
DEATH VALLEY
DEATH
VALLEY
8→12 FEBRUARY 2018
PTYS594A: PLANETARY GEOLOGY FIELD STUDIES
LUNAR & PLANETARY LABORATORY
UNIVERSITY OF ARIZONA

I'm excited to be back in the desert that made me like deserts, and to finally make it up the rest of the way to Death Valley. The Mojave has it all, from salt flats to Mars boulder field analogs to dunes for days, and I first got to explore it on a HiRISE team meeting where we brought dry ice out to Kelso Dunes and marched around in search of the best ventifacts (including up one particularly steep, sweaty hillside that, as promised by one late, great, unfailingly enthusiastic aeolian geomorphologist, had the most awesome ventifacts). The landscape of 20 mule team borax company stages and Mary Hunter Austin is a particularly stark and dramatic reminder of how, even with its record setting temperatures and dried out lake-beds, this place still gets more rainfall than Mars (as the Mohave chub can attest). It also also what I think of now when I consider the West, in its faded 1950s postcard glory while its petroglyphs stand in testament to a long history of humans adapting to and thriving in tough environmental circumstances.

-Margaret

I grew up roadtripping across the American Southwest. "Reluctant" might best describe my first visit to Death Valley as a kid: it apparently took some effort to haul me around the park. I came back again a few years later and was suddenly thrilled to play tour guide to Zabriskie Point, Ubehebe Crater, and Scotty's Castle. (Scotty had a "bullet splitter" so he could take out two would-be robbers at once. Shoot them down, Scotty.) As an adult I traipsed through the salt flats in the Mojave and climbed Amboy Crater, camped in Death Valley and calculated our Mach number (0.14) as we channeled our inner Hunter S. Thompsons in an old diesel sedan across the desert. (If you want a truly intense reading exercise, bring a copy of *Fear And Loathing In Las Vegas* on this trip, but as your attorney I would not recommend engaging in any of the behaviors described therein. Did you say something? Hm? Never mind. It's your turn to drive.)

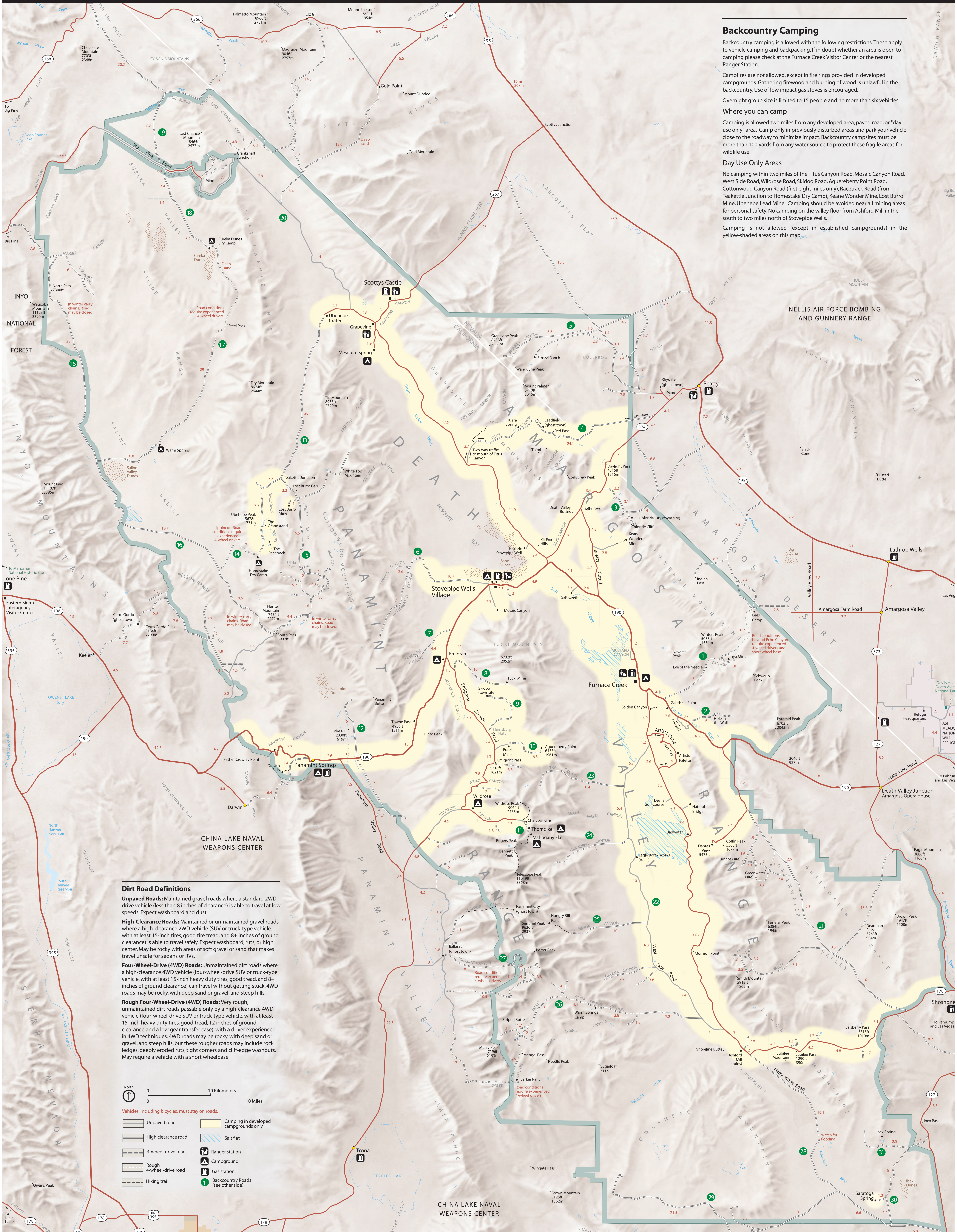
The Mojave and surrounding deserts provide excellent planetary analog study opportunities, without the long flights and/or radiation damage risks. Time out in the field is a great way to get hands-on geology experience to begin understanding processes that shape our world, and others across the Solar System, even if they aren't quite at the triple point of water/STP. Keep your eyes open for interesting location names (that don't have to do with death or dismemberment or the devil), stay hydrated, and May The Force Be With Us as we journey through various Star Wars sets.

-Sondy

*We acknowledge Death Valley National Park and the Mojave National Preserve are (currently) in what is the traditional, occupied, and unceded territories and ancestral lands of the Timbisha Panamint Shoshone Tribe (o'hya and tu'mbica), the Kawaiisu, the Chemehuevi, the 'Aha Makhav (Mohave), and the Vanyume people. Respect the land, respect the water, and remember those who were here first.*

Cover image credit: Eva Landis (evalandis.com, Instagram: @teeth_in_the_inkwell)

# Death Valley Backcountry Roads




## Backcountry Camping

Backcountry camping is allowed with the following restrictions. These apply to vehicle camping and backpacking. If in doubt whether an area is open to camping please check at the Furnace Creek Visitor Center or the nearest Ranger Station.

Campfires are not allowed, except in fire rings provided in developed campgrounds. Gathering firewood and burning of wood is unlawful in the backcountry. Use of low impact gas stoves is encouraged.

Overnight group size is limited to 15 people and no more than six vehicles.

### Where you can camp

Camping is allowed two miles from any developed area, paved road, or "day use only" area. Camp only in previously disturbed areas and park your vehicle close to the roadway to minimize impact. Backcountry campsites must be more than 100 yards from any water source to protect these fragile areas for wildlife use.

### Day Use Only Areas

No camping within two miles of the Titus Canyon Road, Mosaic Canyon Road, West Side Road, Wildrose Road, Skidoo Road, Aguereberry Point Road, Cottonwood Canyon Road (first eight miles only), Racetrack Road (from Teakettle Junction to Homestake Dry Camp), Keane Wonder Mine, Lost Burro Mine, Ubehebe Lead Mine. Camping should be avoided near all mining areas for personal safety. No camping on the valley floor from Ashford Mill in the south to two miles north of Stovepipe Wells.

Camping is not allowed (except in established campgrounds) in the yellow-shaded areas on this map.

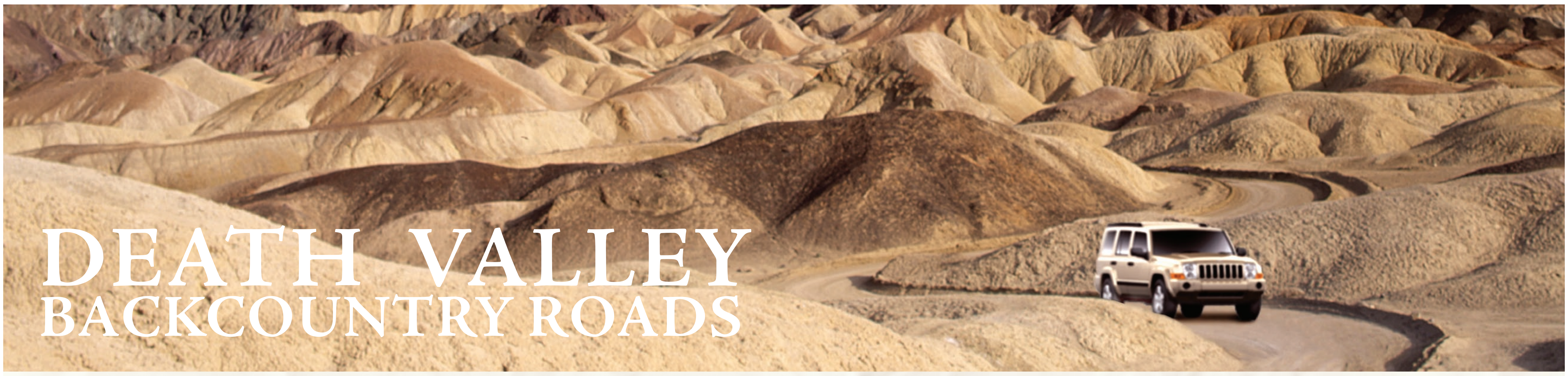
## Dirt Road Definitions

**Unpaved Roads:** Maintained gravel roads where a standard 2WD drive vehicle (less than 8 inches of clearance) is able to travel at low speeds. Expect washboard and dust.

**High-Clearance Roads:** Maintained or unmaintained gravel roads where a high-clearance 2WD vehicle (SUV or truck-type vehicle, with at least 15-inch tires, good tire tread, and 8+ inches of ground clearance) is able to travel safely. Expect washboard, ruts, or high center. May be rocky with areas of soft gravel or sand that makes travel unsafe for sedans or RVs.

**Four-Wheel-Drive (4WD) Roads:** Unmaintained dirt roads where a high-clearance 4WD vehicle (four-wheel-drive SUV or truck-type vehicle, with at least 15-inch heavy duty tires, good tread, and 8+ inches of ground clearance) can travel without getting stuck. 4WD roads may be rocky, with deep sand or gravel, and steep hills.

**Rough Four-Wheel-Drive (4WD) Roads:** Very rough, unmaintained dirt roads passable only by a high-clearance 4WD vehicle (four-wheel-drive SUV or truck-type vehicle, with at least 15-inch heavy duty tires, good tread, 12 inches of ground clearance and a low gear transfer case), with a driver experienced in 4WD techniques. 4WD roads may be rocky, with deep sand or gravel, and steep hills, but these rougher roads may include rock ledges, deeply eroded ruts, tight corners and cliff-edge washouts. May require a vehicle with a short wheelbase.



# DEATH VALLEY
## BACKCOUNTRY ROADS

**Death Valley is the largest national park outside of Alaska and has more miles of roads than any other national park. Though 95% of the park's 3.4 million acres are protected in roadless wilderness areas, more than 1,000 miles of paved and dirt roads provide ample opportunities for recreation and exploration.**

**Road conditions can change quickly. Current road condition information is available at the Furnace Creek Visitor Center or on the Death Valley National Park Morning Report (updated daily) posted throughout the park and on the official park website at www.nps.gov/deva.**

### 1 Echo Canyon Road
**Vehicle needed:** High-clearance first three miles, 4WD required beyond. **Distance:** Ten miles to Inyo Mine. **Start:** Hwy 190, two miles east of Furnace Creek Inn. **Camping:** Yes, after first two miles. No camping at Inyo Mine site. **Lee's Camp Road,** which connects to Amargosa Valley is rough 4WD, requiring short-wheelbase, narrow vehicles. Experienced 4WD drivers only. Vehicle damage is possible going over the dry fall. Travel with more than one vehicle recommended. **Within Echo Canyon's narrows is the Needle's Eye, a natural arch. The Inyo Mine's (private property) old structures and mining equipment are found in the upper canyon.**

### 2 Hole in the Wall Road
**Vehicle needed:** High-clearance first four miles to the Hole-in-the-Wall, then 4WD the next two miles to the road's end due to deep gravel and rocks. **Distance:** Six miles. **Start:** Hwy 190, 5.7 miles east of Furnace Creek Inn. **Camping:** No camping first two miles. **400' deep gap in wall-like ridge.**

### 3 Chloride City Road
**Vehicle needed:** High-clearance first 2.2 miles to Monarch Canyon spur road, then 4WD required next three miles due to steep, rutted sections. 4WD needed on the two mile spur into Chloride City. High-clearance on final segment of the loop in Amargosa Valley. **Distance:** 6.2 miles to Chloride City, 7.4 miles to Chloride Cliff. **Start:** Daylight Pass Road, 3.4 miles east of Hells gate. **Camping:** No camping within first two miles from Daylight Pass Road. **One of the earliest sites of mining in Death Valley can be reached via this loop drive. Continue beyond the townsite to views at Chloride Cliff.**

### 4 Titus Canyon Road
**Vehicle needed:** High-clearance due to steep grades, deep gravel and ruts. Often closed due to flood damage, mud or snow. No RVs, campers or trailers. **Distance:** 26.8 miles. **Start:** NV Hwy 374 (Daylight Pass Road), 2.7 miles east of park boundary. **Camping:** No camping, day use only. **The most popular backcountry road in the park is one-way from east to west. Winding through the Grapevine Mountains, the road passes a ghost town, petroglyphs at Klare Spring and winds through spectacular canyon narrows. A short two-way section at the west end of the road provides hikers access to the narrows of Titus Canyon and nearby Fall Canyon.**

### 5 Phinney Canyon Road
**Vehicle needed:** High-clearance first 15 miles off Hwy 95, then 4WD the last three miles. 4WD section is very steep, narrow and rutted in places. Impassable in winter due to deep snow. Strozzi Ranch Road is a dead-end spur road that requires 4WD on the last three miles due to sections of sand. **Distance:** 21 miles. **Start:** NV Hwy 95, 11.8 miles north of Beatty. **Camping:** Allowed. **Entering the "Nevada Triangle" of the park, this dirt road provides access to the high woodlands of the Grapevine Mountains. Vehicle travel is not allowed beyond the pass.**

### 6 Cottonwood Canyon Road
**Vehicle needed:** High-clearance on first eight miles due to sand, washboard and rocks. 4WD necessary after the road drops into the wash due to deep gravel and large rocks. Final 1.5 miles often washed out. **Distance:** 17.7 miles. **Start:** Stovepipe Wells Campground. **Camping:** No camping first eight miles. **Cottonwood Canyon is named for the tree-lined stream beyond road's end. Hikers can also explore winding narrows in Marble Canyon, a tributary. The Marble Canyon spur road is marked by a metal post about 2 miles above the drop into Cottonwood wash and ends at the first narrows.**

### 7 Lemoigne Canyon Road
**Vehicle needed:** 4WD. Very rutted, crossing numerous gullies. The old road up the canyon is closed beyond the 4.4 mile point. **Distance:** 4.4 miles. **Start:** Hwy 190, six miles west of Stovepipe Wells Village. **Camping:** No camping first two miles. **This rarely visited canyon in the southern Cottonwood Mountains was once the home of prospector Jean Lemoigne.**

### 8 Tucki Mine Road
**Vehicle needed:** 4WD due to large rocks, deep gravel and several dry falls three to four feet high. **Distance:** 10 miles. **Start:** Emigrant Canyon Road (to Wildrose) 1.5 miles south of Hwy 190. **Camping:** No camping first two miles. **The site of gold mining activity as recently as the 1970s, this road is a quiet escape today. After following along the base of the mountains, the road enters Telephone Canyon. 2.5 miles from the canyon mouth, a short walk up the right fork leads to a natural arch. The road continues up the left fork to the ruins of Tucki Mine.**

### 9 Skidoo Road
**Vehicle needed:** High-clearance. Steep grade with protruding rocks at 3.5 miles. Sedans risk undercarriage damage. Subject to snow and mud conditions. **Distance:** 7 miles. **Start:** Emigrant Canyon Road (to Wildrose) 9.4 miles south of Hwy 190. **Camping:** No camping, day use only. **Site of a ghost town dating from the early 1900s. Few visible remains exist today.**

### 10 Aguereberry Point Road
**Vehicle needed:** High-clearance due to rock outcrop in road at 3.5 miles and steep, rocky final 0.5 mile to viewpoint. Sedans may risk undercarriage damage. Subject to snow and mud conditions. **Distance:** 6.3 miles. **Start:** Emigrant Canyon Road (to Wildrose) 11.8 miles south of Hwy 190. **Camping:** No camping. Day use only. **Dramatic view of Death Valley at road's end. The historic Eureka Mine is located at 1.7 miles. Mine tunnel closed in winter to protect hibernating bats.**

### 11 Charcoal Kilns / Mahogany Flat Road
**Vehicle needed:** Most vehicles on unpaved road section to kilns, then high-clearance on final 1.6 miles to Mahogany Flat. 4WD may be necessary beyond Thorndike Campground due to steep sections and ruts. No RVs or trailers. Expect snow and ice during winter and spring. **Distance:** pavement ends 5 miles, 7 miles to kilns, 8.7 to Mahogany Flat. **Start:** Wildrose Campground. **Camping:** Only in designated campgrounds. **High elevation road leads to historic Charcoal Kilns, piñon pine woodlands, summer campgrounds and mountain trailheads.**

### 12 Lake Hill Road (Big Four Mine)
**Vehicle needed:** High-clearance first five miles off Hwy 190, then 4WD for washed out section to mine site. **Distance:** 5 miles. **Start:** Hwy 190, 4.5 miles east of Panamint Springs Resort. **Camping:** No camping the first two miles. **Provides access for hikers to Panamint Dunes.**

### 13 Racetrack Valley Road
**Vehicle needed:** High-clearance due to loose gravel, washboard and rocks. Flat tires are common on this road so be sure your full-sized spare is inflated, all parts of your jack are on hand and tire tread is good. May require 4WD due to changing road conditions and irregular maintenance, so check postings. **Distance:** 28 miles to The Racetrack. **Start:** Ubehebe Crater Road. **Camping:** No camping first two miles and from Teakettle Junction to the southern end of the Racetrack. **The Racetrack is a dry lakebed famous for its mysterious moving rocks. To preserve the rocks' tracks, do not walk on the lakebed when wet and never drive on it.**

### 14 Lippincott Road
**Vehicle needed:** Rough 4WD. Very steep, narrow, and winding with cliff edge washouts. Uphill traffic has right of way. Lower part has very narrow section that is difficult for wide vehicles. Subject to closure after washouts from heavy rains. **Distance:** 5.9 miles. **Start:** 3.5 miles south of the Race-track. **Camping:** Allowed. **This road connecting Racetrack Valley with Saline Valley is for experienced 4WD drivers only.**

### 15 Hidden Valley Road
**Vehicle needed:** High-clearance due to washboard, patches of deep dust, rocks and dips. Subject to flooding, mud and standing water after rains. White Top Mountain Road is a 4WD spur road starting just south of Lost Burro Gap that should be avoided when wet or snow covered. **Distance:** 3.2 miles to White Top Mtn. Road and 13 miles to base of Hunter Mountain. **Start:** Teakettle Junction on Racetrack Valley Road. **Camping:** Allowed. **Intermountain basins and historic mines abound on this dirt road.**

**Hunter Mountain Road** climbs steeply up onto a wooded plateau beyond Ulida Flat and connects to Saline Valley Road. **Vehicle needed:** 4WD. Often impassable in winter and early spring due to mud, ice and snow. Carry chains.

### 16 Saline Valley Road
**South Pass Section** (Hwy 190 to Warm Springs junction) **Vehicle needed:** High-clearance. Maintained dirt road. Section from Hwy 190 to Lee Flat has been surfaced for eight miles but is very potholed. From South Pass through Grapevine Canyon the road can be rocky and rutted. May be closed in winter due to snow or ice. Expect washboard. **Distance:** 46 miles. **Start:** Hwy 190 just outside west park boundary. **Camping:** Allowed.

**North Pass Section** (Big Pine Rd to Warm Springs junction) **Vehicle needed:** High-clearance due to washboard and rocks. With the pass at 7000 feet, this maintained dirt road is higher and more frequently affected by snow than South Pass. Expect washouts during rain. **Distance:** 32.8 miles. **Start:** Big Pine/Death Valley Road, 15.3 miles east of Big Pine, CA. **Camping:** Allowed.

**Warm Springs Road** (Warm Springs Road is marked by a large boulder approximately one mile north of the Saline Valley dunes.) **Vehicle needed:** High-clearance due to sandy stretches first seven miles to the warm springs. May be impassible after heavy rains. **Distance:** 6.8 miles. **Start:** Saline Valley Road. **Camping:** Allowed. **One of the most remote locations in California, Saline Valley is surrounded by rugged mountains on all sides. Sights include a salt marsh, sand dunes, warm springs and Joshua trees at Lee Flat.**

### 17 Steel Pass Road
**Vehicle needed:** Rough 4WD. Experienced 4WD drivers only. Vehicles must be able to climb narrow, sharp dry falls. Sidewall cuts to tires are common so carry multiple spares. No legal spur roads. Travel is easier from north to south. **Distance:** 29 miles. **Start:** Warm Springs in Saline Valley or Eureka Dunes in Eureka Valley. **Camping:** Allowed. **Continuing beyond the warm springs, this road connects Saline Valley with Eureka Valley. Very rugged all the way through.**

### 18 South Eureka Valley Road
**Vehicle needed:** High-clearance to Eureka Dunes. Deep sand near dunes. Beyond the dunes the road becomes Rough 4WD and is called the Steel Pass Road. **Distance:** 9.6 miles. **Start:** Big Pine/Death Valley Road, 33.2 miles north of Ubehebe Crater. **Camping:** Allowed. Dry campground at Eureka Dunes. **Eureka Dunes are the highest sand dunes in California at nearly 700 feet.**

### 19 North Eureka Valley Road
**Vehicle needed:** High-clearance. Eight miles of dirt and gravel road to park boundary. 4WD often required to continue to Hwy 168. **Distance:** 28 miles. **Start:** Big Pine/Death Valley Road, 0.7 miles west of South Eureka Valley Rd. **Camping:** Allowed. **North Eureka Valley Road provides access to Sylvania Mountain Wilderness outside northern park boundary. The Cucomungo Canyon Road forks to the east leading to Hwy 266 in Nevada.**

### 20 Big Pine / Death Valley Road
**Vehicle needed:** High-clearance. Expect dust, heavy washboard and occasional rough spots. The final section from Eureka Valley west to Hwy 168 is paved. Carry chains in winter. **Distance:** 72 miles. **Start:** Ubehebe Crater Road or Big Pine, CA on Hwy 395. **Camping:** No camping first two miles from Ubehebe Crater Road. **As the main backcountry thoroughfare from the Scotty's Castle area to Owens Valley, this maintained gravel road heads up the northern end of Death Valley and across Eureka Valley. Access roads to the Eureka Dunes and the North Pass into Saline Valley diverge from this road.**

### 21 Greenwater Valley Road
**Vehicle needed:** High-clearance. **Distance:** 28 miles. **Start:** Dantes View Road from the north or Hwy 178 from the south. **Camping:** No camping first two miles from paved roads. The spur road to Gold Valley dead-ends at the head of Willow Canyon, an impassable gorge draining into Death Valley. **Vehicle needed:** High-clearance for the first seven miles, then 4WD as the wash narrows and tops out at a 4,400' pass. **Distance:** 12.5 miles. **Start:** 18 miles south of Dantes View Road on Greenwater Valley Road.

**Deadman Pass Road** is an alternative 4WD route to return to pavement, connecting Greenwater Valley directly to Hwy. 127 to the east. **Vehicle needed:** High-clearance to the pass, then 4WD to the highway due to deep, loose gravel. **Distance:** 13.6 miles. **Start:** 18.2 miles south of Dante's View Road. **Greenwater Valley is best known for impressive displays of late spring wildflowers. Once bustling during mining booms, little remains of the ghost towns of Furnace and Greenwater accessible via side roads. Drive slowly to help protect desert tortoise.**

### 22 West Side Road
**Vehicle needed:** High-clearance due to washboard, deep gravel and dust pockets. Amargosa River crossing at southern end may be impassable when flowing. **Distance:** 37 miles. **Start:** Badwater Road six miles south of Hwy 190 (north entrance) or 39.2 miles south of Hwy 190 (south entrance). **Camping:** No camping along road, must be two miles up side roads before camping allowed. **Historic route of the 20-mule team wagons, this road skirts the west side of Badwater Basin and provides access to 4WD roads leading into canyons of the Panamint Mountains.**

### 23 Trail Canyon Road
**Vehicle needed:** High-clearance first four miles to top of the alluvial fan, then 4WD beyond. Passage is slow going with many large rocks. **Distance:** 10.4 miles. **Start:** West Side Road, 6.3 miles via north entrance. **Camping:** No camping first two miles. **This road leads to a spring and old mining area at the forks of the canyon.**

### 24 Hanaupah Canyon Road
**Vehicle needed:** High-clearance first five miles to top of alluvial fan, then 4WD to end of road due to very rocky and rough conditions. **Distance:** 8 miles. **Start:** West Side Road, 11.9 miles via north entrance. **From the summit of Telescope Peak—the park's highest point—to the salt flats at the bottom of Death Valley, this canyon has the greatest vertical drop.**

### 25 Johnson Canyon Road
**Vehicle needed:** High-clearance first six miles to mouth of canyon, then 4WD the last four miles in the rocky wash. Last 0.1 mile of road is over-grown and very wet. **Distance:** 10 miles. **Start:** West Side Road, 21.9 miles via north entrance. **Camping:** No camping first two miles. **Beyond this road's end a two mile hike leads to Hungry Bill's Ranch, with its rock-walled terraces and fruit trees planted in the late 1800s.**

### 26 Warm Springs Canyon Road
**Vehicle needed:** High-clearance first ten miles to Warm Springs Talc mine and camp, then 4WD to Butte Valley due to deep ruts and rocky areas. **Distance:** 20.4 to Butte Valley. **Start:** West Side Road, 3 miles via south entrance. **Camping:** No camping first two miles.

**Goler Canyon Road** continues west into Panamint Valley. Barker Ranch, hideout of the infamous Manson Family is up a short spur road. **Vehicle needed:** Rough 4WD. For experienced 4WD drivers only. Section over both sides of Mengel Pass is challenging, steep and rutted. Canyon narrows at west end is sometimes impassable after floods. **Distance:** 12 miles from pass to canyon mouth. **Start:** Mengel Pass. **Camping:** Allowed. **Although mined for talc as recently as the early 1980s, Warm Springs Canyon is returning to nature.**

### 27 Pleasant Canyon Road
**Vehicle needed:** Rough 4WD. Washouts and large boulders. Narrow, rocky road for experienced 4WD drivers only. **Distance:** 12 miles to South Park. **Start:** Ballarat **Camping:** Allowed. **4WD road off Indian Ranch Road into west side of Panamints. South Park Canyon Road is very rough, but allows a loop from South Park back down into Panamint Valley.**

### 28 Harry Wade Road
**Vehicle needed:** High-clearance most of the time but 4WD when the Amargosa river is flowing. Muddy areas develop quickly during times of heavy rainfall. **Distance:** 31.5 miles. **Start:** Badwater Road, two miles south of Ashford Mill. **Camping:** No camping first two miles. **Possible route of the only Lost '49er pioneers to make it out of Death Valley with their wagons intact. The road follows the Amargosa River (usually dry) into the southern end of Death Valley.**

### 29 Owl Hole Spring Road
**Vehicle needed:** First nine miles high-clearance, then becomes 4WD. **Distance:** 30.5 miles. **Start:** Harry Wade Road, 19.1 miles south of Badwater Road. **Camping:** Allowed. **The only road into the isolated Owls-head Mountains. Keep out of the military bases surrounding the park in this area. Unexploded ordinance and active bombing practice make them extremely dangerous to enter.**

### 30 Saratoga Spring Road
**Vehicle needed:** High-clearance. Washboard and possible muddy areas. Amargosa River crossing will be 4WD or impassable when the river is flowing. **Distance:** Four miles. **Start:** Harry Wade Road, 25.7 miles south of Badwater Road or 5.8 miles west of Hwy 127. **Camping:** No camping at the wetland or parking lot. **Large springs create wildlife habitat.**

### 31 Ibex Spring Road
**Vehicle needed:** High-clearance first 2.8 miles, then 4WD to the spring. Road turns off Hwy 127 south of Ibex Pass. Ibex Valley Road provides a connection to Saratoga Spring Road. Loose gravel and deep sand makes 4WD with a low gear a must. **Distance:** 5.3 miles. **Start:** Hwy 127, 1.9 miles south of Ibex Pass. **Camping:** Allowed. **Site of old silver mill and later talc mines.**

## BACKCOUNTRY SAFETY

### Travel prepared.
Things can go wrong quickly in the backcountry. Pre-trip planning could save your life. Bring basic tools, a shovel, extra water and food with you. In the higher elevations, snow and ice conditions may require tire chains. Top off your gas tank before starting a trip.

Flat tires are a common problem for backcountry visitors due to rough road conditions or from having unsuitable tires. Make sure your vehicle is equipped with "off-road" tires rather than highway or street tires. Carry at least one inflated spare tire (preferably two), a can of fix-a-flat or tire plug kit, a 12-volt air-compressor, a lug- wrench, and be sure all parts of your jack are on hand. Know how to use your equipment before you head out.

### Bring water
Always carry extra water for you and your vehicle. In hot weather you need at least a gallon per person per day. A 5-gallon container of water is standard emergency backup. Springs and other natural water sources may be dry or contaminated. Do not depend on them.

### If your vehicle breaks down
It is best to stay with your vehicle if it breaks down. On main roads, another traveler should come along sooner than you could walk for help. Leave the car's hood up and/or mark the road with a large X visible to aircraft. If you decide to out, stay on the main roads—do not cut cross-country. If it's hot, walk out only if you can carry sufficient water and wait until after sundown. Leave a dated note describing your plan with your vehicle.

Dial 911 in case of emergencies, but remember, cell phone reception is non-existant in most areas of the park. Towing charges are high and AAA often doesn't cover tows on dirt roads.

### Be a good road neighbor
Stop to help those in need. Report anyone in trouble to the nearest ranger. You may need help yourself some time.

### Safety in numbers
Travel in a group of two or more 4WD vehicles in remote areas and on rough roads. If that is not possible, leave a trip plan with a reliable person that will do follow-up on your safe return.

### Don't expect road signs
Most backcountry road junctions are unmarked, so carry good maps and study them in advance. Be alert for washouts and other road damage.

### Know the weather forecast
Rain or snow can alter road conditions and make travel dangerous. Flash flooding is possible almost anywhere in the park, but is more likely in canyons. Do not camp in dry washes or drainages due to the possibility of a flash flood.

### Keep out of mines.
Do not enter mine tunnels, shafts or dilapidated buildings. Always keep children near you, especially in the vicinity of mines.

### Rattlesnakes
Be alert for rattlesnakes, especially near old structures and vegetated areas near water. When climbing or walking, look before you reach or step. Use a flashlight when walking at night.

### Hantavirus
This potentially fatal disease is spread through breathing the dust from feces, urine and saliva of rodents. Avoid disturbing or camping near rodent burrows or dens. Follow the procedures on hantavirus posted at backcountry cabins.

## PARK RULES

### Park Resources
Removal or disturbance of rocks, historic artifacts, plants, or animals is prohibited. Do not feed or approach wildlife. The use of metal detectors is prohibited. Please leave the park undisturbed for others to enjoy.

### Stay on established roads.
Driving off roads is prohibited. The desert environment is extremely fragile and slow to recover from vehicle damage. Honor road closures. If in doubt, do not drive.

### Vehicles
Vehicles must be street legal. Vehicles with off-the-highway registration (California green-sticker) cannot be operated anywhere within the national park. All vehicles must have valid license plates and highway registration including two-wheel-drive and four-wheel drive vehicles, motorcycles, all-terrain vehicles, dune buggies, trail bikes, mini-bikes and every other mechanically-driven means of transportation.

### Bicycles
Bicycles are allowed on paved and dirt roads and the bike path near the Furnace Creek Visitor Center. Bikes are not allowed off roads, on trails, on closed roads, or in the wilderness areas of the park.

### Wilderness
The wilderness boundary is 50 feet from the center line of most backcountry dirt roads. Only foot or horseback traffic is allowed within the park's wilderness.

### Weapons
All weapons are strictly prohibited. This includes firearms, air guns, bow and arrows, slingshots and other similar weapons.

### Horses
Horse use is allowed except in developed campgrounds, on paved roads and many trails. Water and forage is scarce, so grazing is not allowed. Use of weed-free feed is required. See the Superintendent's Compendium for details.

### Pets
Pets are permitted in developed areas and on park roads. Pets are not allowed off roads, on trails, or in the wilderness areas of the park. They must be leashed and restrained at all times. Owners are responsible for clean-up of pet feces.

### Weapons
All weapons are strictly prohibited. This includes firearms, air guns, bow and arrows, slingshots and other similar weapons.

### Campfires
Campfires are prohibited, except in fire pits in developed campgrounds. Gathering wood is unlawful. Campstoves and barbeque grills are allowed. Charcoal ashes must be packed out.

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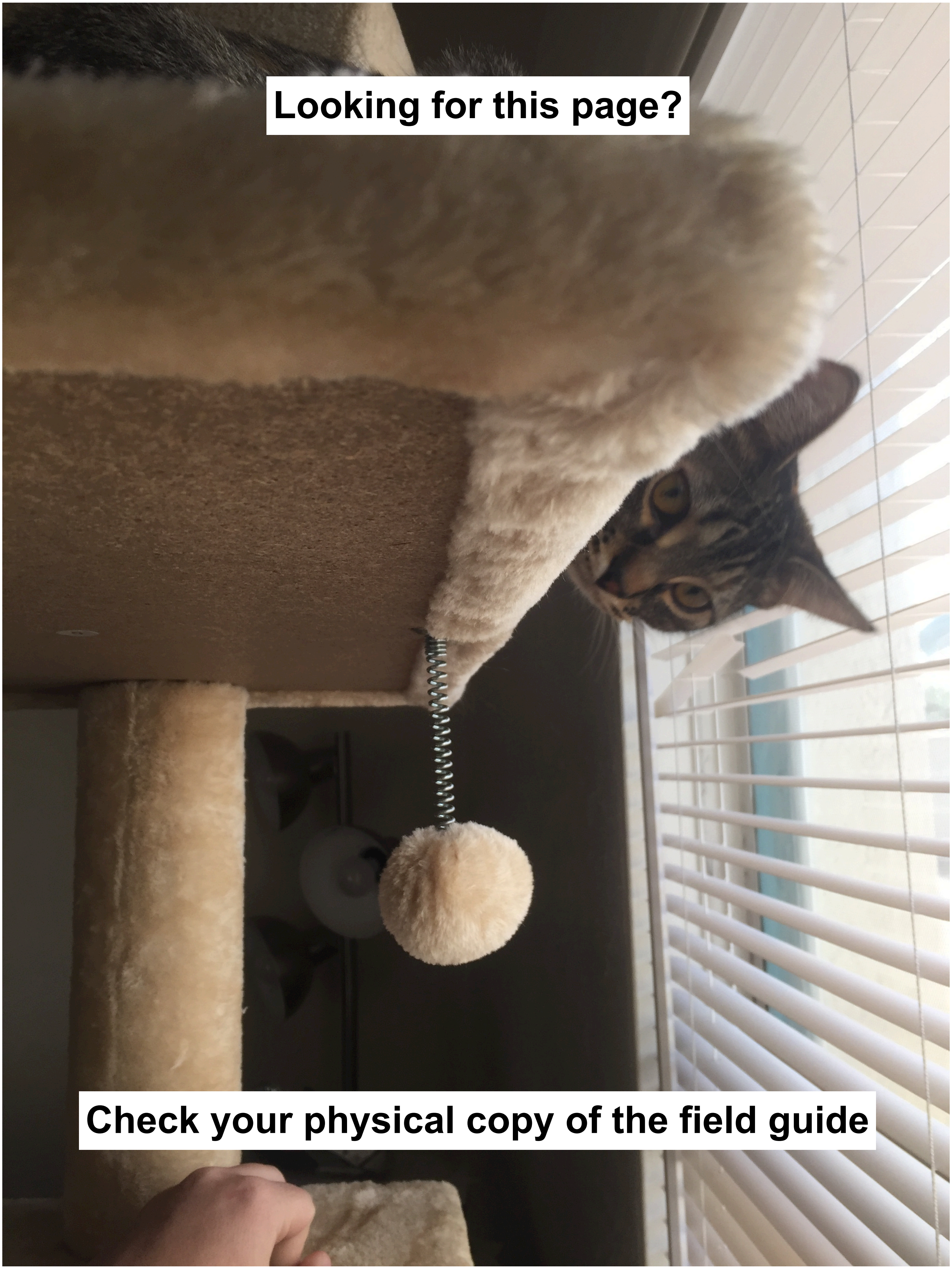
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# Schedule

## THURSDAY 2/8/2018 - All times are AZ times

| | |
|---|---|
| 7 AM | Arrive at LPL loading dock with all our gear including breakfast, coffee, ice etc... |
| 8 AM | Depart LPL<br>Drive north on Cherry -> west on Speedway -> enter I10 westbound. Drive 117 miles west on I10 and I8. Exit onto the 85 north and drive 37 miles. Re-enter I10 west and drive 92 miles to Quartzsite, take exit 19 (Riggles Ave) northbound route 95. |
| 1PM | Arrive Quartzsite - Lunch near here (or maybe further north at Parker). |
| 1.45PM | Left onto Main Street then right onto route 95 north within Quartzsite. Drive 23 miles on the 95, turn left and drive another 12 miles. Cross the Colorado at Parker. Transition here to the 62, drive 18 miles. Turn right onto US route 95 and drive 48 miles. Join I40 westbound at Needles (probably gas up here), drive 65 miles and take exit 78 for Kelbaker Rd.<br><br>Drive north on Kelbaker Road for 14.5 miles.<br>Turn left at Kelso Dunes Road and drive 4-5 miles. |
| 5PM | Arrive at the Kelso Dunes |
| 5.30PM | Camp: Kelso Dunes. Hear about booming dunes from **Tad**. Hike to the top if there's time…<br>Elevation 2500'. Sunset 6.18PM AZ time. |

# FRIDAY 2/9/2018 - All times are AZ times

| | |
|---|---|
| 8 AM | Leave Camp. Sunrise 7:34AM.<br>Backtrack to Kelbaker Road. Drive North to Baker for 43 miles (porcelain break). The road continues as the CA 127, drive another 83 miles. Turn left onto the CA 190W and go 25 miles. |
| 11 AM | Arrive at Zabriske Point where we can talk about the Gower's gulch diversion. **Margaret** will tell us about river profiles and derisively describe the mess made of this situation. |
| 11.30AM | Leave Zabriske Point. Drive 8 minutes (6.2 miles) to Bad Water road on the other side of the divide and see the changes being wrought on Gower's Gulch fan. |
| 12.15PM | Leave Gower's Gulch fan. Drive 27 miles further on the CA 190 and stop at the side of the road to access the Mesquite Flat Dunefield (drive past the turn for Giotto canyon road by ~0.5 miles). |
| 12.45PM | Arrive at the dunes. Have Lunch! |
| 1.30PM | Edge of the dunefield is ~100m from the road (along with the Giotto canyon mudflow). Mudflows will be expounded upon by **Hamish** while doing an impression of David Attenborough. There's a star dune ~1 mile from the road. |
| 2.30PM | Leave the dunes, drive 11 miles further down the CA190 and turn left onto Emigrant Canyon Road. Drive 12 miles and then turn left onto Aguereberry Point Road. Drive 6-7 miles and arrive at Aguereberry Point. |
| 3.30PM | Overview of Death Valley at Aguereberry Point delivered resentfully by a **Randomly Selected Attendee**. Who put the 'Death' in Death Valley? Spoiler alert - **Mattie** has the answers. |
| 4.15PM | Leave Aguereberry Point. Retrace steps to Stovepipe Wells. |
| 5.10PM | About 200m before Stovepipe Wells turn right towards Mosaic Canyon. Drive 2.3 miles to the entrance to Mosaic Canyon (~10 minutes). Within the canyon we'll look for the conglomerated breccia that it's famous for and hear from **Amanda**. |
| 5.50PM | Leave Mosaic Canyon |
| 6.00PM | Camp: Stovepipe Wells. Elevation 0' Sunset 6.22PM AZ time.<br>(Stovepipe Wells had showers last time…) |
| 6.01PM | Discover if the government (and Death Valley) has shut down. |

# SATURDAY 2/10/2018 - All times are AZ times

8 AM Leave Camp. Sunrise 7:15AM.

Drive east on the 190 until Scotty's Castle Road (7 miles), turn left (north) and drive 34 miles. Turn left onto Ubehebe Crater Road and drive 6 miles.

9AM Arrive at Ubehebe crater and listen in stunned silence to **Ali** deliver a blistering diatribe on phreatomagmatic eruptions. Then it's time for enjoyment of the view!

10AM Leave Ubehebe crater.

Drive south on Racetrack Valley road for 27 miles (passing Tin mountain landslide after 15.5 miles and Teakettle Junction after 19 miles). Estimate 90 minutes for this drive.

11.30 Arrive at Racetrack Playa.

A **Randomly Selected Attendee** will muse about playa formation, after which we'll walk out to the fabulous sliding rocks (~2km roundtrip - should be our longest hike). **Saverio** will fill us in on what we know here with breathless excitement. If there's good rock varnish here then **Maria** could deliver a rousing explanation - if not then we'll do it on day 5 at Cima.

1.30PM Delicious lunch at the vehicles

2.15PM Leave Racetrack Playa

Drive back past Ubehebe Crater, Scotty's Castle Road and CA 190 to Stovepipe Wells.

