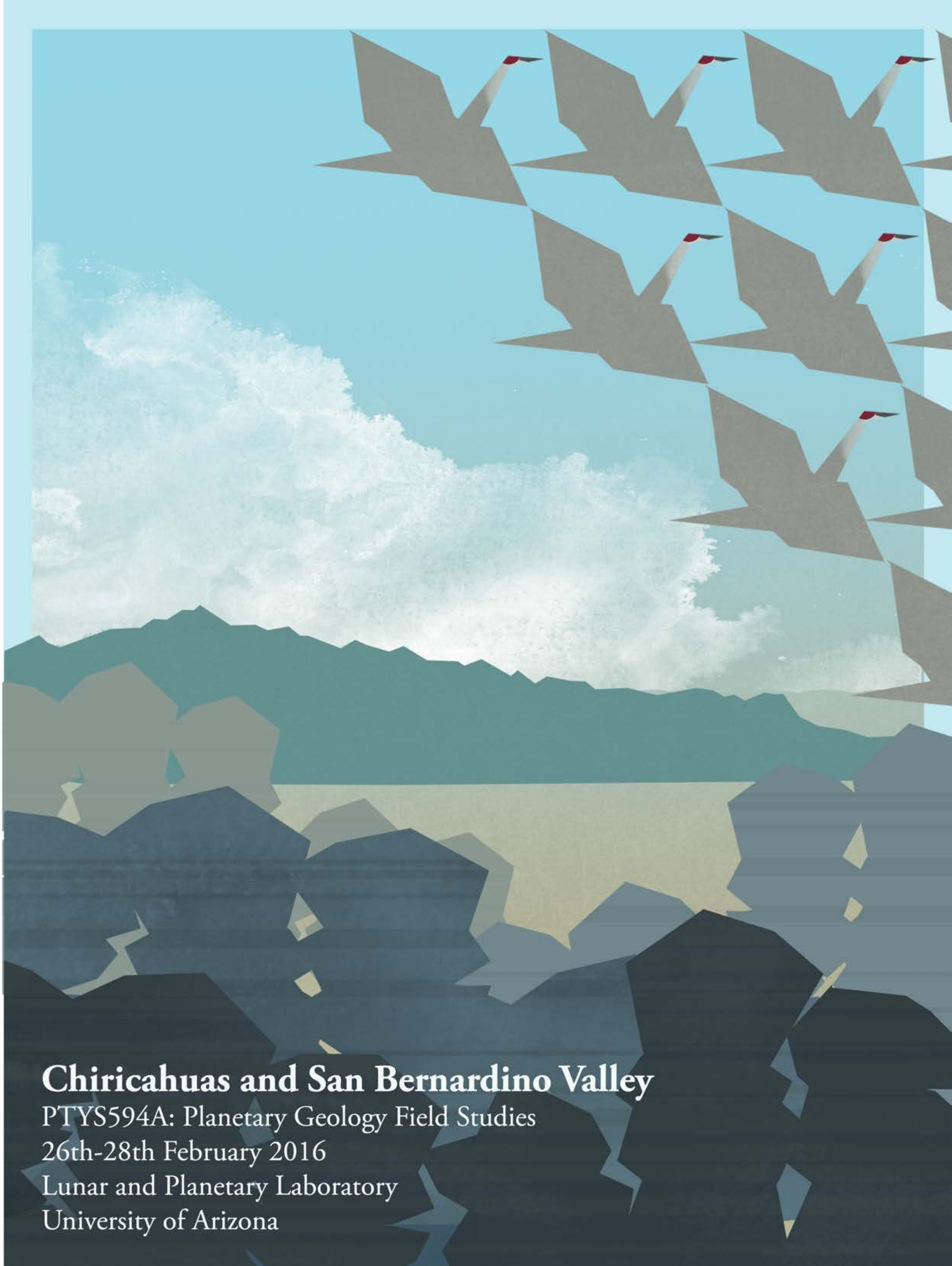

Chiricahuas and San Bernardino Valley

PTYS594A: Planetary Geology Field Studies
26th-28th February 2016
Lunar and Planetary Laboratory
University of Arizona

Letter from the Editor

Hello and welcome to another edition of the LPL field trip guide!

We're going to be exploring Tucson's very own geological backyard this time around, finally stopping at those weird looking rocks on I-10 (previously seen on the New Mexico trips of years past) and exploring the tectonic and volcanic features of the area. We even have a few stops to explore the history of southern Arizona drying out over geologic (and more recent) times.

In addition to the geology, this part of Arizona is rich with human history as well. From interactions between the United States and Mexico (present and historic) to the resistance of Geronimo and the Apache to the reservation system, this part of Arizona reflects many of the issues in the American West to this day.

Since we are going to be close to the US/Mexico border: please remember to have your IDs handy!

It's also going to be cold. Top tips for fighting the cold are: packing lots of coats and a warm sleeping bag, getting chemical hand-warmers, thermoses of tea and hot chocolate, long underwear, and finally getting out there to hike!

Margaret Landis

Table of Contents

Cover:
Eva Landis
http://evalandis.tumblr.com/

Road log for PTYS 594 Spring 2016 – ***All times are AZ times***
Sunrise is ~6.45am and sunset at ~6.15pm

FRIDAY 2/26/2016

7 AM Arrive at LPL loading dock bright-eyed and bushy-tailed with full ice chests, full stomachs, coffee and snacks.

8 AM Depart LPL for some fieldtrip excitement!
Exit the campus and drive south on Campbell/Kino for 4.7 miles, enter I10 eastbound. Drive 58 miles east and exit at the Texas Canyon Rest Area.

9 AM **Daniel - Spheroidal Weathering**

9.30 Back on I10 East. Drive 1.4 miles and take exit 322. Go south on Johnson Road for 4 miles then take a left onto East Dragoon Road and drive 7.4 miles (stop at the corner with Cochise Stronghold Road).

10 AM **Tad - Earth Fissures**

10.30 AM Drive another 2 miles east on Dragoon Road and then 8 miles north on US 191. Turn right off the road onto a small dirt track about 0.3 miles before reaching the railway line. Follow that out onto Wilcox Playa.

10.45 AM We'll play this by ear. Last time we drove south. Everything was dry and if we're lucky then that'll hold this time too. We'll check out the desiccation cracks and have some talks and have lunch at the edge of the playa where we may or may not glimpse a sighting of the elusive clay dune (Clay dunes are basically the bigfoot of LPL field trips—Ed.).

Donna - Playas and southwestern climate history
Corey - Desiccation Polygons
Lunch – Aim to leave the playa between 1 and 2 PM

1.30 PM Leave the playa at the same spot we entered. Drive north on US 191 to I10 (~3.5 miles). Drive 65 miles east on I10 (stop along the way for gas – maybe at San Simon). Take exit 5 (in New Mexico) and travel south on NM80 for 32 miles.

3.30 PM Arrive at the Geronimo Surrender Monument
Jon - Native people

Drive 5.7 miles further south on NM80. Turn right onto Price Canyon Road (use the first turn off to this road), drive 7 miles and turn off this road to the left. The new road will veer North, follow it for 0.6 miles, campsite is on the right.

4.30 PM **Sarah P. - Flora & Fauna**

Camp in National Forest, elevation ~5400'.
Bring something to keep you warm.

Saturday 2/27/2016

8AM Drive back to the 80 along Price Canyon Road. Drive 4 miles south on 80 and take a right turn on Tex/Rucker Canyon road. Drive northwest just under 2 miles. There's two cinder cones on the left – let's aim for the 2nd one. Park at ~8.30AM somewhere convenient and walk up. This is a good site to find mantle nodules.

Ali - History of San Bernardino Volcanism
Anna- Basin and Range
Margaret - 1887 Earthquake (The Wrath of Basin and Range!)
Hamish - Mantle Xenoliths
Hunt around for Xenoliths

9.30 AM Back to the highway and continue south 6.6 miles. There's a small road on the left called Lazy J Ranch Road (probably not signposted) – there may be a locked gate to negotiate. Drive east ~2 miles, then the road veers to the south. Drive another ~3.5 miles, turn left at the 4-way intersection. The rim of Cochise Maar should be right in front of us.

10.15 AM Arrive at Cochise Maar - Hike down into the Maar
Kenny - Border issues and ranching in the valley
Sondy - Maar Volcanoes

12PM Lunch Back at the vehicles, aim to leave by 1PM.
Drive back out the way we came in.

Italicized text may not happen – I'm still trying to get hold of the land owner.
We'll visit a nearby cinder cone mine instead if necessary.

Take a right turn on the 80 and drive ~11 miles. About half a mile north of Price Canyon Road there's a small turnoff to the right. Drive 1.3 miles roughly east and then the road veers to the south. Drive another 3.2 miles and turn right at the T-junction. Drive about half a mile and the rim of Paramore crater will be on the left.

2PM Arrive at Paramore Crater.
Drive back out the way we came in.
(20-30 minutes on dirt road and then a 38 minute drive to Portal)

Take a right turn on the 80 and drive 19.1 miles to NM 533. Turn left toward Portal and drive 7 miles. Stop to freshen up and get gas in Portal.

Portal road turns into Paradise road at the edge of town. Take paradise road into the mountains and pull off to camp in the National Forest area (several sites available within a few miles of Portal).

?? PM Camp in National Forest near Portal, elevation ~5200-5600'.
Bring something to keep you even more warm.

Sunday 2/28/2016

8AM Drive back into Portal to freshen up – lunch may be late today so I recommend gorging on breakfast and whatever cheap nasty gas-station food you deem appropriate. This time we'll exit Portal to the west on Forest Road 42 and pass many exciting locales such as Onion Saddle. After ~15.5 miles Forest Road 42 turns in Pinery Canyon Road. Drive 8.5 miles and turn right on Bonita Canyon Road. Drive 7.4 miles and turn right, drive 0.6 miles to the parking lot at the Sugarloaf trailhead. This is a lengthy drive, but the scenery is beautiful.

10.30 AM Arrive at the Sugarloaf trailhead. The trail is about a mile long (one-way) and has an elevation gain of ~500'. Before we start walking we'll hear about:

Joana- Turkey Creek and Portal Eruptions and Tuff deposits

Along the way, we'll stop at promising sites to hear about:

Rodrigo - Fumaroles
Steve - Case Hardening

12.30 PM Back at the vehicles for Lunch… Yum, Day-3 sandwiches never tasted so good… After eating we'll hear why volcanoes like these matter to most people in Arizona:

Tom - Arizona's copper deposits

1.15PM Drive about a mile to the end of Bonita Canyon Road. Take either trail at the far end of the parking lot for a very short walk to a viewing platform. There'll be lots of:

Maria - Joints and Hoodoos
Sarah S. - The many uses of Precariously Balanced Rocks

2.30 PM Back at the Vehicles and ready to go. Bonita Canyon Road turns into the 181 outside the park, which turns into the 186 (with a right turn). This gets us to the I10 and the rest is easy.

5-5.30 PM Back at LPL. What!!!... In daylight? No way! This class has gone seriously downhill – time for someone new.

PTYS 594 (2016 Spring): Spheroidal Weathering

Spheroidal weathering in granite on Haytor, Dartmor England (from Wikipedia)

Spheroidal weathering is a form of chemical weathering that commonly affects uniform, hard bedrocks which are well jointed, especially granite. Two key ideas are essential in understanding spheroidal weathering:

1. **Spheroidal weathering results in quasi-spherical concentric layers of weathered rock surrounding a central corestone**. The weathered rock is known as saprolite. The rounded shape results from corners being subject to higher weathering rates due to their higher surface area to volume ratio. There is often a clear abrupt change (the weathering front) between the weathered rock and the solid rock.
2. Spheroidal weathering is a type of exfoliation, which generally refers to any process that produces sheets of rock. Spheroidal weathering is distinct from other forms of exfoliation (e.g. flaking, spalling) in that **spheroidal weathering acts in all directions around the corestone**, acting on the underside just as much as the top. Spheroidal weathering has also been observed at considerable depths where "surface processes" (e.g. temperature variations) are unlikely to have played a role. Two separate hypotheses have been put forward as the cause for spheroidal weathering:
    a. Alternating layers with different mineralogy, similar to Liesegang rings, forming concentric shells which are then chemically weathered at different rates. Analysis of the bands in spheroidally weathered micrograms found enriched Al, Si, K, Zr, Y and Rb in the leached zones, with Ca and Fe enriched in the brown zones.
    b. Development of pre-existing micro-cracks into macro-cracks. Water seeps through the micro-cracks and chemically weather biotite and hornblende into limonite which accumulates in the micro-cracks. Individual micro-cracks become connected over time and widened into macro-cracks. Eventually the spheroidal structures are destroyed as cracks become filled with weathering debris. Rock permeability is important in this mechanism. Compared to granite with higher permeability, the weathering front in spheroidally weathered basalt advances by smaller increments, giving rise to thinner layers.

References

Ollier, C. D. (1971) *Causes of Spheroidal Weathering*. Earth-Science Reviews 7: 127-141.

Prepared by Daniel Lo

EARTH FISSURES IN ARIZONA

Thaddeus D. Komacek

1. INTRODUCTION: WHAT'S THE PROBLEM?

Earth fissures (irregular cracks in the ground[1]) have "mysteriously" appeared in Arizona in the last century, disrupting infrastructure and causing many hazards, e.g. cracked/collapsing roads, severed railroads, broken pipes, damaged wells, and livestock/pet injury and death, among other things (Allison & Shipman 2006). Figure 1 shows some guy looking at an Earth fissure, just so you know what they look like. Figure 2 shows a map of the Earth fissures in southern Arizona. Note that the main concentrations of Earth fissures appear near Casa Grande and Wilcox.

These fissures are due to rapid increases in groundwater pumping for irrigation (notably up to 500 times faster than can be naturally replenished in some areas, see Allison & Shipman 2006), with all of the fissures developing since 1951 (Chronic 1983). As a result, these fissures are thought to be caused by compaction of valley sediments due to groundwater removal. They nominally occur above bedrock ridges, as thicker sediments accommodate a greater degree of compaction and hence larger fissures. These fissures propagate upward from these compacted sediments that are near the depth of the lowered water table. Initial subsidence of $\sim 0.5 - 1$ meter is necessary for the formation of Earth fissures, though in some areas (most notably the Picacho basin near Eloy and Luke basin west of Phoenix) land has subsided ~ 20 feet!

Somewhat problematically, some of the largest fissures cross I-10 and the freight train tracks adjacent to them near Picacho peak, near Eloy. Figure 3 shows a map of these fissures near Picacho showing this crossing. This can be a real problem, as monsoon rains can cause widening of these fissures and major problems with infrastructure. Most

Fig. 1.— Man checking out a Earth fissure, from http://www.azgs.az.gov/efresources.shtml.

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Fig. 2.— Map of Earth fissure locations in southern Arizona. Note the concentrations near Casa Grande and Wilcox. From http://data.azgs.az.gov/hazard-viewer/.

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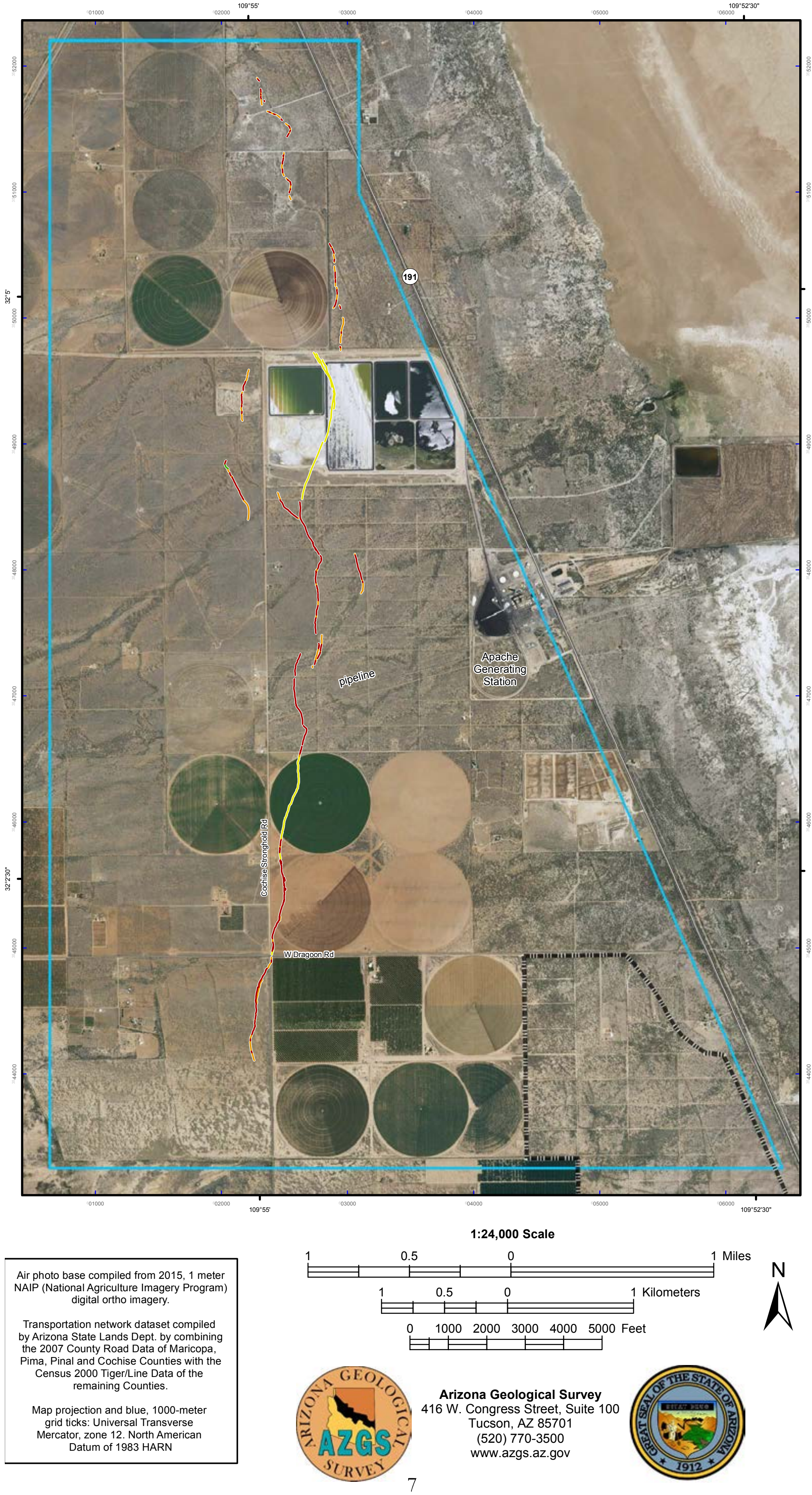
[1] Do not confuse Earth fissures with giant dessiccation cracks (GDCs), which form as a result of drying and shrinkage of fine sediment close to the surface (Allison & Shipman 2006). GDCs are normally polygonal, much different than the nearly linear Earth fissures.

Fig. 3.— Map of Earth fissures near Picacho, from http://www.azgs.az.gov/efresources.shtml. Red lines are continuous mainfested Earth fissures, orange lines discontinuous fissures, yellow lines fissures not confirmed by AZGS but have been by aerial imagery, and green lines are unconfirmed fissures that have been previously reported by non-AZGS professional geologists. Note how the fissures cross I-10.

Fig. 4.— Wrecked cargo from trail derailment near Picacho peak during a storm. From http://www.azcentral.com/story/news/local/pinal/2014/09/16/picacho-peak-train-derailment-abrk/15709847/.

notably, a train derailed right near this location in 2014 (see Figure 4), which as I got to see during my ∼ weekly drives to/from Tempe took almost a month to clean and repair. Though not directly linked to the fissures, this is one of my self-developed conspiracy theories, as it is likely that the tracks are not inspected often enough to catch changes on the order of days to weeks. Perhaps this may be an unspoken issue helping cause the lack of rail transport between Tucson and Phoenix.



Air photo base compiled from 2015, 1 meter NAIP (National Agriculture Imagery Program) digital ortho imagery.

Transportation network dataset compiled by Arizona State Lands Dept. by combining the 2007 County Road Data of Maricopa, Pima, Pinal and Cochise Counties with the Census 2000 Tiger/Line Data of the remaining Counties.

Map projection and blue, 1000-meter grid ticks: Universal Transverse Mercator, zone 12. North American Datum of 1983 HARN

Arizona Geological Survey
416 W. Congress Street, Suite 100
Tucson, AZ 85701
(520) 770-3500
www.azgs.az.gov

Fig. 5.— Map of Earth fissures southwest of Wilcox playa, from http://www.azgs.az.gov/efresources.shtml.

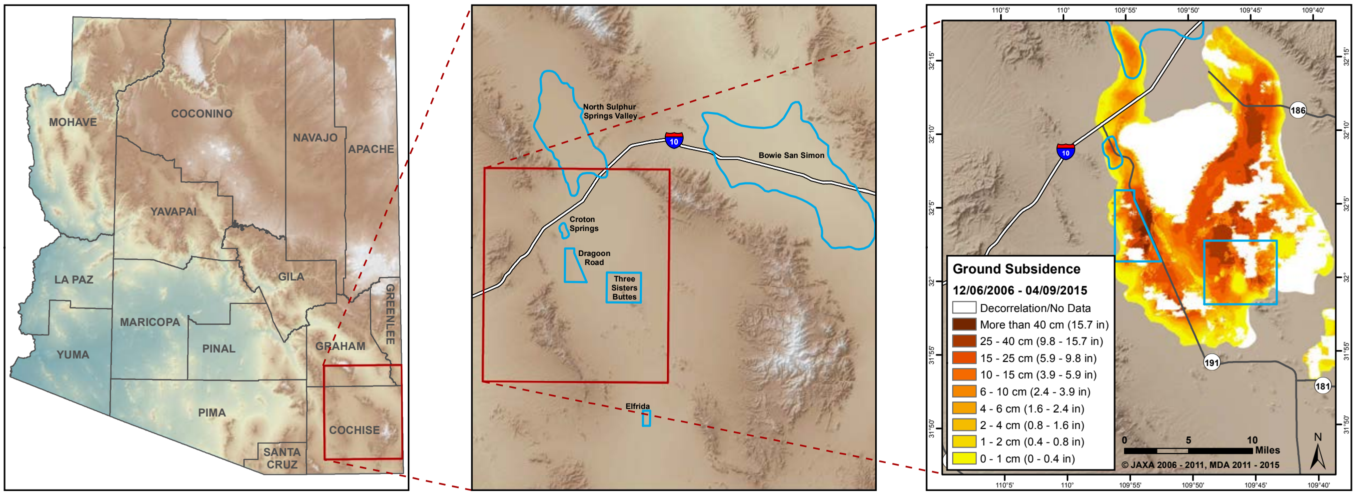


FIG. 6.— Ground subsidence in ∼ 8 years around Wilcox playa. The study area shown in Figure 5 is the Dragoon road study area. Note the high rate of subsidence in this area. There is a remarkable correlation between subsidence rates and occurrence of Earth fissures (not shown). From http://www.azgs.az.gov/efresources.shtml.

