PLANETARY FIELD GEOLOGY PRACTICUM
PTYS 594A

Fall 2008: Water, Chemistry and Fire
November 8-10, 2008

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STOPS AND TALKS

PtyS 594a,

PLANETARY FIELD GEOLOGY PRACTICUM

Fall 2008: Water, Chemistry and Fire

Approximate Itinerary

Saturday, 8 November

8:00 AM	Depart LPL loading dock. Drive North to Speedway, travel West to I-10 and head North toward Phoenix.
9:30 AM	Merge onto I-17 and continue North toward Flagstaff.
11:00 AM	Take Exit 293 onto Beaver Creek road and proceed 4 miles to Montezuma Well National Monument
11:15 AM	Park vehicles, descend to overlook of Montezuma Well. This distinctive feature is a Karst Sinkhole. Kevin Jones will describe the nature of this feature as well as the topography created by such features. Catherine Niesh will describe lakes on Titan that may, or may not, be of similar origin, and Doug Archer will enlighten us about the chemistry behind features of this type. A short walk (1/3 mile loop trail) will take us to the outflow tunnel of this sinkhole.
12:30 PM	Lunch at Montezuma Well.
1:15 PM	Depart Montezuma well for Tonto Bridge State Park. Return to Camp Verde and take Rte 260 East. At junction with Rte 87 turn right (South) and continue through the town of Pine, AZ. About 4 miles South East of Pine, 0.2 miles North of milepost 263, turn West on road to park. Park at start of Gowan Trailhead to observe the bridge.
2:30 PM	At this locality Colin Dundas will briefly describe the formation of spring mounds from solute-laden groundwater. If time permits we will take the short hike to the overlook.
4:00 PM	Depart Tonto Bridge Park and continue East on Rte 87 to Payson. In Payson take Rte 260 East toward Show Low.
5:30 PM	Camp in the vicinity of Christopher Creek in the national forest at the foot of the high Mogollon Rim. Following dinner, Eric Palmer will enlighten us about the resources available in the skies above us and how we can make that mineral wealth available.

Sunday, 9 November

7:30 AM	Break Camp, return to Rte 260 and continue East to Show Low. In Show Low turn left on Rte 60 and proceed toward Springerville. Just outside of Springerville turn North on Rte 180/191 and proceed 10 miles to Lyman Lake. Exit onto Rte 81 at Lyman State Park and park near the boat landing.
9:30 AM	At Lyman State Park we will again press **Colin Dundas** into service to tell us about the spring mounds found here and the research published about them. At this favored locality **Keith Rodgers** will talk about karst on the planet Mars and the presence of carbonates vs. sulfates and **Catherine Elder** will explain how the Mogollon Rim rose up and pushed the Colorado Plateau up to its present elevation.
11:00 AM	Depart Lyman Lake, return South toward Rte 60 and proceed East through Springerville. After departing Springerville we will halt at the crest of a hill at a caliche-covered basalt outcrop. If safe from traffic, Brian Jackson will then describe the Silica-Carbonate reaction that created the prominent white coating (otherwise we will find a more sheltered spot)
11:30 AM	Continue East on Rte. 60 toward Quemado.
12:00 Noon	Lunch stop at a lushly forested rest stop about 1 mile West of Red Hill, 10 miles from the Arizona-New Mexico border. After lunch Peng Sun will continue the silica-carbonate story by describing how this reaction has controlled the atmosphere of the early earth.
1:30 PM	Continue East on Rte. 60 to Quemado.
2:00 PM	Just outside of Quemado, turn South on Rte 32 toward Apache Creek. Note the appearance of light-colored rocks in the landscape. We will make a stop along this road where Kat Volk will describe how all these white rocks got emplaced. At Apache Creek, turn West onto Rte 12 toward Reserve. Continue through Reserve (making a sharp right turn at the stop sign) to Rte 180 South. Turn left at the intersection and continue South through Glenwood and Pleasanton to Rte 78. Turn right onto Rte 78 toward Mule Creek and the Arizona border. If it is late, and not too cold, we may camp just over the border at the Black Jack Campground.
5:30 PM	Stop at the overlook on Rte 78, 1 mile beyond Black Jack Campground. In the fading light Dave O'Brien will describe the mechanics of the flows that emplaced the impressive cliffs around us. After this stop, continue to

lower elevations on Rte 78 to cross Rte 191/75 near Clifton. Drive West on Rte 191 toward Safford up and over the Black Hills.

6:30 PM Turn off Rte 191 at the Black Hills Back Country Byway and make camp. Around the campfire Andrea Phillipoff will describe the history of exploration and discovery of the Mogollon range around which we have passed today.

Monday, 10 November

7:30 AM Break camp and continue along Rte 191 to Safford. Make a left at the stop light in Safford to continue South along Rte 191. Upon encountering I-10 enter the highway and drive West to Exit 340 in Willcox. Exit there, drive carefully through town and continue South on Rte 186 toward Dos Cabezas. Continue through Dos Cabezas to the Chiricahua National Monument.

10:30 AM Arrive Chiricahua National Monument. Drive slowly up the park road to the Massai point overlook.

11:30 AM At this overlook we will discuss the Turkey Creek Caldera and the awesome volcanic eruption that spilled out the rocks that we see in front of us. **David Choi** will further describe these remarkable rocks and tell us how they have been used as indicators of the strength of earthquakes past.

12:30 PM Drive to the Sugarloaf trailhead picnic ground for lunch.

1:30 PM Begin 0.9 mile hike (470 foot elevation change) to the summit of Sugarloaf Mountain, enjoying the magnificent views of the Basin and Range tectonic province and close-up views of the volcanic rocks as we go.

3:30 PM Return to the vehicles, depart for Tucson.

6:30 PM Arrive Tucson, clean out the vehicles and go home.

==Finis==

Drivers:

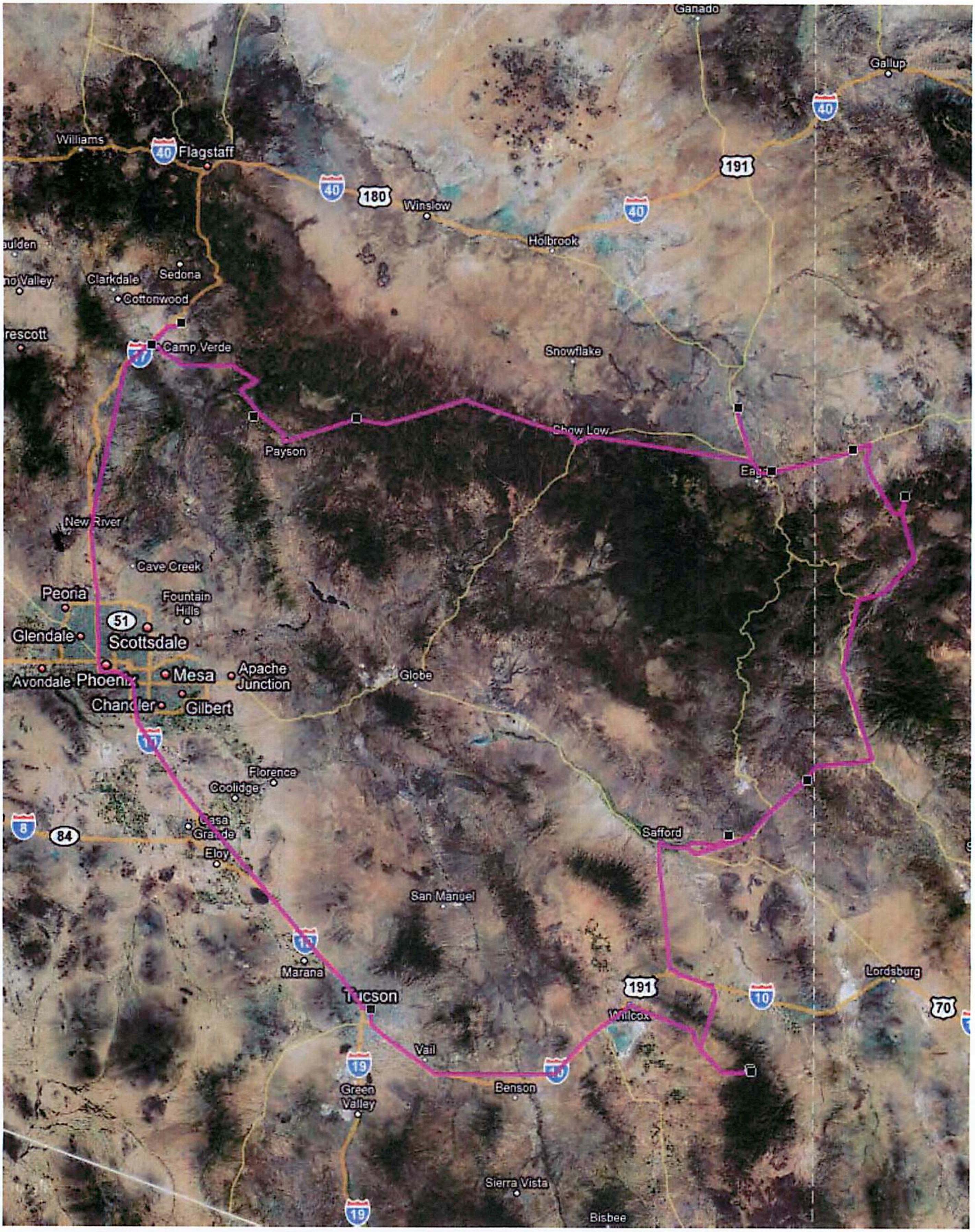
Primary: Dundas, Palmer, Rodgers, and Volk

Leaders: Jay Melosh, Shane Byrne, Alex Pavlov, Dave O'Brien

Participants:

Archer, Doug
Byrne, Shane
Choi, David
Dundas, Colin
Elder, Catherine
Jackson, Brian
Jones, Kevin
Melosh, Jay
Neish, Catherine
O'Brien, David
Palmer, Eric
Pavlov, Alex
Philippoff, Andrea
Rodgers, Keith
Sun, Peng
Volk, Kat

Field Guide Editor: Keith Rodgers


Ganado
Gallup
Williams
Flagstaff
40
180
Winslow
191
Holbrook
Sedona
Clarkdale
Cottonwood
Camp Verde
17
Snowflake
Payson
Show Low
Eagar
New River
Cave Creek
Peoria
Fountain Hills
51
Glendale
Scottsdale
Avondale
Phoenix
Mesa
Apache Junction
Chandler
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Florence
Coolidge
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84
Casa Grande
Eloy
Safford
San Manuel
Marana
Tucson
Willcox
Lordsburg
70
Vail
19
Green Valley
Benson
Sierra Vista
Bisbee

Karst topography and sinkholes

Kevin Jones

What is karst?

Karst topography consists of closed depressions called *sinkholes/dolines/cenotes,* which sometimes coalesce to form larger *uvalas*. Caves are typically present. Drainage networks in karst landscapes are often partly or entirely subterranean and contain sinking streams.

How does karst form?

Karstification occurs by acid dissolution of very soluble bedrock. On Earth, the rock is typically carbonate ($CaCO_3$, limestone or marble), although karst also occurs in dolomite ($CaMg(CO_3)_2$) and evaporites such as gypsum ($CaSO_4 \cdot 2H_2O$) The acid is typically carbonic acid (H_2CO_3) created as atmospheric CO_2 interacts with water, although H_2SO_4 and HCl can also be solvents.

Rock dissolves preferentially along structural weaknesses, such as joints and bedding planes, and often forms caves. Dissolution at the ground surface produces *dissolution sinkholes*. Where subsurface dissolution occurs, caves are created, which may ultimately collapse and form *collapse sinkholes*. If a sinkhole intersects the local water table, or if its drain is clogged with debris, it may fill with water to form a sinkhole pond.

Where can one find karst?

On Earth, karst landscapes are very common, and form in areas of soluble bedrock. Humid, temperate to tropical regions are most favorable for karst, as warm and wet conditions encourage carbonate dissolution. Karstification has also been invoked to explain some extraterrestrial landscapes on Mars and Titan.

Montezuma's Well: a large sinkhole in Arizona. Source: ronslog.typepad.com.

Jamal and Associates, Orlando, Florida

Figure 62. *Spectacular, sudden collapse of the land surface commonly accompanies the formation of a sinkhole, such as this one that formed at Winter Park, just north of Orlando, Fla., in 1981.*

Unfortunately-situated collapse sinkhole in Florida. Source: USGS.

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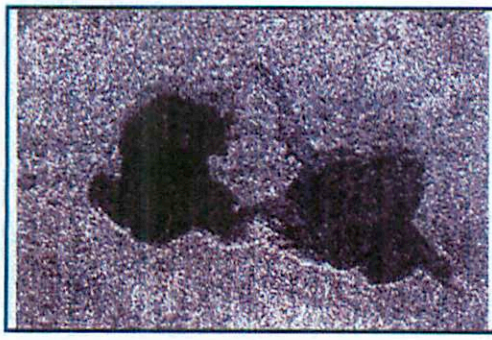

Karst (?) Lakes (?) on Titan (!)

by Catherine Neish

Water, Chemistry, and Fire Field Trip
(Fall 2008)

Lakes on Titan

Cassini's T16 flyby of Titan in July 2006 discovered dark patches near Titan's north pole. Subsequent flybys found a great variety of these dark patches polewards of 70° N (Figure 1).

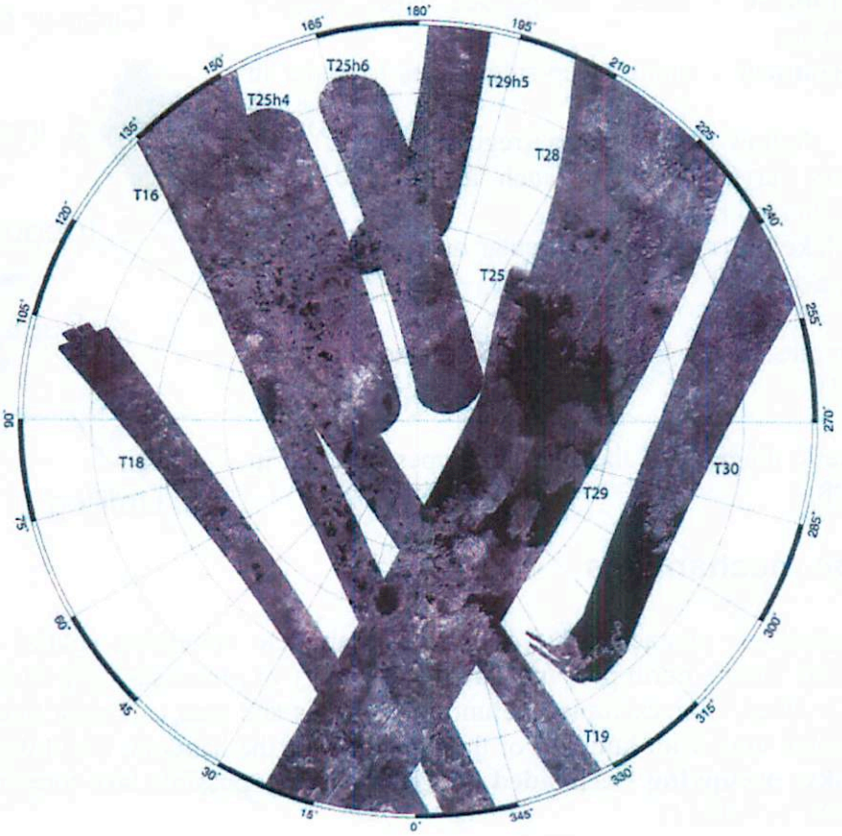

Figure 1: Cassini RADAR images of Titan taken polewards of 60° N over the course of seven flybys. Roughly 650 lakes have been observed in this region. Image taken from Mitchell et al. (2008).

