

LPL Field Trip Spring '26

CHIRICAHUAS



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Note from the editor: A huge thank you to the artists Ruby, Sophie, and Kylie, who created the cover art for this field guide!

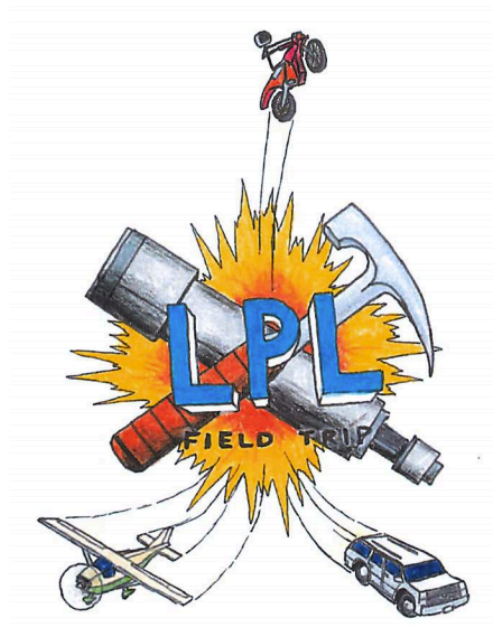
Letter from the editor

I study the atmospheres of planets orbiting other stars. Volcanoes, tuff, jointing patterns, and 27 million years of erosion are about as far from my usual corner of astrophysics as you can get.

Putting together this field guide has been a wild ride through a part of Arizona I've driven past without really seeing. The more I dug in, the more I kept finding connections back to the things I do know: the way a rock records its own history in layers isn't so different from how a planetary atmosphere does, and the erosion eating away at these hoodoos one monsoon at a time isn't so different from the atmospheric escape I model every day. Geology, it turns out, is just physics with better field trips.

I hope this guide helps you appreciate just how much story is packed into these rocks. The Chiricahuas are strange and dramatic and right in our own backyard, and I think that's easy to take for granted. I know I'll never look at a spire of rock the same way again, and I'm hoping by the end of this trip, you won't either.

See you in the field,
Anna :)



Land Acknowledgment

We acknowledge that the Chiricahua Mountains and the surrounding landscape of southeastern Arizona are the ancestral and unceded homeland of the Chiricahua Apache people, the Ndé, meaning "the People", who have lived in, traveled through, and stewarded this rugged mountain terrain since time immemorial. Their deep knowledge of this landscape, from its springs and canyons to its plants and animals, shaped the ecological and cultural history of this region in ways that endure today. We also recognize the presence of earlier peoples, including the Mogollon, whose archaeological record reflects thousands of years of human life in this landscape before them.

The Chiricahua Apache were forcibly removed from their homeland in 1886 and sent thousands of miles away as prisoners of war, and were not permitted to return to Arizona. Their descendants live today primarily within the Mescalero Apache Tribe of New Mexico and the Fort Sill Apache Tribe of Oklahoma, and continue to maintain their connection to, and fight for, these sacred lands.

As we explore Chiricahua National Monument and its surrounding environments, we do so with gratitude and respect for the original caretakers of this place and with recognition of the ongoing displacement they have endured. We acknowledge the importance of honoring Indigenous sovereignty and commit to continuing to learn from Indigenous communities and perspectives in both science and stewardship.

- LPL Graduate Students

PTYS 590 Spring 2026 Itinerary

Day 1 – Friday 4/17

- 8:00am Volunteers pick up vehicles. Meet at the Kuiper loading dock, start loading vehicles
- 9:00am Depart. Hop onto I-10 heading East
- 10:30am Meet at Texas Canyon Rest Area (I-10 Eastbound side)
[32.05990895560647, -110.07619653291482](#)
Restrooms available
- Examine the rocks near the rest area as **Gabe** introduces us to the Granitic Intrusions of Southern Arizona
- 11:00am Depart Texas Canyon Rest Area. Drive Towards Wilcox, take exit to Rte 186, drive southeast towards Chiricahua National Monument
- 11:30am Exit at Kansas Settlement Rd. Meet at Willcox Playa Wildlife Area.
[32.14177278430763, -109.75679545326629](#)
Drive/hike towards the playa
- Walk until we find the clay dunes, which **Cole** will tell us all about
- Lunch***
- 1:00pm Depart the playa, drive back to Rte 186, proceed towards Chiricahua National Monument
- 1:45pm Enter Chiricahua National Monument, stop at the Bonita Creek Loop Trail [32.0098164594169, -109.38416697091607](#)
Restrooms available
- Before we start on the trail, **Lori** will tell us about Sky Islands, explaining why the ecology we are looking at is so different from Tucson
 - As we walk this trail, keep an eye out for various critters, including Coatis, which **Lily** will tell us about
 - Hopefully we don't come across El Jefe or any of the other Big Cats of Southern Arizona, which **Joanna** will tell us about (this is also your reminder to not leave food or trash out around the campsite overnight)

- 3:15pm Depart Bonita Creek Trail, stop at the Visitor's Center
[32.00544826012536, -109.35651330943247](#)
Restrooms available
- After we absorb some of the informational displays in the visitor's center, **Fuda** will educate us all on the Apache Wars
- 4:15pm Depart Visitor's Center. Drive to Organ Pipes Rock Formation (less than 5 minutes away)
[32.01758007413719, -109.35192791921541](#)
- As we gaze upon the Organ Pipe rocks, **Chaucer** will explain the process that carved them out
 - Afterwards, **Carter** will talk about one of the unexpected causes of all these holes in front of us
 - This is a good stop for field sketches
- 5:00pm Depart Organ Pipes Rock Formation, head to camp at the Bonita Canyon Campground. We have campground 26 reserved (the group campsite).
[32.01144409362296, -109.35499410471432](#)
Restrooms available
Water faucets available
Quiet hours start at 8:00pm
- After darkness falls, **Sophie** will talk about dark skies and their importance in National Parks/Monuments (we will have one of the department's telescopes with us to take advantage of these dark skies)

Day 2 – Saturday 4/18

- 7:00am Early morning wake up to avoid hiking in the heat. Depart camp. Drive up Bonita Canyon Dr. towards Massai Point
- 7:45am Arrive at Massai Point. Take the short loop trail if time allows.
[32.00714920596101, -109.31228792147479](#)
Restrooms available
- As we gaze upon the towers of rock, **Anna** will describe how these structures formed, and say the word hoodoo until its not funny anymore
 - **Melissa** will then describe a historical earthquake in the region, as we ponder how all these precarious rocks did not fall over

- 8:30am Depart Massai Point, drive to Echo Canyon Loop Trailhead.
[32.01207576512945, -109.31580799833729](#)
~3 hour, 3.3 mile hike. NPS describes the hike as “moderate”
 - As we walk through this wonderland of silicic volcanic rock, **Elana** will talk about some of the processes for how they formed
 - This will be a good place for field sketches
- 11:30am Depart Echo Canyon Loop Trailhead, head to Sugarloaf Mountain Trail.
[32.016453695924284, -109.32120057666627](#)
Restrooms available
Start hike up to peak. 0.9 miles uphill to peak. NPS describes the hike as “moderate”
- 12:30pm Reach Sugarloaf summit
Lunch
 - From this peak, we look down upon the land and **Ruby** will explain how this all happened
 - We then look towards the terrain in the northeast, while **Kylie** describes some of the fossils that can be found there
- 1:30pm Depart the Sugarloaf Mountain Trailhead. Exit Chiricahua National Monument
- 3:00pm Stop at Pilot Travel Center in San Simon AZ.
[32.273451289852304, -109.24151241103938](#)
 Top off the vehicles, buy snacks.
Restrooms available
- 3:15pm Depart Pilot Travel Center
- 3:45pm Stop at Shady Grove Truck Stop in Red Forks NM.
[32.23411823933919, -108.95263488232331](#)
 - From our majestic truck stop view, **Maddy** will describe the ancient lake that we are about to drive over
- 4:00pm Depart Shady Grove Truck Stop, admire the flats of the paleolake as we drive across it. Head north towards the Black Hills Black Country Byway.

5:30pm Arrive at the Black Hills Country Byway. If the vehicles have separated, we will wait at this information stand location for everyone to arrive.
[33.00361230310983, -109.28625354318372](#)
Hunt for a good spot to camp. This is all BLM land and we can camp anywhere off this road until the Owl Creek campground
([32.96696516886709, -109.30783955185902](#)).
No restrooms
No water source

Day 3 – Sunday 4/19

9:00am Leisurely wake up, plan to depart at 9am, head to Clifton AZ

9:15am Stop at Haunted Arizona Ghost Tours in Clifton
[33.054662556014456, -109.2982407067175](#)
Restrooms available

- Avoid upsetting the spirits as we look upon the outcrop across the street while **Madison** tells us about the volcanic events that formed it

9:45am Depart the haunted outcrop, head up to the Morenci mine outlook

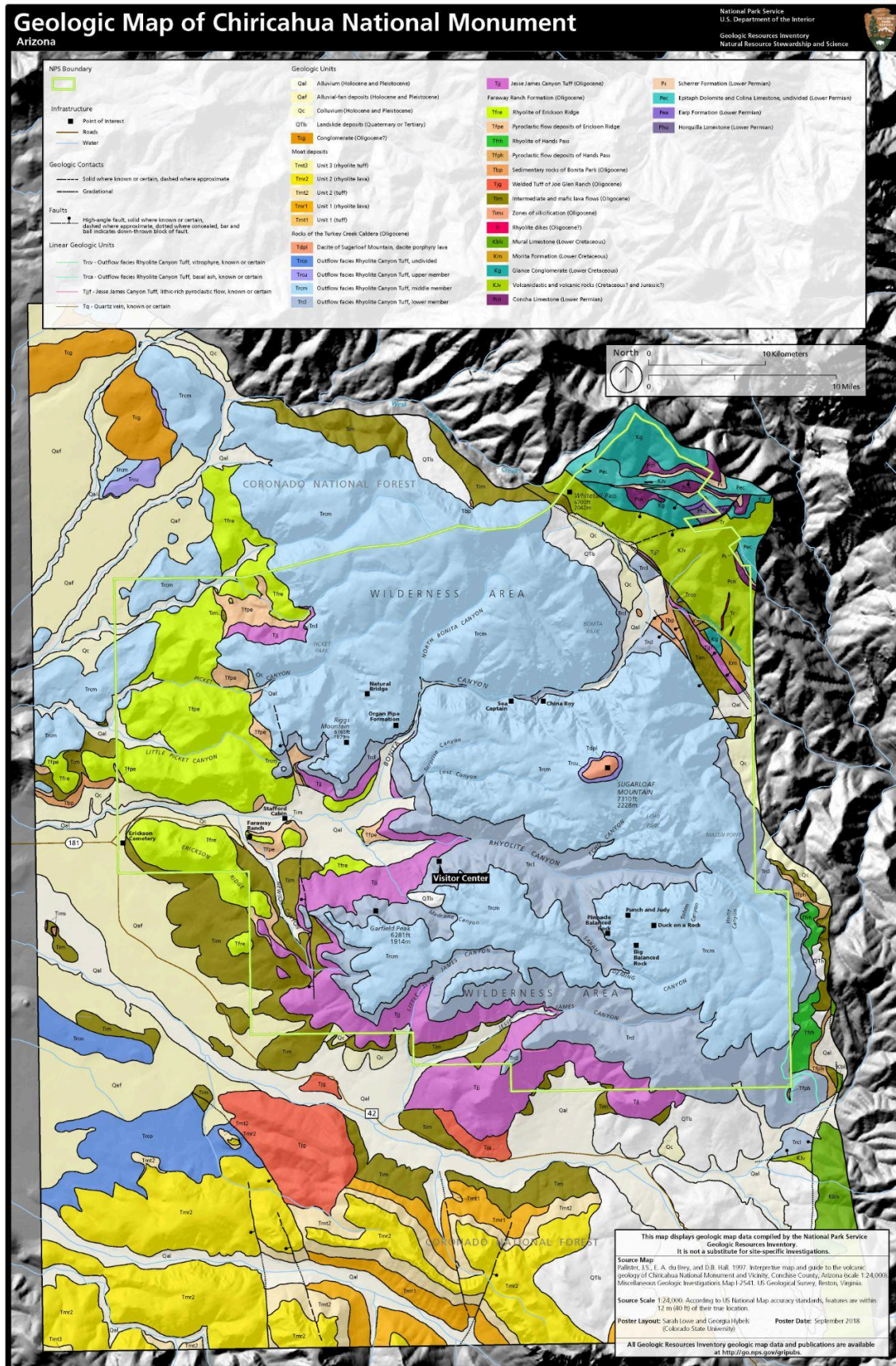
10:00am Stop at the Morenci mine lookout.
[33.10192431920253, -109.36752109842465](#)

- Gaze upon the destructive nature of man as **Carson** describes one of the largest copper deposits in the United States and the history getting it out of the ground

10:30am Depart the Morenci mine lookout, heading back to Tucson. Negotiate with your vehicle about where you want to stop for **lunch** and plan to stop at a gas station to fill up sometime before getting back to Tucson

2:30pm Arrive back at the Kuiper building loading dock,
[32.232837116305205, -110.94706421349379](#)
Start the process of unloading. We will pack all of the equipment back up neater than we found it. Volunteers drive the vehicles back to motorpool.

Supplementary Maps and Figures



Emergency Information

U of A Travel Emergency: 520-307-9576

U of A Travel Incident: 800-243-6124

U of A Risk Management: 520-621-1790

Joe Schools' cell phone: 714-308-2592

Sam Crossley's cell phone: 817-609-3343

Jess Barnes' cell phone: 520-358-8803

Silicic Volcanism | LPL Fall Field Trip: Chiricahuas | April 2026

Elana Alevy

Silicic Volcanism Overview: Silica-rich (SiO_2 -rich) volcanism is pervasive across plate tectonic settings on Earth. The production of evolved, silica-enriched magmas occurs primarily due to the addition of water to a melt as it ascends to Earth's surface at active plate margins. The result is a highly viscous magma that is either emplaced in the subsurface as a slowly cooled felsic intrusion, or as an explosive extrusive eruption of felsic lava into domes and composite volcanic structures. While the production of silicic melts on Earth is common, these features elsewhere in the solar system are rare. Yet few examples of extrusive and intrusive volcanic features have been identified on the Moon, and clasts of felsic materials have been identified at both the outcrop scale on Mars and in lunar meteorites and returned Apollo samples. Ongoing work aims to constrain the formational conditions and magmatic evolution of silica-rich melts on the Moon and Mars in order to better understand end-member volcanism and magmatism on bodies lacking Earth-style geologic processes.

Chiricahua Silicic Volcanism: The Chiricahua National Monument and surrounding areas formed from volcanics of the Turkey Creek caldera, a silicic eruption during the Oligocene, about 26.5 Mya. The eruption produced about 500 km^3 of viscous, volatile-rich lavas, volcanic ash, and pyroclastic flows. Turkey Creek volcanics were high in silica—nearly 77%, which corresponds to the extrusive felsic rock type of rhyolite [1]. The high volumes of extruded material have been eroded over time through fluvial and aeolian activity, resulting in myriad landforms including the iconic columnar hoodoos. The hoodoos formed from early excavation of rock along planes of weakness in joints that expanded as the silica-rich lavas cooled.

Silicic Volcanism on the Moon: The Moon is a relatively dry and geologically inactive planetary body compared to the Earth. In particular, it lacks the same substantial scale of plate tectonic activity and fluid mobilization that are considered necessary for silicic magma generation on Earth. However, a number of landforms and lithic clasts with silicic compositions have been identified on the surface of the Moon and in samples, respectively. Multiple formation mechanisms to produce lunar felsites have been proposed, including basaltic underplating and silicate liquid immiscibility.

Surficial Evidence of Evolved Lunar Volcanism. Remote sensing observations of the lunar surface has revealed the presence of non-basaltic (i.e. nonmare) features including the Gruithuisen Domes, Mairan Domes, Aristarchus, Hansteen Alpha, Montes Rhipaeus, Lassell Massif, and Compton–Belkovich complex (Fig. 1) [2-3]. These provide evidence that evolved lunar magmatism resulted in localized eruptions that produced rocks distinct from the nearby mare units. The silicic nature of these features was confirmed by remote sensing observations through imaging and spectroscopy. These signatures include strong UV absorption as well as low FeO and low TiO_2 abundances, measured by Clementine and M³ [4-5].

Sample Evidence of Evolved Lunar Volcanism. Returned Apollo samples contain a small number of highly evolved, silicic clasts of granitic or felsic lunar materials [6-8]. Microanalysis of these samples confirms their high silica abundances, often in the form of quartz (SiO_2) or a polymorph of quartz like

cristobalite or tridymite, which are stable at higher temperatures than quartz. Silicic lunar clasts have also been identified in select lunar breccia meteorites (Fig. 2), though an extended survey of meteoritic silicic material has not yet been explored. Given that both intrusive (~granitic) and extrusive (rhyolitic) mineralogies have been identified in samples and on the lunar surface, it is likely that some silicic clasts in meteorites and Apollo samples directly represent surface units of silicic magmatic activity. However, it is difficult to match a meteorite to its source location on the surface.

Silicic Volcanism on Mars: Silicic products have been identified recently on the surface of Mars. Early observations of feldspar-rich regions on Mars resulted in uncertain rock classifications [i.e. 9 and references therein] but were also predicted based on surface morphology and thermal signatures from orbital observations [e.g., 10]. However, recent Mars2020 Perseverance rover observations in western Jezero crater have located a quartz-bearing, granitic unit that has coarse grains indicative of slow cooling (Fig. 3) [11]. Finer-grained felsite clasts have also been identified in Martian meteorites, including the regolith breccia suite including Northwest Africa 7034/7533 [e.g., 12]. These occurrences of silicic materials on Mars could be explained through partial melting of an ancient, altered Martian crust; partial melting of sediments; or extensive basalt fractional crystallization. The evolved Martian samples are also evidence of an active fluvial history in the geosphere, resulting in water-rock interactions and potential hydrothermal activity that further enabled silicic volcanic activity.

References: [1] Pallister, J. S. et al. (1993). US Geological Survey. [2] Glotch, T. D. et al. (2010). *Science*, 329(5998), 1510–1513. [3] Jolliff, B. L., (2011). *Nature Geoscience*, 4(8), 566–571. [4] Chevrel, S. D. et al. (1999). *Journal of Geophysical Research: Planets*, 104(E7), 16515–16529. [5] Kusuma, K. N. et al. (2012). *Planetary and Space Science*, 67(1), 46–56. [6] Warren, P. H. et al. (1983). *Earth and Planetary Science Letters*, 64(2), 175–185. [7] Seddio, S. M. et al. (2013). *American Mineralogist*, 98(10), 1697–1713. [8] Valencia, S. N. et al. (2024). *GCA*, 367, 189–212. [9] Payré, V. et al. (2024) *Minerals*, 14, 452. [10] Wray, J. J. et al. (2013) *Nature Geosci*, 6, 1013–1017. [11] Liu Y. et al. (2026). *LPSC 2026*, Abstract #1322. [12] Malarewicz, V. et al. (2025) *Nature Geoscience*, 18, 207–212. [13] Su, B. et al. (2023). *Communications Earth & Environment*, 4(1), 228. [14] Zeng, X. et al. (2021) *Geophysical Research Letters*, 48(13).

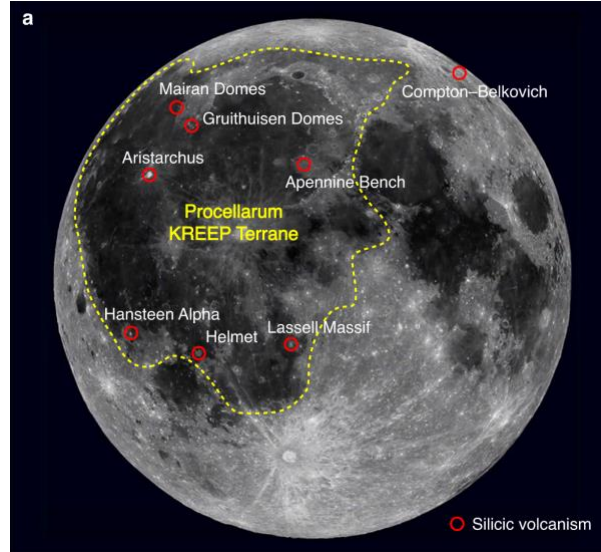


Figure 1. Surficial silicic features on the Moon. From [13].

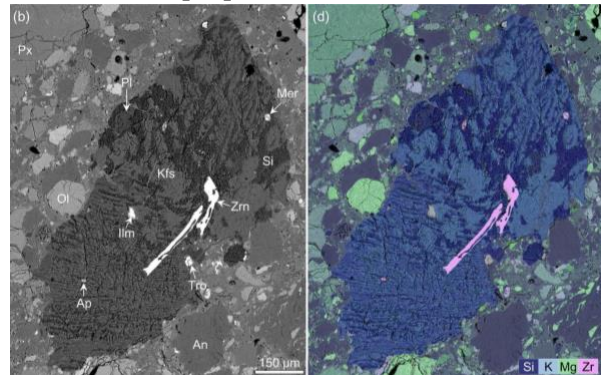


Figure 2. Silicic clasts in lunar meteorite, Northwest Africa (NWA) 10447. False-color maps with silica in purple. From [14].

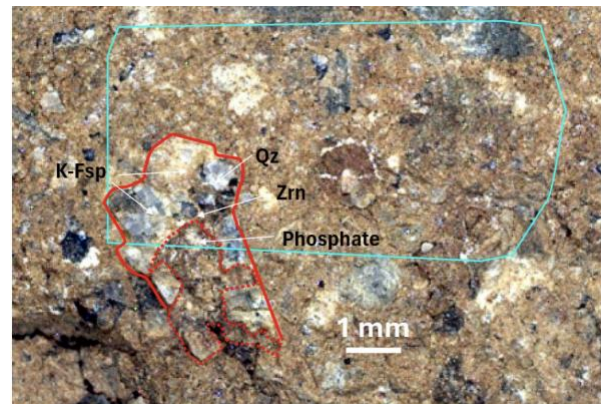


Figure 3. WATSON image of a granitic clast (red line) in the Aitkenodden abrasion patch on Mars. From [11].

Paleolake Animas | LPL Spring Field Trip | April 2026
Maddy Christensen

1. Overview

Former lakes from the late pleistocene cover a zone from the Colorado Plateau in the North to the USA-Mexico boundary in the south, and from the Pecos River Valley in the west to the lower Colorado River Valley in the east (Figure 1). Each of these paleolakes are surrounded by discontinuous block-fault mountain ranges that bound the depositional basins that formed the lakes. Paleolake Animas, the lake I focus on here, was the biggest of the three closed lakes in the region (Fleischhauer and Stone, 1982). It has the most continuous and best preserved shoreline features, which allows climate reconstructions and connections to paleobiology to be more accurate and impactful than other paleolakes in the region.

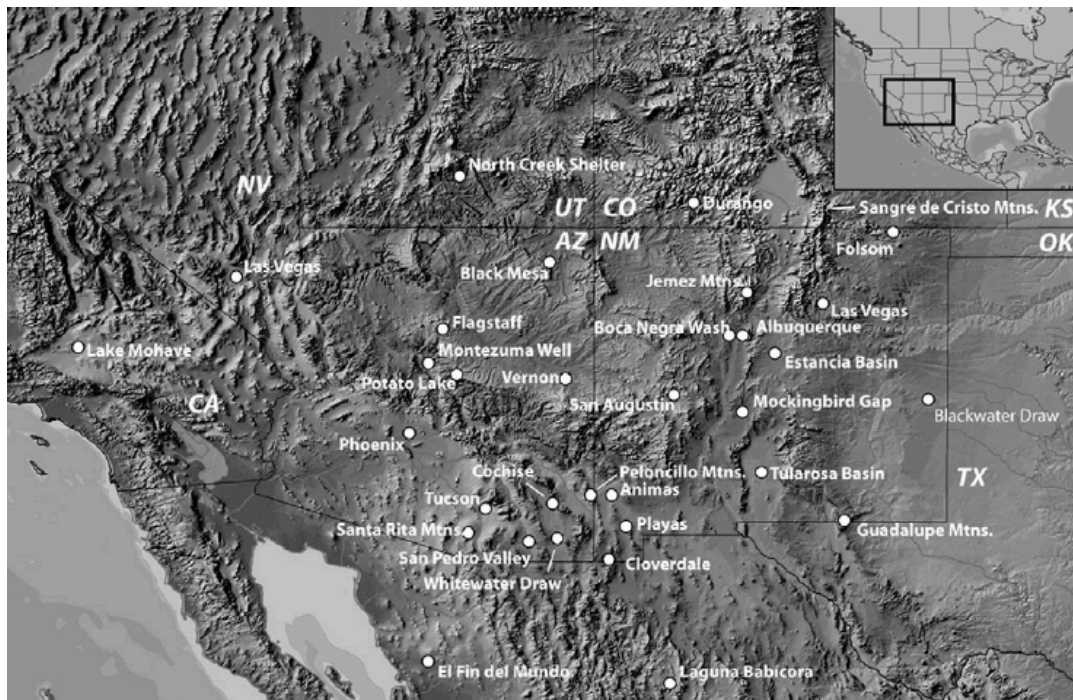


Figure 1: A map of major landmarks and paleolakes within the zone focused on this report. Note Animas is within southwest New Mexico (Balleger et al, 2011).

2. Underlying Geological Mechanisms

Similar to other paleolakes in the region, Animas was surrounded by two mountain ranges that formed a tight valley: the Peloncillo Range on the west and the Animas Range on the east (Schwennesen, 1918). This system is an example of basin and range topography, where mountain ranges are interspaced with valleys in between. This occurs when the crust extends, often due to mantle upwelling, gravitational collapse, crustal thickening, or relaxation of stresses. It's possible to explain these mountains interspersed with valleys by either symmetric or asymmetric faulting. Symmetric faulting can happen when a series of normal faults occur in

groups and dip in opposite directions. As the fractures extend, some blocks of crust rise up and some sink down, forming the valleys and mountain ranges we see. Asymmetric faulting can occur when a similar series of normal faults form with low dip angles, allowing the blocks of crust to slide down the faults. The tilt of the slid blocks creates the basin and range pattern. The paleolake zone throughout New Mexico and parts of Arizona has this topography in common, and most of the paleolakes are located within the Basin and Range Province (Figure 2). The mechanism that caused the province is heavily debated with competing theories.



