

DEATH VALLEY

MARCH 28TH – APRIL 1ST, 2024

LUNAR AND PLANETARY LABORATORY

UNIVERSITY OF ARIZONA

PTYS 590

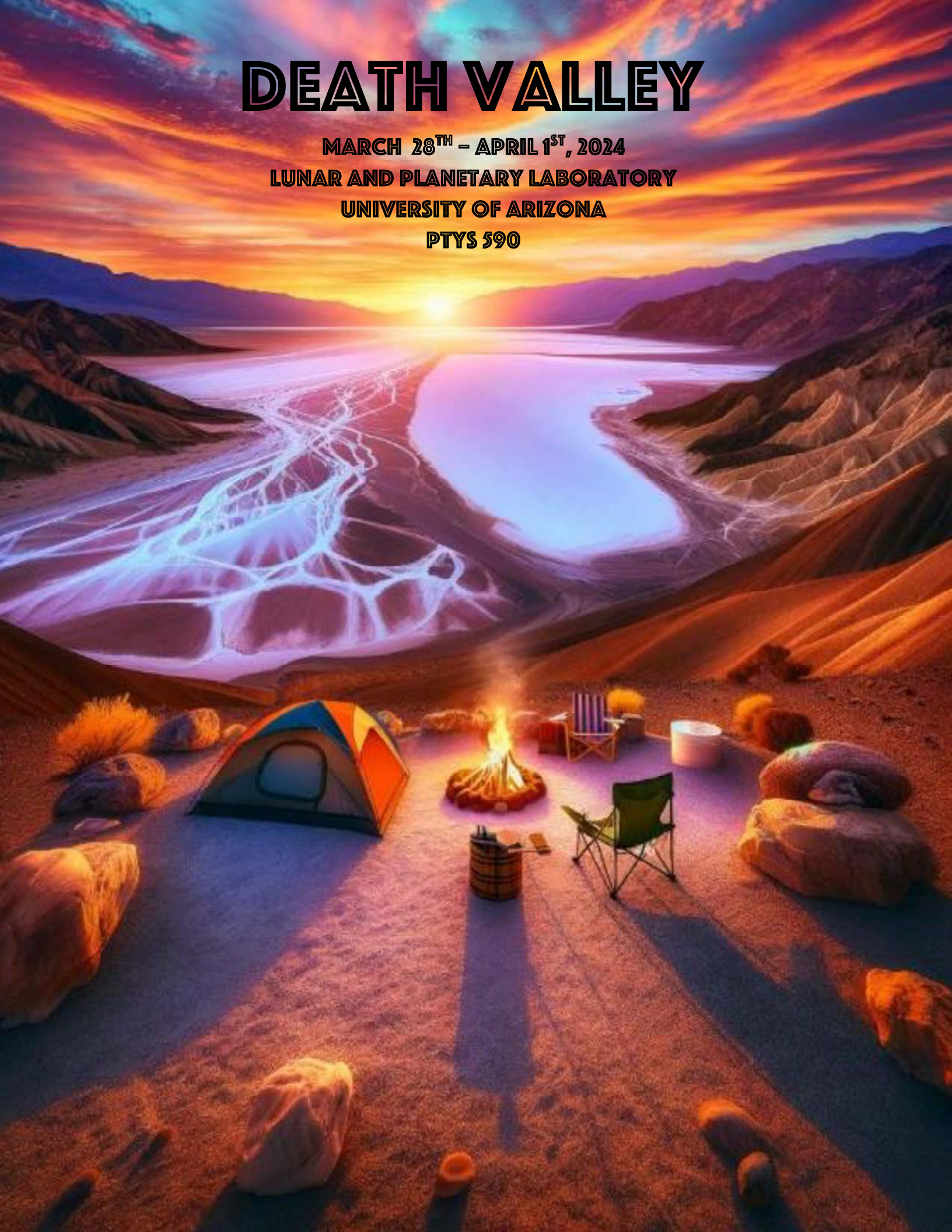


Table of contents

Topic	Student	Page
Emergency contacts	-	2
Maps and itinerary	-	3
Playas	Roberto Aguilar	11
Hot springs	Rahul Arora	16
Desert varnish	Rishi Chandra	20
Lake Manly and paleoshorelines	Michael Daniel	25
Stromatolites	Ruby Fulford	29
Volcanics	Orion Hon	35
Alluvial fans	Rowan Huang	43
Snowball Earth	Rocío Jacobo	48
Lake Tecopa	Arkadeep Roy	53
Dunes and ventifacts	Pratik Santra	58
Habitability and lie detection	Reed Spurling	65
Salt weathering	Beau Prince	71
Pupfish	Anna Taylor	76
Ubehebe Crater	Madison Tuohy	82
Fun & Games	-	87
Geologic Resources	-	91

Compiled by Roberto Aguilar



Logo credit: James Keane

Cover art by Anna Taylor

Emergency Information

U of A Travel Emergency: 520-307-9576
U of A Travel Incident: 800-243-6124
U of A Risk Management: 520-621-1790
Death Valley National Park: 911 or 760-786-2330 (24 hour dispatch)

Jack Holt's cell phone: 512-299-5316

Jack's Garmin InReach: jack.w.holt@inreach.garmin.com

Joe Schools' cell phone: 714-308-2592

DEATH VALLEY - MARCH 28 - APRIL 1, 2024

DAY 1

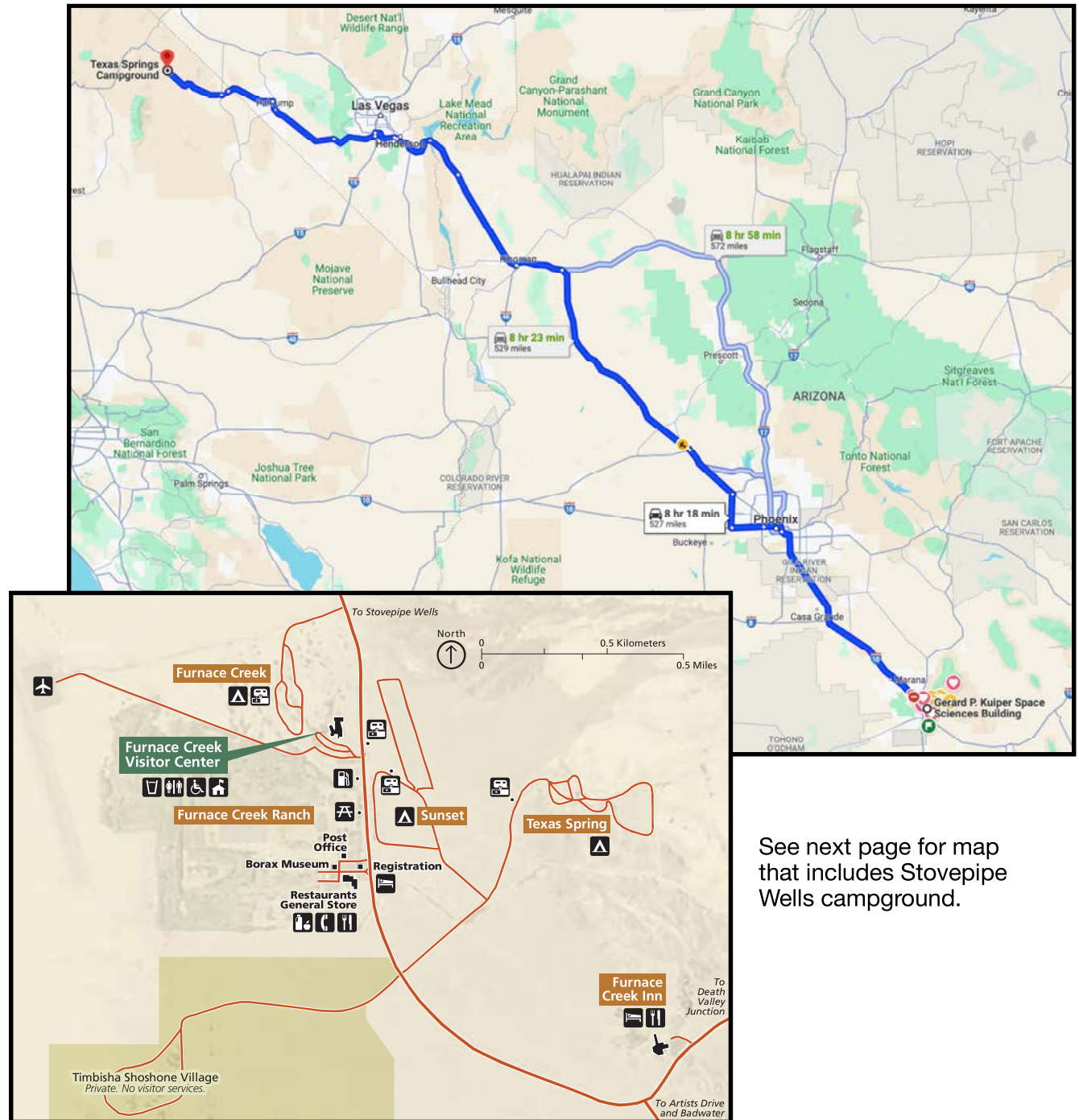
07:00 Meet at Kuiper, load vehicles

08:00 Depart Kuiper

As necessary but not too often - bathroom/fuel/lunch breaks

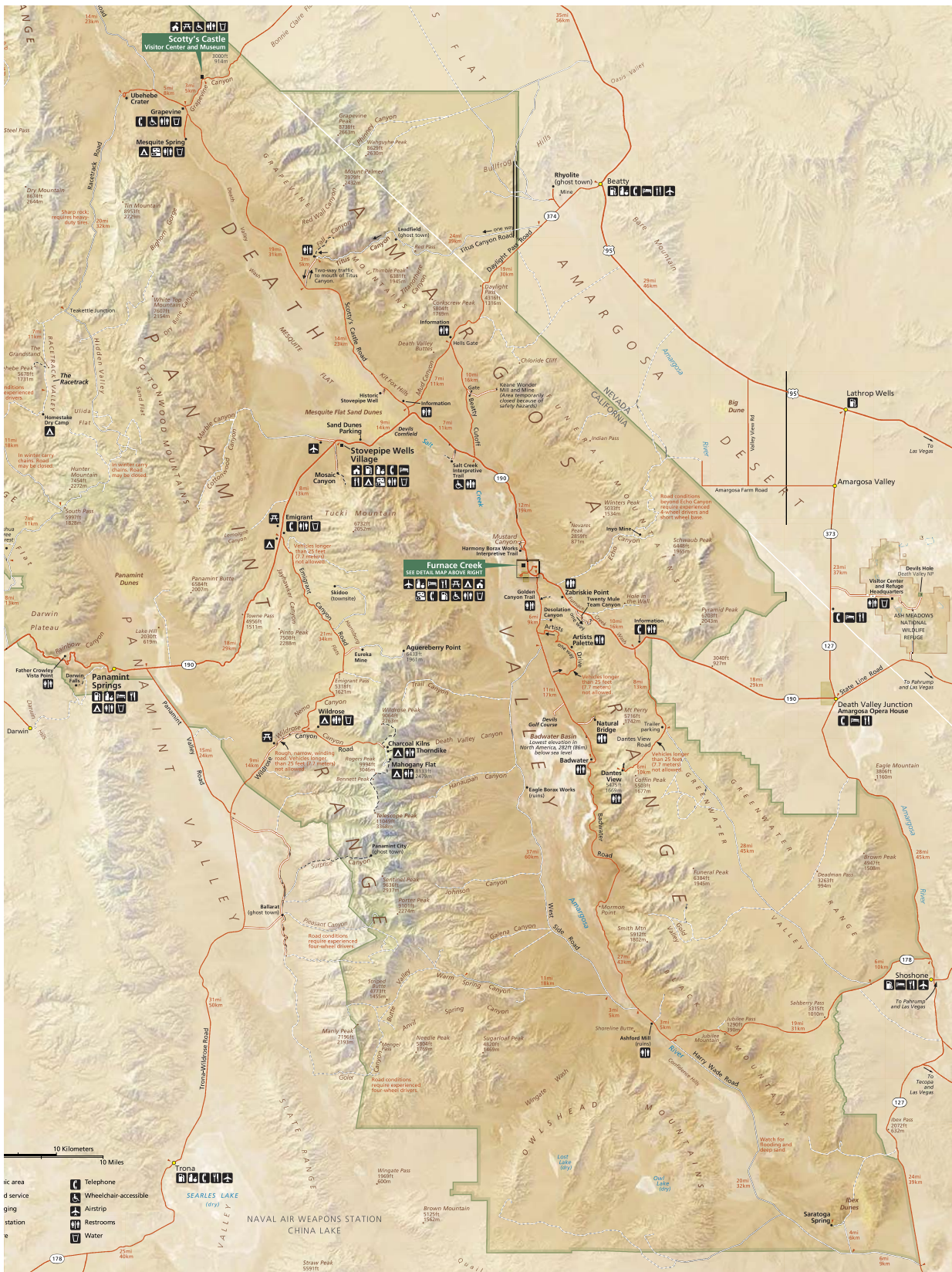
18:00 (hopefully) - Arrive Texas Springs Campground

Backup is Stovepipe Wells campground or Sunset Campground



See next page for map that includes Stovepipe Wells campground.

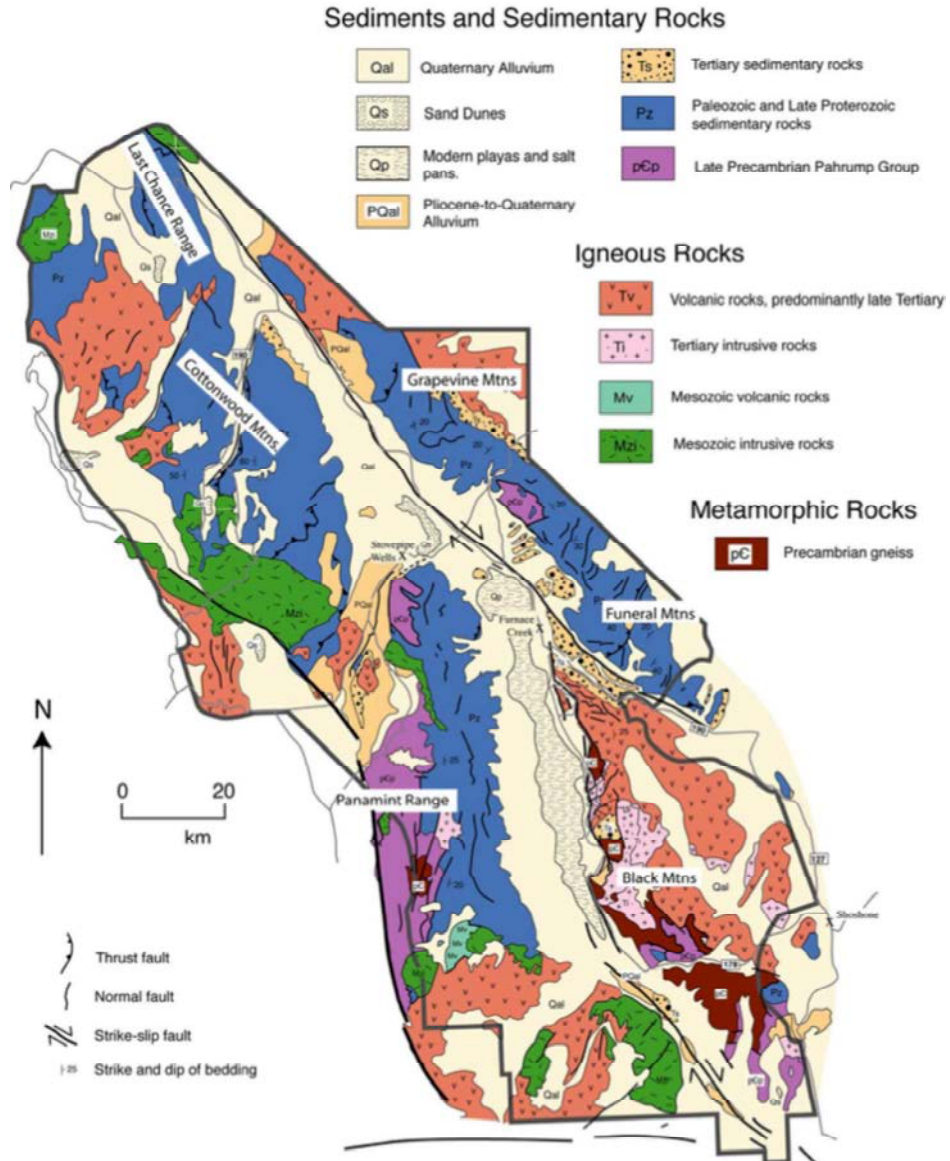
DEATH VALLEY - MARCH 28 - APRIL 1, 2024



Geologic Map

Death Valley National Park, California

compiled by Marli Bryant Miller



DEATH VALLEY - MARCH 28 - APRIL 1, 2024

SOUTHERN VALLEY

08:00 depart camp

08:15 Zabriskie Point, soak in the view, sprinkle in a bit of tectonics, and Orion may begin her story of volcanism (to be continued...)

09:30 Devil's Golf Course - Beau can give us the first scoop on salt polygons

10:30 Badwater Basin - selfies below sea level, walk out on playa if it's not too wet. More polygons if not under water. Reed may be inspired to elucidate us on techniques for life detection. Or maybe later...

11:30 salt weathering site just a bit south, where Beau will continue his salty talk.

12:00 continue south a little more, lunch break where we can join Rowan's alluvial fan club.

13:00 head to a point near Ashford Mill Ruins where we will seek a glimpse of Shoreline Butte, and hike out to it if we are doing okay on time. Michael will explain what we are seeing and invoke images of Lake Manly in its former glory.

14:00 return northbound

15:00 a jaunt up Mars Hill, where Pratik will bestow upon us ventifactual information of weathering. (Don't take any rocks.)

16:00 if we are on time, perhaps a saunter along Artist's drive and Orion will interpret the layers for us, relating tall tales of volcanoes and eruptions.

17:00 back to camp (likely a bit later than this)

Notes:

Somewhere along the way we should have a good opportunity to hear Rishi describe, deliberate upon, and debunk the mysteries of desert varnish.

Optional side trip across to west side of the valley if we have time.



DEATH VALLEY - MARCH 28 - APRIL 1, 2024

NORTHERN VALLEY

08:00 depart camp

08:30 Tatooine (a.k.a. Mesquite flat sand dunes), Pratik explains what this organized mess of sand is all about and what we might find on an actual Tatooine.

09:30 Depart for destinations farther north

10:30 Ubehebe Crater - Madison gives us the explosive story of water and magma and cratering and we can maybe even hike down inside.

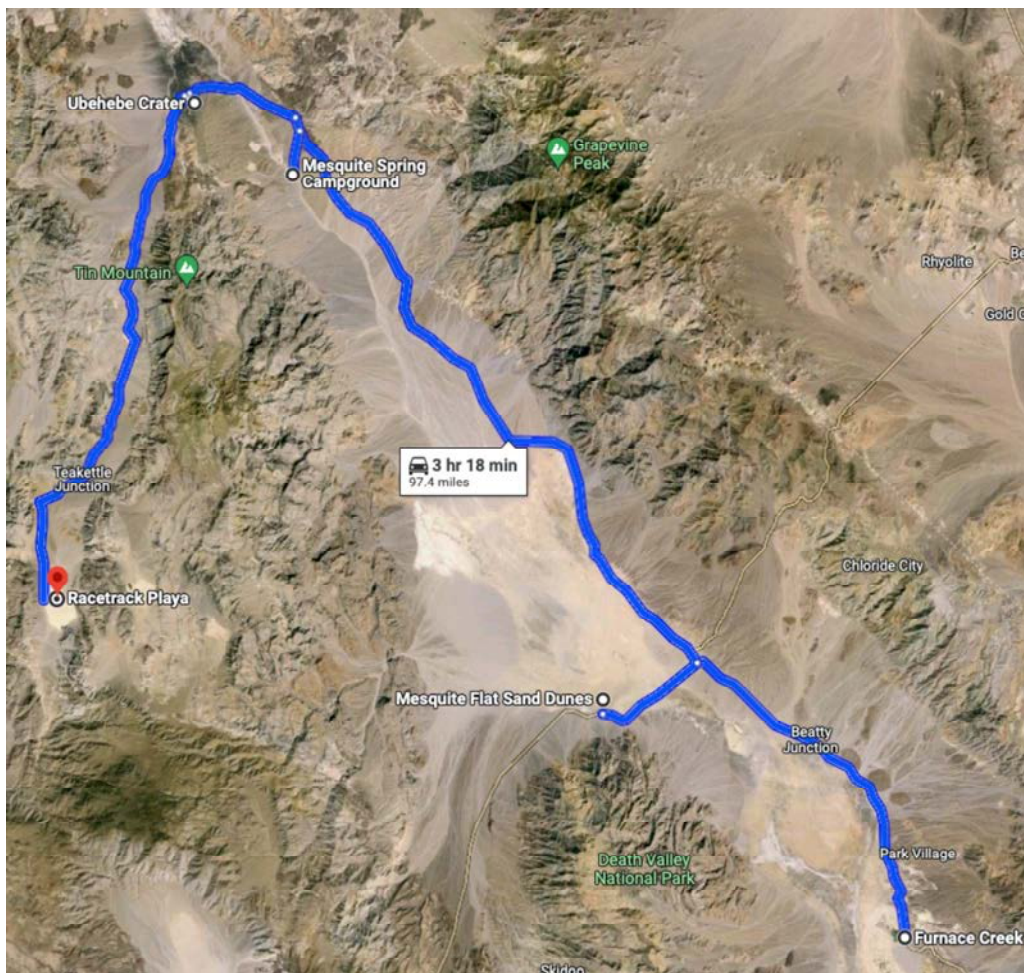
11:30 lunch break on crater rim

12:00 head to Racetrack Playa

14:00 arrive at Racetrack Playa if we don't have too many flat tires or broken suspension parts. Hike out on the playa and hear Roberto's story of playas and maybe magical movement

16:00 head back to camp, could take 2.5 - 3 hours depending on many factors (see last entry)

Note: We may just go first to Racetrack and then work our way back stopping at the other sites. Or do a mix. Might depend on weather if there is some rain coming in.



DEATH VALLEY - MARCH 28 - APRIL 1, 2024

TECOPA BASIN

We will likely arrive in Shoshone around 9-10am Sunday after breaking camp at Furnace Creek. The order of the following sites will be TBD, depending on timing, and we could even do a site or two Monday morning before we head back to Tucson. In order of proximity to Shoshone:

Shoshone springs - this may be Anna's only chance to extol the virtues and uniqueness of the once ubiquitous desert pupfish.

Roadcut along highway toward Pahrump - Orion gets another chance to convince us that volcanic processes are real.

Lake Tecopa - Arka will relate profound insights the desiccated remains of once large lake where are standing.

Tecopa hot springs - Rahul tells us why the heck we are soaking in water in the middle of the desert, and what it could mean for such trivial topics such as our own existence and extraterrestrial life.

Western Talc Mine - We'll take a walk up a wash so that Ruby can show us stromatolites, fossil lifeforms from a billion years ago, give or take a few million (who's counting), and why it matters.



into
a

hot

Dumont Dunes/Amargosa River - We will hike a bit (20 min?) to find an outcrop of the Kingston Peak Formation indicating a much different climate, whereupon Rocio will relate how and why our planet decided to cover itself in ice, and how to avoid such a silly scenario.

Sunday night: We will stay at SHEAR - Shoshone Education and Research center. See info page after next, and take care of it! We want to be welcome to come back in the future.

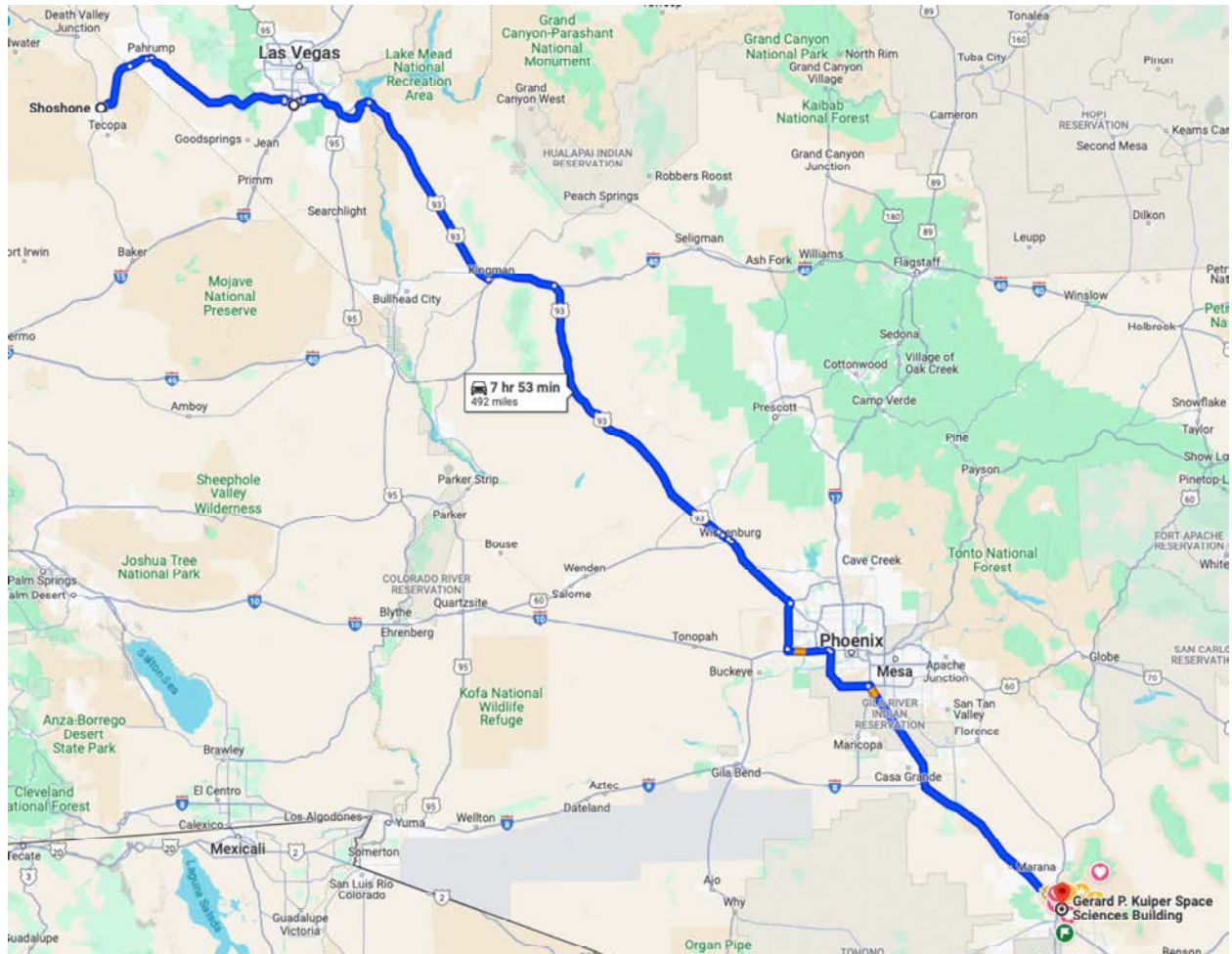
DEATH VALLEY - MARCH 28 - APRIL 1, 2024

April Fool's Day

We will depart SHEAR by 8am, and if needed will visit one or two local sites near Shoshone before heading back to Tucson. Given the drive duration and stops, expect to return around 7-8 pm.

Return all vehicles to Kuiper and unload (unless you arrange something differently with me). Drivers will return the vehicles to motor pool and we will help people get back to their homes/vehicles as needed.

Shortest route below, although there is an alternate route via Baker we can take that is 30 min longer, but we could do the Dumont Dunes stop on the way if we still need to do it.



DEATH VALLEY - MARCH 28 - APRIL 1, 2024

GENERAL INFORMATION ABOUT SHEAR—December 2023

<https://sites.google.com/site/shearshoshonecenter/>

PLEASE READ THIS IMPORTANT INFORMATION:

We now have two places to store any food that might attract mice. At the north end of the snow shed is a pantry: it has been lined with cement and is like a sarcophagus. There is also a tall plastic cabinet in the main room. If you keep doors closed, both serve well. When you leave, remove everything from the freezer unless another group is arriving immediately. Please do not leave perishable items in the fridge unless another group immediately following you in a day or two could use them. Take remaining food home or trash it. Put your bagged trash in the tan dumpster in back of SHEAR. We ask that you do not stack bags of garbage outside in the back yard.

In the main buildings [see map on website], there are two rooms for sleeping up to ten people. One has three bunk beds [sleeps six]; the other has two bunk beds [sleeps four]. Each bunkhouse has bunk beds and can sleep six [12 total]. All beds have mattresses; each person needs a sleeping bag, optional pillow, and a towel. All sleeping rooms have AC and heat. You are welcome to pitch tents and camp in the backyard. The tap water is excellent: local water is run through a reverse-osmosis plant in Shoshone. In the snowshed you will find an ice machine. Makes a lot of ice quickly. Please leave it ON.

KEYS: A new front door to the Quonset features a keypad. Press 1875 and the lock should open. Do not try to unlock the door with the knob above the keypad, or use the deadbolt. There is also a lockbox next to the front door that contains a key to the door in case the keypad is not charged. The combo is the same: 1875. Inside the main building, other keys for the bunkhouses are hanging in a key box on the east side of a little stand holding the router and internet equipment. Keys you may need are labeled "bunkhouse" for the old front door to the south bunkhouse, and a key for the front door to the north bunkhouse is separate, labeled "north bunkhouse." There is also a key for the new side doors in each bunkhouse. PLEASE: don't take any keys home with you. If you do, mail them to Darrel [6519 58th Avenue NE, Seattle, WA 98115]. A list of phone numbers is on the refrigerator.

SHEAR has excellent wi-fi. To use it: "join other network"

Type (not select): SHEAR

Select (from pull down): "WPA2 Personal" from security options. Password: STRESSANDSTRAIN

There is also a wifi extender and that may be the only wifi you can connect to in the trailer and bunkhouse. That has the same password, but is called SHEAR_EXT. There is also fast wi-fi at the café and museum. The network and password are on the counter at the café.

Check the thermostats on the water heaters. Main buildings, in the snowshed. Bunkhouses: in a shed on the east side. You may need to turn them up from "vacation" to almost "hot." Please remember to turn them down when you leave unless another group will follow yours soon.

The kitchen is fully equipped: cookware, dishes, tableware. Please make use of plastic bins below the counter to keep dishes sanitary; rodents are a problem at times and storing dishes ensures clean dishes! To save on dishwashing chores, you can bring paper plates. A good idea is to bring plastic trash bags, paper towels, and TP for your group's use. The little store in Shoshone has limited stuff. There are two propane grills and three picnic tables, in the backyard.

SHEAR residents are NOT welcome in the pool at the RV park. Please do not try to use it. And: NO OPEN FIRES ANYWHERE ON THE PROPERTY.

Roberto Aguilar

Playas

Playa—originally a Spanish word meaning “shore” or “beach,” now denoting in English the flat-floored bottom of an interior desert basin on which smooth, barren, sun-baked microrelief prevails. It is essentially a **dry lake**.

- Dry lakebed
- Vegetation-free
- Flat areas
- Lowest part of an undrained desert basin.



Racetrack playa

- 3 miles long and 2 miles wide.
- Extremely flat (differing in altitude by 5–10 cm from one end to the other)
- At least 10,000 years ago this region underwent climatic changes resulting in cycles of hot, cold and wet periods. As the climate changed, the lake evaporated and left behind beige-colored mud, at least 1,000 feet thick [1].

Sliding rocks - mystery revealed

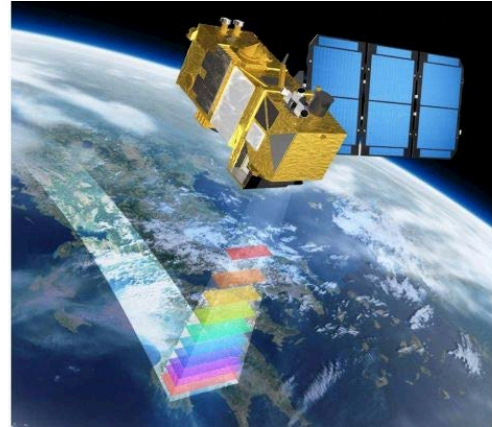
Studies to understand the motion of rocks started in the 1940s [2]. Such a process requires a rare combination of events. First, the playa fills with water, which must be deep enough to allow the formation of floating ice during cold winter nights but shallow enough to expose the rocks. As nighttime temperatures plummet, the pond freezes to form sheets of "windowpane" ice, which must be thin enough to move freely but thick enough to maintain strength. On sunny days, the ice begins to melt and break up into large floating panels, which light winds drive across the playa pool. The ice sheets shove rocks in front of them and the moving stones leave trails in the soft mud bed below the pool surface [3].



Sentinel-2 satellite imagery

I generated the following figures using the following methodology:

- 1) Download Sentinel-2 (multispectral imagery) from Google Earth Engine
- 2) Display the color bands in the background.
 - Red: band 4
 - Green: band 3
 - Blue: band 2
- 3) Display pixels classified as water in the band 15 (Scene classification layer)



2023-07-02	2023-08-26	2023-10-05
		
2023-12-24	2024-02-12	2024-03-13
		

Planetary analogs

Racetrack (RT) playa was included in a study of dried lakes in California and Nevada as a planetary analog for desiccation fractures on Mars [4].

LC: Lucerne Lake (San Bernardino)

CY: Coyote Lake (San Bernardino)

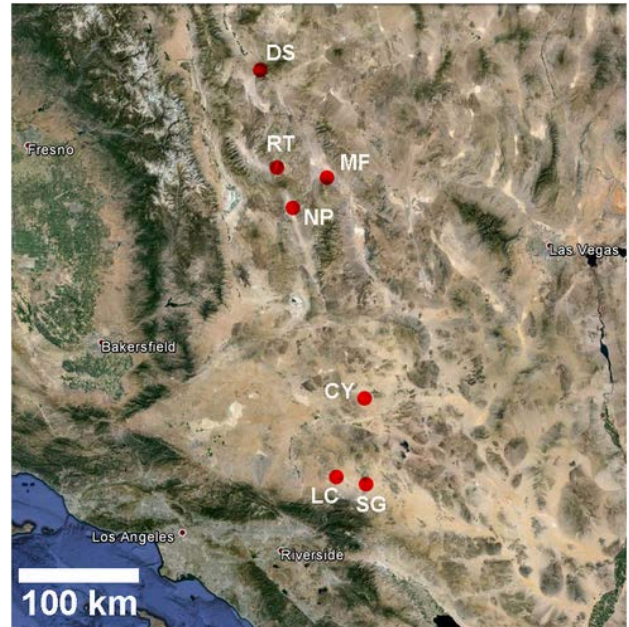
SG: Soggy Lake (San Bernardino)

NP: North Panamint Lake (DVNP)

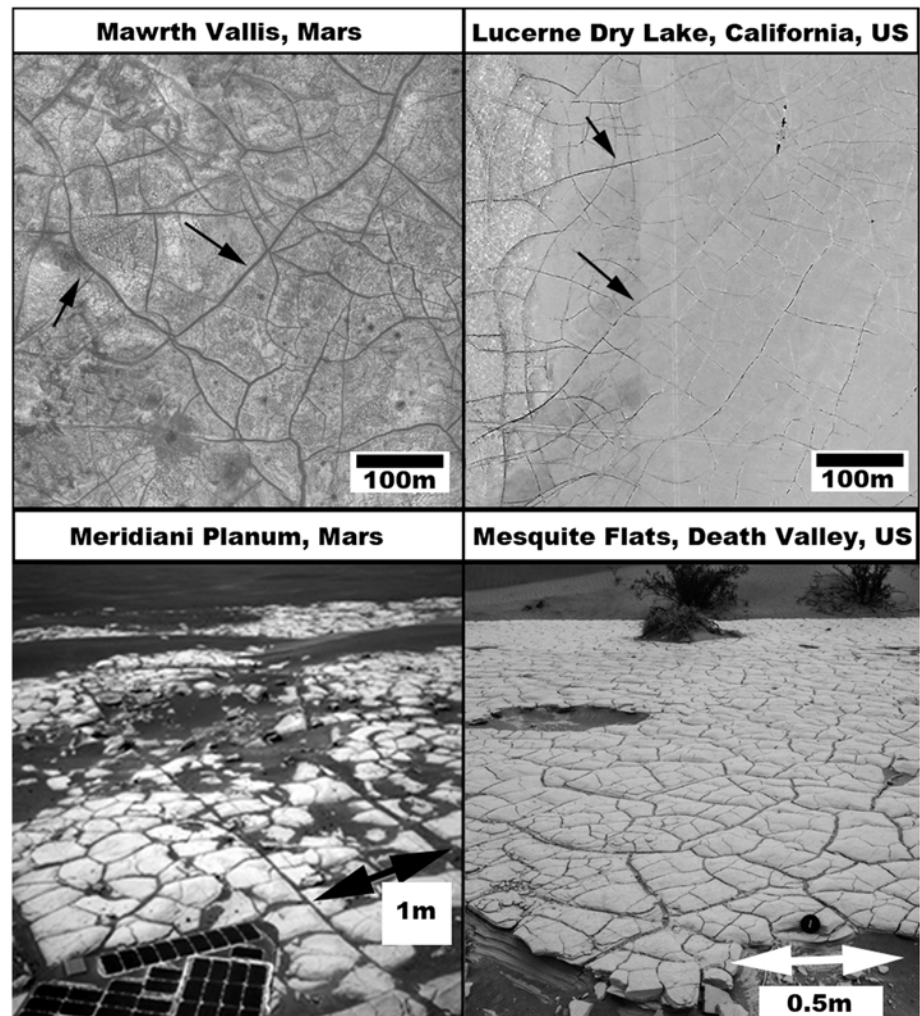
MF: Mesquite flats (DVNP)

RT: Racetrack Playa (DVNP)

DS: Deep Springs Playa (Inyo)



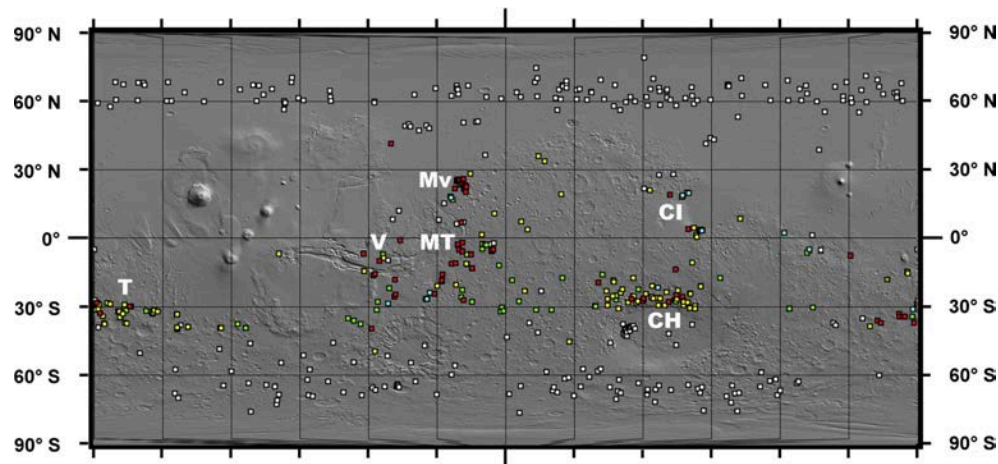
Coyote and Lucerne dried lakes display large polygonal fractures.