2. EXAMPLES NEAR WILCOX PLAYA

Figure 5 shows a map of the Dragoon road study area southwest of Wilcox playa, which I believe (hope) is where we are right now. Note the mostly linear (though somewhat jagged) crack running for a couple miles through what is largely farmland. This is one of the longest fissures in Arizona, and is caused by the massive subsidence in the region around Wilcox, see Figure 6. In the region of this long linear fissure, subsidence (just in the past decade) reaches ∼ 0.5 meters, the largest in the region. There are other sets of fissures in the region (shown by the blue boxes), but the Dragoon road region shows the most coherent set of fissures of the four.

3. PLANETARY CONNECTIONS?

Though there are fossae and similar cracks on Mars (and other planets/moons), these are caused by volcanic/tectonic activity, not groundwater removal. If someone knows of a good example of fissures caused by groundwater removal on another planetary body, let's talk about it!

REFERENCES

Allison, M. & Shipman, T. 2006, Earth Fissure Mapping Program: 2006 Progress Report, Tech. rep., AZGS

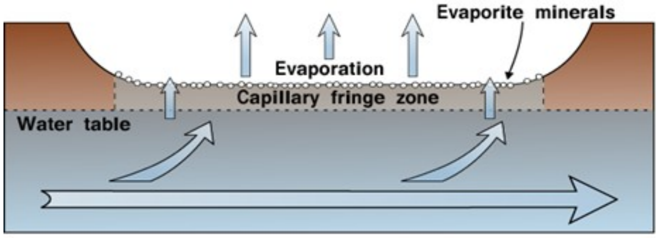
Chronic, H. 1983, Roadside Geology of Arizona, 25th edn. (Missoula: Mountain Press Publishing Company)

Playas and Southwestern Climate History

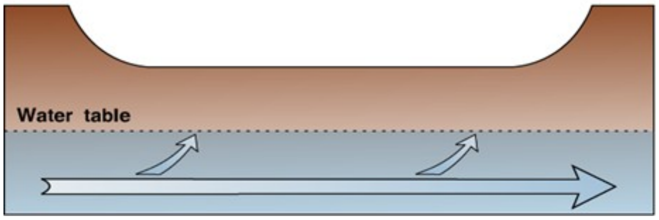
Donna Viola

Types of Playas:

Saline playa vs. salt-free playa: self-explanatory.
Wet playa vs. dry playa: mostly self-explanatory (see figure below).
Sediment types: lacustrine (from a past lake) or modern deposits.



Wet Playa (water table is near the surface)



Dry Playa (water table is deep below the surface)

Playas as Indicators of Climate

Playa sediments can provide evidence for past hydrological regimes. For example, as a lake grows shallower and concentrate minerals, precipitates such as evaporites can form. It is possible to infer past lake levels (and therefore climate conditions) from clasts or minerals found in the sedimentary record.

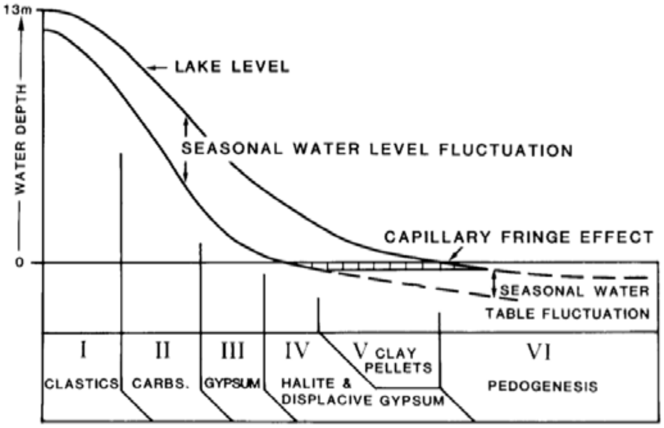
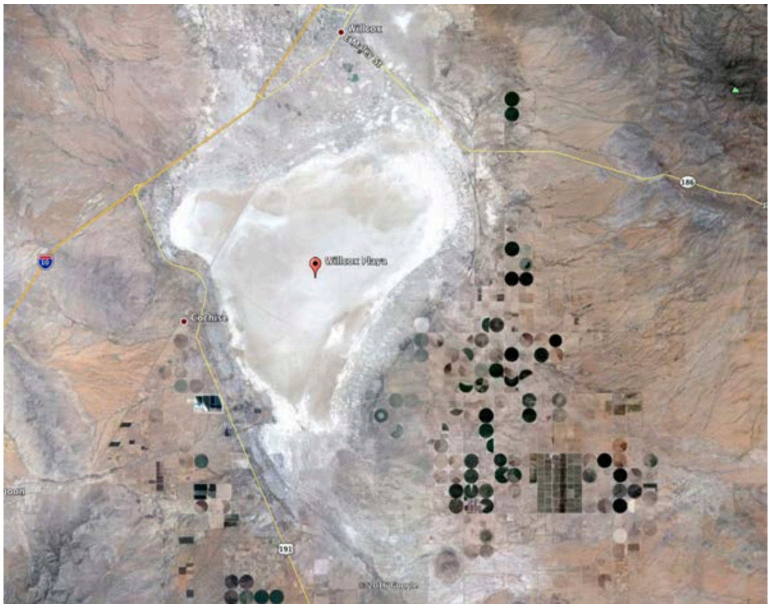


Fig.5. Lake and groundwater level change during a Lake Tyrrell hemicycle of drying, showing potential seasonal fluctuations. Stages of sedimentation and diagenesis (I–VI) related to the changing hydrology are also shown (after Bowler and Teller, 1986).

FIGURE (at left): This example from Lake Tyrrell in Victoria, Australia, shows the expected deposits as the lake level decreases. Credit: Teller & Last (1990) [i]



Willcox Playa Characteristics:

- **Surface area:** 130 sq. mi.
- **Elevation:** 1260 ft.
- **Annual rainfall:** ~23-30 cm/yr. (>1/2 in summer)
- **Mean annual temperature:** 14.8°C (58.7°F)
- **Remnant of Lake Cochise (Pleistocene)**
- **Closed/terminal drainage basin**

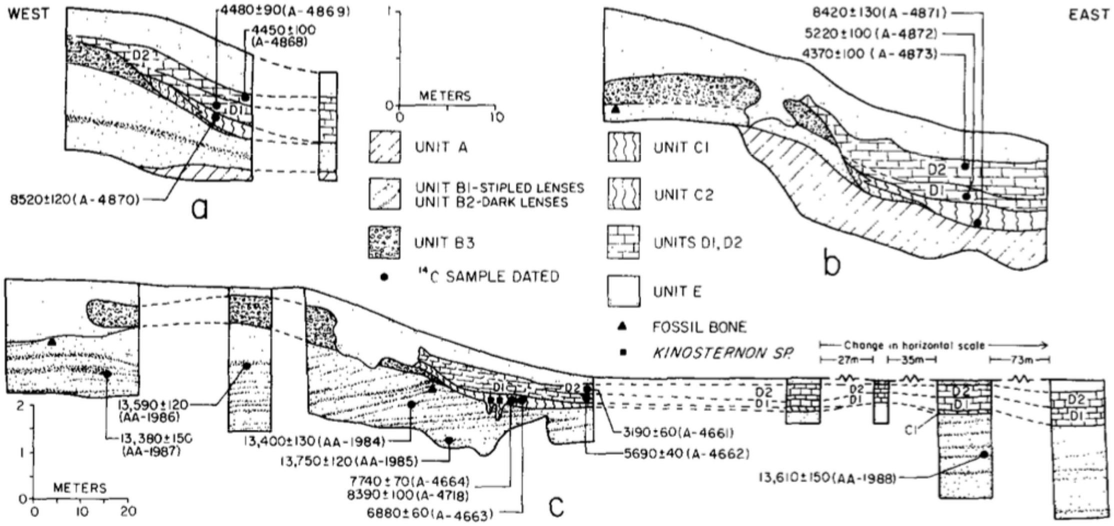


FIG. 3. Cross sections showing the stratigraphic relationships at the Marble locality (a), Grimm locality (b), and Cameron locality (c). Sections are oriented perpendicular to the 1274-m shoreline. For each section, the berm crest is to the west. The position of radiocarbon ages and fossil remains are shown. Ages are given in radiocarbon years B.P. Note the similar stratigraphy between localities. Unusual stratigraphic contacts between unit E and the underlying sediments are the result of faunalturbations.

FIGURE (above): From Water (1989)[ii], cross-sections of the Willcox Playa stratigraphy. Unit A = lacustrine deposits (calcareous to sandy clay). Unit B = beach sands, dating to ~13+ kya (B1 = sand and small gravels; B2 = silt and clay; B3 = sand and gravel cemented with calcium carbonate). Unit C = black clays, dating to ~8.9-6.1 kya (C1 = black- to gray-colored, organic-rich sandy clay; C2 = gray to dark-brown silty sand and fine gravel). Unit D = marl/$CaCO_3$-rich mudstone, representing separate lake stands and dating to ~5.7-3.2 kya (D1 = lower marl, hard/coarse prismatic structure; D2 = upper marl, hard to lithified, with massive structure). Unit E = gravely silty sand, aeolian/alluvial deposition in late Holocene.

Willcox Playa/Lake Cochise: A Timeline (from Waters 1989)

- 13.75-13.4 kya: late Pleistocene glacial period, cooler temperatures, greater winter precipitation → pluvial conditions.
    - Formed the 1274-m shoreline.
- 13-9 kya: dessication/dry conditions.
- ~8.9 kya: early Holocene, warmer temperatures, high precipitation (winter and summer) → pluvial conditions.
    - Lake Cochise filled below Pleistocene level.
- Two additional lake stands in the late-middle Holocene (end of the Holocene thermal maximum).
- Past several thousand years: dry, with intermittent shallow lakes.

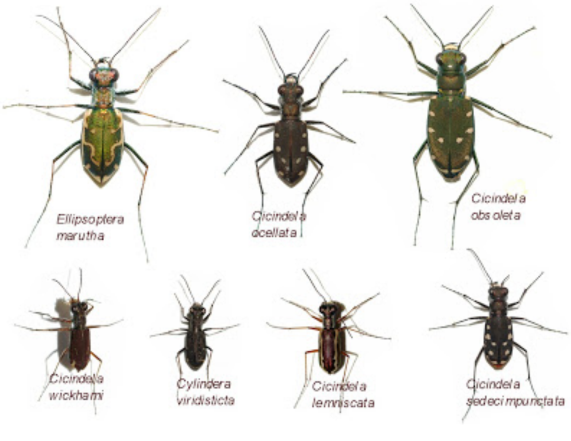
Pluvial conditions indicate past periods with higher humidity (and therefore higher lake stands). Fluvial sediments were also deposited during the late Tertiary (now called the Neogene) and Quaternary (Pleistocene/Holocene) periods, including sources from alluvial deposits.

Some water inflow into Willcox Playa still occurs today (seasonally), but most is lost to infiltration along the way.

Fun facts!

Willcox Playa was named a National Natural Landmark in 1966. It contains

- Fossilized pollen in the black mud deposits.
- The largest diversity of tiger beetles in the United States.
- The roosting site for thousands of sandhill cranes.



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[i] Teller J.T. & Last William M. (1990). *Paaleogeography, Palaeoclimatology, Palaeoecology, 76*:215-240.
[ii] Waters M. R. (1989). *Quaternary Research, 32*:1-11.

Giant Polygons at Wilcox Playa

Spring 2016 Fieldguide – Corey Atwood-Stone

Formed by Giant Desiccation Cracks

- -Up to 3 ft wide and 9 ft deep – Traverse hundreds of ft.
- -Cracks have ~ 90° intersections
- -Form in area rich in clays – especially montmorillinite
- -Found in dozens of places in Arizona alone
- -These are not like mudcracks as one would expect
- -Formation starts deep underground
- -Surface collapse after sheetflow runoff

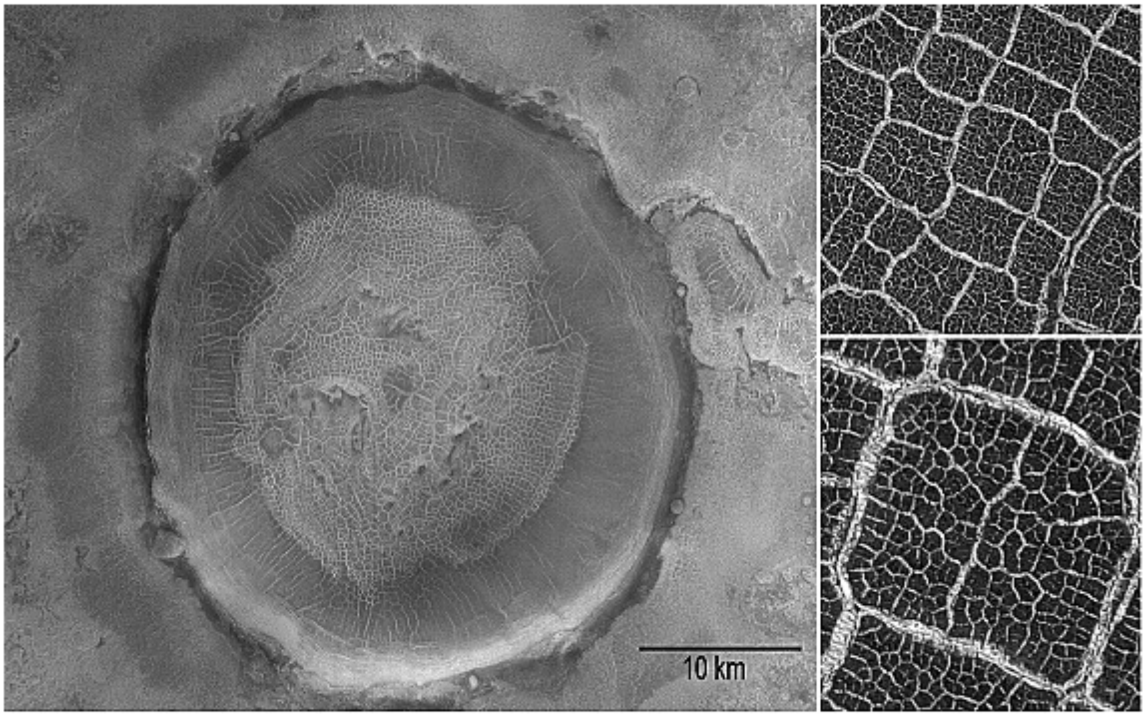
Why Do They Form

- -Dropping water tables due to pumping?
- -Influence of human structures (roads)?
- -Piping – rodent borrows and rotting plant matter?
- -Phreatophyte plants like mesquites?
- -Answer is both complex and unknown

Planetary Connection

Polygons on Mars

-Martian polygons show up in a variety of scales
-Specifically we are referring to intermediate sized polygons (15-350 m)
-Usually these form inside largish craters



Formation of these Martian Polygons

-Sizes are calculated to be too large for Thermal Contraction polygons
    -The smaller interior polygons likely are due to Thermal Contraction
-Form in craters that often show other evidence of having been a lake
-Most of these lakes appear to have formed by thermal heating from the impact
    -As such some of them may be recent
-Eventually the lake evaporates and the underlying surface is desiccated

References

-Harris, R.C. (2004) Giant Desiccation Cracks in Arizona. AZGS Open-File Report 04-01
-El Maarry, M.R. et al. (2010) Crater Floor Polygons: Desiccation Patterns of Ancient Lakes on Mars. JGR Planets

-Color photos from Fall 2009 LPL Fieldtrip

Native Peoples of the Chiricahua Mountains and Geronimo

By: Jon Bapst

1. Early History

Anthropological evidence suggests that the Apache peoples lived in northern regions (e.g., Alaska, western Canada, and the Northwest Pacific Coast) before migrating to the Southwest sometime between AD 1200 and 1500.

The Chiricahuas (of the greater Apache group) are a grouping of three distinct bands: *Chokonen, Chihenne,* and *Ndendahe*.

Many other bands and groups of Apachean language-speakers ranged over eastern Arizona and the American Southwest. The bands that are grouped under the Chiricahua term today had much history together: they intermarried and lived alongside each other, and they also occasionally fought with each other.

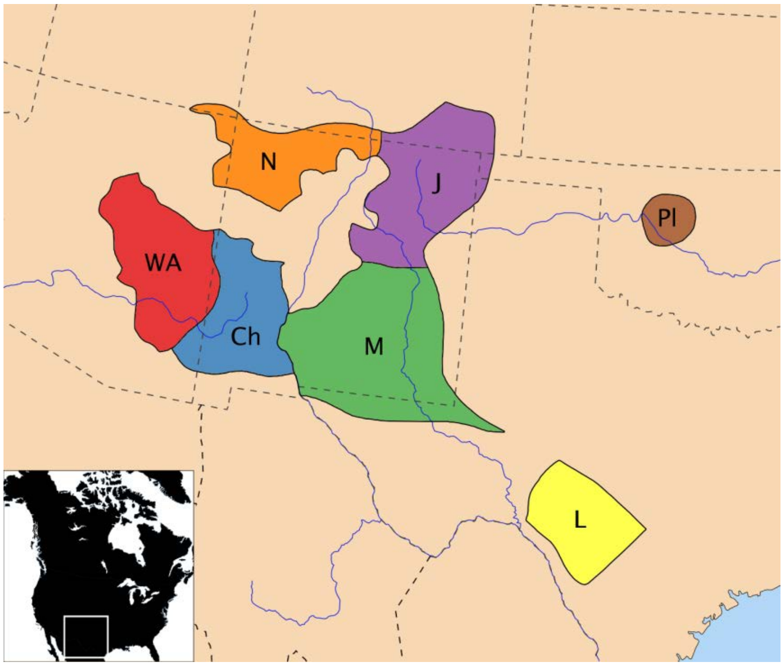


Figure 1. Apachean tribes circa 18th century: WA – Western Apache, Ch – Chiricahua, N – Navajo, M – Mescalero, J – Jicarilla, L – Lipan, Pl – Plains Apache.

2. First Conflicts

The Apache raided enemy tribes and sometimes each other, for horses, food or captives. The first Europeans (Spanish colonists) settled in villages, and Apache bands developed a pattern of interaction over a few centuries. Both raided and traded with each other.

When the United States went to war against Mexico in 1846, many Apache bands promised U.S. soldiers safe passage through their lands.

During the 1850s, American miners and settlers began moving into Chiricahua territory, the beginning of encroachment that sparked conflict. The series of armed conflicts that persisted from 1849-1886 is known as the Apache Wars.

3. Geronimo’s War

In October 1872, after two decades of guerrilla warfare, Cochise, one of the leaders of the Chiricahua band, chose to make peace with the US (surrendered in the Dragoon Mountains). He agreed to relocate his people to a reservation in the Chiricahua Mountains. Soon afterward in 1874, Cochise died. In a change of policy, the U.S. government decided to move the Chiricahua to the San Carlos reservation in 1876. Half complied and the other half, led by Geronimo, escaped to Mexico.

Figure 2. Geronimo kneeling with rifle, 1887.

In the spring of 1877, the U.S. captured Geronimo and brought him to the San Carlos reservation. He stayed there until September 1881. He fled the reservation with 700 Apache and went to Mexico again.

In the spring of 1883, General George Crook (in charge of the Arizona and New Mexico reservations) journeyed to Mexico, found Geronimo’s camp, and persuaded Geronimo and his people to return to the San Carlos reservation. Geronimo did not return until February 1884. Crook instituted several reforms on the reservation, but local newspapers criticized him for being too lenient to the Apache. They demonized Geronimo and on May 17, 1885, he escaped again to Mexico.

Crook was under increased pressure from the government in Washington. He launched a second expedition into Mexico and on January 9, 1886, located the Chiricahua. The Apaches were demoralized and agreed to negotiate for surrender.

Figure 3. Geronimo and his warriors, taken before the surrender to Gen. Crook, March 27, 1886, in the Sierra Madre mountains of Mexico.

Geronimo, camped on the Mexican side of the border, agreed to Crook's surrender terms. That night, a soldier who sold them whiskey said that his band would be murdered as soon as they crossed the border back into the United States. Geronimo and 39 of his followers slipped away during the night (24 of which were warriors).

The War Department reprimanded Crook for the failure, and he resigned. His replacement, General Nelson Miles, coordinated 5,000 soldiers, 500 Apache scouts, 100 Navajo scouts, and thousands of civilian militia against Geronimo and his 24 warriors.

Completely worn out, the small band of Apaches returned to the U.S. and officially surrendered to General Miles on September 4, 1886 at Skeleton Canyon, Arizona.

Geronimo and other Apaches, including the Apache scouts who had helped the army track him down, were sent as prisoners to Fort Sam Houston in San Antonio, Texas. The Army held them there for about six weeks before they were sent to Fort Pickens, in Pensacola, Florida. In October 1893, they were moved to Fort Sill, Oklahoma.

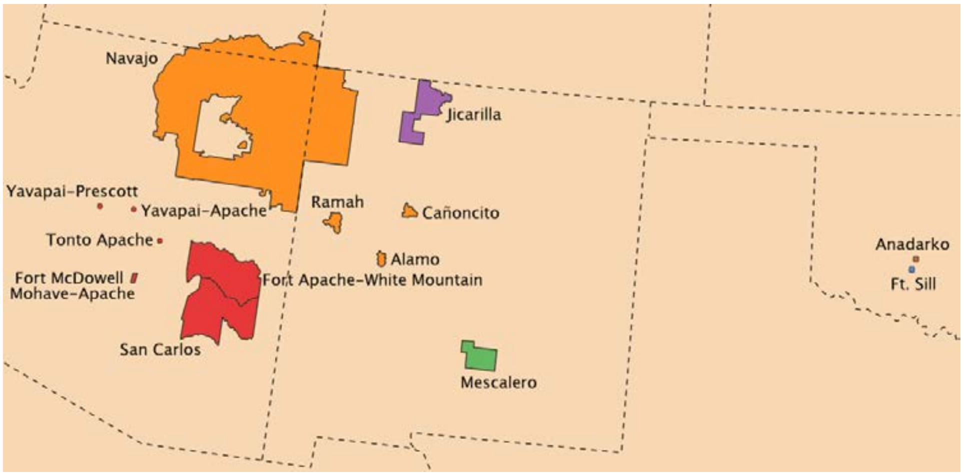


Figure 4. Present-day primary locations of Apachean peoples.