4.45 PM Camp: Stovepipe Wells. Elevation 0'. Sunset 6.22PM AZ time.

It's early. But last time we had three flat tires on Racetrack Playa Road…

**<u>Contingency Plans: Use in case of political incompetence.</u>**

2.15PM Leave Racetrack Playa. Drive back past Ubehebe Crater to Death Valley Road. Take a left (north) and drive 33 miles. Turn left onto South Eureka Road and drive 10 miles to the Eureka Dunes.

5.45 PM Camp: Eureka Dunes. Elevation 3000'. Sunset 6.22PM AZ time.

More realistically: Camp at Homestake campground or in Hidden Valley.

## SUNDAY 2/11/2018 - All times are AZ times

| | |
|---|---|
| 8 AM | Leave Camp. Sunrise 7:14AM.<br>If leaving from Stovepipe Wells - drive 26 miles east on CA 190. Turn right onto Badwater Road and drive south 5 miles to Ventifact Ridge. Along the way stop and gas up at the Furnace Creek gas station.<br>If leaving from the Eureka dunes then add 2 hours to all these times. |
| 9.00AM | Arrive at Ventifact Ridge. Look around and listen to **Sondy** to get the details in rhyming couplets. |
| 9.30AM | Leave Ventifact Ridge. Drive 2.5 miles south to Salt Pool Road, turn right here and drive 1.3 miles. |
| 9.45AM | Arrive Devil's Golf Course. Look around and hear **Ben** rave incoherently about where the heck salt polygons come from. |
| 10.30AM | Leave Devil's Golf Course. Drive back to Badwater Road and a further 5.5 miles south to Badwater itself. Tourist stop - take pictures of the sea level sign etc... View Salt Pan differences from Devil's golf course. |
| 11.15AM | Leave Badwater. Drive south on Badwater Road 12.2 miles to Salt weathering site. |
| 11.35AM | Hear a talk from **Sarah** angrily denouncing salt weathering and have lunch. |
| 12.45PM | Leave Salt weathering site. Drive 15 miles south to shoreline Butte. There's a turnout/vista point on the west side of the road. Or drive 13.3 miles to the west-side road turnoff and drive west on that for ~1 mile. Seems like a 1 mile hike to the Butte either way. We'll make this decision on the fly depending on the time. |
| 1.15PM | Arrive at the Shoreline Butte Stop. Listen to **Teddy** wistfully describe the waxing and waning of lake Manly and the shoreline features we can still see. |
| 1.45PM | Leave. It's 2hrs 15 minutes from here to the Cima Campsite. We'll exit Death Valley via Jubilee Pass. Go a few more miles south on Badwater Road, take a left onto the 178 (east) and travel 25 miles. Turn right onto the 127 and travel 58 miles to Baker. The road continues as Kelbaker Road for another 15.3 miles. A small dirt road called Indian Springs Trail leads off to the left. We'll take that for 1-2 miles before stopping to camp. We should arrive in plenty of time for **Patrick** to effusively describe the Cima volcanic field. We'll be right beside the freshest flow, **Joana** can give a melancholic overview of what happens to flows as they age. |
| By 6PM | Camp: Cima Volcanic Field. Elevation 2400'. Sunset 6.46PM AZ time. |

## MONDAY 2/12/2018 - All times are AZ times

| | |
|---|---|
| 8 AM | Break Camp. Sunrise 7:12AM.<br><br>If we camped at Eureka 2 nights ago then Patrick and Joana will do their talk this morning instead. If it was Stovepipe Wells then we should be ready to leave after breakfast.<br><br>Backtrack on Kelbaker Road a few miles to a site with good examples of desert pavement where **Corey** will deliver the startling truth. |
| 8.30AM | Start driving home. It's 8 hours driving back to LPL.<br>Stops and Lunch along the way means this is probably 9.5 hours minimum. |
| 6PM | Return to LPL. Sunset in Tucson 6:25PM<br>(Add ~1 hour if we had Patrick and Joana talk in the morning) |

**The Cima Volcanic Field: Big Rumbles in Little Cima**

Patrick O'Brien

The **Cima Volcanic Field** is an area containing 40 cinder cones spread out over more than 150 $km^2$ of the Mojave Desert. There are over 65 basaltic lava flows associated with these cones, which erupted from about 7.6 million years ago until the end of the last ice age, about 10,000 years ago.

- **<u>Volcanic field</u>** – an area of the Earth's crust that is or has been prone to volcanic activity, usually contain ~10-100 separate volcanoes
- The Cima Volcanic Field formed during the late stages of the tectonic extension that formed the Basin and Range province of the American Southwest, where the crust was thinned, allowing magma to more easily reach the surface.
- 40 cinder cones, 52 vents, 65 flows
    - Cone heights range from 25 to 155 m
    - Diameters range from 200 to 920 m
    - Most are Pleistocene in age (~2.6 Myr – 11.7 Kyr), based on K-Ar dating

Lava flows are around 10-13 feet thick and some flows extend as far as 10 km from where they erupted. These flows exhibit both a'a and pahoehoe behavior. ***Gas bubbles in the upper layers of a'a can be used to determine the direction of the flow***. With low-viscosity lavas like the basalt flows here in Cima, lava tubes can form when the outer surfaces of the flow cool and harden (see bonus image).

While most of the cones in Cima Field are thought to **<u>monogenetic</u>**, the result of one-time eruption events, at least 4 of the cones are **<u>polygenetic</u>**, having erupted on and off for hundreds of thousands of years.

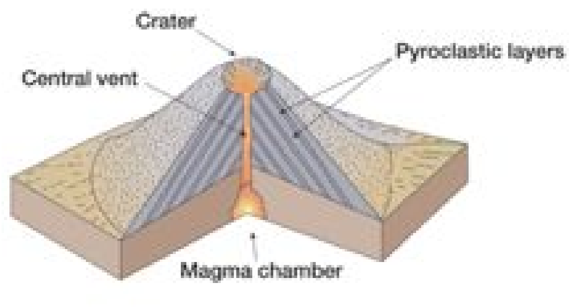
The largest feature in this region is Cima Dome. Just outside the field, this broad, sloping dome reaches **460 m** above the plain and extends over **180 km$^2$**. Cima Dome is a remnant of granite plutons that formed when the Farralon Plate was subducted beneath the North American Plate 180-80 million years ago.

(**pluton** – mass of intrusive igneous rock formed when magma cools and crystallizes beneath the Earth's surface)

When the plutons that eventually became Cima Dome were lifted to the surface by tectonic activity, they formed a rugged, granite mountain. Millions of years of erosion weathered this down to the gently sloping upland dome we see today.

**Cinder cones**

- Steep conical structure composed loose, pyroclastic fragments formed around a volcanic vent (usually during a single eruption event)
- Slopes typically between 30-40 degrees
- Some have an associated lava flow, most have a bowl-shaped crater at the top (e.g. SP Crater)



(a) Cinder cone

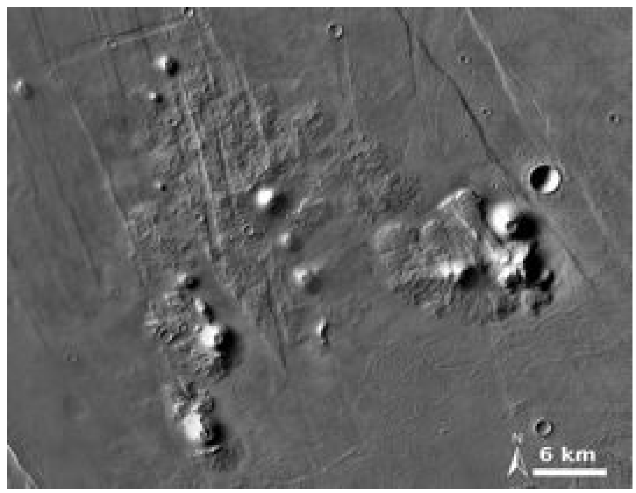
**Cinder cone degradation**

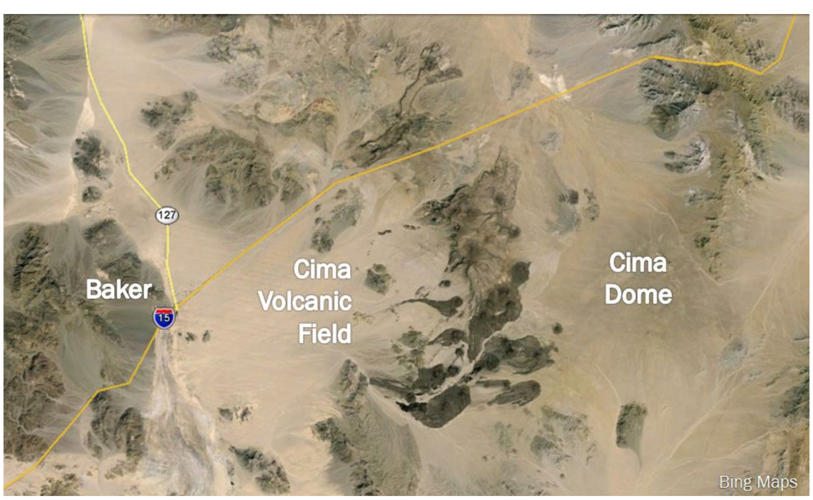
Cinder cones at Cima Field demonstrate a wider range of degradation states. Thus, this area has been used to study the erosion of cinder cones, with implications for degradation studies and dating of volcanic landforms on other bodies.

Cinder cones are highly permeable and very resistant to erosion. The youngest cones have well-preserved symmetrical and steep-sloped shapes. Plant life is sparse on these most recent eruption sites. Intermediate cones show some evidence of degradation from water drainage, with irregular rills and gullies formed on their slopes. The most degraded craters have regularly spaced gullies and full-blown valleys. Additionally, plant communities begin to establish themselves on the oldest cones and lava flows.

**<u>#PlanetaryConnection2k18 - Volcanic fields across the solar system</u>**
Plate tectonics, which may directly or indirectly lead to the development of volcanic fields like Cima, appear to be unique to the Earth. Large scale volcanism, however, is found throughout the solar system, though the mechanisms are varied.

- Mercury/the Moon
  - Massive flood basalt provinces (lunar domes?)
- Venus
  - Thousands of volcanoes, surface has undergone extensive resurfacing, now ~90% basalt, “shield fields”
- Mars
  - Huge volcanic provinces like Tharsis, shield volcanoes
- Outer solar system
  - Io – tidal heating
  - Cryovolcanism



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[3] http://www.nature.nps.gov/geology/usgsnps/mojave/cinder1.html

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http://doi.org/10.1130/0016-7606(1987)99<405:DDOBLF>2.0.CO;2

[8] Brož, P. and Hauber, E. (2012), A unique volcanic field in Tharsis, Mars: Pyroclastic cones as evidence for explosive eruptions, Icarus, doi: 10.1016/j.icarus.2011.11.030.

**Images**
Image 1 - Reference [1]
Image 2 - By LCGS Russ - Own work, CC BY 3.0,
https://commons.wikimedia.org/w/index.php?curid=6491119
Image 3 -
http://web.gccaz.edu/~lnewman/gph111/topic_units/igneous_vulcanism/igneous_vulcanism2.html
Image 4 - http://gotbooks.miracosta.edu/geology/images2/Cinder_Cone_NGL.jpg
Image 5 - PTYS554 Fluvial Processes I Lecture Slides
Image 6 - Reference [8]
Image 7 - Reference [1]

Bonus: Lava tube in Mojave Preserve

# Roughness on aging lava flows: Losing one's edge with age

Joana Voigt

## 1. Surface roughness

Surface roughness can be described as the topographic variation at different length-scales ranging from millimeters to hundreds of kilometers [1]. The roughness can be inferred, from single position and elevation measurements of a set of distinct points on the surface. There are several methods to define the roughness character of a surface. A commonly used parameter is the Root-Mean-Square deviation (RMS):

$$v(\Delta x) = \left\{\frac{1}{n} \sum_{i=1}^{n}[z(x_i) - z(x_i + \Delta x)]^2\right\}^{1/2} .$$

Where $v$ represents the variance, meaning the difference in height $z$ between points separated by a distance $\Delta x$ [e.g., 1].

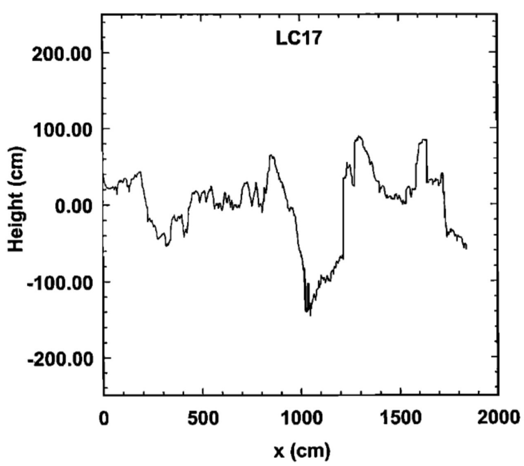


*Figure 1* from Shepard et al. 2001 [1] shows a profile of a rough ʻaʻā lava flow in the Lunar Crater volcanic field, Nevada.

## 2. Lava Morphology

Lava can be classified into different types according to their morphological occurrence. In general, there occur two end-members of lava types, *ʻAʻā* and *Pāhoehoe* (like shown in Figure 2 a and b respectively), as well as several transitional lava types e.g., slabby -, rubbly -, or spiny lava. The *ʻaʻā* end-member is characterized by a rough auto brecciated material, often referred to the clasts as clinker [2]. The opposite endmember, *pāhoehoe,* has a more coherent and smooth surface [2]. Here the descriptive terms "rough" and "smooth" are already used to define the surficial morphology. Since the past two decades the surface roughness was used in a quantitative approach to define basaltic lava morphologies on Earth, e.g. in Mauna Ulu on Hawai'i [3], or at the stratovolcano Mount St. Helens in Washington [4]. Where the morphologies depend on different rheological parameter (which is temperature, pressure, and composition dependent [5]) and topographical parameter (e.g., slope variance [6]). When other factors are equal then *ʻaʻā* is indicative for a high volumetric flow rate and *pāhoehoe* for a lower flow rate [3].

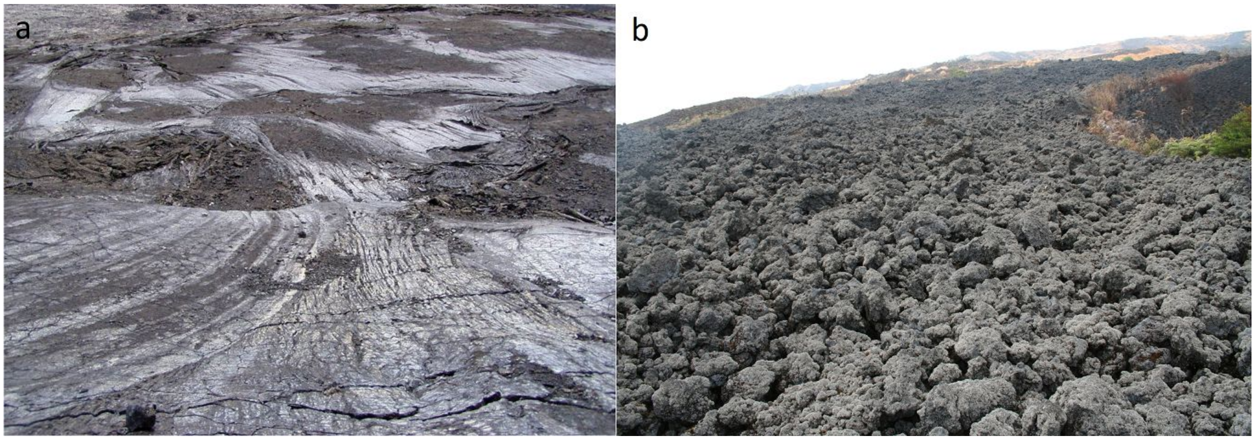


*Figure 2* a) image from Harris et al., 2017 [2] shows a pāhoehoe sheet flow on the eastern flank Kīlauea'sPuʻuʻŌʻō cone emplaced in July 1997. b) Illustrates a fresh and geological young *ʻAʻā* lava flow field.

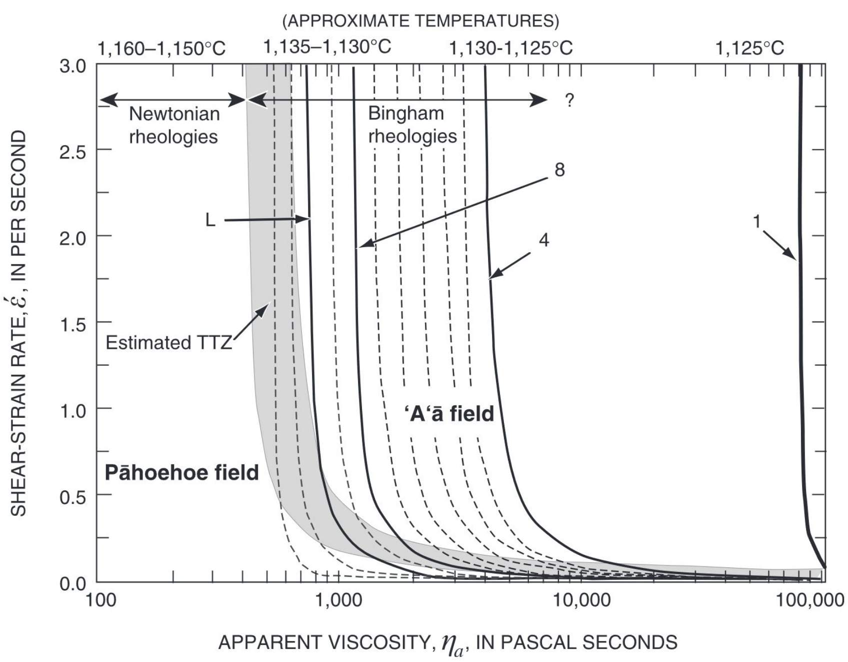


*Figure 3* from Hon et al., 2003 [5] illustrates the relation of a pāhoehoe and *ʻaʻā* lava type according to its shear-strain rate, temperature, and viscosity. The approximate stability fields for Hawaiian lava flow fields is shown with transition threshold zone (TTZ) within Bingham rheology field.

3. <u>Erosion</u>

On Earth vegetation, aeolian, fluvial, and glacial erosion as well as sedimentation processes affects the lava surfaces and thus these landscapes become smooth relatively quick (in geological timescales). Therefore, the roughness parameter can lose their information about the morphological lava types. But can also be used as an indicator for age determination. In the specific region of the Cima volcanic field in the eastern Mojave Desert of California, the landscape evolution is dominated by aeolian mantling processes, like seen in Figure 4 [7] and provides an excellent study site for long-term landscape evolution.

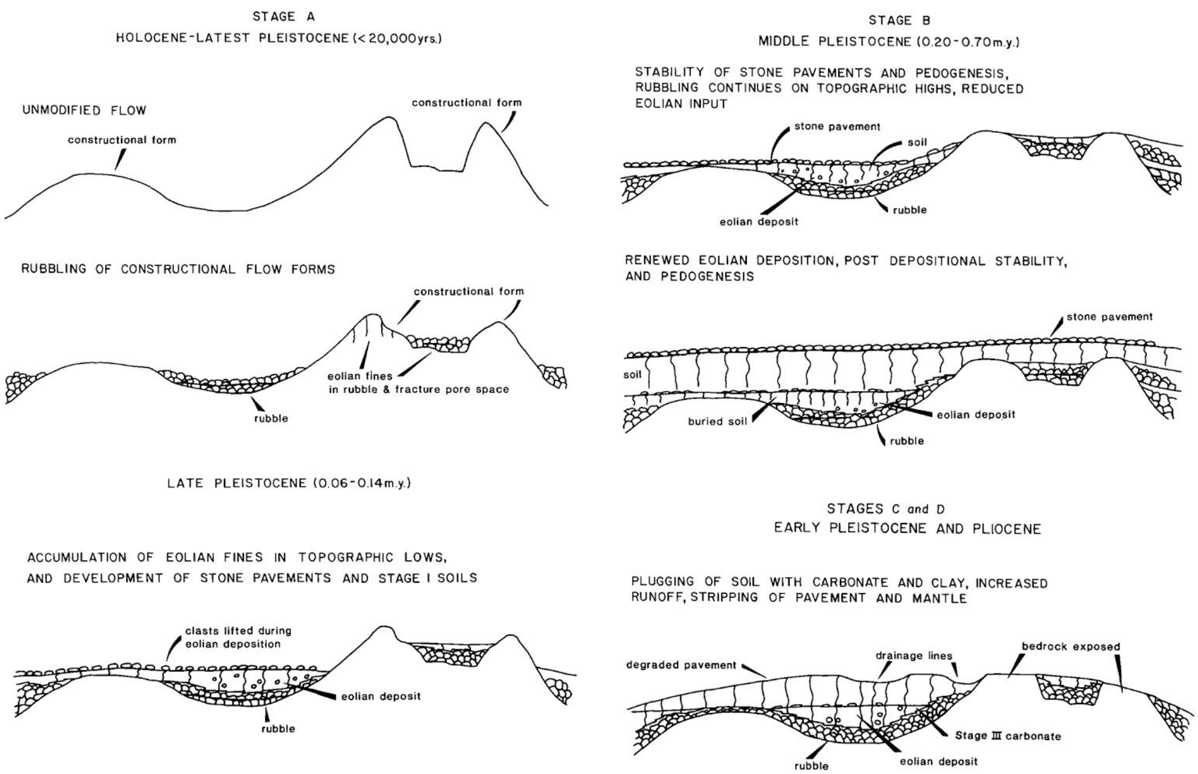


*Figure 4* from Wells et al. 1985 [7] shows a sketch with the topographic and stratigraphic evolution of the Cima volcanic field (Cenozoic age).

4. <u>Connection to Planetary Science</u>

4.1. Lander and Rover Safety on Mars:

In September 2018 NASA's InSight mission will bring a lander to an early Amazonian lava flow in western Elysium Planitia [8]. For the landing site selection, the roughness was derived from MOLA, SHARAD, and HiRISE data and the RMS data all indicate very smooth and flat surfaces (mainly below the 15° engineering constraint). Compared to other Mars landing sites, the terrain of InSight's landing site is smoother at a 1-5 m length scale than all the previous landing sites with the possible exception of Opportunity and Phoenix [8].

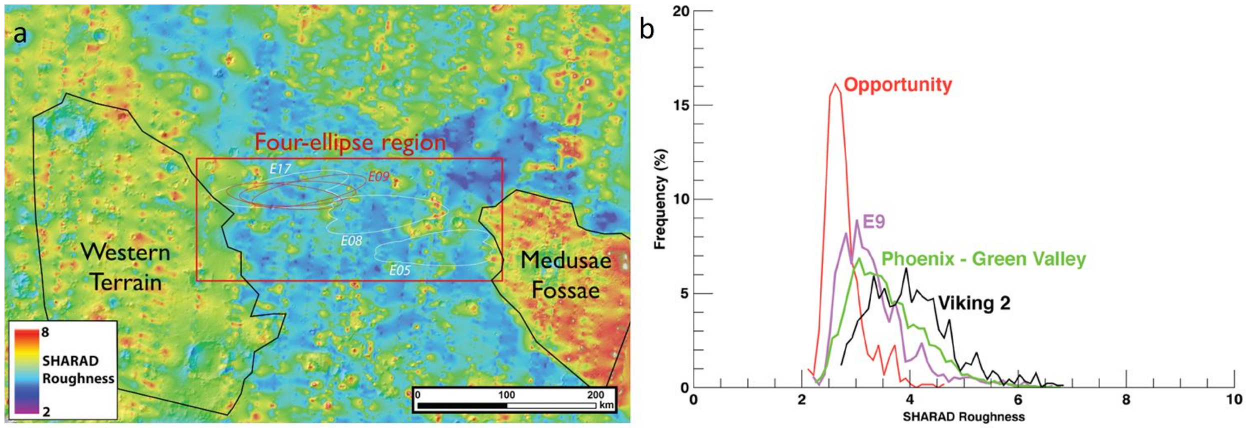


*Figure 5 a)* from Golombek et al. 2017 [8] shows the RMS-slope roughness parameter derived from SHARAD data in the western part of Elysium Planitia. Landing site is marked with the red E-09 ellipse. b) Roughness comparison of landing sites on Mars including Opportunity, Insight, Phoenix and Viking.

## 5. References:

[1] Shepard et al. 2001: The roughness of natural terrain: A planetary and remote sensing perspective. Journal of Geophysical Research, Vol. 106, No E12, p. 777-795.
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# Rock Varnish

Maria Steinrueck

Desert varnish (or more generally, rock varnish) is a thin, dark coating found on rocks in arid regions. It is typically only a few tens of micrometers thin. Desert varnish is composed mainly of clay, with some manganese oxide (birnesite) and iron oxides (hematite), which give the varnish its color. Manganese rich varnish is black, while iron rich varnish tends to be redder. As it takes thousands of years to form, it can only be found on surfaces that are resistant to erosion.

**Formation**

The formation mechanism for desert varnish is still subject to debate. It is clear that desert varnish does not form through weathering of the underlying rock, since there is no relation between the composition of the varnish and the underlying rock. It is thought that the clays in desert varnish are transported there by wind.

Most formation theories involve microbes. This is supported by the fact that desert varnish is associated with microcolonial fungi (MCF) and certain bacteria. Dorn and Oberlander (1981) performed scanning electron microscope and energy-dispersive x-ray analyses of desert varnish. They identified Metallogenium-like and Pedomicrobium-like bacteria and were able to isolate them and grow them in the lab. They were able to show that these bacteria produce a manganese film. There have been several attempts at reproducing desert varnish in the laboratory since, however, all of them fail to account for some of its characteristics, including its hardness.

**Archeology**

Many native cultures of the Southwest have carved art into desert varnish. These carvings, as well as some other archeological artifacts, can be dated based on how much desert varnish has accumulated since their creation.

**Planetary Connection: Rock Varnish on Mars?**

Many rocks photographed by various Mars landers and rovers are covered by a dark, shiny material that looks similar to desert varnish. It has been speculated that this coating could be similar to rock varnish – potentially even produced by microbes or past microbes – but given how hard it has proven to determine the formation mechanism on Earth, this will be hard to prove.

**References:**

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Dorn, R.I., Oberlander, T.M.: *Microbial Origin of Desert Varnish*. Science 11 Sep 1981:Vol. 213, Issue 4513, pp. 1245-1247. DOI: 10.1126/science.213.4513.1245

**Images:**

1. Desert Varnish in Horseshoe Canyon, Canyonlands National Park (Wikipedia/Public Domain)
2. Petroglyphs from the Ancestral Pueblo in Glen Canyon (Personal)

# Desert Pavement

Spring 2018 Field Guide, Corey Atwood-Stone

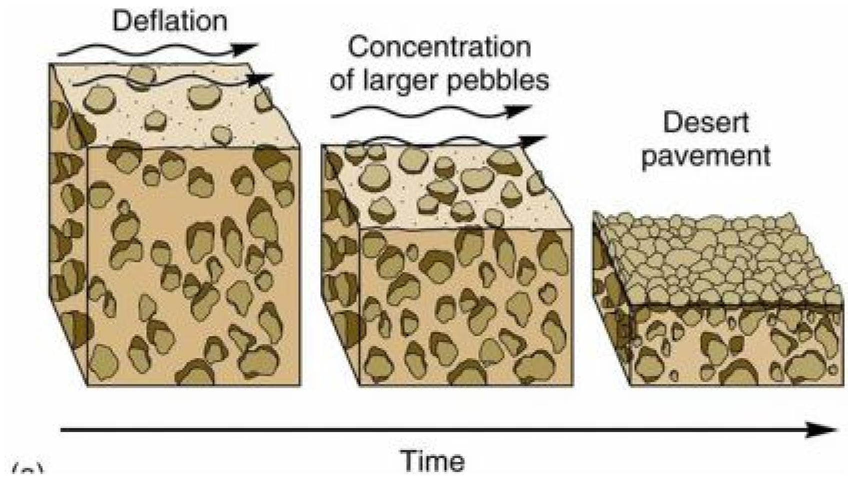
(No not that kind of Desert Pavement)

Desert Pavement is a tightly packed surface of gravel and cobbles, sometimes cemented, overlying and armoring thick layers of fines. The fines below eventually form soil horizons. This surface is common in unvegetated areas of the desert that are not sandy.

This has different names in other parts of the world – Australia = Gibber : Western Sahara = Reg.

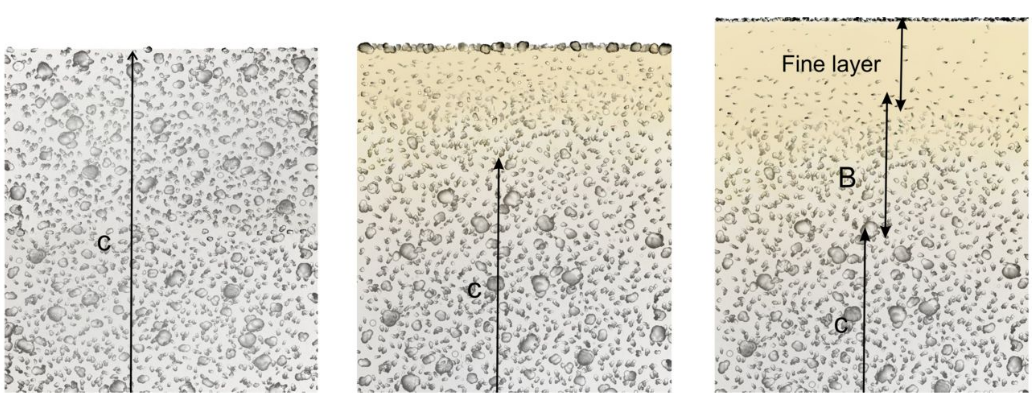
How does Desert Pavement form – The **startling truth** is that there is not one accepted explanation.

**Theory 1:** Fines removed over time by wind/water. Gravel shaken into place by everything from frost heave, to tiny seismic events, to animal feet. Eventually gravel forms an armor preventing further removal of fines from below.




**Theory 2:** Wetting and drying expansion contraction of fines (clays) forms cracks in the material. Overtime the expansion cycles work large fragments up to the surface through these cracks to form the desert pavement.

**Theory 3:** The most recent theory was formed in the Mojave at Cima Dome. Cosmogenic dating shows that the gravel has been at the surface for the same amount of time as the nearby lava flows it is sourced from. The theory for this is that gravels start at the surface and have fines brought in by wind and water deposited underneath them. The gravel remains at the surface by processes of heave while layers of fines build up below – possibly a decent climate record.



## **Planetary connections** – *wild speculation* follows

Ancient Mars may well have had all of the right ingredients to form these pavements, when it was a wetter world, much of it would have been desert. However billions of years of micro (and macro) impacts likely would erase all of this.

Titan also seems to have the right ingredients to form the pavements. Much of its surface is clearly desert, and while the chemistry is different the physics of forming pavements (by any of these theories) should still work. Can't confirm at the moment as our only close up look at the surface was in a streambed, where pavements definitely could not form.

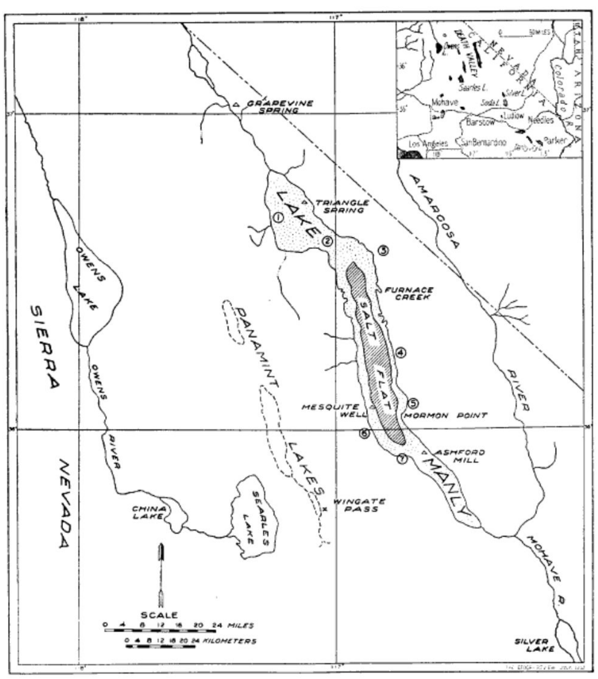
## the once and future lake manly

Teddy Kareta, Basin and Range Province Sycophant

**What is Lake Manly?** Lake Manly is the name given to both the series of ancient pluvial lakes that filled or partially filled Death Valley and the modern day small body of water that forms near Badwater Basin after heavy precipitation.

**Why 'Manly'? Isn't that a bit presumptuous?** Yes, it is, but the modern name is to honor William Lewis Manly, who is said to have rescued the "first" party of westward-moving emigrants to attempt to cross Death Valley in 1849.

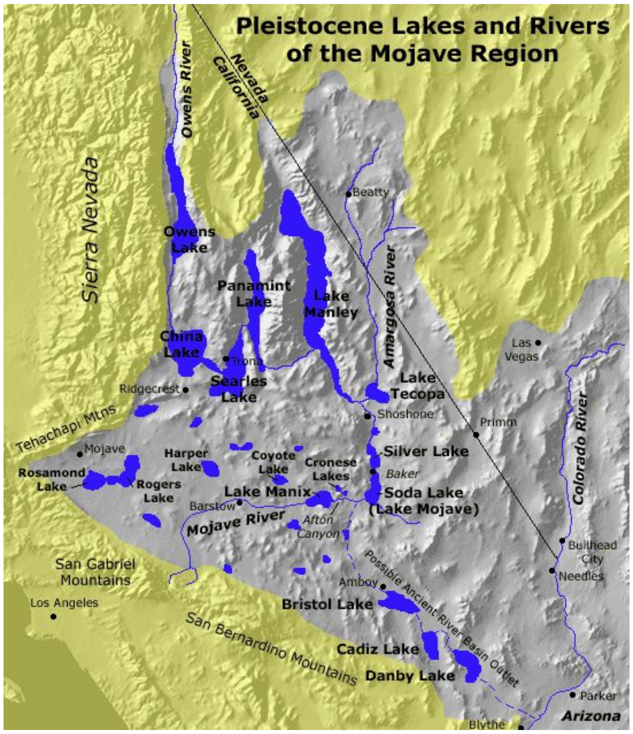
**How big was the lake?** The largest Lake Manly occurred during the Blackwelder Stand, where the water level was at an elevation of 90-100 meters, indicating a depth of somewhere between 175 to 335 meters deep depending on where you are in the valley. Modern dating techniques place this approximately during the Illinois Glaciation (Ku et al., 1998), corresponding to approximately to 185,000 to 128,000 years ago - although at some points it was likely smaller.




**Blackwelder Stand?** The Blackwater Stand is named for the person who discovered it, Eliot Blackwelder, published in 1933. In addition to naming it Lake Manly, he also lamented the transition of the valley from 'gruesome' and 'mysterious' into a 'winter resort for the motoring tourist' (Blackwelder, 1933). Technically speaking, many trained geologists had speculated on the existence of the Lake prior to Blackwelder (including G.K. Gilbert, of course.)

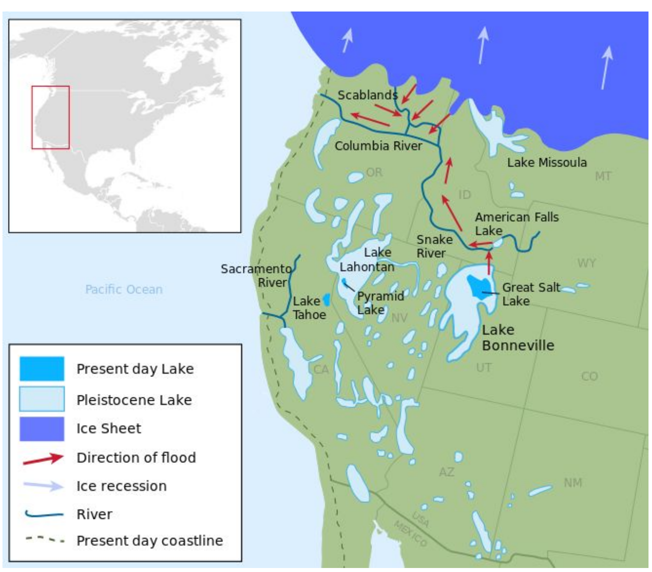
**Why did the lake vary in size?** Lake Manly is a pluvial lake, meaning the existence of perennial standing water is controlled by climatic conditions. Like the many other pluvial lakes of the American West, the modern understanding of them is tied to our understanding of the glaciation of the continent and the associated changes in weather patterns. The newer colder environment slowed evaporation and allowed more bodies of standing water to develop, which was aided by changing precipitation patterns. The history of this pluvial lake is thus part of the history of the climate of the west, and much work has been done comparing Lake Manly's history to that of the other similar lakes.

**Other Similar Lakes?** There are many other pluvial lakes in the Great Basin area, but two of the largest are Lake Lahontan and Lake Bonneville. Lake Lahontan covered a large fraction of northwestern Utah, and slowly dried up, leaving a variety of playas and sinks. Lake Bonneville is the precursor to the modern day Great Salt Lake (and a few others in Utah). Bonneville eventually overflowed in southern Idaho around 14,500 years ago, exiting through and further carving the scablands of Washington on its way to the Pacific.




**Where did the water come in, and where did it exit?** The Amargosa River was the primary source of water to Lake Manly, and only after its previous source, Lake Tecopa, breached and largely drained into Death Valley around the time of the Blackwelder Stand (Blackwelder, 1933). There is evidence for sporadic overflow from other nearby lakes as well. The lake was endorheic, indicating that the water level was largely controlled by evaporation - and thus it was fairly salty. (Notice the salt everywhere?)

**Where can I see the proof?** While there have only been small temporary collections of standing water in the low-lying areas of the Valley in the past 10,000 years (current research notwithstanding), modern evidence of the ancient lake can be seen through wave action features found on many exposed surfaces, like Shoreline Butte. Beatty Junction and Desolation Canyon also show features of wind and water action (Knott et al., 2012). Additionally, If you dig through the five feet or so of salt, you can find a clay layer and beneath that a salt layer and so on, which is characteristic of these transitory lakes. Get digging!




**What is the #PlanetaryConnection2k18 ?** The pluvial lakes of the west are interesting in a planetary context for two reasons. These lakes went away through slow desiccation driven by changes in local and global climate or through violent discharges, creating giant channeled scabland terrain. The giant outflow channels on Mars, and other features related to standing water, have clear terrestrial analogues in the ancient pluvial lakes of the Great Basin Region.

**Images**

The hand-sketched Lake Manly is from Blackwelder, 1933.

The map of the pluvial lakes surrounding Lake Manly is from Phillip Stoffer of the USGS.

The Lake Bonneville flood map is from Wikipedia user Fallschirmjäger, based on a map from Laura DeGrey, Myles Miller and Paul Link of Idaho State University.

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## Furnace Creek, Gower Gulch, and Anthropogenic Streambed Change

Margaret Landis

**One sentence summary:** “The deterioration of California 190 and National Park Service Route 1 provides an imposing testament to the unhappy results of a natural-scale experiment performed just three decades ago to cure what may have been a lesser evil” (Dzurisin, 1975)

### The Situation and 1940s Solution

While Death Valley is a famously arid area, periodic flooding does occur when precipitation reaches the surface. The flooding is directed around fans at the base of the mountains surrounding Death Valley.

The Furnace Creek Inn was built in 1927, as the Pacific Coast Borax Company was trying to rescue their failing railroad venture by bolstering tourism. One of their slogans was: “Would You Enjoy a Trip to Hell?...You Might Enjoy a Trip to Death Valley, Now! It has all the advantages of hell without the inconveniences” (National Park Service). These resorts brought tourists into the area, and the tourism helped Stephen Mather’s campaign to make Death Valley a National Monument and give it protected natural landmark status.

However, Furnace Creek Inn is within the flood discharge area of Furnace Creek. After major floods in 1939 and 1941, unnamed land managers built a small dam and channel into a headwater tributary of Gower Gulch, in order to redirect Furnace Creek into Gower Gulch and prevent further resort flooding (Snyder and Kammer, 2008; Figure 1).

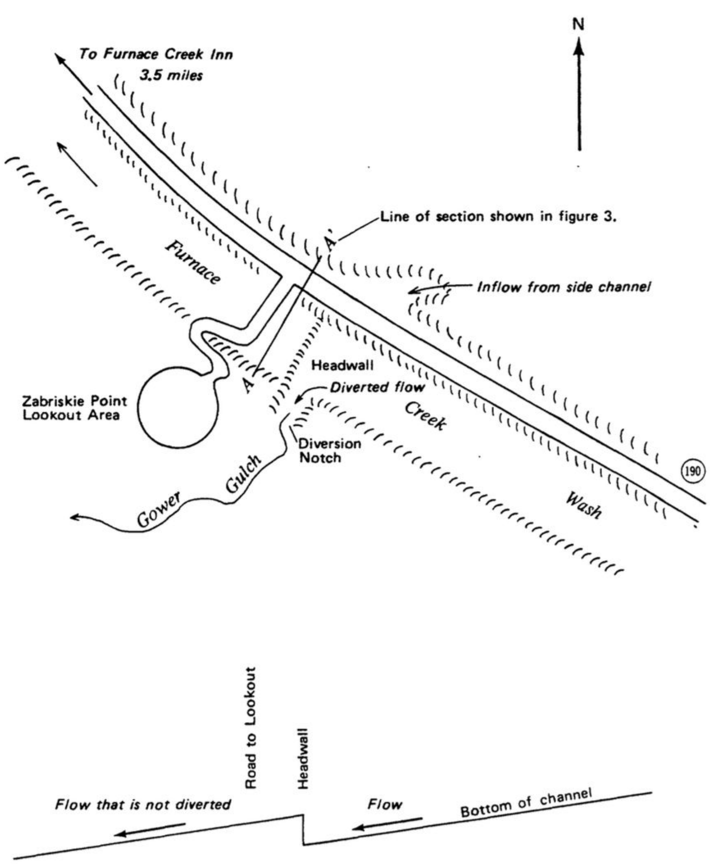



**Figure 1** A schematic drawing of the Furnace Creek Wash, Gower Gulch, and Zabriskie Point showing the road and diversion notch (reproduced from Crippen, 1979).