Mesquite Flats and Racetrack Playa show only small centimeter-sized polygons.

Potential desiccation polygons (PDPs) on Mars

PDPs are sedimentary deposits. Surface patterns are common features in Noachian to Hesperian aged (> 3 Gyr) phyllosilicate and chloride-bearing terrains. The fractured units rich in smectite minerals may have been deposited in a standing body of water [5].



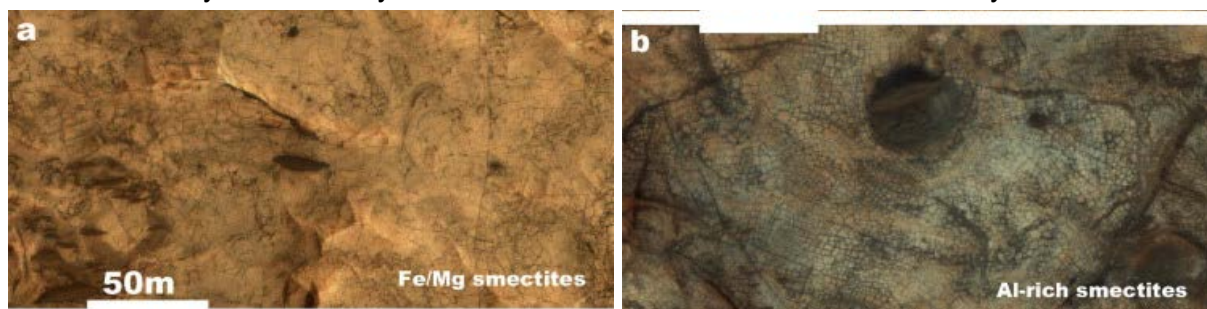
MOLA-based shaded relief map for the surface of Mars containing locations of PDPs. The dataset includes crack patterns in smectite-bearing deposits observed in horizontal beds (yellow), crustal outcrops (red), or deltas/alluvial fans (light blue), crack patterns in chloride-bearing terrains (green), and patterns in impact crater floors (white) [5].

The desiccation mechanism

Desiccation can be achieved from 2 mechanisms:

- evaporation from the surface
- diffusion processes either through the migration of liquid water due to differences in water potential, or vapor transport due to changes in water vapor pressure.

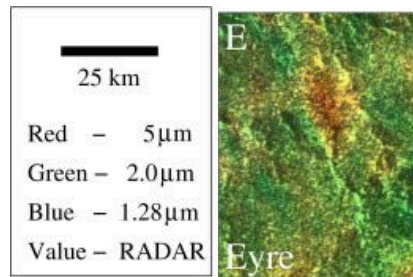
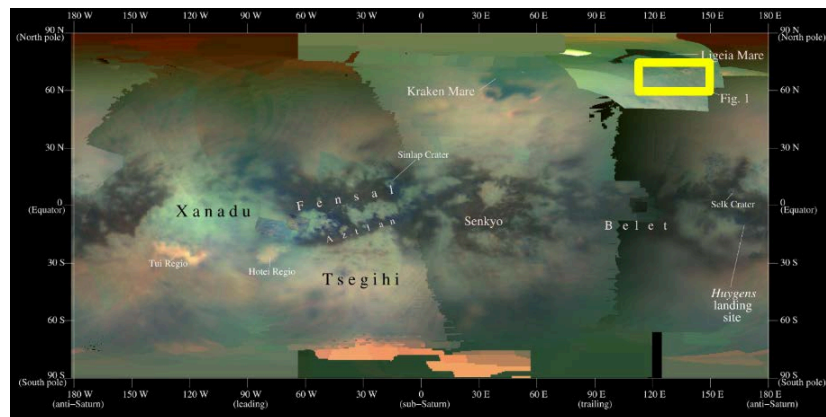
The degree to which a material (soil or sediment) contracts with loss of volatiles (usually liquid water) depends on its capacity for holding this volatiles on a macro scale through having a significant pore or void volume within the solid structure, and on a micro scale through its chemical activity and/or ability to accommodate water molecules within its crystal structure.



Fracture patterns in Mawrth Vallis are generally observed in Fe/Mg smectites [5] Source: HiRISE.

Dry lakebeds on Titan

- Organic sedimentary deposits at the bottom of dry lakebeds near Titan's north pole.
- Titan is the third known planetary body with evaporitic processes after Earth and Mars, and is the first that uses a solvent other than water.



Eyre Lacus in part (E) shows as a dry lakebed in VIMS (Cassini Visual and Infrared Mapping Spectrometer) observations, but was not initially identified as a dry lakebed in the RADAR data [6].

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Hot Springs

Rahul Arora

1 Hot Springs and its origin

Hot springs are a natural water source that is heated underground near active magma reservoirs or cooling igneous bodies where it becomes less dense and rises under pressure to the surface. Most hot springs are distinguished based on their heat source and the depth from which they rise to the surface. For Example, In the case of volcanic heating, the springs acquire their heat near the surface in the form of a magma chamber or a body of cooling igneous rock is present. Artesian springs get heated deep inside the surface due to high pressure, friction, and underground circulation. The composition is further decided by the temperature of the hydrothermal system and the composition of the surrounding rocks. Depending upon the heat source, hot springs are classified into two types: one originated due to volcanic or magmatic systems, and the other has a different source of heating.

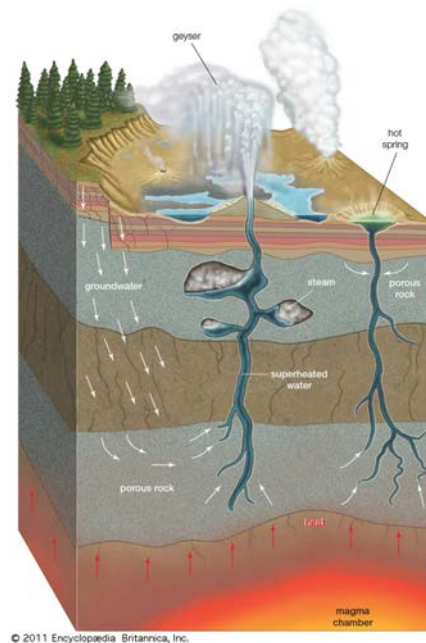


Figure 1: Formation of Hotsprings , Source: Britannica

The occurrence of these hot springs is highly dependent on the geophysical and geochemical processes that are responsible for creating liquid-dominated hydrothermal systems. With increasing temperature of these liquid systems, it is moved through the fractures and faults and through permeable rock layers due to convection as shown in Figure 1. The dominant sources of water in these hydrothermal vents are rain, snow, or seawater, with juvenile water from magmatic sources or water released during metamorphic events being the secondary source. Apart from water, this solution can contain up to 50% of dissolved material, which can be dissolved from the rocks interacting with the water, steams, and volcanic gases. Also, Owing to their often close relationship to volcanic environments, the study and monitoring of these hydrothermal systems can provide essential information about the active volcanoes

2 Tecopa basin

The Tecopa basin is located near the California-Nevada border in southeastern California. The Greenwater surrounds it, the Resting Spring and the Nopah ranges, as well as the Sperry, Ibex, Dublin, and Alexander hills as shown in Figure 2. The Tecopa Basin has sparse vegetation, which is characteristic of most arid climates [10].

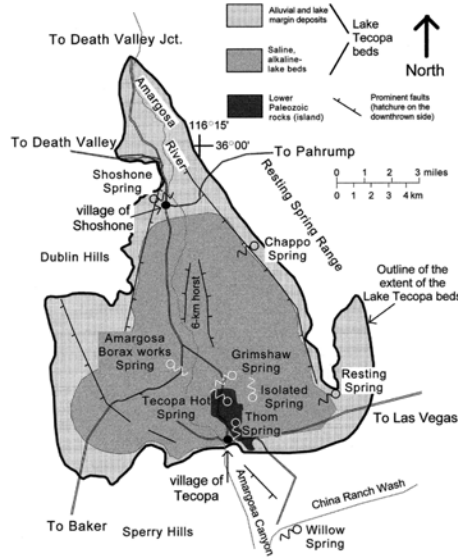


Figure 2: Map of the Tecopa basin [6]

The general geology of the basin includes crystalline basement, Pleistocene lacustrine sediments, alluvial deposits, and Greenwater fans. The oldest rock in the vicinity of the Tecopa Basin is the Gneiss, found in the basement area and intruded by metadiorite dikes (Chesterman et al., 1973). A succession of upper Proterozoic to middle Cambrian marine sedimentary rocks is also found along the eastern side of the Dublin Hills and the Resting Springs Range. The significant deposits within the basin are conglomerate, mudstone, tufa, and volcanic ash from Lake Tecopa (figure 3), which formed during the wet climate in the late Pliocene epochs. The Volcanic ash deposits have been chemically correlated (Hillhouse et al., 1987) to the Yellowstone and Long Valley eruptions, making them Tertiary in age. The presence of the authigenic silicate, located at the central section of the Tecopa basin, gives a high level of salinity and alkalinity to the pore water in the region (Hillhouse et al., 1987).

Death Valley is a very dry region due to minimal rainfall, and the water is replenished from surrounding mountain ranges to Death Valley by underground conduits that consist of porous sedimentary rocks, fractures, and faults (Larsen et al., 2001; Hunt et al., 1996 and Miller, 1977). Most of the water passes below the Amargosa River, which appears to follow a deep fault. It was proposed that active extension and volcanism in the Tecopa basin ended around 7 Ma. Exposed volcanic rocks are generally assumed to be approximately 10 Ma. These age estimates suggest that igneous rocks are too old to be a likely source of heat for the hot spring waters, so deep circulation along faults is considered more likely.

In the case that the Amargosa River faults were the location of water upliftment to the surface for the hot springs, the hot springs would be distributed throughout the length of the river. Instead, the hot springs are limited to small areas around Saratoga and the towns of Tecopa, Shoshone, and Beatty on the eastern side of Death Valley. Studies into the role of faulting were performed using electrical and magnetic data within the regions of Saratoga and Tecopa. Suggesting the role of intersecting faults in the flow of water because they are oriented so that the northwest-oriented tensile stress field opens the conduits.

3 Origin of life

In our definition, habitability is always accompanied by the presence of liquid water, and hot springs are water sources that do not dry even in arid environments. They provide reduced chemical species and

other solutes to more oxidized surface environments, thereby providing redox energy and nutrients[4]. Their chemical composition is highly diverse, and their outflows create thermal gradients causing chemical precipitation, which creates a healthy environment for microbial growth of multiple species. They are expected to be habitats for ancient microbial ecosystems and have been postulated to be the center of origin of life on Earth.

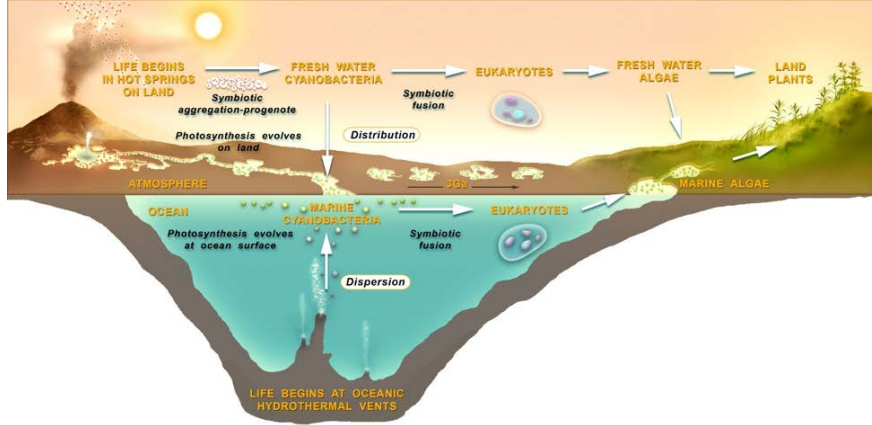


Figure 3: Origin of life in hot springs [2]

In the book "The Limits of Organic Life in Planetary Systems" [1], the authors have identified the following potentially universal attributes of life: (1) Life exploits thermodynamic disequilibrium in the environment in order to perpetuate its own disequilibrium state. (2) Life, as we know it, consists of interacting sets of covalently bonded molecules that include a diversity of hetero-atoms (e.g., C, N, O, P, S in Earth-based life) that promote chemical reactivity. (3) Life requires a liquid solvent that supports these molecular interactions. (4) Life employs a molecular system capable of Darwinian evolution. The types of environments in hot springs are suited for these particular attributes of the formation of life to flourish.

Detecting extremophiles and many microbial communities in modern-day springs around the globe also provides evidence of the sustainability and adaptability of microbes in such harsh conditions. The origin of life in the hot spring hypothesis is also supported by the fact that it was one of the environments that were rich enough in nutrients to provide energy to the early chemotrophic organisms. Along with hot springs, deep oceans and deep hydrothermal vents have also had nutrient-rich environments. However, the lack of sunlight in these two environments introduces the problem of evolution from chemotrophs to organisms using photosynthesis as their source of energy [2].

4 Planetary Analog (Enceladus and Mars)

Continuously submerged environments such as hydrothermal vents clearly support highly adapted forms of life on Earth today and might possibly harbor life on ocean worlds such as the icy moons Europa and Enceladus Figure 4. In 2005 Cassini discovered plumes emerging through cracks of Enceladus' icy shell were discovered by the Cassini mission as shown in[7], suggesting that hydrothermal vents might be operating at a rock interface deep in an interior ocean containing water and multiple organic compounds. However, with the possibility of being habitable, due to their submarine setting and lack of wet-dry cycling Enceladus may not possess the chemical or thermodynamic for origin of life [3].

A recent study [5] has detected sodium-salt-rich grains being emitted out by the plumes on Enceladus, which suggests that the plumes are formed from a liquid reservoir in contact with sodium-rich rocks. The analysis of salt-rich ice grains by Cassini's Cosmic Dust Analyzer also leads to the detection of a few significant solutes in the ocean water (Na^+ , K^+ , Cl^- , HCO_3^- , CO_3^{2-}) and its alkaline pH. Further observations and laboratory experiments in [8] present the presence of phosphorus in its oceans in the form of orthophosphates. The phosphorus concentration was analyzed to be 100 folds of Earth's ocean concentration. Along with this chemical analysis, a gravitational field measurement was performed, suggesting a regional polar subsurface ocean of approximately 10 Km thick stuck below a 30-40 Km

thick ice sheet on the surface. These measurements fulfill most of the potential universal attributes of life, making Enceladus a perfect candidate for the search for biological activity.

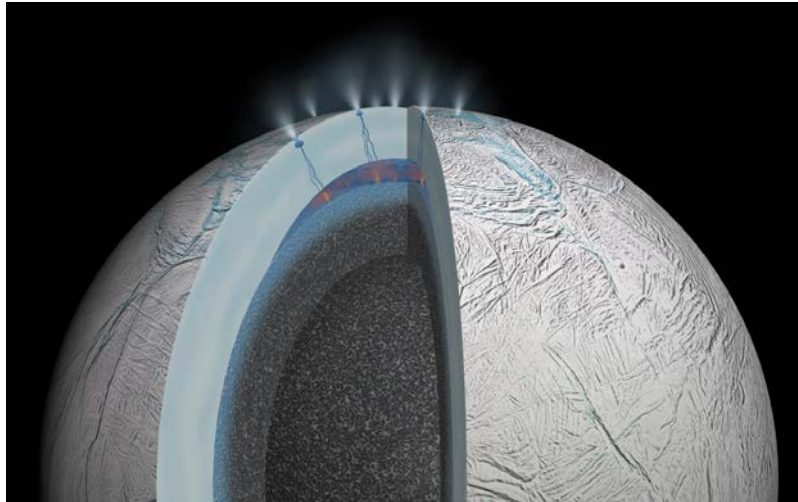


Figure 4: Hot Springs on Saturn’s Moon Enceladus Powered by Hydrothermal Vent [2]

Another candidate, Mars shows evidence of silica deposits which are hints of subaerial hydrothermal systems of a similar age as those discovered in the Pilbara. This site at Columbia Hills discovered by the Spirit rover also resembles hot spring environments that preserve biosignatures of microbial communities on Earth [9]. These hints towards potential biological activity can also guide future missions.

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Desert Varnish

What the heck is desert varnish:

Desert varnish is a term sometimes used interchangeably with rock varnish, and sometimes used to refer to all dark rock surface coatings in arid environments, including coatings such as rock varnish, case hardening, heavy metal skins, and silica glaze. **We will use desert varnish and rock varnish interchangeably.**



Dark streaks of desert varnish at Capitol Hill National Park, photo credit: NPS

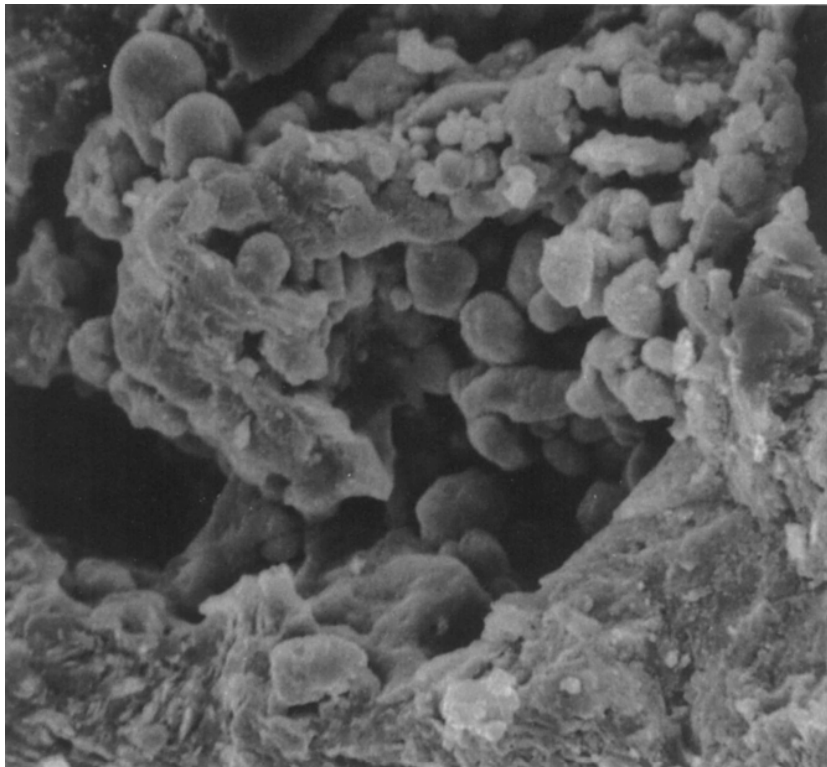
Identifying desert varnish:

Desert varnish is **orange-yellow to black**. It can only form on surfaces that do not suffer wind erosion or frequent precipitation. Desert varnish **can appear streaky** when it forms on surfaces conducive to its preferential formation, as a consequence of water flowing down linear paths or compositional variations. Past researchers have confused basalt ventifacts, geothermal deposits, iron films, and weathering rinds for desert varnish.

Chemistry and physical nature of desert varnish:

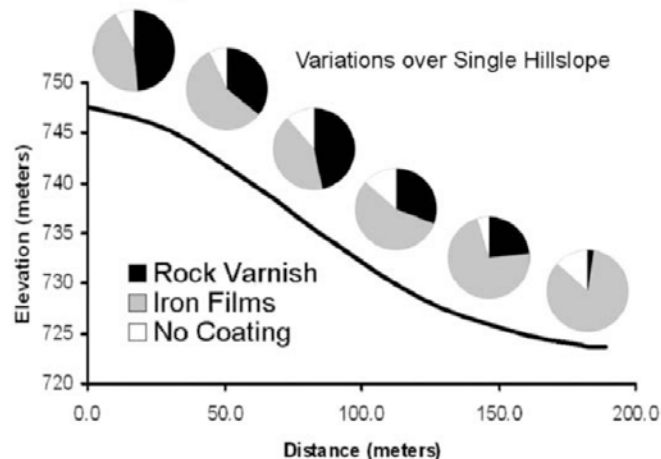
Desert varnish is composed of amorphous silica, clay minerals, and manganese and iron oxides. It displays a surprising enrichment in manganese, as much as 100x bulk crustal concentrations of manganese.

Electron microscopy reveals that desert varnish has a cross-sectional layered texture, which indicates that it is accretionary in nature. It is not caused by chemical alteration of the underlying rock, but rather by accretion of wind-blown material onto the surface of the rock.



Varnish layers are about as thin as the sheet of paper you're reading this on—10 to 100 μm thick. It can have a micromorphology ranging from botryoidal (top of photo on the left) if it formed in dust-poor conditions, to lamellate if it formed in dust-rich conditions. This is believed to be because if less dust is present, then varnish production clusters around the little dust present, where an excess of dust tends to smother the tendency of varnish to form around nucleation centers.

Desert varnish has a tendency to occur in greater abundance near the tops of hill slopes, and in less abundance near the bottoms of hills. Microcolonial fungi, cyanobacteria, and lichens tend to destroy varnishes. As such, moisture is the natural predator of desert varnish.





How does desert varnish form?

This is a debated and contentious topic. A complete model describing how desert varnish forms must answer at least the following questions:

- Why is manganese so enriched, at least relative to iron?
- What is the specific relation between clay and manganese oxides that causes it to be desert varnish?

The several leading models, at least as of 2005, are the following:

1. Abiotic genesis
2. Lithobionts producing and binding varnish
3. Silica binding
4. Some combination of the above three models

Abiotic genesis:

The model of abiotic genesis is built on the fact that divalent manganese ions are more easily mobilized by water than ferrous ions, allowing water films to preferentially concentrate manganese. This process is highly pH dependent, however, and at least a pH of 8.5 is needed in order to homogeneously oxidize manganese without needing additional biological processes to accelerate the process to a shorter timescale. This model is challenging to reconcile with observations that relatively wet, acidic climate varnishes display a greater Mn enrichment than dry, alkaline climate varnishes.

Lithobionts

Biological processes are widely held to mediate the oxidation of manganese, permitting it to concentrate at the high levels observed in desert varnish. This model is built on observations of biological and organic matter in desert varnish, such as DNA,

amino acids, and an abundance of microbial life such as lichens, cyanobacteria, microcolonial fungi, peptides, refractory organic fragments, and cocci bacteria. Under this model, it is believed that microbes are responsible for the oxidation and concentration of manganese in desert varnish. This model struggles to find support in observations, however, because evidence only demonstrates a spatial correlation between the presence of these microbes and desert varnish. There is no in-situ evidence that microbes are directly responsible for and necessary to the formation of desert varnish. Further, some microbial life is already known to only either coexist with or destroy desert varnish it lives on, such as lichens, cyanobacteria, and microcolonial fungi. It is challenging to assert a causal link between the presence of microbiota and the formation of desert varnish.

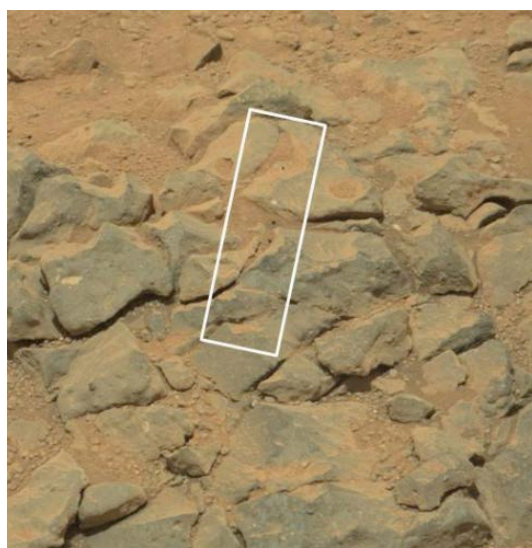
Silica Binding

This model explains how desert varnish accretes, by postulating that water dissolves silica from hydrous and anhydrous minerals, and then dries and bakes under the hot desert sun to gel, condense, and harden into the desert varnish we see. This would place silica glazes and desert varnish in the same class of material, giving them a common formation mechanism.

Silica binding does not explain where the manganese concentration comes from. It must be combined with either abiotic genesis or a model of biologically mediated manganese concentration in order to explain the observed chemistry of desert varnish. It is additionally contentious to what extent silica is the dominant phase in desert varnish, and to what extent it's clay. The greatest challenge to the model of silica binding is that desert varnish is regularly observed in locations where the hot sun doesn't bake silica, such as in joints in rocks in Norway, in subsurface environments, and in Antarctica. Silica binding is entirely compatible with the other models presented above, and doesn't necessarily compete with them.

Planetary Analogs

Some rocks on the surface of Mars have been interpreted as potentially bearing desert varnish. The picture to the right here is from Curiosity, which used its Laser Induced Breakdown Spectrometer (LIBS) instrument to analyze the composition of a rock which may bear rock varnish. LIBS found the high manganese concentration distinctive to desert varnish. Our best models of how desert varnish form on Earth demand liquid water and possibly life—if microbiota really are essential to the formation of desert varnish, then a Martian sample of desert varnish may be a key target in the search for extraterrestrial life.



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Lake Manly, Paleoshorelines, and Pluvial Lakes

By: Michael Daniel

Lakes

Lake Manly is a major pluvial lake that formed during recent glacial periods in what is now Death Valley. Lake Manly is the name given to all late Pleistocene (240,000-10,000 yrs ago) water bodies at this location (Figs. 1 and 2) (Sharp and Glazner, 1997). Other paleolakes formed throughout the surrounding area and across the American West, including Lake Bonneville. Pluvial lakes are fed mainly by precipitation, though other sources can contribute, such as rivers, glaciers, and springs (Sharp and Glazner, 1997). Glaciers in the Sierra Nevada (major glaciation) and the San Bernardino (minor glaciation) Mountains were within the expanded Death Valley watershed (Sharp and Glazner, 1997) and contributed water. Pluvial lakes could survive through the increased precipitation and reduced evaporation that occurred during glacial periods. During interglacials, these lakes would become much smaller or completely disappear as precipitation decreased and evaporating increased.

The highest stand (level) of Lake Manly recorded was likely during the penultimate glacial period and the start of the following interglacial ~186-120 Kyr (Craig et al. 2012) and had a water depth of ~152-183 m (Sharp and Glazner, 1997). Lake Manly from 30-10 Kyr ago may have only reached elevations of -22 m (~56 m deep) (Craig et al. 2012). Due to the complex network of basins and history of paleolakes, identifying when each lake stand occurred can be challenging and changes the interpretations of the climate history (Enzel et al., 2002). Depths could reach up to 183 m (600 ft) before overtopping out of Lake Manly, and would need to reach a depth of 610 m (2000 ft) to leave the Death Valley region (Sharp and Glazner, 1997). The present salt pan is likely not from Lake Manly, but a more recent lake no more than ~9 m (30 ft) deep present in the last thousands of years (maybe ~5,000-2,000 years ago) (Sharp and Glazner, 1997).

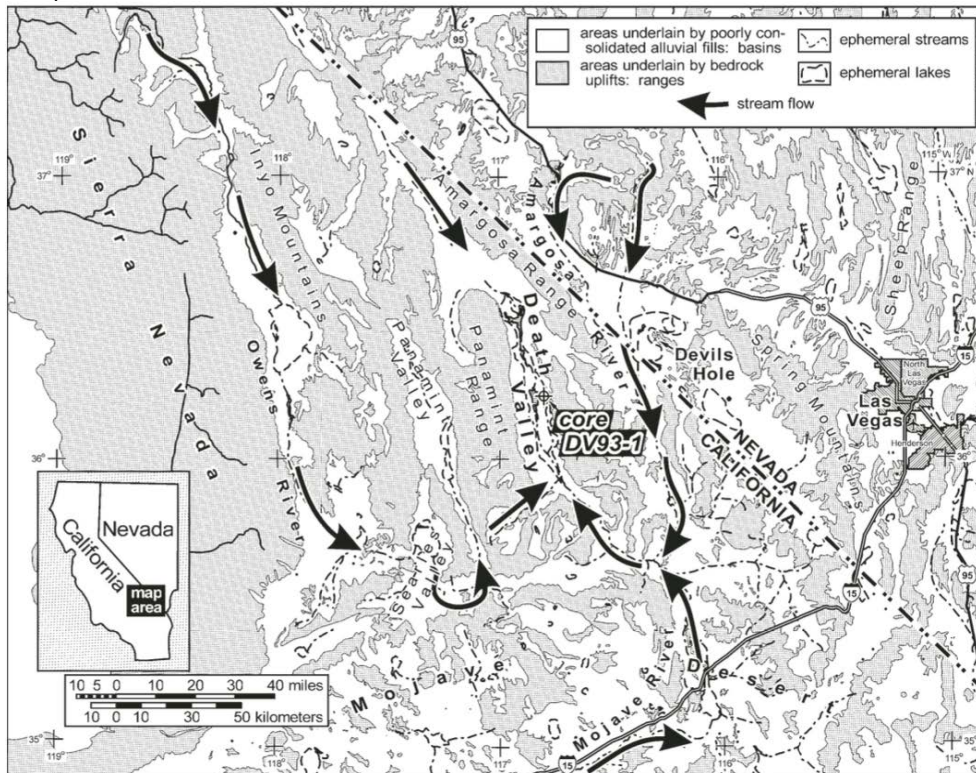


Figure 1: Paleolakes in the Death Valley region with associated stream locations and flow. Flow between lakes are marked by the black arrows. (Fig. 1 from Forester et al., 2005).

Shorelines

The identification of shoreline features can be used to identify paleolake levels. Common features are strandlines, which are incisions into existing rock such as Manly Terraces and Shoreline Butte (Fig. 3), and the creation of barriers and bars such as Beatty Junction (Figs. 4 and 5). Both strandline and barrier creation is highly dependent on wave strength for cutting power (strandlines) or the ability to move gravel (barriers). Wave strength is the strongest in areas of high fetch which allows for shoreline features to be created and preserved at locations such as Shoreline Butte and Manly Terrace (Fig. 2). The numerous strandlines indicate that lake levels regularly fluctuated (Sharp and Glazner, 1997). The highest clear shoreline on Shoreline Butte is at 79 m (258 ft), 174 m (570 ft) above the floor of Death Valley, similar to the highest shorelines elsewhere (Sharp and Glazner, 1997). Most well-preserved shorelines are found between 30 and 90 m a.s.l. (Craig et al. 2012). Older shorelines will be harder to preserve than more recent ones, especially low elevation shorelines.

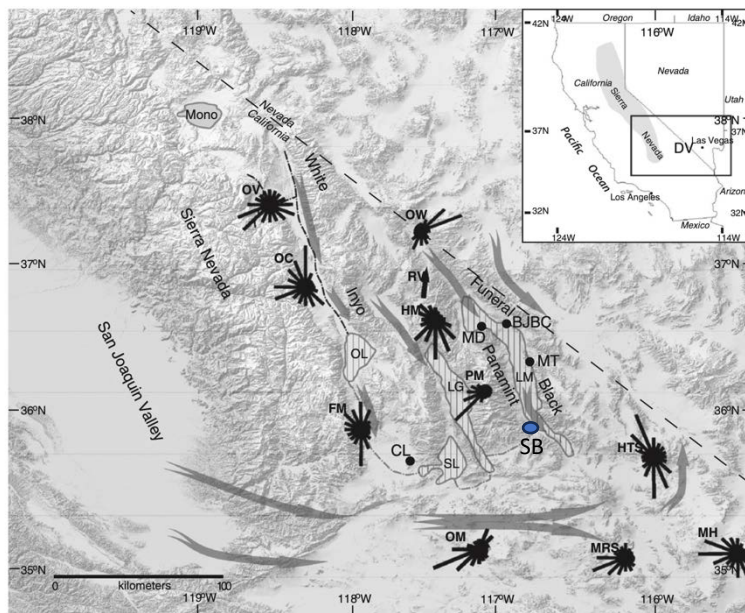


Figure 2: Prevailing wind directions (grey arrows) for basins in and near Death Valley SB: Shoreline Butte, MT: Manly Terrace, BJB: Beatty Junction, LM: Lake Manly (Modified from Fig. 1 from Knott et al. 2012).

Tectonic factors: As Death Valley is in a tectonically active and complex area, it is necessary to quantify differential elevation changes across basins. This is needed to ensure that identified shoreline features correspond to the correct lake levels (Craig et al., 2012). As example, there is a major strike-slip fault near Shoreline Butte with significant lateral displacement in the last 600,000 yrs and potential modest uplift identified from a nearby scarp and may lead to 1-10s of meters of difference from current elevation (Sharp and Glazner, 1997). Also, the current lowest elevation of ~ -86 m (-282 ft) may not have been at that depth during these shorelines, leading to a shallower lake, but despite these factors the depth was likely between 152-183 m (500-600 ft) (Sharp and Glazner, 1997).



Figure 3: Shoreline Butte, located in Southern Death Valley, is one of the best-preserved locations of strandlines and paleoshorelines in its basaltic slopes (USGS).



Figure 4: A road cut through the Beatty Junction Barrier with the lakeward direction to the left. Humans performing GPR studies as scale. Modified from Fig. 2 from Craig et al. 2012.

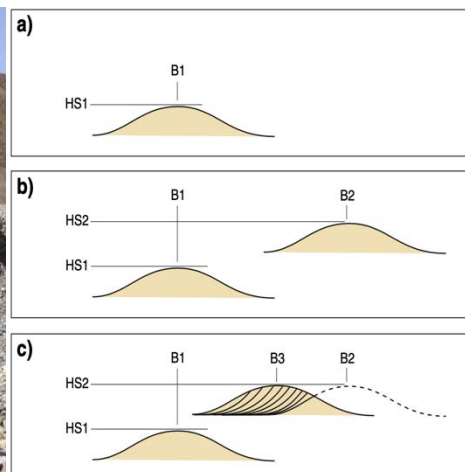


Figure 5: Model showing the formation of Beatty Junction Bar. B1 is formed first at high stand 1 (HS1), with B2 formed later at high stand 2 (HS2). Continued lake levels as HS2 allows changes in B2 into B3 through progradation on the lake side and erosion on the back side. Fig. 8 from Craig et al. 2012.

Analog to Mars lakes

Pluvial lakes in the Death Valley region may be a good planetary analog to Martian lakes formed in impact craters. Martian lakes occurred early in Mars's history with most lakes disappearing by the late Noachian/Early Hesperian (~3700 Myr) (Goudge et al., 2018).

The detection of shorelines from topography is unlikely due to the scale and preservation of these features (Irwin et al., 2012). Pluvial shoreline features on Earth are on the order of meters to 10s of meters, so to detect these on Mars the best option is DEMs from HiRISE (Irwin et al., 2012). While the resolution may be enough, it may still be difficult to resolve shoreline features due to lack of surface contrast. The higher resolution imagery and DEMs for Earth features make them easier to locate on Earth. Additionally, the preservation of these features since the Noachian would be difficult due to erosional processes, reducing the likelihood of finding these features on Mars's current surface (Irwin et al., 2012).

While shorelines are hard to identify, erosional features from water overtopping and outflowing from crater-based lakes is observed such as with Licus Vallis (Fig. 6) (Goudge et al., 2018). These features can be identified as they have higher topographic variation than shorelines. The overtopping waters from the crater lake likely initiated the incision of this valley which was further eroded by longer-term fluvial activity (Goudge et al., 2018). The terraces formed in this valley likely due to the increased vertical-to-lateral erosion

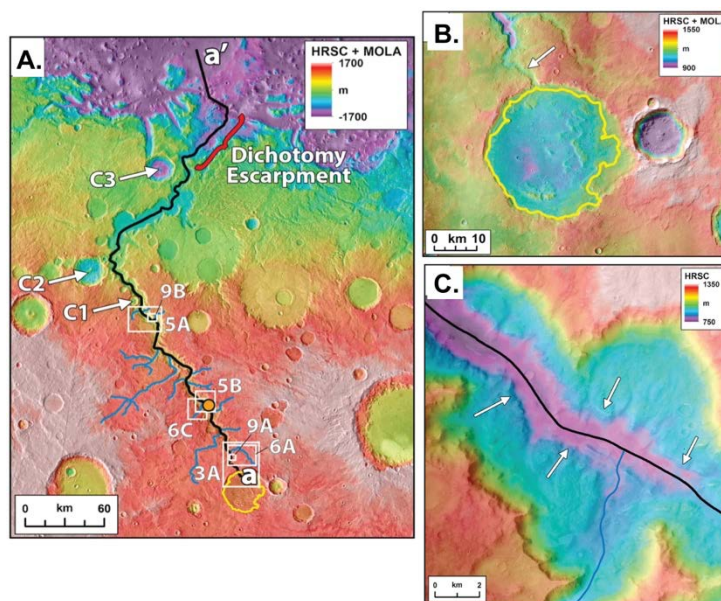


Figure 6: The presence of erosional features caused by the outflow of water from the crater at the head of Licus Vallis. (A) Overview of Licus Vallis, (B) crater source, and (C) part the terraced valet located at 5B in panel A. Modified from Figs. 1 and 5 from Goudge et al, 2018.

and are markers of fluvial erosion. Prior to overtopping the crater and incising into the rock, the crater was likely similar to a pluvial lake, fed by precipitation and losing water to evaporation and ground infiltration.

Another method of identifying paleolakes is through the identification of dry lakes and the associated potential desiccation polygons (PDPs) (Fig. 7). Desiccation polygons are widely found in dried lakebeds and can exceed 50 m in width (El-Maarry et al., 2015). Seven terrestrial sites reveal desiccation polygons tend to have a soil matrix mostly made out of clays and fine silts with significant amounts of illite/muscovite dominated clays and smectites. Also, these features have variable amounts of chloride and sulfate salts, and roughly the same spectra signatures in the VIS-NIR with absorption features at ~ 1.4 , 1.9 , 2.2 , and 2.3 μm . (El-Maarry et al., 2015). These features can be used to identify paleolakes on Earth and Mars, assuming that PDPs are a planetary analog to Martial pluvial lakes. Several Mars PDP sites occur in phyllosilicate- and chloride-terrains implying a similar formation environment to terrestrial desiccation polygons.