In his old age, Geronimo became a celebrity. He appeared at fairs and rode in President Theodore Roosevelt's inaugural parade in 1905. He was never allowed to return to the land of his birth. He died of pneumonia on February 17, 1909, as a prisoner of the United States.

In 1913, the Chiricahua Apaches were freed.

> *General Crook said to me, "Why did you leave the reservation?" I said: "You told me that I might live in the reservation the same as white people lived. One year I raised a crop of corn, and gathered and stored it, and the next year I put in a crop of oats, and when the crop was almost ready to harvest, you told your soldiers to put me in prison, and if I resisted to kill me. If I had been let alone I would now have been in good circumstances, but instead of that you and the Mexicans are hunting me with soldiers".*
> ***— Geronimo, 1909***

Flora and Fauna of Willcox Playa

Sarah Peacock

Flora:

Willcox Playa is a desert grassland that is sparsely vegetated by grasses and shrubs. Most common grasses include alkali sacaton and saltgrass. There is an increase in shrub coverage towards the outside boundary of the playa, most typically the saltbush and the non-native tamarisk. Tamarisks are a highly invasive plant species that often nearly completely replace the native vegetation. The playa is also home to a population of rare plant species: the Chiricahua Mountain fleabane. The fleabane is a flower with purple petals belonging to the daisy family that is commonly found on north facing rocks surrounded by moss and lichen.

Photo by William Skaradek USDA NRCS

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The fleabane genus is found all over the world in dry, mountainous areas and grasslands. There are hundreds of species throughout North America, with the Chiricahua mountain fleabane only being found in Arizona, near the Chiricahua mountains.

Fauna:

Willcox Playa is well known for the thousands of Sandhill Cranes that migrate to the area in winter to feed and court. The cranes leave after February back to their summer breeding grounds in the northern Great Plains. Sandhill Cranes are very large, tall birds with long necks and legs and very broad wings. They have long tracheas that coil into their sternums, helping develop a low pitch in their loud, rattling calls. Each call lasts a few seconds can be heard up to 2.5 miles away. The cranes are also known for their dancing skills. Courting cranes stretch their wings, pump their heads, and leap into the air in a graceful and energetic dance. The earliest Sandhill Crane fossils are estimated to be 2.5 million years old.

Willcox Playa is also home to other large water-birds including the white-faced ibis, as well as many raptors, including several wintering hawks. Red tailed hawks, prairie falcons, bald and golden eagles, as well as caracaras, great horned owls, and burrowing owls all make use of the diverse habitat. Sometimes more than 10,000 birds will congregate at the playa.

White-faced Ibis: A dark bodied wading bird with curved-down bill

The Red-Tailed Hawk is the most common hawk in North America. They are large hawks with broad wings and a short, wide tail. Large females seen from a distance are commonly confused for eagles.

The Red-Tailed Hawk has a raspy, shrill scream that Hollywood directors commonly use in movies as the soundtrack for any hawk or eagle.

Birds are amazingly adapted for life in the air. The Red-Tailed Hawk is one of the largest birds in North America (12-26" long, 45-53" wingspan), yet the biggest females weigh only about 3 pounds.

Caracara: A tropical falcon version of a vulture, the Crested Caracara is found mainly in South America, up into Arizona, Texas, and Florida.

Burrowing Owl are owls with bright yellow eyes. They live underground in burrows they've dug for themselves or taken over from a prairie dog, squirrel, or tortoise.

Several other vertebrates inhabit Willcox Playa. Surveys have revealed several distinctive amphibians and reptile species, including Chiricahua and plains leopard frogs as well as Texas horned lizards. Mammals include desert cottontails, black-tailed jackrabbits, kangaroo rats, and javelinas.

The relationship of leopard frogs has baffled herpetologists for over 100 years. There used to be just 3 varieties total, but now there are 5 separate varieties in Arizona alone, two of which reside in the Willcox Playa. The Chiricahua leopard frog is large and stocky with upturned eyes, a rounded snout, and no webbing between its front toes. They can darken their skin color in response to colder water temperatures and reduced reflectance off the water's surface. They are unique from other leopard frogs in exhibiting a salt and pepper pattern on the rear of the thigh:

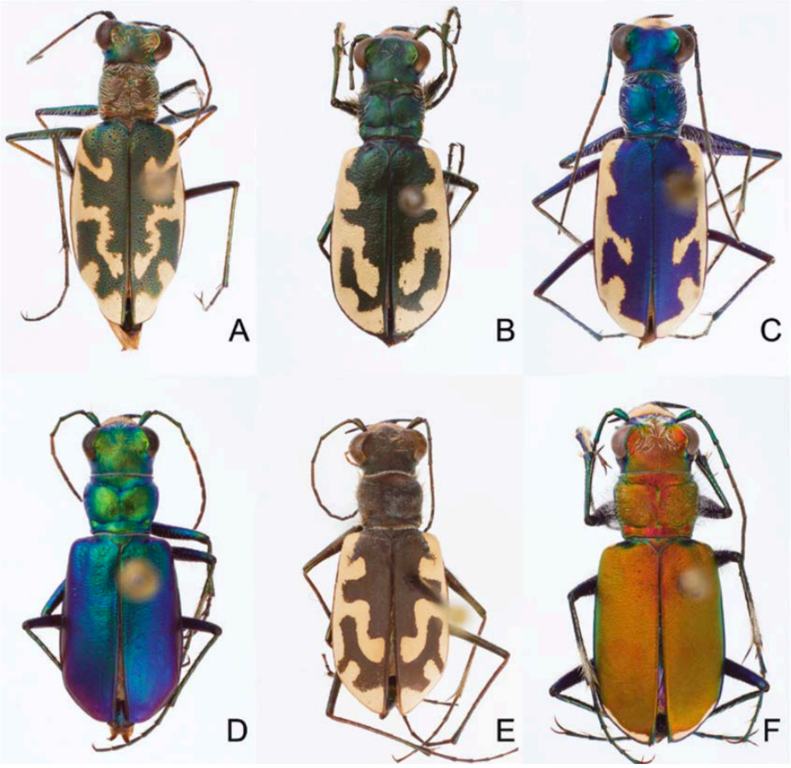
While calling, males have been observed to engage in fisticuffs with other males, presumably to defend prime calling locations.

The other species of leopard frog to inhabit the Willcox Playa is the Plains leopard frog. These frogs are large and typically tan or olive-green with dark spots. They are distinguished from other leopard frogs by their dorsolateral folds. They deposit a whopping 4000-6500 eggs in March-May and again in August!!

The Texas Horned Lizard is the state reptile of Texas (Arizona's is the Arizona ridge-nosed rattlesnake). A flat-bodied and fierce-looking lizard, the head has numerous horns, all of which are prominent, with two central head spines being much longer than any of the others.

Although its coloration generally serves as camouflage against predators, when threatened, the horned lizard will puff up and become very flat, which causes its body scales to protrude, making it difficult to swallow. The Texas Horned Lizard also has the ability to squirt an aimed stream of blood from the corners of its eyes and sometimes mouth for a distance of up to 5 feet! This not only confuses predators, but the blood is also mixed with a chemical that is foul tasting to canine predators like wolves and coyotes. This strange behavior is observed to be a very effective defense.

Unlike the squirrel and chipmunk that eat sitting up on their hind legs and can hold food with their front paws, while spinning it in circles to devour it quickly, the desert cottontail, like all cottontails, eats on all fours. It can only use its nose to move and adjust the position of the food that it places directly in front of its front paws on the ground. The cottontail rabbit will turn the food with its nose to find the cleanest part of the vegetation (free of sand and inedible parts) to begin its meal.



Less well known is the extraordinary diversity of tiger beetles found at Willcox Playa—one of the highest concentrations in a single small area in the United States. These beautiful, metallic, day-flying predators are found in the grass and open patches of soil near water (11 species) and in the uplands (6 species) around the playa. Several native species exist there, including the Willcox Nevada tiger beetle (A) and the Sulphur Springs Williston's tiger beetle (B). The high diversity of tiger beetles on and around the playa may be related to the quality of the habitat and the proximity of the site to northern Mexico, which has a great abundance of tiger beetle species.

Worldwide, there are approximately 2600 subspecies of tiger beetles. They are known not only for their beauty, but also aggressive predatory habits and fast running speeds (up to 5.6 mph, ~125 body lengths per second).

(Six-spotted green tiger beetle attacking a wasp)

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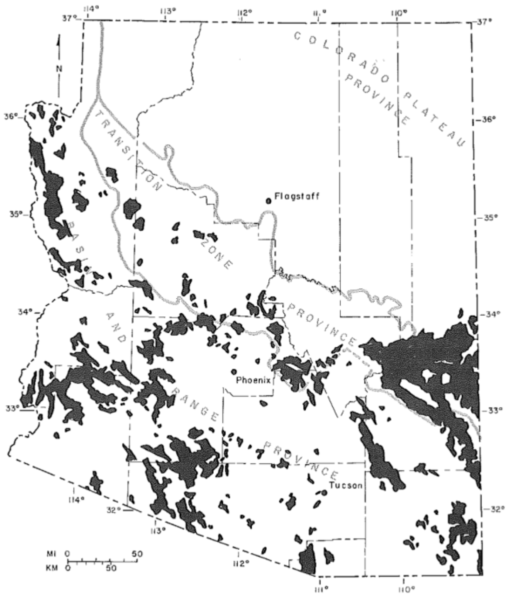
History of San Bernardino Volcanism

Ali M. Bramson

The lava flows of the San Bernardino volcanic field are younger compared to some of the
(a) billion-year-old Precambrian volcanism,
(b) Mesozoic-to-Jurassic volcanism of 200-140 Myr ago, and
(c) late Cretaceous/early Tertiary volcanism of 85-45 Myr ago
that occurred in other parts of Arizona [Reynolds et al. 1986]. The flows can be seen within the Chiricahua Mountains and from Highway 80 east-ward of milepost ~384 between Bisbee and New Mexico and looking east from Arizona Highway 186 past highway milepost ~347 [pg 104 and 273, respectively, Roadside Geology of Arizona]. The San Bernardino region contained two major volcanic episodes, one around 30-25 Myr ago and another within the last 3 Myr.

#1: Oligocene Volcanism

The Chiricahuas are almost entirely volcanic though the range does contain some exposures of Precambrian (~1 Ga) schist and granite that were involved in the Laramide, mid-Tertiary and Basin and Range epochs of Arizona mountain building (the same rocks are exposed in the Dos Cabezas Mountains a bit northwest along Highway 186). The eastern side of the Chiricahuas also contains some slivers of Paleozoic and Cretaceous sedimentary rocks (which generally are the underlying basement rock of the region, including under the nearby Peloncillo Mountains), but most of these older rocks are hidden by the three volcanic rock units from the 30-25 Myr Oligocene volcanism [Biggs et al. 1999; Roadside Geology of Arizona].



DISTRIBUTION OF MID-TERTIARY (40-15 m.y.) VOLCANIC ROCKS

Figure from Reynolds et al. 1986

- Unit 1: Bright red/reddish-brown rocks in small, isolated patches. Deposited siltstone and sandstone that accumulated in small, short-lived lakes which were dammed by lava flows and faulting.
- Unit 2: Thicker unit (though same age as unit 1) of sandstone and conglomerates (originally deposited in alluvial fans) which contain volcanic rock fragments. Deposited with the volcanic ash, tuff and lava flows. An exposure of this unit can be seen near (and downstream from) the Chiricahuas National Monument visitor center.
- Unit 3: Younger unit (25 Myr) of ~2000 feet thickness which makes up the rocks of the erosional spires, columns and hoodoos. These rocks formed from welded tuff -- molten pellets of glass and pumice which avalanched across the region and fused together, compacting under their own weight while hot, gas-charged ash rained out of the sky (oh nbd…). These tuff layers are made of rhyolite (silicate volcanic rock) and can be seen along Bonita Canyon Road and are also exposed below Massai Point and along Echo Canyon, Rhyolite Canyon (aptly named) and some park trails.

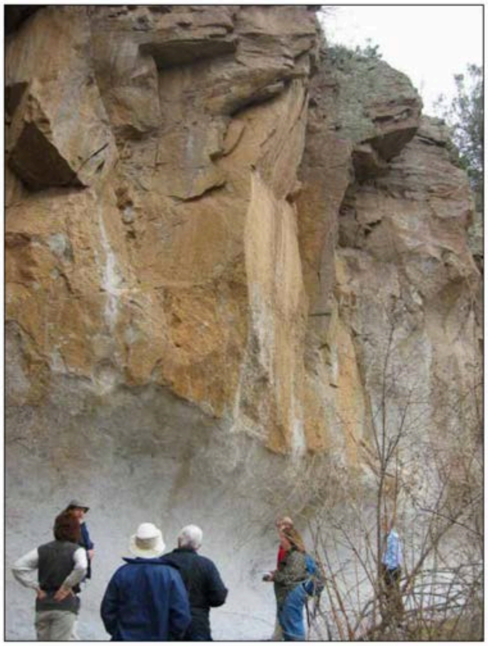


Figure 5. Surge deposits (white) and welded tuff deposits (brown) along Sugarloaf Mountain Trail pose a landslide hazard at Chiricahua National Monument. Photograph by John Graham (Colorado State University), April 5, 2006.

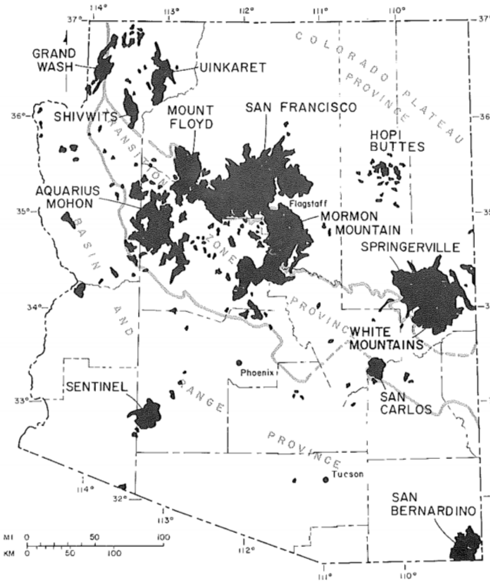
Volcano refresher: because rhyolite is very silicic, it is stiff and sticky and thus erupts very violently (unlike flowy, less-viscous basaltic lavas).
There are 8 individual ash flow units that have been recognized within this tuff unit, each between 2 and 880 feet thick. The 880-foot unit is the one that most of the column features are eroded from. The layers alternate between thicker welded tuff avalanches and surge deposits and thinner, ash layers [see figure on left, from US National Park Service, 2009]

The amount of welding of each layer depends on the speed the material fell/cooled and the amount of pressure from overlying ash, which also affects the shape of the pumice chunks (some which were very hot and then quickly buried have a squashed shape). The cooling of this unit led to some cooling cracks and vertical joints which aided in the erosional columns and spires seen in the unit.

This unit is topped off by a single lava flow, which can only be seen today as the top unit of the Sugarloaf Mountain which is fine-grained and dark grey in color with crystals of white feldspar and vesicles filled with chalcedony.
[pgs 273-278, Roadside Geology of Arizona]

#2: Pleistocene Volcanism

Drilling of the San Bernardino Valley (which is a ~20-50 km wide, <1600 ft deep graben from the Basin and Range “Disturbance” ~ 10-13 Myr ago) shows that most of the valley is filled with even younger lava flows of the relatively quiet, basaltic variety; radiometric dating has indicated the field was active in the Pleistocene, between 3 million to 275,000 years ago [pgs 103-105, Roadside Geology of Arizona]. Volcanoes in this fairly localized field are mostly cinder cones (now covered by grass) but also includes a few maar craters (broad, shallow, low-profile craters from steam eruptions). Small flows erupted from the base of some of the cinder cones or from vents which are obscured today by infilling and erosion. A few of the larger landforms in the region are likely formed from multiple eruptive vents and at least 8 maar craters and tuff rings are



DISTRIBUTION OF UPPER CENOZOIC (0-15 m.y.) VOLCANIC ROCKS AND VOLCANIC FIELDS

Figure from Reynolds et al. 1986

present indicating some steam-blast eruption activity. [Biggs et al. 1999].

The older of these (1-8 Myr) flowed into the valley from the Peloncillo and Pedregosa Mountains, with the younger (~260,000 – 750,000 years old) flows and pyroclastic deposits coming from over 130 separate vents. These vents were mostly monogenetic (erupting only once), forming the cones seen around the region, and suggesting the eruptions were relatively benign Strombolian-style (mmmm, that makes me hungry for Italian food). These flows are quite thin, overlapping each other and generally following the valley slope towards the south. They can be hard to see today, as much of the landscape is covered by clay-rich soils, grasslands and basalt cobbles (See figures below, from Biggs et al. 1999)

Figure 7. Typical lava flow surface (F4003) in the San Bernardino volcanic field (San Bernardino Ranch quadrangle). Angular to subangular boulders and cobbles of vesicular basalt are abundant; soils are chocolate brown to reddish brown and very clay-rich vertisols.

Figure 6. False-color aerial photograph of the Cinder Hill area. Recent cinder mining is evident on the northeast flank of Cinder Hill volcano (V3017a). This is one of the youngest eruptions in the San Bernardino field and primary flow features are still evident on the surface of the lava flow (F3017a).

These basaltic lava flows often contain some white/honey-colored feldspar crystals as well as black rods of feldspar and green olivine crystals. The magma that formed these rocks came from the upper mantle and rose to the surface with minimal contamination from the crustal rocks it traveled through. Lab experiments have shown that these mineral crystals form in a rock of this composition at ~2000°F under pressures at depths of ~40 miles below the surface [pg 103-105, Roadside Geology of Arizona].

Many flows contain somewhat rounded ultramafic mantle xenoliths ranging in size from a few millimeters to more than 40 cm in diameter [Figure to right, from Biggs et al. 1999].

Many of the flows are separated by erosional materials and alluvial gravels. Sediments (mostly moderately to poorly sorted conglomerates) eroded from the nearby mountains, including from alluvial fans, make up some of the basin fill. Erosional incision is most prominent in the southern portion of Paramore Crater, exposing the interbedded lava flows and alluvium (see figure on next page, from Biggs et al. 1999).

Figure 21. Xenoliths (including lherzolite and pyroxenite) and megacrysts are abundant in some flows and vent lavas from the San Bernardino volcanic field. Xenoliths up to 0.5 meters have been found, and up to 20 cms are not uncommon.

References:

Figure 10. Interbedded alluvial deposits and basalt flow in Cottonwood Draw, Lazy J Ranch quadrangle. Basalt flow forms the prominent black ledge and it is covered by Qm gravels (light orange matrix containing clasts of mixed lithologies that are partially carbonate-coated); late Tertiary to early Quaternary (TQo) alluvial fan deposits underlie the basalt (partially obscured by basalt- and Qm-derived colluvium).

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TL;DR version:

Most of the Southeastern Arizona region of the Chiricahua Mountains is made up of layers upon layers of volcanic ash and welded tuff that "*accumulated during a wild orgy of explosive volcanism around 30 million years ago*" [pg 50, Roadside Geology of Arizona]. During this time, a series of explosions resulted in deposition of the Rhyolite Canyon Tuff and other ash beds to a thickness of about 2,000 feet. These units were subsequently eroded to form spectacular pinnacles and columns. [Fellows 2000]. The San Bernardino Valley underwent even more recent volcanism, with basaltic eruptions occurring in the last 3 Myr and forming maar craters and cinder cones across the region.