### Why is this a problem from a geological perspective?

*1. Increased erosion rates*

Erosion rate depends on slope, and the slopes in a drainage basin are proportional to the area of the drainage basin. The erosion rate mathematically given by the stream power equation:

$$\frac{dz}{dt} = \frac{k\rho g Q S}{W}$$

where k is a constant

reflecting the material strength of the bedrock, $\rho$ the density of the fluid, g the acceleration due to gravity, Q the water discharge rate, and S the slope of the basin, and W the width of the channel (Anderson and Anderson, 2010). The slope of the basin, assuming that there is some constant uplift (U), is given by

$$S = \left(\frac{U}{k}\right)^{1/n} A^{\left(\frac{1-m}{n}\right)}$$

where k is the same constant reflecting the material strength of the rock and other constant parameters, A the area of the drainage basin, and n and m are parameters describing whether or not the process is diffusive (m<1) or concentrative (m>1). If m=1 and n=1, then the equation is modeling creep. Usually, a drainage basin has some combination of diffusive (where the channel is incising) and concentrative (e.g. alluvial fan) areas.

This means that the erosion rate for a bedrock channel where it is erosion is occurring in a diffusive way is:

$$E \sim \frac{QA^{(1-m)/n}}{W}$$

What happens if we quadruple the drainage area? The erosion rate increases. This will change the channel fan morphology (the increased volume of sediment needs to terminate somewhere) as well as the geometry of the channel (Figure 2). How this erosion occurs plays a role in the changing geomorphology of the channel as well.

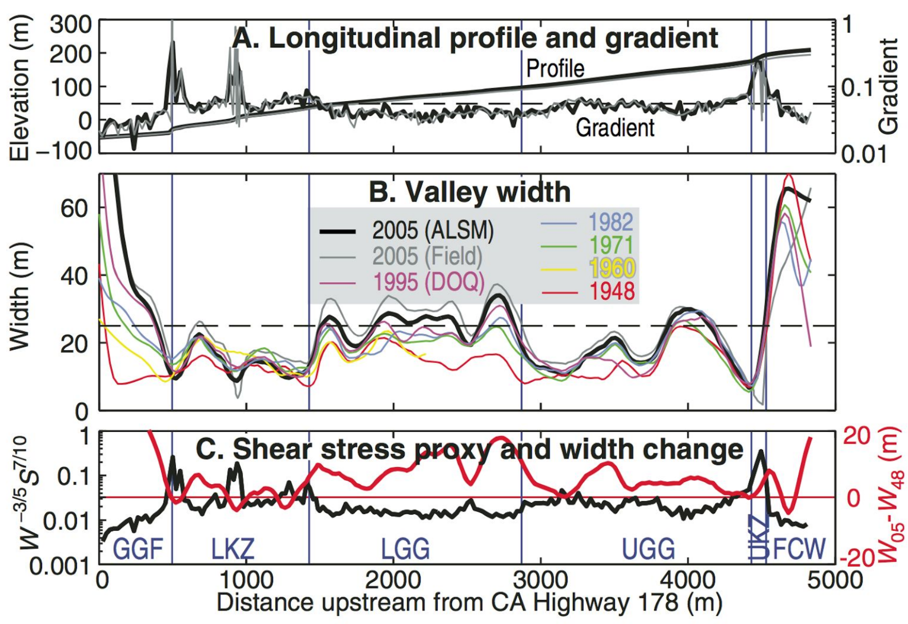



**Figure 2** Data from the Gower Gulch fan (GGF), lower knickzone (LKZ), upper and lower Gower Gulch (LGG and UGG), upper knickzone (UKZ) and Furnace Creek Wash (FCW) that shows the channel adjustment with time to the diversion of Furnace Creek into Gower Gulch (from Snyder and Kammer, 2008).

*2. Creation and migration of knickpoints*

Knickpoints are sudden jumps in the elevation of the streambed (Figure 3) that have been argued to play a large role in streambed erosion. Their initial formation depends on bedrock lithology, faulting, and uplift, and the style of knickpoint erosion depends on the bed shear stress along the knickpoint, the bed-load being transported, and the spatial variability of bedrock resistance to erosion (Figure 4). The relative contribution of overland water flow and groundwater table to knickpoint migration has been debated (Higgins, 1984). Experiments replicating knickpoint formation and migration in the lab find that once knickpoints are generated by an uplift event, they erode quickly (on the scale of 10s to 100s of hours) and the base level of the streambed is smoothed out (Gardner, 1983).

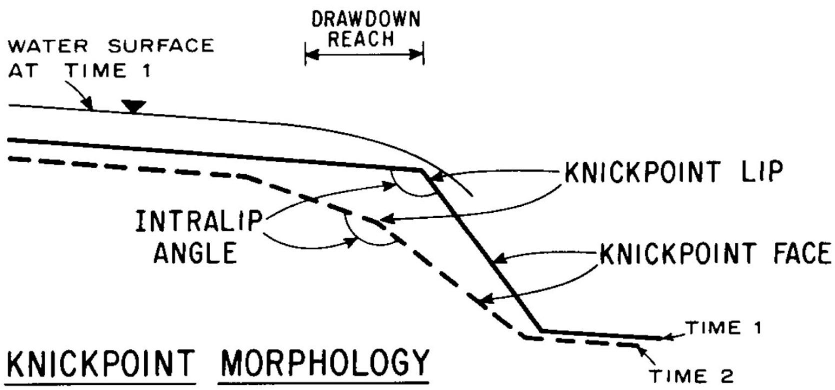
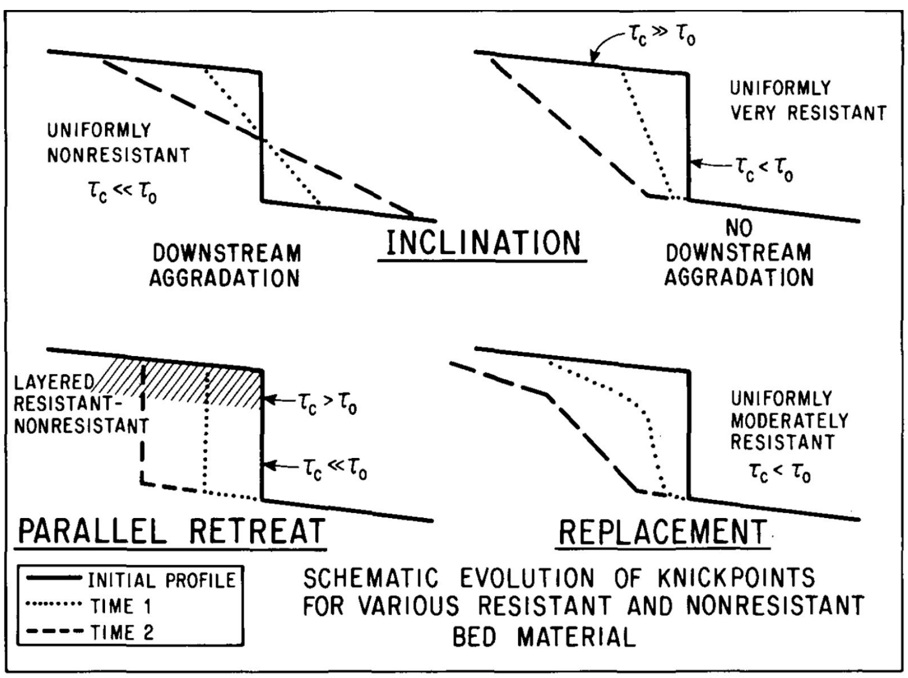



**Figure 3** The names of features within knickpoint are labeled within a cross-section (from Gardner, 1983).

**Figure 4** Knickpoint migration modes for different configurations of bed material (from Gardner, 1983).



Regardless of how knickpoint formation is initialized, erosion rates at other locations inside the channel are relatively constant except for when a knickpoint migrates headward through that part of the channel. This is because of the spike in shear stress along the channel bed caused by the jump in elevation of the knickpoint (Figure 5). This speed of migration is given by

$$\frac{e\lambda}{H} = C$$

where e is the mean lowering rate of the bedrock channel, $\lambda$ the spacing between knickpoints, H the height of the knickpoint, and C the celerity, or the speed at which the knickpoint is migrating headward in the channel (Anderson and Anderson, 2010). If the erosion rate of the channel suddenly increases with all other parameters being the same (for example, if a high discharge rate channel was re-routed through channel that formerly had a low discharge rate), the speed of knickpoint migration is going to increase.

The construction of a dam and blast point created a human-made knickpoint in a channel redirection area that triggered this process to occur, and the effects of the headward migration of this knickpoint are discussed in the next section.

**Results of the Diversion of Furnace Creek**

Many years of aerial images have allowed for detailed, decades-long study of the effects on Gower Gulch (Troxel, 1974; Dzurisin, 1975; Snyder and Kammer, 2008). On one hand, this artificial diversion allows for the detailed study of incision of a real bedrock channel (which would include effects, like groundwater, that are difficult to replicate in the lab, e.g. the debate between Gardner, 1983 and Higgins, 1984). On the other, this redirection of water has lead to cascading environmental effects.

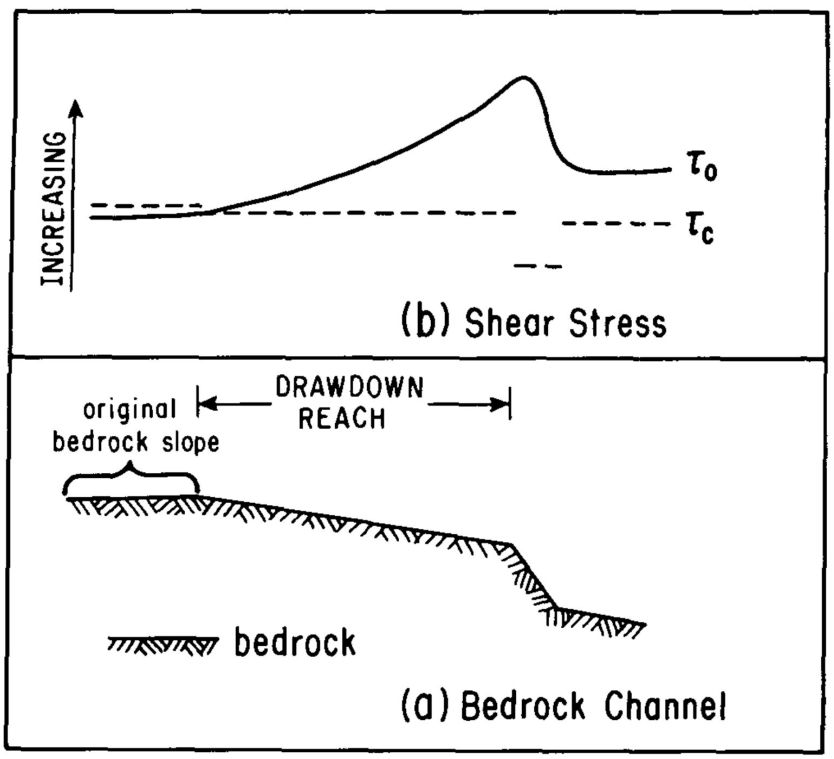



**Figure 5** Panel (a) shows the configuration of the bedrock channel and panel (b) the corresponding downstream shear stress. The shear stress peaks right before the jump in elevation at the end of the drawdown reach within the knickpoint, driving additional erosion at that point (from Gardner, 1984).

The observations of Gower Gulch span a long time and have lots of quantitative data. Troxel (1974) noted that in the decades since the diversion, the floor of Gower Gulch had been lowered by ~10 to 15 feet. Furnace Creek Wash has had headward erosion up 1.7 miles from the diversion point, which has begun to undercut State Highway 190 (Figure 1). Dzurisin (1975) estimated 10% of Furnace Creek's original erosional load has now been transported into Gower Gulch. They also noted that the stream bedload had changed from fine-grained silt to pebble- to boulder-sized material. All of this data is useful in understanding how changes in channel beds occur in planets with hydrological processes, and is a comparison point for landscape evolution models where surface flow or hydrological controls are important (e.g. Howard, 1994).

However, there are significant effects on the local environment. Most notably, the headward erosion of Furnace Creek and Gower Gulch are undercutting Route 190. Until the entire re-directed creek bed is eroded to one constant gradient, the diversion knickpoint (and any other knickpoints generated by changes in channel composition downstream) will erode headward through this area, causing periods of rapid erosion that pass right under the road. National Park Service Route 1/California State Route 178/Badwater Road passes across part of the Gower Gulch fan, and Dzurisin (1975) noted that a small cloudburst had cased 1m of debris to build up at the intersection point between road and fan.

In addition to the road degradation, there is evidence of major environmental impacts. The shorter, mostly bedrock channel of Gower Gulch and its small terminal fan means there are few opportunities for runoff to be incorporated into the Death Valley water table, which means more water will be lost to evaporation (Troxel, 1974). This already arid climate will locally become drier and more saline (even without the effects of climate change), and sapping or outflow of groundwater can initiate further knickpoint formation.

**Planetary Connection**

Terrestrial environmental disasters/mishaps/great-ideas-gone-wrong are a reminder that even on a planet with abundant resources and habitable environments, it's still hard to get geoengineering right and there are lots of unexpected consequences.

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# Mudflows: Not the one that swept through Oprah's house

Hamish Hay

### 1. *THE MUDFLOW THAT SWEPT THROUGH OPRAH'S HOUSE*

The mudflow that swept through Oprah's house, with Oprah (5' 7") for scale. The property suffered only minor damage.

### 2. *WHAT IS A MUDFLOW?*

A mudflow is a type of mass wasting/debris flow event where partially or fully fluidized sediment rapidly moves under the action of gravity [1].

- Typical speed of 1 to 25 $m\ s^{-1}$
- Contain loose soils and significant clay materials
- Can pick up debris such as large boulders and biological material
- Looks like a "muddy" fluid
- Can travel distances up to 100 km
- Lobate appearance and well defined edges
- Usually behaves like a Bingham plastic

The presence of clay makes them significantly more fluid than most debris flows.
A mudflow that is a consequence of volcanic activity is called a Lahar, and contains significant amounts of fine-grained ash deposits.

### 3. *WHAT CAUSES MUDFLOWS?*

The most common causes of mudflows are

- heavy precipitation,
- snowmelt,
- high ground water levels,
- lack of stabilizing vegetation.

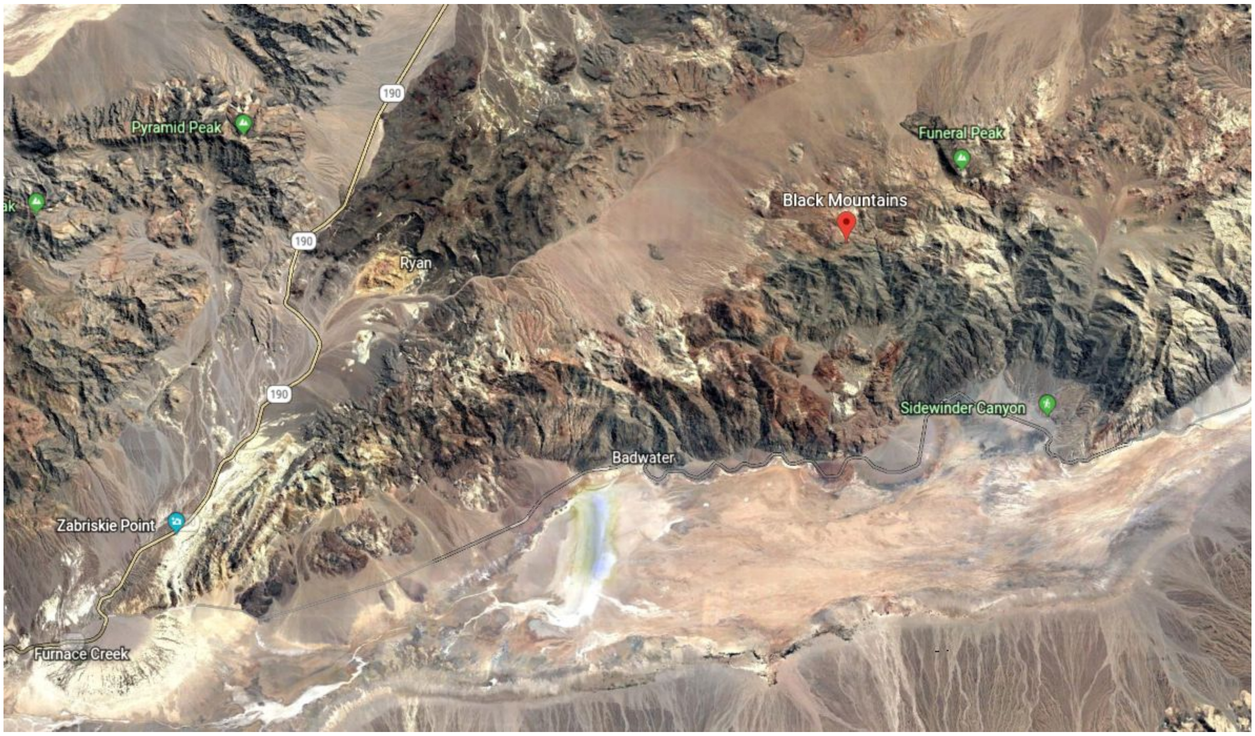
Mudflows also require slopes > 10 % to begin moving, but have been observed to spread over gentle (~1 %) slopes after initiating.

The initial movement of a mudflow begins with water lubricating the area between the base of the soil deposit and bedrock. At this point, the sediment may already be saturated and readily flow. Alternatively, the sediment will entrain water along its flow path and become increasingly fluidized. In this case, the debris flow starts as a mudslide, only becoming a mudflow after gaining sufficient water.

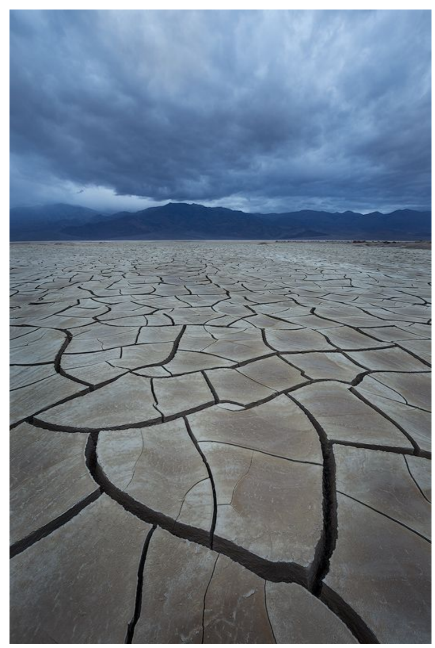
One of the most catastrophic mudflows in modern times, known as the Vargas tragedy, occurred in Venezuela in December 1999. Vargas is a coastal town surrounded by extremely steep slopes on its inland side. A combination of unusually severe rainfall and thin soils overlying the metamorphic bedrock in these slopes lead to several waves of mudflows, culminating in over 10,000 fatalities.

Above: The extent of mudflows in a small part of Vargas, Venezuela. Large boulders carried by the flows helped to cause major damage.

### *4. MUDFLOWS IN DEATH VALLEY*




Above: Black Mountain region of Death Valley. North is to the left of the image.



The Black Mountains are a NNW-SSE trending mountain range in Death Valley.

- Northern slopes composed of fine-grained sediments
- Any flooding in the area discharges as mudflows.
- Impermeable bedrock allows the mudflows to travel right up to the salt pan.
- Mudflows eventually dry producing mudflats [2]

### *5. MUDFLOWS ON MARS?*

[3] interpret “platy” ground textures in Kasei Valles on Mars as deposits from waning mudflows (see below), although the evidence is a bit tenuous.

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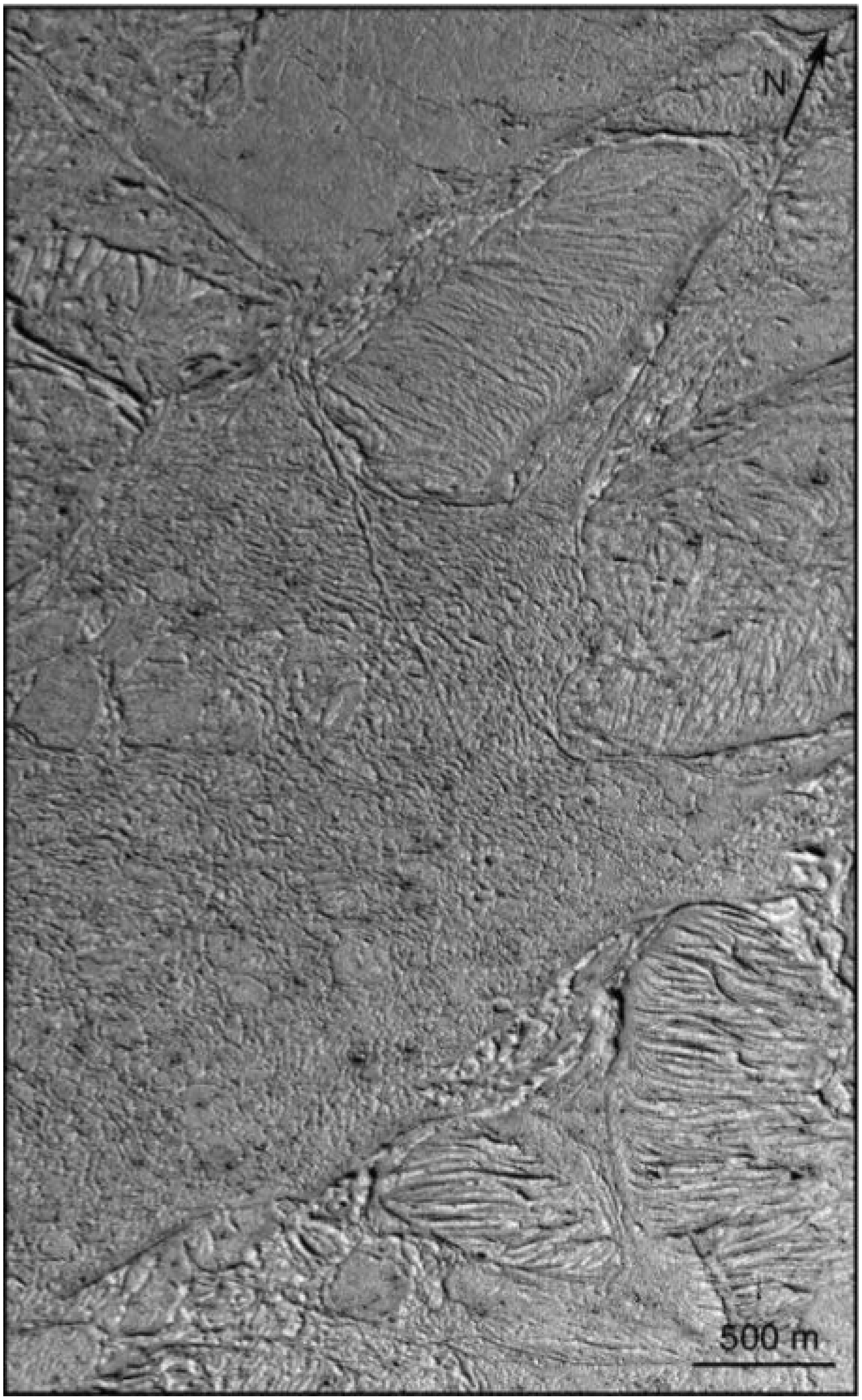



Platy textures in Kasei Valles on Mars, interpreted as mudflow deposits [3].

# *Breccia? I only just met ya!*

Amanda Stadermann

**Breccia** is a type of rock that has fragments of *angular* rock cemented together in a fine-grained matrix.

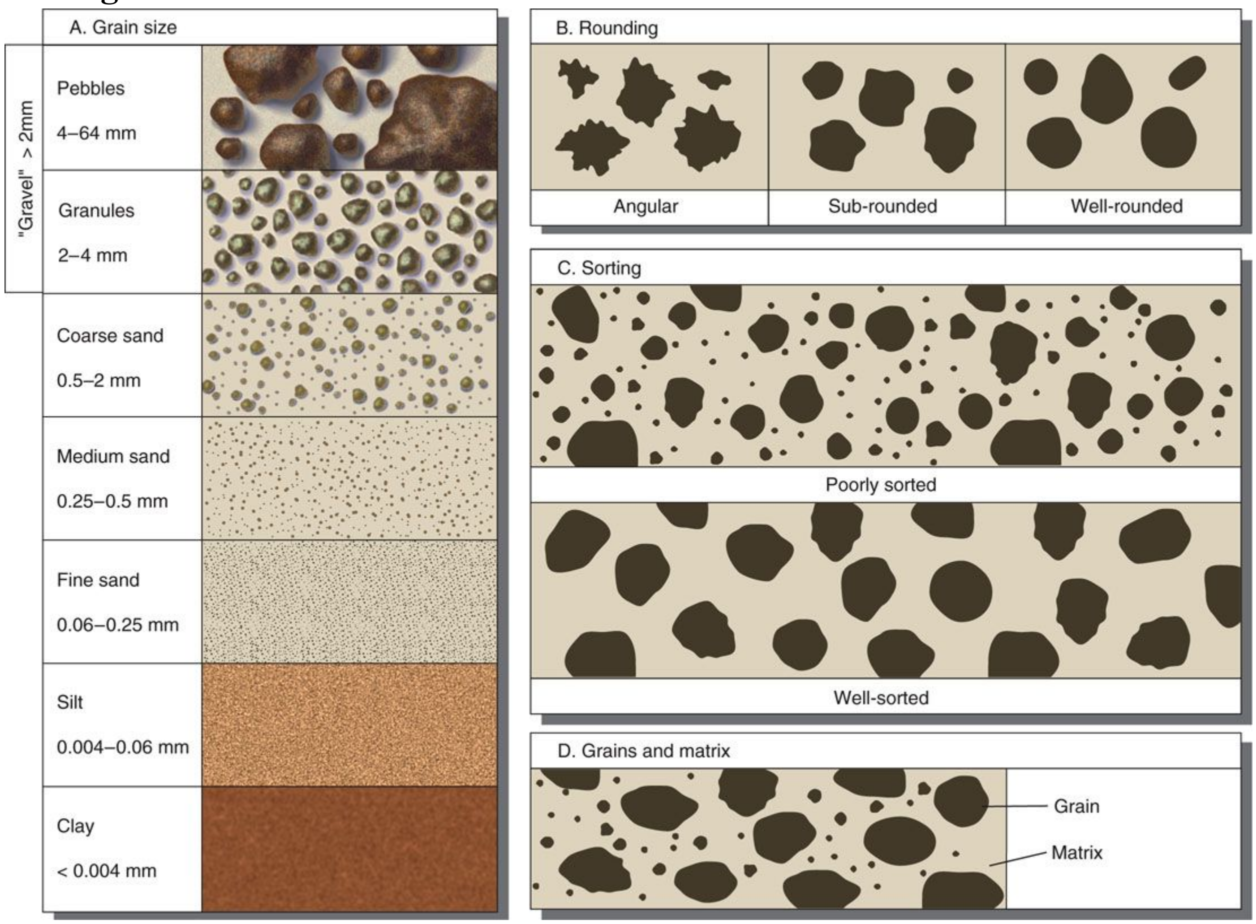
**Clast** is the fragment of rock included in the bigger rock. Can be minerals or rocks. Shapes of clasts are typically angular.
**Matrix** is the stuff, or glue, that holds the rock together.

There are several different types of breccias, of varying degree of importance to planetary science. Some of them are:

1. **Sedimentary breccia** is a rock that is composed of (usually) *angular* sedimentary clasts, held together by a very fine matrix. It is usually formed in places of *mass wasting*, where material from rocks breaks apart and falls downslope to form *talus slopes*.
    a. **Conglomerate** is NOT a breccia because the clasts are *rounded*. This indicates that the clasts have travelled far from their source.
2. **Tectonic breccia** (also **fault breccia**) is a breccia that forms at a brittle part of a fault zone (where rocks fracture, and don't flow). 30% of its clasts are larger than 2 mm.
3. **Igneous breccia** is a rock where the clasts are igneous rocks. Can form in a pyroclastic flow or lava flow. Also can be used to describe intrusive rocks that have bits of (igneous or other) rock in their otherwise igneous rock.
4. **Impact breccia** is a breccia formed in an impact event. The matrix is often glass and the clasts are usually part of the target material or impactor.

In *Death Valley National Park*, there are sedimentary breccias. In *Fall Canyon*, there is an outcrop of very large breccia, with clasts >2 m in length. The rocks may have been in a streambed, an alluvial fan, in a debris flow, or **in a cave collapse**. They are cemented together by a mineral precipitate or cement, or by much smaller rock fragments that fill the gaps between angular pieces.

**Sorting and Clast Size**:



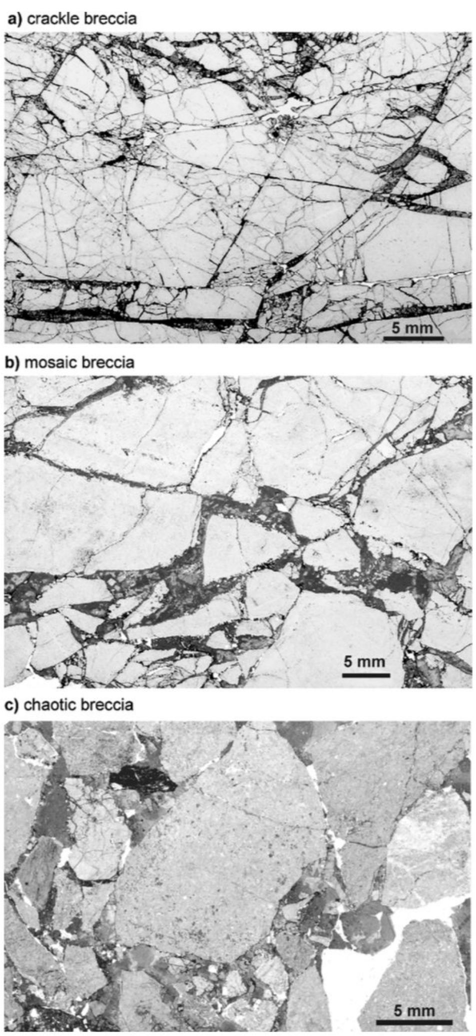

| | Clast name | Diameter Range |
|---|---|---|
| Coarse-grained | Boulder | Larger than 256 mm |
| | Cobble | 64 mm - 256 mm |
| | Pebble | 2 mm - 64 mm |
| Medium-grained | Sand | 63 µm - 2 mm |
| | coarse | 500 µm - 2 mm |
| | medium | 250 µm - 500 µm |
| | fine | 63 µm - 250 µm |
| Fine-grained | Silt | 2 µm - 63 µm |
| | Clay | Smaller than 2 µm |

**Images of breccia!**

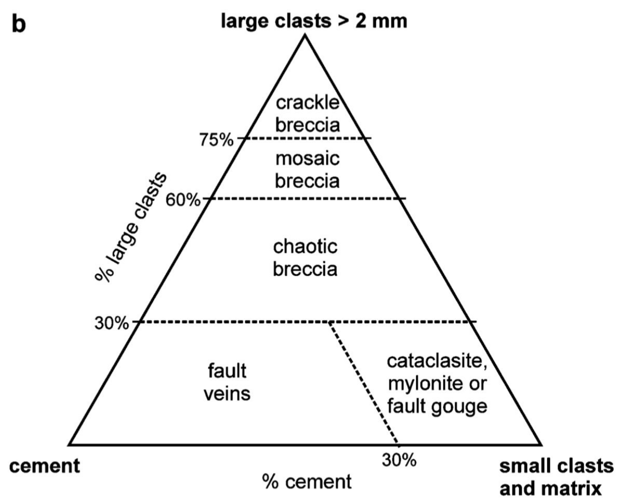
Lunar impact breccia


Sedimentary Breccia

Fault Breccias




Fault breccia classification

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# Phreatomagmatic Eruptions: The Steampunk of Volcanism

Ali Bramson

<u>Let's break it down:</u>

Phreatic: relating to underground water – a phreatic eruption is driven by steam and does not directly involve any new magmatic material erupting. Heated groundwater drives explosions and eruptions may contain/granulate older, pre-existing rock. Phreatic eruptions can occur when groundwater or snow melt seeps into a volcanic edifice and heats up enough to be flashed into steam. This typically happens when a new intrusion of magma comes up into the upper part of the volcano.

Magmatic: molten rock from under the crust – a magmatic eruption is driven only by the gases originally in the magma, and fresh magma is erupted.

Phreatomagmatic: volcanic activity involving *both fresh magma and external water* (e.g. groundwater, lake water, sea water, etc) causing an eruption of magmatic gases and steam from groundwater.

**Phreatic Eruptions:**

Process: hot temperatures of the magma cause ground or surface water to be superheated, leading to near-instantaneous evaporation of the water into steam. (Again, these eruptions involve no release of magma.)

Example: This happened at Mount St. Helens before its 1989 volcanic eruptions. Hundreds of these eruptions occurred as magma rose and boiled groundwater, causing these explosive eruptions of steam (right). A less geothermally-intense version of a phreatic eruption can cause mud volcanoes.

**Magmatic Eruptions:**

Process: *Decompression* of gas within the magma (e.g. thermal expansion of the magma). Magma ascends through the crust in the first place because of the internal gas pressure (magma contains a lot of dissolved gases). When the vapor pressure in the magma becomes greater that the confining pressure of the surroundings, the dissolved gases expand and create vesicles within the magma. These gas bubbles reduce its density so it ascends towards the surface (like your soda 'erupts' when you decompress it by opening it- shaking it before mixes more of the gas into the soda so it erupts more).

The nature of a magmatic eruption depends on gas content (depends on the material that melted to form the magma) and viscosity (which is often a function of silica content). More gas means more violent eruptions. and higher viscosity means the gas bubbles have a harder time escaping and so they push more material up and lead to more violent eruptions.

Examples: Most of the stereotypical volcanic eruptions, with the standard eruption types you might have learned already:

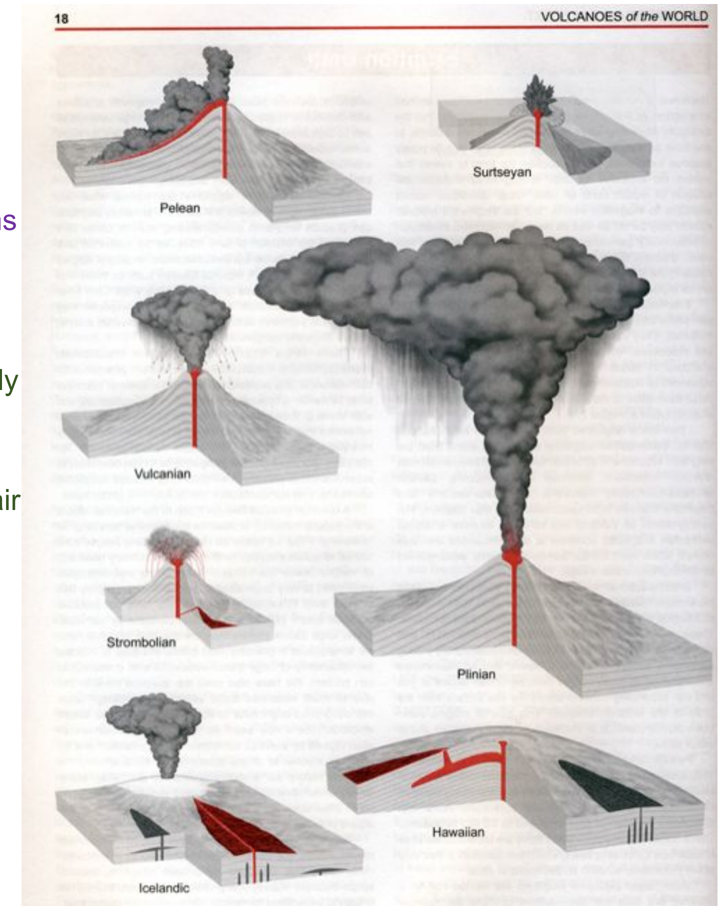


**Figure 7.** Types of eruptions. The great range in explosivity depends upon many factors, particularly the magma's gas content and viscosity. Artist John Norton.

· Icelandic: effusive, basaltic lava flows from long, parallel fissures
· Hawaiian: effusive lava flows and fire fountains that generally come from a volcano's center and radial fissures; forms shield volcanoes and involves minimal pyroclastic materials
*~~~low viscosity; low gas content~~~*
· Strombolian: many moderate-sized, fairly frequent, bursts of lava and ashy tephra; usually no lava flows; fairly high viscosity but material only gets launched into the air ~100 feet
· Vulcanian: many moderate sized explosions made of mostly ashy, pyroclastic materials; usually no lava flows; eruptive column generally bigger than Strombolian
*~~~moderate to high viscosity, high gas content~~~*
· Pelean: explosive eruptions of pyroclastic flows (dense slurries of destructive and fast-moving hot volcanic fragments and gas)
· Plinian: by far the most dangerous and deadly (e.g., Pompeii), can erupt pyroclastic material 30 miles into the stratosphere at 100s ft/sec that can cover a huge area (and often is affected by direction of the wind); can also produce very fast lava and pyroclastic flows
*~~~highest viscosity and gas content~~~*

**Phreatomagmatic Eruptions:**
Process: *Compression* of gas (e.g. thermal contraction of the magma upon contact with cooler water) within the magma – opposite of the process powering magmatic eruptions. These eruptions involve interactions between magma and water, which often explosively generates steam and pyroclastic materials. The ash that is produced in these eruptions is generally much finer than eruptions not involving water.

Example: The 2010 Eyjafjallajökull eruption started as a phreatomagmatic eruption when the magma came in contact with the melting ice cap overlying the volcano.

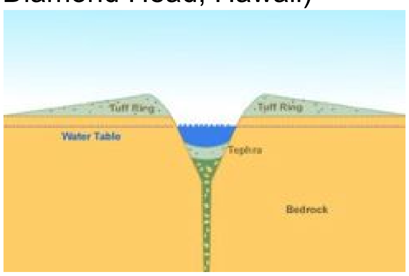
Types of phreatomagmatic eruptions:

1. Surtseyan (hydrovolcanic): eruptions caused by shallow water interactions between water and lava. These are the wet version of Strombolian eruptions but much more explosive due to the temperature difference between water and lava.

These often form:

· Maars: broad, low-relief volcanic craters in the ground formed from the explosions excavating a hole in the subsurface surrounding rock (substrate), thus exposing older rocks in the inner walls (example: 1 km-diameter maar in Saudi Arabia)

· Tuff rings/cones: circular structures from rapidly quenched lava that form on the substrate (example: Diamond Head, Hawaii)




· Littoral cones: small cones of fragmented material that forms when lava flows into a body of water (often seawater). These cones lack a vent which helps distinguish them.

The 1963 eruption of Surtsey off the coast of Iceland is an example of a hydrovolcanic eruption. It started as a submarine eruption but eventually it reached the surface. It gives hydrovolcanic eruptions their name: Surtseyan.

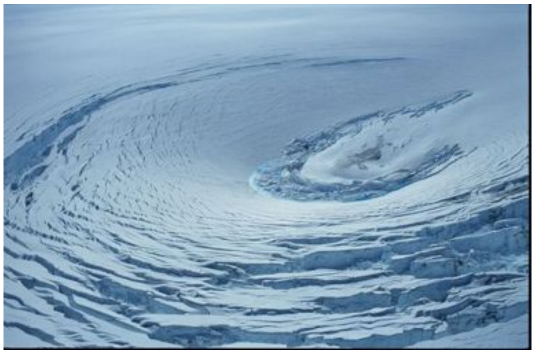
2. Submarine: eruptions that occur underwater (~75% of Earth's total volcanic eruptive volume is likely generated in submarine eruptions at the mid-ocean ridges)

· "Rooster tails"

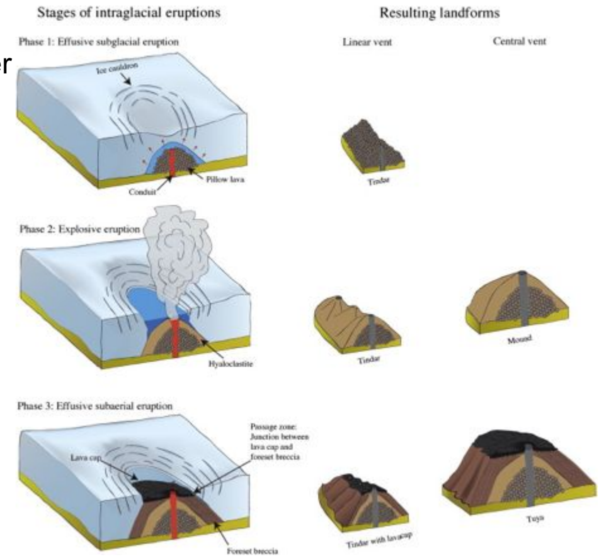
Eruption of the Hunga Tonga Hunga Ha'apai volcano in Tonga in 2009 and 2014-2015 (below left) and El Hierro in the Canary Islands in 2011 (below right two images).

3. Subglacial: eruptions in which the lava interacts with ice; often from magma eruption under a glacier

- Ice cauldrons
- Tindars
- Tuyas



Ice cauldron formation in Iceland's Vatnajökull ice cap
Photo Oddur Sigurðsson/Icelandic Meteorological Office




From Pedersen and Grosse (2014)

A tuya, subglacial volcano Hlöðufell.  Photo taken by Dr. Dave McGarvie

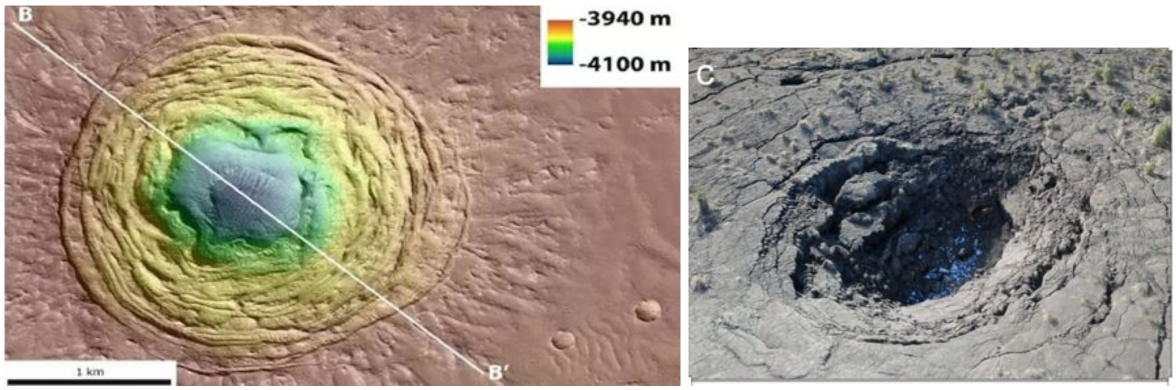
**Additional terminology:**

Hyaloclastite: basaltic glass formed by non-explosive quenching at depth under water where hydrostatic pressure prevents vesiculation

Hyalotuff: type of rock that forms from the explosive fragmentation of glass at shallow water depths. Often finer grained than magmatic counterparts.