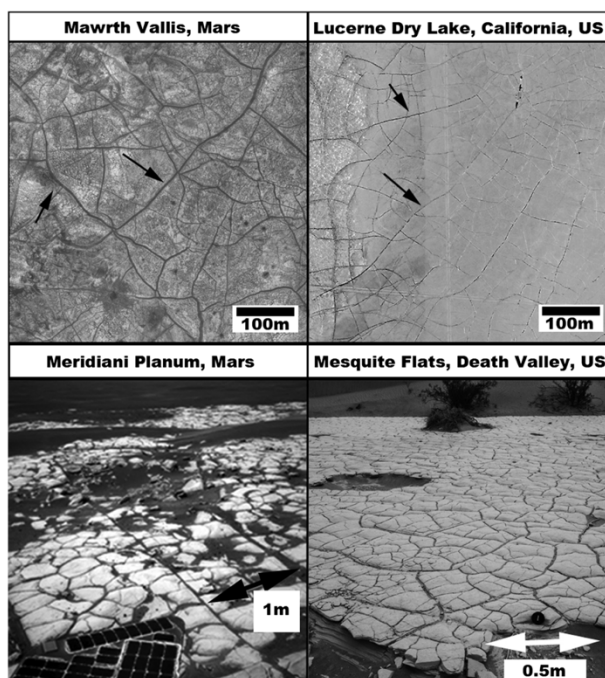


Figure 7: Potential Desiccation Polygons on Mars (left column) and desiccation polygons on Earth (right column). Fig 1 from El-Maarry et al., 2015.

Fun tangentially related facts:

- 1) Lake Chelan in Washington State and some large lakes in Canada's Northwest Territory have bottoms lower than Death Valleys -86 m (-282 ft) but are filled with water, making Death Valley the lowest dry surface in North America (Sharp and Glazner, 1997).
- 2) Many dry lakebeds are inaccessible to the public due to their association with air force bases and military test sites (El-Maarry et al., 2015).

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Planetary Field Geology Project: Stromatolites

Death Valley Field Trip, Spring 2024

1 Stromatolites Overview

Stromatolites are finely layered laminated deposits, usually made up of carbonate minerals, formed by metabolic outputs from photosynthetic microorganisms living in bodies of water. These deposits are formed by a variety of single-celled organisms, often cyanobacteria living in extensive microbial mat communities. Stromatolites that formed before the modern era serve as fossil records of prehistoric single-celled organisms, and offer insight into ancient aquatic environments (Whitton, 2012). Stromatolites themselves are not body fossils, but do sometimes contain the calcified fossils of the microorganisms that formed them. Elongated stromatolite columns form when currents and tides mold partially or wholly lithified microbial mats. Therefore, axes along which stromatolites are elongated indicates the direction of the paleo current (Creveling et al., 2016). Stromatolites can exhibit a variety of morphologies depending on the environment in which they formed, including columnar, domal, nodular, and planar (Marian & Osborne, 1992). It is yet unknown which specific microbial species form each type of stromatolite, but stromatolites are organized into many different taxa based on morphology and age (Howell, 1971).

Some stromatolites are still actively being created by modern-day microorganisms, but many were formed by prehistoric organisms in the Proterozoic eon or as far back as the Archean. The oldest stromatolites are around 3.5 billion years old and record some of the earliest life on Earth. Archean stromatolites are especially interesting because they can record information about the origin time of cyanobacteria. The cyanobacteria and other organisms that generate stromatolites thrived in the Proterozoic, and therefore created an extensive record of Proterozoic stromatolites. Stromatolite generation declined in the Neoproterozoic and into the Phanerozoic (Lee, 2021), as microbial mat communities conducive to stromatolite formation became disrupted by metazoan activity (Whitton, 2012). Active, modern day stromatolites exist where microbial communities can remain undisrupted for long periods of time.

2 Stromatolites of Death Valley

Death Valley, California, USA is home to a variety of Stromatolite formations. One particularly well-exposed group of deposits is known as the Pahrump Group. The Pahrump group is a notable assemblage of siliclastic and carbonate rocks located between the Panamint range and the Kingston range, and it is the oldest formation of sedimentary rocks in Death Valley (Marian & Osborne, 1992). Figure 1, taken from Smrzka et al. (2022), illustrates the locations of the Pahrump group rocks and the Noonday formation in the Death Valley region. The Pahrump group consists of the Crystal Spring Formation, the Horse Thief Springs formation, the Beck Spring Dolomite, and the Kingston Peak formation (Marian & Osborne, 1992). The Horse Thief Springs Formation was previously considered an upper member of the Crystal Spring Formation (Smrzka et al., 2022).

The Crystal Spring Formation is the oldest member of the Pahrump group. It features finely layered columnar stromatolites that resemble a chevron pattern, thought to have formed in a shallow marine setting with currents (Douglas et al., 2015). Figure 2 shows an example of these formations. Zircon grain dating places the upper crystal springs formation at younger than 787 Ma and the lower-middle formation around 1250-1070 Ma. The Horse thief springs formation, overlying the Crystal Spring formation, is thought to have formed in current-influenced environments in which the stromatolite-forming microbes were periodically

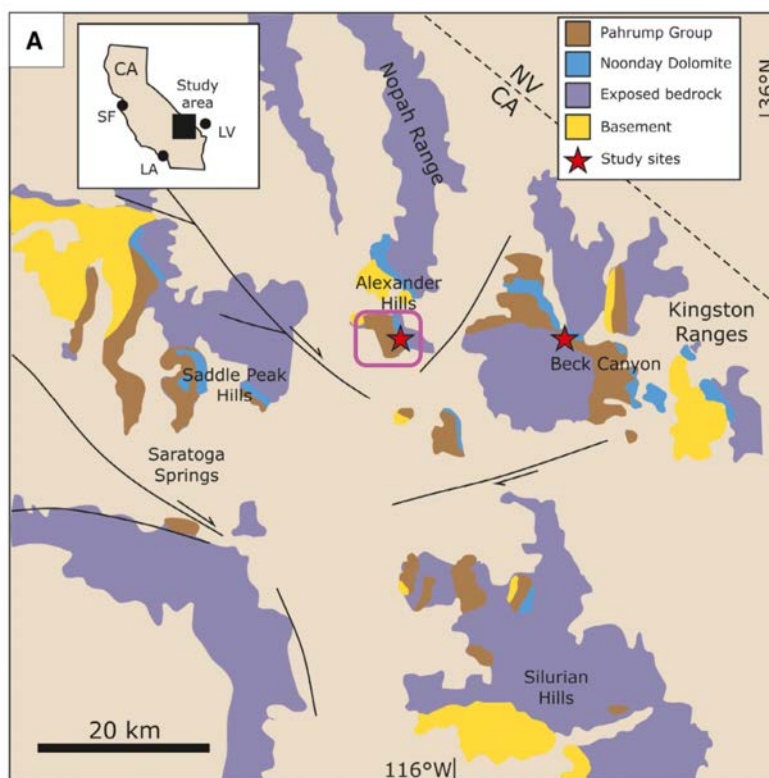


Figure 1: A simple geological map showing the locations of the Pahrump group strata and noonday dolomite in the Death Valley region. This map is taken from Smrzka et al. (2022), and the study sites indicated by red stars reference a study by Macdonald et al. (2013). The Kingston ranges, the Nopah range, and the California-Nevada border are shown to provide the reader with a reference for the geographic location of these stromatolite formations. The pink rectangle was added for the purpose of this report, and shows the region of the Pahrump group that will likely be visited for this field trip.

exposed to air (Mahon et al., 2014). In the region indicated by the pink rectangle in Figure 1 is an accessible Crystal Spring formation outcrop that is a potential area of study for the upcoming field trip.

The Horse Thief Springs formation smoothly transitions into the Beck Spring Dolomite, which includes conical columnar, irregular columnar, nodular, and stratiform stromatolites. The conical stromatolites likely formed in a low-energy environment in which the microbial mat was completely submerged in water, like a lagoon. Irregular columnar stromatolites indicate exposure to moderate or high energy currents. Stratiform stromatolites are associated with a variety of environments; the Beck Spring stratiform stromatolites have similar morphology to modern day tidal flats. The structure of the Beck Spring Dolomite indicates a dominant role of algae in the prehistoric environment. The Kingston Peak formation overlies the Beck Spring dolomite and underlies the Noonday formation. The formation's age is poorly constrained but is estimated to be ~750-700 Ma (Corsetti et al., 2003). Several morphologies of microfossils are preserved in Kingston and Beck Spring formations. These fossils are poorly preserved, but have been interpreted to include cyanobacteria, algae, and possibly other eukaryotes. Many of these fossils were found in the Kingston Peak formation's carbonate unit. Figure 3 shows a location at which these fossils are found (Corsetti et al., 2003).

The newer Noonday Dolomite overlies some parts of the Pahrump group (Mahon et al., 2014), and is thought to have been deposited in the Ediacaran age (Creveling et al., 2016). The Noonday dolomite formation is made up of decimeter to meter scale domal stromatolites as well as columnar stromatolites. An example of columnar stromatolites in the Noonday dolomite is shown in Figure 4. The texture of the carbonate found in the Noonday formation is similar to structures known to be created by blue-green algae



Figure 2: Columnar stromatolites in the Crystal Spring formation, photo taken from Howell (1971). Dark chert surrounds the round "heads" of the stromatolites, emphasizing their shape.



Figure 3: A photograph of the upper portion of the Kingston Peak formation's carbonate unit, taken from Corsetti. The round features in the rock are oncolites, structures formed by depositions from algae or bacteria. These structures were found to contain preserved microfossils.

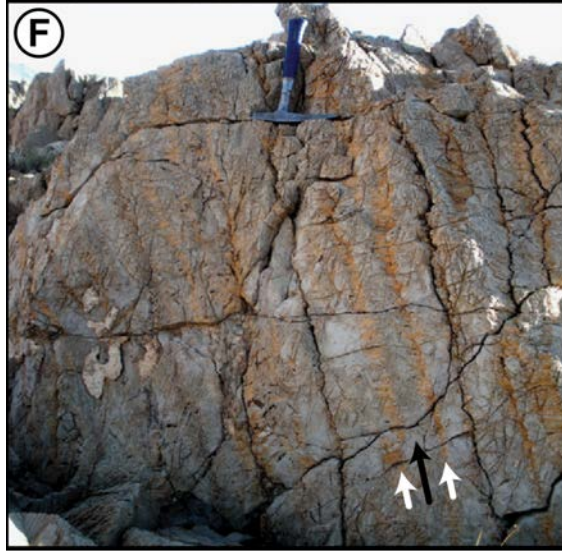


Figure 4: Columnar stromatolites of the Noonday formation, photo taken from Cerveling.

(Cloud et al., 1974). Within some dome structures in the lower member of the Noonday formation are vertical tubes that are thought to be defluidization channels, probably created by a mixture of water and biologically produced gases, infilled with various types of dolomite (Cloud et al., 1974).

3 Mars Analogue

There is extensive evidence suggesting that Mars once hosted liquid water on its surface. Whether or not this water ever hosted life remains an open question. Because stromatolites record evidence of primitive water-dwelling life on Earth, Martian structures resembling terrestrial stromatolites are possible indications of past life on Mars.

The Spirit Rover observed nodular silica outcrops in the Home Plate formation in Gusev crater. These silica deposits strongly resemble terrestrial microstromatolites formed by microbes living in hot springs (Ruff & Farmer, 2016). Figure 5 shows these opaline silica deposits on Mars in comparison to silica structures found in hot spring discharge channels in El Tatio, Chile. There is not sufficient data to confirm whether or not these silica deposits are of biologic origin, so they are an interesting topic for further astrobiological study.

The arid climate of Death Valley is closer to Mars's climate than many other terrestrial locales. Because Death Valley is obviously much warmer and wetter than present day Mars, it is often used as an analogue for the early Martian climate (Douglas et al., 2008). Therefore, methods developed for identifying stromatolites in Death Valley could be useful for seeking Martian stromatolites. Douglas et al. (2015) suggest the Crystal Spring formation as an analogue site for testing Martian stromatolite detection. They find that the Ca/Si ratio in layers containing stromatolites is higher than in those without stromatolites. Douglas et al. (2015) suggest that a Mars rover could visually identify potential stromatolites and test the Ca/Si ratio for further confirmation. Stromatolites are an invaluable tool for studying the origin of life on Earth, and could potentially be a vital tool for studying life on Mars.

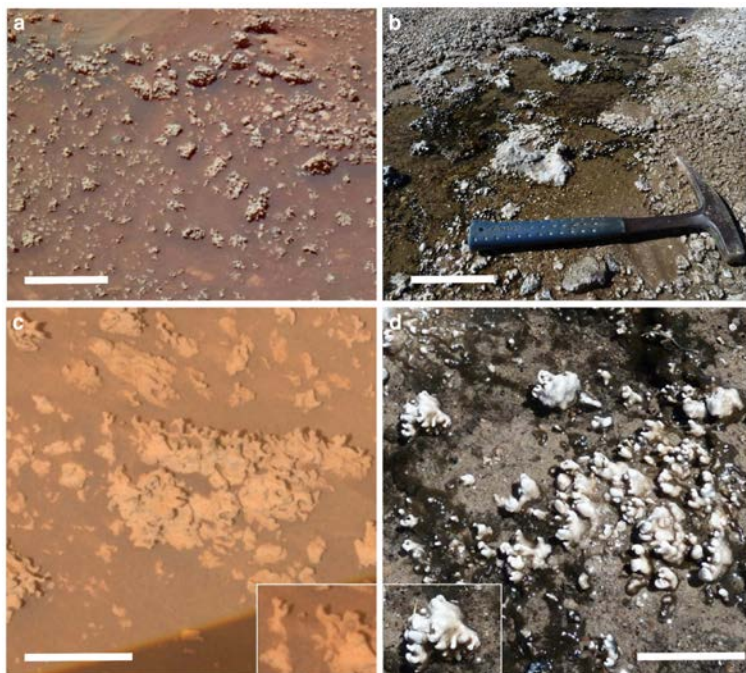


Figure 5: Opaline-silica deposits at Gusev Crater, Mars observed by the Spirit Rover (left) compared to silica deposits formed by microorganisms in hot springs in El Tatio, Chile (right). There are clear morphological similarities between the Martian and terrestrial deposits. Image taken from Ruff & Farmer (2016).

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Volcanics of Death Valley, CA
Orion Hon | PTYS 590 - Spring 2024

Introduction

Death Valley is a north-south trending depression, in both a structural and topographic sense, which is bounded to the East and West by mountains. It is a geologically diverse landscape that has been shaped through time by a combination of geologic processes, including volcanism. There are many types of volcanic products in Death Valley, however, in many cases they have been altered by tectonic activity and sedimentary processes since their formation. This post-emplacement alteration can make the identification of these units and their subsequent geologic interpretation difficult. This section of the field guide therefore serves to inform field trip participants about the less prominent volcanic features scattered throughout this spectacular landscape (in contrast to several significant stand alone volcanic features in Death Valley, which are covered separately).

Terminology

- Andesite - An extrusive volcanic rock of intermediate compositions (meaning the silica content of the rock is between that of a highly-silicic rhyolite and a low-silica basalt) and moderate viscosity which allows it to form thick lava flows and domes.
- Basalt - An extrusive volcanic rock formed by relatively low viscosity lava flows. They have low silica content and primarily contain the minerals pyroxene, plagioclase, and olivine.
 - Basaltic lava flows typically have ‘a’ā or pahoehoe morphological forms (though a variety of intermediate morphologies are possible) and are erupted from a variety of volcano types including shield volcanoes (ex: Hawai’i), Cinder Cones, fissure volcanoes, and monogenetic volcanic fields.
- Cinders or scoria - Vesicular volcanic ejecta, typically of andesitic or basaltic composition.
 - Less vesicular and more dense than pumice
- Extrusive igneous rock - A rock formed by a magma which erupted onto the surface of the Earth.
 - In contrast to intrusive rocks which form when magma solidifies into older rocks beneath the surface. These types of rocks are also distinguished by texture and mineral composition means, as intrusive rocks are more coarse-grained (phaneritic) than extrusive rocks and different minerals form because of the differences in emplacement environments and cooling rates. Examples of extrusive igneous rocks include lava flows and pyroclastic deposits (which are glassy to finely crystalline in texture).
- Fiamme (plural) - Lens-shaped structures (i.e. ellipsoidal biconvex shape) of volcanic ejecta that were altered during welding of the volcanic ash deposit they are contained within. They are often small (mm to cm in scale) bits of pumice that have been reshaped by compaction or shear.
 - The term comes from the Italian word for “flames” because of their shape, fiamma is the singular “flame”.
- Ignimbrite - The rock formed from the consolidation of a pyroclastic flow.
 - Also referred to as welded tuff or ash tuff flow.
- Pumice - A pyroclastic igneous rock, typically silicic in composition and highly vesicular.
 - Formed by magma with very high gas content is ejected from a volcano, where sudden depressurization and cooling creates a very frothy lava due to rapidly escaping gasses, resulting in a very low density rock.

Death Valley Volcanics

- Pyroclastic Flow - A hot (>800 C), gaseous current of volcanic ash and rock fragments which travels rapidly across the ground away from a volcanic vent during an eruption.
- Tephra - Any rock that was explosively ejected from a volcano that has an airborne path during an eruption.
 - Not limited by size or composition, it includes ash, lava bombs, and scoria.
- Tuff - An igneous rock formed by ejecta from an explosive volcanic eruption that becomes compacted and cemented into a rock.
 - It is composed of materials that were thrown into the air by the eruption and then landed surrounding the volcano, making it typically thickest closest to its origin point (volcanic vent), or on the downwind side of the vent (as the materials' trajectory were likely affected by wind during the eruption).
 - Tuffs become hard and form blocks with a characteristic orangish cast upon weathering.
- Type Locality - The sequences of units in a formation are not constant throughout the extent of the formation and certain units may only be present in specific outcrop locations. Therefore the formations are often described based on the location which displays a specific set of units in a formation.
- Stratigraphy - The layering of rock units and their relationship to each other and within geologic timescales (primarily applied to sedimentary and layered volcanic rocks).
- Unconformity- A type of geologic contact between rocks where some unit(s) is missing from the stratigraphic sequence because of a period of erosion/lack of sediment accumulation, followed by sediment deposition.
- Vitrophyre - A porphyritic volcanic rock in which larger crystals (phenocrysts) are contained within a glassy (aka no distinct crystals/amorphous) matrix.
 - TLDR: *A type of volcanic glass.*
- Volcanic Ash - Fine grained (0.004-2 mm diameter) materials (pieces of rock, minerals, and glass) formed during explosive eruptions. It has many erosive properties as it is hard, abrasive, and mildly corrosive and is spread long distances by wind.

Geologic Ages Associated with these Death Valley Volcanics

- Cenozoic: A *Geologic Era* spanning 66 Ma - present day (current era)
- ◆ Neogene: A *Geologic Period* from 23.03-2.58 Ma (total of 20.45 My)
 - Miocene: A *Geologic Epoch* from 23.03-5.33 Ma
 - Pliocene: A *Geologic Epoch* from 5.33-2.58 Ma

General Overview

Death Valley has been shaped over the course of nearly two billion years by geologic forces. Within a relatively recent time frame (geologically speaking) there have been multiple periods of volcanic activity in Death Valley responsible for the formation of the volcanic deposits we will see on this trip. Four stages of eruptions associated with Neogene volcanism (12-0.7 Ma) in central Death Valley, which coincided with significant regional extension, were defined by Thompson et al. (1999).

- Stage 1 eruptions (12 - 8.5 Ma): Associated with the onset of extension, minor basaltic andesite lava flows, major calc-alkalic dacite to rhyolite lavas (eruption origin unknown). Includes the Rhodes tuff (9.6 Ma) which is a regional rhyolite ash-flow sheet. These deposits were intruded by late Miocene silicic, hypabyssal plutons, stocks and dikes.

- Stage 2 eruptions (8.5-7.5 Ma): Consists mostly of dacite to rhyolite lava flows, with some basalt flows, and minor pyroclastic deposits (in the south-central and SE part of the volcanic field).
- Stage 3 eruptions (7.0-5.5 Ma): Occurred after major tectonic denudation (wearing away of surface topography by tectonic means) and was confined to the central portion of the volcanic field. It consisted of basaltic to rhyolitic lava flows and small volume, weakly welded ash flow tuffs and associated ash-fall deposits.
- Stage 4 eruptions (5.0-0.7 Ma): All volcanic products were basaltic to andesitic in composition and are primarily found in the northern part of the volcanic field, though there were low-volume eruptions in the southern portion.

These ages were based on K-Ar dating of a variety of the volcanic features in the central Death Valley volcanic field, which include the $>700 \text{ km}^3$ of lava flows, domes, and pyroclastic deposits formed by a multitude of volcanic centers (Thompson et al., 1999).

Notable Volcanic Deposits

Shoshone: Welded Tuff

The Resting Spring Tuff or Charlie Brown Outcrop

Northeast of Shoshone, along the Resting Spring Pass, is a road cut on California Highway 178 featuring a band of vitrophyre contained in the Miocene-aged Resting Spring Tuff (fig. 1). The volcano where this eruption originated is unknown, but it produced a thick pyroclastic flow which deposited ash and rock fragments along a paleo-slope (the pre-existing topography at the time). The presence of vitrophyre (figs. 1 and 3) at this deposit's center, which grades into densely welded tuff above and below it (figs. 1 and 2), indicates more rapid cooling of the surface and base of the deposit but sustained high temperatures at its center. This is due to the thickness of the ash deposit insulating the heated ash at its center to the point where it melted to form the glassy material. The heat from this ash also altered the ash around it, creating the densely welded tuff layer directly around the vitrophyre, which contains fiamme (fig. 4).



Fig 1. The Charlie Brown outcrop displays a color gradation which correlates with the changes from lighter colored welded tuff at its top and bottom, to darker densely welded tuff, and finally the black band of volcanic glass at its center. Students (soon to be us) for scale. (Image source: Wooster Geologists)



Fig 2 (left). A sample of vitrophyre from the Resting Spring Tuff. (Image source: Geologic Specimen Supply)



Fig 3 (right). Welded tuff composed of ash, pumice, and rock fragments (clasts) which were welded together by the heat of the pyroclastic flow which deposited them. (Image source: University of Pittsburgh, Department of Geology and Planetary Science)



Fig 4. An example of fiamme in the Resting Spring Pass Tuff. (Image source: Mark A. Wilson, Department of Geology at The College of Wooster)

Furnace Creek Basin

Between the Black and Funeral Mountains is the Furnace Creek Basin which contains a Cenozoic succession of three formations, approx. 3600 m in total thickness (Cemen and Wright, 1988). These specific formations are of interest because they contain preserved evidence of Death Valley's past volcanism. The formations (listed from oldest to youngest) are The Artist(s) Drive, Furnace Creek, and Funeral Formations, which unconformably overlay each other (Fleck, 1970) and are exposed in several different areas within a ~32 km long NW-trending belt. There have been discrepancies in the ages associated with these formations found by different researchers. This indicates possible faulting of the formations which causes younger ages for features in underlying formations or problems with the age dating methodologies of one (or more) of the studies.

1. Artists Drive Formation

- Volcanic products: Rhyolite and Andesite flows, ignimbrites, tuff-breccia

- The Artist Drive Formation is the oldest of the Cenozoic succession in Furnace Creek Basin and it is found stratigraphically underlying the Furnace Creek Formation. Rocks in this formation have been dated (using potassium-argon) between 9-6 Ma (Fleck, 1970) and 14-7.5 Ma (Cemen and Wright, 1988), placing its formation during the Miocene. Very few fossils are contained in this unit, but it does have lots of volcanic materials.

2. *Furnace Creek Formation*

- Volcanic products: Pumiceous Tuffs and Tuffaceous sandstone and siltstone
- The Furnace Creek Formation is stratigraphically located above the Artists Drive Formation and below the Funeral Formation in Furnace Creek Basin. It is composed of interbedded basalts, siltstones, sandstones, conglomerates, and tuffs. The upper part of this formation contains a sequence of volcanic tuffs that are Pliocene in age, known as the Mesquite Spring tuffs. This sequence of tuffs have been separated into at least two (and up to 6) distinct tuffs based on differences in the glass shard composition of the biotite phenocryst tuffs (Knott et al., 2005) which are 3.1 Ma for the upper tuff and 3.35 Ma for the lower tuff, based on stratigraphic, geochronologic, and paleomagnetic age (Machette et al., 2001). A good exposure of these tuffs is found at Double Ash Wash, located near the southern margin of the Furnace Creek Basin (Machette et al., 2001). Figure 5 (below) shows the stratigraphic column associated with this formation and its contact with the Funeral Formation above it.
- The pumiceous nature of these tuffs suggests a local source within the Pliocene drainage basin, due to transport limitations of pumice clasts >1 cm in diameter (limited to a range of 50-60 km from the source) which are found in this deposit (Machette et al., 2001).
- The tuffs were deposited in a lacustrine (quiet-water) environment.

3. *Funeral Formation*

- Volcanic products: Andesite and basalt flows, tuffs
- The youngest of the Cenozoic succession at Furnace Creek Basin, the Funeral Formation is stratigraphically located above the Furnace Creek Formation. This formation is composed of tilted and uplifted alluvial-fan conglomerates interbedded with sparse basalt flows. Exposures of these basalt flows are best seen in the upper reaches of the Furnace Creek Basin (Knott et al., 2005), though there are extensive deposits also within Artists Drive, Copper Canyon, and Kit Fox Hills. Initial potassium-argon age dating of the basalt flows in this formation placed it at ~4 Ma (McAllister, 1973), however the underlying Furnace Creek Tuffs dated to be ~1 million years younger, have thrown that into question which leads some groups to classify the transition between the Furnace Creek and Funeral formations higher up in the Funeral Formation than was initially done (by McAllister, 1970).

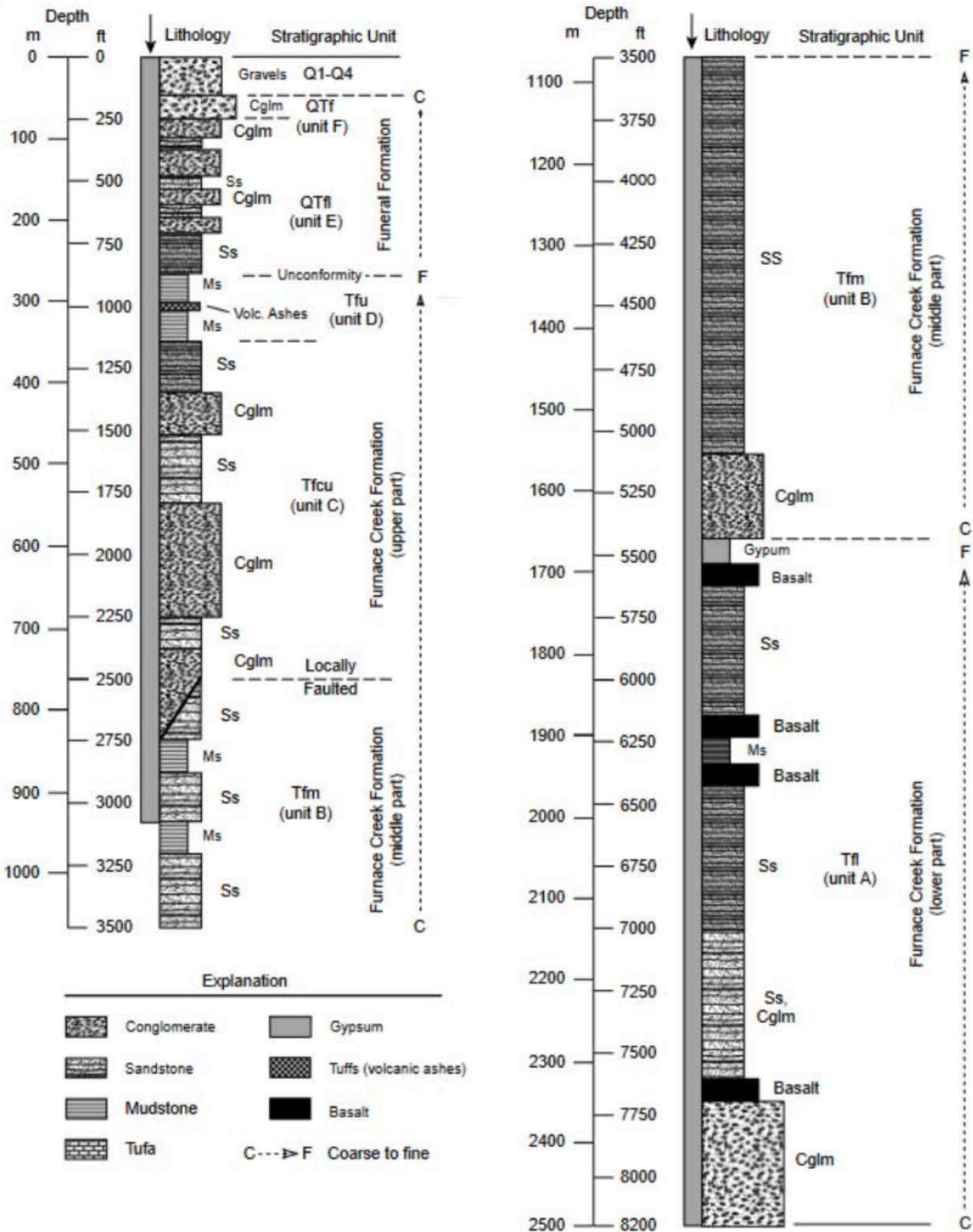


Fig 5. The Stratigraphic column of geologic units in the Furnace Formation to the Funeral Formation in the Furnace Creek Basin. Figure adapted from Machette et al. (2001) who used the original McAllister (1970) mapping as the basis for their schematic.

Artists Drive

Located west of the Black Mountains, across the Black Mountains fault zone. The outcrops of the Cenozoic sequence of formations here contain different units than those seen at the Furnace Creek Basin type locality.

1. Funeral Formation

- At the Artists Drive type locality there have been multiple tuffs of varying ages and distinguishing glass shard composition identified in the Funeral Formation.. This includes the upper Mesquite Spring tuff (3.1 Ma) which is located above the Nomlaki Tuff (3.28 Ma). Below the Nomlaki tuff is the lower Mesquite Tuff (3.35 Ma), which in turn overlies the lower Nomlaki tuff(>3.58 Ma). These tuffs were dated using similarities to other identified tuffs across the formation and by using a combination of stratigraphic relations and paleomagnetic methods (Knott et al., 2005).
- Ash beds are also located in the upper portions of the Funeral Formation at the Artists Drive type locality. The lower Glass Mountain ash beds are 1.7-1.9 Ma (Sarna-Wojcicki et al., 2001), thereby constraining the upper Funeral Formation's age.

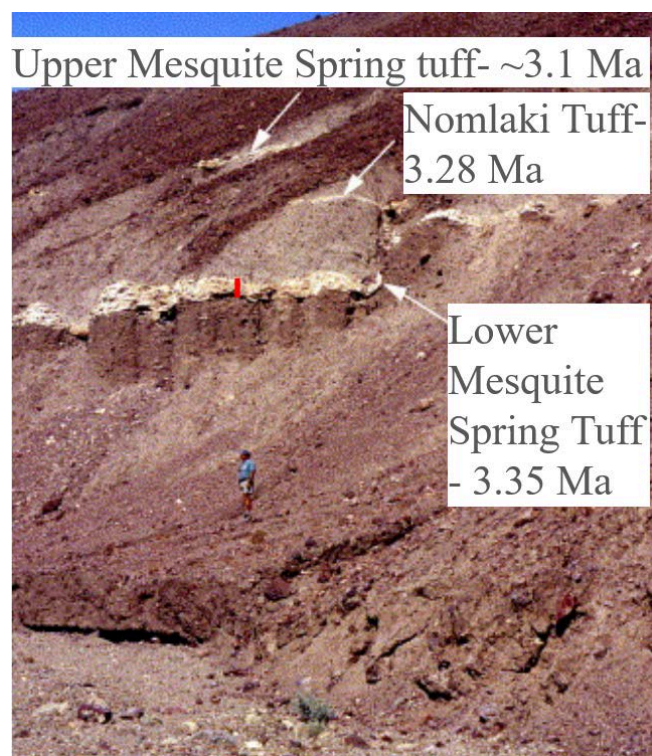


Fig 6. Outcrops of the tuffs interbedded between breccias and conglomerates in the Funeral Formation at the Artists Drive type locality (Hunt Canyon). Red line of lower Mesquite Spring tuff is ~ 1 m for scale. (Figure adapted from Knott et al., 2005)

Planetary Analogs: Mars

Due to the history of faulting and weathering throughout the volcanic deposits of Death Valley, examples of Martian volcanism are the best planetary analogs for this topic. Several sites on Mars are thought to have experienced wetter climates than observed today which led to the creation of possible tuff cones on the southern edge of Utopia Planitia (Broz and Hauber, 2013). Alteration products of volcanic materials are also present on Mars in the Noctis Labyrinthus region, created by water interacting with volcanic ash deposits on the surface (Mangold et al., 2010), similar to those found within the Artist Drive Formation of the Furnace Creek Basin.

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Alluvial Fans!
Rowan Huang
Death Valley - Spring 2024

Terminology

<i>Piedmont</i>	Sloping surface that connects mountains or elevated blocks to the adjacent plains
<i>Alluvial fan</i>	Fan-shaped or conical sediment deposits where a channel draining an upland catchment emerges from the mountains
<i>Bajada</i>	Coalesced group of alluvial fans
<i>Alluvium</i>	The sediment product of fluvial (associated with rivers or streams) accumulation
<i>Colluvium</i>	The sediment product of gravity-driven mass movement

Introduction

Alluvial fans are radial sediment deposits originating from a single point where a stream leaves a source area [3]. They form at the base of mountains in the piedmont environment. Alluvial fans can be distinct and isolated, like in the image on the right, or coalesce into a group of fans called a bajada.

Since alluvial fans record transport from the drainage basin, they can be used to study climate, tectonic uplift, and precipitation in the basin over time.



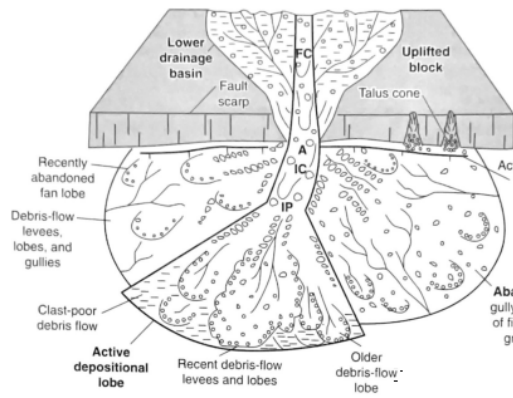
Badwater Basin, Death Valley alluvial fan.
Photo by M. Miller, U. of Oregon

Fan morphology

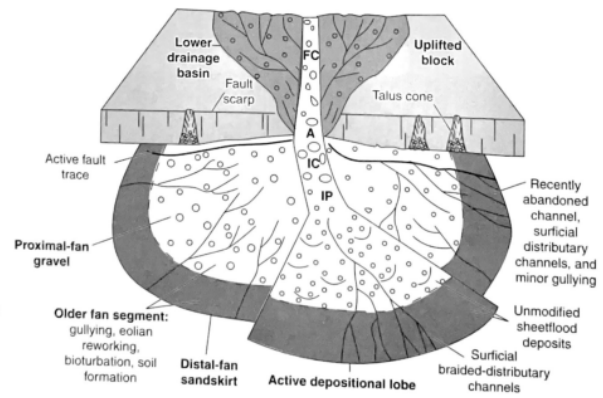
Alluvial fan shape is commonly described as fan-shaped in plan view and a conical segment in 3-D. They have the highest slope at their apex (the highest part of the fan) which decreases moving down the fan.

Blair and McPherson (1994) [1] sort alluvial fans into two morphometric types based generally on their water-to-sediment (w/s) ratio, seen in the schematic diagram below:

- Type I (debris-flow dominated; left): lower w/s; debris flow lobes; poor grain sorting of clayey pebbles to boulders; poor stratification; higher average slopes; low porosity and permeability
- Type II (fluvially dominated; right): higher w/s; sands, gravels to boulders decreasing in size distally; well-stratified layers; lower average slopes; high porosity and permeability



(A)



(B)

Both of these fan types have basic fan components of an apex (A); feeder channel (FC) which is the primary river channel connecting the fan to the upland drainage basin; incised channel on the fan (IC) connected to the feeder channel; and an intersection point (IP) where flow leaves the channel and spreads onto the surface of the fan. Downfan from the intersection point may be the only place on the fan where new material is being deposited, creating an active depositional lobe. This active lobe can move when there is deposition in the current lobe that backfills the channel, which creates abandoned channels on the surface of alluvial fans. Gullies can also form on the fan from precipitation directly onto the fan surface.

Alluvial fans can resemble other sediment depositional features, such as talus cones and deltas. These also form on and near slope breaks, but differ in what transports the sediment and their setting.

Alluvial Fan	Talus Cone	River Delta
 <i>M. Miller</i>	 <i>A. Rapp</i>	 <i>E. Busey</i>
Form subaerially in piedmont settings Channels: Feeder channel, with sparse distributary channels Size: 1-10 km ₁ Slopes: moderate-low; 1.5-25° ₁ Sediments: pebbles-boulders ₁	Form on steep slopes due to gravitational mass-wasting Channels: No channels Size: <10 km ₂ Slopes: high (>25°) ₄ Sediments: blocky pebbles-boulders ₄	Form mostly subaqueously in continental settings Channels: Trunk channel, with distributary channels Size: 1-100s of km ₁ Slopes: low (<1°) ₁ Sediments: mud-pebbles ₁

Sediment transport and deposition

There are generally two types of deposits on alluvial fans: incised channel flow and sheetflood [1]. The deposition of sediment in a channel occurs when some change reduces the shear stress of sediment-carrying water on the bed, so there is not enough energy to continue to transport the sediment. Commonly, the dimensionless shear stress (the Shields parameter) is used to measure critical shear (the shear stress required to transport a grain) [2]:

Critical shear stress θ_t :

$$\theta_t = \frac{\tau_0}{(\rho_s - \rho)gD}$$

Bed shear stress τ_0 :

$$\tau_0 = \rho ghS$$

θ_t = critical shear stress

τ_0 = boundary/bed shear stress

ρ_s = particle density

ρ = fluid density

g = gravitational acceleration

D = particle diameter

h = water depth

S = slope

In general, particles are in motion at higher θ_t , and still at lower θ_t . The exact value that determines when a particle is in motion depends on the parameters above, as well as the flow turbulence. Therefore, sediment is deposited in alluvial fans when the slope S decreases, such as at a mountainfront [4], or a change in hydraulic geometry like channel depth h occurs [3]. This can also explain why we see grain size D decrease moving downfan in fluvial fans [4], as larger grains are deposited first.