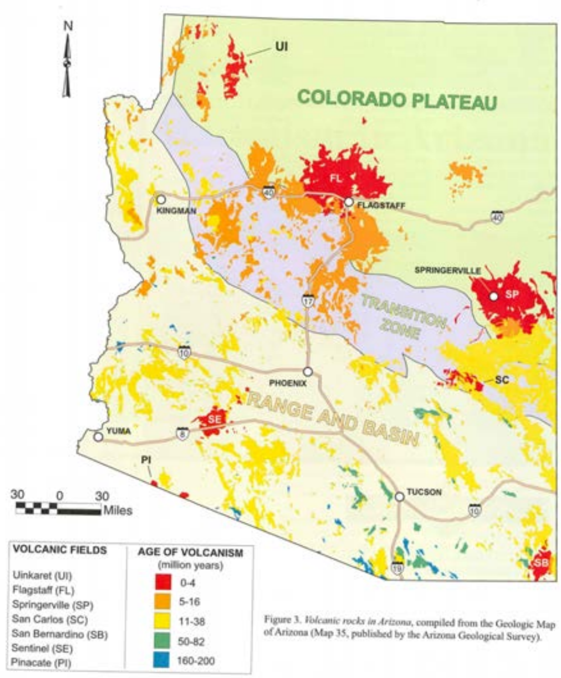
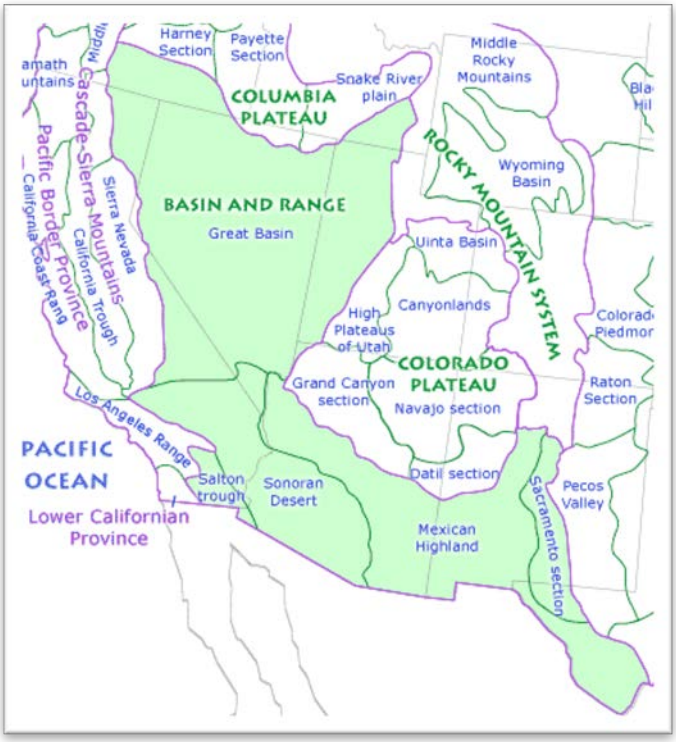
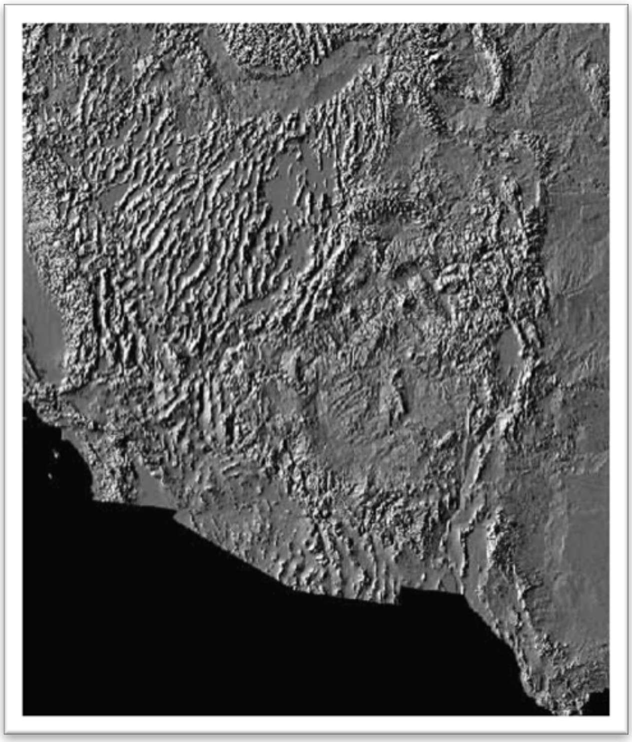


Figure 3. *Volcanic rocks in Arizona*, compiled from the Geologic Map of Arizona (Map 35, published by the Arizona Geological Survey).

Basin and Range

Anna Urso

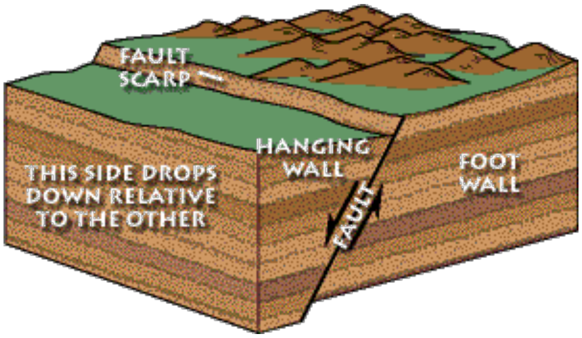




Geologic subprovinces of the Southwest U.S.

Shaded relief showing elongated mountain ranges interspersed with flat, dry deserts.

Formation:

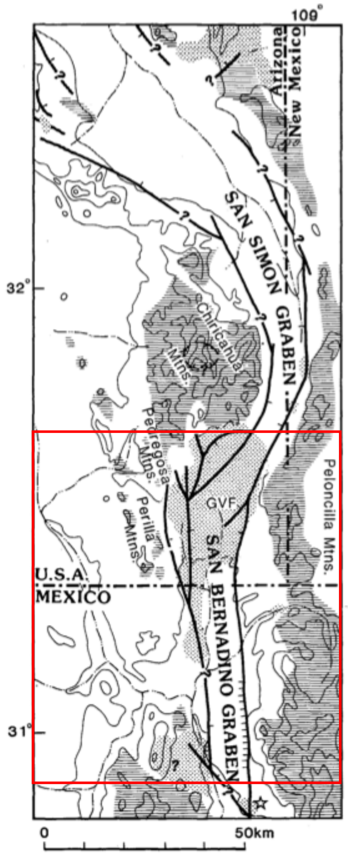


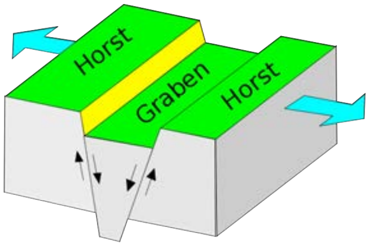
a) Crust and upper mantle stretched up to 100% original width
b) Thinning and cracking formed large faults (predominantly N/S oriented normal faults)
c) Mountain uplift and valley drop down created distinctive Basin and Range topography (see shaded relief)
d) Sediment collects in basins from the weathering and erosion of rocky ranges

Images from USGS, Google Earth, Wikipedia and NASA

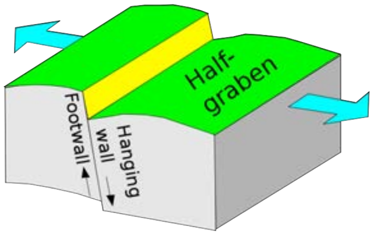
Basin and Range Continued

San Bernardino Valley:



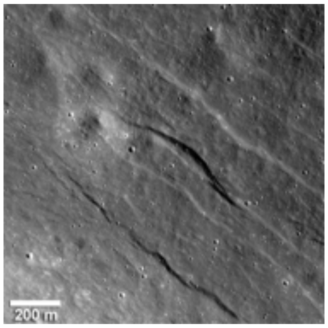


- a) Asymmetric or half graben: rift flank lift due to isostatic compensation of the lithosphere
- b) Valley is deepest along the western edge
- c) Most sedimentation occurs on the hanging wall; the footwall slopes away form the valley



Planetary Connections:

- There are no examples of basin and range
- Some extensional features occur due to cooling
- Graben on the moon (see image)



Images from USGS, Google Earth, Wikipedia and NASA

1887 San Bernardino Earthquake

Margaret Landis

Main points

- A large (intensity XI, magnitude ~7.4) earthquake occurred May 3rd, 1887 and predominantly affected the Arizona/Sonora border region.
- Loss of life and total destruction of buildings occurred in Bavispe, Sonora, Mexico but damage in Tucson, AZ was minor.
- The earthquake was caused by three faults with long recurrence intervals (26-37 kyr).

1. The modified Mercalli intensity scale: a quick review

Based on qualitative factors observed during an earthquake, the modified Mercalli intensity scale was first developed in 1931 (DuBois and Smith, 1980; descriptions of intensities from http://earthquake.usgs.gov/learn/topics/mercalli.php). This scale is what the USGS public earthquake reporting tool uses to evaluate the strength of an earthquake, and the intensity can also be determined for historical earthquakes if there are enough photographs and reliable eyewitness accounts. It ranges from I ("not felt") to XII ("Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air"). For example, a V intensity is an earthquake that was felt outdoors, and anyone who was sleeping was woken up. The earthquake felt in Tucson in summer 2014 would have be at maximum a III ("Felt indoors, vibration like passing of light trucks, duration estimated, may not be recognized as an earthquake"). This also means that in uninhabited areas without buildings, a Mercalli intensity cannot be well determined.

As the modified Mercalli intensity scale is based on qualitative descriptions of the disruption and destruction in an area, it can be used to compare historical earthquake reports in a standard way (e.g. the rest of this write up). Moment magnitudes, now in common usage, can also be used if the amount of slip along a fault and affected area can be determined.

2. What happened?

On 3 May 1887, at about 2:13pm (the exact time at the epicenter is uncertain, see section 3) an earthquake occurred with an epicenter in Bavispe, Sonora, Mexico along a suspected fault line in the Fronteras/Sierra Madre region (Goodfellow, 1887; Fig. 1-2). Within minutes, Tombstone, AZ, felt a major tremor lasting ~40 seconds at 2:11pm local time. Tremors were felt in Tucson at 2:12 pm, including shaking buildings and causing one schoolteacher to faint (Bennett, 1977). Otherwise, little damage was done to buildings and people on the US side, though the earthquake was felt from Phoenix to El Paso (Bennett, 1977). Many contemporary accounts in Tucson suggested that the Catalina Mountains were now erupting volcanically, a common mistake as rock slides triggered dust clouds that could be mistaken for smoke (Bennett, 1977; DuBois and Smith, 1980). From reconstructions, the intensity of the 1887 earthquake in Tucson was a VII-VIII. Magnitude estimates suggest this earthquake was a 7.4 (Suter and Contreras, 2002).

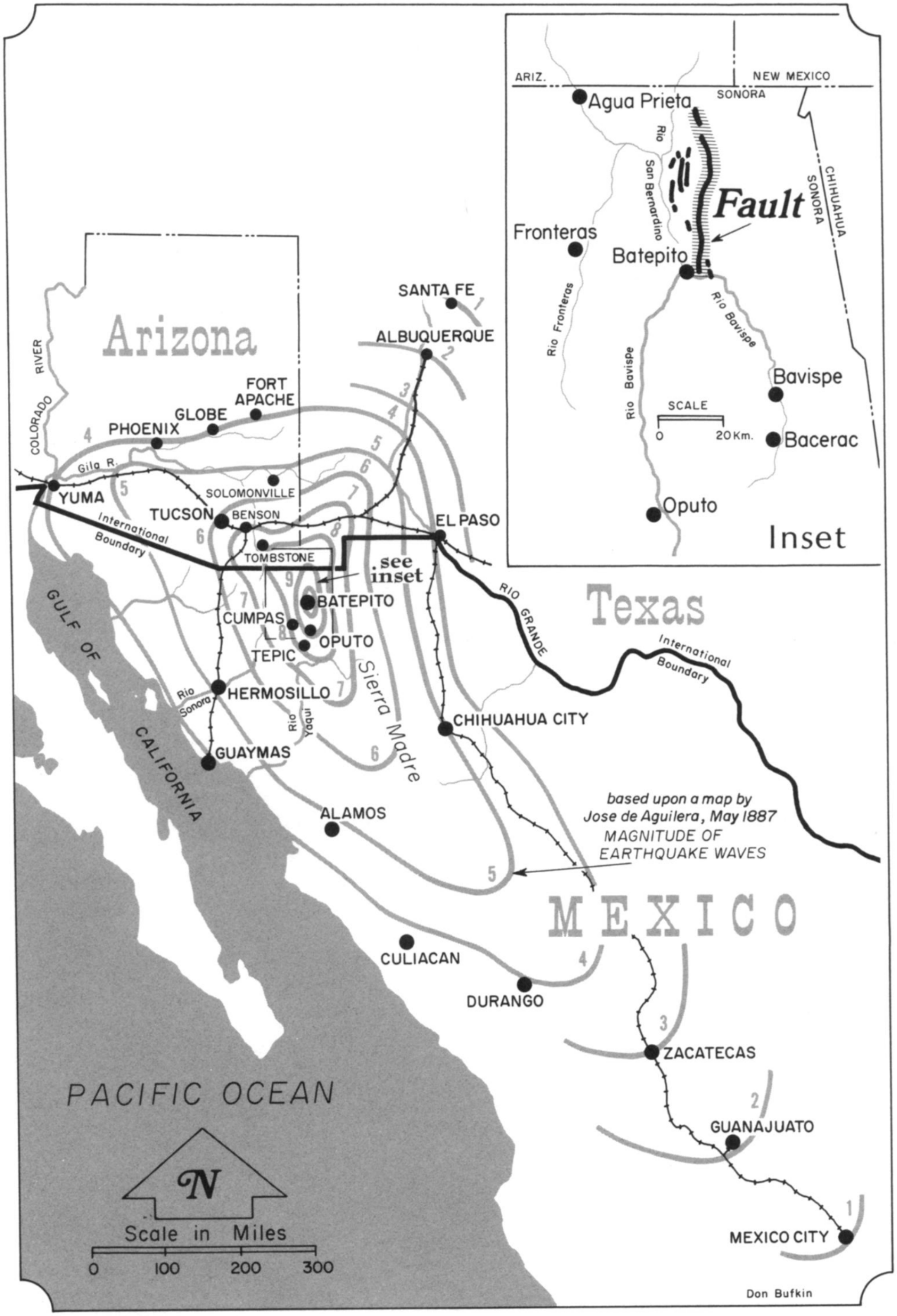


Fig. 1 Map from Bennett (1977) shows the affected area as well as the relative magnitudes (of some kind, Aguilera (1888) predates the Richter magnitude scale) reported from the earthquake.

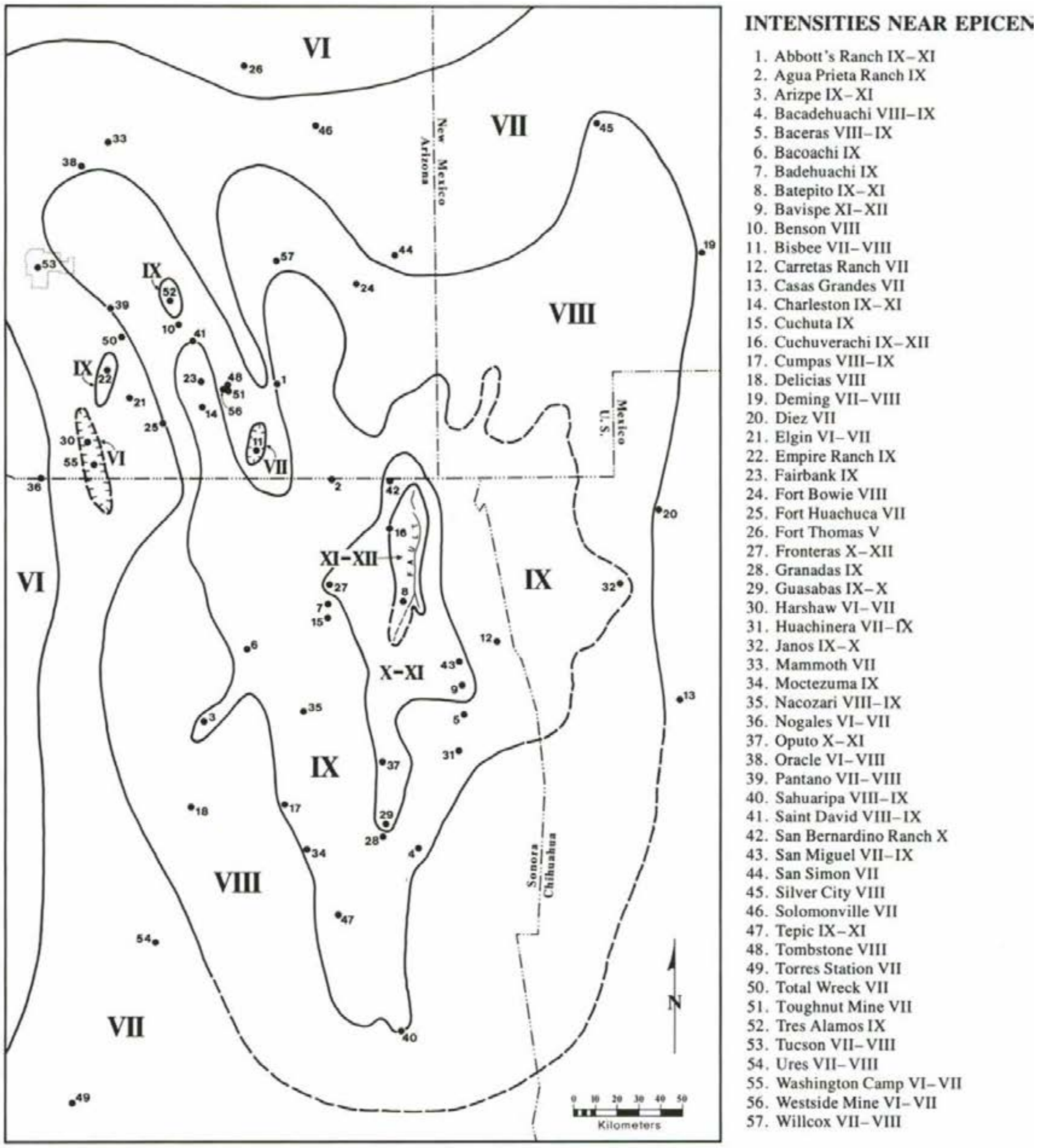
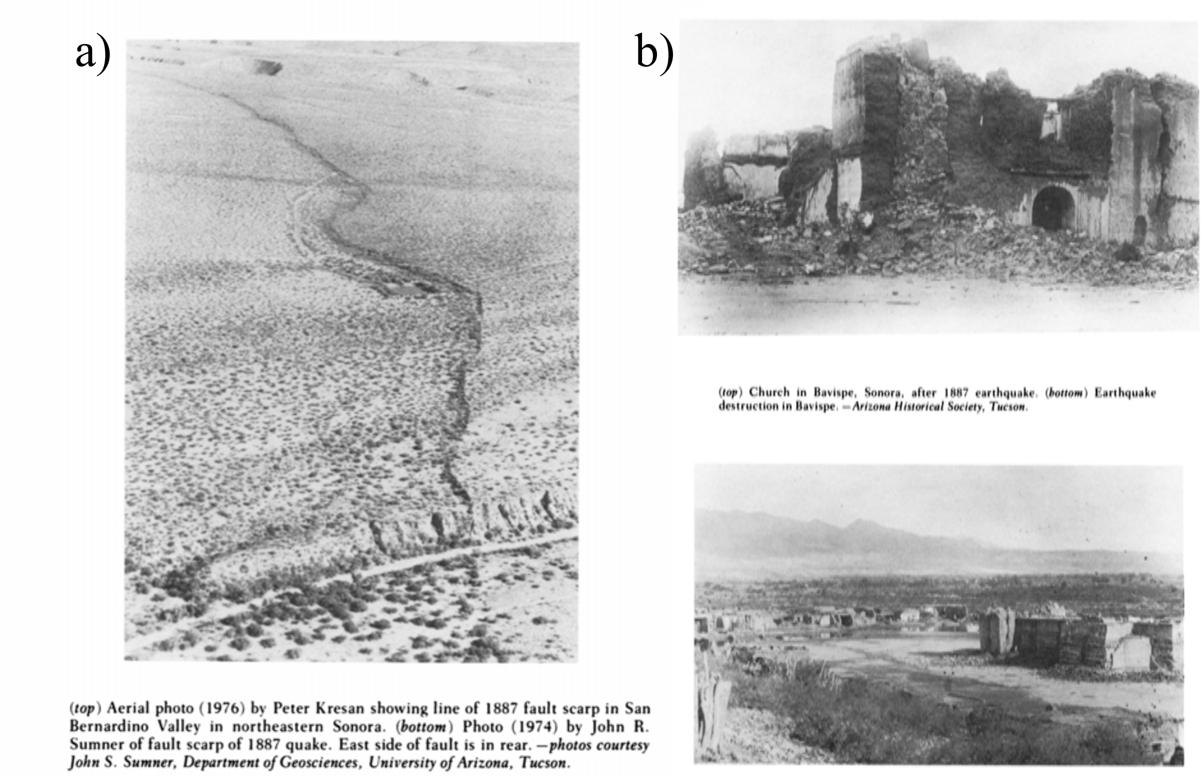


Fig. 2 From DuBois and Smith (1980), this map shows the isoseismic lines of the area closest to the epicenter. Compare to Fig. 1.

Nearer the epicenter, the damage was much more severe. Buildings in Bavispe were leveled (Fig. 3), and other towns in the Fronteras and San Bernardino valleys experienced intensities from IX-XII (DuBois and Smith, 1980). Reports of new springs erupting from the ground and rivers changing course were common in both Arizona and Sonoroa (Bennett, 1977; DuBois and Smith, 1980). Observations made by Aguilera (1888) also suggest that the earthquake was a composite of several shocks arriving only a few seconds apart (Suter and Contreras, 2002).

Modern mapping has uncovered three north-south-striking and west-dipping normal faults that run for about 300km (~185 miles), the fault zones of which were ruptured in 1887 (Suter and Contreras, 2002). This system of faults (Pitaycachi–Teras–Otates) are part of the Basin and

Range province that extends into northern Mexico, and are also part of the Sierra Madre Occidental volcanic province.



(*top*) Aerial photo (1976) by Peter Kresan showing line of 1887 fault scarp in San Bernardino Valley in northeastern Sonora. (*bottom*) Photo (1974) by John R. Sumner of fault scarp of 1887 quake. East side of fault is in rear. —*photos courtesy John S. Sumner, Department of Geosciences, University of Arizona, Tucson.*

(*top*) Church in Bavispe, Sonora, after 1887 earthquake. (*bottom*) Earthquake destruction in Bavispe. —*Arizona Historical Society, Tucson.*

Fig. 3 a) From Bennett (1977), an aerial image of the fissure opened up along the fault almost a century after the earthquake occurred. b) From DuBois and Smith (1980), images of the desruction in Bavispe, Sonora.

3. How did geologists at the time react?

The head of the United States Geological Survey (USGS) was in Charleston, South Carolina at the time and had no one he could easily send west. In order to collect some data before memories faded, he telegraphed a printer in Tucson to make up and distribute questionnaires about the intensity of the earthquake (Bennett, 1977).

A range of initial reactions from geologists of the time went from speculation that the earthquake was related to a gas explosion in Canada and an earthquake in Italy as some sort of “convulsion in the bowels of the earth”, to the earthquake being caused by “a slip of the surface of the earth along one of the geological breaks” (Bennett, 1977). Initial reports, including one from the *Tucson Weekly Citizen,* tried to clear up that the epicenter of the earthquake was in Mexico rather than in Tucson and that the Catalina Mountains had not begun to erupt. However, it took a USGS sponsored expedition by George E. Goodfellow and Jose G. Aguilera to determine the amount of damage and to describe the earthquake in detail.

Goodfellow and Aguilera ran into some problems as the area around the epicenter was mostly rural and lacked reliable clocks, making a determination of when the earthquake actually started difficult (Bennett, 1977). It had also rained significantly by the time they arrived, obscuring some of the features they needed to observe (Bennett, 1977). Still, Goodfellow was able to publish his report as a letter to *Science* within weeks of the earthquake (Goodfellow, 1887). He describes the destruction of the San Bernardino ranch buildings but reports the loss of life was relatively light. Other sources report death tolls in the Bavispe region in northeastern Sonora (closer to the epicenter) of ~40 dead and ~30 injured (Bennett, 1977).