Figure 2: The Basin and Range Province within the United States and Mexico. Note the bounding between the San Andreas Fault and Colorado Plateau.

Paleolake Animas in particular had an irregular coastline that caused embayments, where a curved section of coastline creates a protected beach (Figure 3). These curved beaches often have sand transport and experience erosion at a faster rate than straight beaches. There does not currently seem to be a connection between these embayments and a major impact that they would have on the observed paleoshorelines, but it is a unique factor seemingly not present in other paleolakes within the Basin and Range Province.

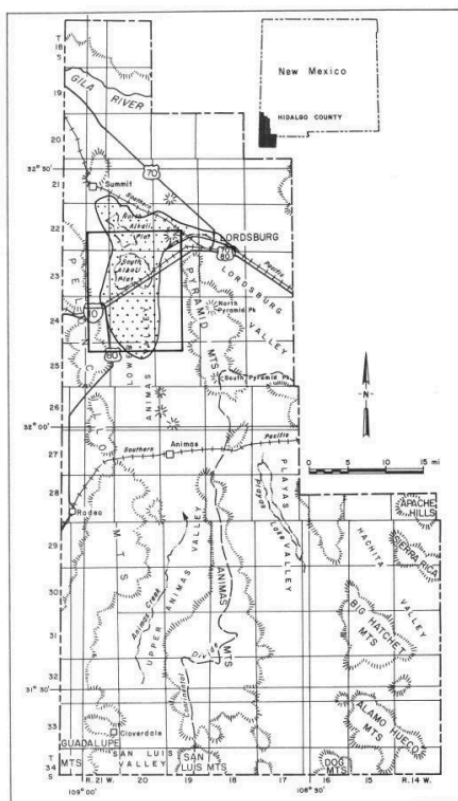


Figure 3: A map of Paleolake Animas (shaded in the upper left) and the surrounding area of New Mexico (Fleischhauer and Stone, 1982).

3. Observations of Paleoshorelines

Stratigraphic isolation of paleoshorelines makes the reconstruction of shorelines and any applications to climate difficult. For example, it is difficult to clarify if three separate shorelines correspond to three separate lake cycles, or one period with three different water levels. However, as the biggest and best preserved lake of the three in the Animas Basin, research has been done to connect the observed shorelines to climate at the time.

There appear to be three separate lake stages observable in the area. These stages are identifiable by the location of the shoreline: low shoreline, medium shoreline, and high shoreline. Dating of the soil has isolated the dates to be pleistocene in age, but further dating does not seem to have been explored (Fleischhauer and Stone, 1982; Kowler, 2013).

In May of 1961, the partial remains of two mammoths were found within the understood boundaries of the paleolake. They were found buried within lacustrine clay beds with a paleosol in the beds. Both the clay and the paleosol are overlain by alluvial fan deposits that make up the modern surface of the bed. The mammoths were not dated, and so the relationship between the remains and the lake are not fully understood. They are currently used as a cap to the possible age of the paleolake as being Pleistocene at the latest, especially in relation to the highest shoreline. Native American pottery fragments have been found on the surface of the paleolake, meaning the earliest the lakes could have formed is 2,000 years ago. Paleoclimate reconstructions from plants within a 2m section suggests the presence of a lake in the Playas

Valley until approximately 4,500 yrs ago with potential recurrences. These results roughly correlate with similar studies of paleolakes in the surrounding area (Fleischhauer and Stone, 1982).

4. Planetary Implications

Closed and open basin paleolakes, similar to Paleolake Animas, are currently being researched on Mars. These lakes, as well as whether they were caused by basin and range processes, are still being debated, but there is reasonable evidence to suggest that paleolakes have existed on Mars (Fasset and Head, 2008).

Sources:

Ballenger, J. A. M., Holliday, V. T., Kowler, A. L., Reitze, W. T., Prasciunas, M. M., Shane Miller, D., & Windingstad, J. D. (2011). Evidence for younger Dryas global climate oscillation and human response in the American Southwest. *Quaternary International*, 242(2), 502–519. <https://doi.org/10.1016/j.quaint.2011.06.040>

Fassett, C. I., & Head, J. W. (2008). Valley network-fed, open-basin lakes on mars: Distribution and implications for noachian surface and subsurface hydrology. *Icarus*, 198(1), 37–56. <https://doi.org/10.1016/j.icarus.2008.06.016>

Fleischhauer, Jr., & Stone, W. J. (1982). Quaternary geology of Lake Animas, Hidalgo County, New Mexico. *Journal of Volcanology and Geothermal Research*. <https://doi.org/10.58799/c-174>

Kowler, A. L. (2013). Lake shoreline evidence of hydrologic conditions in the Southern Basin and Range Province during the late pleistocene and early holocene: Paleoclimatic and archaeological implications. *SpringerBriefs in Earth System Sciences*, 1–27. https://doi.org/10.1007/978-3-642-36880-6_1

SCHWENNESEN, A. T. (1918). Ground water in the Animas, playas, Hachita, and San Luis Basins, New Mexico, with analyses of water and soil. *UNITED STATES GEOLOGICAL SURVEY*. <https://doi.org/10.3133/wsp422>

Effects of Light Pollution in National Parks & Monuments

I. What is light pollution?

Light pollution is an umbrella term describing the negative effects of artificial light produced by human activity. Most of the time, it refers to artificial skyglow produced by human civilizations. Approximately 83% of humanity and 99% of North Americans live in areas affected by light pollution. Without it, everyone on Earth could see the Milky Way at night, and the only sources of light would be the Moon, the stars, and faint zodiacal light. Today, only 2/3 of the human population can see the Milky Way at night, including only 20% of people in North America [4]. To see how pervasive this issue is, you can look at a map of global light pollution at www.lightpollutionmap.info.

Unlike other forms of pollution, whose effects would persist long after efforts to reduce them, light pollution is easily reversible—a few years ago, all we would have had to do is turn off our lights at night. Nowadays, it is becoming more difficult to combat, with the prevalence of extensive satellite constellations and proposals to project advertisements onto the night sky introducing more permanent sources of artificial light. Light pollution has slowly been creeping into designated protected dark sky areas, despite studies illustrating its adverse effects on the environment and human health. Naturally, higher levels of light pollution are associated with higher population densities and higher levels of economic activity; without proper mitigation, we can expect light pollution levels to increase as the world continues to industrialize and increase in population.

II. Effects on the environment & human health

In the past two decades, light-emitting diodes (LEDs) have become a popular form of artificial lighting. In 2011, they only took about a 9% share of the light

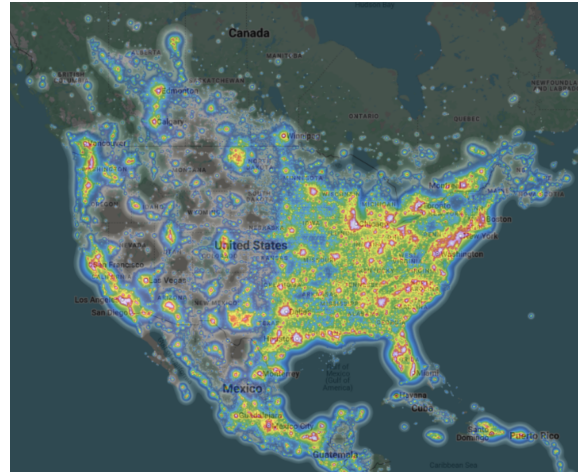


Figure 1: Screenshot from www.lightpollutionmap.info showing light pollution levels across the US. White and red correspond to areas with the highest levels of light pollution, while blue and transparent correspond to the lowest.



Figure 2: A mountain lion photographed by a motion sensor camera in the Verdugo Mountains in 2016, with Los Angeles city lights in the background (from Dark Sky International & the National Park Service)

market, and by 2014, that share had already grown to 45% [3]. They've been advertised as more efficient and brighter than their alternatives, and have even been said to mitigate climate change due to this increased efficiency. However, studies have shown that LED lighting produces 2.5 times as much light pollution as more traditional high-pressure sodium (HPS) lighting [4]. LED lights emit at a broad range of wavelengths, peaking at a significantly lower (and bluer) wavelength than HPS, low-pressure sodium (LPS), and metal halide (MH) lights. This wavelength breadth increases the likelihood of disrupting the activities of both nocturnal and diurnal species; one concern is that an excess of artificial light will cause diurnal species to believe that the day continues past sunset, and begin competing with nocturnal species for resources. While HPS, LPS, and MH lights still produce high-intensity light, the fact that they emit only at a high wavelength and with a narrow range means they are likely to affect less species than LED lights [3].

Light pollution is known to affect a wide variety of species, including birds, bats, sea turtles, marsupials, rodents, fish, moths, spiders, ants, crustaceans, corals, and plants. The most prominent effects are on reproductive development and timing, habitat selection, circadian disruption, and plant phenology. Many of these effects have not been sufficiently studied and thus their population-wide impacts are unknown, largely due to the absence of sufficient light pollution measurements [3]. According to DarkSky International, an organization dedicated to limiting light pol-

lution, effects are most well-understood for sea turtles and birds. Newborn sea turtles use moonlight to guide them to the ocean; when an abundance of artificial light is on the shoreline, they instead wander away from the water, where they are found by predators or wander into roads. Nocturnal birds rely on moonlight and starlight to hunt, and will often collide with illuminated buildings and structures when they're unable to distinguish their artificial light from natural light. In addition, artificial light will cause birds to migrate at incorrect times, disrupting mating and reproduction timelines [1].

In 2007, the World Health Organization (WHO) established that circadian disruption is a carcinogen, and there have since been a plethora of studies showing that poor and/or little sleep can have tremendous negative impacts on human health (such as high blood pressure and stress hormones). LEDs in particular peak at blue wavelengths that are the most likely to suppress melatonin production, making it difficult for humans to sustain a stable circadian rhythm [3]. This issue is yet another environmental manifestation of socioeconomic inequality; those that can afford to live away from industrialized areas (i.e. power plants, factories, etc.) can escape the effects of light pollution, while those that are forced to live in those areas are more likely to suffer the adverse health effects associated with light pollution. This is not to mention the cultural effects of our growing separation from the night sky and natural environment due to the introduction of artificial lights; human culture has been highly influenced by our connection to the cosmos for as long as we've existed, and who knows what will come of this connection once only a small fraction of humans will be able to see the Milky Way.

III. Sustaining dark skies in National Parks/Monuments & beyond

National Parks and Monuments host some of a shrinking number of locations in which you can see the night sky uncontaminated by artificial light. According to the National Park Service (NPS), 60% of all species are nocturnal, and thus it is crucial to preserve habitats in which animal behaviors won't be disrupted by light pollution. National Parks and Monuments can act as dark sky sanctuaries for species sensitive to artificial light, and it is crucial that urban growth in nearby areas is prevented from polluting these habitats. To measure light pollution, the NPS uses a camera that mimics the sensitivity of the human eye. Despite most NPS areas being fairly remote, skyglow from distant towns and cities can still be seen with substantial intensity on the horizon in their measurements [2]. Thus, preserving dark skies in National Parks isn't the NPS's job—it's ours.

The NPS coordinates with a variety of organizations to support light pollution mitigation, one of them being the aforementioned DarkSky International [1]. This organization works to institute laws and regulations that preserve dark skies and es-

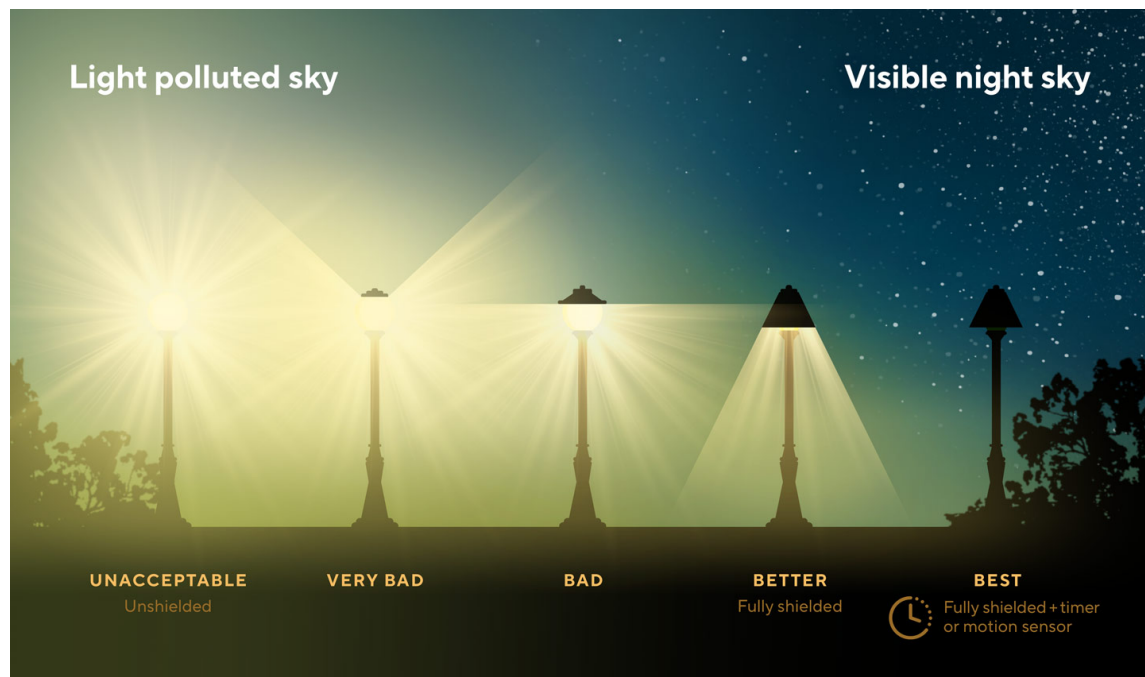


Figure 3: Illustration of how proper shielding of outdoor lighting can mitigate light pollution (from Dark Sky International).

establish proper outdoor lighting practices. They estimate that about 30% of lighting in the US is wasted, which corresponds to wasting over 20 million tons of carbon dioxide per year. Most of this waste is due to improper shielding practices, which allow a large fraction of light emitted from a fixture to be directed above the horizontal, thus contributing significantly to skyglow. Figure 3 shows how shielding can be implemented to eliminate light pollution in a fixture's vicinity.

Instituting proper shielding can decrease energy usage (and thus costs) while limiting light pollution, as less total flux is required to illuminate the same area on the ground. On an individual level, this is one of the best things you can do to decrease your light pollution footprint. In addition, installing warm (not blue-toned, cool) LEDs and motion sensors can drastically cut your energy bill while reducing light pollution; DarkSky estimates that proper outdoor lighting practices could cut energy costs by over 60% [1]. Chiricahua National Monument has been certified by DarkSky International as a Dark Sky Park, so while we're here, take a look at how beautiful the night sky is, and start thinking about how you can reduce your light pollution footprint when you get back home.

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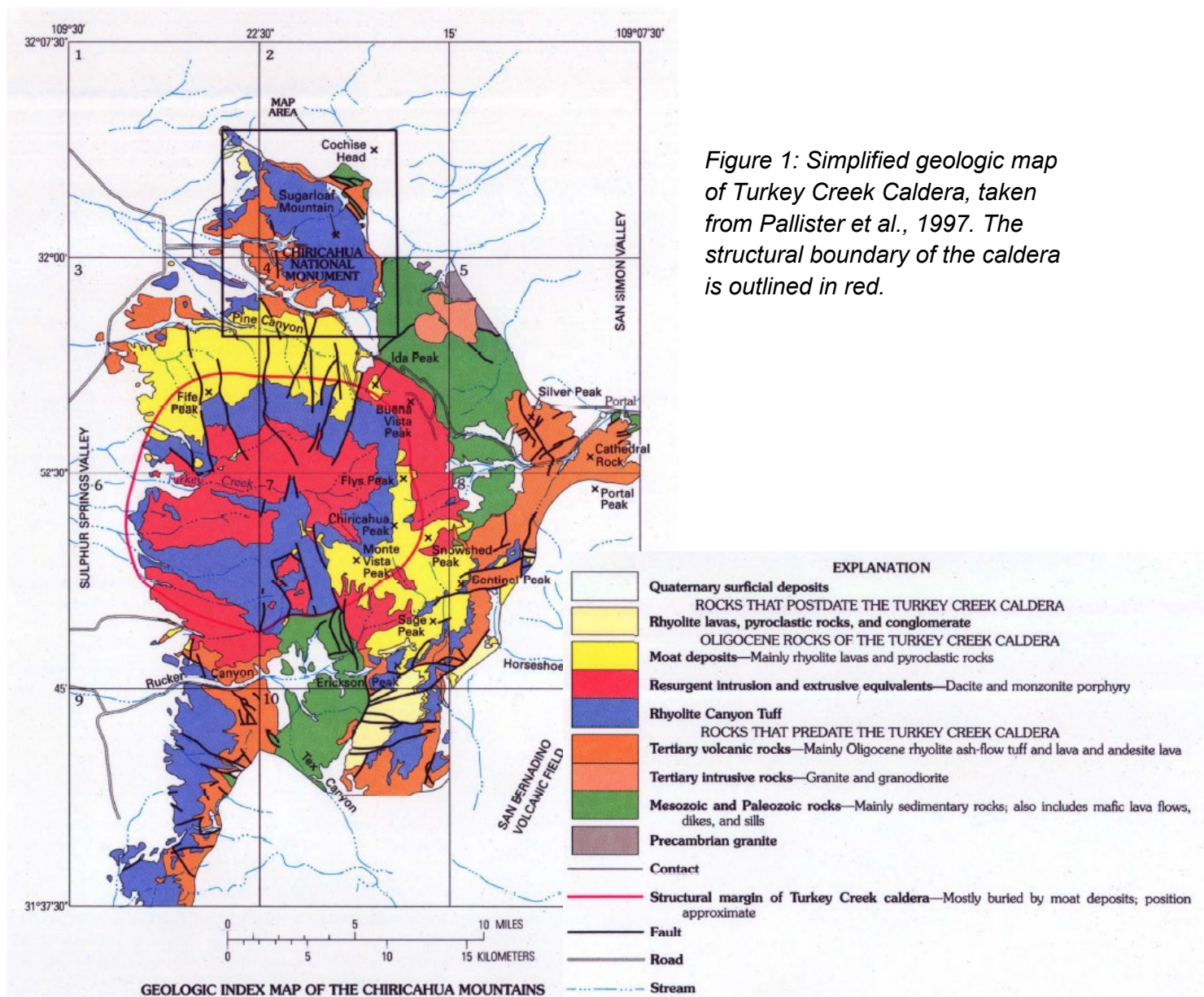
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Turkey Creek Caldera and the Geologic History of the Chiricahuas

Ruby Fulford | April 2026

Geologic Setting and Overview

The Turkey Creek caldera is a ~20 km, near-circular depression located to the south of the Chiricahua national monument. It formed ~27 million years ago when a subsurface magma chamber collapsed during a cataclysmic volcanic eruption. The caldera and associated lava flows can be observed from the top of Sugarloaf mountain.



Early Geologic History of the Region

Precambrian: A basement of crystalline Precambrian schist and granite (1.7-1.4 billion years old) underlies the Chiricahua National Monument and the Turkey Creek caldera (du Bray and Pallister, 1991; Pallister et al., 1997). These rocks are older than Arizona as we know it today! They formed from volcanic eruptions when the southwest was made up of volcanic islands separated by seas, which were eventually accreted onto the North American continent. **Most of Arizona was attached to the continent by 1.4 billion years ago** (Pallister et al., 1997).

Paleozoic and Mesozoic: Precambrian rocks are adjacent to Paleozoic sedimentary rocks, 510-570 million years old. The 800 Myr gap in the ages of these rocks is due to a nonconformity in the geologic record. **During the Paleozoic and the early Mesozoic, Arizona was covered by an ancient sea**, which deposited thick layers of limestone and sandstone visible in the Northeast corner of the national monument. A 150 million year nonconformity resulting from uplift and erosion separates Paleozoic sediments from younger Mesozoic sediments (Pallister et al., 1997). Paleozoic and Mesozoic sediments underlie younger volcanic deposits throughout the Chiricahuas.

Subduction-driven volcanism

During the Mesozoic, the Pacific plate was subducting beneath the north American plate, driving volcanism in the Southwest (Eaton, 1982; Pallister et al., 1997). Subducted oceanic crust brings volatiles (mostly water) into the overlying mantle, lowering the melting point and creating volatile-rich melt that either ascends directly to the surface or collects in near-surface magma chambers (Melosh, 2011). Magma in a shallow chamber can become unstable and erupt in a catastrophic caldera-forming eruption.

Mesozoic subduction under the west coast of North America caused huge caldera eruptions in southeast Arizona ~160 million years ago. Another burst of volcanic activity occurred ~65 million years ago during the **Laramide orogeny**, an intense episode of volcanic mountain building near the end of the Mesozoic (Pallister et al., 1997).

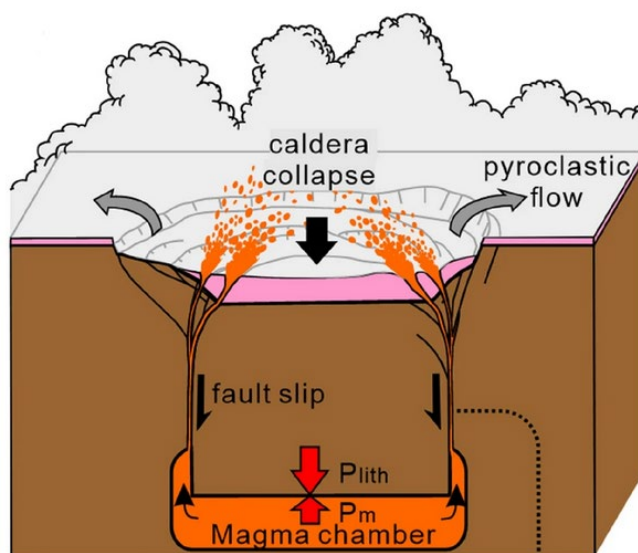


Figure 2: Schematic of magma chamber eruption and caldera formation

Subduction-driven volcanism in the southwestern US continued into the tertiary period. **The peak of volcanic activity in the Chiricahuas occurred 35-25 million years ago.** Scattered eruptions of lava flows occurred, including dark, silica-poor basalt flows and lighter, viscous, silica-rich rhyolite flows. By ~28 Ma, the northern Chiricahua mountain range consisted of uplifted Mesozoic and Paleozoic sedimentary rocks, surrounded by ash and lava from nearby active volcanic fields (du Bray and Pallister, 1991; Pallister et al., 1997).

Formation of the Turkey Creek Caldera

Around 26.9 Ma, a magma chamber, rich in volatiles provided by the subducting Pacific plate, began to accumulate just south of the National Monument (Pallister et al., 1997). The magma collected in this chamber consisted of an upper rhyolite layer (~77% silica) separated from a lower dacite layer (~63-70% silica) by a sharp interface (du Bray and Pallister, 1991). A cataclysmic volcanic eruption led to the collapse of the magma chamber, forming the 20 km Turkey Creek Caldera. The eruption can be broken down into three phases (du Bray and Pallister, 1999; 1991).

Stage 1: Volatile bubble formation in the Rhyolite magma triggered a massive, violent eruption of pumice and ash. Over 500 km³ magma erupted, **~1000x the volume that erupted from Mt St. Helens in 1980.** Explosion of gas bubbles propelled fast-moving clouds of ash and pyroclastic flows, which filled valleys to a depth of at least 485 meters and solidified to form the **Rhyolite Canyon Tuff**, the principal rock of the Turkey Creek area (Pallister et al., 1997). Tuff is a type of volcanic material mainly composed of ash and pumice. The Rhyolite Canyon Tuff is densely welded, meaning it fused under its own weight. Layers in the Rhyolite Canyon Tuff indicate that it was formed by three separate

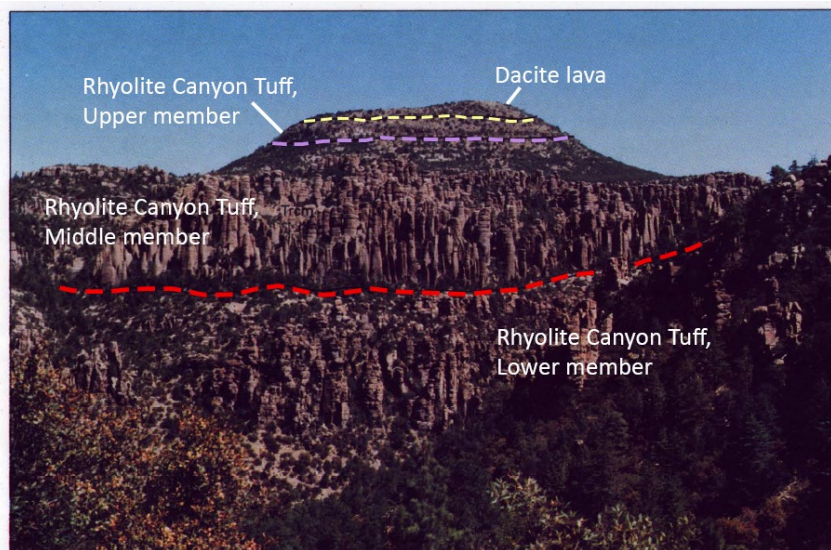


Figure 3: A view from inside Rhyolite canyon, looking up at the canyon wall and Sugarloaf Mountain. The three layers of the Rhyolite canyon tuff, along with the dacite atop Sugarloaf mountain, are visible and labeled. Rhyolite has been eroded into columns. Image modified from Pallister et al., 1997

pyroclastic flows. White, ash-rich surge beds separate these layers, and are **well exposed along the trail to the summit of Sugarloaf Mountain**. Along this trail one can also see fossil fumaroles, where steam blasted to the surface forming irregular vertical pipes (Pallister et al., 1997).

Stage 2: The **dacite magma erupted shortly after the rhyolite, much less violently due to lower volatile content**. Some dacite intruded into the previously erupted rhyolite tuff in the caldera to form dacite laccoliths (du Bray and Pallister, 1991). Some of the magma erupted onto the surface as lava flows, including flows confined to the caldera moat (du Bray and Pallister, 1991) and the Sugarloaf lava flow that escaped the caldera (Pallister et al., 1997). The Dacite lava at the top of Sugarloaf mountain is the youngest volcanic rock in the national monument. The dacite at the top of Sugarloaf Mountain was once at the bottom of a valley, but because dacite is more erosion-resistant than rhyolite, the dacite is now left intact after surrounding Rhyolite was eroded away (Pallister et al., 1997).

