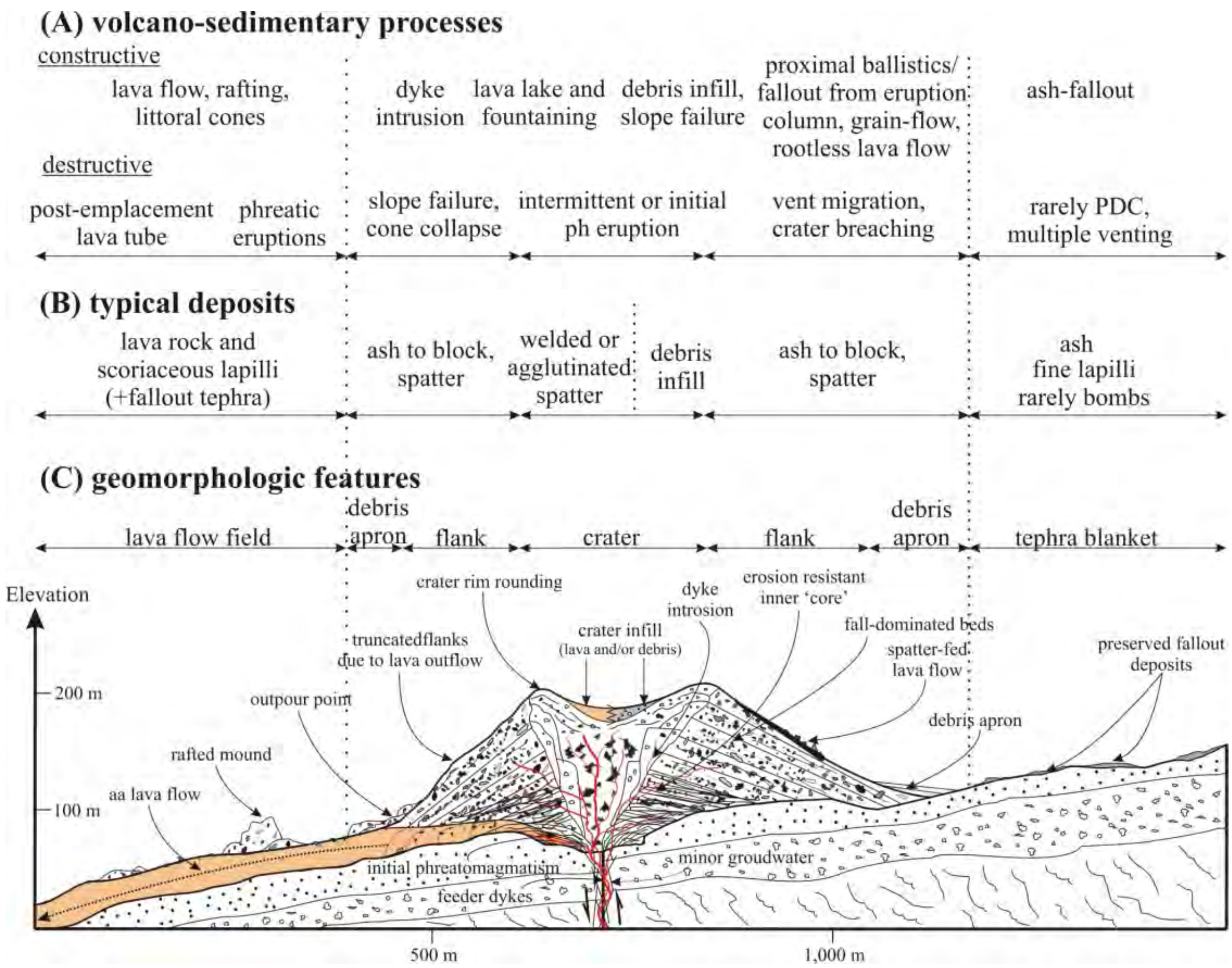


Figure 3 Schematic sketch of a cinder cones with (A) volcano-sedimentary processes, (B) typical deposits, and (C) geomorphological features. From Kereszturi and Németh (2012) [5].

2.2. Sources and ages

Similar to other volcanic fields in the Basin and Range province, the San Bernardino volcanic field is mainly composed of alkali-olivine and basanitic basalts with amounts of xenoliths and Megacrysts commonly including plagioclase, pyroxene, amphibole, and spinet [1, 5].

In general, alkali-olivine basalts are likely sourced from partial melting within the mantle. Evan and Nash 1987 [6] suggested that the source region of the San Bernardino basalts was at a depth of ~67 km, with local magma reservoirs at around 30–46 km (derived from megacrysts within the basalt).

Based on radiometric K-Ar ages dating, the oldest basalt is 3.30 ± 0.12 Ma old and is located at a mesa north of the Joe Glenn ranch (Pedregosa mountains; [1]). The second youngest lava flow is 0.54 ± 0.05 Ma old and is not associated with any pyroclastic deposits and is fissure-fed [1]. The youngest flow has an age of 0.27 ± 0.05 Ma and can be found north of Cinder hill [1].

3. References

[1] D. J. Lynch, 1978: The San Bernadino volcanic field of southeastern Arizona. In Land of Cochise (Southeastern Arizona), Callender, J. F.; Wilt, J.; Clemons, R. E.; James, H. L.; [eds.], New Mexico. Geological Society 29th Annual Fall Field Conference Guidebook, 348 p.

[2]https://written-in-stone-seen-through-my-lens.blogspot.com/2015/05/anatomy-of-cinder-cone-roadcut-in-land.htm

[3] H. D. Drewes and C. H. Thorman, 1978: Major geologic structures between Lordsburg, New Mexico, and Tucson, Arizona, pp. 291-295, in: Land of Cochise (Southeastern Arizona), Callender, J. F.; Wilt, J.; Clemons, R. E.; James, H. L.; [eds.], New Mexico Geological Society 29th Annual Fall Field Conference Guidebook, 348 p.

[4] G. Kereszturi and K. Németh (2012): Monogenetic basaltic volcanoes: genetic classification, growth, geomorphology and degradation. In Updates in Volcanology-New Advances in Understanding Volcanic Systems.

[5] W. P. Leeman, and J. J. W. Rogers, 1970, Later Cenozoic alkali olivine basalts of the Basin-Range province, U.S.A.: Contr. Mineral. and Petr., v. 25, p. 1-24.

[6] S. H. Evans, and W. P. Nash, 1978, Quaternary mafic lavas and ultramafic xenoliths from southeastern Arizona [abs.] Geol. Soc. Amer. Abs. with Programs, v. 10, p. 216.

Maar Volcanoes

Mackenzie Mills
PTYS 590
Fall 2021

What is a Maar volcano?

A Maar volcano is a broad volcanic crater which forms from explosive episodes when subsurface magma flows intrude and interact with buried groundwater reservoirs[1,2,3]. It is also possible for lava flows to interact with lakes to form maar volcanoes. There may be an associated cone or ring of debris surrounding the crater[1,2,3]. After formation, the crater often fills with water, forming a lake. Figure 1 shows a maar volcano in the Pinacate volcanic field. The main crater is in the center of the debris ring, and is the primary feature that gives the maar volcano its name. Figure 1 also shows the debris ring surrounding the volcanic crater, labeled as "Palagonite Tuff". Another name commonly used when discussing

Figure 2: An example of a maar volcano in the Pinacate volcanic field in Arizona/Mexico[9]. The primary maar volcano is labeled, along with the debris ring that forms from episodic explosive eruptions while the maar volcano was created. There is a low-lying area near the maar crater feature where it appears to be altered by standing water. This is a ubiquitous feature for maar volcanoes because the craters, created by subterranean explosions, become low points where water collects.

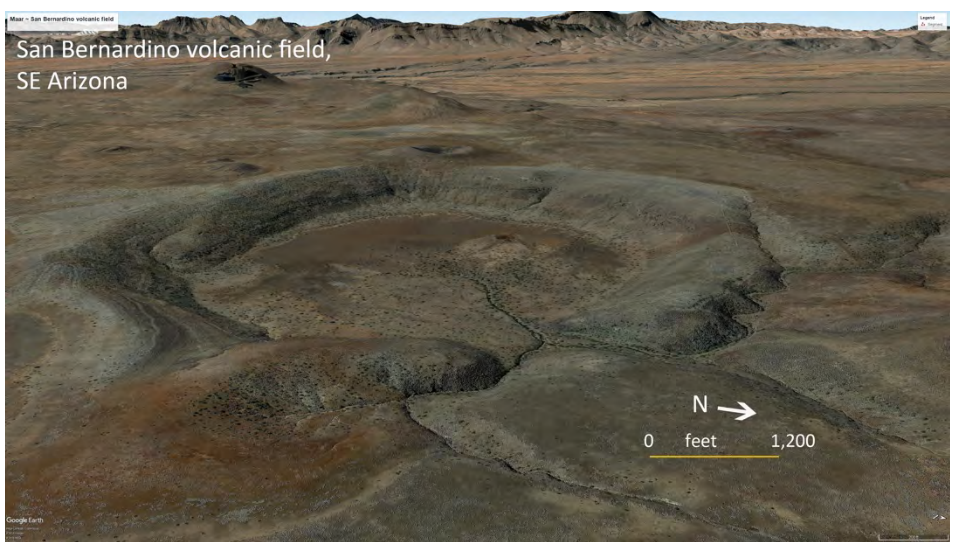


Figure 2: Another example of a maar volcano in the San Bernadino volcanic field in Arizona/Mexico[11]. The primary maar volcano is labeled, along with the debris ring that forms from episodic explosive eruptions while the maar volcano was created.

maar volcanoes or maar craters is diatreme. This is the term for an eroded maar volcanic structure[1].

What is the structure of a Maar volcano?

A Marr volcano has five primary portions of its structure[1]. These are described from the bottom of the structure to the top. The country rock in which the maar forms has a strong control on the structure of the resulting maar diatreme[4]. The first is the feeder channel/conduit, also called the diatreme, from where the magma erupts into a situation. This is the channel connected with the larger body of magma, through which episodes of magma can cause explosions.

The second is unbedded lower diatreme facies; these do not have cohesive structure and are composed primarily of erupting magma and fragments of country rock that have been emplaced through various episodes of eruptions.

The third portion is upper bedded diatreme facies. These are compositionally similar to the lower unbedded diatreme structures being made of erupting lava and pieces of country rock; however, they do differ because the upper facies are made of more country rock instead of being primarily erupting magma. These upper facies have coherent layers which tend to be oriented in similar together.

The fourth part of this structure is the Maar crater, which is often filled with post-eruptive

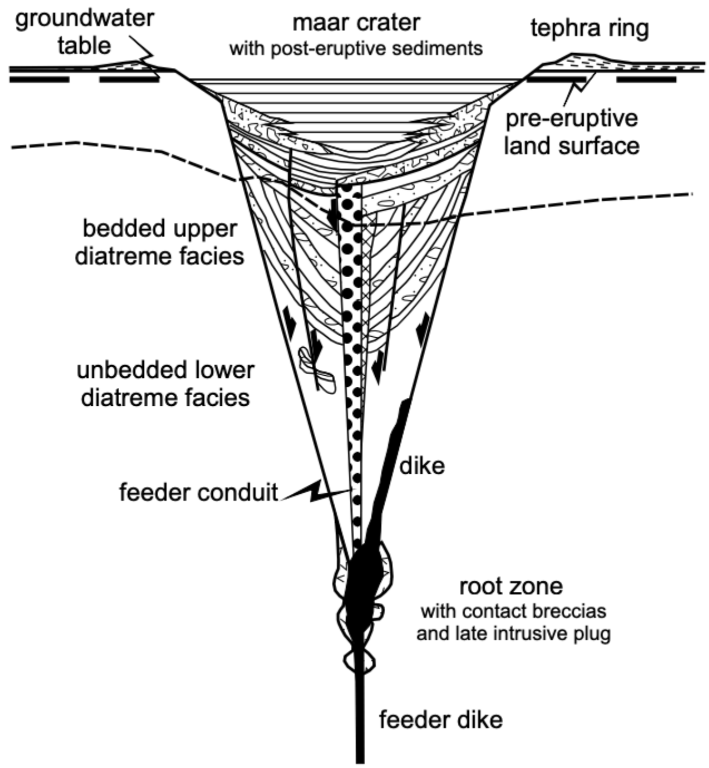


Figure 3: Shown here is a cut-away of the maar volcano feature and diatreme structure[3]. This includes the feeder dike, the unbedded lower diatreme facies, bedded upper diatreme, tephra ring, and maar crater.

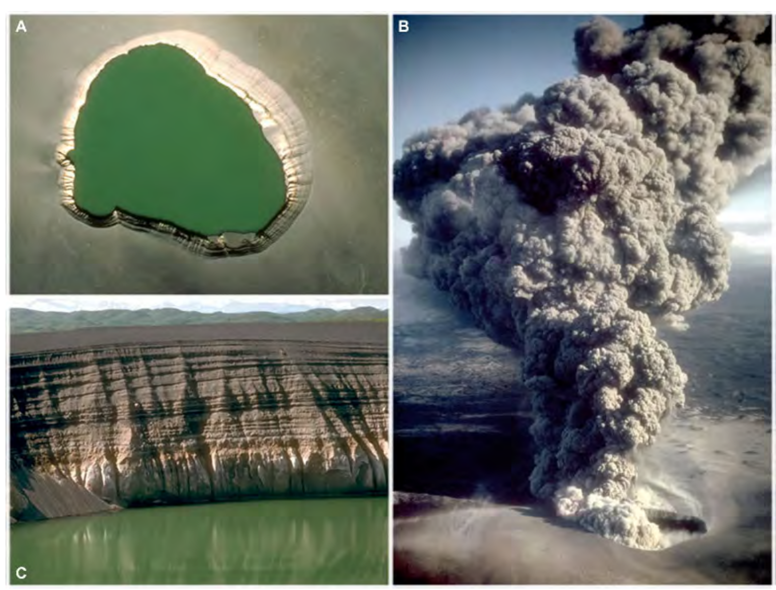


Figure 4: Shown here is an overview of the maar volcano crater, side-cut of the same crater, and an image of an explosion from a maar crater[11]. The explosion is an example of how maar craters form.

sediments that have been deposited in a lacustrine environment.

The fifth and final part of the feature is the tepha ring, or the ring of sediments ejected out of the feature and onto the surface, creating a ring/cone feature through episodic eruptions. The fourth and fifth parts of the structure are the ones that can be noticed from the surface, so they are generally the primary structures that define a Maar volcano.

Why are Maar volcanoes interesting in the geologic record?

Maar volcanoes are useful to track past subterranean groundwater deposits. These deposits wouldn't have a very significant surface effect, but the presence of the maar craters and their distributions can be an excellent tracer of where the reservoirs were. It's also possible to look at magma intrusions and where magma was spreading in the subterranean environment, assuming that groundwater was present everywhere for the magma to interact with.
On Earth, geophysical measurements can probe the structures of maar volcanoes. Gravity data has been used to probe magma volumes that have erupted out of a maar [5,6]. Maar volcanoes often display negative gravity anomalies[4]. Geophysical measurements have also been used to probe for subsurface feeder dikes; however, surprisingly, geophysical data does not probe the diatreme structure under the maar volcano [5].

Have scientists identified planetary analogs of Maar volcanoes?

Maar volcanoes could be excellent study areas for planetary objects because they represent areas

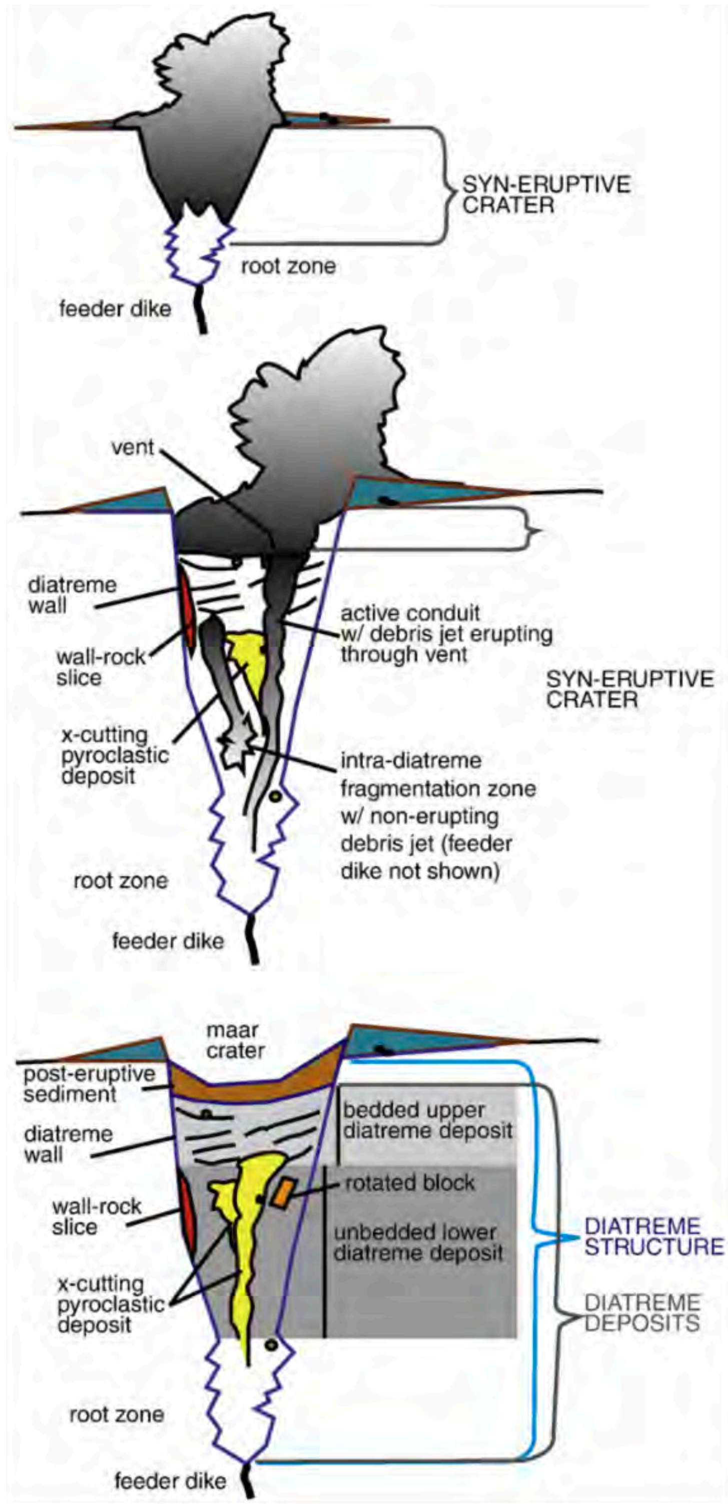


Figure 5: An example of maar volcano eruption from explosion initiation to settling of debris. The last image in this composite shows the evolved feature, created from multiple eruptions building both the crater and debris shield[6].

Figure 6: An example of the raised residual shield of tuff/debris of a maar volcano, covered in water collected after the volcano formed[6]. The central crater is not visible under the water level.

where liquid water (or a liquid of some compound) once existed in the surface or the shallow subsurface. They also are associated with feeder dikes, which can be studied for chemical and petrological evidence of the magma chamber. Understanding water reservoirs is important for planetary objects to search for extraterrestrial life. From a purely geological viewpoint, the chemical and geologic evidence of magmas on other bodies is important to understanding how they evolved. So far, maar volcanoes have been proposed as features that could be on the Moon, Venus, and Mars[7]; however, there have not been recent positive identifications of maar volcanoes. There are crater-like landforms on planetary bodies, but it is difficult to differentiate them from impact craters.

References:

1. White and Ross., 2011. Maar-diatreme volcanoes: A review, Journal of Volcanology and Geothermal Research 201, pp. 1–29.

2. Sottili et al., 2012. Origins and energetics of maar volcanoes: examples from the ultrapotassic Sabatini Volcanic District (Roman Province, Central Italy), Bull Volcanol, 74, pp. 163–186.

3. Valentine et al., 2011. Models of maar volcanoes, Lunar Crater (Nevada, USA), Bull Volcanol, 73, pp. 753–765.

4. Skácelová et al., 2012. Geophysical research on structure of partly eroded maar volcanoes: Miocene Hnojnice and Oligocene Rychnov volcanoes (northern Czech Republic), Journal of Geosciences, 55, pp. 333–345.

5. Cassidy et al., 2007. Gravity and magnetic investigation of maar volcanoes, Auckland volcanic field, New Zealand, Journal of Volcanology and Geothermal Research 159, pp. 153–163.

6. Blaikie et al., 2014. A geophysical comparison of the diatremes of simple and complex maar volcanoes, Newer Volcanics Province, south-eastern Australia, Journal of Volcanology and Geothermal Research 276, pp. 64–81.

7. Garvin, J., 2000. North Polar Region Craterforms on Mars: Geometric Characteristics from the Mars Orbiter Laser Altimeter. Icarus 144, pp. 329–352.

8. Lorenz. 2003. Maar-Diatreme Volcanoes, their Formation, and their Setting in Hard-rock or Soft-rock Environments, GeoLines 15, pp. 72-83.