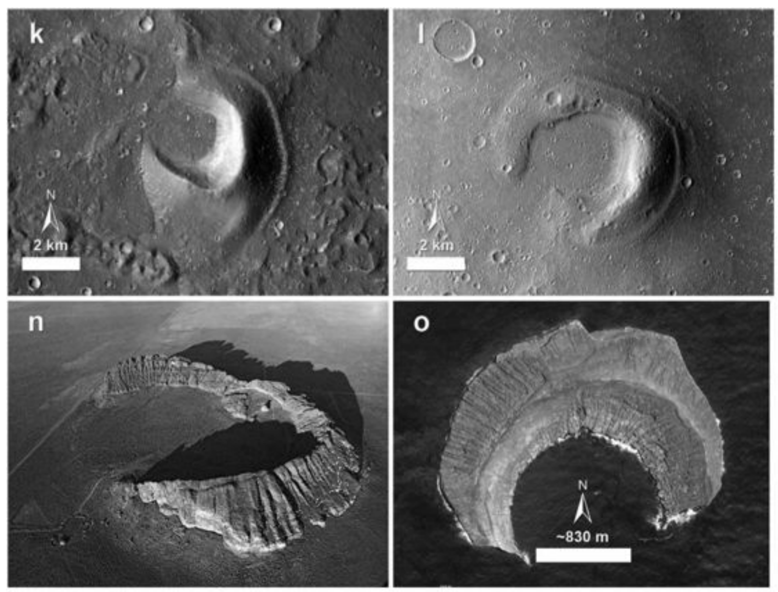

Lapilli: clast of tephra (material that falls out of the air during a volcanic eruption). Accretionary lapilli are fairly diagnostic of phreatomagmatic eruptions where moisture helps cement ash in concentric layers to form the clasts. (right: image by David Lynch)

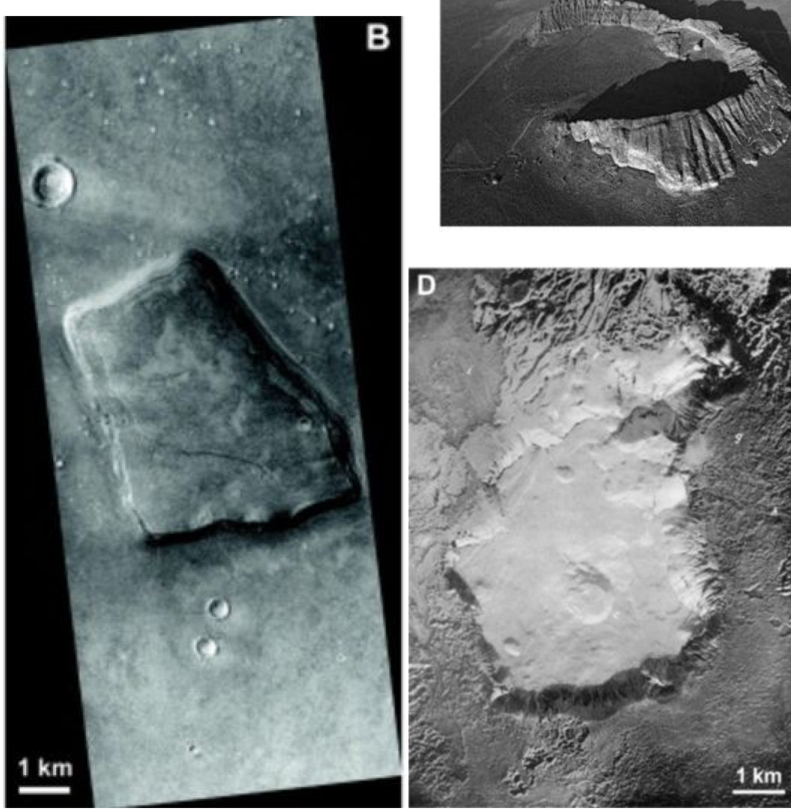
## Planetary Connections:




Levy et al. (2016) found surface features on Mars they suggest are ice cauldrons from volcanic melting of ice. However, our own Dr. Christopher Hamilton thinks they are lava-rise pits (image below from McCarty's lava flow, NM; Hamilton et al. (submitted)).

It is thought that Mars has had phreatomagmatic activity. Brož and Hauber (2013) identified many geomorphological features on Mars (top) that exhibit similarities to terrestrial tuff rings and cones (bottom).




HiRISE image of mesa in Acidalia Planitia, Mars (left) that has been proposed to be a tuya from subglacial volcanism. Comparison to mesa in Iceland on Earth (right). Martínez-Alonso et al. (2011)

**Big ugly list of reference URLs in middle school book report format:**
https://www.volcanodiscovery.com/photoglossary/phreatomagmatisk.html
https://www.wired.com/2011/11/hydrovolcanism-when-magma-and-water-mix/
https://science.howstuffworks.com/nature/natural-disasters/volcano3.htm
A textbook! Volcanoes of the World, 3rd Edition by Siebert, Simkin and Kimberly
https://www.britannica.com/science/volcano/Six-types-of-eruptions#ref388825
https://www.volcanodiscovery.com/photoglossary/phreatomagmatisk.html
https://www.gns.cri.nz/gns/Home/Learning/Science-Topics/Volcanoes/Types-of-Volcanoes-Eruptions
https://www.wired.com/2011/10/el-hierro-eruption-continues-but-not-likely-to-form-new-island/
http://blogs.discovermagazine.com/rockyplanet/2011/11/05/renewed-eruptions-at-el-hierro-in-the-canary-islands/#.WnSXeJM-dE4
https://earthandsolarsystem.wordpress.com/2013/11/06/phd-fieldwork-in-iceland-a-tale-of-fire-and-ice/
https://mic.com/articles/159647/could-mars-ice-cauldrons-signal-early-life-on-the-red-planet#.UAgng4fN2
http://epod.usra.edu/blog/2013/04/accretionary-lapilli.html
http://volcano.oregonstate.edu/hydrovolcanic-landforms
http://eos.higp.hawaii.edu/education/oldslide_set4/pwfpart4.html
http://www.geology.sdsu.edu/how_volcanoes_work/Hydrovolcanic.html
http://www.hilo.hawaii.edu/~csav/gallery/littoral.php
http://icelandreview.com/news/2014/09/29/great-volcanoes-surtsey-island
https://www.wired.com/2011/11/eruption-at-el-hierro-creeping-towards-the-surface/
http://www.roosterscafe.net/images/rooster-sm.png

Oh look, real papers from the literature!

Pedersen, G.M.B. and P. Grosse (2014), Morphometry of subaerial shield volcanoes and glaciovolcanoes from Reykjanes Peninsula; Iceland: Effects of eruption environment. Journal of Volcanology and Geothermal Research, 282.

Levy et al (2016) Candidate volcanic and impact-induced ice depressions on Mars. Icarus 285.

Brož and Hauber (2013) Hydrovolcanic tuff rings and cones as indicators for phreatomagmatic explosive eruptions on Mars. JGR Planets 118, 1656–1675.

Martínez-Alonso et al. (2011), Evidence of volcanic and glacial activity in Chryse and Acidalia Planitiae, Mars. Icarus 212, 597–621.

P.S. Here is what a rooster looks like, in case you were wondering how similar a “rooster tail” eruption looks to an actual rooster tail.

**The mystery of the sliding rocks**

Sliding rocks (known also as sailing rocks, rolling stones, moving rocks) are geological phenomena where rocks move and inscribe long tracks along a smooth valley floor without humans and animal intervention. Trails of sliding rocks have been observed and studied in various locations, including Little Bonnie Claire Playa in Nevada, and most famously at **Racetrack Playa, Death Valley National Park, California**, where the number and length of tracks are notable.

**Not a mystery!** The phenomenon is quite bazar, but the mechanism is well understood today. I report on the geological mechanism in Figure 1.

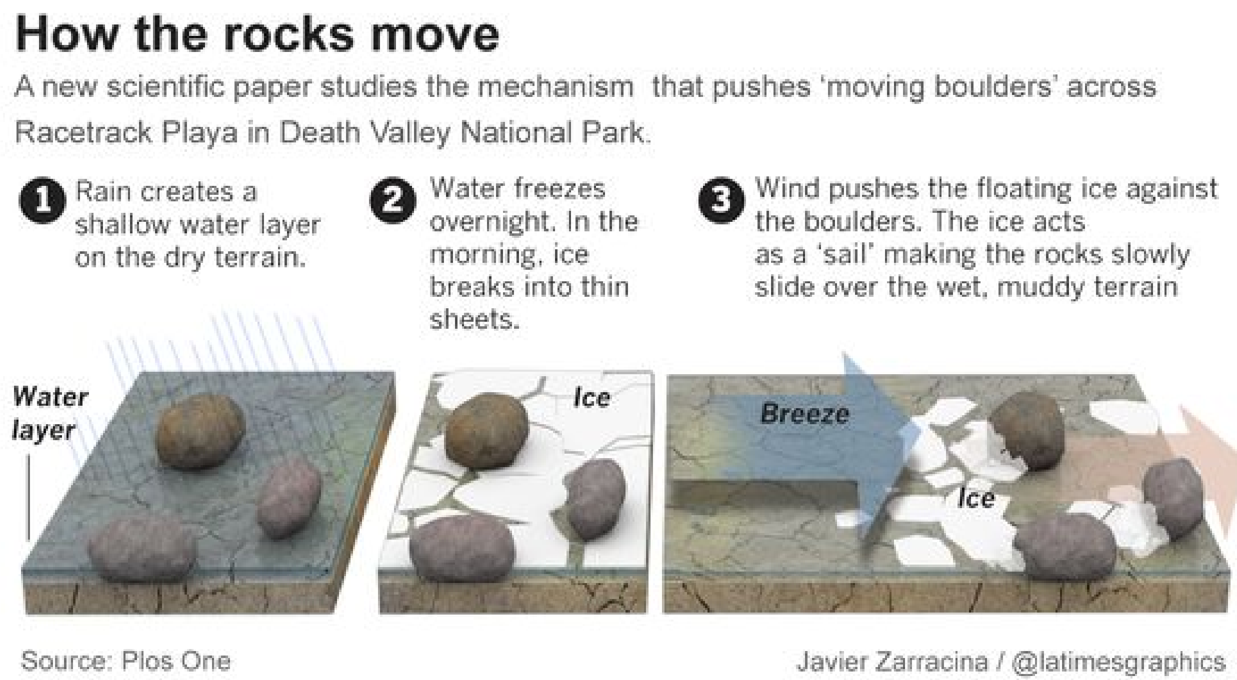



**Figure 1.** As you noticed, the playa is quite dry. When it rains, a shallow water layer is created on the dry terrain and under boulders present on the terrain (1). Overnight, temperature drops significantly during winter nights and so water freezes. The freezing usually creates ice sheets a few millimeter thick that float in the pond. The ice sheets breaks up in sunny days (2), and the wind push them against the boulders; the ice sheets act as a sail, making the rocks slowly slide over the wet, muddy terrain (3).

As a result, a **balance** of very **specific conditions** is thought to be needed for stones to move [1]: A flooded surface (1); A thin layer of clay (1); Warming temperature causing ice breakup (2); Ice floes (2); Wind up to 90 miles/h (3).

A focus on Racetrack's playa

The sliding rocks speckle the playa floor predominantly in the southern portion.

- Most of the stones are found r**elatively close to their respective originating outcrops**, but some stones around 100 m from shore have been identified.
- The **width** of the tracks ranges between 8 to 20 cm and the depth is usually less than 2.5 cm.
- The **tracks** can be striated or smooth, depending on the roughness of the stone. However, the stones sometimes turn over, exposing another edge and leaving different tracks along the same path.
- Track directions depend on the wind direction, but also on intersecting trajectories that can stop the sliding of two rocks (a sort of **car accident**).

**Three different lithologic types**:

1. **Syenite**, found most abundant on the west side of the playa;
2. **Dolomite,** surrounded blue-gray stones with white bands;
3. **Black dolomite**, almost always in angular joint blocks or slivers (most abundant type).

The source of **dolomite** has been identified as a steep promontory, 260 m high, paralleling the east shore at the south end of the playa. The rocks are 15 to 46 cm in diameter.

**Figure 2.** Sailing stones Racetrack Playa, Death Valley National Park, California, which is named after the tracks leaved by the sliding rocks. The wind pushes the floating ice sheets, which make the boulders sliding at speed up to 5m/min (corresponding to ~195 feet/hour!).

Research history

People started studying the tracks in early 1900s.

● In the mid '50s, the phenomenon achieved international coverage after of a set of photographs on Life magazine. This publication fostered different interpretations of the causes, ranging from the supernatural (aliens!!!!) to the very complex.

● The development of inexpensive time-lapse digital cameras allowed capturing of transient meteorological phenomena including dust devils and playa flooding.

● Video evidence of the rock movements have been published only in August 2014 (see article on Nature, [2]). These videos have been used to identify the causes of the tracks.

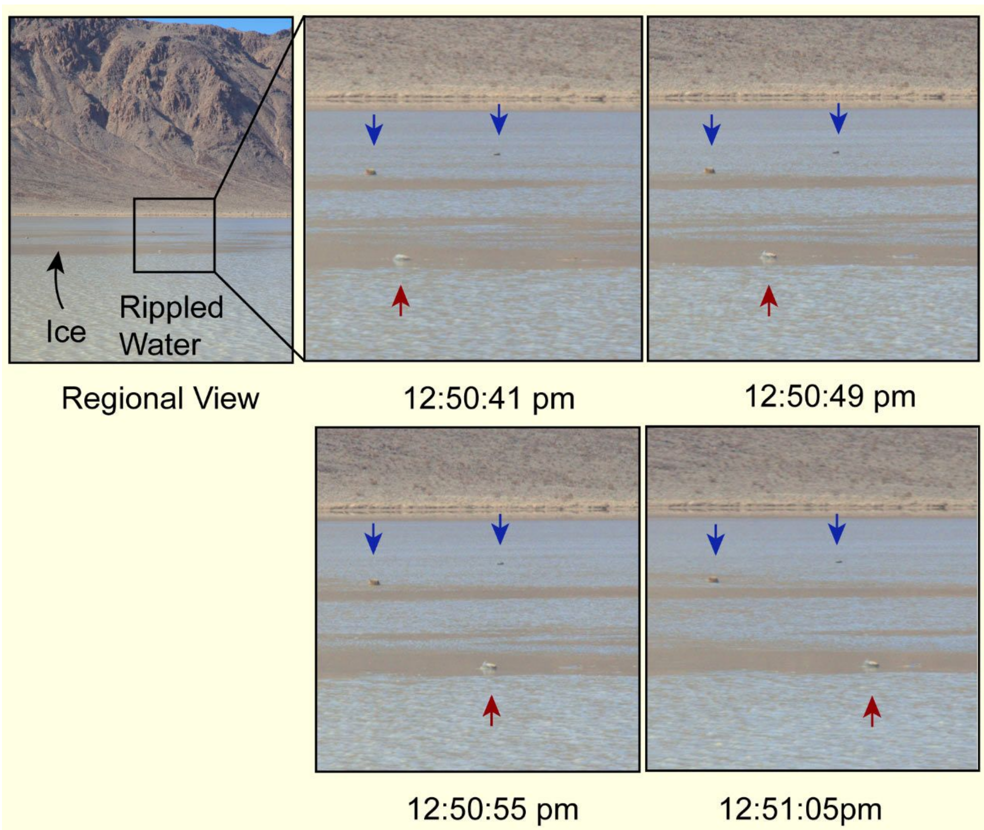



**Figure 3.** Time evolution of sliding stones in Death Valley. As you can see, they move very fast. The video frames were recorded on January 9, 2014 and the video lasts 18 seconds.

Possible influence of climate change

Rock movements relies on a very rare set of circumstances, as we saw in page 1. Such balance is endangered by climate change. A statistical study by Ralph Lorenz and Brian Jackson examining published reports of rock movements suggested an apparent decline between the 1960s -1990s and the 21st century [3].

Bonus facts

- Some researchers observed rocks movement using GPS and time-lapse photography in 2013. These measurements were useful to rule out the involvement of *thick* ice floating rocks off the surface.
- Starting in 1968, researches decided to assign the stone women's name to help track them Examples are Karem, a 700-pound stone, and Hortense, a pretty speedy girl: 820 feet in one winter.
- A 2013 Los Angeles Times report shows that Death Valley National Park officials had to investigate the theft of "several" sailing stones at Racetrack Playa. Quoting a ranger of the park: "I don't know whether people think they're 'magic rocks. But of course, as soon as you remove them from the playa, all 'magic' is lost."

Planetary connection!

The very peculiar conditions at which this phenomenon occurs are very rare to be found on other bodies in the Solar System. A possible place is Titan, whose Ontario Lacus has been found to resembled the conditions in Racetrack Playa at Death Valley National Park [4], Figure 4.

While the famous moving rocks on the Racetrack Playa may be exceptional on the Earth, the lower gravity and thicker atmosphere may render wind-induced rock transport comparatively common on Titan.

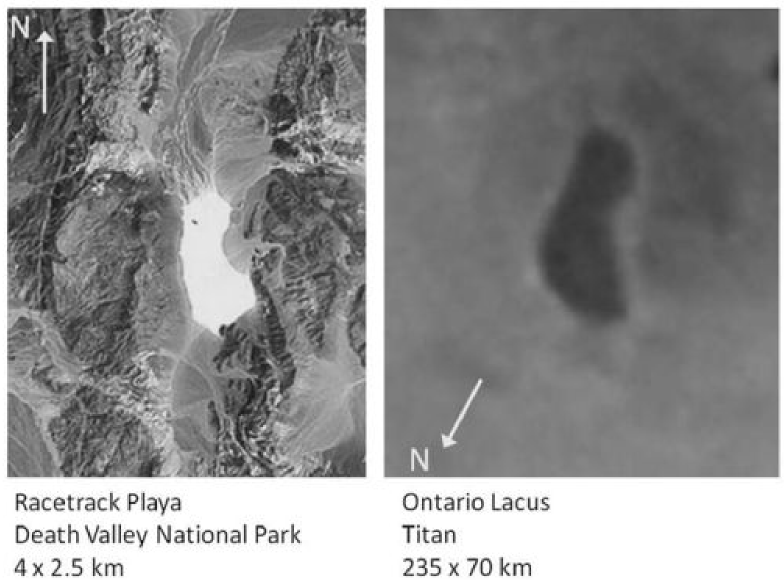



**Figure 4.** Racetrack playa (left) and Ontario Lacus (right). The pictures are not in scale: Ontario is definitely bigger than Racetrack playa.

- **Rain?** On Titan, methane can precipitate and creates ponds at the surface.
- **Clays?** On Titan, likely crustal materials are organics and ice, with a density of 1000 kg/m3 as against typical terrestrial rocks of 2700 kg/m3.
- **Ice?** Freezing due to evaporative cooling could occur in methane lakes on Titan.
- **Winds?** For a 10 cm rock, the corresponding threshold wind speeds are 51 and 5.4 m/s on Earth and Titan, respectively. It is, however, impossible to say how frequently such winds might be encountered on Titan.

Thus, Racetrack Playa is a compelling Titan analog for its shape, topography, and processes. However, since the conditions for rock transport at the Racetrack are not known, it is difficult to make a confident assessment whether analogous processes are significant or even possible on Titan.

Reference

[1] Lorenz, R. D., et al. "Trail formation by ice-shoved" sailing stones" observed at Racetrack Playa, Death Valley National Park." Earth Surface Dynamics Discussions 2 (2014): 1005-1022.

[2] 'Wandering stones' of Death Valley explained. http://www.nature.com/news/wandering-stones-of-death-valley-explained-1.15773.

[3] Lorenz, Ralph; Jackson, B. "Declining Rock Movement at Racetrack Playa, Death Valley National Park: An Indicator of Climate Change ?". Geomorphology. 211: 116–120.

# Salt Weathering: The Salient Facts

Sarah Sutton

## Background

The literature goes way back (e.g. Herodotus, 420 B.C.; Thury, 1828). Two branches of the research focus on either building degradation or erosion of natural stone.

Geomorphology terms for salt weathering include:

- tafoni (plural; tafone is singular)
- alveolar weathering (or alveoli)
- stone lattice
- fretting
- honeycomb weathering

Tafoni Canyon, Death Valley. Photo Steve Hall
http://www.panamintcity.com/saline/tafonicanyonsouth.html

Salt weathering can form pits or small caverns in rock faces. It can also break apart rock on salt flats and alluvial fans. Salt weathering occurs in arid climates (e.g. Death Valley) or coastal salt-rich environments (e.g. the California coast). It also has been noted to occur in cold, dry, and salt-rich climates such as the Dry Valleys of Antarctica.

Death Valley is a basin formed by a fault trough in the Basin and Range terrain of the American southwest. It is extremely arid, receiving about 4 cm of rain annually, in very sporadic events. Salts are sourced from an evaporated Holocene lake. During heavy rains, the salt pan floods up to 1 m deep. Dominant salts in the flats are chlorides (predominantly NaCl) and sulfates, including gypsum and thenardite ($Na_2SO_4$) (Goudie & Day, 1980).

In addition to cliff-face weathering such as tafoni, gravel and pebble-size rocks can also be degraded rapidly when they come into contact with the salt zone. This occurs in alluvial fans in Death Valley and nearby arid valleys such as Owens and Panamint. (Goudie & Day, 1980). Many of the rocks affected by salt weathering in these alluvial fans are derived from volcanic units, but also include metamorphic and sedimentary rocks.

## Process

The mechanism for weathering requires porous solid material, with supersaturated solution filling the pore spaces, where crystallization pressure breaks apart the mineral grains of the rock. Crystallization within pore space causes pressure via (possibly) three mechanism, breaking apart the surface of the rock:

1) Crystallization due to evaporation and/or cooling;

2) Hydration of salt crystals causes volume change;

3) Thermal expansion of salt crystals due to day-night temperature cycling (Cooke, 1981).

Capillary action can wick moisture through pore space near the surface of rock, causing the surface to crumble or flake off. The eroded material is then blown away by winds or washed away by rains. Moisture can also be absorbed by salts in the near-surface pores by deliquescence when the relative humidity (RH) reaches a high enough percentage. The RH required to deliquesce depends on the salt. Sulfates deliquesce at a lower RH than chlorides (Cooke, 1981). Salts can also be left behind when frost or snow sublimates, which is indicated in the Antarctic Dry Valleys (Cooke, 1981).

Salt weathering of gneiss on the floor of Death Valley. Photo Ron Wolf https://www.flickr.com/photos/rwolf/16895653650/in/photostream/

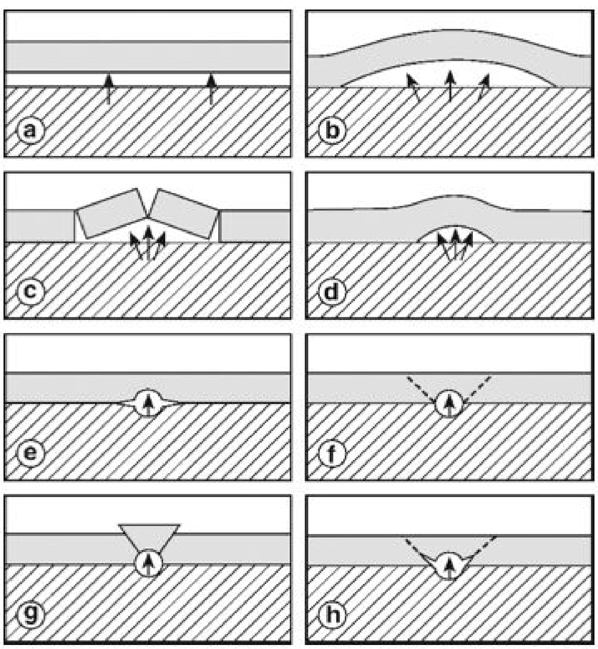



**Fig. 4.6** Patterns of salt crystallization within a porous rock: (**a**) subsurface deposition where there is a high rate of surface evaporation and salt solution drawn from within the rock; (**b**) surface deposition where the rate of evaporation is less than the potential rate of outward salt solution migration; (**c**) surface and subsurface salt deposition after evaporation of surface-wetted rock (sodium sulphate, magnesium sulphate); (**d**) surface salt deposition after evaporation of surface-wetted rock (sodium chloride)

(Smith. 2009)

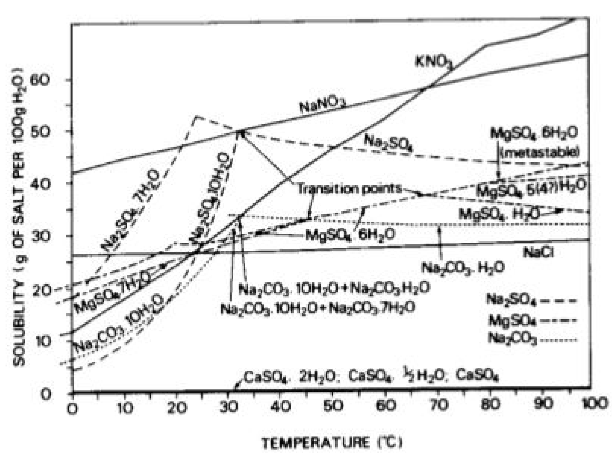



**Fig. 5. Relations between solubility and temperature for some relatively common desert salts (after Sperling and Cooke, 1980a, from various sources).**

The rate of erosion in tafoni is thought to be non-linear. After salt weathering starts, the rate of erosion accelerates due to positive feedback of salt accumulation, and then slows again as the tafone deepens, inhibiting further salt accumulation (Doehne, 2002).

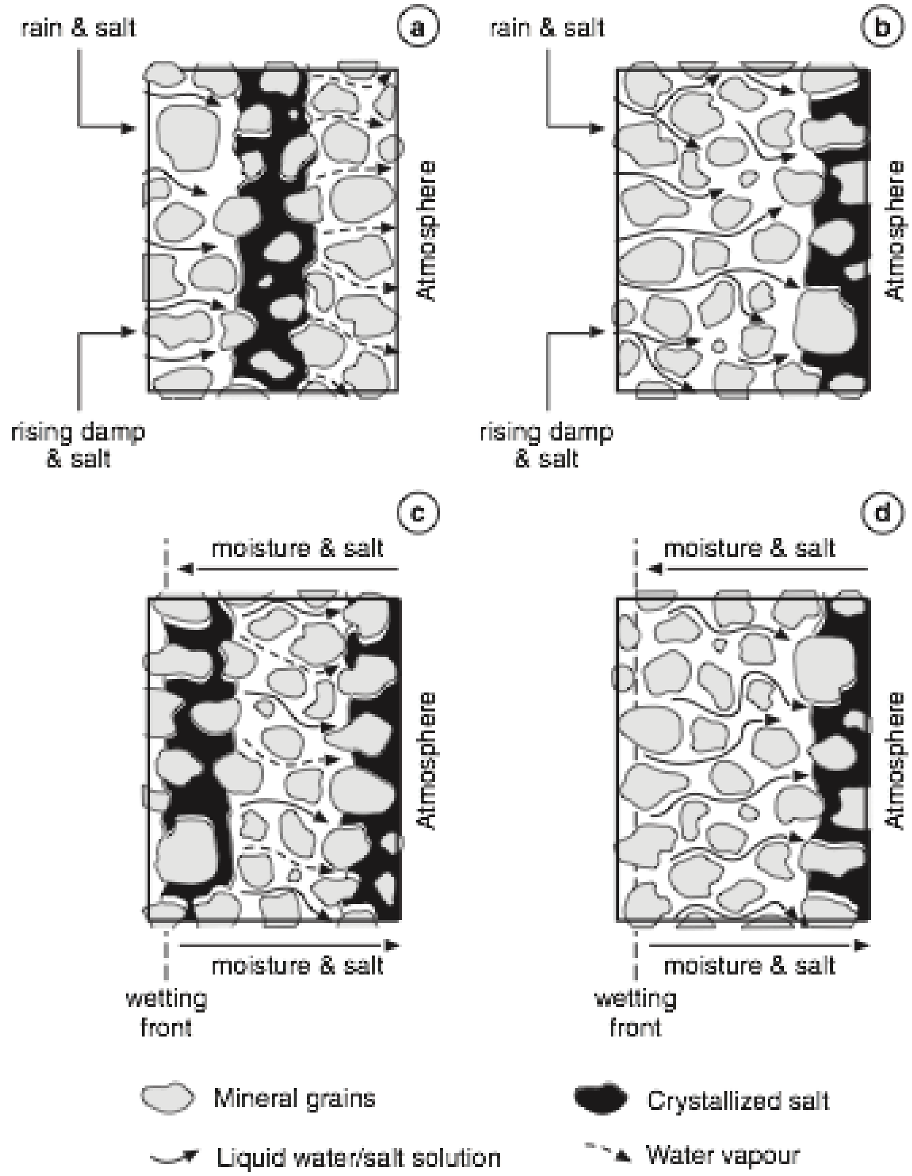
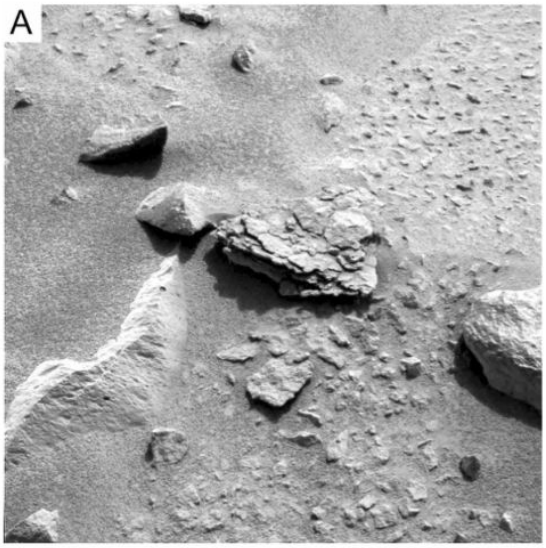



**Fig. 4.5** Influences of pore and capillary characteristics upon moisture deposition and condensation at a rock–air interface. $r_p$ = pore radius, $r_m$ = radius of meniscus of liquid water (which increases with relative humidity such that $r_m = \infty$ at RH = 100%), $r_c$ = capillary radius. (**a**) Hemispherical cavity facing large pore or external environment; (**b**) spheric cavity open to the environment through a small hole; (**c**) pore connected to environment by wide capillary ($r_c > r_p/2$); (**d**) pore connected to environment by narrow capillary ($r_c < r_p/2$) (adapted from Camuffo 1984)

Smith (2009)




Rock flakes separating from the surface in an image from Gusev Crater. (Thomas et al., 2005)

## Applications to Mars

It is thought, based on morphologic observations of martian terrain, as well as the arid climate, that salt weathering might be a viable erosional process on Mars (e.g. Malin, 1974; Moore & Bullock, 1999; Thomas et al., 2005). Mars is especially abundant in sulfates, which are more effective at erosion than chlorides via the processes discussed above. The source of water (RH or ground water) would be a critical factor in the martian erosional process under the present climate, although it is known that seasonal frosts are common. The theoretical existence of martian brines could be a source of salt deposits at or near the surface.

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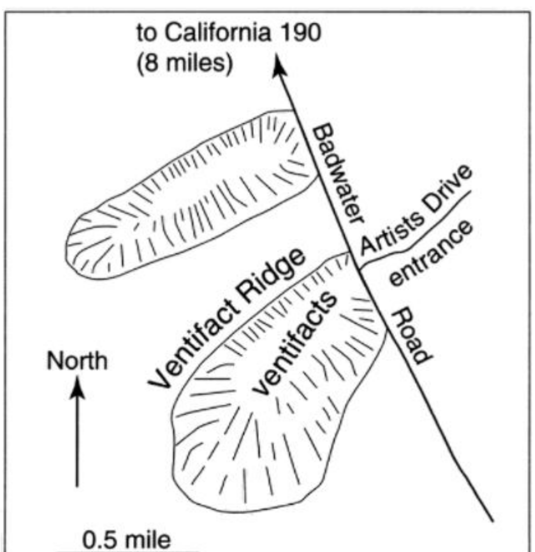
# Ventifacts, not alternative facts - Alessondra Springmann

Ventifacts are rocks eroded by aeolian processes, not water. Death Valley has some fabulous ventifact specimens! Fun fact: ventifact means “wind made”. Don’t collect rocks here or elsewhere in the park!

## Formation

Most erosional processes we’re familiar with on Earth are caused by water[1]. However, Death Valley has a dearth of water, so aeolian erosion becomes important, similar to its rock sculpting effect on Mars. Additionally, the lack of vegetation allows the wind to pick up large quantities of sand and silt. Strong winds, laden with fine- to medium-grained sand, abrade either boulders or bedrock. Ventifacts in deserts occur near ancient shorelines (Pleistocene), downwind of rivers, or in corridors of regional sand transit, forming mainly during a dry middle Holocene period (8-5 Ka, Laity 1995). Windblown particles need adequate kinetic energy to abrade rock, so ventifact formation requires high winds and saltating sand particles.



Ventifact Ridge map, from Sharp & Glazner 1997

## Location

Ventifacts in Death Valley are located on the aptly named Ventifact Ridge, which extends west from the southern intersection of Artists Drive with Badwater Road. The ridge is approximately 45 m above the surrounding desert, and is made of a conglomeration of stones and sand from the mountains to the east, including lots of black basalt (Sharp & Glazner 1997). The northwest side lies along a fault and is steeper than the southeast side. Strong, fast winds from the north and south concentrate at the top of the ridge as the entire valley acts as a wind tunnel, creating ventifacts.

[1] In addition to deserts, we also see ventifacts in formerly glaciated/periglacial areas and along the coast in California (Laity 1995).

## Ventifacts Specifics

As a result of being sandblasted by grit, polishing, grooving, and fluting result on the target rocks. The textures depend on the original rock shape, composition, and texture. Polishing requires fine-grained grit; however, the ventifacts here are mostly grooved and fluted due to regular variation in abrasive intensity resulting from movement of wind (Maxson 1940). Don't confuse existing vesicles in the basalt with grooves! Freshly exposed vesicles are circular and lack linear features. Sandblasted vesicles will be elongated, sometimes merged with adjoining vesicles. Compared ventifacts to fresh, unprocessed basalt! Can you determine the (current or past) dominant wind direction(s) from the ventifacts?

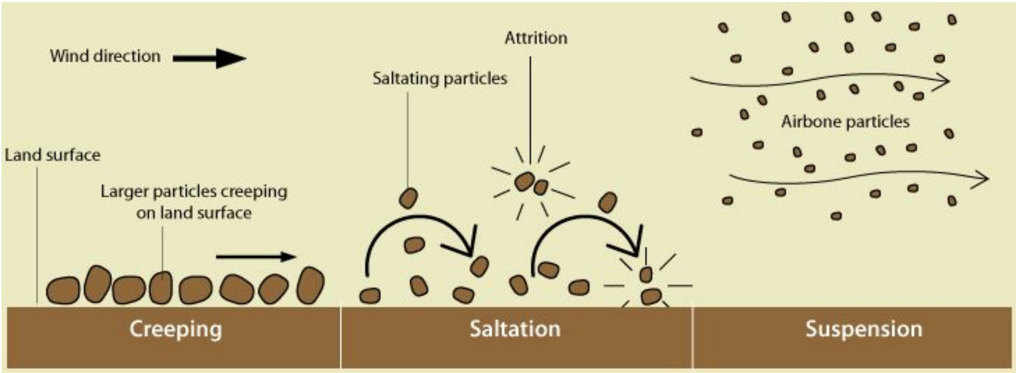
**Flutes**: ~2 cm long, deep, and U-shaped cross-section. Look like half a shallow canoe.
**Grooves**: ~>5 cm long, parallel grooves, U-shaped cross-sections, <1 cm wide and deep. Larger than flutes, closed at upwind end.
***Kanter***: when facets intersect and form a sharp edge.
**Luster**: can be shiny or dull (like sea glass).
**Pits**: Larger, more irregular, and deeper than basalt vesicles.

## Saltation of Sand Grains/Aeolian Processes

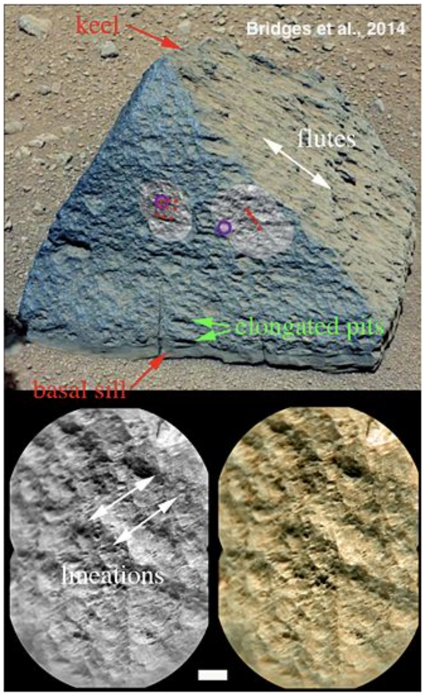
We need to know how sand moves due to saltation, and then how it impacts rock surfaces.  Our buddy Bagnold (1941) modeled these processes over 75 years ago and came up with an equation to describe mass transport of sand, *q*.

$$q = C\,\frac{\rho}{g}\sqrt{\frac{d}{D}}u^3$$

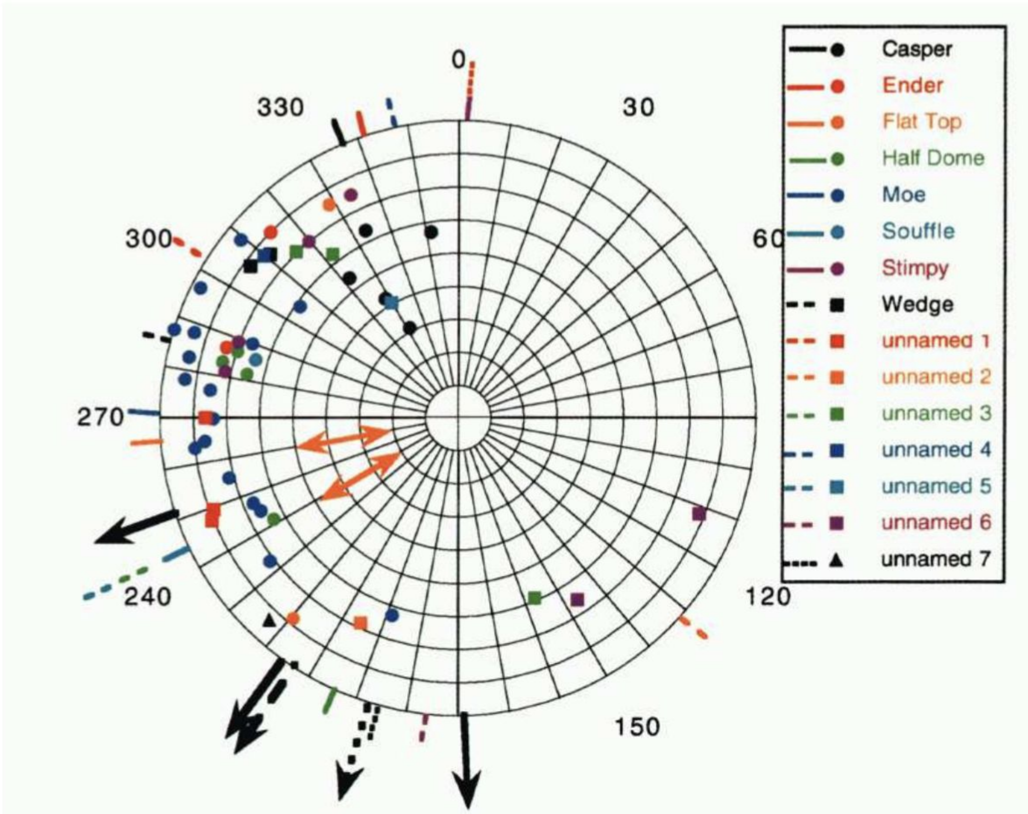
*C* is a dimensionless unit, *ρ* is air density, *g* is the local acceleration due to gravity, *d* is the grain size, *D* is the grain size Bagnold used in his experiments (~250 μm), and *μ* is the friction velocity (∝√ shear stress between the wind and sheet of moving sand).