These dark patches have been interpreted to be lakes (Stofan et al. 2007). Why is that?

a. The dark patches are *very* dark, some darker than the noise floor of the RADAR instrument on Cassini (< -25 dB). Such a low backscatter requires an extremely smooth or a highly absorbing surface, such as a **liquid**, or a **low density solid**. The latter option is hard to reconcile with the data. If there were porous, unconsolidated sediments filling basins near Titan's north pole, we may also expect to see aeolian features there, but none are observed. Also, it would be hard to account for the differing backscatter of the lakes – some are dark, and some are bright. The basins would have to be filled with two different solids.

b. The outlines of the dark patches bear resemblance to lakes on Earth, and interact morphologically with fluvial features such as channels.
c. Brown et al. (2008) found absorption features consistent with liquid ethane in the extremely low albedo feature "Ontario Lacus" located near the south pole of Titan.
d. Mitri et al. (2007) demonstrated that ethane/methane lakes covering only 0.2-2 % of Titan's surface could maintain Titan's current relative methane humidity of ~50% over short timescales. For reference, Lorenz et al. (2008) estimate that lakes cover ~0.5% of Titan's surface.

Classification of lakes on Titan

Mitchell et al. (2008) classified Titan's lakes using qualitative, geomorphological criteria such as size, shape, and degree of fill. They identified five major lake types (Figure 2):

- **Circular-rimmed** – small, steep-sided lakes roughly circular in shape
- **Irregular-rimmed** – small, steep-sided lakes irregular in shape
- **Irregular** – shallow-rimmed lakes irregular in shape
- **Seas** – very large lakes (as much as 100,000 km^2), resembling flooded river valleys
- **Unfilled** – lakeforms similar to circular or irregular lakes, but lacking a dark fill

Representative samples of the five lake types are shown on the next page (Figure 3).

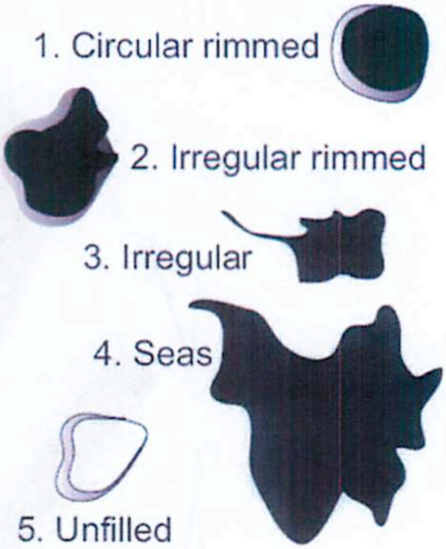

Figure 2: Schematic diagram of the five lake types outlined in Mitchell et al. (2008).

Lake formation mechanisms

The differing morphologic characteristics of the lakes and the noticeable spatial clustering of these characteristics around Titan's north pole indicate that a variety of processes contributed to the origin and evolution of Titan's lakes. For example, the unrimmed lakes and seas can most likely be explained by infilling of topographic lows with liquid. For the remainder of the handout, I will therefore focus on the formation of the **lakes occupying steep-sided depressions**. Ten possible lake formation processes were outlined in Blair (1987) (Table 1).

Table 1: Processes responsible for terrestrial lake formation, and a determination of whether or not the processes could have shaped the steep-sided lakes on Titan.

Formation process	Examples	Formed the steep-sided lakes on Titan?
1. Tectonic	tilting, rifting	No – low occurrence of linear margins in lakes
2. Volcanic	caldera collapse	**Maybe?**
3. Colluvial	landslides	No – slopes of features generally shallow
4. Glacial	glacial scour	No – glaciers unlikely on present day Titan
5. Solution	sinkholes	**Maybe?**

6. Fluvial	oxbow lakes	No – many lakes lack any association with channels
7. Coastal	lagoons	No – many lakes found far from seas
8. Aeolian	interdune lakes	No – lack of aeolian landforms in northern latitudes
9. Impact	craters	No – inconsistent with size-frequency distribution
10. Life	beaver dams	No – lack of beavers on Titan

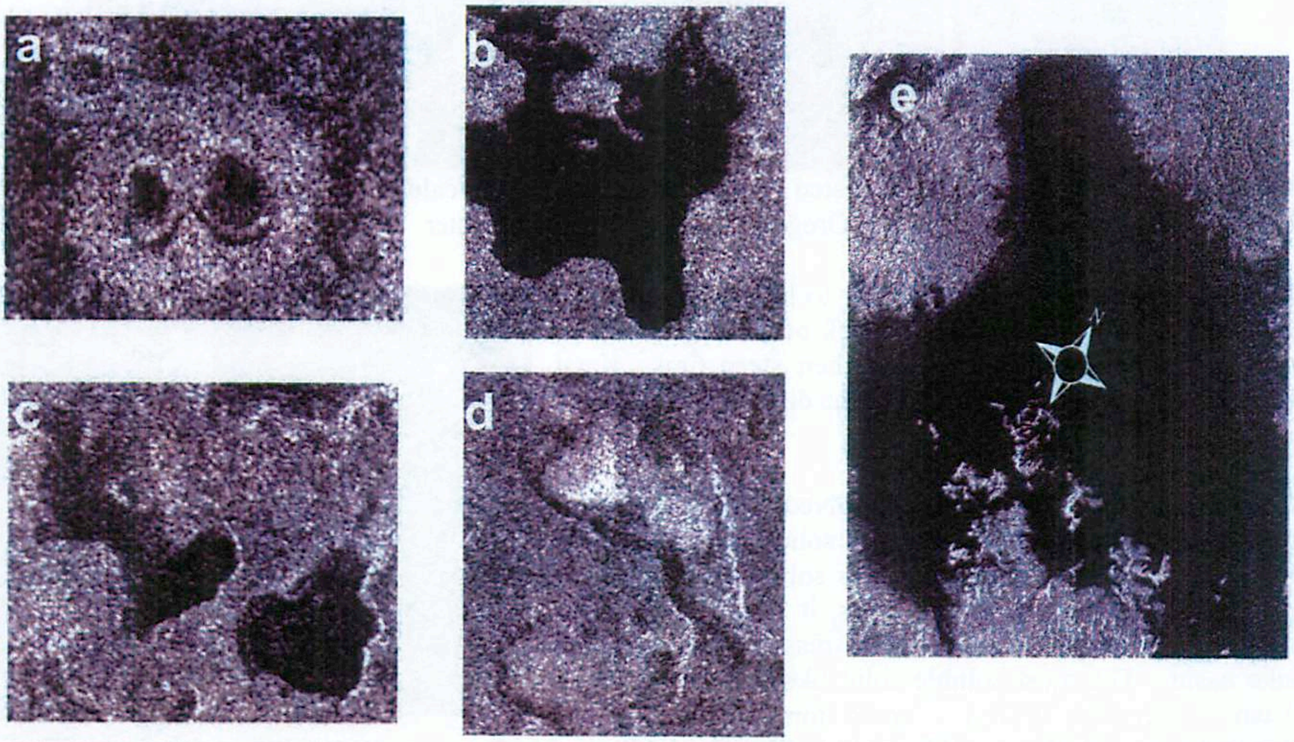

Figure 3: Representative samples of the five lake types outlined in Mitchell et al. (2008). (a) Circular-rimmed (image ~30 km across), (b) irregular (image ~40 km across), (c) irregular-rimmed (image ~100 km across), (d) unfilled (image ~50 km across), and (e) seas (image ~300 km across). All images taken with the Cassini RADAR instrument at 2.2 cm.

The two most likely formation mechanisms for the steep-sided lakes, as determined by Mitchell et al. (2008), are **volcanic** and **solution (aka karst)** processes.

Volcanic hypothesis:

Volcanic basins are formed by collapse over inflating and deflating magma chambers.

Pros: Volcanism is possible on Titan, and several lakes have the appearance of a nested caldera (Figure 4). It would explain the lack of drainage patterns, the circularity of some lakes, and their steep rims.

Cons: Volcanism is unlikely to be able to explain all of the lake basins. That would require an unusual focusing of volcanic activity at the north pole. Also, it is harder to explain the irregular lakes.

Karst hypothesis:

Karst basins are formed by the differential chemical erosion of soluble bodies of rock. Karst formation is aided by extensive fracturing in the rocks.

Figure 4: Radar images of (a) a nested lake on Titan, and (b) the caldera of Kilauea Volcano, Hawai'i. Landsat image of (c) Crater Lake in Oregon, a caldera filled with water.

Pros: Morphologically very similar to lakes seen on Titan (Figure 5). It would explain the lack of drainage patterns, the circularity of some lakes, and their steep rims. Karst lakes are often clustered, similar to the distribution observed on Titan.

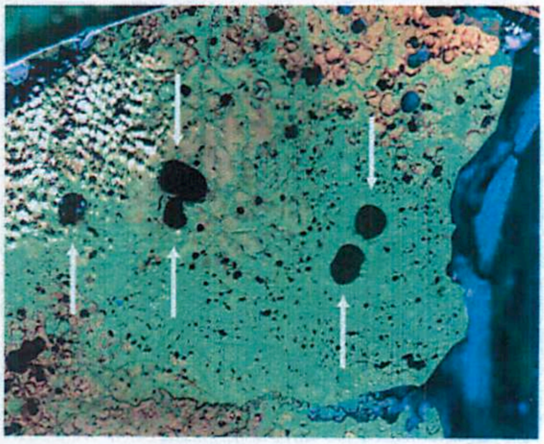

Figure 5: El Tejo karstic lakes, Spain (copyright Wayne Wurtsbaugh/Photopost).

Cons: What the heck is being dissolved? Karst formation requires a substantial thickness of a solid that is soluble in liquid methane and/or ethane. This solid cannot be ice – with a solubility of $<10^{-11}$ by mass, it would take longer than the age of the solar system to dissolve a discernable lake basin. The most soluble solid likely to be found on Titan – acetylene (C_2H_2) – could form a layer several hundred meters thick over 100s of Ma. With a solubility of 8×10^{-5} to 8×10^{-4} by mass, it would take ~5 ka to 750 Ma years to dissolve a basin 600 m in depth (Mitchell et al. 2008). Most terrestrial karst regions form over much shorter timescales, << 1 Ma. Also, acetylene has yet to be observed on the surface of Titan. In addition, terrestrial karst lakes are generally smaller than those seen on Titan, and a karst origin does not account for the bright, raised halos observed around some of Titan's lakes.

More constraints on the composition and porosity of the solid material present in the north polar regions, the rainfall rate, and the composition of the working fluid, will aid in determining the feasibility of solution processes as a mechanism for lake formation on Titan.

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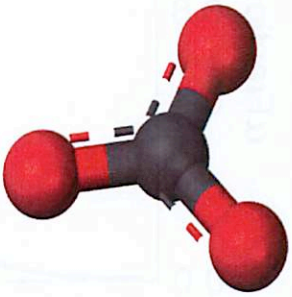
Carbonate-water interactions: Solution and Precipitation

Doug Archer

Carbonate Facts

- Carbonate itself is soluble in water
- Carbonate can form ionic compounds with a variety of cations. Most of these compounds are insoluble in water.
    - Calcite or Calcium Carbonate, $CaCO_3$ is the most common naturally occuring carbonate salt (mineral)



Carbonate, the star of the show

Ocean Chemistry

- In water, carbonate, bicarbonate, and water exist in a dynamic equilibrium that is dependent on pH and the concentration of available cations.
- Most important reactions in ocean carbonate chemistry:

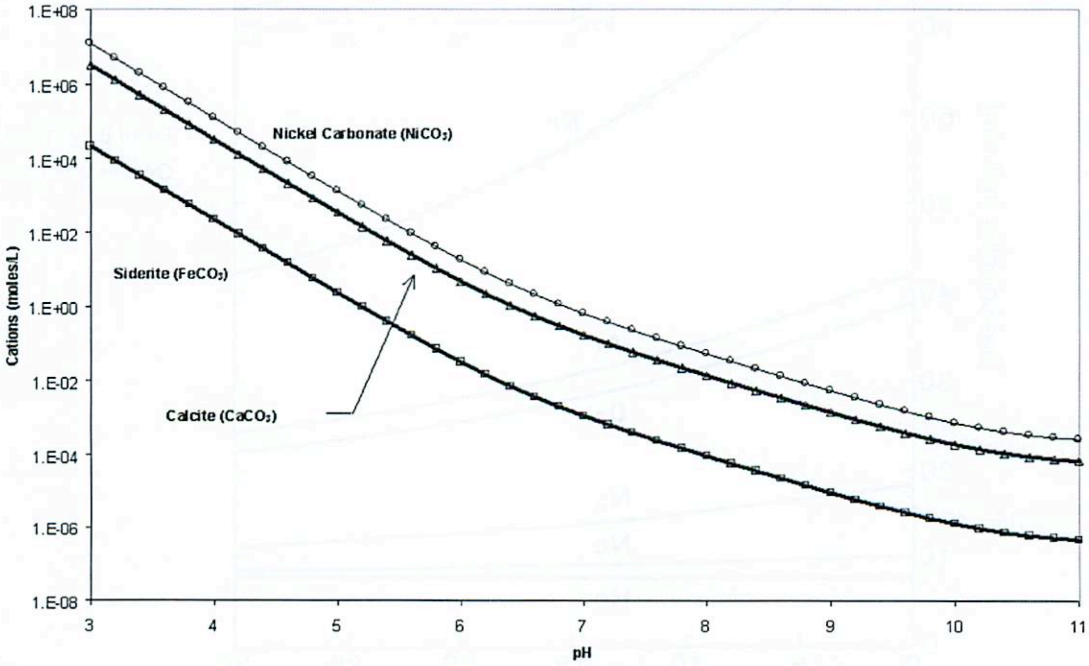
$$CO_2 \Leftrightarrow H_2CO_3 \Leftrightarrow HCO^{3-} \Leftrightarrow CO_3^{2-}$$

Slightly more complicated version:

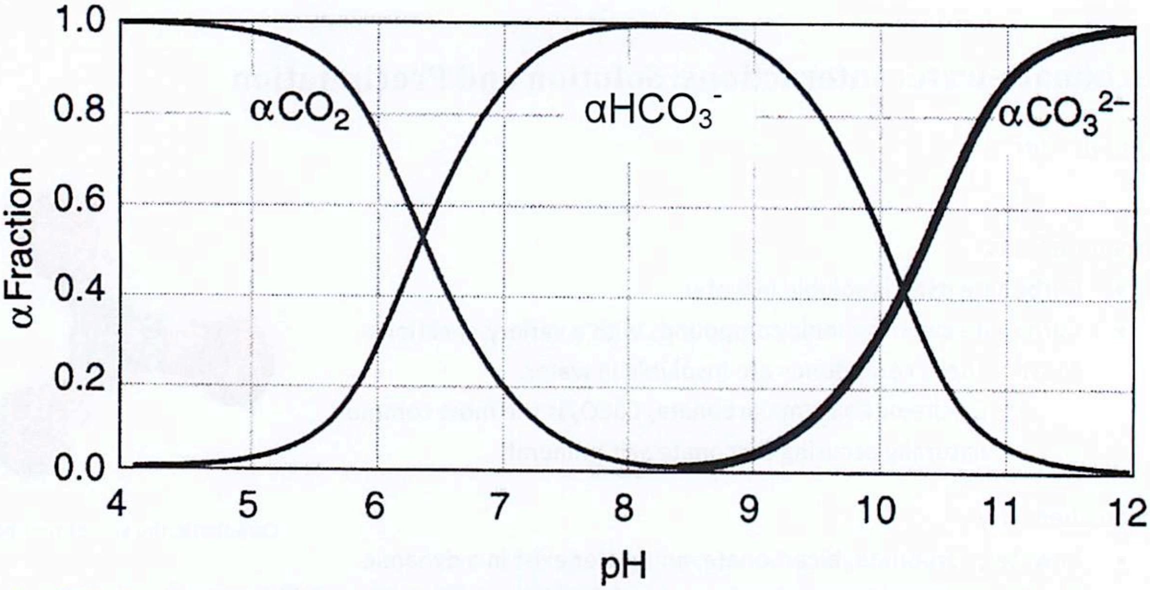
$$CO_2(g) \Leftrightarrow CO_2\,(l) \overset{+\,H_2O}{\Leftrightarrow} H_2CO_3 \overset{+\,H_2O}{\Leftrightarrow} \begin{matrix} HCO_3^- \\ +\,H_3O^+ \end{matrix} \overset{+\,H_2O}{\Leftrightarrow} \begin{matrix} CO_3^{2-} \\ +\,H_3O^+ \end{matrix} \overset{+\,Ca^{2+}}{\Leftrightarrow} CaCO_3 \downarrow$$

Important factors in solution vs. precipitation:

- pH of water

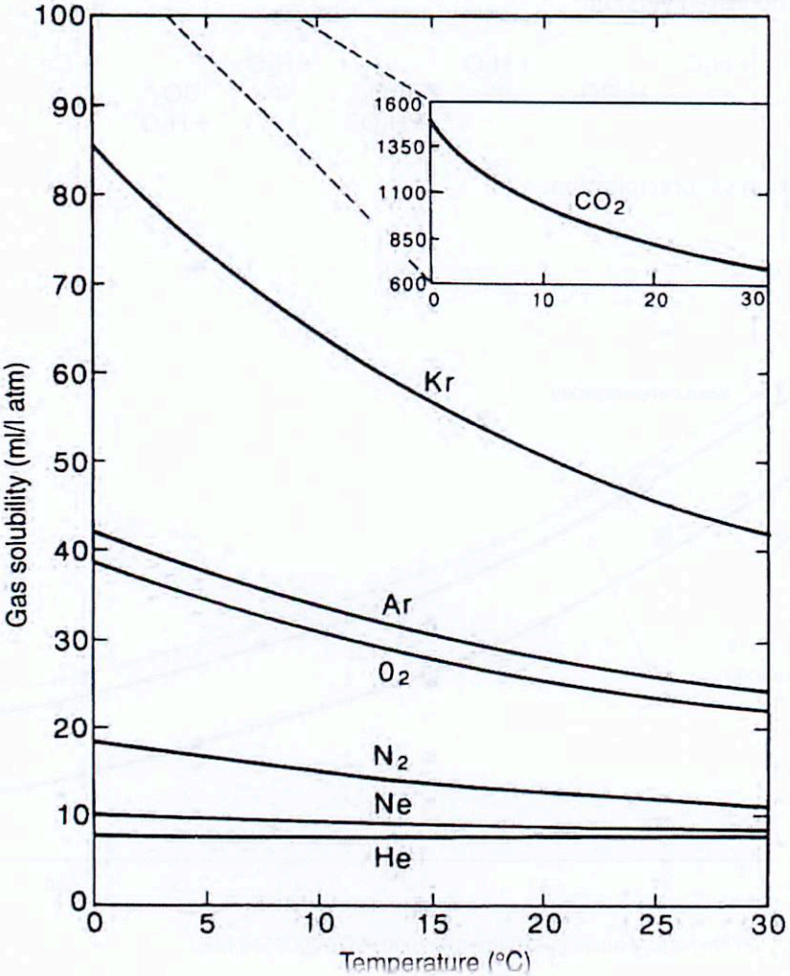


From http://sti.srs.gov/fulltext/tr2000146/tr2000146.html



Plot of Dissolved Inorganic Carbon vs. pH (ocean is about pH 8) – from Environmental Chemistry. The α stands for the fraction of total dissolved inorganic carbon present in the given form (CO2, CO3, or HCO3)

- water temperature



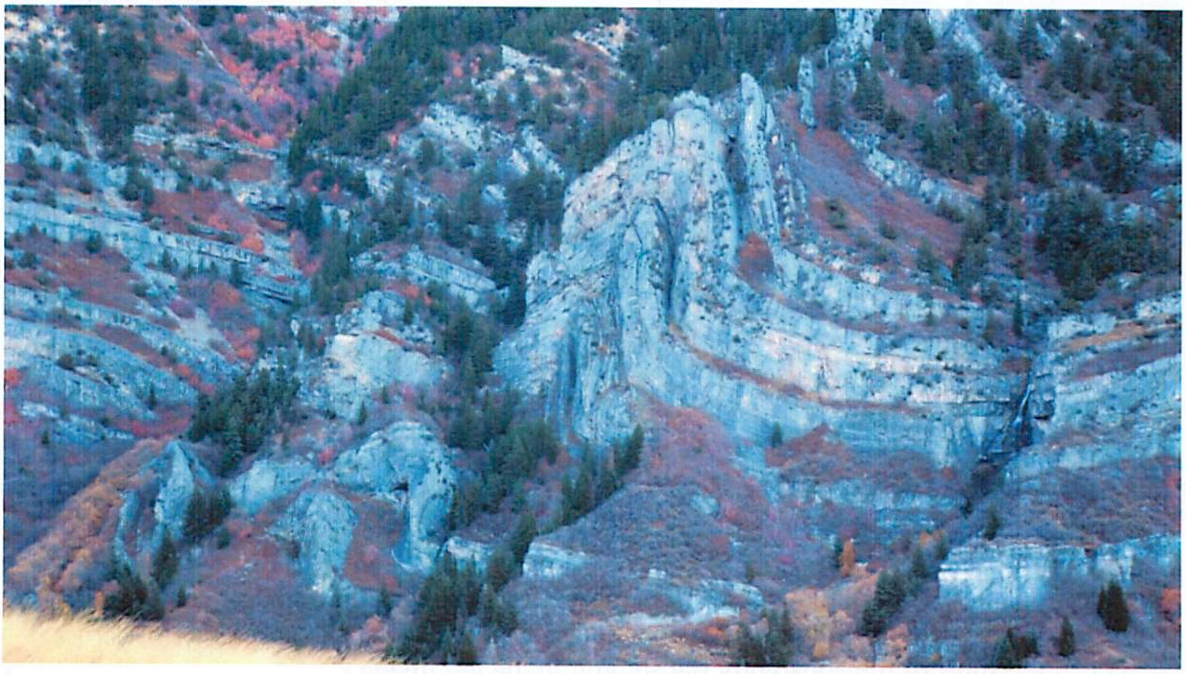
From Bigg, 1998, The Oceans and Climate

- Cation abundance
    - Erosion rates – very low during glacial periods, for example.

Importance

- Very important to climate!
    - Ocean as a sink vs. source of CO2
    - Can buffer climate
- Determines limestone formation and destruction

Limestone at Etretat, France. From http://www.mjausson.com/2004/may2004Normandie.html



Folded Limestone - Provo Canyon, UT. From http://www.panoramio.com/photos/original/2534169.jpg

Spring Mounds

Colin Dundas

Definition

Spring Mounds are evaporitic features formed by deposition of precipitates around a spring. They may include tufa, travertine, and gypsum, as well as some other sediment.

More Definitions (per Ford and Pedley, 1996)

Tufa is calcium carbonate precipitated from ambient-temperature water. Travertine is precipitated at higher temperatures. Sinter is a siliceous deposit from a hot spring. The actual distinctions may be much more complicated (and subject to debate) and aren't critical for present purposes, particularly since deposition may be related to biology (e.g. Chafetz and Folk 1984).

Morphology

Spring mounds are extremely morphologically diverse in detail, but the basic shapes range from irregular mounds to distinct cratered cones. The craters of active, flowing spring mounds are filled with pools of water, and the internal structure may be complex and layered. The mounds can vary widely in size and can reach quite large scales; some examples from New Mexico are hundreds of meters in diameter and ~125 m high (Harrington, 1948). The craters may also be remarkably deep relative to their diameter; Harrington notes one particular example that is 25 feet wide and 80 feet deep. (Note antiquated units). Large examples are also observed in North Africa (Roberts and Mitchell, 1987; Akdim and Julia, 2005). The mounds in the Springerville area may not exhibit quite this much relief, but are quite broad and readily apparent in aerial photos (Moore et al., 2005). Distinct mounds are only a part of a wide range of spring deposit morphologies, which depend on factors such as the slope and the water flow rate.

Figure 1: Small spring mound in Utah near Green River. Left image shows relief (profile); right image is oblique view from adjacent hill. The central pool is ~1 m across and occupies most of the apparently flat summit in the left image.

In addition to mounds, other morphologies can be constructed by spring flow. Akdim and Julia (2005) describe several from Morocco, including fissure ridges, terraces, fans and mantles. Tufas can also form at waterfalls or other sites of localized deposition.

Process

Readers may have already deduced the major processes at work here: spring flow and precipitation. Springs occur wherever groundwater reaches the surface. If this water is laden with precipitable chemicals like calcium carbonate, they may be deposited upon reaching the surface, particularly in environments where water evaporates rapidly. A further influence may be reduced solubility at low pressure, leading to precipitation. Deposits build up around the spring and tend to fill in low areas, so the mound builds higher over time.

The mounds can be quite sensitive to the formation of new springs, as water supply can be cut off by formation of a new spring at lower elevation. This will draw down the water table and cut off formation of the old mound. The height of the mounds is controlled by the height of the water table, and is, to some extent, self-limiting; as the mound builds higher, the hydraulic head increases at the base of the mound, raising the potential for a new breakout at lower elevation. Generations of mounds formed in succession have been reported on Earth (e.g. Harrington, 1948).

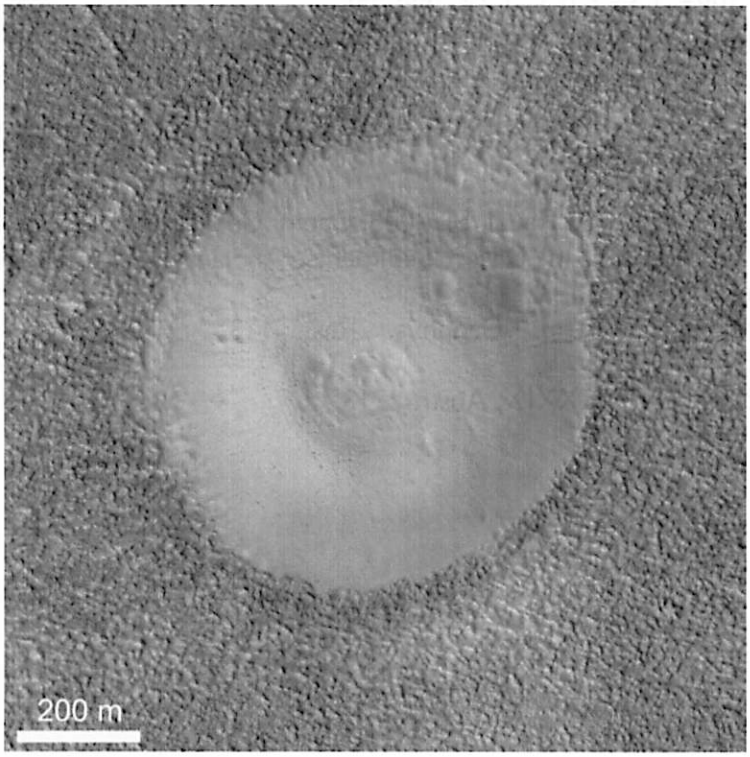


Figure 2: Possible spring mound or mud volcano on the northern plains of Mars. (HiRISE PSP_002232_2225, illumination from left).

Spring Mounds on Mars?

The basic ingredients to form spring mounds are clearly present on Mars: water and minerals that may be dissolved in it. (In the case of Mars, it is possible that sulfates rather than carbonates are involved). Several features have recently been proposed as spring deposits.

Rossi et al. (2008) recently proposed that light-toned deposits in Valles Marineris were deposited by springs. These deposits are very extensive and form extremely large structures well beyond the scale of any mounds on Earth. Crumpler (2003) also noted a number of possible spring mounds, although most of the features in question have a variety of proposed origins. Farrand et al. (2005) considered spring mounds and mud volcanoes the best analogues for a variety of northern-plains cratered cones. A hydrothermal origin has also been proposed for very silica-rich material at Home Plate in Gusev Crater (e.g. Ruff et al. 2008).

These are all recent suggestions that have not been fully evaluated, and a number of other conference abstracts discuss possible spring mounds. The hydrogeochemistry of Mars is a rapidly progressing subject and many new developments are likely in the near future. The many possibilities under discussion have implications for the geology and chemistry of the planet and will certainly be relevant to astrobiology as well.