9. AZ Geological Survey, https://twitter.com/AZGeology/status/528554585095303168

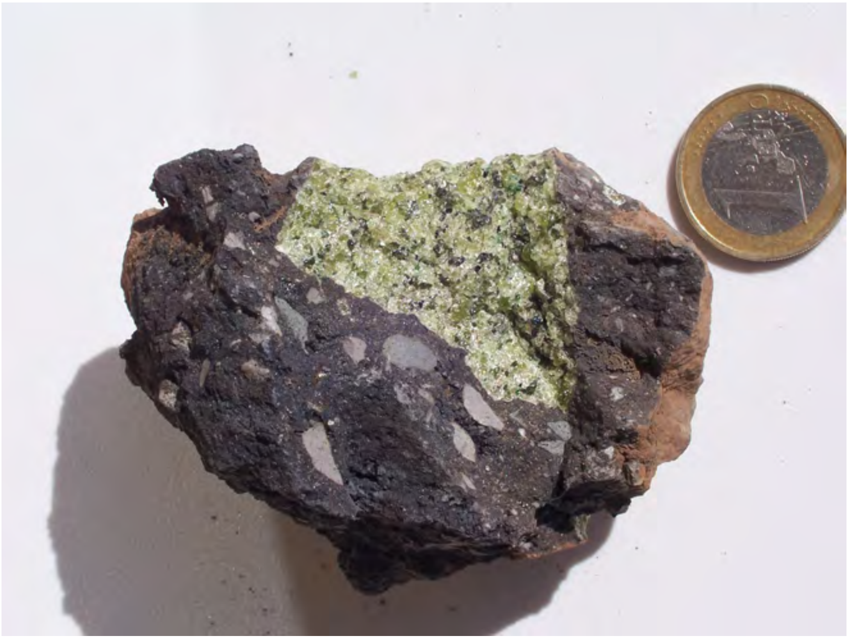
10. Maar volcano of the San Bernardino volcanic field, https://azgs.arizona.edu/photo/maar-volcano-san-bernardino-volcanic-field

11. Maars and Phreatic Eruptions, geology.com, https://geology.com/stories/13/maar/

Mantle Xenoliths

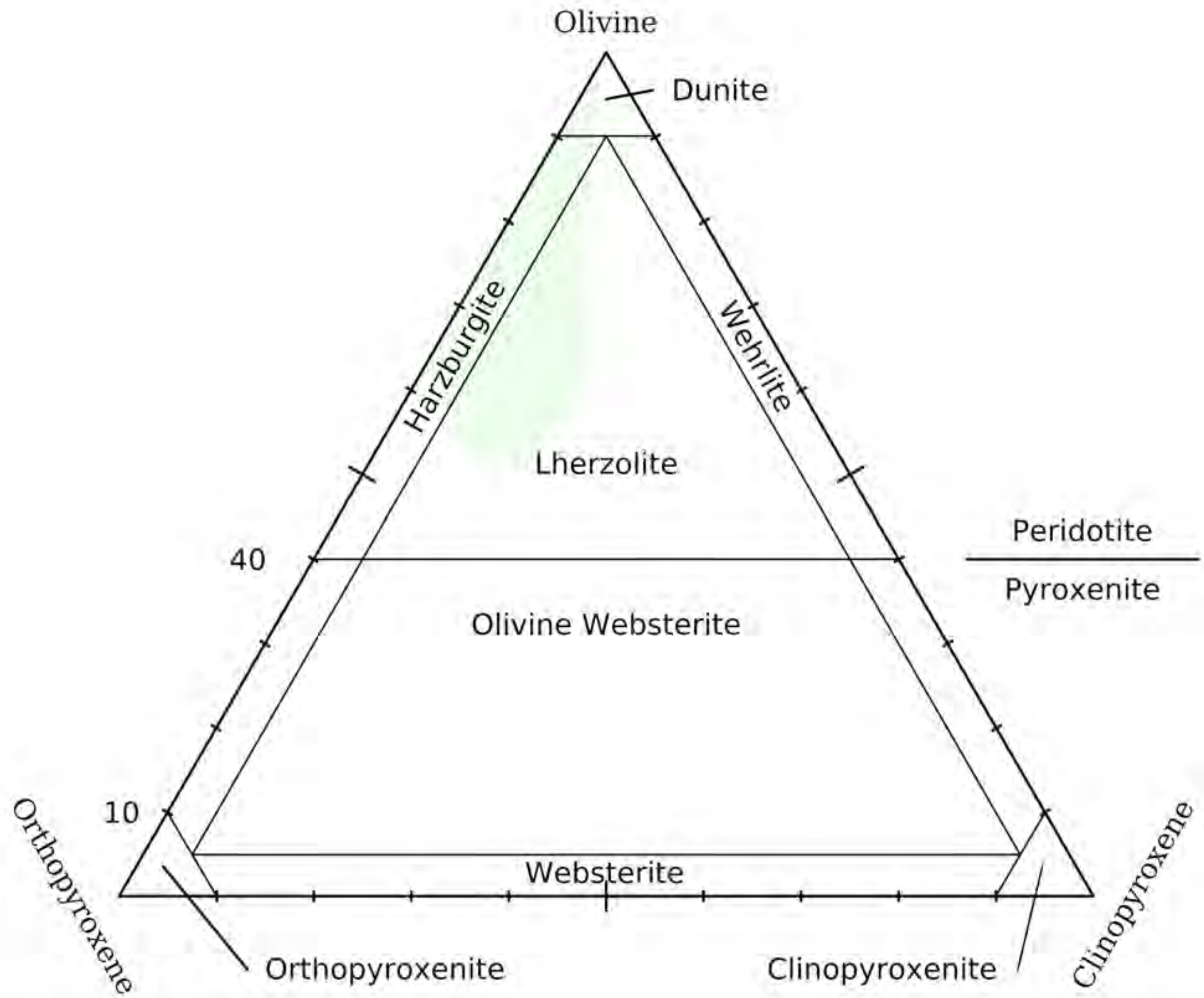
The term xenolith is derived from Greek roots "xeno," meaning foreign, and "lith", meaning rock. Xenoliths are foreign clasts, or pieces of rock, found intruding in another rock which has its own distinct origin. Mantle xenoliths, then, are small pieces of mantle material that hitchhiked from the Earth's deep interior to the surface in upwelling magma, erupting onto the surface from volcanoes. At Chiricahua National Monument, we are likely to observe mantle xenoliths at Turkey Creek Caldera, the remains of a volcano that violently erupted hundreds of cubic miles of material at supersonic speeds over 25 million years ago (Pallister et al, 1997).

These extruded samples are invaluable for research of the physical and chemical properties and processes in the mantle, as they represent material from beyond the reach of the deepest boreholes humans have ever dug (Pearson et al, 2003). While some mantle derived rocks are thrust onto Earth's surface by tectonic forces as massifs the sizes of large cities or small nations, these centimeter to meter sized samples of mantle material often ascend rapidly enough that they do not chemically equilibrate. As such, they can be considered more chemically pristine samples of the mantle.



A volcanic rock with an inclusion of peridotitic composition, via Wikimedia Commons

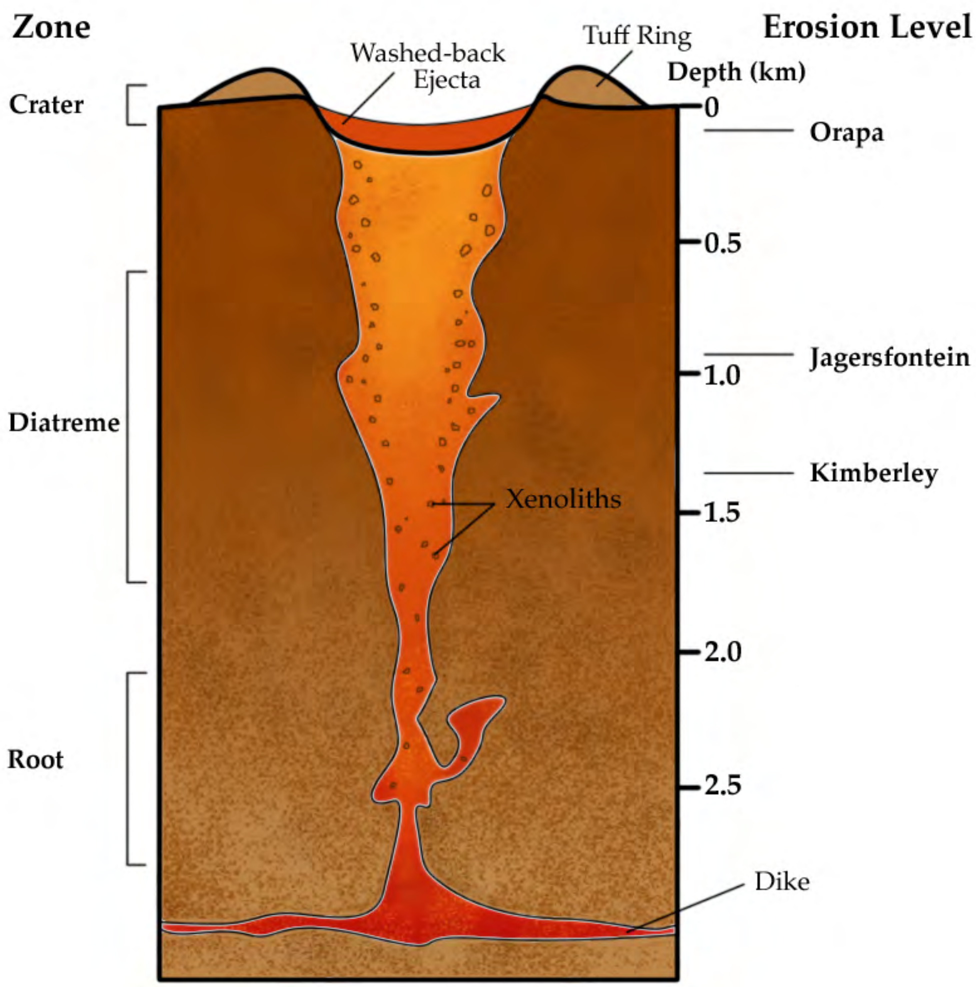
The most common mantle xenoliths are peridotitic in lithology, and their mineralogy is correspondingly dominated by olivine (Pearson et al, 2003). Additional minerals besides olivine typically include pyroxene and an aluminous phase, which is often spinel or garnet, or rarely plagioclase in the case of xenoliths of exceptionally shallow origin.



Peridotite ternary diagram, from Wikimedia Commons. The highlighted region between Harzburgite and Lherzolite contains most samples of peridotite from Earth's upper mantle, including the compositions of most mantle xenoliths.

Significantly more rarely, mantle xenoliths have been found with an eclogite lithology (Pearson et al, 2003). Eclogite is an unusually dense metamorphic rock believed to contribute to driving plate motion: as subducting oceanic plates metamorphose into eclogite in the mantle, their increased density reduces their buoyancy causing them to sink and pull the oceanic plate behind them. Eclogite xenoliths appear in kimberlite pipes, and though they are regularly observed in kimberlite pipes alongside peridotite xenoliths, but there are exceedingly few localities where eclogite xenoliths represent a majority of intact xenoliths over peridotite xenoliths.

Mantle xenoliths can be found in both oceanic and continental volcanic rocks (Pearson et al, 2003). Kimberlite pipes are the type example of where one would find material rich in mantle xenoliths. These structures are best known for their reserves of diamonds, which form in the upper mantle and are genetic cousins of mantle xenoliths. Below is a cross section of a kimberlite pipe. These are a relatively rare volcanic structure, representing the remains of violent, supersonic eruptions of water and gas from sources at as much as triple the depth of typical volcanic sources. This type of structure is similar to what we observe at Turkey Creek Caldera, the remains of a similar explosive volcano.



Kimberlite pipe diagram, via Wikimedia Ccommons

Works Cited:

Pallister, J. S. GUIDE TO THE VOLCANIC GEOLOGY OF CHIRICAHUA NATIONAL MONUMENT AND VICINITY, COCHISE COUNTY, ARIZONA. 16.

Pearson, D. G., Canil, D. & Shirey, S. B. Mantle Samples Included in Volcanic Rocks: Xenoliths and Diamonds. in Treatise on Geochemistry 171–275 (Elsevier, 2003). doi:10.1016/B0-08-043751-6/02005-3.

Alluvial Fans

Presented by Rowan Huang

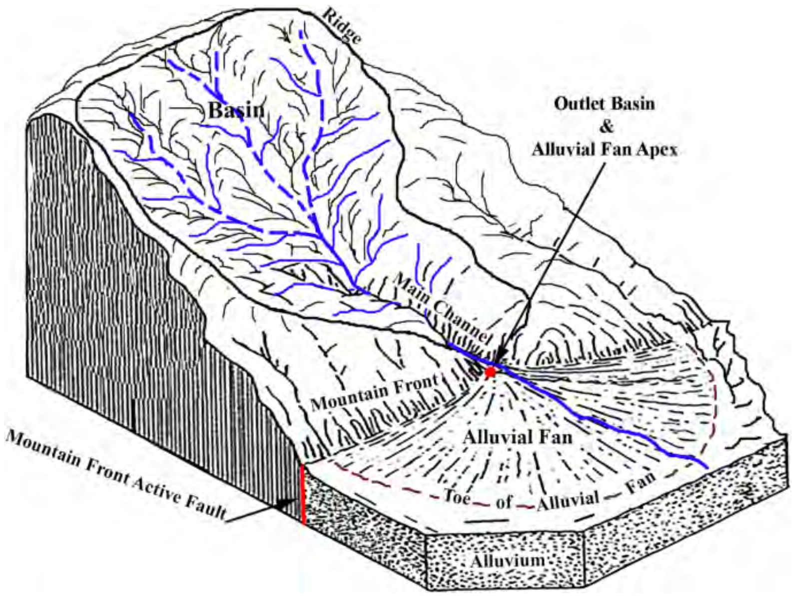
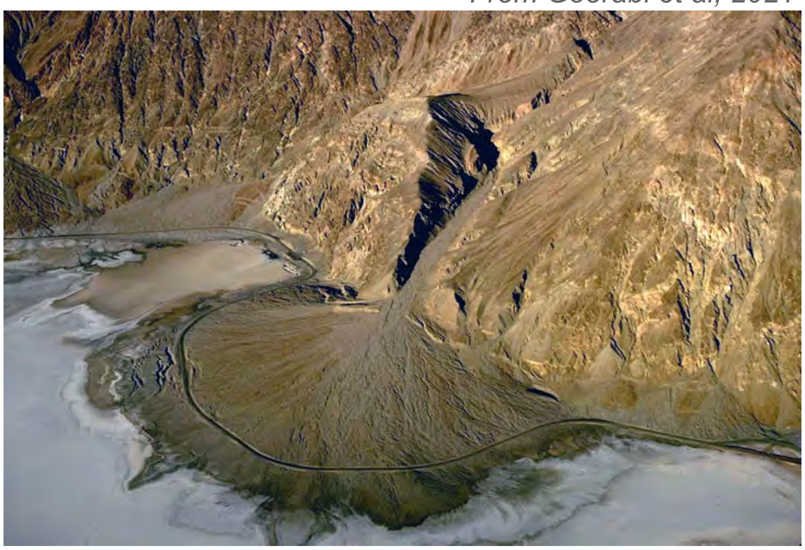


Diagram of a basin depositional system with alluvial fan.
From Goorabi et al, 2021



Alluvial fan in Badwater Basin, Death Valley, California.
Photo credit Marli Miller

Alluvial fans are deposits that form on the downslope end of a basin depositional system. These systems are composed of:

- The drainage basin (where precipitation is collected at its highland source)
- A connecting river channel,
- And the alluvial fan (also called the depositional apron) (Ritter et al, 2011).

These depositional fans form when the previously confined river channel spreads out into a wide, shallow channel when it exits a high-elevation front. The flow in the feeder river can carry sediment particles, but when it spreads out, the carrying capacity is reduced and the particles are deposited.

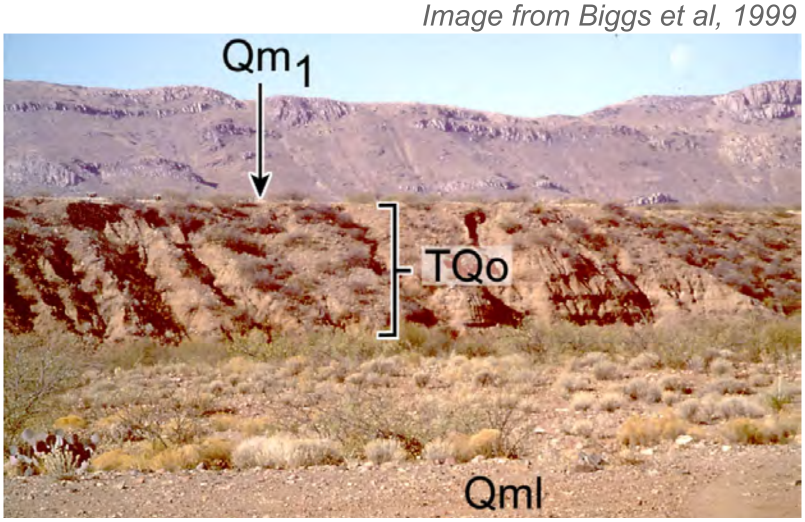
Alluvial fans are important because they record local geologic and hydrologic processes in their sediments. Fans can vary in their shape, sediment size, slope, and deposition rate and style. Thus, they can be loosely classified into two groups (Ritter et al, 2011):

- **Type 1:** formed by debris flows, with less fluid and more small sediments; form on short, steep slopes
- **Type 2:** formed by river (fluvial) processes, with lots of water carrying the sediments. These can form on less steep slopes and carry sediments for longer distances.

Alluvial Fans

Interpretation of small coalesced alluvial fans (also called a bajada) in Paramore Crater, Southeastern Arizona
Base image from Google Maps

Interbedded basalt (dark columns) and alluvial fan deposits (lighter, vegetated soil) in the San Bernardino Valley, Southeastern Arizona
Image from Biggs et al, 1999



Alluvial fan units (TQo) draped by younger gravels (Qm1)
Image from Biggs et al, 1999

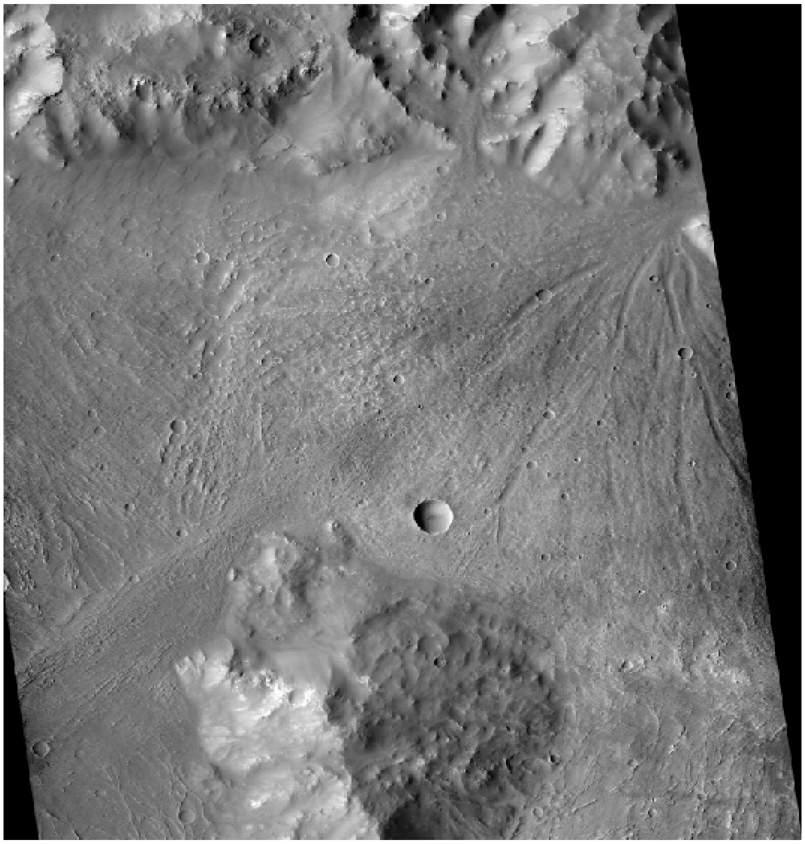
In the San Bernardino Valley, alluvial fans contribute to the sediments filling the basin (Biggs et al,1999).

In this region, the alluvial fan deposits are generally Pleistocene in age (2.58-0.0117 Mya). They were likely formed when the climate transitioned into one of enhanced monsoons and winter precipitation (Biggs et al, 1999).