Stage 3: A resurgent dome began to form in the caldera after the first eruption, filled first with dacite and then rhyolite magma. **About 135 km³ of this silica-rich rhyolite magma erupted to the surface** (du Bray and Pallister, 1991). This magma was less volatile-rich than the previously erupted rhyolite magma, so it erupted less violently as lava flows confined to the within the caldera (Du Bray and Pallister, 1999).

Basin and Range Tectonics

The Chiricahua mountains are part of the **Basin and Range province**, a region of the western US characterized by broad, low valleys between long parallel mountain ranges (Eaton, 1982; Scarborough, 2021). After subduction under the west coast ceased, volcanism in the southwest declined, leading to crustal extension beginning about 20 million years ago. Extension continues today at a rate of ~5 mm per year (Link and Pearson, 2019).

As the crust of the basin and range province pulls apart, the underlying tectonic plate stretches, and the crust becomes weaker and thinner. The extensional strain is accommodated by parallel, steeply-dipping normal faults (Link and Pearson, 2019). Normal fault footwalls rise to form



Figure 4: The Basin and Range Province

mountains, while the hanging walls drop to form valleys (Eaton, 1982; Link and Pearson, 2019). This type of high-angle normal faulting created the topography of the Chiricahua range flanked by the San Simon and Sulphur Springs Valleys. The most recent tectonic activity is thought to be the formation of Whitetail valley, indicated by the steeply tilted layers of the Rhyolite canyon tuff plunging into the valley (Pallister et al., 1997).

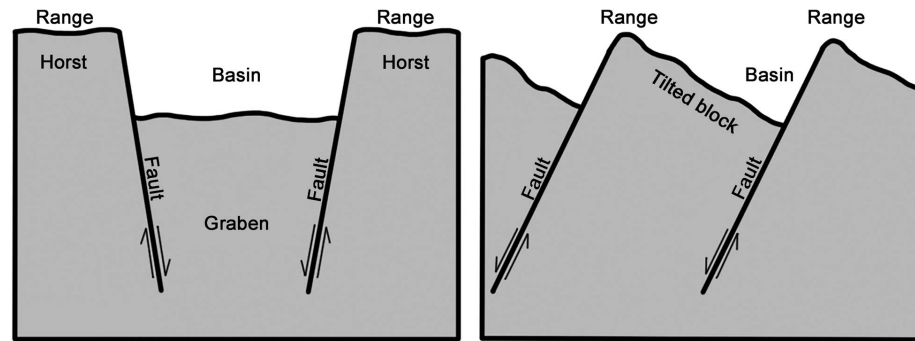


Figure 5: Types of basin and range faulting. Left: Horst and Graben blocks. Right: Tilted blocks.

Columnar jointing and column erosion

As lava cools and contracts, joints form perpendicular to the cooling surface in a process called **columnar jointing**. Columnar jointing occurred as the Rhyolite canyon Tuff cooled. Erosion and weathering occurred along these weakened joints, forming the separated columns we see today (See Fig. 3). Based on calculations of erosion rate in this area, the eroded hoodoos are estimated to be less than three million years old, though the tuff itself and the joints are 26.9 million years old (Pallister et al., 1997).

Calderas on Mars

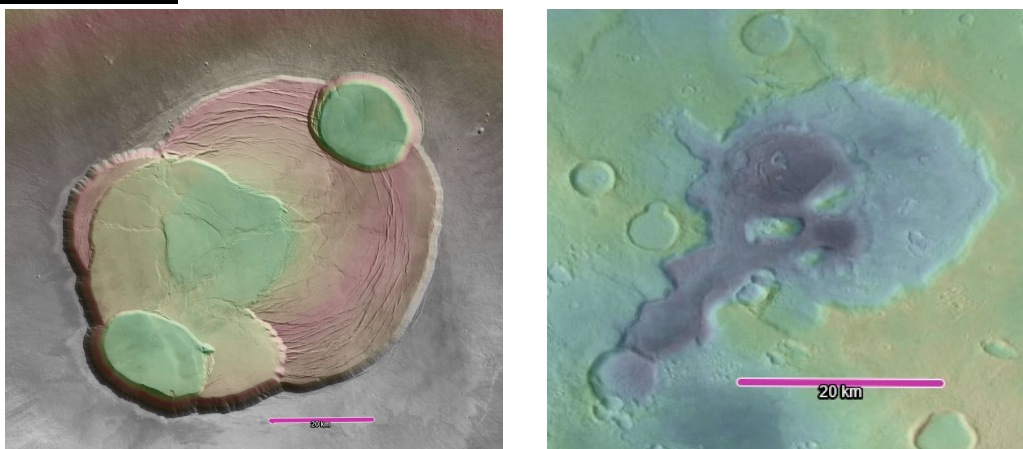


Figure 6: Calderas on Mars. Left: The caldera on top of Olympus Mons. Right: A feature in Arabia Terra interpreted to be a Caldera. Both images are MOLA elevation data overlaid with CTX imagery. Scale bars are 20 km.

There is extensive evidence of Caldera formation on Mars. Many Martian shield volcanoes have calderas at their summits, which likely formed due to collapse of depleted magma chambers. There is also evidence of violent caldera formation on Mars, akin to the eruption at Turkey Creek. The Arabia Terra region is home to several large craters interpreted to be calderas (Michalski and Bleacher, 2013), adjacent to layered deposits with compositions resembling pyroclastic flow deposits (Whelley et al., 2021). The total volume of material erupted from these calderas is estimated at $3.5 - 7.0 \times 10^6 \text{ km}^3$.

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Porphyry Copper Deposits and the Clifton-Morenci Mine, Arizona

Carson Fuls, PTYS 590 Planetary Geology Field Studies

April 2026

1. Introduction

Porphyry copper deposits are the world's most important source of copper, providing roughly three-quarters of global supply along with significant amounts of molybdenum and gold (Sillitoe, 2010). Porphyry itself refers to an igneous rock with coarse-grained crystals in a fine-grained silicate-rich matrix. They form where oceanic plates dive beneath continental plates, creating chains of volcanoes and associated underground magma bodies that release metal-rich fluids into the surrounding rock. This paper reviews how these deposits form, how our understanding of them has developed over the past century, and then turns to a detailed look at the Clifton-Morenci mine in southeastern Arizona, the largest copper producer in North America. The mine's geology, as well as its economic and environmental impacts, will be discussed.

2. How Porphyry Copper Deposits Form

2.1 Setting and Process

Porphyry copper deposits are found along the edges of continents where one tectonic plate is being pushed beneath another in a process called subduction. The sinking plate releases water into the overlying mantle, which lowers the melting point of the rock and generates large bodies of magma. These magma bodies rise toward the surface and collect in chambers several kilometers deep (Cloos, 2001; Richards, 2005; Sillitoe, 2010).

As these magma chambers cool and crystallize, they release hot, metal-rich fluids. These fluids rise through cracks and fractures, reacting with the surrounding rock and depositing copper, molybdenum, gold, and other metals along the way.

2.2 Alteration Zones

One of the most useful features of porphyry deposits is that the hot fluids chemically change the surrounding rock in a predictable pattern of concentric zones. This pattern was first described in detail by Lowell and Guilbert (1970), who studied the San Manuel-Kalamazoo deposit in Arizona, a deposit that had been tilted on its side by later faulting, allowing geologists to see both the horizontal and vertical structure.

Working outward from the center, Lowell and Guilbert identified four zones. The innermost *potassic* zone, nearest the heat source, is marked by newly formed potassium feldspar and biotite. The next zone outward, which they called *phyllic*, is dominated by the white mica sericite

along with quartz and pyrite. Beyond that, the *argillic* zone is characterized by clay minerals like kaolin. The outermost *propylitic* zone shows milder changes: chlorite, epidote, and calcite partially replacing the original rock minerals. In many porphyry systems, economically important copper mineralization is concentrated mainly where the potassic and phyllic zones overlap. Illustrations of this structure are shown in Figure 1. By comparing 27 major deposits, Lowell and Guilbert showed this pattern is consistent enough to estimate how deeply eroded a given deposit is.

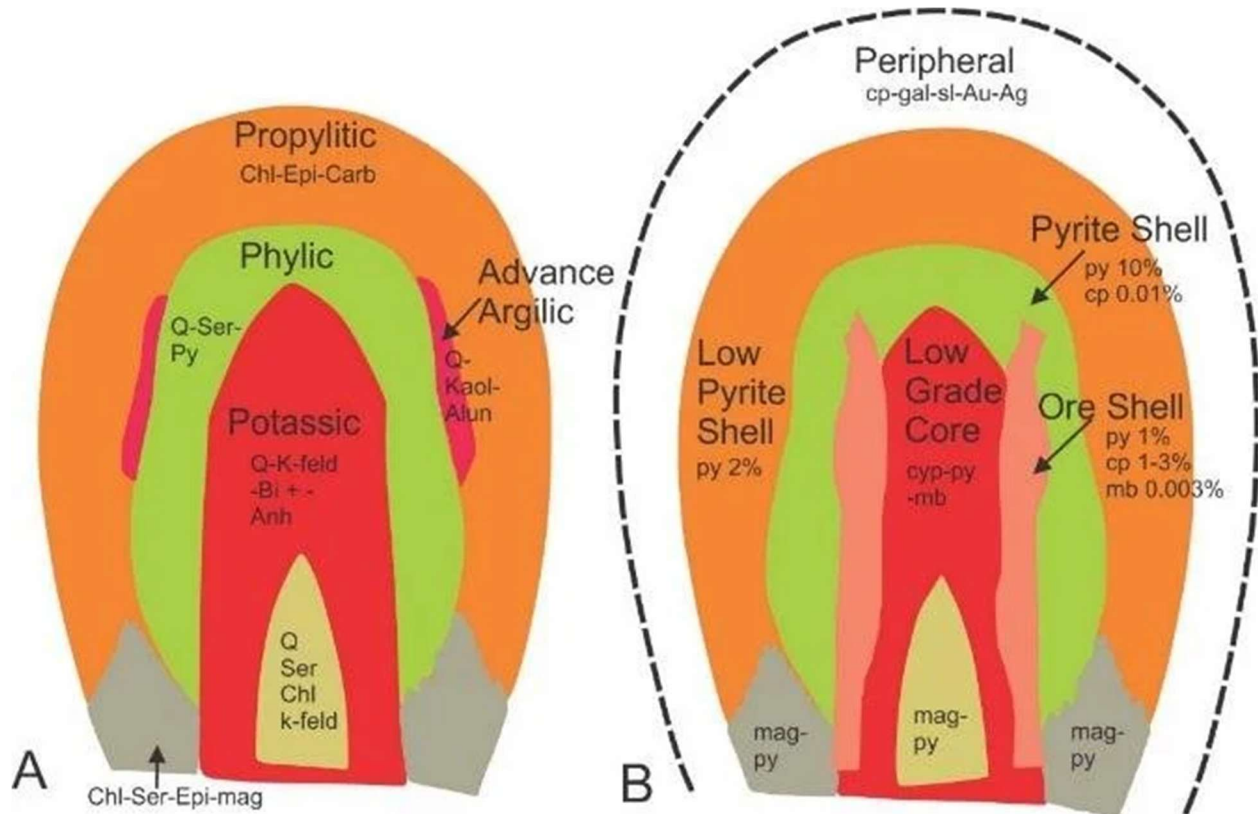


Figure 1. Porphyry copper alteration and mineralization model. Adapted from Murad et al. (2021), based on Lowell and Guilbert (1970). The representative model indicates the hydrothermal alteration minerals and their types (A). The model represents the ore mineralization associated with each type of alteration (B).

Sillitoe (2010) later expanded this framework to include the full range of deposit types that can form within a single porphyry system: not just the central copper deposit, but also surrounding skarn deposits in limestone, replacement bodies in carbonate rocks, and shallower gold-silver deposits formed at lower temperatures. He showed that as the system cools over time, the shallower, lower-temperature mineral assemblages overprint the deeper, earlier ones in a process called telescoping. The sulfide minerals also change systematically: copper-iron sulfides like chalcopyrite and bornite dominate the hot inner zones, while iron sulfides with arsenic-bearing copper minerals appear in the cooler, shallower parts of the system.

3. The Clifton-Morenci Mine

3.1 Geology

The Morenci deposit sits in the transition zone between Arizona's Basin and Range province and the Colorado Plateau. The copper mineralization is hosted in a roughly 65-million-year-old intrusive body (part of the Laramide magmatic event that produced many of the Southwest's copper deposits) that was emplaced into much older Precambrian granite and overlying Paleozoic and Mesozoic sedimentary rocks (Lindgren, 1905; Mining Technology, n.d.). The deposit contains three types of copper mineralization: oxide minerals like chrysocolla near the surface, secondary sulfides (mainly chalcocite) at intermediate depth, and primary sulfides (chalcopyrite and molybdenite) deeper down.

Lowell and Guilbert (1970), drawing on earlier work by Moolick and Durek (1966), noted that Morenci's surface exposes mainly the phyllic (sericite-pyrite) zone, without the deeper potassic zone visible at the surface. This placed Morenci relatively high in their model and suggested that the potassic core should be found at depth beneath the pit. The mineralized area extends about 8 km north-south and 6.4 km east-west, and remaining reserves are estimated at roughly 3.9 billion tons at about 0.27% copper (Burron, 2021; Mining Technology, n.d.).

3.2 Discovery and Development

Prospectors Robert and James Metcalfe and Joe Yankie discovered copper outcrops here in 1871 while traveling from Silver City, New Mexico (Cogut and Conger, 1999). The Longfellow Copper Company was incorporated in 1874, and early operations relied on mules to haul ore. The Arizona Copper Company took over in 1883 and built a narrow-gauge railroad connecting the mines to the Southern Pacific line at Lordsburg, completed in 1884, which made it economically viable to ship ore out of this remote area (Ascarza, 2020).

Phelps Dodge began operations in the 1880s and converted to open-pit mining in 1937. Freeport-McMoRan acquired Phelps Dodge in 2007 for \$25.9 billion and has since invested heavily in expansion, including a 2015 mill upgrade that more than doubled processing capacity to about 115,000 metric tons of ore per day. Today the mine employs over 3,000 people, and recent annual production has been on the order of hundreds of millions of pounds of copper, approaching roughly 0.9 billion pounds in some recent years. The mine area itself covers roughly 62,000 acres over three pits with a projected final depth of 4,500 ft. Operations are expected to continue until approximately 2041 (Burron, 2021; Mining Technology, n.d.). A view of the open pits is shown in Figure 2.



Figure 2. Morenci Open Pit Copper Mine, eastern Arizona. Photograph by Mike Conway, circa 2017, via Arizona Geological Survey.

4. Economic and Environmental Impact

Morenci is the largest copper producer in North America. Its remaining proven and probable reserves contain an estimated 15.7 billion pounds of recoverable copper (Mining Technology, n.d.). With copper demand rising due to electric vehicles and renewable energy systems, continued investment in mine and processing infrastructure could extend the mine's productive life beyond current projections.

A century and a half of mining has also left a significant environmental footprint. The site includes massive open pits, waste-rock piles, tailings ponds, and five historic smelters. In 2012, Freeport-McMoRan paid \$6.8 million to settle federal and state claims that acidic runoff from mine waste, windblown tailings dust, and old smelter emissions had contaminated the San Francisco and Gila River watersheds, harming water quality, soils, wildlife habitat, and migratory birds (U.S. Department of Justice, 2012).

5. Labor and Cultural History

Morenci's labor history is deeply tied to the experience of Mexican and Mexican-American workers in the Southwest. From the 1870s onward, Mexican workers did much of the most difficult and dangerous mining work while being paid far less than their Anglo counterparts and excluded from white-run labor unions.

In June 1903, when a new Arizona law shortened the workday from ten to eight hours but effectively cut pay by 10%, Mexican workers walked out in one of the first major strikes organized by Mexican immigrants in the United States. The strike ended tragically when a flash flood swept through the mining camps, killing between 40 and 50 people (Park, 1977). A larger strike in 1915, involving about 5,000 workers, succeeded in winning wage increases and showed that workers could organize across ethnic lines (Clifton Arizona Labor History, n.d.).

The most far-reaching labor dispute came in 1983–1986. When copper prices collapsed, Phelps Dodge broke with the industry practice of uniform contract bargaining and demanded concessions. Workers struck, and the company hired permanent replacements. Arizona’s governor deployed over 750 law enforcement officers, including National Guard troops with armored vehicles, in one of the largest such actions in the state’s history (O’Leary, 2018). Then, in September 1983, catastrophic flooding of the San Francisco River destroyed 300 homes and 86 of Clifton’s 126 businesses. With both jobs and homes gone, the community was devastated. Workers voted to decertify the unions in 1984, and the strike ended in February 1986. The Morenci strike is widely considered a turning point in American labor history, establishing the precedent of using permanent replacement workers to break strikes, a tactic that spread to other industries in the years that followed (O’Leary, 2018).

6. Conclusion

The alteration zoning models developed by Lowell and Guilbert (1970) and expanded by Sillitoe (2010) explain not only how Morenci’s copper got there, but also how geologists find and evaluate similar deposits worldwide. At the same time, the mine’s 150-year history of labor struggles, environmental challenges, and economic booms and busts offers a window into the broader social costs and benefits of large-scale resource extraction. As copper demand grows in the transition to clean energy, Morenci’s remaining reserves will ensure it will remain relevant to both geoscience and society for decades to come.

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Granitic Intrusions of Southern Arizona

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1. INTRODUCTION

The geology of Southern Arizona reflects a combination of several factors. This area is part of the Basin and Range Province, meaning that tectonic extension has produced alternating high- and low-elevation areas including the Tucson Basin that the city of Tucson developed in. Many of the mountains in this area reflect that same basin and range topography, yielding north-south-oriented mountain ranges across much of Southern Arizona (see stripes in Fig. 1a).

Across the state of Arizona, landscapes were shaped by volcanism, erosion, sedimentation, and metamorphism. In some areas, including southern and southeastern Arizona, intrusive activity also introduced further complexity to the geologic timeline. Here I will summarize some major intrusions relevant to the surroundings of Tucson and the Chiricahua Mountains.

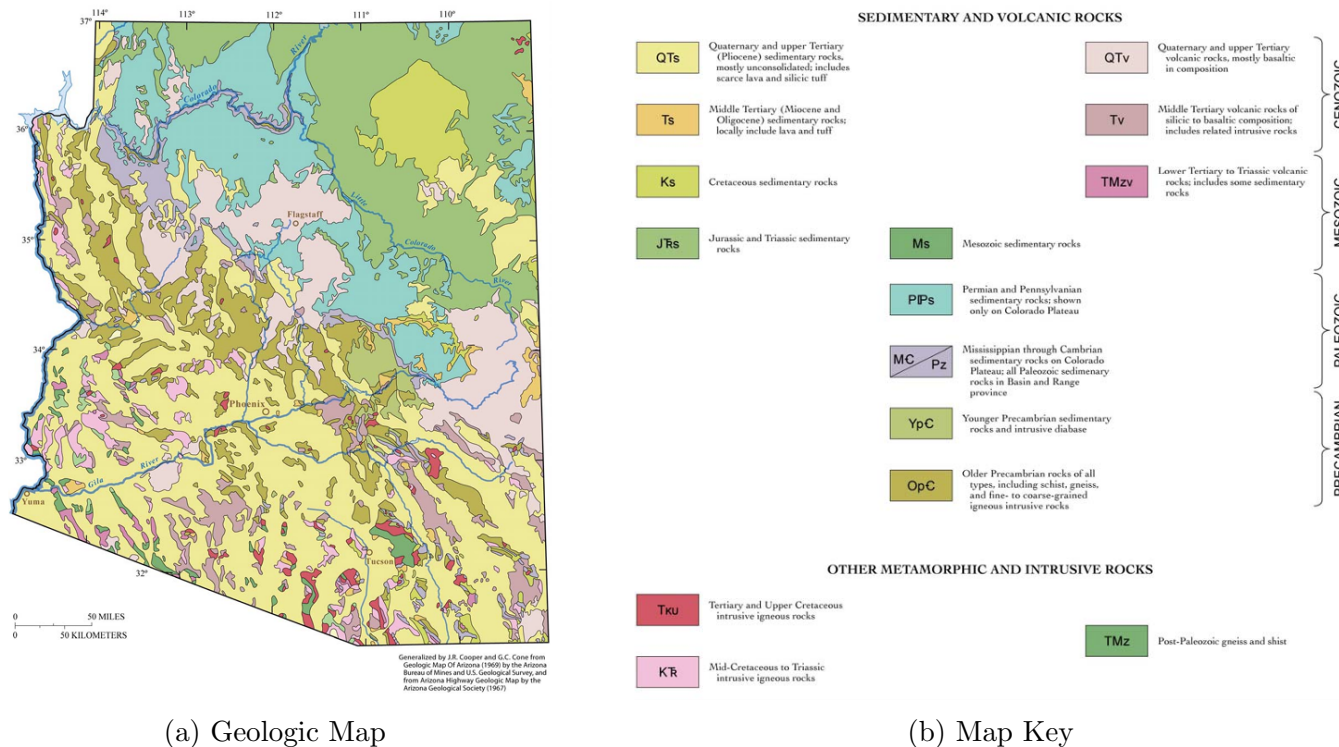
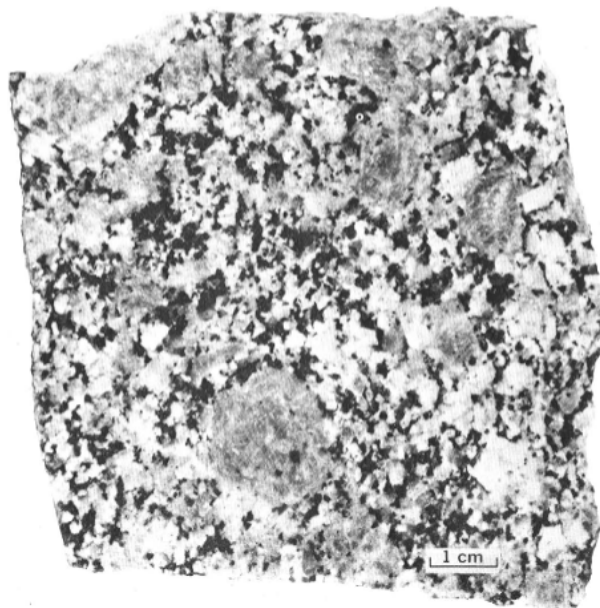


Figure 1. Geologic map of Arizona (J. C. Rasmussen 2012). Intrusive rocks are marked in red (Tertiary to late Cretaceous) and pink (Mid-Cretaceous to Triassic).



(a) Image of an exposure of Oracle Granite on Mt. Lemmon. Photo by M. Conway.



(b) Sample of Continental Granodiorite from the Santa Rita Mountains (H. D. Drewes 1976).

Figure 2. Proterozoic granites.

2. PRECAMBRIAN ERA TO PROTEROZOIC EON (1800–542 MA)

During the Precambrian Era, preexisting rocks across Arizona experienced metamorphism, creating several schist formations. In southern Arizona, the most common metamorphic rock by the time of the Proterozoic Era was the Pinal Schist. The protolith varied in different places; however, in the Santa Rita Mountains (southeast of Tucson), this formation was metamorphosed from an earlier granitic pluton (H. D. Drewes 1976). From approximately 1450 to 1400 Ma, granite and pegmatite intrusions formed in the Pinal Schist and similar formations, creating faults and fractured that later allowed for veins of rare and exotic elements and minerals (J. C. Rasmussen 2012). One example is the Oracle Granite, which can be observed around Tucson and the Santa Catalina Mountains (Fig. 2a). Granitic gneisses and schists can also be found across southern Arizona, with later granitic rocks intruded into them with ages in excess of 1700 Ma (e.g., Fig. 2b; H. D. Drewes 1976).

3. TRIASSIC AND JURASSIC PERIODS (252–143 MA)

Igneous activity in southern Arizona this period was predominantly extrusive, but with some intrusions in the late Triassic and early-to-middle Jurassic periods. This activity ended a long period of regional quiescence in magmatic activity, but trailed off again in the late Jurassic (H. D. Drewes 1976).

4. CRETACEOUS PERIOD AND LATER (<143 MA)

By the time of the Cretaceous Period (143–66 Ma), volcanism had generally ceased in Arizona (moving into California instead), and the surface geology of southern Arizona was dominated by sediment deposition in waterways and a shallow sea (J. C. Rasmussen 2012). At this time, large igneous bodies continued to intrude below the surface. Large granite and granodiorite intrusions (approaching batholith-sized) occurred contemporaneously with a period of elevated tectonic activity

at about 90–63 Ma, including in the Santa Rita Mountains and particularly at Madera Canyon (H. D. Drewes 1976).

In the early Tertiary Period (66–55 Ma), granitic intrusions formed throughout southern Arizona, bringing with them the deposits of porphyry copper that earned Arizona the title of the Copper State (S. B. Keith & J. C. Wilt 1985; J. C. Rasmussen 2012).



Figure 3. Image of the Wilderness Granite in the west face of the Santa Catalina Mountains, formed by 43 Ma (J. C. Rasmussen 2012).

By 54–43 Ma, granitic plutons were intruded into the surrounding rocks at great depth, up to ~23 km below the surface as a result of a deep subducting plate. As this subduction continued, rocks further north were pushed upwards and eroded. Ultimately, some of these deeply emplaced granitic deposits were exposed to the surface through later processes. One such example is the Wilderness Granite, which can be observed today on the western face of the Santa Catalina Mountains in Tucson (Fig. 3; J. C. Rasmussen 2012).

During the intrusion of the Wilderness Granite, the surface was uplifted and faulted, allowing large sections of rocks to become

mobile. One such block slid west over millions of years and formed the present-day Tucson Mountains (United States National Park Service 2025). Intrusive (and extrusive) activity in southern Arizona generally settled down by the end of the Tertiary Period. Since then, uplift and erosion have exposed and reshaped these plutonic rocks into the landscape we observe today.

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Paleozoic Fossils of the Chiricahuas

Kylie Hall

April 2026

1 Background: Paleozoic History

The Paleozoic Era occurred from 541 to 252 million years ago. The first animal species on Earth appeared only a few hundred million years before the start of the Paleozoic, but by the time the Paleozoic began many invertebrates and the earliest fish and amphibians had evolved. The Paleozoic was composed of the following periods, from earliest to most recent: Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian [8].