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Asteroid Resources
Eric E. Palmer

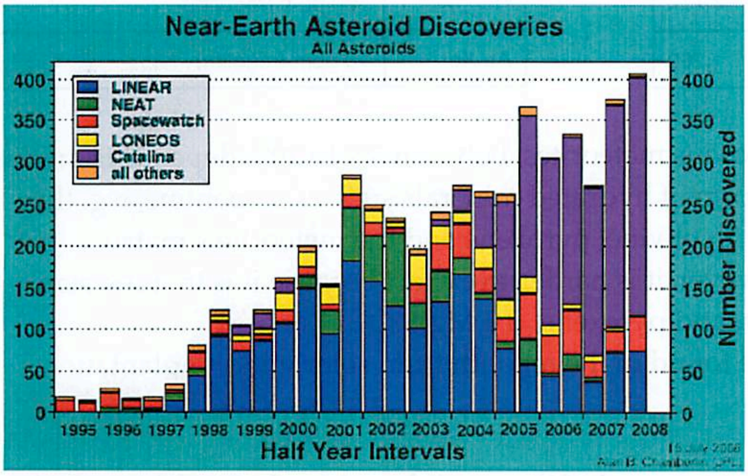
Resources

There are two types of asteroids that are the most useful for asteroid mining, metal rich and volatile rich. The general belief is that a subtype of the M-type asteroids are the parent bodies of iron meteorites. Additionally, we expect that the C-type asteroids are the source for carbonaceous meteorites. For this work, I'll assume that a CM meteorite, such as Murchison, is representative of C-type asteroids. This linkage between meteorites and asteroids is a bit tentative and much still needs to be done. The best information that we have for the composition of an asteroid is from the NEAR-Shoemaker mission that landed on Eros, a S-type asteroid, which appears to be similar to the ordinary chondrites. While S-type asteroids have ample resources, we'd be better off focusing on high-density-M and C type asteroids that have more of what is interesting.

Number of Asteroids

While the main asteroid belt has a huge number of asteroids (with over 200,000 asteroids in the Minor Planet Center's database), their distance makes them less useful. First, the transportation cost would be very high. Secondly, the lower amount of sunlight reduces the effectiveness of solar cells by a factor of nine.

Near Earth Asteroids. Predominately due to the cost in delta V to reach the main asteroid belt, NEAs are the most realistic location for in-situ production of material. So far, there have been over 5,500 detected and cataloged NEAs. 90% of the asteroids larger than 1 km have been found. The estimate is that there is over 100,000 NEAs with a diameter greater than 100m.



Iron Asteroids

Iron meteorites are formed mostly of Kamacite, $Fe_{19}Ni$. Additionally, there are many siderophile elements which would be in solid solution with the iron including the valuable Pt group elements. Let's consider an iron asteroid with a diameter of 300 m. Table 1 shows the amount of valuable metals, the current market price and total value they could sold for, a grand total of

$2.2 trillion. Of note, selling large quantities of precious metals would greatly depress the price. The mass of the 6 most valuable metals is 80 KTons.

Resource	Mass (KTon)	Value ($ Billion)
Iron	32,002.8	9.9
Nickel	2,808.0	4.9
Gold	4.9	131.5
Platinum	34.7	996.9
Iridium	16.9	234.7
Osmium	17.1	240.2

Resource	Mass (KTon)	Value ($ Billion)
Rhenium	1.3	15.5
Silver	7.0	2.4
Palladium	19.7	134.9
Rhodium	4.7	289.7
Ruthenium	25.0	153.9
Cobalt	158.0	10.6

Carbonaceous Asteroids

Let's use CM chondrites as an example of C-type asteroids. CM chondrites have more volatiles than any meteorite except for the CI type. They contain the following volatiles components.

Resource	Percent	Amount (tons)
Oxygen	50%	12,600
H_2O	10%	2,520
Iron	11%	2,772
Carbon	5%	1,260

Resource	Percent	Amount (tons)
N	0.1%-0.3%	25-76
Cl & F	.01%-.03%	2-8
He	100 ppm (regolith)	2
Ar, Xe	10 ppm (regolith)	0.2

Water is very common in carbonaceous meteorites, between 3% to 20% depending on the subtype. Most of the water is in the form of hydrated minerals such as serpentine, e.g. they have undergone a chemical reactions with olivine, pyroxene and the meteorite's matrix.
Oxygen is also very common; however, it is harder to extract because it is in more stable silicate minerals, olivine $(Fe,Mg)_2SiO_4$ and pyroxene, $(Fe,Mg)SiO_3$.
The nobel gases are expected to be found in the regolith from solar wind implantation.

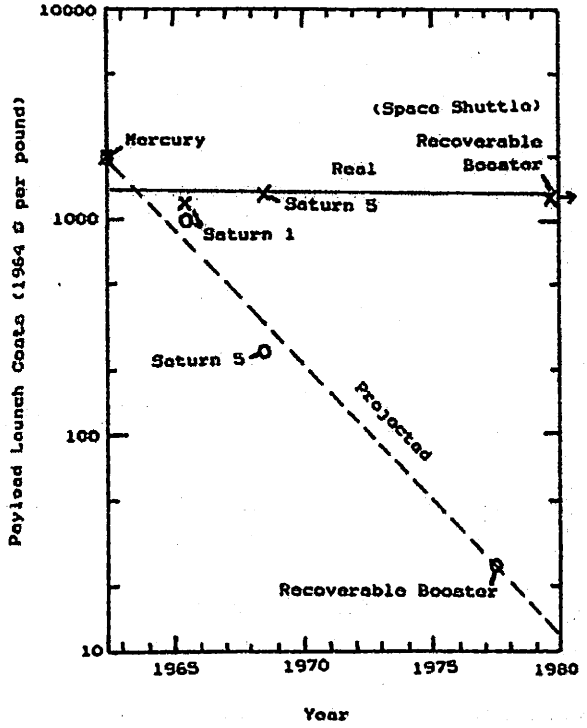
Mining Issues

Some of the methods of mining are: removal of the regolith and top layers (akin to strip mining), burrowing out tunnels in the asteroid (traditional mining), or drilling a hole and heating the surrounding rock to release volatiles.

Low gravity. Unlike on the Earth and the Moon, asteroids have negligible gravity. that means that all equipment will have to be tethered to the asteroid. Landing on a spinner asteroid with a highly variable gravity field is difficult.
Cosmic rays. Asteroids provide no protection for cosmic rays. Fortunately, most asteroids appear to have a layer of regolith that could be used to provide shielding.
Debris. Mining operations, regardless of method, will create detritus (small fragments of unwanted rock). Without substantial effort, this detritus will form a floating cloud of space debris around the asteroid that can interfere with landings and mining operations.

Transportation
Transportation is a critical element with mining asteroids in terms of what resources are useful where. The cost to move material reduces the benefit of material extracted from asteroids. If resources could be used in space itself, that would make them much more useful. However, without some space-based consumer (a colony or science outpost), the savings wouldn't be seen.

Operations in space, until in-situ production becomes well established, will require all fuel and equipment to be launched from the Earth. The high gravity well of the Earth makes reaching LEO a very pricey operation. The original projections for launch vehicles were overly optimistic (with $500/Kg expected). In reality, they price has stayed nearly constant around $10,000/Kg.



To operate in space, fuel will have to be launched from Earth at this very high price. Let's look at the fuel cost of brining only the precious metals from our 300 meter iron asteroid back to Earth.

Cost to move 80 tons of precious metals from the asteroid to the Earth.
Assume delta V = 1 km/s
Aerobraking in Earth's atmosphere
LH/LO_2: 20,000 tons
Xe: 2,700 tons (if using ion engines)
Cost to bring fuel to asteroid
Delta V = 5.0 km/s
LH/LO_2: 42,000 tons
Xe: 3,600 tons
Total Required in LEO
LH/LO_2: 62,000 tons ($620 Billion)
Xe: 6,300 tons ($63 Billion)

Alternatively, the benefit of generating fuel, such as liquid hydrogen and liquid oxygen, on a NEA can be very high. A carbonaceous asteroid could be used as a refueling station for missions for any location out of Earth's gravity well. This would allow spacecraft to carry only enough fuel to reach the asteroid-refueling station rather than the entire flight. The fuel needed to get to its final destination would not need to be carried from the Earth's surface. It requires 1.7 Kg of extra fuel to get 1 Kg of fuel from LEO to outside of Earth's gravity well (assuming a delta V of 4.5 km/s). Thus, it costs $27,000 to get a single Kg of fuel out of Earth gravity well so it can then be used to accelerate your spacecraft.

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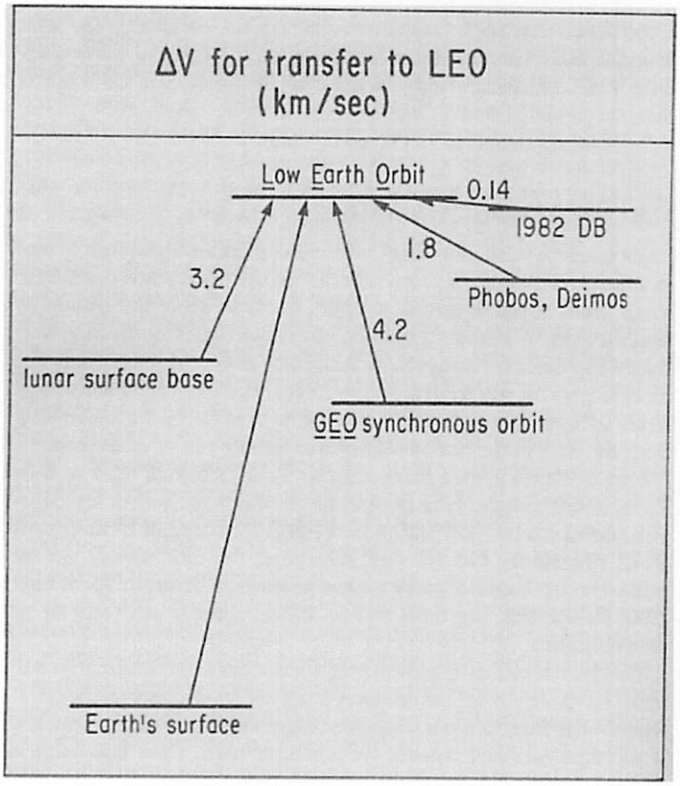

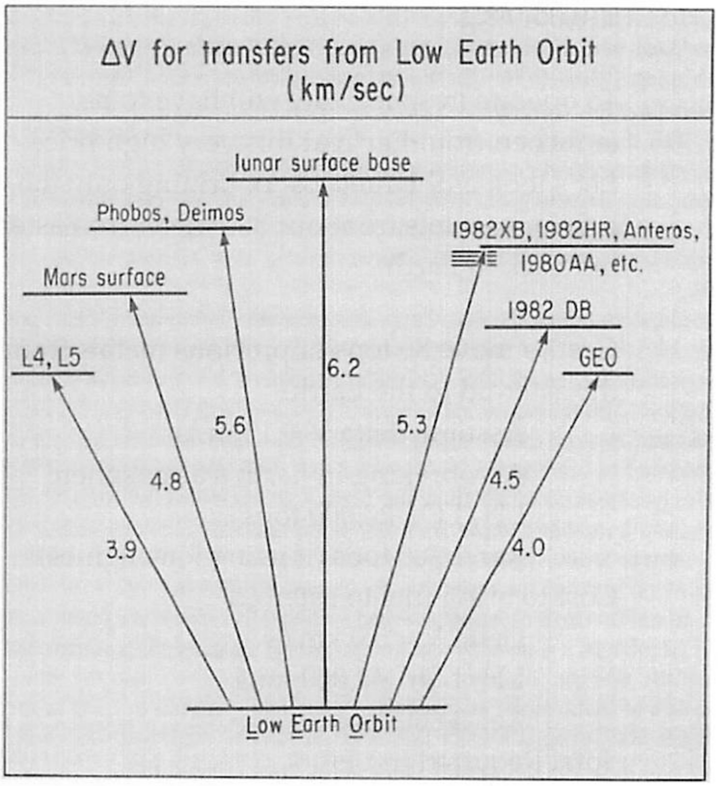

Is there Karst on Mars? Carbonates vs. Sulfates

"Indy" Keith Rodgers

Karst Topography on Mars

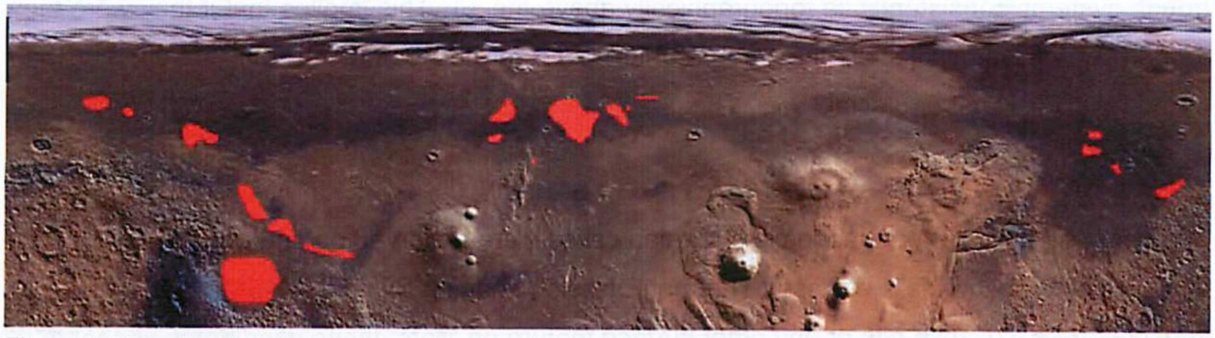

Figure 1: Map showing distribution of TT (red) in northern hemisphere (from [3]).

The Mars "thumbprint" terrain (TT), so called because of its resemblance to the lines and whorls of a human thumbprint, is observed on the northern plains and bears an uncanny resemblance to an uncommon type of karst terrain, formed under arid conditions, which is found in the Nullarbor Plain of Australia. It is reasonable to suggest that this morphological similarity is caused by a similarity in the underlying geology of the two regions. The TT is found on the northern plains, in what appears to be level, relatively low-lying ground, near the boundary between the plains and the highland terrain to the south. There are three major localities where the thumbprint terrain is found: in Arcadia Planitia, in western Utopia Planitia, and in eastern Acidalia Planitia. The terrain is typically found near the termini of large channels. Such areas are logical candidates for ancient sedimentary basins. The TT has been divided into three types: (1) discontinuous, parallel arcs of ridges and depressions, (2) curvilinear arrays of sleep-sided, flatfloored depressions, and (3) albedo markings with no discernable topographic expression [4].