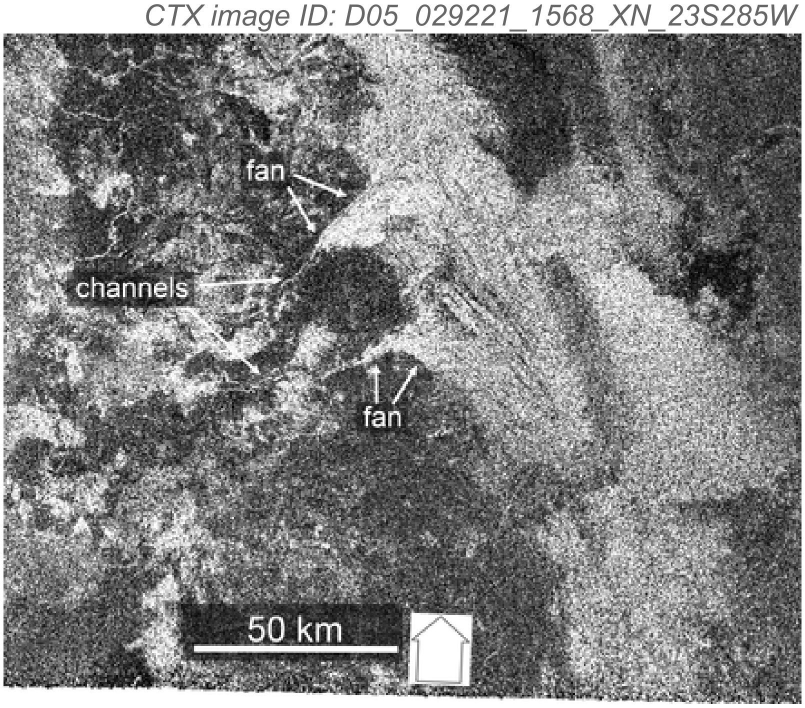
Here, alluvial fans record volcanic, tectonic and climatic changes:

- In some canyons of the San Bernardino valley, alluvial fan deposits are cut into the valley floor, rather than their material sitting on top. This suggests that the highlands are currently being uplifted, prompting downcutting.
- Some alluvial fan deposits have interbedded fingers of basalt, recording volcanic eruptions (Biggs et al, 1999; Lynch, 1978).
- Currently, the alluvial fans guide water to the basin floor, where the water likely infiltrates the ground and recharges aquifers (Biggs et al, 1999).
- Differences in grain size and sorting in alluvial fan layers show periods of varying precipitation (Biggs et al, 1999).

Alluvial Fans



Alluvial fan in an unnamed crater, Mars
Referenced in Moore and Howard,
CTX image ID: D05_029221_1568_XN_23S285W



Leilah Fluctus fans imaged by Cassini on Titan, Saturn
From Radebaugh et al, 2016

As far as we know, only two bodies in the solar system have alluvial fans on their surface:

- Mars has alluvial fans all over its surface; mostly found on the walls of craters in Mars' highlands. These are generally late-Noachian to Hesperian in age (Moore and Howard, 2005) and come from a time liquid water was stable on the surface of Mars.
- Titan, a moon of Saturn, has alluvial fans in which grains of ice and organic compounds are carried by a flow of liquid methane (Radebaugh et al, 2016).

Alluvial fans are important because they are visible indications of fluid flow on the surface of a planet. They are also useful in determining when these liquids were stable on the planets' surface.

References:

A. Goorabi, M. Karimi, G. Norini (2021), Semi-automated method for the mapping of alluvial fans from DEM, Earth Science Informatics v. 14, pp. 447–1466

D.F. Ritter, R.C. Kochel, J.R. Miller, (2011) Process Geomorphology Waveland Press

D.J. Lynch (1978) The San Bernadino volcanic field of southeastern Arizona, New Mexico Geological Survey 29th Field Conference Guidebook, pp. 261-268

J.M. Moore, A.D. Howard (2005) Large alluvial fans on Mars, JGR Planets v.110

J. Radebaugh, D. Ventra, R.D.. Lorenz, T. Farr, R. Kirk, A. Hayes, M.J. Malaska, S. Birch, Z. Yung-Chun Liu, J. Lunine, J. Barnes, A. Le Gall, R. Lopes, E. Stofan, S. Wall and P. Paillou (2016) Alluvial and fluvial fans on Saturn's moon Titan reveal processes, materials and regional geology, Geological Society, London, Special Publications, v. 440, pp.281-305

T.H. Biggs, R.S. Leighty, S.J. Skotnicki, and P.A. Pearthree (1999) Geology and Geomorphology of the San Bernardino Valley, Southeastern Arizona, Arizona Geological Survey Repository

PTYS590 – Fall 2021

The 1887 Sonora Earthquake

Patrick O'Brien

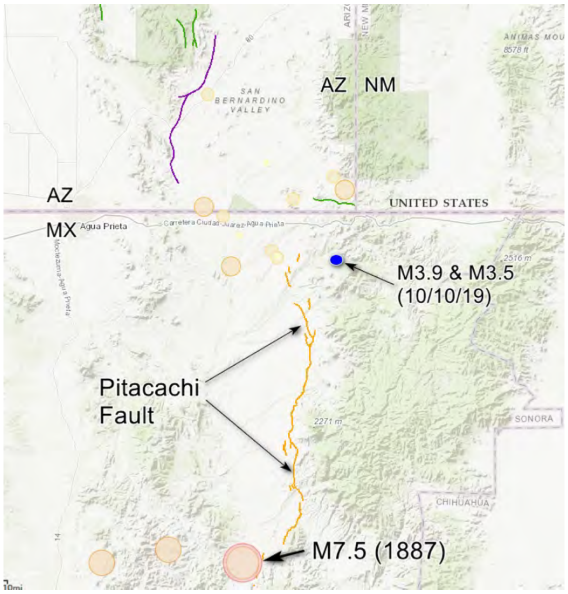


Figure 1. Map of major faults and recorded seismic events in Sonora and southeastern Arizona [1].

Overview

On May 3, 1887, a 7.5 magnitude earthquake struck northern Mexico and the southwestern US. The epicenter was along the eastern edge of the San Bernardino Valley near the Teras Mountains, ~60 km south of Douglas, AZ. Surface fault ruptures extended for over 80 km with vertical displacements reaching nearly 5 m. The effects of the earthquake were felt up to 700 km away.

Tectonics of Southern Arizona

Far from a plate boundary, the main driver of recent tectonic activity in southern Arizona is **faulting associated with the formation of the Basin and Range Province** (Figure 1). During periods of extension, crustal blocks drop down producing fault scarps and the horst and graben topography characteristic of this region, as seen in Figure 2.

The formation of the Southern Basin and Range, beginning ~25 Ma, created a system of north-south striking, west-dipping faults that bound mountain ranges like the Sierra Madres in northeastern Sonora. The 1887 Sonoran Earthquake was caused by reactivation of three such faults: the Pitáycachi, Teras, and Otates.

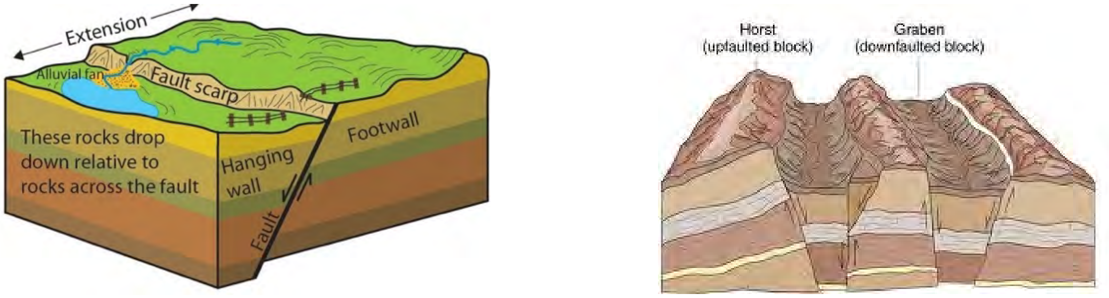


Figure 2. (left) Schematic of a normal fault created by tectonic extension [2] (right) Fault scarps delimit the edges of horst and graben blocks characteristic of the Basin and Range Province [3].

Figure 3. Sierra Madre range seen from WNW. The Pitáycachi fault surface rupture can be seen as a white ribbon across the lower part of the image. The scarp is ~4 m high [4].

	Pitáycachi	Teras	Otates
Rupture length	41.0 km	19.9 km	18.2 km
Mean offset	2.32 m	1.12 m	1.89 m
Max offset	4.87 m	1.84 m	2.70 m
Recurrence interval	100-200 kyr	15–26 kyr	30–42 kyr

Displacement of early to middle Pleistocene (1.5 Ma – 125 kya) alluvial deposits indicate that this fault system has been intermittently active over the last 100,000 years. On May 3, 1887, slipping occurred sequentially along these three faults before being stopped in both the north and the south by major cross faults. **The total length of surface rupturing was nearly 100 km** across the three distinct faults. **Vertical scarp offsets peaked at ~5 m** near the center of the Pitáycachi fault and decreased to zero approaching the bounding faults (Figure 4).

The aftermath

It has been estimated that the 1887 quake released twice as much energy as any other event recorded around Arizona. A low rumbling noise was followed by multiple violent shocks. Reports of the duration of ground motion ranged from a few seconds to 10 minutes.

The earthquake caused extensive damage throughout northern Mexico and southern Arizona. There were many injuries and 51 deaths, most from the town of Bavispe, Mexico, where a church collapsed. Several towns in Sonora were completely destroyed (Figure 5).

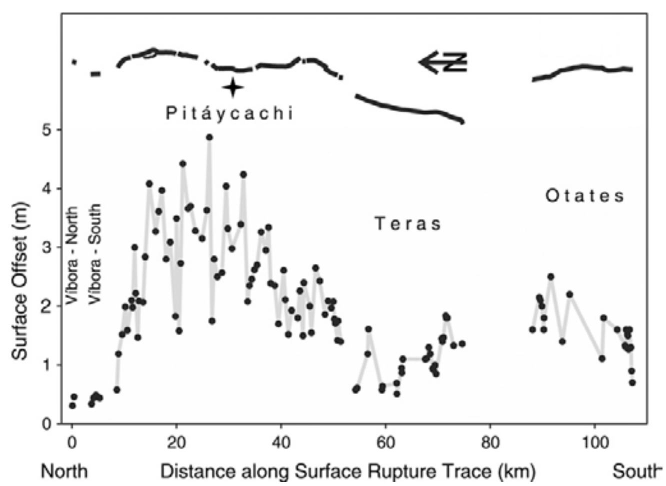


Figure 4. Fault trace map and scatter plot of surface offset measurements. North is to the left. [4].

At the distance of Tucson, “water in tanks slopped over, railroad cars were set in motion on tracks, chimneys were thrown down, and buildings were cracked” [7]. The intensity at Tucson was classified as VII-VIII on the Modified Mercalli Intensity Scale (difficult to stand, everybody runs outdoors; damage to buildings varies depending on quality of construction). In the town of Charleston, AZ, one colorful character noted that **“the walls of the saloon did a two-step and the floor did a shimmey”** [8]. Other effects of the earthquake included:

- Fissures up to 0.8 m wide (Figure 6)
- Liquefaction of the surface reported up to 100 km from the epicenter
- Changes in water conditions (e.g., wells, lakes)
- Forest fires triggered by landslides and rockfalls

Figure 5. Damaged buildings in Bavispe, Mexico which lies close to the Otates fault [9].

Risk of future earthquakes

Large intraplate earthquakes can dominate the local strain energy budget for thousands of years. Small seismic events concentrated near the fault ruptures are interpreted to be aftershocks of the 1887 quake (Figure 1). Aside from events linked to this recent episode, the background seismicity of southern Arizona is relatively low as **young Quaternary (<~2.6 Ma) intraplate faults typically have low recurrence rates**. Based on measurements of present-day slip rates (0.02–0.06 mm/yr), the recurrence interval of the Pitáycachi, Teras, and Otates faults range from tens to hundreds of thousands of years (compared to hundreds of years for the San Andreas fault).

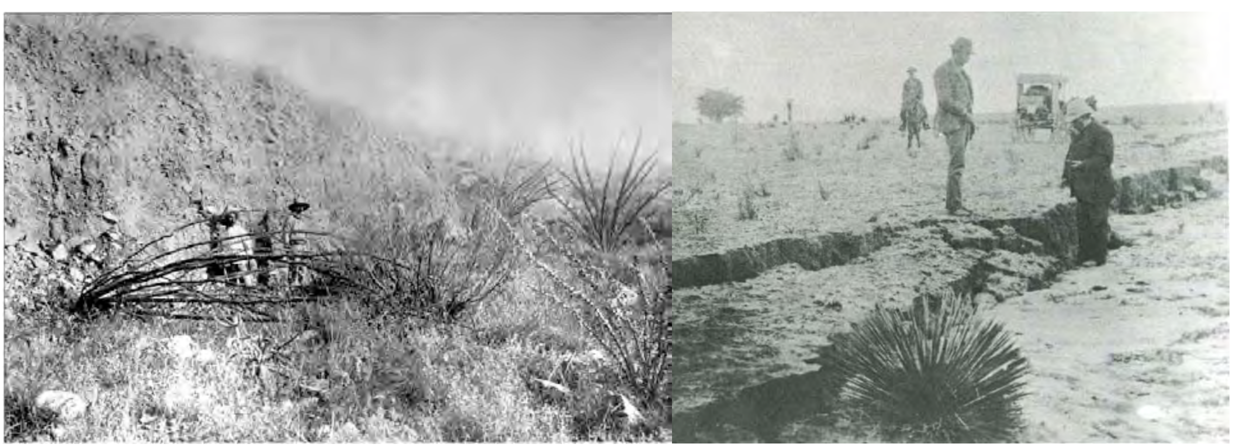


Figure 6. Historic 1887 photographs of fissures formed by the earthquake [9].

While this fault system is unlikely to see another large earthquake in the foreseeable future, faults like the Pitáycachi are not uncommon in the southwest. There have been approximately five surface rupturing events in the area surrounding southeastern Arizona and northern Sonora over the last 20,000 years and the numerous Quaternary faults in the southern Basin and Range Province represent potential seismic hazards.

References

[1] Pearthree, P. (2019, October 11). *Are small magnitude earthquakes in N. Sonora aftershocks of the 1887 M7.5 earthquake?* AZGS - Arizona Geology e-Magazine. https://blog.azgs.arizona.edu/blog/2019-10/are-small-magnitude-earthquakes-n-sonora-aftershocks-1887-m75-earthquake.

[2] Thornberry-Ehrlich, T. L. (2020, April 22). *Faults and Fractures*. National Parks Service. https://www.nps.gov/articles/faults-and-fractures.htm.

[3] DeMets, C. (n.d.). *The Basin-and-Range Province*. http://geoscience.wisc.edu/~chuck/Classes/Mtn_and_Plates/BsnRng_SAFZ.html.

[4] Suter, M. (2015). Rupture of the Pitáycachi fault in the 1887 M w 7.5 Sonora, Mexico earthquake (southern Basin-and-Range Province): Rupture kinematics and epicenter inferred from rupture branching patterns. *Journal of Geophysical Research: Solid Earth*, *120*(1), 617–641. https://doi.org/10.1002/2014jb011244

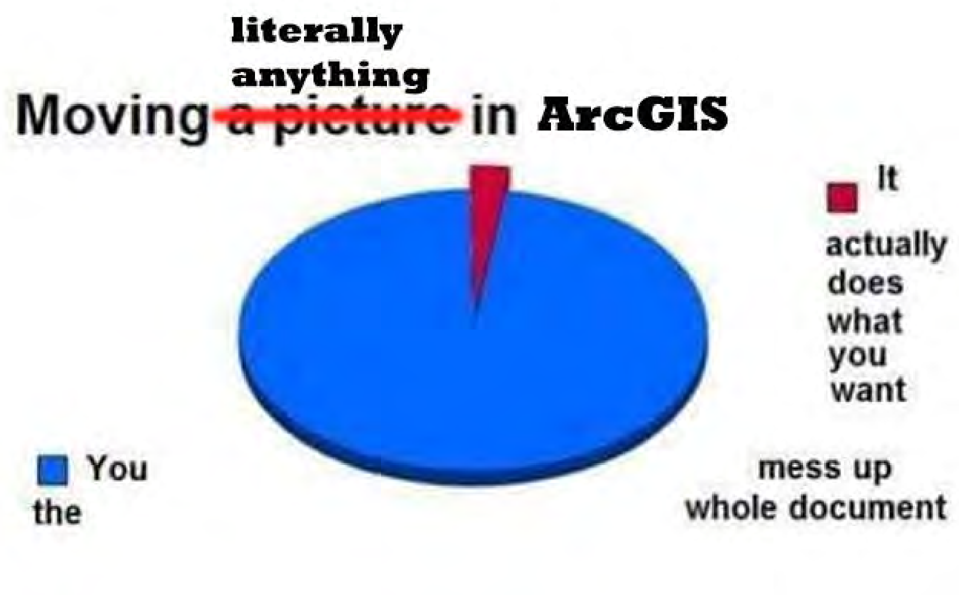
[5] Suter, M. (2008). Structural configuration of the Teras fault (southern Basin and Range Province) and its rupture in the 3 May 1887 M_w 7.5 Sonora, Mexico earthquake. *Revista Mexicana De Ciencias Geológicas*, *25*(1), 179–195. http://www.scielo.org.mx/pdf/rmcg/v25n1/v25n1a11.pdf

[6] Suter, M. (2008). Structural configuration of the Otates Fault (southern Basin and Range province) and its rupture in the 3 May 1887 M_w 7.5 Sonora, Mexico, Earthquake. *Bulletin of the Seismological Society of America*, *98*(6), 2879–2893. https://doi.org/10.1785/0120080129

[7] USGS. *M 7.6 - The 1887 Sonora Earthquake, Mexico*. Earthquake Hazards Program. https://earthquake.usgs.gov/earthquakes/eventpage/official18870503221300000/impact.

[8] McGarvin, T. G. (1987). The 1887 Sonoran Earthquake: It Wasn't Our Fault. *Arizona Bureau of Geology and Mineral Technology Field Notes*, *17*(2).

[9] DuBois, S. M., & Smith, A. W. (1980). *The 1887 earthquake in San Bernardino Valley, Sonora: Historic accounts and Intensity patterns in Arizona*. State of Arizona, Bureau of Geology and Mineral Technology, University of Arizona.


literally anything
Moving a picture in ArcGIS
It actually does what you want
You mess up the whole document


HALLOWEEN
What scares you the most?
"Werewolves!"
-Paul
What scares you the most?
"Sharks"
-Nina
What scares you the most?
Reacting with residual melt and undergoing a discontinous reaction to form orthopyroxene
What scares you the most?
"Ghosts!"
-Catherine

Field Trip Guidelines

Field Instructor(s):
Christopher Hamilton (Trip Lead), Email: chamilton@arizona.edu, Phone: 301-305-3818
Joseph Spitale, Email: jnspitale@psi.edu, Phone: 520-245-9887

Communication:
An open dialogue between all participants is key for a safe and enjoyable trip. All participants are strongly encouraged to communicate their questions, concerns, and/or comments directly to the instructor(s) at any point before, during, or after the field trip. The earlier concerns are voiced, the more quickly and effectively any issues can be dealt with before they develop into a larger problem.

Participation:
All participants are required to complete a presentation on a topic as discussed in the syllabus. Participants should be aware that participation in other activities is encouraged but optional and not required to receive a P (see Health and Safety section below).

"Classroom" Behavior Policy as it Applies in the Field:
When in the field or vehicles collaborative behavior is expected and an environment free of threatening, discriminatory, or harassing behavior. Students should not take risks that put themselves or the group in danger – this includes negligent behavior that creates risk. Anyone who observes what appears to be threatening behavior must report it to the Dean of Students Office and, in the appropriate case, file a Student Code of Conduct Complaint (see ABOR 5-403). See https://policy.arizona.edu/education-and-student-affairs/threatening-behavior-students.

UA Nondiscrimination and Anti-harassment Policy:
Harassment or discrimination of any kind will not be tolerated. The University of Arizona is committed to creating and maintaining an environment free of discrimination and harassment; see http://policy.arizona.edu/human-resources/nondiscrimination-and-anti-harassment-policy.

Responsible Reporters on This Trip:
University employees (these are the field trip instructors) are responsible for promptly reporting any concern of sex discrimination related to a student to the Title IX Coordinator, Deputy Coordinators, UAPD, or staff in the Office of Institutional Equity or Dean of Students Office. Students (all students enrolled or participating in the field trip course) are encouraged to similarly report any incident.

At the University of Arizona, everyone is encouraged to report to OIE incidents of potential discrimination, harassment, and retaliation. University employees (these are the field trip instructors) are responsible for promptly reporting any concern of discrimination related to a student or a subordinate to OIE (all students enrolled or participating in the field trip course). See http://policy.arizona.edu/human-resources/nondiscrimination-and-anti-harassment-policy.

Office of Institutional Equity (OIE): Phone - (520) 621-9449, Email - equity@arizona.edu

Environmental and Cultural Considerations:
We are guests at our field sites. Respecting local cultures and the landscape we are in is the responsibility of all participants for the duration of the field trip. “Leave no trace” applies. Do not disturb the landscape in an irreparable way or leave garbage or debris behind. We are ambassadors for the University of Arizona and the Lunar and Planetary Laboratory.

Some regions we visit are sacred and existing Native cultures still inhabit their ancestral lands throughout the American Southwest. Treat the land with the dignity and respect any religious site would require. Be respectful and do not disturb any artwork, images, artefacts, or formations you may encounter. All parties are expected to abide by any laws, in addition to State and Federal laws, put in place by Native sovereign nations with no exceptions.