4. Could another big one happen today?

Two additional historical earthquakes have been attributed to the same system of faults described in Suter and Contreras (2002): a 1928 6.5 magnitude in Parral, Chihuahua, and a 1931 6.4 magnitude in Valentine, Texas. However, based on the slip rates and vertical displacements from the 1887 earthquake, Suter and Contreras (2002) estimate that the recurrence interval of the Pitaycachi–Teras–Otates faults is in the range from 26-37 kyr for large earthquakes. For comparison, the recurrence interval for large earthquakes along the San Andreas fault is ~100 years (e.g., Fumal et al., 1993).

While the basin and range province is still active, it is a significant amount of time (e.g. ~1/8 of the amount of time that humans have existed as a species) before a large earthquake could be expected to come from the Pitaycachi–Teras–Otates faults again.

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Mantle Xenoliths

Hamish Hay

1 Introduction

A xenolith is a rock fragment that has become encased inside a larger foreign rock during some entrainment process. For terrestrial rocks, this is almost exclusively reserved for fragments that are found within igneous bodies, such as basalts and granites. The entrainment process tends to be during eruption or emplacement of the igneous bodies themselves, which allow for plucking of the xenoliths from their country rock units. Mantle xenoliths are then pieces of rock from the upper mantle that have been removed from their country rock and entrained within some igneous host.

(a) A xenolith of diorite found in a granitic host. In this case, the xenolith may be genetically related to the host rock, rather than an entirely different country rock.

(b) A pyroxenite xenolith entrained in a foreign igneous extrusion. Pyroxenite is an ultramafic rock type, close in composition to that of the upper mantle.

Figure 1: Two examples of xenoliths in terrestrial rocks.

2 Sampling the Upper Mantle

The base of the crust marks a distinct and abrupt change in seismic wave speed. The region where this happens is known as the Mohorovičić discontinuity, or more commonly referred to as the “Moho”. Under continents, the Moho can be found between 30 to 70 km beneath the surface. For oceanic crust, it lies at depths of 4 to 8 km.

Despite some recent attempts to directly sample the mantle, the sheer depth and lack of funding needed to drill to the base of the crust has so far rendered these attempts fruitless. Instead, mantle xenoliths can provide us with important constraints on the composition, pressure, and temperature conditions of the upper mantle and Moho.

Most mantle xenoliths found are compositionally known as *peridotites*. Consisting of mostly olvine, it is generally accepted to be the primary rock type in the upper mantle. Peridotite is an ultramafic rock which includes the subcategories dunite, wehrlite, harzburgite, and mostly commonly lherzolite. Pyroxenite is the other common mantle xenolith, which differs from peridotite through its higher pyroxene abundance. This is shown in the ternary diagram below (Figure 2).

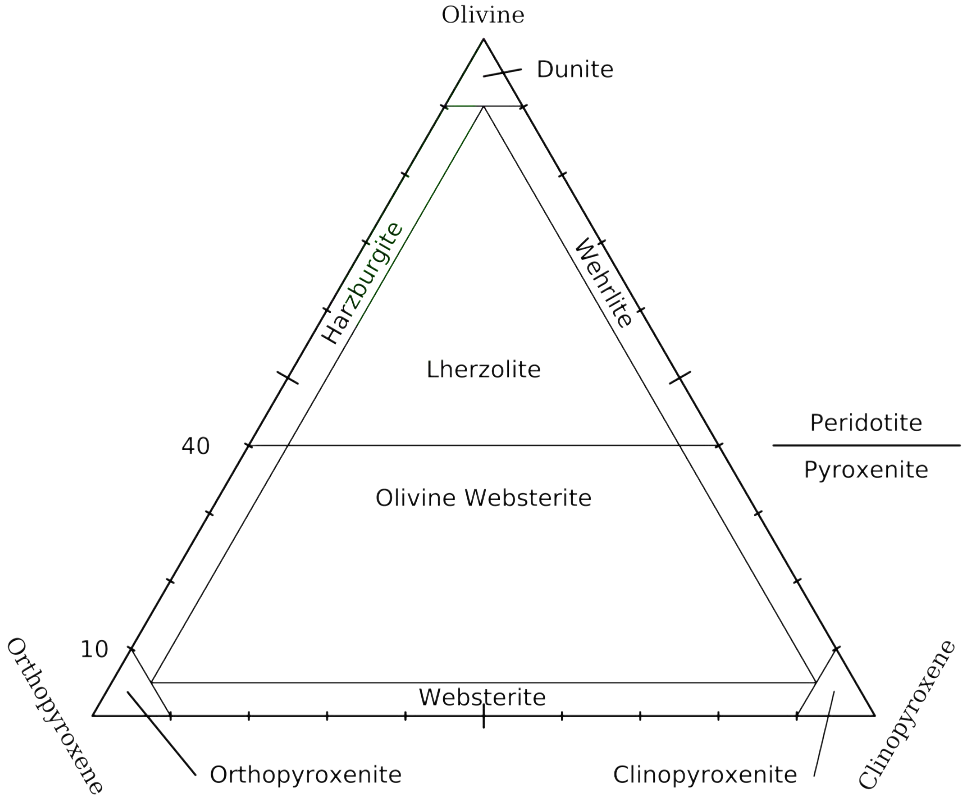


Figure 2: Ternary diagram for distinguishing between peridotite and pyroxenite, two ultramafic rock types. Peridotites have more than 60 % olivine, whereas pyroxenites are dominated by orthopyroxene (enstatite) or clinopyroxene (diopside).

These ultramafic rock types by definition have a very low abundance of silica, instead consisting of mainly olivine and pyroxenes.

Metasomatism, a hydrothermal alteration process, can also effect the mineral composition of mantle xenoliths. A *metasomite* is a mantle xenolith which has undergone this process. Mineral phases introduced by metasomatism include micas, amphiboles, and sulphides.

3 Depth of Sampling

Two other mineral phases that can be found in mantle xenoliths are garnet and spinel. Spinel is usually a red, blue or black mineral, which has been commonly mistaken as ruby throughout history. Garnet is usually coloured red with a cubic or rhombic crystal habit. Both are aluminium rich minerals and so are only found in small amounts within the ultramafic peridotites and pyroxenites. At a certain temperature and pressure level, peridotites transition from spinel bearing to garnet bearing. As a result, garnet peridotites can originate from depths of 60 to 300 km in the mantle. Spinel peridotites by contrast usually come from shallower depths, as shown through the phase diagram in Figure 3.

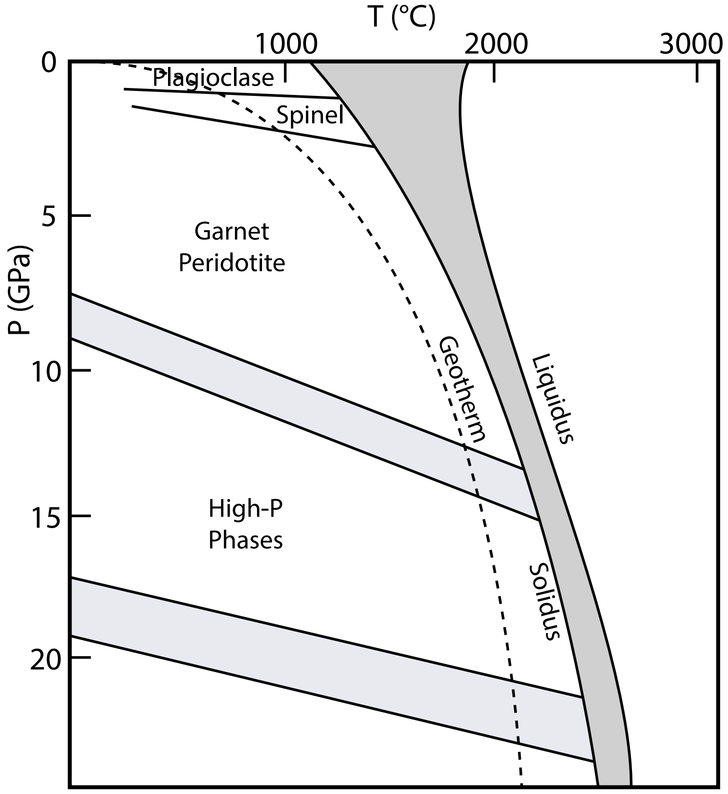


Figure 3: Phase diagram for mantle peridotites.

Based on the presence of either of this minerals and the chemical percentages of olivine, clinopyroxene and orthopyroxene, the temperature and pressure conditions of the upper mantle can be reasonably well determined. This is currently the only way to accurately estimate the environment of the upper mantle. Examples of both spinel and garnet peridotite are shown in Figure 4.

(a) Spinel peridotite in a fine grained igneous host rock. This sample must have originated from a depth less than 60 km. The small black minerals are spinel.

(b) A sample of garnet peridotite, which could have originated between 60 to 300 km depth. The rounded red minerals are garnet.

Figure 4: Two different type of aluminium-mineral bearing mantle xenoliths, both of which originate from different pressure/depth conditions.

4 Entrainment and Ascent Timescale

In order to preserve mantle xenoliths (i.e., avoid complete settling to the bottom of the host's melt/magma), these rock fragments must be entrained and brought to the surface in very little time. This means that the host magma is likely to be relatively unchanged from fractional crystallisation due to the small ascent time. The has two implications. Firstly, the mantle xenolith bearing magmas are primitive, having not been stored in crustal magma chambers for any significant period of time. Secondly, the ascent time can be dramatic. For example, Kimberlites, which bear xenoliths in the form of diamonds, have ascent times on the order of 1 to 2 days corresponding to ascent rates of $4\,\mathrm{m\,s^{-1}}$. In order to achieve such rapid ascent the host magma must be reasonable volatile rich. It should be noted that the host magma (usually basalt) for mantle xenoliths is often formed through partial melting of the peridotite/pyroxenite upper mantle itself, meaning that the xenoliths and melt come from the same host.

5 Upper Mantle Heterogeneity

Some host rocks exhibit many different varieties of mantle xenoliths. An excellent example of this is the San Carlos basalt field in Arizona (Figure 5). Such compositional variation in what should be a rather localised source suggests that the upper mantle has significant compositional heterogeneity. This of course then as implications for mantle mixing and convection timescales, at least for the upper mantle.

(a) Peridotite xenoliths from the San Carlos basalt field in Arizona. Four different compositions of peridotite exist in this single host basalt.

(b) Image of mantle xenoliths in the San Carlos basalt field in Arizona.

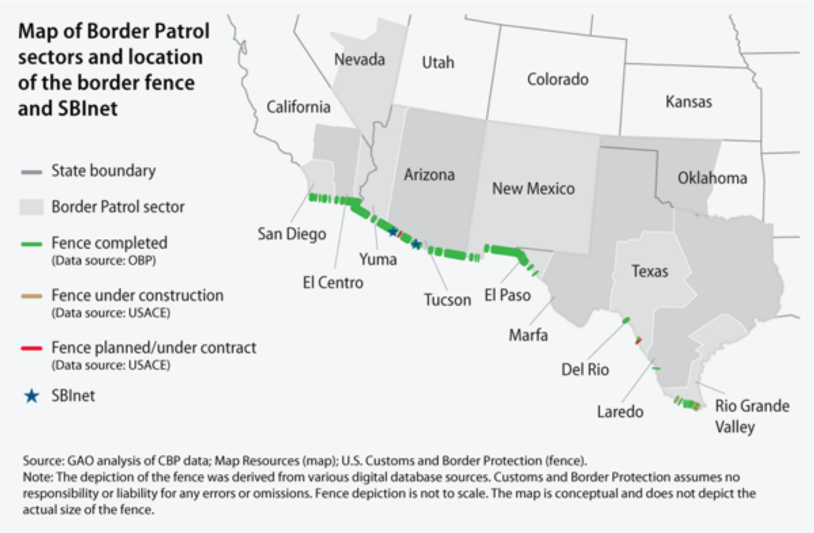
Figure 5: Many varieties of mantle xenolith can be found in a single host rock, as shown in these two images. This suggest that significant compositional heterogeneity exists in the upper mantle.

27 Feb 16
Kenny Furdella
PTYS 594

Border Issues

United States-Mexican Border

- The total length of the U.S.-Mexican border is 1,954 miles (3,145 km). It is the most frequently crossed international border in the world, with around 230,000 legal crossings a day.
- The U.S.-Mexican border starts in Imperial Beach, California and ends in Brownsville, Texas.
- The states that border Mexico are California, Arizona, Utah, and Texas (accounts for the largest portion of the international border).
- The Mexican states are Baja California, Sonora, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas.
- There are 45 U.S.-Mexican border-crossing stations with approximately 350 million legal crossings a year.
- The landscape of the border can range from mountainous regions to desert terrain to large rivers beds.
- The U.S. border patrol agents are the main source of defense against trafficking of illegal weapons, substances, and illegal immigration.
  - As of 2011, there are more than 21,000 patrol officers.
  - The majority of the officers are found near highly populated areas with only 700miles (36%) of the border effectively patrolled.
    - From 2006-2010, during the Bush administration, 640 miles of the fence was build. The fence on average cost around $2.8 million a mile.
    - The location of the border fence is shown in figure 1.



Source: GAO analysis of CBP data; Map Resources (map); U.S. Customs and Border Protection (fence).
Note: The depiction of the fence was derived from various digital database sources. Customs and Border Protection assumes no responsibility or liability for any errors or omissions. Fence depiction is not to scale. The map is conceptual and does not depict the actual size of the fence.

Figure 1: Border fence locations

Figure 2: Images of border fences

- Major drug trafficking routes into the U.S. are shown in figure 3.
- In 2013, there were 22,215 cases involved in drug trafficking. The majority of cases were involving powdered cocaine and meth (see figure 4).
- Some interesting drug trafficking statistics:
    - 85.5% of traffickers were males.
    - The average age at sentencing was 35 years old.
    - About 50% of the offenders were Hispanics.
    - Most were first time offenders.
    - Marijuana trafficking is still high but has dropped.
    - Almost half of the criminal cases filed by the federal government take place near the border.
    - Annually, the illegal drug trade market is a $13 billion to $50 billion industry.
    - The drug war death estimates are in the ballpark of 120,000 people.

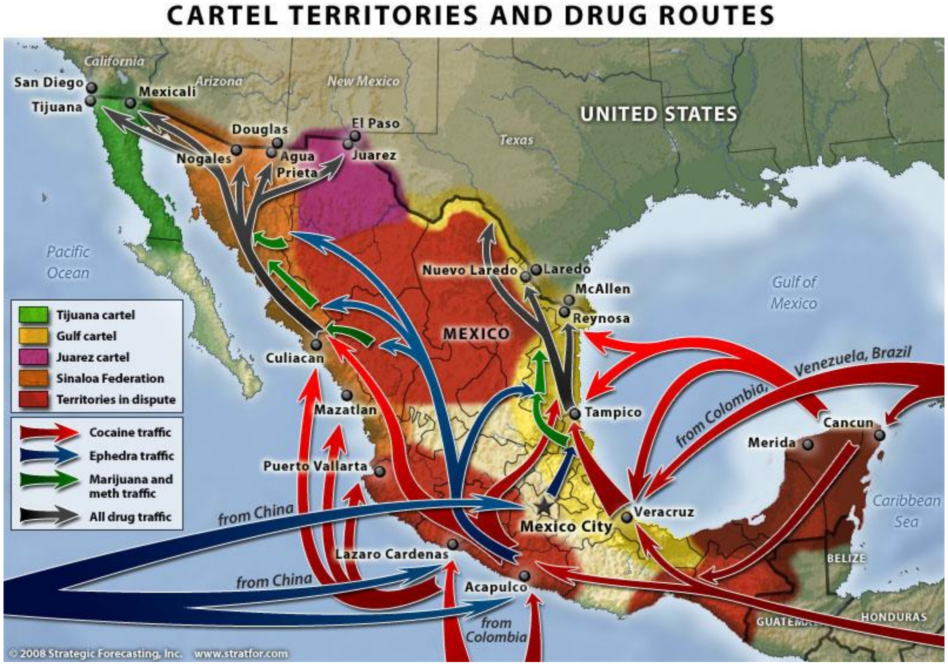


Figure 3: Cartel territories and drug routes

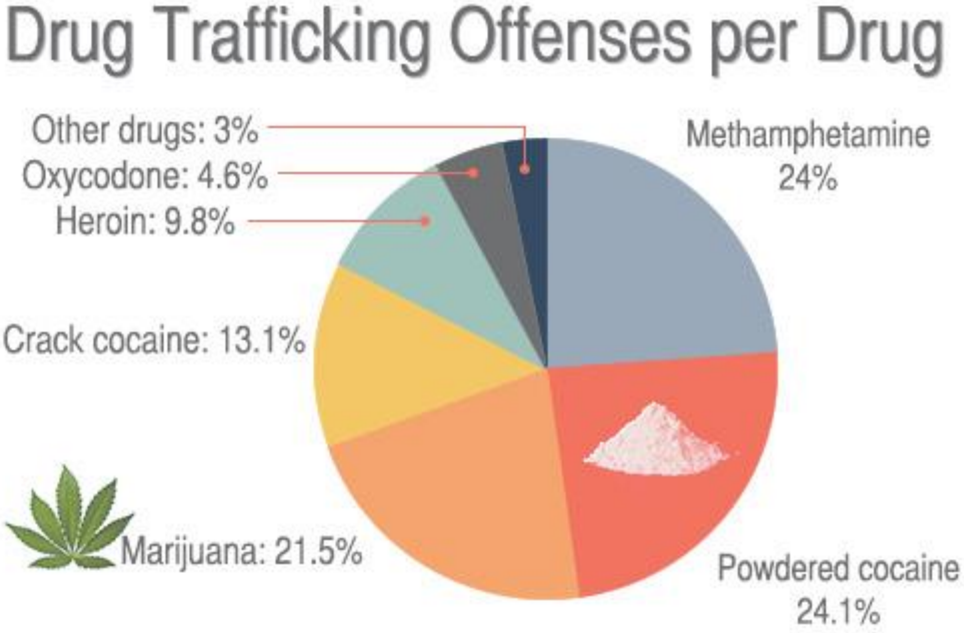


Figure 4: Drug trafficking offences

- Illegal immigration is another major border issue.
    - Should we just build a wall?
- As of January 2012, there is an estimated 11.3 million unauthorized immigrants (figure 5).
- Illegal immigration peaked in 2003-2007 with around 850,000 people per year.
- 2008-20012, illegal immigration dropped significantly to around 300,000 people per year.
- The majority of illegal immigrants take place in rural mountainous and desert areas.
- Data has shown that number of illegal immigrants intercepted has dropped significantly from 2000 to 2012 (figure 6).

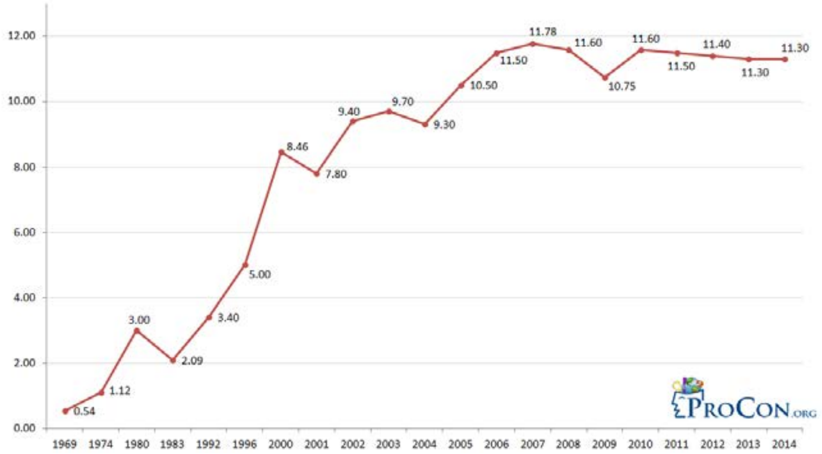
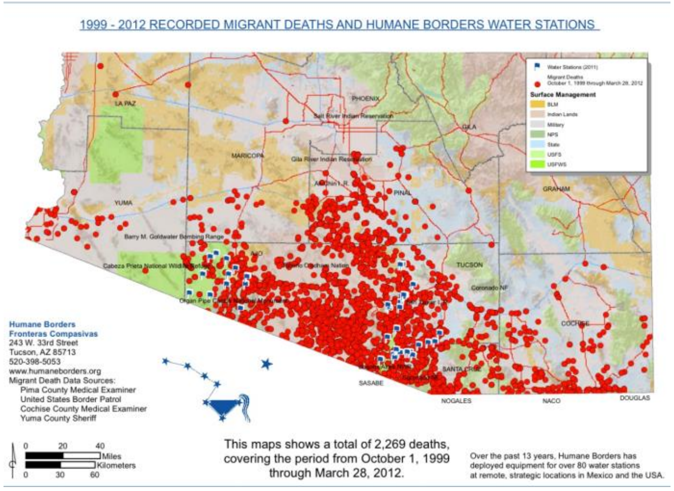


Figure 5: Illegal immigrant population in the U.S.

Figure 6: Number of illegal immigrants intercepted in 2000 and 2012

Arizona Border Issues

- The Arizona Mexican Border is 389 miles long, with 323 miles of the border having some type of fence.
- Arizona borders Sonora and Baja California, Mexico.
- Drug trafficking in Arizona can be broken up into two regions Yuma and Tucson (figure 6).
    - The three major U.S. bordering drug trafficking cities are Nogales, Douglas, and Yuma.
    - Some of the major drug trafficking cities in Mexico are Agua Prieta, Nogales, San Luis Rio Colorado, Sonoyta, and Sasabe.
- Over 2000 deaths in Arizona, from 1999-2012, occurred from migrants crossing the desert (figure 7).
- The major drug trafficking cartel in Arizona is Sinaloa Cartel (figure 3).
    - Leader of the cartel is Joaquin El Chapo.
    - U.S. government considers this cartel to be Mexico's most powerful cartel.
- Drugs seized in Arizona from 2005-2009 can be seen in figure 8.


1999 - 2012 RECORDED MIGRANT DEATHS AND HUMANE BORDERS WATER STATIONS

Humane Borders
Fronteras Compasivas
243 W. 33rd Street
Tucson, AZ 85713
520-398-5053
www.humaneborders.org
Migrant Death Data Sources:
Pima County Medical Examiner
United States Border Patrol
Cochise County Medical Examiner
Yuma County Sheriff

This maps shows a total of 2,269 deaths, covering the period from October 1, 1999 through March 28, 2012.