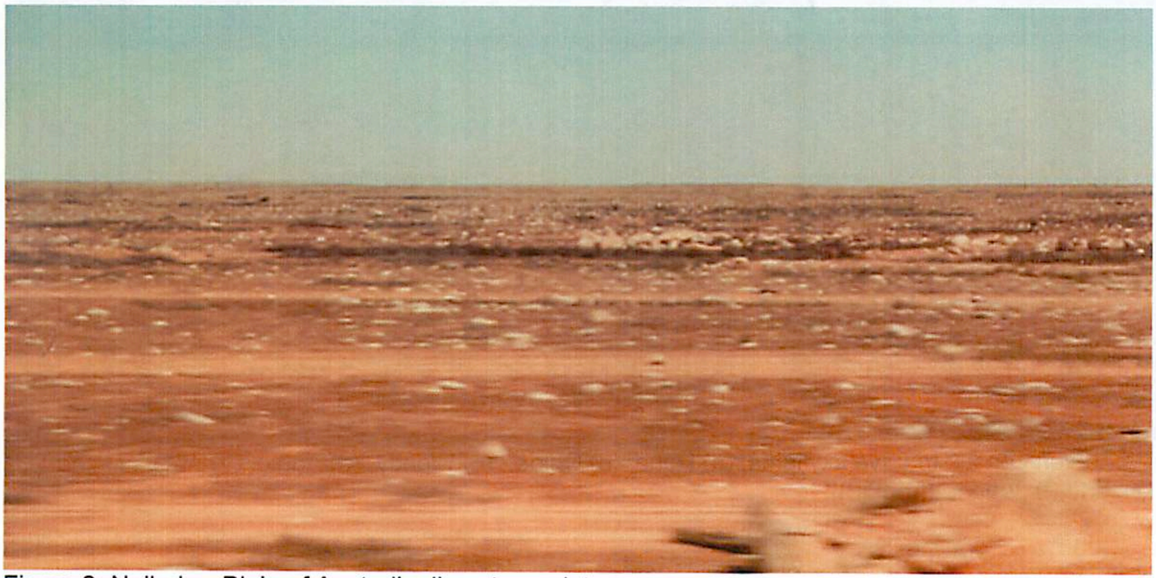

Figure 2: Nullarbor Plain of Australia, limestone plateau.

However, recent authors claim that the TT as well as the associated trough systems were formed by a glacial mechanism. Mars Orbiting Laser Altimeter (MOLA) data show that the trough systems consistently lie topographically above the TT. This implies that if they were they formed by the same glacier, the troughs must have formed before the glacier retreated and formed the TT. Karst or glacial?

Caves on Mars

Seven possible skylight entrances into Martian caves were observed on and around the flanks of Arsia Mons by the Mars Odyssey Thermal Emission Imaging System (THEMIS). Distinct from impact craters, collapse pits or any other surface feature on Mars, these candidates appear to be deep dark holes at visible wavelengths while infrared observations show their thermal behaviors to be consistent with subsurface materials. Diameters range from 100 m to 225 m, and derived minimum depths range between 68 m and 130 m. Most candidates seem directly related to pitcraters, and may have formed in a similar manner with overhanging ceilings that remain intact [2].

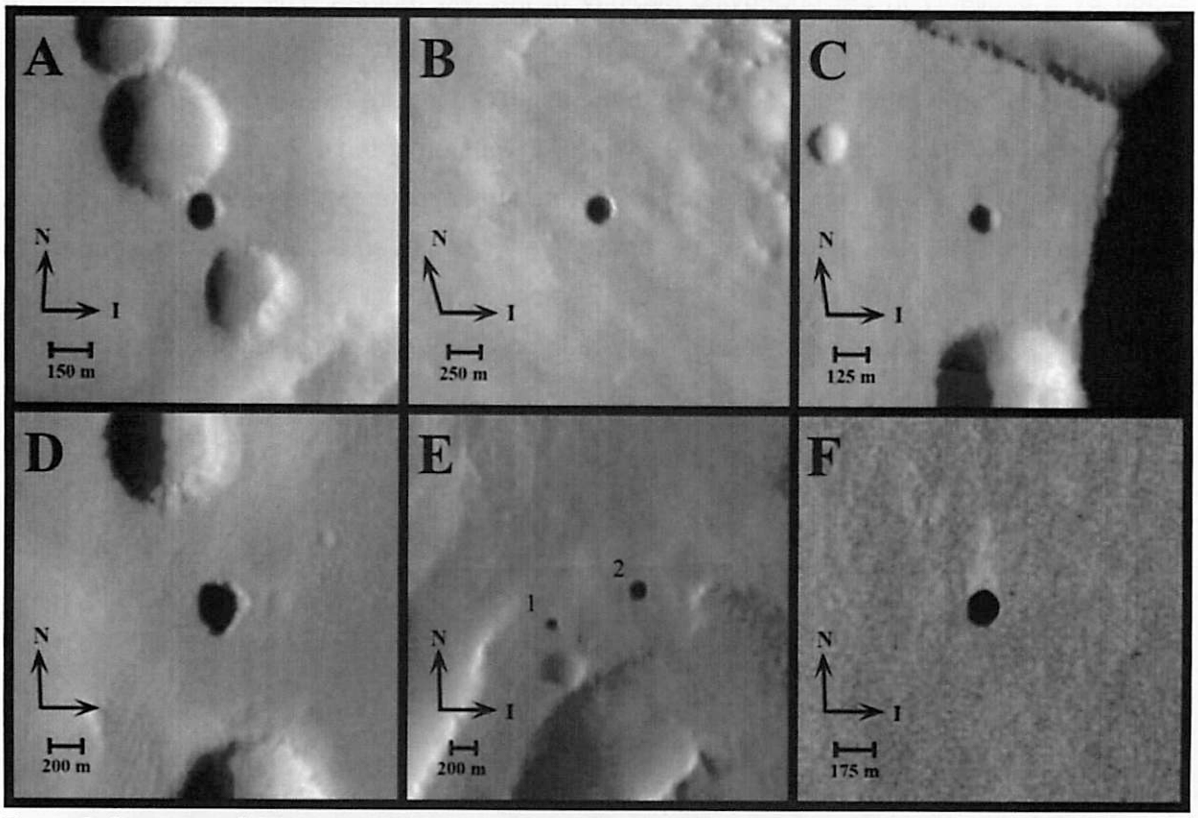

Figure 3: Seven candidate cave skylights: (a) Dena, (b) Chloe¨, (c) Wendy, (d) Annie, (e) Abby (1) and Nikki (2), and (f) Jeanne (from [3]).

Carbonates

It has been suggested that some of the missing CO_2 on Mars is tied up in carbonate deposits in the regolith, perhaps folded into the cratered uplands and covered by later volcanics, or forming large, flat-lying deposits in the region of Valles Marineris. Evidence from SNC meteorites indicates the possible presence of abundant crustal carbonates. Previous spectroscopic evidence indicates the presence of carbonates in atmospheric dust [3]. However, the lack of expected evidence of carbonate deposits from the Mars Orbital Camera (MOC) remains a mystery [1].

Sulfates

There is little doubt that liquid water has chemically altered the surface of Mars. Stacks of mixed sulfate-siliciclastic layers appear to be sands that were alternately saturated with water and cemented by its products. MOC and THEMIS images show that the exposed outcrops are merely a portion of light-toned sediments that are up to 800 m thick and several hundred thousand km^2 in extent and at least some of these layers have been identified as evaporitic salts. In particular, OMEGA has imaged spectacular layered sulfates in the Interior Layered Deposits (ILDs) of the Valles Marineris system. Near-IR spectral analysis shows a remarkable decrease in the hydration state of the sulfate as a function of altitude. While finding exposed sulfate-rich sediments on Mars is not a huge surprise, the attendant lack of evidence for carbonate deposits remains a mystery. Fundamentally, a body of water in contact with a carbon dioxide atmosphere should have laid down massive carbonates, as happened on Earth during the Archean. So where are the water-lain carbonates on Mars [1]?

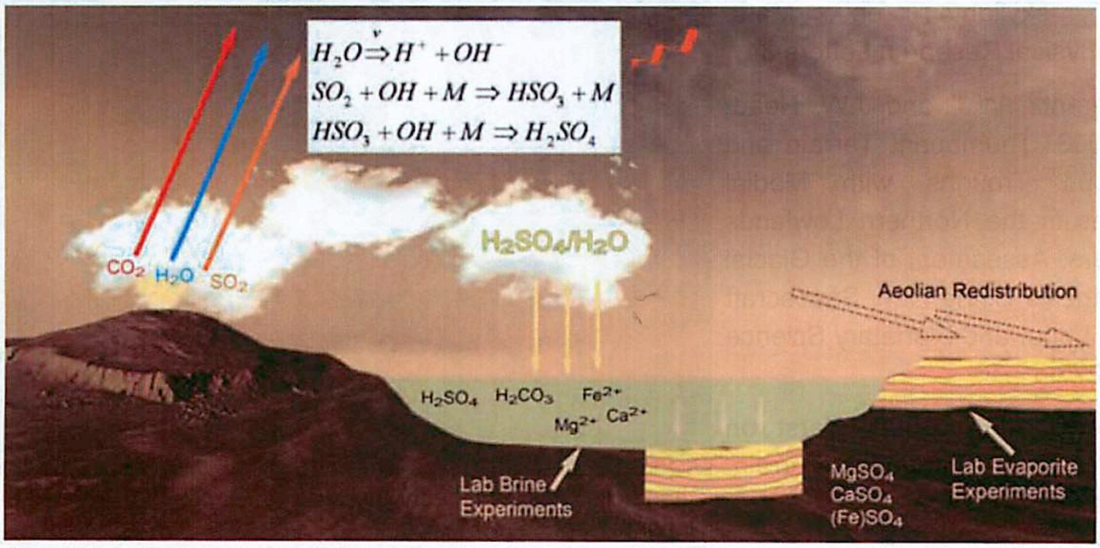

Figure 3. Atmospheric and aqueous conditions on early Mars that probably led to the existence of massive sulfate rich layers, but no water-lain carbonates (from [1]).

During the volcanic formation of Tharsis during the Late Noachian, large amounts of CO_2, H_2O, and SO_2 were outgassed. SO_2 was rapidly oxidized to H_2SO_4 in the humid atmosphere via photochemical reactions very similar to what happens on Venus today. Sulfuric acid rain from the photochemically produced clouds acidified standing bodies on Mars, allowing sulfates, but not carbonates, to precipitate. As long as volcanism allowed the production of sulfates and kept surface water acidic, carbonates could not form and the atmosphere was propped up. As volcanism waned, small amounts of carbonates formed in fractures and as a globally extensive patina on the surface of rocks, where it was subjected to erosion and incorporation into dust [1].

Karst or no Karst?

So what's the deal? If there's no carbonate, how could there be karst or caves on Mars? The answer is simple. Cave systems are not formed exclusively from carbonate materials. Any rock that is highly soluble in water can form karst and caves. Many large cave systems are formed from the dissolution of gypsum (calcium sulfate). Is there any of this material on Mars?

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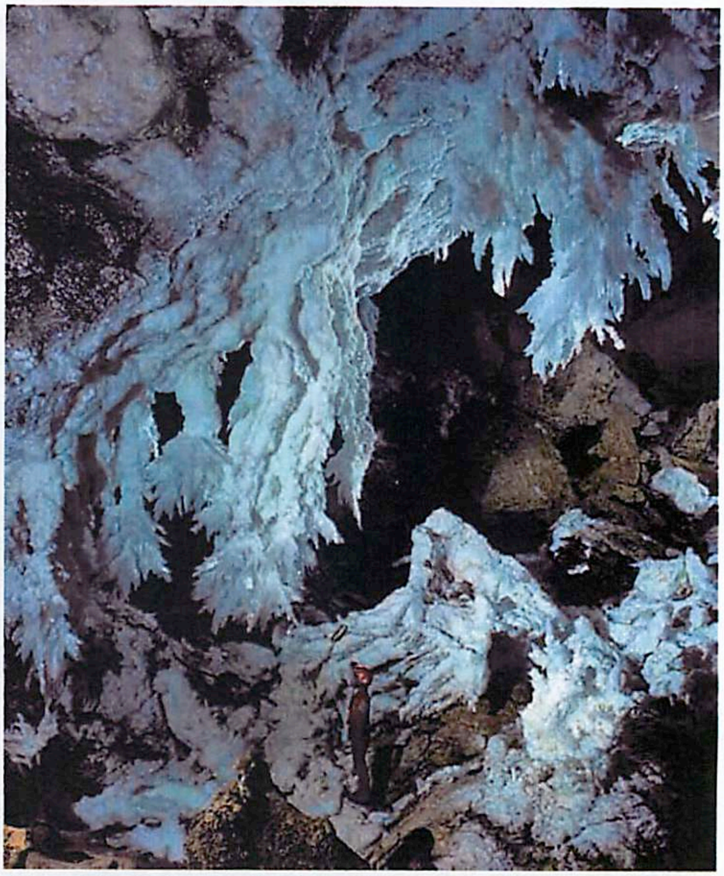

Chandelier Ballroom, Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico.
The largest known gypsum stalactites in the world, each tipped with a spray of gypsum crystals.

Colorado Plateau Uplift – Causes and Timing

Catherine Elder

1. Introduction

The Colorado Plateau is currently at an elevation of ~2 km and has a crustal thickness of 45 km (McQuarrie, 2000). Marine sediments on the plateau from the Cretaceous indicate that uplift could not have happened earlier than 65 Ma (Spencer, 1996). Gravity measurements show that the Plateau is close to isostatic equilibrium (Morgan, 1985).

2. Constraints on Timing

2.1 Paleobotany

The presence of fossils of plants that are known to grow at a certain elevation can be used to estimate the paleoelevation of the Colorado Plateau. The rate of uplift can be found by comparing the paleoelevation to the current elevation and using the age of the fossil. Fossil leaves in central Colorado indicate a paleoelevation of 2.4 to 2.7 km 35 Ma which suggests that the elevation has not changed much in the past 35 Myr (Spencer, 1996).

2.2 Vesicular basalt-derived paleoelevations

Sahagian et al. measured the paleoelevation of the Colorado Plateau using the vesicularity of basaltic flows (2002). They use X-ray tomography imaging to determine the size and distribution of bubbles throughout the lava flow. The size of vesicles (bubbles) at the top of the flow is only due to air pressure, whereas the size of the vesicles at the bottom is affected by air pressure and hydrostatic pressure from the lava Using the atmospheric pressure inferred from vesicle size and the standard atmospheric lapse rate, Sahagian et al. calculated the paleoelevation of the Colorado Plateau. To test the method, they looked at nine samples from recent Hawaiian flows at a range of elevations and found that the method was reliable to ±400m. They applied the method to the Colorado Plateau by sampling basalts from four regions around the perimeter of the plateau (figure 1). They found the amount of uplift by subtracting the paleoelevation from the current elevation. The results (figure 2) show slow uplift of ~40 m/m.y. Between 25 Ma and 5 Ma (800 m uplift total during that time) and rapid uplift of 220 m/m.y. Since 5 Ma (1100 m total).