Health and Safety in the Field:
Participants are strongly encouraged to read background material on the field area that we will be visiting. It is your responsibility to make decisions for your personal health and safety and use your common sense if something feels uncomfortable. Report to the instructor(s) immediately if at any time you feel you are in danger or your health (including mental health) is in jeopardy. **Go everywhere with a buddy. Nobody should travel anywhere alone**. Pay attention to what’s around you as there are many dangerous plants and animals that could negatively impact you.

Hydration is key, no matter what environment you are in. Participants are strongly encouraged to utilize hydration packs. Several liters of water are recommended to be carried by each individual; ~1L per hour of activity. Snacks with salt are also encouraged to promote retention of fluids.

Hikes on this Trip:
This trip typically involves hiking. If a hike is or becomes uncomfortable, notify the instructor(s) immediately.

Students are encouraged to ask the instructor questions about the nature of any hikes in order to be more prepared. Consulting trail guides and being aware of likely weather conditions could also be helpful.

What to do if you or others are injured while in the field:
- If you are in immediate danger or sustain a life-threatening injury injury threatening **stop what you are doing**. Call 911 immediately if you cannot end the risk to yourself or others
- If already injured, **do not** continue participating in physical activities and immediately notify the instructor(s) that you have been injured and need to seek medical help or receive first-aid
- If you believe yourself or another participant may have sustained a back or neck injury, **do not attempt to move yourself or the injured party**, notify the instructor(s) immediately - Emergency services will be contacted
- **All injuries (even if perceived to be minor) must be reported to the course instructor.**

Driving Safety:
The number one priority of driving is safety and not "sticking to the schedule" or keeping the caravan together at all costs. We can not write a guideline for every driving eventuality, but in general every driving decision should be the one that minimizes risk. Whether you are a passenger or driver, communicate any safety concerns to the instructor(s) as soon as possible. A non-exhaustive list of safety considerations are:

- **Do not speed.** It is the leading cause of all motor accidents. If you receive a speeding ticket then UA will not reimburse you or represent you if you're contesting it.
- **Excessive slowness also constitutes a risk**, if the rest of the convoy needs to constantly slow down or pull off the road to wait for you. Try to keep pace with the rest of the vehicles as much as traffic and road conditions allow - if you're uncomfortable with the convoy speed then please speak to the instructors or use another driver. Do not speed to catch up with the convoy if separated – use the CB/cell phone to notify the lead vehicle to slow down.
- **Do not drive if you are excessively tired**. Please exchange another driver if this occurs.
- **The front seat passenger (not the driver) should manage the CB** or phone communication with other vehicles.
- **Do not make unscheduled stops unless it is an emergency.** If anyone needs a bathroom break then notify the lead vehicle to look for a place to stop – others will be also grateful for the break. If you need to stop in an emergency then notify the instructor(s) as soon as it is safe to do so.
- **Report any accident or mechanical problem** with the vehicle (no matter how slight) to the instructor(s).
- If stopped at a **border patrol checkpoint** then the driver will be asked if everyone in the vehicle is a US citizen. You must answer accurately - confirm your answer with your passengers while waiting in line.
- **CB conversations are public**, it is akin to shouting across a crowded room. Use good judgement about what you say, as we are not on private channels and others in the vicinity may hear you.

Campsite Expectations and Personal Gear:
Students should expect campsites to have **no running water or toilet/bathing facilities.** They must take whatever camping and food supplies are needed themselves. Only water is provided by the University. If these conditions present a barrier to your participation, then please consult the instructor(s) as early as possible.

Students should consult a suitable weather forecast in advance when deciding what they should take with them. Please consult the instructor(s) if unsure and always err on the side of caution. You will not be expected to carry your gear far from the vehicle so taking too much with you is not a liability.

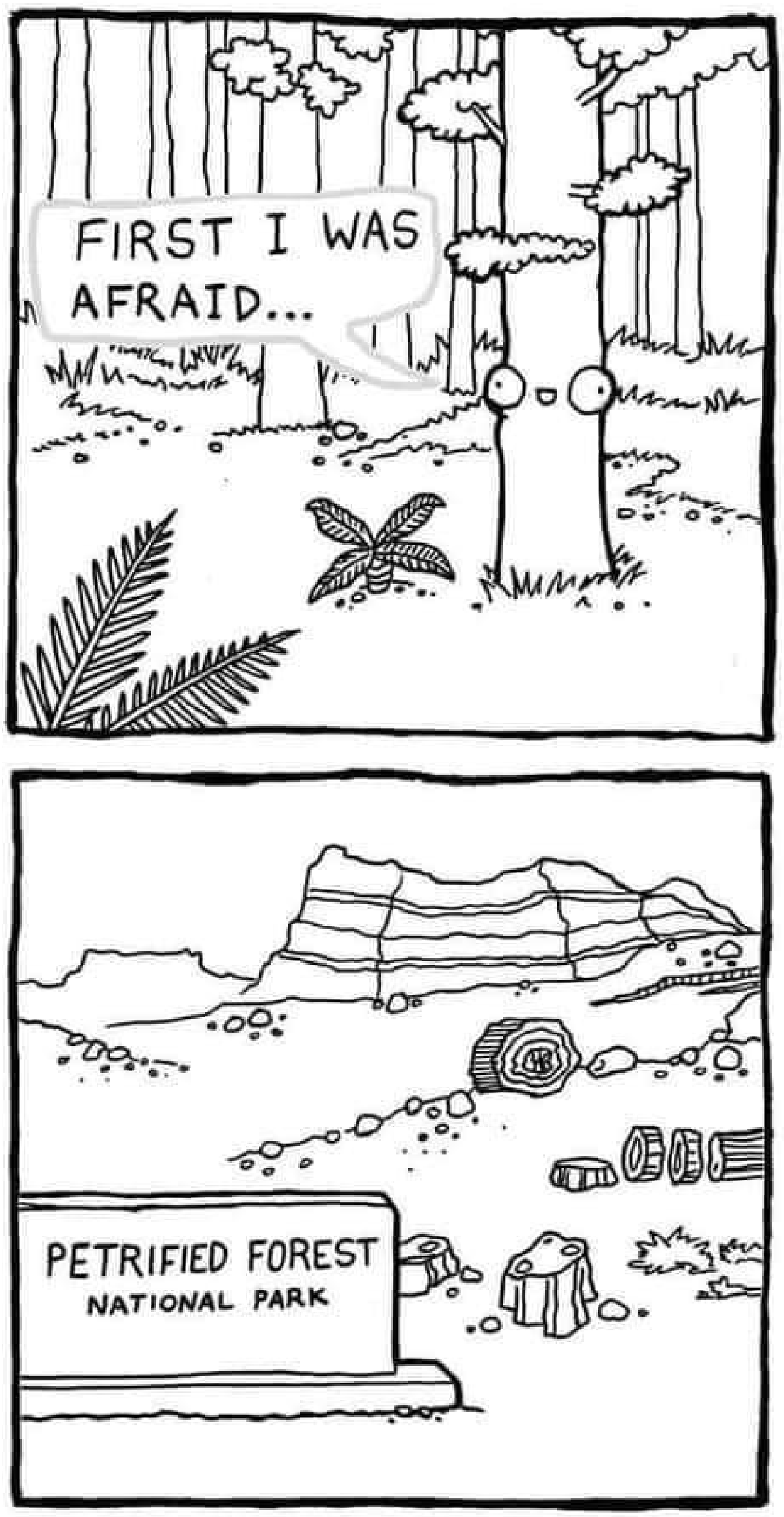
Most campsites are remote, but we sometimes have neighbors. Considerate behavior toward anyone we encounter is expected.

Student Camp Liaisons:
You may feel more comfortable directing any additional questions regarding camp life to your fellow students. These students have been on several field trips and have volunteered to be liaisons to field any questions you may have:

Indujaa Ganesh, indujaa@email.arizona.edu, (510) 925 7056

Photography/Videos
Please ask before taking a photo or video of others unless they are at such a distance as to be unidentifiable. **If you are asked to stop at any point, this equates to not having permission. Always obtain consent before posting images or videos of others online.**

Prohibited Conduct as Defined by ABOR 5-308: Photographing, videotaping, filming, digitally recording, or by any other means secretly viewing, with or without a device, another person without that person's consent in any location where the person has a reasonable expectation of privacy, or in a manner that violates a reasonable expectation of privacy. This section does not apply to lawful security or surveillance filming or recording that is authorized by law enforcement or authorized university officials. See https://public.azregents.edu/Policy%20Manual/5-308-Student%20Code%20of%20Conduct.pdf.



FAIRLY_DECENT_COMICS

Common Rock Forming Minerals

Dark-Colored minerals

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

Light-colored minerals

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

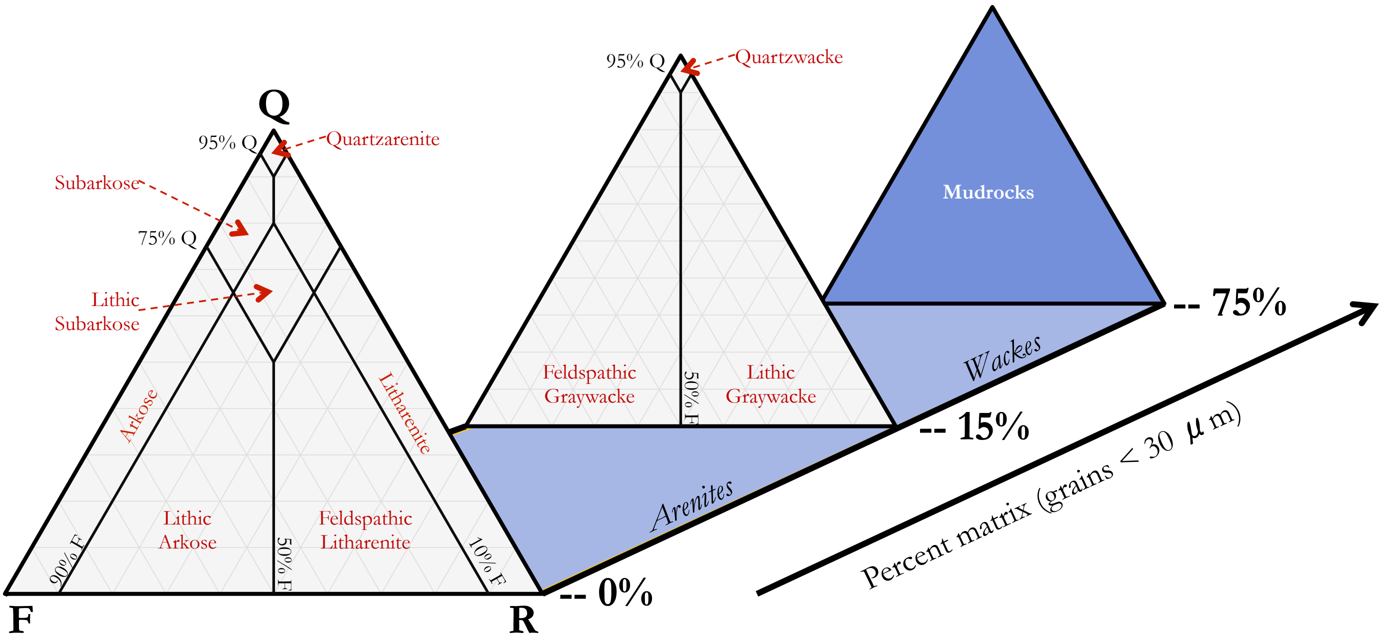
Metallic

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

Sedimentary Rocks

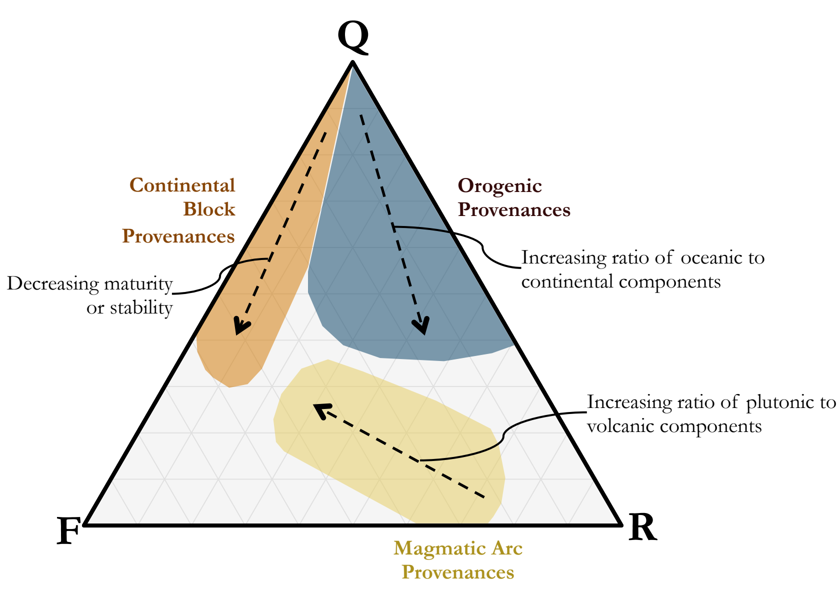
McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

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



Tectonic Setting for Clastic Sedimentary Rocks

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



Sedimentary Rocks

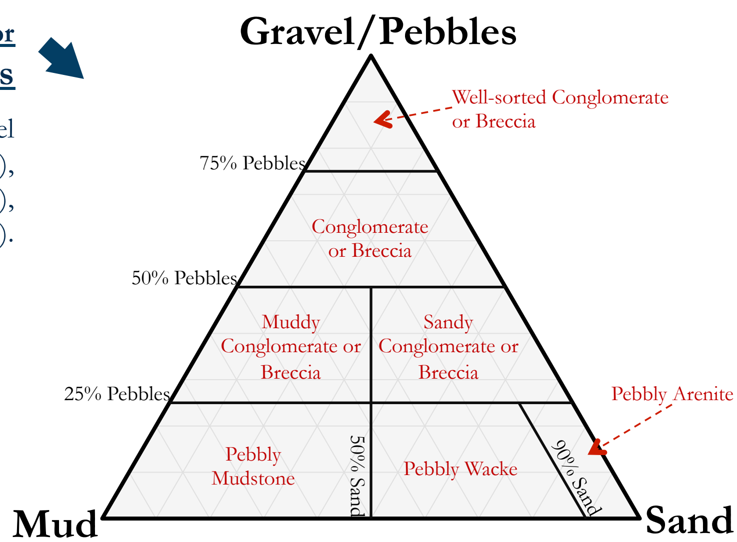
	Mudrocks (containing > 50% mud)			Rocks with <50%mud
	Silt dominant (> 2/3 of rock)	Clay and Silt	Clay dominant (> 2/3 of rock)	Sand-sized or larger grains dominant
Non-laminated	Siltstone	Mudstone	Claystone	Conglomerates, Breccias, Sandstones, etc.
Laminated	Laminated Siltstone	Mudshale	Clayshale	

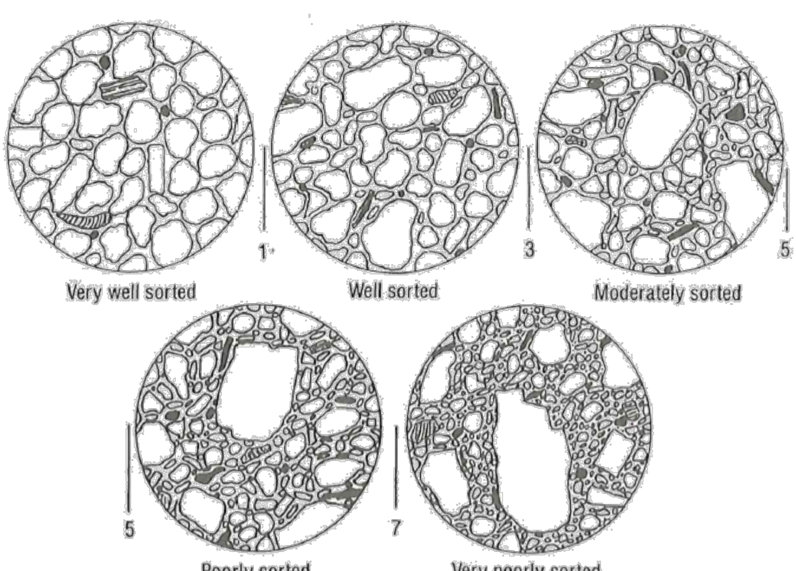
Classification Scheme for Mudrocks

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

Classification Scheme for Sub-Conglomerates and Sub-Breccias

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





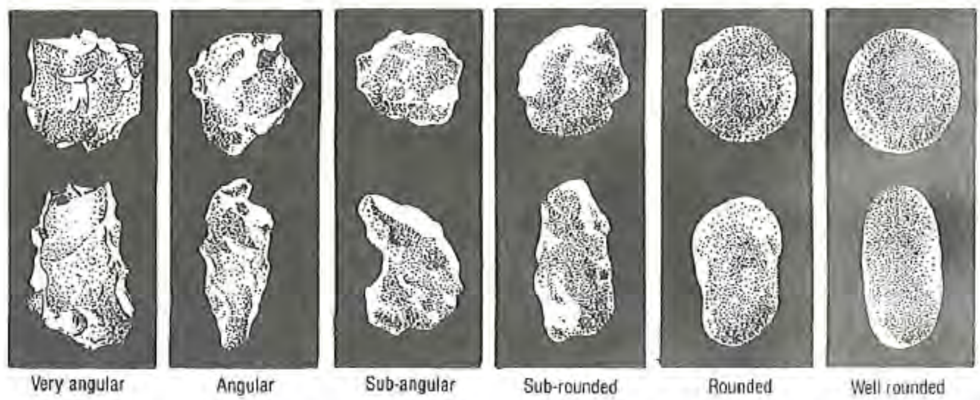
Estimating Sorting

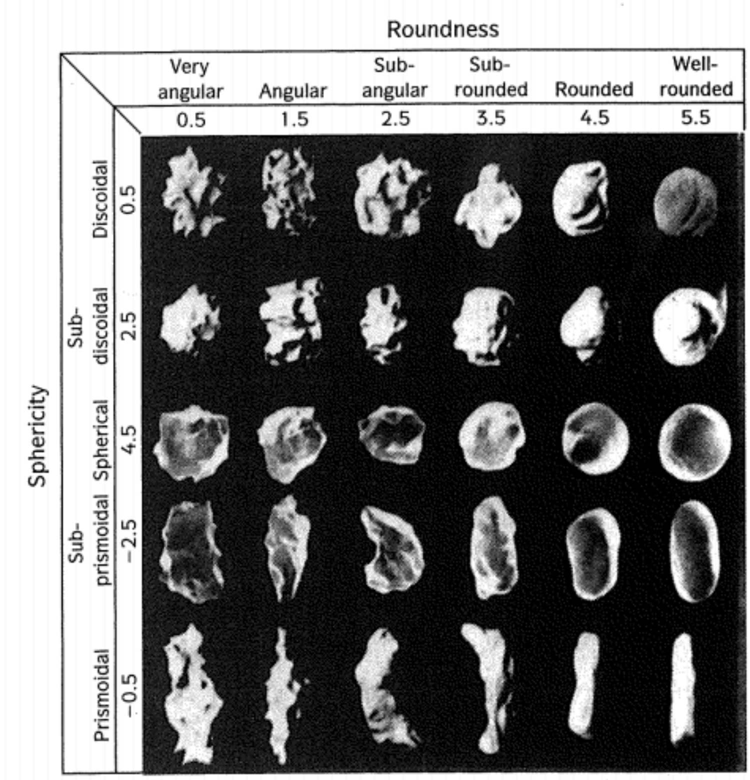
Example hand-lens view of detritus. From Compton, 1985