This is different for sheetfloods, which are broad, unconfined (not in a channel) deposits of mixed, sediment-laden water (20-45% sediment) [2]. Similarly, debris flows are >40% sediment, and form leveed channels and lobes due to their higher viscosity. These sediment-laden flows are driven by gravity rather than channel velocity, and the cohesion of the grains is reduced by the water.

Planetary Alluvial fans

Death Valley

One of the most common sedimentary features in Death Valley are its alluvial fans. Death Valley alluvial fans are often studied to examine the effects of tectonics on sedimentation and associated landforms [6].

- Fans on the west side of Death Valley are much larger and coalesce, while fans on the east side are small and distinct
- Death Valley tilts slightly eastward, so there is less sediment transport from the east
- Lake sediments provide potential dates for deformation and deposition

Alluvial fans in Death Valley have also been used commonly as analogs for planetary fans because of their lack of vegetation. They also make an appropriate analog for Mars because Mars is also thought to be arid, with intermittent periods of wetting.



Image of Death Valley fan morphology difference between east and west. Image credit: M. Miller, U. of Oregon



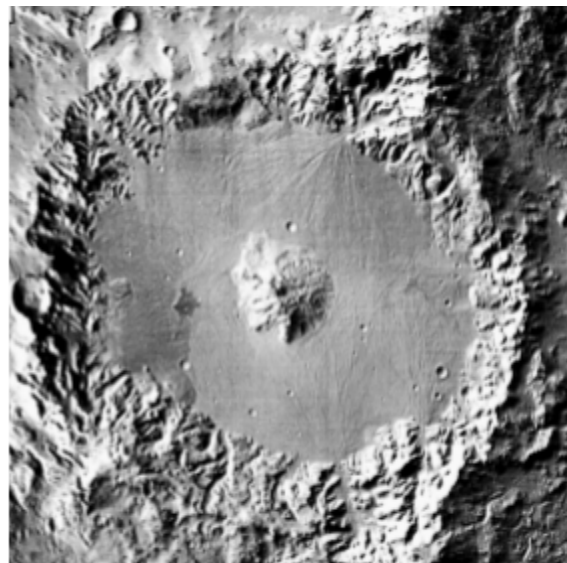
Alluvial fans can record tectonic activity in Death Valley. Here, scarps deform the alluvial fan, showing that recent tectonic activity has occurred. Photo credit: M. Miller

Mars

Alluvial fans on Mars have been recognized in large impact craters and massifs [9]. Morphometric comparison to terrestrial fans like those in Death Valley is one way to verify this origin. The identification of these fans can tell us about Martian hydrology, sediment types, and paleoclimate. Moore and Howard studied Martian fans, finding:

- Large fans → extended period of development
- Large and gently sloping → fluvial origin?
- Similarity to Death Valley fans → gravelly sediment?

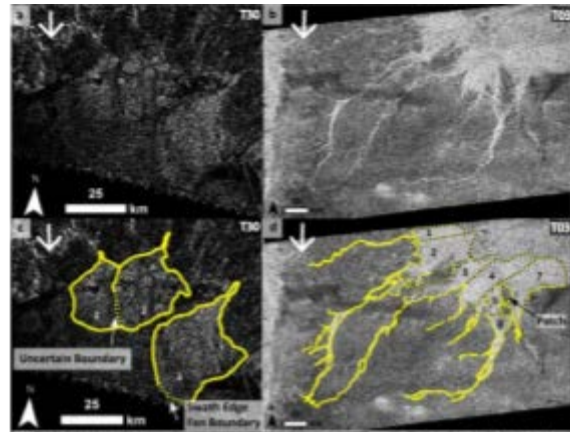
As represented above in the Shields parameter, it is thought that Mars' lower gravity makes it easier to transport sediments compared to Earth. However, the low gravity also affects the yield stress, so it may be harder to entrain grains or move debris flows [9].



THEMIS Day IR image of a ~66-km crater with several alluvial fans. The fan on the north side has a wide fan shape, while those on the south side are more elongate. Image from Moore and Howard, 2005

Titan

Saturn's moon Titan is thought to have alluvial fans, seen in images by Cassini SAR (Synthetic Aperture Radar). Unlike terrestrial fans, fans on Titan are thought to be composed of water ice and organics transported by liquid methane and ethane. These fans are found in areas with relatively high precipitation in Titan climate models and generally match the morphology of terrestrial fans, but they are smaller than expected [10].



Possible alluvial fans on Titan identified in Cassini SAR images with distinct boundaries delineated. Image credit: Cartwright and Burr, 2017

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Snowball Earth

Rocío Aurelia Jacobo Bojórquez

Introduction

The Snowball Earth occurred when our planet underwent global glaciation periods. Earth's surface became completely frozen with no liquid water (oceanic or continental) exposed to the atmosphere. Based on the geologic record Earth has experienced two big periods of glacial activity. The first one occurred during the Paleoproterozoic at about 2.4 Ga, and the other during Neoproterozoic time between about 0.8 and 0.6 Ga. There have been younger glaciations on Earth, but the deposits of two Precambrian glacial periods are related to tropical rather than polar paleolatitudes indicators (carbonate rocks, red beds, and evaporites). In this review, we are going to focus on the glacial activity from the Neoproterozoic (Hoffmann and Schrag, 2000; Kirschvink et al., 2000).

Evolution of a Snowball Earth event from Hoffmann and Schrag, 2000.

Stage 1. Around 770 million years ago the continents were scattered near the equator after the breakup of a single landmass. After that, more areas were closer to oceanic sources of moisture. Increasing rainfall improved erosion. The temperature dropped down and

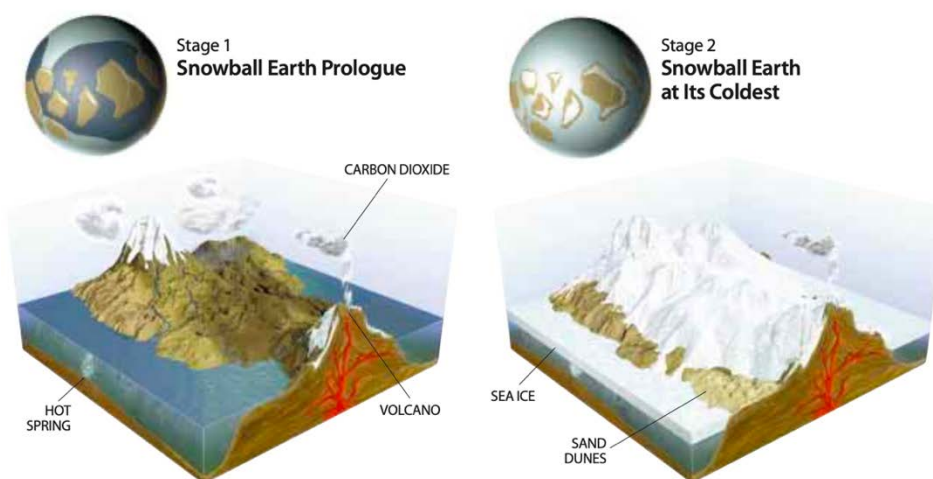


Figure 1. Evolution of a Snowball Earth Stages 1 and 2 (Hoffmann and Schrag, 2000).

large amounts of ice started to accumulate in the polar regions. The white ice reflected more solar energy in comparison with the seawater making the temperature lower, creating a cycle that cooled the planet until it was covered with ice (Fig. 1).

Stage 2. The temperature dropped to an average of -50 C and the ocean ice had an average depth of 1 km limited by the heat received from Earth's interior. The surviving marine microorganisms lived around volcanic hot springs. The water cycle stopped and with the lack of rain, the carbon dioxide from the volcanoes started to accumulate in the atmosphere warming the planet again. The isolation of the oceans from the atmosphere would have produced a metalliferous, reducing ocean chemistry (Fig. 1).

Stage 3. The accumulated carbon dioxide in the atmosphere created a greenhouse effect. The water at the equator started to melt and refreeze at higher elevations feeding the growth of land glaciers. The ocean water absorbed more solar energy making the temperature rise faster (Fig. 2).

Stage 4. The global water cycle restarted, and with the carbon dioxide, created more intense greenhouse conditions. The surface temperature rose to more than 50 C, creating an intense cycle

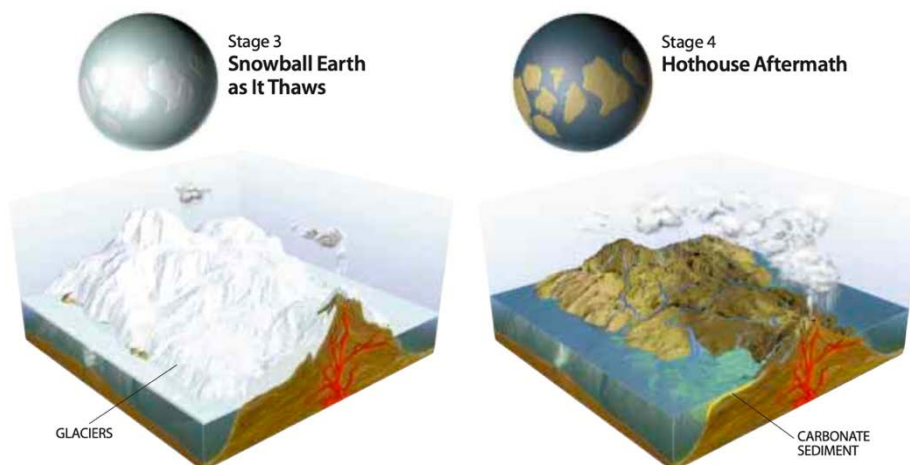


Figure 2. Evolution of a Snowball Earth Stages 3 and 4 (Hoffmann and Schrag, 2000).

of evaporation and rainfall. Carbonic acid rain eroded the rock debris from the glaciers and the rivers bringing bicarbonate and other ions into the oceans that formed carbonate sediment. New life forms emerged populating the planet while the global climate went back to normal (Fig. 2).

The glacial deposits and the carbonate rocks of the Neoproterozoic extended worldwide showing us a Snowball Earth followed by a greenhouse event. What are the causes of such events? The first possibility is that the Sun was weaker (6 %) making the Snowball Earth more possible, but there is no geologic evidence that suggests that such glaciations occurred around a billion years before the Neoproterozoic when the Sun was cooler. The location of the continents closer to the equator could explain how the Snowball events work. When the continents present a configuration like today's (closer to the poles) the amount of carbon dioxide in the atmosphere keeps the planet warm. When the temperatures drop enough that ice covers the high-latitude continents preventing the erosion of the rock beneath the ice, the carbon dioxide stabilizes at a level that prevents the growing of the glaciers. If the continents are compiled close to the equator, they would stay ice-free even if the temperature on Earth is cooler and approaching the critical limit for a runaway freeze, but the erosion caused by the rainfall would destabilize the levels of carbon dioxide in the atmosphere, making more possible a global glaciation (Hoffman et al., 1998, Hoffmann and Schrag, 2000; Kirschvink et al., 2000).

Geologic evidence

The fragmentation of a supercontinent was accompanied by widespread glaciation. Most glacial deposits are overlain by carbonate rock or contain carbonate debris, they also include inorganic sea-floor precipitates (limited to warm weather). Some glacial units contain large sedimentary iron formations (reappearing after a 1-billion-year hiatus). The glacial events are separated by the decrease of $\delta^{13}\text{C}$ value of the surface ocean. The carbon dioxide produced in volcanoes that moves into the oceans is composed of 1 % carbon 13 and the rest is carbon 12. Algae and bacteria growing in seawater use carbon from the water preferring carbon 12 over carbon 13. The carbon that forms carbonate rocks in a life-filled ocean has a higher ratio of carbon 13 to carbon 12 than does the carbon from volcanoes. Paleomagnetic data imply that the ice line reached sea level close to the equator during at least two Neoproterozoic glacial episodes (Hoffman et al., 1998).

Death Valley geologic setting

Like on other parts of Earth, Neoproterozoic deposits in Death Valley, California, contain eukaryotic microfossils and glacial deposits used to describe snowball Earth events and their climate consequences on life. This geologic record contains evidence for synsedimentary faulting related to the rifting of Rodinia (Macdonald et al., 2013).

The geologic units exposed in the Death Valley region evidence the geological evolution of the southwestern margin of Laurentia (Figs. 3 and 4).

- Basement rocks: 1.76 Ga granitic gneisses of the Mojave crustal province intruded by ca. 1.4 Ga porphyritic quartz monzonite.
- The Pahrump Group (Unconformably overlying): a 1.5–4-km-thick mixed carbonate and siliciclastic succession. Formed by the Crystal Spring Formation, the Beck Spring Dolomite, and the Kingston Peak Formation. The lower portions of the Crystal Spring Formation are intruded by 1.08 Ga diabase sills.
- Noonday Formation: the lowest member (635 Ma) was identified as a basal Ediacaran cap dolostone.
- Johnnie Formation.
- Stirling Quartzite.
- Early Cambrian Wood Canyon Formation (Precambrian-Cambrian boundary).

The region underwent multiple extension episodes during the late Neoproterozoic and the development of the Cambrian passive margin. Following the Permian contraction and magmatism, then the Mesozoic Cordilleran orogeny and Neogene extension. This extension was accommodated by breakaway detachment faults with felsic and mafic intrusions (Macdonald et al., 2013).

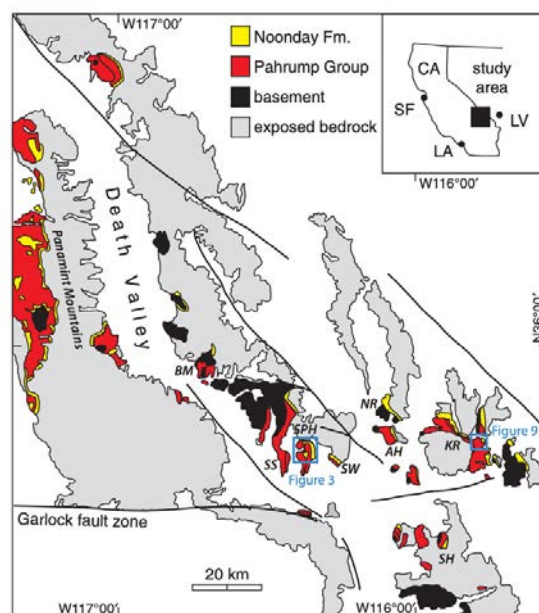


Figure 3. Geological map of the Pahrump Group and Noonday Formation in Death Valley (Macdonald, 2013).

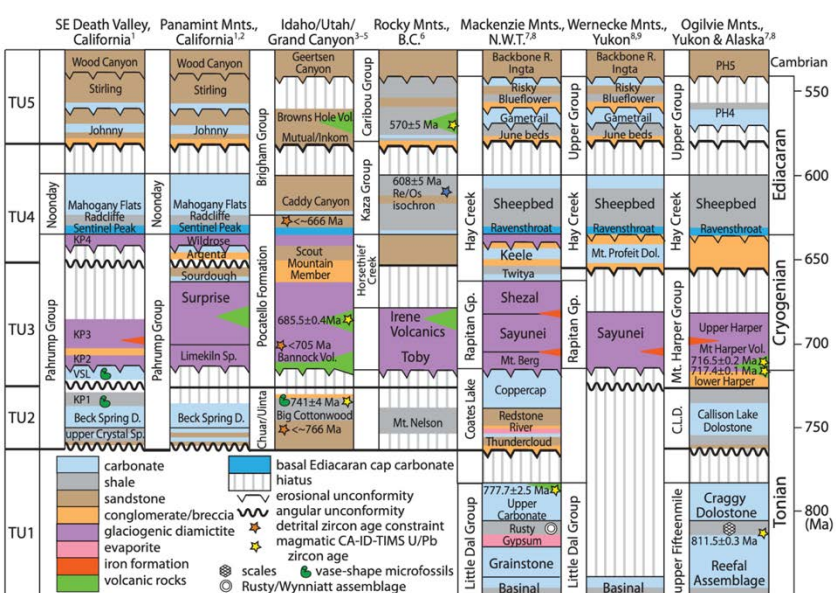


Figure 4. Correlation chart of some Neoproterozoic successions on the western margin of Laurentia (Macdonald, 2013).

Mars's recent glaciations

Mars, unlike Earth, undergoes significant variations in incident sunlight which influences the distribution of ice across its surface. Mars experiences ice ages determined by climatic changes caused by alterations in its obliquity. The subsurface ice on Mars is located from mid-latitudes to higher latitudes (regions where ice remains stable due to temperature and atmospheric conditions). Mars's rotational axis has experienced changes over the planet's history, altering the stability of ice regions. Simulations suggest major ice ages occurred in the past five million years (Fig. 6), leading to the formation of subsurface ice layers observed today. Climate simulations indicate high obliquity leads to ice precipitation in the tropics and redistributing to mid-latitudes as obliquity decreases. As ice sheets evolve, they become buried and reach equilibrium with atmospheric humidity (Schorghofer, 2007).

Spacecraft data from Mars Global Surveyor (MGS) and Odyssey missions revealed evidence supporting recent almost periodic climate change on Mars. These observations include topographic smoothing, distribution of geological formations, and the presence of specific surface deposits, all exhibiting a strong correlation with latitude.

The most recent ice ages on Mars occurred from approximately 2.1 to 0.4 million years ago and led to the formation of dusty, water-ice-rich mantling deposits across both hemispheres, extending from mid-latitudes to the poles. The deposits, several meters thick and layered extended to latitudes of approximately 30°.

Currently, Mars is in an interglacial period, marked by the degradation, reworking, and retreat of the ice-rich deposits due to the instability of near-surface ice. Martian ice ages are different from Earth's because they feature warmer polar climates and increased transport of atmospheric water and dust toward lower latitudes, resulting in widespread smooth deposits extending to mid-latitudes (Head et al., 2003).

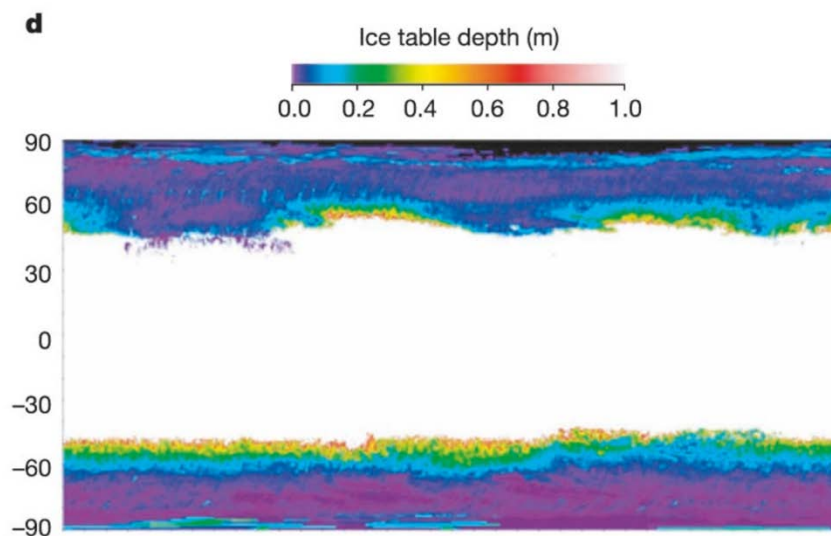


Figure 5. Map of ice table depth for an annual mean of 10 precipitable micrometers of atmospheric water vapor based on a near-surface ice stability model (Head et al., 2003).

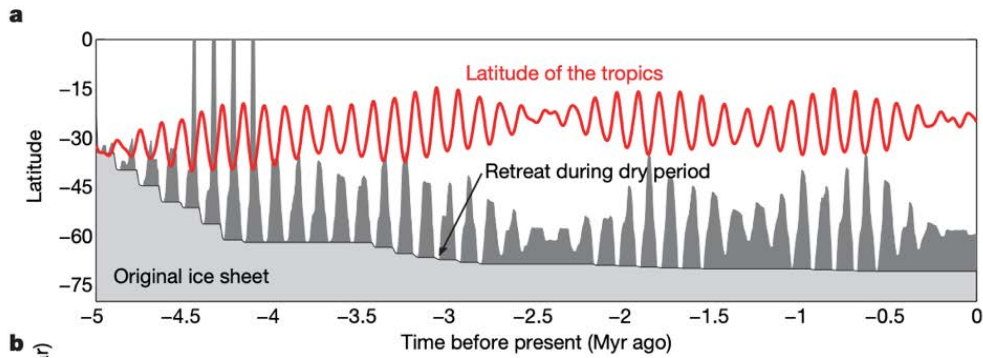


Figure 6. Evolution of southern hemisphere ice over the past five million years. Latitudinal extent of ice in the topmost meter of soil (Schorghofer, 2007).

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Lake Tecopa

Arkadeep Roy

Geological Setting

The Lake Tecopa basin, situated near the California-Nevada border within Death Valley, is an internally drained hydrologic basin in the western central United States (Fig. 1). It's characterized by its Cenozoic age and location along the southern part of the Amargosa River drainage system, which ultimately feeds into Death Valley [1]. Filled with several hundred meters of alluvial deposits and capped by up to 170 meters of late Cenozoic lakebeds known as the Lake Tecopa beds [2], the basin's surface exposes late Pliocene to middle Pleistocene saline and alkaline-lake deposits [3]. These beds also feature numerous small-displacement faults and fractures, some of which reveal visible springs and seeps. The overall climate in Death Valley is extremely dry, with minimal rainfall. Water is replenished from surrounding mountain ranges to Death Valley through underground conduits consisting of porous sedimentary rocks, fractures, and faults. Most water passes below the Amargosa River which is connected to a deep fault in the region [4].

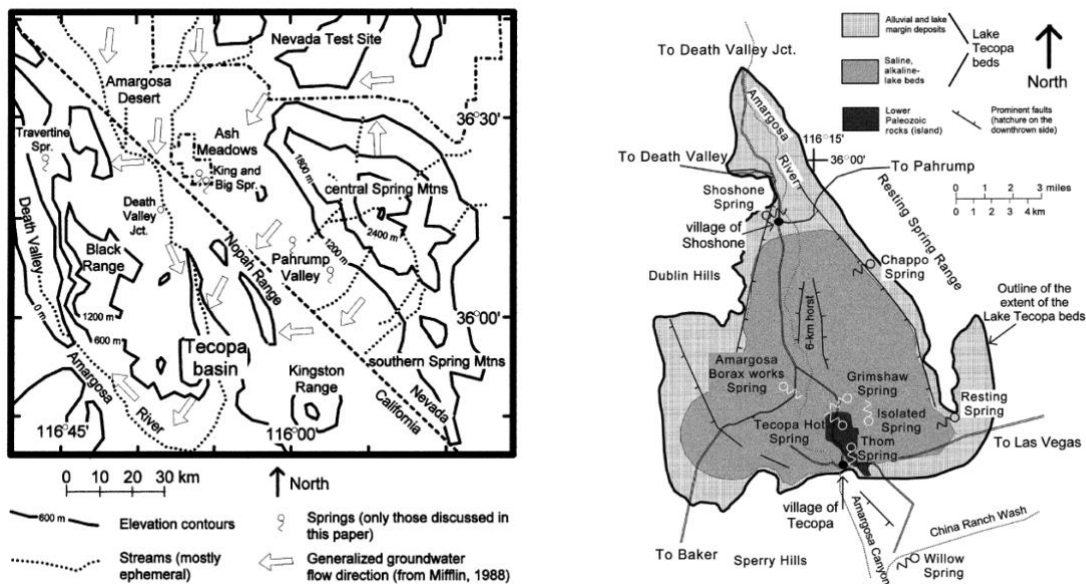


Figure 1. (Left) Map of Death valley marking the location of Lake Tecopa. (Right) Detailed map of the Lake Tecopa basin [4].

Geologically, the basin comprises a crystalline gneissic basement overlain by Pleistocene lacustrine sediments and alluvial fan deposits. Along the eastern side of the Dublin Hills and the Resting Springs Range, a succession of upper Proterozoic to middle Cambrian marine sedimentary rocks is found. The basin's major deposits, including conglomerate, mudstone, tufa, and volcanic ash, formed during the wet climate of the late Pliocene epochs. These volcanic ash deposits have been chemically correlated with eruptions from Yellowstone and Long Valley, indicating a Tertiary age.

During the late Pliocene and early to mid-Pleistocene periods, the Tecopa basin served as the terminal basin for the ancestral Amargosa River, with present-day flow being intermittent. Groundwater likely originates from the central Spring Mountains and Amargosa Desert due to the basin's flow directions. Despite the

presence of volcanic rocks in the region around 10 Ma, hot spring activity is not attributed to recent volcanic activity as the youngest volcanic rocks have been dated to be ~ 7 Ma. Instead, deep circulation of water along faults is considered the primary cause. Hot springs are associated with intersecting faults rather than exclusively occurring along the Amargosa River faults. Electric and magnetic surveys of the region also support the role of intersecting faults in the heating and transport of water to produce hot springs.

Paleo-evolution of Lake Tecopa

Previous studies [5,6] have reconstructed the history of Tecopa Lake levels. Four main phases of lakes in the basin were identified, ranging from early Pleistocene shallow lakes to larger lakes terminating with significant ash bed depositions. Another later study [7] identified perennial lakes marked by green muds beneath the Tecopa tuff which suggested additional lake-level fluctuations. The Tecopa basin's hydrology is influenced by abundant felsic volcanics in the Amargosa River watershed, resulting in high ALK/Ca water compositions. In contrast, groundwater and carbonate aquifers in the Tecopa basin contribute water with lower ALK/Ca compositions. The presence of specific ostracode species further indicates the source of water within the basin to either have connection to the Amargosa River or local groundwater sources. The highly alkaline water coupled with long stretches of dryness, fluctuating water level, and high salinity provides the opportunity for chemical weathering of the felsic silicates in the basin which results in the precipitation of clay (or zeolite) minerals found throughout the basin (Fig. 2).

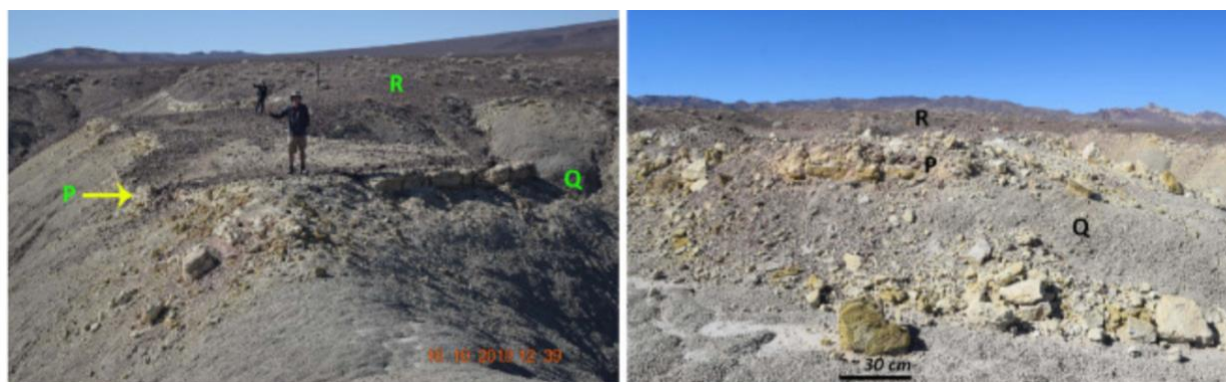


Figure 2. (Left) Thin layer of zeolitic tuff bed (marked as P) and, (right) mixing of zeolitic tuff bed with surrounding sedimentary beds because of physical weathering in Lake Tecopa [8].

The historical sediment record of the Tecopa basin spans over 2 million years, with episodic presence of shallow lakes and wetlands during the early Pleistocene. The Amargosa River's influence sustained larger lakes for most of the basin's evolutionary history, with a hiatus in lake records around 300,000 years ago when the river's flow into the basin ceased. The river's return around 185,000 years ago led to the formation of significant lakes, impacting the landscape and contributing to the paleoclimate record of the region. Contrary to earlier studies [5,6] inference of increasing pluvial episodes, the reconstruction of lake highstands does not support this trend. Instead, there's evidence of ongoing basin deformation, with significant uplift and subsidence over the past several hundred thousand years. This deformation contributes to the complexity of interpreting shoreline elevations and correlations within the basin, highlighting the importance for accurate measurements and understanding of tectonic influences on the landscape.

A Martian Analog Candidate

Hot springs offer a potential habitat for life to evolve and thrive, not only on Mars but also in places on Earth like Death Valley (Fig. 3). These environments, with their constant flow of liquid water, provide a

safe haven amidst the Martian arid landscape. Thus, hot springs in the Lake Tecopa can act as an analog environment where life can potentially survive. Near Lake Tecopa, the hot springs are likely Artesian, where water is heated deep beneath the Earth's surface due to factors like high pressure, friction, and underground circulation. The composition of the water is influenced by the temperature of the hydrothermal system and the surrounding rocks. Hot springs transport a variety of chemical species and solutes to the surface, enriching surface environments with redox energy and nutrients [9]. This diverse chemical composition, coupled with thermal gradients created by the outflows from the spring which fosters chemical precipitation and supports microbial growth. It is believed that such ancient microbial ecosystems may have thrived in such environments, possibly serving as the origin of life on Earth (and possibly in ancient Mars as well). The geological and hydrological characteristics of Lake Tecopa create a unique environment where all the essential conditions for life are met. The presence of extremophiles and diverse microbial communities in modern-day hot springs worldwide highlights that life can adapt to such harsh conditions.

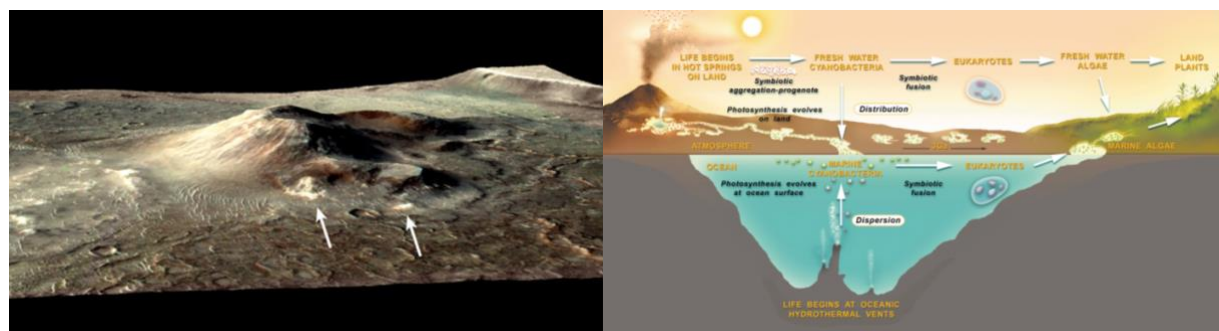


Figure 3. (Left) Volcanic cone in the Nili Patera caldera on Mars has hydrothermal mineral deposits on the southern flanks and nearby terrains – a potential ancient hot spring location on Mars [10]. (Right) Alternative scenarios for an origin of life including hot springs, freshwater hydrothermal field pools or saltwater hydrothermal vents [9].

Due to the arid climate of Death Valley area along with the availability of highly saline water in the Lake Tecopa region, there is an abundance of aqueously altered clay minerals and evaporites deposits. The zeolite group of minerals are a common authigenic mineral deposits seen in Lake Tecopa (Fig. 2), which is consistent with the deposits of saline, alkaline nonmarine environments found in the region. Particular zeolite mineral groups are associated with changing water chemistry and kinetically controlled precipitation and dissolution reactions [11]. Thus, discriminating the form of zeolite can help investigate the paleo-environment of both Mars and Earth. Understanding the paleoenvironment via zeolite mineral deposits can reveal more information about the climate and hydrochemistry of early Mars [8].

Remote sensing of Martian surface reveals a warm and wet past where predominant landforms included open and closed basin lakes, channels deposits, alluvial fans, and deltas. Such paleolakes hold critical information regarding the hydrological evolution of Mars (e.g., neutral, saline, saline-alkaline, or acidic). The chemistry of zeolites thus is a function of both seasonal and orbital changes, as well as local geological processes occurring in the catchment area of the paleoponds due to changes in hydrologic conditions [11,12]. Global Surveyor Thermal Emission Spectrometer (TES) data in Mars has absorption features at 6.134 and 12.048 μm (Fig. 4) have identified spectral evidence of zeolite mineral groups in the atmospheric dust [12].

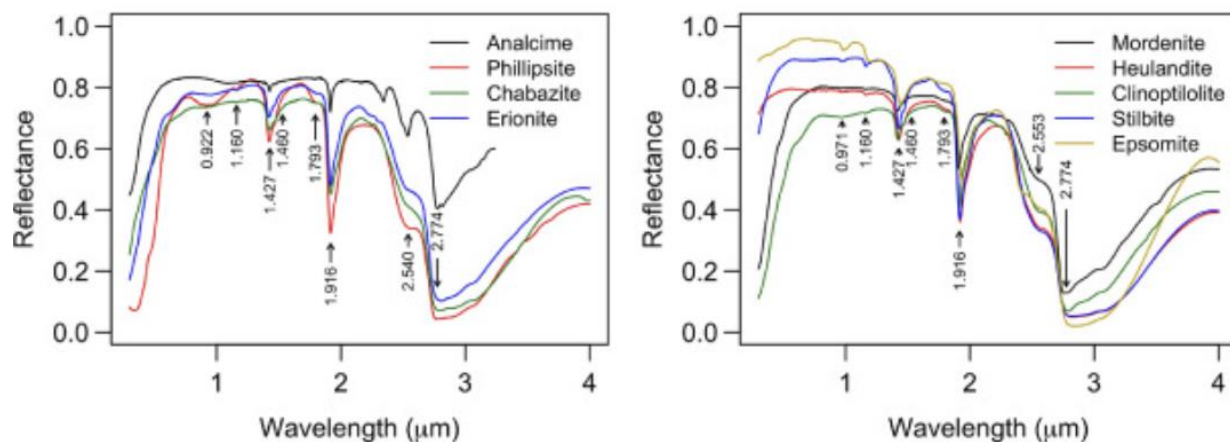


Figure 4. RELAB spectra of different zeolite minerals (particle size <45 μm) [8].

Therefore remote sensing with targeted analysis of zeolite group of minerals in Martian paleo-basins can address the local-scale basin evolution as well as long term climatic evolution of the red planet. Conclusions from Lake Tecopa's unique mineralogical and hydrological environment are very interesting analog locations which can be studied to understand the climatic changes which have occurred on Mars as well as how extremophile life may have potentially evolved.

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Sand dunes represent an exquisite manifestation of natural patterns, arising from the aggregation of loose sand particles through the influence of aeolian forces. These formations are predominantly observed in desert and coastal ecosystems, serving as a testament to the formidable power of wind-driven processes. The genesis of sand dunes necessitates specific conditions: primarily, an abundant source of loose sand. This requirement is met in various environments such as sandy coastlines, riverine sandbars or alluvial deposits within fluvial valleys, and sandy substrates in arid desert regions. Moreover, a critical factor in the development of dunes is the presence of robust wind activity. Coastal areas benefit from the persistent onshore winds propelled from bodies of water, while deserts are often subjected to strong, sometimes protracted, wind events.

Formation of Sand Dunes

1. **Wind Transportation of Sand:** Sand is moved by wind through three main mechanisms: surface sliding, rolling, and saltation. Saltation involves sand grains leaping and being temporarily suspended in a flow of air or water.
2. **Obstacle Circumvention:** As sand moves, grains navigate around obstacles, eventually settling in areas where wind velocity is lower, known as wind shadows, located downstream from the obstruction.
3. **Wind Shadow Effect:** Within these wind shadows, the wind velocity is significantly reduced compared to the air flow around the obstacle. This reduction in speed allows sand grains to deposit and accumulate.
4. **Formation of Sand Drifts:** The accumulated sand grains form a nascent pile, or sand drift, on the sheltered side of the obstacle, initiating the foundational stage of dune formation.
5. **Evolution into a Dune:** With continuous sand accumulation and consistent wind direction, the sand drift becomes larger and acts as an obstacle itself, eventually growing into a fully formed dune.

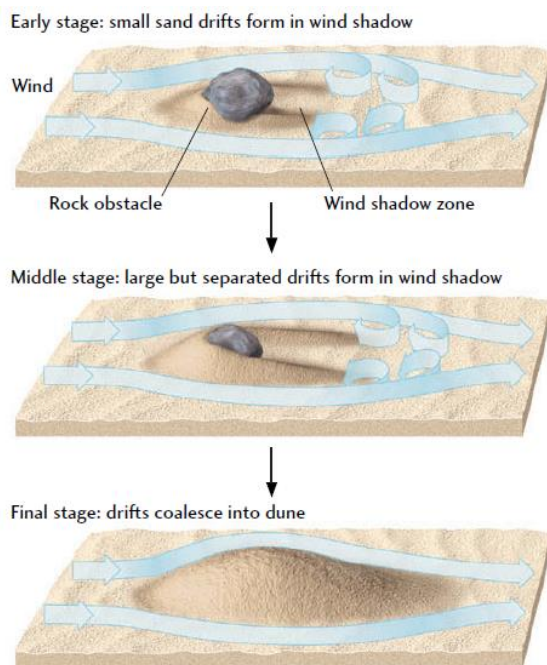


Figure 1:
The obstacle divides the wind streamlines, forming a wind shadow with weaker eddies compared to the main flow. This allows airborne sand grains to settle in the shadow, accumulating in drifts that eventually merge into a dune.

Migration of Sand Dunes

1. Initiation of Dune Migration: A dune's migration downwind is driven by the collective movement of sand grains, which move via saltation. These grains jump to the peak of the dune's windward slope before sliding into the leeward slope's wind shadow, initiating the growth and movement of the dune.

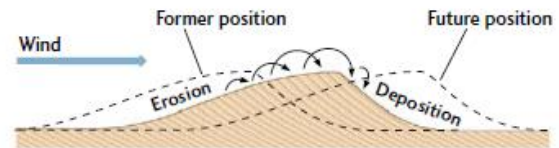
2. Formation of the Slip Face: The continuous deposition of sand grains on the leeward slope leads to the development of a steep, unstable layer. This layer periodically collapses, forming a slip face with a gentler incline, known as the angle of repose, which is determined by the size and shape of the sand particles.

3. Cross-Bedding Creation: The repetitive deposition at the angle of repose results in cross-bedding, characteristic of aeolian dunes. This geological feature, preserved even as dunes evolve or become buried, helps in reconstructing ancient wind patterns and indicates the presence of large, ancient dunes.

4. Growth in Height: The dune grows in height as more sand accumulates on the windward slope than is lost on the leeward side. This process continues until the dune reaches a significant height, often ranging from several meters to, in extreme cases, up to 250 meters.

5. Equilibrium and Height Limitation: The height of a dune is naturally capped when the wind speed at its summit increases to the point where it removes sand grains as quickly as they are deposited.