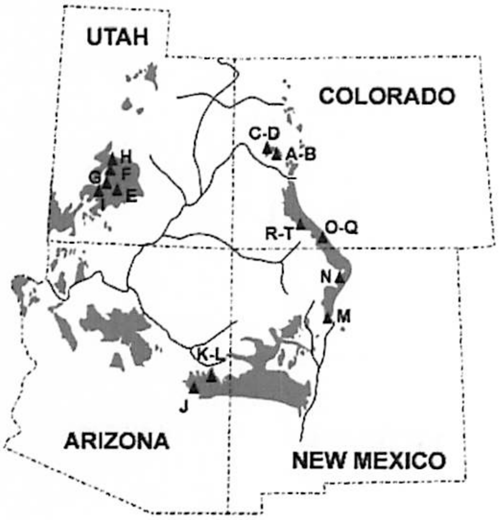

Figure 1

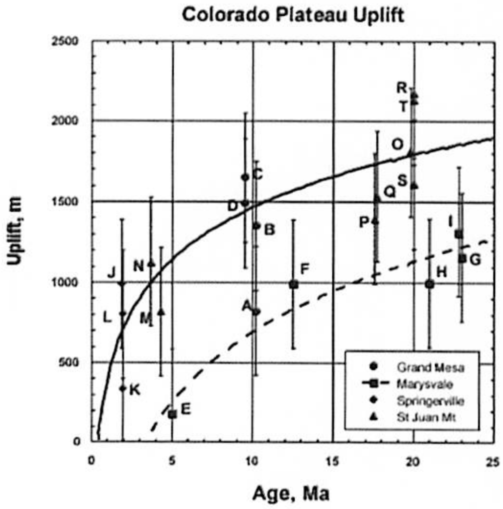

Figure 2

3. Causes of Uplift

3.1 Intracrustal Flow

McQuarrie and Chase (2000) propose that pressure from nearby mountain building cause intracrustal flow that thickened the crust and isostatically raised the Colorado Plateau. If the crust was ~30 km thick and isostatically balanced at sea-level, addition of 14.5 km of crust would lead to the currently observed 2 km elevation of the Colorado Plateau (figure 3). This crustal flow would require a 30 km decrease in the crustal thickness of the Sevier Plateau (McQuarrie, 2000).

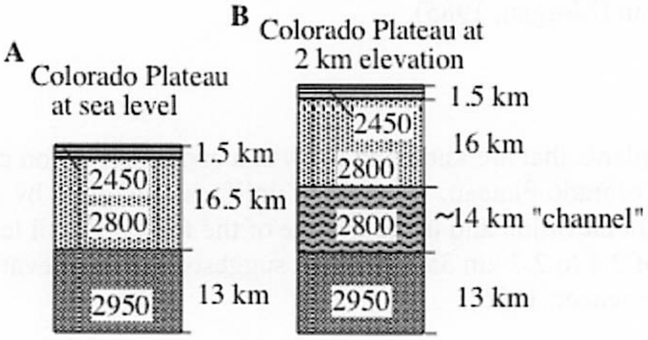

Figure 3

Figure 4 shows the crustal evolution of the Colorado Plateau and Basin and Range region as proposed by Mcquarrie and Chase. The region transitions from the Seivier plateau with a crustal root to present day structure because of intracrustal flow. Thickening the Colorado Plateau by crustal flow preserves the isotopic and geochemical signatures of the Proterozoic crust and upper mantle.

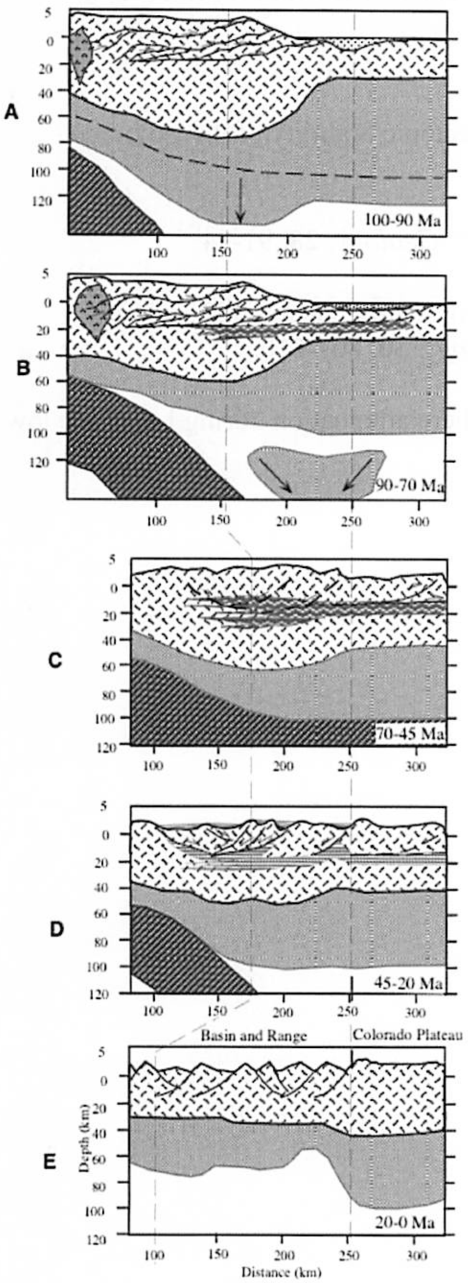

Figure 4

3.2 Delamination of Lithosphere

Bird proposed that low-angle subduction displaced the mantle lithosphere beneath southwestern North America, and the slab fallback in the mid-Tertiary caused upwelling of the asthenosphere to the base of the crust which caused the uplift of the Colorado Plateau. This method of uplift is inconsistent with observed isotopic signatures and Pn velocities that indicate a cool mantle lithosphere below the Colorado Plateau (Spencer, 1996). However, Spencer used finite element heat flow calculations to show that low angle subduction can generate the required uplift if 120 km of mantle lithosphere is tectonically removed from an initally 200 km thick lithosphere (1996). The original lithosphere that remains can account for the observed isotopic signature, and it is consistent with Pn velocities in the upper mantle below the Colorado Plateau.

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Caliche: Carbonate Deposit or Salvadorian Rap Group?

PtyS 594a, Fall 2008: Water, Chemistry and Fire
Brian Jackson

What is caliche?

> "… a calcareous [containing calcium carbonate] formation of considerable thickness and volume found a few inches or a few feet, beneath the surface-soil."
> --Reeves (1976)

> "…a collection of slang words that originated in El Salvador….Caliche employs techniques of Nahuatl word construction, such as combining parts of two words to form a new one."
> --Wikipedia

Figure 3-1. Soft powdery caliche in situ, Western Transvaal, Southwest Africa (courtesy F. Netterberg).

What does caliche look like?

Caliche can take on a wide variety of forms. Photographs from Reeves (1976).

Figure 3-10B. Caliche nodules in Estosha Game Preserve, Southwest Africa (courtesy F. Netterberg, 1973).

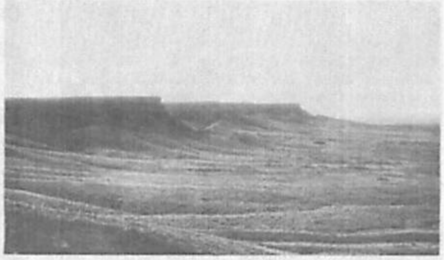

Figure 3-2. Massive cliff outcrop of hard indurated caliche, western escarpment of the Southern High Plains, New Mexico. The caliche forms the upper part of the escarpment, the lower part being draped by eroded fluvial sands and eolian sands (courtesy of W. Armstrong Price).

Figure 3-12. Caliche plates formed on West Texas caliche.

Figure 3-16B. Exhumed root casts on San Miguel Island, California (courtesy D. W. Johnson).

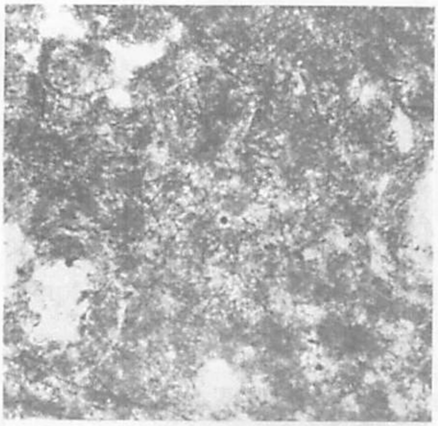

Figure 3-17. Fungal borings (thin dark, randomly oriented lines) in caliche from Isla Mujeres, Yucatan, Mexico. Bar scale = 200 μ (courtesy W. C. Ward).

How does caliche form?

Weathering of silicate rocks consumes 2 moles of CO_2. Precipitation of $CaCO_3$ releases 1 mole of CO_2, for a net loss of 1 mole of CO_2 from the atmosphere.

$2CO_2 + 3H_2O + CaSiO_3 \rightarrow H_4SiO_4 + 2HCO_3^- + Ca^{2+}$
$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2$

On the other hand, dissolution of carbonates consumes a mole of CO_2, but releases the same amount when the carbonate re-precipitates.

In dry environments, HCO_3^- sticks around, allowing re-precipitation of carbonates, but in wet environments, HCO_3^- washes into lakes and rivers, and eventually into the ocean, thereby preventing re-precipitation of carbonates (Nordt et al. 2000).

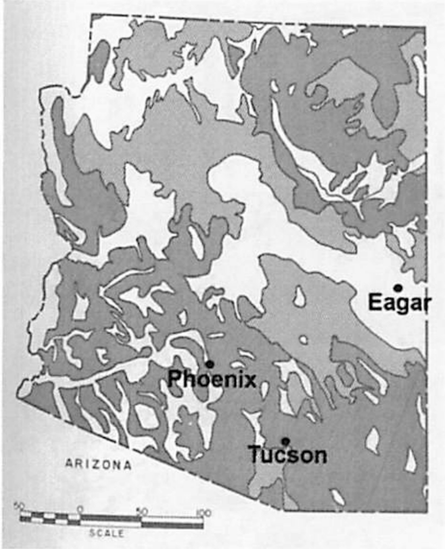

Figure 1: Probable distribution and types of caliche in AZ, based on soil-types. Caliche is: indurated (fine dots), soft to nodular but not necessarily continuous (coarse dots), soft discontinous (slant lines), and silicified (X's). From Reeves (1976).

Where is caliche found?

All over the world, anywhere conditions are dry enough that water does not wash away dissolved salts, like arid and semi-arid regions.

How does carbon content of Earth's soil compare to atmosphere?

Earth's atmosphere contains about <u>750 Pg of C</u> (Nordt et al. 2000).

Table 2. Estimates of carbon pools in world soils

Pool	0-30 cm	0-100 cm	0-200 cm
		Pg C	
Soil organic C (SOC)	684-724	1462-1548	2376-2456
Soil carbonate C (SIC)	222-245	695-748	–
Total	906-969	2157-2296	–

Modified from Batjes, 1996.)

Table 1: From Lal & Kimble (2000).

Planetary Connection

Carbonate deposits are rare on Mars, which is puzzling since there is so much evidence that Mars was once wet. However, carbonate deposition may have been inhibited by low pH or low pressure of CO_2 in the atmosphere.

The carbon cycle may also operate on extra-solar terrestrial planets. Evidence for the carbon cycle and carbonate deposition may be present in the atmospheric compositions.

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The Chemistry of Earth's Early Atmosphere

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Abstract The early Earth's atmosphere's (before ca 2.3 Ga) components has been investigated and inorganic weathering reactions related to carbon cycle among atmosphere, continents and ocean are analyzed to explain their influence to the early Earth's atmosphere.

Components of Early Atmosphere

It is speculated that the atmosphere of the Earth might originate from the volcanic eruption (degassing process) to initially bring nitrogen, carbon dioxide and methane from the internal Earth when the planetary Earth accreted enough mass to hold them (Alfven et al 1976). Water, which might be from comets and asteroids from the outer solar system, is another component as water vapor in the atmosphere.

From the star evolution theory, the Sun's irradiance would be significantly less than that today prior to ca 2.3 Ga (Gough 1981) which would freeze water on Earth with the same concentration of greenhouse gases in the atmosphere as today. However, geological evidences of sedimentary rocks require flowing water since even earlier time in the history of Earth. This contradiction (faint young sun paradox, *Sagan and Mulle 1972*) shows that the concentration of greenhouse gases in early earth's atmosphere should be much higher than present level to sustain the necessary temperature for the existence of flowing water (Kasting 1993, Pavlov et al 2003). Actually the carbon dioxide's partial pressure was estimated as high as 10 bars (Walker, 1985).

From the mass-independent sulfur isotope fractionation (Farquhar et al 2001, 2002) provides evidence of the trace amount of oxygen or even anoxic environment in early Earth's atmosphere, which could favor another greenhouse gas methane's existence without fast oxidization in early Earth's atmosphere.

Therefore, the ancient atmosphere could be composed mainly of nitrogen, carbon dioxide, water vapor, some methane and only trace amount of oxygen, if any, before ca 2.3 Ga (*Wiechert 2002*).

Inorganic Carbon Cycle

Carbon is reserved in carbonate in rocks, resolved in ocean water, in carbon dioxide in atmosphere, and in organic matters. Among these reservoirs, carbonate in rocks reserves most of

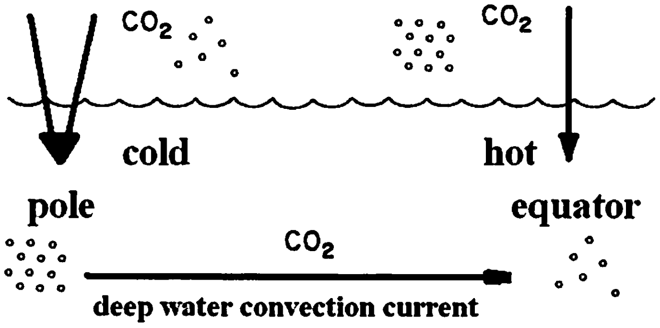

Fig. 1. Schematic representation of the global exchange of carbon dioxide between atmosphere and ocean

the carbon on Earth. Because of the trace amount of oxygen and hence the inexistence of organic carbon reservoir, inorganic carbon cycle could be the only way for carbon to affect the composition of the early Earth's atmosphere.

Firstly consider physical cycle of the. It is between the atmosphere and the ocean. As the solubility of carbon dioxide decreases with higher water temperature, the pole region sea water could contain more than that of the equator. With the deep water current, the excess carbon dioxide would be transported to tropic region and then return to the atmosphere (Budyko et al 1985). This cycle does not change the bulk concentration of carbon dioxide in the atmosphere.

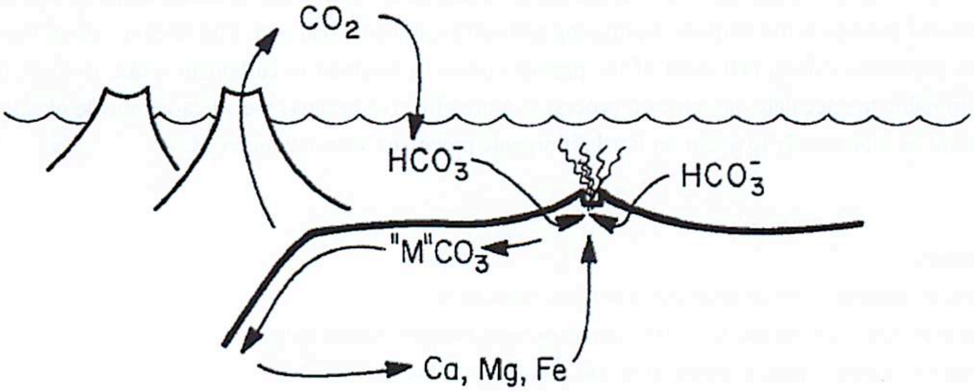

Fig.2. Geochemical carbon cycle on early Earth with no continents, From Walker 1985.