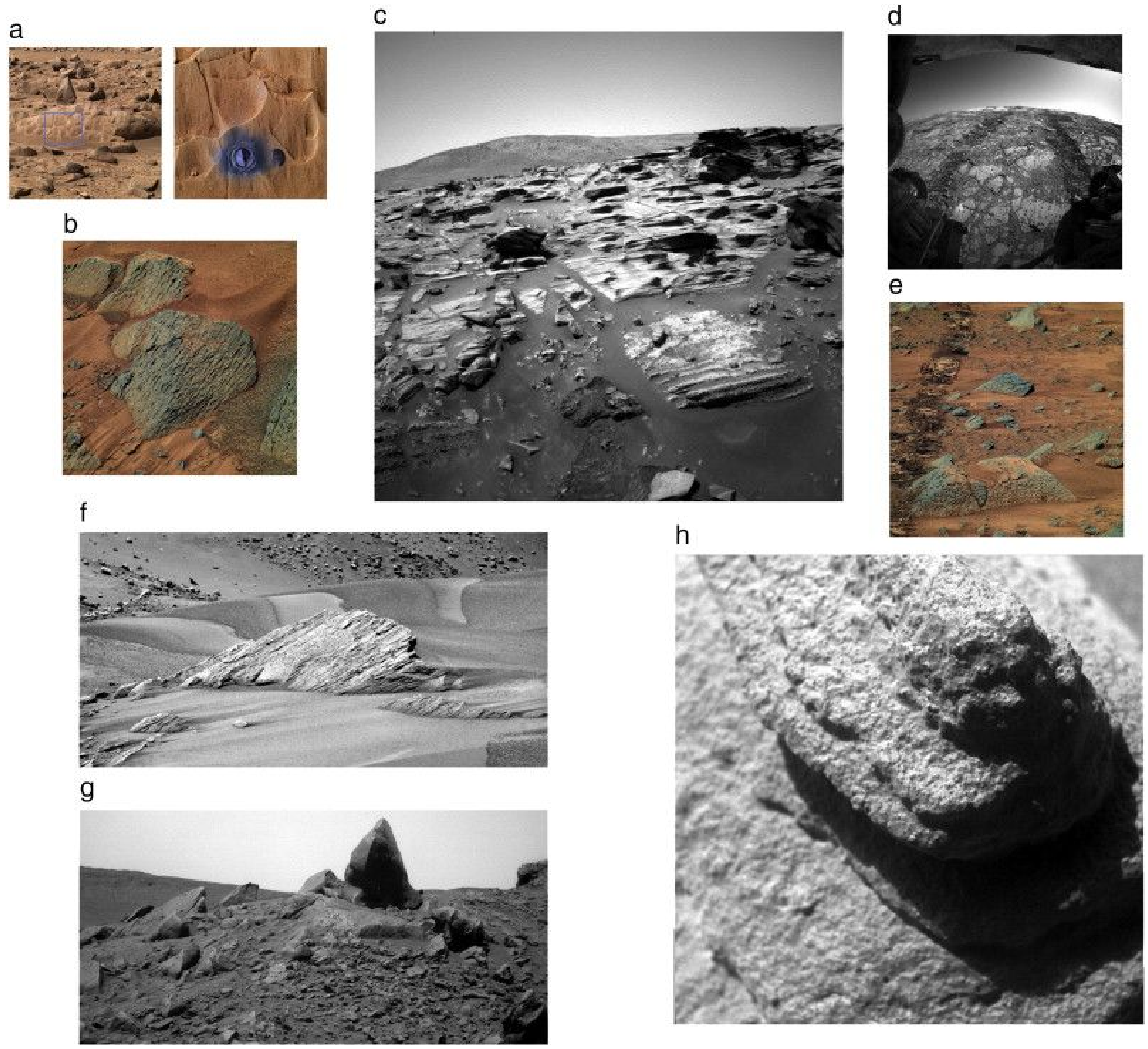

## Ventifacts on Mars




Rocks interpreted to be ventifacts are seen on Mars, dating back to the Viking landing sites (Binder et al. 1977), as well as by the Pathfinder, Spirit, Opportunity, and MSL rovers. The lower atmospheric density on Mars requires higher friction speeds and wind velocities than on Earth to form ventifacts.  Understanding Martian ventifact formation is complicated by the variable correlation between the drag coefficient and Reynold's number (*Re*) for sand grains at Mars atmosphere dynamic viscosities; thus, there is some uncertainty in the ratio of drag to gravitational forces. The drag to gravity force ratio determines the degree to which vertical velocities of grains vary on Mars compared to Earth, thereby affecting predictions of particle concentration profiles within a saltation cloud, and therefore the ability of Martian winds to form ventifacts.
Gale Crater, visited by the MSL rover, has obvious ventifacts. With active sand dunes and a central mound, the morphology of which has been affected by various aeolian processes, wind has been and remains a major geologic process. The study of ventifacts in Gale therefore provides insight into the formation, erosion, and likely exhumation of this feature.




Polar projection showing trends and plunges of [ventifact] flutes at the Pathfinder landing site. The circumferential axis represents trend and the radial axis plunge. Plunges are oriented downward toward the center of the plot and increase inward. Colored symbols correspond to the rocks upon which the flutes are located. Colored lines projecting outward from the edge of the plot show the direction the rover cameras were pointed when images used to derive flute orientations were taken (e.g., for the Moe observations, the rover had a heading of 271˚). The association between the rock and rover orientation symbols is shown in the legend at right. The orange arrows represent the range of trends of groove-like features on the surface of Flat Top, as determined from IMP images projected to a bird's eye view using the Ames MarsMap virtual reality system [Stoker et al., 1997]. Solid black arrows are minimum, average, and maximum values of local wind tail directions [Greeley et al.,1997; Smith et al., 1997a]. Arrow with large dashes represents the average trend of wind streaks as seen in orbital images [Greeley et al., 1997; Smith et al., 1997a]. Arrow with small dashes is the predominant wind direction predicted by the General Circulation Model [Pollack et al., 1981; Greeley et al., 1997; Smith et al., 1997a]. (From Bridges et al., 1999)



Ventifacts and abrasion textures on Mars: (a) The fluted rock “Mazatzal” at the Spirit site (Pancam composite color). (b) Fluted rocks at the Spirit site (Pancam composite color, Sol 584). (c) Bedded rocks that have preferentially abraded along weak layers, Columbia Hills, Spirit site (Pancam, Sol 754). (d) “Tails” in the lee of resistant nodules within sulfate-rich soft rock at the Opportunity site (Hazcam, Sol 142). (e) Faceted and fluted rocks at the Spirit site (Pancam, Sol 585). (f) Faceted rocks near bedforms at the Spirit site (Pancam, Sol 620). (g) Faceted rocks at summit in Columbia Hills, Spirit site (Pancam, Sol 1344). h) Microscopic image of rock texture in vicinity of (c) (image width is 3 cm, Sol 753). (Laity & Bridges, 2009)

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Two ventifacts in the Dry Valleys of Antarctica, a climate supposedly similar to that of Mars. (Becker 2009)

## Salt polygons (see Diddy et al.) - Ben

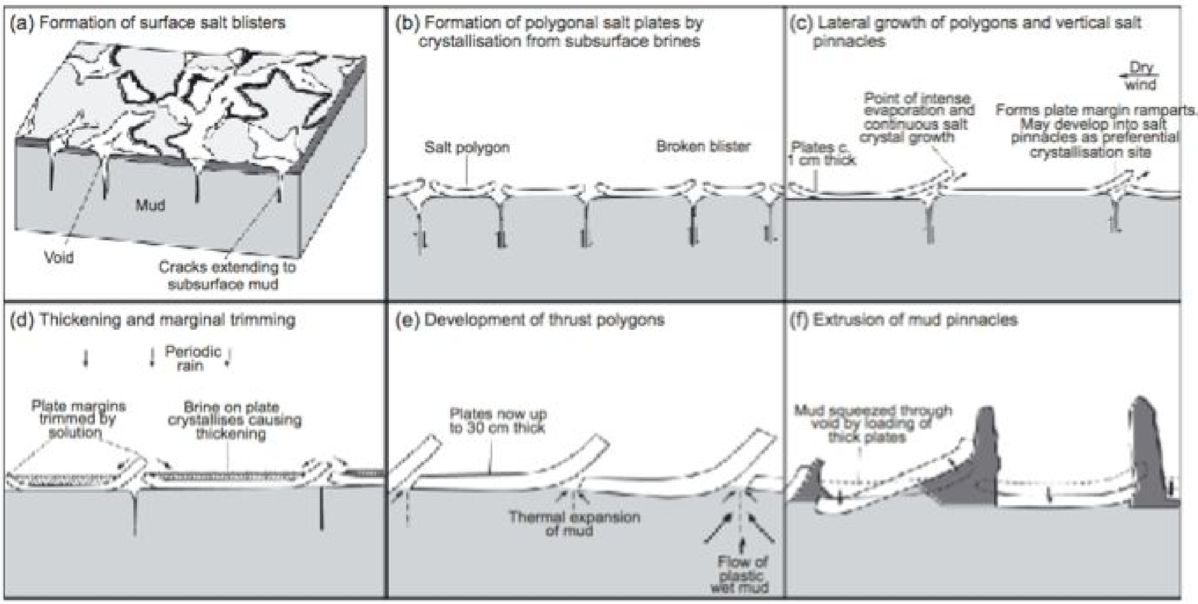


Figure 1: The formation process of salt polygon (Shaw 2011).

### 1.1 Formation Process

1a: Wedged-shaped crack formed in the mud due to repeated brine's dissolution and crystallization, similar to the repeatedly melting and freezing ice in permafrost.
1b: The water-capillary motion brings the subsurface brine from crack to the surface. Thermal contraction and desiccation cause the salt flat to break into polygon.
1c: The prevailing wind direction cause one edge has higher water evaporation rate, crystal growth, and corresponding growth of the edge.
1d: The lateral growth limit is limited by water-capillary motion and dissolution caused by inflow of water.
1e: Mud's thermal expansion push itself to the surface through the cracks, uplifting and tilting the overlying salt polygon.

### 1.2 The Shape of Cracks

The cracks develop in the ways that minimize the tensile stress that caused by thermal contraction or desiccation, similar to columnar jointing of lava flow. For a perfectly homogeneous material, hexagon-shaped ("Y-junction") crack is the most effective shape in minimizing the crack's area and the center of crack is equidistant from each other (Huang, 2015). However for mud cracks, the cracks often truncate each other orthogonally so cracks only have four sides on average ("T-junction") and mostly have rectangular shapes (N.H. Gray, 1976)

## 1.3 Size and Thickness

When water evaporates, salt flat contracts, but the bottom layer of salt flat is still adhered to the mud beneath it, generating strain on the salt flat. Assuming the strain of salt flat is independent to the thickness, (A. Groisman, 1994) 's experiment with coffee-water mixture showed that the polygon areas is linearly depend on the layer thickness. The size of salt polygon is up to 10m in diameter and 50cm above the playa floor (Paul A. Shaw, 2011) (Krinsley, 1970).
For the cracks that caused by thermal contraction, such as permafrost polygon, the size of depends on the cooling rate, non-linear stress-perturbation of single crack, and mechanical flaw distribution (Lachenbruch, 1962).

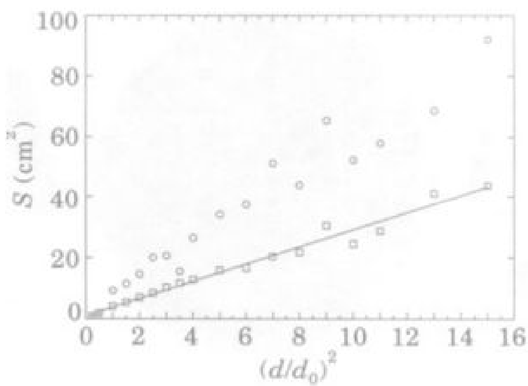


Fig. 5. – Dependence of the polygon areas on the thickness of the layer $d$. $d_0$ corresponds to the layer thickness of 4 mm, when dried out. Squares: average area of the polygons. Circles: maximal area of the polygons. The average areas designated by the squares with crosses inside were obtained for layers, where no polygonal pattern was present, by calculating the average distance between cracks along randomly chosen lines.

## 1.4 Polygon in the Solar System

Polygon-shaped features are commonly found on other planetary surfaces, but their formation process can be totally different and have different spatial scales.

On Mars, the observed polygons in South Polar Trough (SPT) are not due to desiccation or thermal contraction from lava cooling, but the large seasonal temperature gradients. The size of polygons ranges from 20m to 100m in diameter. The thickness is still unconstrained.(S. van Gasselt, 2005)

For Pluto, the convection of nitrogen ice causes the km-size polygon features in Sputnik Planum. (A. J. Trowbridge, 2016)

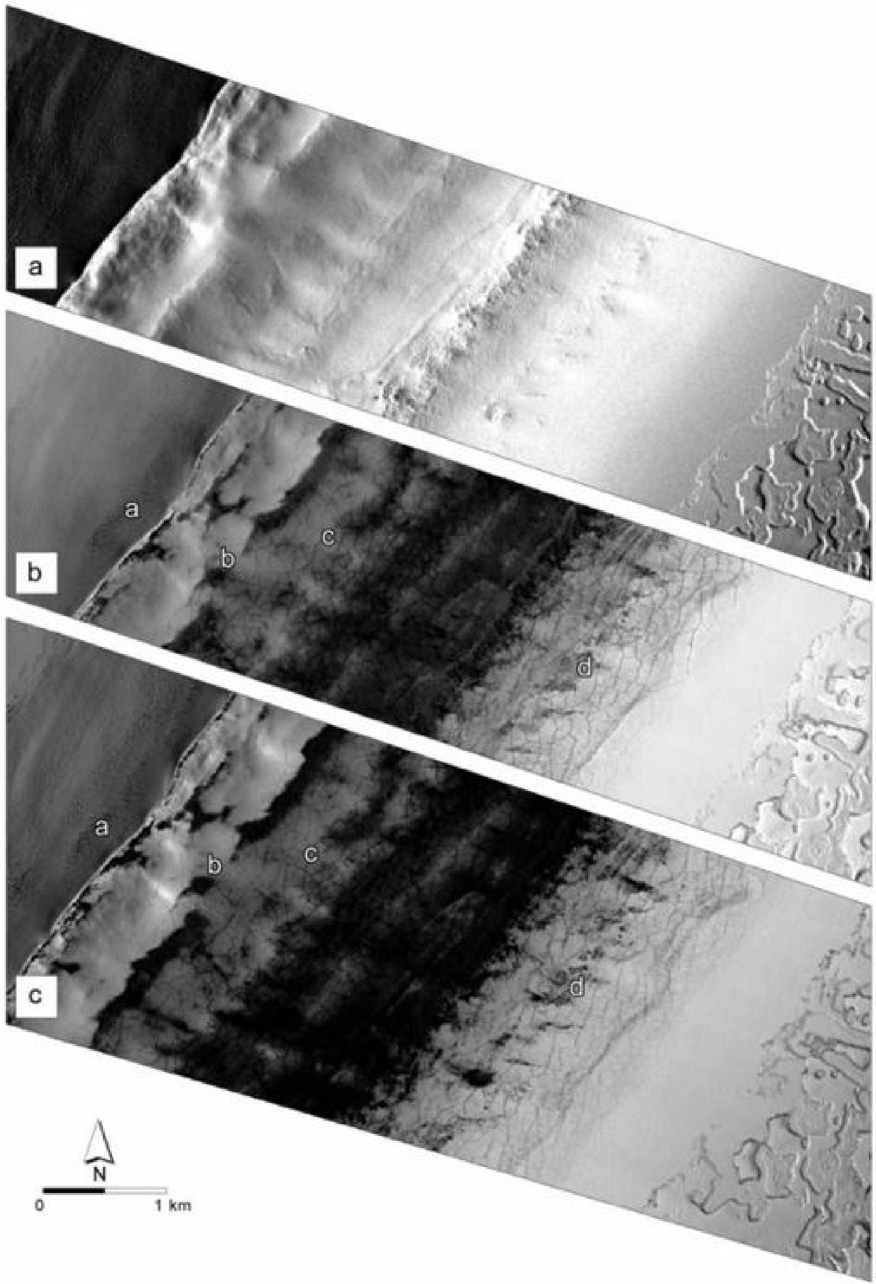


**Figure 3.** Three overlapping MOC-NA image scenes at location A crossing a south polar trough which is incised into the residual cap at 281.4°E and 87.0°S. (a) MOC-NA M07/02129 was acquired in mid-September 1999 at $L_S = 204.1°$ with a scaled pixel width of 1.38 m. (b) MOC-NA M12/00730 was taken in February 2000 at $L_S = 296.7°$ with a scaled pixel width of 1.38 m. (c) MOC-NA E11/03905 was acquired in late December 2001 at $L_S = 297.6°$ with a scaled pixel width of 1.45 m. Lowercase letters in Figures 3b and 3c refer to image scenes in Figure 11. Also note, that within the "Swiss cheese" terrain slight enlargements of intra-mesa pits can be observed in the summertime image data, as described in detail by, e.g., *Thomas et al.* [2000], *Malin et al.* [2001], and *Byrne and Ingersoll* [2003]. The images have been processed and stereographically projected with a center longitude of 281.4°E and a map scale of 1.70 m per pixel. Sun illumination comes from the west in all three images.

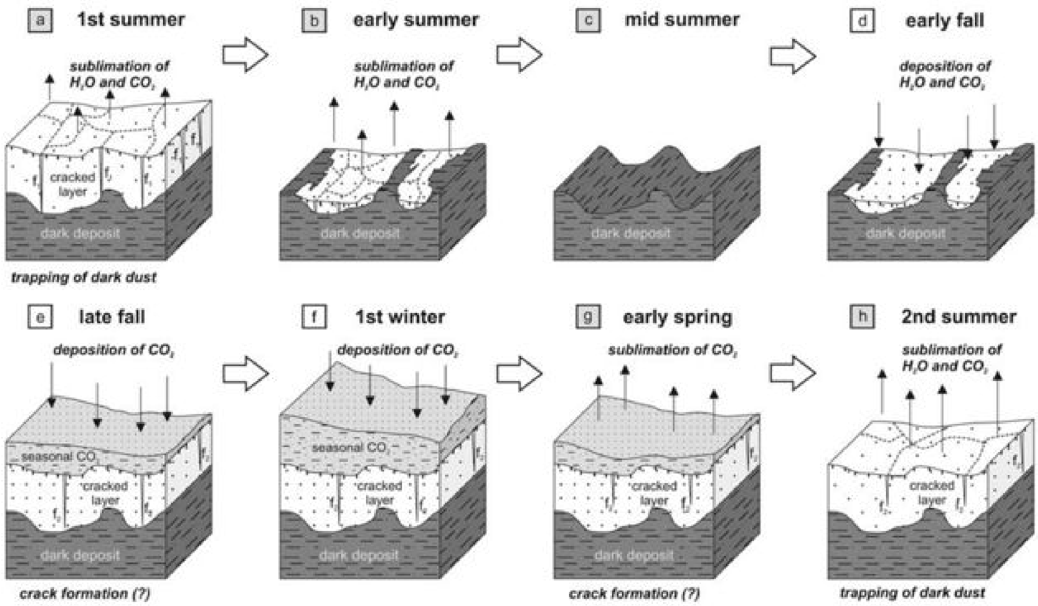


**Figure 13.** Three-layer model for seasonal changes in the SPT during one Martian year starting in summer. Top layer is seasonal $CO_2$ snow and -ice with a thickness of several centimeters [*Smith et al.*, 2001; *Aharonson et al.*, 2003]. The second layer represents a thin veneer of cracked material which might be $H_2O$ ice. The third (bottom) layer is the SPT infill of dark material. Thicknesses of individual layers are highly exaggerated for display purposes. Gray boxes with letters represent scenarios which are covered by image observations. The time and time span for formation of contraction cracks is uncertain. The letters $f_1$ and $f_2$ are first-generation and second-generation fissures, respectively. For a detailed description see main text.

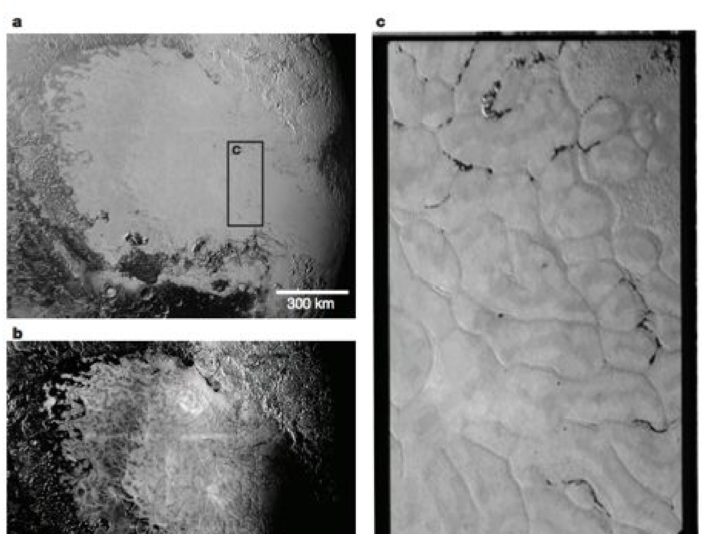


**Figure 1 | New Horizon's image of Sputnik Planum on Pluto.** A mosaic image of Sputnik Planum is shown in **a**. Within the centre of the ice field, where the ice is presumably thickest, the polygons are approximately 30 km across[1]. Close to the edge, the average polygon diameter decreases to 20 km and then vanishes, leaving a smooth surface. A contrast-enhanced version of **a** is given in **b** to better illuminate the polygons. The 'floating mountains' are observable within the edges of these polygons, and can be seen in **c**, the zoom of the rectangle in **a**. Image credit: NASA/ John Hopkins University-Applied Physics Laboratory/Southwest Research Institute (2015).

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And

Diddy et al. 2010, Coming Home, *Bad Boy/Interscope Records,* https://www.youtube.com/watch?v=k-ImCpNqbJw,

# Booming Dunes - Tad

## What are booming sand dunes?

Booming sand dunes are sand dunes that emit large-amplitude sound waves that in some cases can be heard from miles away. These dunes are common in both the Mojave National Preserve and in Death Valley National Park. There are ~40 sand dunes that can boom across the world (Hunt & Vriend 2010), and they were first noted in 800 A.D. in China (China has seven booming dunes). There are eight booming sound dunes in the United States: Kelso, Dumont (Mojave); Eureka, Panamint (Death Valley); Crescent Dunes, Sand Mountain, Big Dune (Nevada); Great Sand Dunes (Colorado).

The dominant frequency of booming sound dunes is 70 - 110 Hz. Note that the lower limit of human hearing is ~20 Hz, so these dune sounds are very low frequency compared to most sounds that we hear. The frequency of a boom can be larger, up to ~500 Hz from localized perturbations (e.g., rubbing your foot in the sand), but these higher-frequency sounds are lower-amplitude and hence harder to hear.

Natural booms are caused by sand avalanches near the crest of the dune, and can last for a few minutes. The average grain diameter of these sand avalanches is 0.26-0.38 mm, and the grains that move are well-sorted. There are two main types of "booming" sounds that can be created on a sand dune: "roar" due to short movements, "hum" when sand continuously flows down slope, with roars always preceding hums for naturally caused booms (Hunt & Vriend 2010).

## Frequency Analysis

Figure 1 shows the characteristic sound spectra of a dune while booming, from Vriend et al. (2007), Hunt & Vriend (2010). The sound builds over first few seconds of the avalanche, peaking at around ~20 seconds after the sand avalanche starts. One can see that the base frequency of this specific dune is ~90 Hz, with harmonics going all the way up to ~500 Hz. The lower frequencies (lower-n harmonics) last longer than the higher frequencies. Note that the frequencies change over time, with the dominant mode dropping to ~80 Hz from over the time interval from  20-30 seconds after the avalanche starts.

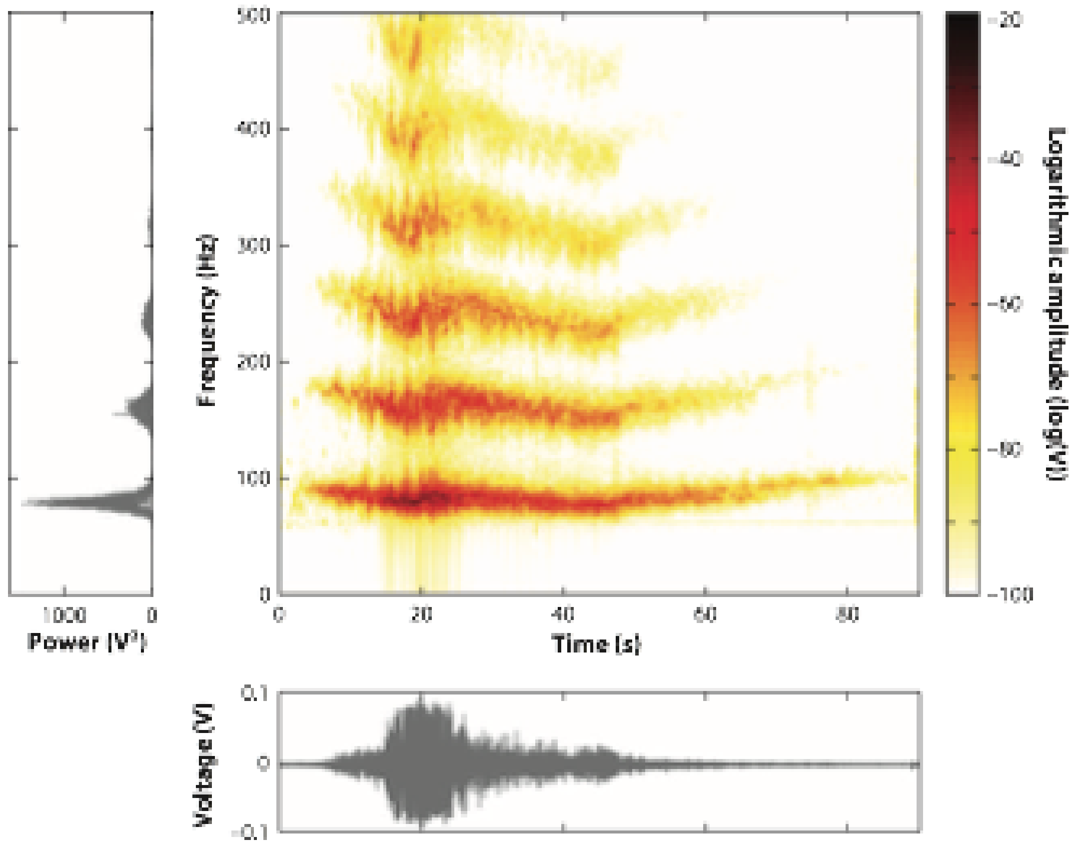


Figure 1: Microphone recording of boom at Eureka Dunes (Hunt & Vriend 2010)

As can be seen in Figures 1 and 2, booming dunes have resonances created by some natural resonator. The leading hypothesis for this resonator is the stationary sand beneath the moving sand that creates the boom acting as a “sounding board” (Hunt & Vriend 2010). This has led to the waveguide model for booming dunes, in which waves are trapped between the surface and a fixed layer of compressed sand. For more on this waveguide model, see the section below on wave propagation in booming dunes.

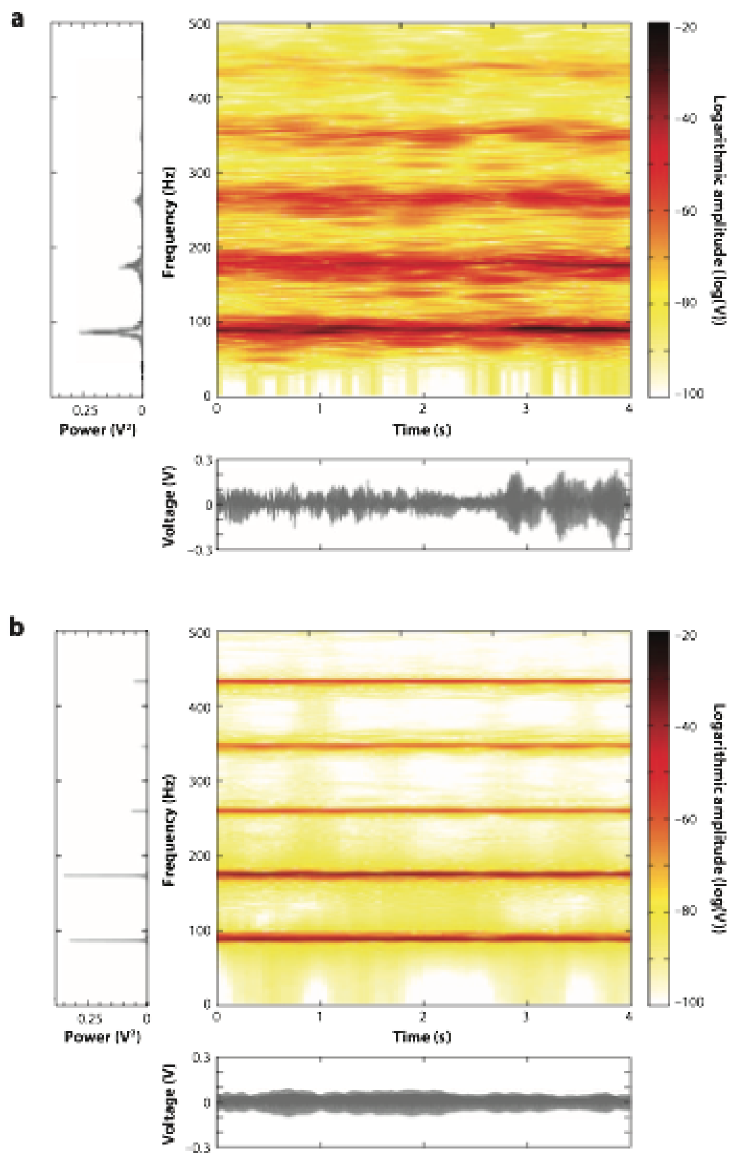


Figure 2: Comparison of Dumont dune spectral distribution (a) and the F2 note played by a cello (b) (Hunt & Vriend 2010).

Importantly, the seismic wave speeds in booming dunes increase with depth (see Figure 3). The speeds of P-waves in the dune are approximately 200 m/s near the surface, increasing to 550 m/s in the nearly stationary layer deep (~50 m) below. Additionally, the seismic velocity increases going from the crest to base of the dune, as sand grains near the bottom of the dune are more compacted. This causes the waves near the base of the dune to have a higher frequency and lower power than those found near the crest of the dune, and as a result booms are easier to produce near the top of the dune (Hunt & Vriend 2010). Additionally, Figure 3 shows that high-amplitude waves are much more easily excited in the hot, dry summer months than in the colder winter months when the sand is wetter.

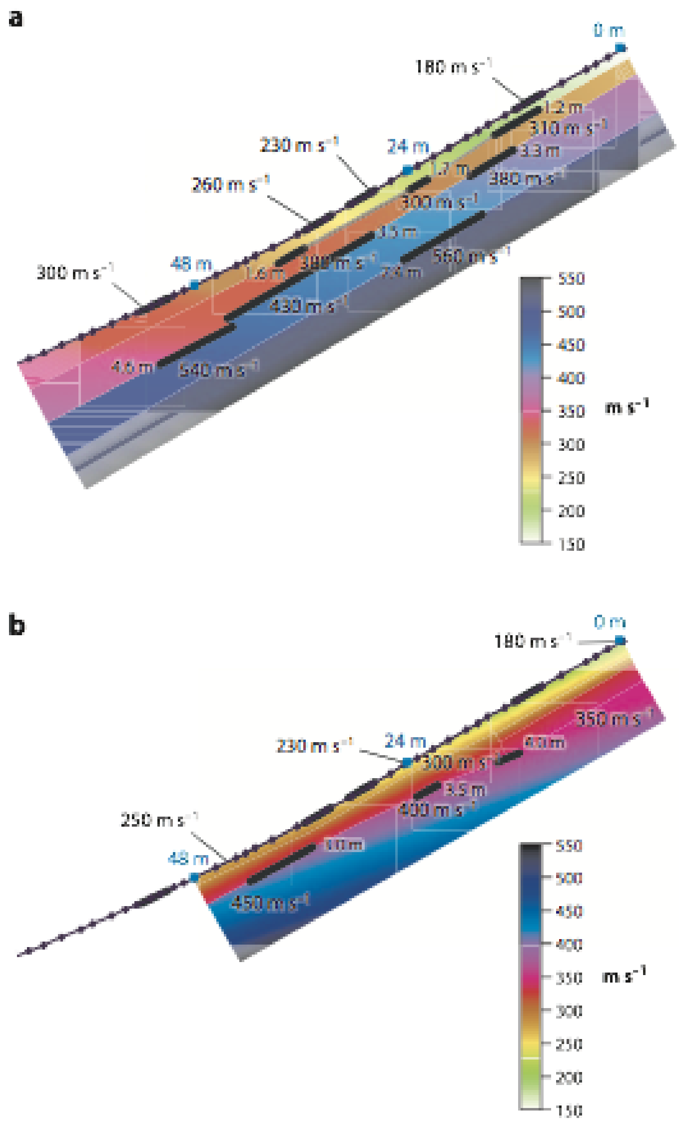


Figure 3: Distribution of seismic speeds of Dumont Dunes in the upper 48 m of the leeward side in (a) summer and (b) winter (Hunt & Vriend 2010).

## Criteria for a dune to boom and analogous features:

There are three main empirical criteria for a dune to boom:

1) The dune must be > 120 feet tall
2) The slope of the dune must be > 30 degrees. Note that sand's angle of repose is 31 degrees, so this agrees well with basic expectations.
3) The dune must be hot (> 100 degrees F is ideal). Additionally, the sand must be relatively dry.

Here's some planetary connections:

1) Thermal moonquakes (Criswell & Lindsay 1974) are a useful analogy to booming sand dunes. Thermal moonquakes occur due to natural slumping of material when the slope exceeds the angle of repose, and are essentially lunar avalanches. These moonquakes normally occur on the slopes of craters on the moon, and could occur on other planetary bodies (e.g., Mars).
2) Because sand dunes on Mars are very dry, it may be possible that dunes on Mars also boom (perhaps if we landed InSight on a sand dune we might find out?).

Note that beach sands also make noise, which is called "singing sand," but this occurs at a much higher frequency (~1000 Hz). One might remember stepping on the hot dry sand at the beach and it making a "squeaking" noise, this is the equivalent to the "roar" of a booming dune. These sounds aren't quite as impressive due to the lower movable sand depth on the beach, but are much more common and can be found throughout many beaches of the world (including those of lakes, e.g., Lake Michigan).

## Wave propagation in booming dunes:

In an early model, Bagnold (1966) derived that the frequency $f = (g\lambda/8d)^{1/2}$, where g is gravitational acceleration, $\lambda$ is the "linear concentration," essentially a fitting constant, and d is the grain size. Using a derived value for sheared sand of $\lambda = 12.4$, Bagnold (1966) showed that the frequency computed is comparable to observations.

More recently, booming dunes have been modeled assuming that the waves are trapped in a surface layer of sand, or "waveguide," see Figure 4. One can use the analogy of a cello string for this waveguide motion, where the avalanching of the surface provides energy (like a cello bow) and waves propagate through the dune (like they propagate through the string) while contained between the surface and substrate (like they are contained within the cello string itself). As in the case of purely standing waves, waves can constructively/destructively interfere with one another due to the different wave speeds excited within different parts of the dune (see Fig. 3). Using this waveguide approach, one can show that the frequency of the waves is inversely related to the depth of the waveguide and directly proportional to the speed of the waves and the wave harmonic as:

$$f_n = \frac{n\,c_1}{2H[1-(c_1-c_2)^2]^{1/2}} ,$$

Where n is the wave mode, $c_1$ is the wave speed, H is the depth of the waveguide, and $c_2$ is the wave speed in the substrate. This theory matches well with observations of wave frequencies in the sand dunes (Vriend et al. 2007) while still being analytically tractable.

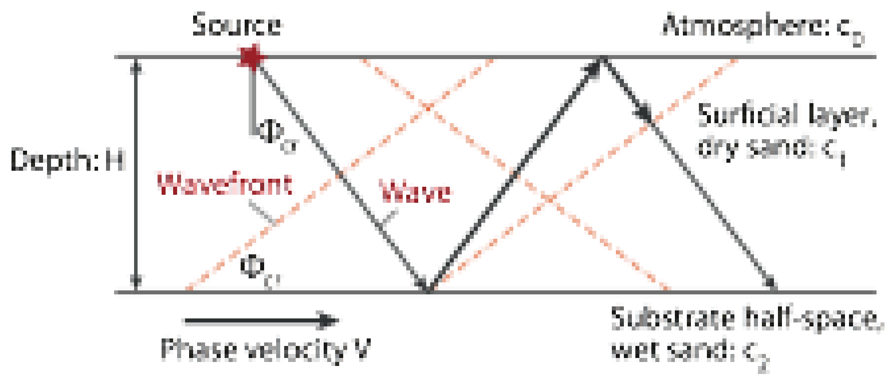


Figure 4: Waveguide model for dunes (Hunt & Vriend 2010).

Reality is somewhat more complicated (see Figure 5). There are both high-amplitude P-waves that occur within the sand "body" (i.e., that do not reach the surface) and surface Rayleigh waves acting in concert to cause the booming. One can distinguish these waves through their different seismic speeds (P-waves are faster) and their amplitudes (Rayleigh waves are higher-amplitude). Note that these waves can interact near the body-surface interface, leading to non-linear behavior.

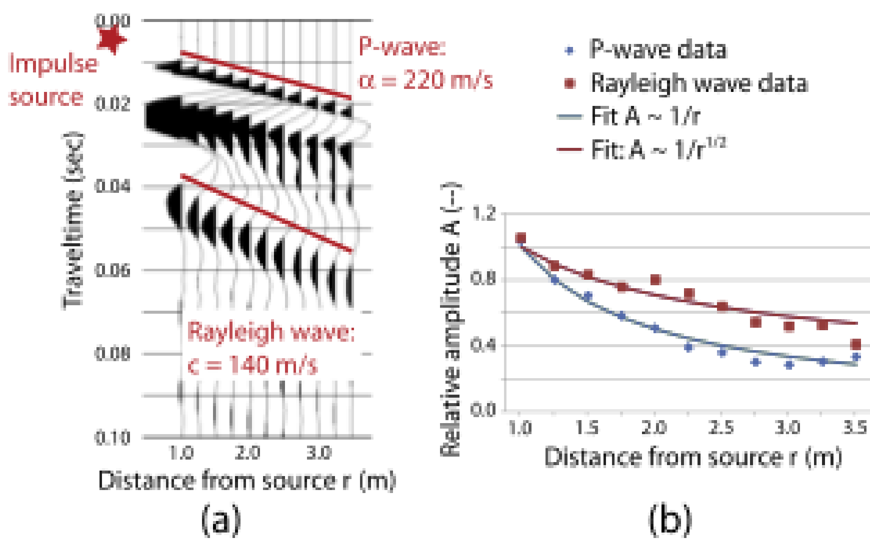


Figure 5: Observed wave types triggered by a pressure impulse at Dumont dunes (Vriend et al. 2015)

## DIY booming sand dune:

We might be able to create our own boom! Note that this may not work well because it's winter so the dune is cold and relatively wet. Here's what we do. We'll slide and/or walk downhill in a group, side-by-side, starting near the crest of the dune and all going down at nearly the same pace. This should create a sand avalanche which will destabilize dune crests causing collapse and hopefully leading to a boom! For an example of a group of people doing this at Kelso dunes, see video #2 below.

## Some videos to watch:

1) https://www.youtube.com/watch?v=4mbypyJjqhk (National Geographic) - Eureka, Death Valley
2) https://www.youtube.com/watch?v=QI6goi9nXpM (group of people walking down dune - Kelso, Mojave National Preserve)
3) https://www.youtube.com/watch?v=m4Oz12YNhwo (homemade, including pupper) - Kelso, Mojave National Preserve
4) https://www.youtube.com/watch?v=4yFaMsUawi4 (some guy making low frequency sounds in Morocco)

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# Boom and Bust, Baby!
## Mining and Ghost Towns in Death Valley - Mattie

Borax

Talc

Gold

<u>Mining History</u>

1849: Gold found, began earliest American exploration of Death Valley

Gold and silver drew “colorful and crusty ‘Single blanket jackass prospectors’” until the Great Depression hit in the 1930’s

Borax and Talc were abundant and ended up being most profitable

Borax "cotton ball"

1880’s: Borax mining took off!

Ulexite was initially the borate of choice. The “cotton balls” were scraped from the salt pan and then refined by evaporation and crystallization. Those nerds thought that this was the only form of naturally occurring borax that was commercially profitable. Continued exploration confirmed that the playa borates that were presently being worked were actually a secondary deposit resulting from the leaching of beds of borate lime.

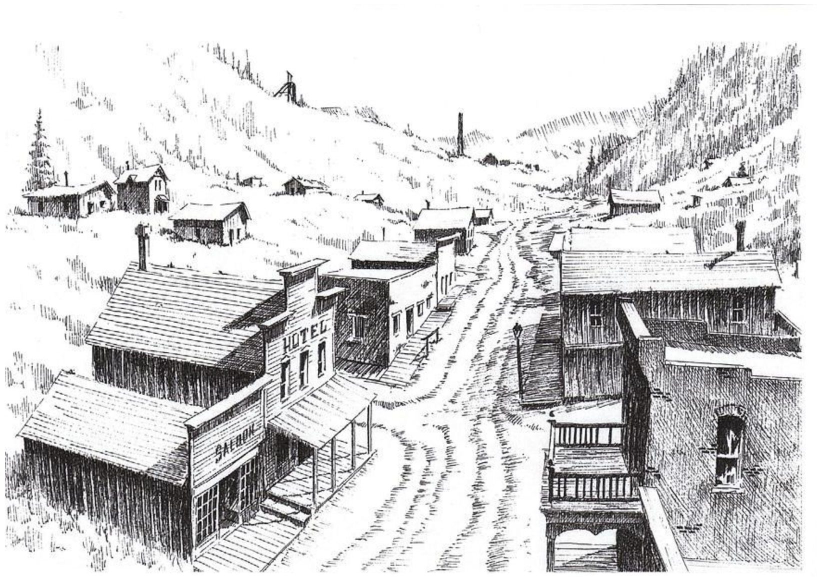
Pacific Coast Borax Co. was born and figured out how to haul 20-ton loads 165 mi out of Death Valley... make the mules do it!

Early 1900’s: gold was found at Bullfrog, Skidoo, and Chloride Cliff- Death Valley mining boomed again
1907: Financial panic slowed/stopped most mining- all metallic mining shut down by 1915

1976: New claims couldn't be filed after the passage of the Mining in the Parks Act of 1976

2005: For over a decade the Billie Mine (borax mine along the road to Dante's View) was the only active mine. It got got in 2005

Panamint City




The "toughest, rawest, most hardboiled little hellhole that ever passed for civilized." Started in the early 1870's as a silver mining town, it was home to several thousand people. It had a mile long main street, red light district, post office etc. Most of the city was wiped out by a flash flood that killed many residents. In 1983, another flash flood washed out the only road to the city, so everything had to be abandoned. Womp womp.

Rhyolite

Started in 1905 with the promise of gold. It became so big (almost 10,000 people big) that it had a stock exchange within two years, a symphony, 50 saloons, two undertakers, lots of prostitutes… all the essentials. The gold mining was a bust and Rhyolite became an old-West movie set in the 1920s. Some of the original buildings still stand today, making it a popular tourist attraction

Planetary Connections: Asteroid mining, moon mining

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# Useful Geologic References and Safety Material!

From the NPS:

**Drink plenty of water**: Drink at least one gallon (4 liters) of water per day to replace loss from sweat, more if you are active. Be aware of balancing fluid and electrolyte levels.

**Avoid hiking in the heat**: Do not hike in the low elevations when temperatures are hot. The mountains are cooler in summer, but can have snow and ice in winter.

**Travel prepared to survive**: Stay on paved roads in summer. If your car breaks down, stay with it until help comes. Carry extra drinking water in your car in case of emergency.

**Watch for signs of trouble**: If you feel dizzy, nauseous, or a headache, get out of the sun immediately and drink water or sports drinks. Dampen clothing to lower body temperature. Be alert for symptoms in others.

**The main cause of death in Death Valley:** More people die in single-car accidents than by any other means. To avoid an accident, follow the speed limits, shift to a lower gear on steep downhill grades, and wear your seatbelt.

**Dangerous Animals**: Never place your hands or feet where you cannot see first. Rattlesnakes, scorpions, or black widow spiders may be sheltered there.

**Hantavirus**--a potentially fatal respiratory disease--is spread through contact with infected rodents or their urine and droppings. Although no cases have been reported in Death Valley, the virus has been found in deer mice and cactus mice here. Use caution in rodent infested locations such as cabins and mine structures.