1 A ripple or dune advances by the movements of individual grains of sand. The whole form moves forward slowly as sand erodes from the windward slope and is deposited on the leeward slope.



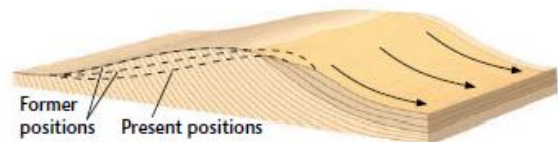
2 Particles of sand arriving on the windward slope of the dune move by saltation over the crest,...



3 ...where the wind velocity decreases and the sand deposited slips down the leeward slope.



4 This process acts like a conveyor belt that moves the dune forward.



5 The dune stops growing vertically when it reaches a height at which the wind is so fast that it blows the sand grains off the dune as quickly as they are brought up.

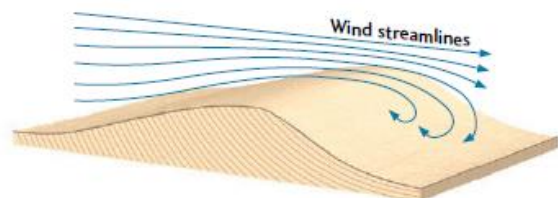


Figure 2: Sand dunes grow and move as wind transports sand particles by saltation.

Types of Dunes

The overall forms and configurations of sand dunes are influenced by the volume of sand present, along with the wind's direction, duration, and intensity. Four primary categories of dunes are identified by geologists:

Barchan dunes: Barchans are crescent-shaped dunes, usually but not always found in groups. The horns of the crescent point downwind. Barchans are the products of limited sand supply and unidirectional winds.

Blowout dunes: Blowout dunes are almost the reverse of barchans. The slip face of a blowout dune is convex downwind, whereas the barchan's is concave downwind.

Transverse dunes: Transverse dunes are long ridges oriented at right angles to the wind direction. These dunes form in arid regions where there is abundant sand and vegetation is absent. Typically, sand-dune belts behind beaches are transverse dunes formed by strong onshore winds.

Longitudinal dunes: Longitudinal dunes are long ridges of sand whose orientation is parallel to the wind direction. These dunes may reach heights of 100 m and extend many kilometers. Most areas covered by longitudinal dunes have a moderate sand supply, a rough pavement, and winds that are always in the same general direction.

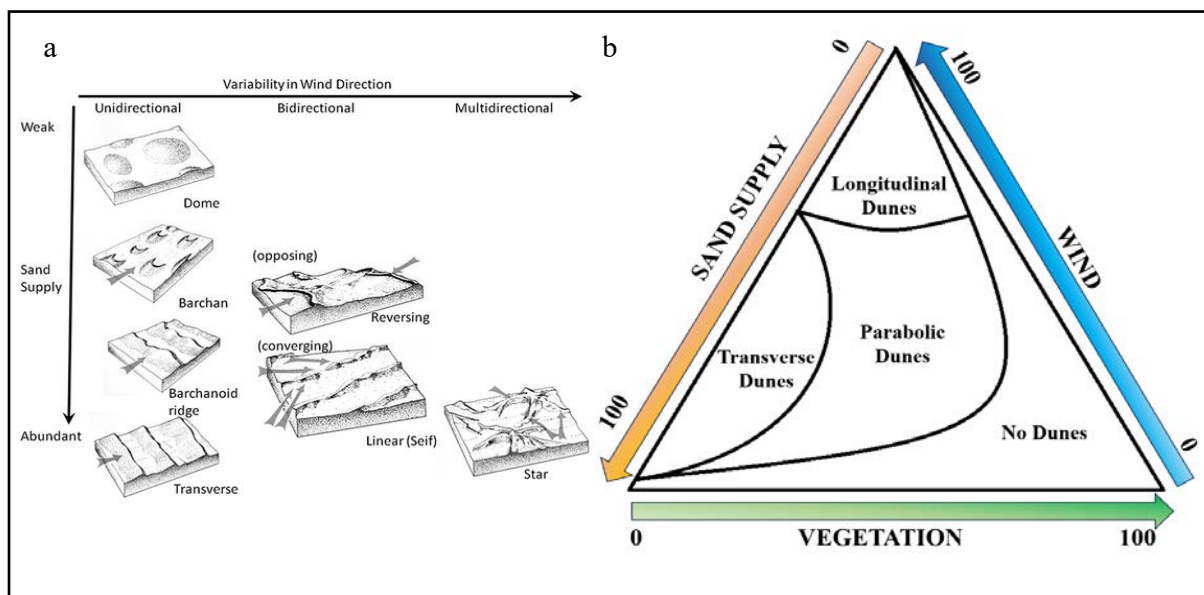


Figure 3: (a) McKee (1979) categorized the principal types of dunes in a schematic that correlates sand availability with variations in wind conditions. (b) Model of dune type evolution modified from Hack (1941).

Research indicates that the landscapes of Mars, Venus, and Titan (a moon of Saturn) have been significantly influenced by the action of winds, known as aeolian processes. Studies involving geological and atmospheric analyses, coupled with detailed imagery, have led to the finding that existing wind currents are capable of transporting dust and sand, facilitating the formation of dunes and other wind-related deposits. While wind alone plays a minimal role in the erosion seen on these celestial bodies, it becomes a potent erosive force when laden with sand particles and rock debris, particularly in dry environments. This natural sandblasting effect, primarily occurring near the surface where sand grains are most abundant, smoothens and wears down rock formations, boulders, and pebbles, leading to the creation of ventifacts - rocks shaped and polished by wind-driven sand.

Ventifacts are rocks sculpted by wind forces, with the term "ventifact" deriving from Latin, meaning "shaped by wind." These formations are typically located in expansive, flat, or desert areas where sand or blowing snow is present in moderate quantities. They vary greatly in form and scale, ranging from substantial rocky formations to individual pebbles.

Environments of Ventifact Formation

Ventifact formation occurs in settings defined by several factors: (a) the availability of abrasive materials, (b) sparse or nonexistent vegetation, (c) potent wind forces, (d) topography conducive to unobstructed wind flow or that amplifies wind speed locally, and (e) stable ground surfaces. Such environments typically include deserts, periglacial regions, and coastal areas on Earth, with ventifacts being even more prevalent on the Martian surface.

Erosional Forms

Ventifact surfaces display a diverse array of erosional patterns, varying in both shape and size. These variations stem from factors such as the type of rock, the angle of the surface, its weathering history, the availability of eroding sediment, and the velocity of the wind.

Type of Ventifacts	
Facet: A relatively plane surface cut at right angles to the wind, regardless of the original shape of the stone. Facets commonly join along a sharp ridge or keel. Multiple wind directions are represented by several facets.	

Pits: A pitted surface is one indented by closed depressions, often of irregular shape. Pits occur on surfaces that are inclined at high angles to the wind (55–90°) and thereby indicate the windward side of boulders. As the angle between the face and the wind decreases, a transition from pits to deep flutes with overhanging ends occurs.	
Flutes: Flutes are open at one end and closed at the other, and broadly U-shaped in cross-section. They may appear as “arrowheads” that point in a downwind direction. Flutes form independently of material hardness, composition, or rock structure on surfaces that are nearly horizontal or inclined at low angles (less than 40°) to the wind: flutes become shorter and deeper as the inclination of the surface steepens.	
Grooves: Grooves are longer than flutes and open at both ends. They are best developed on surfaces gently inclined or parallel to the wind. However, they are sometimes seen on the vertical sides of rocks, particularly where the wind has accelerated between adjacent large boulders.	
Helical Forms: Helical forms are uncommon. They begin as shallow grooves, deepen and spiral in a downwind direction, and terminate in a sharp point; range from several millimeters to several centimeters in width and depth; and maintain a consistent form as their scale increases. They develop on the upper face of the ventifact and have been observed in marble, basalt, and granite.	

Table 1: Types of ventifacts. Images from (Laity, 2009).

Planetary Analogs of Sand Dunes and Ventifacts

Evidence suggests that the surfaces of Mars, Venus, and Titan, one of Saturn's moons, have been extensively shaped by wind-driven (aeolian) processes. Analysis of geological and atmospheric data, along with high-resolution imagery, supports the conclusion that prevailing wind patterns are capable of moving dust and sand, resulting in the creation of dunes and various other aeolian formations.

The Martian landscape is marked by numerous rocks with features indicative of ventifacts, shaped by wind-driven particles. These wind-sculpted rocks are more prevalent at the Pathfinder site compared to the Viking sites, suggesting most erosion occurred under past climatic conditions unlike today's. The ventifacts' orientation at Pathfinder, along with signs of sand-driven erosion, hint at formation during a different climate period with plentiful sand. It's believed that massive floods from Ares and Tiu Valles around 1.8-3.5 billion years ago deposited the sand, which was then swept up by southeast winds to shape the ventifacts. Since then, remaining Martian sand has gathered in depressions, protected from the wind and reducing further erosion of rocks.

Implications

Martian dunes form under conditions with a higher rate of saltation and larger splash events due to grains traveling at higher velocities, resulting in different dune shapes and sizes. Martian wind speeds, generally below 3.0 m/s, shape the dunes' elongated structure and affect their minimum size. Martian dunes move much slower than Earth's, suggesting that it would take a dune approximately 4,000 years to move 1 meter, making it improbable that dune movement would be detected by orbiting spacecraft.

The discovery of ventifacts on Mars holds significant implications for the study of Martian geology and for planning upcoming exploratory missions. The extensive abrasion observed on Martian rocks, coupled with the presence of widespread dust and potentially other types of surface modifications, suggests that pristine rock surfaces are relatively uncommon on Mars. Analyzing the directional patterns of ancient winds, inferred from ventifacts, offers crucial insights into Mars past climatic conditions, insights that cannot be readily obtained from orbital imagery alone. Therefore, ventifact analysis is proposed as a critical element of geomorphological research in future missions involving landers and rovers.



Figure 4:
Example of enigmatic Transverse Aeolian Ridges (TARs) near Juventae Chasma, Mars (HiRISE image [PSP_004990_1755](#)). These and other fascinating topics highlighted the Aeolian Processes session at LPSC. Image: NASA / JPL-Caltech / U. Arizona

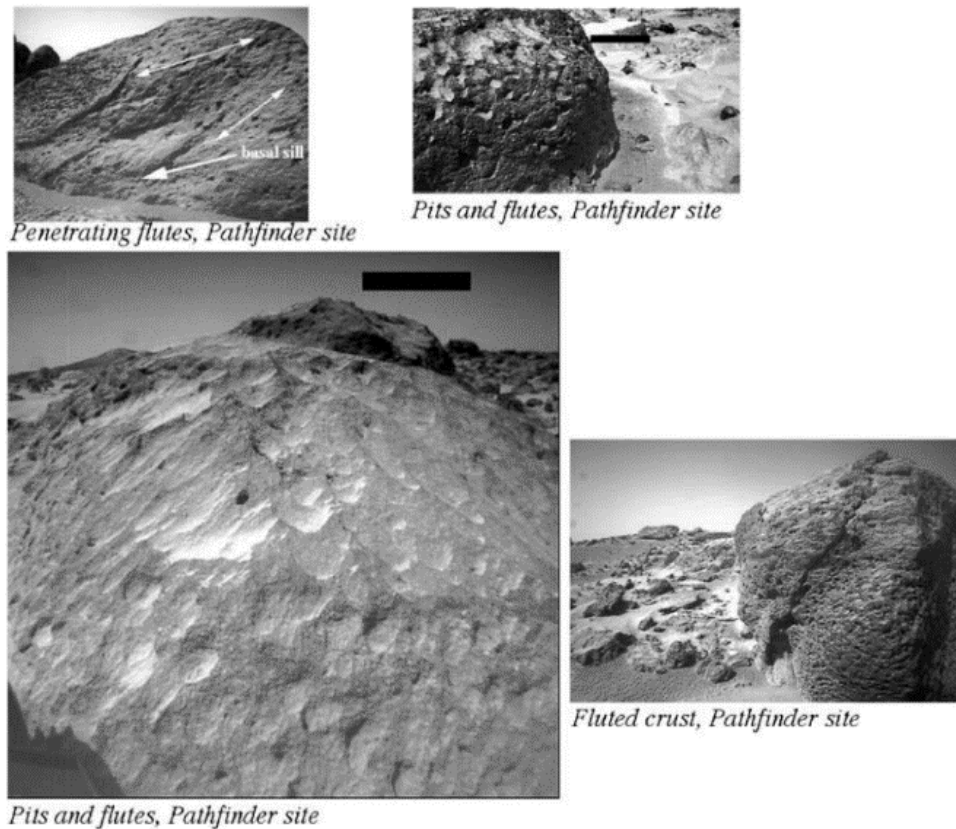


Figure 5: Example of ventifacts on Mars. Source: [HiRISE | Image Catalog \(uahirise.org\)](https://uahirise.org)

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Habitability and Life Detection

Death Valley is, perhaps unintuitively, an excellent place to observe life. The harsh conditions here, dry and hypersaline, render the landscape uninhabitable to many life forms found elsewhere, but support hundreds of species well-adapted to this environment. Cacti and lizards, among other desert dwellers, live here because they benefit from living here. The relative low density of predators and competition is one such benefit. Through studying the things that live in Death Valley, we can learn about the limits of life—and the detectability of life—on Earth, sharpening our understanding of habitability. This can help us to better predict where and how we might find extraterrestrial life.

Habitability can have different meanings for different sorts of life. For example, Death Valley is an ideal habitat year-round for some plant species. Mesquite trees, with their long roots, are in this category; they survive by accessing water deep beneath the surface.



Figure 1. Mesquite trees and sand dunes in Death Valley. Image credit: NPS/ C. Augustson



Figure 2. A wildflower bloom next to Badwater Basin, 15 February 2016. Image credit: NPS / Alan Van Valkenburg

For other plant species, Death Valley is only sometimes habitable. Like the wildflowers that periodically bloom in the park after rainstorms, lying dormant as seeds until the time is right, species like these wait out the inhospitable seasons. This is relevant to our search for life elsewhere in the solar system, as research suggests that Mars, though dry like Death Valley, may have periodically had liquid water on or near its surface throughout its geologic history (e.g., Clifford & Parker, 2001; Cousins & Crawford, 2011; Rodriguez et al., 2015). Even if it may not be possible for life to continually thrive on Mars today, there may be ephemeral habitable conditions that permit occasional reproduction in certain locations on the planet. Microbial life could take advantage of these local conditions. Understanding such ephemerally habitable environments—and life’s response to them—on Earth is therefore informative in our search for life elsewhere.

In addition to knowing *where* to look for extraterrestrial life, we also must know what to look for. Signs of life, or biosignatures, are detectable in a variety of ways that depend on the sort of life being observed. The more ways we have to detect life on Earth, the better chances we have of finding life off Earth.

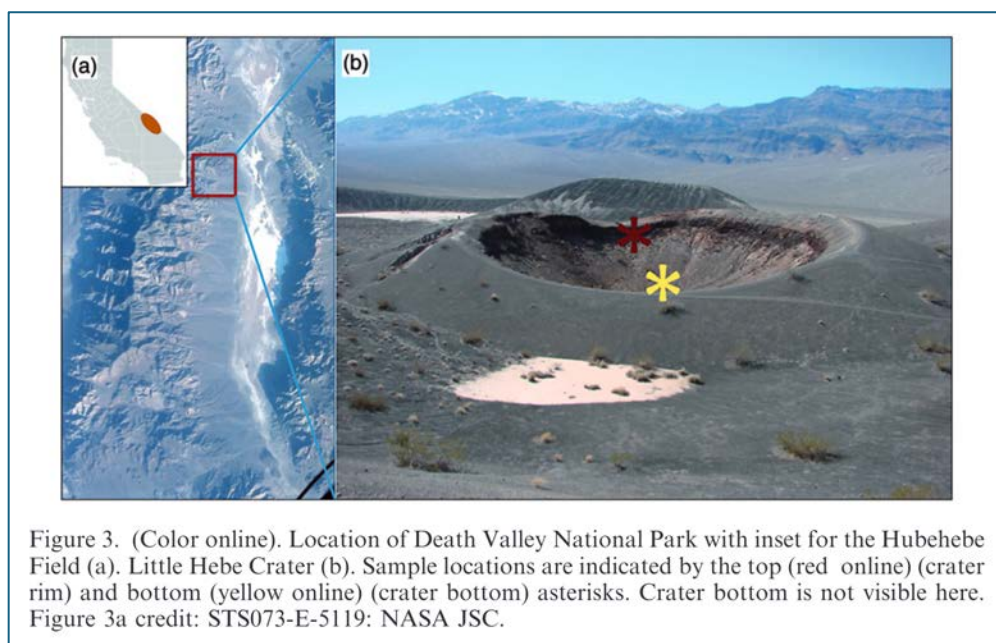


Figure 3 from Bonaccorsi et al., 2013.

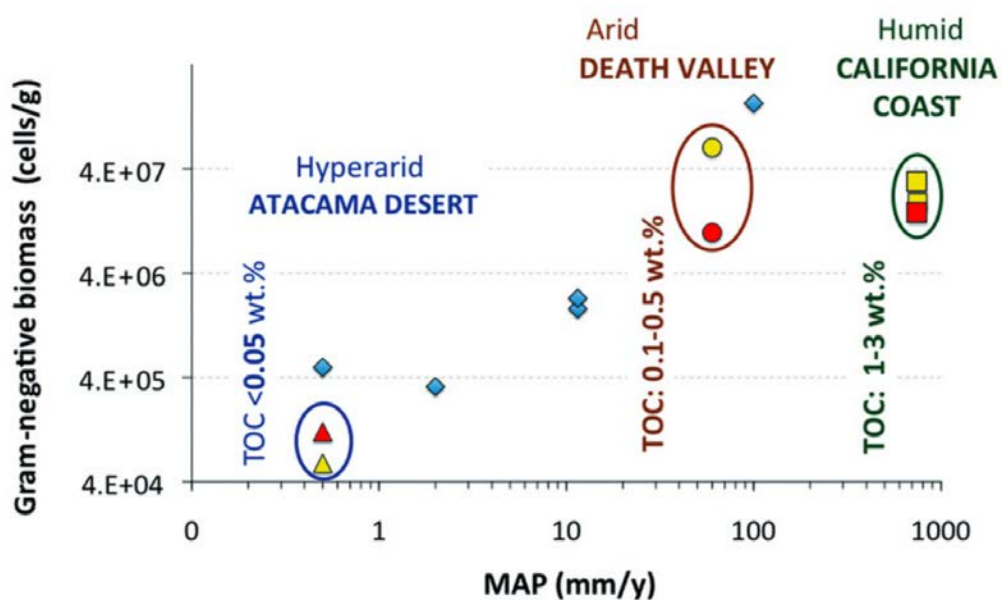


Figure 4. Example of results from one biosignature detection method, the LAL assay, used at three sites on Earth, including the Ubehebe volcanic field in Death Valley. Mean Annual Precipitation is on the horizontal axis. Source: Bonaccorsi et al., 2013.

The Limulus Amebocyte Lysate (LAL) assay is a biosignature detection method, demonstrated in Death Valley by Bonaccorsi et al. (2013). This method uses blood cells, specifically amebocytes, from *Limulus polyphemus* horseshoe crabs! When they encounter bacterial endotoxins, these cells as a defense mechanism produce chemicals that cause clotting. The LAL assay therefore measures clotting as a proxy for the presence of bacteria (gram-negative biomass) that has endotoxins. Note that in the Ubehebe volcanic field, and even at a far drier location in Chile's Atacama Desert, this method still indicated the presence of thousands of cells per gram of sample material.

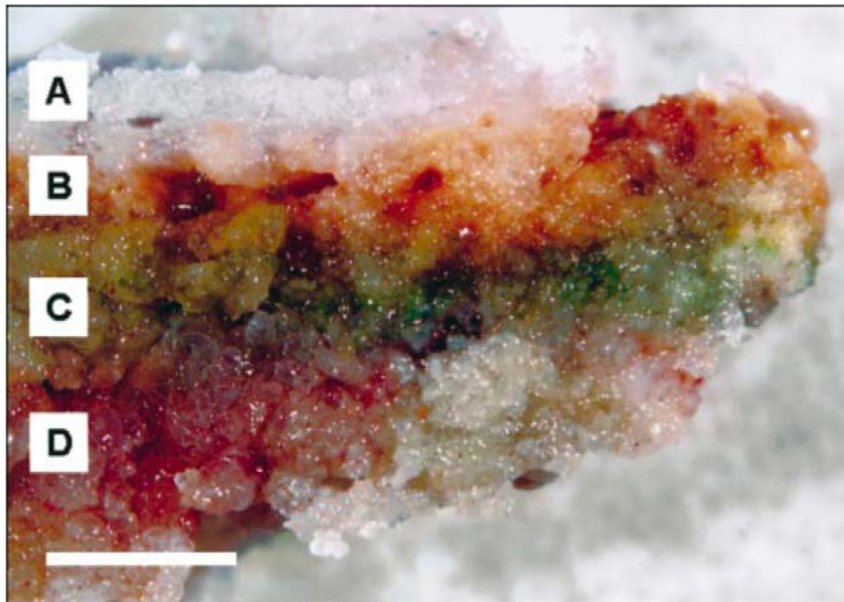


Figure 5. Colorful halophile colonies in salt crystals from Badwater Basin. Scale bar is 2mm long. Source: Douglas & Yang, 2002.

Visual and spectroscopic techniques are also powerful tools in the search for biosignatures. Colonies of halophilic (salt-loving) microbes in Death Valley can produce colors that stand out to the naked eye. Looking at some of these colonies under a scanning electron microscope, Douglas & Yang (2002) noticed something interesting: corroded gypsum crystals alongside slender crystals of sulfur in an unexpected form. They used X-ray diffraction spectroscopy to identify these sulfur crystals as rosickyite, a mineral not

expected to be thermodynamically stable at Earth's surface. These researchers suggest that the halophilic cyanobacteria in these salt deposits are actively contributing to the dissolution of gypsum and the growth of rosickyite.

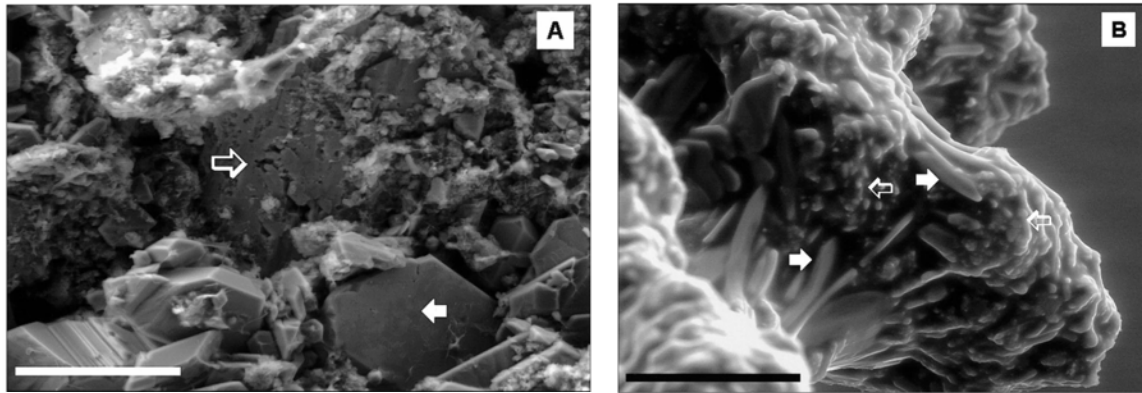


Figure 6. (A) Hollow arrow indicates corroded gypsum crystals, potentially “pitted by microbially driven dissolution”. (B) Solid arrows indicate rosickyite crystals, hollow arrows indicate cyanobacteria. Scale bars are 100 μm long. Source: Douglas & Yang, 2002.

This is a potential biosignature, and something to look for in analogous hypersaline environments on other planetary bodies. For example, some terrains on Mars may have formed through dissolution of salt-rich materials (Naor et al., 2023), and could be past or present habitats for halophiles. Farther out in the solar system, the oceans of Enceladus are estimated to have a high salt content, and halophilic bacteria in those oceans could potentially be detectable in erupting plumes (e.g., Perera, 2023).

Extreme environments like Death Valley give us opportunities to stretch our understanding of life and our ability to detect it, improving our chances of detecting life in other extreme environments throughout the solar system and beyond.

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Salt Weathering

Beau Prince

Salt weathering is a set of processes in which salts (namely halides and sulfates) crystallize inside pores in a material such as rock or building materials (e.g. concrete and mortar). The stress induced by crystallization can then fracture the surrounding material, leading to the material's disintegration over time (Scherer, 2001). In geological contexts, salt weathering is of particular interest for its generation of weathering forms such as honeycombs, tafoni, and rock debris, all of which have been observed on Earth and Mars. In other fields, such as construction and historical preservation, salt weathering is relevant as an important obstacle to overcome.

How Salt Weathers Rock

There are numerous ways in which salt can enter pores and subsequently crystallize. However, while the source of a brine might change in each scenario, each case relies on capillary action to draw the brine into the interior of the porous material. For simplicity, let's focus on the scenario in which a porous rock is sitting atop hydrated soil.

In this case, capillary action draws moisture from the soil upwards, as shown in Figure 1. The salt to then crystallize may be dissolved in the fluid drawn from the underlying soil, or it may come from the rock. As water is drawn further up the rock, it will evaporate out of the sides of the rock. At a certain height, the water will be absent from the exterior of the rock but present in the rock's interior, leading to crystal growth in pores below the rock's surface, a process known as subflorescence. At this height, the solution is often supersaturated from the slow rate of capillary rise.

When the solution is drawn into pores during in the zone of subflorescence, salt crystals will precipitate from the supersaturated solution. Figure 2 shows the main three cases in which this can occur. In the first case, shown in Figure 2a, crystallization occurs in a cylindrical pore with wide openings. Assuming precipitation from a supersaturated solution, the crystal will grow to fill the pore until it is blocked by the wall of the pore. Here, crystal growth is stopped, and the crystal correspondingly exerts a force on the pore wall, resulting from repulsive electrostatic and solvation forces between the crystal and the thin film of solution between the pore wall and the crystal. The strength of this force is proportional to the temperature, volume of the crystal, and the solubility product (i.e. equilibrium constant)

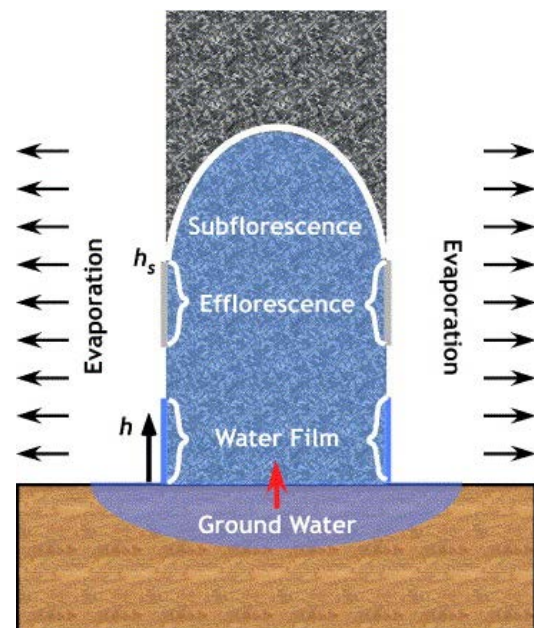


Figure 1: A cartoon of a porous medium drawing water from underlying moisture via capillary action. h_s denotes the height at which evaporation and capillary rise are equal. Above this height, subflorescence occurs. The region marked by efflorescence denotes where supersaturated solution precipitates salts on the exterior of the medium.

of the faces of the crystal. In general, for a macroscopic pore, the crystallization pressure, p , is given by Correns' equation,

$$p = RTV_c \ln QK$$

Where R is the gas constant, T is temperature, V is molar volume of the crystal, Q is the solubility product, and K is the solubility of the crystal in the solution.

The case of small pore openings (Figure 2b) is similar, except the crystallization pressure is inversely proportional to the radius of the opening, greatly increasing the amount of pressure generated by crystallization. This case can generate pressures on the order of the tensile strength of rock if the supersaturation of the solution is great enough to support continued crystal growth.

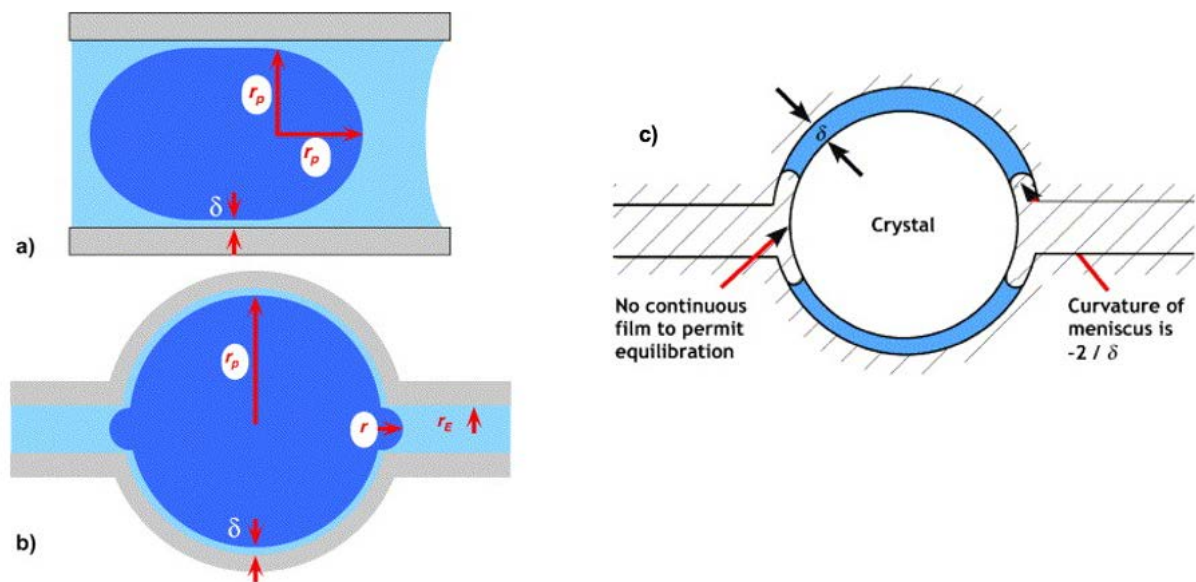


Figure 2: **(a)** A crystal precipitating from supersaturated solution in a cylindrical pore. Pressure is generated radially outwards from the crystal growing towards the pore wall. **(b)** A crystal precipitating from supersaturated solution in a pore with small openings. Here, the crystallization pressure is approximately the curvature of the crystal in the pore entries. This scenario can produce large crystallization pressures for large crystals and small pore openings. **(c)** The nonequilibrium case in which evaporation has created an isolated film surrounding the crystal which cannot equilibrate with the bulk solution. Continued evaporation will supersaturate the solution, stimulating crystal growth, which is blocked by the pore wall. This will create increasing pressure in the pore until the pore wall yields. (Scherer, 2004)

Finally, crystal growth can occur in pores where evaporation has dried the pore entries, creating a discontinuous film of solution around the crystal (Figure 2c). In this case, ions cannot diffuse into the bulk solution through the pore openings and so the supersaturation of the solution can only increase. If the humidity in the pore is low enough for evaporation to continue, the solution will continue to become supersaturated, but the crystal is still confined by the pore wall and cannot grow further. This generates increasing pressure until the pore wall or crystal deforms. Since the tensile strength of salts are generally higher than rock (100s of MPa vs 10s of MPa, respectively), this usually results in the pore wall breaking. (Scherer, 2004).

Salt Weathering in Action: Death Valley

As we'll see in Badwater Basin (if it's not flooded), the floor of Death Valley is home to a large

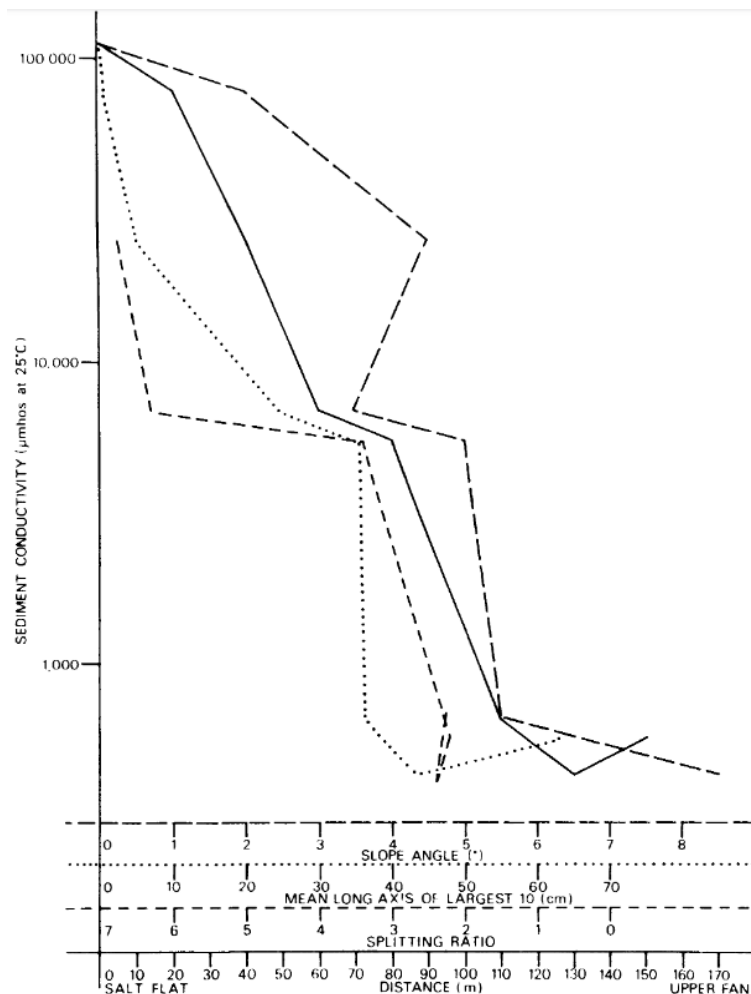


Figure 3: Soil conductivity measurements collected along an alluvial fan at various distances from the Badwater Basin salt pan. Grain size increases as distance from the salt pan increases. The rise in conductivity near the salt pan indicates an increase in brine concentration in the alluvial material. (Goudie & Day, 1980).

salt pan. Extremely high evaporation rates and sporadic water input has caused evaporite minerals to accumulate on the surface of the valley. Alluvial fans often discharge into the salt pan. In these areas, the average grain size of fan materials decreases precipitously as the fan contacts the salt pan. This change in grain size can occur over the course of distances of ~100 m and can result in grain sizes going from cobble sizes upslope to sand/silt sizes at the salt pan. Figure 3 shows a profile of soil conductivity along an alluvial fan terminating at the salt pan 800 m north of Badwater Basin. The dramatic increase in soil conductivity near the salt pan indicates the materials have incorporated more salt and/or water near the salt pan. Correlating this with the extreme reduction in grain size, it has been determined that salt weathering, by a mechanism similar to that described above, is causing the breakdown of alluvial cobbles into sand/silt-sized particles. (Goudie & Day, 1980)

Another common form of salt weathering which we may get to see is the formation of “honeycomb” or “alveoli” in weathered rocks, as shown in Figure 4. These features manifest as distinct pits within a larger rock. There are several proposed formation mechanisms for honeycomb weathering, but most rely on some degree of mechanical disruption by salt crystallization within pores in the rock. As proposed by Rodriguez-Navarro et al. (1999), breakdown of a rock resulting from salt weathering, as described above, can lead to pits on the rock’s exterior. These pits can then catch wind more efficiently than the surrounding surface of the rock increasing evaporation rates in the pit and therefore breakdown from salt crystallization. Iterating this process across the rock’s surface can create a deeply pitted honeycomb weathering pattern.

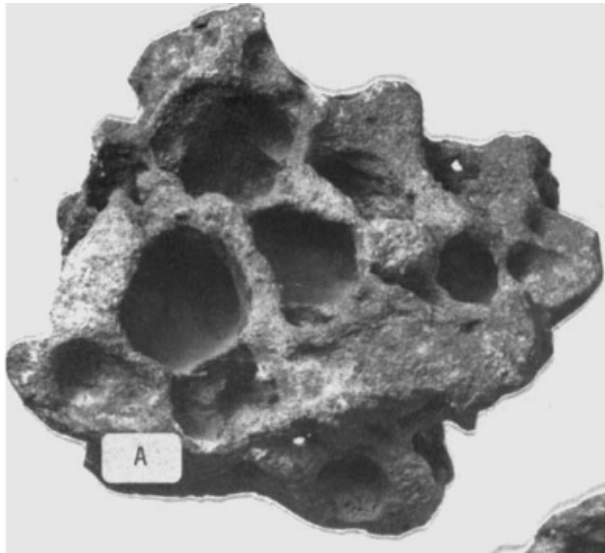


Figure 4: A weathered quartzite (~10 cm across), collected from a wave-produced bench near Salt Spring Hills in Death Valley, displaying honeycomb (or alveoli) pits. The authors (Butler & Mount, 1986) suggest these pits form through a combination of mechanical disruption from salt crystallization along grain boundaries followed by dissolution from exposure to high-pH lake water. (Butler & Mount, 1986)

polygons on the salt surface. Prior to sinking, the plumes of saturated salt at the surface create areas of high salinity that can precipitate salt faster than the surrounding, lower-salinity fluid. This enhanced precipitation creates the characteristic ridges along the polygon boundaries. (Lasser et al., 2023).

Salt Weathering on Mars

Salt-induced breakdown on rocks on Mars has been used to explain a number of weathering features in Martian rocks. One such feature is the honeycomb-like structures identified in various Martian rocks by the Sojourner Rover shown in Figure 6. While the temperature and vapor pressure of water on Mars are too low to sustain an aqueous solution exposed to the atmosphere, it has been shown that water can be adsorbed onto mineral surfaces or condensed as frost. Adsorbed water likely occurs only as a monolayer, but if the rock

Another Salt Process: Polygon Formation

A characteristic feature of salt flats across Death Valley are the polygonal patterns that form across their surface, as shown in figure 5. Beneath this salt crust is mud saturated by groundwater flow. Recently, this system has been modelled as a Darcy flow in a porous medium (the mud) with evaporation occurring at the flow's surface. Just underneath the crust, the water in the soil is saturated, and as you move downwards away from the crust, the concentration of dissolved salts decreases. This creates a concentration gradient that can in turn generate convection of the mud. Near-surface water saturated in salt will sink, forcing unsaturated water to the surface. This unsaturated water will then saturate as it comes in contact with the salt layer on the surface and then sink again. Convection cells resulting from this process manifest as

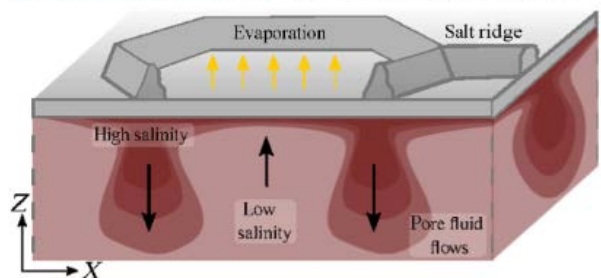


Figure 5: Salt Polygons in Middle Basin (a), Owens Lake (b), and Badwater Basin (c) in Death Valley. Below: A schematic of the convection that leads to the polygon formation. Figures from Lasser et al., 2023.

contains salt, adsorbed water can create an adsorbed solution along pore walls. It has been shown experimentally that an adsorbed solution can accumulate more monolayers than the pure solvent, so the creation of a solution along pore walls can then drive the accumulation of more solution. When temperatures rise enough to evaporate the solution, the dissolved salt can then precipitate out. The crystallization pressure generated by this precipitation can lead to the disintegration of the host rock. The disintegration of small areas of the rock is likely assisted by occasional frost shattering (frost is not expected to be common near the Pathfinder landing site), chemical weathering induced by the adsorbed saline solution, and the removal of weathered rock though wind. The combination of these processes may explain the honeycomb-like structures seen on Mars. (Rodriguez-Navarro, 1998).



