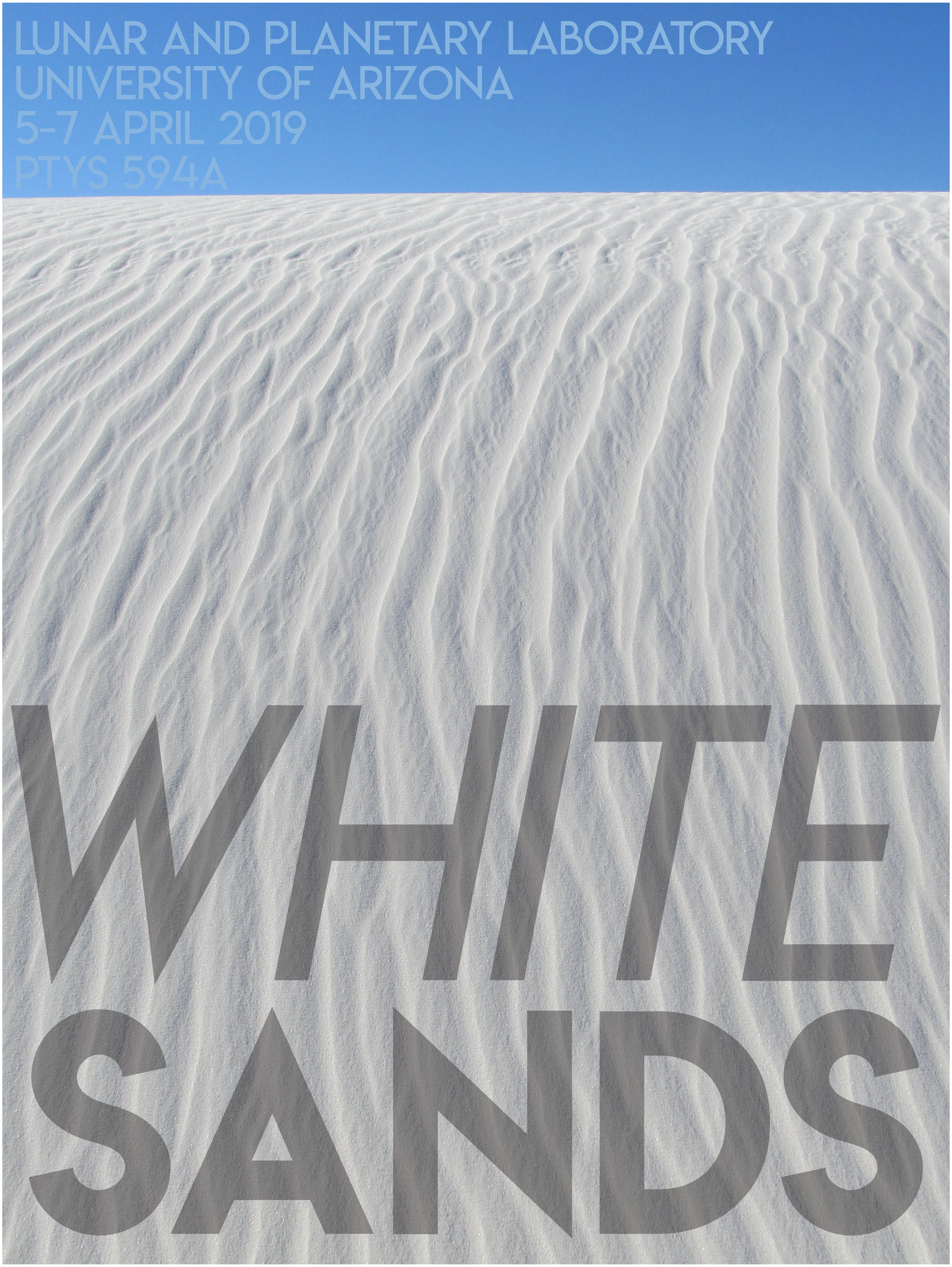


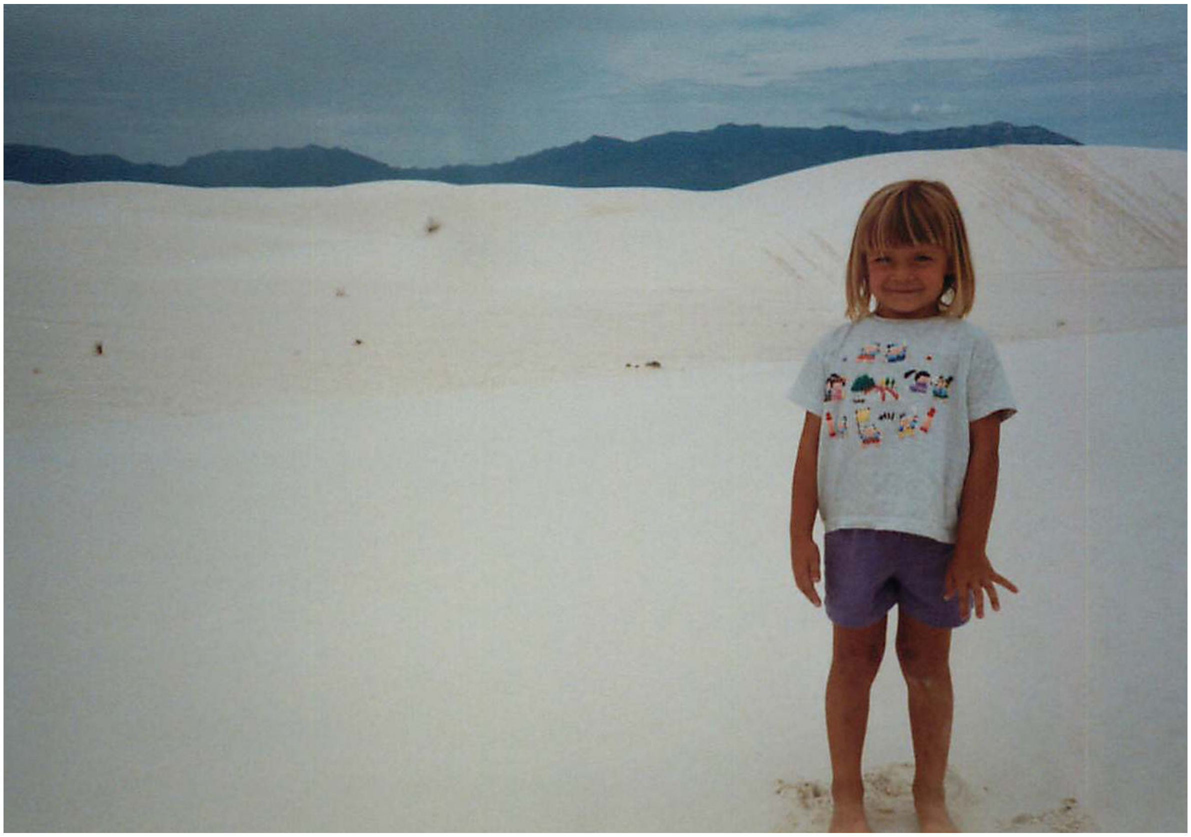
LUNAR AND PLANETARY LABORATORY
UNIVERSITY OF ARIZONA
5-7 APRIL 2019
PTYS 594A

WHITE SANDS

White Sands National Monument was one of my favorite places growing up. My family would regularly take Southwest trips in the summers, every few years or so. Seeing the rocks, seeing the wide open sky, all under sweltering heat while packed in a white mini-van was the meaning of summer. White Sands NM particularly took my attention because the huge dunes (to a 5 year old) were just barely mountable and sledding down with my sisters was the most fun I could imagine.

Now, returning 20 years after the picture below was taken, I am thrilled to see the region with a different lens. After visiting geologic sites as a child and as an adult, I can say that learning the mechanisms that formed the sights only increases my wonder and awe for the Earth. The geologic processes that dominate the Earth's surface are based in simple laws of physics but create such vast diversity across not only Earth, but all terrestrial planets. I am, of course, still very excited about running down the dunes and feeling gypsum sand under my feet.

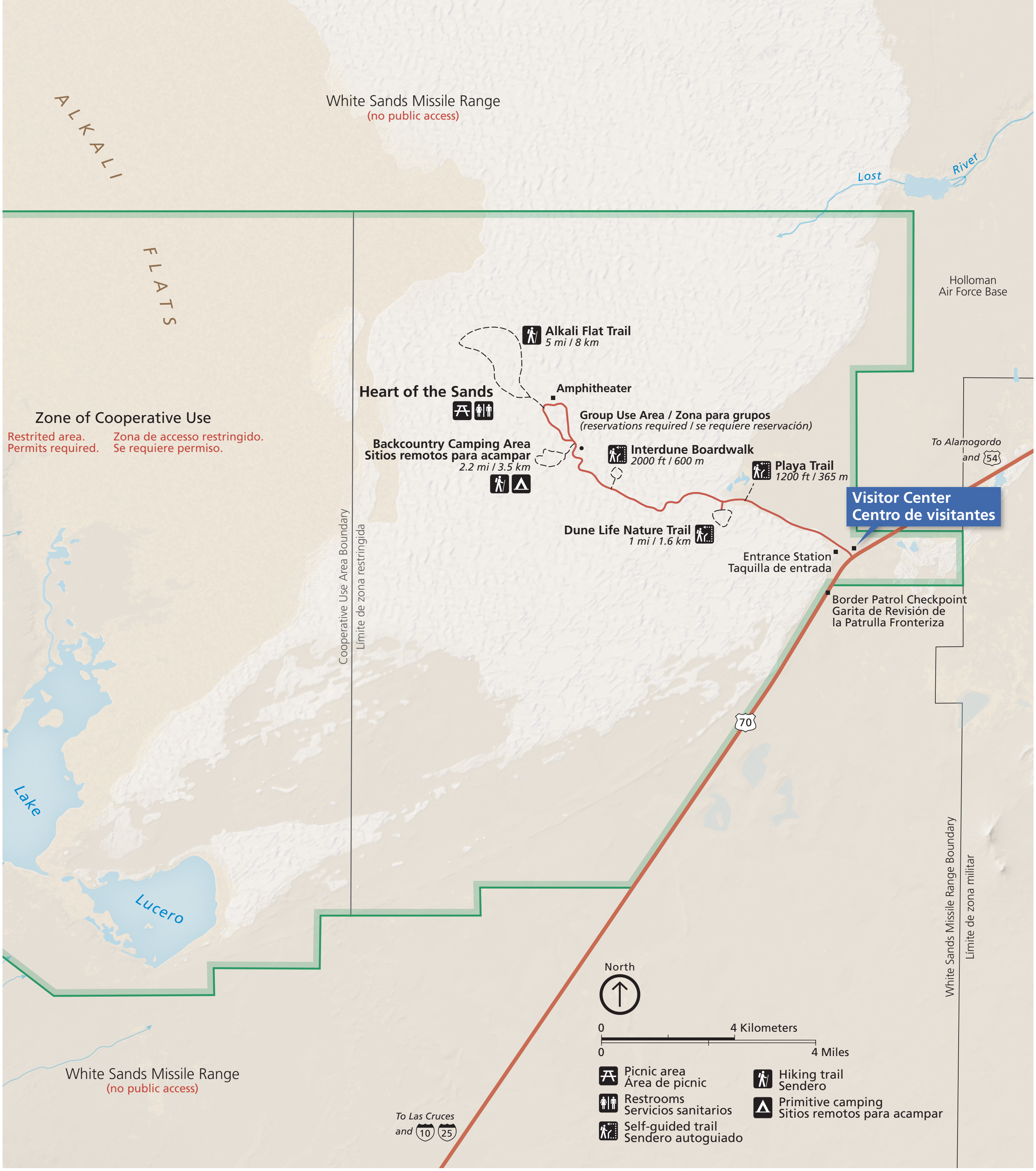
–Amanda Stadermann



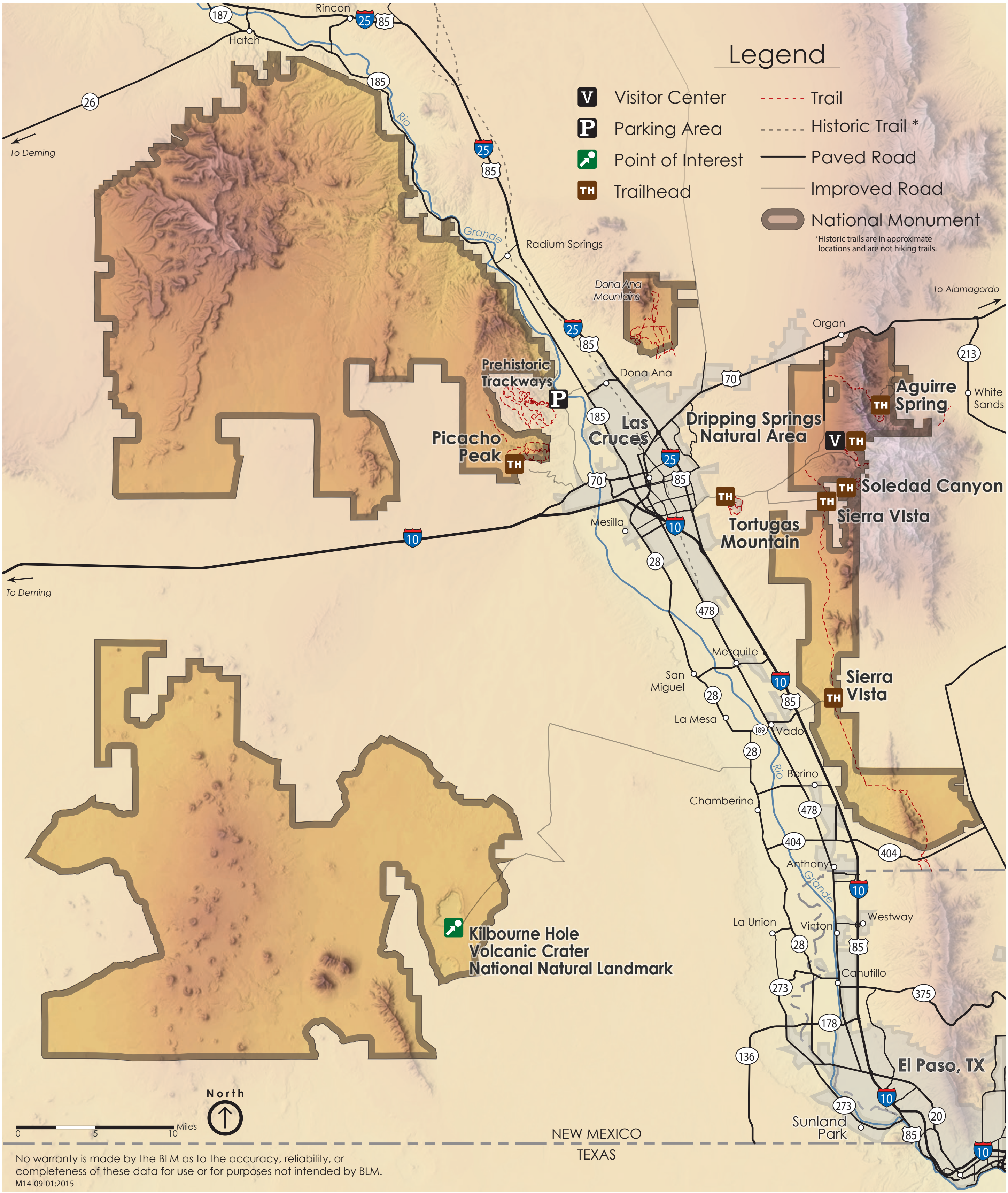
We acknowledge White Sands and Organ Mountains-Desert Peaks National Monuments are in what is the traditional, occupied, and unceded territories and ancestral lands of the Mescalero Apache, the Chiricahua Apache, the Pescado, and the Mansos people. Respect the land, respect the water, and remember those who were here first.

Table of Contents

White Sands Map



Organ Mountains-Desert Peaks Map



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Schedule

Friday April 5, 2019

All times in MST

7 AM Arrive at LPL loading dock with all your gear

8AM Leave the loading dock. Drive south on Campbell, continue south on Kino. Take the I10 East towards El Paso – drive 245 miles.

Take exit 116, keep traveling East on NM 549 and continue when it becomes county road B004. This road parallels the freeway for 2-3 miles and then veers abruptly south and later veers back to head southeast. After ~9 miles form the freeway we take a right turn to cross the railroad and then a left to get back on B004. Continue driving SE on the south side of the tracks (roads B001 and B002). After a little over 7 miles we'll be at the Aden Lava flow. Take a right turn just before the flow reaches the tracks. Drive 200m SW to an 'intersection' and stop.

1PM Lunch at the Aden lava flow

2PM Check out inflated structures and polygons near the periphery of the flow

Patrick Lava Flow Inflation Mechanisms and Domes, Pits, Rises, Tumuli, etc.
Laci Flora and Fauna of Southern NM

Drive ~4 miles further SW down this dirt road. There's a turn-off to the left that leads up to the caldera. This road may or may not be drivable – either drive or walk about half a mile on this road to get to the rim – avoid stepping on any rattlesnakes (Seriously? Yes, seriously.).

Here we can hike around the interior of the central vent of the Aden Flow.

Allison Rio Grande Rift History
Joana Aden Volcanic Field and Volcanism in Southern NM for the last few Ma

5PM Back to the vehicles and backtrack to the railroad. Take a right and drive 4 miles. There's a turn off to the right, take it and drive ~1.6 miles until the road dead-ends at our campsite. If this road is blocked we'll backtrack and use an alternate.

Kyle Human History of Southern NM

5.30PM Camp at the Aden Lava Flow. Elevation: 4400 feet.
(Sunset is ~6.22pm.)

Schedule

Saturday April 6, 2019

All times in MST

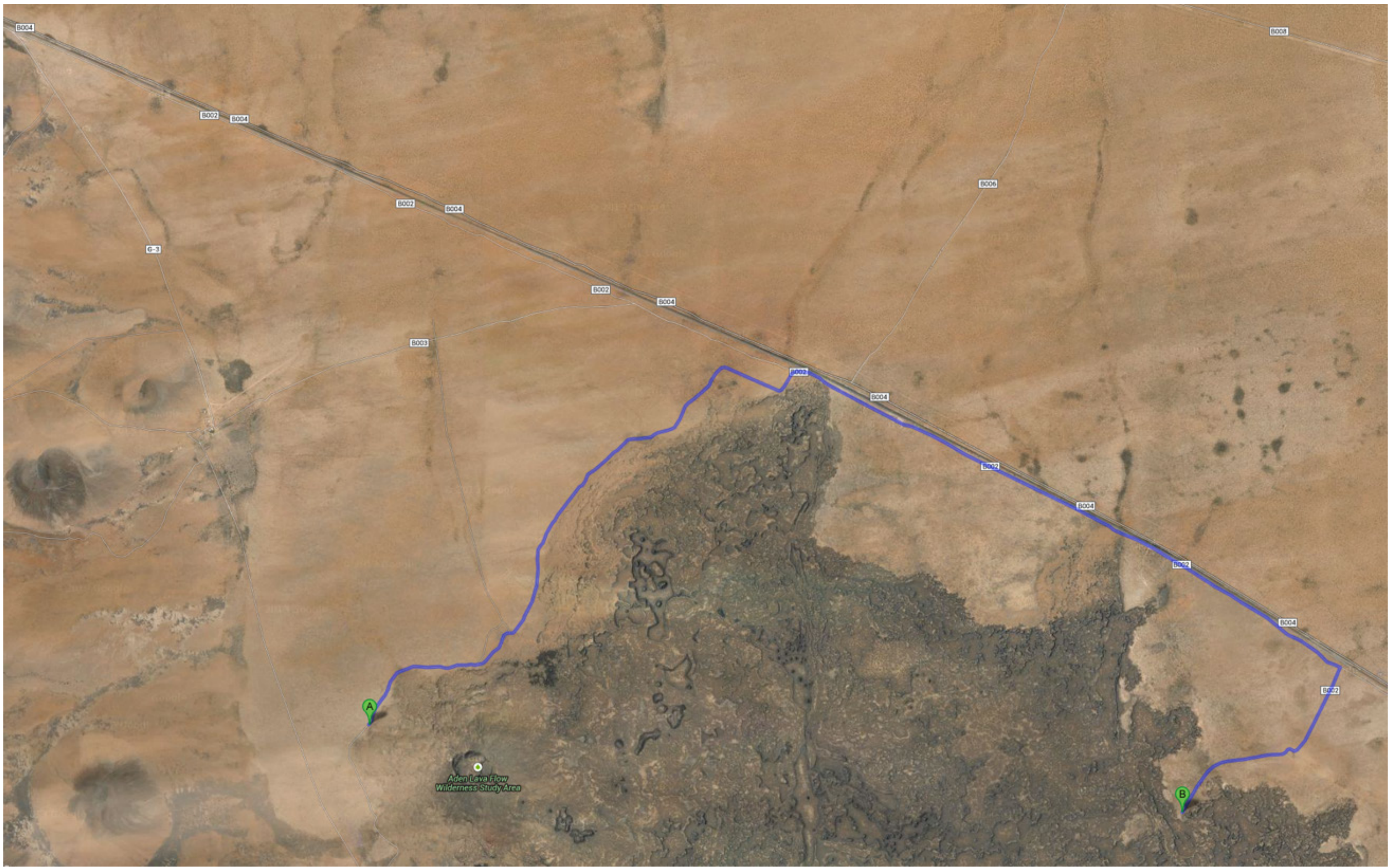
8AM	Leave the campsite (sunrise is ~6 am). Backtrack 1.6 miles to the railroad, take a right and drive SE 12 miles alongside the tracks. Take a right at Lanark onto county road A011 and drive 8 miles to Kilbourne Hole.
9AM	Arrive at Kilbourne Hole.
Xiaohang	**Physics of Volcanic Surges**
Mattie	**Volcanic Surge Bedforms**
Amanda	**Mantle and Lower Crustal Xenoliths**
12PM	Lunch
1PM	Leave Kilbourne Hole
	Backtrack to the railway line. Take a right and continue SE on county roads A12, A14 and A17 for 11 miles. Turn left on Industrial Drive and cross the railroad, take a right at the T-junction onto Airport Road and then a left onto NM136 E (later turns into TX 178 E/Artcraft Road). Join the I10W after about 7.5 miles. Drive 27 miles, transfer to I25N and drive another 6 miles. Take exit 6 onto US70; drive 49 miles to the White Sands Visitor Center.
	(2.5 hrs driving – add 0.5 hour stop)
4PM	Arrive at White Sands (Gates Close at 6PM)
Maureen	**Dune Geomorphology (at roadside stop near dune broadwalk)**
Daniel	**Dune Footprints (at group use area)**
5PM	Camp at White Sands. Elevation: 4000 feet (Sunset is ~6.22pm.)

Schedule

Sunday April 7, 2019

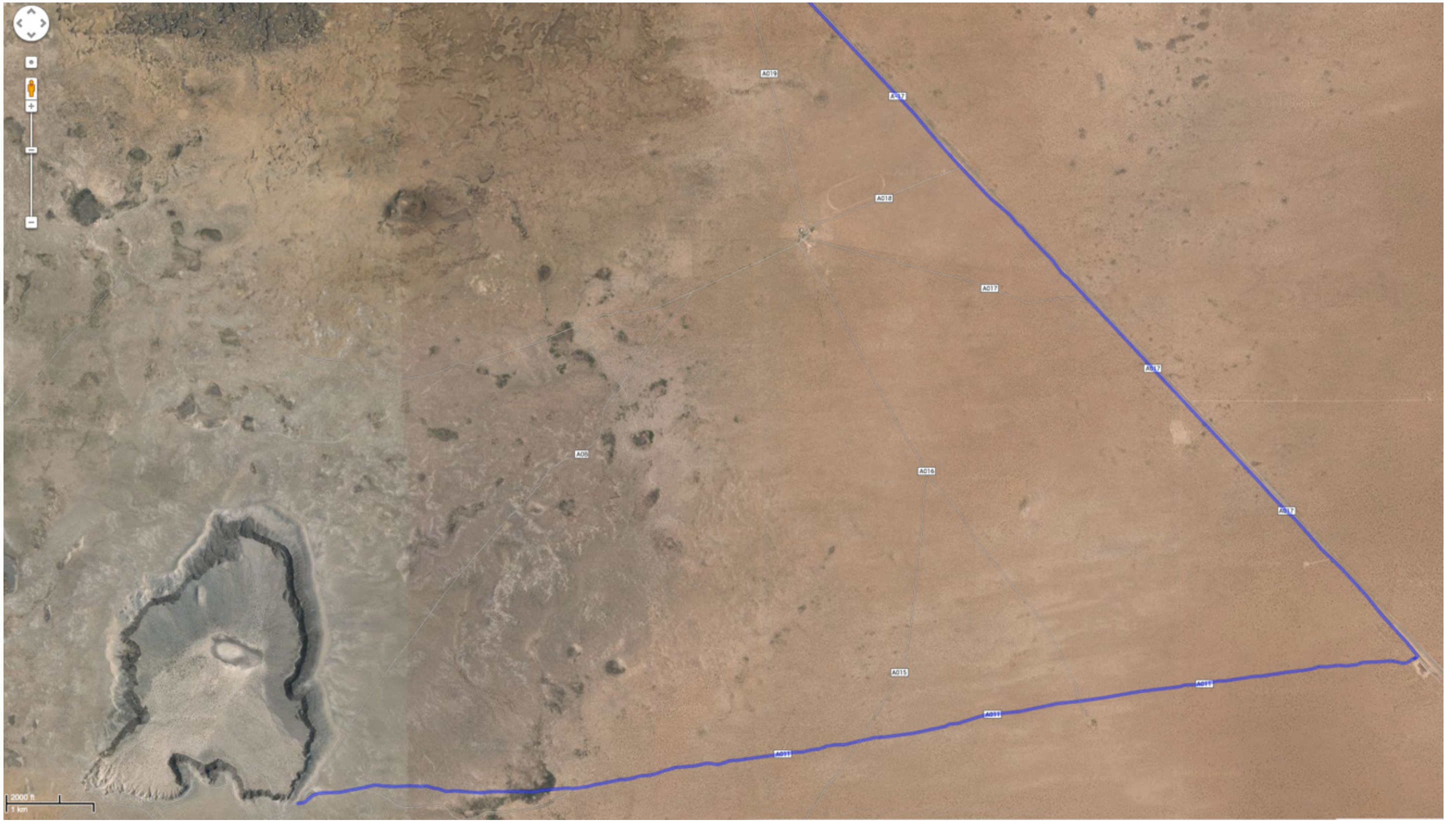
All times in MST-

8AM	Leave the campsite (sunrise at 6am). Drive to Alkali Flat trailhead.
Saverio	**Determining Dune/Ripple Migration Rates from Remote Sensing**
	Hike to Alkali flats – 1hr
Maria	**Climate History of Southern NM for the last few ka**
Adam	**Gypsum Sources and Sinks**
	Hike Back – 1hr
12PM	Lunch
Rachel	**White Sands Missile Range**
1PM	Leave White Sand National Monument
	Drive west on US 70 for 58 miles. Join the I10 West and travel 263 miles, exit Kino Parkway. Go north, Kino becomes Campbell. Turn left into University Blvd ~4 miles after leaving the freeway.
6.00PM	Arrive back at LPL.



Above: Map to Aden Volcanic Field (Friday April 5)

Below: Map to Kilbourne Hole (Saturday April 6)



RIO GRANDE RIFT HISTORY

The Rio Grande Rift represents a tectonic structure emplaced from widespread extension occurring over the past 35-26 million years. From the southern-most edge of the Rocky Mountains, through central New Mexico, the Rio Grande Rift is marked by 3 major basins in a north to south trend, scarped by major fault boundaries and asymmetrical half-grabens that alternate along the rift through transform faults. It is no coincidence that the Rio Grande River follows the north to south trending basins descending southbound from the southern end of the Rocky Mountains in Colorado. This large river erodes through faults, creating canyons, picking up sediments, and eventually making its way into the Gulf of Mexico through the Rio Grande Rift. Not to mention all the NM green chile that it delivers water and nutrients for from farming in these basins! Much like the passage of water through the Rio Grande River, the major cities of New Mexico also reside within the N-S trajectory of the Rio Grande Rift, which has provided a major conduit for native people for thousands of years, and now the Interstate-25. Major cities of New Mexico follow the Rift from the bottom of the Colorado Plateau to the Gulf of Mexico: Albuquerque, Taos, Santa Fe, Espanola, Las Cruces, El Paso, Cuidad Juarez.

THE BASINS

The Rio Grande Rift consists of 3 major basins (all less than 100 Km^2), from N-most to S-most:

- San Luis Basin: (120 km N-S x 40 km E-W) w/ smaller basins inside like the Alamosa Basin, bounded by San Juan and Tusas Mountains to the west, and the Sangre de Cristo mountains to the East
- Espanola Basin: (smallest)
- Albuquerque Basin: (largest 150 km N-S x 86 km E-W) oldest, contains a 7,350 meter-thick unit of Paleogene (66-43 Ma) clastic sediment units deposited on Precambrian (4.6 Ga – 551 Ma) basement (Figure 2) + pre-rift volcanic deposits in the southern portion, the north has volcanic deposits during rifting activity

Moving through the southern portion of the rift, it becomes defined by a smaller network of less topographic-distinct alternating basin & ranges, which becomes indistinct with the Basin & Range Province (Russell & Snelson 1994; Keller et al. 1999).

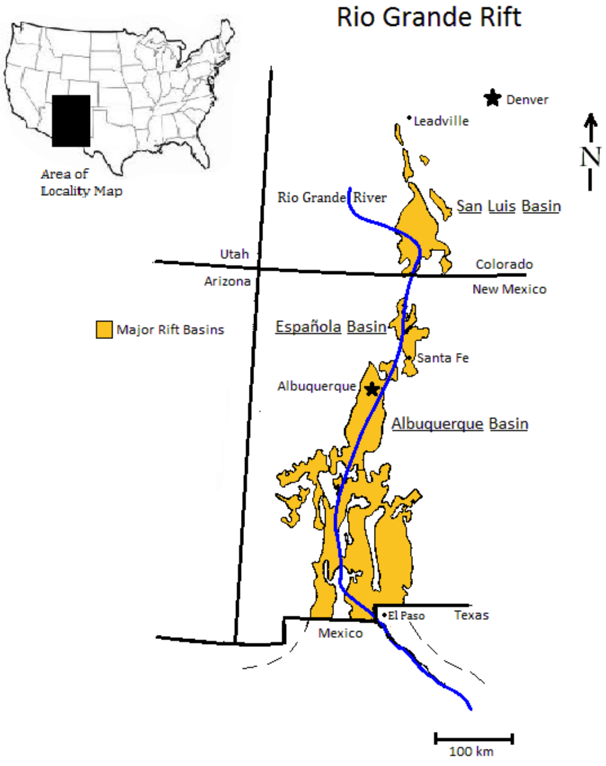


Figure 1: Locator map for the Rio Grande Rift

CROSS-SECTIONAL GEOMETRY

In cross-section, the geometry of the basins within the Rio Grande are asymmetrical half-grabens with major fault boundaries on one side and a downward hinge on the other, which side of the rift that has the fault or the hinge alternates back and forth along transfer faults and tends to trend across the rift to connect the major basin bounding faults/in between basins, and sometimes within basins (Russell & Snelson 1994).

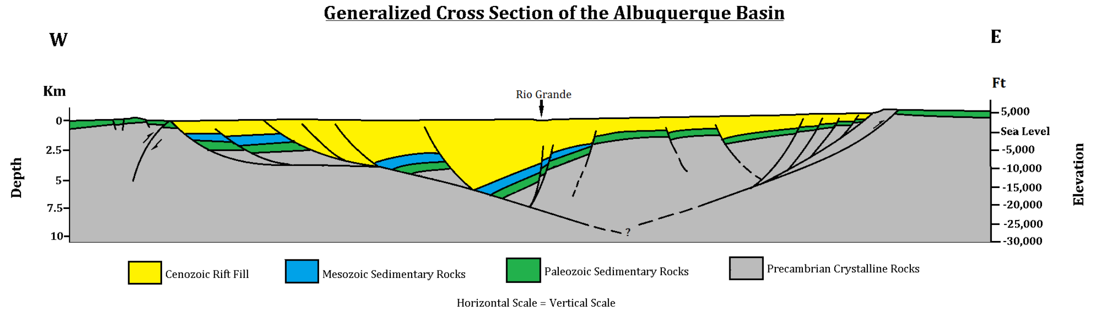


Figure 2: The depositional units of the Albuquerque Basin.

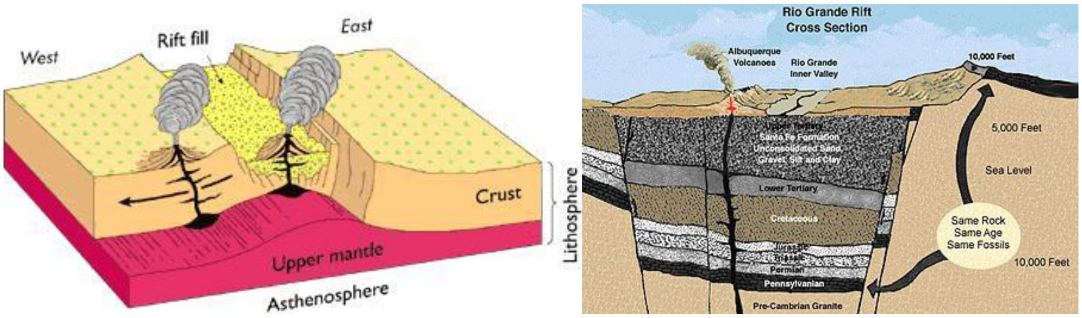


Figure 3: Left: Cross-section of generalized rift. Right: Cross-section of the Rio Grande Rift Albuquerque Basin showing geologic units as well as the normal-faulting down-block drop. Image credit: USGS.

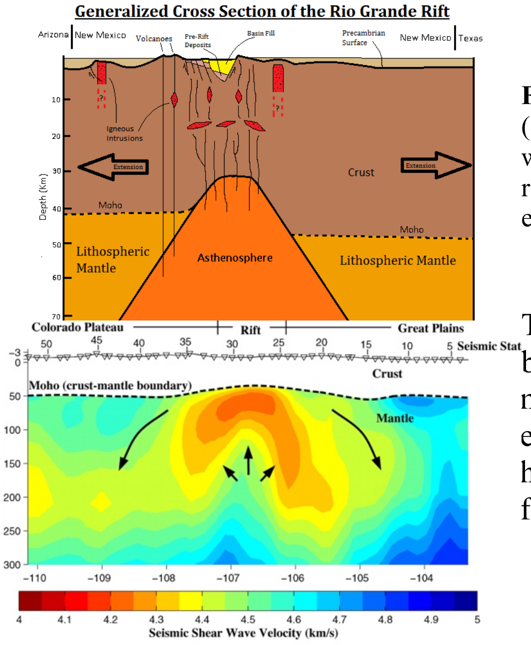


Figure 4: Bottom: Differences in density, shear waves travel faster (dependent on bulk & shear modulus) deep, hot lower-density material welling up from asthenosphere→ the shear waves move slower in rifting zone. Top: cross-section showing hot asthenosphere rising up as extension occurs. (Wilson et al. 2005)

The dropped down block of the normal fault makes the basins (graben), while the uplifted portions make the mountains on either side of the Rio Grande Rift (horst). The extension pulling part the lithosphere (like taffy) allows the hot mantle material/partial melts to intrude → responsible for most of the volcanism in the rift.

TECTONIC SETTINGS

Complex! Fundamentally, instigated by a major change in the western margin of the North American during Cenozoic (66 Ma-today) that went from a subduction zone, to that of a transform boundary (Keller & Cather 1994; Chapin & Cather 1994).