Sedimentary Rocks

Degrees of Rounding

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

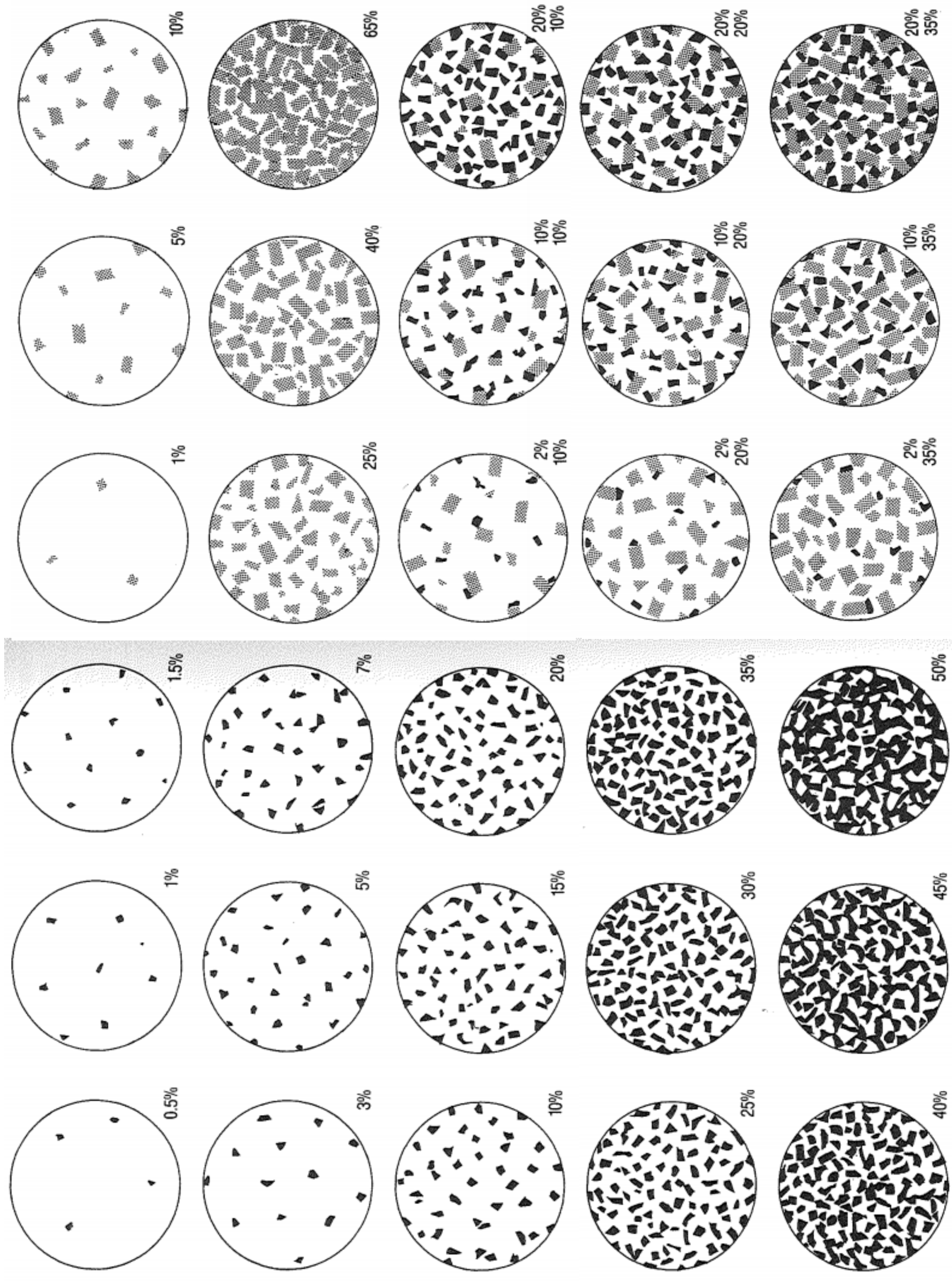




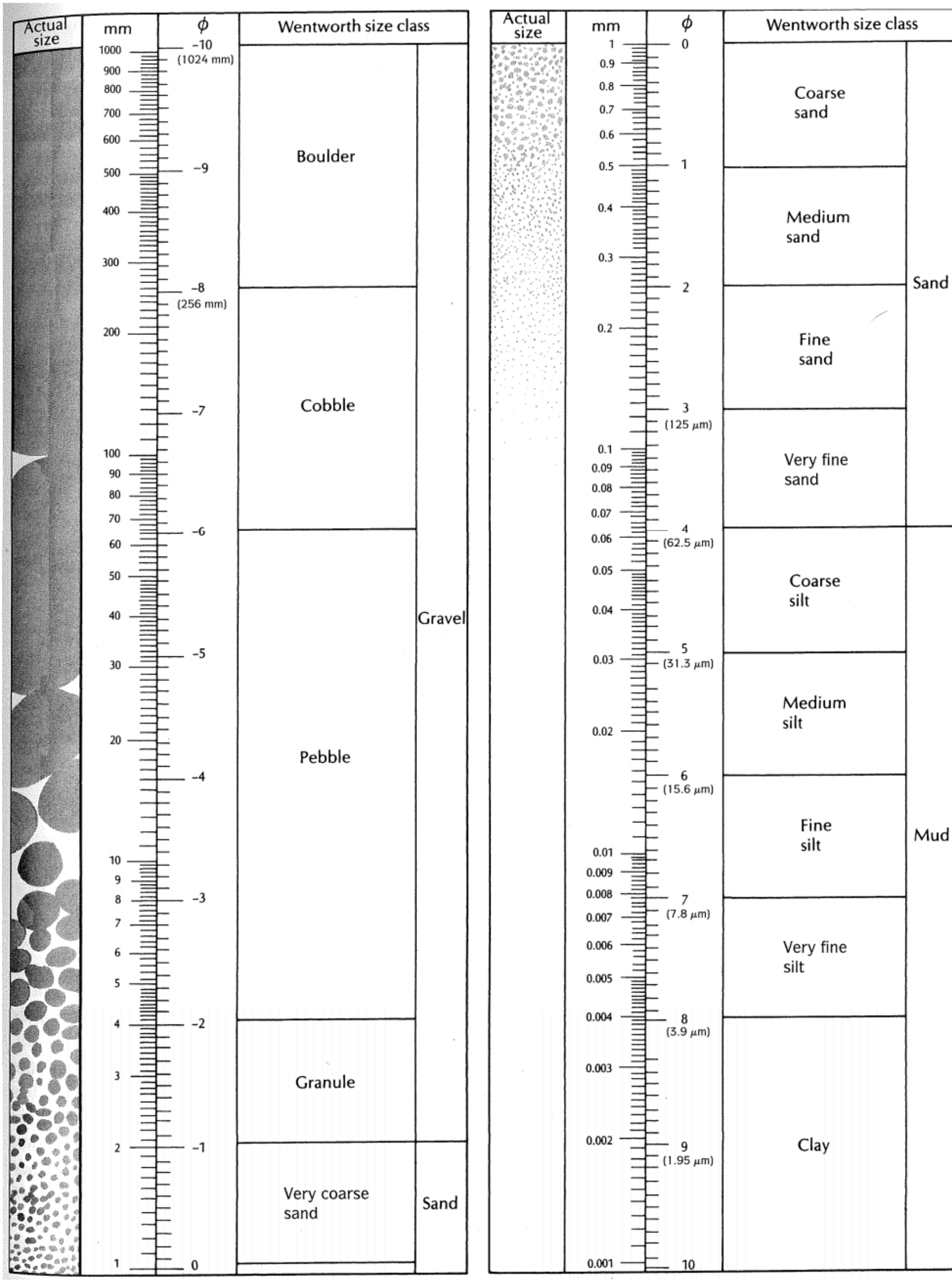
Sedimentary Rocks

Percentage Diagrams for Estimating Composition by Volume

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



Sedimentary Rocks

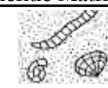
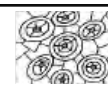
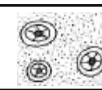
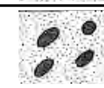
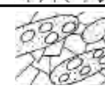
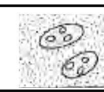
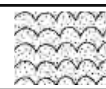
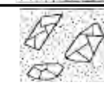


From Prothero and Schwab, 2004

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

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

<table>
<tr><th rowspan="2">Principle Allochems in Limestone</th><th colspan="4">Limestone Type</th></tr>
<tr><th colspan="2">Cemented by Sparite</th><th colspan="2">Cemented by Micritic Matrix</th></tr>
<tr><td>Skeletal Grains (Bioclasts)</td><td>Biosparite</td><td></td><td>Biomicrite</td><td></td></tr>
<tr><td>Ooids</td><td>Oosparite</td><td></td><td>Oomicrite</td><td></td></tr>
<tr><td>Peloids</td><td>Pelsparite</td><td></td><td>Pelmicrite</td><td></td></tr>
<tr><td>Intraclasts</td><td>Intrasparite</td><td></td><td>Intramicrite</td><td></td></tr>
<tr><td>Limestone formed in place</td><td>Biolithite</td><td></td><td>Terrestrial Limestone</td><td></td></tr>
</table>

Dunham Classification Scheme for Carbonate Rocks

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

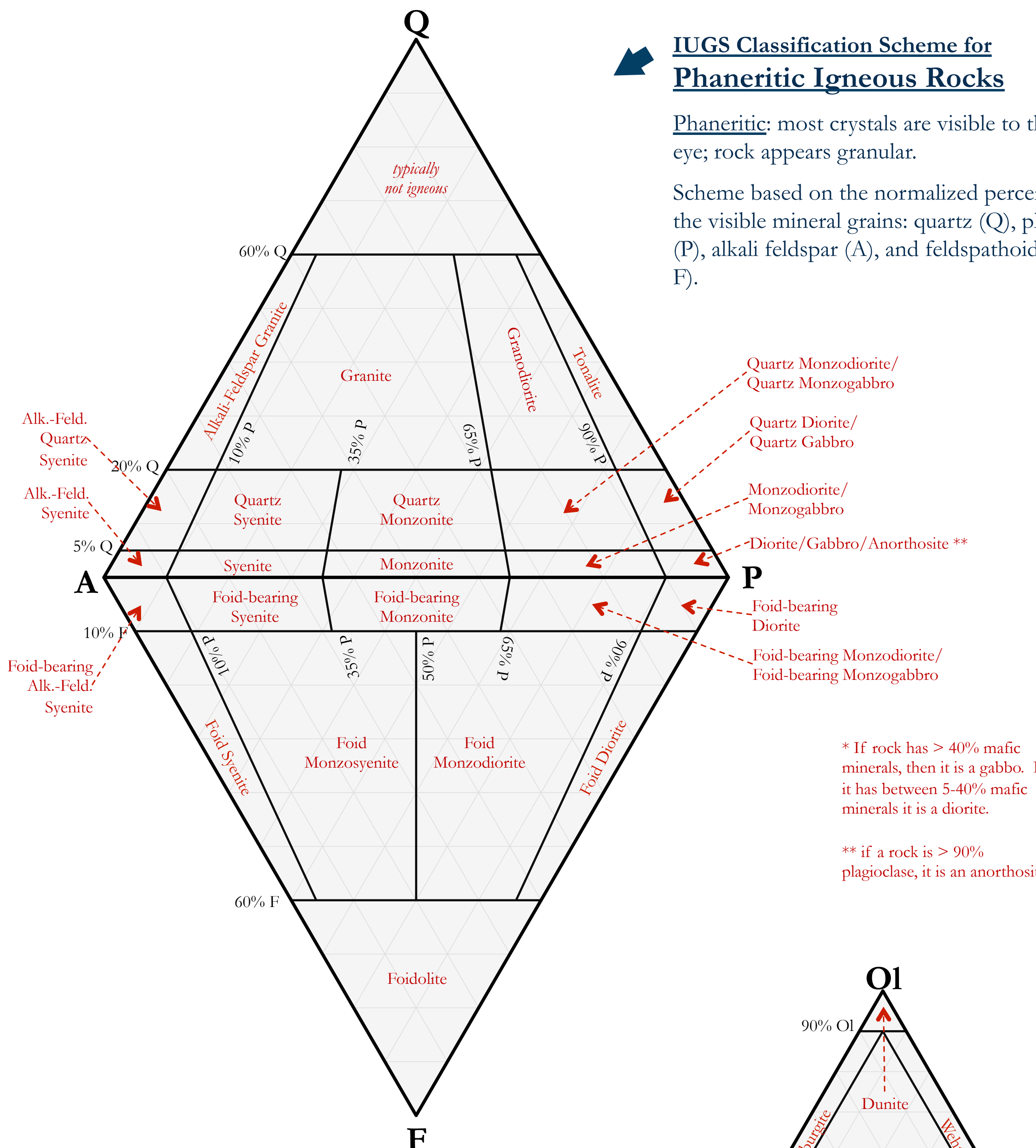
<table>
<tr><th colspan="6">Allochthonous Limestone
(original components not organically bound during deposition)</th><th colspan="3">Autochthonous Limestone
(original components organically bound during deposition; reef rocks)</th></tr>
<tr><td colspan="4">Of the allochems, less than 10% are larger than 2 mm</td><td colspan="2">Of the allochems, greater than 10% are larger than 2 mm</td><td colspan="3"></td></tr>
<tr><td colspan="3">Contains carbonate mud</td><td>No mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">Grain supported</td><td rowspan="3">Organisms acted as baffles</td><td rowspan="3">Organisms are encrusting and binding</td><td rowspan="3">Organisms building a rigid framework</td></tr>
<tr><td colspan="2">Grain supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

Igneous Rocks

IUGS Classification Scheme for
Phaneritic Igneous Rocks

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

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



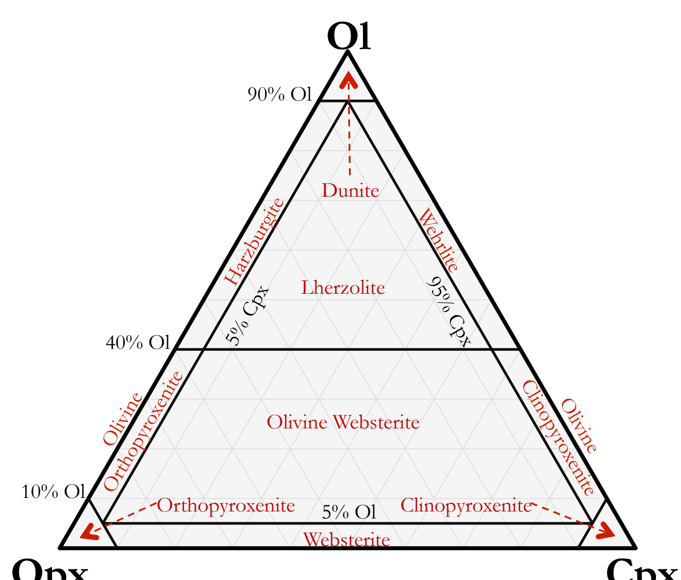
* If rock has > 40% mafic minerals, then it is a gabbo. If it has between 5-40% mafic minerals it is a diorite.

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

IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (1)

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

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

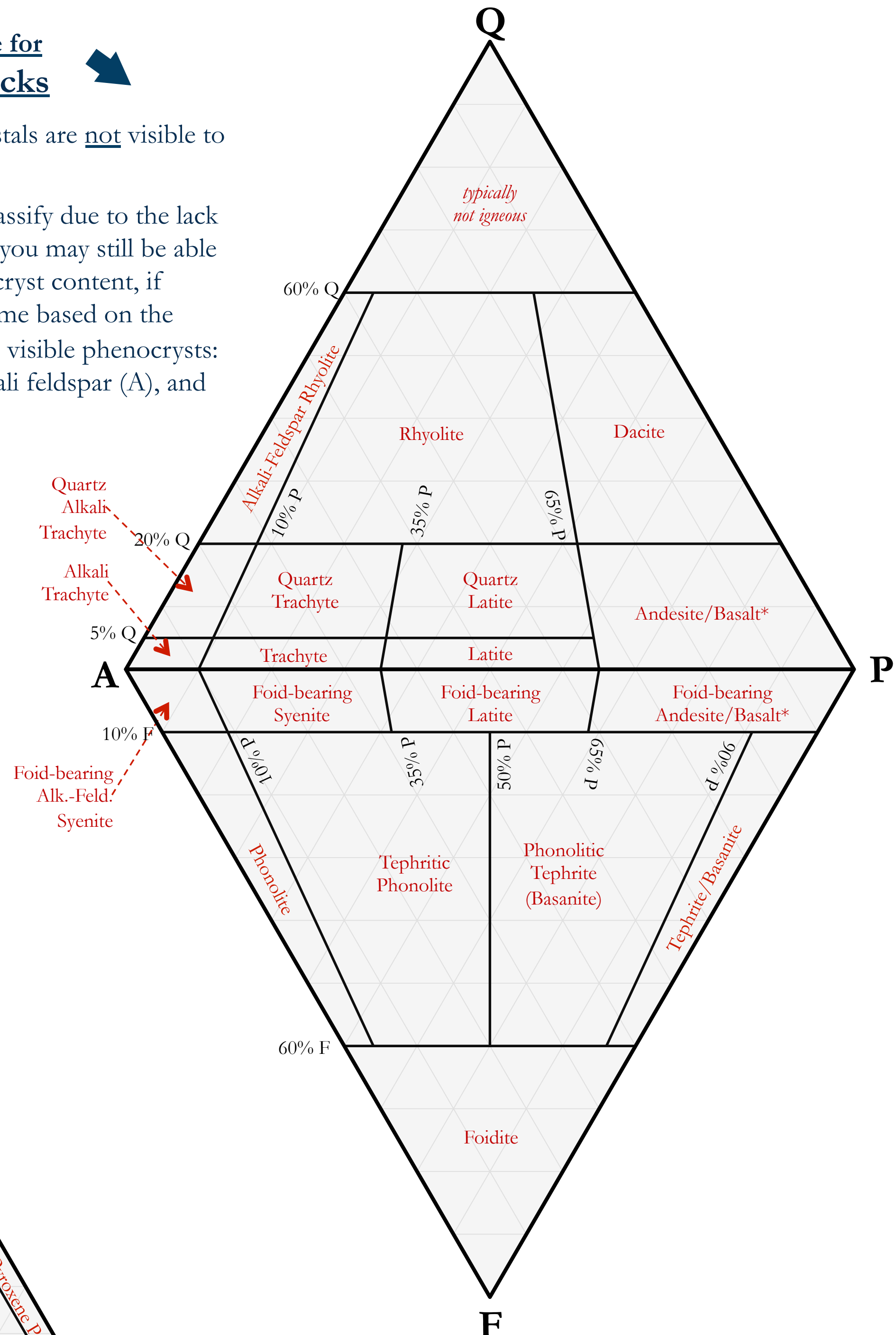


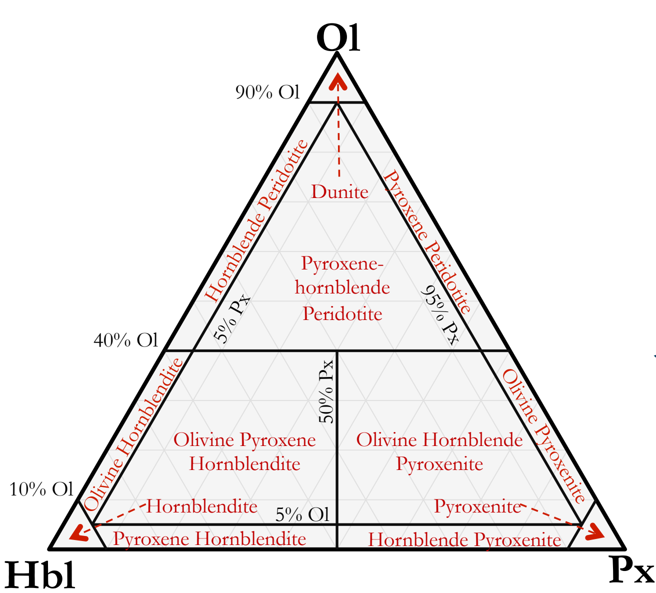
Igneous Rocks

IUGS Classification Scheme for Aphanitic Igneous Rocks

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

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





IUGS Classification Scheme for Phaneritic Ultramafic Igneous Rocks (2)

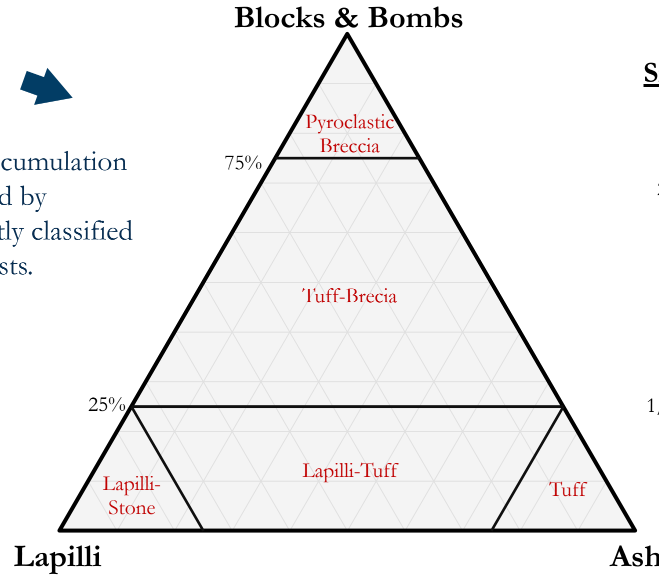
Ultramafic: more than 90% of the total minerals are mafic.

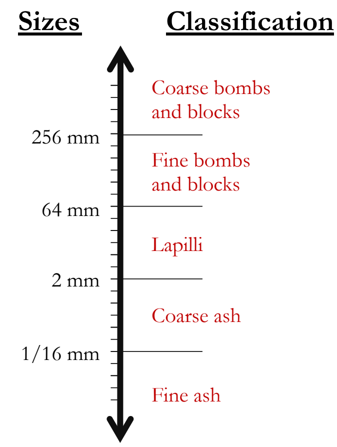
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

Igneous Rocks

Classification Scheme for Pyroclastic Igneous Rocks

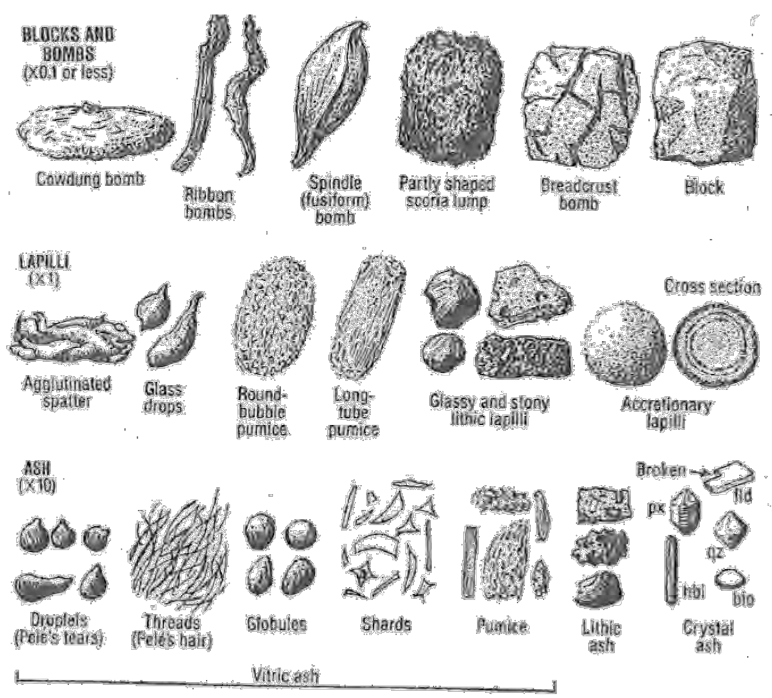
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.