1.1 Permian History

All of the Paleozoic fossils in Chiricahua National Monument are from the Permian period [14], so we will focus mostly on this period. The Permian period occurred from 299 to 252 million years ago. The supercontinent Pangaea persisted throughout this entire time period, causing large climactic variation due to the concentration of all landmass in one continent. The shallow seas and swamps that were common in previous periods were beginning to disappear by this point, so the creatures living in them were also beginning to disappear [8]. However, the area that would become southern Arizona was still covered by a shallow sea that led up to an arid desert [12]. Figure 1 shows the location of the modern-day Chiricahuas in Pangaea.



Figure 1: The supercontinent Pangaea, which existed during the Permian period. The location that would become the site of the Chiricahua National Monument is marked with a red star. Figure adapted from [11].

The Permian period ended with one of the largest mass extinction events in Earth's history; approximately 96% of all species in existence at the time went extinct [13]. This was likely caused by a series of massive volcanic eruptions that released methane into the atmosphere and caused a rapid temperature increase; a large comet impact event may also have contributed [8, 10].

Era	Period	Formation/Unit	General Lithology
CENOZOIC	Quaternary	Alluvium, colluvium	Various subdivisions of sand, silt, and gravel
	Tertiary	Conglomerate	Poorly sorted fine- and coarse-grained sediments
		Rocks of the Turkey Creek Caldera	Moat deposits: mostly rhyolite lava flows Dacite of Sugarloaf Mountain: dacite lava flow Rhyolite Canyon Tuff: welded-ash-flow deposit
		Jesse James Canyon Tuff	Welded ash-flow deposit
		Faraway Ranch Formation	Assemblage of rhyolite, dacite, and andesite lavas & pyroclastic rocks
		Sedimentary rocks of Bonita Park	Red-weathering clay-rich sandstone, siltstone, and claystone
		Welded tuff of Joe Glen Ranch	Welded rhyolite ash-flow deposit
		Volcanic flows and dikes	Andesite and dacite lava flows; rhyolite dikes
		Regional Unconformity	
MESOZOIC	Cretaceous	Bisbee Group Mural Limestone	Tan, thin-bedded silty limestone
		Bisbee Group Morita Formation	Siltstone, sandstone, shale, conglomerate
		Glance Conglomerate	Cobble, pebble, & boulder conglomerate
		Volcaniclastic and volcanic rocks	Metamorphosed greywacke, andesite, and basalt
		Regional Unconformity	
PALEOZOIC	Permian	Concha Limestone	Dark-gray, cherty, fossiliferous limestone
		Scherrer Formation	Light-gray fine-grained sandstone and quartzite
		Epitaph Dolomite and Colina Formation	Dark-gray, coarse-grained slightly cherty limestone and light-gray, fine-grained dolomite
		Earp Formation	Pale-red siltstone and argillaceous limestone
		Horquilla Limestone	Upper member: limestone and siltstone

Figure 2: The stratigraphic column of Chiricahua National Monument. Paleozoic fossils are found in the strata from the Permian period. Figure from [14].

2 Fossils in the Chiricahua

2.1 Where Are They Found?

The only Paleozoic rocks exposed in Chiricahua National Monument are limestone and dolomite strata on the flank of Timber Mountain from the Permian period, which are an order of magnitude older than the surrounding hoodoos [14, 6]. These strata indicate that the area was covered in a shallow sea with reefs during the Permian period [14]. Fossils are found in the Concha Limestone, Colina Limestone, Epitaph Dolomite, Earp Formation, and Horquilla Limestone strata [7]. See Figure 2 for a depiction of the stratigraphy of the Chiricahuas.

2.2 What Are They?

The limestone strata contain a wide variety of fossils. Families represented include brachiopods, gastropods, echinoids, pelecypods, fusulinid foraminifera, sponges, corals, bryozoans, brachiopods, scaphopods, ammonoid cephalopods, and crinoids. In this section, we'll focus on a few of these families.

2.2.1 Brachiopods

Brachiopods are one of the most frequently found marine invertebrate fossils in Paleozoic rocks in national parks. They are organisms that appear similar to bivalves, a class of organisms with two mirror-image shells (e.g. clams, mussels, oysters). However, unlike bivalves, brachiopods' shells are not mirror images of each other. See Figure 3 for examples of brachiopod fossils. Internally, bra-

chiopods have a feeding and breathing organ that grows as two arms. Their shells are made of calcium phosphate (the same materials that human bones are made of) or calcium carbonate. Brachiopods still exist today, but unlike in the Permian period, they now mostly inhabit deep, cold marine waters [3].

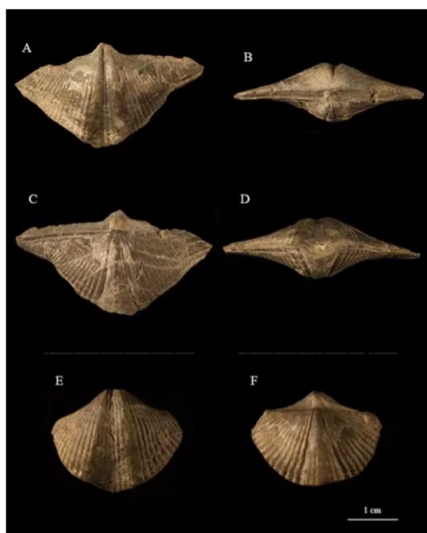


Figure 3: Examples of brachiopod fossils. Figure from [3].

2.2.2 Echinoids

Echinoids are a class of organism that includes sea urchins. They have lived in the seas since about 450 million years ago and still exist today. Many fossil echinoids are similar to modern sea urchins. Echinoids have a hard shell covered in small knobs that connect to spines. Spines were/are occasionally poison-tipped to protect echinoids from predators. The spines and shells are made of calcite, and they are normally what are found as fossils. Geologists use the presence of echinoid fossils as an indication that the rocks that contain them were formed in a marine environment. They are also typically used to date rocks, but Paleozoic echinoids are less frequently used for this purpose because they

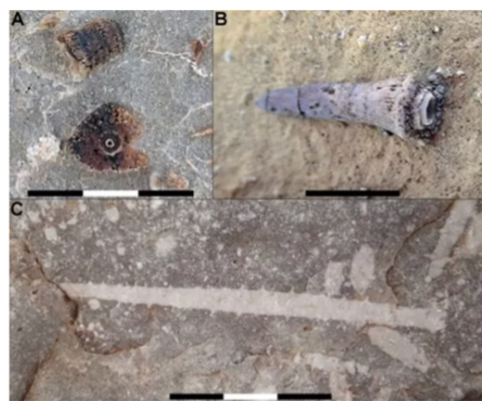


Figure 4: Examples of echinoid fossils; panels b and c show fossilized echinoid spines. Figure from [1].

tend to be rarer and more fragile [2]. See Figure 4 for an image of echinoid fossil examples.

2.2.3 Gastropods

Gastropods are a group of mollusk organisms that have a muscular foot, eyes, tentacles, and a rasp-like feeding organ with many tiny teeth. Many also have a coiled or cone-like shell. They evolved in the early Cambrian period (the first period in the Paleozoic era), and still exist today. They currently inhabit all types of aquatic environments, including deep trench environments and small freshwater ponds. Some even live on land [4]. During the Permian period, gastropods mostly lived in shallow water environments like those that covered the land that is now Chiricahua National Monument [15]. They were not as badly affected by the extinction event that occurred at the end of the Permian period [4]. See Figure 5 for an example of gastropod fossils.

2.3 Fossil Protection

Legislation exists to protect and preserve fossils found on national lands like Chiricahua National Monument. In particular, the Paleontological Resources Preservation Act

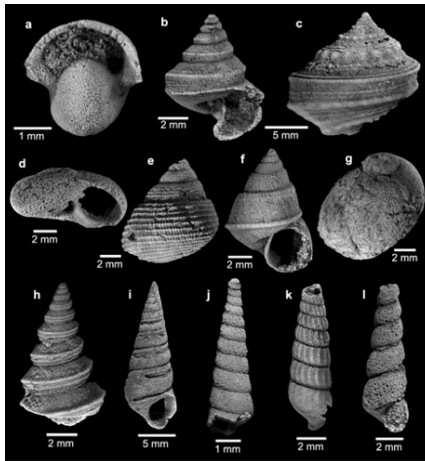


Figure 5: Examples of gastropod fossils from the Permian period.

(PRPA) of 2009 was passed to regulate the management, collection, and curation of paleontological resources like fossils from these lands [9]. The PRPA requires the treatment of these materials to follow scientific principles and expertise, and it prohibits the removal or destruction of any fossils from federal lands without first obtaining a research permit [9, 5].

The PRPA also directed federal land management agencies to establish public outreach programs to increase awareness of the importance of paleontological resources like fossils. In order to comply with this legislation, the National Parks Service established National Fossil Day [5]. This year, National Fossil Day will occur on October 14, 2026.

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Big Cats of Southern Arizona

1 Introduction

Southern Arizona, particularly the sky island mountain ranges of the southeastern corner of the state, is one of the most ecologically significant landscapes in North America for large wild cats. The pine-forests of these tall mountains combined with the Sonoran grasslands provides a unique ecology. This combination of habitats supports primarily two resident big cat species: the mountain lion (*Puma concolor*) and, in much smaller numbers, the jaguar (*Panthera onca*). This makes southern Arizona a critical area for big cat conservation in the United States.

2 Jaguars

Historic records place jaguars as far north as the Grand Canyon, the White Mountains, and the Mogollon Rim during the first half of the twentieth century (Brown & González, 2000). By the late twentieth century, hunting and habitat loss had eliminated the species from nearly half its historic range, with particularly severe losses in the southwestern United States and northern Mexico (Hatten et al., 2005).

Jaguar records are concentrated in the forested mountain habitats of southeastern Arizona, particularly around the sky island ranges near Tucson: the Santa Ritas, Baboquivaris, Rincons, and Chiricahuas, among others. Hatten et al. (2005) conducted a GIS-based habitat suitability analysis using 25 verified sighting records, finding that all sightings fell within 10 km of a water source, 92% occurred in rugged terrain, and most were concentrated between 1,220 and 1,829 meters elevation. Their models identified 21–30% of Arizona as potential habitat (Figure 2).

An important question in the literature is whether these records reflect a resident population or dispersing animals from Mexico. Brown and González (2000) note that records before 1925 include females and cubs (more consistent with residency) while later records are overwhelmingly male (71%), suggesting more recent occurrences are dispersing males from breeding populations south of the border. The 1996 photographic records from the Peloncillo and Baboquivari Mountains reinvigorated this debate and prompted the jaguar's formal listing as endangered under the U.S. Endangered Species Act (Hatten et al., 2005; Sanderson et al., 2022).

Regardless of historical status, recent habitat modeling suggests the region could support a viable population. Sanderson et al. (2022) synthesized twelve habitat models spanning 25 years of research and found consistent support for suitable jaguar habitat extending well north of I-10 with an area of 82,442 km². They estimated this habitat to have a carrying capacity of 90–151 adult jaguars, far exceeding the U.S. Fish and Wildlife Service's 2018 estimate of only six.



Figure 1: A jaguar that was observed in the Santa Rita Mountains for many years, named “el jefe”.

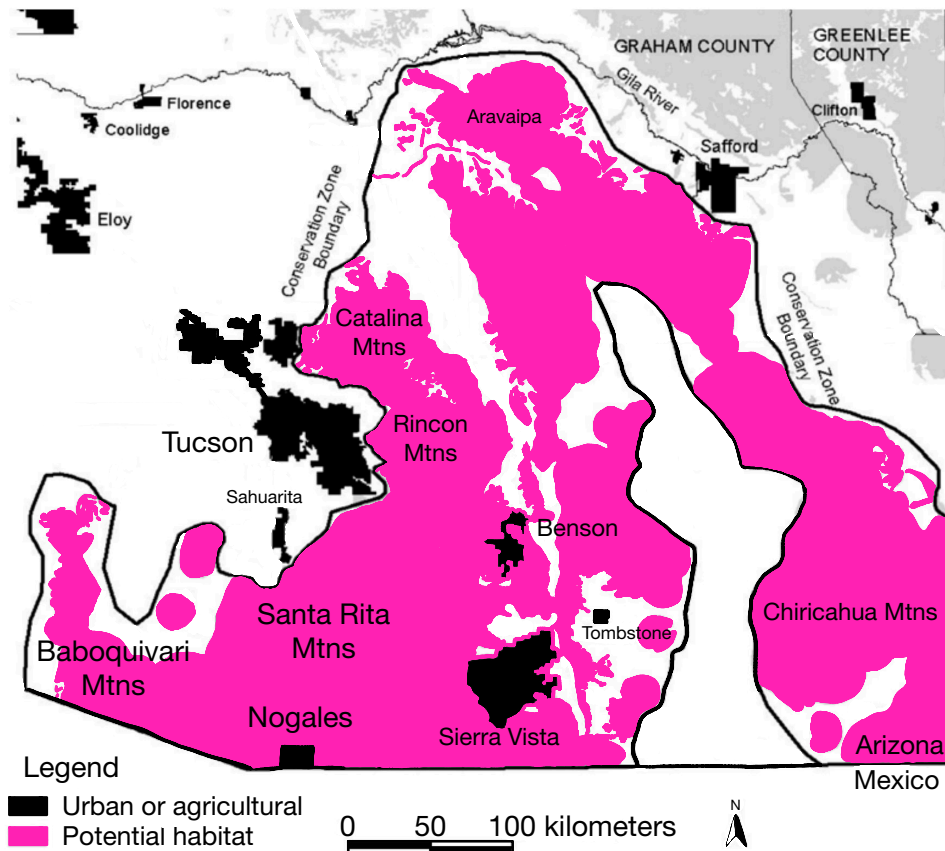


Figure 2: Potential jaguar conservation area in southeastern Arizona identified from historical sighting records from Hatten et al. (2005). Potential habitat areas shown in pink, urban or agricultural areas excluded from the study in black.

3 Mountain lions

Mountain lions in Arizona inhabit a wide range of habitats from desert mountain ranges to forested plateaus. Unlike the jaguar, mountain lions maintain a stable breeding population throughout the state. Dickson et al. (2013) modeled habitat quality and connectivity for pumas across Arizona and New Mexico, finding that woodland and forest cover, rugged terrain, and canyon topography were the strongest predictors of high-quality habitat, while road density and human population density predicted habitat decline. The sky islands region is the largest high-quality habitat zone, connecting genetically distinct populations across the international border.



Figure 3: A mountain lion geologist admiring a red rock outcrop.

Arizona's statewide mountain lion population ranged from approximately 1,100–1,700, with no apparent long-term trend. This statewide stability in population is significant given concurrent habitat pressures from wildfire, drought, and urban expansion.

Howard et al. (2020) used statistical population reconstruction methods to estimate that

4 The border wall and habitat connectivity

Both jaguars and mountain lions depend on connectivity with populations in northern Mexico, making the U.S.-Mexico border a critical conservation concern. Research along the Arizona-Sonora border found that the steel bollard wall effectively blocked crossings by mountain lions, deer, and black bears, compared with much higher crossing rates at older vehicle barriers (Harrity et al., 2024). Small wildlife passages built into the wall allowed occasional crossings by mountain lions and other smaller animals, but were too narrow for jaguars and too widely spaced to meaningfully sustain connectivity across the border (Harrity et al., 2024). Since all known breeding jaguar populations are south of the border, the progressive walling of wildlife corridors has direct implications for any prospect of natural recolonization or reintroduction in the U.S.

5 Conclusions

Southern Arizona has well-documented, sustained populations of North America's two largest native wild cats. Mountain lions persist in stable numbers across the region's sky island habitats, while jaguars cling to a marginal but continued presence at the northern edge of their range. Habitat modeling consistently identifies central and southeastern Arizona as priority conservation areas with meaningful carrying capacity for jaguars. However, increasing border infrastructure threatens the connectivity with populations south of the border that both species depend upon. Effective conservation will require not only habitat protection within the U.S. but binational cooperation to maintain the landscape linkages that have sustained these populations over time.

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SKY ISLANDS

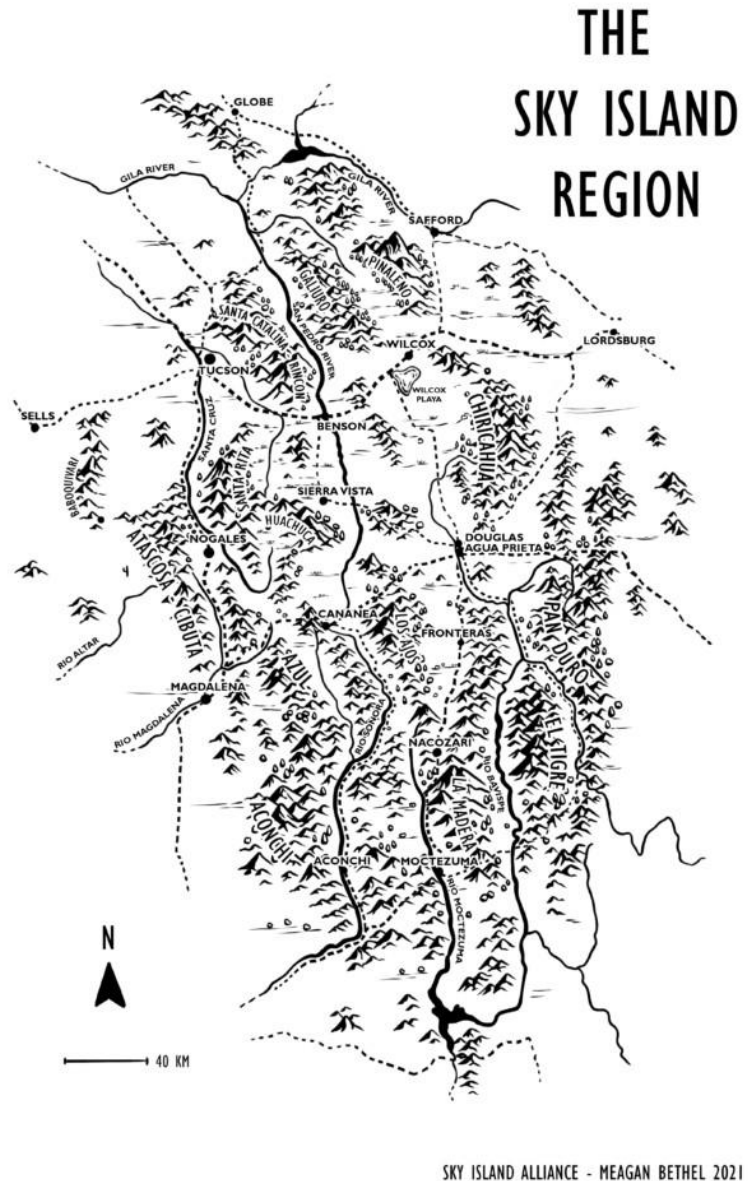
Lori Huseby

Background

The Sky Islands can be defined as isolated “island” mountain ranges that stand up among the surrounding desert. The Sky Island region spans southern Arizona, southwest New Mexico, and northern Sonora for a total of 55 mountain ranges of the Madrean Archipelago. There are four notable ones in Arizona: Santa Catalina and Rincon mountain around Tucson (Mt. Lemmon yay!), Pinaleno, Santa Rita, and the Whetstone Mountains.

The Sky Islands were first published in 1943 by Natt N. Dodge, where they were conceptually called the “Monument in the mountain” and the term was made popular in 1967 by nature writer Weldon Heald as he drove 35 miles and gained 5,600 feet of elevation. The term Sky Islands are no longer limited to just the sky island region anymore, but rather applied all around the world where mountains are isolated from each other by lowland areas.

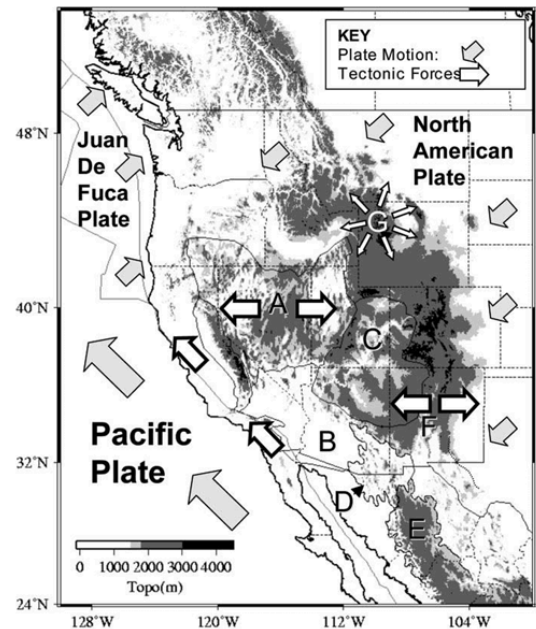
These islands reach up between 3,000 to 10,000 feet (915 - 3,300m) in elevation, where both the plant and wildlife change as you go up. Ecosystem zones change at different elevations.



Geology

Many biologic, geologic, and geographic factors have played a role in the creation of the Sky Islands. They are a sub-region of the southwest basin and range from interactions between the Pacific, North American, and Juan de Fuca plates. There were three general stages in the tectonic history of the Sky Islands:

- 1) Deposition of thick Paleozoic limestone 300 million years ago when the area was once a sea floor.
- 2) A compressional phase 200 - 60 million years ago as the North American plate converged with the East Pacific Rise.
- 3) Transition between compressional and extensional tectonics 30 million years ago as the North American plate overrode the Farallon plate. The elevated topography began to collapse due to these transitions between compression and extension, creating north-south oriented mountain ranges with valleys filled in with weathered rock fragments.



The Sky Islands are characterized by a unique mix that spans all three major rock types including:

- 1) Igneous rocks in the form of Precambrian and Tertiary granites and Mesozoic to Quaternary volcanics.
- 2) Metamorphic rocks of Precambrian and Mesozoic age including gneisses and schists.
- 3) Paleozoic, Mesozoic, and Cenozoic age sedimentary rocks in the form of limestones, quartzites, and shales.

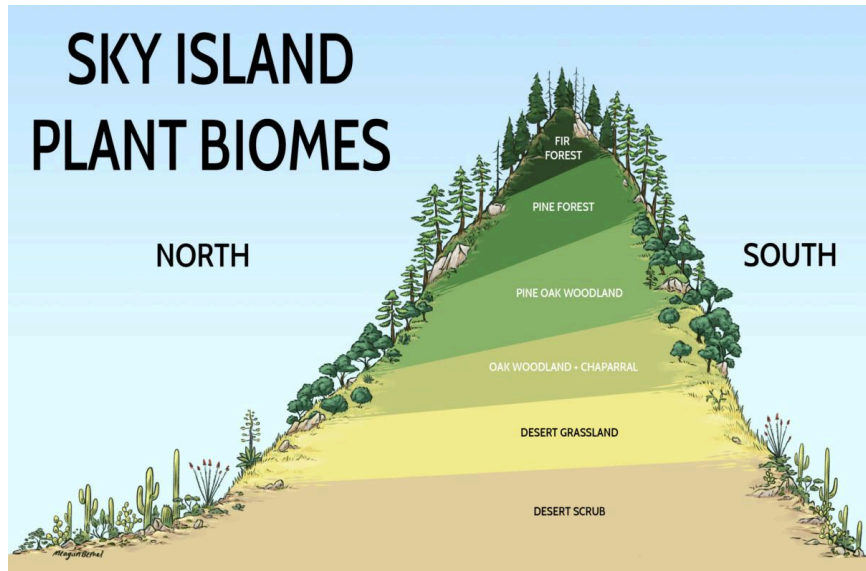
Biomes

The Sky Island region has exceptional biodiversity and important implications for areas of geocology, biology, and conservation management. More than 7,000 species of plants and animals can be found in the Sky Islands. Depending on the elevation, there are different animal and plant biomes as seen in the figure below.

A unique aspect to this area is the mix of floristic affinities, where trees and plants that are found at higher elevations are more representative of northern latitudes and the flora that is found at lower elevations is representative of the desert and southern mountains. This straddles three major climatic zones; Tropical, Subtropical, and Temperate.

The USGS estimates that for every 1,000 feet in elevation that you gain is equivalent to driving 165 miles north. Each biome can include the following fauna (not-exhaustive):

Desert Scrub (Below 3,500 feet): Mixture of herbs, succulents, shrubs, and grasses: Creosote bush, paloverde, ocotillo, pricklypear, jumping cholla.



Desert Grassland (3,500 - 5,000 feet): Perennial bunch grasses and annual grasses: oats gramma, scratchgrass, vine mesquite, plains lovegrass, agave, yucca.

Oak Woodlands (4,500 - 6,000 feet): Broadleaved evergreen oaks: Arizona white oak, Alligator juniper, Emory oak, Mexican pinyon.

Pine Oak Woodlands (5,500 - 7,000 feet): Species with southern origins and short stature: Chihuahuan pine, Apache pine, silverleaf oak.

Pine Forests (7,000 - 8,500 feet): Closed canopy and little vegetation: Ponderosa pine, Arizona pine with understory of Apache pine and silverleaf oak.

Fir Forests (6,000 - over 8,800 feet): Strong connection to Rocky Mountains: Douglas-fir, white fir, Bigtooth maple, and southwestern white pine.