- The old Farallon plate subducted underneath the North American Plate for ~100 Ma years during late Mesozoic (252-66 Ma) and into the early Cenozoic
- Compressional and transpressional deformation incurred by the Laramide Orogeny (80-35 Ma) went until 40 Ma in New Mexico → the rift itself may have been the coupling/suture between the subduction of the Farallon plate and the overlying North American Plate!
  - Crustal thickening occurred from the compressional forces
- After Laramide Orogeny, major volcanism occurred throughout entire SW United States: injections of hot magma → weakened lithosphere → allowed for later extension of the region
- Cenozoic extension started at 30 Ma in two phases:
  - Late Oligocene: produced broad/shallow basins bounded by low-angle faults, ~50% crustal extension
  - Middle Miocene: Widespread magmatism in the mid-Cenozoic suggests that the lithosphere was hot and that the brittle-ductile transition was relatively shallow
- Volcanism "plumbing system" in the SW, from upwelling asthenosphere/partial melts
  - Youngest is the Valley of Fires ~5,400 years (Aber 2006)

Is the Colorado Plateau acting like a semi-independent microplate? One possible way of explaining the creation of the Rio Grande Rift is to rotate the Colorado Plateau 1-1.5 degrees in a clockwise direction relative to the N. American craton (Steiner et al. 1998).

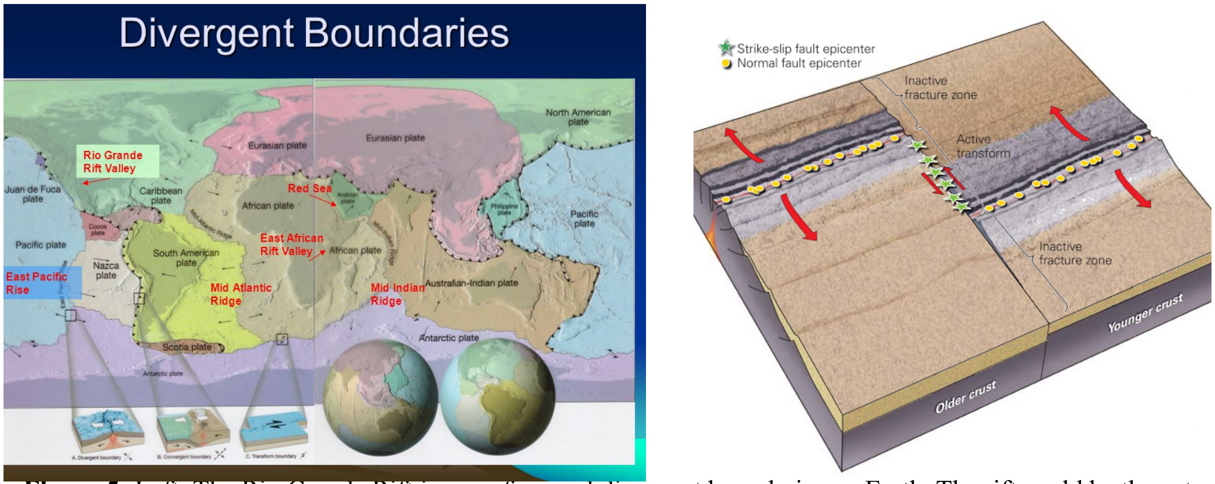
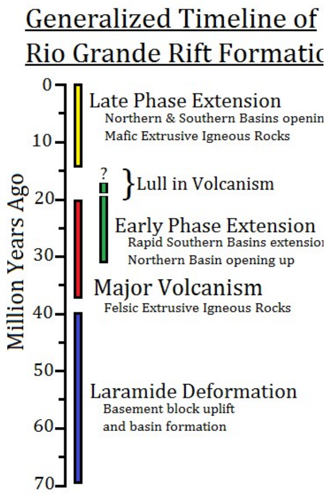


Figure 5: Left: The Rio Grande Rift is one of several divergent boundaries on Earth. The rift could be the suture between the old Farallon plate to the North American plate. The Farallon Plate is now leftover as the Juan de Fuca plate and the Cocos plate. Right: At divergent boundaries, two types of faults form; normal faults along spreading portions and transform faults from the strike-slip displacement. This produces earthquakes; a big one is likely within ~10,000 years in the Rio Grande Rift.



ON THIS FEILD TRIP

From White Sands National Monument:

We are in the Tularosa Basin, between two mountains: to the west we have the San Andres Mtns. and the Sacramento Mtns. to the east, they are both pushed up along normal fault lines and are comprised of Permian Sea (during Paleozoic, 542-251 Ma) sediment deposits (limestones with fun fossils). When the Rio Grande Rift formed, this basin became isolated from the shallow sea that was present, run-off from these uplifted mountains produced Lake Otero which has since evaporated, leaving behind the selenite (the crystalline form of gypsum).

Along the Interstate:

For our field trip, we are within the Albuquerque Basin, mostly in the area where the ambiguity of the Basin & Range Province blurs the distinction of the Albuquerque Basin. On either sides of the I-25, the mountains ranges are hoisted up through the normal faulting (horst) as we drive along the down-block (graben). Sometimes you can see the transformed offsets in the uplift.

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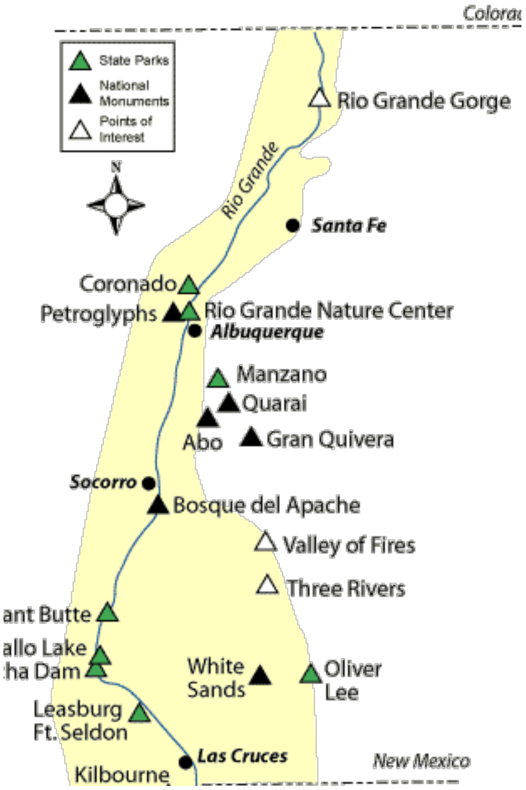


Figure 6: Rio Grande Rift basins with New Mexico State Parks and monuments (Keller & Cather 1994)

Aden Volcanic Field and Volcanism in Southern New Mexico for the last few Million Years

Joana Voigt

Geographical and Geological Background:

The Potrillo Volcanic Field located in Doña Ana County in the Southwest of New Mexico is a monogenetic volcanic field approximately 40 km from Las Cruces. The whole field occupies 1000 km^2 and is composed of the West Potrillo volcanic field with Mt. Riley Maar and Malpais Maar; the Aden Lava Flows with the Aden shield; the Gardner Flows with Kilbourne Hole and Hunt's Hole; and the Black Mountain (see Figure 1). The field exhibits more than 150 cinder cones, five maars, and associated lava flows [2]. The Potrillo Volcanic Field occupies the southernmost part of the Rio Grande rift system [1].
In general, the western part of the Potrillo Volcanic Field is much older (260–900 ka, [3]) than the young eastern fields (0–80 ka; [3]). The West Potrillo Volcanic Field is composed of more than a 100 cinder cones with a basaltic composition. Whereas the Aden–Afton in the east presents one of the youngest volcanic deposits in New Mexico [1, 3].

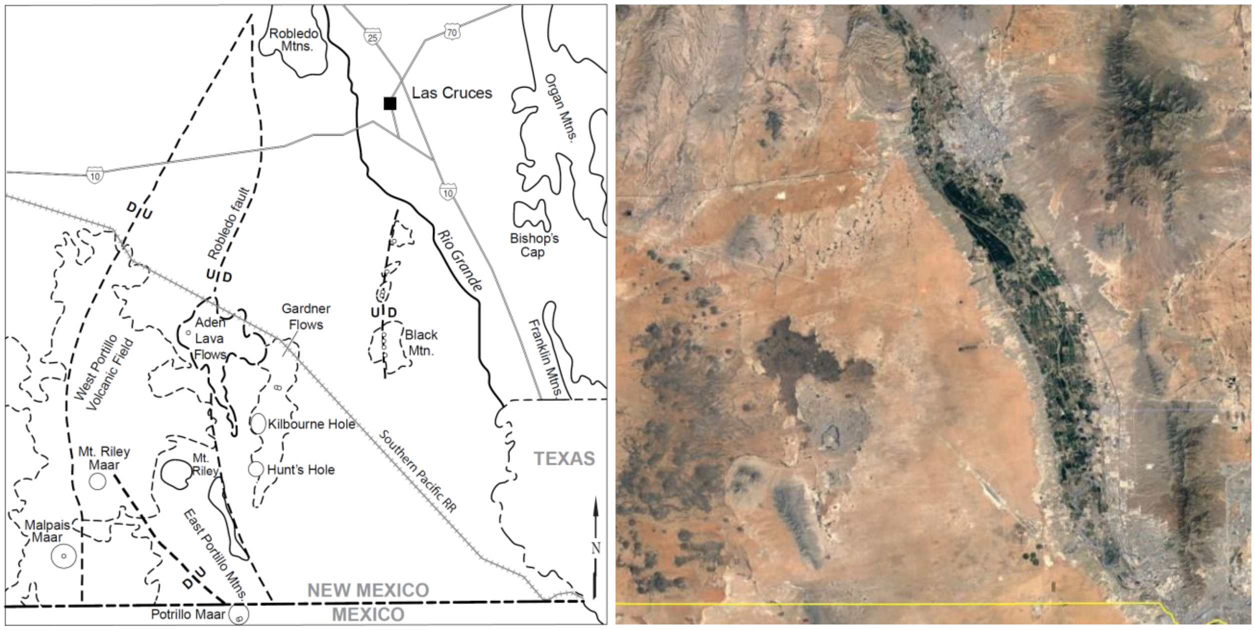
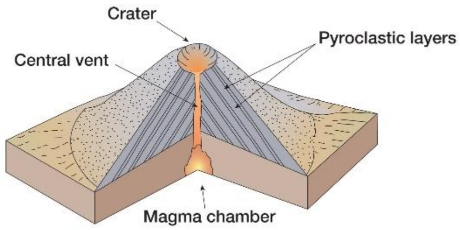


Figure 1: Left: labeled map for geographical and geological context. Right: Satellite image from the same section like image on the left [1]. Dark fields in the Southwestern part of the image represents the Potrillo volcanic field including from west to east: The West Potrillo volcanic field with Mt. Riley Maar and Malpais Maar; Aden Lava Flows with the Aden shield; Gardner Flows with Kilbourne Hole and Hunt's Hole; and Black Mountain.

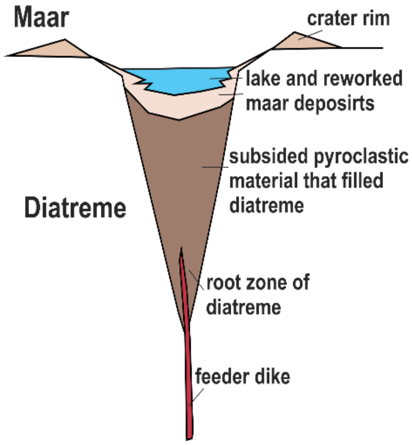
Volcanic Types:

In the Potrillo Volcanic Field were four different types of volcanic products emplaced: Cinder Cones; Maar; Shield Volcano, and associated lava flows.



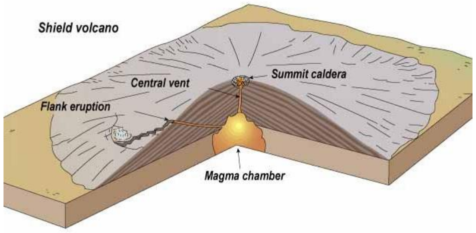
Cinder Cone:

- Steep (slopes between 30–40°) sided cone with a conical shape
- Built of loose pyroclastic debris including ash, cinders/scoria, and clinkers surrounding the vent
- Glassy and highly porous fragments



Maar:

- A small, low-standing type of volcano
- Very wide, bowl-shaped crater
- Crater floor lies below level of surrounding topography
- Formed in presence of water = Phreatomagmatic eruption
- Steam explosions excavate a large crater
- When rising magma comes in contacts with & mixes with ground- or surface water -> diatreme



Shield Volcano:

- Low profile edifice
- Mostly composed of lava flows
- slow-moving, effusive eruptions
- highly fluid basaltic lavas with low gaseous content

Aden Volcanic Field:

The Aden Volcanic Field is the youngest volcanic material exposed to the surface and covers 75 km^2 [1]. The Aden basalts are super imposed by the Afton basalts and were dated to be 72,000–81,000 by K-Ar chronology [4], including the Garten Crater complex, Kilbourne and Hunt's Holes [1,3]. The latter are both formed by Phreatomagmatic eruptions resulting in maars. The results in dating of the Aden flow are ambiguous. The lava lake deposits filling the Aden crater were dated to be 0.53 Ma based on Ar-K geochronology [4]. However, the geomorphology suggests a much younger formation age and further age estimates based on ^{3}He surface-exposure gave ages ranging from 18.3–15.7 ta [5] to 22 ta [6], which is more consistent with the observed geomorphological features (see Figure 5).

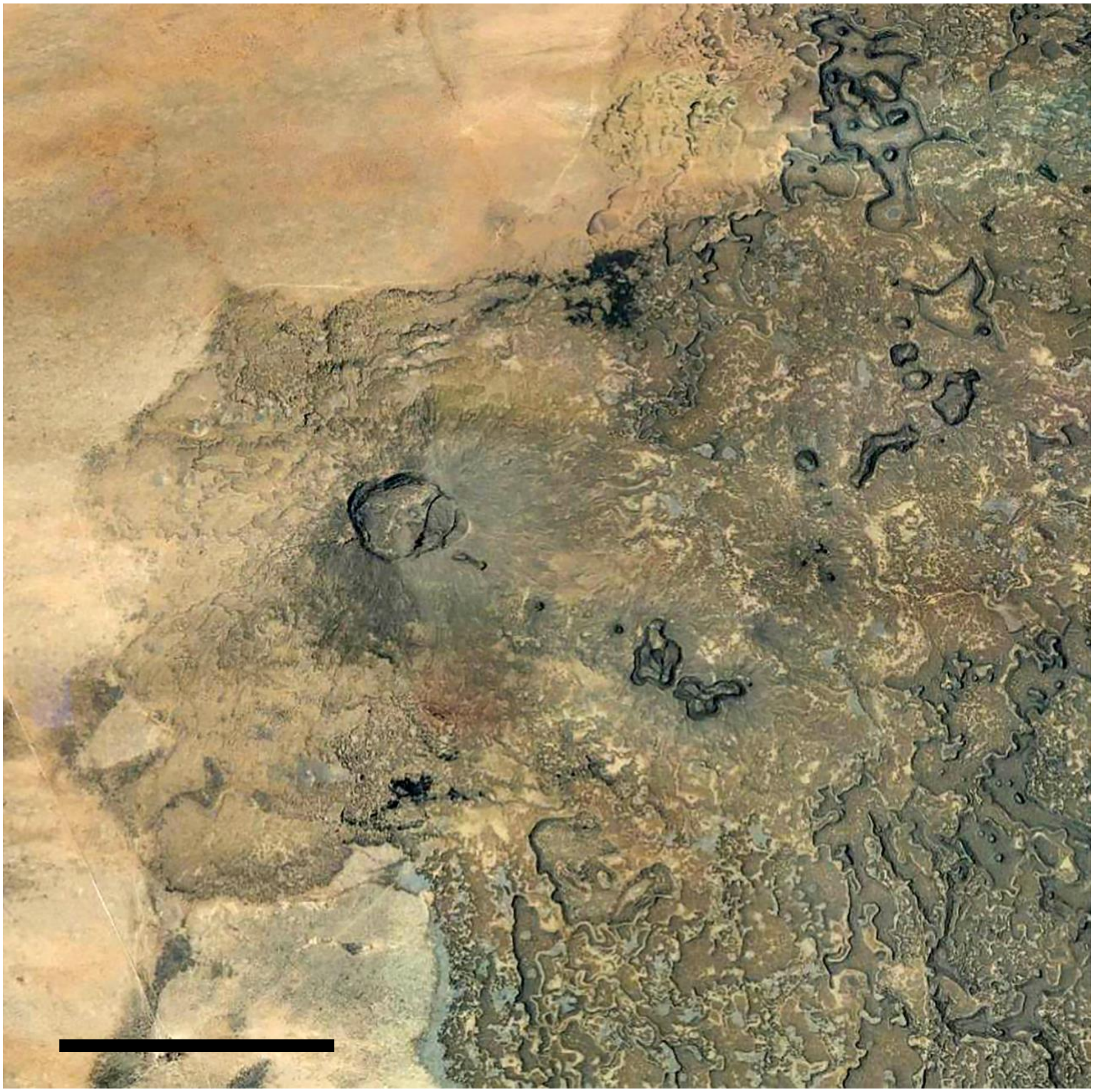


Figure 5 shows the Northwestern part of the Aden basalt field with the shield containing the Aden crater and the adjacent lava flows experienced intense inflation including lava rise pits, plateaus, and tumuli. Figure is from De Hon and Richard A. Earl (2018) [1]. The scale bar represents 1 km.

Planetary Analogs

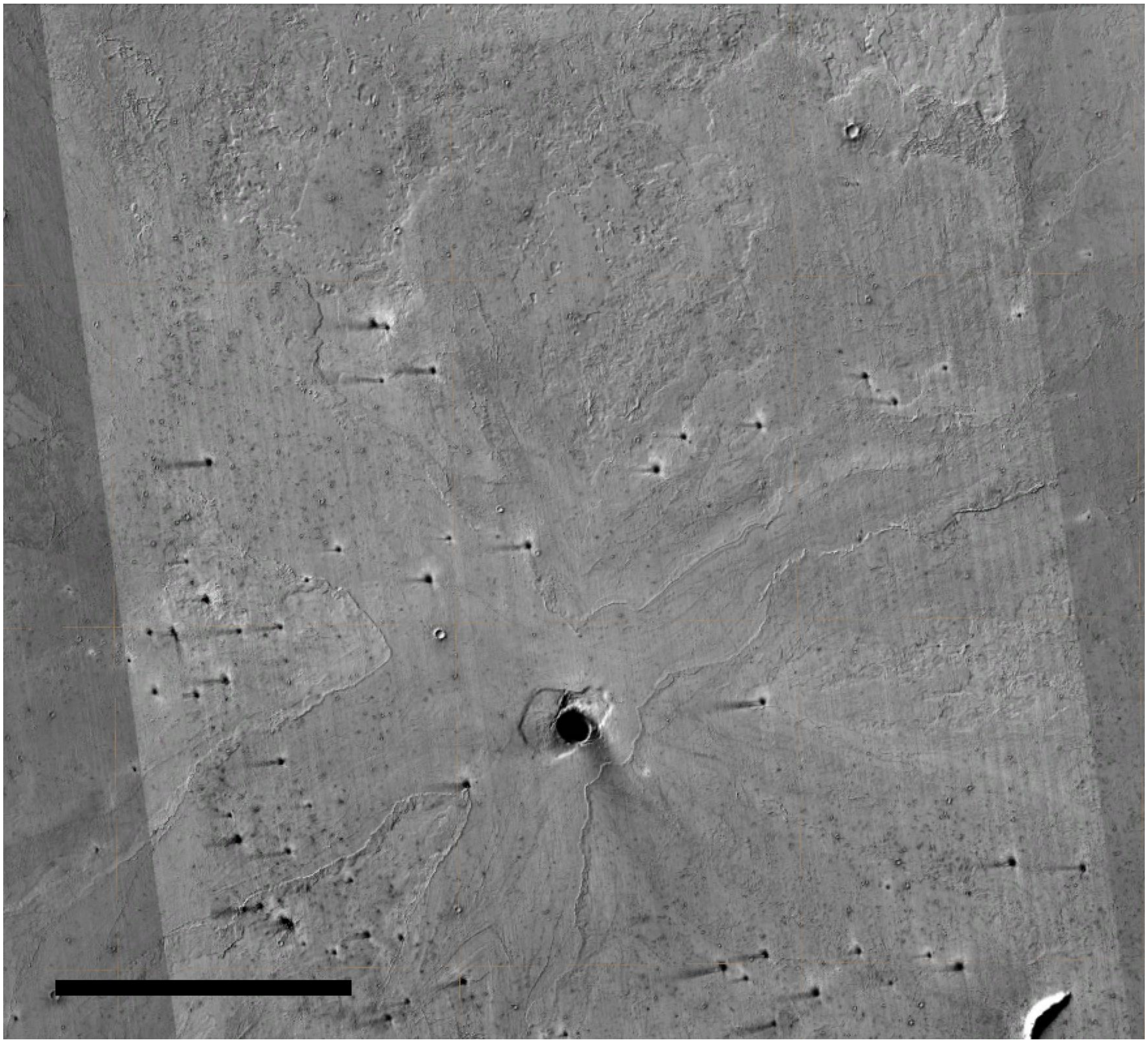


Figure 6 shields with associated lava flows exhibiting lava channel and inflation features in Cerberus Palus, central Elysium Planitia, Mars. Scale bar represents 12 km.

References:

[1] De Hon and Richard A. Earl (2018): Reassessment of features in the Aden Crater lava flows, Doña Ana County, New Mexico. Spring 2018, Volume 40, Number 1. New Mexico Geology.

[2] https://volcano.si.edu/volcano.cfm?vn=327810

[3] Hoffer, J. M., B. S. Penn, O. A. Quezada, and M. Morales, 1998. Qualitative age relationships of late Cenozoic cinder cones, southern Rio Grande rift, utilizing cone morphology and Landsat thematic imagery: a preliminary assessment, New Mexico Geological Society Guidebook, 49th Field Conference, Las Cruces Country II, 123-128.

[4] Seager, W.R., Shafiqullah M., Hawley, J.W, and Marvin, R.F., 1984, New K-Ar dates from basalts and evolution of the southern Rio Grande Rift: Geological Society of America Bulletin, v. 95, p. 87–99.

[5] Anthony, E.Y., and Poths J., 1992, 3He surface exposure dating and its implications for magma evolution in the Potrillo volcanic field, Rio Grande Rift, New Mexico, USA: Geochimica et Cosmochimica Acta, v. 56, p. 4105–4108.

[6] Williams, W.J.W. and Poths, J., 1994, The Potrillo volcanic field, southern Rio Grande Rift; 3He surface exposure dates and petrogenetic considerations [abstract]: New Mexico Geology, v. 16, p. 81.

Lava flow inflation mechanisms

Patrick O’Brien

Figure 1. A human geologist stands on a 12 m tall inflated lava flow in New Mexico

Background

Lava flow inflation occurs when liquid lava is injected beneath an overlying brittle cooling crust which raises the hardened surface. Inflation is typically seen in pahoehoe flows emplaced on shallow slopes (< 1°). Flows are initially emplaced as thin (10-50 cm) flows but after inflation and subsequent cooling, the solidified flow can be several meters tall. Inflated lava flows are best studied in Hawaii, but these flows are morphologically similar to some thick flows in Iceland as well as submarine sheet flows and features on the Moon and Mars, suggesting that inflation is an important volcanic process throughout the solar system.

Figure 2. Pahoehoe toe flows and has not froze

Pahoehoe: Smooth, ropy basaltic lava. Flows are very fluid and have temperatures of ~1200 °C

As the top of a lava flow cools, the resulting crust begins to behave rigidly when it reaches a thickness of 2-5 cm. If this rigid lid is able to resist the force of the flowing lava, the hydrostatic (magmastatic?) pressure at the front of the flow will increase and as lava continues to flow, the brittle lid is uniformly uplifted. The overlying crust is able to float due to its higher vesicularity relative to the lava beneath, which continues to degas as it remains liquid.

Inflation rates typically follow a power law dependence on time. One flow inflated to 1 m in 1-2 hours and had reached a height of 4 m after ~350 hours. Crustal cooling typically goes as the square root of time. Inflation rates decrease rapidly as the rigid crust thickens and as liquid lava breaks out from the edges of the inflating flow. Eventually, the flow will backfill or freeze in place. If flow rates are low, flows will spread laterally and inflate to form wide, flat sheets. If the flow is bounded by pre-existing topography, inflation can produce thin, sinuous ridges.

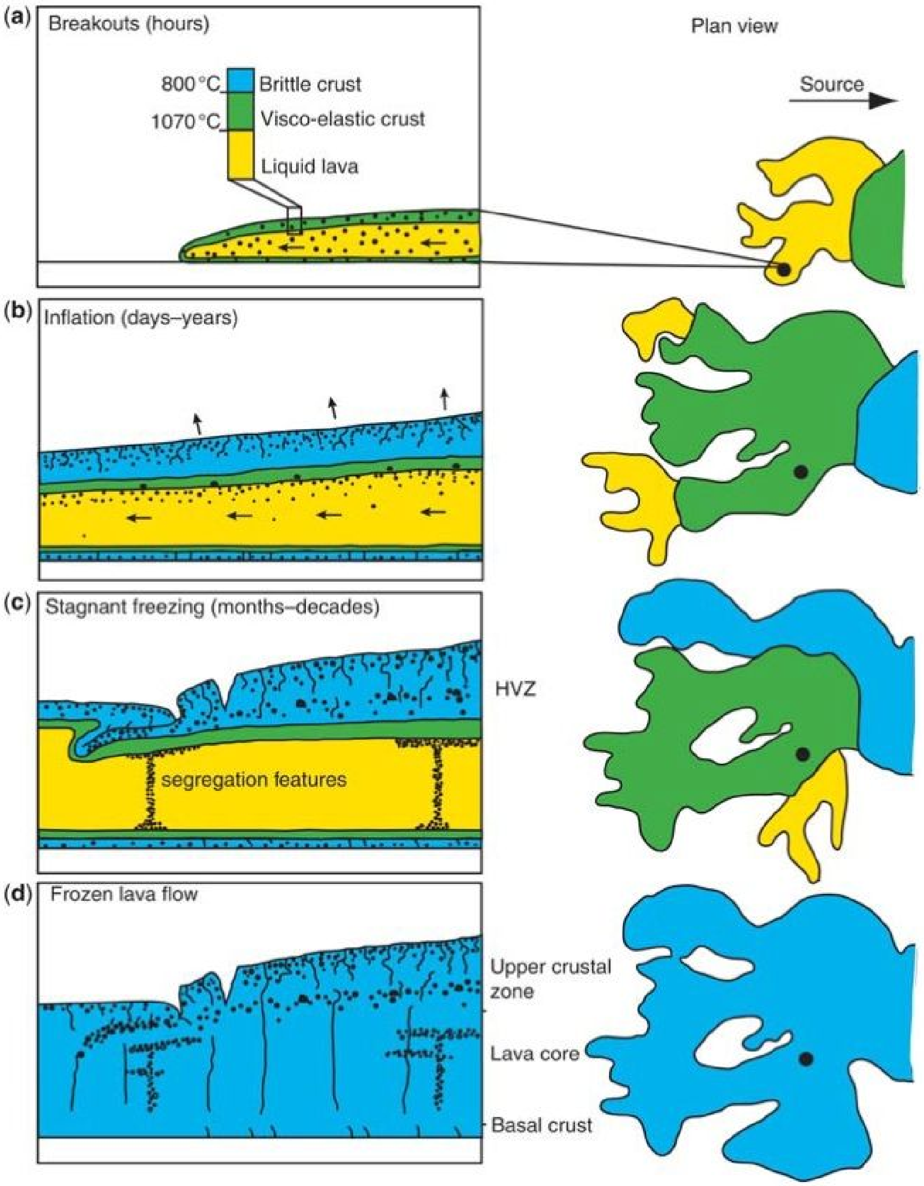


Figure 3. Diagram of flow inflation (adapted from Hon et al. 1994)

A four-stage diagram illustrating emplacement of lava by lobes and lobe-breakouts.

<u>Lava flow inflation features</u>

The classical case of lava flow inflation produces widespread uniformly uplifted, flat-topped pahoehoe sheet flows (PSFs). However, inflation operating on smaller scales can produce localized features through the same mechanism. **Lava rises** are small flat-topped features formed by uniform uplift of a crustal block. **Tumuli** are mounds or ridges 1-10 m high, often crossed by deep clefts which form as the crust is uplifted. **Lava rise pits**, once thought to be the result of subsidence or collapse, more often form when an un-inflated region is simply surrounded by uplifted crust.

Figure 4. 5.3 m tall tumulus with human geologist for scale (Walker 1991)

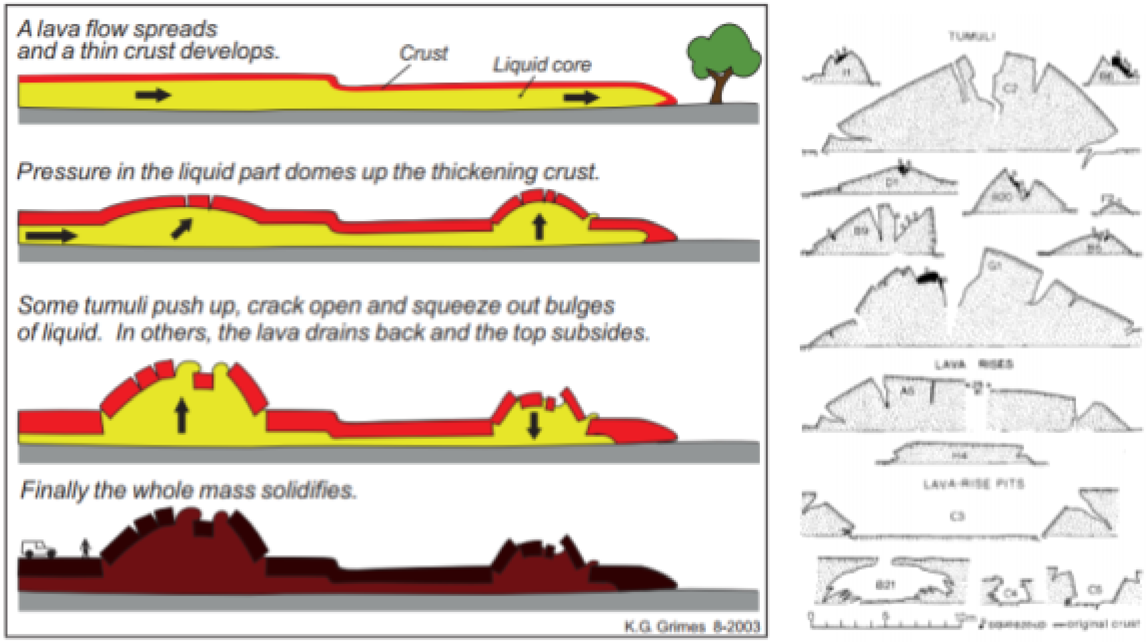


Figure 5. a) Formation mechanism for tumuli **b)** Morphology of various inflation features

The Planetary Connection

Large terrestrial flood basalts have been proposed to from from many overlapping inflated flow lobes, but modeling shows that the hydraulic head needed to do so is unreasonable. However, flood basalts are common throughout the solar system and inflation could play a more significant role on other planetary bodies. The morphology associated with terrestrial inflated flows (e.g. plateaus, hummocky surface textures, terraced flow margins, tumuli, lava rise pits) have been observed (rarely) on the Moon and (extensively) on Mars.

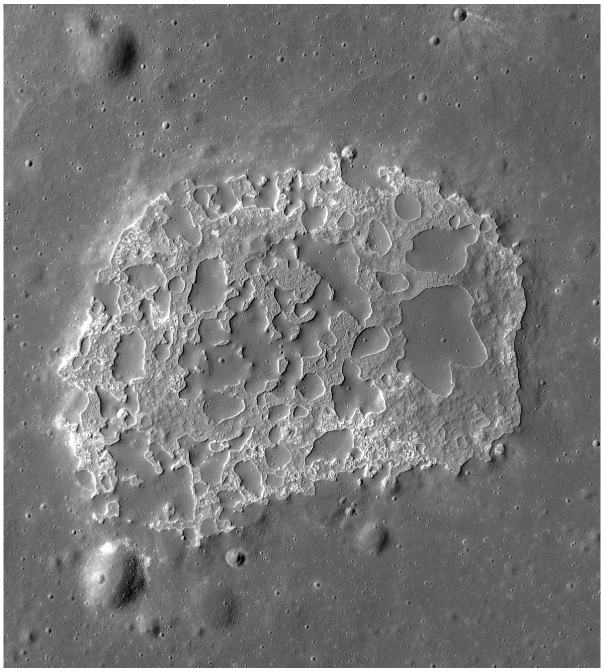


Figure 6a. Ina, mysterious lunar feature thought to be comprised of inflated lava mounds

Figure 6b. Rootless cones on Mars surrounded by rings of inflated lava (HiRISE, NASA/JPL/University of Arizona)

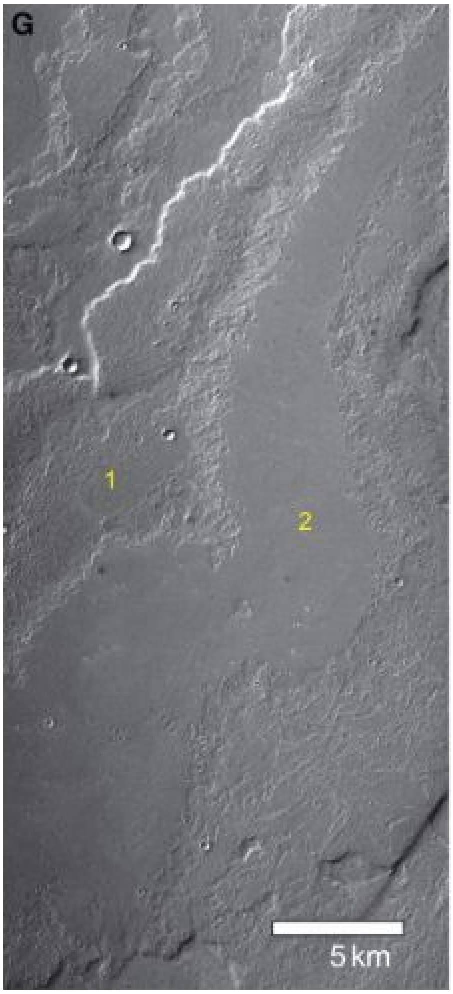


Figure 6c. Smooth, inflated (?) flow in the Arsia Mons flow field (Crown and Ramsay 2017)

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Image credits
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Physics of Volcanic Surges

Xiaohang Chen

Introduction

Pyroclastic density currents (PDCs) are turbulent flows of hot gas and volcanic particles travelling at high velocity up to ~700 km/hour and about 1000 °C (Wilson 2005). They can transport large volumes of hot debris swapping the ground for many kilometers and constitute a destructive volcanic hazard. Figure 1 presents the eruption of Mayon Volcano, Philippines in 1984. The maximum height of the eruption collapse was 15 km above sea level, and pyroclastic density currents travelled about 50 km toward the west. Figure 2 presents the deposit of PDCs (Sulpizio et al. 2014). The initiation and transport behavior of pyroclastic density currents can originate in different ways and from various sources. Here we will briefly introduce the transport mechanisms.

Figure 1 Pyroclastic flows sweep down the flanks of Mayon Volcano, Philippines, in 1984.