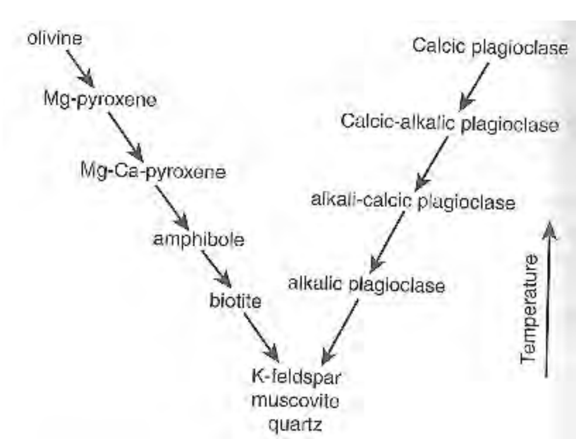




Types of Tephra (Pyroclasts)

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





Bowen's Reaction Series

From Winter, 2010.

Metamorphic Rocks

Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

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

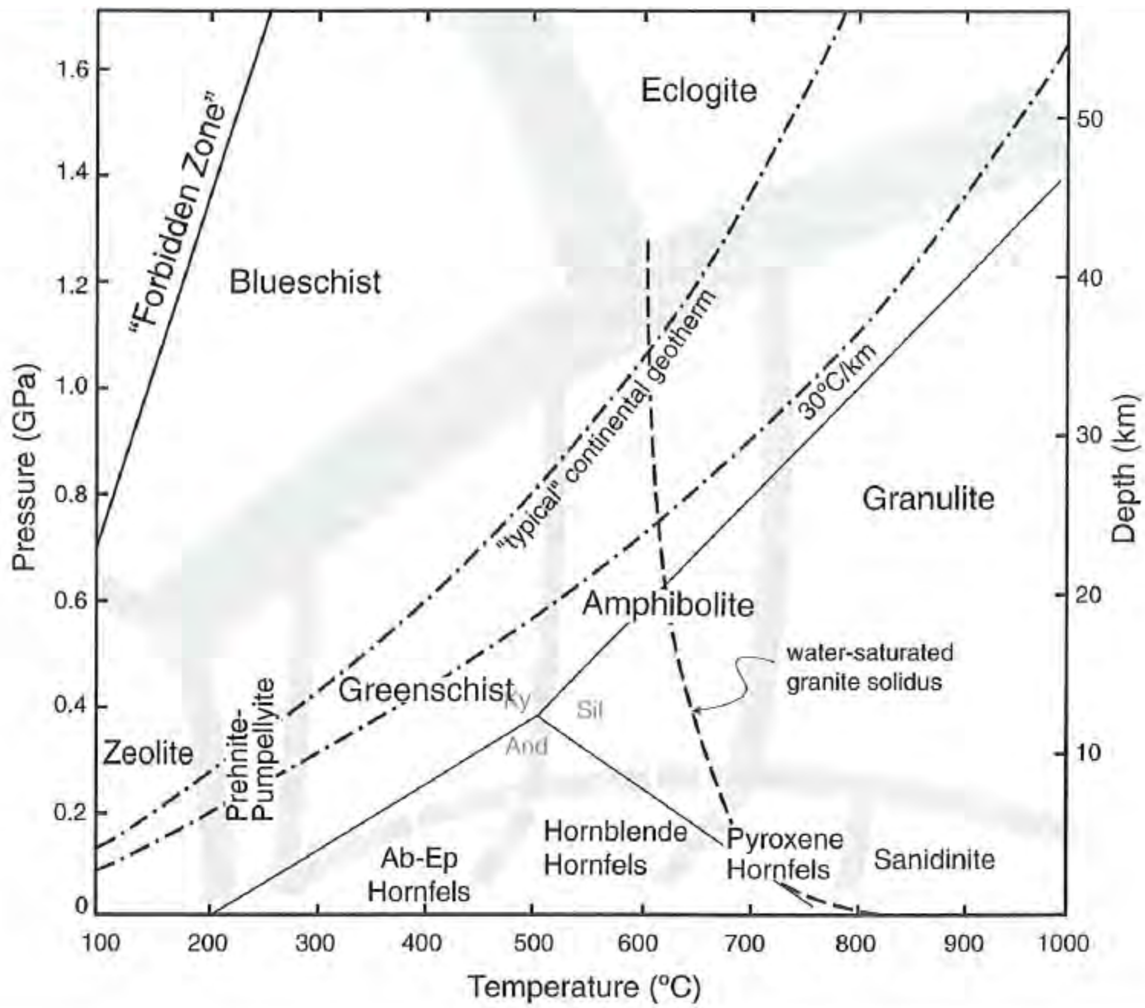
Mineralogy for Metamorphic Rock Facies

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

Metamorphic Rocks

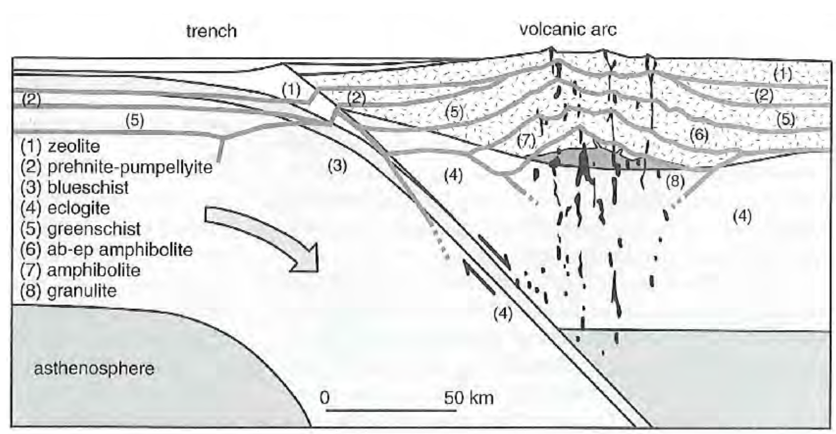
Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010



Schematic of Island Arc, and the origins of Metamorphic Facies

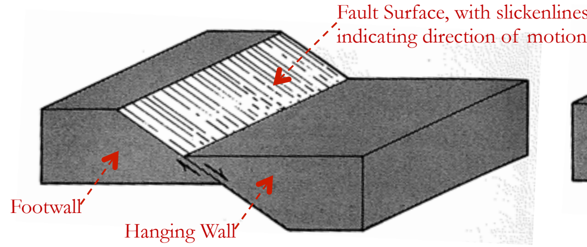
A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010



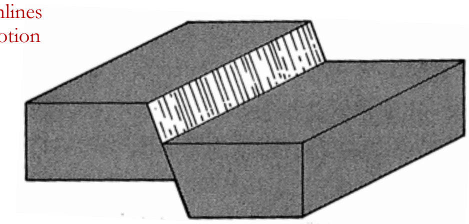
Structural Geology: Normal Faults

Normal Faults

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



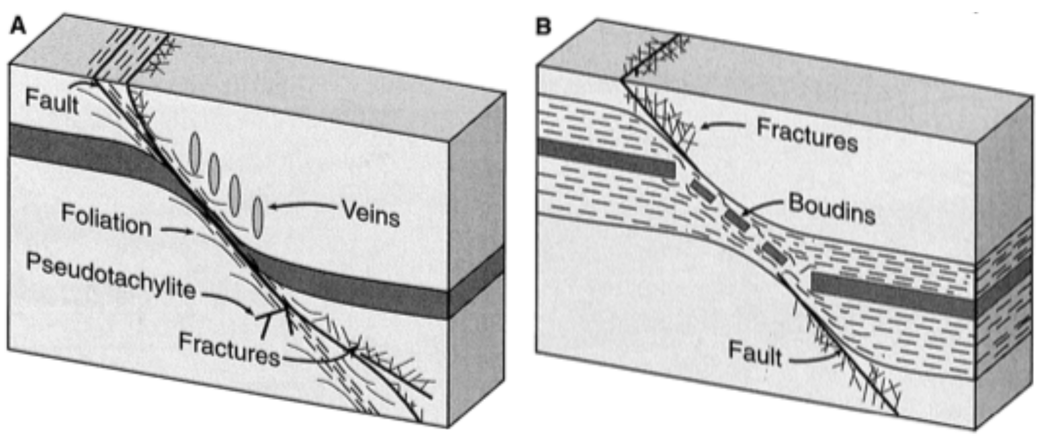
Low-angle Normal Slip Fault



Normal Slip Fault

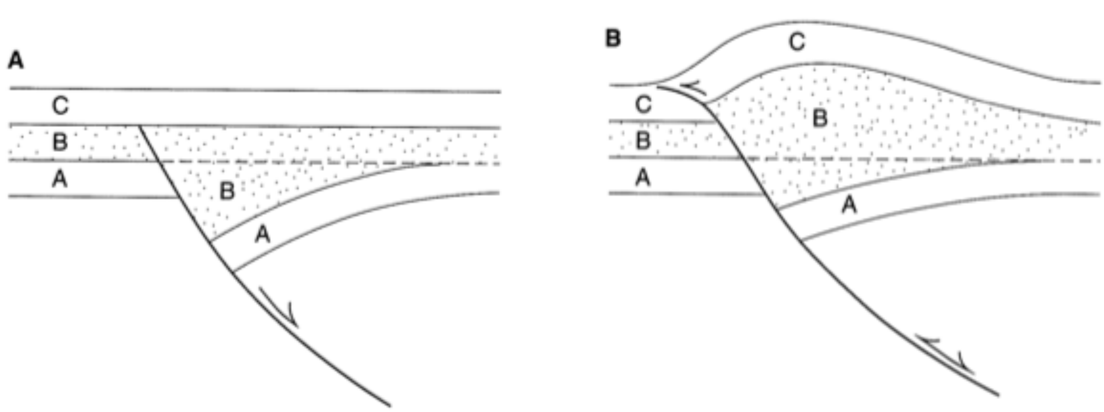
Effects of Brittle or Ductile Shear in Normal Faults

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



Inversion Tectonics

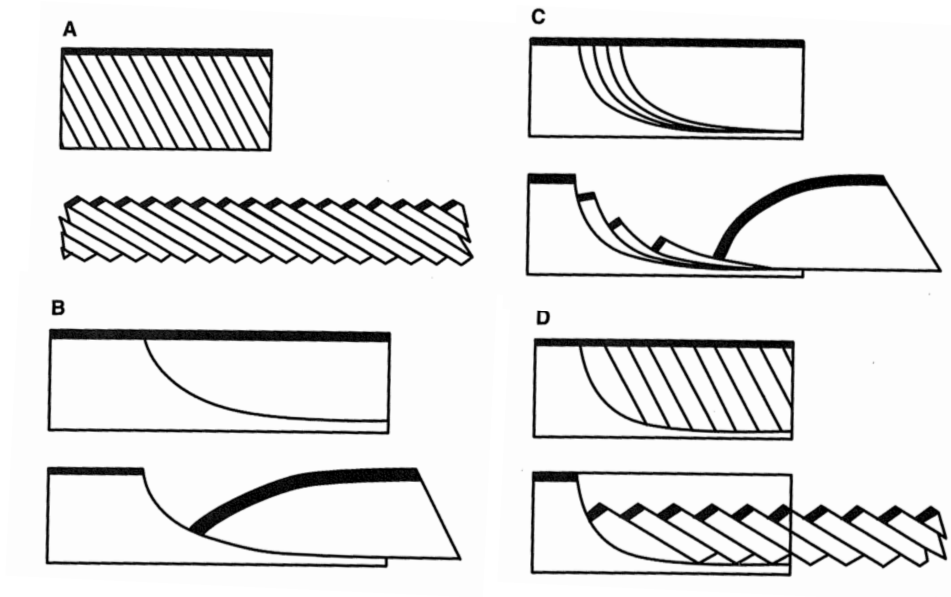
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right,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

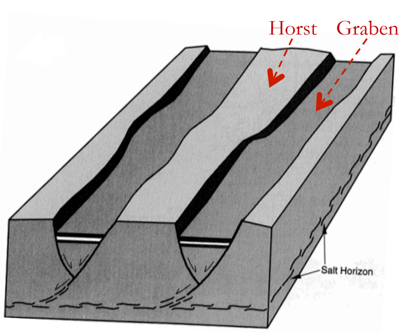


Structural Geology: Normal Faults

Normal Faults Geometries

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



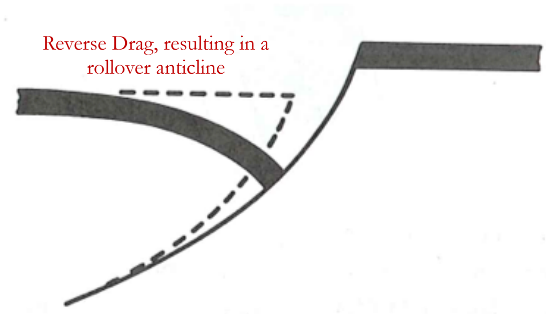


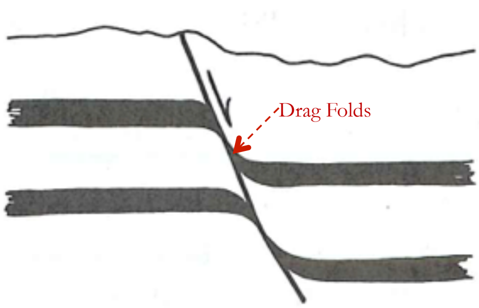
Horsts & Grabens

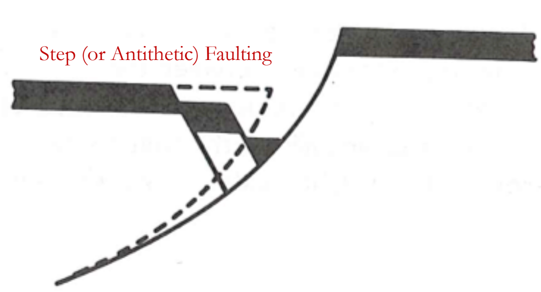
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

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



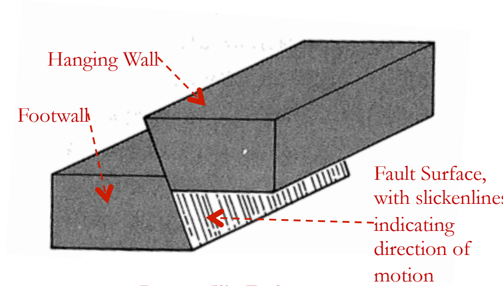




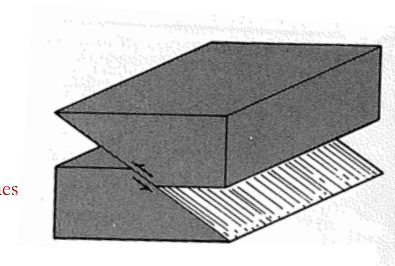
Structural Geology: Reverse & Thrust Faults

Reverse Faults

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

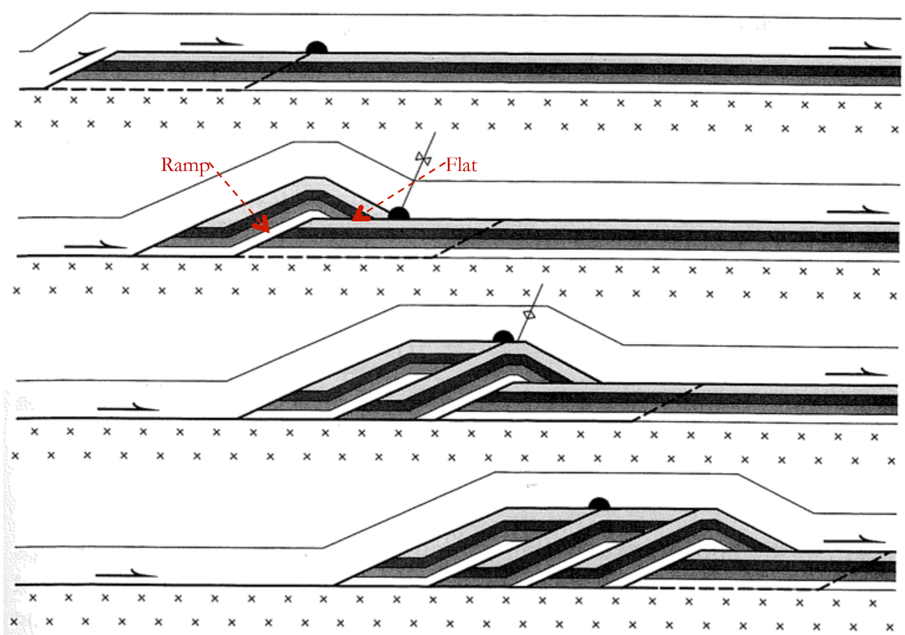


Reverse Slip Fault


Thrust Slip Fault

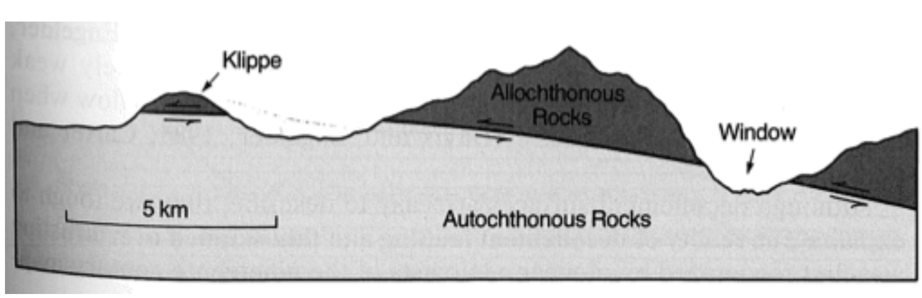
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

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

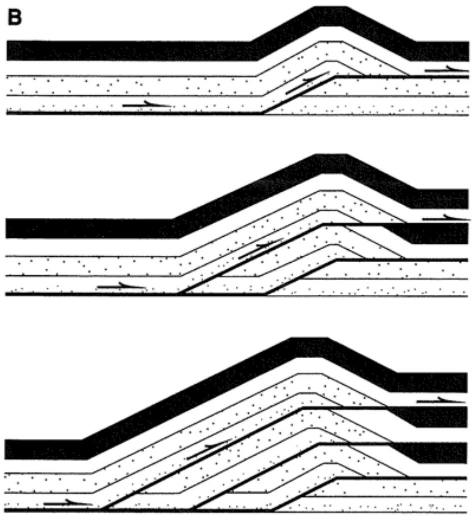


Klippe & Windows

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



Structural Geology: Reverse & Thrust Faults

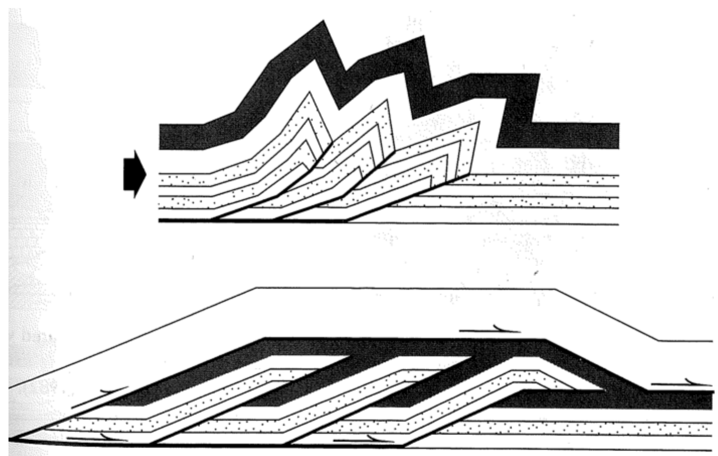


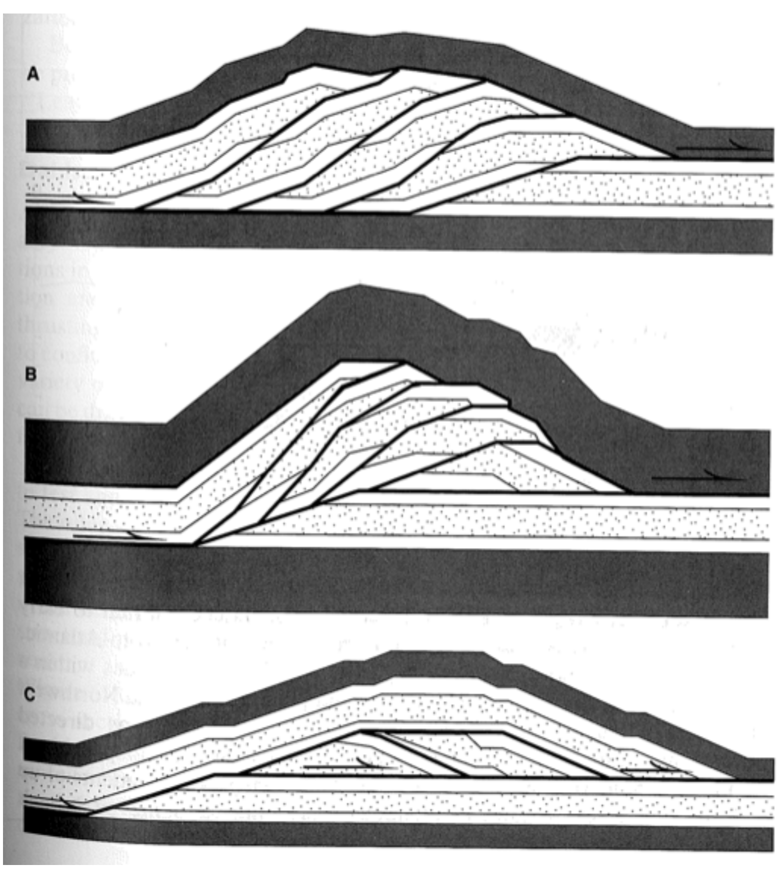
Out-of-Sequence Thrust Fault System

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

Imbricate Fans vs. Duplexes

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





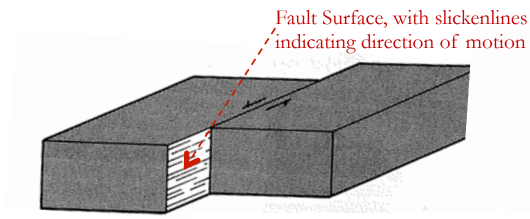
Forms of Duplexes

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

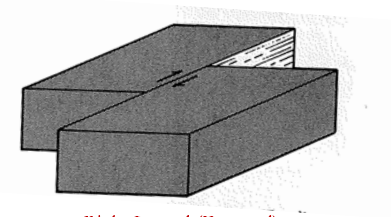
Structural Geology: Strike-Slip or Transform Faults

Strike-Slip Faults

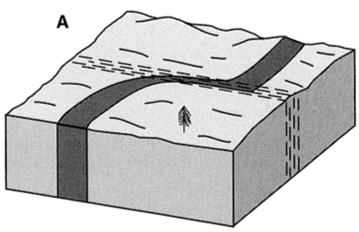
In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.