Figure 6: Three examples of honeycomb weathering patterns near the Pathfinder landing site on Mars. The arrow in (c) marks an example of large honeycomb separated by very thin walls. These honeycomb-like patterns may be due to a combination of salt weathering, frost shattering, chemical weathering, and honeycomb excavation by the wind. (Rodriguez-Navarro, 1998).

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Death Valley Pupfish

PTY5 590 - Planetary Geology Field Study - Final Report

Introduction

Death Valley, a landscape synonymous with extremes, stands as a testament to the forces sculpting our planet over millennia. Nestled within this arid environment lies a unique ecological phenomenon – the pupfish of Death Valley. As we explore the geological intricacies of this otherworldly terrain, the interaction between planetary processes and the resilience of pupfish habitats becomes a focal point of inquiry. Death Valley's geological history, marked by tectonic upheavals and the deposition of distinct sedimentary layers, sets the stage for an unparalleled study in planetary geology. Against this backdrop, the pupfish species inhabiting the valley's various ecosystems reveal themselves as both survivors and indicators of the region's geological dynamics. This report delves into the geological context of Death Valley, examining the tectonic events that shaped its formidable features and the sedimentary deposits that influence the habitats of the pupfish. Furthermore, this exploration extends to the fascinating adaptations of pupfish species, offering insights into their unique survival strategies in the face of extreme planetary conditions. As we unravel the intricate tapestry of Death Valley's planetary geology and the pupfish that call it home, this study aims to contribute to a deeper understanding of the interplay between geological processes and the delicate balance of life in extreme environments. In doing so, we illuminate not only the wonders of Death Valley but also enrich our comprehension of planetary systems and their broader implications.



Figure 1: A spawning pair of Salt Creek pupfish. Female specimen to the left, male to the right. (Image Credit: National Park Service)

Geological Context of Death Valley

Situated within the expansive Mojave Desert, Death Valley encapsulates a captivating geological narrative shaped by millennia of tectonic activity and sedimentary deposition. The valley, situated at the convergence of multiple fault lines, has experienced extensive stretching and subsidence, leading to its renowned low elevation point at Badwater Basin. Tectonic forces, notably the boundary interaction between the Pacific and North American plates, have played a pivotal role in sculpting the surrounding mountain ranges, such as the Panamint Range and the Black Mountains. Additionally, the sedimentary deposits within Death Valley provide a geological chronicle, with distinct layers unveiling a history of ancient lakes, volcanic activity, and climatic fluctuations. The interplay of these geological processes has bestowed upon Death Valley a diverse and visually striking landscape, rendering it a paramount field site for the study of terrestrial planetary geology. Death Valley serves as the home for a population of true survivors, the Death Valley pupfish. The state of the environment greatly impacts the pupfish population and its behavior. Figure 2 shows a map of the region of the Death Valley pupfish which are a very diverse population.

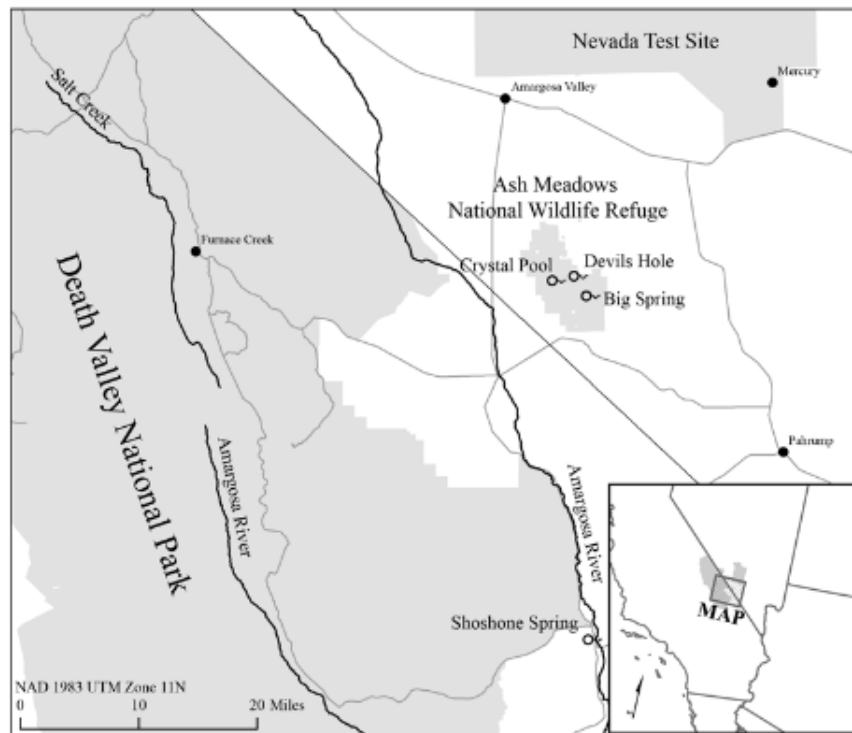


Figure 2: “Map depicting the region around Devils Hole, with selected springs and rivers shown. The broader Death Valley region is home to nine extant pupfish species and subspecies, and one extinct subspecies [1].”

The population size of the pupfish has been found to correlate with the water level [2]. Water temperature also affects the pupfish’s ability to mate and reproduce. A laboratory study found that pupfish’s egg production was optimal at constant temperatures 24 through 32 C [3]. The pupfish have created a home in one of the harshest environment on Earth.

Pupfish Species and Habitats

History

The origin story of pupfish in the Death Valley region traces back to approximately two million years ago, during a period of milder climatic conditions when connections with the Colorado River allowed their ingress into the area. However, as the climate gradually shifted towards increased aridity over the past 8,000 to 10,000 years, the once-lush lakes of Death Valley began to desiccate, leaving behind isolated remnants of permanent aquatic habitats. Today, the sustenance of these habitats relies not on direct rainfall but rather on the replenishment from an underground aquifer. This aquifer holds water that originated as precipitation during pluvial periods, which was subsequently sequestered underground for millennia before resurfacing through seeps and springs. Pupfish populations also inhabit two desert streams within the Death Valley region, enduring significant temperature and habitat fluctuations. Salt Creek, fed by a spring at its marshy headwaters, exhibits high salinity levels, while the Amargosa River, stretching approximately 200 kilometers from its headwaters to its terminus on the valley floor, primarily functions as an underground watercourse, resurfacing only where bedrock forces water upward, despite being dry along about 90 percent of its length in the absence of recent rainstorms. The pupfish have demonstrated a remarkable tolerance to fluctuations in temperature and salinity, with some species enduring temperatures exceeding 49 degrees Celsius (120 degrees Fahrenheit) during scorching summers and surviving in highly saline environments such as Salt Creek. Their ability to withstand such harsh conditions is attributed to various physiological and behavioral adaptations. Pupfish possess specialized mechanisms to regulate their internal salt concentrations in response to changes in external salinity, allowing them to maintain osmotic balance in highly saline environments. Additionally, they exhibit behavioral adaptations such as seeking refuge in cooler, deeper waters during periods of extreme heat and actively seeking out areas with optimal salinity levels for reproduction and feeding. By embracing a multifaceted approach to adaptation, pupfish species have not only survived but thrived in the challenging ecosystems of Death Valley, embodying the resilience of life in extreme environments.

Pupfish population

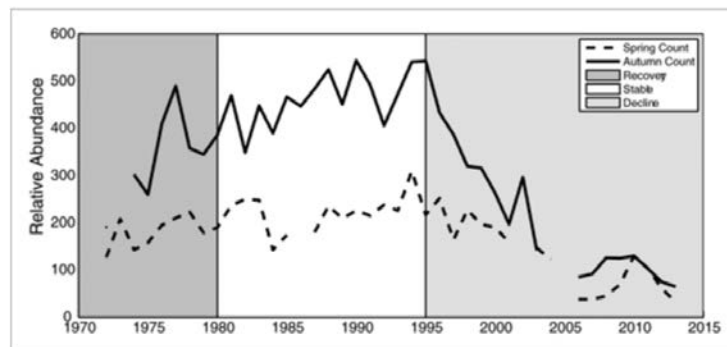


Figure 3: “Population surveys of *C. diabolis* in Devils Hole, showing both the earlier recovery (1970–1980) and the recent (post-1995) unexplained decline of the population.” [4]

The pupfish population in Death Valley encapsulates a compelling tale of resilience and adaptation over geological time scales. Evolving in isolated environments, these unique fish species have weathered the dynamic geological history of Death Valley. As the valley underwent transformations, such as the intermittent formation and drying of ancient lakes, pupfish populations faced periods of isolation and connectivity. These shifts in hydrological conditions, coupled with geological events, have influenced the genetic diversity and ecological strategies of pupfish. Today, the surviving pupfish populations stand as living relics, embodying the intricate interplay between the geological evolution of Death Valley and the evolutionary

trajectories of its inhabitants. Today, Death valley pupfish is a federally listed endangered species [5]. Despite its distinctiveness, this species has experienced a significant and puzzling decline in its population over the last two decades as seen in Figure 3, hitting a record low of 35 individuals during a survey in early 2013 [4]. Thriving in a geothermal pool with fluctuating nutrient levels, the pupfish has evolved to survive in conditions fatal to other pupfish species. With a relatively short lifespan of around one year, the annual recruitment of new individuals in Devils Hole becomes vital for the species' ongoing existence. However, challenges arise due to elevated temperatures on the shallow spawning shelf, a critical habitat within the ecosystem, leading to decreased egg viability and increased mortality of the pupfish larvae.

Genetic Diversity

The genetic diversity of Death Valley pupfish species, including *Cyprinodon nevadensis* and *Cyprinodon diabolis*, offers valuable insights into their evolutionary history and conservation needs. Studies have revealed significant genetic differentiation among populations, indicating a complex interplay of factors driving their divergence. Historical climate fluctuations, such as glacial maxima and subsequent aridification, likely played a crucial role in shaping genetic diversity by fragmenting and isolating populations across different aquatic habitats within Death Valley [6, 7]. Genetic analyses have provided evidence for both recent isolation and incomplete sorting of genetic variation among pupfish populations, suggesting a dynamic evolutionary process characterized by genetic drift and gene flow. For instance, the Ash Meadows Wildlife Refuge hosts distinct populations of *Cyprinodon nevadensis*, with varying degrees of genetic divergence attributed to differences in habitat characteristics and isolation. Additionally, Devil's Hole pupfish (*Cyprinodon diabolis*) populations exhibit genetic differentiation associated with their unique subterranean aquifer habitat and isolation within the Devil's Hole pool [6].

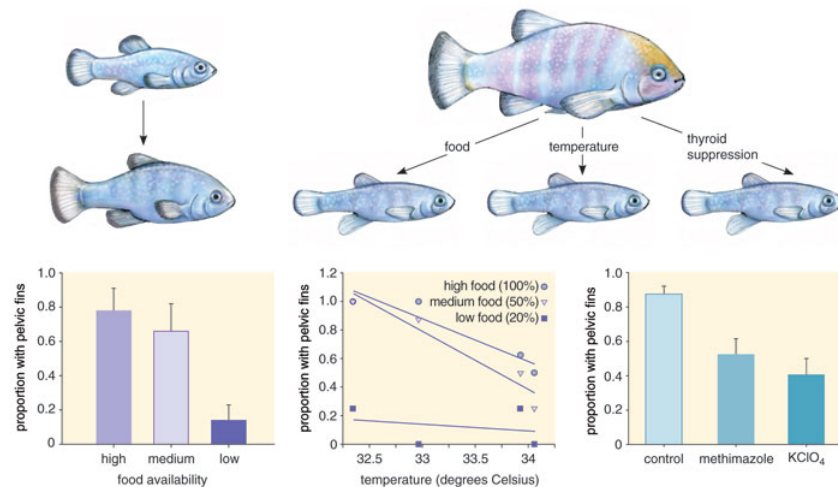


Figure 4: “Morphologic changes arose when Devils Hole pupfish were placed in refuges (upper left). To explore what the biological mechanisms for such changes might be, the author performed experiments with Amargosa pupfish (upper right). Food restriction, increased water temperatures and the introduction of anti-thyroid compounds methimazole and potassium perchlorate (KClO₄) all produce similar morphological shifts. Changes in thyroid-hormone status also result from food restriction or higher water temperature. A male Devils Hole pupfish is typically about 20 millimeters long.” [8]

Similar to Darwin’s finches of the Galapagos Islands, Death Valley’s pupfishes offer a glimpse into the process of evolution, with variations in body shape and behavior driven by phenotypic plasticity—a flexibility influenced by environmental conditions experienced during early life. Through studies on phenotypic plasticity, researchers are unraveling the mechanisms shaping the phenotypic diversity of Death Valley’s pupfishes, shedding light on the adaptive strategies of organisms thriving in extreme environments [8].

Figure 4 shows results of what may have happened to these pupfish abandoned in Death Valley, to make their body shape and behavior so unique. Genetic analyses have been conducted on pupfish populations to estimate the time since their isolation and divergence. By examining the DNA sequences of different populations and calculating genetic divergence based on mutation rates, researchers can infer the approximate timing of population isolation and subsequent divergences. One study found that pupfish have a much higher mutation rate than humans (around 2 orders of magnitude), showing that the pupfish can adapt much more quickly than other species [6]. These genetic studies provide valuable insights into the evolutionary history of pupfish populations and help elucidate the processes driving their genetic differentiation.

Planetary Analogs

Exploring planetary analogs of the pupfish in Death Valley opens a window to understanding the potential habitability of extraterrestrial environments. The extreme conditions of Death Valley, characterized by arid landscapes and thermal fluctuations, share intriguing parallels with certain celestial bodies in our solar system. Environments such as the subsurface oceans of icy moons like Europa or the hydrothermal vents on Enceladus exhibit analogous conditions where life could potentially thrive. By scrutinizing the adaptive strategies and resilience of pupfish in Death Valley, we gain valuable knowledge that can inform hypotheses about the existence of analogous organisms in these distant locales. This comparative study not only enhances our understanding of potential astrobiological processes but also underscores the significance of Death Valley as an Earthly laboratory for unraveling the mysteries of life in extreme environments and beyond.

Conclusion

In conclusion, our exploration of Death Valley’s pupfish populations unveils a remarkable saga of adaptation and resilience in the face of extreme environmental challenges. From their origins two million years ago to their current distribution in isolated aquatic habitats, pupfish species have evolved intricate strategies to navigate the dynamic landscapes of Death Valley. The interplay of geological processes, historical climate fluctuations, and hydrological dynamics has shaped the genetic diversity and distribution of pupfish populations, offering valuable insights into the mechanisms driving evolutionary divergence and speciation. Moreover, the study of phenotypic plasticity underscores the adaptive flexibility of pupfish species, enabling them to thrive in habitats characterized by fluctuating temperatures and habitat availability.

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UBEHEBE CRATER

Formational history, geology, observations using modern technology, and the potential for a Martian analog

Madison Tuohy

Formational History

Ubehebe Crater is situated within the 3 km² Ubehebe Maar Field, comprised of 16 tuff cones and craters ("maars"). These features resulted from intense, brief phreatomagmatic eruptions occurring at the junction of the Tin Mountain and Northern Death Valley faults in northern Death Valley, California (von Engel 1932; Knott et al. 2005; Fig. 1, Fig. 2). These eruptions are characterized by groundwater being vaporized due to ascending magma creeping through the weakened crust caused by the faulting. As the largest and most recent maar in the field, Ubehebe Crater has an 800-meter diameter and is carved into the coarse-grained alluvial fan conglomerates and sandstone facies of the Miocene Navadu Formation (Fierstein and Hildreth 2017). Surrounding the maar field is a substantial blanket, about 50 meters thick, of loose, non-cohesive granular ejecta, comprising air fall tephra and base surge deposits, which extends over approximately 15 km² and partially fills Ubehebe Crater. Evidence suggests that the erupting craters erupted within a relatively short amount of time (Fierstein and Hildreth 2017).

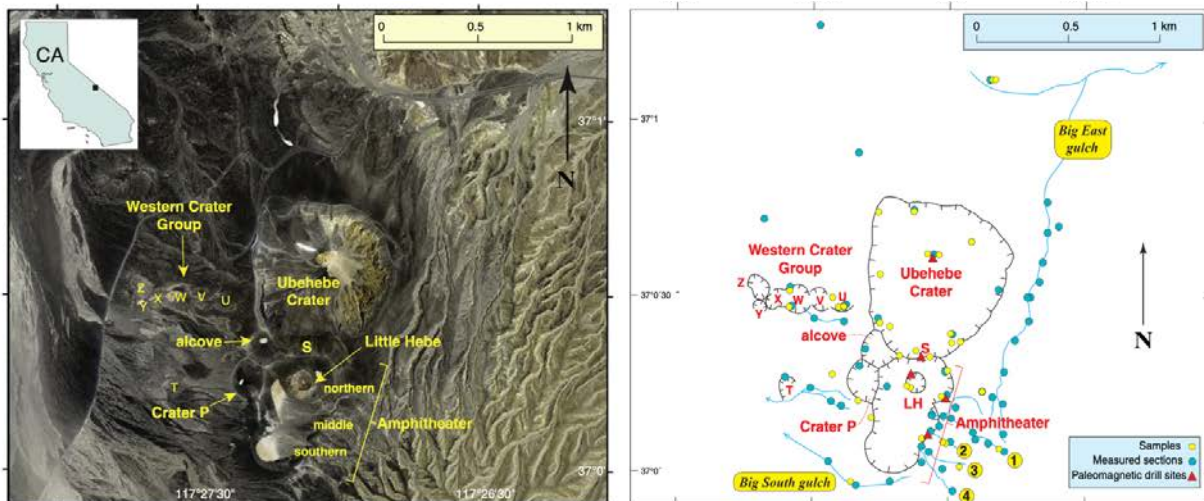


Figure 1. Location and setting of Ubehebe Crater group (Fierstein and Hildreth 2017).

Internal geologic setting

The eruptions and subsequent formation of the Ubehebe Crater field created the stratigraphic column that we see today. These exposed layers were emplaced via three general processes (Valentine, Fierstein, and White 2022):

1. Pyroclastic currents, comprising mixtures of gas and particles, flow along the ground due to their higher density compared to the surrounding air, resulting in diverse deposits.
2. Fallout, characterized by well-sorted deposits that cover the landscape and diminish gradually away from the source.
3. Ballistic deposition of coarse **lapilli**, blocks, and bombs.

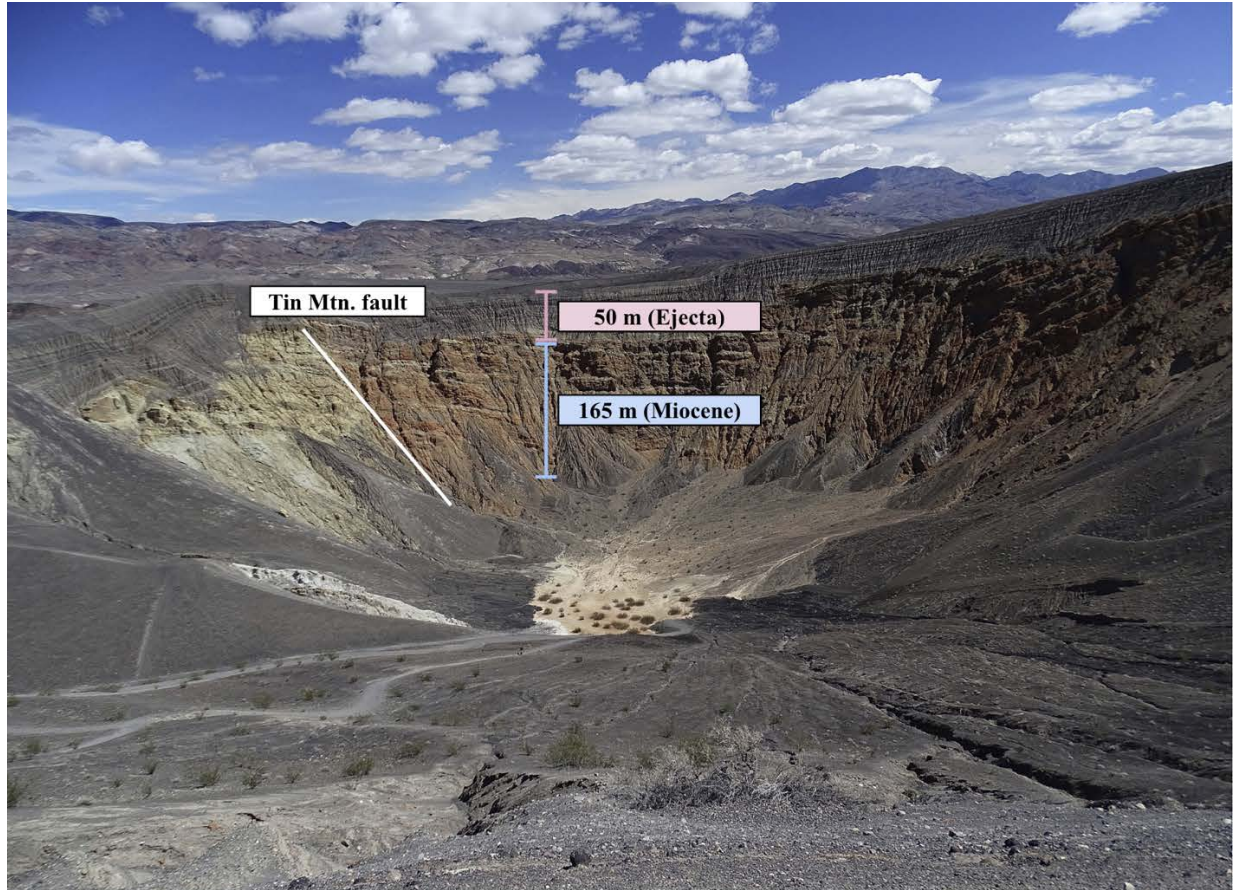


Figure 2. Looking eastward towards the western-facing wall of Ubehebe Crater reveals a predominantly orange and yellow composition, comprised mainly of Miocene fanglomerates and layers of sandstone, towering approximately 165 meters high. These formations are topped by approximately 50 meters of thinly stratified tan and black phreatomagmatic ejecta originating from Ubehebe Crater.

What can be learned from the cross-bedding?

Base surges emanating radially from Ubehebe Crater deposited **cross-bedded** sequences, manifesting as both small and large dune-like formations. These structures exhibit spacing and morphological characteristics akin to antidunes, with migration patterns somewhat resembling climbing ripples. The most sizable dunes in the vicinity are composite structures, capturing a sequence of bed forms deposited during high-flow conditions (CROWE and FISHER 1973).

In a single bedding set, the lower laminae typically feature wide crests with extremely shallow angles on both the upstream and downstream sides. As one progresses upward within the bedding set, the crests become more defined and steeper, gradually shifting downstream. Research based on observations and photographs of base surges (Moore 1967; Waters and Fisher 1971) suggests that energy dissipation during flow occurs quickly, leading to a rapid deceleration of base-surge currents.

Utilizing Ground Penetrating Radar (GPR) to image Ubehebe Crater

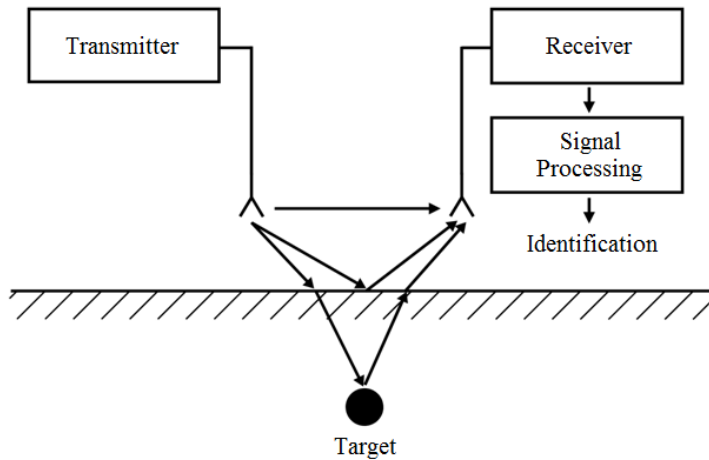


Figure 3. GPR block diagram

differences in water content, composition, and texture of layers underground. Receiving antennae capture the reflected signals, which are then recorded (Cagnoli and Russell 2000; Cagnoli and Ulrych 2001). GPR was used to image the subsurface of various locations within the Ubehebe Crater group, including at the baser surge deposits and inside select craters. A line of GPR from the surge deposits (Fig. 4a) exhibits uniform, parallel reflections with occasional breaks in continuity. It was acquired in proximity to the Ubehebe Crater rim, where the base surge deposits measure 50 meters in thickness. GPR was further collected in small and large craters. Surveys conducted in the larger craters yielded no valuable data, likely due to a shallow surface layer of clay significantly limiting the radar signal's penetration depth. Surveys in the smaller craters (Fig. 4b), however, indicated promising reflections with visible bowl-shaped reflections and angular uniformities.

Ground-penetrating radar (GPR) is a geophysical method employing the reflection of electromagnetic waves to create images of near-surface geological features (Davis and Annan 1989). A powerful pulse generator and transmitting antennae produce broad-spectrum electromagnetic signals with known frequencies. These signals travel through the subsurface, bouncing off interfaces where there are changes in electrical conductivity and dielectric permittivity (Fig. 3).

These changes can be due to

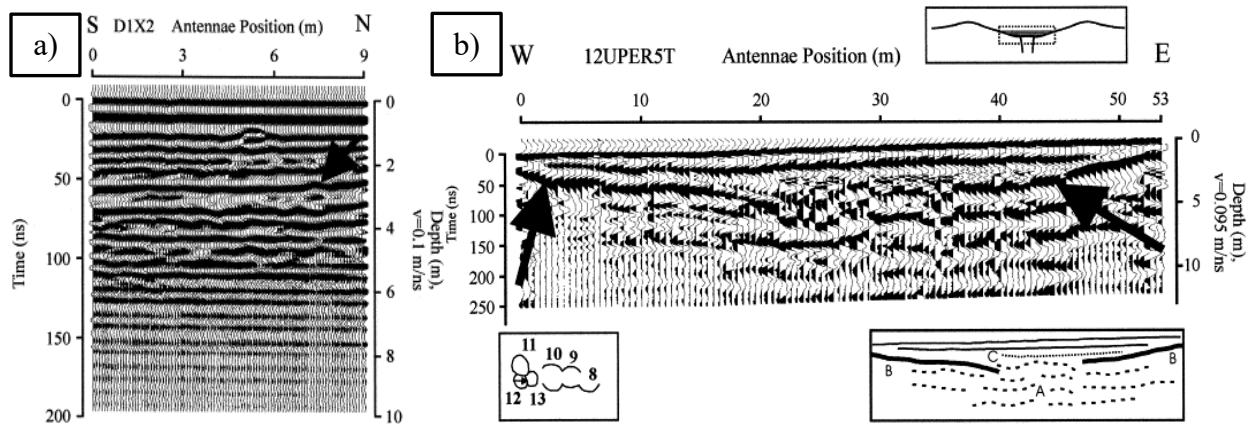


Figure 4. a) Segment of a GPR profile obtained along line A employing 200 MHz antennae. The reflections appear parallel but occasionally exhibit discontinuities or undulations (indicated by the arrow). b) GPR profile of crater No. 12 with 50 MHz antennae. Insets show survey location (lower left), profile position relative to an idealized crater cross-section (upper right), and a line diagram interpretation highlighting bowl-shaped reflections B (arrows) and an angular unconformity between reflections B and C (lower right) (Cagnoli and Russell 2000).

Planetary analog

Geology

The Ubehebe Crater field serves as an analog for **Martian gullies**. The pyroclastic flows that occurred during the eruption of the late Holocene provides an analog specifically for the flow dynamics and characteristics that are seen in Martian gullies (Conway, de Haas, and Harrison 2019; Fig. 5a). Additionally, Ubehebe Crater serves as an accessible analog for **interior debris lobes** that have been observed in impact craters on Mars. The maar volcanos, which erupted during the Late Holocene, were seemingly formed during a Little Ice Age, therefore the formation conditions of the slopes were like the arid environment that is present on Mars today (Bonaccorsi, McKay, and Chen 2010; Eyles and Daurio 2015; Fig. 5b)

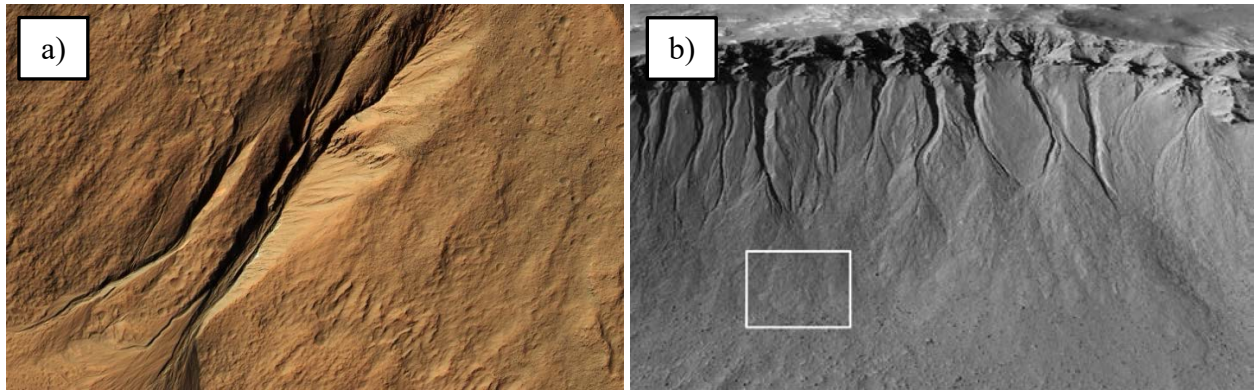


Figure 5. a) Martian gullies; HiRISE image credits: NASA/JPL/University of Arizona. b) Interior debris lobes in a crater on Mars; HiRISE image credits: NASA/JPL/University of Arizona.

Biology

The distinct features of the crater and its location near Death Valley National Park present avenues for investigating **extremophilic** microorganism's adept at surviving in harsh conditions, including volcanic soils and hydrothermal zones. Using modern techniques, such as X-ray diffraction, microRaman spectroscopy and SEM/EDX, assessment of the living biomass and habitability potential of Ubehebe Crater has been conducted. Analyzing extremophiles in Ubehebe Crater aids in assessing the viability of life in comparable environments on Mars, thereby informing astrobiological exploration missions to Mars (Bonaccorsi, McKay, and Chen 2010).

Glossary

Base surge: A rapid outward flow of hot gas and volcanic material along the ground during an explosive volcanic eruption.

Cross bedding: Layers found in sedimentary rocks that are formed by sediment migration due to water, wind, or current flow.

Extremophiles: Microorganisms that thrive in extreme environments, such as high temperatures, acidity, or pressure, where most life forms cannot survive.

Interior debris lobe: An interior debris lobe of a crater is a mound of debris found within the crater's basin, often formed by collapsed walls or material ejected during impacts or eruptions.

Lapilli: Small rock fragments ejected from volcanoes during eruptions, typically ranging in size from 2 to 64 mm in diameter

Maar: A volcanic crater formed by explosive eruptions caused by magma interacting with groundwater.

Martian gullies: Trench-like features on Mars' surface, likely formed by water or dry material flow.

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Field Trip Bingo

Snake	Tailgating	Lane change without signaling	Reading papers in vehicle	Orogeny
Dust clouds	Military vehicles	Satellite sighting	Flat tire	Rain
Wildflowers	Vic says "That's not how geologists think"	FREE SPACE	Useless CB radio chatter	Scorpion
Rocks moving	Stove not working	Campfire songs	Jack says "I should've brought my airplane"	Ghost town
Wifi searchin'	Someone is late	Tumbleweeds	Polygons!	Sunburn

CROSSWORD PUZZLE

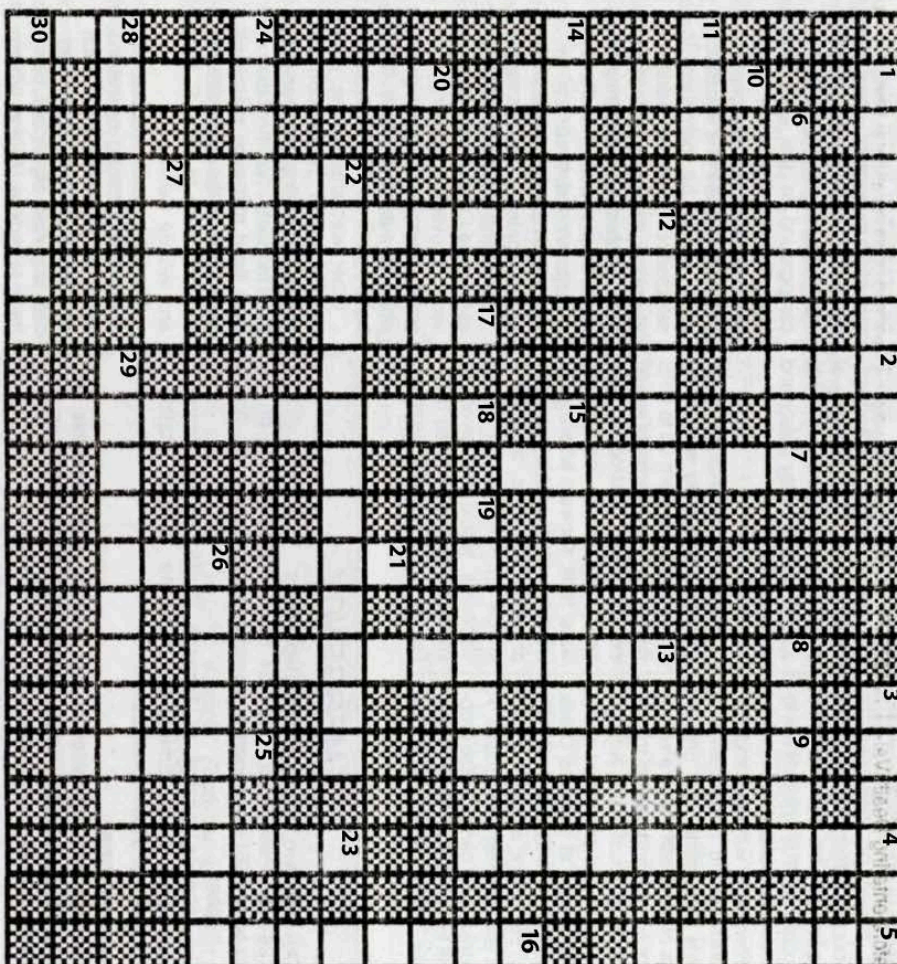
by Mike and Wendy Lawrence

ACROSS CLUES

1. Brown-eyed _____
3. Bunny
6. Use their fruit for bread
8. Humble or rock _____
11. Zane Grey's Riders of the Purple
12. Jumping or Teddybear
14. Parasitic orange spaghetti
15. Deciduous tree, honey _____
19. Find this sausage-shaped plant at Salt Creek, _____ weed
22. This buckwheat has a hollow swollen stem
24. This common desert plant has no leaves
26. Brew a laxative drink with this plant
27. Without this the flowers won't bloom
28. Another name for 26-down
29. Yellow gourd favored by Canis Latrans
30. Desert bighorn eat the Mojave _____

DOWN CLUES

2. Bell / flower daisies, desert _____
4. Shiny magenta flowers decorate this pricklypear
5. _____ back; gray-leaved plant shaped like a tortoise shell
7. Stick-y-leaved plant with yellow, snapdragon-like flowers
9. Even the state flower of Texas grows here
10. Orange, poppy-like flower; globe or apricot _____
12. Larrea tridentata
13. This cactus bears a fruit that makes good jelly
16. Common purple or lavender flower
17. Bristlecone _____ grows at high elevations
18. This shade tree grows naturally in some canyons
20. A very rare plant, also known as Goldcarpet
21. Before it's a flower, it's a _____
22. Indians used this to induce visions
23. Death Valley's prettiest, desert five-_____
25. This saltbush has silvery leaves which may remind you of a Christmas plant
26. Purple-_____, another belly-plant
28. Forget-me-_____



Answer on page 7
ask Roberto

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

#88886

Difficulty: moderate

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

#122639

Difficulty: moderate

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

#166435

Difficulty: moderate

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

#92122

Difficulty: hardest

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

#143978

Difficulty: easy

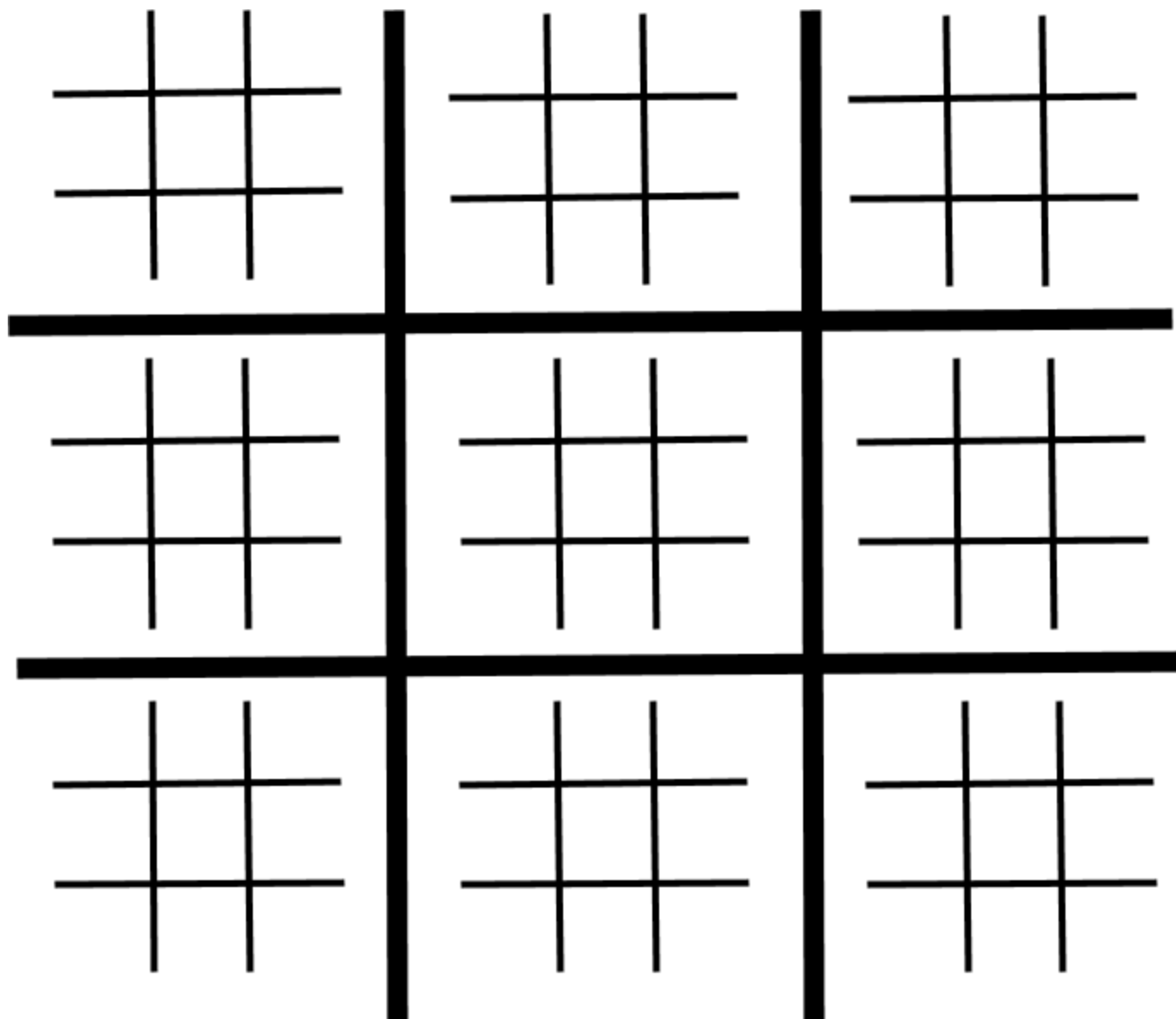
					7	2		
2			6	3				
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		8	7	2				
						5	3	
	6				9	1		
7		2		6	5	4		
8	3							
			1			8	5	

#195077

Difficulty: easy

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.