Credit: C.G. Newhall https://volcanoes.usgs.gov/Imgs/Jpg/Mayon/32923351-020_caption.html

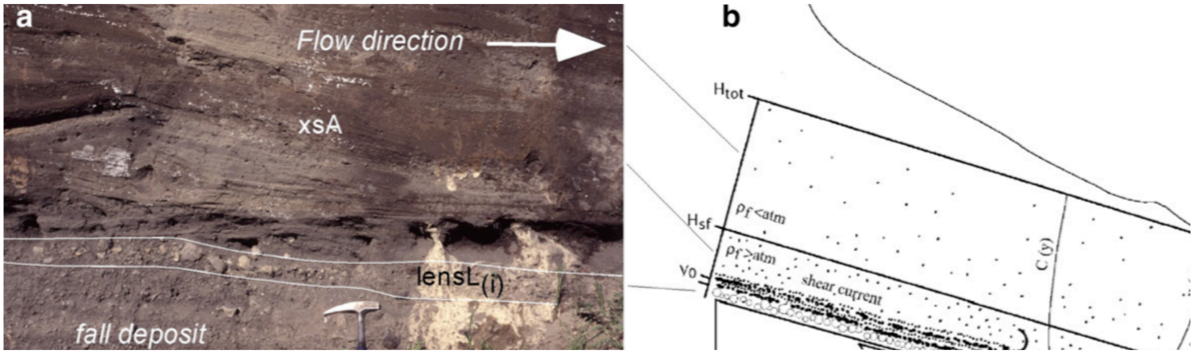

Figure 2 Schematic representation of the main features of a dilute pyroclastic density current.

Transport mechanisms of PDCs

PDCs are heterogeneous mixtures of fluid and solid phases materials. They are commonly recognized into two categories: Pyroclastic surges and Pyroclastic flows (Wilson 2005). Pyroclastic flows contain most of solid particles mixed with gases while pyroclastic surges only contain 1~2 percentage of solid particles (Druitt 1998). To describe this temporal frame, Branney and Kokelaar (2002) proposed the concept of flow-boundary zone which can be considered as the lower part of the flows where particle–particle interactions dominate the transport mechanisms (Figure 3). This model can be used to describe deposition of both fully turbulent and granular flow-dominated PDCs, in which the thickness of the flow-boundary zone can range from several centimeters to meters, respectively (Burgisser & Bergantz 2002).

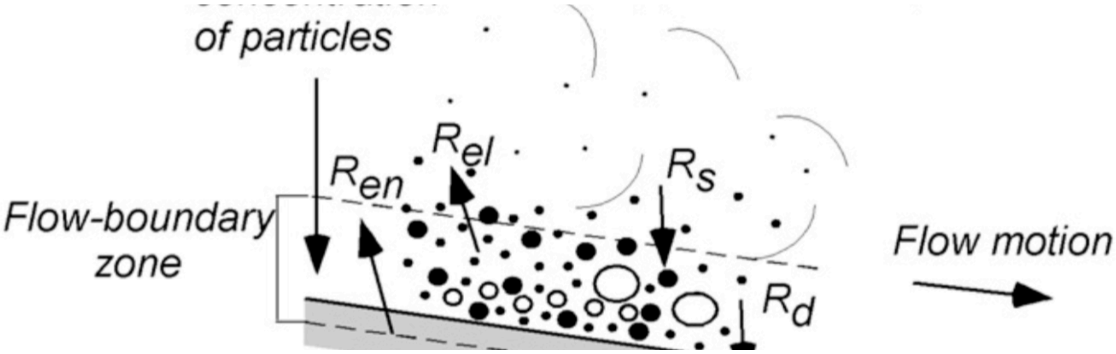

Figure 3 Sketch of the flow-boundary zone.

In the upper turbulent part (Figure 3), scalar quantities are well mixed, but the materials in the flow-boundary zone are not. To understand the interplay between these particles and the turbulence, three in dimensionless numbers are introduced here:

(1) The stokes number: $S_T = \frac{t_v}{f}\frac{\Delta U}{\delta}$

(2) The Froude number: $F_R = \frac{\Delta U}{\sqrt{g\delta}}$

(3) The stability factor: $\sum_T = \frac{S_T}{{F_R}^2}$

where ΔU is the eddy rotation speed; δ is the diameter of eddy; t_v is the response time of particles; f is a drag factor function of the particle Reynolds number; g is the acceleration of gravity (Burgisser & Bergantz 2002).

S_T represents the coupling between gas and particles. If $S_T \ll 1$, particles couple with the gas. If $S_T \sim 1$, particles tend to gather at the eddy periphery. If $S_T \gg 1$, particles decouple from turbulence. $\sum_T$ is the evaluation of the steady state of particles in the eddy. If $\sum_T \ll 1$, particles are governed by the turbulent motion and tend to stay in the eddy. If $\sum_T \gg 1$, particles are influenced by gravity and tend to sediment from the eddy (Figure 4).

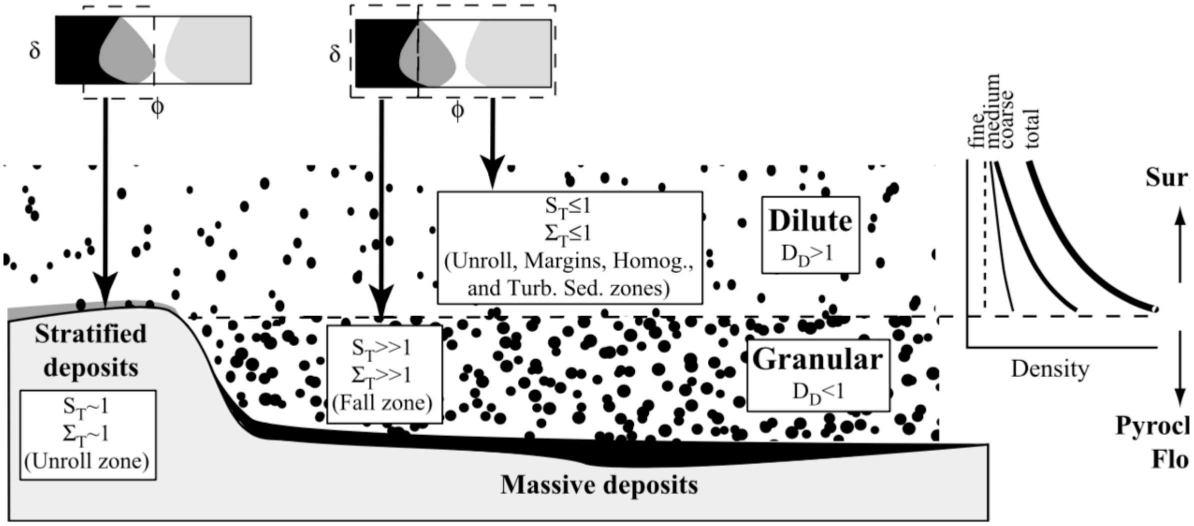

Figure 4 Schematic cross-section of a pyroclastic density current perpendicular to the flow direction.

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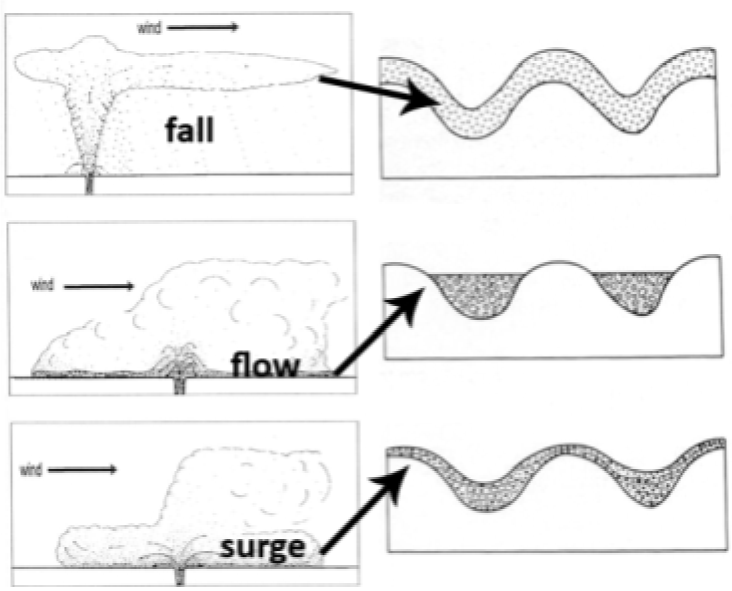
Volcanic surge bedforms- analog to the MER site at home plate or festoon bedding at the Opportunity site?

Mattie Tigges



Pyroclastic deposits (Image from www.luckysci.com)

Causes of pyroclastic flows (image from www.luckysci.com)

Pyroclastic deposits

Fall

Uniform deposit of ash or tuff from an eruption or plume

Flow

Gravity driven clouds of rock fragments, hot gasses, entrapped air that hug the ground
Contain <1% solid material
Can reach 100-160 km/hr
Deposits are thick and poorly sorted
Types: nuée ardente (glowing cloud), pumice flows
Nature of flows are determined by deposits
Mt Pelée, Martinique, 1902- destroyed town of St. Pierre

Surge

Low density flow
Contain >10% solid material
Result in cross bedded layering
Deposits can occur with (on top or beneath) flow deposits or by themselves

Surge turbulence

$Re = \frac{\rho V L}{\mu}$

Where
ρ= density of fluid [kg/m^3]
V= mean fluid velocity [m^3/s]
L= Characteristic linear dimension [m]
μ= dynamic viscosity

What causes a surge?

Phreatomagmatic eruption or direct frothing over at the vent of magma undergoing rapid gas loss
If the surge meets water, hot ash causes water to boil → water vapor decreases density of the surge and increases speed → can travel >100 km over water
Composition and temperature are partially dependent on ratio of water to magma

Surge deposits show both laminar and dune bedding forms at La Breña maar, México. The thin beds (pen for reference) were created by successive explosive eruptions that produced high-velocity, laterally moving pyroclastic surges that moved radially away from the volcano. Photo by Jim Luhr, 1988 (Smithsonian Institution).

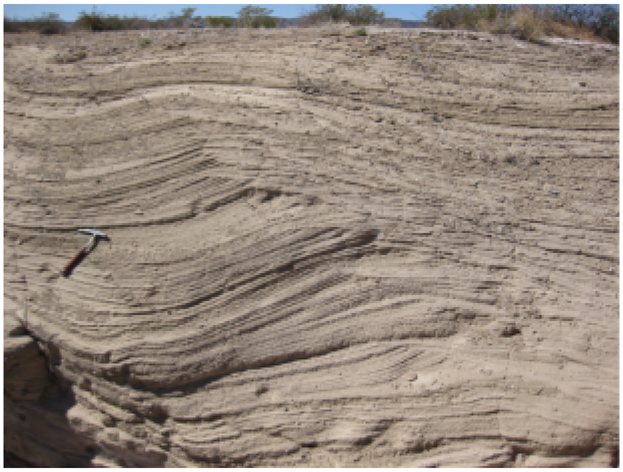
Sources of energy

Gravity
Fluidization- buoyancy created by entrained and heated air and hot gasses released from particles and clasts

Types of surge

Ground surge
Cause: eruption column collapse
Deposits: found at the base of pyroclastic flows
Very thinly bedded, usually cross-bedded, and laminated
Typically ~1 m thick
Mostly consist of lithic and crystal fragments
Hunt's Hole, NM

Base surge
Violent steam explosion
Deposits: typically found at the base of pyroclastic flows
Cause: explosive hydrovolcanic plume collapse
Magma and water interact, form wedge-shaped deposits that are characteristic of maars
Deposits rarely spread farther than 5-6 km



Surge deposit, Hunt's Hole, NM. Hammer for reference. (Image from www.blogs.agu.org)

Ash cloud surge
Cause: elutriation (sizing particles by means of an upward current of fluid- usually water or air) from the top of a pyroclastic flow
Deposits: Thin, 3-10 cm thick
Travel at 10 – 100 m/sec
Carry debris like trees and bricks

MER site at Home Plate and Festoon bedding at Opportunity site

Was sediment deposited in subaqueous conditions or was it part of a base surge deposit?

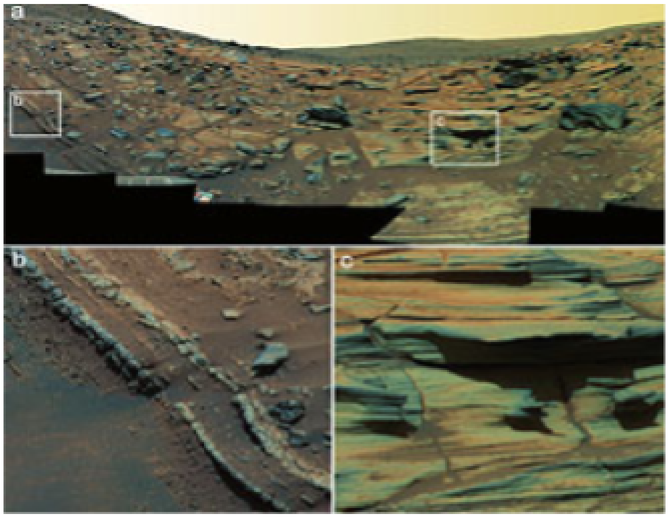
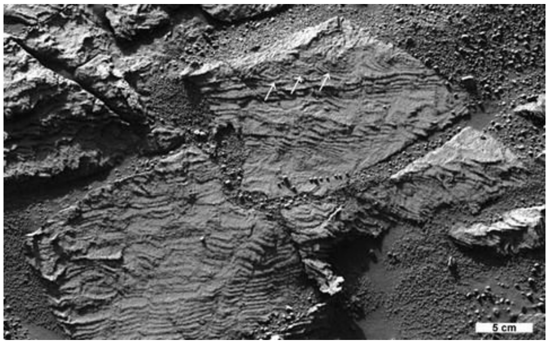


Image to right: NASA's Mars Exploration Rover Spirit acquired this high-resolution view of intricately layered exposures of rock while parked on the northwest edge of the bright, semi-circular feature known as "Home Plate." The rover was perched at a 27-degree upward tilt while creating the panorama, resulting in the "U" shape of the mosaic. (A) The northern edge of Home Plate, (B) the coarse-grained lower unit, (C) the fine-grained upper unit. Spirit acquired 246 separate images of this scene using 6 different filters on the panoramic camera (Pancam) during the rover's Martian days, or sols, 748 through 751 (Feb. 9 through Feb. 12, 2006). The field of view covers 160 degrees of terrain around the rover. Credit: NASA/JPL-Caltech/USGS/Cornell



Festoon cross-bedding in sedimentary rocks have been observed in the Burns formation, Mars (Squyres et al 2006)

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Mantle and Lower Crustal Xenoliths

By Amanda Stadermann

The term ***xenolith*** has Greek and Latin roots; 'xeno' meaning foreign or strange, and 'lith' meaning stone. In geologic contexts, 'xenolith' is used to refer to rocks that have fragments that are unrelated to the rest of the rock. Xenoliths are *almost* always igneous rocks that have fragments of foreign rock that the magma tore loose from the walls of the conduit or chamber in which the magma erupted or resided. Importantly, xenolith is a large fragment of multicrystalline rock. If the foreign item is a single crystal, it is referred to as a ***xenocryst***. Despite being almost always found in igneous rocks, the concept can be extended to sedimentary rocks and meteorites.

Since xenoliths are often drudged up from lower parts of the crust and possibly upper mantle, xenoliths are important fragments of rock that can teach us about regions of the Earth that humans cannot access.

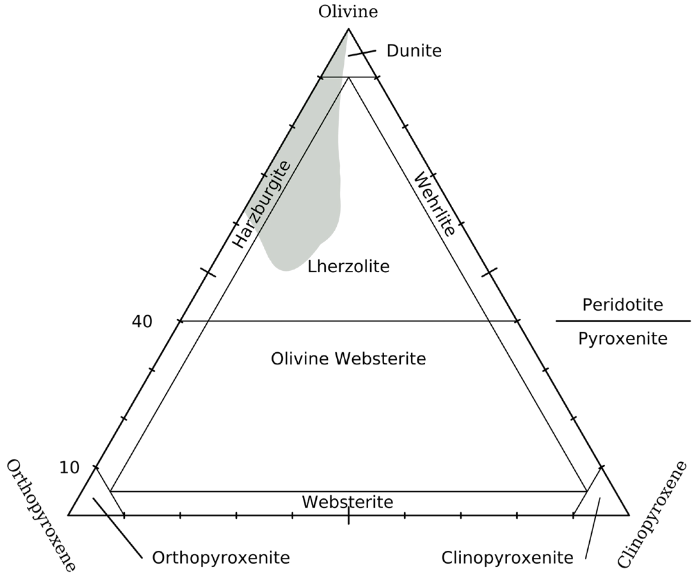

Figure 1. *Ternary plot with apexes of olivine (Mg,Fe)2SiO4, orthopyroxene and clinopyroxene (XYSi2O6), where X can be Mg or Fe, and Y can be Mg, Fe, or Ca. The green zone represents terrestrial compositions found in mantle xenoliths.*

Figure 2. *Image of a mantle xenolith and its host rock, basalt, from the San Carlos Volcanic Field*

One of the most famous examples of xenoliths inona are from the San Carlos Volcanic Field, which erupted basalts and also ***peridotite***, which is a rock composed of olivine and pyroxene (Figure 1, 2). This type of xenolith would be termed a 'mantle xenolith' because the xenoliths originate from the mantle.

The xenoliths we will hopefully see on our trip occur at Kilbourne Hole. Kilbourne Hole is a maar crater, as we have or will learn from Mattie, which means it was a phreatomagmatic eruption. Kilbourne Hole is partially interesting because it has both crustal and mantle xenoliths. The mantle xenoliths, like that in Figure 2, primarily consist of peridotite of some sort, with perhaps varying ratios of pyroxene to olivine. The crustal

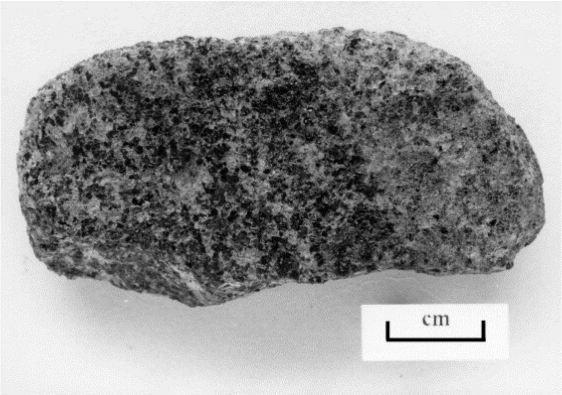

Figure 3. *Granulite from Lahtojoki kimberlite pipe, Finland.*

Figure 4. *Anorthosite from Tamil Nadu, India.*

Figure 5. *Peridotite from Kilbourne Hole, New Mexico, USA.*

xenoliths originate in the mid to lower crust, and consist of highly metamorphosed or intrusive volcanic rocks. Specifically at Kilbourne Hole, we see ***granulite***, peridotite, and ***anorthosite*** (Figure 3, 4, 5).

Granulite (Figure 3) is metamorphic facies that corresponds to high temperature (800 to >1000ºC) and moderate pressure (0.2 to 1.4 MPa, or about 10 to 40 km depth in Earth). The composition of granulite depends primarily on the parent rock that it formed from, but (if of igneous origin) commonly include plagioclase feldspar, pyroxene, garnet, and other mafic minerals. Anorthosite (Figure 4) is a rock consisting of almost entirely of plagioclase feldspar ($NaAlSi_3O_8$ – $CaAl_2Si_2O_8$). On Earth, anorthosite is thought to form through density separation in crystallizing magma chambers, where plagioclase crystals rise to the top of the chamber due to their low density (this theory has been debated, but is probably 75% right). On the Moon, the highlands (higher topography, higher albedo, heavily cratered regions) consist of primary anorthosite crust. It is generally thought that as the lunar magma ocean crystallized, the plagioclase feldspar grains crystallized and floated to the top of the magma ocean. The peridotite (Figure 5) at Kilbourne Hole is thought to originate in the mantle, 65 km below the Earth's surface.

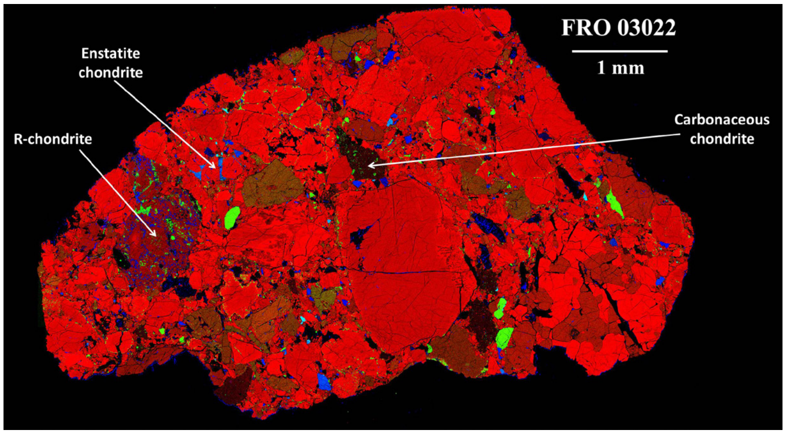

Figure 6. *Polymict Urelite meteorite from Antarctica, containing clasts of impacting material (xenoliths), along with native Urelitic material.*

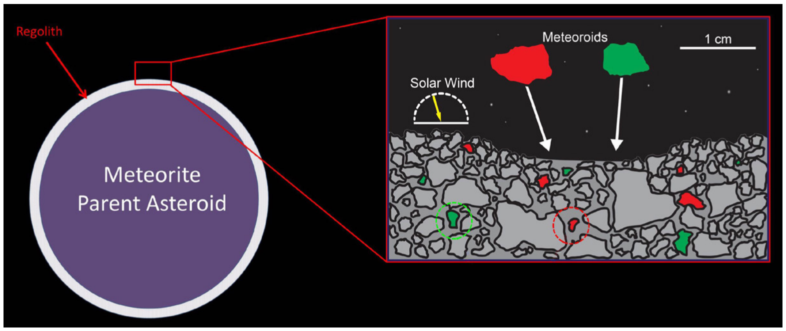

Figure 7. *Schematic showing how polymict breccias form on a parent asteroid.*

Extraterrestrial xenoliths have been seen in meteorites and lunar samples. The xenoliths we have found in these extraterrestrial rocks have their origin in impact breccias and impact rocks. ***Urelites***, a type of meteorite from a differentiated asteroid, sometimes are ***polymict***, meaning that they are rocks formed from the regolith of the asteroid, and contain bits of meteorite that impacted the surface of the asteroid (Figure 6, 7). The xenoliths in Urelite meteorites are very diverse and have the oxygen isotopes to prove it. The diversity seen in the Urelites may indicate that this parent asteroid or group has an unusual migration history.

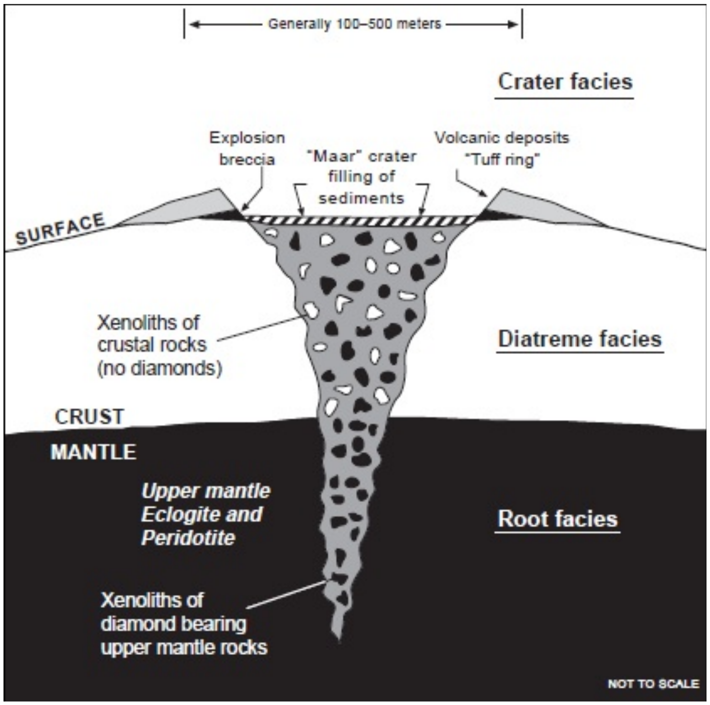

Figure 8. *Schematic showing the internal structure of a Kimberlite pipe. Not to scale.*

Notable diversion: Kimberlites

Kimberlites are a type of igneous rock that may contain diamond xenocrysts. They erupt through ***kimberlite pipes*** that originate in the mantle at depths of 150 – 450 km. They are thought to possible dredge up enriched mantle—that is, mantle that hasn't been depleted through plate tectonics and partial melting. Kimberlite pipes, like other volcanic pipes, originate deep in the mantle and has a supersonic, gaseous eruption. Kimberlites are often found on continental

cratons, the oldest and thickest parts of continental crust. Because kimberlites originate in the enriched part of the mantle, they contain diamonds. After kimberlite pipes erupt, the surface may erode away the original crater and the upper portion of the pipe, revealing the diamond xenocrysts in the central part of the pipe (Figure 8). This is the most common place to find diamonds at the Earth's surface.

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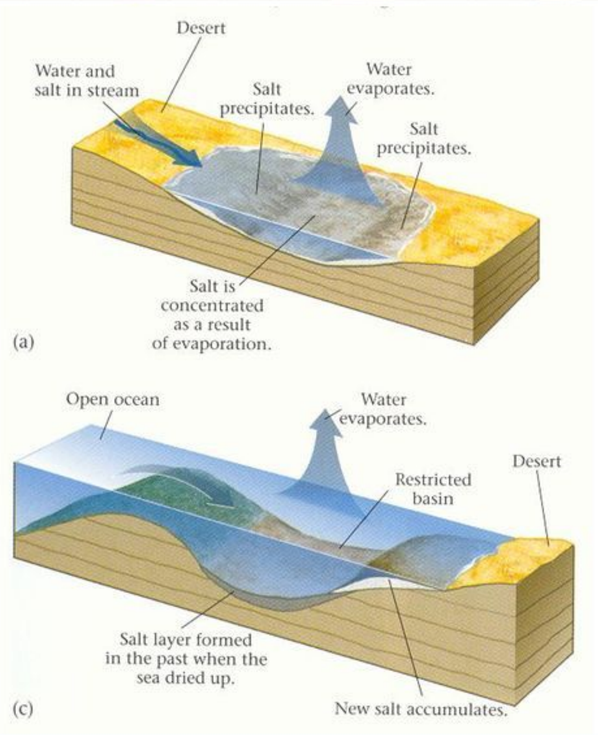
Gypsum Sources and Sinks
Adam Sutherland

Would you rather build castles out of fish poop at a beach or gypsum? -WSNM website

Gypsum is a sulfate mineral composed of calcium sulfate dihydrate,$CaSO_4 \cdot 2H_2O$. When salty water evaporates, gypsum is left behind in an evaporite deposit.



a) In a lake with no outlet, tiny amounts of salt brought in by streams stay behind as water evaporates. When the water evaporates entirely, a white crust of salt remains.

b) Precipitation can occur along the margins of a restricted basin if salt water evaporates faster than it can be resupplied.

Types of evaporites deposited depends on the amount of evaporation.
80% of water evaporated -> gypsum
90% of water evaporated -> halite
If you were to evaporate seawater entirely, it would consist of 80% halite, 13% gypsum and the rest other salts and carbonates.

A large number of industrial uses. Plaster, drywall, fertilizer, and alabaster sculptures.

Figure 1. (Marshak, page 193)

White Sands

The largest gypsum dunefield in the world, 710 km^2. WS is made up for 98% pure gypsum. Such large concentrations of gypsum are rare since gypsum is very water soluble.

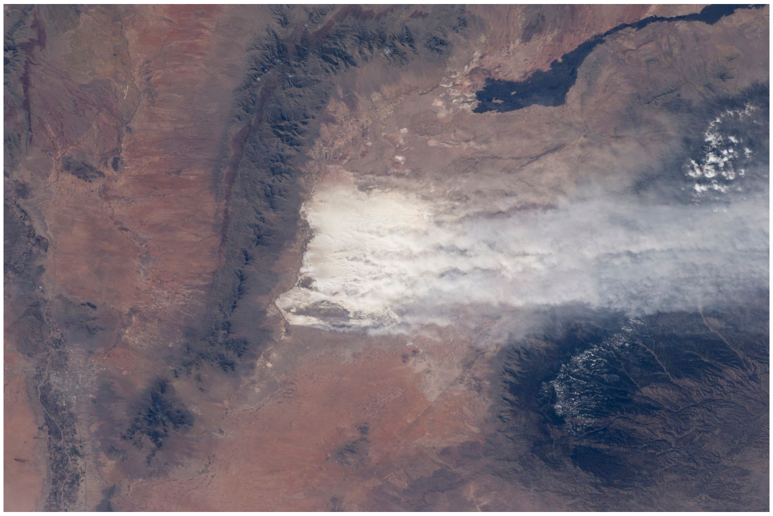
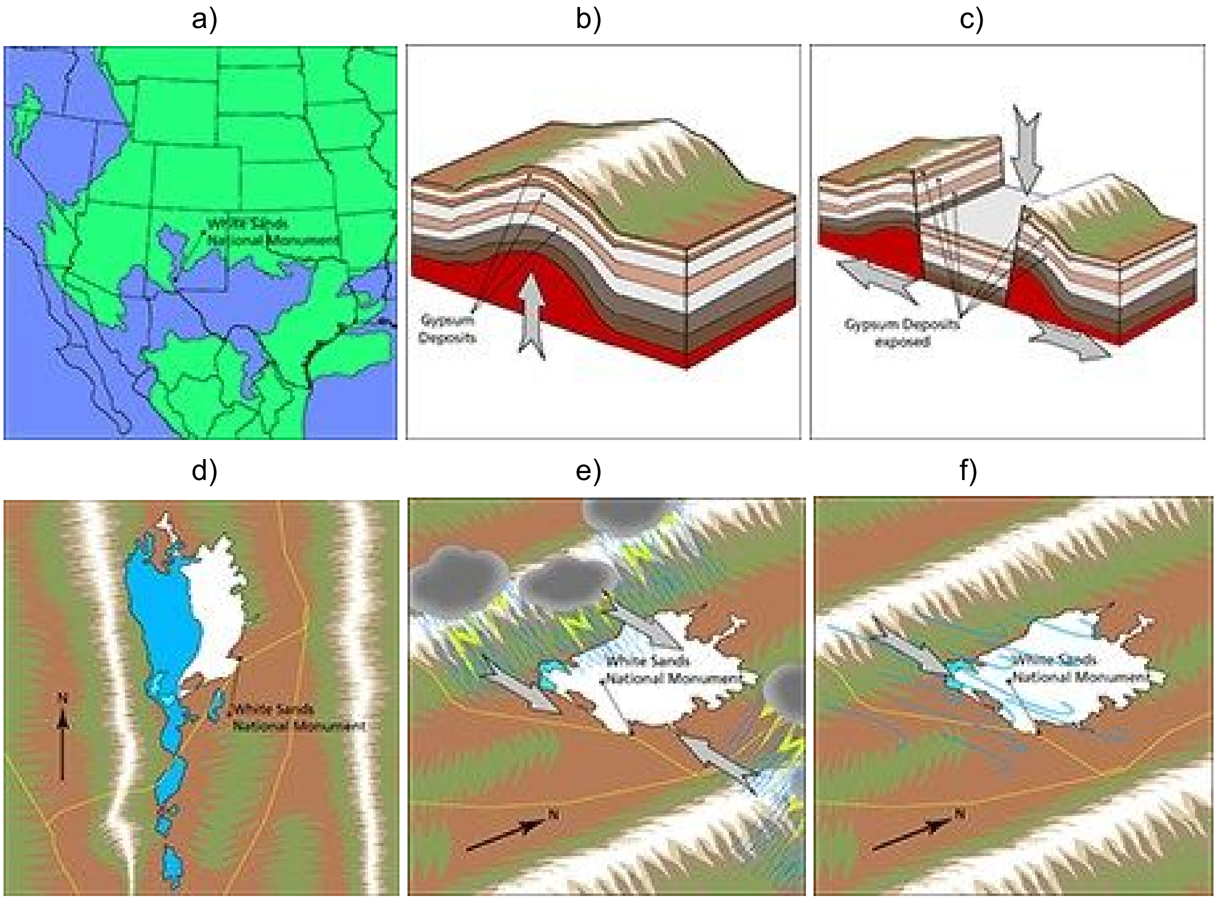


Fig 2. 75 mile dust plume from WS blowing over Sacramento Mountains. (NASA)

Fig 3. Lake Lucero and Lake Otero Extent (NPS)

Figure 4. (NPS)



a) During the Permian Period, 280-250 mya, WS was covered by a shallow inland sea, the Permian Sea. Millions of years of changing sea levels accompanied by evaporate deposited gypsum.
b) 70 mya, mountain building associated with the Laramide orogeny created the mountains around WS today.
c) 30 mya, rifting caused the Tularosa basin to form in between the San Andres and Sacramento Mountains, exposing the gypsum deposits and blocking drainage to the sea.
d) 24 kya, snowmelt and rain carried gypsum to Lake Otero. With no drainage outlet, Lake Otero evaporates to form a playa, or dry lake bed.
e) Lake Otero's remnant is Alkali Flat and seasonal lake, Lake Lucero. Gypsum crystals are broken down by the wind to form the dunes.
f) Today in Lake Lucero there is a cycle of water dissolving gypsum, evaporating to form dark Selenite, crystallized gypsum, this then erodes to form white sand.

Gypsum in Mars North Polar Region

The north polar Olympia Undae sand sea contains a large dunes field. These dunes are made up of 35% pure gypsum grains, 65% gypsum grains with dark, spectrally featureless material.