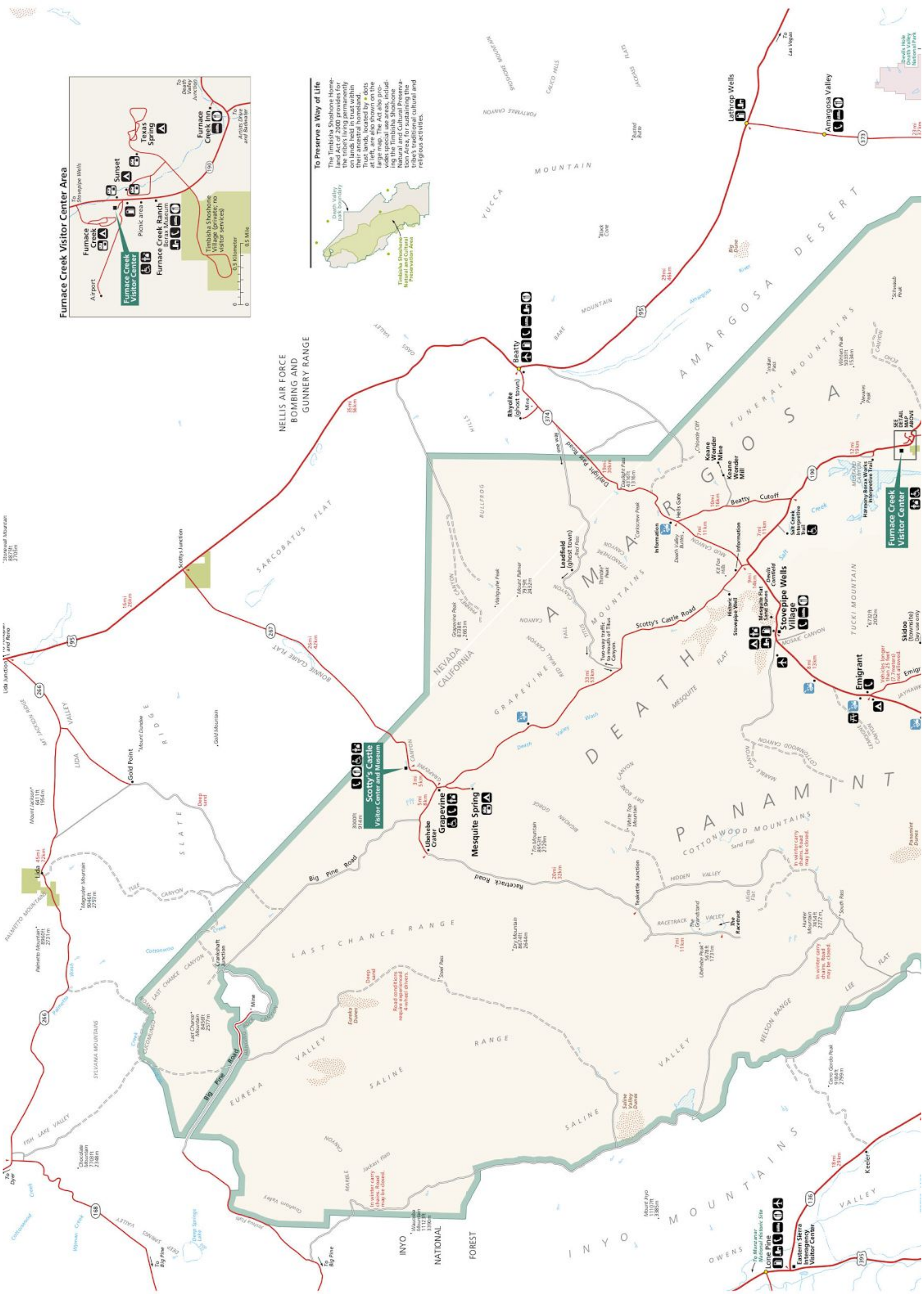
**Flash Floods**: Avoid canyons during rain storms and be prepared to move to higher ground. While driving, be alert for water running in washes and across road dips.

**Mine Hazards**: Do not enter mine tunnels or shafts. Mines may be unstable, have hidden shafts, pockets of bad air and poisonous gas.

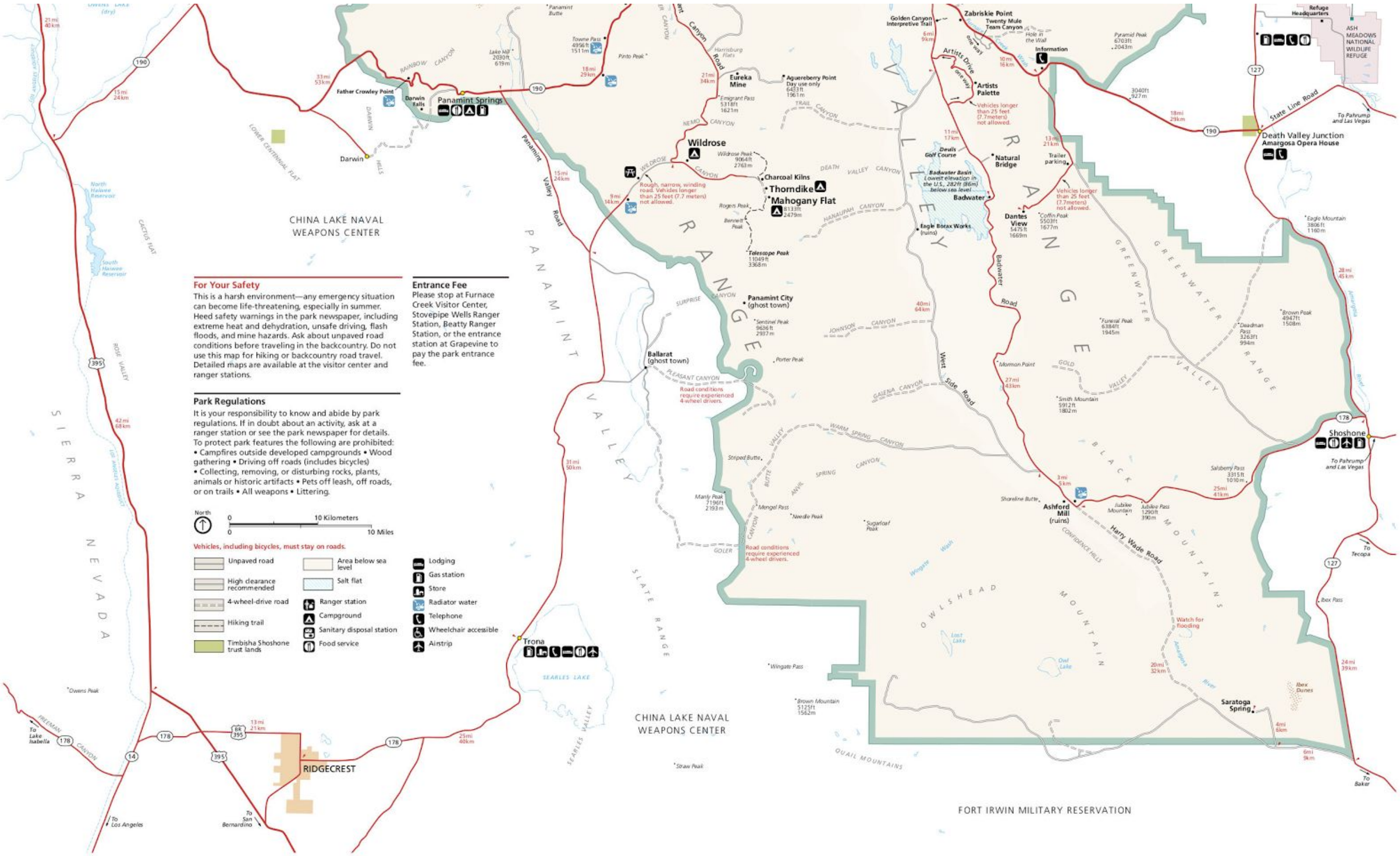
**Backcountry Travel**: Hikers, backpackers and four-wheelers need to be self reliant and well prepared. Always plan ahead, carry detailed maps and let someone know your plans. Backpackers should obtain a free backcountry permit from any visitor center.

**In Case of Emergency**: Dial 911 from any telephone or cell phone. Cell phones may not work in many parts of the park. Do not depend on them.


Gratuitous MTB photo for map layout purposes



Furnace Creek Visitor Center Area
Furnace Creek Visitor Center
Furnace Creek
Sunset
Texas Spring
Furnace Creek Ranch
Borax Museum
Furnace Creek Inn
Airport
Picnic area
Timbisha Shoshone Village (private; no visitor services)
0.5 Kilometer
0.5 Mile
To Preserve a Way of Life
The Timbisha Shoshone Homeland Act of 2000 provides for the tribe's living permanently on lands held in trust within their ancestral homeland. Trust lands, located by dots at left, are also shown on the large map. The Act also provides special use areas, including the Timbisha Shoshone Natural and Cultural Preservation Area, for sustaining the tribe's traditional cultural and religious activities.
Death Valley park boundary
Timbisha Shoshone Natural and Cultural Preservation Area
NELLIS AIR FORCE BOMBING AND GUNNERY RANGE
Beatty
Rhyolite (ghost town)
Lathrop Wells
Amargosa Valley
AMARGOSA DESERT
YUCCA MOUNTAIN
BARE MOUNTAIN
Scotty's Castle Visitor Center and Museum
Grapevine
Mesquite Spring
Ubehebe Crater
Scottys Junction
SARCOBATUS FLAT
BONNIE CLAIRE FLAT
Gold Point
Lida
Lida Junction
SLATE RIDGE
NEVADA
CALIFORNIA
GRAPEVINE MOUNTAINS
AMARGOSA RANGE
DEATH VALLEY
FUNERAL MOUNTAINS
PANAMINT RANGE
COTTONWOOD MOUNTAINS
LAST CHANCE RANGE
SALINE VALLEY
SALINE RANGE
EUREKA VALLEY
Big Pine Road
Racetrack Road
Teakettle Junction
The Racetrack
Scotty's Castle Road
Daylight Pass Road
Beatty Cutoff
Leadfield (ghost town)
Keane Wonder Mine
Keane Wonder Mill
Hells Gate
Stovepipe Wells Village
Mesquite Flat Sand Dunes
Salt Creek Interpretive Trail
Harmony Borax Works Interpretive Trail
Furnace Creek Visitor Center
Emigrant
Skidoo (townsite)
INYO NATIONAL FOREST
INYO MOUNTAINS
Lone Pine
Eastern Sierra Interagency Visitor Center
Keeler
SEE DETAIL MAP ABOVE




## For Your Safety

This is a harsh environment—any emergency situation can become life-threatening, especially in summer. Heed safety warnings in the park newspaper, including extreme heat and dehydration, unsafe driving, flash floods, and mine hazards. Ask about unpaved road conditions before traveling in the backcountry. Do not use this map for hiking or backcountry road travel. Detailed maps are available at the visitor center and ranger stations.

## Park Regulations

It is your responsibility to know and abide by park regulations. If in doubt about an activity, ask at a ranger station or see the park newspaper for details. To protect park features the following are prohibited:
• Campfires outside developed campgrounds • Wood gathering • Driving off roads (includes bicycles)
• Collecting, removing, or disturbing rocks, plants, animals or historic artifacts • Pets off leash, off roads, or on trails • All weapons • Littering.

## Entrance Fee

Please stop at Furnace Creek Visitor Center, Stovepipe Wells Ranger Station, Beatty Ranger Station, or the entrance station at Grapevine to pay the park entrance fee.

# Common Rock Forming Minerals

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

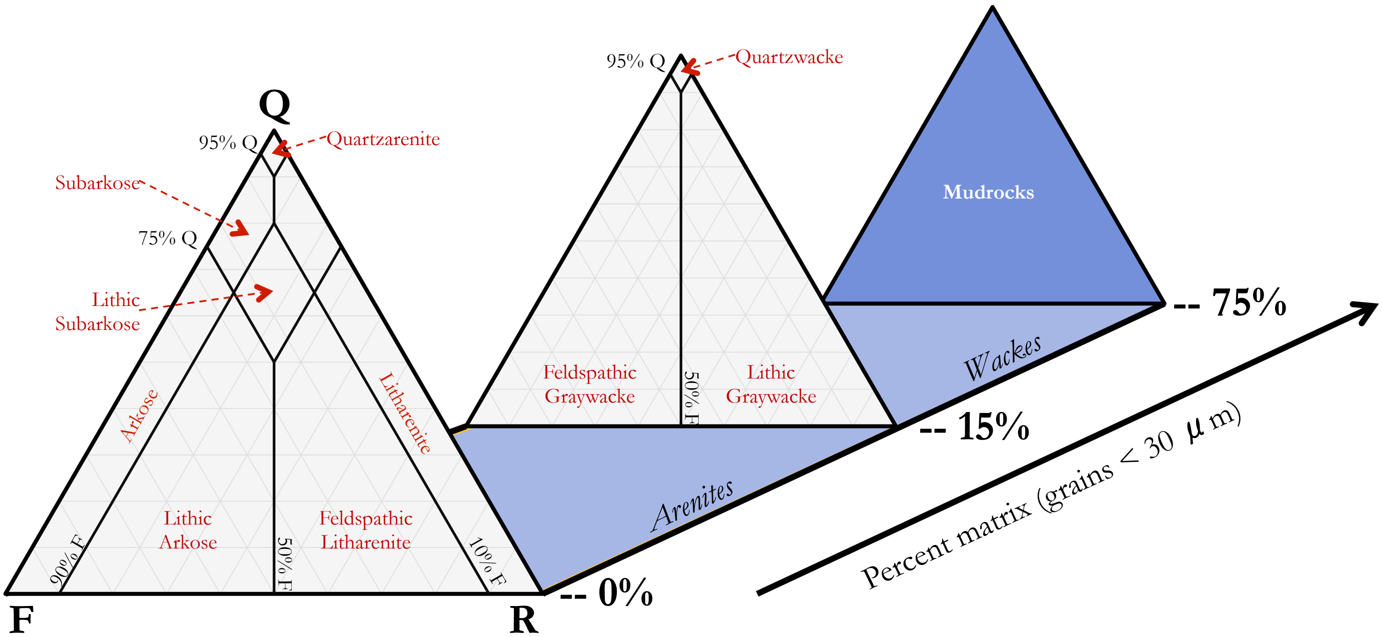
| Light-colored minerals | | | |
|---|---|---|---|
| **Hardness** | **Cleavage** | **Physical Properties** | **Name** |
| Hardness >5 | Excellent or good | White or gray, Cleavage in 2 planes at nearly right angles, Striations. Hardness-6 | **Plagioclase Feldspar** |
| | | Orange, brown, white, gray,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

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

# Sedimentary Rocks

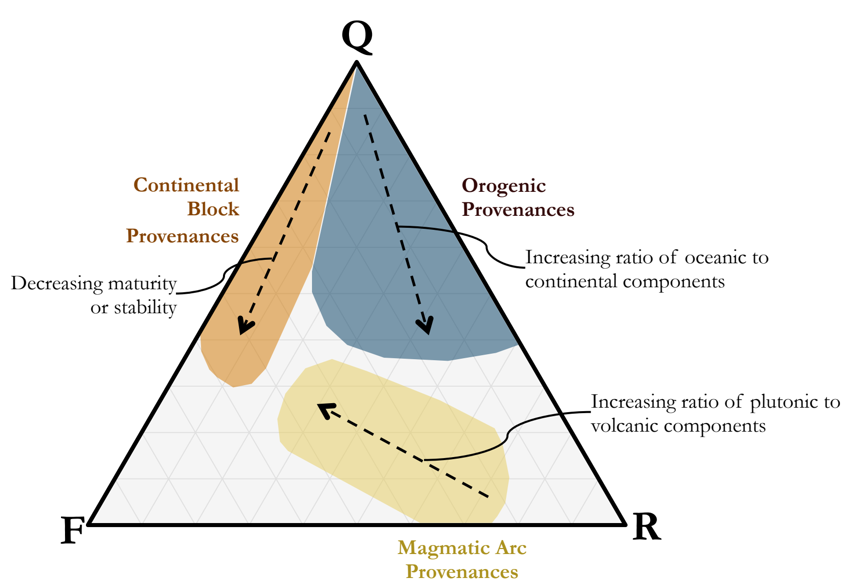
## McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

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




## Tectonic Setting for Clastic Sedimentary Rocks

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



# Sedimentary Rocks

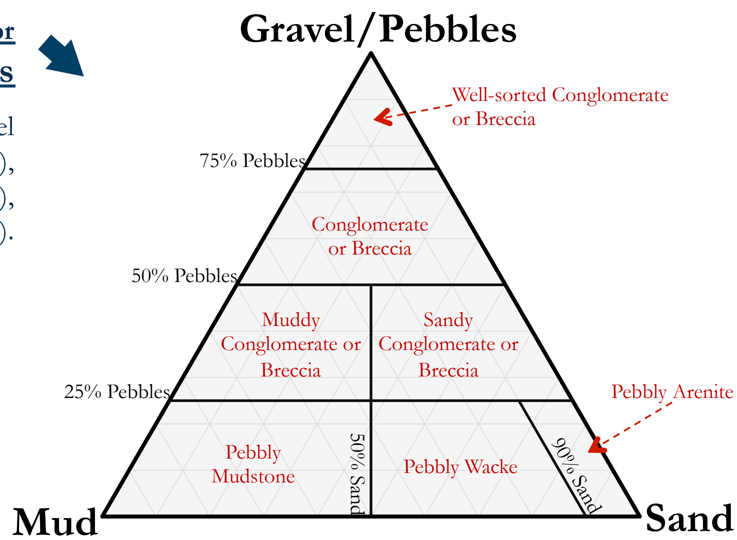
| | Mudrocks (containing > 50% mud) | | | Rocks with <50%mud |
|---|---|---|---|---|
| | Silt dominant (> 2/3 of rock) | Clay and Silt | Clay dominant (> 2/3 of rock) | Sand-sized or larger grains dominant |
| **Non-laminated** | Siltstone | Mudstone | Claystone | Conglomerates, Breccias, Sandstones,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

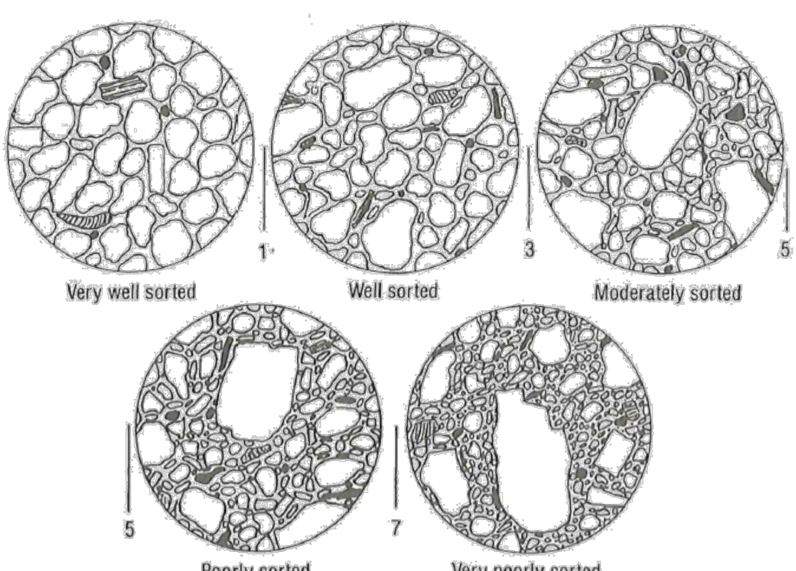
## Classification Scheme for Mudrocks

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

## Classification Scheme for Sub-Conglomerates and Sub-Breccias

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



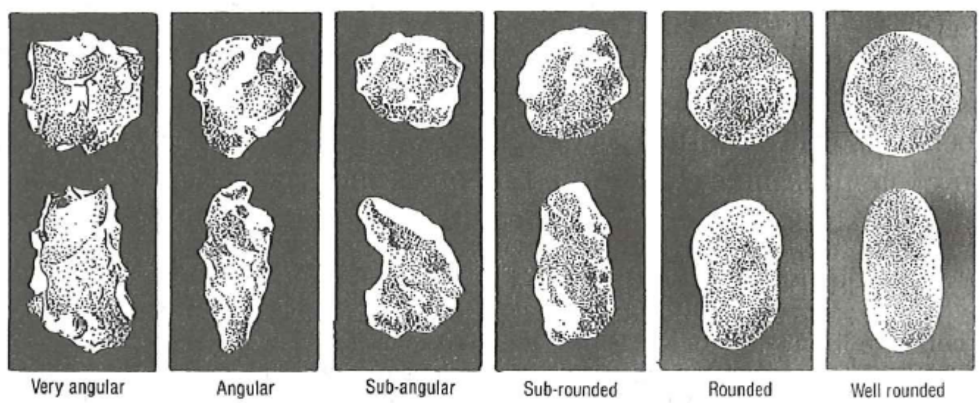

## Estimating Sorting

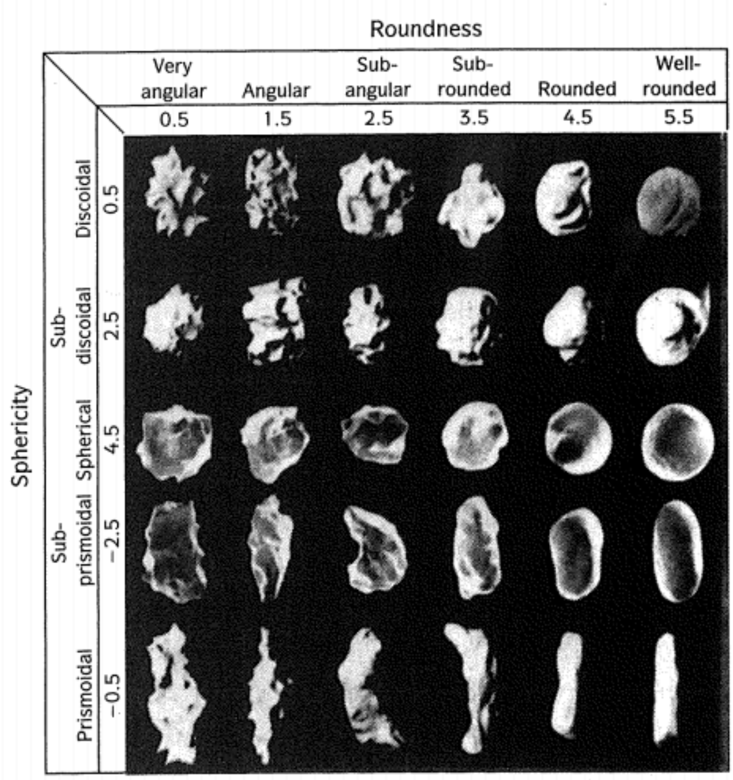
Example hand-lens view of detritus. From Compton, 1985

# Sedimentary Rocks

## Degrees of Rounding

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

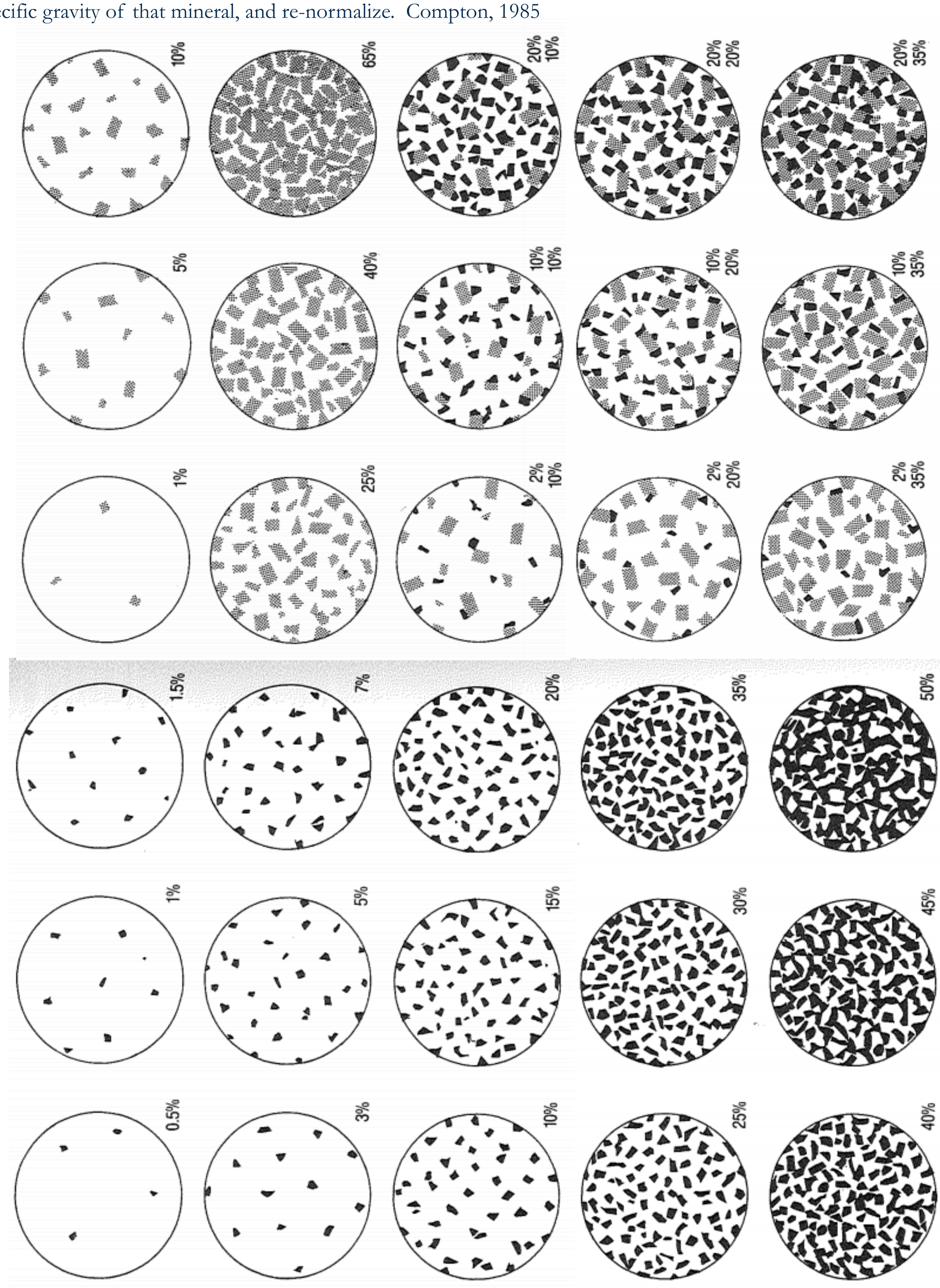


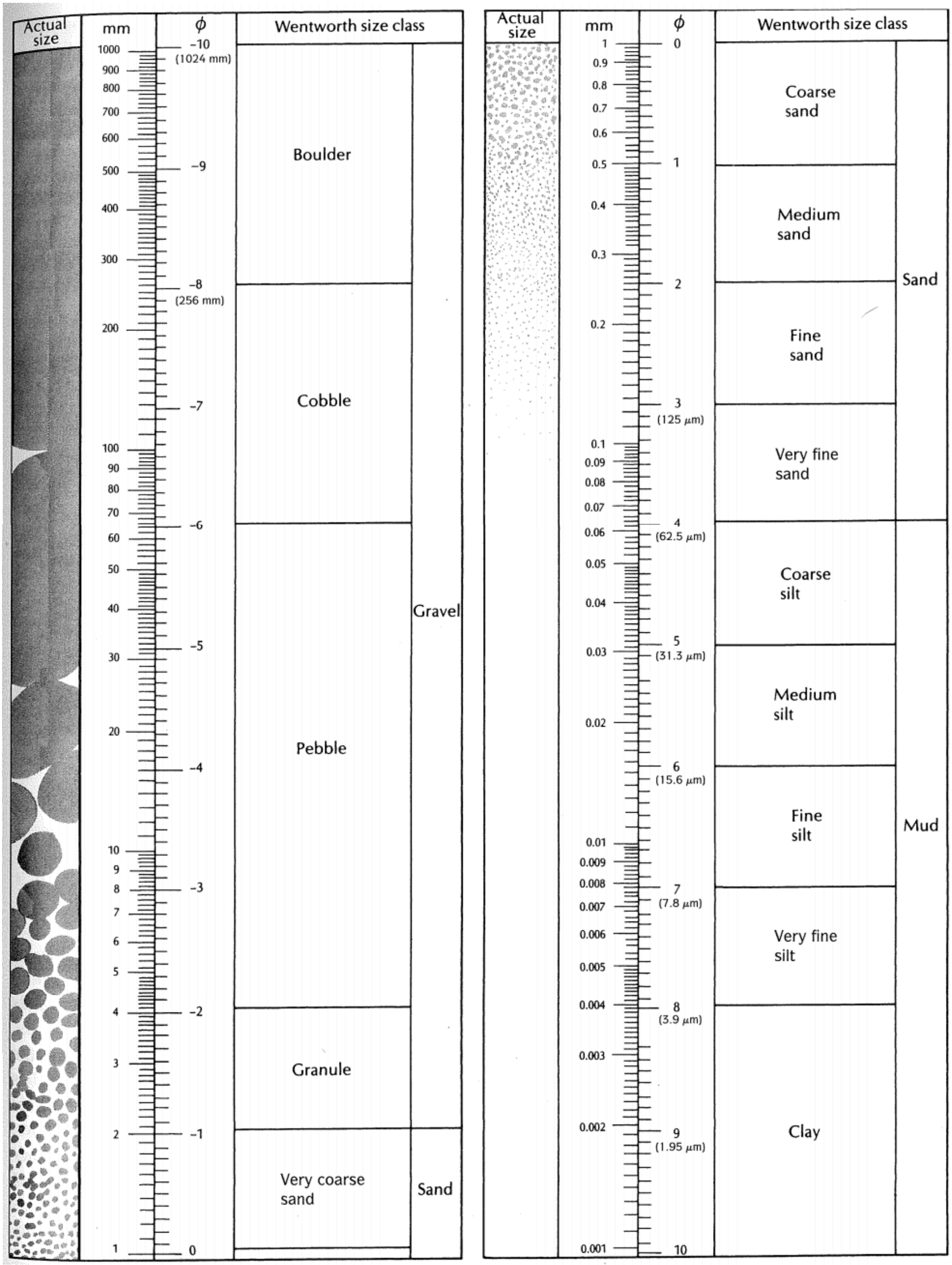
# Sedimentary Rocks

## Percentage Diagrams for Estimating Composition by Volume

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



# Sedimentary Rocks

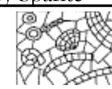
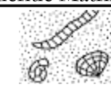
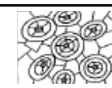
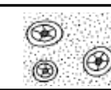
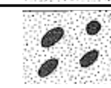
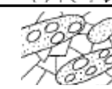
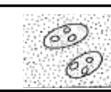
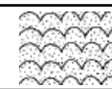



From Prothero and Schwab, 2004

# Sedimentary Rocks: Carbonates

## Folk Classification Scheme for Carbonate Rocks

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

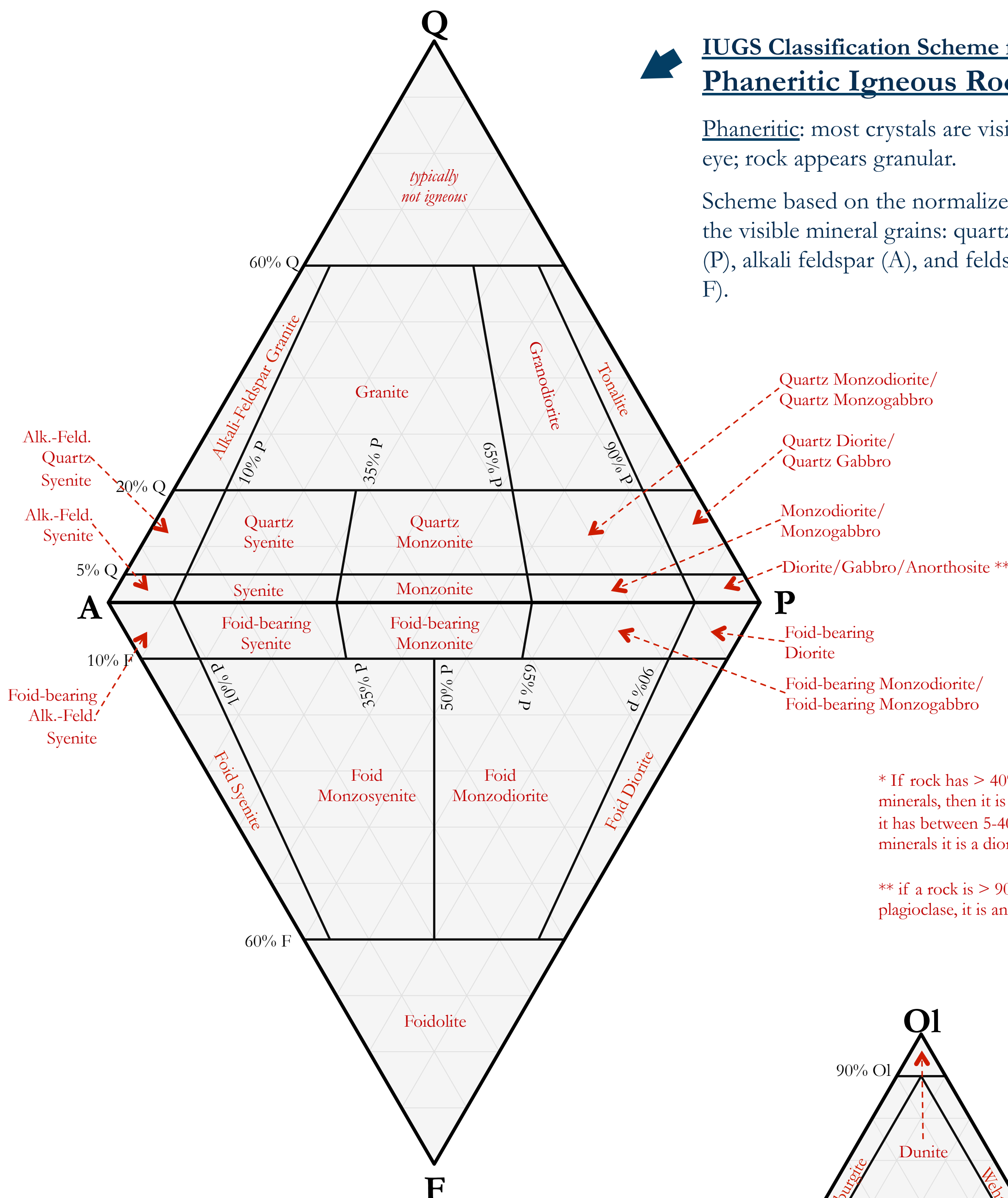
| Principle Allochems in Limestone | Limestone Type | | | |
|---|---|---|---|---|
| | Cemented by Sparite | | Cemented by Micritic Matrix | |
| Skeletal Grains (Bioclasts) | Biosparite |  | Biomicrite |  |
| Ooids | Oosparite |  | Oomicrite |  |
| Peloids | Pelsparite |  | Pelmicrite |  |
| Intraclasts | Intrasparite |  | Intramicrite |  |
| Limestone formed in place | Biolithite |  | Terrestrial Limestone |  |

## Dunham Classification Scheme for Carbonate Rocks

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

| **Allochthonous Limestone** (original components not organically bound during deposition) | | | | | | **Autochthonous Limestone** (original components organically bound during deposition; reef rocks) | | |
|---|---|---|---|---|---|---|---|---|
| Of the allochems, less than 10% are larger than 2 mm | | | | Of the allochems, greater than 10% are larger than 2 mm | | | | |
| Contains carbonate mud | | | No mud | Matrix supported | Grain supported | Organisms acted as baffles | Organisms are encrusting and binding | Organisms building a rigid framework |
| Grain supported | | Grain supported | | | | | | |
| Less than 10% grains | More than 10% grains | | | | | | | |
| Mudstone | Wackestone | Packstone | Grainstone | Floatstone | Rudstone | Bafflestone | Bindstone | Framestone |

# Igneous Rocks




## IUGS Classification Scheme for Phaneritic Igneous Rocks

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

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

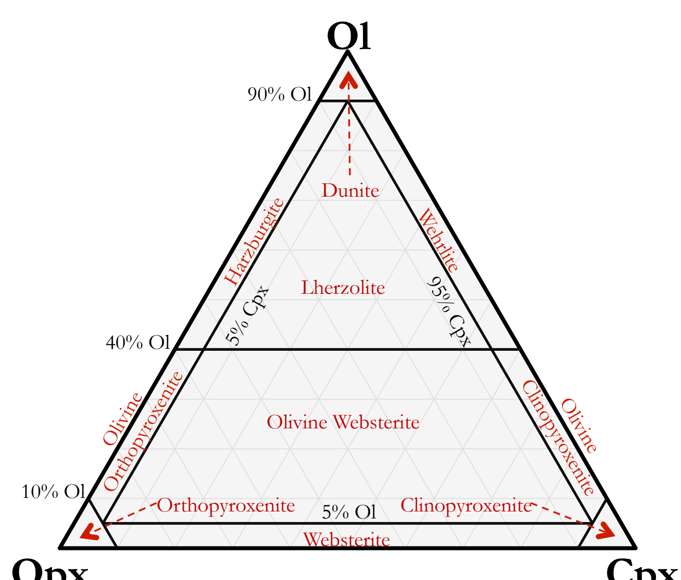
* If rock has > 40% mafic minerals, then it is a gabbo. If it has between 5-40% mafic minerals it is a diorite.

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

## IUGS Classification Scheme for Phaneritic Ultramafic Igneous Rocks (1)

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

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

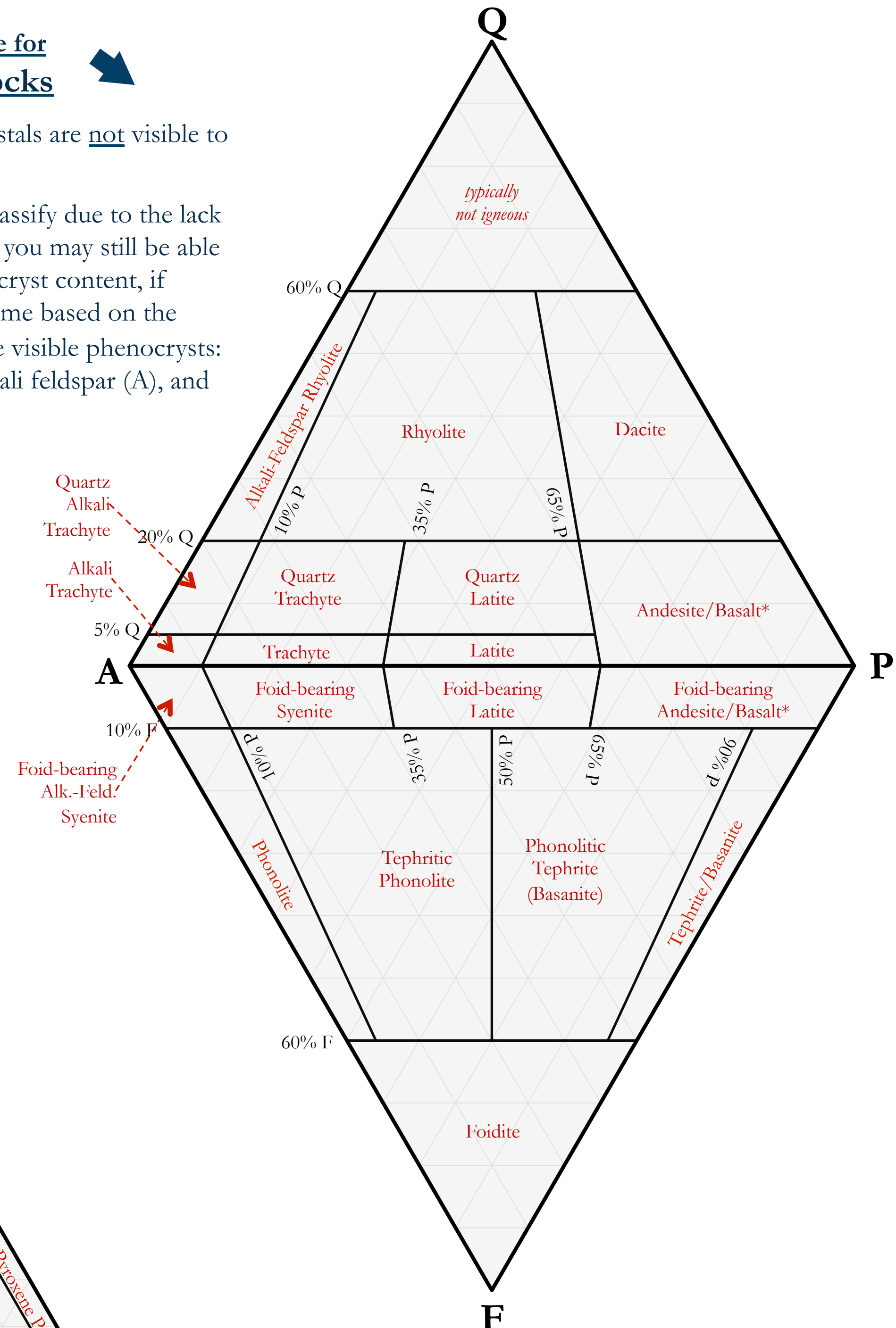


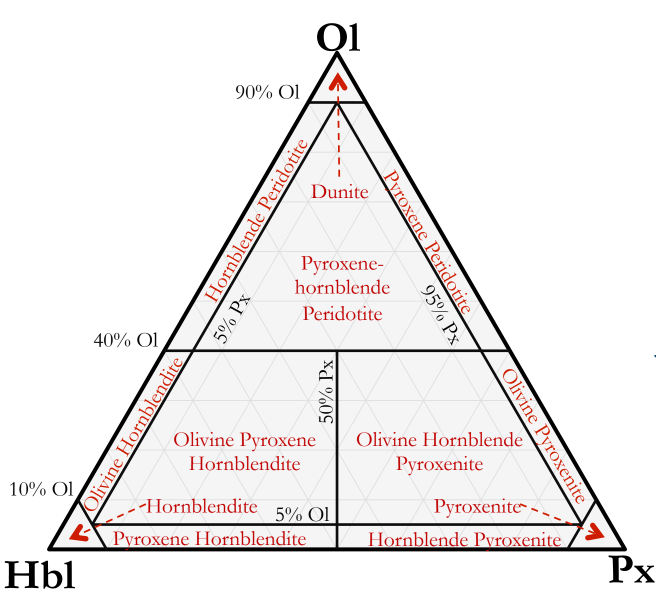
# Igneous Rocks

## IUGS Classification Scheme for Aphanitic Igneous Rocks

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

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




## IUGS Classification Scheme for Phaneritic Ultramafic Igneous Rocks (2)

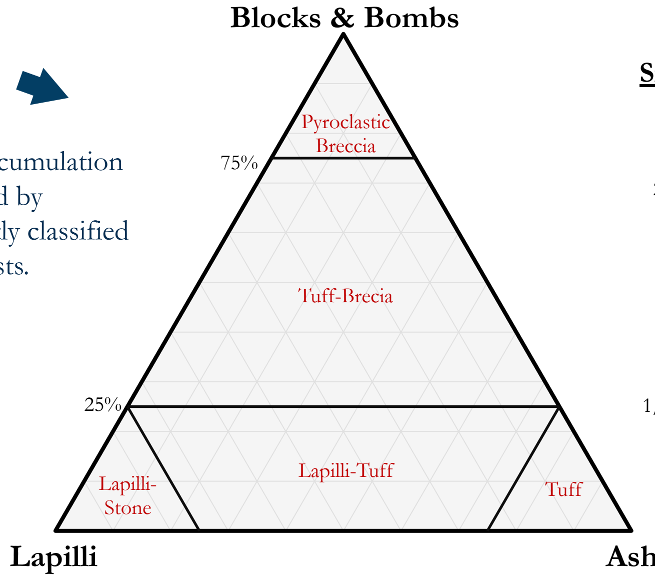
Ultramafic: more than 90% of the total minerals are mafic.