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	
Hardness < 5	Excellent or good	Transparent- translucent dark red to black. Hardness- 7	Garnet
		Colorless, purple, green, yellow, blue. Octahedral cleavage. Hardness- 4	Flourite
		Green. Splits along 1 excellent cleavage plane. Hardness- 2-3	Chlorite
	Poor or absent	Black to dark brown. Splits along 1 excellent cleavage plane. Hardness- 2.5-3	Biotite mica
		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
	Poor or absent	Colorless, yellow, brown. Splits along 1 excellent cleavage plane. Hardness- 2-2.5	Muscovite mica
		Yellow crystals or earthy masses. Hardness 1.5-2.5	Sulfur
		Opaque green, yellow or gray. Silky or greasy luster. Hardness- 2-5	Sepentine
		Opaque white, gray or green. Can be scratched with fingernail. Soapy feel. Hardness- 1	Talc
		Opaque earthy white to light brown. Hardness- 1-2	Kaolinite

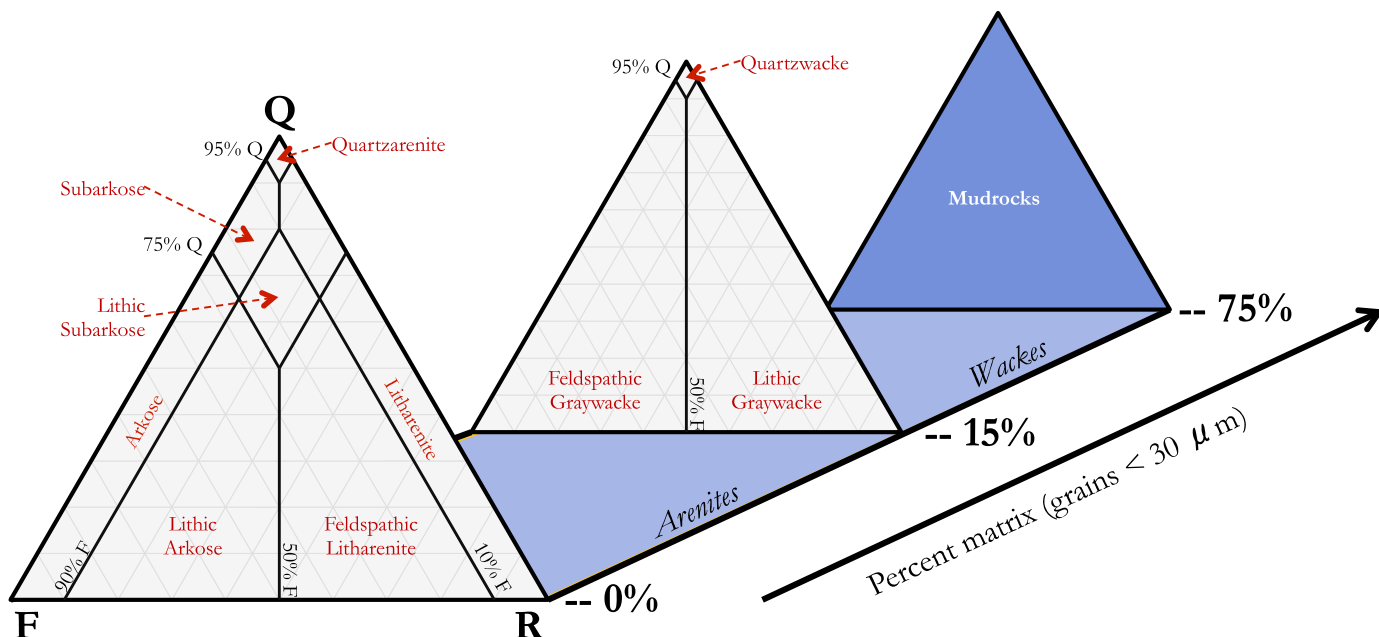
Metallic			
	Streak	Physical Properties	Name
Hardness > 5	Dark Gray	Brass yellow	Pyrite
		Dark gray-black, attracted to magnet	Magnetite
	Brown	Silvery black to black tarnishes gray	Chromite
Hardness < 5	Red-Red/Brown	Silvery gray, black, or brick red	Hematite
	Dark Gray	Brass yellow, tarnishes dark 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

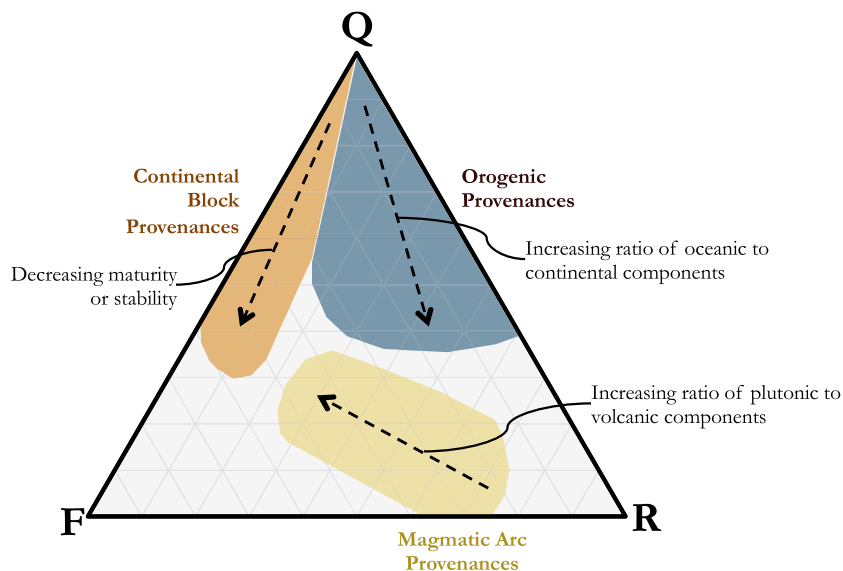


Scheme based on the normalized percentages of the visible grains: quartz and chert (Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt)



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

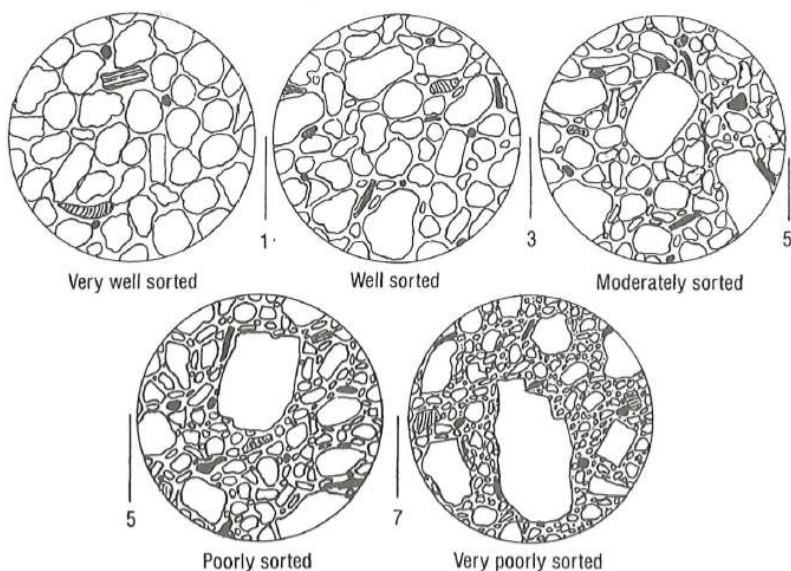
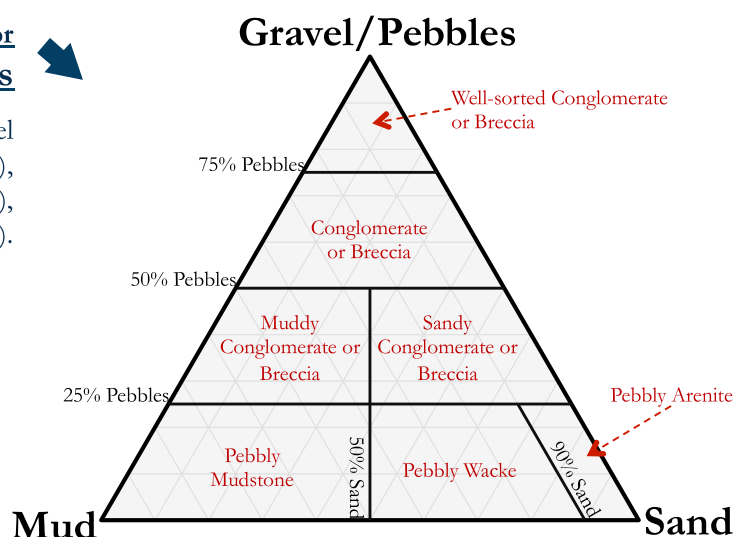
	Mudrocks (containing > 50% mud)			Rocks with <50% mud
	Silt dominant (> 2/3 of rock)	Clay and Silt	Clay dominant (> 2/3 of rock)	Sand-sized or larger grains dominant
Non-laminated	Siltstone	Mudstone	Claystone	Conglomerates, Breccias, Sandstones, etc.
Laminated	Laminated Siltstone	Mudshale	Clayshale	

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

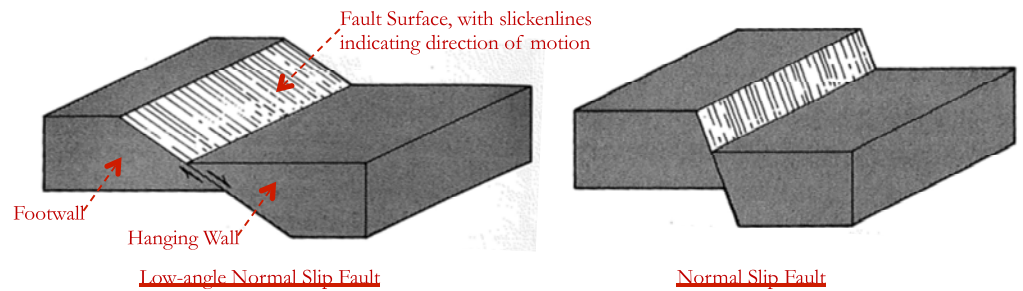
Example hand-lens view of detritus.
From Compton, 1985

Structural Geology: Normal Faults

Normal Faults



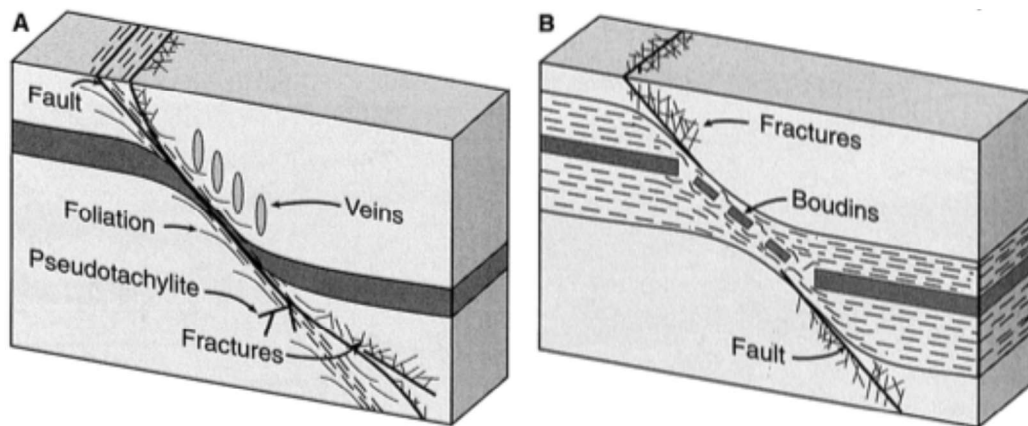
In normal faults, the footwall goes up with respect to the hanging wall. Normal faults are indicative of extension. Figures from Davis & Reynolds, 1996.



Effects of Brittle or Ductile Shear in Normal Faults



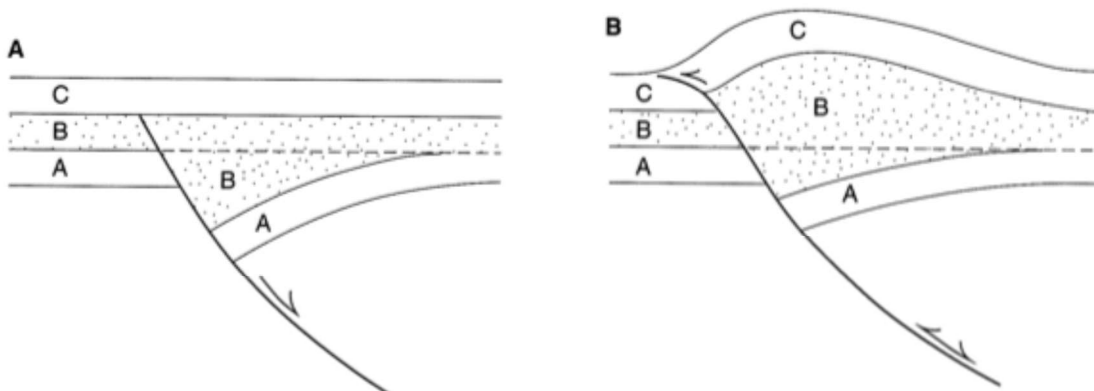
The block diagrams below illustrate the effects of changing the nature of deformation, between brittle deformation (which results in clear fault planes, fractures and fault rocks), ductile deformation (which causes deformation over a larger shear zone). Often, strata of different rheologies will behave 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.

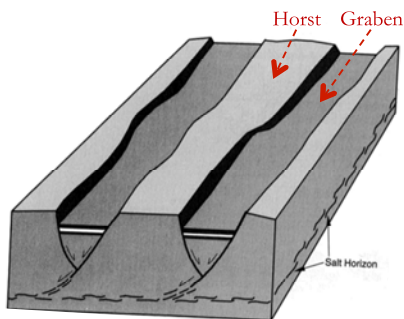
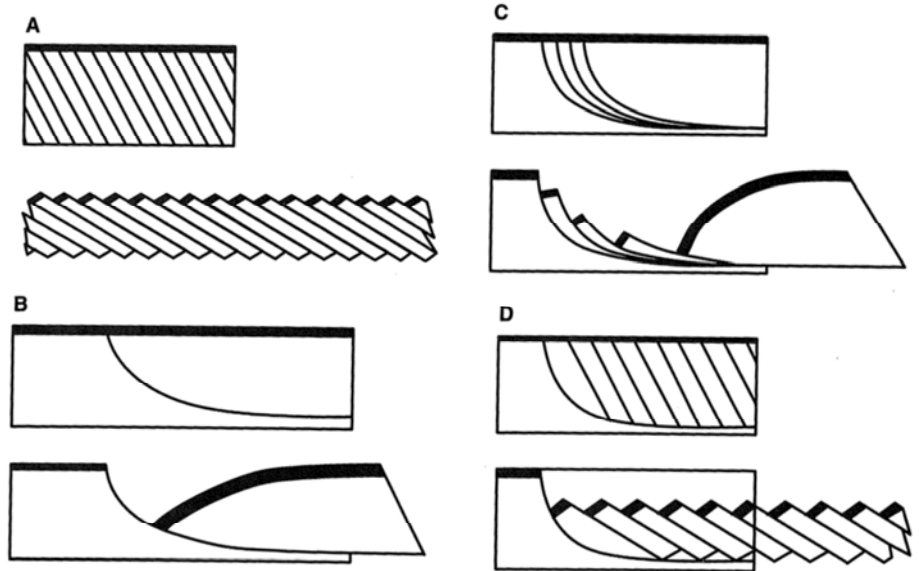


Structural Geology: Normal Faults

Normal Faults Geometries



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



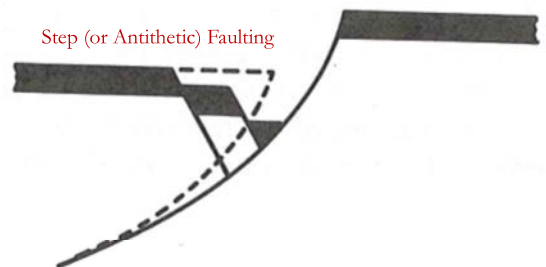
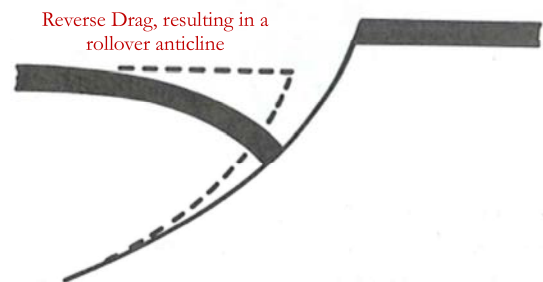
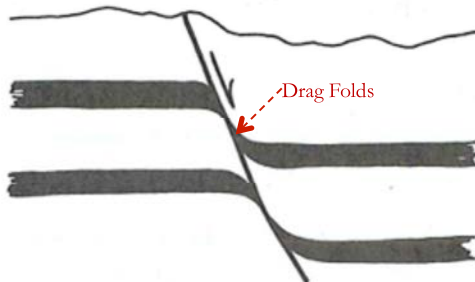
Horsts & Grabens

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.

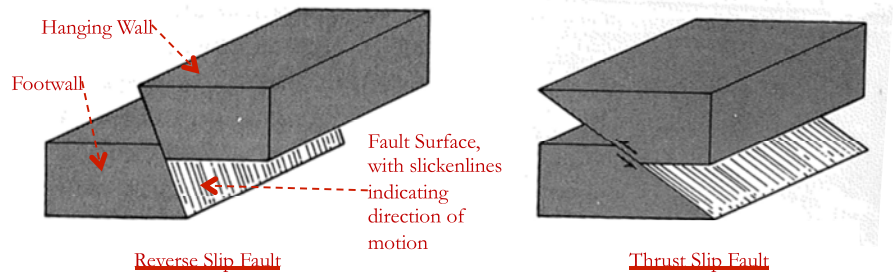


Structural Geology: Reverse & Thrust Faults

Reverse Faults



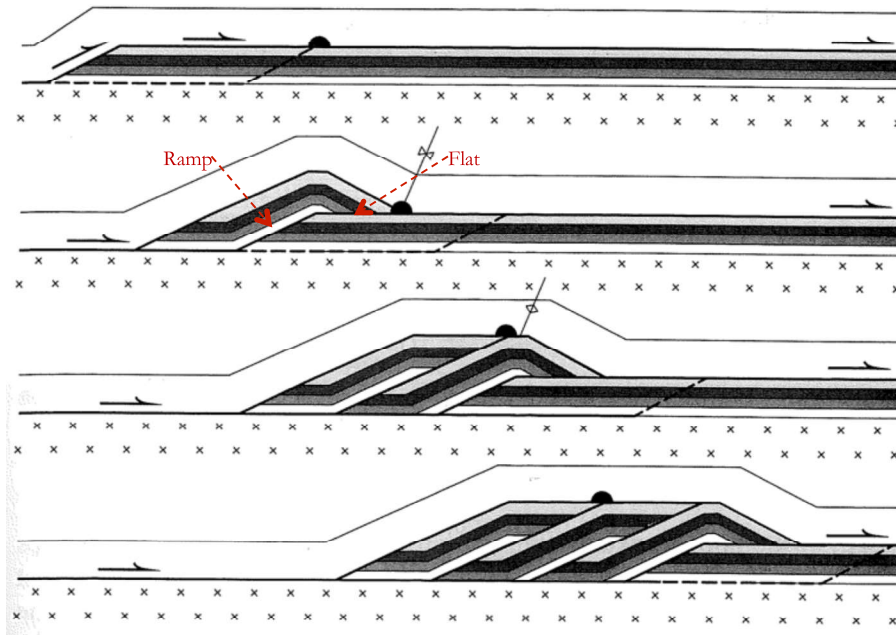
In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips < 45 degrees. Figures from Davis & Reynolds, 1996.



“Ramp-Flat” Geometry of Typical Thrust Fault Systems



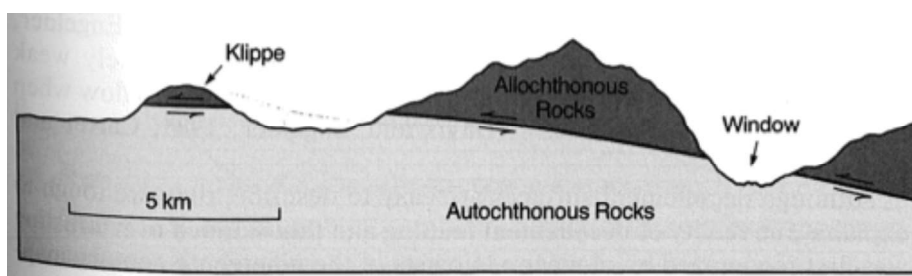
In a regional thrust, faulted blocks are “thrust” on top of younger strata. The exact geometry of these thrust systems can vary significantly. Figures from Davis & Reynolds, 1996.



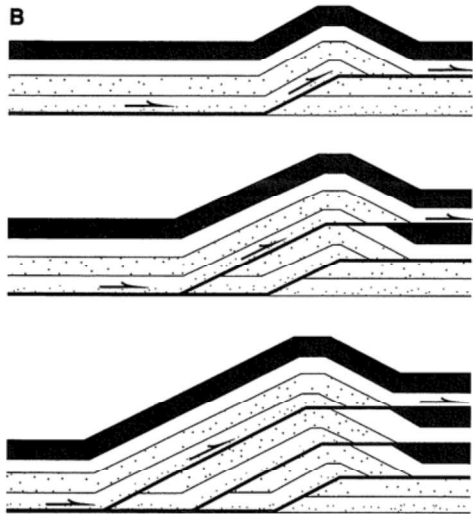
Klippe & Windows



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



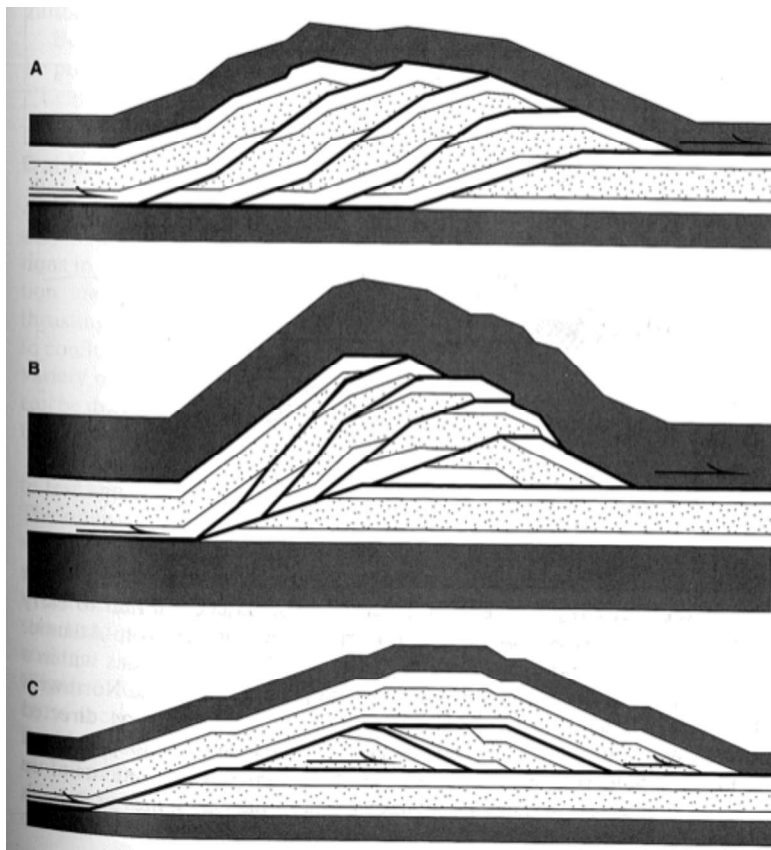
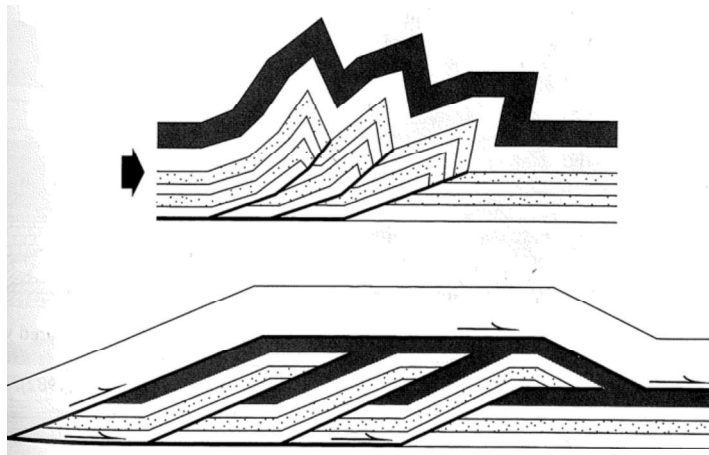
Out-of-Sequence Thrust Fault System

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.



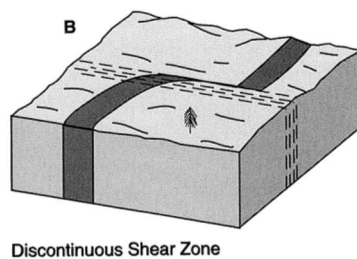
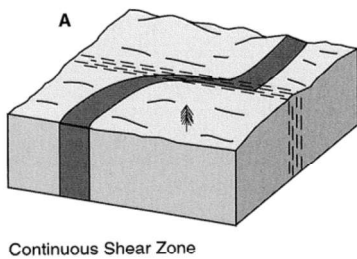
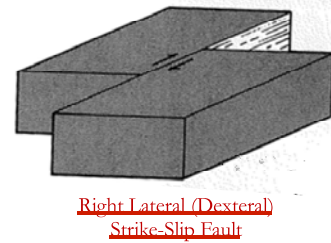
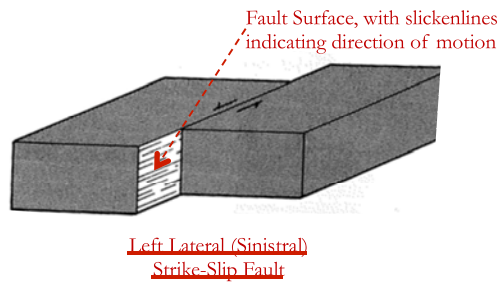
Forms of Duplexes

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.

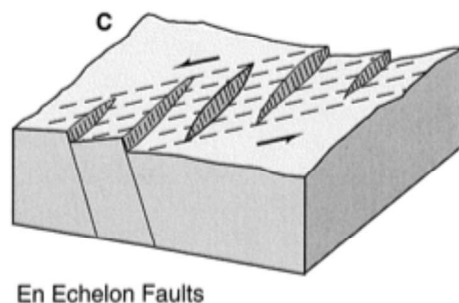
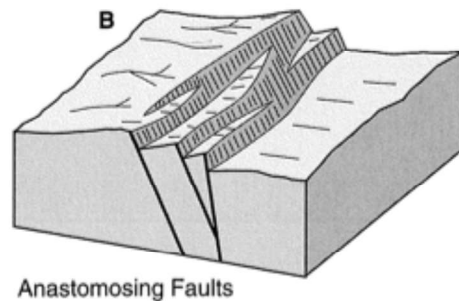
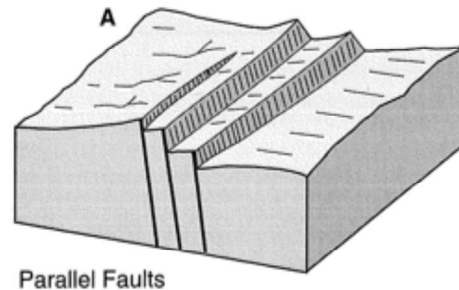
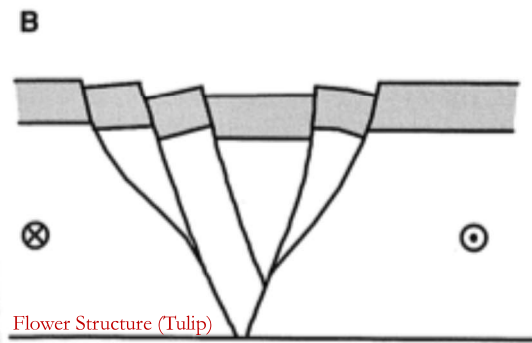
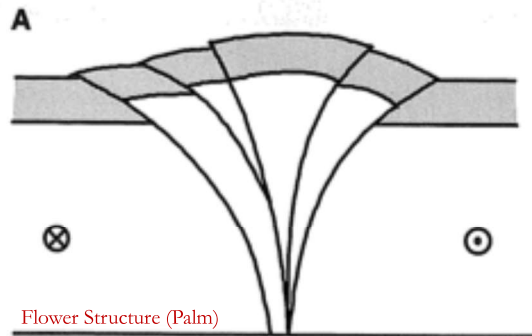


⬅ Ductile Shear Zones

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

Brittle Shear Zones ➡

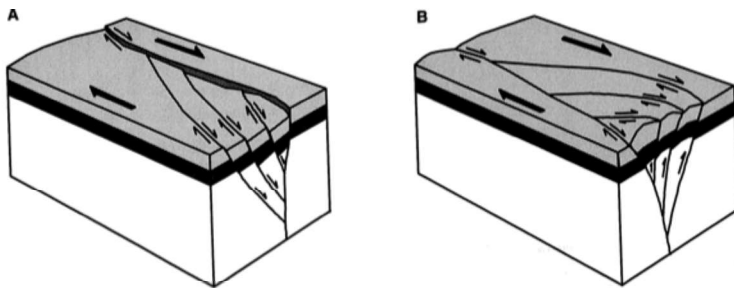
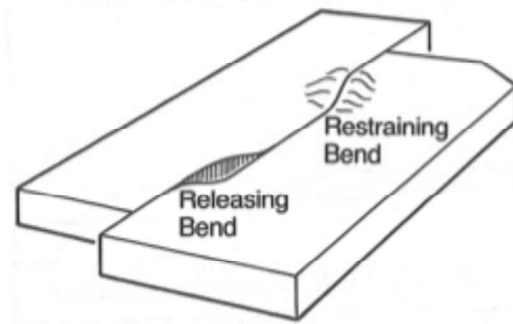
Figures from Davis & Reynolds, 1996.



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.

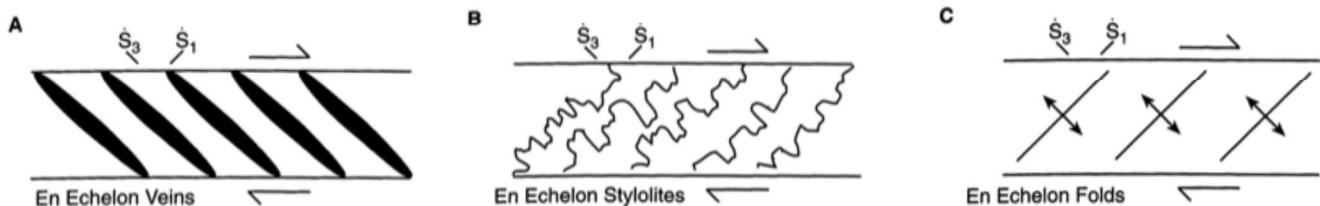


➡ Strike-Slip Duplexes

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

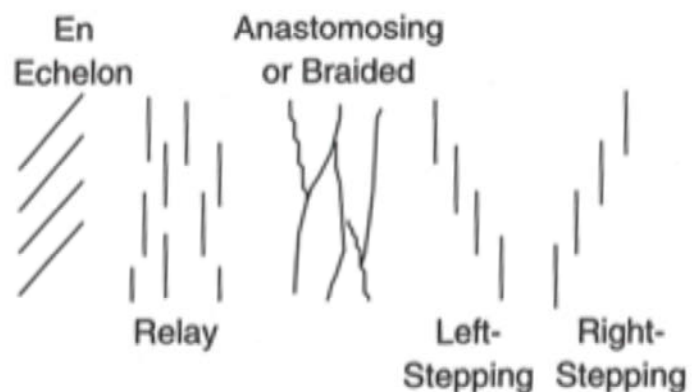
Slip Indicators in Strike-Slip Systems ↓

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.



Fault Scarps in Death Valley: Active Tectonics in a Pull-Apart Basin

Adina Alpert

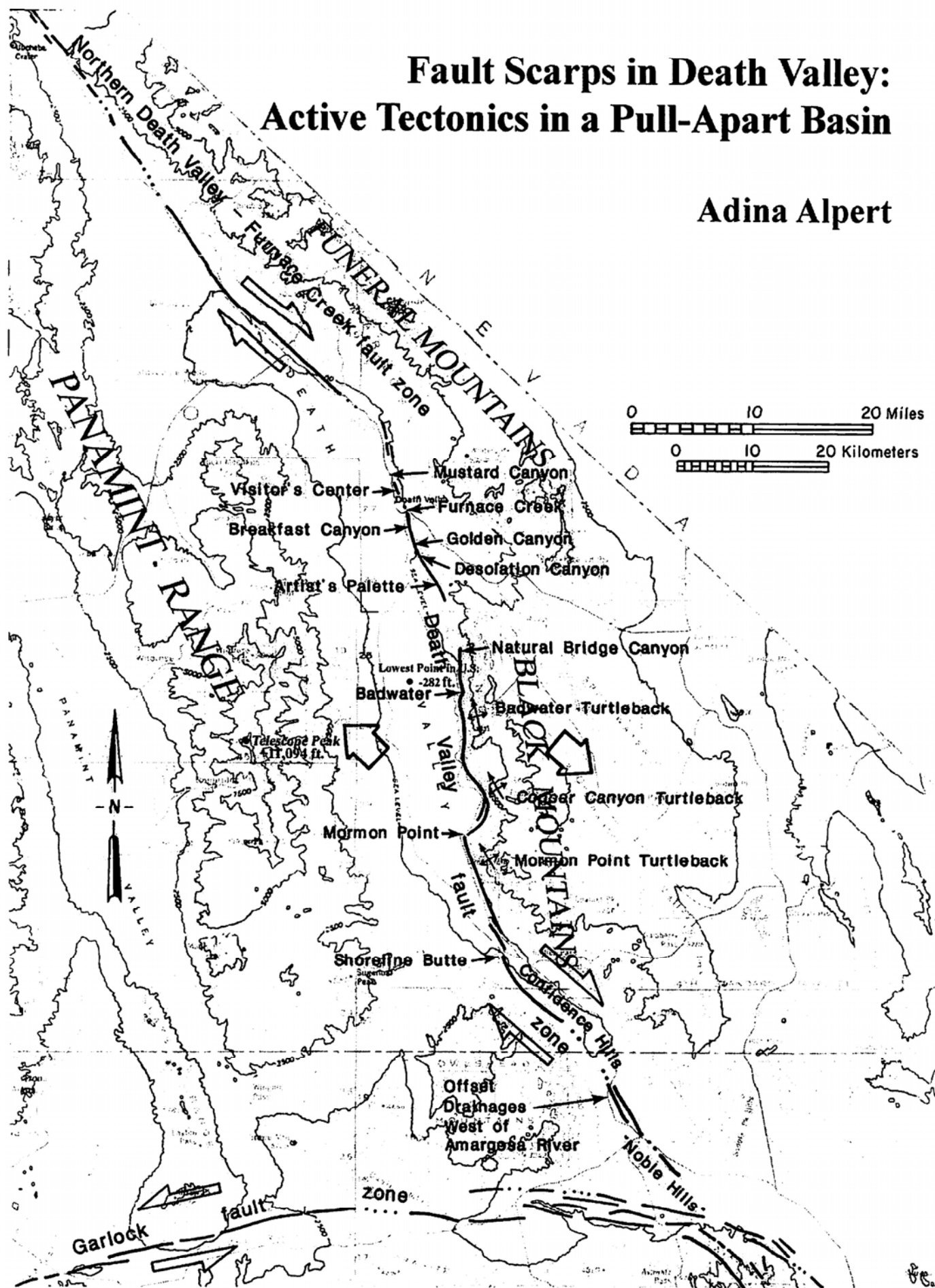


Fig. 1 (after Wills 1989)

The Death Valley – Furnace Creek – Garlock fault system

Geologic setting

Death Valley is situated at the intersection of three major fault zones: the Death Valley fault zone (DVFZ), the Furnace Creek fault zone (FCFZ) and the Garlock fault (GF) (Fig. 1), which are related to extension within the southern Basin and Range province (*Stewart* 1983). The Furnace Creek and southern Death Valley faults are northwest-trending, right-lateral, strike-slip faults, while the Garlock fault is left-lateral, strike-slip. The central Death Valley fault zone has a normal offset in addition to its strike-slip component, and it is considered to be a low-angle detachment fault in that section. The Garlock fault has been described as an intracontinental transform that accommodates greater extension to the north than to the south and can be viewed as the southern boundary of the region of relatively great extension.