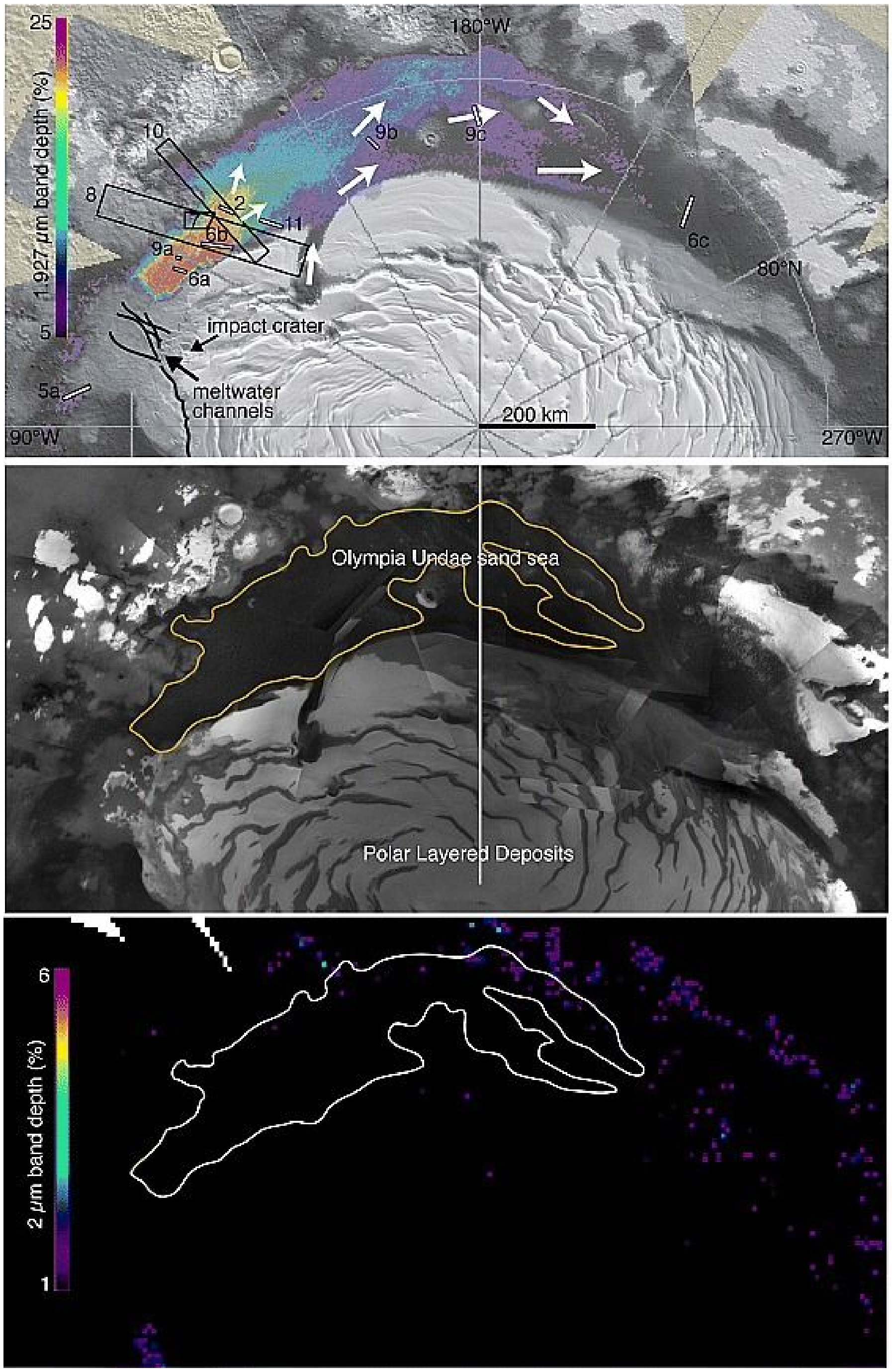


Figure 5. (Fishbaugh et al.)
Map of the 1.94-μm absorption feature (diagnostic of gypsum) using the 1.93-μm OMEGA band. White arrows indicate main near-surface wind directions as mapped by Tsoar et al. [1979]. Meltwater channels are traced in black. Boxes outline locations of other figures.

(b) Portion of 64 pixel/degree MOC wide-angle image mosaic. The area containing gypsum is outlined in orange.

(c) Map of pyroxene as detected by OMEGA. The pyroxene is identified using the band in the 1- to 1.3-μm range. The area containing gypsum is outlined in white.

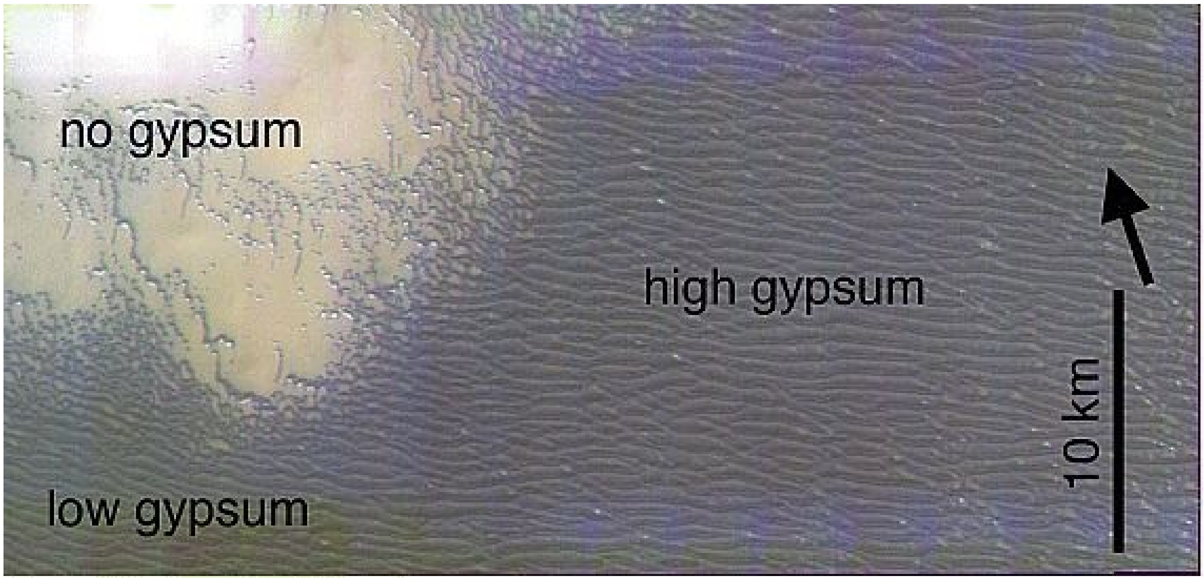


Figure 6. (Fishbaugh et al.) The gypsum-rich dunes exhibit no color anomalies in relation to the low-gypsum dunes. The gypsum-free area is reddish relative to the bluish dunes, likely due to the presence of dust. THEMIS false color visible image V04067010. Blue = Band 1 (0.425 mm), Green = B2 (0.540 mm), and Red = B3 (0.654 mm). Arrow indicates illumination direction. See Figure 5 for image location.

How was the gypsum deposited?

- The order in which minerals precipitate can change with pressure. Using carbonates will precipitate before gypsum, but if the partial pressure of CO_2 is high, gypsum can precipitate first.
- We can trace the movement of the dunes by gypsum fraction. Grains eventually wear down too much to saltate anymore.
- No evidence of a basin, so lake or mudflat origin is unlikely.
- Too much deposition for fluvial origin. The toe of alluvial fans can deposit gypsum but eventual incorporation in dunes is unlikely.
- Most likely source is saline soils.

Water from nearby channels percolated through the dune sea. Gypsum formed via evaporative grains and direct alteration of sand dunes. Secondary oxides during the alteration are the spectrally featureless dark material. The liquid water was provided by the Chasma Boreale melting event or melting of the nearby polar cap.

White Sand National Monument NPS website, https://www.nps.gov/whsa/geology.htm
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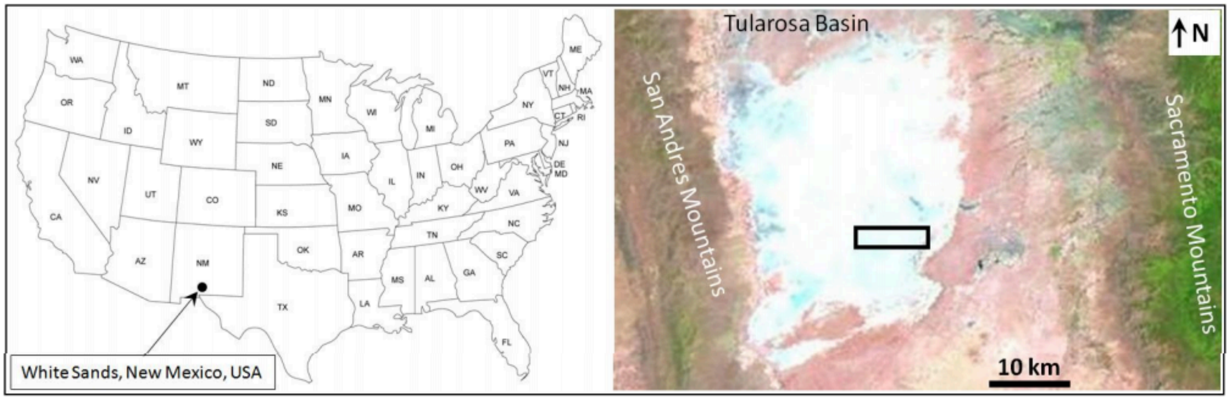
Remote sensing of dunes migration rate

Saverio Cambioni Spring 2019

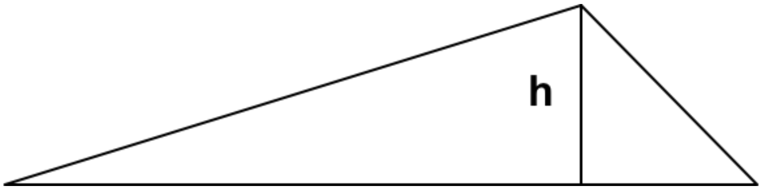


The White Sands Dune Field, situated within the Tularosa Basin of the Rio Grande Rift between the San Andres and Sacramento Mountains in southern New Mexico, is the largest (~ 500 km^2) known field of gypsum dunes globally (Kocurek et al. 2006).

Why do dune and ripple fields migrate?

- Typically, the process that moves sand on dune surfaces is aeolian transport

$$\frac{\Delta x}{\Delta t} = \left(\frac{2fq}{\rho_{dune}}\right)h^{-1}$$



q – mass of sand being transported
f – fraction of sand coming from the dune itself
ρ – density of sand (1442 kg/m3)
h – height of the dune

"the higher the dune, the slower it is"

Why do we want to monitor the evolution of dunes?

The above equation is solved for mass of sand being transported:

- In some countries (e.g., Egypt, El-Magd et al. 2013), sand dune movement is an hazardous phenomenon and creates a threat on existing land use and land cover as well as developmental plans;
- On planetary surfaces, sand transport informs about the wind field at the surface, thus providing precious boundary conditions for atmospheric circulation models.

How can we remotely monitor the evolution of dunes?

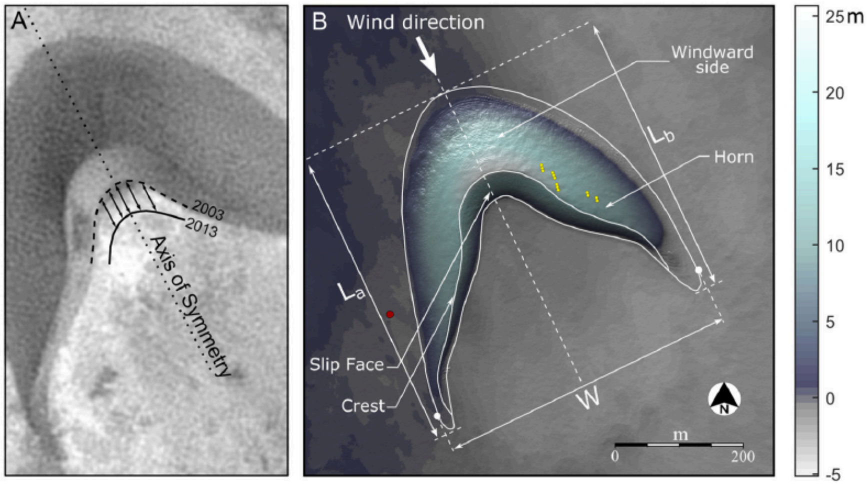
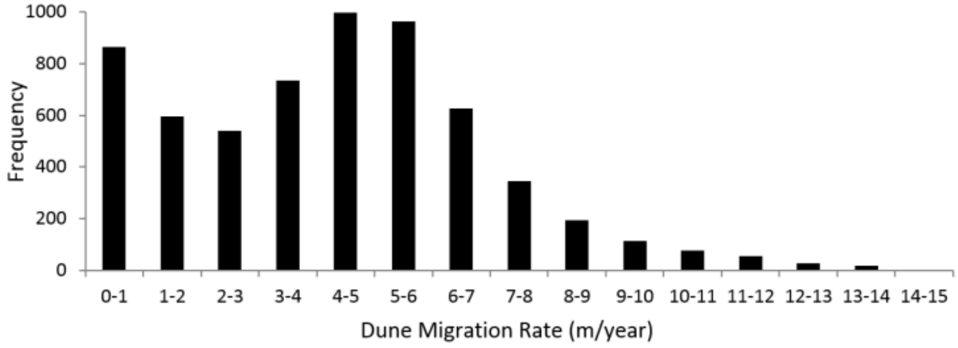


Figure 1 (A) Dune displacement measurement method. The black dashed and solid line correspond to the outline of the dune lee front toe in 2003 and 2013, respectively (data from Michel et al. 2018) . The arrows show examples of the dune displacement measurements, which are taken parallel to the dune axis of symmetry (dotted black line). (B) Characterization of a dune's geometrical feature and DEM of the dune.

For more than four decades remote sensing images have been used to document and understand the evolution of aeolian sand dunes (Levin et al. 2012 and references therein).

- Early work involving RS imagery focused mainly on dune mapping and taxonomy
- Extended mission lifetimes allow to monitor sand dune movements through comparing the multi-temporal satellite images.
- The technique involves sub-pixel correlation of co-registered images.



(*a*) Histogram of dune migration rates (m/year) for 5936 target points.

Figure 2. Results from Dong et al. 2015 for White Sands, NM, USA. Moving dunes have a migration rate in the order of 4-6 meters/year. Dune slip faces were automatically extracted from LiDAR – derived DEM.

New technologies involves the use of stereo-images for the construction of time-dependent Digital Terrain Models (DTMs). To do so, we need to resolve volumetric changes in dune fields.

- As an example, dune form transition has been studied at White Sands Dunefield using LiDAR
- A multi-temporal LiDAR dataset may be used to assess erosion and deposition rates on dune surfaces along a morphological gradient.
- Machine Learning algorithms to automatically detect both the location and the outlines of barchan dunes (e.g., Azzaoui et al. 2019).

Accurate measurements offer evidence to support modeling predictions that suggest the transition from barchan to parabolic dune occurs when surface change rates are approximately half the vegetation growth rate.

Which are the advantages and limitations of remote sensing of dunes?

Pros	Cons
Regular and wide coverage for analysis and measurements	Interpretation is highly affected by satellite geometry and illumination conditions
Combination of different techniques that are complementary (e.g. LiDar and imaging)	Remote-sensing data may be too expensive to acquire at suitable resolution
It allows accessibility to regions where field-based investigation may not be possible	The coverage of satellite-based remote sensing is limited by the satellite orbit

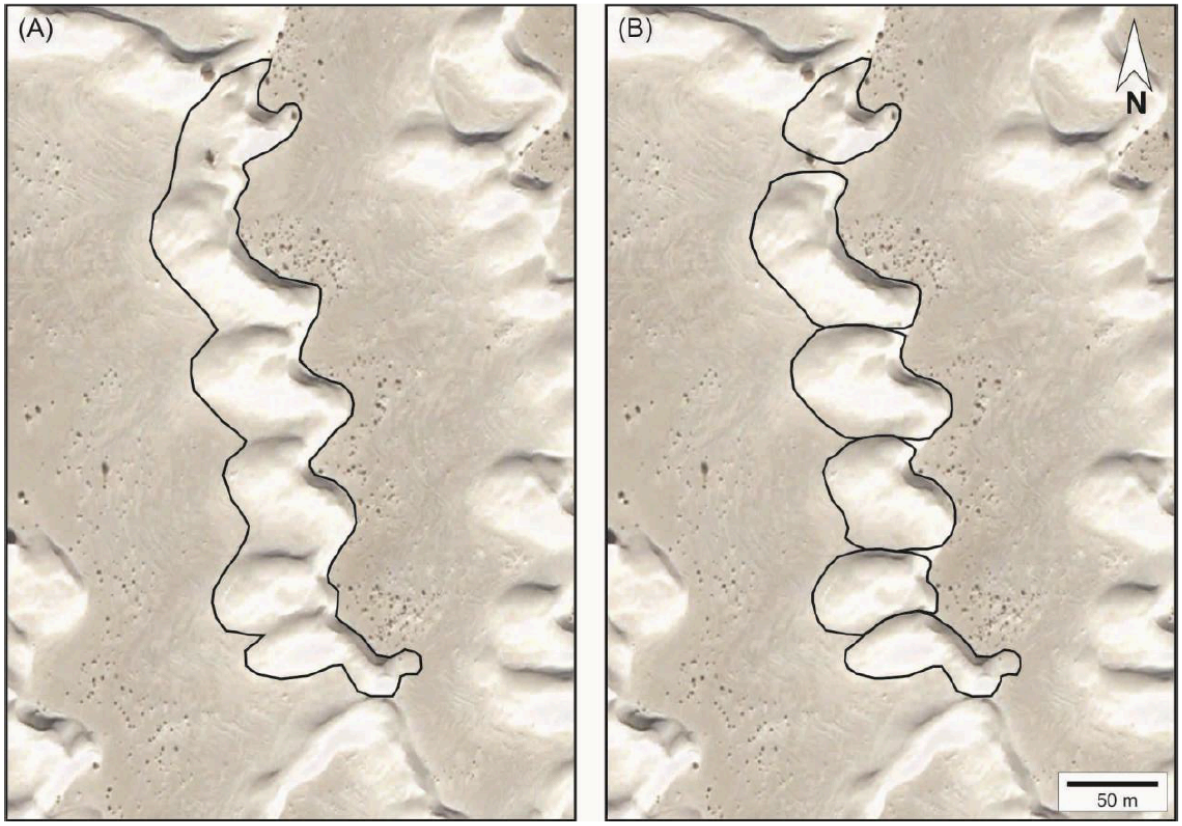


Figure 3. Defining the boundaries of sand dunes for the purpose of spatial analysis can add a high degree of subjectivity to the outcome. Panel A and B are two contrasting interpretations of the boundaries of dune at White sands, New Mexico, USA (image source: Google Earth, 01 Feb 207; image from Levin et al. 2012).

The effectiveness of remote-sensing interpretation is highly affected by the definition of the boundaries of the sand dunes to be tracked (Figure 3). Considerations of the topography in a general sense could overcome subjectivity problems.

Field-based survey methods uses GPS and measurements stations to constrain dunes field.

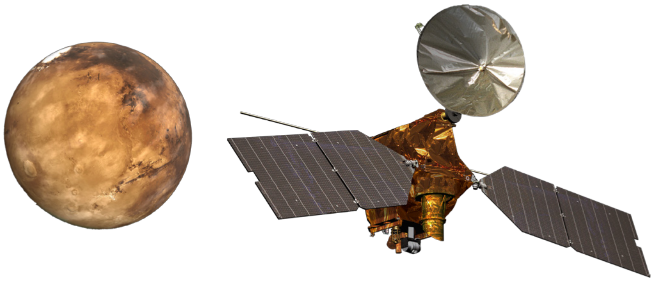
The coverage is limited, while the resolution is very high. Data collected on the field provide ground truth data for models and allow mitigation of ambiguities related to remote sensing.

Figure 4. Oblique view of sand dunes at Bigstick Sand Hills, Saskatchewan, Canada, which uses imagery and digital elevation data from UAV. The data were collected in approximately 3 hours.

- Recently, Unmanned Aerial Vehicle (UAV) have been proved to merge the best of field analysis and remote sensing data (Figure 4).

Planetary connection

Beginning with images from the early 1970s, remote sensing (RS) has 77 revealed a rich diversity of dune field patterns on Earth, Mars, Venus, and Titan (Levin et al. 2012 and references therein).



Dune movements have been detected and measured using HIRISE and CTX cameras on Mars.

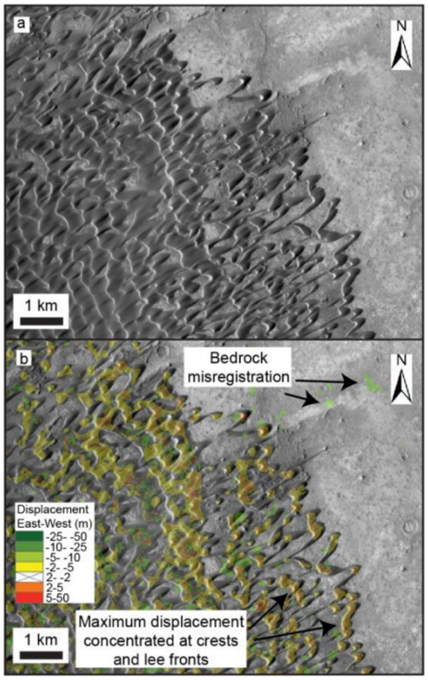


Figure 5. (a) CTX image of Nili Patera dune field on Mars. The dunes are migrating towards the southwest. (b) Color map showing east-west displacement between 2007 and 2016 overlaid on a CTX image. Figure from Davis et al. 2019

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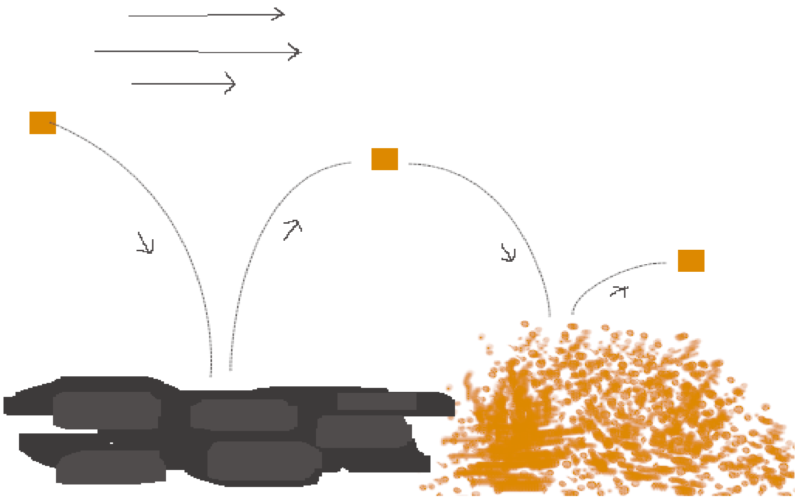
Dune Geomorphology
by Maureen Palmer

Dune behavior may be described as "vaguely disturbing" (Bagnold 1941). Details to follow.

Why are there sand dunes instead of flat layers of unsorted sand and rocks?

Wind-blown sand grains can easily bounce when they land on hard/rocky surfaces, but lose a lot of energy in the process of bouncing off of squishy piles of sand. This means that sand grains tend to be transported away from non-sandy areas and accumulate on areas that already have a lot of sand, leading to the growth of large dune structures. (Melosh 2011)

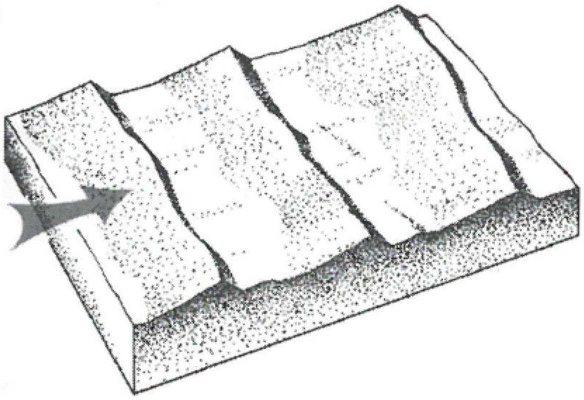


Types of dunes at White Sands

Photo credit: Las Cruces Visitors Bureau

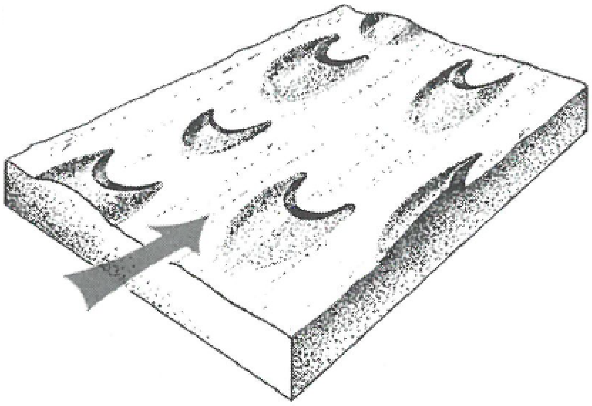
Dune morphology is mostly determined by wind patterns and the amount of sand available, along with vegetation patterns and moisture levels. White Sands is dominated by unidirectional winds, so we expect to see the following four dune patterns (McKee 1966):

1. Transverse Dunes



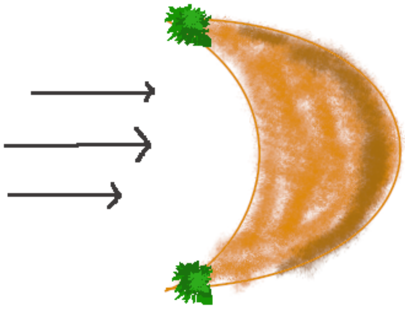
Transverse dunes form when there are unidirectional winds and a large supply of sand. The dune ridges are *perpendicular* to the principal wind direction.
In situations with slightly less sand available, the dune ridges may be wavier; these are “Barchanoid ridges.”
(Figure & info from Melosh 2011)

2. Barchan Dunes



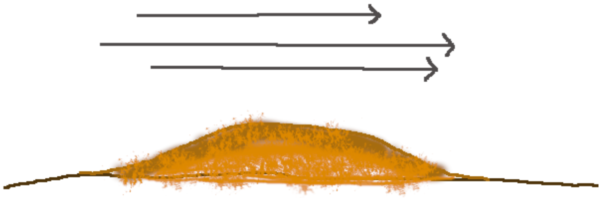
These form when there are unidirectional winds and a limited supply of sand.
As Barchan dunes grow, they can shed sand that forms smaller new Barchans. Bagnold (1941) described this splitting process as “breeding, in a manner which, by its grotesque imitation of life, is vaguely disturbing to an imaginative mind.”
(Figure & info from Melosh 2011)

3. Parabolic Dunes



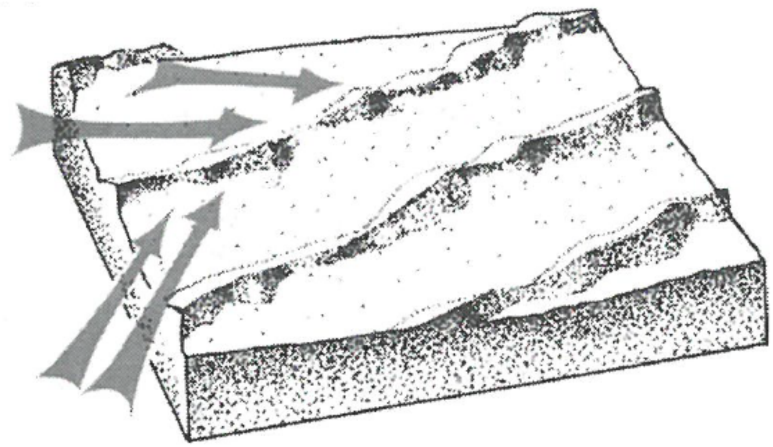
Parabolic dunes are like Barchan dunes, but facing the other way because the arms are held in place by vegetation (McKee 1966).

4. Dome-shaped Dunes



These dunes form when there is intense, unobstructed wind that prevents the dune from becoming tall or having a defined crest (McKee 1966).

Dunes on Titan



Dunes cover 12.5% of Titan's surface.

Like the dunes at White Sands National Monument, Titan's dunes are young surface features that are not cratered.

Unlike the dunes at White Sands National Monument, dunes on Titan are primarily longitudinal dunes oriented East–West. This suggests that the dunes are formed by bi-directional winds (as in this figure), or possibly that they are stabilized by cohesive forces between dune particles.

Also unlike the dunes here on Earth, Titan's dunes are primarily composed of "sand grains" made of organics (probably hydrocarbons).

Source for all Titan dune info: Aharonson et al. 2014 review article. Figure from Melosh 2011.

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Dune Footprints

"Dune footprints" is the informal term for the lithified remains from the bottom of a dune after the dune has moved on. Cementation and adhesion by water results in the individual sediment grains making up the dune sticking to one another, making them more resistant to being eroded by the wind than the rest of the dune. These dune footprints are usually exposed in interdunal regions, with ridged patterns indicating the direction of dune migration in the area.

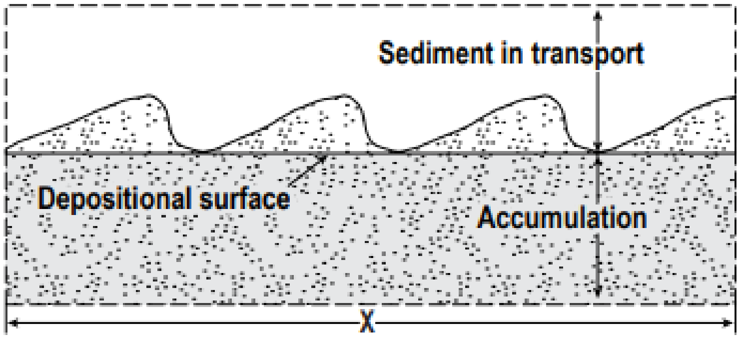
Dune footprints at White Sands National Monument. Credit: http://maps.unomaha.edu/Maher /geo117/part2/117deserts.html

White Sands National Monument

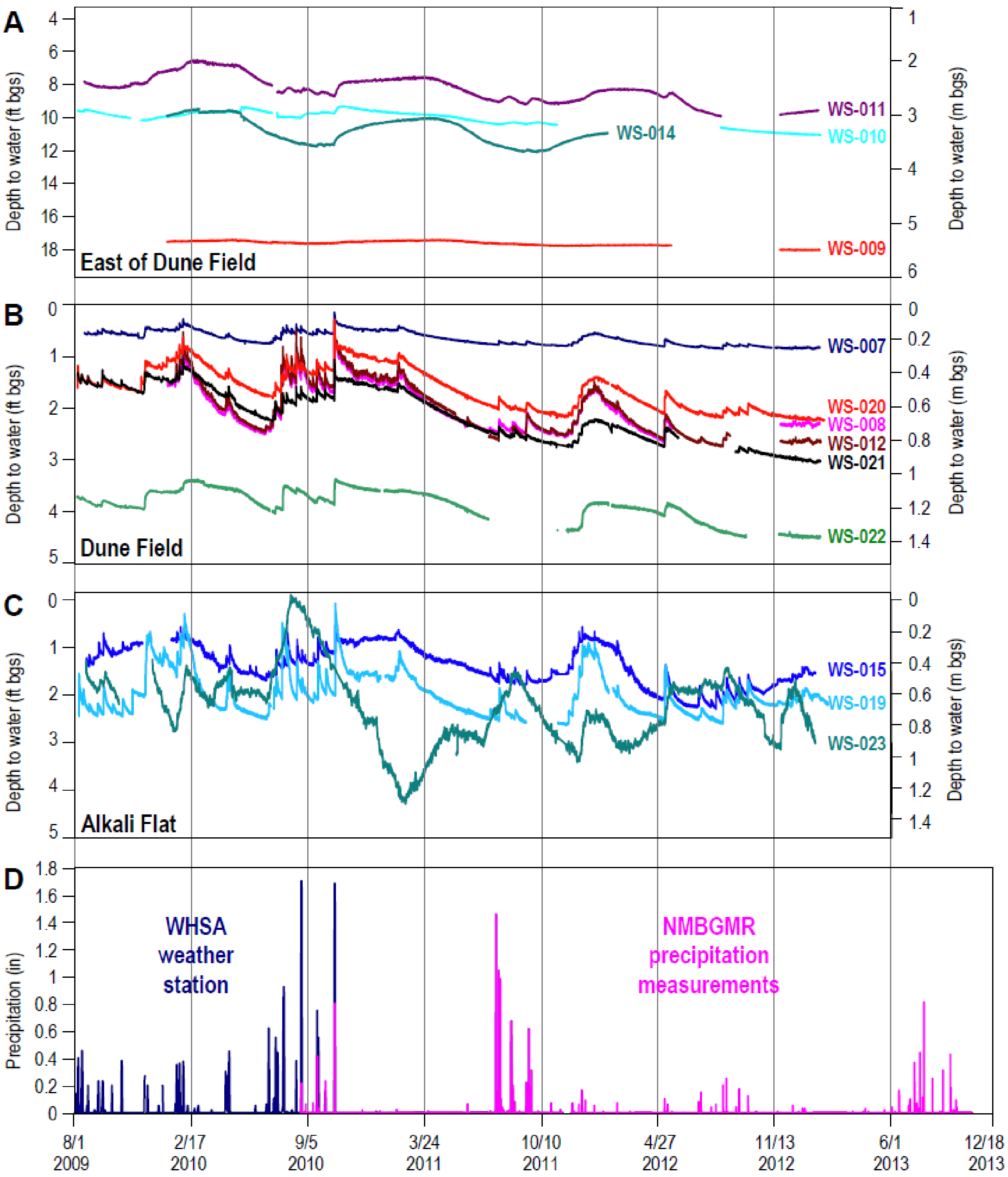
At the White Sands National Monument, gypsum from the San Andres and Sacramento Mountains was eroded to form the largest gypsum dune field on the planet. In contrast to the quartz that constitute most dune fields, gypsum is significantly more soluble in water, making dune footprints at the White Sands National Monument particularly prominent. The water table at White Sands is close to the surface, often even going above the surface resulting in flooding of interdunal areas during the monsoon season after heavy rains or during the winter when evaporation rates are low. Rising groundwater levels in the dunes also occasionally results in springs that discharge from the western edge of the dune field. This water usually flows into Lake Lucero.

Deposition Process

The White Sands Dune Field is primarily a wet aeolian system in which the behavior over time of the accumulation surface is a function of the water table [Newton and Allen, 2014]. The accumulation surface is the surface connecting the interdune troughs and underneath the dunes. In such systems, the capillary fringe of the water table is at or near the accumulation surface. Accumulation occurs with a relative rise of the water table, whereas deflation occurs when the water table falls, and bypass occurs with a static water table. Dunes do not just migrate over the accumulation surface (i.e., bypassing), but they also leave sets of cross-strata (the dune footprints). These can then be eroded or buried beneath interdune deposits, before the next dune comes along to deposit the next set of cross-strata. While erosion is typical in the interdunal



Transportation, deposition and accumulation in a dune field. Credit: Newton and Allen [2014]



Groundwater levels at three locations in the White Sands National Monument.
bgs is "below ground surface". Credit: Newton and Allen [2014]

areas in aeolian systems, there is instead significant accumulation in the interdunal areas for wet aeolian systems such as White Sands because moisture both fosters deposition and hinders erosion. Specifically at White Sands, surface cementation of the gypsum further stabilizes the surface against deflation [Newton and Allen, 2014].

Bedding patterns associated with longitudinal (top) and transverse (bottom) dunes.
Credit: https://walrus.wr.usgs.gov/seds/bedforms

Cross-Strata Structures

Analysis of the dune footprints can provide clues to the history of dominant wind direction and sediment deposition in the dune field [McKee, 1965]. Different types of dunes give rise to different bedding patterns, and closer examination of the texture of the beds provide further details on the depositional processes.

Cross-bedding in Coconino sandstone at Walnut Canyon.
https://www.geocaching.com/geocache/
GCZ5H6_walnut-canyon-geologic-sampling

Trenching studies at White Sands have found a consistent bundling of foresets separated by erosional bounding surfaces that occur on average every 1.4 m (with a range of 0.5–2.5 m). These bounding surfaces manifest on the surface as salt ridges on the interdunal floor. These ridges form along surfaces along which groundwater can rise through capillary action and precipitate gypsum. This is often also accompanied by the growth of mats of microorganisms and algae. Development of these ridges occurs from late fall to early spring when the capillary fringe is highest. At other times of the year, the salt ridges and associated mats are typically dry, brittle with an admixture of wind-blown sand, and susceptible to erosion. Thus these ridges are interpreted to be annual reactivation surfaces.

Foresets between the bounding surfaces can be distinguished by stratification types as grainflow, grainfall and wind-ripple laminae. Grainflow cross-strata, representing transverse wind conditions, result from progradation of the slipface with the predominant winds from the SW. They often manifest on the surface as dips of the dune footprint due to their relative erodibility. Grainflow cross-strata then truncated with development of reactivation surfaces with the onset of N–NW winds during the late fall and winter. These same winds give rise to wind-ripple laminae overlying the reactivation surface, reflecting the oblique nature of the wind incidence angle to the dune crestline.