Wildlife

Key wildlife includes jaguars, Mexican gray wolves, javelinas, mountain lions, black bears, ocelots, 29 species of bats, pygmy owls, chiricahua leopard frog, and over half of North America's bird species. You can go to iNaturalist to see more pictures of Sky Island animals, lichens, and plants. Each biome can include the following wildlife (not-exhaustive):

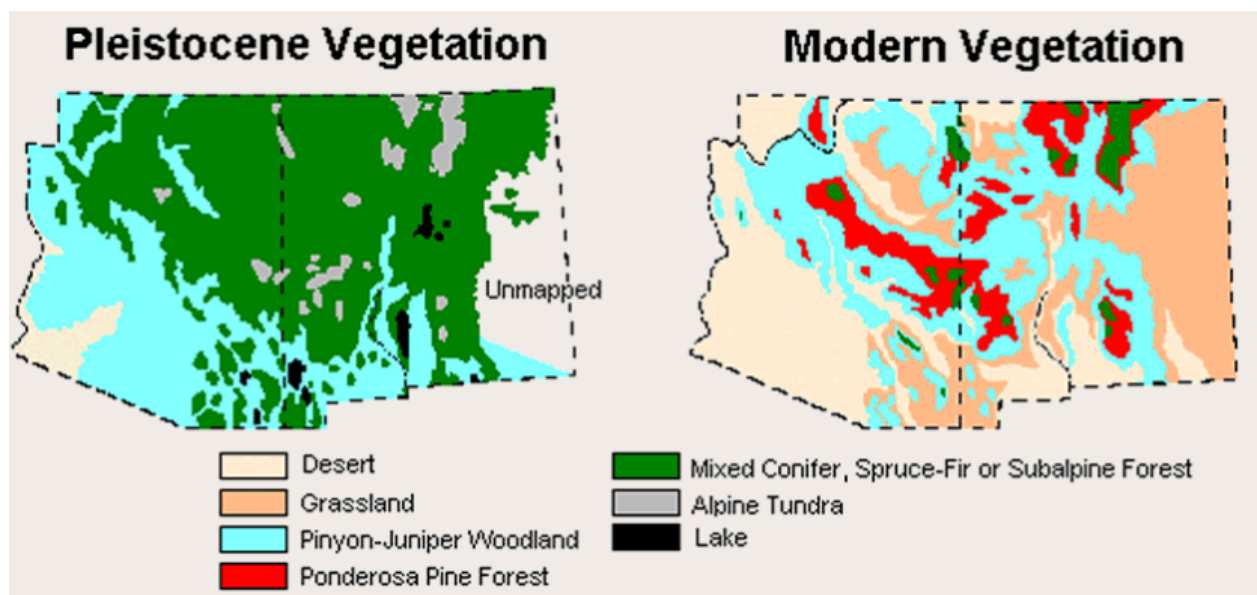
Desert Scrub (Below 3,500 feet): Yarrow's spiny lizard, kangaroo rat, javelina, greater roadrunner, desert tortoise, gila monster, various toads.

Desert Grassland (3,500 - 5,000 feet): Coyote, jackrabbit, horned lizard, prairie dog colonies, Mexican long-tongued bats, milksnake.

Oak Woodlands (4,500 - 6,000 feet): Javelinas, black-tailed rattlesnake, mule deer, porcupine, ocelot, Chiricahua fox squirrel, jaguar, Arizona grey squirrel.

Pine Oak Woodlands (5,500 - 7,000 feet): Coues deer, black bear, voles, weasels, cliff chipmunk, wild turkey, bats.

Pine Forests (7,000 - 8,500 feet): Mountain lion, bobcat, Mount Graham red squirrel, Mexican spotted owl.



Conservation

In the past 10 years, the Sky Island area has been facing higher than average warming temperatures. Due to their small size and isolation, the Sky Islands are vulnerable to extreme weather events, like droughts and severe freezing, in addition to man-made events like fires and climate change. Some effects include decrease in falling snow, less moisture, changes in species life cycles, and vegetation mortality. Conservation efforts have included protecting bat habitats, re-establishing black-tailed prairie dogs, reintroducing Mexican wolves, wildlife viewing programs, and conducting inventory of the biodiversity of the Sky Islands. Visit the websites of the Sky Island Alliance and Arizona Wildlife Conservation Strategy to see more efforts and future projects.

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1887 Sonora Earthquake

PTY5 590 Trip Spring 2026

Melissa Kontogiannis

Introduction + Tectonic Setting

The Basin and Range province, which stretches across much of the western United States and northern Mexico, is characterized by extensional tectonics due to mantle upwelling, forming parallel faults in the crust (Castro et al., 2010; IRIS; Liu and Shen, 1998). The movement of crustal blocks between these faults creates the unique topography of the region, characterized by alternating uplifted mountains and deep valleys (IRIS). Despite the fact that the Basin and Range Province is positioned away from tectonic plate boundaries, areas more prone to earthquakes, the extension of the crust creates friction, which can be released through movement of the faults in the region, causing earthquakes. One of the largest earthquakes in this region was the 1887 Sonora Earthquake, which occurred in the southern

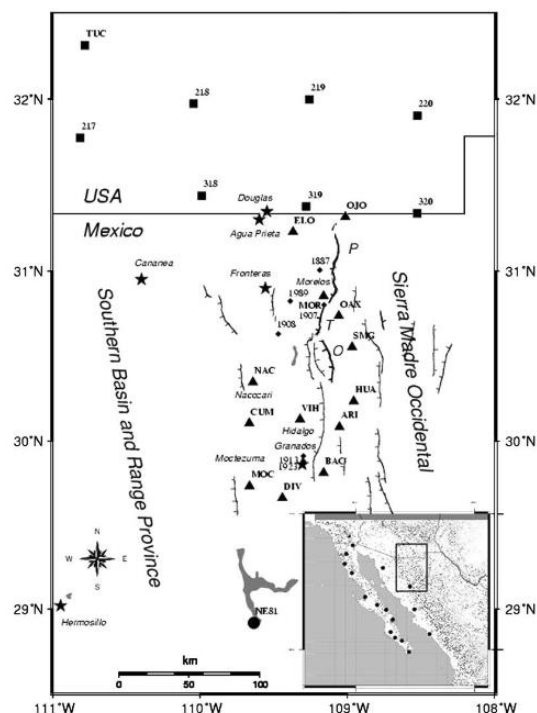


Figure 1: The location and regional context of the 1887 Sonora earthquake. The fault network that ruptured during the earthquake is made up of the Pitaycachi (P), Teras (T), and Oates (O) fault segments (Castro et al., 2010).

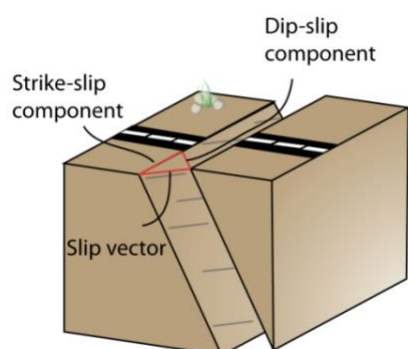


Figure 2: Diagram of surface movement along a normal left-lateral extension fault (Girty, 2009).

Basin and Range province on May 3rd, 1887 (Aguilera, 1920; Goodfellow, 1887; Sumner, 1977). The earthquake occurred in a network of north-south striking, west-dipping faults just south of the Arizona/Mexico border, on the western edge of the Sierra Madre Occidental Plateau in the Sonoran Basin and Range Province (Fig. 2) (Suter, 2015). The arid climate of the region, and the relatively erosion-resistant composition of the ruptured surface (alluvium cemented by caliche) means the resulting rupture scarp is relatively well preserved (Sumner, 1977; Suter, 2015).

Earthquake Event

The magnitude of the 1887 Sonora Earthquake is generally estimated at 7.2-7.6, with most studies converging on a magnitude of 7.5 (DuBois and Smith, 1980; Suárez and Hough, 2008; Suter, 2015, 2006). Near the epicenter, major ground fissures formed and structures were nearly completely destroyed, corresponding to a Modified Mercalli Intensity of XI (DuBois and Smith, 1980). The earthquake was felt over an area of approximately 2 million square kilometers, reaching as far as Mexico City and Sante Fe, NM. No volcanic activity was associated with this earthquake, though early reports mistake wildfires caused by rockslide-generated friction as evidence of volcanism (DuBois and Smith, 1980). The earthquake was characterized by normal oblique left-lateral extension, which is illustrated in Figure 2, and produced an average vertical displacement of 3m and an average surface offset of 2.6m (DuBois and Smith, 1980; Suter, 2015). This earthquake ruptured three faults- the Pitaycachi, Teras, and Otates faults (Fig. 1)- forming a rupture trace 101.8km from end to end (Suter, 2015). The earthquake is thought to have originated in the Pitaycachi fault, the northern-most fault in the system, producing a rupture in this fault segment estimated to be 41-50km in length (Fig. 3) (Suter, 2015, 2006). This rupture was the segment observed by both (Goodfellow, 1887) and Aguilera, (1920).



Figure 3: A photo of the earthquake rupture scarp taken by C.S. Fly. The rupture scarp is visible into the distance, as indicated by the arrow (Goodfellow, 1887; Suter, 2006).

Historical Accounts

Despite the occurrence of this earthquake in a relatively remote location before the advent of most modern seismic instruments, the event and its aftermath are well documented by the expeditions of both Jose Aguilera Serrano and Dr. George E. Goodfellow, accompanied by photographer C.S. Fly (Aguilera, 1920; Goodfellow, 1887; Suter, 2006). Goodfellow, (1887) included the first known

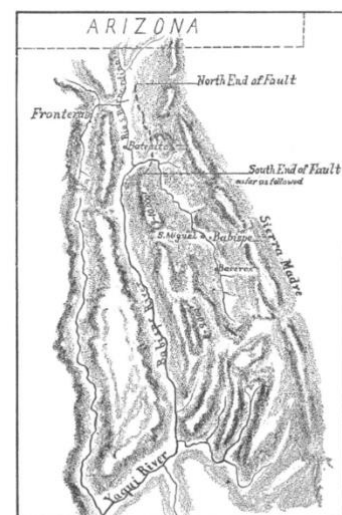


Figure 4: The surface rupture map drawn by George E. Goodfellow, describing the location and approximate size of the fault segment he observed (Goodfellow, 1887).

surface rupture map of a North American earthquake (Fig. 4) as well as the earliest known photos of an earthquake surface rupture taken by C.S. Fly (Fig. 3). This map, though not to scale, illustrates the approximate location of the fault segment studied by Goodfellow, providing context for his observations. This study also documents effects of the earthquake, including fires, rockslides, destruction in the town of Bavispe, as well as the appearance of new springs and other changes in the region's hydrologic system, but strongly disputes claims of volcanism following the earthquake (Goodfellow, 1887). Aguilera, (1920) provides a detailed description of the main observed fault segment, including the location and measurements of displacement at various points along the fault, but also discusses smaller cracks observed parallel to the fault. This study additionally included a more scientific perspective, attempting to calculate the velocity and depth of seismic waves based on the recorded time of the earthquake in different locations (though the calculations are inaccurate, again likely due to inconsistent timekeeping systems), and is the first to infer the direction of rupture propagation based on northward-pointing bifurcations observed in the fault scarp (Aguilera, 1920). These pioneering studies provide invaluable insight into the impact of the earthquake on both the land and the people in the surrounding region, establishing a foundation for continued analysis with a more modern approach.

Impact

The small town of Bavispe was situated closest to the fracture network from which the earthquake originated, and consequently suffered the greatest impact; nearly all structures were completely destroyed, and 42 fatalities occurred, in addition to numerous additional serious injuries (Aguilera, 1920; DuBois and Smith, 1980; Goodfellow, 1887). Injuries and fatalities were also reported in the nearby town of Oputo and Fronteras, for a total of 51 casualties as a result of the event (DuBois and Smith, 1980). This human and structural devastation may be largely owed to the widespread use of adobe bricks in construction in the region; adobe is relatively weak and brittle, cracking easily in the force of the earthquake, and is relatively heavy, making structural collapse particularly dangerous (DuBois and Smith, 1980). No injuries were reported in Tucson, but widespread panic occurred and some buildings were damaged (DuBois and Smith, 1980). Additionally, significant changes were observed in the hydrologic system following the earthquake, which disrupted the water supply across the region (Goodfellow, 1887). In some areas, water became unexpectedly abundant; geysers emerged and mild flooding occurred in some areas, the San Bernadino River was described as flowing "from head to mouth," which was unusual given the dry season, and tributaries of the Yaqui River experienced an increase in water volume (Aguilera, 1920; DuBois and Smith, 1980). Conversely, other wells unexpectedly ran dry, and a few lakes and streams in the region disappeared shortly

following the earthquake (DuBois and Smith, 1980). Though the relatively sparse population in the vicinity immediately surrounding the fault network likely minimized the devastating impacts of the event, the history of low seismicity in the region left residents unprepared and more vulnerable to the effects of a strong, unexpected earthquake (DuBois and Smith, 1980).

Conclusions

The 1887 Sonora earthquake is one of the most significant seismic events in the recent history of the southern Basin and Range province. This event was uniquely informative in the fact that it illustrated that substantial seismic events are not only limited to plate boundaries, and offered an opportunity for some of the earliest detailed seismic studies (Aguilera, 1920; Goodfellow, 1887), creating a foundational understanding of the human and environmental impacts of seismic activity in the Basin and Range province.

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Introduction: Cavernous weathering is a form of rock decay that creates pits, cavities, and hollows. These pits can occur in many different types of rock and in a variety of climates, but are easily visible in the desert since their shapes aren't obscured by soil and vegetation.

This type of weathering and its pitted products have some standard jargon we can define here:

1. Tafoni: small holes or caves on the surface of a rock formed by weathering, also known as caverns or pits; can be large or small
2. Stonepecker holes: another fun way to refer to tafoni
3. Alveoli: pits formed by salt weathering
4. Potholes: pits formed by stream flow erosion near coastal areas
5. Honeycomb weathering: cavernous weathering which causes regular, tightly adjoining patterned cavities resembling a honeycomb

Tafoni can range from the size of bottle caps up to several yards in diameter and are commonly aligned along joints, bedding planes, or other zones of weakness (Figure 1).

There are several key locations in Arizona where the results of cavernous weathering have been observed, including Papago Park [1], Meteor Crater [2], and importantly for us, the Chiricahua National Monument!

Mechanism: Cavernous weathering consists of several processes acting together. Early studies of cavernous weathering invoked wind as the cause, as well as removing the weathering products from the rock [3], but this idea has been refuted [4]. Now, cavernous weathering is attributed to chemical weathering processes [5]. The three commonly-argued mechanisms to generate caverns are:

1. Salt weathering (relevant here)
2. Stream flow erosion near coastal areas
3. Acidic weathering of carbonate minerals

For example, caverns in sandstone could be the result of the reaction of water and organic acids with iron and silica. As for caverns in sandstone, they may be produced by the solution of calcium and magnesium carbonates.

Of relevance to us, sometimes a rock face can develop a hardened crust of mineral salts drawn from the

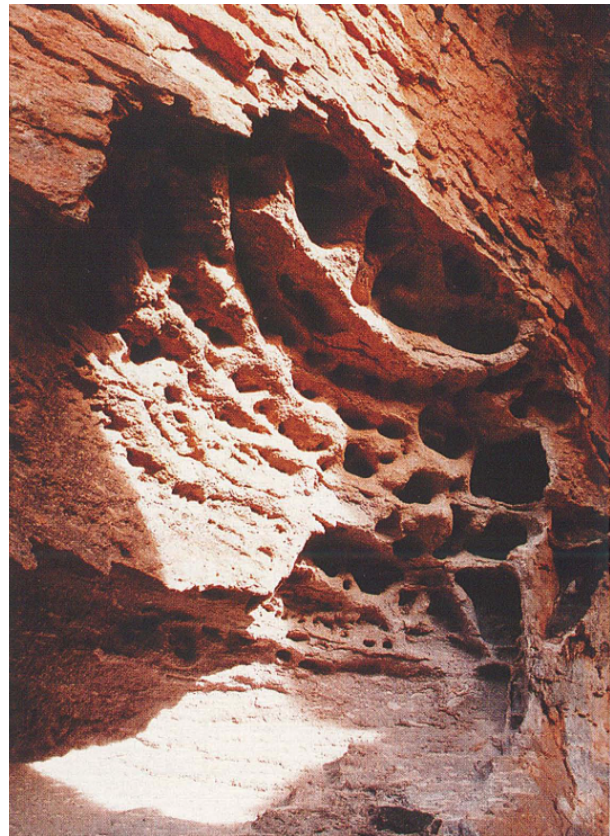


Figure 1: Tafoni in the Chiricahua National Monument.

interior of the rock in a process called *case hardening* (Figure 2). Water evaporation at the rock's surface draws moisture from within the rock, which in turn evaporates from the surface and leaves behind deposits of amorphous silica (SiO_2). The silica accumulates, hardens, and enhances the rock strength, protecting the rock from weathering and erosion. On the other hand, the underlying rock becomes weaker as the silica is removed.

However, this process can still small openings where the softer underlying rock is exposed to differential erosion. This causes tafoni to form and grow due to higher humidity and lower temperatures within the shaded cavities, causing the rock to disintegrate more rapidly than the outside [6].

This form of weathering acts as a self-reinforcing, positive feedback process [5] which dominates the early growth of the tafoni (Figure 3). Any early small pits or imperfections trap moisture and salt, which in turn leads to faster, deeper decay in the interior of the rock while the outer shell remains mostly intact. However, the rate



Figure 2: This rock surface in the Chiricahuas has been case hardened (arrow). The inner, weaker rock has been weathered away, leaving just the stronger shell that developed into a hardened crust of mineral salts and silica.

of growth of the pit eventually becomes dominated by a negative feedback loop which puts a limit on its growth [2]. As the rock surface weathers, the most reactive minerals are removed first and the less reactive minerals remain, so the pit weathers more slowly over time.

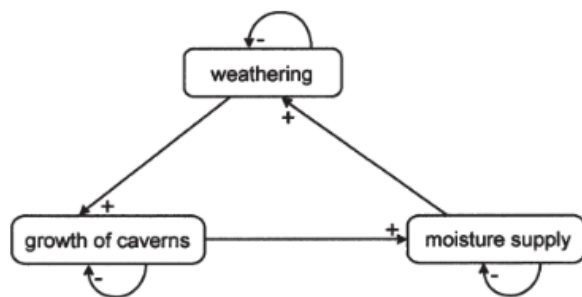


Figure 3: Feedbacks in the cavernous weathering system [5]. Plus signs (+) indicate destabilizing relationships, whereas negative signs (-) indicate stabilizing ones. More rapid weathering enlarges the hollows, which concentrates moisture in the interior, which further increases weathering rates. If the climate had a decline in moisture availability, that would reduce weathering rates and cavern growth.

Environmental Factors: Cavernous weathering was previously considered to be a diagnostic feature of arid environments, and is most prolific in salt-rich environments like deserts and coastal zones. However, tafoni can occur under cold, temperate, hot, humid and arid envi-

ronments, and are found on a variety of rock types. Common factors between this large range of environments include high salt concentrations and frequent desiccating conditions.

Tafoni can form on sandstone surfaces and on granite surfaces, as well as lacustrine silts, tuff, and conglomerates. These caverns could be due to a range of weathering processes discussed above, and they can have different sizes and forms.

Climate Significance: Cavernous weathering features serve as valuable indicators of past climatic conditions. By analyzing their formation and characteristics, geoscientists can glean insights into historical environmental changes. One way to interpret these features is by examining their size and distribution. Larger tafoni formations often indicate prolonged periods of weathering, suggesting stable climatic conditions that allowed for sustained moisture availability. In contrast, smaller features may reflect intermittent wet and dry cycles. Mapping the distribution of these cavernous structures can provide additional context; a high density of tafoni in specific areas might suggest localized climatic conditions, such as increased humidity or salt availability, potentially linked to ancient water bodies.

Assessing the mineral composition of the rocks is another critical aspect of interpreting past climates. The presence of salt weathering features, such as alveoli, indicates arid or semi-arid conditions where evaporation exceeds precipitation. Analyzing the types and concentrations of salts can offer clues about past salinity levels in the environment. Additionally, the dissolution of carbonate minerals can signal the influence of acidic weathering processes, often associated with biological activity or increased precipitation in the past.

Studying the depth and patterns of weathering is equally important. Measuring the depth of weathered zones within rock formations can reveal how long these features have been exposed to weathering processes, which may correlate with stable climatic conditions over time. Observing weathering patterns around joints and bedding planes can provide insights into past tectonic activity and how it may have influenced climatic conditions.

Biological indicators also play a significant role in understanding past climates. The presence of lichens, mosses, or other organisms within tafoni can indicate historical climatic conditions; a high diversity of flora suggests a more stable and moist environment, while a lack of biological life might indicate harsher conditions. Additionally, organic materials trapped within weathered features can provide further context for reconstructing past climates.

Geochemical analysis, including isotopic studies, can deepen our understanding of climatic changes. Varia-

tions in isotopic ratios of minerals found in weathered rock can help identify changes in precipitation patterns and temperature fluctuations over time. In areas where weathering products may have been transported, analyzing sediment layers for composition and grain size can reveal how erosion and deposition rates have varied with climatic changes.

Integrating these findings with existing climate models and proxy data, such as ice core samples and sediment records, allows for a more comprehensive understanding of past climates. Comparative studies can help validate interpretations, while radiometric dating methods can correlate the timing of weathering features with known climatic events, such as glacial and interglacial periods. Through these interpretive steps, geoscientists can effectively utilize cavernous weathering features to reconstruct past climates, enhancing our understanding of Earth's climatic history and the processes that have shaped it.

Cavernous Weathering in the Solar System: Since field surveys on Earth have been investigating cavernous features formed by coastal processes and weathering of carbonates by acidic alterations, we can apply this knowledge to the morphology of pits on Martian rocks! Surface images from rovers and landers (including Perseverance rover and Viking Lander 2) have shown rounded pits with diameters of centimeters on Martian rock surfaces (Figure 4). These pits seem similar to terrestrial cavernous weathering features generated by processes like salt weathering, stream flow erosion, and acidic weathering [7].

Given that Jezero Crater once contained large lakes early in the history of Mars, the rounded pits could have been generated by weathering processes like salt weathering. Alternatively, the pits might have formed by dissolution of rock surface due to alteration by acidic fluids, but overall they don't seem consistent with potholes.

As it turns out, the geomorphology of cavernous weathering features due to these different processes can be distinguished by number density and diameter, and when applied to Mars, [7] found that the morphological characteristics of rounded pits on Jezero Crater rocks seem to be an intermediate between salt weathering and acidic weathering. If the pits on Jezero Crater rocks were formed by salt weathering, then salt weathering on Mars may have been less effective than those in coastal areas on Earth. But, these Martian pits might have been formed by other processes too (e.g., vesicles in volcanic breccia, eolian process, or freeze-thaw cycles of porewater).

This morphological similarity between tafoni on Earth and pit formations on Mars suggest that similar weathering processes could occur on other planets, broadening our understanding of planetary geology. The presence of weathering features indicative of liquid wa-

ter, even in past environments, can inform astrobiologists about the habitability of other planets. Understanding how cavernous weathering occurs can provide clues about the potential for life in extraterrestrial environments.

And of course, the study of cavernous weathering on Mars, particularly in areas like Jezero Crater, emphasizes the importance of continued exploration and analysis of planetary surfaces. The morphological characteristics of Martian pits may guide future missions in selecting landing sites and focusing on areas with the highest potential for past biological activity.

Summary: Cavernous weathering features, such as tafoni and honeycomb structures, provide critical insights into past climatic conditions by revealing information about historical environmental changes. Through the analysis of their size, distribution, and mineral composition, geoscientists can infer climatic stability or variability, as well as the presence of arid or humid conditions. The depth and patterns of weathering further indicate exposure to weathering processes over time, while biological indicators and organic materials offer clues about past ecosystems. Additionally, geochemical analyses, including isotopic studies, enhance our understanding of precipitation patterns and temperature fluctuations. By integrating these observations with climate models and proxy data, researchers can reconstruct past climates, contributing to a deeper understanding of Earth's and Mars' climatic histories and the geological processes that have shaped them.

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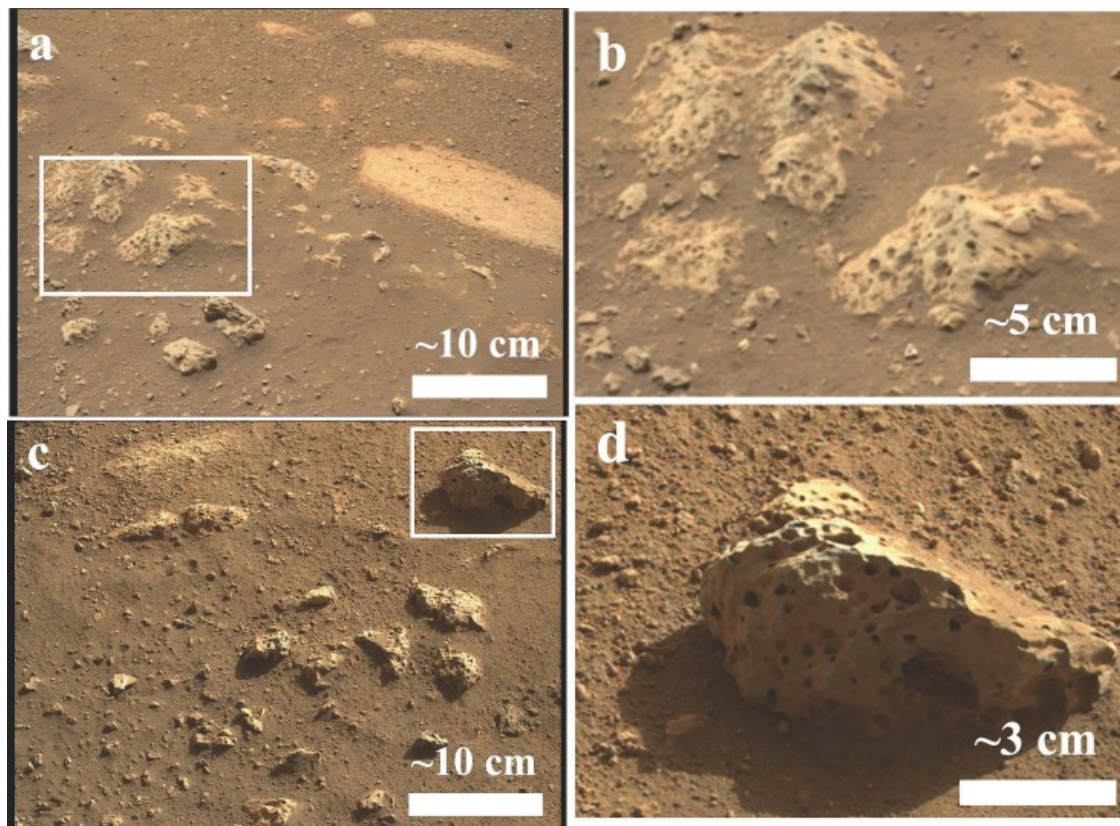


Figure 4: Images of rounded pits on Martian rocks in Jezero Crater [7]. Photographs were taken by the Perseverance rover. The pits on rock surfaces are several millimeters to centimeters in diameter and have a high number density.

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Clay Dunes of Willcox Playa, Arizona

PTY5 590 S26 | Chiricahua National Monument, AZ

Cole Meyer

Introduction and Geologic Setting

The Willcox Playa (Figure 1) is a large dry lakebed located in southeastern Arizona within the Sulphur Springs Valley, bordered by several mountain ranges including the Chiricahua Mountains to the southeast (Meinzer 1913). It represents the remains of an ancient lake system, commonly referred to as Lake Cochise, which existed during cooler and wetter climatic conditions in the late Pleistocene (Waters 1983). As regional climate shifted toward warmer and more arid conditions, the lake gradually evaporated, leaving behind a broad, flat basin filled with fine-grained sediments. Today, the playa spans several miles across and is characterized by its extremely low relief, minimal vegetation, and highly reflective, light-colored surface (Schreiber 1978).