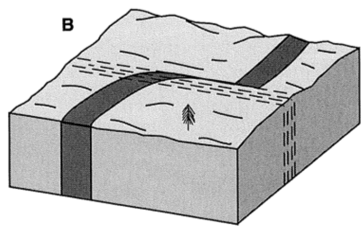
Left Lateral (Sinistral) Strike-Slip Fault



Right Lateral (Dexteral) Strike-Slip Fault



Continuous Shear Zone



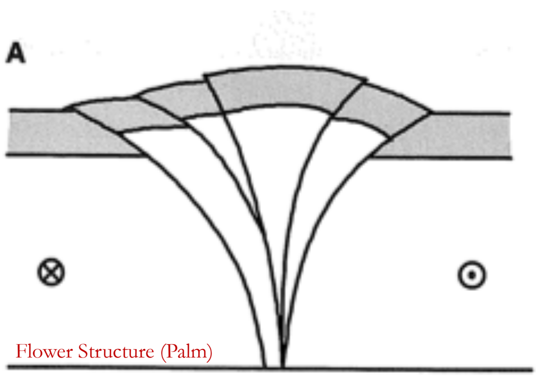
Discontinuous Shear Zone

Ductile Shear Zones

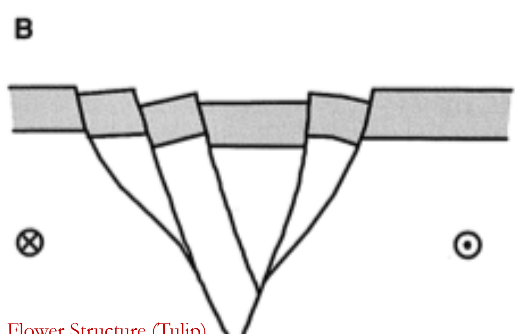
Shear in a strike-slip fault is not always located in a single plane. Sometimes, shear takes place over an extended region. Figures from Davis & Reynolds, 1996.

Brittle Shear Zones

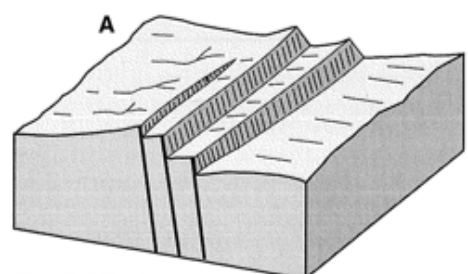
Figures from Davis & Reynolds, 1996.



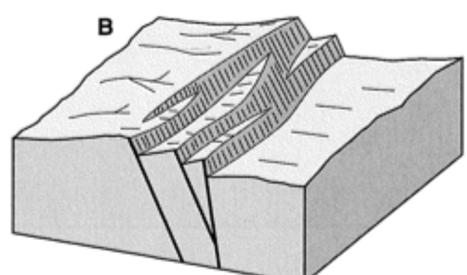
Flower Structure (Palm)



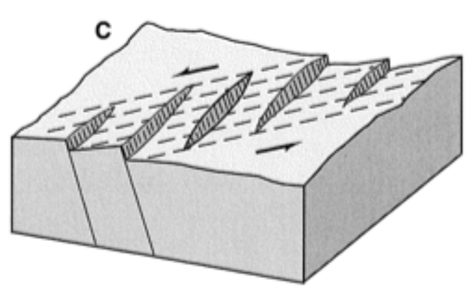
Flower Structure (Tulip)



Parallel Faults



Anastomosing Faults

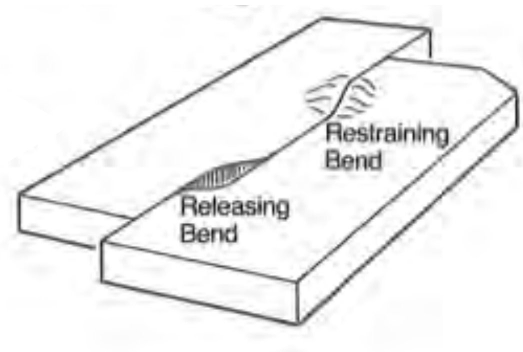


En Echelon Faults

Structural Geology: Strike-Slip or Transform Faults

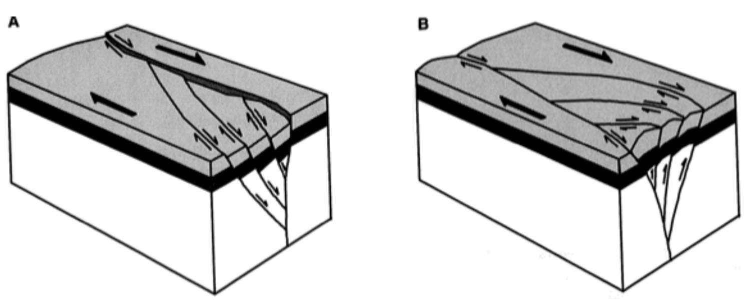
Bends in Strike-Slip Faults

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



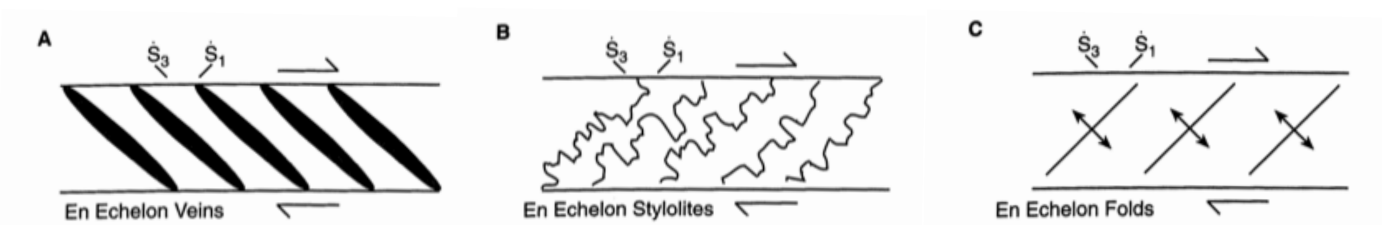
Strike-Slip Duplexes

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



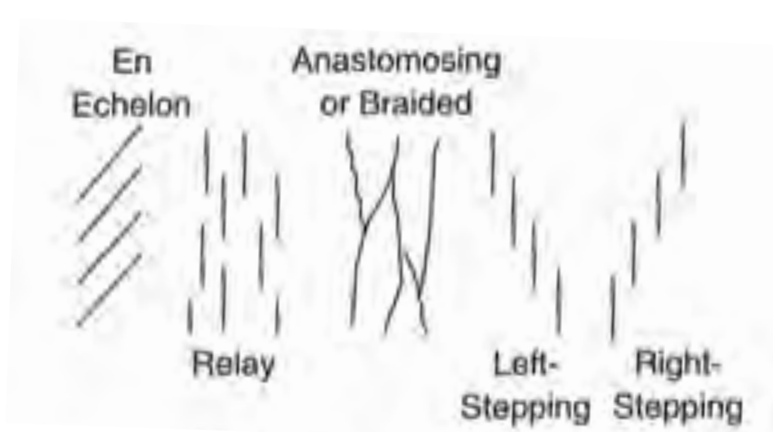
Slip Indicators in Strike-Slip Systems

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



Even more Geometric Arrangements of Strike-Slip Faults

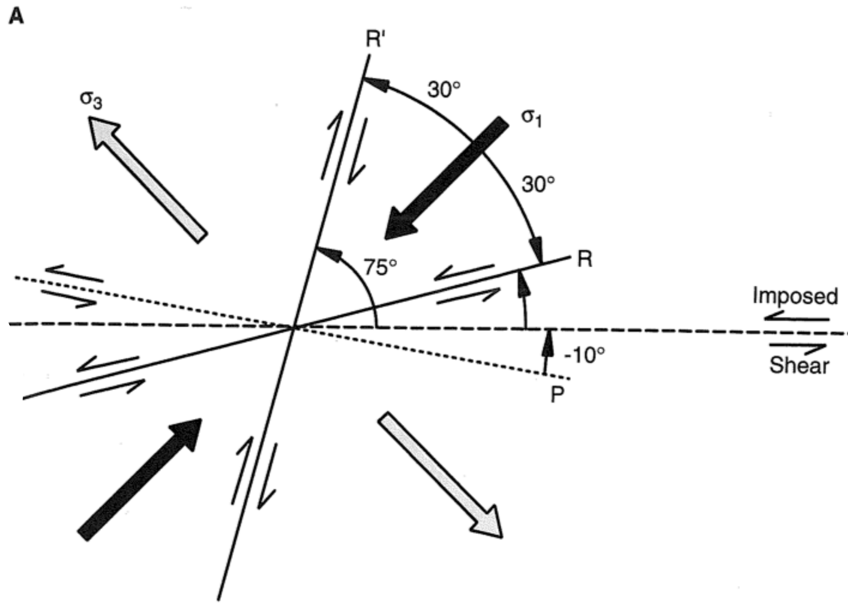
Figures from Davis & Reynolds, 1996.

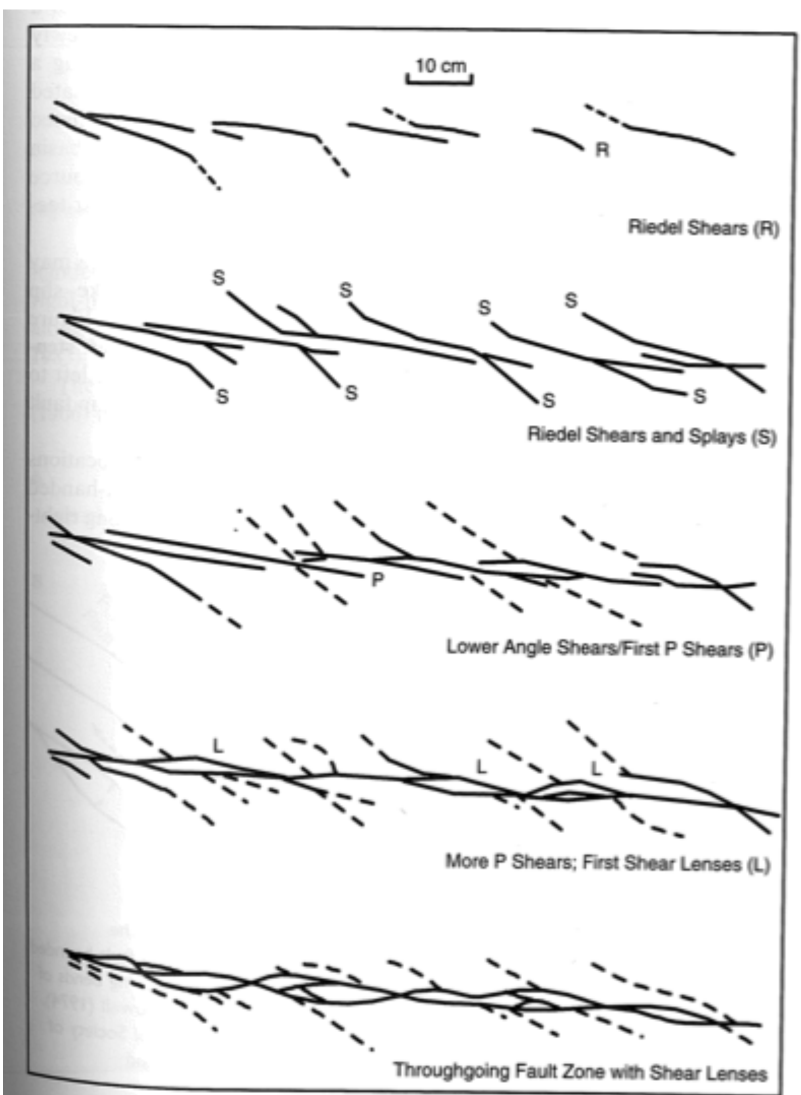


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

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





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

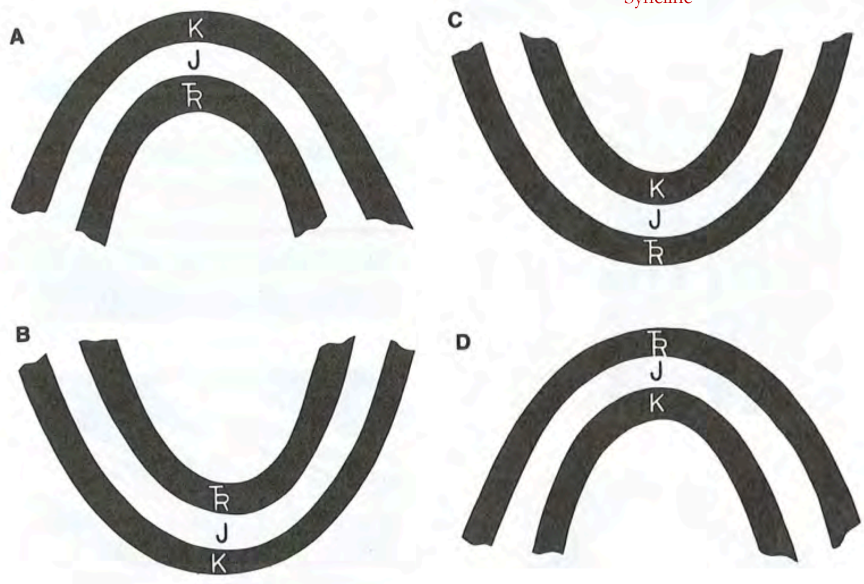
Structural Geology: Folds

Anticlines & Antiforms, and Synclines & Synforms

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

Anticline

Syncline

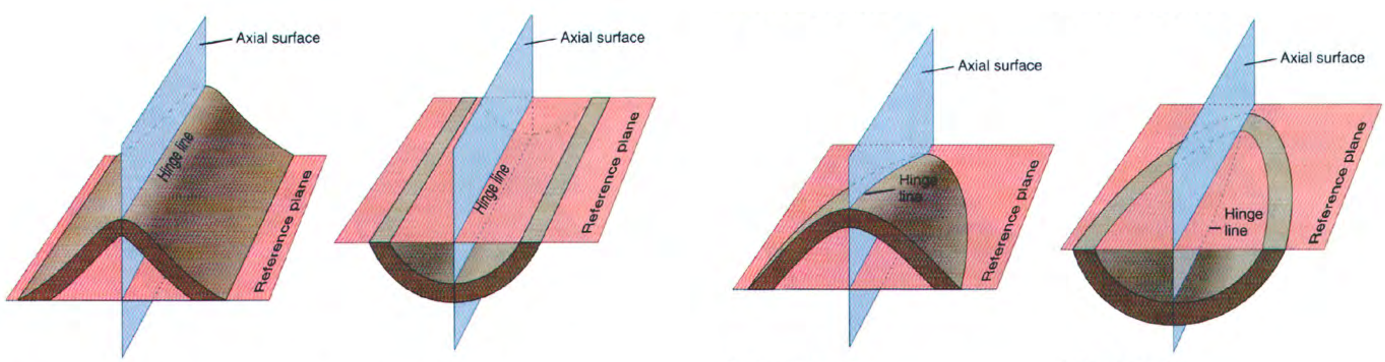


Antiform

Synform

Plunging Folds

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



Non-plunging antiform

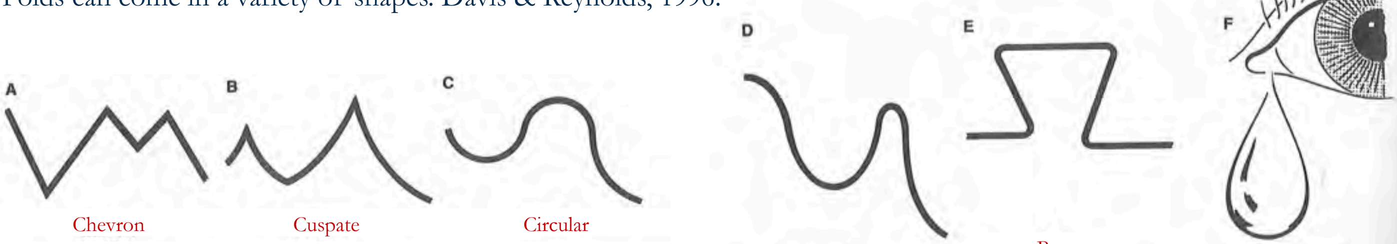
Non-plunging synform

Plunging antiform

Plunging synform

Fold Shapes

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



Chevron

Cuspate

Circular

Elliptical

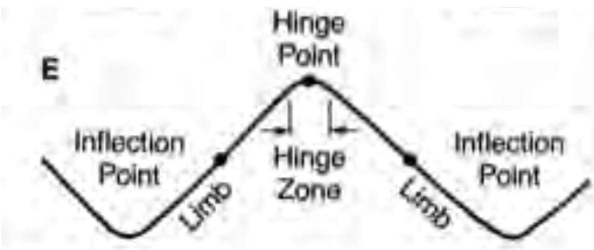
Box (Conjugate)