Over the past 13 years, Humane Borders has deployed equipment for over 80 water stations at remote, strategic locations in Mexico and the USA.

Figure 7: Migrant deaths 1999-2012

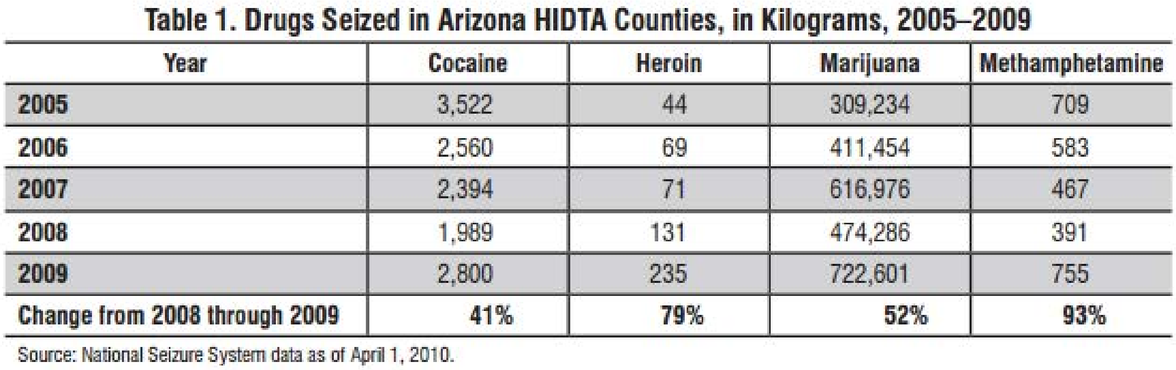


Table 1. Drugs Seized in Arizona HIDTA Counties, in Kilograms, 2005–2009

Year	Cocaine	Heroin	Marijuana	Methamphetamine
2005	3,522	44	309,234	709
2006	2,560	69	411,454	583
2007	2,394	71	616,976	467
2008	1,989	131	474,286	391
2009	2,800	235	722,601	755
Change from 2008 through 2009	**41%**	**79%**	**52%**	**93%**

Source: National Seizure System data as of April 1, 2010.

Figure 8: Drug seizures in Arizona 2005-2009

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https://en.wikipedia.org/wiki/Mexico%E2%80%93United_States_border

Maar Volcanoes on Earth and Mars

Alessondra Springmann - 2/23/2016

Maars are shallow, wide volcanic craters from explosions of magma or lava interacting with groundwater. While there is typically minimal igneous extrusion, maar volcanoes can erupt mantle xenoliths such as olivine (dunite) in the form of lava bombs.

Diatremes, sometimes known as maar-diatreme volcanoes, are volcanic pipes formed by gaseous explosions. Magma rises up through a crack in the crust and contacts with a shallow body of groundwater causing rapid expansion of heated water vapor and volcanic gases, which results in explosions as well as shallow craters and the actual diatreme, a rock-filled fracture.

Quaternary maar craters on Earth are typically between 0.6 and 1.0 km in diameter, with <10 % of craters with diameters 3.0-5.0 km. Although small maar craters are found at all latitudes on Earth, the maximum size for craters increases with latitude, where the largest (>3.0 km) craters occur predominantly above 40 degrees. These largest craters fall into two categories: permafrost-hosted craters and polygenetic craters. Some of the largest maar craters are seen in Alaska [1, 2].

Much of the volcanism in Cochise County/the San Bernardino Valley occurred in the Mesozoic period, though the most active period of volcanism in the region occurred 30 million years ago, chiefly the Turkey Creek eruption that produced prodigious amounts of rhyolite magma [3].

Maars on Mars

Maar craters would be larger on Mars as a result of the reduced gravity, and to a lesser degree the thinner atmosphere. However, collapse processes are important to final crater shape and may be diminished in martian conditions, reducing the potential increase in martian maar crater diameter [1].

As early as the 1970's it has been suggested that there could be maar volcanoes on Mars [4].

Maar volcanoes such as Kilbourne Hole are believed to be a terrestrial analogue for Home Plate on Mars due to its explosive origin. Squyres et al. (2007) proposed that the Home Plate feature visited by the Spirit Mars Exploration Rover on Mars shows evidence of pyroclastic activity, and that observations from orbit and by Spirit "indicate that the lower strata were emplaced in an explosive event, and geochemical considerations favor an explosive volcanic origin over an impact origin." Kilbourne Hole shows lava bombs and bomb sags, which "are found in volcaniclastic deposits on Earth… causing downward deflection of layering" [5].

San Bernardino Volcanic Field Maar Volcano

Credit: R.Weller/Cochise College [6]

Recent Fieldtrip Maar Volcanoes
Kilbourne Hole, New Mexico

Rattlesnake Crater, Arizona

Layers in Rattlesnake Crater (credit: author)

Other Maar Volcanoes

Ubehebe Crater, Death Valley, California

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Turkey Creek and Portal Eruptions

Joana Voigt

Turkey Creek caldera and Portal caldera

- Turkey Creek and Portal caldera are both formed by volcanic eruptions at 26.9 Ma (late Oligocene)
- Basement is composed of Precambian crystalline rocks
- Overlain by a thick layer of sedimentary rocks, deformed by tectonics (palezoic and cretaceous)

Portal caldera:

- Eruption of rhyolite tuff or ignimbrite
- Was the first event, but the isotopic ages are not distinguishable to Turkey Creek event
  ➔ Implies Portal and Turkey Creek erupted close in time [1]

Turkey Creek caldera:

- Actual caldera
- Turkey Creek caldera is a high-silica rhyolite and dacite magmatic system that formed in a relatively short term [2]
- Eruption was ~ 1000 times greater than the eruption of Mount St. Helens (1980)
- Partial filling of the Portal caldera valley
  ➔ Stratigraphic relationship tells Turkey Creek caldera is younger

Geological context

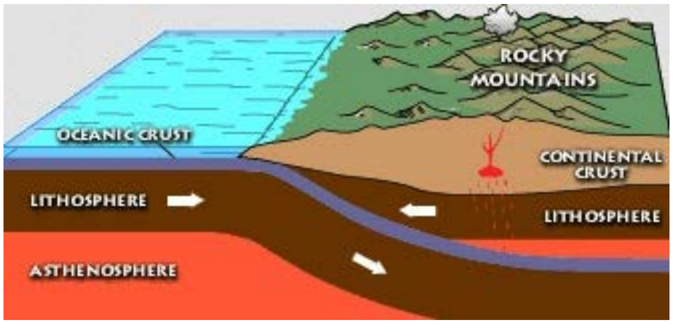


Figure 1: schematic sketch showing the subduction of the Farallon plate blow the North American plate during the Laramide orogeny [4].

- Eruptions are associated with continental drifting during the formation from Laramide orogeny
- Subduction of Farallon and Kula plates beneath the North American plate
- As a consequence of that, a period (35-25 Ma) of intensive volcanism took place as well as formation of compressional faults

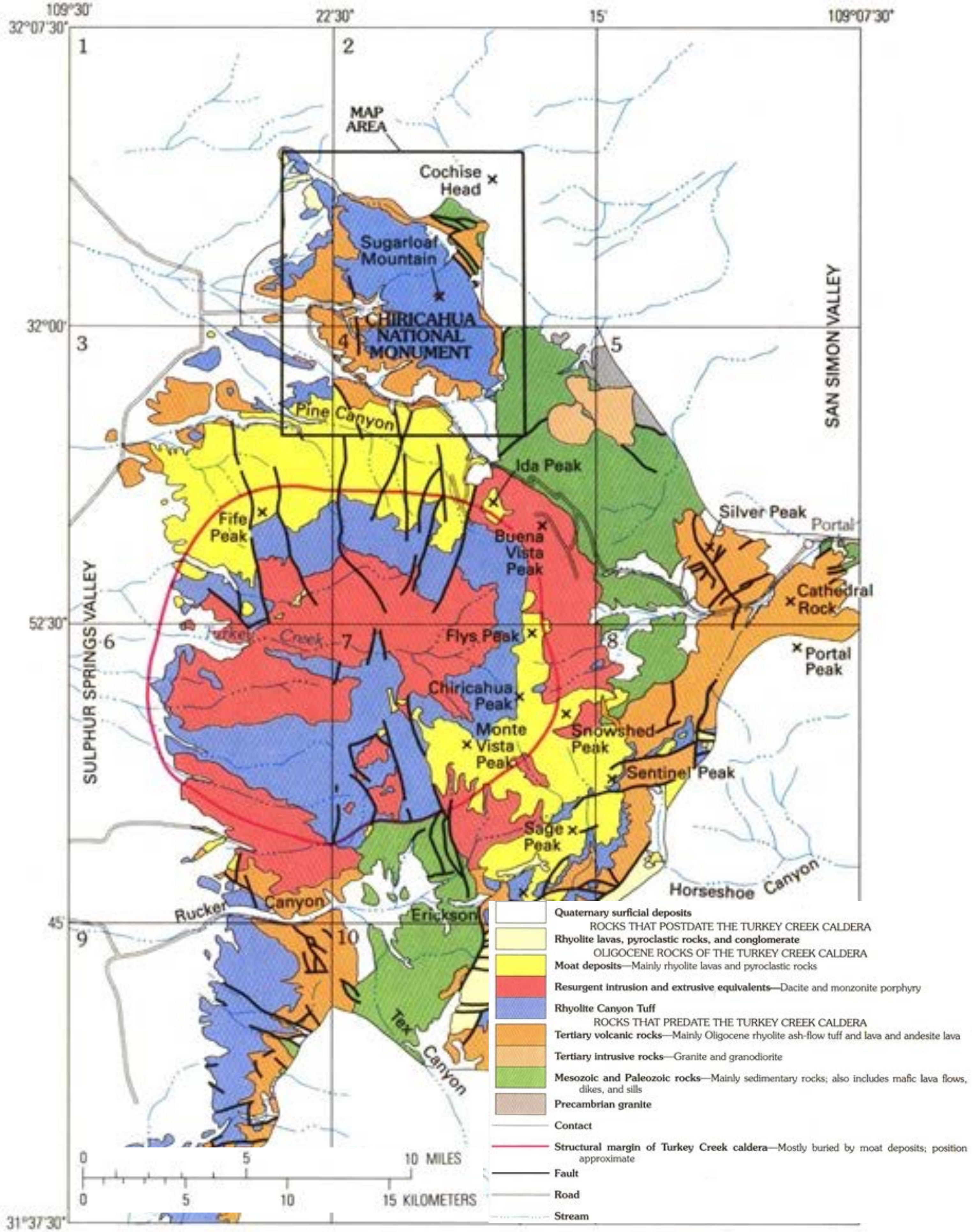
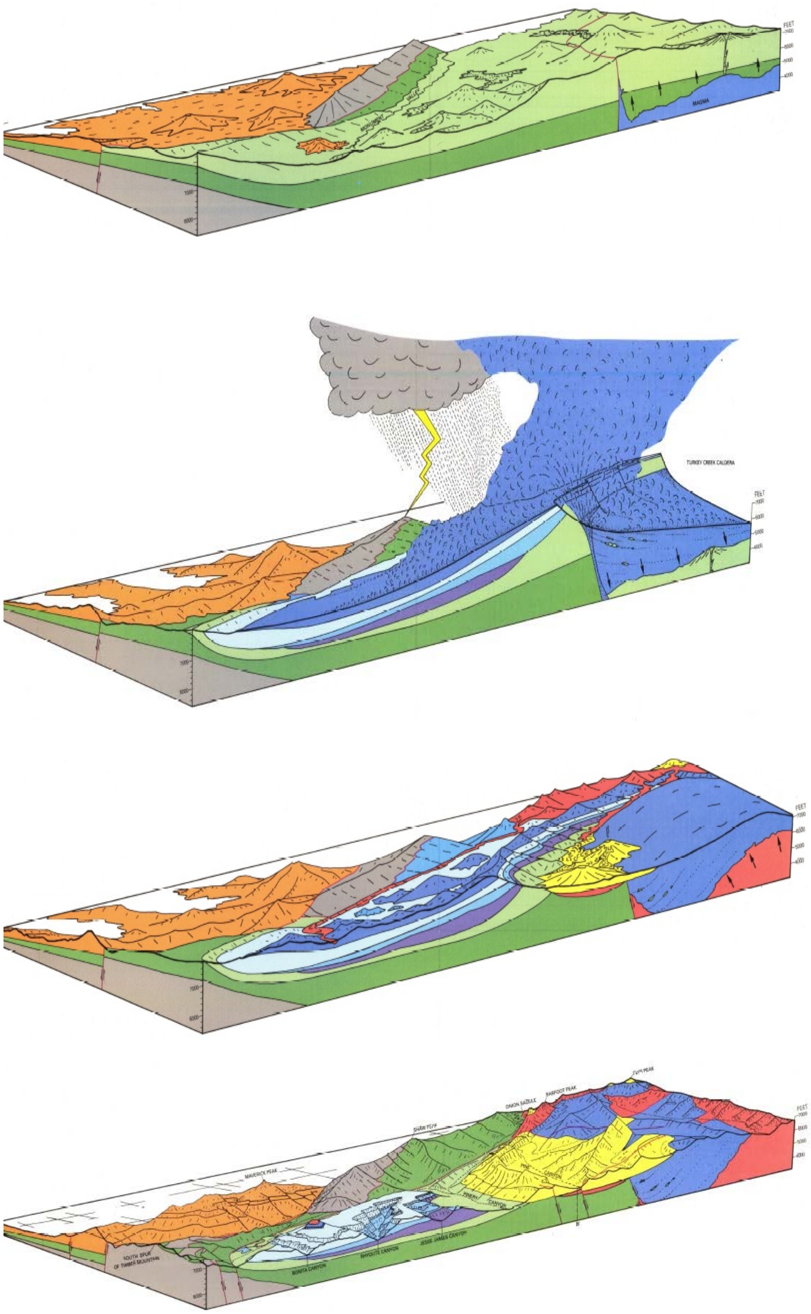


Figure 2: Geologic map of the Chiricahua mountains in southeast Arizona [4].

Geological evolution of the Chiricahua



Stage 1: Pre-caldera state ~27-23 Ma

- Uplift of sedimentary rocks (grey & dark green)
- Overlain and surrounded by andesite, dacite and rhyolite (light green & orange), produced by lava activity
- ~ 27 Ma ago body of rhyolite magma (blue) accumulated beneath

Stage 2: Caldera-formation & eruption 26.9 Ma

- Eruption series with pumice and ash
- Dense clouds blanketed an area of southern Arizona and New Mexico
- Flows of ash, pumice and gasses filled Monument valley (500 m thick)
- 3 major eruptions have been deposited the Rhyolite Canyon Tuff (marked in shades of blue)
- Eruption created a 20 km diameter caldera
- During activity the caldera floor subsided

Stage 3: Moat lava eruption 26.9-26.6 Ma

- Eruption of Rhyolite Canyon Tuff (blue)
    - ➔ Uplift of dacite magma/caldera (red)
    - ➔ Formation of circular valley/moat
- Eruption of dacite magma and formed lava flows that flowed into the moat
- Eruption of rhyolite again (yellow), material also accumulated within caldera moat

Stage 4: Erosion Today

- Erosion by streams, wind and landslides
- Erosion of sedimentary rocks is more rapid than the hard rhyolite
    - ➔ Inversion of topography

Figure 3: Evolution of the Chiricahua landscape shown as a block diagram along a cross section through the National Monument based on the geologic map [4].

References:

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Fumaroles

Rodrigo Savage 2016

In Latin, fumus mean smoke. A fumarole, is an opening in a planet crust which emits steam and gases as carbon dioxide, hydrogen chloride and hydrogen sulfide. The steam forms when superheated water vaporizes as its pressure drops when it emerges from the ground.

A fumarole field is an area of thermal springs and gas vents where magma or hot igneous rock near the surface releases gasses or interacts with ground water. Fumaroles could also be described as a hot spring that boils off all its water before the water reaches the surface.

Fumaroles may persist for decades or centuries if located above a persistent heat source; or they may disappear within weeks to months if they occur atop a fresh volcanic deposit that quickly cools

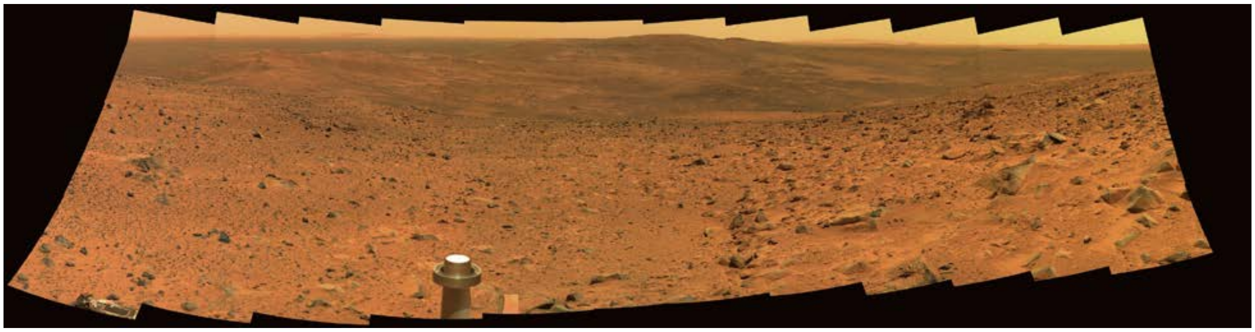
Fumaroles on Mount Redoubt

Fumaroles at Namafjall, Iceland

A fumarole at Halema`uma`u crater

On Mars

The formation called Home Plate at Gusev Crater on Mars which was examined by the Mars Exploration Rover (MER) Spirit is suspected to be the eroded remains of an ancient and extinct fumarole



Case Hardening

Stephen Nickels

Overview

Case hardening is a process by which rocks develop a crust, or rind, of material that resists weathering better than the underlying core of the rock. As a result, weathering processes erode the underlying material more easily, often leaving cavities and depressions around the hardened areas.

Figure 1. Example of case harderning and differential weathering of underlying material
http://alliance.la.asu.edu/rockart/stabilityindex/4WeatheringDeposits/Coat_CaseHard_WC91_66.jpg

Case hardening takes place as a result of chemical weathering, typically by water, and occurs in two different forms: the interior material of the rock may weaken, leaving harder original material on the outer edge (also known as *core softening*), or the outer layer of material may be strengthened, leaving weaker original material below. The former is more common in crystalline materials such as granite, while the latter is seen with sedimentary or clastic material such as sandstone and pumice. As the rocks of the Chiricahua Mountains are primarily sedimentary or volcanic in nature, we will restrict ourselves to this latter definition.

In addition to being found in all different types of terrestrial environments that involve weathering, case hardened rocks have been discovered on Mars. As case hardening generally implies chemical weathering, these discoveries provide further evidence that water once flowed on that planet.

Process

Case hardening in clastic material takes place when a chemical weathering agent, typically water, is able to remove certain minerals from the surface of a rock more easily than others. These softer minerals get transported away from the rock surface, leaving more resistant materials such as aluminum, silica, and iron. As a result, these materials become concentrated at the surface of the rock, and, combining with some of the natural cementing compounds found in clastic rocks, form a millimeters-thick hard crust that is more resistant to weathering than the rest of the rock. In some cases, parts of the crust material may even be introduced externally, as some crusts have been found to contain minerals that are not present in the underlying rock.

Results

The result of case hardening is differential weathering of a rock's surface, with a higher degree of weathering occurring where the hardened crust was not formed. This can take the form of a simple layer of less weathered material, as in Figures 2 and 3, or it can result in more complex, highly weathered structures, known as Tafoni, as in Figures 4 and 5.

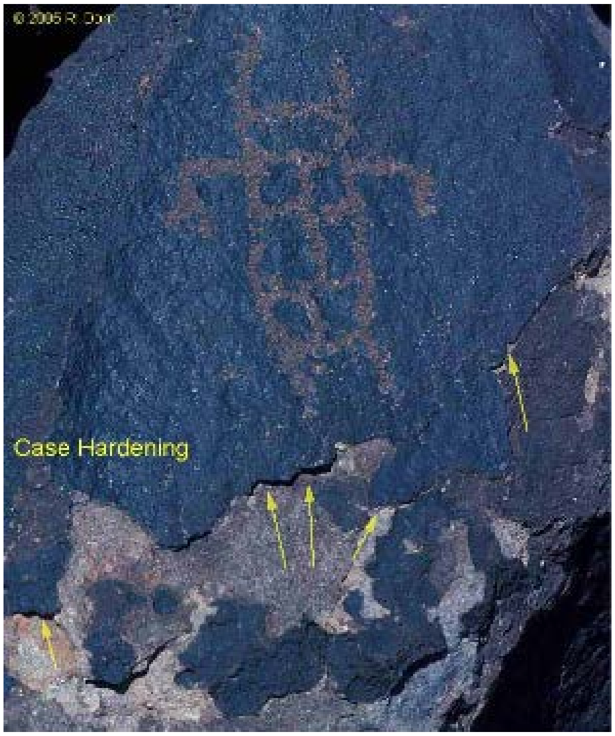


Figure 2
http://alliance.la.asu.edu/rockart/stabilityindex/4WeatheringDeposits/Coat_CaseHard_BigPetCoso.jpg

Figure 3
http://alliance.la.asu.edu/rockart/stabilityindex/4WeatheringDeposits/Coat_CaseHard_KahoK22.jpg

Figure 4
https://upload.wikimedia.org/wikipedia/commons/thumb/a/a8/Tafoni_at_Elgol%2C_Isle_of_Skye.jpg/1024px-Tafoni_at_Elgol%2C_Isle_of_Skye.jpg

Figure 5
https://upload.wikimedia.org/wikipedia/commons/b/bd/Korea-Mokpo_Gatbawi_11-01716.JPG

Extra-Terrestrial Examples

In June of 2004, the Mars rover *Spirit* investigated a number of rocks in the “Hank’s Hollow” area of Gusev crater that appeared to display the differential weathering characteristics typical of case hardening. These rocks, including “Pot of Gold” and “Bread Box”, displayed solid exteriors, with “cavernously-weathered” interiors, leading scientists to theorize that they had experienced case hardening, and then differential weathering by wind erosion later. Since terrestrial case hardening processes all involve chemical weathering by water, this provided further evidence that flowing liquid water once existed on the surface of Mars.