Interdune Deposits

Interdune deposits refer to flat-bedded laminae that form on top of the dune footprints. These deposits are thin (± 1 cm) and relatively continuous (some traced for tens of metres), except for those occurring within isolated erosional hollows scoured into the cross-strata. They reflect deposition on the interdunal areas in which sand is blown onto the surface and incorporated into the seasonal cycle of the salt ridges and organic mats. The banding of laminae in these interdune deposits, similar to the cross-strata, is also interpreted to correspond to seasonal wetting with a rise of the capillary fringe through wind-blown sand, sand trapped by adhesion onto the damp surface, and culminating in development of the organic mats during periods of maximum wetness. The increase in the number of laminae upwind reflects the increasing time that the interdune surface has been an exposed surface, whereas the thickening of the laminae upwind and the increase in the organic content vertically reflects relatively lateral passage of the interdunal area into lower and wetter areas with dune migration. These laminae display seasonal light and dark banding, and thus they are interpreted as interdune varves. If their preservation is complete, the number of varves (one light and dark couplet) should correspond to the dune migration rate. However, only 1/3 of the varves are represented, suggesting a lack of deposition or removal by deflation in some years.

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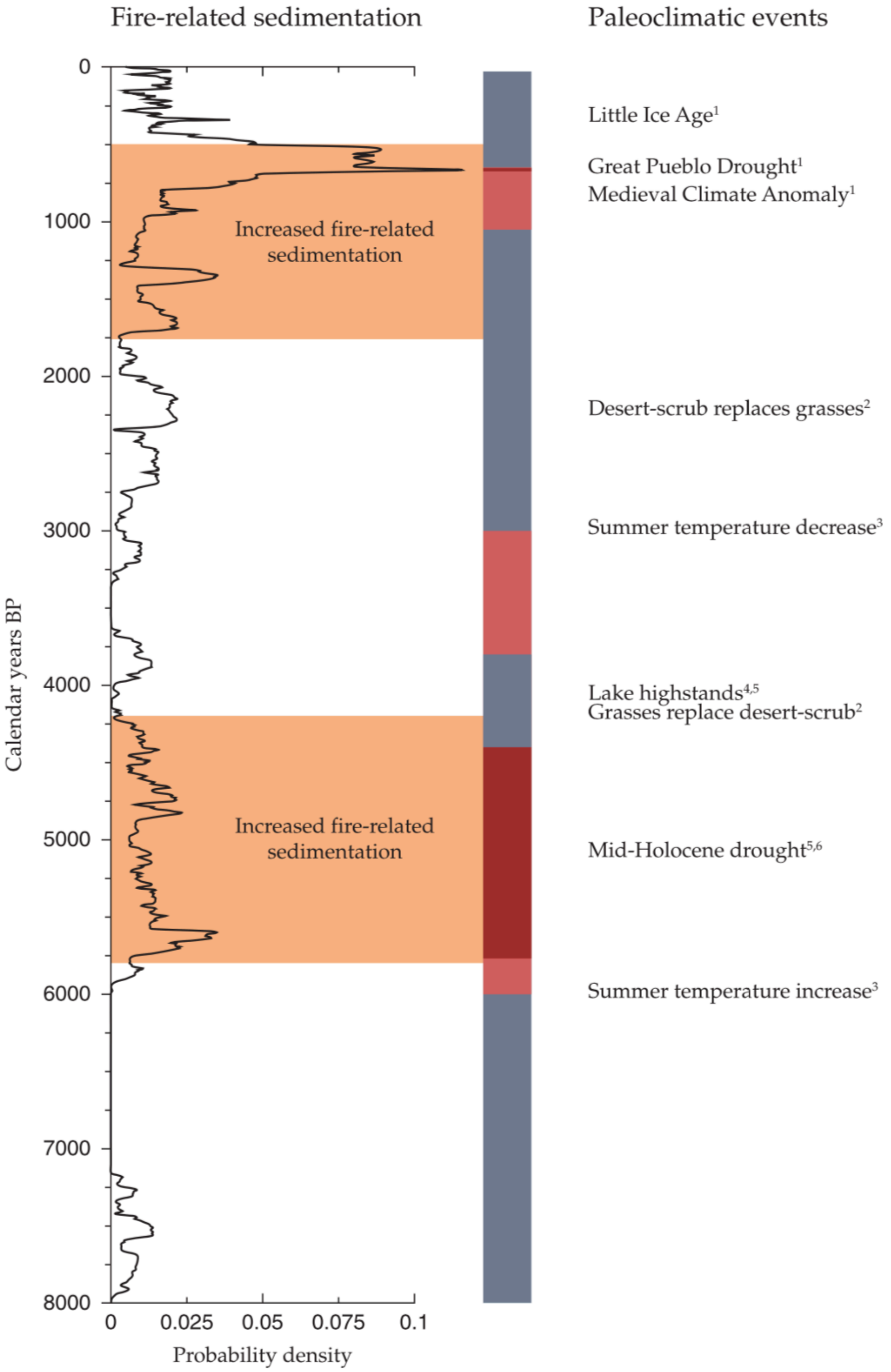
Prepared by Daniel Lo

Climate History of Southern New Mexico in the Holocene

Maria Steinrueck



(Fig. 3, Meyer & Frechette, 2010)

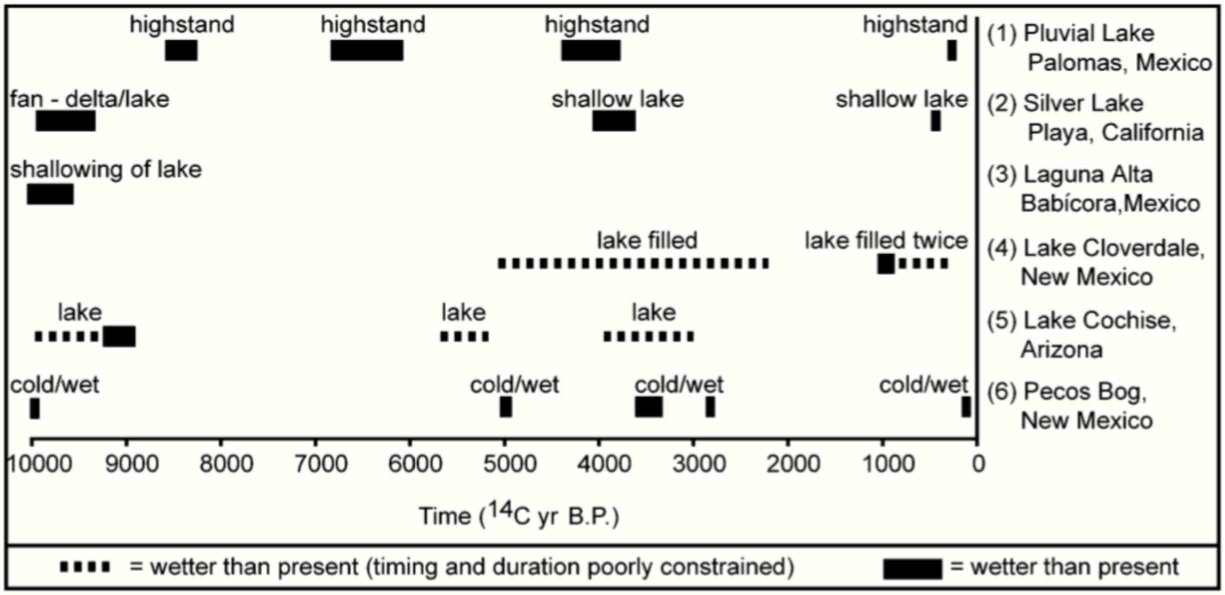
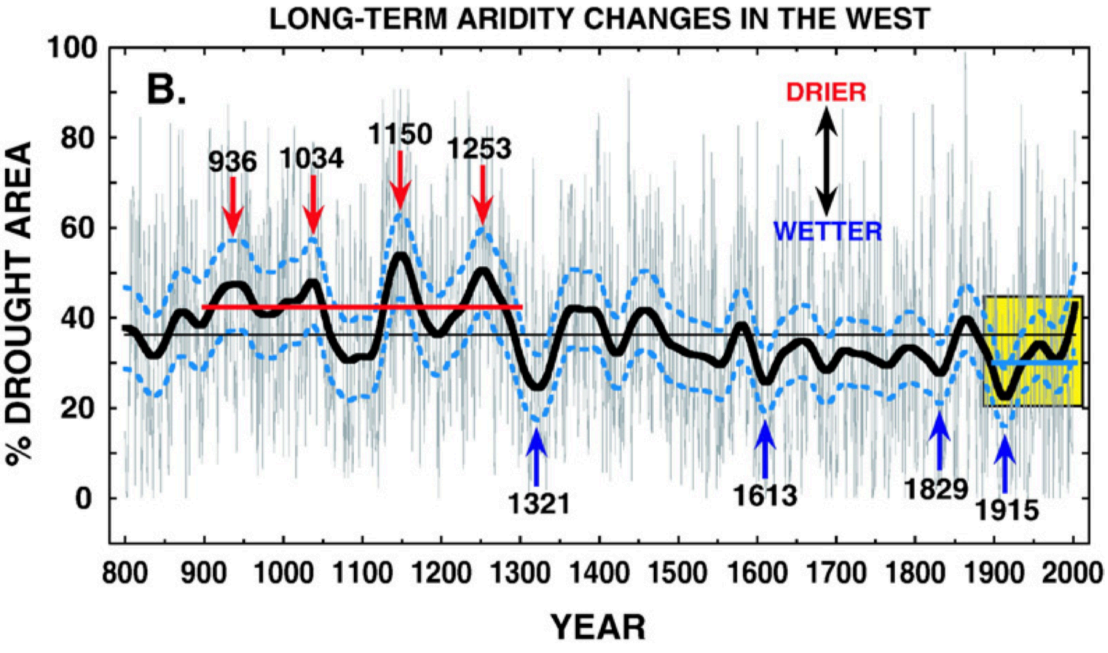


Figure 3. Evidence for wet and/or cold periods recorded in sediments throughout southwestern United States and northern Mexico. Black lines represent wet and/or cold periods. 1—this study; 2—Enzel et al. (1989); 3—Metcalfe et al. (1997); 4—Krider (1998); 5—Waters (1989); 6—Armour et al. (2002). All records with exception of Enzel et al. (1989) are within modern monsoon moisture regime as defined by Douglas et al. (1993).

(Castiglia & Fawcett, 2005)



(From Fig. 10, Cook et al., 2007)

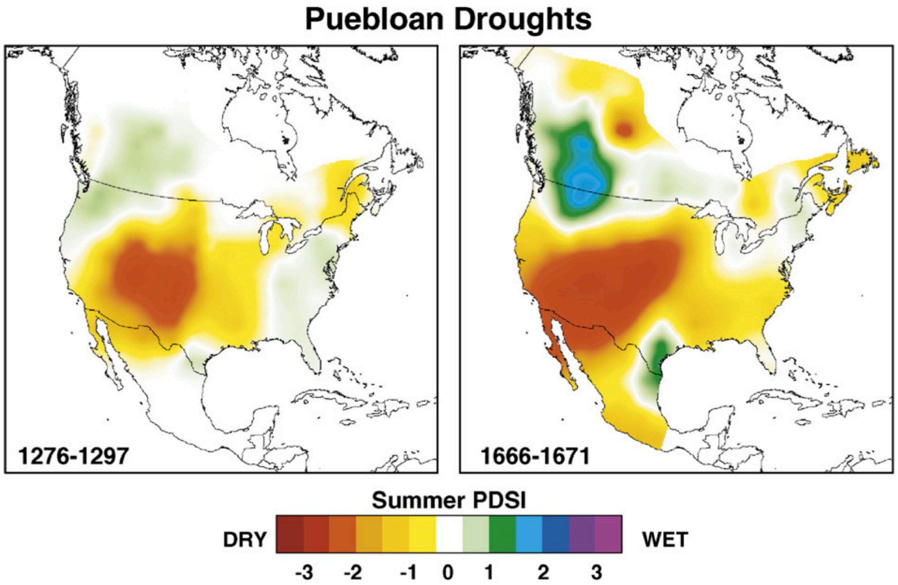


Fig. 11. Tree-ring reconstructed summer PDSI during two multi-year droughts centered over the Puebloan cultural area. The "Great Drouth" (Douglass 1929, 1935) lasted for at least 22 yr (left). The social and environmental effects of the six-year drought during the mid-17th century (right) were mentioned by Spanish archivists and may provide useful insight into the consequences of multi-year drought on prehistoric farmers in the region.

(Cook et al., 2007)

Evidence for climate variations in NM during the Holocene comes from

- Lake-level variations (beach ridges, can be dated through carbon-dating of pelecypods as in Castiglia & Fawcett, 2005)
- Vegetation changes recorded in buried soils (e.g., Buck & Monger, 1999)
- Packrat middens
- Tree-ring records (only date back to ~500-1,000 years, e.g. Cook et al. 2017))
- Records of fire-related erosion in alluvial fans (Meyer & Frechette, 2010)

References:

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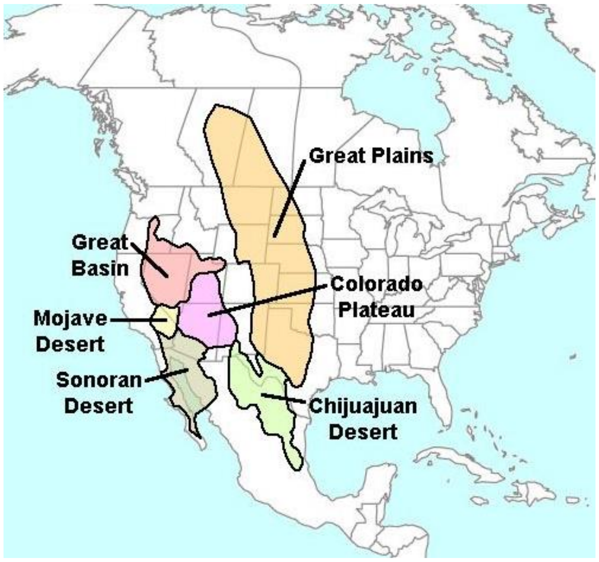
Laci Brock

Chihuahuan Desert
flora & fauna

The Chihuahuan Desert covers 647,500 square kilometers with over 90% of its area is within Mexico. It is the largest desert in North America.



The location and changing climate of the Chihuahuan region from a wetter past to a drier present contributed to species isolation and differentiation, leading to the unique Chihuahuan flora and fauna we see today. The region is rich in plants and animals, specialized habitats, and unique biological communities. Vegetation ranges from desert shrublands at lower elevations to conifer woodlands at the highest points. It is one of the richest deserts for plants and contains the largest assemblage of endangered cacti in America. The World Wildlife Federation (WWF) considers the Chihuahuan Desert the most biologically diverse desert in the world.

Some interesting facts about the flora and fauna of this desert include:

- 3,500 plant species
- 1,000 endemic plants
- 25% of the world's cactus species (350)
- 130 types of mammals
- 500 different bird species
- 110 native freshwater fish

Flora

The flora here are hardy. They must be drought tolerant and able to survive in temperatures that range from sub-freezing to over 100°F (38°C). Plants must constantly adapt to a shifting landscape as well as be successful in finding water sources and nutrients. Plants growing on the dune fields of White Sands "hold on" to the dunes at by

Purple sand verbena at White Sands

using their compacted root structure. The roots tap all the way down into the water table to absorb water, and some of this water gets absorbed into the surrounding sand creating a hard mound called a pedestal. Many plants must learn to grow fast to flourish in soil with limited nutrients.

The largest edaphically restricted floras in North America are found within the Chihuahuan Desert.

Edaphic: *referring to the conditions of the soil (e.g., texture, drainage) rather than climactic factors.*

Gypsum deposits (hydrated calcium, $CaSO_4 \circ 2H_2O$) are common throughout the desert. Gypsum is a soluble mineral that tends to accumulate and/or be exposed in desert environments in high amounts. Typically, gypsum-based soils might be considered inhospitable for plants. High levels of calcium and sulfur can be toxic to many plants. The ion concentrations in gypsic soils can be too high, which impedes the osmotic flow of water into roots, and the hard surface crusts can prevent seedlings from establishing. However, there are a large group of Chihuahuan Desert plants that have adapted and evolved to tolerate gypsic soils (gypsovags) and some plants which require it (gypsophiles).

Gypsophiles have adjustments that help them deal with the chemical limitations present in gypsum-based soils. For example, these plants might have succulent-like leaves or specialized root structures that help to counteract undesirable ions. The majority of gypsophiles are perennials. These plants are not very good at distributing their seeds, which is why they are endemic to a restricted area. Examples of endemic gypsophiles in the area include species in the following generas:

- *Acleisanthes and Anulocaulis*
- *Nerisyrenia*
- *Nama and Tiquilia*
- *Drymaria*
- *Xanthisma*
- And many others

Crinklemat in the Chihuahuan Desert

The most dominant plant species in the northern portion of the desert region is the creosote bush, tarbush, and viscid acacia. The middle portion of the desert is abundant in Yucca and Opuntia, whereas the southern portion is rich with Mexican fire-barrel cactus and Arizona rainbow cactus. Here are two common plants and one of the endangered cacti in the region.


Creosote bush


Soaptree Yucca


Kingcup cactus

Fauna


Burrowing owl

White Sands National Monument is home to more than 800 different types of animal species, many of them being nocturnal. There are more than 130 species of mammals in the area. Most of the mammals are found on the outer edges of the dune field including bats, cottontail rabbits, kit foxes, coyotes, bobcats, porcupines, and more. The desert region is also home to mule deer, pronghorn, jaguar, javelina, and grey foxes. Pallid bats can be found around the Visitor Center. On the dunes, an endemic species of mouse called the Apache pocket mouse is a resident of the dunes.

The Chihuahuan Desert is home to around 400 different species of birds. Over 220 species have been recorded at White Sands National Monument. Some common visitors are barn swallows, black-chinned hummingbirds, burrowing owls, cactus wrens, and roadrunners. Many birds retreat from the Great Plains in North American to the desert for winter. Some of the declining species include the mountain plover, ferruginous hawk, and Baird's sparrow.

Over 500 different species of invertebrates live at White Sands. If you're worried, most arachnids at White Sands have weak venom and are not life threatening to humans. You can also find more than 170 species of amphibians and reptiles in the Chihuahuan Desert. Of these numbers, 18 are considered endemic to the region. There are 7 species of amphibians and 33 species of reptiles at White Sands.

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The Human History of Southern New Mexico

Kyle Pearson

The precise origin of humans prior to settling in New Mexico is slightly unclear however it's suspected to arise from neighboring ancestral regions. Figure 1 shows a map of the Americas prior to the settling of the first ancient culture in New Mexico, the Clovis. Predecessors of the Clovis people may have migrated south along the coastlines or come north through Mexico. Known as "Clovis First" the predominant hypothesis among archaeologists in the latter half of the 20th century had been that the people associated with the Clovis culture were the first inhabitants of the Americas. The primary support for this was that no solid evidence of pre-Clovis human habitation had been found. It's thought, the Clovis people crossed the Beringia land bridge during the period of lowered sea levels during the ice age, then made their way southward through what is present day Canada as the glaciers retreated. It wasn't until two recent studies debated the origin and time frame of the Clovis people that this origin hypothesis changed. The first was a study in 2011 that revealed an archaeological site that predates the Clovis culture at Buttermilk Creek, Texas. Another study in 2016 argued it was unlikely for the early American inhabitants to have come from Siberia via the Bering land bridge. They explained the ice-free corridor may have occurred too late compared to radiocarbon dates of some archaeological sites. Instead, they suggest the Clovis people likely came from the south, perhaps following wild animals such as bison.

Figure 1. Map of the Americas showing pre-Clovis sites.

Humans have occupied New Mexico as early as ~11,000 years ago. The Clovis culture is a prehistoric Paleo-Indian culture named for their distinct use of stone tools which were used on fauna during the Pleistocene era. First evidence of these tools was found in Eastern New Mexico at Blackwater Draw which is an intermittent stream channel about 140 km long. The first large-scale excavation occurred in 1932 although local residents had been collecting bone and other artifacts for decades before. These tools were made from bone or stone and shaped into a point typically used as the head of a spear or arrow (see Figure 2).

Figure 2. A collection of Clovis projectile points

The Clovis artifacts are associated with the remains of extinct late Pleistocene megafauna including the mammoth, camel, horse, bison, saber-toothed cat, sloths and dire wolf. The most common idea about the end of the Clovis culture was the decline in availability of megafauna referred to as the Pleistocene overkill hypothesis. It's unclear whether the Clovis culture drove the mammoth and other species to extinction via overhunting. It has also been hypothesized that the Clovis culture had it's decline due to the Younger Dryas cold phase. The Younger Dryas was the most recent change to the gradual warming of Earth's climate since the last glacial maximum. The change was relatively sudden, and it resulted in a decline of 2-6 degrees Celsius over much of the northern hemisphere. It was caused by a decline in the strength of the Atlantic Meridional circulation, which transports water from the Equator towards the North Pole. The change in circulation was caused by an influx of fresh cold water from North American into the Atlantic.

Since the time of the Clovis other Ancestral Puebloans have inhabited the area (see Table 1).

Culture or Group	Time	Location Found	Important Development
Clovis	9200 BC	Eastern Plains	Hunted big game
Folsom	8200 BC	American Southwest	Hunted big game
Desert Culture I	6000-2000 BC	American Southwest	Hunted small game, gathered seeds, nuts and berries
Desert Culture II	2000-500 BC	American Southwest	Developed early gardening skills. Baskets and milling stones
Mogollon	300 BC – 1200 AD	Southwestern NM	Farmed crops, made pottery and lived in pit house villages
Anasazi: Basketmaker	1 – 500 AD	Northwestern NM	Gathered food and made fine baskets

Modified basketmaker	500 – 700 AD	Northwestern NM	Lived in pit house villages, used the mano and metate, learned pottery-making and used bow and arrows
Developmental Pueblo	700 – 1050 AD	Northwestern NM	Built adobes houses, used cotton cloth and infant cradlebeds
Great Pueblo	1050 – 1300 AD	Northwestern NM	Built multistories pueblos, practiced irrigation and laid out road systems
Rio Grande Classic	1300 – 1600 AD	West-central NM	Abandoned northwester NM sites, migrated to new areas of settlement and changed building and pottery style.

Mogollon

Mogollon is one of four major prehistoric archaeological Oasisamerica culture areas of the American Southwest and Northern Mexico (see Figure 3). The American Indian culture known as Mogollon lived in the southwest from approximately 300 BC to 1200 AD. The name Mogollon comes from the Mogollon mountains, which were named after Don Juan Ignacio Flores Mogollon, Spanish Governor of New Mexico from 1712 – 1715. The Mogollon archaeological area was first recognized by Emil Haury in the early 1930s. Side notes: Emil Haury got his B.S. and M.A. in Archaeology from the University of Arizona. Haury recognized similarities in the Mogollon culture with those from Hohokam and Ancient Pueblo (“Anasazi”) archaeological culture including the brown-paste pottery and the use of surface “pueblo” dwellings. It took a lot of research from institutes like the Field Museum of Natural History, the Arizona state museum at the University of Arizona, the Amerind Foundation and the Mimbres Foundation in order to firmly characterize the inhabitants of the Mogollon as a division of the local cultures. Today, the distinctiveness of the Mogollon culture is defined by its pottery, architectural construction, ground-stone tool design and habits and customs of residence location and mortuary treatment. The origins of the Mogollon culture are suspect to have emerged from preceding “Desert Archaic” traditions that link Mogollon ancestry with the first (late Pleistocene) prehistoric human occupants of the area (around 9000 BC). The cultural distinctions emerged in the larger regions when populations grew great enough to establish villages and even larger communities. An alternative possibility is that the Mogollon were descendants of early farmers who migrated from farming regions in central Mexico around 3500 BC.

Research on Mogollon culture has led to the recognition of regional variants, of which the most widely recognized and popular is the “Mimbres culture”. Others include the Jornada, Forestdale, Point of Pines, San Simon and Upper Gila branches.

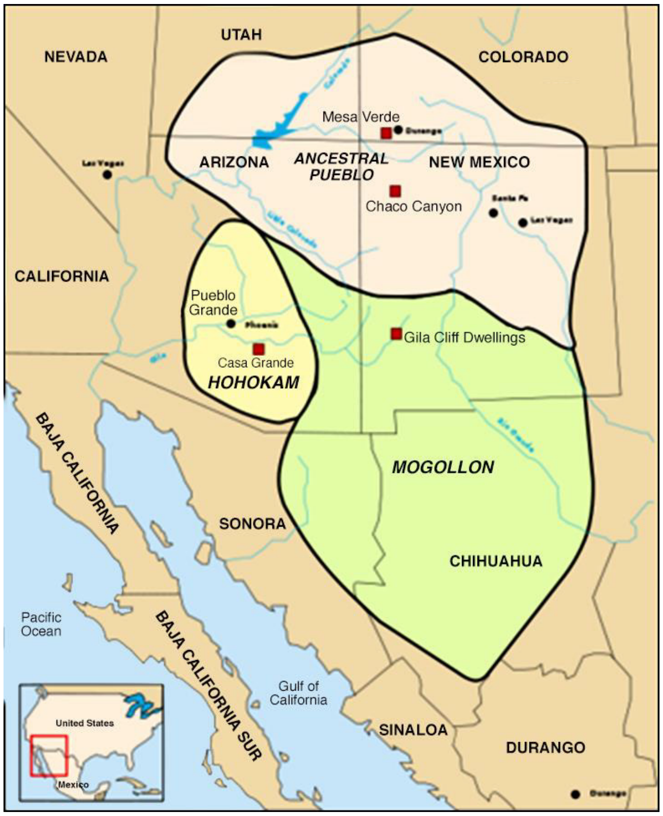

Figure 3. Populations in the Oasisamerica region.

The Mimbres culture refers to a tradition within a subregion of the Mogollon culture area or to an interval of time around 1000-1200 AD. The Mimbres branch is centered in Mimbres Valley and encompasses the upper Gila River and parts of the upper San Francisco river as well as the Rio Grande Valley. Differentiation between the Mimbres branch and other areas of the Mogollon culture is most apparent in the architectural construction and black and white painted pottery. The houses are consistently quadrilateral, usually with sharply angled corners, well plastered floors and walls along with an average size of ~17 meters^2 in floor surface area. Pueblos from this time can be quite large, with some composed of clusters of compounds or roomblocks, each containing up to 150 rooms, and grouped around an open plaza. The largest Mimbres sites are located near wide areas of well-watered floodplains suitable for maize agriculture.

The pottery produced in the Mimbres region, often finely painted bowls, is distinct in style and is decorated with geometric designs and figurative paintings of animals, people and cultural icons in black paint on white backgrounds (see Figure 4). Some images suggest familiarity and relationships with cultures in northern and central Mexico. The elaborate decoration indicates that these people enjoyed a rich ceremonial life. Over time, both geometric and figurative designs became increasingly sophisticated and diverse. The designs are characterized by elaborate geometric patterns, refined brushwork, including very fine linework, and may include figures of animals and humans. Birds are prominent on Mimbres pots too. Including images such as turkeys feeding on insects and a man trapping birds in a garden. Mimbres bowls are often found associated with burials. The bowls have been found covering the face of the person. Wear marks on the insides of the bowls show they were used and not just burial items.

The Descendants

The different groups in the Mogollon culture eventually merged into or with the native American cultures we see today. The area originally settled by the Mogollon culture was eventually filled by the unrelated Apache people, who moved in from the North. However, the modern Pueblo people in the southwest claim descent from the Mogollon and related cultures although these people generally

assert that their descent was from more than one group and location. Archeologists believe that the western Pueblo villages of the Hopi and Zuni are likely related to the Mogollon.

Figure 4. Mimbres pottery at Standford University.

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White Sands Missile Range

Rachel B. Fernandes

The US Army White Sands Missile Range is the largest military installation in the US. It is located in the southern New Mexico, US, and is home to White Sands Test Centre, where the world's first atom bomb was test exploded in 1945. The missile range occupies around 3,200 square miles of area. It is equipped with a range of facilities for testing, research and development, evaluation and training activities conducted by the US Army, US Navy, US Air Force, NASA, other government agencies and private industry.

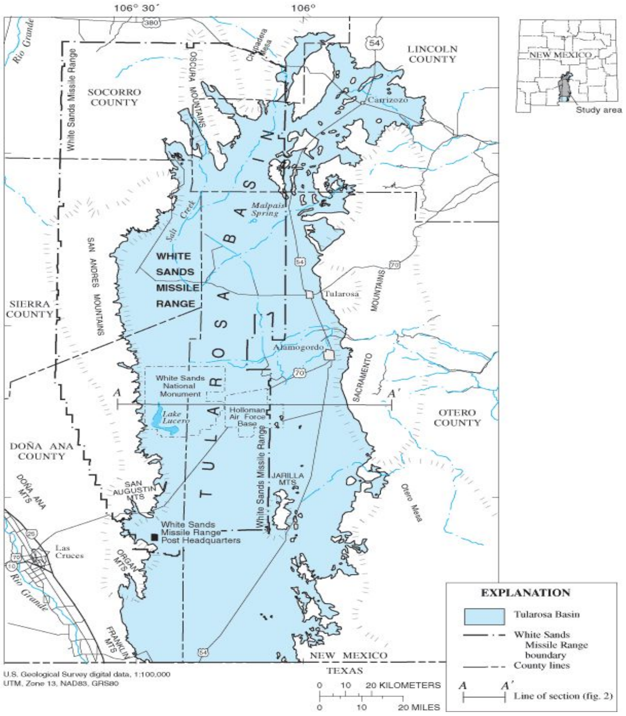

Figure 1: Most of the northern Tularosa basin (blue) is used for the WSMR (area within dashed perimeter), which encloses numerous areas that are not military land, as well as USAF facilities.

White Sands missile range history

The plans for establishing the land-based test range were conceptualised in the fall of 1944 in the wake of Robert Goddard's rocket research and the successful launch of the German-made V-2 rocket. Major General G M Barnes played a major role in the establishment of the missile range.

The Trinity (nuclear test) site was selected for missile research in November 1944. The White Sands Proving Ground was sanctioned by the Secretary of War in February 1945. The first V-2 missile was launched in April 1946. The US Navy's Viking No.1 rocket was launched to an altitude of 51.5 miles from White Sands Proving Grounds in May 1949. The USS Desert Ship, a concrete blockhouse with shipboard condition simulations, was built in 1958. The Trinity site was announced as a national historic landmark in 1975.

White Sands missile range construction

The original site plans were concluded in May 1945 and construction began in June of the same year. The main site was divided into four independent areas, allowing for the development of each individually. Some temporary buildings were also moved from Sandia Base in Albuquerque, New Mexico, to the White Sands Missile Range.

The construction initially used the water that came from a well close to the new post. The water from desolated mines in the Oregon mountains was used in the construction. Most of the structures built in 1945 have since been replaced with modern facilities. However, several of the original major facilities, such as missile assembly building and blockhouse, still exist.

White Sands missile range facilities

The White Sands Test Facility tests and evaluates hazardous materials, spacecraft components and rocket propulsion systems. Other organisations located at the missile range are the 46th Test Group, Second Engineer Battalion, the 746th Test Squadron, Army Research Laboratory, Centre for Countermeasures and the National Geospatial-Intelligence Agency. The Balfour Beatty Communities manages the family housing units at White Sands Missile Range. The missile range has an aquatic centre, auto skills centre, gymnasium, Italian café, museum, bowling centre and a frontier club. A family and morale, welfare and recreation organisation offers golf, bowling, skeet shooting, childcare and youth programmes.

Air facilities

The White Sands Test Facility has two operational, laser-levelled runways at White Sands Space Harbour. Each measures 11,000 m in length and 91 m in width. A third runway allows pilots to practice transatlantic abort landings. The primary runways can accommodate all NASA and large aircraft, such as the C-17, C-5A, B-52 and Boeing 747. White Sands Space Harbour is equipped with microwave scanning beam landing system, tactical air navigation system, precision approach path indicators, visual approach slope indicators, distance-to-go indicators, high-intensity xenon lights, global positioning system, and sideline and centreline indicators. It is also used as an alternate orbiter landing site and a training area for astronauts participating in shuttle missions. Shuttle training aircraft such as Grumman Gulfstream corporate jets are stored in a hangar situated 75 miles away at El Paso International Airport. These aircraft are specially modified to simulate the cockpit configuration and flight characteristics of a shuttle orbiter.

White Sands Missile Range Museum

The White Sands Missile Range Museum is located within the premises of the military facility, about 100 km south of the Trinity Site. The missile museum is crammed with information about the origin of America’s nuclear program, its pioneering ventures into space and the development of rockets as weapons, and about the accomplishments of scientists like Dr. Wernher von Braun and Dr. Clyde Tombaugh.

The most fascinating display of the museum is the missile park. It’s an outdoor display of more than 60 different rockets used in combat from WWII to the Gulf War. These include everything from the WAC Corporal and Loon (U.S. version of the V-1) to a Pershing II, a Patriot and the V-2, the world’s first long range ballistic missiles and the first man-made object to reach the fringe of space. The rockets are installed outside the museum building in an acre-sized garden, with most of them pointing towards the sky as if ready to blast off.

Aside from housing a wealth of missile related technology, the museum has sections dedicated to the local flora and fauna, the indigenous peoples who once lived on the land, and a room of paintings by a survivor of the brutal Bataan forced march of WWII, in which up to 10,000 Filipinos and 650 Americans died at Japanese hands.