The playa functions as a closed drainage basin, meaning that water entering the system from surrounding highlands has no external outlet. During rainfall events, water flows into the basin and temporarily accumulates, forming shallow lakes that may persist for days or weeks depending on evaporation rates. Over time, these periodic flooding events deposit layers of fine sediment, primarily clay and silt, across the basin floor. This continuous cycle of flooding and drying is essential for shaping the physical characteristics of the playa surface and plays a direct role in the formation of clay dunes (Glennie 1987)

Surface Processes and Sediment Characteristics

The surface of Willcox Playa is dominated by very fine-grained material, particularly clay, which behaves quite differently from coarser sediments such as sand. When the playa is inundated with water, clay particles ($< 2 \mu\text{m}$) remain suspended for long periods before eventually settling out in calm conditions. This leads to the formation of a smooth, uniform surface layer. As the water evaporates, the saturated sediment begins to dry and contract, producing a network of polygonal cracks across the surface (Weinberger 1999; Figure 2). These cracks divide the playa into thin plates or flakes of hardened mud.



Figure 1: Aerial view of Willcox Playa.



Figure 2: Flaking polygonal mud cracks.

This drying process is a critical mechanical step in sediment mobilization. The thin plates formed by desiccation are relatively lightweight and can be lifted or pushed by strong winds, which are common in this region. Seasonal and daily wind patterns play a major role in redistributing these materials. Unlike sand grains, which move individually by rolling or bouncing, clay fragments often move as small aggregates or flakes. This difference in transport behavior strongly influences the types of landforms that develop on the playa (Gillette et al. 1980).

Clay Dunes

Formation

The clay dunes at Willcox Playa form through an interaction between sediment supply, drying cycles, and wind transport. After flooding events deposit fine material across the basin, evaporation initiates the formation of cracked mud surfaces. These surfaces break apart into thin fragments that can be transported by wind. Because the particles are cohesive, they tend to move in clusters rather than as individual grains, which gives rise to distinct depositional behavior. As winds sweep across the playa, they carry these clay fragments toward the margins of the basin or into zones where airflow slows down. Slight variations in topography, vegetation, or surface roughness can cause the wind to lose energy, allowing transported material to accumulate. Over repeated cycles of transport and deposition, these accumulations gradually build into low mounds or ridges that are recognized as clay dunes (Bowler 1973). The process is incremental and episodic, with each flooding and drying cycle contributing additional material to the growing features.

An important distinction is that these dunes do not form through continuous grain-by-grain movement like typical sand dunes. Instead, they are constructed from discrete fragments that are intermittently mobilized. This gives the dunes a more irregular structure and limits their mobility compared to sandy environments (Milling & Behrens 1966).

Morphology

The morphology of the clay dunes reflects both the physical properties of the sediment and the environmental conditions under which they form. In general, these dunes are relatively low in height and lack the steep, well-defined slopes commonly associated with sand dunes. Their shapes are often irregular, appearing as rounded mounds or elongated ridges rather than sharply crested forms (Hills 1940). Because clay particles tend to adhere to one another, the dunes are more stable and less prone to rapid reshaping



Figure 3: Example of colored clay dunes.

by wind. This cohesion prevents the development of classic dune features such as slip faces, which require continuous movement of loose material (Patton et al. 2019). Instead, the surfaces of clay dunes may appear rough or clumpy, with visible fragments of dried mud contributing to their texture. The orientation of these features is often influenced by prevailing wind directions, although the relationship is less direct than in sandy dune systems. Overall, the morphology can

be described as subdued and irregular, reflecting the balance between limited mobility and repeated cycles of sediment input (Kocurek et al. 2005).

Environmental Variability and Field Observations

One of the most notable aspects of Willcox Playa is the degree to which its surface conditions can change over short time scales. Following rainfall, the playa may become a shallow lake with a smooth water surface reflecting the sky. As drying progresses, the surface transitions into a soft, muddy state before eventually hardening into a cracked, brittle crust. These changes directly influence both sediment transport and the visibility of landforms such as clay dunes.

In the field, I expect that we will notice the extreme flatness of the basin and the absence of significant vegetation across much of the playa interior. The margins, however, may show more variation, including the presence of clay dunes and other depositional features. Wind activity is often evident, with dust movement or even small dust devils indicating active transport processes. The overall environment is dynamic despite its seemingly barren appearance, with subtle processes continually reshaping the surface.

Relevance to Planetary Science

The processes observed at Willcox Playa provide a useful comparison for interpreting similar environments on Mars. Orbital and rover data from missions such as Mars Reconnaissance Orbiter have identified numerous dry lakebeds, or paleolakes, that show evidence of fine-grained sediment deposition and surface cracking. A well-known example is Gale Crater, explored by the Curiosity rover, where clay-rich sedimentary rocks and preserved mud cracks indicate that water once pooled, evaporated, and left behind layered deposits (Stein et al. 2018). These features closely resemble the flooding, settling, and drying cycles that shape the surface of Willcox Playa today.

A similar case is Jezero Crater, the landing site of the Perseverance rover, which contains an ancient river delta and fine lake sediments. While distinct clay dunes like those at Willcox Playa have not been clearly identified on Mars, wind-driven movement of fine particles is widespread, and low-relief accumulations of sediment may form through comparable processes. Studying how clay behaves in a setting like Willcox Playa, especially how it cracks, moves, and builds up over time, helps scientists better understand Martian surface features and reconstruct past environmental conditions, including the role of water (Grotzinger et al. 2014).

Conclusion

The clay dunes of Willcox Playa represent a distinctive landform shaped by the interaction of water, sediment, and wind within a closed basin environment. Their formation depends on repeated cycles of flooding, drying, and sediment transport, with the unique properties of clay playing a central role in determining their structure and behavior. Although they differ significantly from traditional sand dunes, they provide a clear example of how subtle physical processes can produce recognizable geomorphic features. In addition to their geological interest, these dunes offer valuable insights into similar environments beyond Earth, reinforcing the importance of terrestrial analog sites in planetary science research.

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Lichens: Extremotolerant Symbiosis in the Chiricahua National Monument

How do lichens work?

Lichens as a Symbiotic Partnership

Lichens are not a single organism, but a complex symbiotic relationship between a fungus and a green algae (protist) and/or cyanobacteria [1, 2]. In fact, the term “symbiosis” was

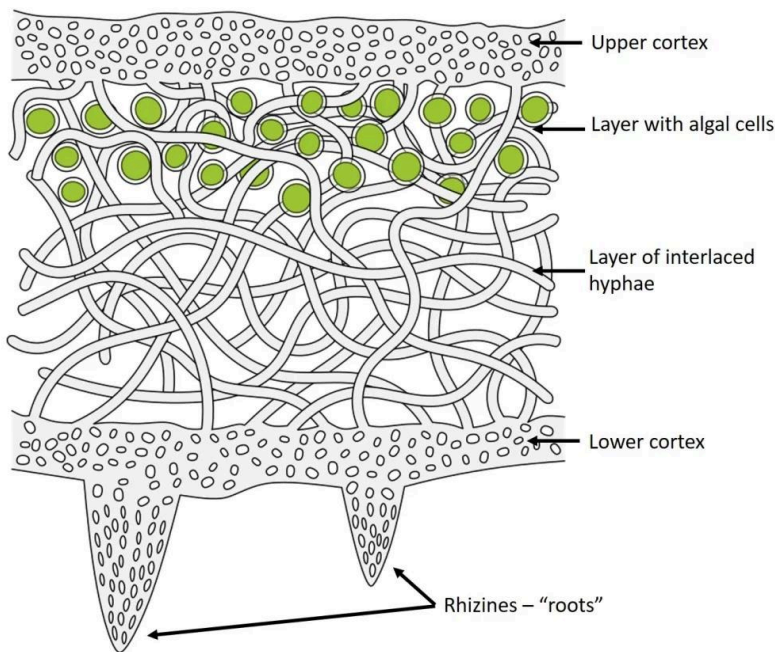


Diagram of the basic lichen structure [13]

The fungal symbiont, known as the mycobiont, is a heterotrophic organism responsible for providing water vapor harvested from the atmosphere, and also providing protective shade [2]. The fungus is the dominant partner, lending shape and morphology to the lichen [1]. Fungi are typically (> 98%) in the phylum ascomycota, and the remainder are basidiomycetes [2, 4].

The photosynthetic algal or cyanobacterial symbiont, known as the photobiont, forms

first used in a biological context in reference to lichens, by Albert Bernhard Frank in 1876 [3], though the basic recognition of lichens as a partnership between a fungus and an alga was made in 1867 [3, 4]. It is unknown when the first photosynthetic partnership occurred, but it was after each organism had developed separately [2], and it is suspected that several (3-5) independent origins of the symbiotic partnership took place [4]. The symbiotic relationship of the lichen organism can generally be classified as mutualistic (both participants benefit) [5], though some primitive lichen systems such as crustose lichens may be closer to fungal parasitism [5].

Lichen Terminology

Thallus	Composite body of a lichen [2]
Cortex	Outer layer of the thallus, thicker and more densely packed than other fungal cells in the lichen (provides protection and color in some species) [1]
Medulla	Loosely packed fungal filaments which a fibrous network underneath the outer cortex. Comprises the largest part of the lichen thallus [1]

simple carbohydrates absorbed by fungal cells, which are then transformed into essential carbohydrates and nutrients [2]. The photobiont also conducts nitrogen fixation, which is the process of converting atmospheric nitrogen into a biologically useful form [1]. The primary photobiont can be a complex network of multiple strains of algae/cyanobacteria, rather than just one [3]. The complexity of the lichen symbiosis has become appreciated in recent study [4], and lichens are now interpreted as “miniature ecosystems,” with multiple organisms operating at different trophic levels [3] in a community [2]. This complexity contributes to the resilience of the organism [3].

“A lichen is a self-sustaining ecosystem formed by the interaction of an exhabitant fungus and an extracellular arrangement of one or more photosynthetic partners and an indeterminate number of other microscopic organisms” [3]

Lichen Structure and Morphology

Lichens are composed of layers of fungus and alga, with no vascular system (roots, stems, or leaves) or waxy cuticle as is common in mosses or plants [1]. The algal layer is typically responsible for the color of the lichen, and appears gray when dry and vibrant when wet, as fungal cells become transparent, allowing the algal color to show through [1]. Lichens are attached to their substrates through one of two basal attachment strategies: rhizines, which are fungal filaments extending from the medulla which attach to the substrate, and holdfast, an extension of the thallus attached to the substrate [1].

There are three main types of lichens, (1) Foliose, which have a top and bottom side, and can be flat, leafy, or complex and ridged, (2) Fruticose, which can be pendant-like, hair-like, upright and shrubby, or upright and cup-like, and (3) Crustose, which form a crust over a substrate in a variety of bright colors.

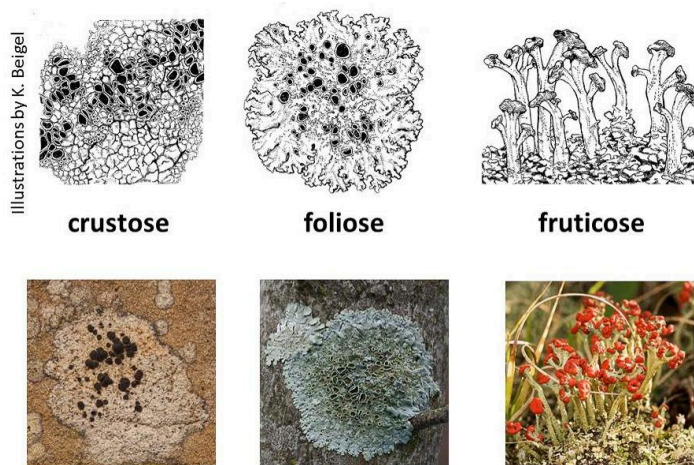


Diagram of the three main types of lichens [6]

Lichen Classification

Lichens are assigned species names according to the dominant partner, which is the mycobiont [5]. Only ~100 photobiont species have been identified to associate with >13,500 lichen-forming fungi [4]. Lichens are also classified by the ratio of phycobiont cells to mycobiont cells [2], where homoeromerous thalli consist of many algal cells and fewer fungal

cells, and heteromerous thalli consist of a higher ratio of fungal cells to phycobiont cells [2]. So far, 15,000 species of lichens have been discovered [2], with 3,600 known species in North America alone [1].

Lichen Habitat

The structure of a lichen is complex, and diverse morphologies allow for organisms to adapt to a wide array of extreme environments, from deserts to rainforests to alpine zones [1]. Therefore, lichens are found in nearly all terrestrial habitats, and are the dominant life forms in about 8% of the terrestrial land surface [4]. Lichens have the ability to colonize a variety of substrates (epilithic, meaning on the surfaces of rocks, or endolithic, meaning within rocks), as epiphytes (inside the bark of woody plants), or on vascular plants, soil, or other lichens [4].

Lichens have the ability to withstand a range of water availability, as they can desiccate and rehydrate in periods of dehydration, an adaptation known as “poikilohydry” [1]. This permits survival in harsher environments than vascular plants [5]. In this way, the fungal symbiotic partnership of lichens provide habitat spaces in environments where algae would not otherwise survive [1].

Lichen Reproduction

Lichens are long lived (surviving for decades to millennia), and slow growing (as slow as <1 mm/yr) [2, 4]. They reproduce through one of two mechanisms, in a complex cycle which accounts for the propagation of both symbionts. The more common mechanism is sexual reproduction, in which fungal spores find a new photobiont upon germination (horizontal transmission of photobiont) [1, 4]. Mycobionts can find suitable new photobionts through three mechanisms: (1) propagation from adjacent thalli, (2) association with a temporary photobiont prior to encountering permanent one, and (3) desiccation tolerance of the photobiont [4]. Lichens are also able to reproduce via asexual reproduction, which involves the vegetative transfer of both the photobiont and mycobiont to the new generation (vertical transmission of photobiont) [1, 2, 4]. In this mechanism, the lichen system sheds a thallus fragment, which develops into an adjacent full sized thallus [1, 2].

Lichens in the Chiricahuas

Air quality in the Chiricahuas

Lichens absorb pollutants from the atmosphere directly into their cortex (i.e. heavy metals, sulfur), meaning they require clean fresh air and are not common in cities or polluted regions [1]. They can therefore be used to monitor atmospheric pollutants [1, 7]. Epiphytic macrolichens, lichens growing on boles, branches, and tree trunks above ground, are common in the Chiricahua National Monument [8]. Studies of Chiricahua lichens have revealed a high ecosystem sensitivity to nitrogen enrichment and acidification relative to other national parks [8]. Studying lichen community responses to pollutants can assist with efforts to preserve ecosystem stability in the Chiricahua National Monument [8].

Substrates in the Chiricahuas

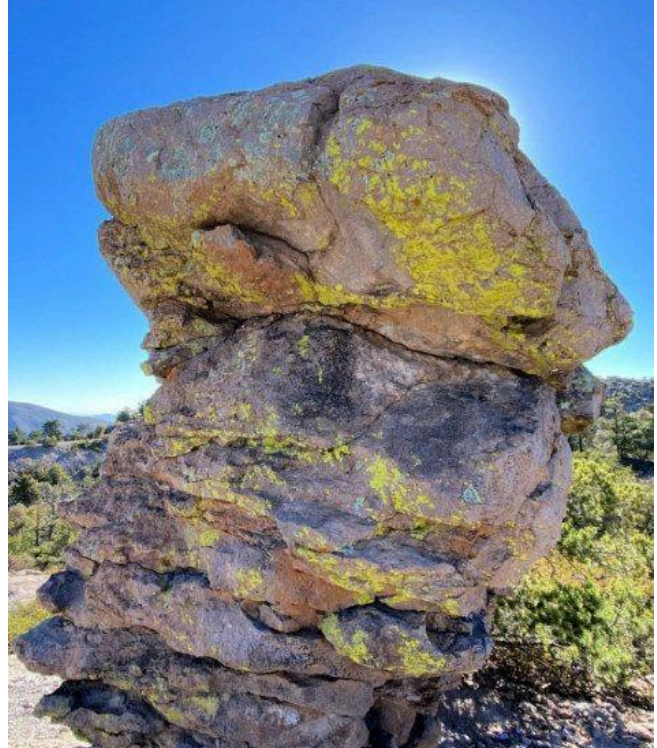
The Chiricahua National Monument hosts an abundance of lichens, which cover the surfaces of rock units. The majority of pillars are composed of a welded rhyolite tuff emplaced ~26 Ma, with ash-rich beds which are contacts in geologic units between pyroclastic flow deposits [9]. The characteristic columns of the Chiricahuas are erosional features, carved from the welded tuff layer by water and wind. Additionally, jointing generated by the initial cooling of the tuff contributed to the production of new surfaces, as fracture spaces were opened by erosive processes [9].

Lichens: Connections to Astrobiology

Lichens as a Terrestrial Model Organism

Lichens are one of the most resistant extremotolerant organisms (capable of growth and survival in extreme ranges of temperature, humidity, and radiation) [11], and are therefore considered a valuable model organism in astrobiology [12]. For example, they can grow in Antarctica's Dry Valleys, in a temperature range of 0° to -50°C, with an annual precipitation of <50 mm [11]. Three significant adaptations contribute to their extremotolerance: (1) poikilohydry, or the ability to enter into an anhydrobiotic state, (2) the production of secondary metabolites in the outer layer of the thallus which offer radiation shielding by absorption [11], and (3) the ability of a lichen thallus to morphologically adapt to environmental conditions [12].

To investigate the extremotolerance of lichens, ESA's 2005 BIOPAN V experiment exposed *Rhizocarpon geographicum* and *Xanthoria elegans* species to space, finding a high survival rate (70 – 90% of organisms) and very little degradation of symbiotic associations. Other experiments have also been conducted to investigate tolerance to high UV and cosmic radiation, vacuum conditions, and extreme temperatures, which have confirmed the status of lichens as extremotolerant organisms with relevance to astrobiology research [11]. The morphology and anatomy of lichens contribute to their resilience in these extreme conditions, making them valuable study targets for current and future astrobiological research [12].



Characteristic tuff pillar in Chiricahua National Monument [10]

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The Apache Wars: A History of Colonization and Land Seizures

I. Introduction

The Apache Wars (1849-1886) constitute the longest continuous armed conflict in United States military history: 38 years of campaigns, sieges, and running battles across the Arizona and New Mexico territories, and into northern Mexico. For comparison, the U.S. war in Afghanistan lasted 20 years: nearly half as long. Some historians extend the conflict to 1924, bringing the total to 74 years of active hostilities [1], [2].

The conventional narrative frames these wars as a collision between American expansion and Apache resistance: a tragic but inevitable consequence of two incompatible ways of life meeting on a contested frontier. However, it should be argued that the Apache Wars were not incidental to American expansion in the Southwest but its key instrument: military force broke organized resistance; the reservation system confined and desolated the surviving population; and once the land was emptied of effective opposition, railroads, mining operations, and settler agriculture moved in. The wars were not accidental but rather the operating logic of territorial colonization.

The Chiricahua Mountains and rock formations, canyons, and high passes served as the stronghold of Chiricahua Apache resistance for decades. It is not backdrop for history but really the prize: a strategic resource that Apache leaders like Cochise actively defended, and the prize American military and commercial interests sought to control.

II. From Bascom to Bayonets

The Chiricahua War began with a lie. In January 1861, U.S. Army Lieutenant George Bascom summoned Cochise - the leader of the Chiricahua Apache and one of the most capable military commanders in the Southwest - to a meeting at Apache Pass under the pretense of negotiation. Bascom accused Cochise of kidnapping a settler's child and attempted to take him prisoner. Cochise escaped, but the confrontation triggered a cycle of hostage-taking and execution on both sides that rapidly escalated into full-scale war across Arizona Territory [2]. There is no evidence Cochise was responsible for the kidnapping. The Bascom Affair revealed the underlying logic that stuck through subsequent wars: that Apache leaders operated under no presumption of good faith from the U.S. military, and that Apache life and Apache land were inherently available for exploits in the American territorial thinking.

The murder of Mangas Coloradas two years later made that logic explicit. Coloradas, the principal chief of the Warm Springs Apache and father-in-law of Cochise, agreed to surrender under a flag of truce to Brigadier General Joseph West at Fort McLane in January 1863. He was taken into custody and, on West's orders, tortured through the night with heated bayonets. When he protested, soldiers shot him, claiming he had attempted to escape. He was then decapitated, and his skull shipped to a phrenologist¹ in New York City for study [2]. This was a deliberate killing of a

¹ 19th-century practitioner of the pseudoscience of phrenology, which claimed to determine an individual's personality, intelligence, and character traits by measuring the shape and bumps of their skull.

surrendered leader under formal custody, followed by the desecration of his body in the name of pseudoscience. The treatment of Mangas Coloradas occurred *within, not despite*, American institutional structures. Cochise responded by waging a guerrilla campaign from the Dragoon and Chiricahua mountain ranges for nearly a decade, using high terrain, mobility, and intimate knowledge of the land to hold U.S. forces at a persistent disadvantage. The cumulative pressure of unlimited federal military resources was not something any Apache leader could indefinitely absorb. This conflict was an asymmetric one against a well-resourced imperial power. Cochise negotiated a peace in 1872.

The most protracted resistance came from Geronimo, a Bedonkohe Apache leader and medicine man who had lost his family to a Mexican Army massacre in 1851. Geronimo became the most relentlessly pursued Indigenous leader in American military history. He repeatedly escaped from reservation confinement, conducted cross-border raids between the U.S. and Mexico, and required a joint military operation involving some 5,000 U.S. army troops to bring to heel [2]. He surrendered finally in Skeleton Canyon, Arizona in 1886. Geronimo and 30 of his followers were promised terms that the U.S. government almost immediately violated, shipping them as prisoners of war to Florida and later Oklahoma, far from their homeland [2]. This is generally considered the end of the Apache Wars, although conflicts continued between citizens and Apaches.

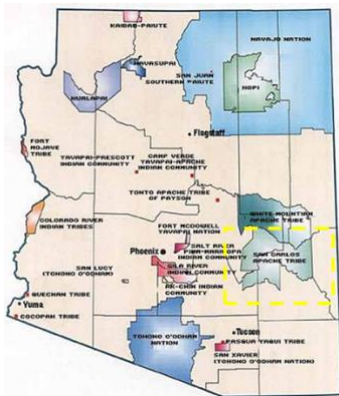


Figure 1. Map of San Carlos Apache Indian Reservation (Western Apache: Tsék'áádn) and other Tribal Nations.

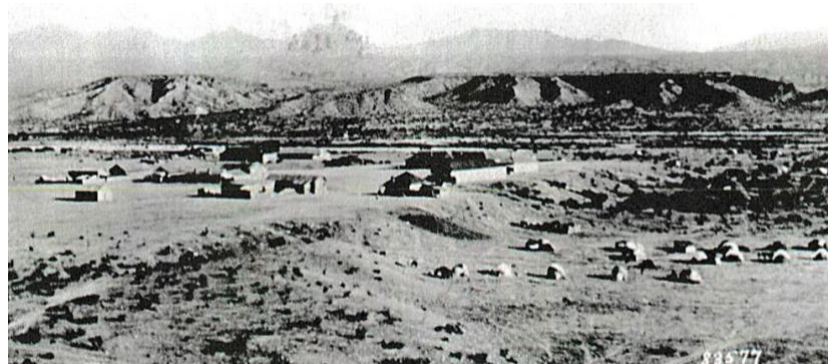


Figure 2. San Carlos Reservation in 1895. The Gila River was in the distance. Apache encampments can be seen to the right side of the photo.

III. Infrastructure and war as the same project

The violence documented in the previous section did not occur in an economic vacuum. While U.S. military campaigns against Apache leaders were ongoing, the Southern Pacific Railroad was already advancing eastward across Arizona. Its tracks reached Tucson in 1880; construction crews worked under military escort through Apache territory, and the railroad's own historical records note plainly that Geronimo's surrender in 1886 removed the final obstacle to unimpeded operations [5]. Senior military commanders understood this sequence explicitly: in 1877, General William Sherman advocated for the railroad's completion in part because it would, in his assessment, greatly aid military efforts to defeat the Apaches [5]: infrastructure and war as the same project.

Before capital could move into Apache land, the Apache themselves had to be moved out of it. In 1875, all Apache tribes were consolidated onto a single reservation at San Carlos in the Sonoran Desert - a place so desolate it became known as "Hell's Forty Acres." The land was deliberately unproductive: too arid and rocky for the farming life the U.S. government nominally expected Apache to practice. The population was crowded onto the overpopulated reserve without adequate food, clean water, or medical supplies. Smallpox and malaria spread through the camps. U.S.-appointed traders charged exploitative prices for basic goods. The conditions were not an administrative failure; they were an administrative outcome. The reservation did not aim to support the Apache; it aimed to contain them while the surrounding territory was made available for other uses [4].



Figure 3. Map of the Southern Pacific Railroad (Sunset Limited) and Other Transcontinental Railroad Lines Buildout with years of official opening for each segment denoted.



Figure 4. In 1886, many of the Yavapai ethnic group joined in campaigns by the US Army, as scouts, against Geronimo and other Chiricahua Apache. The wars ended with the Yavapai's and the Tonto's removal from the Camp Verde Reservation to San Carlos on February 27, 1875, now known as Exodus Day.[84][85] 1,400 were relocated in these travels and over the course the relocation the Yavapai received no wagons or rest stops.

The mining economy told the same story with equal bluntness. In 1877, a U.S. Army reconnaissance patrol from Fort Bowie, dispatched to track Apache, camped in the Mule Mountains of southeastern Arizona and discovered what would become the Copper Queen Mine, the richest copper deposit in the territory [6]. The first mining claim was staked not by a prospector but by a soldier. By the 1880s, Bisbee had grown into a major industrial camp; by 1910, it was the largest city in the Arizona Territory², with a population of over 25,000 [7]. Silver had already been struck at Tombstone in 1879, and within two years its population reached 10,000, making it Arizona's largest town a city named, with unselfconscious irony, for the threats Apache resistance posed to those who came to extract the land's wealth [8].