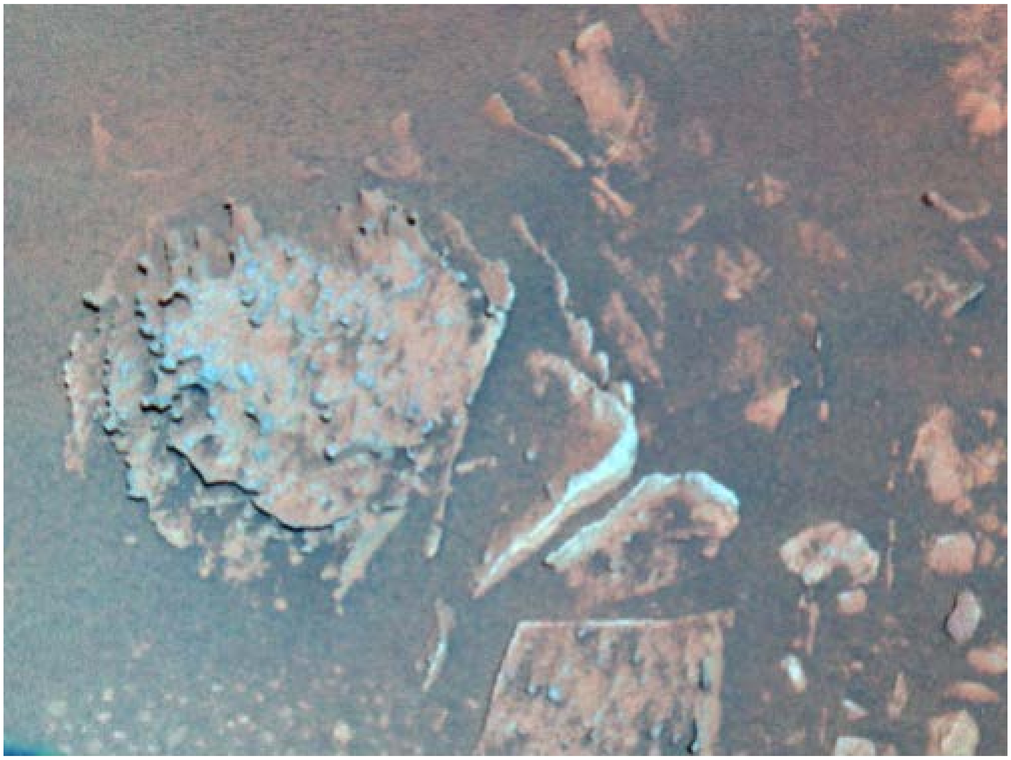


Figure 6. *Pot of Gold* rock showing indications of differential weathering due to case hardening
https://upload.wikimedia.org/wikipedia/commons/8/81/Pot_of_gold_upclose.jpg

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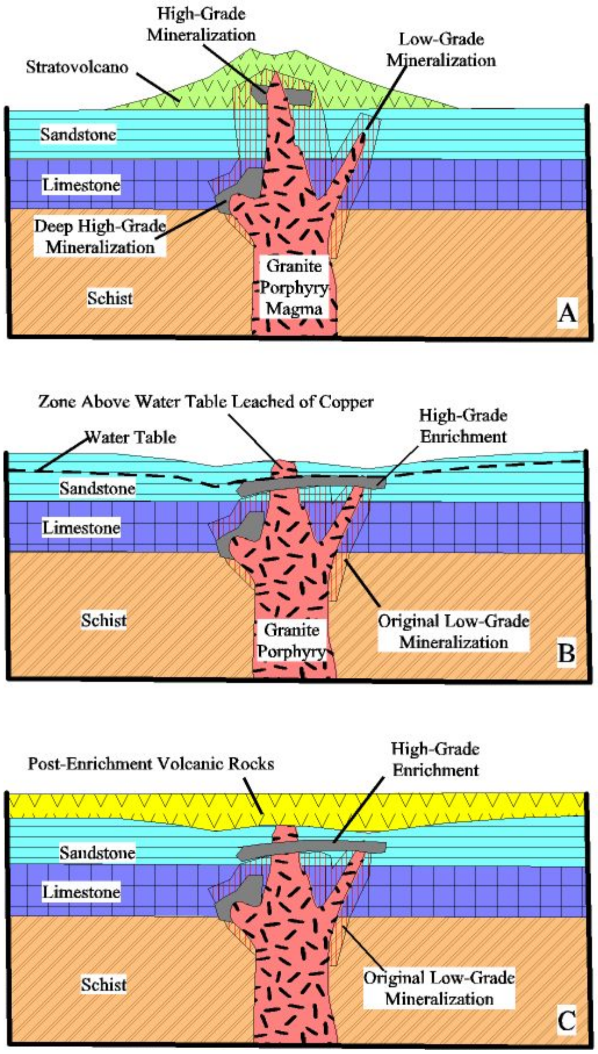
Arizona Copper Deposits

Tom McClintock

Geologically speaking, AZ has *Porphyry* copper deposits. These deposits formed within the last ~500 million years (Phanerozoic eon). They are formed when magma formed above a subducted place (often part of a volcanic arc) that is rich in Cu-Au-Ag-Mo rises up through the crust before cooling. When it does, the rock cracks, and the still-liquid elements mentioned above fill the cracks and crystallize. Eventually, erosion and tectonic activity cause these deposits to reach the surface.



Porphyry copper deposits are mined using open-pit mining techniques. As it's name suggests, open-pit mining is not extractive, i.e. there are no tunnels. It's just a big-ass hole (note the hyphen placement). It is commonly used when the deposit is found at the surface or under a thin overburden, or when tunnelling would be structurally unstable. Open-pits are dug on "benches" or terraces, which can serve as ramps for trucks carrying ore and waste.

Open-pit mines can cause serious environmental harm for a number of reasons. For instance, if the mine contains sulfides, then sulfuric acid will tend to accumulate and sometimes drain away. Gold extracted from these mines is treated through the cyanide leach process, and remains in the tailings, or slurry left over in the waste dump of an open-pit.

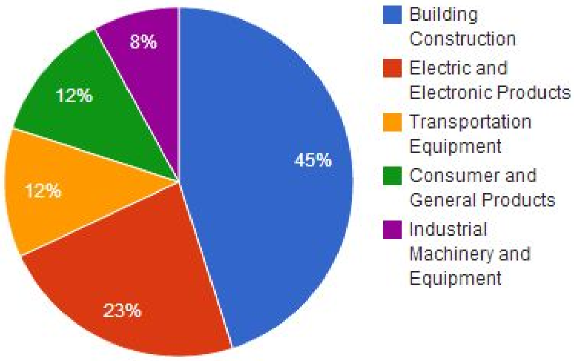
Copper mining in Arizona began in 1954 at the Ajo mine owned by the Arizona Mining and Trading Company. Before that time, a few prospectors dating back to Spanish explorers in the 1600s had primarily searched for precious metals such as silver and gold, but saw little success. The mining industry in AZ exploded, and was critical in the growth of the territory during the 1860's. At this time roughly one fifth of all Arizonans were miners. In 1912 when Arizona achieved statehood, there were 445 active mines.

Historically, copper was the first metal worked by people. Combining copper with tin pushed humans into the Bronze Age. Today, copper is primarily used in the US for building materials, specifically in copper wiring and plumbing systems. While copper is not a renewable resource, Kesler & Wilkinson estimated that at the present rate of consumption humans had ~5500 years of copper deposits left.

In the Chiricahuas and San Bernardino Valley, the largest of these mines is the Bisbee mine, owned by Freeport-McMoRan based in Phoenix.

Fun fact: the Mining and Geological Engineering Department is one of the oldest at the school, having been founded in 1888, only three years after UA itself was founded.

Uses of Copper in the United States During 2011



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Joints and Hoodoos

Maria Steinrueck

Joints are fractures in rock layers or rock bodies along which there is no measurable movement parallel to the surface plane (as opposed to shear fractures and faults). They form as a result of tensile stresses within the rock body, caused by tectonic movements or cooling. Often joints are regularly spaced and thus form joint systems. Irregular spaced and oriented joints are called non-systematic joints.

Columnar Joints form when lava flows cool and contract. The joints form perpendicular to the surface where cooling is happening. As lava flows are cooled from the top and the bottom, the joints are usually vertical. Typically, the joints intersect at large angles, creating polygonal patterns when viewed from top. Thus, the rock is divided into columns.
Famous examples of columnar joints are Giant's Causeway in Northern Ireland and Devil's Postpile in California.

Columnar joints have been found on crater rims on Mars, where they have been exposed and tilted during the impact, making them visible from space.

Figure 1: Columnar Joints at Devil's Postpile National Monument, California (Frank Kovalchek)

Figure 2: Columnar Joints at Giant's Causeway, Northern Ireland (Wikipedia)

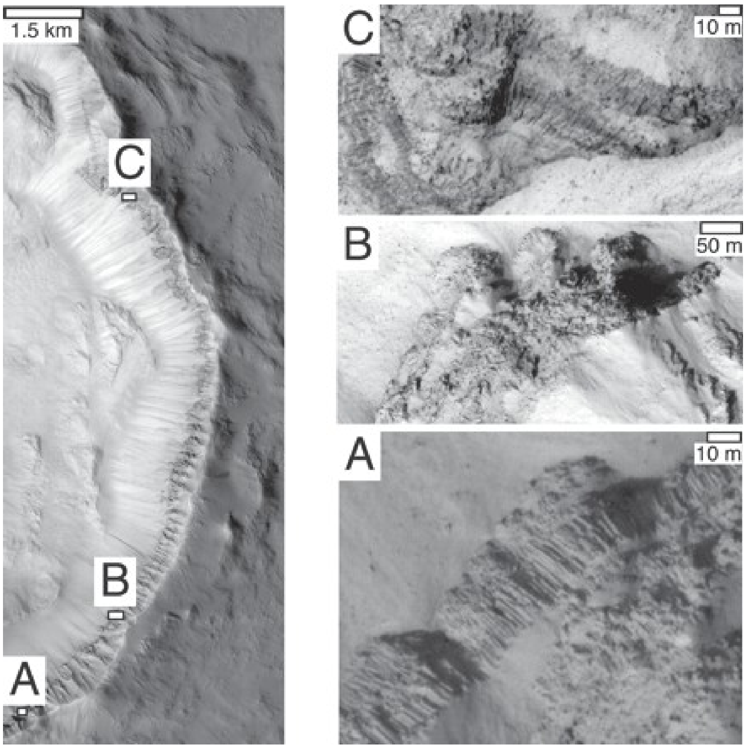

Figure 3: Columnar Joints in the crater wall of a crater in Marte Vallis on Mars. The left picture shows part of the crater, panels A-C show the columnar joints. (Milazzo et al., 2009)

Figure 4: Hoodoos in Cappadocia (Wikipedia)

Hoodoos are spires/pinnacles/pillars of rocks formed by erosion. They are also called fairy chimneys, earth pyramids or tent rocks. Some of the most famous hoodoos can be found in Bryce Canyon, Utah and in Cappadocia, Turkey.

Formation of hoodos: Preexisting joints are widened by erosion. The main erosion processes are frost wedging and chemical erosion by slightly acidic water. Frost wedging happens when water sips into the joints and freezes. As it expands, it shatters some of the surrounding rock, thus widening the joints. Plants can also contribute to erosion. The joints widen, until eventually only the hoodoos remain.
For some hoodoos (e.g. the ones in Bryce Canyon National Park) an important factor is that they are covered by a thin layer of a different rock type, which is more resistant to erosion, on top. This protects the rock below the this layer from erosion through rain, such that the pillar underneath the more resistant rock remains. For example, many of the hoodoos in Bryce Canyon consist of limestone, but are capped by dolomite.
However, this process seems to not have played a role in the creation of the Chiricahua hoodoos.

The hoodoos at Chiricahua National Monument consist of rhyolitic tuff of volcanic origin. When the tuff cooled, columnar joints formed. Erosion preferentially occurred along these joints, eventually shaping the hoodoos.

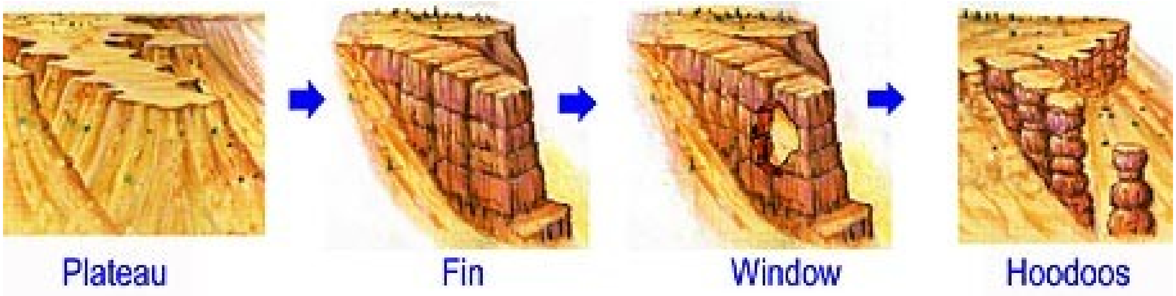

Figure 5: Formation of Hoodoos (National Park Service)

Figure 6: Hoodoos in Bryce Canyon National Park ([Luca Galuzzi - www.galuzzi.it](www.galuzzi.it))

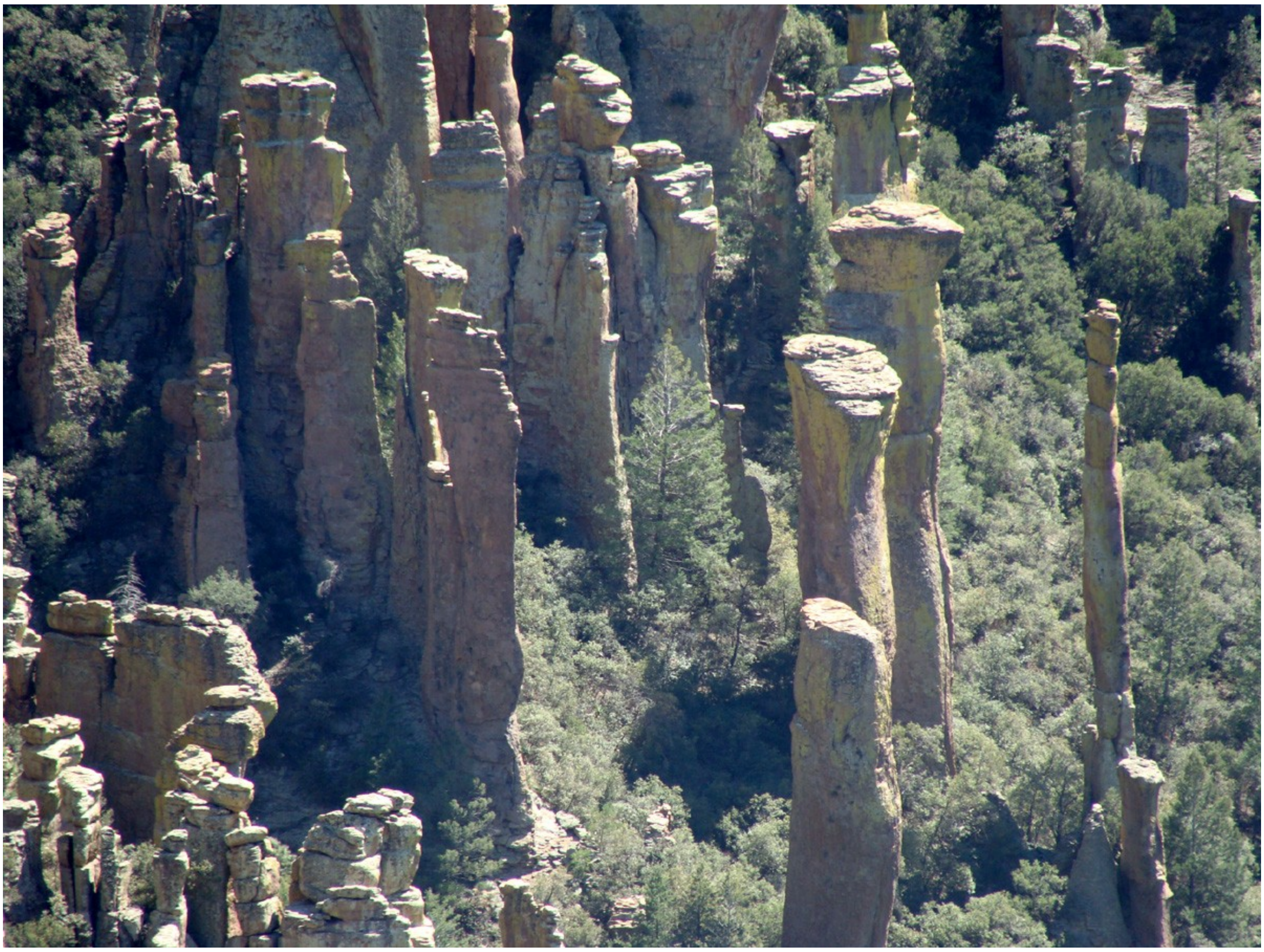

Figure 7: Hoodoos at Chiricahua National Monument (Wikipedia/User:Zereshk)

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PRECARIOUSLY BALANCED ROCKS

SARAH SUTTON

Precariously balanced rocks (PBRs) are rocks that have been eroded along vertical and horizontal joints, leaving a column with only a narrow point of horizontal contact (Fig. 1) [1]. They occur in various lithologies including granite (Fig. 2) and welded tuff, such as in the Chiricahuas (Fig. 3). Two (really three) kinds of processes can knock down a PBR. One is weathering, which eventually will erode away the supporting rock. The other is earthquake shaking. The third is idiot humans (Fig. 4).

The presumable instability of PBRs has implications for the seismicity of the areas in which they are found [2]. They are considered negative indicators of strong earthquakes within nearby seismic zones. PBRs are used to assess paleoseismicity, but this is dependent on accurately quantifying their exposure age, morphologic history and mechanical stability.

Age dating is carried out by analyses of desert varnish and cosmogenic age using ^{36}Cl [2][1]. Analysis of desert varnish is done by correlating layers within the coating with paleoclimatic episodes of more or less aridity [1]. Age dating of desert varnish surfaces suggest that some PBRs in California and Nevada have been in their current state for up to a few tens of thousands years [2][1]. This is in contradiction to estimated seismic hazard of nearby faults in some cases, which indicates the horizontal ground motion is not as strong as had been thought [2][1].

There could be planetary analogs of PBRs, but orbital data is not be the ideal data set to observe and measure them. The near-nadir view makes it difficult to observe the characteristic hourglass shape of PBRs. However, perched rocks (a similar phenomenon, where a rock is placed precariously on another rock [4]) have been observed in MER images (Fig. 5). The height of the perched rocks observed on Mars are thought to be a measure of minimum removal of material by aeolian processes [4]

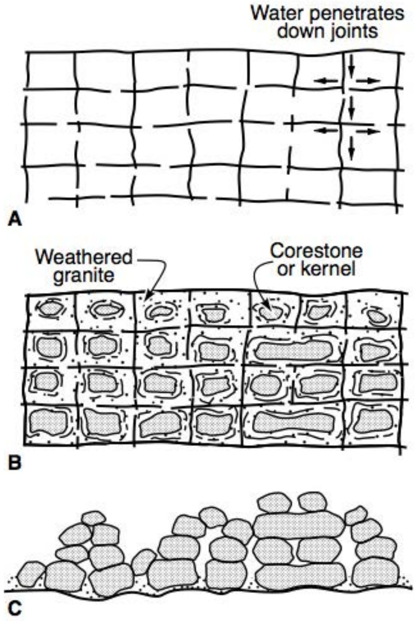

Figure 2. Two-stage development of precariously balanced rocks. In first stage, meteoric water infiltrates fractured rock (A) and grüs develops around corestones (B). In second stage (C), grüs is eroded, leaving corestones stacked in precarious positions (modified from Twidale, 1982).

Figure 1. Cartoon of PBR formation by weathering along joints [1].

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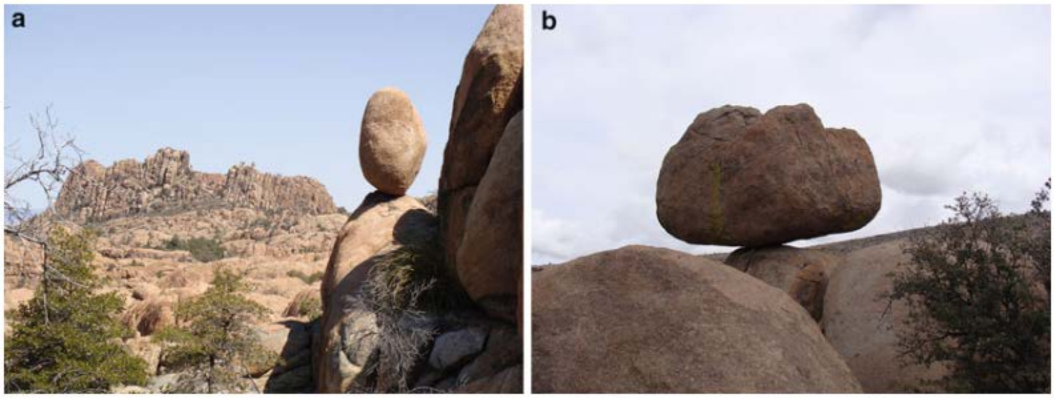
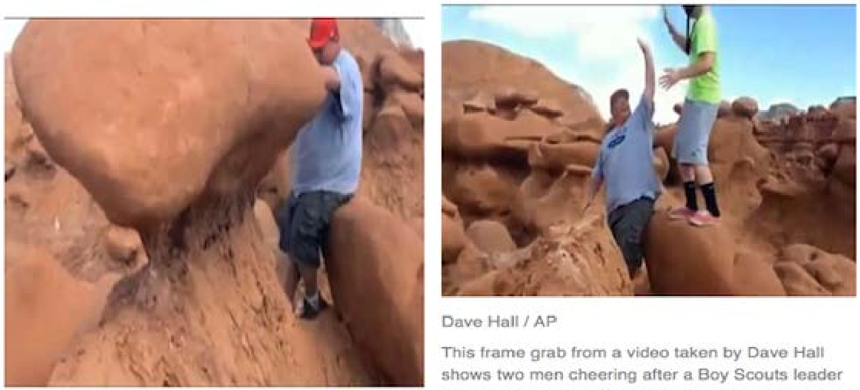


Balanced Rock, Fig. 1 (**a**) Example of a typical granitic landscape (*background*) in which balanced boulders form and a precariously balanced rock (*foreground*) from Arizona, USA (Copyright 2010 David E. Haddad). (**b**) Example of a granitic precariously balanced rock from the Mojave Desert, California, USA (Copyright 2009 David E. Haddad)

Figure 2. Examples of PBRs in Arizona and California [4].