Figure 2: Missile Park display at the White Sands Missile Range Museum

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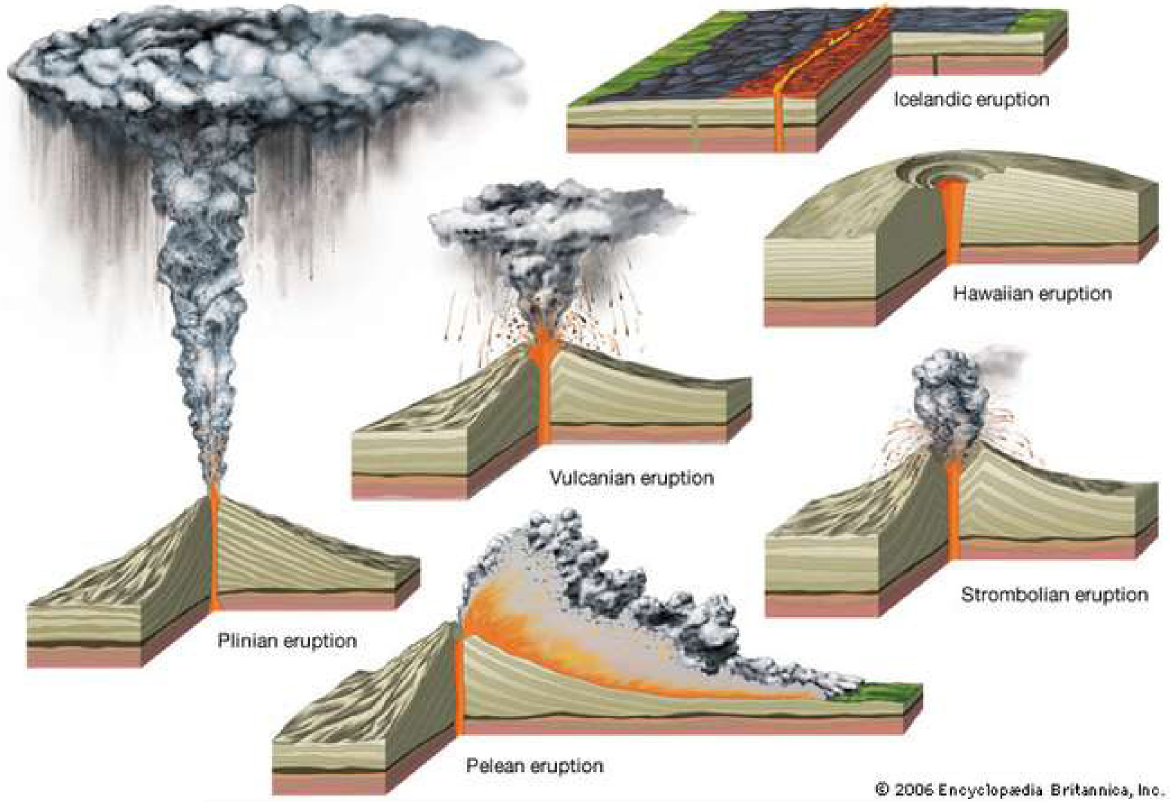
Geological References

Igneous Rocks



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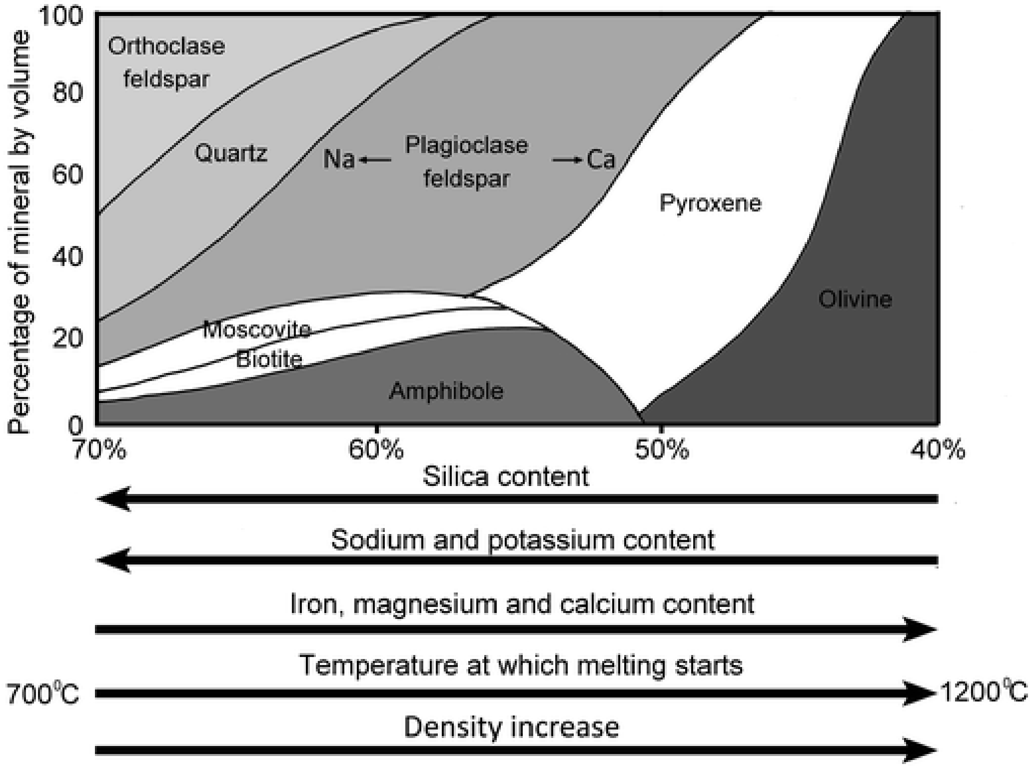
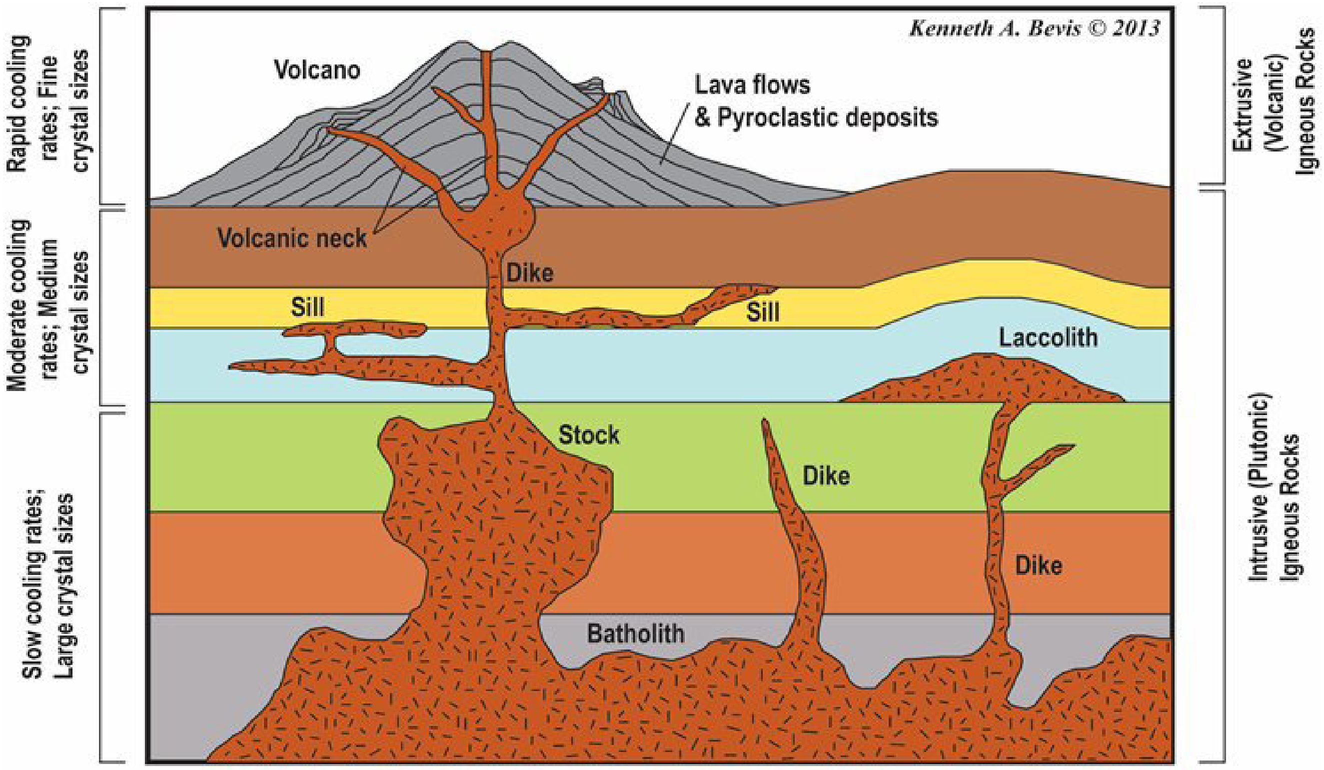
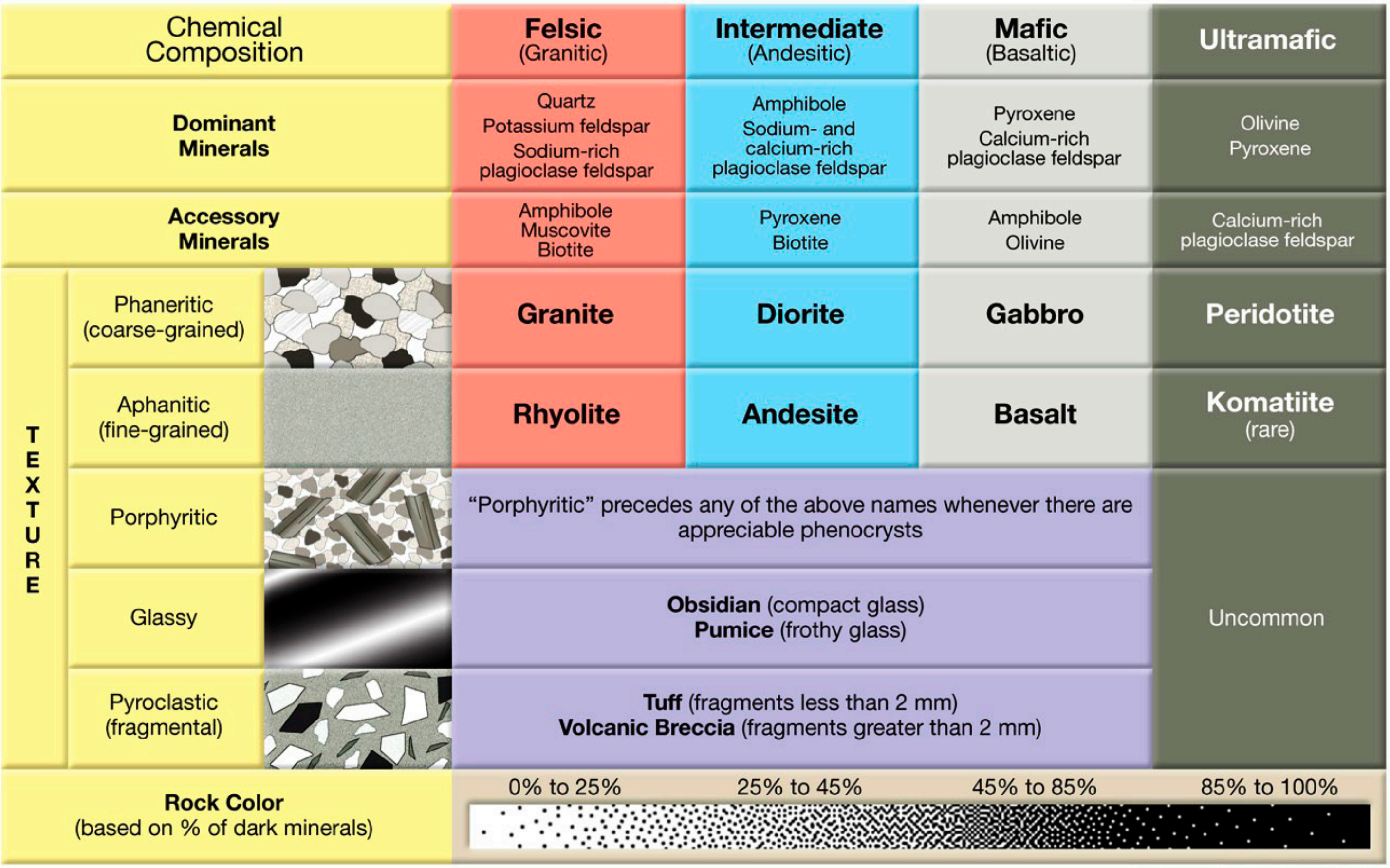
Composition	Felsic	Intermediate	Mafic	Ultramafic
Rock types	Granite Rhyolite	Diorite Andesite	Gabbro Basalt	Peridotite



Geological References

Igneous Rocks

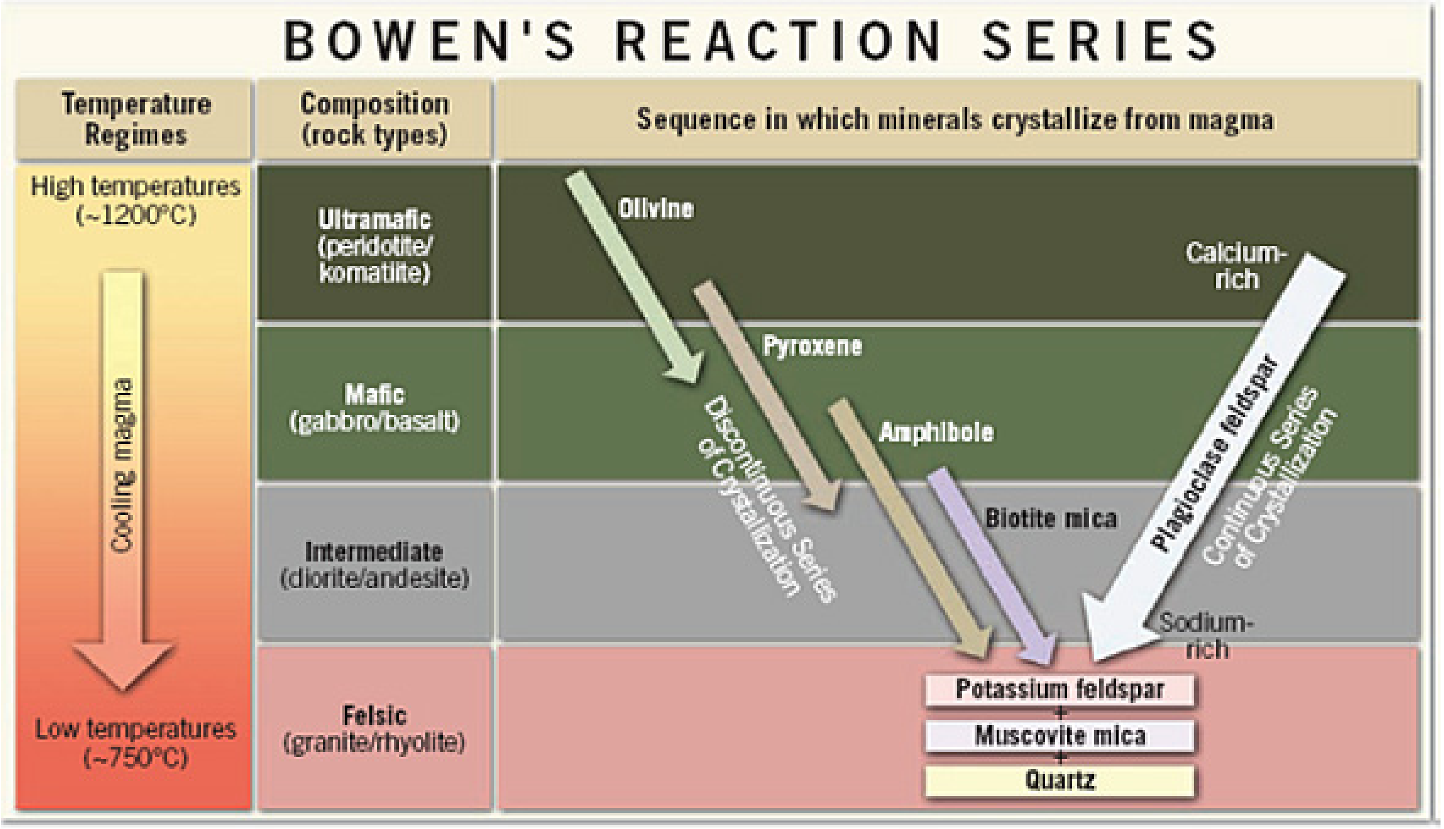


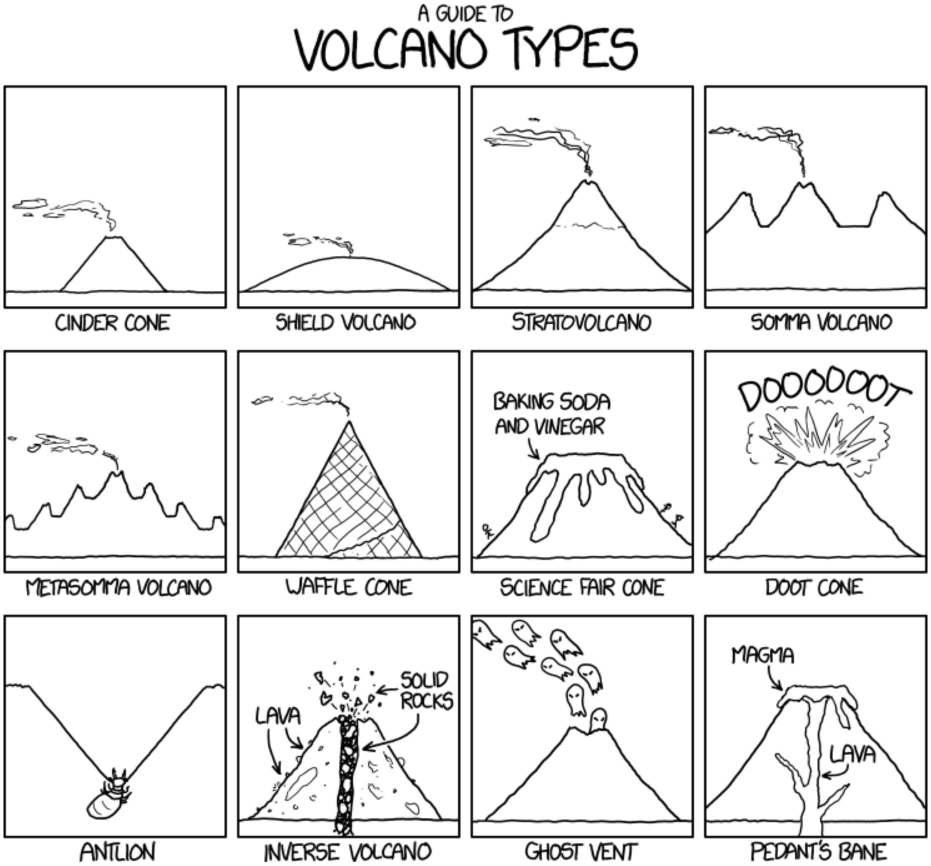


Chemical Composition		**Felsic** (Granitic)	**Intermediate** (Andesitic)	**Mafic** (Basaltic)	**Ultramafic**
Dominant Minerals		Quartz Potassium feldspar Sodium-rich plagioclase feldspar	Amphibole Sodium- and calcium-rich plagioclase feldspar	Pyroxene Calcium-rich plagioclase feldspar	Olivine Pyroxene
Accessory Minerals		Amphibole Muscovite Biotite	Pyroxene Biotite	Amphibole Olivine	Calcium-rich plagioclase feldspar
TEXTURE	Phaneritic (coarse-grained)	**Granite**	**Diorite**	**Gabbro**	**Peridotite**
	Aphanitic (fine-grained)	**Rhyolite**	**Andesite**	**Basalt**	**Komatiite** (rare)
	Porphyritic	"Porphyritic" precedes any of the above names whenever there are appreciable phenocrysts			Uncommon
	Glassy	**Obsidian** (compact glass) **Pumice** (frothy glass)			
	Pyroclastic (fragmental)	**Tuff** (fragments less than 2 mm) **Volcanic Breccia** (fragments greater than 2 mm)			
Rock Color (based on % of dark minerals)		0% to 25%	25% to 45%	45% to 85%	85% to 100%

Geological References

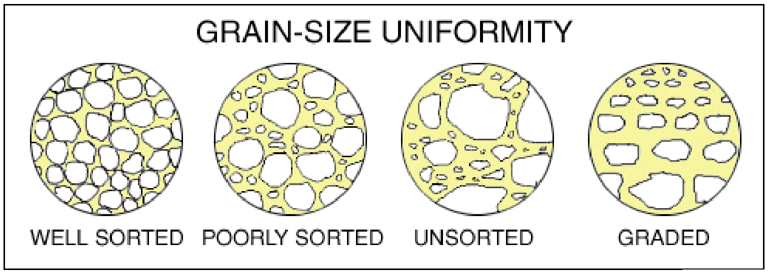
Igneous Rocks

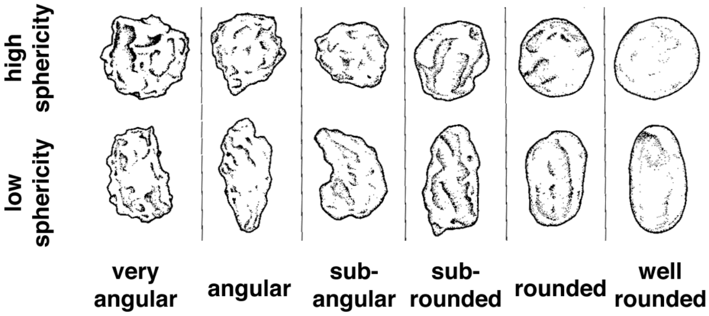


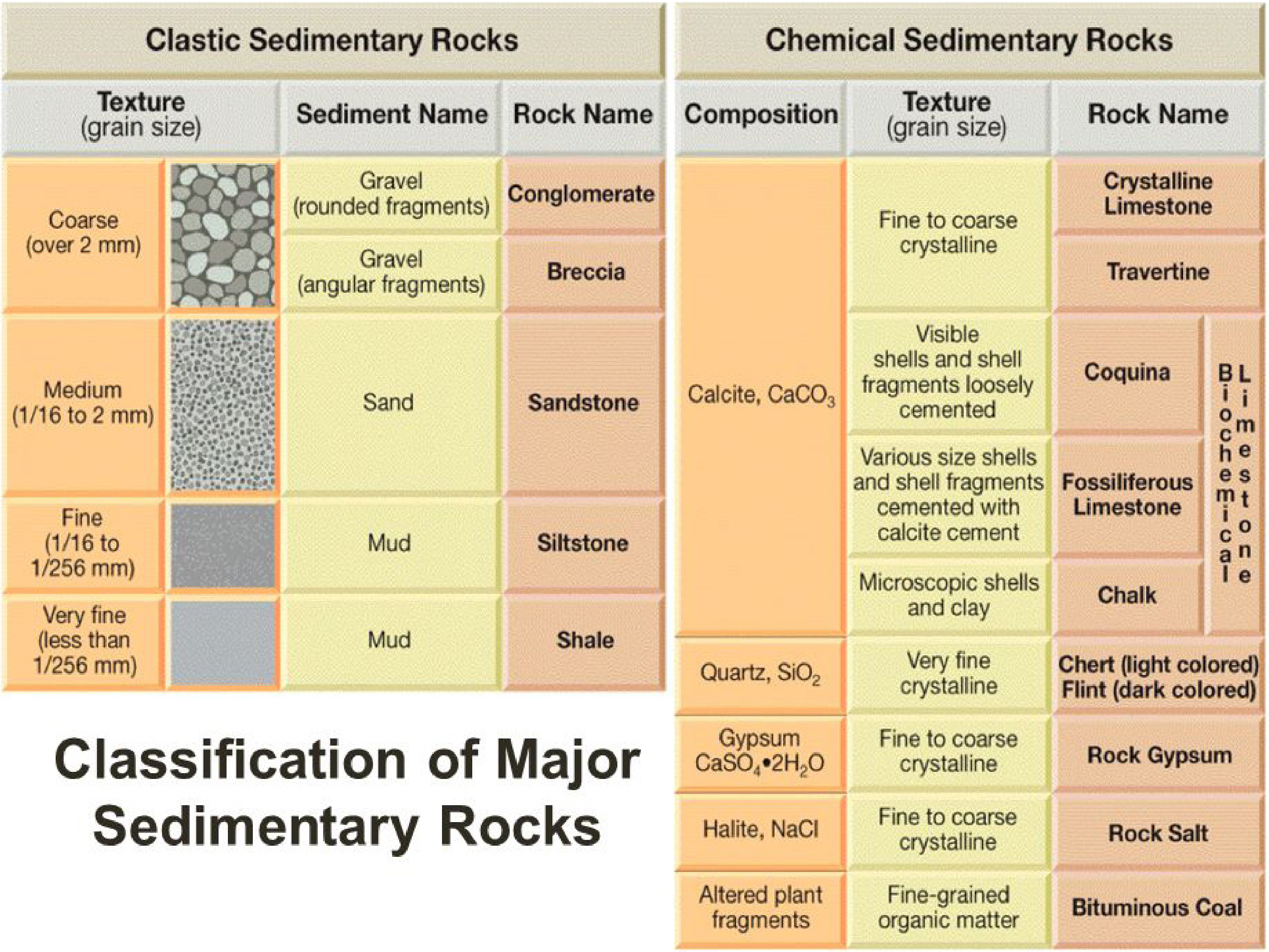


Geological References

Sedimentary Rocks







Classification of Major Sedimentary Rocks

Clastic Sedimentary Rocks

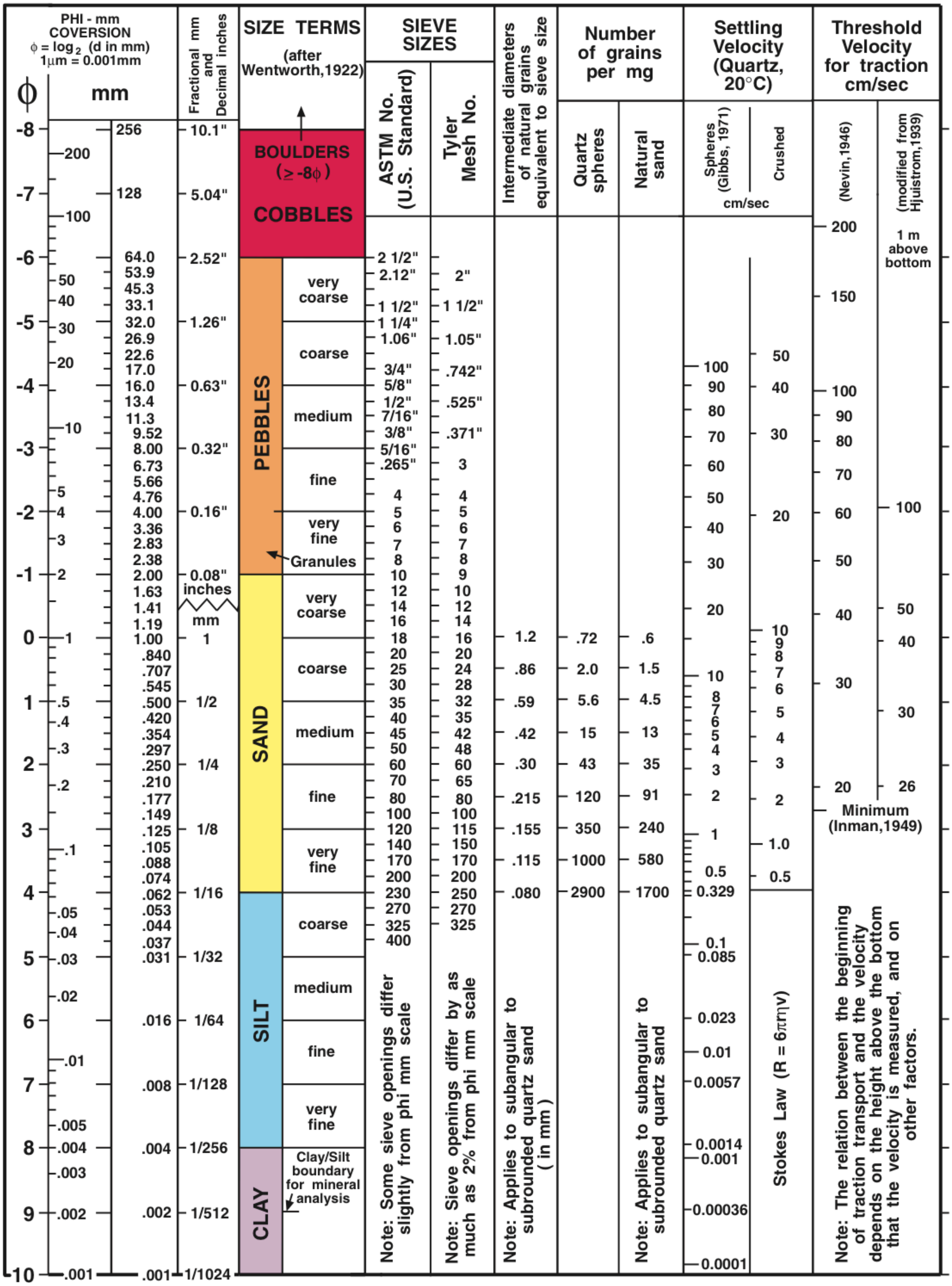
Texture (grain size)		Sediment Name	Rock Name
Coarse (over 2 mm)		Gravel (rounded fragments)	**Conglomerate**
		Gravel (angular fragments)	**Breccia**
Medium (1/16 to 2 mm)		Sand	**Sandstone**
Fine (1/16 to 1/256 mm)		Mud	**Siltstone**
Very fine (less than 1/256 mm)		Mud	**Shale**

Chemical Sedimentary Rocks

Composition	Texture (grain size)	Rock Name	
Calcite, $CaCO_3$	Fine to coarse crystalline	**Crystalline Limestone**	
		Travertine	
	Visible shells and shell fragments loosely cemented	**Coquina**	**Biochemical Limestone**
	Various size shells and shell fragments cemented with calcite cement	**Fossiliferous Limestone**	
	Microscopic shells and clay	**Chalk**	
Quartz, SiO_2	Very fine crystalline	**Chert (light colored)** **Flint (dark colored)**	
Gypsum $CaSO_4{\cdot}2H_2O$	Fine to coarse crystalline	**Rock Gypsum**	
Halite, NaCl	Fine to coarse crystalline	**Rock Salt**	
Altered plant fragments	Fine-grained organic matter	**Bituminous Coal**	

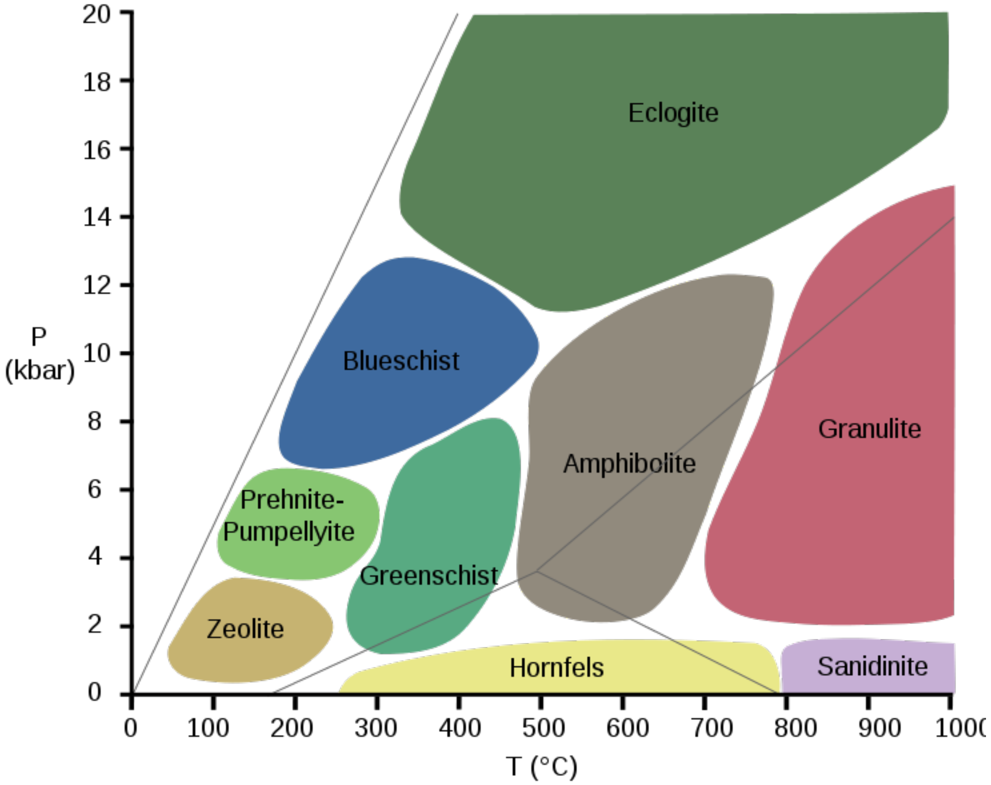
Geological References

Sedimentary Rocks

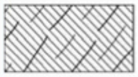
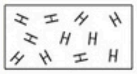


Geological References

Metamorphic Rocks

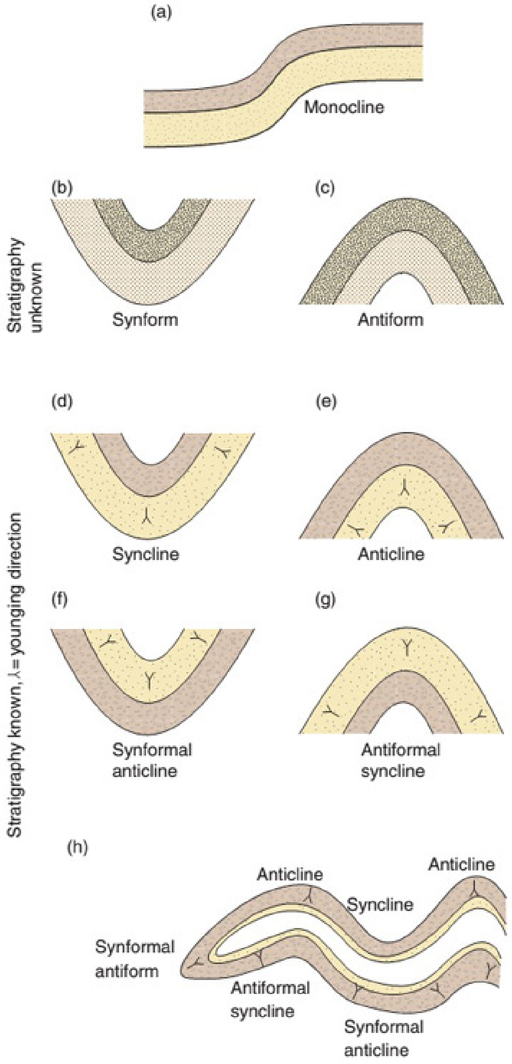


Scheme for Metamorphic Rock Identification

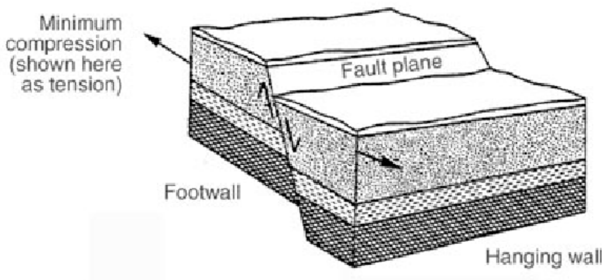
TEXTURE		GRAIN SIZE	COMPOSITION	TYPE OF METAMORPHISM	COMMENTS	ROCK NAME	MAP SYMBOL
FOLIATED	MINERAL ALIGNMENT	Fine	MICA	Regional (Heat and pressure increases)	Low-grade metamorphism of shale	**Slate**	
		Fine to medium	QUARTZ FELDSPAR AMPHIBOLE GARNET		Foliation surfaces shiny from microscopic mica crystals	**Phyllite**	
					Platy mica crystals visible from metamorphism of clay or feldspars	**Schist**	
	BAND-ING	Medium to coarse	PYROXENE		High-grade metamorphism; mineral types segregated into bands	**Gneiss**	
NONFOLIATED		Fine	Carbon	Regional	Metamorphism of bituminous coal	**Anthracite coal**	■
		Fine	Various minerals	Contact (heat)	Various rocks changed by heat from nearby magma/lava	**Hornfels**	
		Fine to coarse	Quartz	Regional or contact	Metamorphism of quartz sandstone	**Quartzite**	
			Calcite and/or dolomite		Metamorphism of limestone or dolostone	**Marble**	
		Coarse	Various minerals		Pebbles may be distorted or stretched	**Metaconglomerate**	