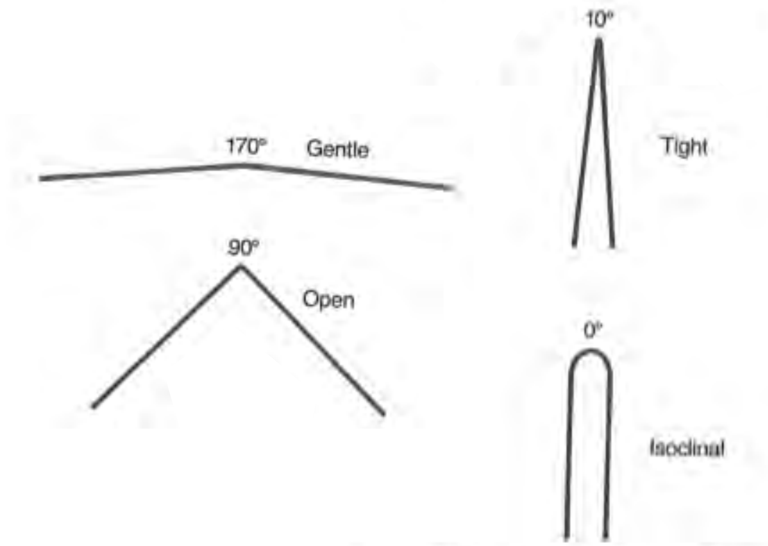
Teardrop

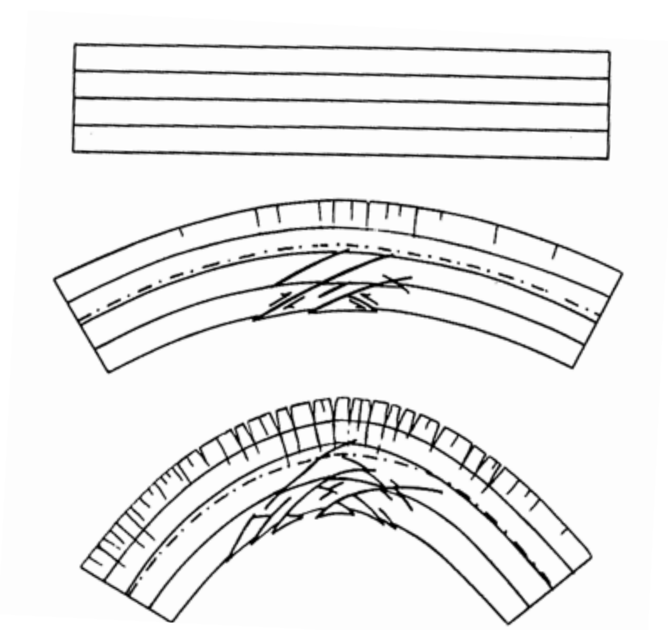
Structural Geology: Folds

Fold Tightness

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





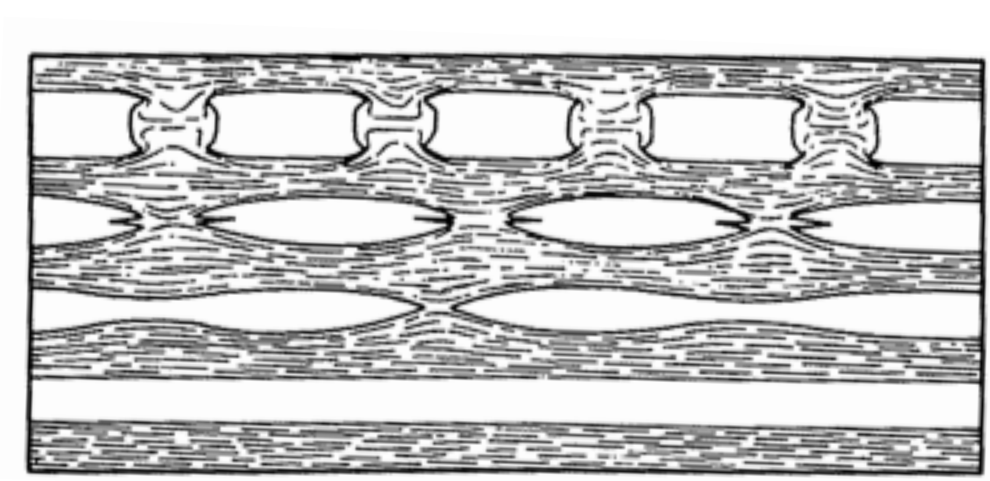


Minor Structures in Folds

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

Boudins

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



Geologic Map Symbols

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

From Compton, 1985

Geologic Map Symbols

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

Fossil and Structural Symbols for Stratigraphic Columns

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

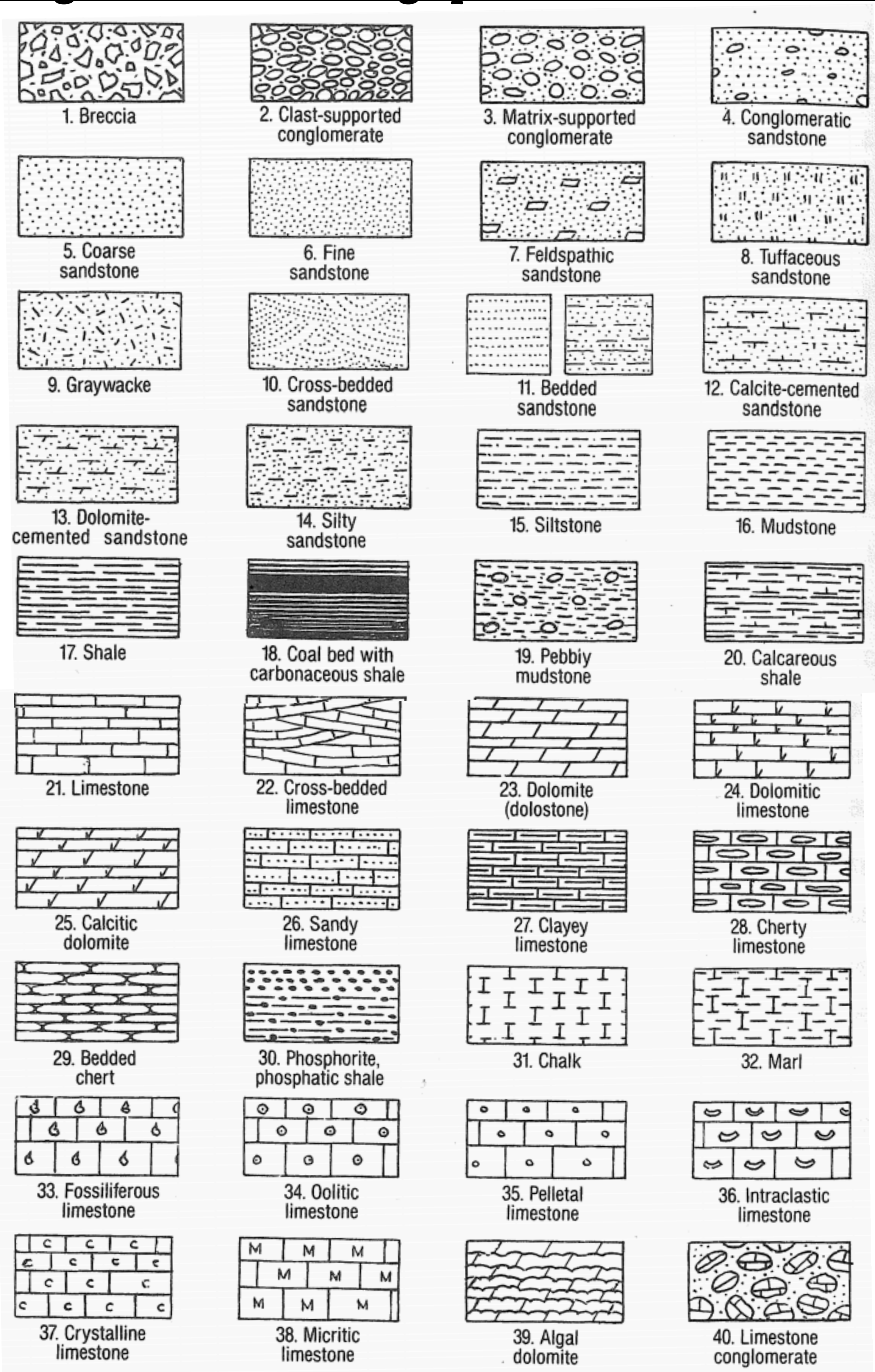
Tree trunk fallen
Trilobites
Vertebrates
Wood
Beds distinct
Beds obscure
Unbedded
Graded beds
Planar cross-bedding
Trough cross-bedding
Ripple structures
Cut and fill
Load casts

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

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

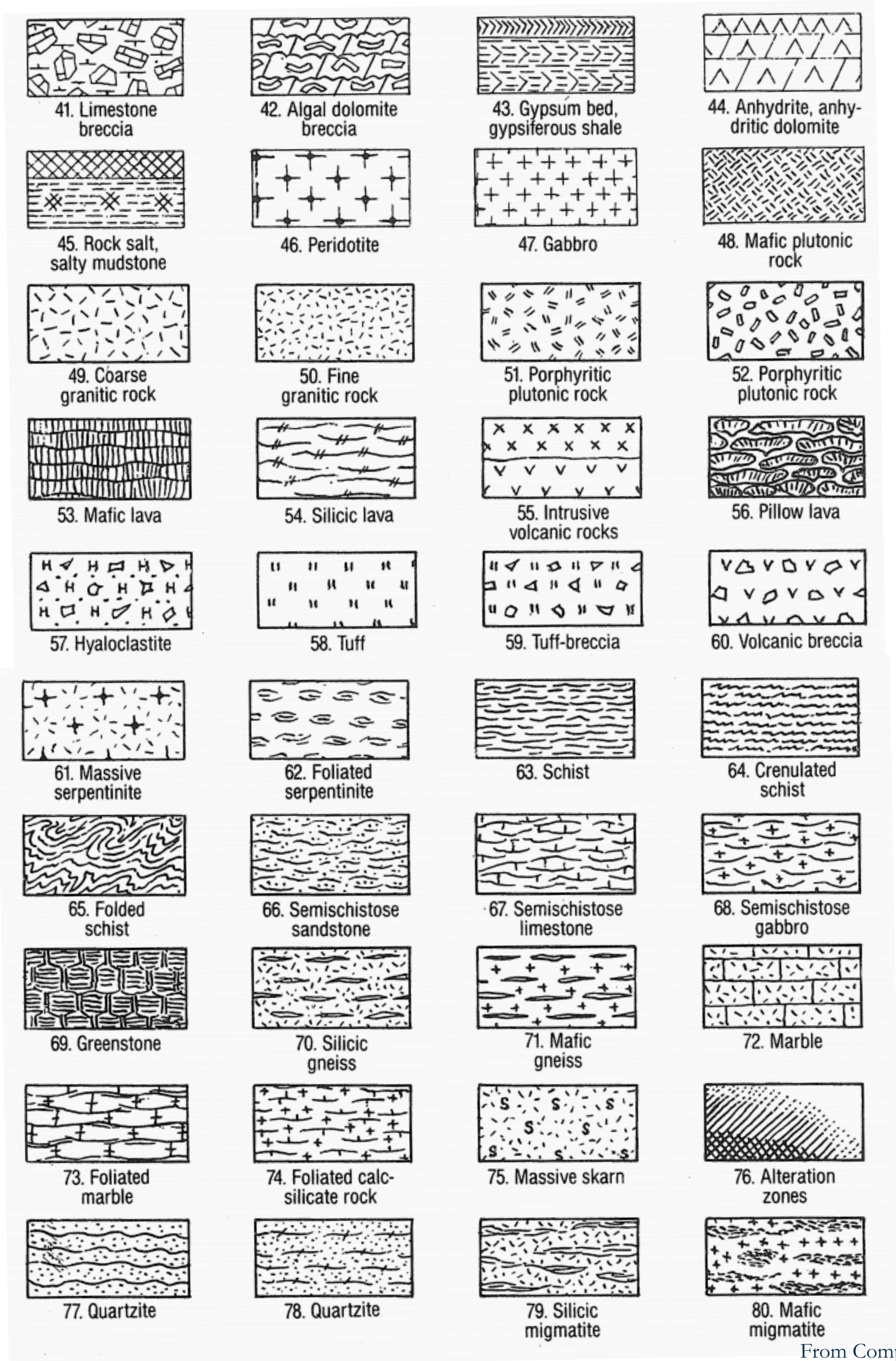
From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections



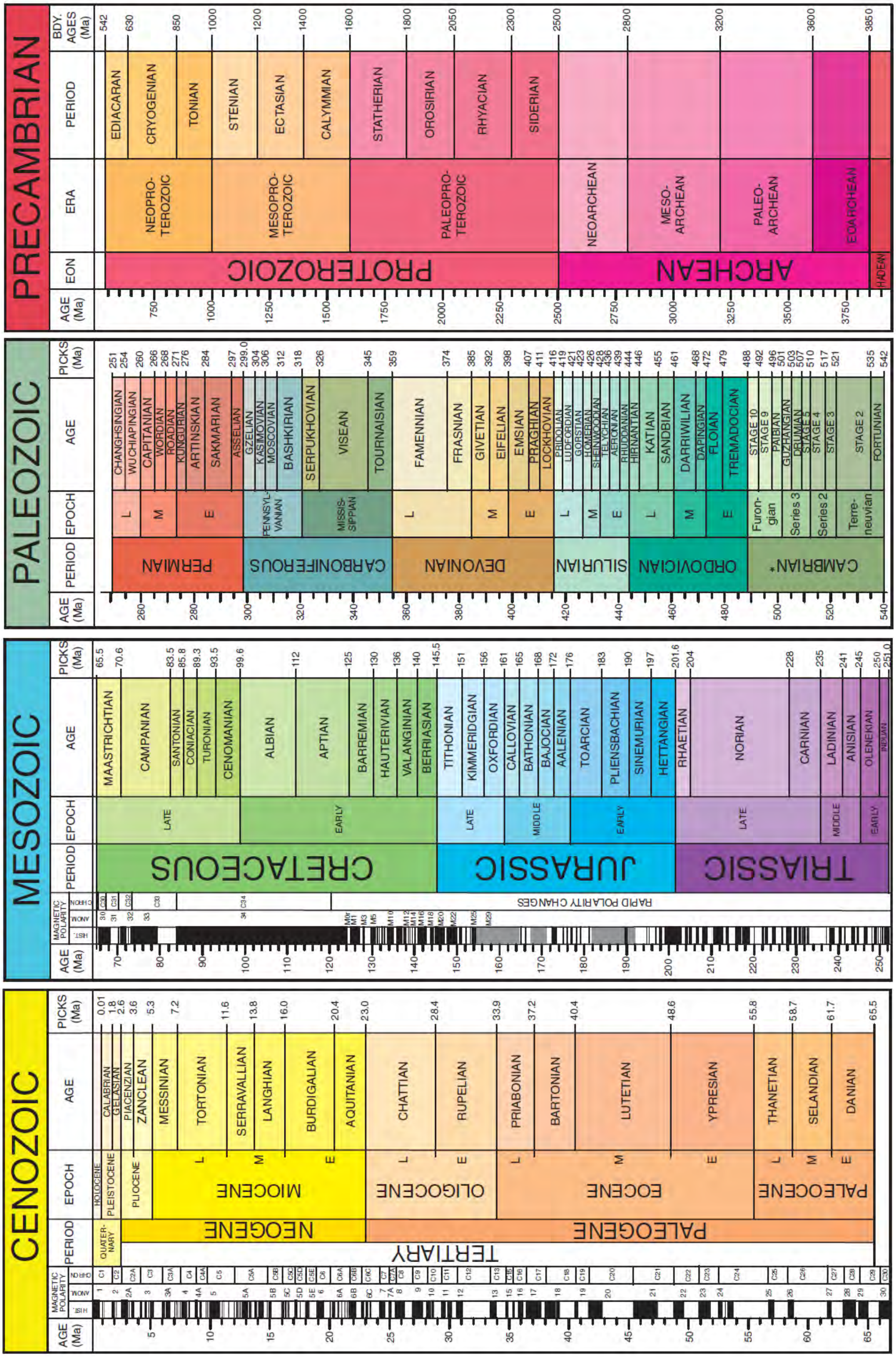
From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections



From Compton, 1985

Geologic Timescale

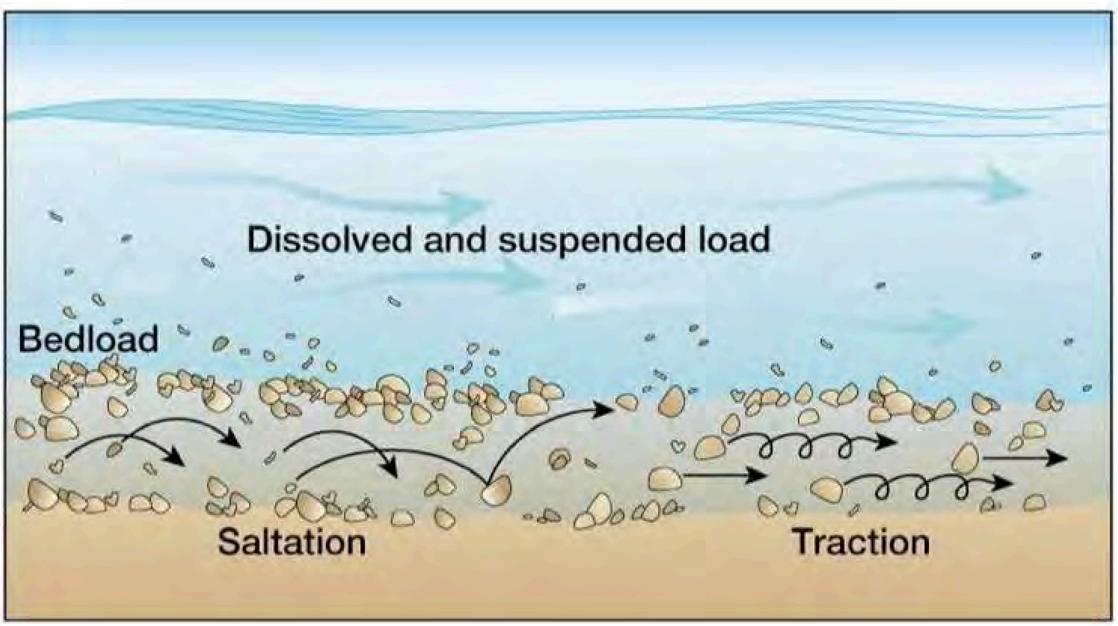


2009 version, from the Geologic Society of A bae: come over

me: I can't, i'm stationary clastic sediment

bae: my parents aren't home

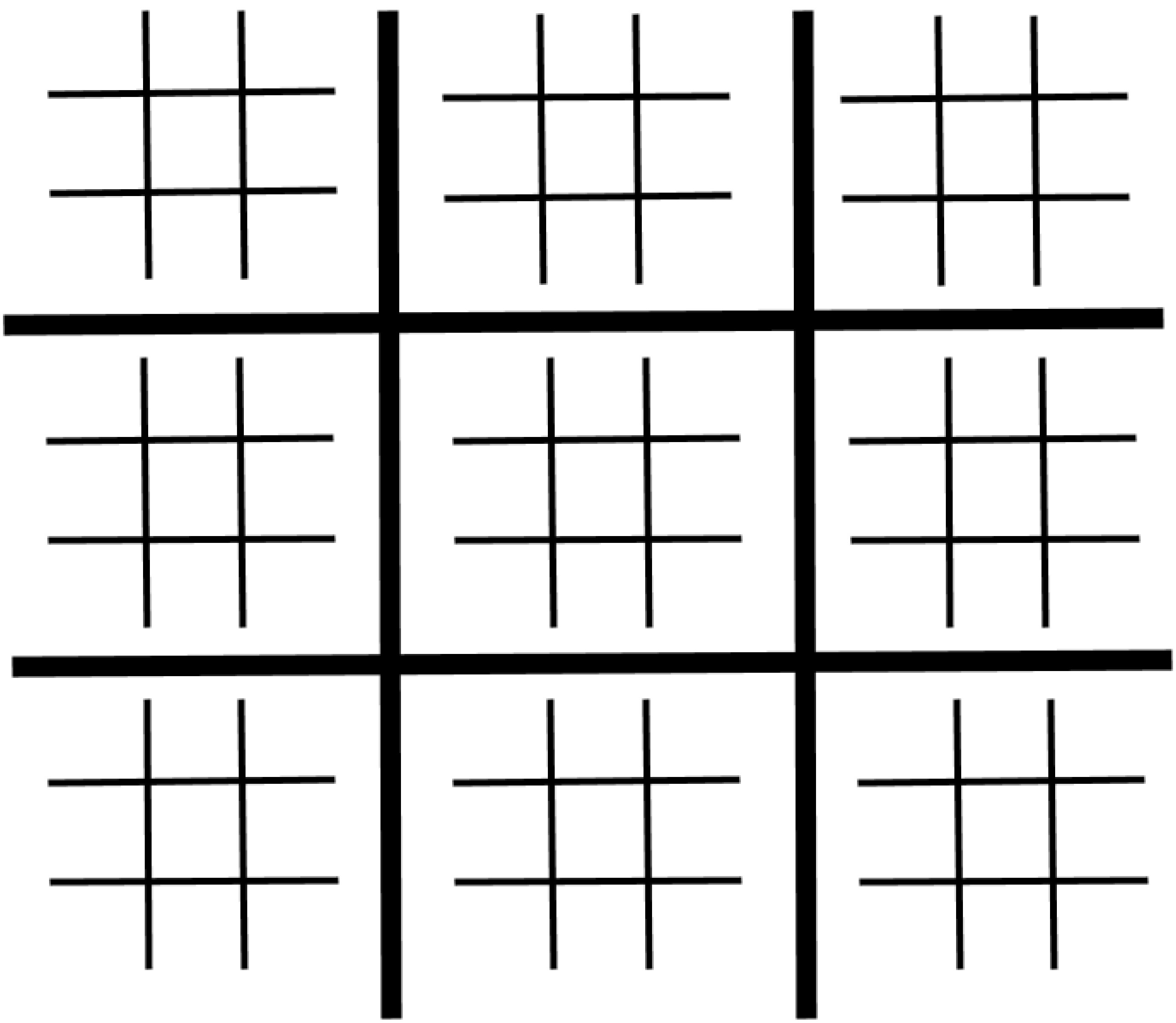
me:



When you look back at your fieldnotes after the trip

SUPER TIC TAC TOE

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



1

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

2

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

3

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

4

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

5

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

6

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

7

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

8

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

9

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

10

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

11

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

12

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

Battleship

Another fun activity from:

www.funorama.com

Defensive Grid

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

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

1 - Aircraft Carrier

A	A	A	A	A

1 - Battleship

B	B	B	B

1 - Cruiser

C	C	C

2 - Destroyers

D	D		D	D

Offensive Grid

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

Instructions (2 Players Required):

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