Secondly consider the chemical cycle. Carbon dioxide would undergo the following chemical exchange in the ocean

$$\mathbf{CO2 + H2O \leftrightarrow HCO3(-) + H(+)}$$

Carbonates on the seafloor could be weathered by the carbon dioxide dissolved in the sea. For example

$$\mathbf{CaCO3 + CO2 + H2O \leftrightarrow 2\,HCO3(-) + Ca(2+)}$$

And then carbon dioxide would be released by volcano back to the atmosphere. The whole process is as figure 1. If the ocean is frozen, there would be net increase of carbon dioxide's partial pressure in the atmosphere by the volcanic eruption, which will enhance the greenhouse effect and thus give rise to the global warming and ice melting.

On the other hand, if the continents emerged on surface Earth, rocks exposed to the atmosphere

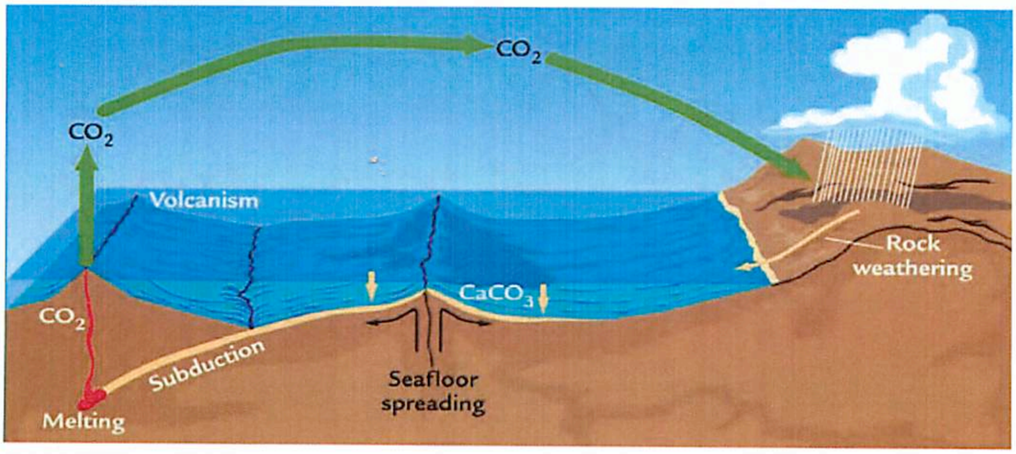

Fig. 3. Full geochemical carbon cycle. From online lecture notes

would undergo another important inorganic weathering, the silica-carbonate reaction which will convert silicate rocks to carbonate. For example

$$CaMgSi_2O_6 + CO_2 \leftrightarrow MgSiO_3 + CaCO_3 + SiO_2$$

So the reaction will remove the carbon dioxide input in the atmosphere. The whole picture, shown as figure 3, is that carbon dioxide would be removed from atmosphere by chemical weathering, deposited in ocean sediments, subducted and returned by volcanism. In the absent of organic activities, this might be the whole carbon cycle picture at the early Earth era.

In a word, as for the Atmosphere, the input of carbon dioxide is the volcanic eruption and the removal process is the seafloor weathering and silica-carbonate reaction. The relative rate of these two processes. Given that most of the present carbon is reserved in carbonate rocks, it might be reasonable to speculate the removal process is more effective because the silica-carbonate reaction would be more easily to occur on Earth, if organic processes are not concerned.

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Mechanisms of Pyroclastic Eruptions

Kat Volk

Three Basic Stages of the Eruption

(1) The growth of gas bubbles in the magma leads to fragmentation of the magma into discrete blobs of melt in the expanding gas.

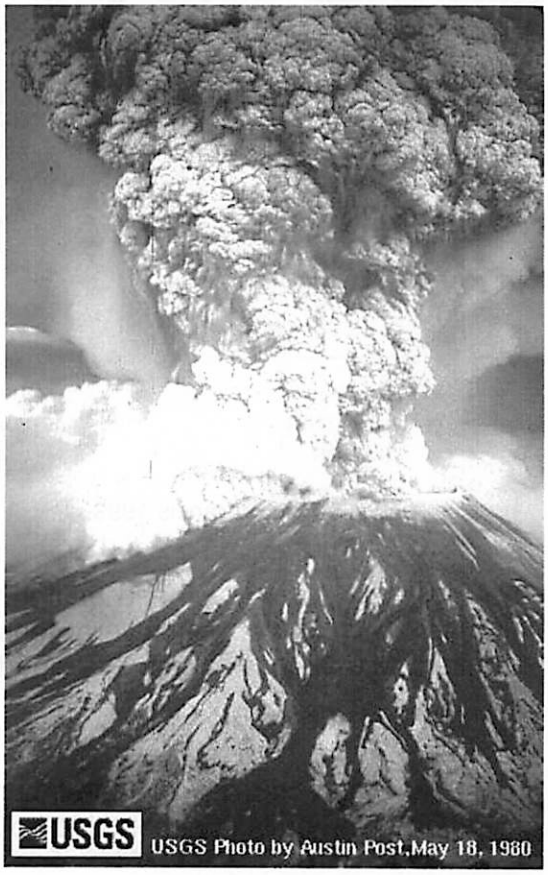
(2) Magma fragments are blasted through the vent at high velocities.

(3) The eruption column rises, driven by the energy of the eruption.

Driving Factors

The eruption is driven by the thermal energy stored in the magma. The thermal energy is converted to kinetic energy by the expansion of gasses in the magma.

The nature of the eruption is governed by the viscosity of the magma, the volatile content of the magma (and ground water interactions), the eruption rate (mass per unit time), the ejection velocity, and the confining pressure of the atmosphere.



USGS Photo by Austin Post,May 18, 1980

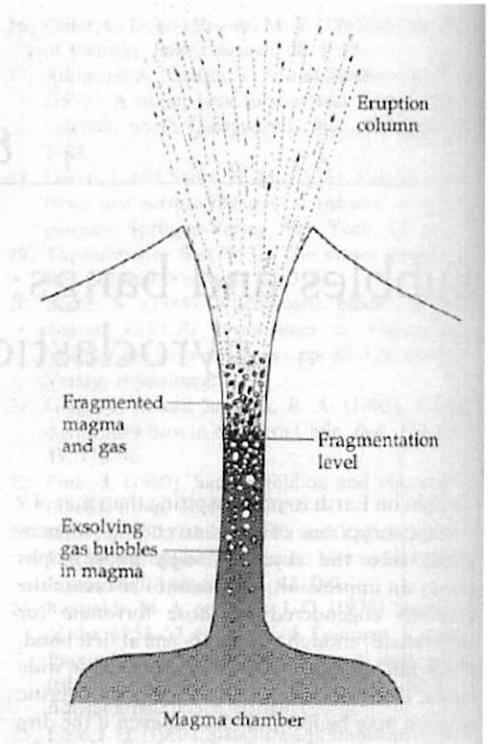


Figure 8.1 from Francis 1993

Plinian Eruptions

Eruptions characterized by sustained jets of material that last for minutes to hours.

A key feature is that the gas bubbles rise at about the same rate as the magma. This can happen for highly viscous magmas where the gas can't move quickly through the magma or for low viscosity magmas that rise too quickly to allow for the gas bubbles to rise relative to the magma.

The velocity of material being erupted is on the order of several hundred meters per second.

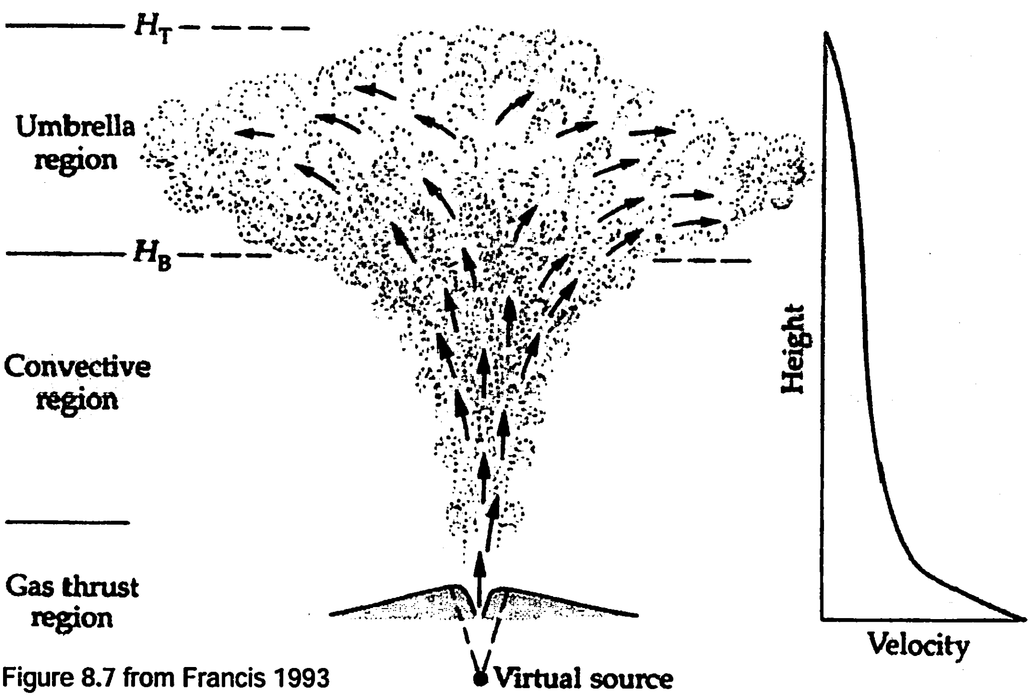


Figure 8.7 from Francis 1993

The eruption column will rise until its density is roughly equal to that of the surrounding atmosphere (this can be several tens of kilometers on Earth). It then expands outward forming a mushroom or umbrella cloud.

Strombolian Eruptions

Eruptions characterized by short bursts of activity repeated at intervals of seconds to hours.

Unlike the plinian eruptions, the magma is rising very slowly (at a few meters per second) so the gas bubbles rise through the magma and accumulate into larger pockets. The pockets can be a few meters across with internal pressures of a few bars.

When these gas bubbles reach the surface of the vent, the rapid expansion of the gas causes the magma and gas to explode upwards.

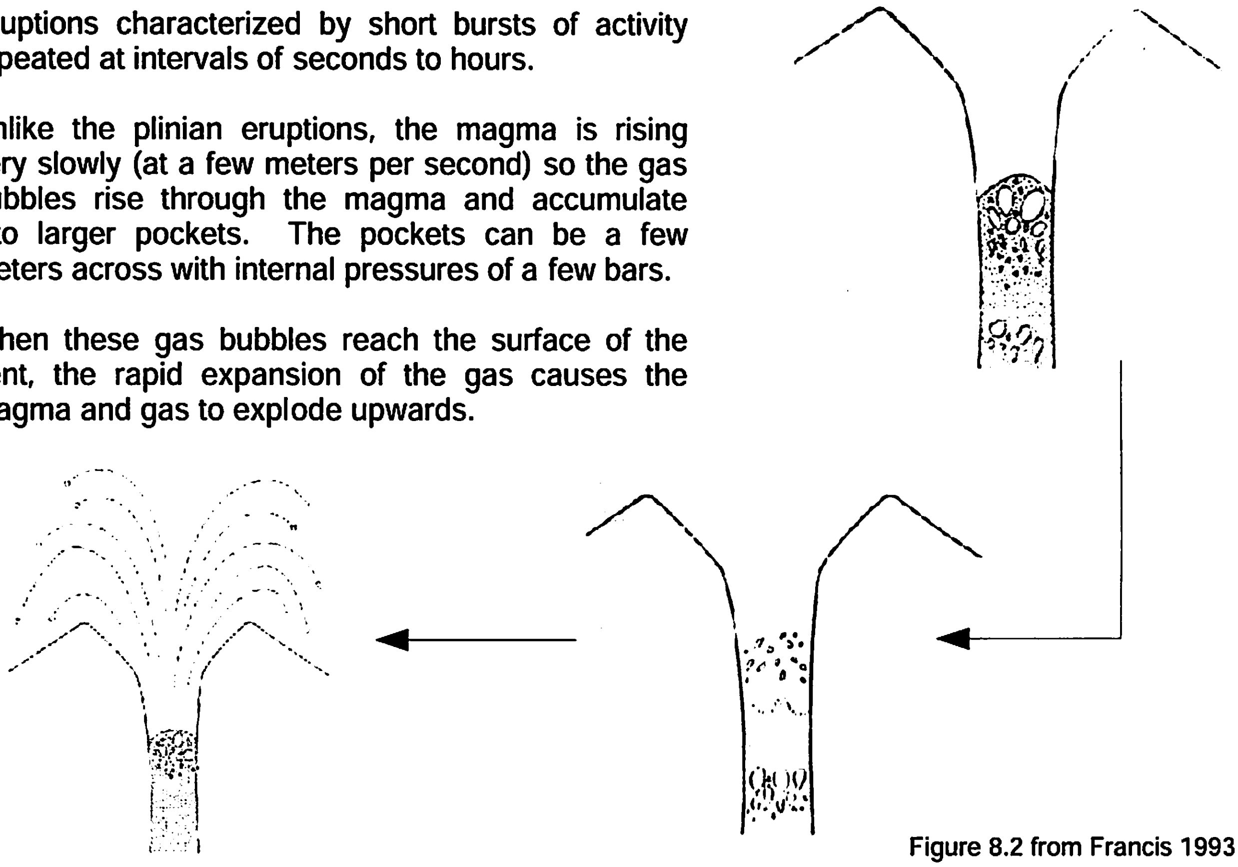
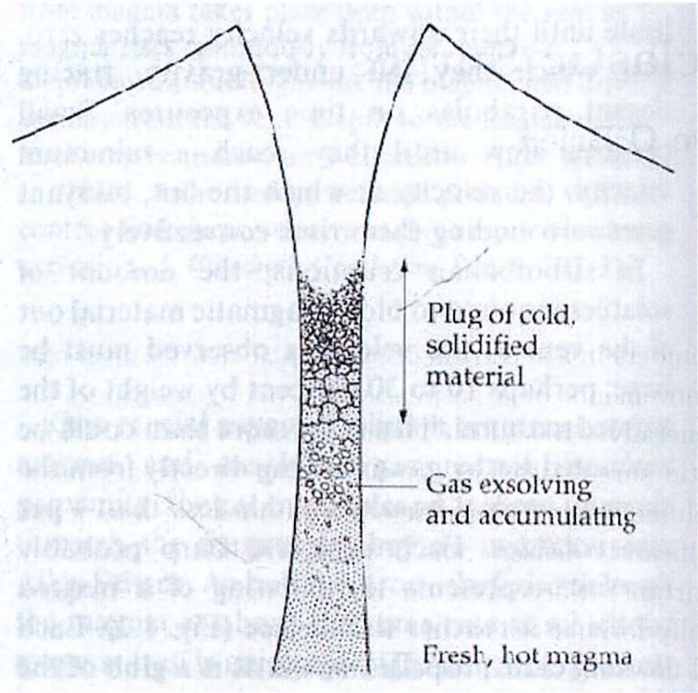


Figure 8.2 from Francis 1993



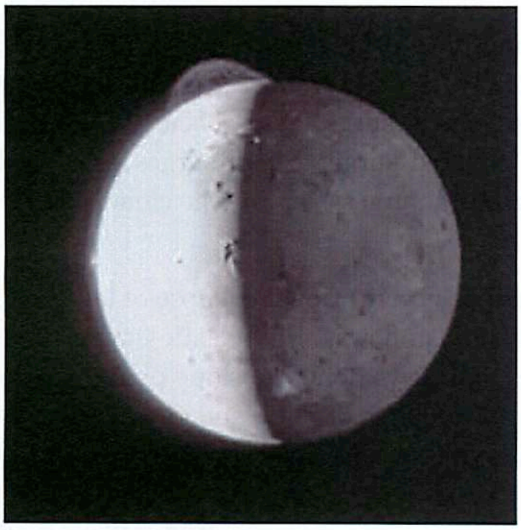
Vulcanian Eruptions

These are discrete eruption events that occur at minute to hour intervals.