Geological References

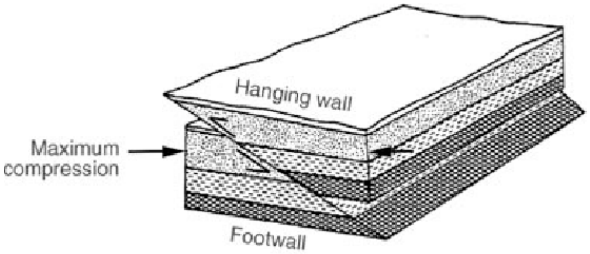
Strucutral Geology



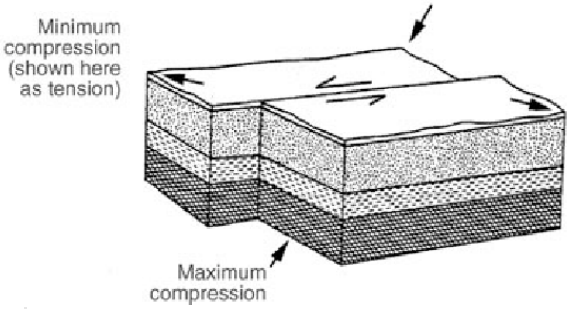
Normal fault

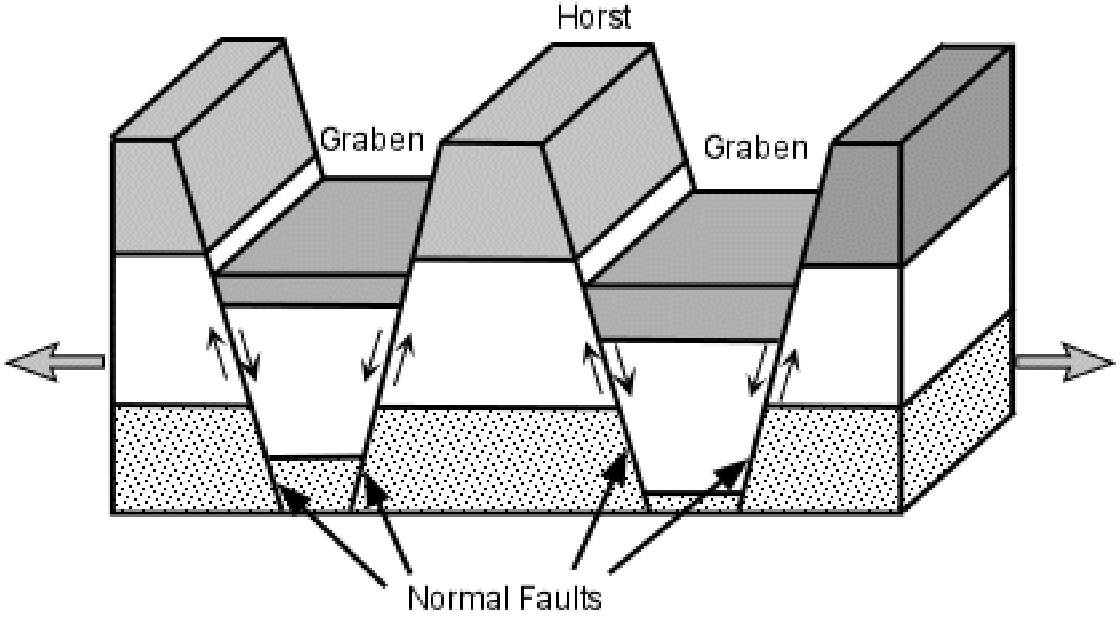


Reverse (thrust) fault



Strike-slip fault



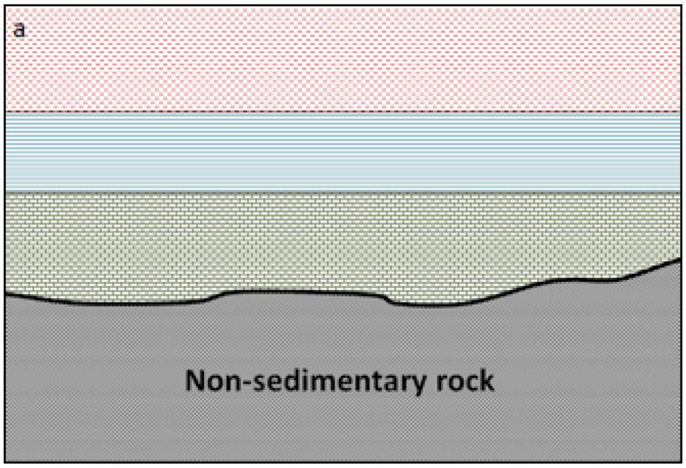


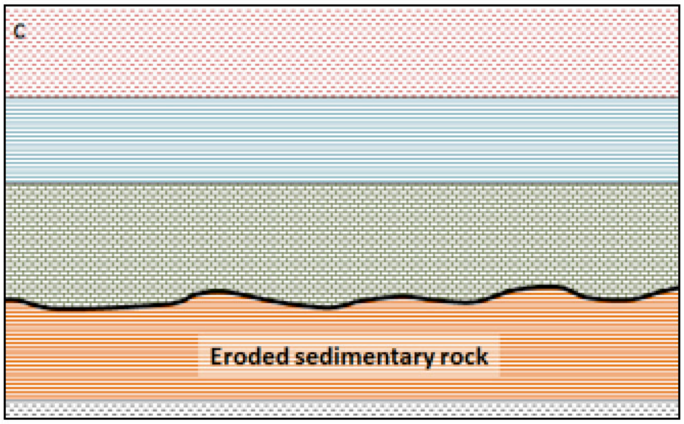
Geological References

Strucutral Geology

Types of Unconformities

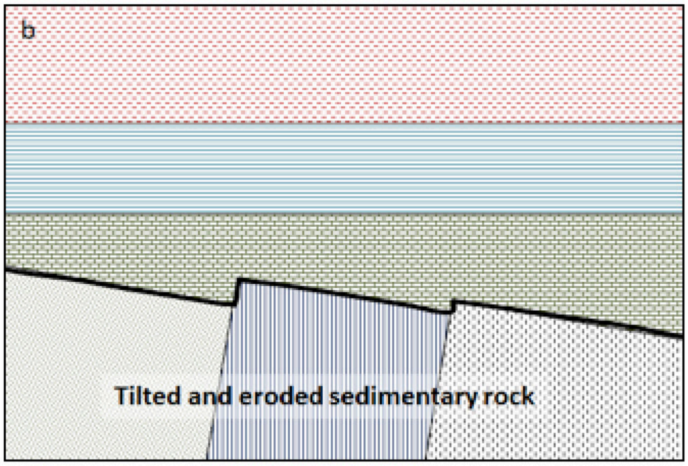
Nonconformity: between sedimentary rocks and metamorphic or igneous rocks when the sedimentary rock lies above and was deposited on the pre-existing and eroded metamorphic or igneous rock

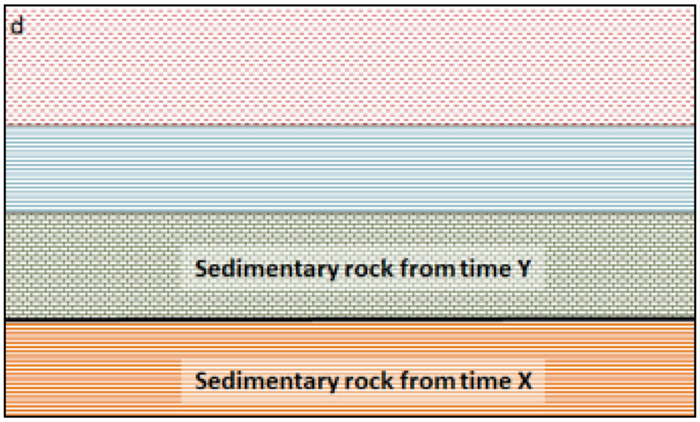




Disconformity: an unconformity between parallel layers of sedimentary rocks which represents a period of erosion or non-deposition

Angular unconformity: an unconformity where horizontally parallel strata of sedimentary rock are deposited on tilted and eroded layers, producing an angular discordance with the overlying horizontal layers.

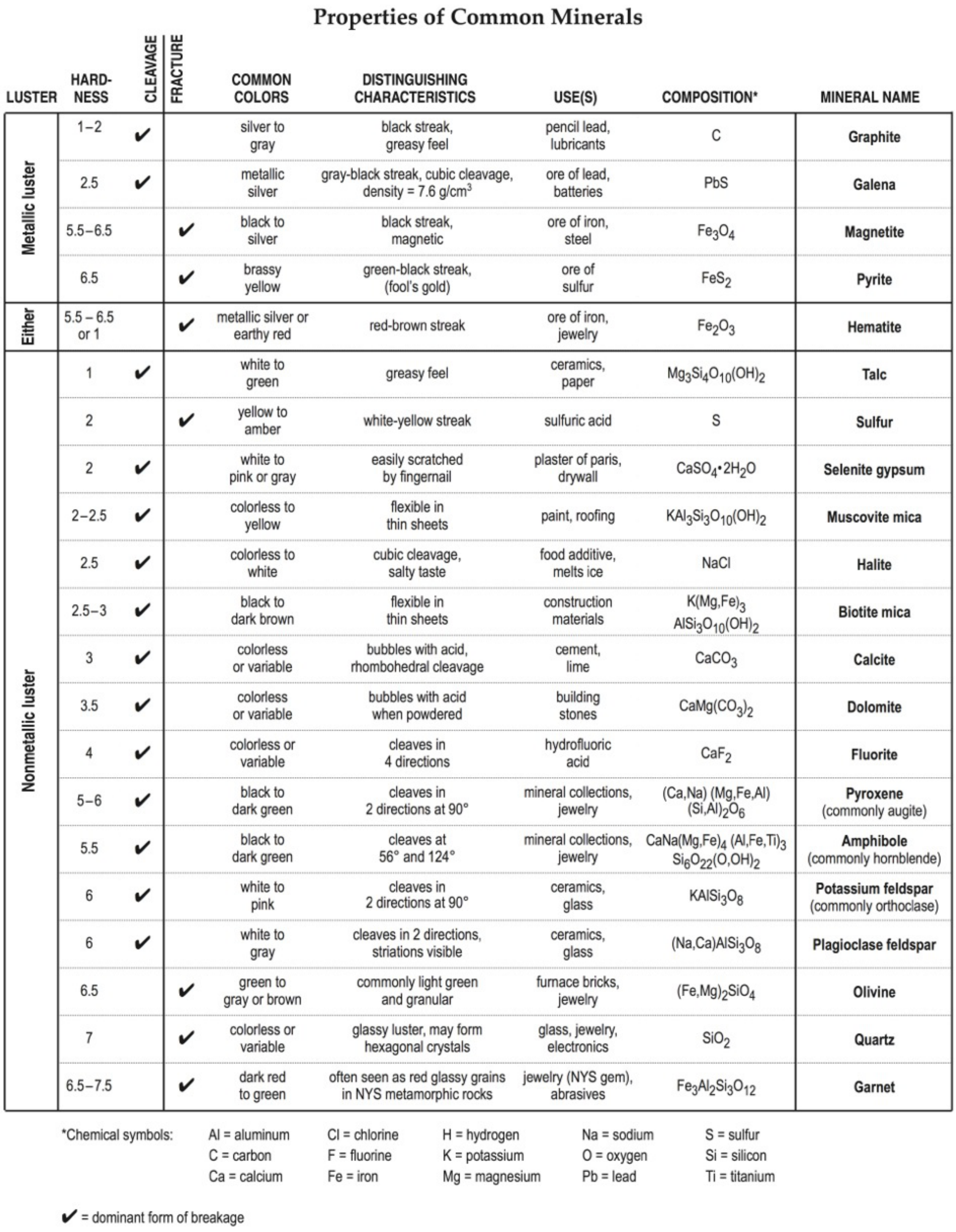




Paraconformity: a type of unconformity in which strata are parallel; there is no apparent erosion and the unconformity surface resembles a simple bedding plane.

Geological References

General Guides



Properties of Common Minerals

LUSTER	HARD-NESS	CLEAVAGE	FRACTURE	COMMON COLORS	DISTINGUISHING CHARACTERISTICS	USE(S)	COMPOSITION*	MINERAL NAME
Metallic luster	1–2	✔		silver to gray	black streak, greasy feel	pencil lead, lubricants	C	**Graphite**
	2.5	✔		metallic silver	gray-black streak, cubic cleavage, density = 7.6 g/cm^3	ore of lead, batteries	PbS	**Galena**
	5.5–6.5		✔	black to silver	black streak, magnetic	ore of iron, steel	Fe_3O_4	**Magnetite**
	6.5		✔	brassy yellow	green-black streak, (fool's gold)	ore of sulfur	FeS_2	**Pyrite**
Either	5.5 – 6.5 or 1		✔	metallic silver or earthy red	red-brown streak	ore of iron, jewelry	Fe_2O_3	**Hematite**
Nonmetallic luster	1	✔		white to green	greasy feel	ceramics, paper	$Mg_3Si_4O_{10}(OH)_2$	**Talc**
	2		✔	yellow to amber	white-yellow streak	sulfuric acid	S	**Sulfur**
	2	✔		white to pink or gray	easily scratched by fingernail	plaster of paris, drywall	$CaSO_4 \cdot 2H_2O$	**Selenite gypsum**
	2–2.5	✔		colorless to yellow	flexible in thin sheets	paint, roofing	$KAl_3Si_3O_{10}(OH)_2$	**Muscovite mica**
	2.5	✔		colorless to white	cubic cleavage, salty taste	food additive, melts ice	$NaCl$	**Halite**
	2.5–3	✔		black to dark brown	flexible in thin sheets	construction materials	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	**Biotite mica**
	3	✔		colorless or variable	bubbles with acid, rhombohedral cleavage	cement, lime	$CaCO_3$	**Calcite**
	3.5	✔		colorless or variable	bubbles with acid when powdered	building stones	$CaMg(CO_3)_2$	**Dolomite**
	4	✔		colorless or variable	cleaves in 4 directions	hydrofluoric acid	CaF_2	**Fluorite**
	5–6	✔		black to dark green	cleaves in 2 directions at 90°	mineral collections, jewelry	$(Ca,Na)(Mg,Fe,Al)(Si,Al)_2O_6$	**Pyroxene** (commonly augite)
	5.5	✔		black to dark green	cleaves at 56° and 124°	mineral collections, jewelry	$CaNa(Mg,Fe)_4(Al,Fe,Ti)_3Si_6O_{22}(O,OH)_2$	**Amphibole** (commonly hornblende)
	6	✔		white to pink	cleaves in 2 directions at 90°	ceramics, glass	$KAlSi_3O_8$	**Potassium feldspar** (commonly orthoclase)
	6	✔		white to gray	cleaves in 2 directions, striations visible	ceramics, glass	$(Na,Ca)AlSi_3O_8$	**Plagioclase feldspar**
	6.5		✔	green to gray or brown	commonly light green and granular	furnace bricks, jewelry	$(Fe,Mg)_2SiO_4$	**Olivine**
	7		✔	colorless or variable	glassy luster, may form hexagonal crystals	glass, jewelry, electronics	SiO_2	**Quartz**
	6.5–7.5		✔	dark red to green	often seen as red glassy grains in NYS metamorphic rocks	jewelry (NYS gem), abrasives	$Fe_3Al_2Si_3O_{12}$	**Garnet**

*Chemical symbols:

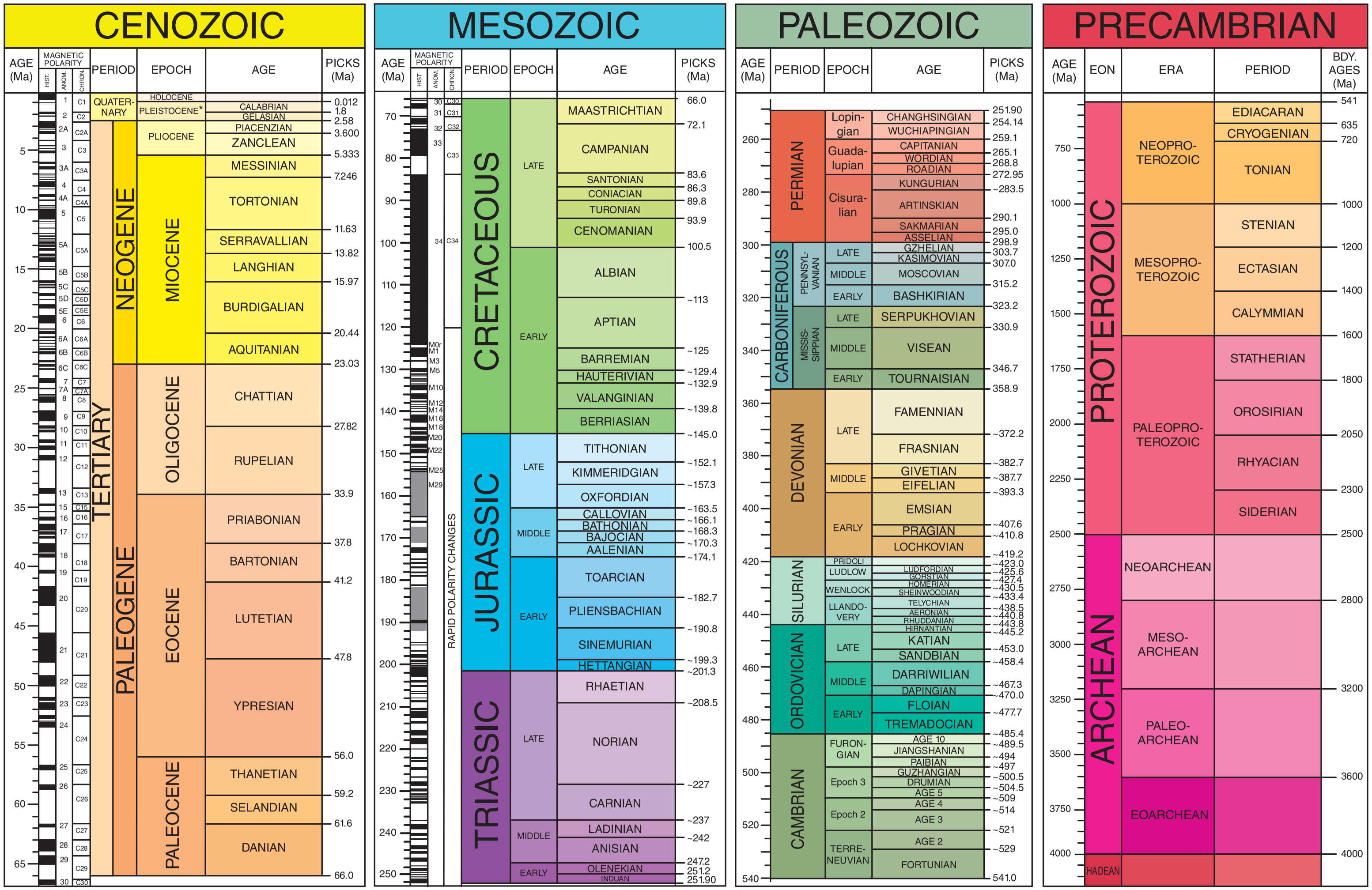
Al = aluminum
C = carbon
Ca = calcium
Cl = chlorine
F = fluorine
Fe = iron
H = hydrogen
K = potassium
Mg = magnesium
Na = sodium
O = oxygen
Pb = lead
S = sulfur
Si = silicon
Ti = titanium

✔ = dominant form of breakage

Geological References

General Guides

GSA GEOLOGIC TIME SCALE v. 5.0



THE GEOLOGICAL SOCIETY OF AMERICA®

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2018, Geologic Time Scale v. 5.0: Geological Society of America, https://doi.org/10.1130/2018.CTS005R3C. ©2018 The Geological Society of America

*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages—Calabrian from 1.80 to 0.781 Ma, Middle from 0.781 to 0.126 Ma, and Late from 0.126 to 0.0117 Ma.

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 over 1.6 Ma.

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Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, www.stratigraphy.org (accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane, Australia, 5–10 August 2012.)
Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart: Episodes v. 36, no. 3, p. 199–204 (updated 2017, v. 2, http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed May 2018).
Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, https://doi.org/10.1016/B978-0-444-59425-9.00004-4.

Previous versions of the time scale and previously published papers about the time scale and its evolution are posted to http://www.geosociety.org/timescale.

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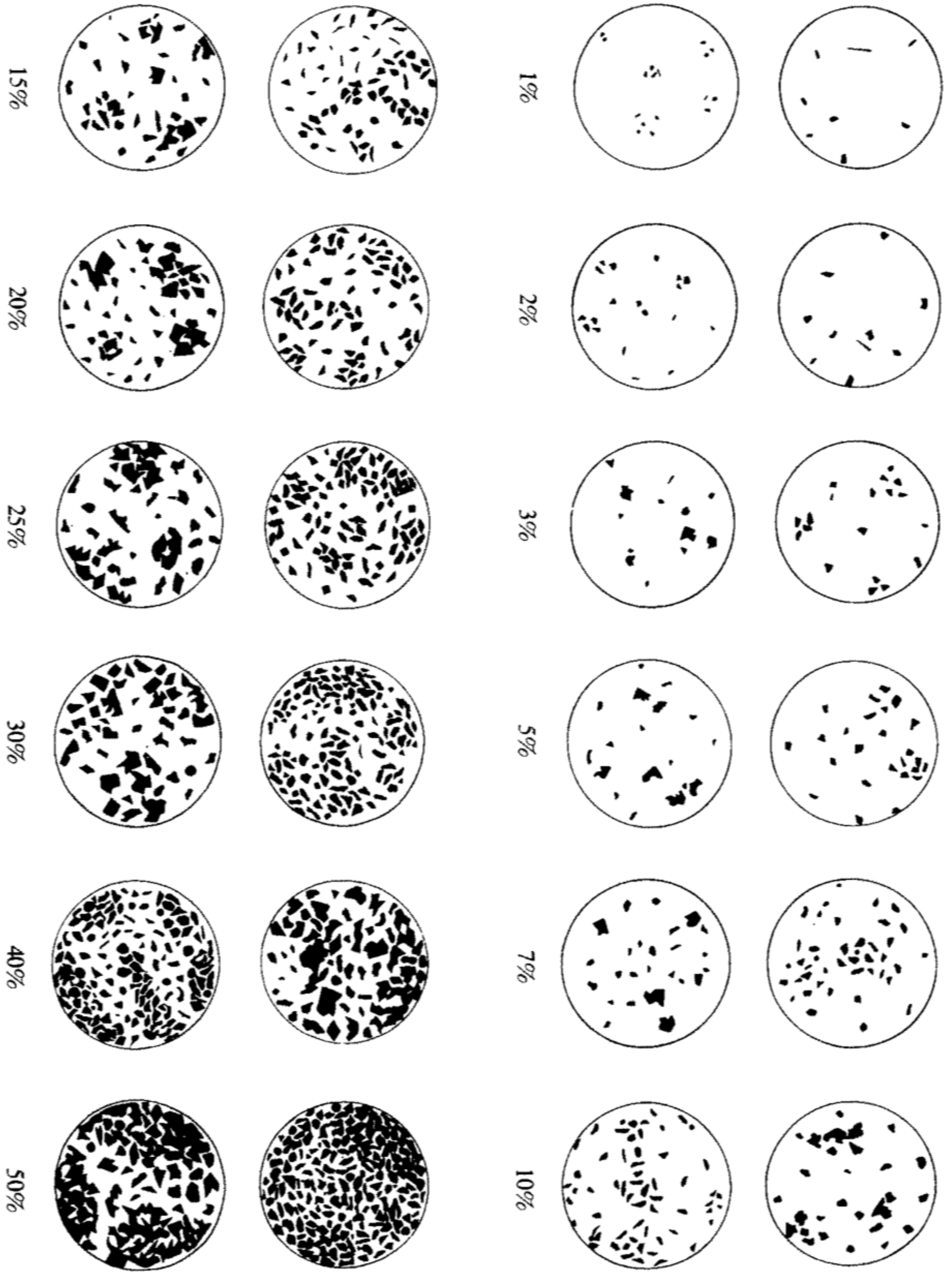


Geological References

General Guides

Steno's Laws

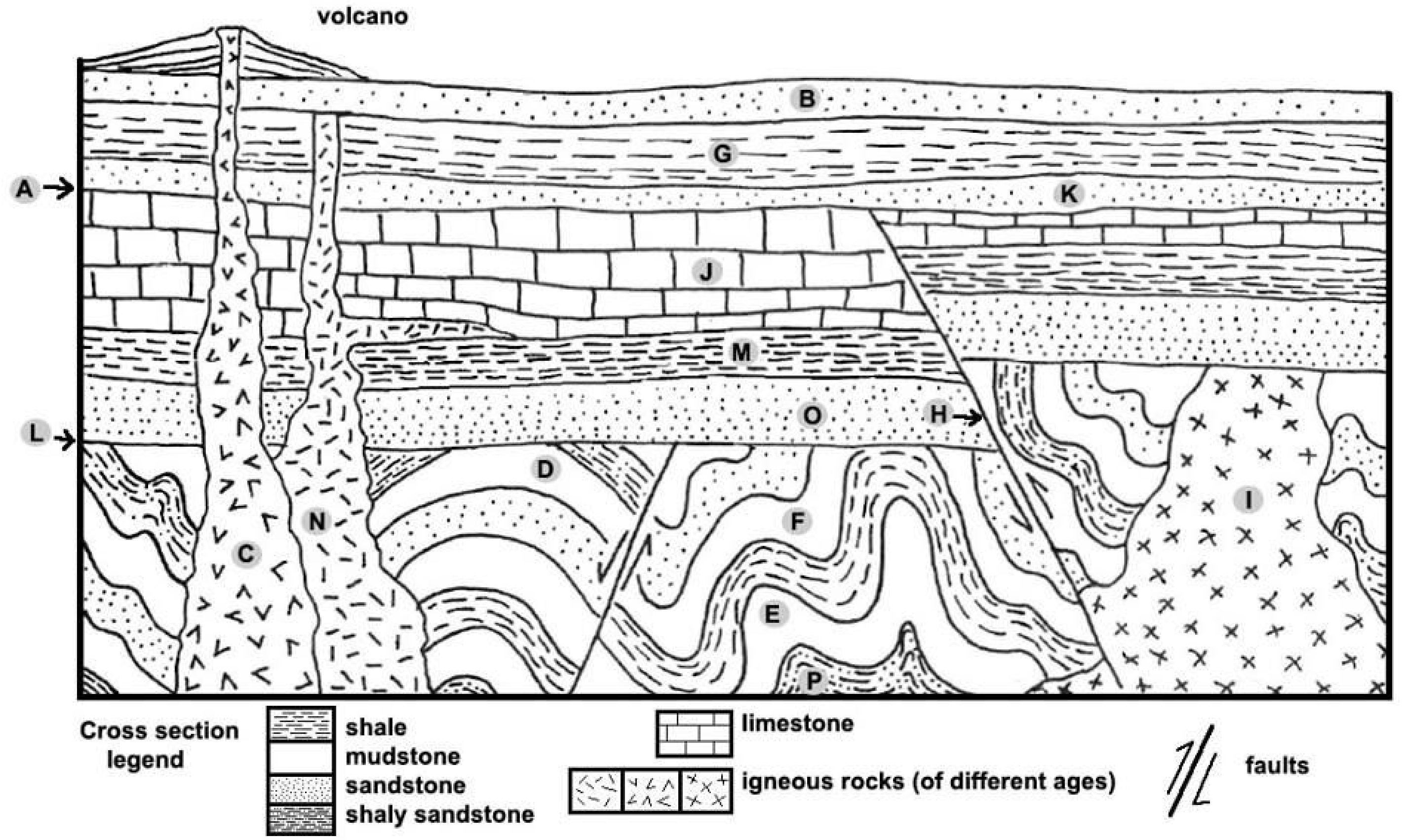
1. Law of Superposition: oldest strata will be on the bottom of a sequence

2. Principle of Original Horizontality: sediments are originally deposited horizontally

3. Principle of Lateral Continuity: layers of sediment initially extend laterally in all directions

4. Principle of Cross-Cutting Relationships: the geologic feature which cuts another is the younger of the two features

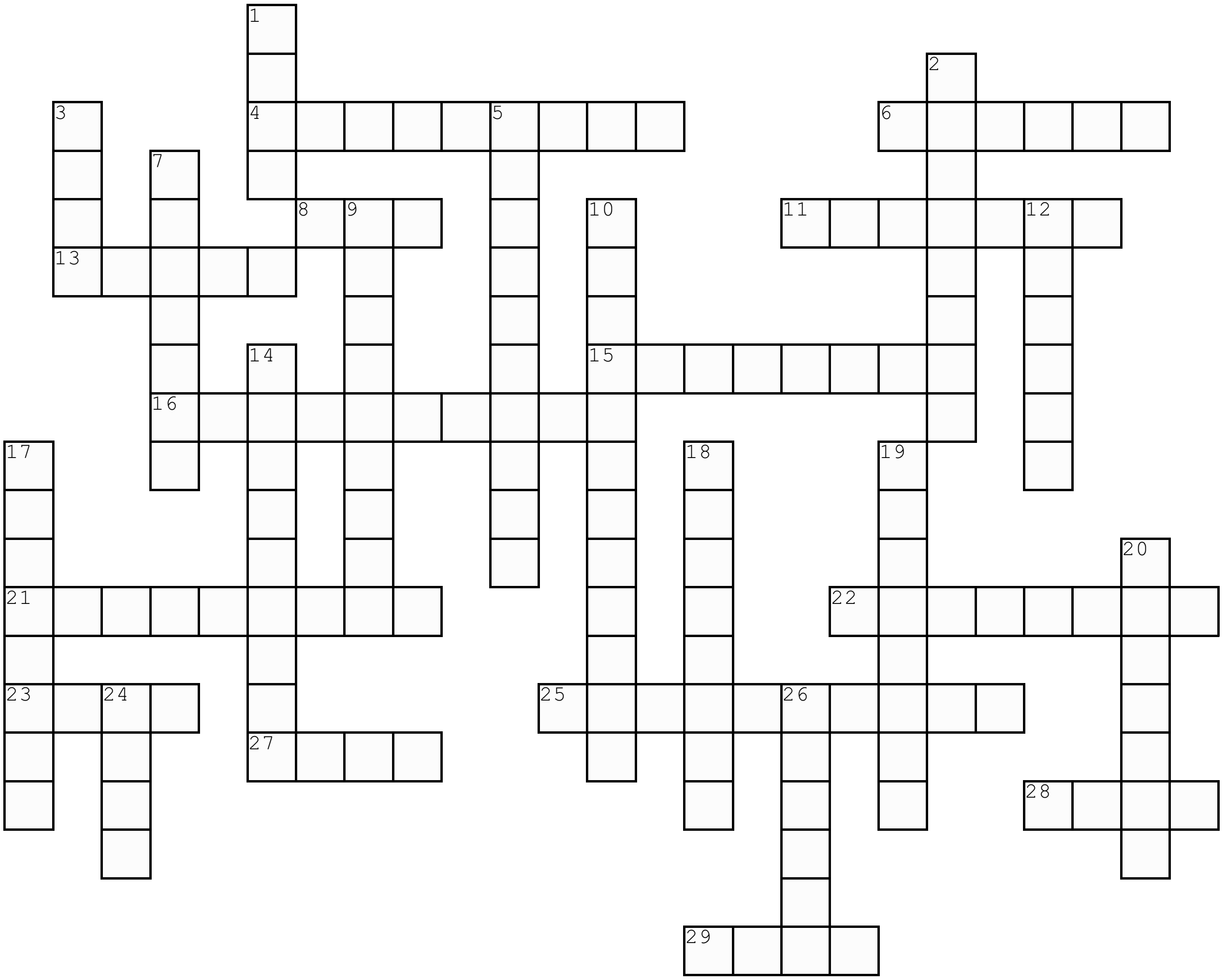
In the figure below, in what order did the rocks/faults/surfaces form? What kind of fault is H? What type of boundary is A? What type of boundary is L?



Name:________________

White Sands Crossword

Complete the crossword below. If you need help, remember who made it.



Across

4. Tech company started in ABQ garage
6. Accidental target of runaway German V-2 rocket from White Sands
8. '''___ is no damn good.'''
11. Thank you (en español)
13. Goodbye (en español)
15. Illegal to dance while wearing—or around–one of these
16. Straight dune; merged barchan
21. State gemstone
22. Caverns
23. NM has the highest of these per capita of any state
25. 'NM state question: ''___ __ ____?'''
27. More of these in NM than people
28. Where magma and groundwater mix
29. Delivery mechanism for peridot

Down

1. low mounded dune
2. In Las Cruces it is against the law to carry a ______ down Main St
3. Hello (en español)
5. Apollo astronaut Jack Schmidt born here near Silver City
7. Site of first atomic bomb explosion
9. Correct answer to state question
10. Town named for gameshow: Truth or ________
12. Beings who invaded Roswell
14. inverted barchan dune
17. Minor league baseball team: the ABQ _____
18. White Sands basin
19. Pecos League baseball team: The Roswell _____
20. Common type of dune
24. The town of Deming is known for its annual ___ races
26. White Sands mineral

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

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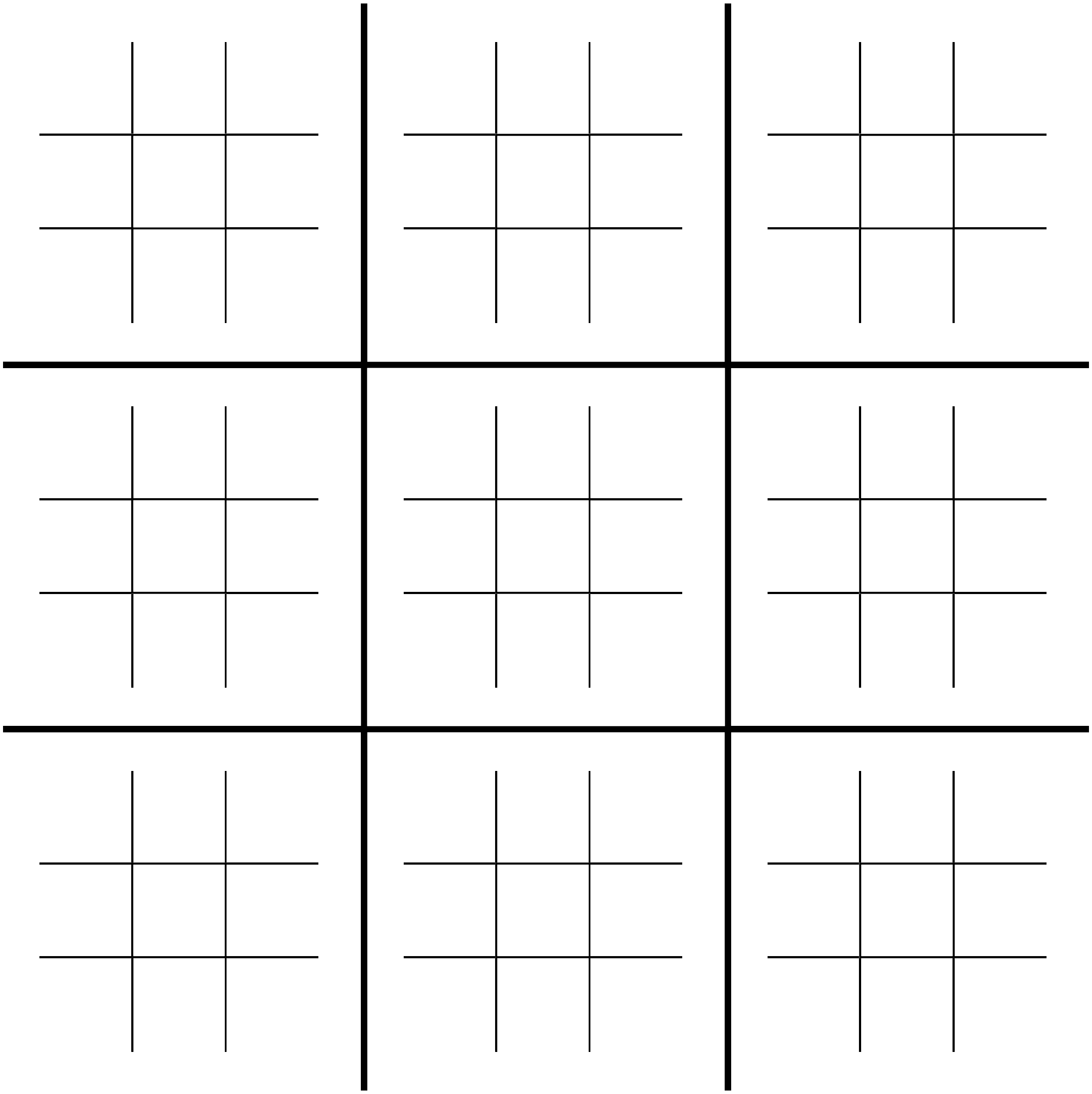
9			4			3		
3							7	2
		9			5			
8				1				
7			6			5	2	9
			1			7		
6		1		5				8
	4						1	

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. Maybe you'll get mad at your opponent.