“Pull-apart” basin formation

The accepted interpretation for the formation of Death Valley is that it is a pull-apart basin which resulted from the interaction between the FCFZ and DVFZ (Fig. 2), first proposed by *Burchfiel and Stewart* (1966). When a system of right-lateral strike-slip faults has a step or “jog” to the right, the region along the jog becomes extended and forms a valley. The central DVFZ, with its normal component, is the modern manifestation of the jog along the Death Valley – Furnace Creek combined fault zone (DV-FC).

Geologists have measured the relative right-lateral, strike-slip displacements along the FCFZ and the southern DVFZ to be 80-90 km and <8 km, respectively, over the past 10-12 Ma. For the pull-apart basin model to be correct in its aforementioned form, the displacements along these two faults should be roughly equivalent, but they are not. In 1983, *Stewart* offered a model to reconcile this apparent contradiction. He proposed that the initial position of the Panamint Range, prior to extensional activity in the region, was atop the present-day Black Mountains (Fig. 3). This theory is supported by the absence of a 10 km thick group of Precambrian and Paleozoic strata in the Black Mountains. Subsequently, the Panamint Block was transported 80 km northwestward tectonically along a single northwest-dipping, low-angle detachment fault or a system of such faults. According to this model, strike-slip motion began along the FCFZ first, coupled with motion of the GF, in order to move the Panamint Block off of its position on top of the Black Mountains. Only later, during the pull-apart phase, did the DVFZ develop, so the measured displacement along that zone would be necessarily less. A recent model by *Serpa and*

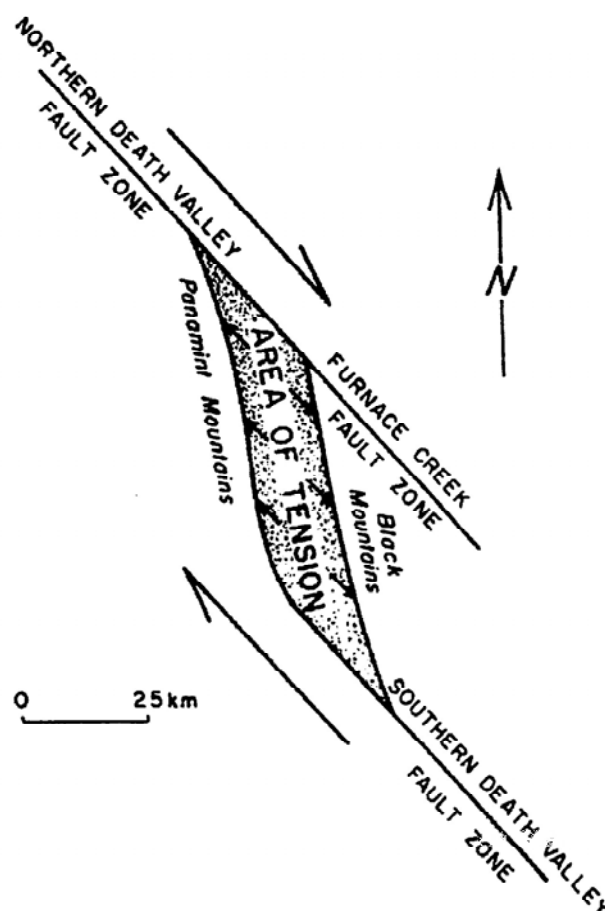


Fig. 2 – A model for the “pull-apart” basin in central Death Valley (after Burchfiel and Stewart 1966).

Pavlis (1996) has suggested that the movements of the structural blocks must be considered in three-dimensions, and rotations of the blocks about horizontal axes, as well as the vertical, must have also occurred.

Present-day motion

Paleoseismological analyses of the Death Valley fault zone indicate that 4 to 6 separate moderate to large ($M > 6.5$) earthquakes have occurred along various segments of the fault since 10 ka (Brogan *et al.* 1991). Using GPS measurements taken between 1991 and 1996, Bennett *et al.* (1997) have estimated that the slip rate of the Death Valley fault is 3 to 5 mm/yr (in the strike-slip direction). This motion implies 30-50 m of strain accumulation over the next 10,000 years, which Bennett *et al.* project will result in 5 to 10 M_w 6.5-7.5 earthquakes over that period. This finding is consistent with the paleoseismological studies of the fault zone.

With those numbers in mind, it should be said that Yucca Mountain, which lies 50 km east of this region, is the proposed location for the disposal of high-level nuclear waste in the United States!

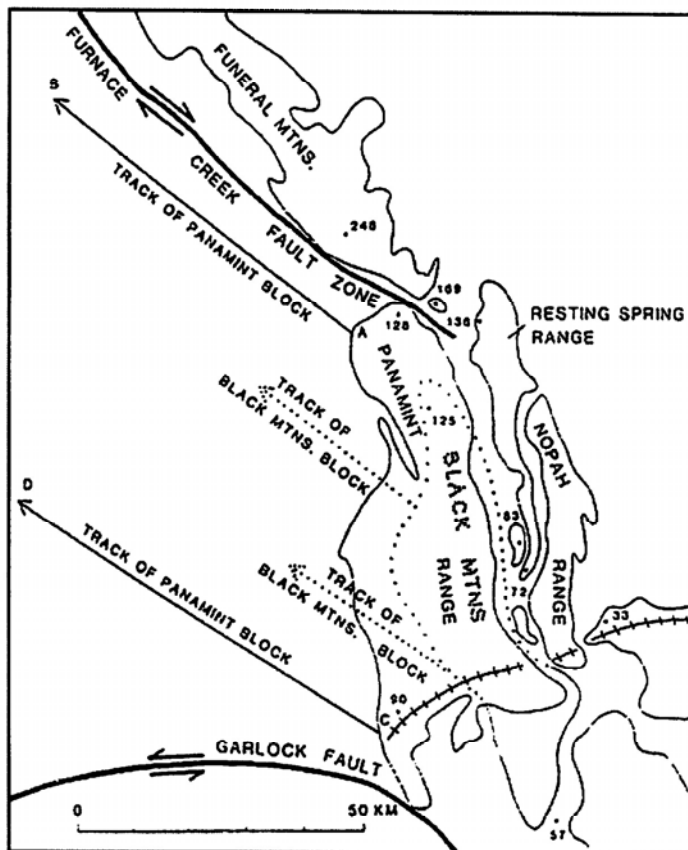


Fig. 3 – Reconstruction of Death Valley area prior to detachment faulting according to the Stewart model. Dotted pattern indicates pre-faulting position of Black Mountains block below Panamint Range block. (from Stewart 1983).

Fault scarps in the Death Valley fault zone

The locations referred to within this section are labeled on the map in Fig. 1. Information is derived from Wills (1989) and Sharp & Glazner (1997).

Evidence of fault motion can be found throughout the fault systems in and around Death Valley. Lateral strike-slip motion is observed on the FCFZ where stream channels are offset. Perhaps more dramatically, the normal-fault motion of the DVFZ can be seen along the length of the western edge of the Black Mountains as fault scarps (vertical offset). Most of these fault scarps cut across recently deposited gravels on alluvial fans, which indicates the recency of the downward and lateral movement of the Death Valley graben. Fan drainage running along scarp bases undercuts and steepens them. This erosional enhancement is a common obstacle to estimating fault scarp ages.

• **Visitor's Center / Mustard Canyon**

– Here the fault scarp shows evidence of a dominant strike-slip and minor normal displacement (Fig. 4). Long ridges of late Pleistocene alluvium are abruptly truncated by scarps and a linear trough. Recent movement is indicated by right lateral deflections of minor gullies and a subtle scarp in the young alluvium in one of the major channels.

• **Breakfast Canyon** – This scarp (Fig. 5) is in young alluvium (Holocene age) that has very weak soil development and poor development of desert varnish. The scarp has a maximum height of 2.5 m and may have been formed by two separate earthquakes. At one location, two crests are observed, one about 0.5 m higher than the other. Small gullies cross the scarp with a consistent northwest trend, about 30° clockwise from the trend of the scarp. This unusual arrangement of gullies has no relationship to the local drainage pattern but could have formed as a set of secondary shears during an earthquake. The scarp's abrupt northern terminus is caused by stream erosion and burial by gravel from the next fan north.

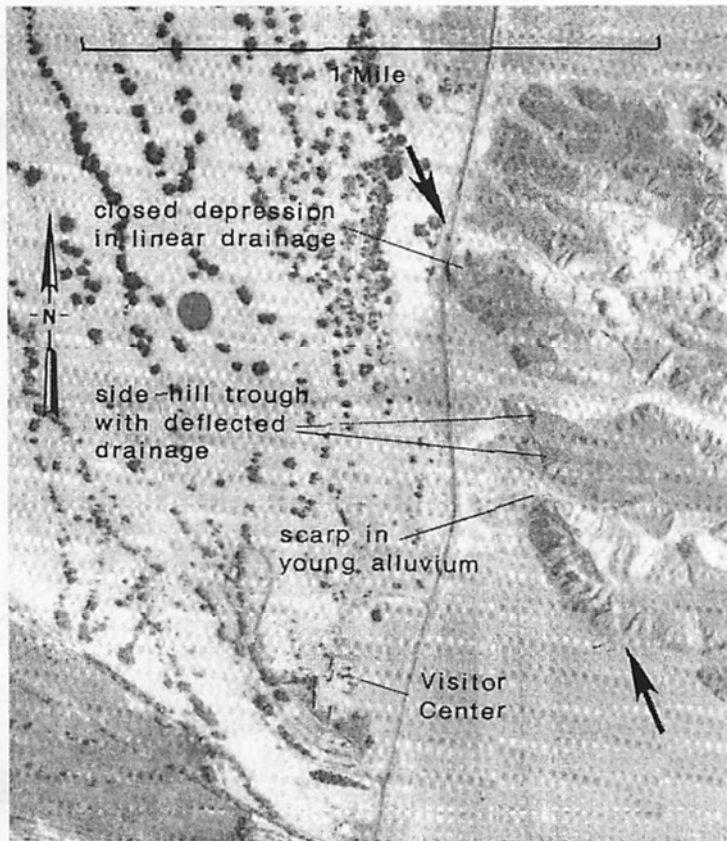


Fig. 4 – Aerial photo showing geomorphic features that identify the Death Valley fault zone northeast of the Visitor's Center. The trace of the fault is between the arrows. (From Wills 1989)



Fig. 5 – Fault Scarp near Breakfast Canyon site, looking south with Furnace Creek formation beds in the mountains. (From Sharp and Glazner 1997)

• **Desolation Canyon/Artist's Palette** – Scarps in bedrock are well developed east of Desolation Canyon and south of Artist's Palette. South of Artist's Palette the fault is exposed in several gullies as a zone of sheared bedrock and alluvium. A high bedrock scarp and right lateral deflection of many minor drainages indicate recent offset.

• **Badwater** – Just south of Badwater are the most dramatically high and steep scarps in Death Valley (Figs. 6 and 7). Many of these are erosionally enhanced. Near the apex of the Badwater alluvial fan, there is a section of scarp which does not appear to be enhanced by erosion. This scarp is 10 m high and has a 3 m high “free face.” This fan’s deposit is very young, and these scarps almost certainly formed during Holocene time and possibly occurred from a single large earthquake.

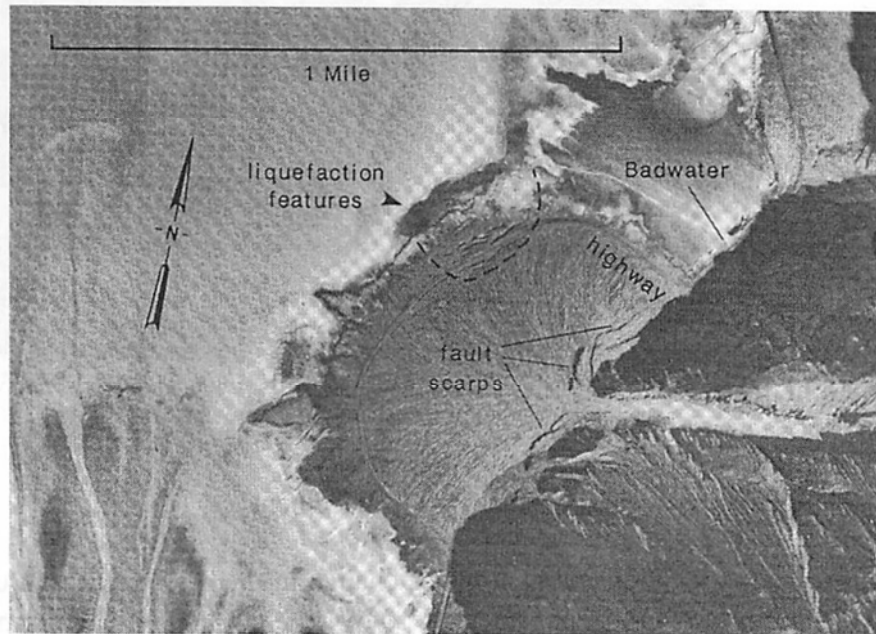


Fig. 6 – Aerial photo showing fault scarps at the apex of an alluvial fan in the lower center of photo. (From Wills 1989)



Fig. 7 – View to the southwest from Badwater showing fault scarps on the Badwater alluvial fan. Scarps that are erosionally enhanced identify the approximate location of the fault that has offset fan surface. Two fault scarps join to form a single scarp on the horizon. (From Wills 1989)

- **Mormon Point** –

North of Mormon Point, the fault zone makes a nearly 4.8 km right step. Normal faults are distributed across the alluvial fans in this stepover zone. At Mormon Point, the fault zone resumes its N-NW trend. About 8 km to the south, the fault makes the first of several en echelon right steps away from the Black Mountains. The scarps at Mormon Point attain a maximum height of about 9 m between alluvial fans where they are best preserved.

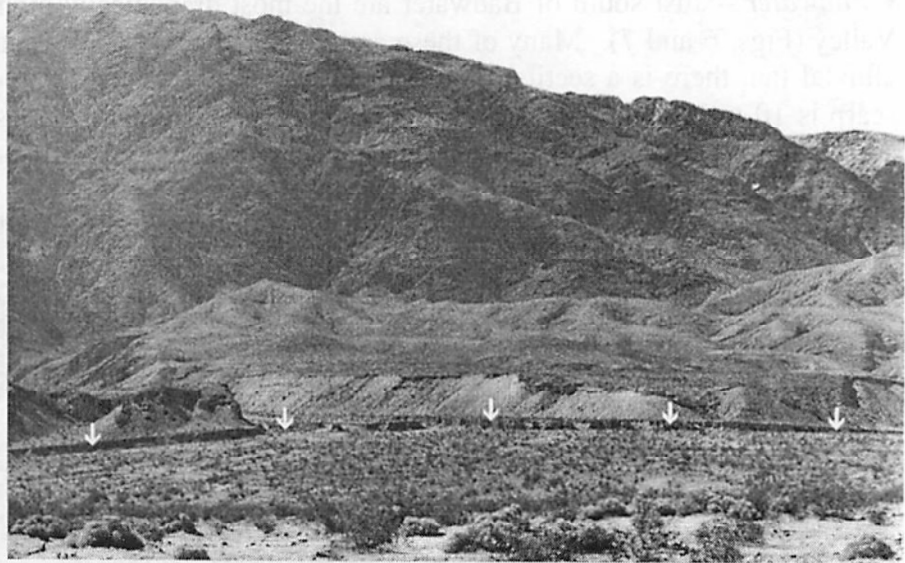


Fig. 8 – A low, young fault scarp crossing a wide arroyo, between alluvial fans, in Mormon Point cove. (From Sharp and Glazner 1997)

Such scarps probably records several episodes of displacement.

- **Shoreline Butte** – This location marks a major change in the orientation and character of the fault zone – to the north the fault trends about N 10°W and has a significant normal component. To the south the fault trends about N 40°W and is almost completely strike-slip. Drainages that flow across the fault zone are right-laterally offset by as much as 1/3 km for a major wash. Locally the fault is expressed as a sharp side-hill bench in soft mudstone.

- **Amargosa River** – West of the Amargosa River, the fault zone is defined by a linear ridge 20-50 cm high and has a sharp tonal contrast that is visible on aerial photos and on the ground. The sharpest right-lateral offsets are commonly about 3 m.

- **Noble Hills** – Evidence for Holocene offset on the DVFZ becomes less clear here. It appears to play out as it approached the Garlock fault.

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Recent fault scarps in Death Valley

Chris Okubo

Location/geometry

The most recently active faults in Death Valley are part of the Northern and Southern Death Valley Fault Zones and Black Mountain Fault Zone (Figure 1). These fault zones are defined at the surface by a through-going series of surface ruptures that extend from the Fish Lake Valley Fault Zone in Nevada to the Garlock Fault Zone in California. The Death Valley and Black Mountain Fault Zones as we see them today are approximately 14 million years old.

The Death Valley and Black Mountain Fault Zone system is comprised primarily of right lateral strike slip faults and normal faults (Figure 2). There is a minor component of thrust faulting in each Fault Zone. The formation of Death Valley is linked to the growth of these fault zones. Death Valley is located within an extensional stepover between the Northern and Southern Death Valley Fault Zones, which primarily accommodate right lateral strike slip displacement. Death Valley is currently developing as a half-graben, bounded on the eastern side by the Black Mountain Fault Zone, which primarily accommodates normal fault displacements. Slip along the Northern and Southern Death Valley Fault Zones drives slip along the Black Mountain Fault Zone by decreasing the horizontal compressive stresses acting in the Death Valley region. This enables normal faulting to occur within the Black Mountain Fault Zone and thereby leading to the growth (i.e. deepening and lengthening) of Death Valley.

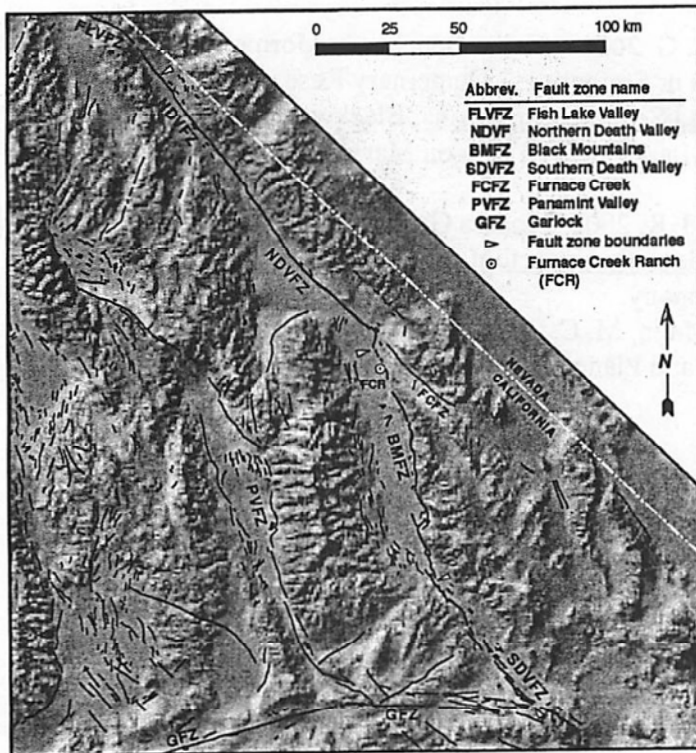


Figure 1. Structural map of faults within the Death Valley region. Southern Death Valley is bounded on the east by the Black Mountain Fault Zone (BMFZ). Figure from Machette et al., 2001.

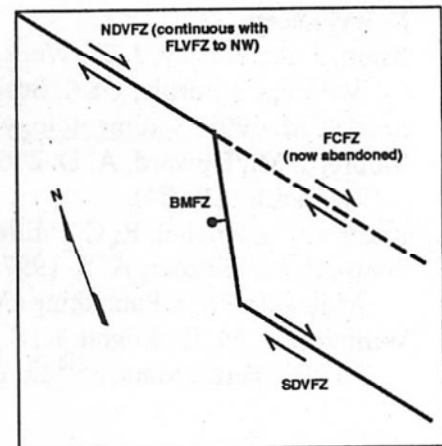


Figure 2. The Black Mountain fault zone and southern Death Valley occur within an extensional stepover between the Northern and Southern Death Valley Fault Zones. Figure from Machette et al., 2001.

Regional context

Death Valley is a part of the Basin and Range. This physiographic province stretches across the southwestern United States and northern Mexico. Formation of the Basin and Range province is thought to be driven by the movement of the Pacific plate below the North American plate. This movement causes extension of the overlying crust and the subsequent normal faulting responsible for typical Basin and Range Topography. Up to 3 km of vertical displacement has been proposed for some of these Basin and Range normal faults. As a result, the lithosphere below the Basin and Range is amongst the thinnest in the world (~30 km compared to 150-250 km average thickness of the continental lithosphere). The Basin and Range province is thought to have accommodated up to 100% extension over the past c. 20 million years.

Death Valley originated as a typical basin and range, but has since been modified by slip along the Northern and Southern Death Valley Fault Zones and Black Mountain Fault Zone. These fault zones now form the longest and most active fault systems in the Basin and Range province. These fault zones are part of the Eastern California Shear Zone, which parallels San Andreas Fault Zone. The Eastern California Shear Zone is an example of distributed deformation, whereas the San Andreas Fault Zone represents localized deformation. Slip along both the Eastern California Shear Zone and the San Andreas Fault Zone is driven by the relative motion between the Pacific and North American plates.

Recent activity

The minimal evidence of erosion visible on many faults in the Death Valley region suggests recent slip events have occurred along these faults. There are a few reports of historic activity along the faults of the Death Valley and Black Mountain Fault Zones. Slip along the normal faults of the Black Mountain Fault Zone was reported in 1908 and may be related to a M 6.5 earthquake that occurred in the region (Clements, 1954). Unfortunately these reports are difficult to verify and a causal relationship between fresh-looking fault scarps in the Black Mountain Fault Zone and the 1908 earthquake have not been established. Other reports have also been reported in the literature, however the credibility of these reports has not been established.

Trenching across faults of the Black Mountain Fault Zone has revealed an average recurrence rate of 1 event every 6700 years, where each event has an average of 0.3 m of normal fault displacement, or an average slip rate of 0.1 to 0.5 mm/yr over the past 100,000 years (Machette et al., 1999).

Fault-controlled fluid flow

There are a multitude of springs in Death Valley. Many of these springs occur along faults of the Death Valley and Black Mountain Fault Zones. These are excellent examples of fault-controlled fluid flow; groundwater utilizes these faults as highly-permeable (low-resistance) conduits to the surface. Examples of these fault-controlled springs are Salt spring, Sand spring, Triangle spring, and Travertine spring.

Faults on Mars are expected to serve as analogous conduits to the subsurface movement of volatiles. Faults on Mars are therefore excellent places to explore for evidence of past geochemical, and potential biogeochemical, processes.

Paleo-shorelines or faults?

Death Valley is largely a fault-controlled terrain; faults significantly influence the topography and morphology that we see today. This means that fault traces commonly follow the topography (or more precisely, the topography follows the faults; Figure 3). The tendency for faults to follow topography has significant implications for mapping the locations of paleo-shorelines in the Death Valley basin. Since both the fault traces and shorelines follow topography, detailed field studies are required to discern between terraces due to shoreline processes and morphologically similar fault scarps (Figure 4). How would you discern between paleo-shorelines and fault scarps on Mars?

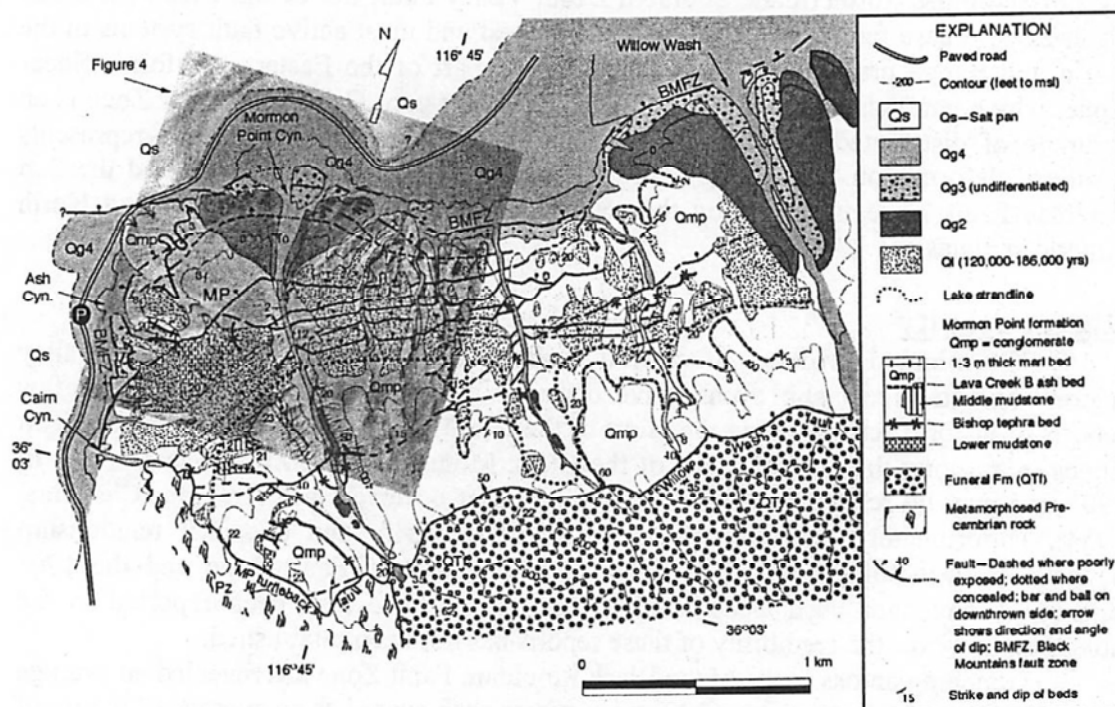


Figure 3. Structural map of faults in the Mormon Point area. Normal faults are part of the Black Mountain Fault Zone (BMFZ). The surface traces of these normal faults follow topography, making it difficult to distinguish them from paleo-shorelines in aerial photographs. Figure from Machette et al., 2001.

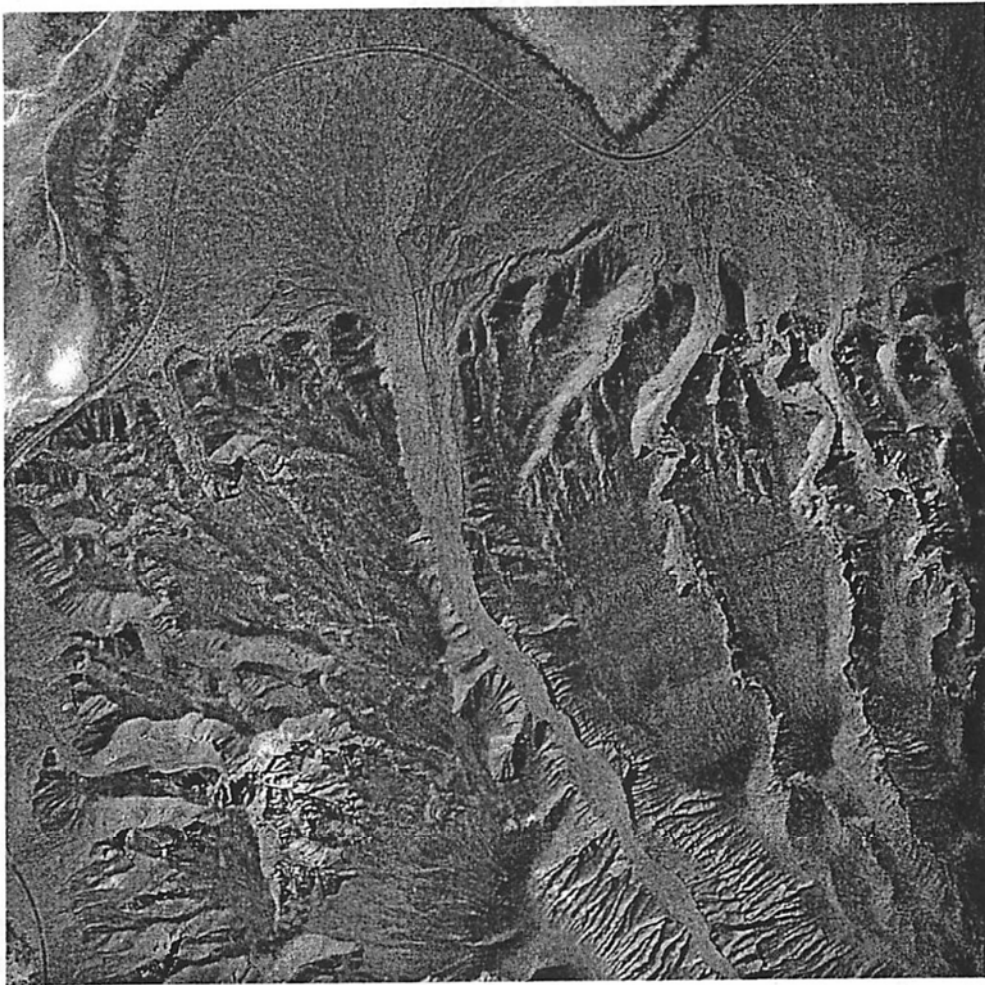


Figure 4. Aerial photograph of the Mormon Point area. Location and scale shown in figure 3. In this photograph, the surface ruptures (scarps) of normal faults in the Black Mountain Fault Zone appear very similar to the paleo-shorelines. In fact, there is only one true paleo-shoreline and one present-day shoreline in this photograph. Can you find the real paleo-shoreline? See Figure 3 for the answer.

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TURTLEBACK FAULTS OF DEATH VALLEY, CALIFORNIA

Windy Jaeger

Turtleback - An extensive smooth curved topographic surface, apparently unique to the Death Valley region, California, that resembles the carapace of a turtle; it is a large elongate dome with an amplitude up to a few thousand meters [Dictionary of Geologic Terms, 3rd Edition].

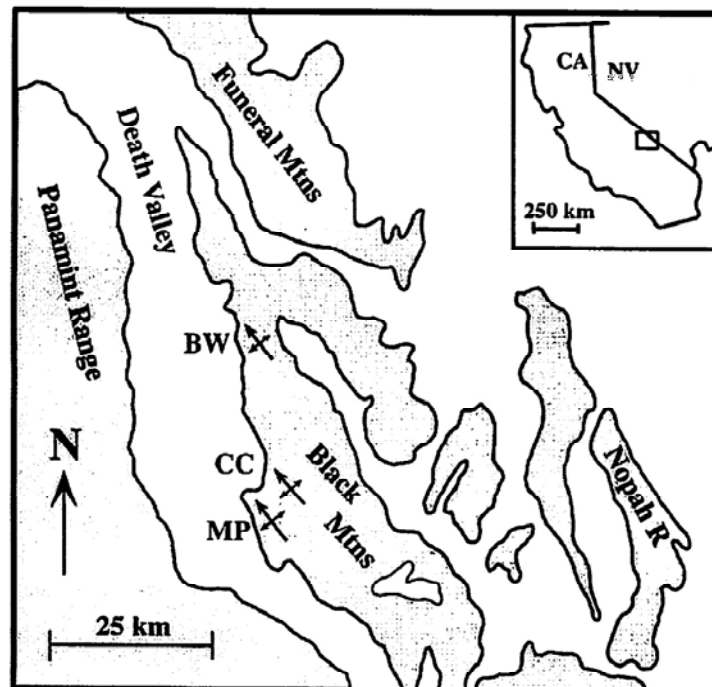


Figure 1. Map of the Death Valley region. Gray areas are pre-Quaternary (>1.6 Ma) highlands and white areas are Quaternary lowlands. Plunging antiform symbols mark the three turtlebacks: BW, Badwater Turtleback; CC, Copper Canyon Turtleback; MP, Mormon Point Turtleback [after Miller, 1992].

MODELS FOR THE FORMATION OF TURTLEBACK STRUCTURES:

- The domical turtleback structures were caused by the intrusion of shallow plutons [Sears, 1953].
- The turtleback surfaces were initially planar thrust faults that were subsequently folded and later exhumed [Curry, 1954].
- High-angle normal faulting along the western flank of the Black Mountains coupled with mass wasting and erosion unroofed the folded Precambrian basement rock from its mantle of Tertiary sedimentary rock. An Upper Tertiary fan conglomerate (cemented alluvial fan) formed on this surface, and renewed high-angle normal faulting left it

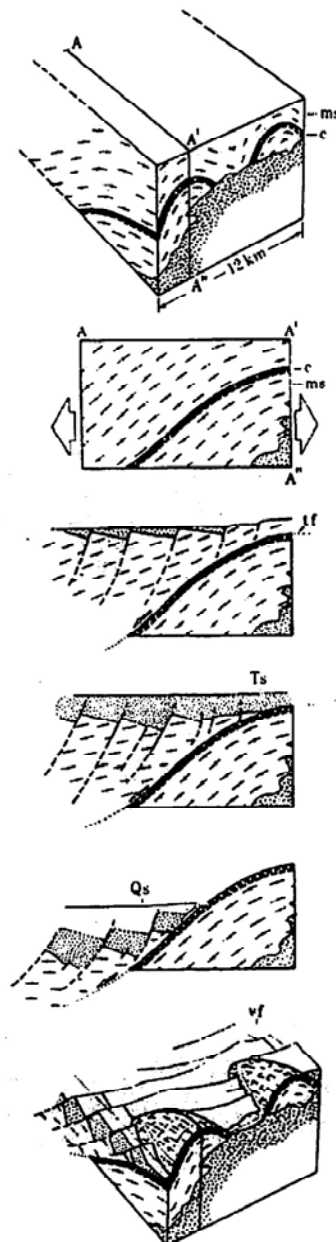
unsupported. Gravitational collapse of the unsupported conglomerate took the form of Plio-Pleistocene low-angle normal faulting (i.e. the turtleback faults) [Drewes, H., 1959].

- Regional folding of both the Precambrian basement rocks and the Tertiary rocks that mantled them produced the turtlebacks in an essentially autochthonous process whereby the less resistant cover rocks unroofed the basement rocks as they folded [Hill and Troxel, 1966].
- The turtleback surfaces are the footwalls of normal faults that formed along carbonate layers during Tertiary extension [Wright *et al.*, 1974].

EVIDENCE SUPPORTING THE PULL-APART MODEL OF WRIGHT *et al.*, 1974:

- The relative motion of the hanging wall and the footwall of the turtleback faults is recorded in small- and large-scale features exposed on the footwall. For the three turtlebacks in the Death Valley region, these movement indicators show that the hanging walls were translated downward and northwest.
1. **slickenside** - a polished and striated rock surface that results from friction along a fault plane.
 2. **fault mullion** - large grooves on a fault surface parallel to the direction of displacement.
- Fractures in the surrounding metasedimentary rocks are oriented perpendicular to the movement direction and to the long axes of the turtlebacks.

Figure 2. Block diagrams and cross-sections, illustrating the pull-apart model for turtleback formation; c = carbonate layers, ms = mixed metasedimentary rock, Qs = Quaternary sediments, tf = turtleback fault, Ts = tertiary sedimentary rock and vf = valley floor [from Wright *et al.*, 1974].



PALEOMAGNETISM OF THE BLACK MOUNTAINS:

- Paleomagnetic data suggests that much of the Black Mountains experienced recent (<6.5 Ma) clockwise rotation (50° to 80°) related to dextral shear motion along the Death Valley fault zone.

⇒ The slickensides and fault mullions observed on the turtleback surfaces reveal the relative motion between the hanging wall and the footwall; however, they need to be examined in conjunction with paleomagnetic data in order to determine the initial orientation of the fault plane.

TURTLEBACK (FOOTWALL) ROCKS:

- Mostly crystalline Precambrian (1.7 Ga) metasediments [Asmerom *et al.*, 1990]

Mylonites (rocks that have strong flow texture)

1. Quartzofeldspathic gneiss
gneiss - a foliated rock formed by regional metamorphism
2. Calcite (CaCO₃) marble
3. Dolomite (CaMg(CO₃)₂) marble
4. Pegmatite
a coarse-grained igneous intrusive rock; roughly granitic in composition; the last and most hydrous portion of a magma to crystallize, thus it can have high concentrations of minerals present only in trace amounts in granites; generally occurs as dikes around the margins of batholiths

Non-Mylonites

1. Minor pelitic schist (i.e. metamorphosed mudstone)
 2. Rocks that post-date the foliation
 - a. variably striking, highly altered mafic dikes
 - b. N20°E striking latite dikes
latite - a porphyritic extrusive rock with phenocrysts of plagioclase and potassium feldspar and little or no quartz
- The footwall mylonites vary in thickness due to ductile deformation such as folding and the formation of **boudinage structures** (i.e. pinches and swells formed by stretching a layer that was initially uniform in thickness).
 - Both crosscutting relationships [Miller, 1992] and U/Pb dating of zircons [Asmerom *et al.*, 1990] indicate that the mylonitization was concurrent with early stages of brittle deformation in the Black Mountains (i.e. Upper Tertiary, <11.6 Ma).

CHARACTERISTICS OF A METAMORPHIC CORE COMPLEX:

- local upwarps in areas with contemporaneous extension and magmatism
- a decollement (detachment fault) separates the metamorphic basement rock from its mantle of unmetamorphosed rock
- gravitational collapse occurs along low-angle, *en echelon*, listric normal faults
- major fold axis is parallel to the regional extension and the minor axis is perpendicular (Yin, 1991)

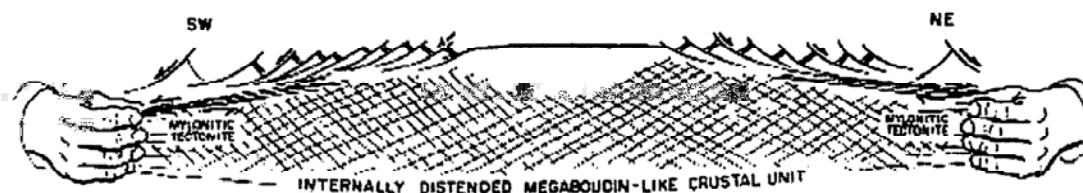


Figure 3. Schematic diagram of a metamorphic core complex [from Davis and Reynolds, 1996].

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Geologic Timescale