IV. Conclusion: Invasion as a structure, not an event

The Australian anthropologist Patrick Wolfe, in his foundational essays on settler colonialism and treatment of indigenous population of Australia, argued that what distinguishes settler colonial

² Arizona achieved full statehood in 1912, the endpoint of a process that had begun with military campaigns in Apache Pass half a century earlier [5]. The population grew rapidly through the 1880s and surpassed 100,000 by the turn of the century. The Chiricahua National Monument, no longer a battle ground, was established in 1924.

projects from other forms of conquest is their organizing logic: not simply to exploit an indigenous population but to remove them from the land entirely to be replaced with a new society. Wolfe called this the "logic of elimination," and he was careful to note that elimination does not require extermination, rather, it can be accomplished through spatial removal, legal dispossession, controlled confinement, and the gradual dismantling of the conditions required for a people to sustain themselves. Wolfe wrote, "'Invasion is a structure, not an event" [9].

The Apache Wars, viewed this way, were not a conflict that happened and ended. They were one phase of a structure that continued: from the battlefield at Apache Pass, to the starvation camps of San Carlos, to the copper mines of Bisbee, to the statehood proclamation of 1912.

Wolfe's framework was explicitly comparative. His analysis drew direct lines between the United States, Australia, and Israel-Palestine, arguing that these were not analogous cases but structurally related ones [9]. The Gaza Strip, under Israeli military blockade since 2007, holds more than two million people on 365 square kilometers of land, with controlled scarcity of food, water, and medicine; deliberate destruction of agricultural and civilian infrastructure. The same administrative logic that governed San Carlos was reproduced in a different geography and a different century. In both cases, the population kept alive but not sovereign, held in conditions that made resistance the only available form of agency, and then punished for that resistance as though the confinement were not its cause.

The parallel is not offered to flatten the differences between these histories, which are real and significant, rather converts a pattern into a series of isolated incidents. It asks us to mourn the Apache Wars as history while encouraging us to name what is happening now in other corners of the world. *"Violent resistance to violent colonization is not an unexpected turn of events"* [3].

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Coatis
Lily Robinthal
PTY590, Spring 2026

Introduction

The sky islands of Arizona, of which the Chiricahua National Monument is a part, serve as a much needed refuge from the harsh conditions of the surrounding desert. At these high altitudes, the more temperate climate allows for thriving biodiversity. Mammals of all shapes and sizes make this region their home, and it could be compellingly argued that in terms of endearing qualities, none hold a candle to the splendor of the coati.



Figure 1: I mean, come on. Just look at it. (Image via San Diego Zoo)

At first glance, the coati could almost appear to be the frankensteinian amalgamation of the leftover parts of a variety of animals: it has a snout not unlike that of a badger, a striped tail like a lemur, feet and claws akin to those of a bear. It is about the size of a small dog and climbs in trees like a monkey. In fact, the coati is closely related to raccoons; both are of family Procyonidae [1]. There are four species of coati, and this work will focus on the only one native to North America, the White-Nosed Coati.

Lifestyle

We are lucky to be in one of the rare regions where the White-Nosed Coati's habitat extends into North America; they exist only as far north as southern Arizona, as well as in a small portion of New Mexico and Texas (see figure 2). They range as far south as Central America and the very northernmost parts of South America.



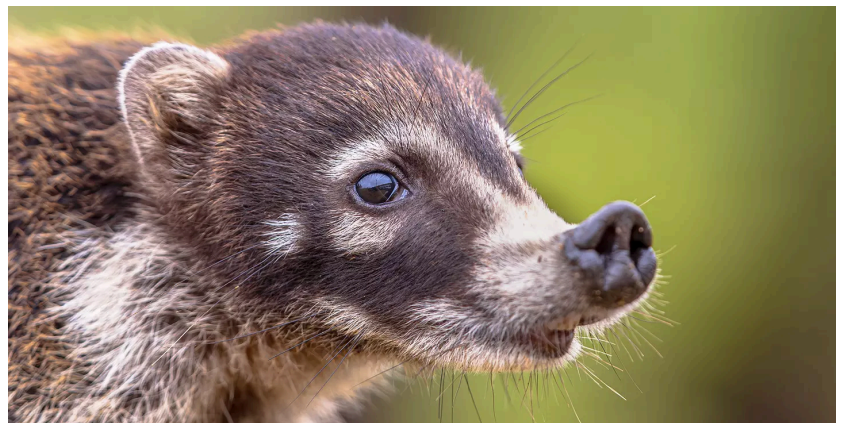
Figure 2: The range of the White-Nosed Coati. The patch in the middle of Mexico is the more arid region of the country where coatis do not reside. (Image via Turpentine Creek Wildlife Refuge)

They are diurnal, unlike their raccoon relatives, and at night they sleep in trees or other elevated places. Dietarily, they are foragers and what is known as “opportunistic omnivores”--they eat insects and other invertebrates, fruit, eggs, leaves, and even small vertebrates and carrion [2]. They use their long snouts and keen sense of smell to root out their meals from undergrowth and leaf litter.

Figure 3 (right): Take a closer look at that snout! (Image via London Zoo)

Coatis are social creatures, and often live in bands of 20 or more. When moving together, they hold their tails aloft, which provides an interesting visual effect (see figure 4).

Figure 4 (below): An easy mistake to make. (Image via reddit)



Baby coatis are born in litters of 2-7 typically in early summer [3]. They are unbelievably cute (see figures 5, 6, 7).



Figure 5: I told you so. (Image via Brevard Zoo)



Figure 6: You’ve got to be kidding me.

(Image credit: Chuck Homler via Focus On Wildlife)



Figure 7: Majestic (Image credit: National Geographic)

Babies are cared for by the whole community in a system known as reciprocal altruism. Coati bands partake in many other social activities as well, including mutual grooming and play, and they communicate through a wide variety of vocalizations including chirps, squeaks, and barks.

A Linguistic Sidenote

You may have heard coatis referred to as “coatimundis”. While this is not necessarily incorrect, technically it refers to a special case. The word “coatimundi” means “lone coati” in Guarani, an indigenous language of Brazil, and was used to refer to the fact that the males of the species are solitary after the age of two and typically only join the bands during mating season [2]. So, a lonesome male coati can be referred to as a coatimundi.



Figure 8: Coatis (left, image credit: Rhett A. Butler), and a coatimundi (right, image via New Hampshire PBS)

Gallery

Which coati do you feel like today?

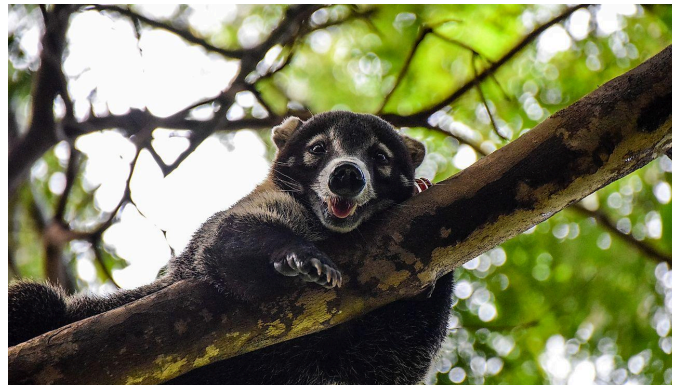
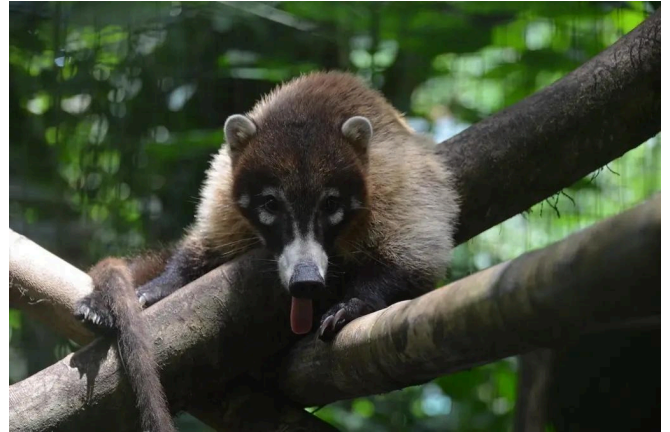


Photo Credits: Arizona-Sonora Desert Museum (top left), Institut Oasis (top right), World Coati Day (middle left), World Atlas (middle right), London Zoo (bottom left), DesertUSA (bottom right)

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Hoodoos: Formation, Physics, and Planetary Analogs

PTYS 590 - Planetary Geology Field Study - Final Report

1 Introduction

Hoodoos are tall, thin spires of rock sculpted by differential erosion, where a harder caprock protects softer material beneath from weathering while the surrounding terrain is stripped away. The Chiricahua Mountains of southeastern Arizona host one of the most striking hoodoo fields in North America, carved not from sedimentary rock like the famous examples at Bryce Canyon, but from a thick sheet of volcanic material deposited by a catastrophic eruption 27 million years ago. The Chiricahua Apache called this landscape the “Land of Standing-Up Rocks”; today it is protected as Chiricahua National Monument [Chronic, 2003]. This report examines how the Chiricahua hoodoos formed, what we can see in the field, and what they tell us about erosional processes on other worlds.

2 Geological Setting

The hoodoos at Chiricahua are carved from the Rhyolite Canyon Tuff, a welded ignimbrite produced by the Turkey Creek Caldera eruption approximately 27 Ma [Marrett and Allmendinger, 1989]. A welded ignimbrite forms when a hot pyroclastic flow settles and partially fuses under its own weight; the degree of fusion, or *welding*, varies vertically through the deposit. The interior of the sheet cooled slowest and is most intensely welded, and therefore hardest, while the top and base cooled faster and remain more porous and weak [Lipman, 1976]. It is this vertical contrast in rock strength, rather than a difference in rock type, that drives differential erosion and produces hoodoos. The Rhyolite Canyon Tuff reaches 200–300 m thick within the monument and is rhyolitic in composition ($> 70\% \text{SiO}_2$), with sanidine feldspar, quartz, and biotite phenocrysts set in a glassy groundmass [Chronic, 2003]. Basin and Range extension has since uplifted and faulted the tuff sheet; the canyon systems incised into it expose the full thickness of the ignimbrite and the hoodoos eroded from it.

3 Formation Processes

As the Rhyolite Canyon Tuff cooled, thermal contraction fractured it into a polygonal joint network — the same process that produces columnar basalt at Devils Postpile [Goehring et al., 2009]. These joints are the templates for hoodoo geometry: joint spacing controls pillar width, and joint orientation controls the alignment of rows and intervening gullies. Erosion proceeds in four stages illustrated in Figure 1: the plateau is first dissected into elongated fins along joint planes, windows are carved through the thinnest sections of fins, and final isolation produces individual hoodoo pillars, each capped by a more resistant welded horizon.

The dominant weathering mechanisms at Chiricahua are chemical hydrolysis of silicate minerals and monsoon-driven moisture cycling. Sanidine feldspar reacts with weakly acidic rainwater to produce kaolinite clay, which has far lower cohesive strength than the original mineral, disaggregating the rock matrix [Goudie, 2004]. Seasonal monsoon rainfall saturates exposed surfaces, and the subsequent rapid drying causes clay minerals to swell and shrink repeatedly, spalling grains from pillar faces. Winter freeze-thaw cycling widens existing joints. Runoff from monsoon storms incises the gullies between pillars, continuously lowering the surrounding terrain and leaving resistant columns standing in higher relief. The result

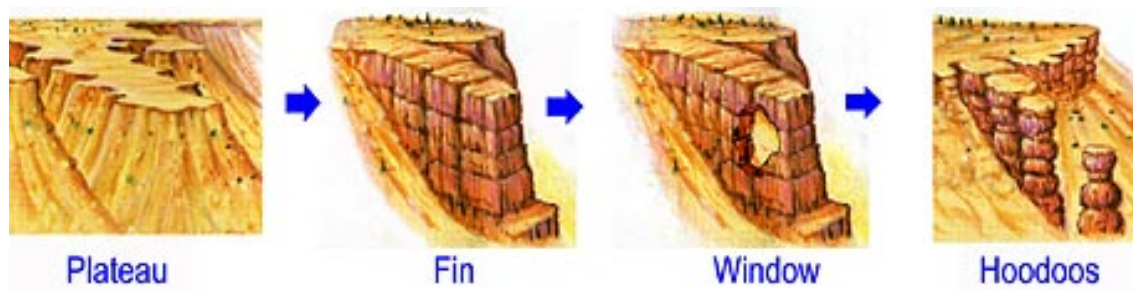


Figure 1: Stages of hoodoo development: plateau, fin, window, and isolated hoodoo. Erosion exploits joint planes and weaker welding zones to progressively isolate pillars from the surrounding rock mass. All four stages are visible simultaneously at Chiricahua, providing a natural cross-section through the hoodoo lifecycle. Adapted from National Park Service interpretive materials.

is an actively evolving landscape: new hoodoos are being isolated from canyon walls today at the same time that older ones are collapsing.

4 Field Observations at Chiricahua

The hoodoo spires visible from Echo Canyon and the Heart of Rocks loop range from a few meters to over 20 m tall (Figure 2). The stacked ledge morphology on each pillar, pronounced caps and shoulders separated by narrower waists, directly reflects the alternation of densely and loosely welded zones through the tuff column. Yellow-green lichen colonizes exposed surfaces throughout, and the orange-brown surface staining on pedestals results from oxidation of iron-bearing biotite and magnetite to hematite (Fe_2O_3) and goethite (FeOOH) [Biek et al., 2009].

Among the most iconic individual features is Big Balanced Rock, a roughly 1,000-metric-ton boulder perched on a narrow pedestal, an extreme case of differential welding in which an exceptionally resistant cap has outlasted rapid erosion of the softer material beneath [Chronic, 2003]. Natural arches elsewhere in the monument represent the next stage: once a pillar is isolated on multiple sides, erosion perforates the thinnest cross-section through a less-welded zone, leaving a more resistant interval as the arch crown.



Figure 2: Hoodoo spires along Echo Canyon, Chiricahua National Monument. The tabular ledges on each pillar reflect alternating resistant and weaker welding zones within the Rhyolite Canyon Tuff. Pillar widths are controlled by the original cooling joint spacing of the Oligocene ignimbrite.

5 Planetary Analogs

The same differential erosion principle operating at Chiricahua has been directly observed on Mars. The Curiosity rover imaged small spike- and spire-like structures protruding from eroded sedimentary outcrops in Gale Crater (Figure 3), formed by wind and sand abrasion selectively removing softer surrounding material and leaving more resistant projections standing [Grotzinger et al., 2014]. These Martian features are far smaller than the Chiricahua hoodoos, but the underlying process is identical: differential erosion of layered rock along pre-existing weakness planes. On present-day Mars, aeolian abrasion replaces the water-driven weathering dominant at Chiricahua, and the extremely low erosion rates in the thin Martian atmosphere allow such delicate structures to persist for millions of years. Their presence in Gale Crater, a site with a well-documented history of aqueous sedimentation, suggests that the resistance contrasts being exploited today were set up by differential cementation and diagenesis during an earlier, wetter Martian epoch [Grotzinger et al., 2014].

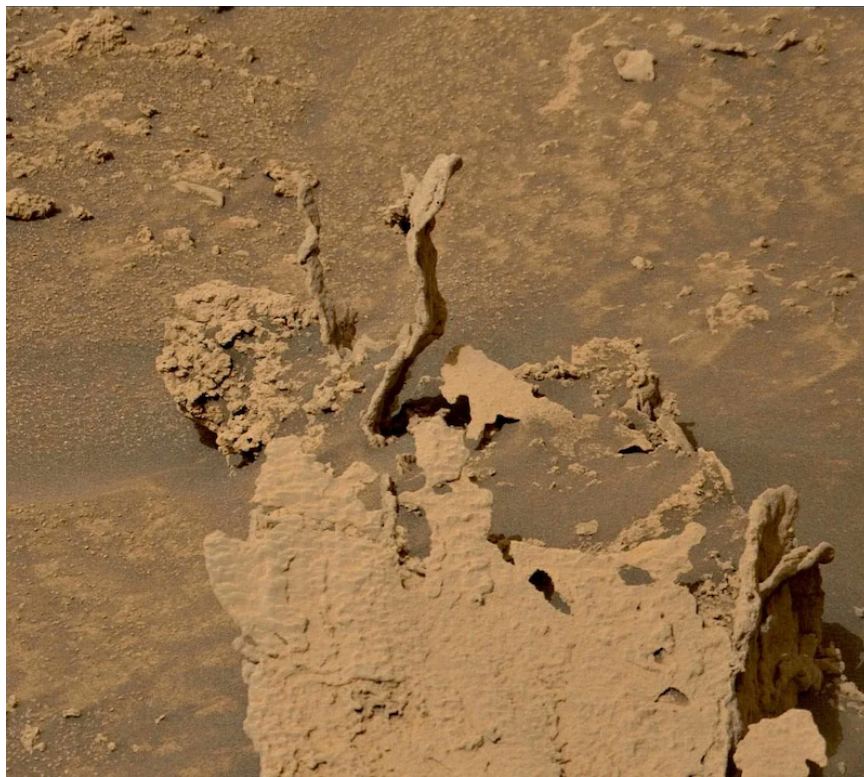


Figure 3: Hoodoo-like spire structures imaged by the Curiosity rover in Gale Crater, Mars (NASA/JPL-Caltech/MSSS). Thin projections of more resistant rock protrude from an eroded sedimentary outcrop; aeolian abrasion has selectively removed the surrounding softer material. Although far smaller in scale than the Chiricahua hoodoos, these features reflect the same fundamental process of differential erosion acting on layered rock of varying resistance.

Beyond Mars, Saturn’s moon Titan is sculpted by a methane precipitation cycle analogous to Earth’s water cycle, with layered organic sediments that could exhibit differential resistance to fluvial erosion [Stofan et al., 2007]. Whether hoodoo-like pillars exist on Titan remains unresolved at available imaging resolution, but the Dragonfly mission (arriving in the 2030s) may settle the question from the surface. The Chiricahuas’ volcanic lithology, arid climate, and joint-controlled erosion also make them a practical field analog for training rover operations in Mars-like volcanic terrain, and the porous interiors of hoodoo pedestals host endolithic microbial communities sheltered from UV radiation [Cockell and Herrera, 2002], a compelling model for potential subsurface habitats on Mars.

6 Conclusion

The hoodoos of the Chiricahua Mountains record 27 million years of differential erosion acting on a single volcanic deposit. The vertical contrast in welding intensity within the Rhyolite Canyon Tuff, guided by a cooling joint network, has produced a landscape of spires, balanced rocks, and natural arches that makes the Chiricahuas one of the most geologically instructive field sites in the American Southwest. Crucially, the Curiosity rover has shown that the same process is active on Mars today, scaled to the gentler erosion regime of the Martian atmosphere. A field trip to the Chiricahuas is therefore not just a study of local geology: it is a window into a planetary-scale geomorphic process.

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The Mogollon-Datil Volcanic Field

Madison Tuohy | Planetary Science

1. Introduction

The Mogollon-Datil Volcanic Field (MDVF) of south-central New Mexico preserves one of the most complete records of the Cenozoic ignimbrite flare-up, spanning approximately 40 to 18 Ma (McIntosh et al., 1992). This sustained pulse of intense silicic magmatism was a direct consequence of tectonic reorganization following the Laramide Orogeny, and the MDVF represents a critical archive for understanding crustal thermal evolution during continental extension (Figure 1).

The initial episode of activity (ca. 36.5-33.8 Ma) is the focus of this report. It is defined by rhyolitic eruptions from three primary caldera complexes (Organ, Dona Ana, and Emory), alongside extra-caldera vent activity. Together, these eruptions track a progression from the extraction of crystal-poor melts during the earliest stages to the remobilization of large crystalline mushes as mantle thermal flux increased, reflecting the maturation of a continental magmatic system responding to slab removal and lithospheric thinning (Chapin et al., 2004).

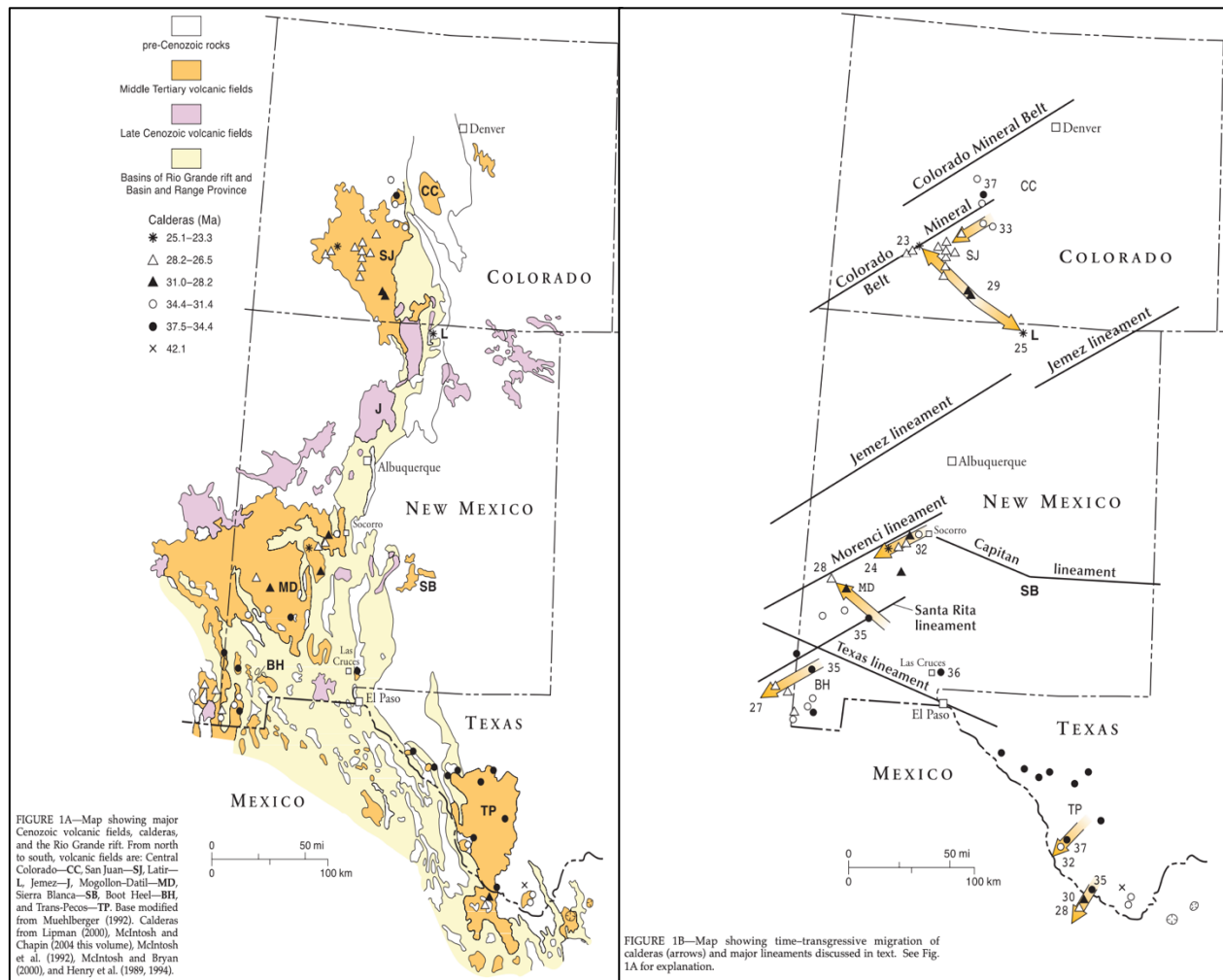


Figure 1. Cenozoic volcanic fields. Mogollon-Datil indicates in the western portion of the map (1A). Tectonics of the region indicated in figure 1B.

2. Tectonics and Regional Framework

The initiation of the MDVF is directly tied to rollback and foundering of the Farallon slab, which had driven shallow-angle subduction and crustal thickening during the Laramide Orogeny (ca. 80-40 Ma). Following that contractional event, a roughly 3-million-year magmatic hiatus preceded the ignimbrite flare-up, reflecting the time required for the steepening slab to detach and for hot asthenospheric mantle to upwell into the vacated space (Coney and Reynolds, 1977; Chapin et al., 2004).

The MDVF was constructed on Proterozoic Mazatzal province basement (ca. 1.7-1.6 Ga). As the system evolved, progressively higher mantle-derived heat flux drove underplating and remelting of previously stagnant crustal material.

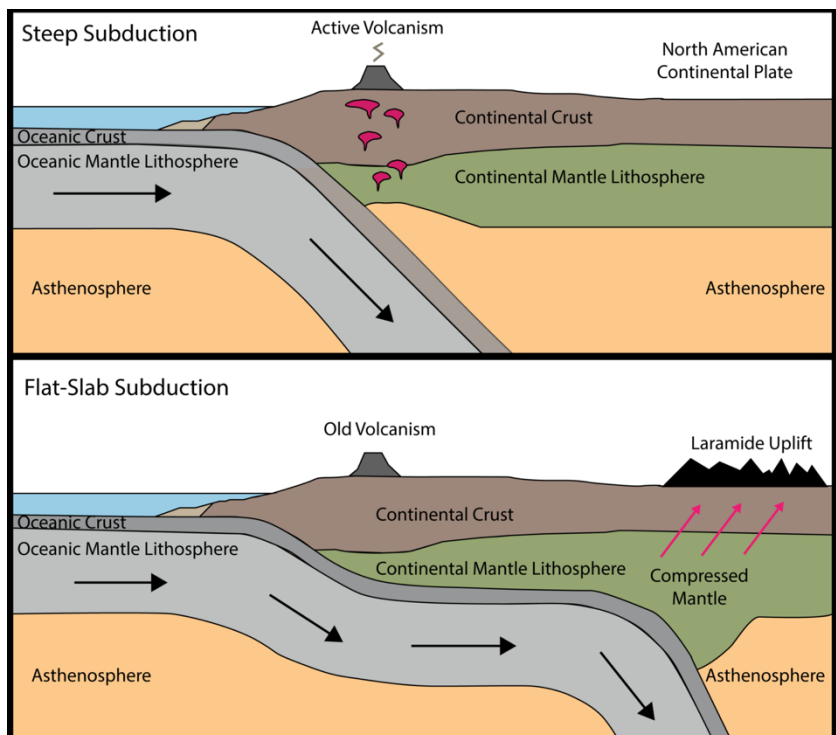


Figure 2. Schematic cross-sections contrasting steep and flat-slab subduction geometries of the Farallon plate beneath the North American continental plate. Top panel depicts steep subduction, in which the descending slab generates decompression melting at depth.