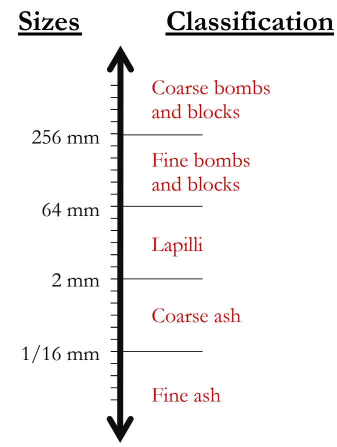
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

# Igneous Rocks

## Classification Scheme for
## Pyroclastic Igneous Rocks

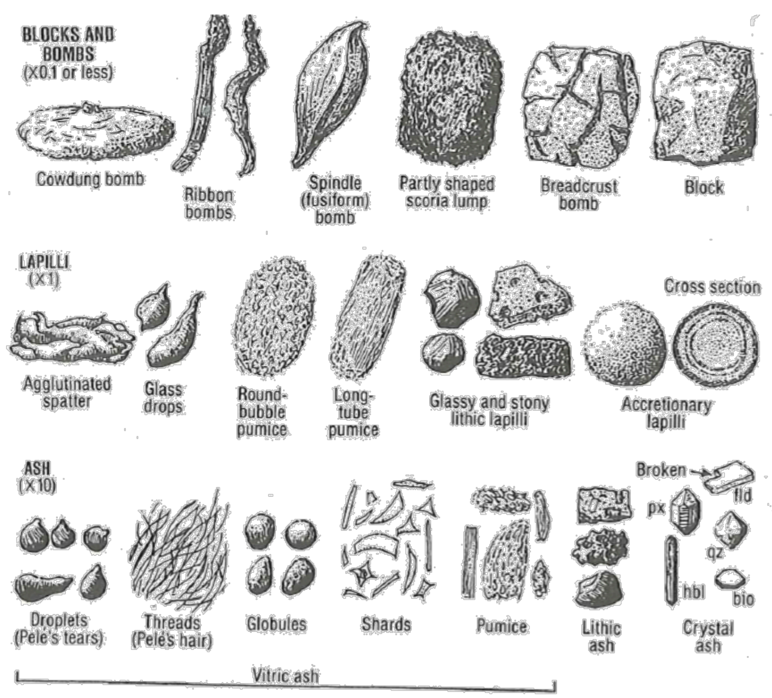
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.

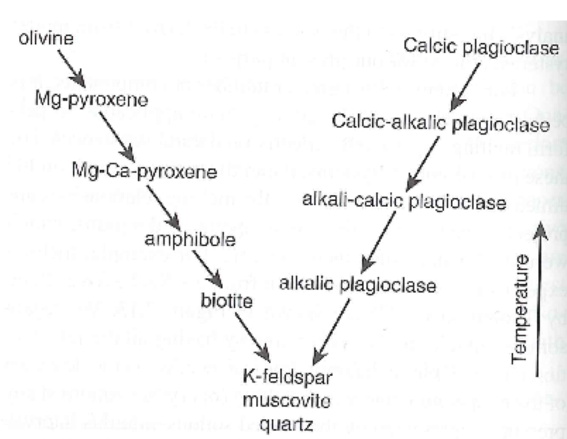



## Types of Tephra (Pyroclasts)

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




## Bowen's Reaction Series

From Winter, 2010.

# Metamorphic Rocks

## Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

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

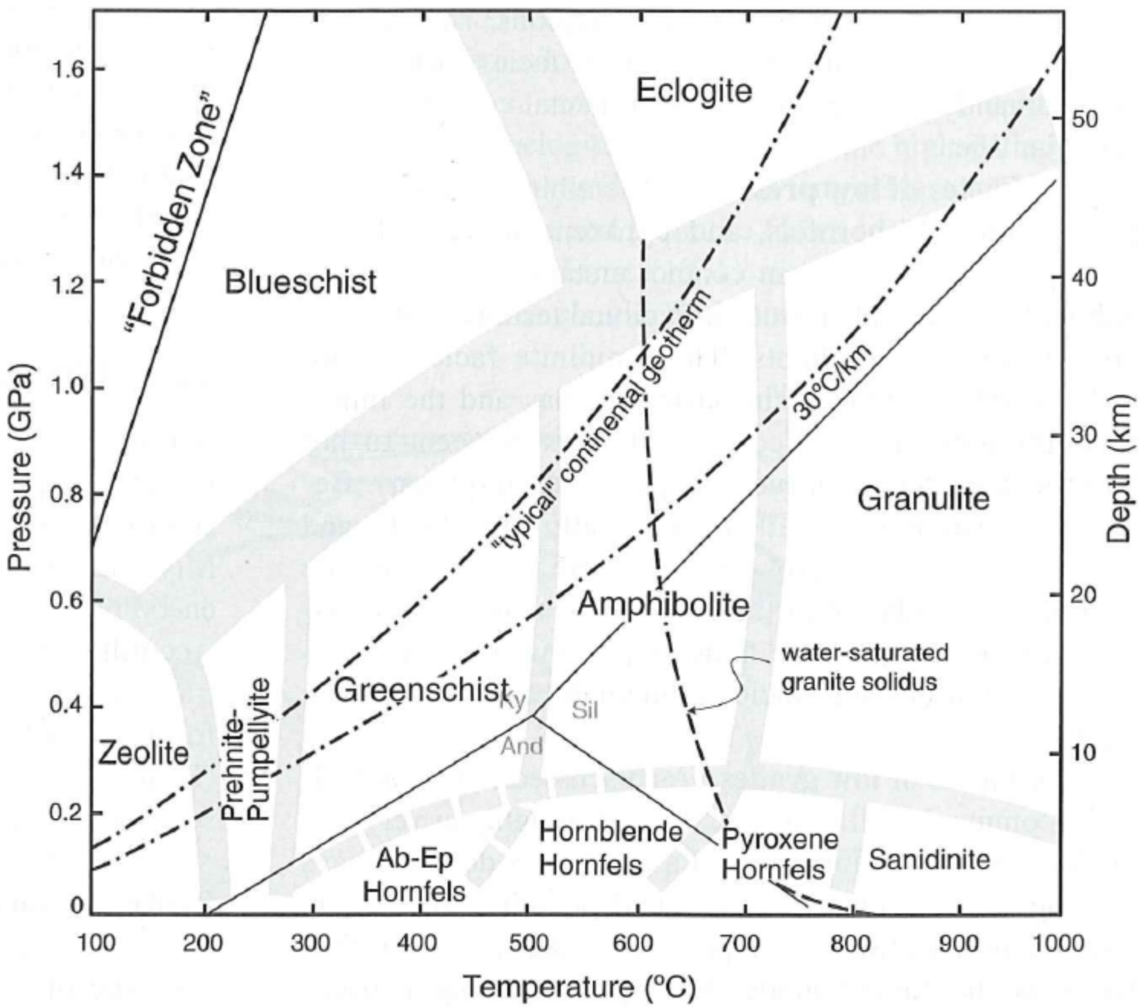
## Mineralogy for Metamorphic Rock Facies

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

# Metamorphic Rocks

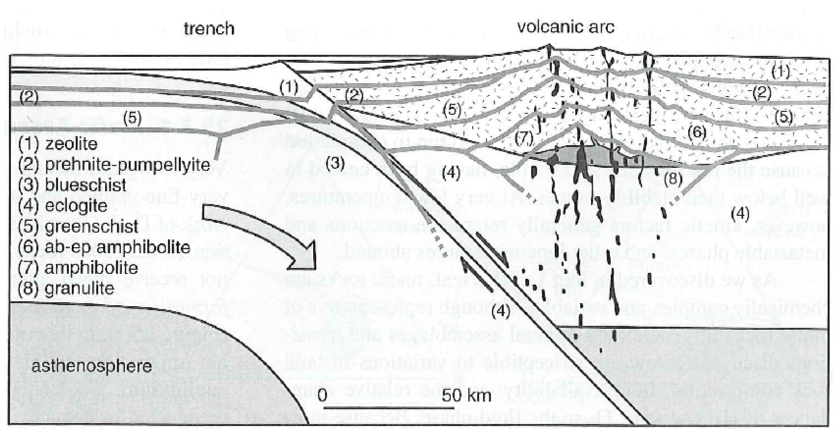
## Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010




## Schematic of Island Arc, and the origins of Metamorphic Facies

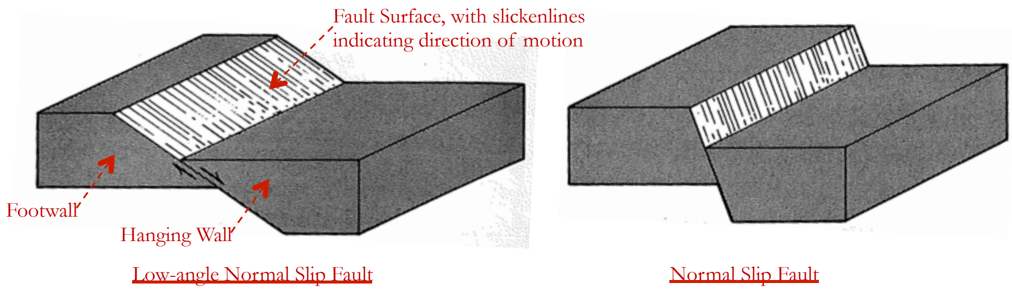
A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010



# Structural Geology: Normal Faults

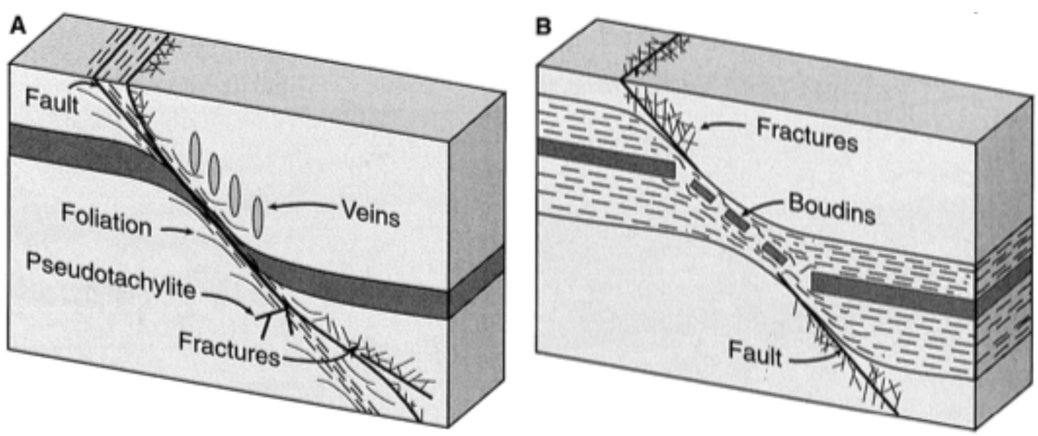
## Normal Faults

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



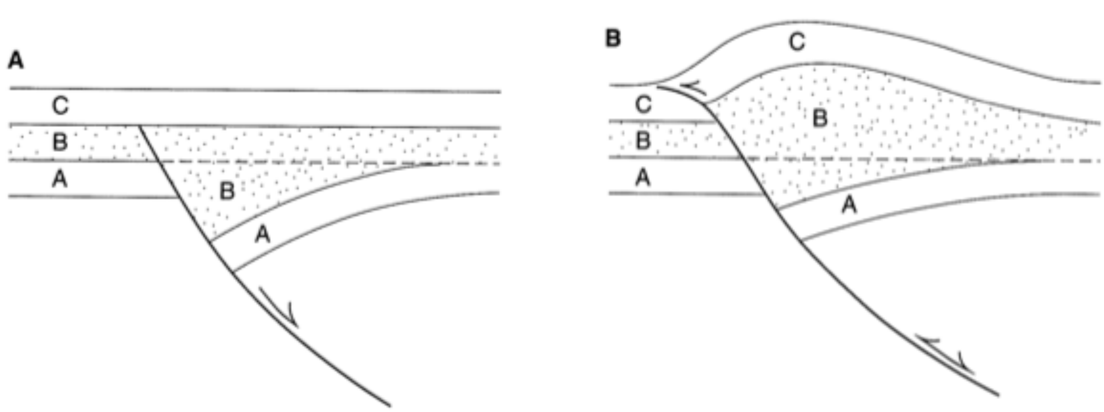

## Effects of Brittle or Ductile Shear in Normal Faults

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




## Inversion Tectonics

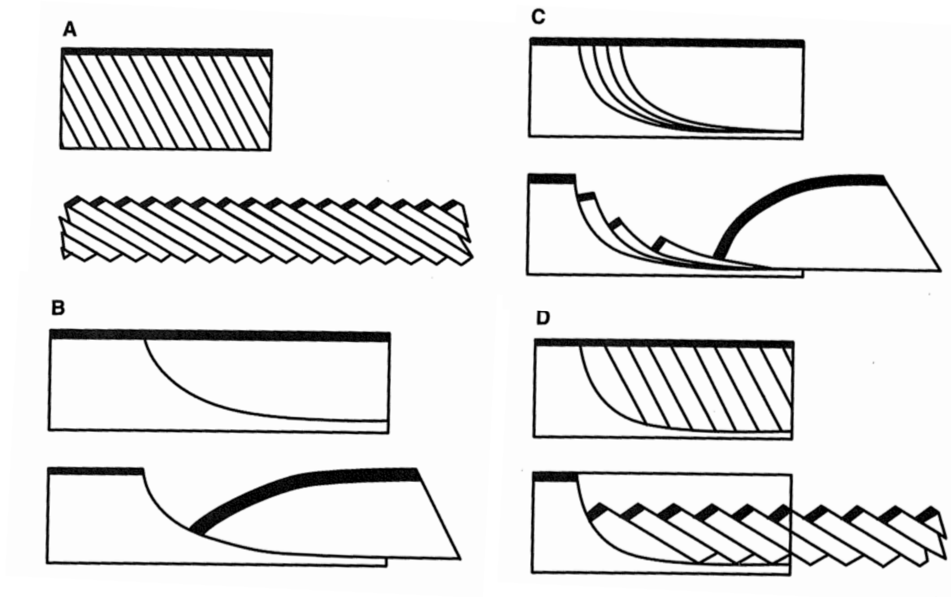
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right,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

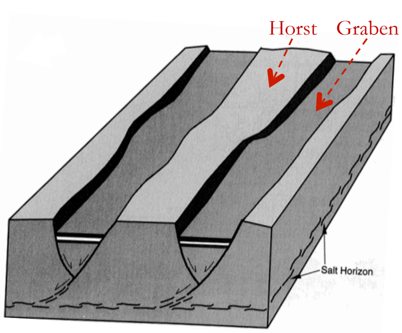


# Structural Geology: Normal Faults

## Normal Faults Geometries

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



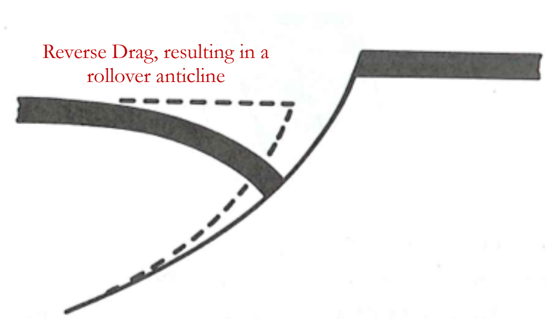



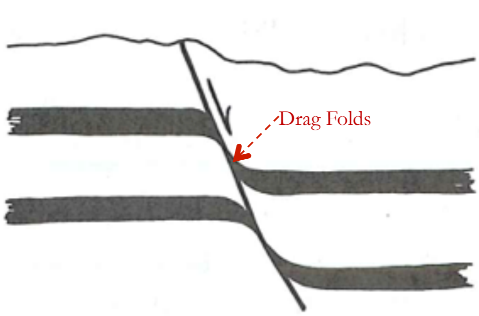

## Horsts & Grabens

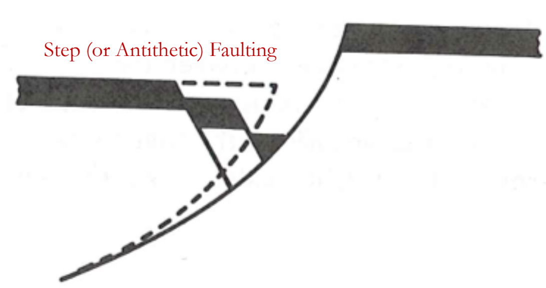
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

## Drag Folds, Reverse Drag, and Step Faulting

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



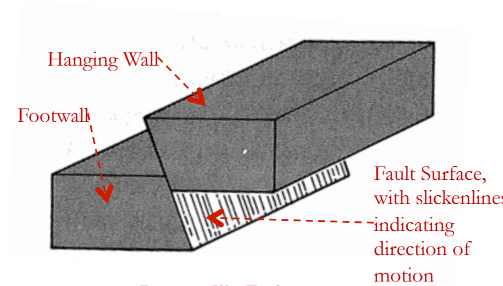



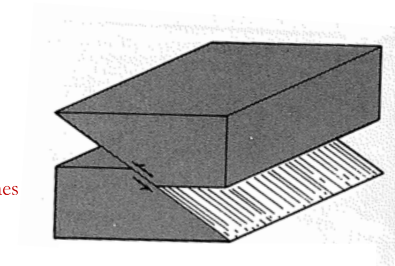
# Structural Geology: Reverse & Thrust Faults

## Reverse Faults

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



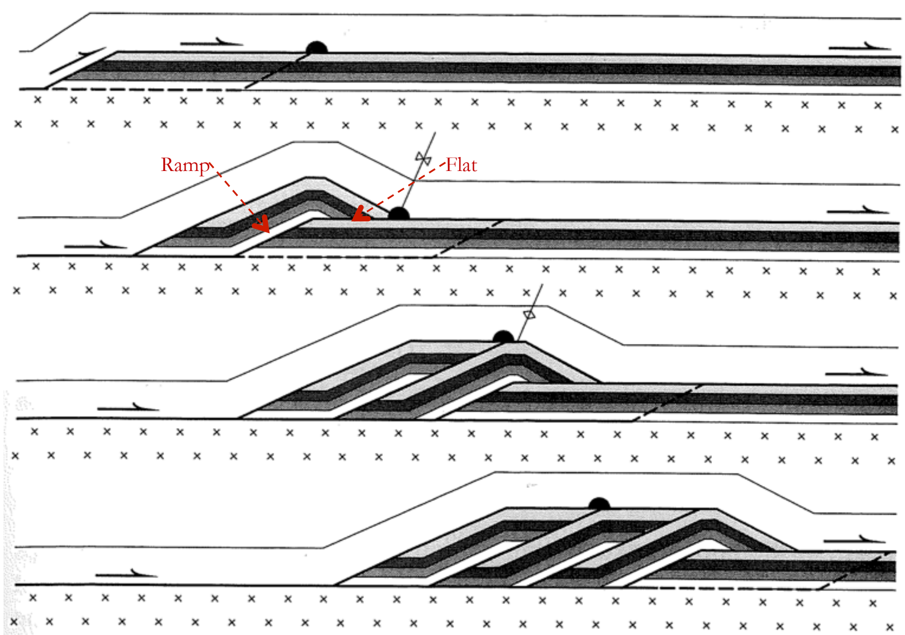

Reverse Slip Fault



Thrust Slip Fault

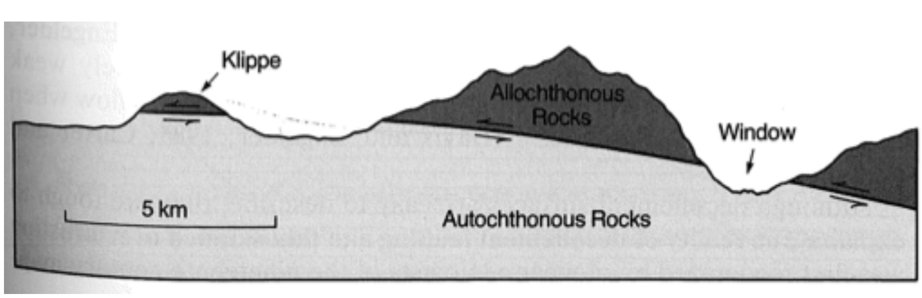
## "Ramp-Flat" Geometry of Typical Thrust Fault Systems

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

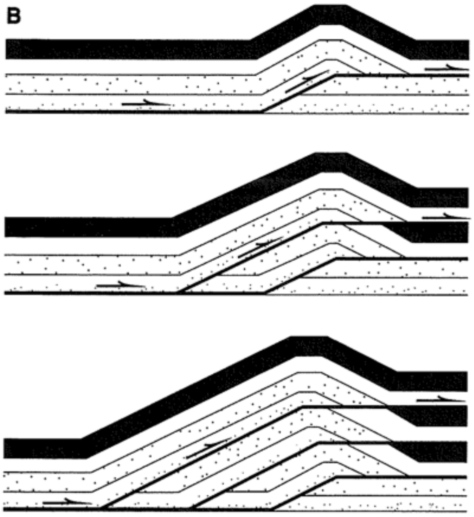



## Klippe & Windows

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



# Structural Geology: Reverse & Thrust Faults

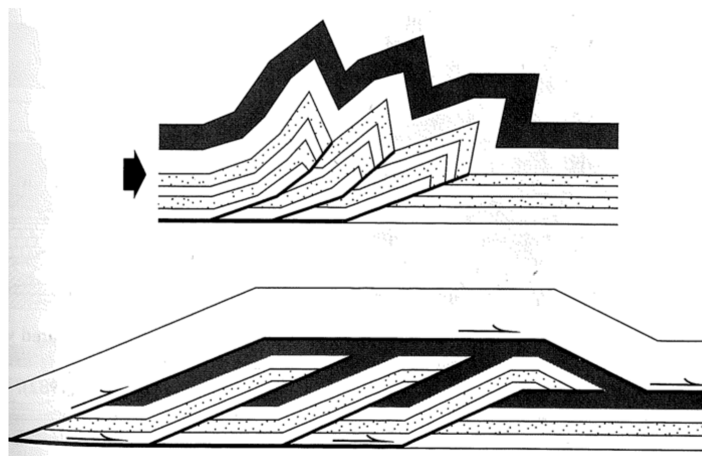


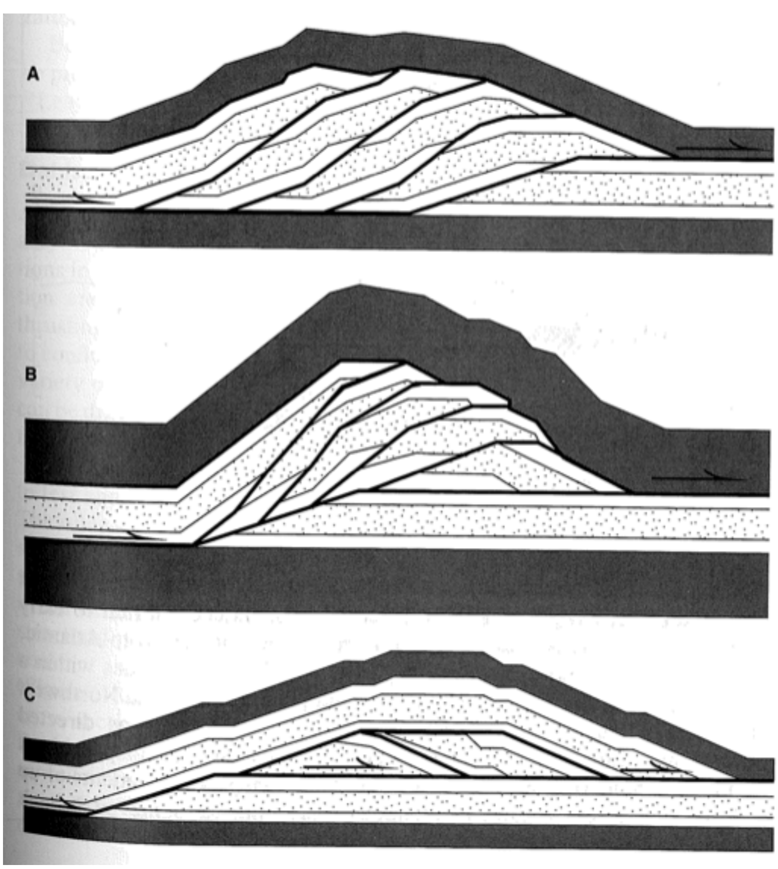

## Out-of-Sequence Thrust Fault System

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

## Imbricate Fans vs. Duplexes

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





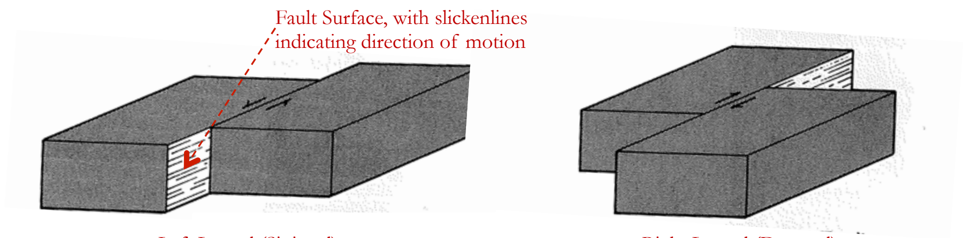

## Forms of Duplexes

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

# Structural Geology: Strike-Slip or Transform Faults

## Strike-Slip Faults

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

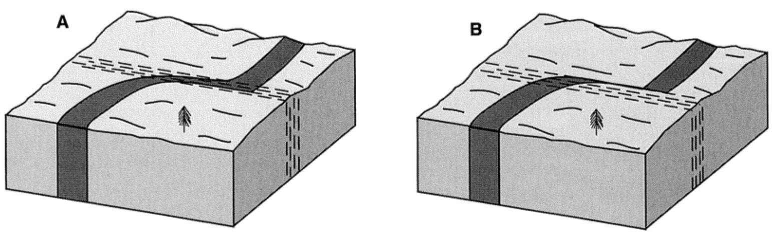



Left Lateral (Sinistral) Strike-Slip Fault

Right Lateral (Dextral) Strike-Slip Fault

## Ductile Shear Zones

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

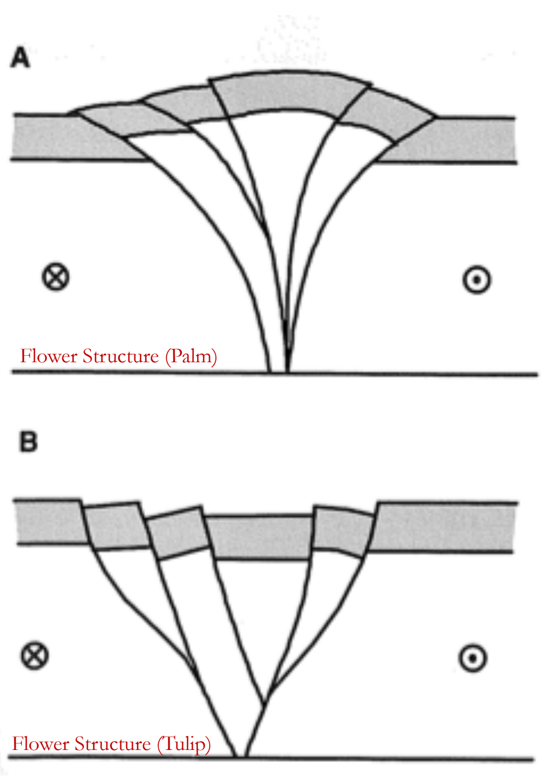



Continuous Shear Zone

Discontinuous Shear Zone

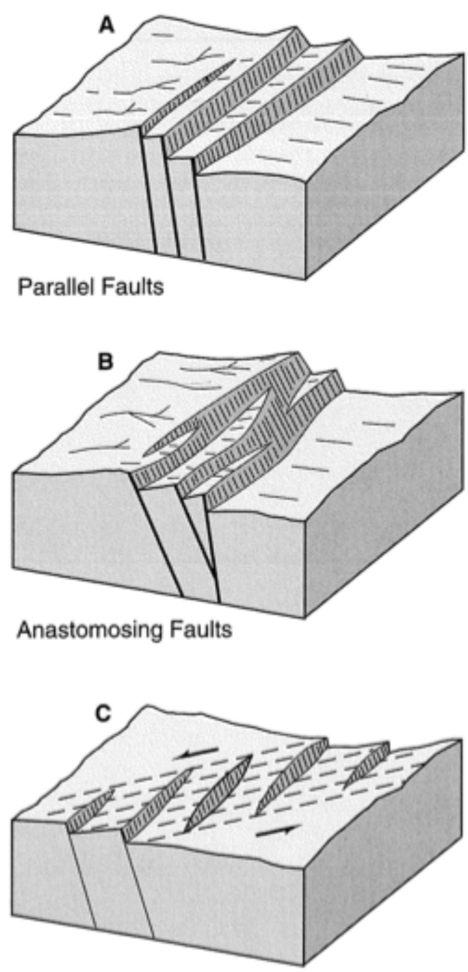
## Brittle Shear Zones

Figures from Davis & Reynolds, 1996.




Flower Structure (Palm)

Flower Structure (Tulip)




Parallel Faults

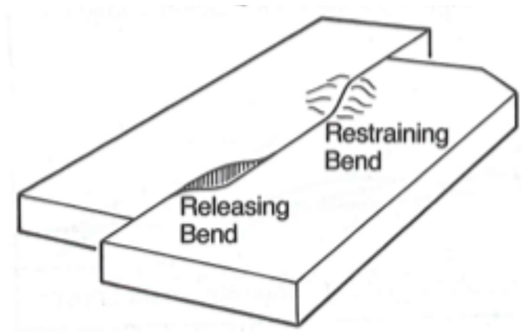
Anastomosing Faults

En Echelon Faults

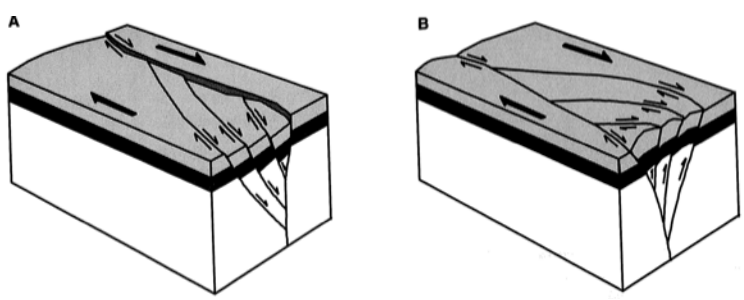
# Structural Geology: Strike-Slip or Transform Faults

## Bends in Strike-Slip Faults

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



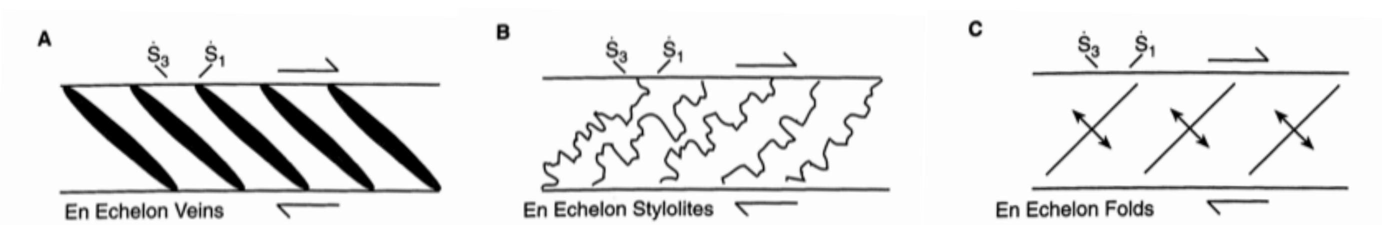

## Strike-Slip Duplexes




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

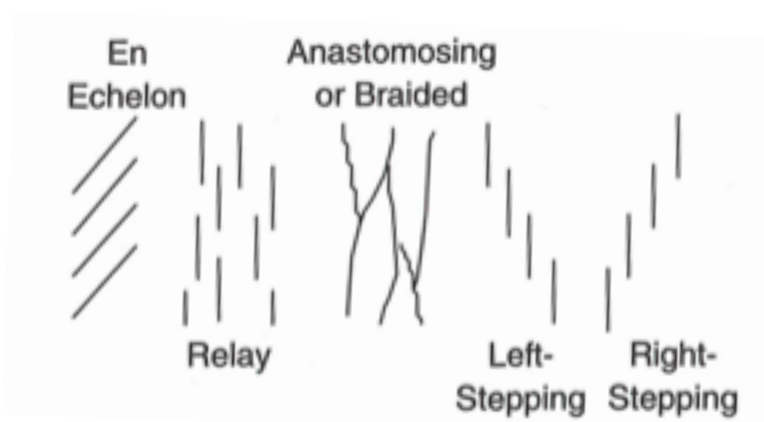
## Slip Indicators in Strike-Slip Systems

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




## Even more Geometric Arrangements of Strike-Slip Faults

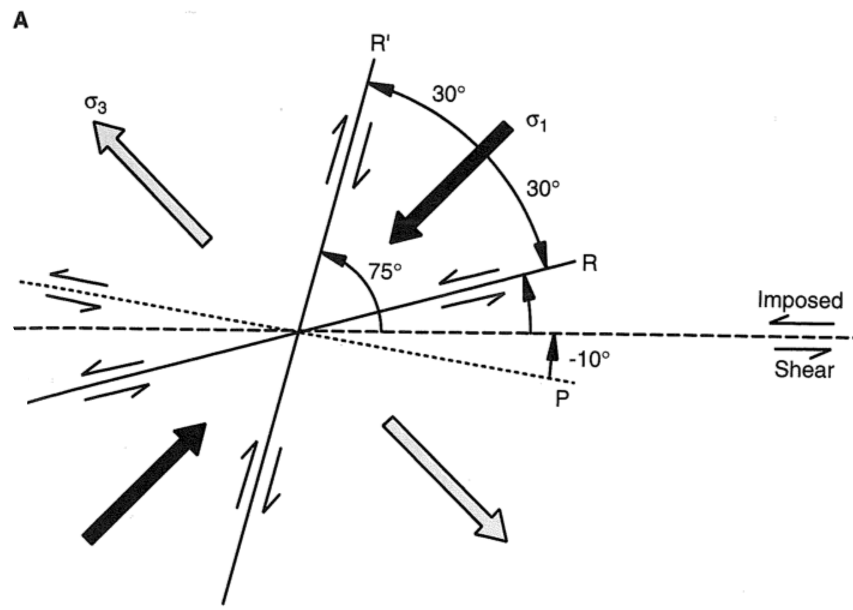
Figures from Davis & Reynolds, 1996.

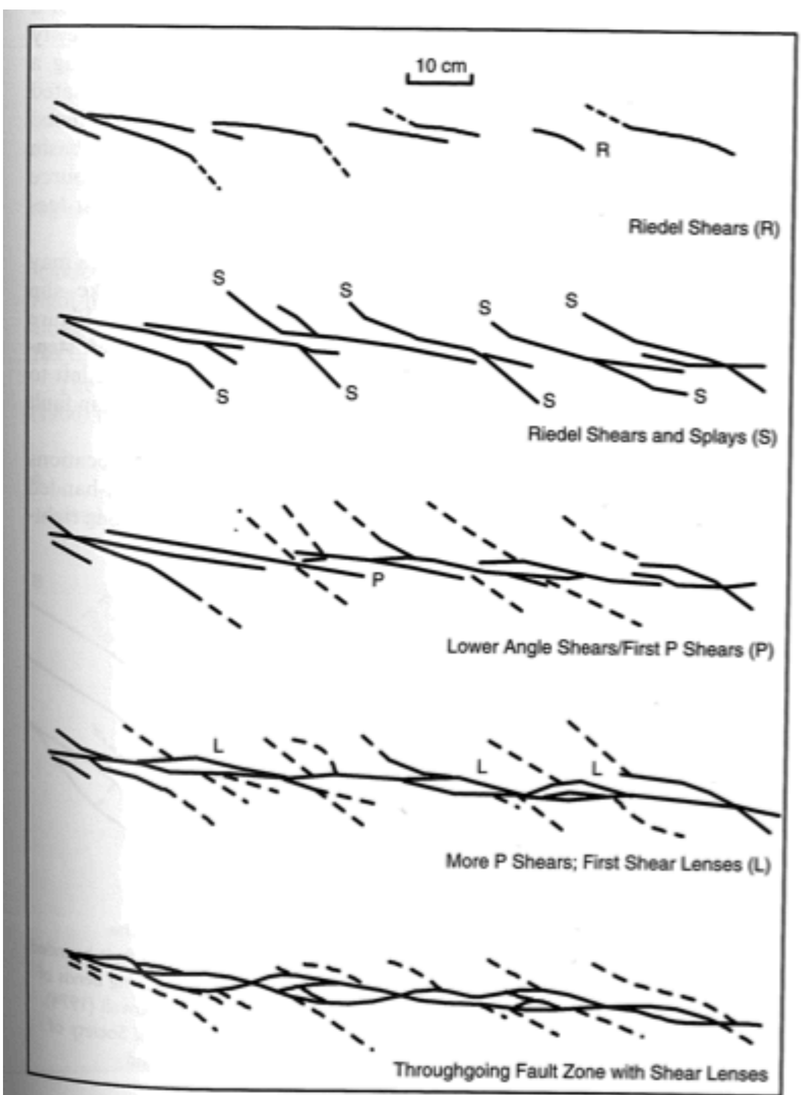


# Structural Geology: Strike-Slip or Transform Faults

## Riedel Shears

When under compression, rocks tend to form fail with faults forming 30° from the primary compressional stress. In a strike-slip fault, the primary compressional stress ($\sigma_1$) is 45° away from the plane of strike-slip shearing. The combination of these two facts results in fractures at interesting angles with respect to the motion of shear. These are called Riedel shears. The figure below shows a left-handed strike-slip zone. Figures from Davis & Reynolds, 1996.




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

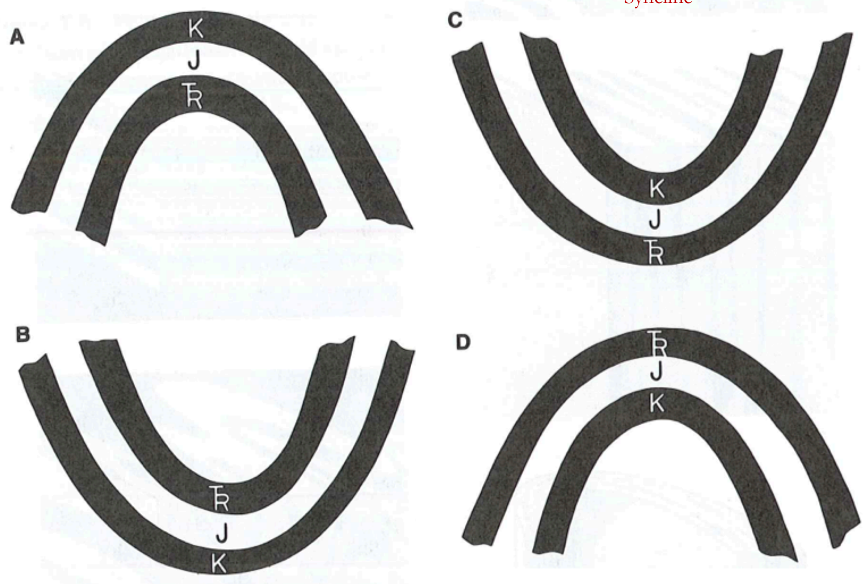
# Structural Geology: Folds

## Anticlines & Antiforms, and Synclines & Synforms

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

Anticline

Syncline

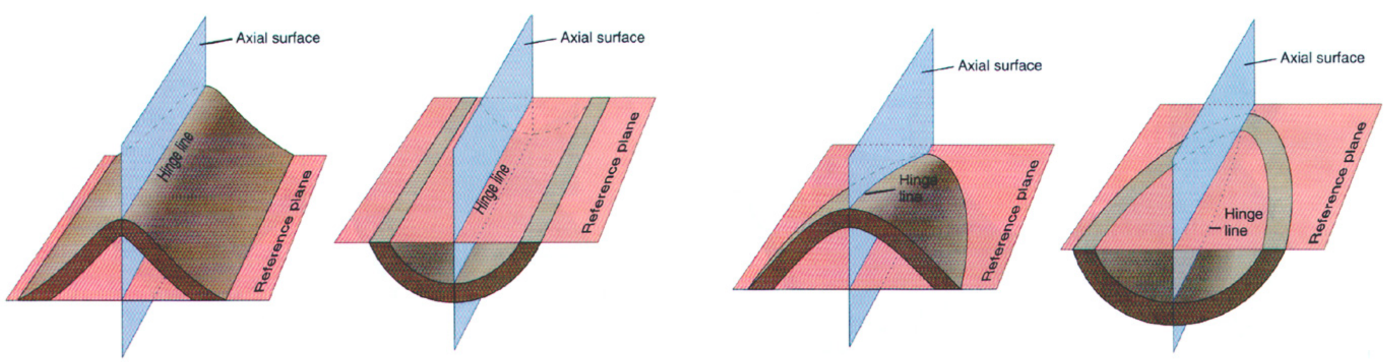



Antiform

Synform

## Plunging Folds

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




Non-plunging antiform

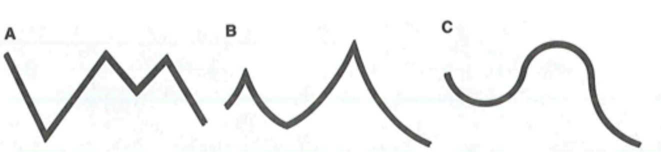
Non-plunging synform

Plunging antiform

Plunging synform

## Fold Shapes

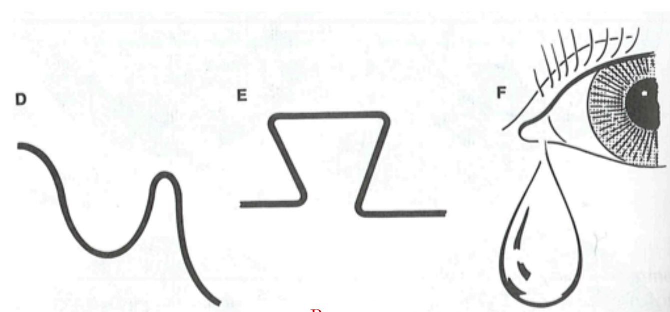
Folds can come in a variety of shapes. Davis & Reynolds, 1996.