Balanced Rock, Fig. 3 Example of spires formed in welded tuff deposits of the Chiricahua National Monument, Arizona, USA (Copyright 2009 David E. Haddad)

Figure 3. PBRs in the Chiricahua National Monument [4].

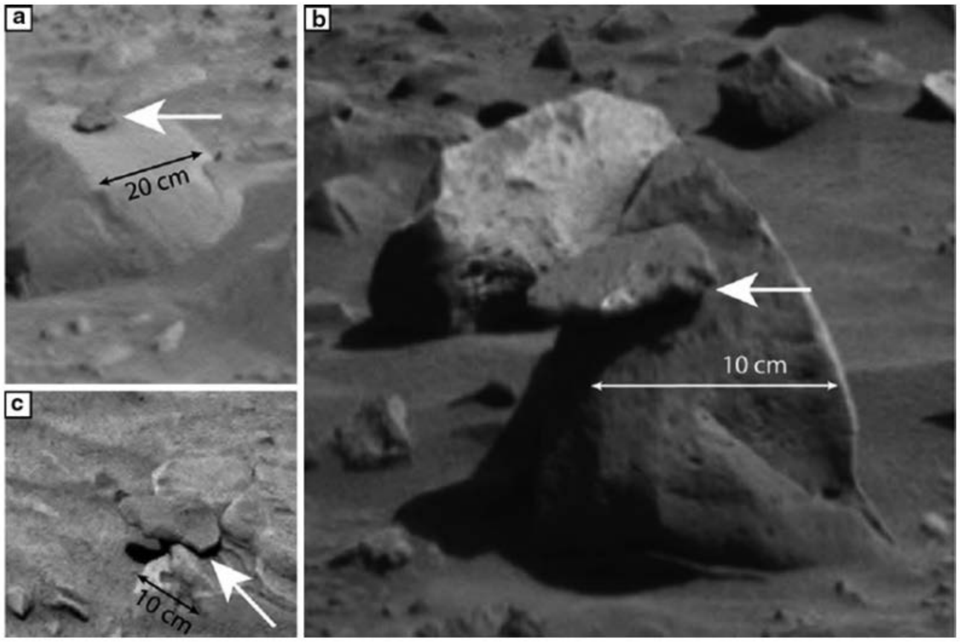


Dave Hall via AP file

Dave Hall / AP

This frame grab from a video taken by Dave Hall shows two men cheering after a Boy Scouts leader knocked over an ancient Utah desert rock formation at Goblin Valley State Park.

FIGURE 4. Stills from a video of two Boy Scout leaders toppling a PBR in Goblin Valley State Park, Utah, in 2013 (accessed from http://tinyurl.com/lj77xg4 February 21, 2016).



Balanced Rock, Fig. 4 Examples of balanced rocks on Mars from the Pancam camera of the Spirit rover (Greeley et al. 2006). (**a**) Navcam 2N132143228FFL1600P1835L0M1 "Navcam Pan" (**b**) Pancam 2P135943222FFL3200P2392C2 M1 "Midfield Rock Survey" (**c**) Pancam 2P132 404360FFL1800P2286L2M1 "Bonneville Crater Pan"

FIGURE 5. Examples of perched and balanced rocks on Mars, from MER rover Pancam images [4][3].

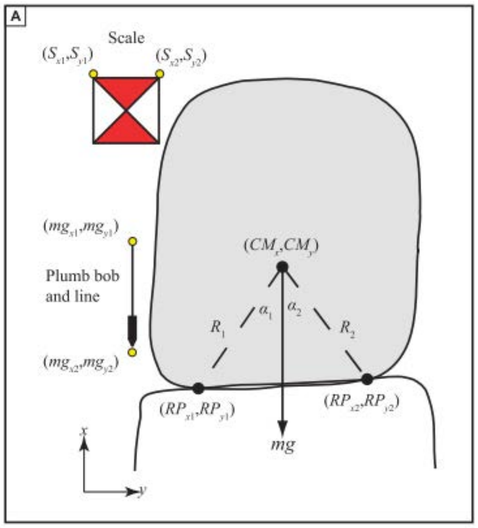


Figure 6. 2D geometry in a program developed to estimate stability of PBRs based on digital photos, where CM is center of mass, and RPs are rocking points. The stability is modeled as an inverted pendulum, set in motion by a horizontal acceleration [5].

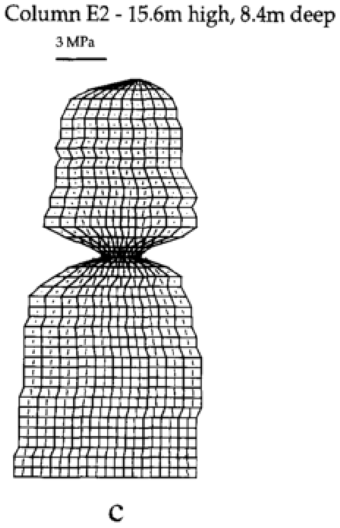


Figure 7. 2D finite element model of PBR photographed in the Chiricahuas [6].

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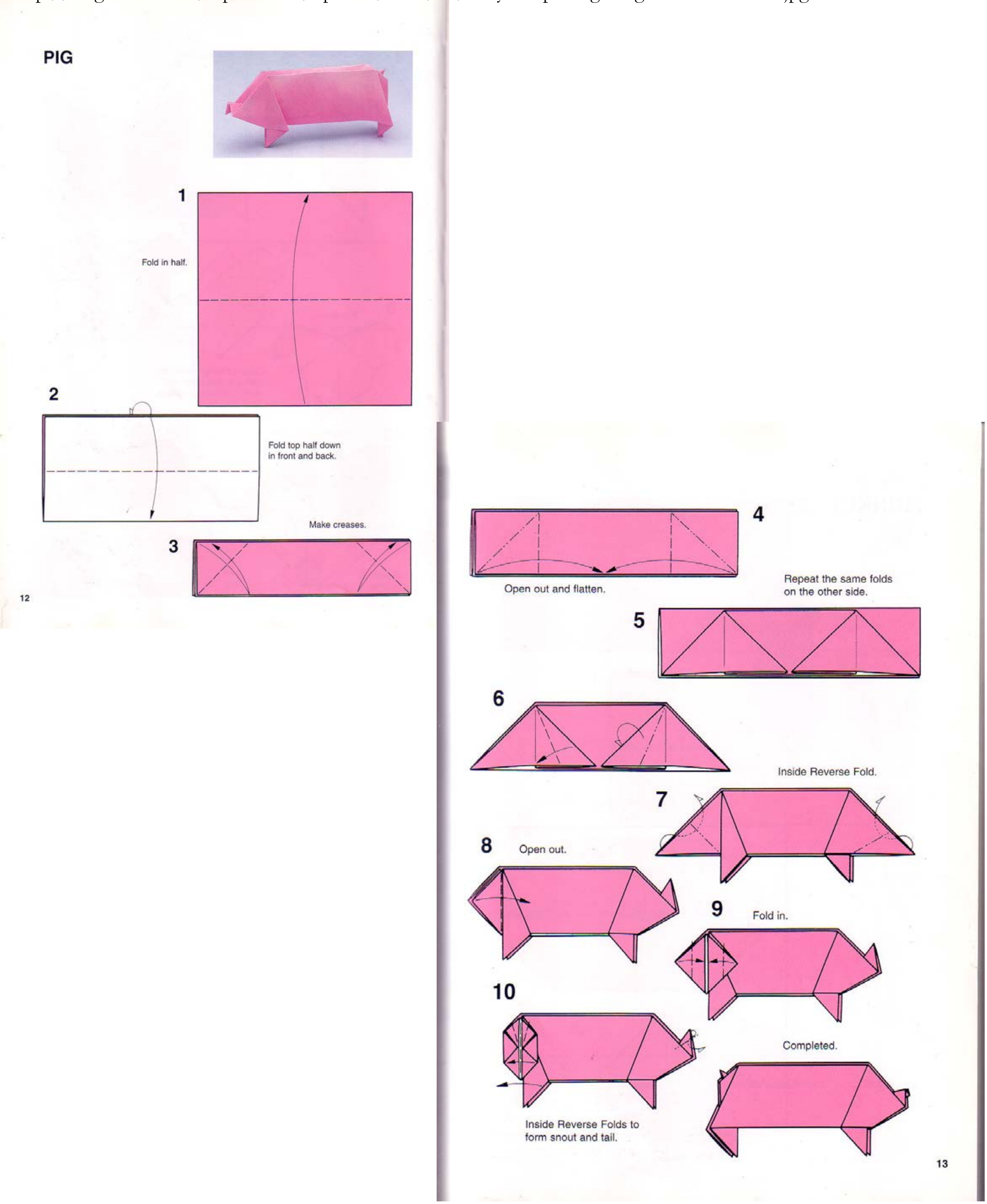
Activities!!

http://origamiers.com/wp-content/uploads/2014/03/Very-Simple-Pig-Origami-Instructions.jpg



PIG

1

Fold in half.

2

Fold top half down in front and back.

Make creases.

3

12

4

Open out and flatten.

Repeat the same folds on the other side.

5

6

Inside Reverse Fold.

7

8

Open out.

9

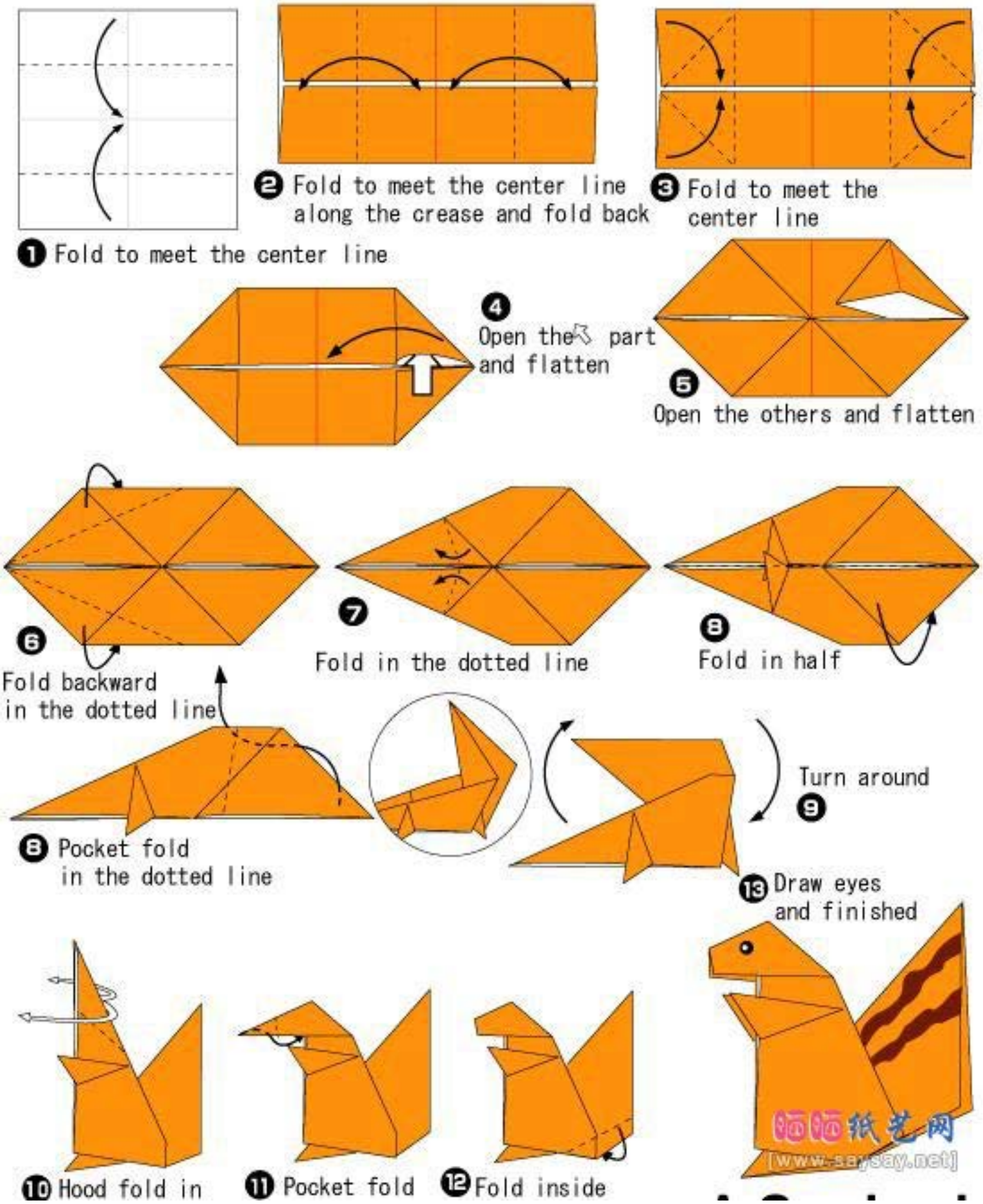
Fold in.

10

Inside Reverse Folds to form snout and tail.

Completed.

13



❶ Fold to meet the center line

❷ Fold to meet the center line along the crease and fold back

❸ Fold to meet the center line

❹ Open the ⇧ part and flatten

❺ Open the others and flatten

❻ Fold backward in the dotted line

❼ Fold in the dotted line

❽ Fold in half

❽ Pocket fold in the dotted line

Turn around ❾

❿ Hood fold in

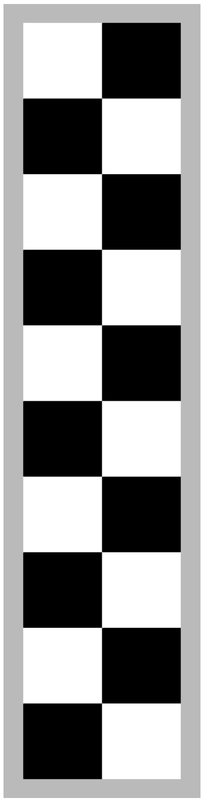
⓫ Pocket fold

⓬ Fold inside

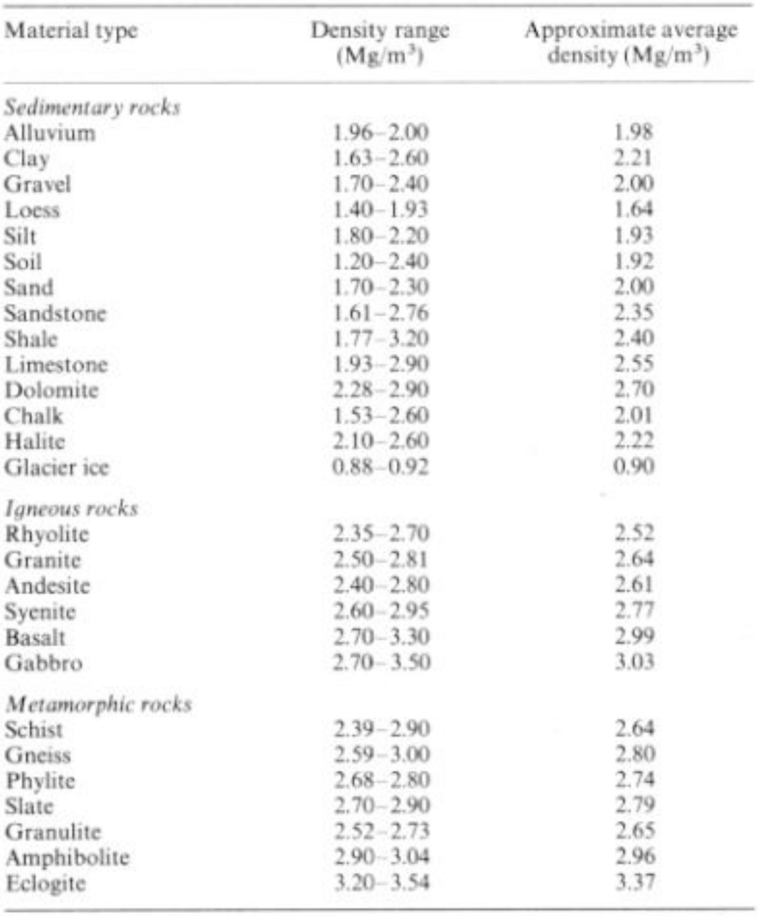
⓭ Draw eyes and finished

http://origamiers.com/wp-content/uploads/2014/02/easy_origami_squirrel_instructions.jpg

10 cm ruler



ROCK DENSITIES

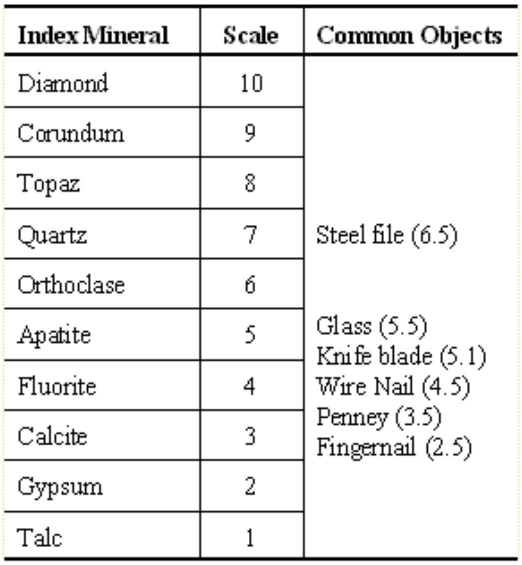


Material type	Density range (Mg/m³)	Approximate average density (Mg/m³)
Sedimentary rocks		
Alluvium	1.96–2.00	1.98
Clay	1.63–2.60	2.21
Gravel	1.70–2.40	2.00
Loess	1.40–1.93	1.64
Silt	1.80–2.20	1.93
Soil	1.20–2.40	1.92
Sand	1.70–2.30	2.00
Sandstone	1.61–2.76	2.35
Shale	1.77–3.20	2.40
Limestone	1.93–2.90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

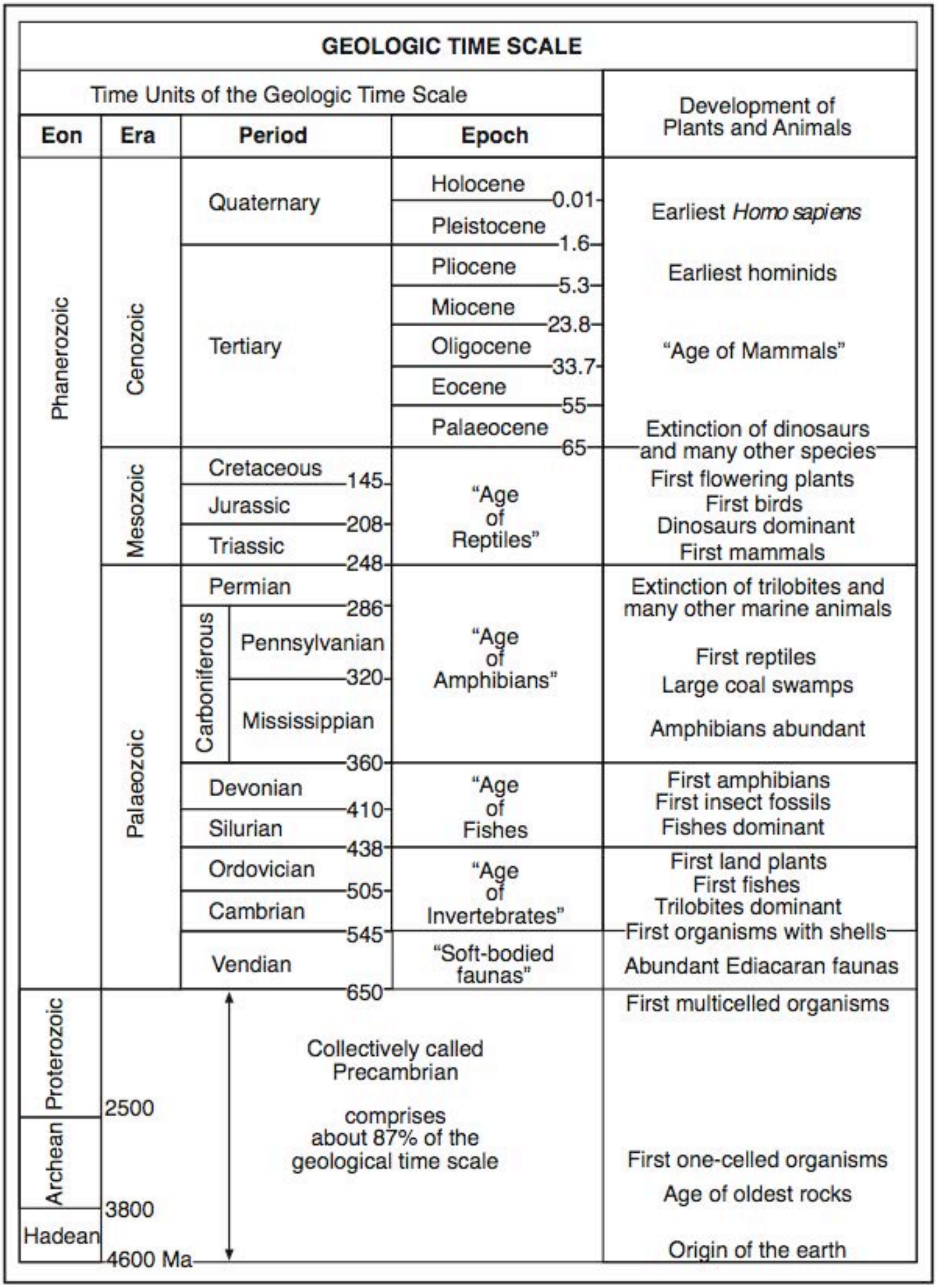
Udden-Wentworth Grain Size Scale

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

MOHS HARDNESS SCALE



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



GEOLOGIC TIME SCALE

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

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