Rift subsequently fragmented the original outflow sheets, so what were once laterally continuous ignimbrite deposits are now preserved as discontinuous exposures across fault-bounded basins (McIntosh et al., 1992).

3. Magma Processes

The MDVF records a fundamental shift in magmatic character over its initial 2.7-million-year episode, from crystal-poor melt extraction to eruption of the crystalline mush itself (Figure 3).

Early Phase (36.5-35.4 Ma)

The earliest eruptions from the Organ and Dona Ana calderas produced crystal-poor, high-silica rhyolites representing interstitial melts extracted from a partially crystalline mush, likely sourced from partial melting of garnet-free, amphibole-bearing mafic lower crust. Elevated fluorine and lithium contents, with quartz-hosted melt inclusions in the Cueva Tuff reaching up to 0.5 wt% F and 0.7 wt% Li, produce a distinctive

Models for Slab Removal and Magma Generation

Two primary models have been proposed for the transition from subduction-related magmatism to widespread silicic volcanism (Figure 2). The first invokes decompression melting of upwelling asthenosphere following slab removal. The second calls on conductive heating of the cold, hydrated subcontinental lithosphere by normal-temperature asthenosphere. These are not mutually exclusive; the MDVF record suggests both operated in sequence (Farmer et al., 2008; Chapin et al., 2004).

Basin and Range extension and development of the Rio Grande

topaz rhyolite geochemical signature (Verplanck et al., 1995). Storage temperatures exceeded 850 °C, alkali feldspar compositions cluster in the Or20-50 range, and large negative Eu anomalies with Ba concentrations as low as 14 ppm indicate extensive feldspar fractionation and efficient melt-mush separation.

Late Phase (35.3-33.8 Ma)

By 35.3 Ma the system had cooled and stiffened. The Kneeling Nun Tuff (KNT), the largest eruption of the episode at ~900 km³, erupted the crystalline mush itself rather than a crystal-poor cap melt, with phenocryst contents of 32-58% and a two-feldspar assemblage (alkali feldspar + plagioclase) alongside quartz and hornblende, indicating near-eutectic storage at 670-820 °C (McIntosh et al., 1992). Alkali feldspar Or content shifts to Or50-70. The most likely trigger was injection of basaltic magma into the base of the silicic system, reheating and destabilizing material that had been near-frozen in the crust (Bachmann and Bergantz, 2006).

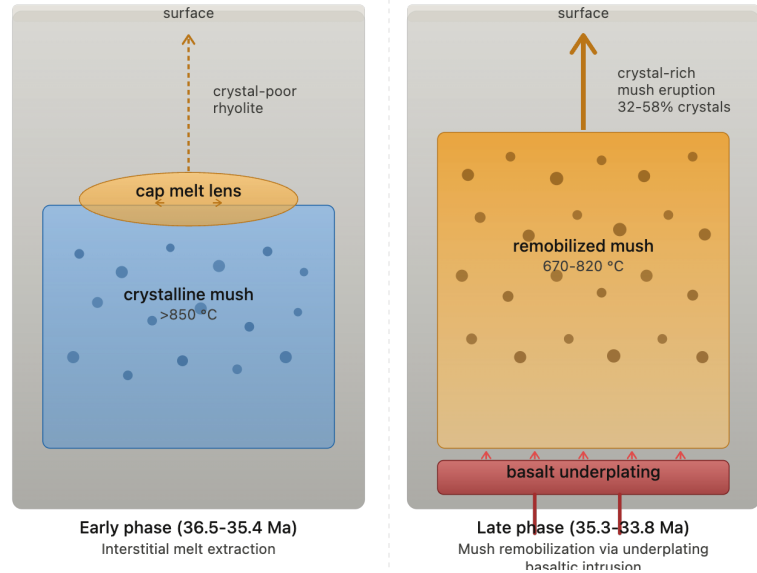


Figure 3. Schematic cross-sections comparing early and late eruptive phases of the MDVF magmatic system.

Table 1. Comparison of Early and Late Eruptive Phase Magma Characteristics

Feature	Early Tuffs (36.5-35.4 Ma)	Late Tuffs (35.3-33.8 Ma)
Mineral Assemblages	Single-feldspar; minor quartz; trace biotite/plagioclase	Two-feldspar; quartz; hornblende/amphibole
Storage Conditions	Crystal-poor melt lenses above crystalline mush	Crystalline mush near eutectic minimum
Estimated Temperatures	>850 °C	670-820 °C
Thermodynamic Triggers	Interstitial melt extraction	Mush remobilization via mantle underplating
Feldspar Or Content	Or20-50	Or50-70

4. Volcanic Products and Stratigraphy: Regional Context and the Chiricahua Mountains

The 36.5-33.8 Ma MDVF episode produced a minimum total erupted volume of approximately 1,350 km³ across at least 15 distinct events distributed across the Organ, Dona Ana, and Emory calderas and the extra-caldera Bell Top Formation (McIntosh et al., 1992). The broader mid-Tertiary ignimbrite flare-up driving this activity extended well beyond New Mexico (Figure 4). The Chiricahua Mountains of southeastern Arizona represent a direct expression of that same tectono-magmatic episode and provide an immediate field analog for the processes described in this report.

The Turkey Creek Caldera and Rhyolite Canyon Tuff

The defining volcanic event of the Chiricahuas is the eruption of the Rhyolite Canyon Tuff (RCT) and collapse of the Turkey Creek Caldera at approximately 26.9 Ma (du Bray et al., 1991), placing it roughly 8-10 million years after the main MDVF pulse but within the same long-lived regional flare-up driven by Farallon slab rollback. The RCT consists of 500-1,000 km³ of rhyolite erupted from a normally zoned reservoir, with compositions becoming systematically less evolved over time as progressively deeper reservoir levels were tapped (du Bray, 2004). This zonation directly parallels the two-phase extraction model documented in the MDVF: crystal-poor cap melts erupted first, followed by less evolved, crystal-rich material from deeper in the system.

Caldera collapse was immediately followed by emplacement of a dacite porphyry intrusion, likely a thick laccolith, into the caldera fill and extrusion of dacite along ring-fracture feeders (du Bray et al., 1991). The crystal-poor rhyolite and crystal-rich intrusion appear to represent coeval magmas that coexisted in the source reservoir, rhyolite over dacite, separated by a sharp interface



Figure 4. Ignimbrite outcrop in Tenerife, Spain. Note the light color, well sorted clasts, welded by fine-grain sized particles and larger clasts (lapilli) within the ash matrix.

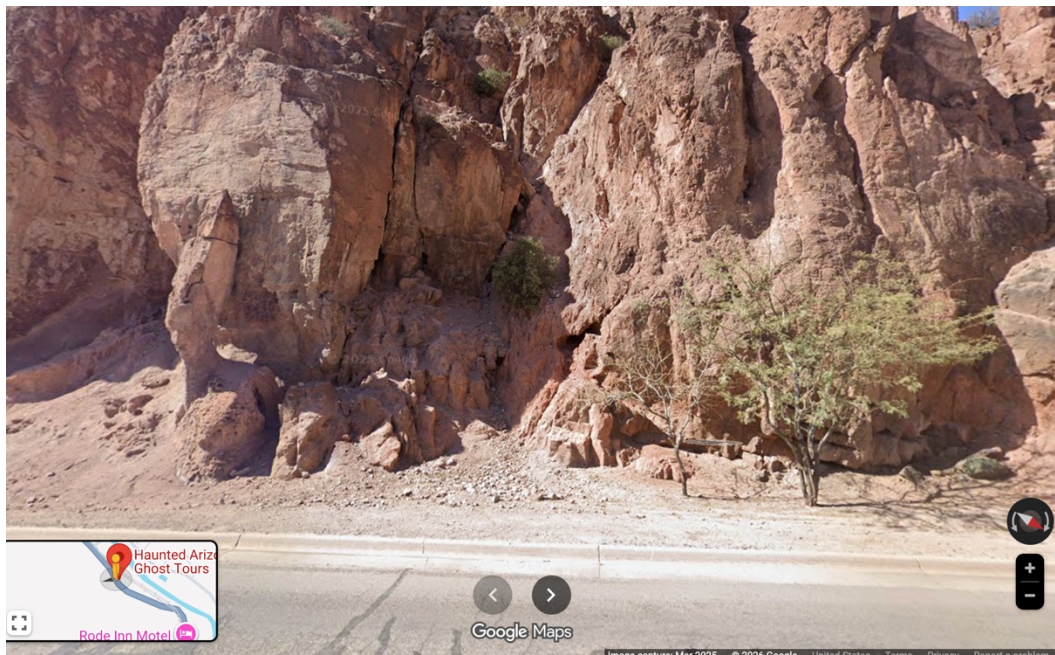


Figure 5. Volcanic products of the Mogollon-Datil volcanic field, as seen from the spooky Haunted Ghost Tour viewpoint. Credit: Google Earth

(Dilles et al., 2014). This rhyolite-over-dacite architecture mirrors the mush-plus-cap-melt geometry of the MDVF calderas, and the dacite intrusion represents the plutonic residue left behind after eruption of the silicic cap. The RCT mineralogy is a quartz-sanidine rhyolite ash-flow tuff consistent with the high-K, high-silica character of the broader Boot Heel volcanic field (du Bray et al., 1991).

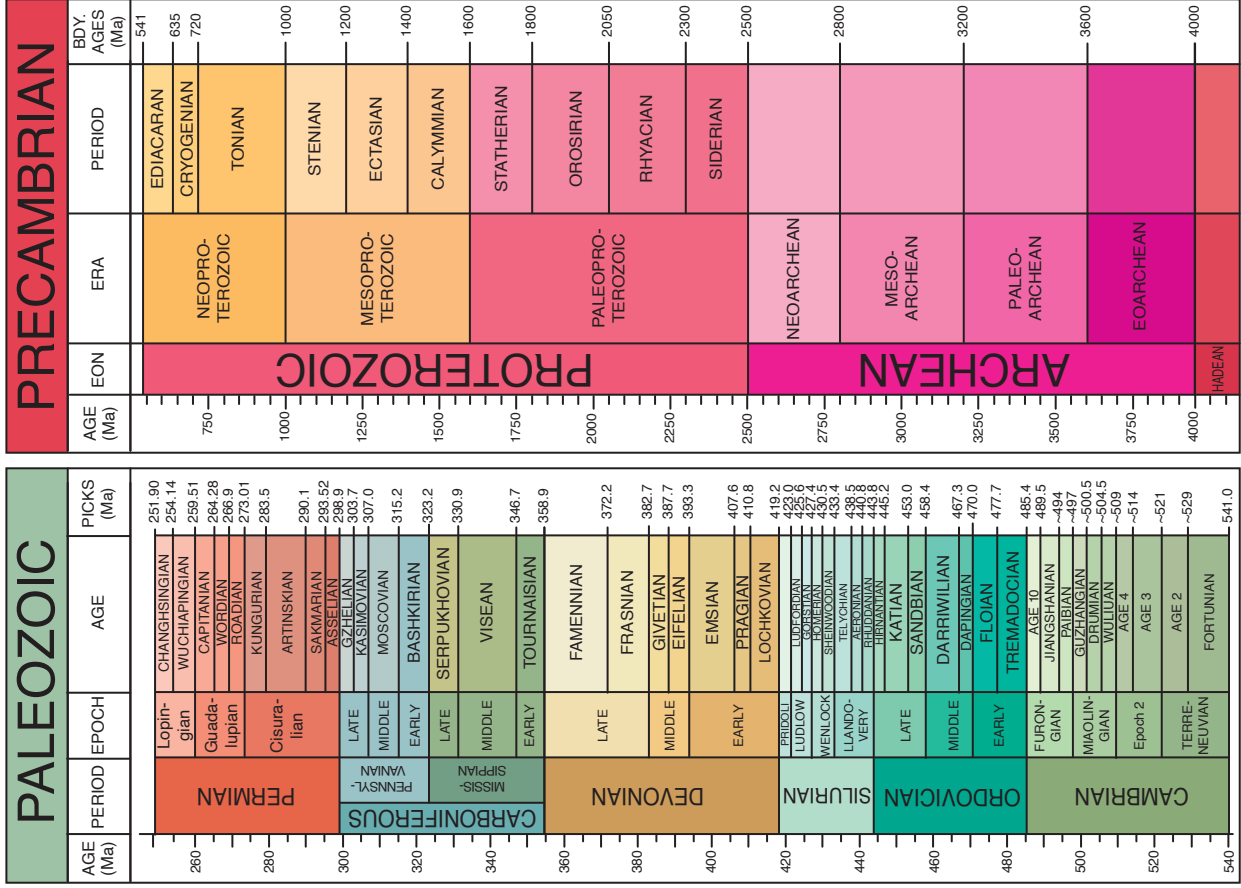
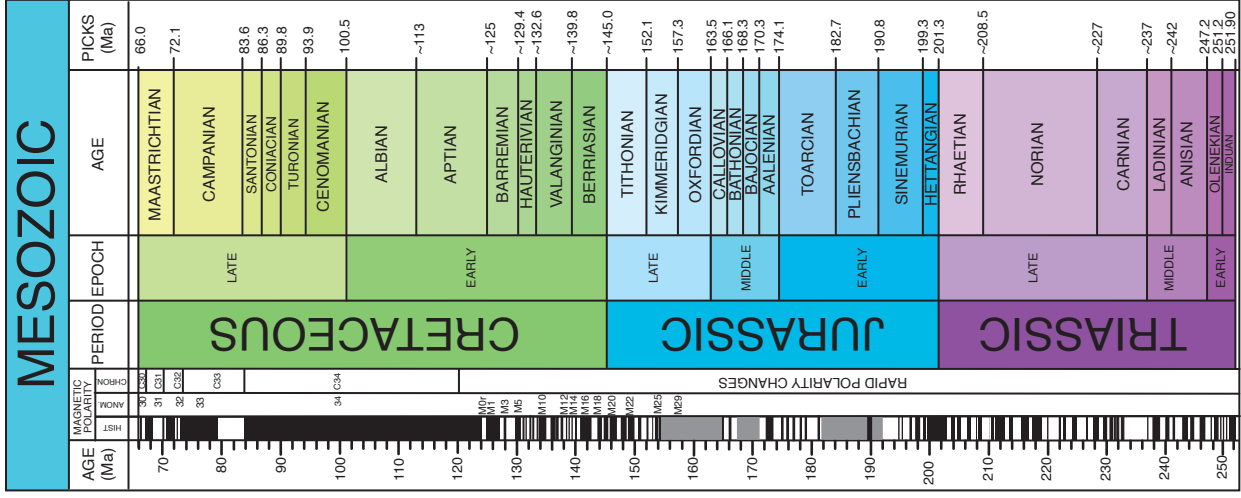
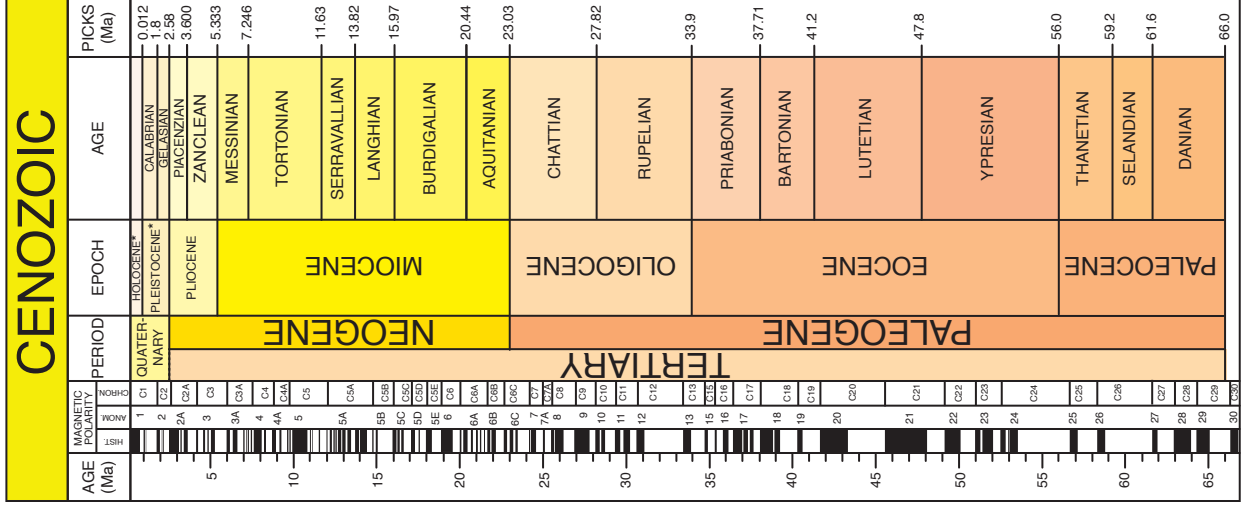
Outcrop at the Haunted Ghost Tours

The welded RCT forms a deposit at least 490 m thick (NPS, 2024). Upon cooling, vertical contraction joints formed in the resistant tuff and provided conduits for water infiltration. Over 27 million years of weathering and erosion, differential breakdown along those joints produced the stone spires, columns, and hoodoos of Chiricahua National Monument. Those hoodoos are the direct erosional legacy of a supereruption-scale ignimbrite comparable in volume and eruptive style to the Kneeling Nun Tuff. The Turkey Creek system also records the same subduction-to-extension tectonic transition documented earlier in the MDVF, with geochemistry consistent with a transitional calc-alkalic to alkalic setting (du Bray et al., 1991).

Generative AI (Claude, Anthropic) was used to assist with document formatting, editing, and figure 3. All scientific content, interpretations, and sources were author's own.

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*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages: Calabrian from 1.8 to 0.774 Ma, Chibanian from 0.774 to 0.129 Ma, and Late from 0.129 to 0.0117 Ma. The Holocene is divided into three ages: Greenlandian from 0.0117 to 0.0082 Ma, Northgrippian from 0.0082 to 0.0042 Ma, and Meghalayan from 0.0042 to present. The geologic community broadly recognizes the Anthropocene as a proposed new time interval of Earth history, partly coincident with the Holocene. Currently, the Anthropocene has an informal designation, with a proposed age span extending from the present to a beginning point between ca. 15,000 yr B.P. and as recent as 1960 CE. The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries usually follow the Gradstein et al. (2012), Cohen et al. (2012), and Cohen et al. (2013, updated) compilations. Numerical age estimates and picks of boundaries usually follow the Cohen et al. (2013, updated) compilation. The numbered epochs and ages of the Cambrian are provisional. A " - " before a numerical age estimate typically indicates an associated error of ± 0.4 to more than 1.6 Ma.

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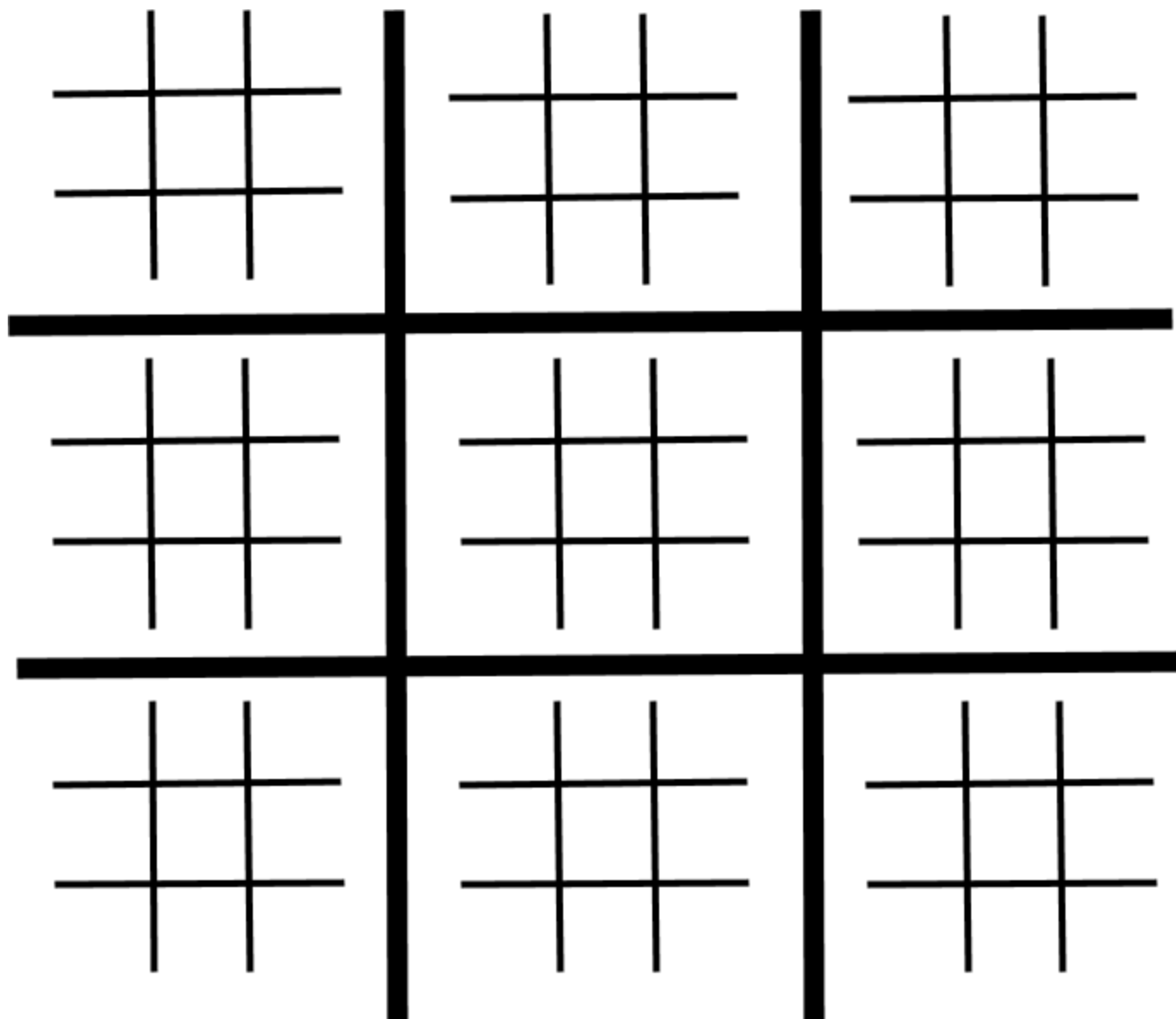
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SUPER TIC TAC TOE

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



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8			7	6			2	
							4	7
1		7	4				75	

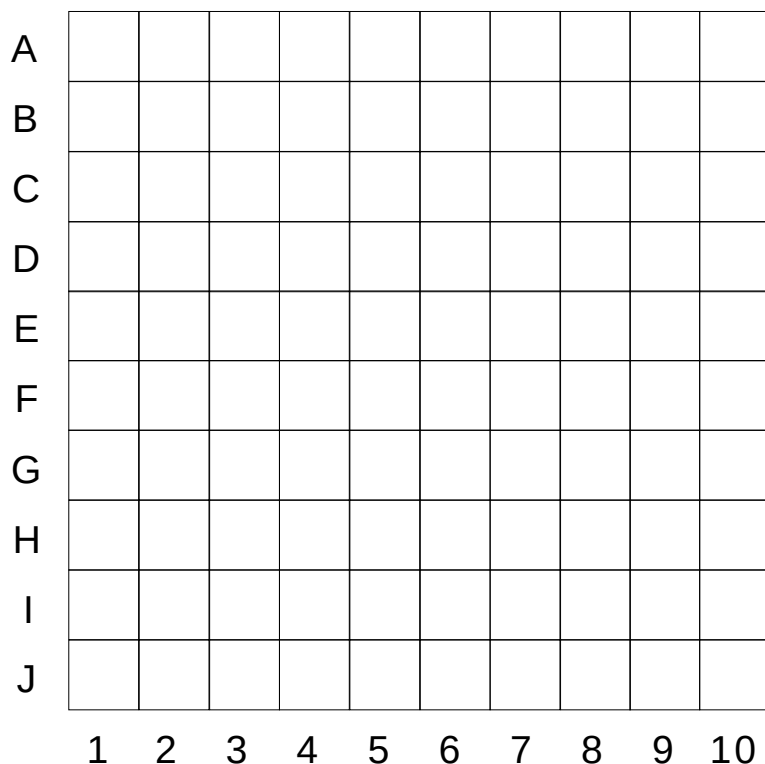
Battleship



Another fun activity from:

www.funorama.com

Defensive Grid



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

1 - Aircraft Carrier



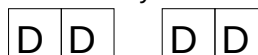
1 - Battleship



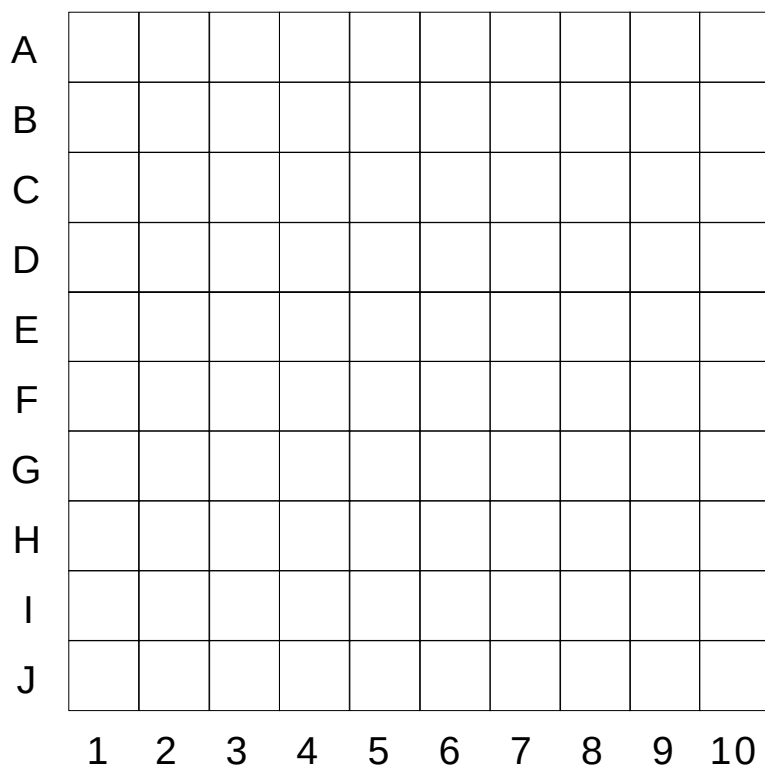
1 - Cruiser



2 - Destroyers



Offensive Grid



Instructions (2 Players Required):

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