A Very LPL Field Trip

"How could anyone have __________ past tense verb this? How could anyone have known this would happen?" asked ______________ grad student A. The field trip was ______ number hours behind schedule and the ______________ field trip equipment in ______________ faculty member A's vehicle wasn't working. At the side of the road while ______________ verb ending in -ing a ___________ adjective + noun, ______________ grad student B wiped their brow and exclaimed, "I should have gone to ________________________ planetary science grad program (not LPL)." When the graduate students arrived at the campsite and opened the cooler, they found all the __________________ plural beverage had been stolen. "Curse you, Tim Swindle!" The field trip camped in the dark and woke up in the middle of a ____________________ ridiculous outdoor event. Terrified of _________________________ person at ridiculous outdoor event, the grad students quickly packed their _____________ plural field trip item and took off. That day, they traveled to _________ field site and saw some lithified ______________ plural noun in a _________________ geologic feature. Around _____________ time of day, the group headed out to have lunch at ________________ unsavory location, where _______________ grad student C wandered off into the nearby ____________________ different location, requiring ____________________ faculty member B to go chasing after them. After lunch, it was time to head back toward Tucson, and everyone got in the ________________ plural vehicle type. It was only _________ number hours later when ____________________ grad student D realized ____________________ person on field trip A was missing, and ___________________ LPL alum A had taken their place. "Where did you come from?" asked ____________________ grad student D. ____________________ LPL alum A replied "I always go on the field trips. I haven't missed one yet." Resigned to _________________ verb ending in -ing with _________________ LPL alum A instead of _______________ person on field trip A, they continued on their way down ____________ road toward LPL. Back at the ________________ location near LPL, the field trip participants got as much ____________ type of detritus out of their vehicles as possible, knowing that Motor Pool would probably get ________ mood at them anyway.

Questions to Ask Fellow Travellers

If you didn't have to sleep, what would you do with the extra time? What's your favorite piece of clothing you own / owned? What hobby would you get into if time and money weren't an issue? What would your perfect room look like? How often do you play sports? What fictional place would you most like to go? What job would you be terrible at? When was the last time you climbed a tree? If you could turn any activity into an Olympic sport, what would you have a good chance at winning medal for? What is the most annoying habit that other people have? What job do you think you'd be really good at? What skill would you like to master? What would be the most amazing adventure to go on? If you had unlimited funds to build a house that you would live in for the rest of your life, what would the finished house be like? What's your favorite drink? What state or country do you never want to go back to? What songs have you completely memorized? What game or movie universe would you most like to live in? What do you consider to be your best find? Are you usually early or late? What pets did you have while you were growing up? When people come to you for help, what do they usually want help with? What takes up too much of your time? What do you wish you knew more about? What would be your first question after waking up from being cryogenically frozen for 100 years? What are some small things that make your day better? Who's your go to band or artist when you can't decide on something to listen to? What shows are you into? What TV channel doesn't exist but really should? Who has impressed you most with what they've accomplished? What age do you wish you could permanently be? What TV show or movie do you refuse to watch? What would be your ideal way to spend the weekend? What is something that is considered a luxury, but you don't think you could live without? What's your claim to fame? What's something you like to do the old-fashioned way? What's your favorite genre of book or movie? How often do you people watch? What have you only recently formed an opinion about? What's the best single day on the calendar? What are you interested in that most people haven't heard of? How do you relax after a hard day of work? What was the best book or series that you've ever read? What's the farthest you've ever been from home? What is the most heartwarming thing you've ever seen? What is the most annoying question that people ask you? What could you give a 40-minute presentation on with absolutely no preparation? If you were dictator of a small island nation, what crazy dictator stuff would you do? What is something you think everyone should do at least once in their lives? Would you rather go hang gliding or whitewater rafting? What's your dream car? What's worth spending more on to get the best? What is something that a ton of people are obsessed with but you just don't get the point of? What are you most looking forward to in the next 10 years? Where is the most interesting place you've been? What's something you've been meaning to try but just haven't gotten around to it? What's the best thing that happened to you last week? What piece of entertainment do you wish you could erase from your mind so that you could experience for the first time again? If all jobs had the same pay and hours, what job would you like to have? What amazing thing did you do that no one was around to see? How different was your life one year ago? What's the best way to start the day? What quirks do you have? What would you rate 10 / 10? What fad or trend do you hope comes back? What's the most interesting piece of art you've seen? What kind of art do you enjoy most? What do you hope never changes? What city would you most like to live in? What movie title best describes your life? Why did you decide to do the work you are doing now? What's the best way a person can spend their time? If you suddenly became a master at woodworking, what would you make? Where is the most relaxing place you've ever been? What is the luckiest thing that has happened to you? Where would you rather be from? What are some things you've had to unlearn? What are you looking forward to in the coming months? What website do you visit most often? What one thing do you really want but can't afford? Where do you usually go when you when you have time off? Where would you spend all your time if you could? What is special about the place you grew up? What age do you want to live to? What are you most likely to become famous for? What are you absolutely determined to do? What is the most impressive thing you know how to do? What do you wish you knew more about? What question would you most like to know the answer to?

White Sands Word Search

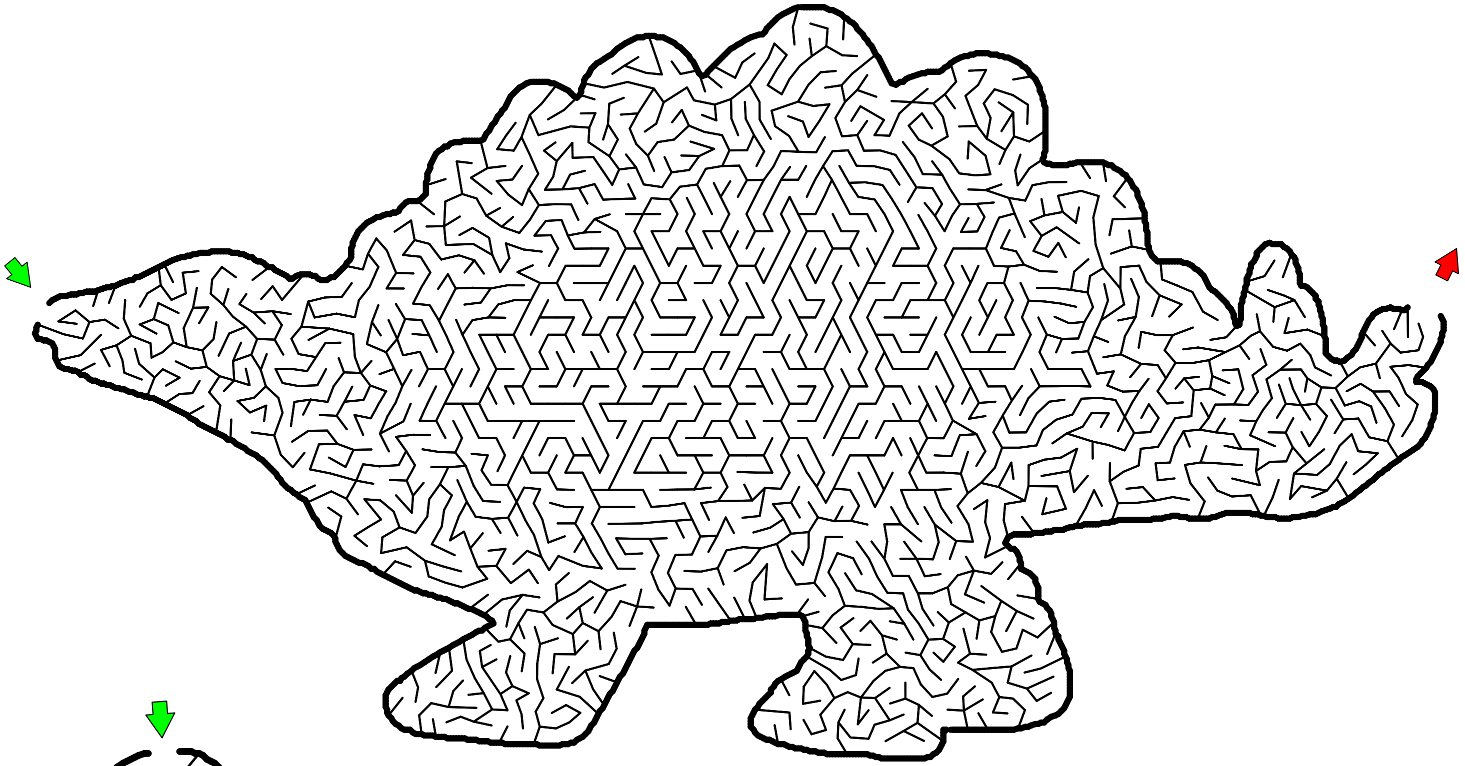
V E A K A P F Z W H Q V H D E S E R T X G L E I G
O T P V Y V R A L O O B Z N S N K P M R Q G G Y N
L I S X A D Z E R Y S J Y D L U N A R O V L N G I
C R J O D L C M K A E U N P M Q E I Q C I X A O P
A O L E R I G R Z K L A B L L R Y Z P K U S R L M
N E F L K O D Q T Z S L N U C Q W A M G A M R O A
O T Q A U D G U C E F E O E R P A H O E H O E E C
Y E I T P G K E T W W M C N M B T E B N J V J G B
Q M G I O H X I N M C I T A M G A M O T A E R H P
K K R P U R H F E E P G H P H J R N F U Q V X V L
K Z A S M W Q X U V B G N E I S S M S B W I O J S
W W N E Z Q I P N O I P R O C S H T U P B D D B X
P T I O J C B B X E N O L I T H A L J T T D N T M
K A T J O C O W B O Y N R D M I N J P W E K L E M
T R E R O C D L U Z U K F S D U E Z K J L P I D F
C I F H G N I S S A P S E R T C B D T A T J T E N
N Z O V B O N O T U L P C Z B I Y B G W N M H N C
I O C H E W S J X K M B Z V P B R A X B A F O F O
S N B A N E E Y G Y P S U M S E N I S I M E S B P
A A O Y N K X O I D A R O E I V E H H J R V P A R
B K K U B X F A K I L B O U R N E H O L E U H S O
H H D F I E L D T R I P M W P J C C M E F E E A L
N G O E G N A R E L I S S I M F L Q N H J B R L I
L A B O R A T O R Y B E T I I T A M O K P N E T T
B V Z K Y R A T E N A L P P E B Z M E S C M R P E

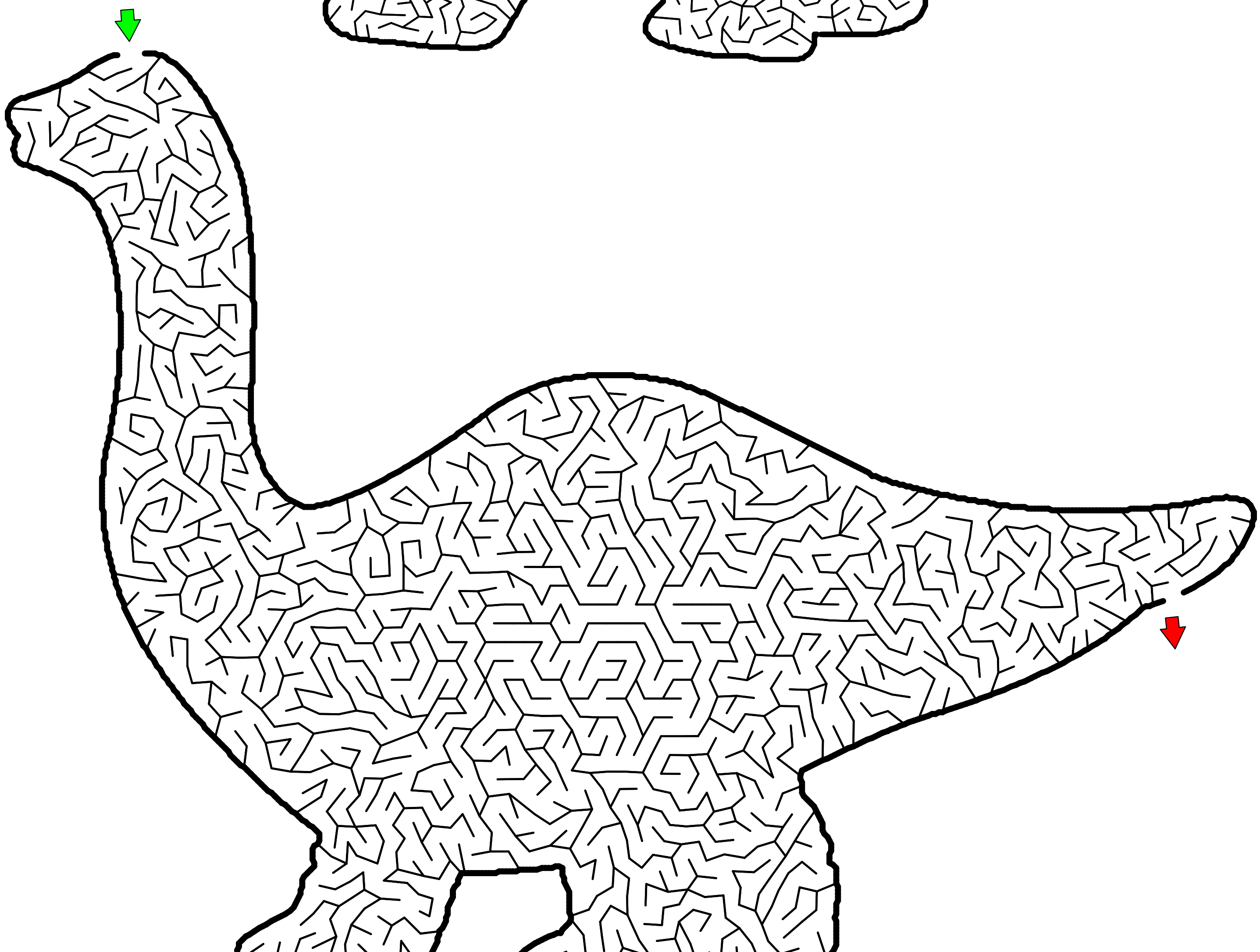
ARIZONA
BASALT
BASIN
CAMPING
COPROLITE
CORE
COWBOY
DESERT
DUNES
FARALLON
FIELDTRIP

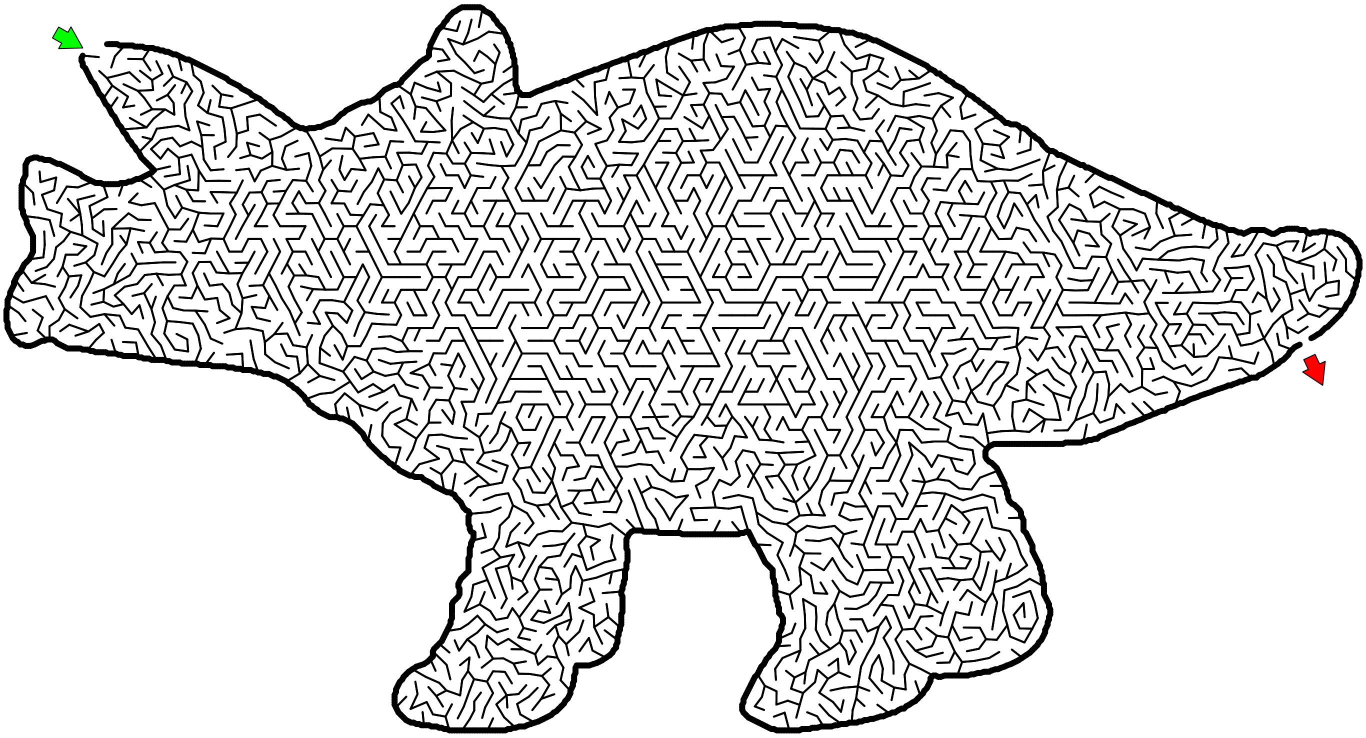
GEOLOGY
GNEISS
GRANITE
GYPSUM
ICECREAM
JOESPITALE
KILBOURNEHOLE
KOMATIITE
LABORATORY
LAVA
LITHOSPHERE

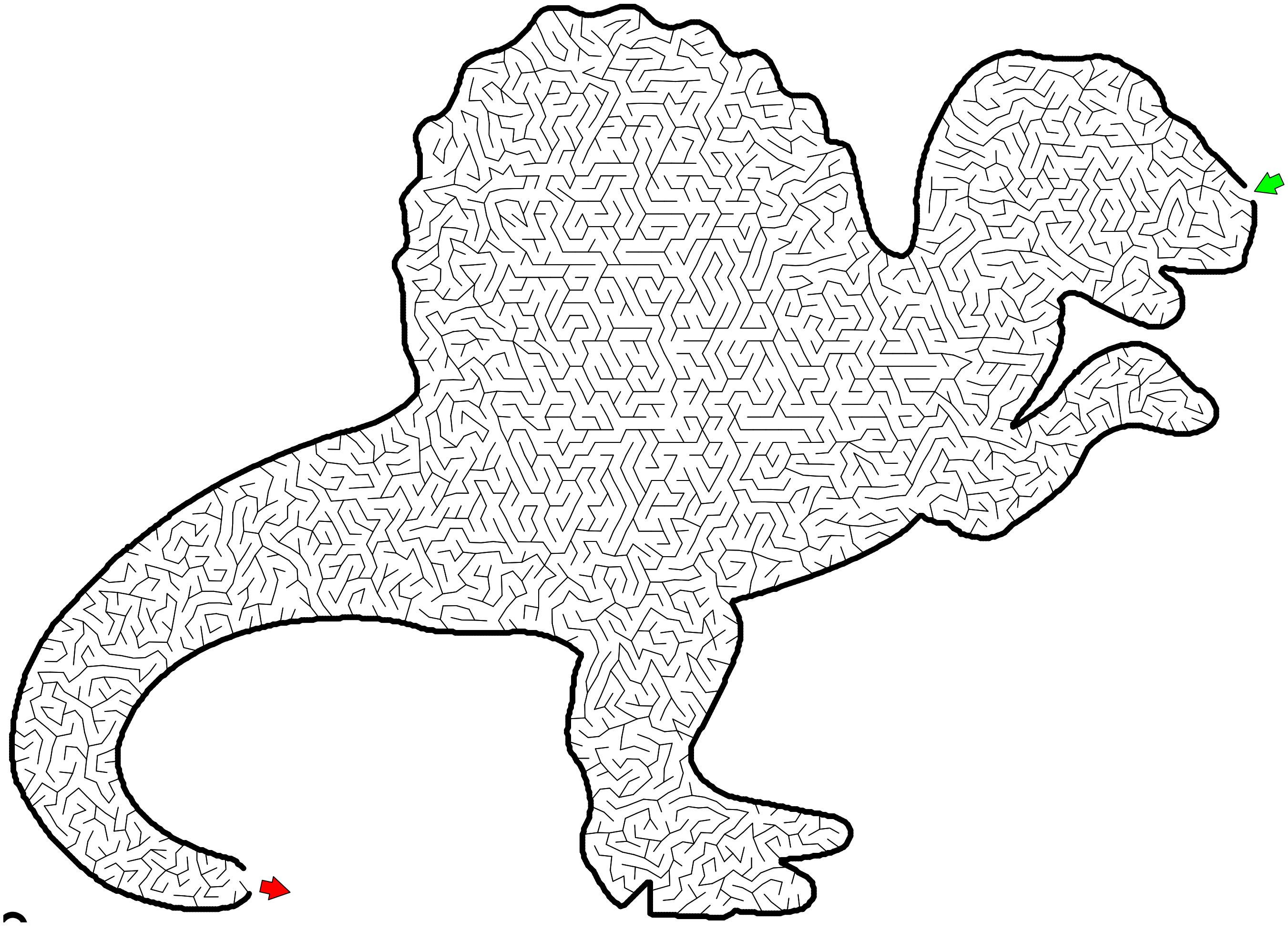
LUNAR
MAGMA
MANTLE
METEORITE
MISSILERANGE
NEWMEXICO
OROGENE
PAHOEHOE
PHREATOMAGMATIC
PLANETARY
PLUTON

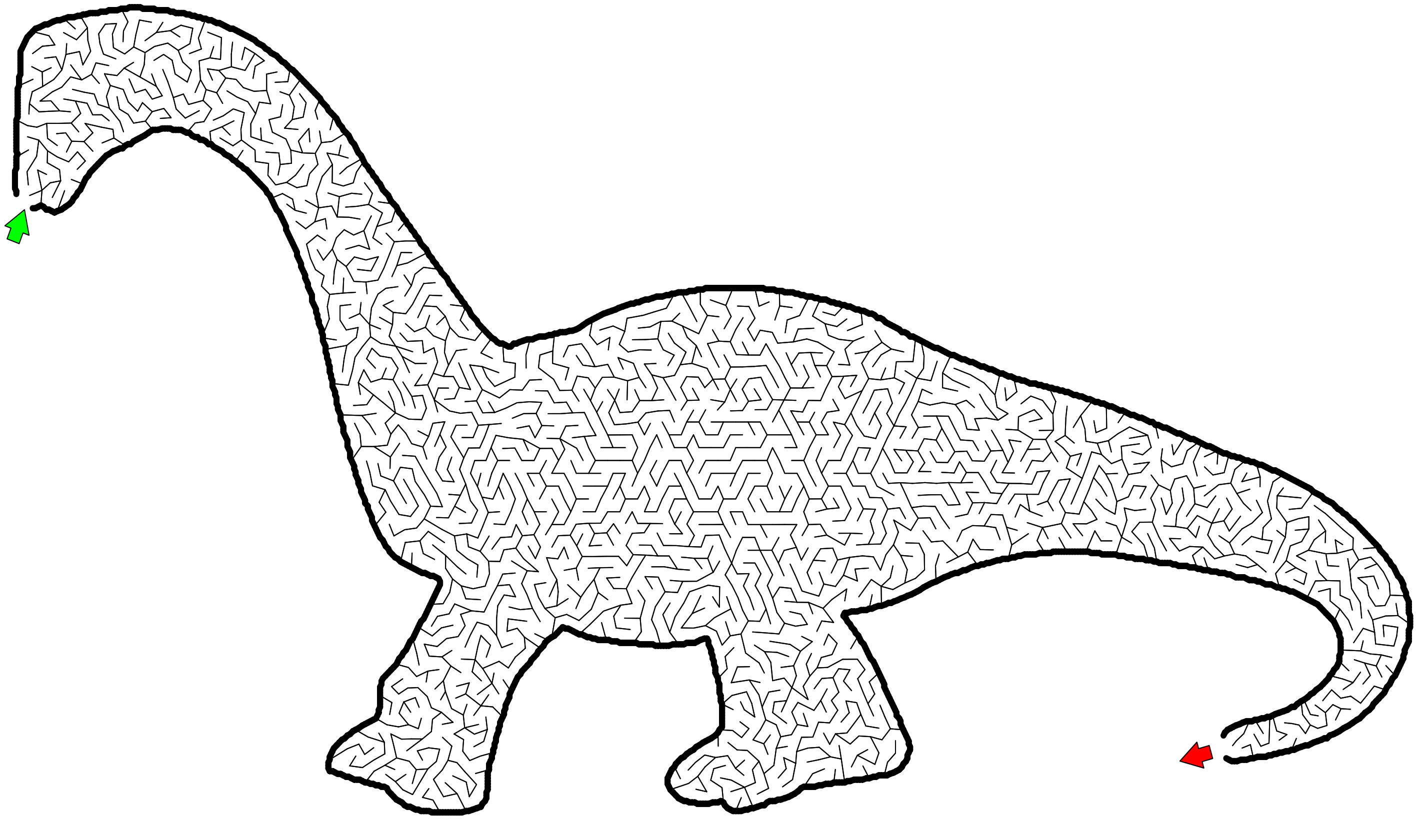
RADIO
RANGE
ROCK
SCORPION
SHANEBYRNE
SUBURBANS
TRESPASSING
VOLCANO
WHITESANDS
XENOLITH

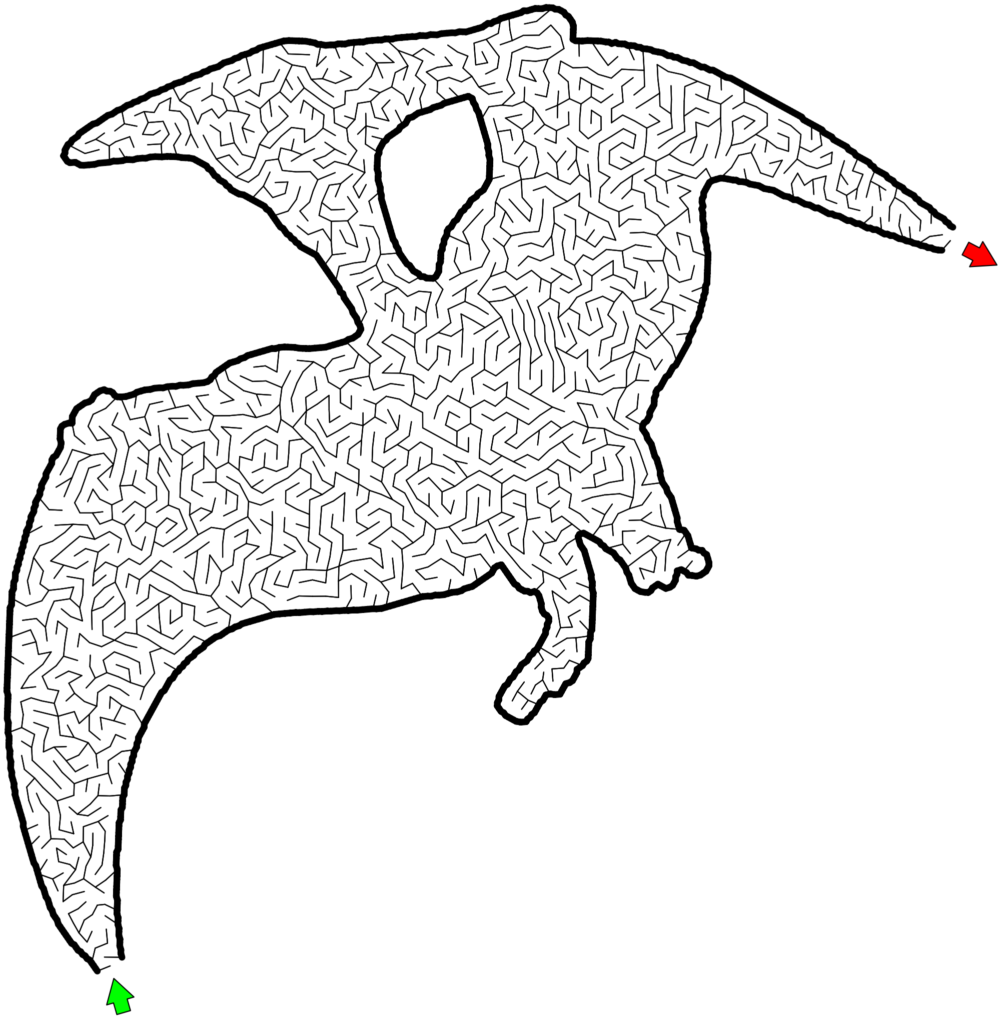












Battleship

OPPONENT'S SHIPS

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

Aircraft Carrier
AAAAA

Battleship
BBBB

Cruiser
CCC

Submarine
SSS

Destroyer
DD

MY SHIPS

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

Aircraft Carrier
AAAAA

Battleship
BBBB

Cruiser
CCC

Submarine
SSS

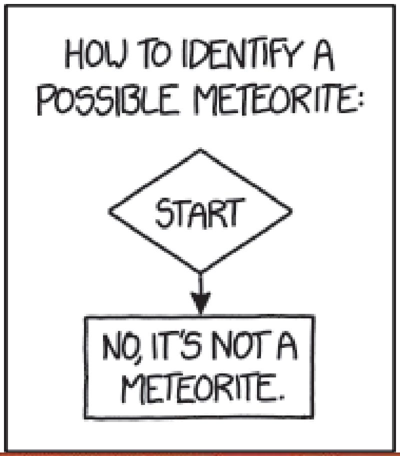
Destroyer
DD

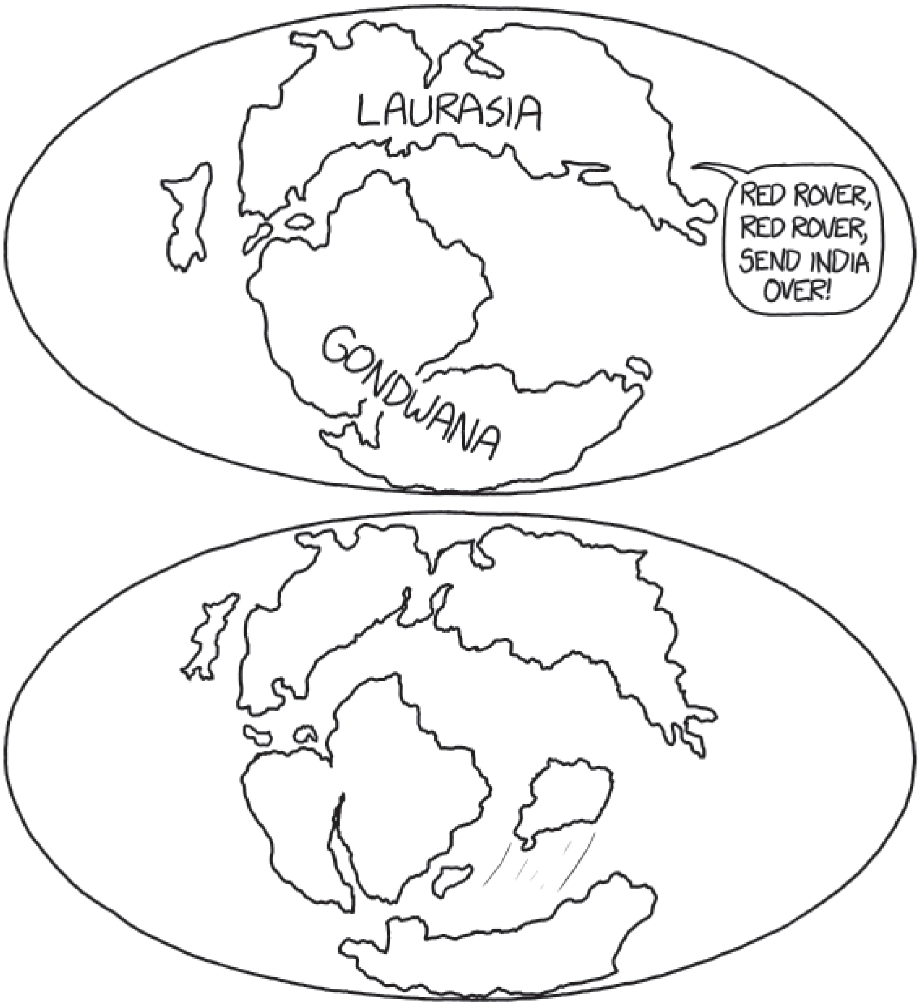
White Sands Bingo

SP Crater reference	Braking uphill on interstate	Tractor	Clay dunes	Rusted truck
Coyote	Shane uses a selfie stick	Playa/player jokes	Fox	Spherical weathering
Diving Farallon Plate	Someone is late	Free	Columnar basalt	Friability
Boxed in by big rigs	Rock hammer	Joe buys, eats ice cream	Tumbleweeds	Joe kvetchin’
Directions in metric	Pluton	Bacon smells from the meat food group	Impostor vehicles	Campfire songs

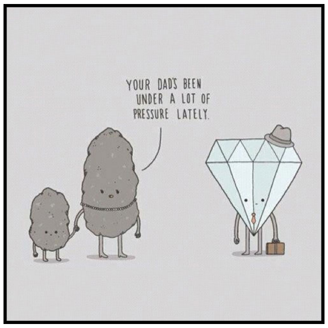
White Sands Bingo

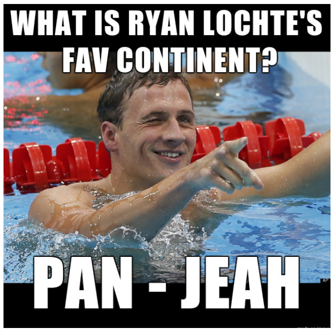
Truth or Consequences	Temperature above 80 ºF	Reading papers in vehicle	Spherical weathering	Tractor
Flat tire	Rusted truck	Joe buys, eats ice cream	Bacon smells from the meat food group	Basalt
Facilities Management at loading dock	Rock puns	Free	Campfire songs	No Service
Two types of dunes	Braking uphill on interstate	Fox	Wildlife encounter	Asking around for an AUX cord
Scorpion	Sunburn	Lava: it's the bomb	Basin & Range	Shane uses a selfie stick

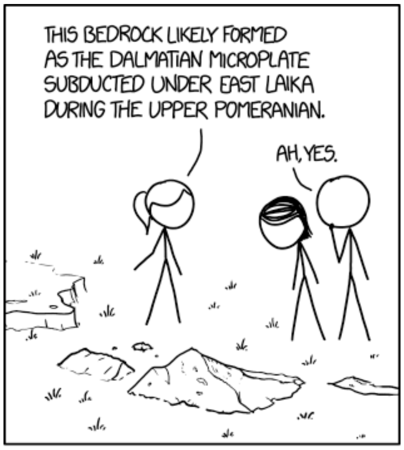




HOW THE HIMALAYAS FORMED







GEOLOGY TIP: THERE ARE SO MANY MICROPLATES AND AGES THAT NO ONE REMEMBERS THEM ALL, SO IN A PINCH YOU CAN BLUFF WITH DOG BREEDS.