Chevron

Cuspate

Circular




Elliptical

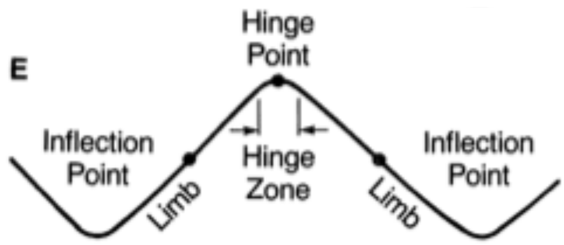
Box (Conjugate)

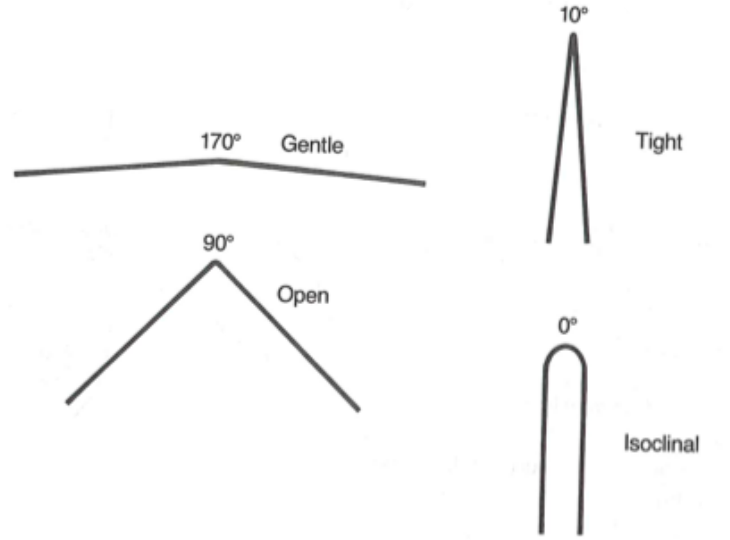
Teardrop

# Structural Geology: Folds

## Fold Tightness

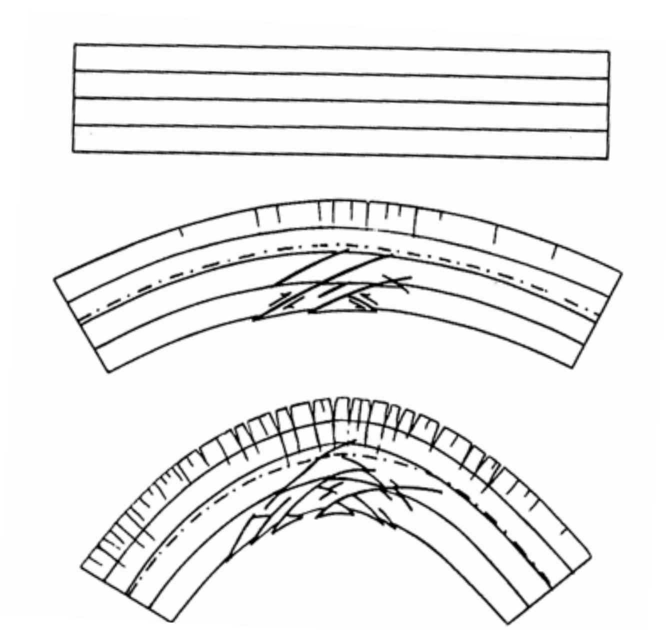
Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.



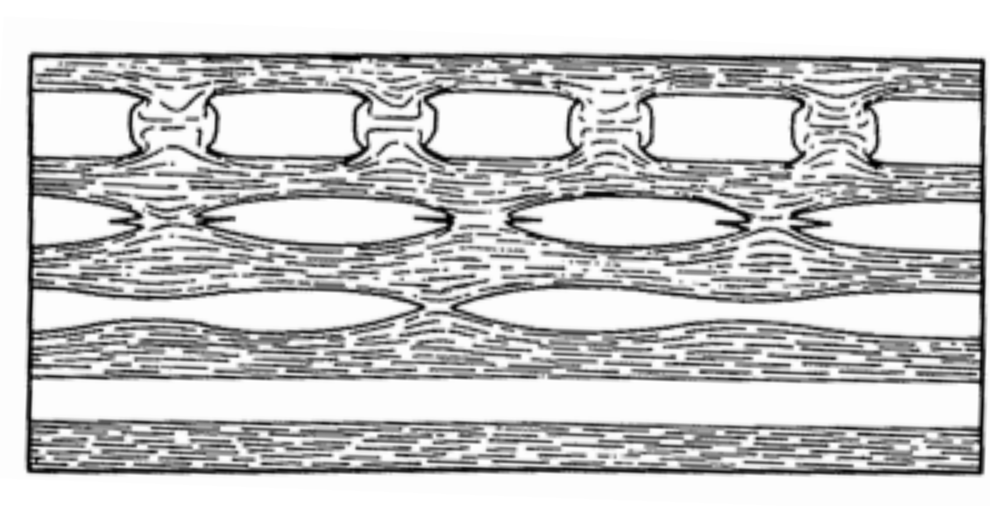

## Minor Structures in Folds

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



## Boudins

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



# Geologic Map Symbols

| No. | Symbol labels | Description |
|---|---|---|
| 1 | 65 40 | Contact, showing dip where trace is horizontal, and strike and dip where trace is inclined |
| 2 | | Contact, located approximately (give limits) |
| 3 | | Contact, located very approximately, or conjectural |
| 4 | | Contact, concealed beneath mapped units |
| 5 | | Contact, gradational (optional symbols) |
| 6 | | Fault, nonspecific, well located (optional symbols) |
| 7 | | Fault, nonspecific, located approximately |
| 8 | | Fault, nonspecific, assumed (existence uncertain) |
| 9 | | Fault, concealed beneath mapped units |
| 10 | 75 50–65 ~60 | Fault, high-angle, showing dip (left) and approximate dips |
| 11 | ~25 32 | Fault, low-angle, showing approximate dip and strike and dip |
| 12 | 67 D | Fault, high-angle normal (D or ball and bar on downthrown side) |
| 13 | 72 R | Fault, reverse (R on upthrown side) |
| 14 | 90 | Fault, high-angle strike-slip (example is left lateral) |
| 15 | 36 T | Fault, thrust (T on overthrust side) |
| 16 | D | Fault, low-angle normal or detachment (D on downthrown side) |
| 17 | | Fault, low-angle strike-slip (example is right lateral) |
| 18 | 20 | Fault, low-angle, overturned (teeth in direction of dip) |
| 19 | D1 D2 D3 | Optional sets of symbols for different age-groups of faults |
| 20 | | Fault zone or shear zone, width to scale (dip and other accessory symbols may be added) |
| 21 | 18 75 | Faults with arrows showing plunge of rolls, grooves or slickensides |
| 22 | 32 | Fault showing bearing and plunge of net slip |
| 23 | | Point of inflection (bar) on a high-angle fault |
| 24 | 45 T | Points of inflection on a strike-slip fault passing into a thrust |
| 25 | | Fault intruded by a dike |
| 26 | | Faults associated with veins |
| 27 | 5 | Anticline, showing trace and plunge of hinge or crest line (specify) |
| 28 | 10 80 | Syncline (as above), showing dip of axial surface or trough surface |
| 29 | | Folds (as above), located approximately |
| 30 | | Folds, conjectural |
| 31 | | Folds beneath mapped units |
| 32 | | Asymmetric folds with steeper limbs dipping north (optional symbols) |
| 33 | | Anticline (top) and syncline, overturned |
| 34 | | Antiformal (inverted) syncline |
| 35 | | Synformal (inverted) anticline |
| 36 | | Antiform (top) and synform (stratigraphic sequence unknown) |
| 37 | | Separate dome (left) and basin |
| 38 | | Culmination (left) and depression |
| 40 | | Vertically plunging anticline and syncline |
| 41 | 45 | Monocline, south-facing, showing traces of axial surfaces |
| 42 | 47 | Steeply plunging monocline or flexure, showing trace in horizontal section and plunge of hinges |
| 43 | 9 | Plunge of hinge lines of small folds, showing shapes in horizontal section |
| 44 | 30 | Strike and dip of beds or bedding |
| 45 | 22 | Strike and dip of overturned beds |
| 46 | 15 15 90 | Strike and dip of beds where stratigraphic tops are known from primary features |
| 47 | | Strike and dip of vertical beds or bedding (dot is on side known to be stratigraphically the top) |
| 48 | | Horizontal beds or bedding (as above) |
| 49 | | Approximate (typically estimated) strike and dip of beds |
| 50 | ~90 30 ~30 | Strike of beds exact but dip approximate |
| 51 | 12 12 | Trace of single bed, showing dip where trace is horizontal and where it is inclined |
| 52 | 15 15 15 | Strike and dip of foliation (optional symbols) |
| 53 | | Strike of vertical foliation |
| 54 | | Horizontal foliation |
| 55 | 12 12 12 | Strike and dip of bedding and parallel foliation |
| 56 | 10 5 | Strike and dip of joints (left) and dikes (optional symbols) |
| 57 | | Vertical joints (left) and dikes |
| 58 | | Horizontal joints (left) and dikes |
| 59 | qz-py | Strike and dip of veins (optional symbols) |
| 60 | qz-py | Vertical veins |
| 61 | qz Py | Horizontal veins |
| 62 | 35 | Bearing (trend) and plunge of lineation |
| 63 | L | Vertical and horizontal lineations |
| 64 | 20 | Bearing and plunge of cleavage-bedding intersection |
| 65 | | Bearing and plunge of cleavage-cleavage intersections |
| 66 | bio | Bearings of pebble, mineral, etc. lineations |
| 67 | 40 | Bearing of lineations in plane of foliation |
| 68 | 15 | Horizontal lineation in plane of foliation |
| 69 | | Vertical lineation in plane of vertical foliation |
| 70 | | Bearing of current from primary features; from upper left: general; from cross-bedding; from flute casts; from imbrication |
| 71 | | Bearing of wind direction from dune forms (left) and cross-bedding |
| 72 | | Bearing of ice flow from striations (left) and orientation of striations |
| 73 | | Bearing of ice flow from drumlins |
| 74 | | Bearing of ice flow from crag and tail forms |
| 75 | | Spring |
| 76 | T T | Thermal spring |
| 77 | M M | Mineral spring |
| 78 | | Asphaltic deposit |
| 79 | BIT | Bituminous deposit |
| 80 | | Sand, gravel, clay, or placer pit |

From Compton, 1985

# Geologic Map Symbols

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

# Fossil and Structural Symbols for Stratigraphic Columns

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

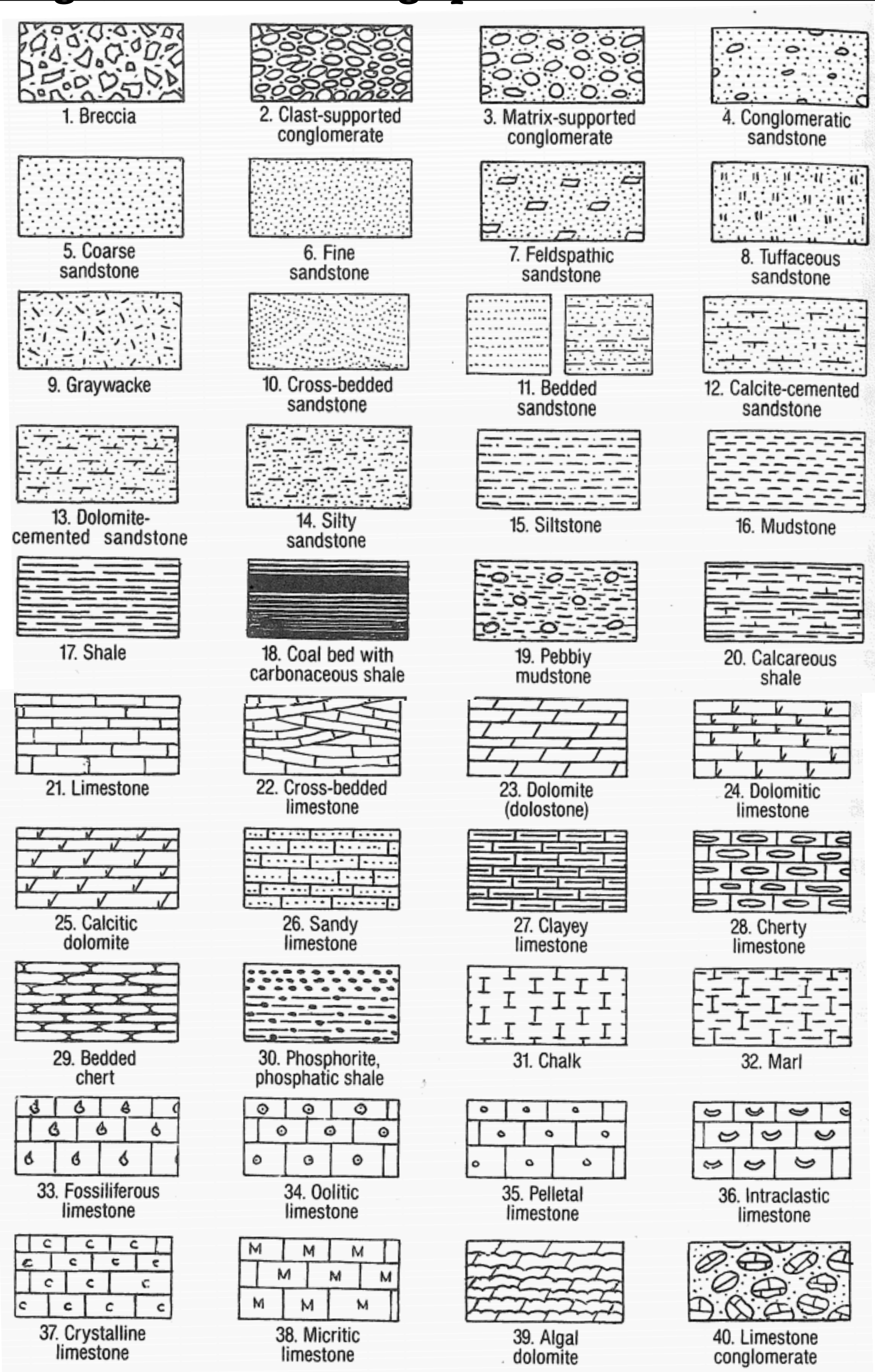
Tree trunk fallen
Trilobites
Vertebrates
Wood
Beds distinct
Beds obscure
Unbedded
Graded beds
Planar cross-bedding
Trough cross-bedding
Ripple structures
Cut and fill
Load casts

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

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

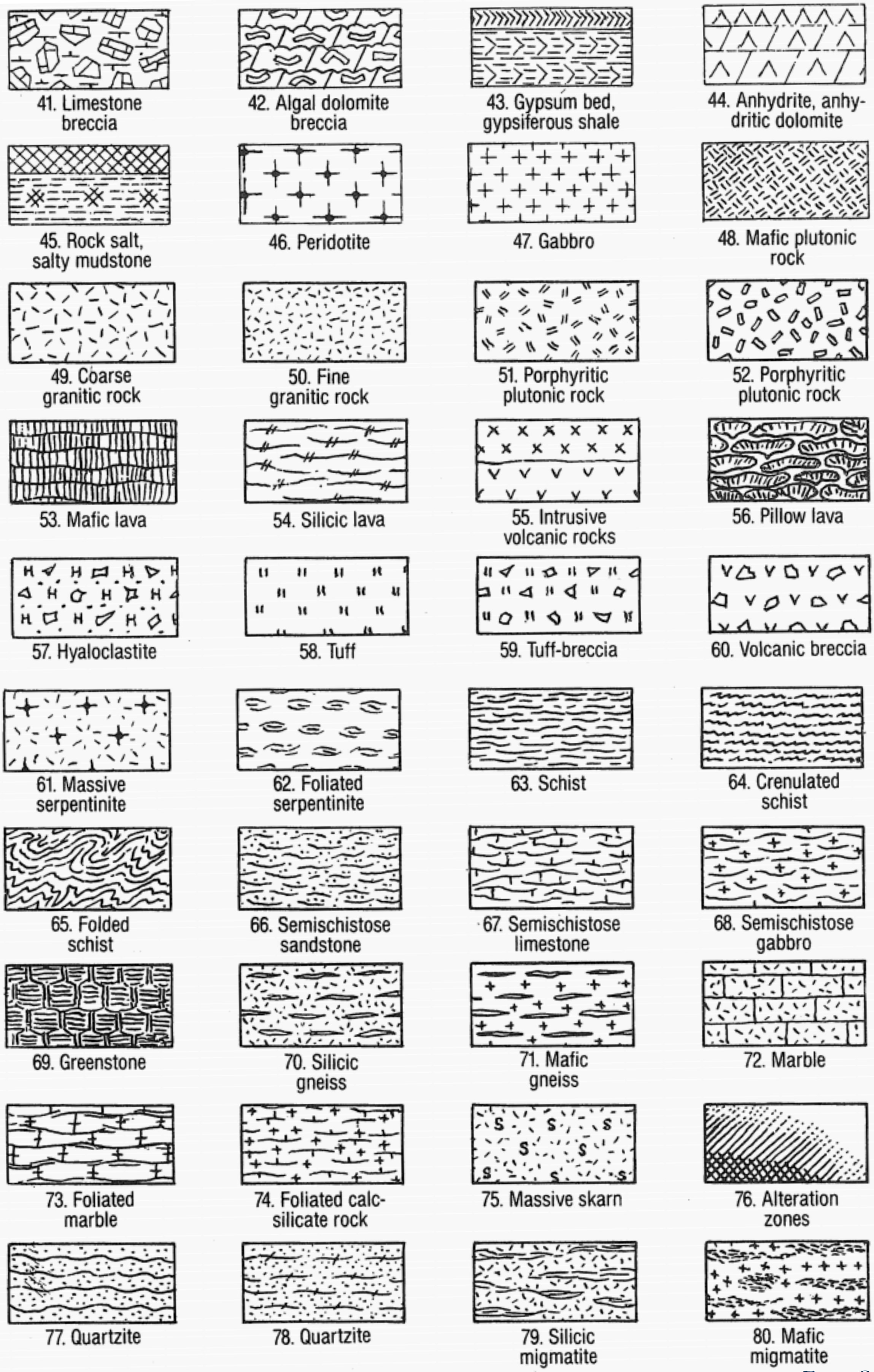
From Compton, 1985

# Lithologic Patterns for Stratigraphic Columns & Cross Sections



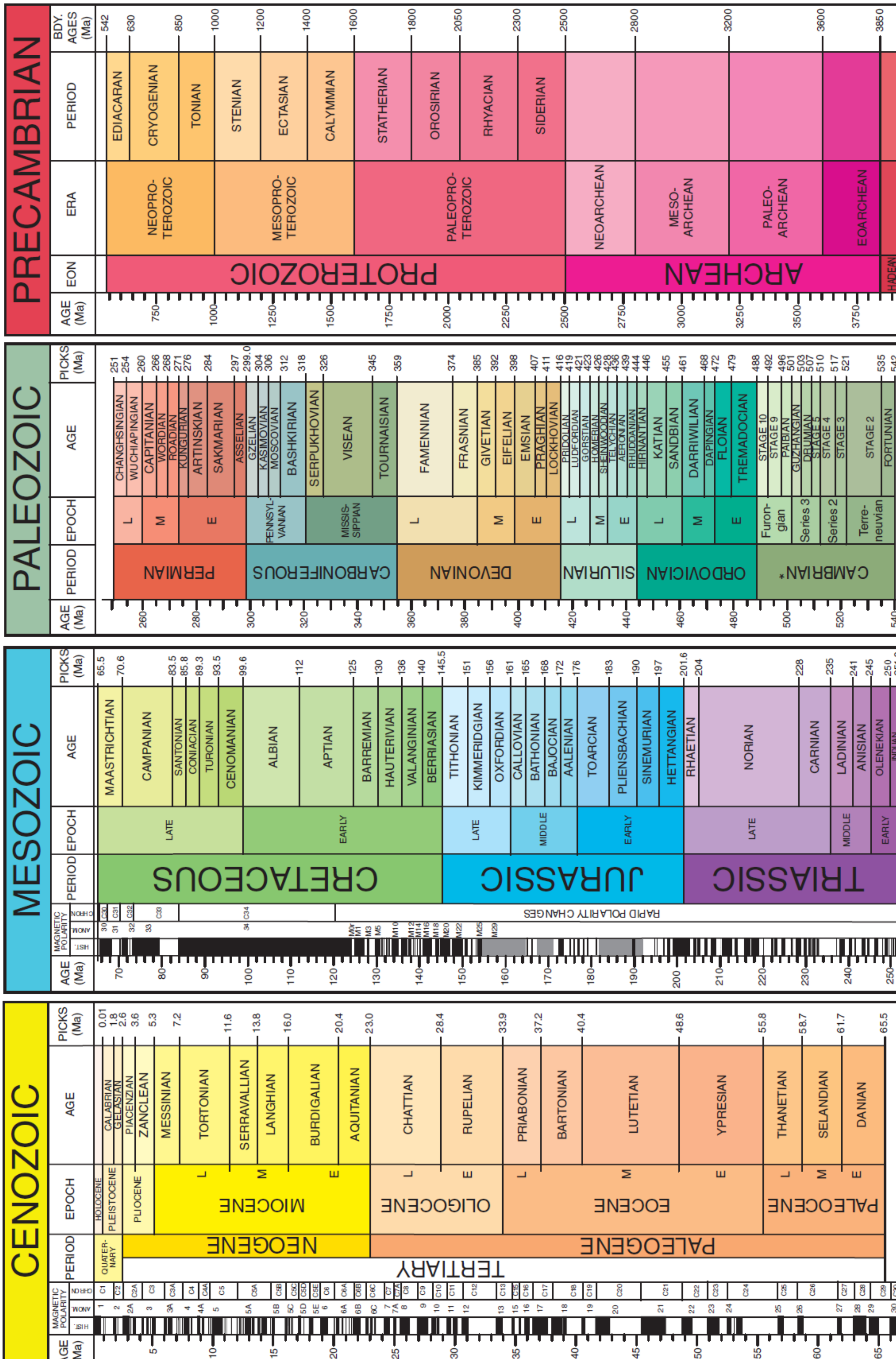

From Compton, 1985

# Lithologic Patterns for Stratigraphic Columns & Cross Sections




From Compton, 1985

# Geologic Timescale

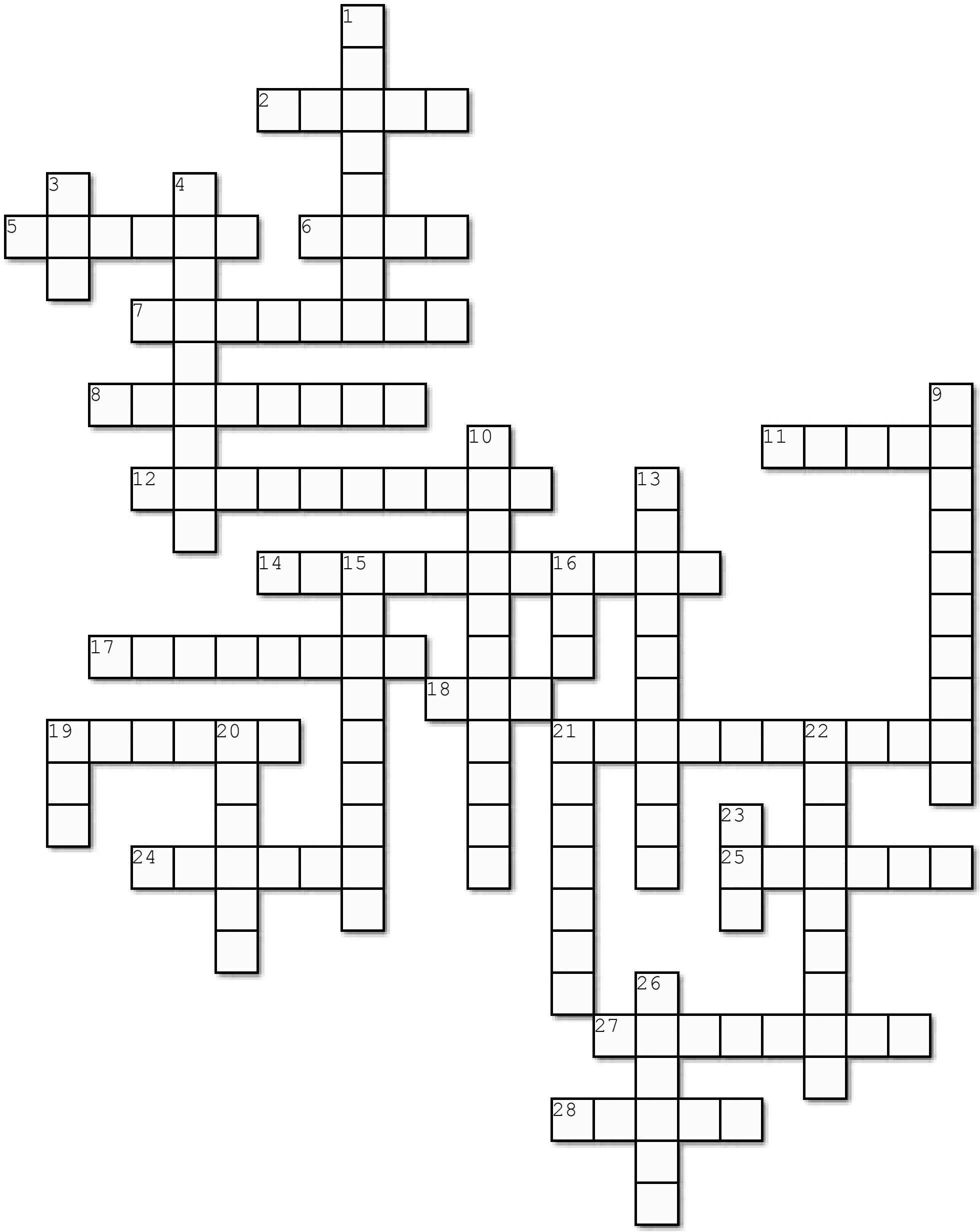



2009 version, from the Geologic Society of A

Name: ______________________________

# LPL Field Trip Crossword!

Complete the crossword below. Remember who put this together if you need help with clues.



## Across

**2.** There's a movie about this place
**5.** Communication tools
**6.** Volcanics
**7.** Death Valley's previous name
**8.** Field trip guide assembler!
**11.** Final field trip location
**12.** Initial field trip location
**14.** MER
**17.** What we're driving
**18.** A friendly pet
**19.** Preserve
**21.** Burnt, like ice cream
**24.** Where we work
**25.** Free _______ (MER)
**27.** Lowest point in the US
**28.** Fearless Leader

## Down

**1.** Igneous rock
**3.** Where we work, abr.
**4.** The first Mars rover
**9.** U2
**10.** Main field trip location
**13.** An early Mars lander
**15.** Type of science
**16.** Folks who administer this area
**19.** Margaret's cat, for short
**20.** The first Mars lander
**21.** We drive in a
**22.** Another name for MSL
**23.** Big Mars rover
**26.** Rock from a volcano

SURVIVING AT AN OBSERVATORY
OR: HOW TO TALK TO ASTRONOMERS

## Conversation Prompts:

So what's your favorite branch of the H-R diagram? Mine is the yellow part!
Isn't hydrogen neat? Especially when it's burning!
Do you like submarines? (Note: this is universal, everyone likes submarines)
What's your Tisserand parameter (with respect to Jupiter)?

## How to end a conversation quickly:

What's your sign? (If this is used on you, recover by saying 'positive' or 'negative')
Look over there! A population 3 star!

## If they ask what you do:

I'm interested in low-redshift dynamics.
I study stellar remnants at T_eff ~ 200K.
I study debris disks in the post-disk phase.
I shoot lasers at rocks to see if the rocks are slightly different rocks than the rocks I expected.
I infer texture from point sources.

## Humor:

If I could rearrange the alphabet, I'd put O, B, A, F, G, K, and M together!

An active galaxy walks into a bar. The bartender asks "What'll it be, Quasar?" The galaxy turns to face the bartender, who says "Oh excuse me, what'll it be, Blazar?"

Lord Rayleigh and Lord Jeans go flower picking and start with the red ones and then the yellow ones and conclude the flowers are well described by a power law and return back to the bar to write a theory about England's infestation of blue and purple flowers.

## Translation Guide:

James Webb Space Telescope = 'tenure decision maker' (see also: mechanical failure)

High Redshift Dusty Star Forming Galaxy = 'fitting a power law to four blobs'

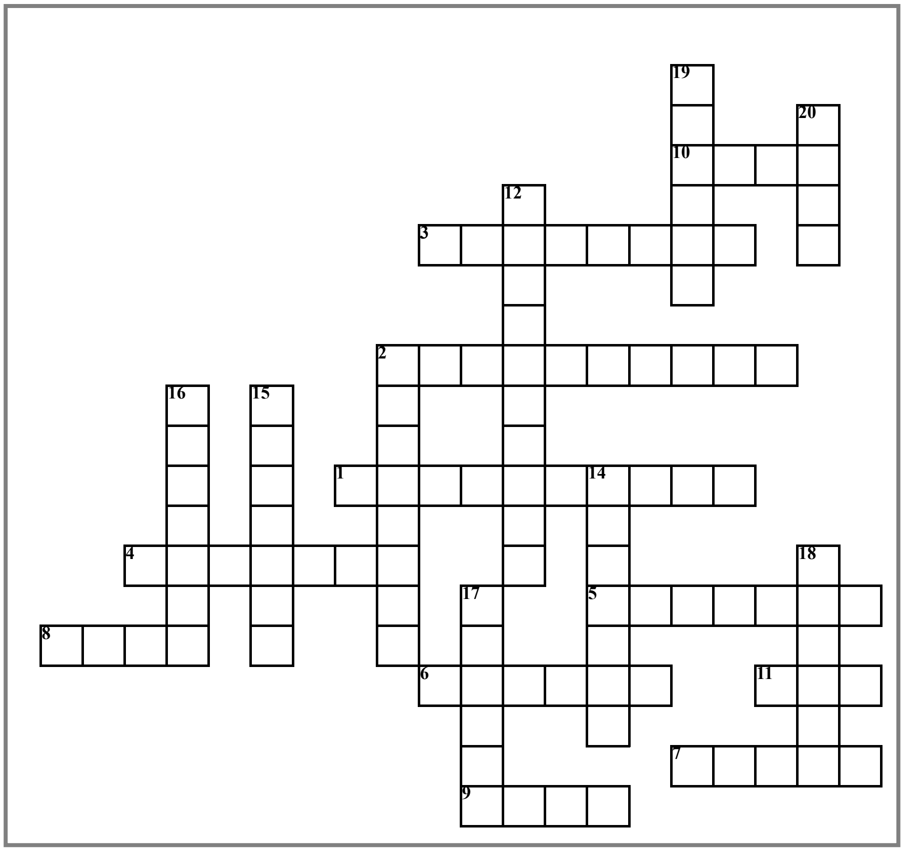
Cosmology = 'astronomy for people who like math'

# Mortal Kombat

This crossword is for all Mortal Kombat fans out there. It's an small introduction to some of the main characters.

Created by Anonymous






## ACROSS

1. Lieutenant of Special Forces
2. Soul stealer
3. Fire spectre
4. Kitana's false sister
5. Shaolin monk with razor hat
6. Princess of Outworld
7. Cyborg nicknamed "Mustard"
8. Kitana's best friend
9. Brotherhood of shadow
10. Leader of Black Dragon
11. Major in Special Forces

## DOWN

12. Movie star
2. Emperor of Outworld
14. Savior of Earthrealm
15. Ice assassin
16. Reptilian humanoid
17. Thunder god
18. Tarkartan
19. Cyborg nicknamed "Ketchup"
20. Grand Champion of Mortal Kombat

# SUDOKU

Created by Peter Ritmeester / Presented by Will Shortz

## SUDOKU 1

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

597A

## SUDOKU 2

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

597B

### ANSWERS TO SUDOKU 1

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

### ANSWERS TO SUDOKU 2

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

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

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

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

9

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| | | 8 | 2 | | | | 1 | 5 |
| 2 | | | 3 | 6 | | | | |
| 9 | 5 | 6 | | | | | 2 | |
| | | | | | | | | 4 |
| 7 | | 5 | | 3 | 2 | | | |
| | | | 6 | 5 | 7 | | 8 | |
| | 6 | 1 | | | | 4 | | |
| | | | 1 | 4 | 3 | 5 | | |
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| 8 | 2 | | | | | 9 | 3 | |
| | 6 | | | | 2 | | | |
| | | | 3 | 2 | | | | 7 |
| | | 5 | | 9 | | | 8 | 2 |
| 6 | 1 | | | | | | | |
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| 9 | | 6 | | 5 | | | | |
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11

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| | | 7 | 6 | 1 | | | | |
| | 1 | 6 | 5 | 9 | | | 8 | |
| | | | 7 | | | | | 1 |
| | 9 | 8 | | | | 6 | 2 | |
| 8 | | | | | 9 | | 4 | |
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| | 6 | 2 | | | 9 | 1 | | |
| 9 | | | | 8 | 4 | | | |
| | 9 | | | | | 6 | | 5 |
| 3 | | 8 | | 2 | | | | |
| | | 5 | | | 8 | 2 | 1 | |
| 8 | | | 7 | 6 | | | 2 | |
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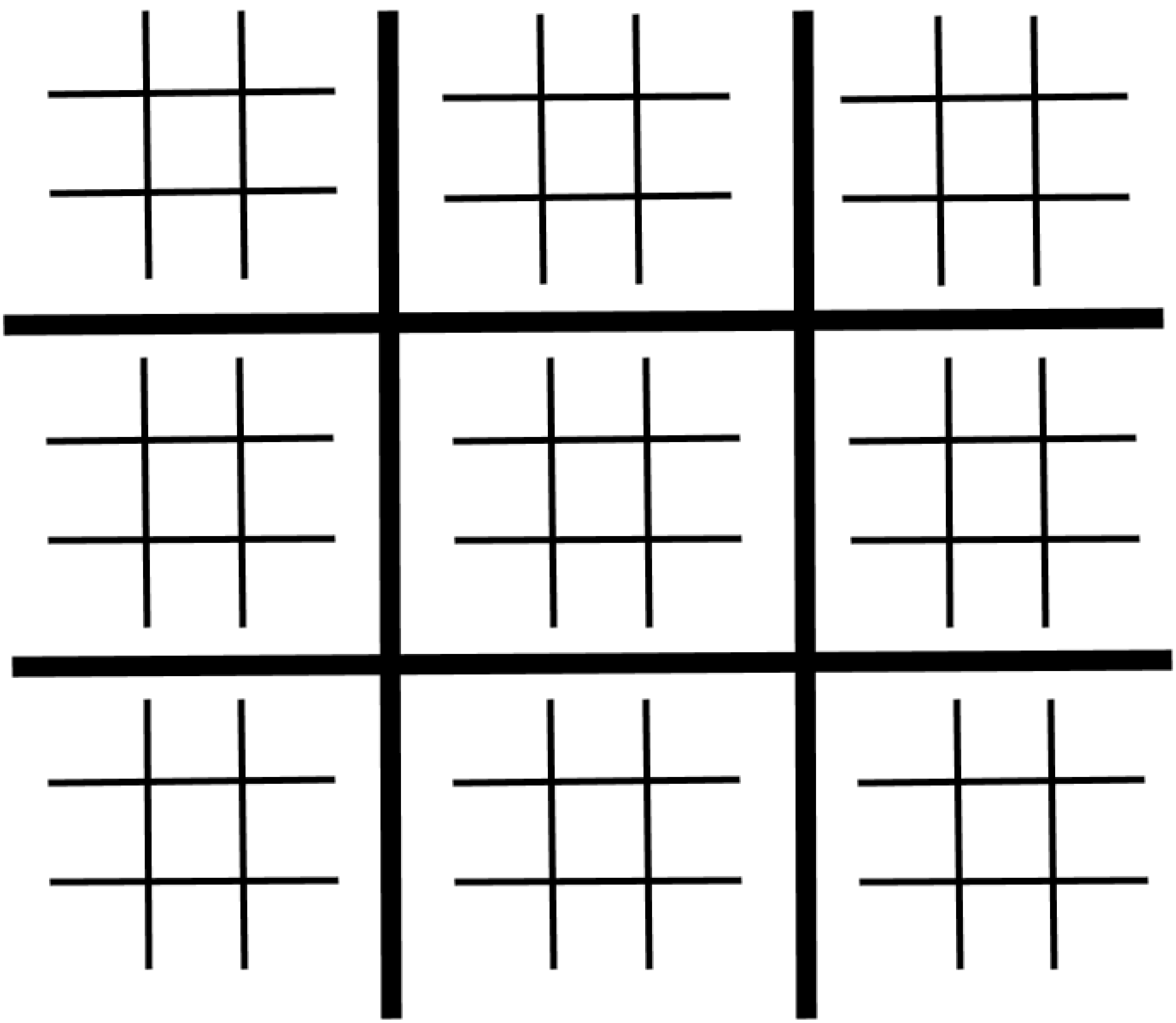
# SUPER TIC TAC TOE

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



**Riddles:**

1. What goes up and down stairs without moving?
2. Give it food and it will live; give it water and it will die.
3. What can you catch but not throw?
4. I run, yet I have no legs. What am I?
5. Take one out and scratch my head, I am now black but once was red.
6. Remove the outside, cook the inside, eat the outside, throw away the inside.
7. What goes around the world and stays in a corner?
8. What gets wetter the more it dries?
9. The more there is, the less you see.
10. They come at night without being called and are lost in the day without being stolen.
11. What kind of room has no windows or doors?
12. I have holes on the top and bottom. I have holes on my left and on my right. And I have holes in the middle, yet I still hold water. What am I?
13. I look at you, you look at me, I raise my right, you raise your left. What is this object?
14. It has no top or bottom but it can hold flesh, bones, and blood all at the same time. What is this object?
15. The more you take the more you leave behind.
16. Light as a feather, there is nothing in it; the strongest man can't hold it for much more than a minute.
17. As I walked along the path I saw something with four fingers and one thumb, but it was not flesh, fish, bone, or fowl.
18. What can run but never walks, has a mouth but never talks, has a head but never weeps, has a bed but never sleeps?
19. I went into the woods and got it, I sat down to seek it, I brought it home with me because I couldn't find it.
20. What can fill a room but takes up no space?
21. It is weightless, you can see it, and if you put it in a barrel it will make the barrel lighter?
22. No sooner spoken than broken. What is it?
23. Only two backbones and thousands of ribs.
24. Four jolly men sat down to play, and played all night till the break of day. They played for cash and not for fun, with a separate score for every one. When it came time to square accounts, they all had made quite fair amounts. Now, not one has lost and all have gained, Tell me, now, this can you explain?
25. Jack and Jill are lying on the floor inside the house, dead. They died from lack of water. There is shattered glass next to them. How did they die?
26. Why don't lobsters share?
27. A barrel of water weighs 20 pounds. What must you add to it to make it weigh 12 pounds?
28. Big as a biscuit, deep as a cup, Even a river can't fill it up. What is it?
29. Clara Clatter was born on December 27$^{th}$, yet her birthday is always in the summer. How is this possible?
30. He has married many women but has never married. Who is he?
31. If a rooster laid a brown egg and a white egg, what kind of chicks would hatch?
32. If you have it, you want to share it. If you share it, you don't have it. What is it?
33. You can't keep this until you have given it.
34. Take off my skin, I won't cry, but you will. What am I?
35. What book was once owned by only the wealthy, but now everyone can have it? You can't buy it in a bookstore or take it from the library.
36. What can go up and come down without moving?
37. What do you fill with empty hands?
38. What do you serve that you can't eat?
39. What do you throw out when you want to use it but take in when you don't want to use it?
40. What goes up and never comes down?
41. What has a foot on each side and one in the middle?
42. What has to be broken before it can be used?
43. What kind of coat can be put on only when wet?
44. What question can you never answer "yes" to?
45. What's the greatest worldwide use of cowhide?
46. Which is correct to say, "The yolk of the egg are white?" or "The yolk of the egg is white?"
47. You answer me, although I never ask you questions. What am I?

Answers: Carpet 2. Fire 3. A cold 4. A nose 5. A match 6. Corn 7. A stamp 8. Towel 9. Darkness 10. Stars 11. A mushroom 12. A sponge 13. A mirror 14. A ring 15. Footsteps 16. Breath 17. Glove 18. River 19. Splinter 20. Light 21. A hole 22. Silence 23. Railroad 24. Four men in a dance band 25. Jack and Jill are goldfish. 26. They're shellfish. 27. Holes 28. A kitchen strainer 29. She lives in the Southern Hemisphere. 30. A priest 31. None. Roosters don't lay eggs. 32. A secret 33. A promise 34. An onion 35. A telephone book 36. The temperature 37. Gloves 38. A tennis ball 39. An anchor 40. Your age 41. A yardstick 42. An egg 43. A coat of paint 44. "Are you asleep?" 45. To hold cows together 46. Neither, the yolks are yellow. 47. A telephone