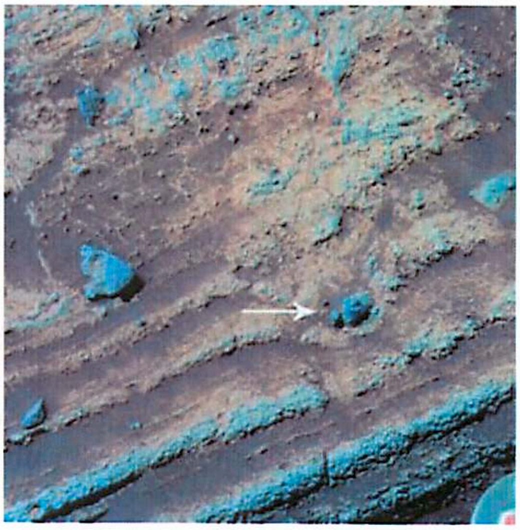
They differ from strombolian eruptions in that the ejected material is mostly a cooled lava plug from the top of the vent. The gas pressure that drives the eruption originates at greater depth. Once the pressure exceeds the strength of the lava plug, the eruption occurs.

Ground water seeping into the vent can greatly contribute to the gas pressure.

Planetary Connection



Eruptions on Io (lpi.usra.edu)



pyroclastic deposits near Home Plate on Mars (cornell.edu)

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The Physics of Pyroclastic Surges and Flows

Dave O'Brien

Description

Pyroclastic surges and flows are two end-members in a spectrum of pyroclastic density currents. These 'pyroclastic density currents' are movements of a suspension of pyroclastic material (fragments of volcanic rock) and hot gas (generally ~100-1000 C) which emanate from a volcano and move along the ground. A 'pyroclastic surge' is a low-density turbulent suspension of particles in a gas (few percent solids by volume, such that particle interactions are minimally important), and a 'pyroclastic flow' is significantly denser (tens of percent solid content, such that interactions between particles are important). Surges often move at a higher velocity than flows, due to differences in how they generally form. Because of the differences in velocity and the amount of suspended solids, surges and flows move and deposit material differently.

How are they formed?

Pyroclastic surges are often formed when magma comes into contact with water, and literally explodes, creating a 'base surge' that spreads out radially. A 'lateral blast', in which a magma chamber is suddenly decompressed, can create a pyroclastic surge. This occurred when the flank of Mt. St. Helens collapsed, and resulted in a directed surge. Small surges can also be formed at the leading edge of a pyroclastic flow ('ground surges') or in ash clouds above a pyroclastic flow ('ash-cloud surges').

Pyroclastic flows are formed by several main processes. Gravitational collapse of lava domes which are forming on a slope leads to so-called 'block-and-ash flows.' Pyroclastic flows can also form when all or part of an eruption column collapses and flows done the slope of the volcano. The collapse of an eruption column can be due to a widening of the vent or a decrease in pressure driving the column upwards. Finally, a 'boil-over,' or sustained low fountaining from a vent, can drive long-duration flows.

On Earth, pyroclastic flows and surges are generally associated with silicic volcanism, which by nature is generally more violent and explosive, although basaltic volcanism can produce surges and flows as well, for example by the interaction of magma with groundwater.

How do they move?

Flows can travel 100-200 km/hr, and surges can exceed 500 km/hr. Due to their higher velocity and lower density, surges can move over topography, while flows tend to follow pre-existing

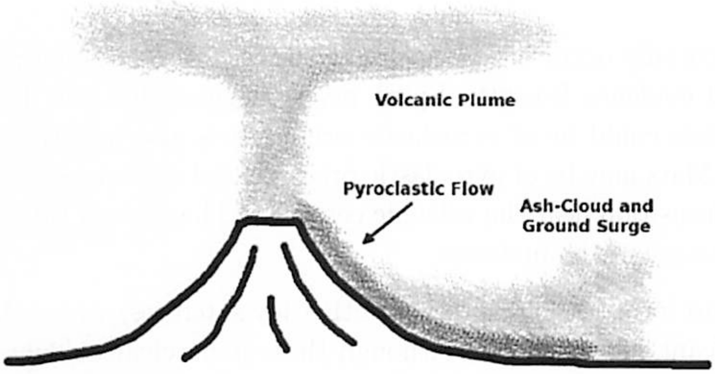

Figure 1: Diagram illustrating a pyroclastic flow produced by the partial collapse of an eruption plume. An ash-cloud surge and a ground surge form at the top and leading edge of the flow, respectively.

topography, such as valleys. Surges can travel up to about 25 km from their source volcano (further if they are ground surges or ash-cloud surges associated with a flow), and pyroclastic flows can travel over 100 km from their source. When the momentum driving the flow or surge outwards from its source decays, the surge or flow may loft into the air as a 'phoenix plume' which can stop the flow or slow it somewhat.

Surges tend to transport material primarily by turbulent suspension, while in the more dense pyroclastic flows, processes such as particle-particle collisions are more important. Because of this, flows tend to have a well-defined boundary below which the particle density is large and above which it is more diffuse, while in surges there is no such boundary, although the particle density is generally somewhat larger nearer to the ground.

How do they deposit material?

Both surges and flows generally transport and deposit 1-10 km^3 of material, although smaller ones can occur, and the largest flows can transport thousands of km^3 of material. Surges tend to give a relatively uniform thickness deposit, while flows tend to preferentially fill in topographic lows. Surges tend to form thin, sorted, finely bedded deposits, while flows generally give massive, poorly sorted deposits consistent with deposition from a dense suspension. Flows can carry larger particles due to their higher density, and can transport and deposit particles tens of centimeters to meters in size.

Surges and flows in the Chiricahuas area

The Rhyolite Canyon Tuff, as well as other deposits in the Chiricahuas area, were emplaced primarily as pyroclastic flows, interspersed with surge and airfall deposits. 27 My ago, the Turkey Creek Caldera erupted roughly 500 km^3 of material, producing deposits over 500 m thick in some areas, particularly in the paleobasin north of the caldera which is now the Chiricahua National Monument.

The planetary connection

Pyroclastic flows and surges can potentially occur in association with volcanism on other planets. Geochemical and morphological evidence from the Spirit rover suggests that the 'Home Plate' feature in Gusev Grater on Mars could be of pyroclastic origin. It is also hypothesized that the Medusa Fossae formation of Mars may be of pyroclastic origin, based on factors such as its location in the highland-lowland transition near the volcanic centers of Tharsis and Elysium, and the apparently easily-erodable nature of the material.

'Cryoclastic' flows and surges could form (eg. on Europa or other icy satellites) where there is icy volcanism involving the significant release of gas, although there is no clear evidence of such features to date. It has been hypothesized that the depressurization of CO_2 reservoirs on Mars could lead to cryoclastic flows that could explain flow features such as the large outflow channels and small gullies without having to invoke liquid water. Recent evidence, however, seems to favor liquid water.

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Discovery and Exploration of the Mogollon Mountains

Andrea Philippoff

A summer storm over the Mogollon Mountains. Photo by Bob Ingraham, 1962.

Introduction

To understand what Mogollon is like, you need only pronounce the name correctly. If ever there was an onomatopoedic place name, this is it. Say it this way: Muggy-own. Now close your eyes and picture a small mining camp with a stream running down the middle, smell the fresh wet earth on your sneakers, feel the cool, damp air around you. Welcome to Mogollon.

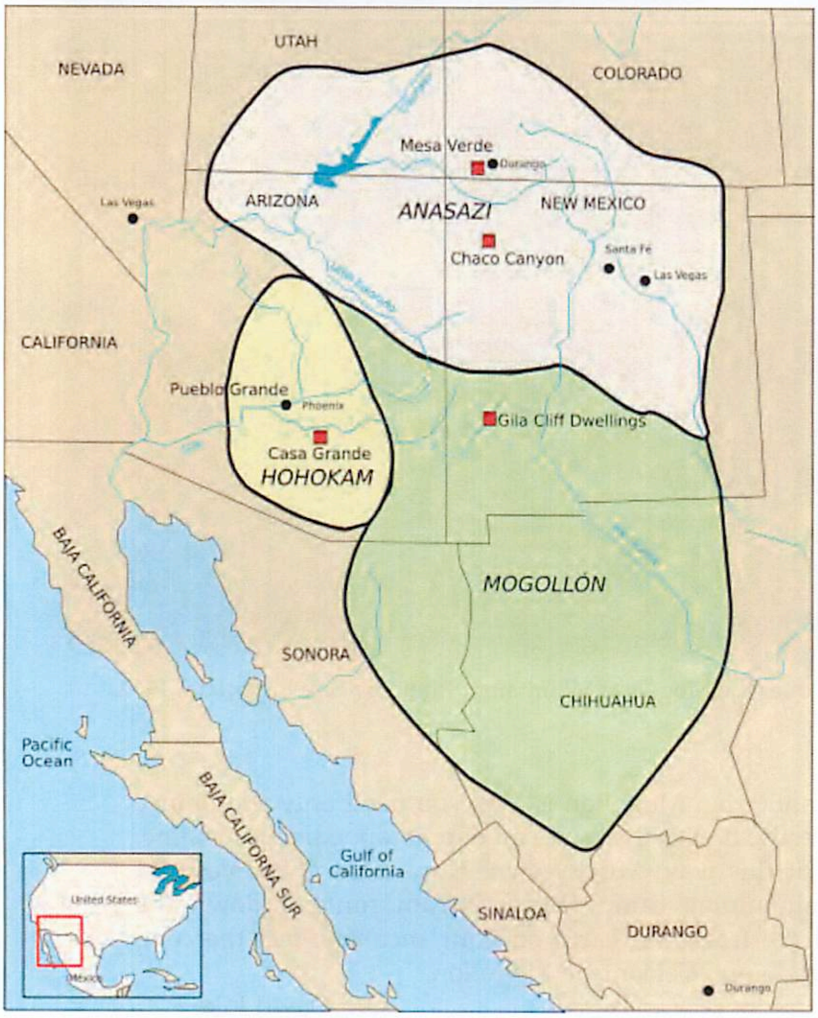
David Pike

Discovery

The initial discovery of the Mogollon Mountains is not documented in any records I could find. Perhaps it is still passed down as stories among the descendants of the first people to set foot on the forested mountain masses, intricately carved by nature's most talented sculptors: wind, water, ice, and time. Perhaps the greatest grandchildren of the first to hunt and build and celebrate and mourn in the hidden acres still hear tales of what it was like to travel to this unknown land and make it home. Unfortunately, I could not find these stories of triumphs and perils, of life and death, of discovery and establishment.

I did find records of the first Caucasians who arrived on the scene, touting their writing implements as well as their guns, proclaiming that they had "discovered" a new land. But recognize, that though we may have been the first to publish our travels, we were not the first to live on, breathe in, or explore these mighty mountains (Hibben, 1946).

Ancient Cultures



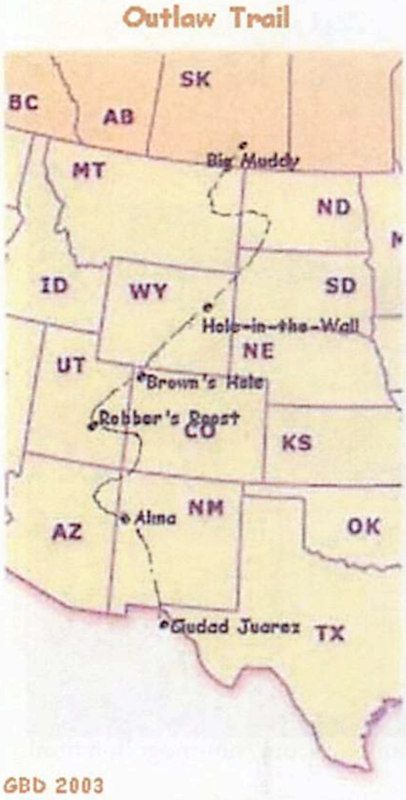
Ancient extent of Anazazi, Hohokam, and Mogollon cultures. Note the location of the Gila Cliff Dwellings, a type locality of Mogollon culture. This prehistoric culture was active between AD 150 and AD 1300 or 1400. Photo credit http://en.wikipedia.org/wiki/Mogollon_culture.

There's Gold in Them Hills!

Mogollon Mine and Mill, 1940. Photo credit www.legendsofamerica.com/nm-mogollon.html.

Cinco de Mayo in Mogollon, 1914. Photo credit www.legendsofamerica.com/nm-mogollon.html.

A Rough-and-Tumble Past



Left: Diagram of the Outlaw Trail. This trail connected favorite hideouts of the gang the Wild Bunch, including Big Muddy in Canada, Brown's Hole in Colorado, Robbers' Roost in Utah, Whitewater Canyon near Alma, New Mexico, and may have even reached to Ciudad Juarez in Mexico.
Photo credit
http://www.wyomingtalesandtrails.com/butch3.html.

Below: The Wild Bunch, seated left to right: Harry Longabaugh (a.k.a. the Sundance Kid), Bill Kilpatrick, Robert L. Parker (Butch Cassidy). Standing: Bill Carver, Harry Logan (Kid Curry). Photo taken in Fort Worth, Texas, 1900.
Photo credit
http://library.thinkquest.org/04oct/01737/pages/butchcassidy.htm.

Ghost Town

All that remains of the Mogollon saloon. Mogollon, New Mexico. Photo by Geoff Dobson.

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G. B. Dobson; January 6, 2004

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David Pike

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Using Precariously Balanced Rocks as Paleoseismometers

by David “Rock-Tipper” Choi

The Concept

A precariously balanced rock (PBR) is defined as a large boulder that is perched in a unique position on a ledge or outcrop and could theoretically be toppled or tipped over if exposed to ground accelerations from seismic events. PBRs are used to constrain the timing of the last significant seismic event, as the existence of a PBR proves that an earthquake of sufficient magnitude has not happened in the area for some time. Surface exposure dating techniques such as desert varnish analysis and cosmogenic ^{36}Cl help estimate an age for the rock’s exposure.

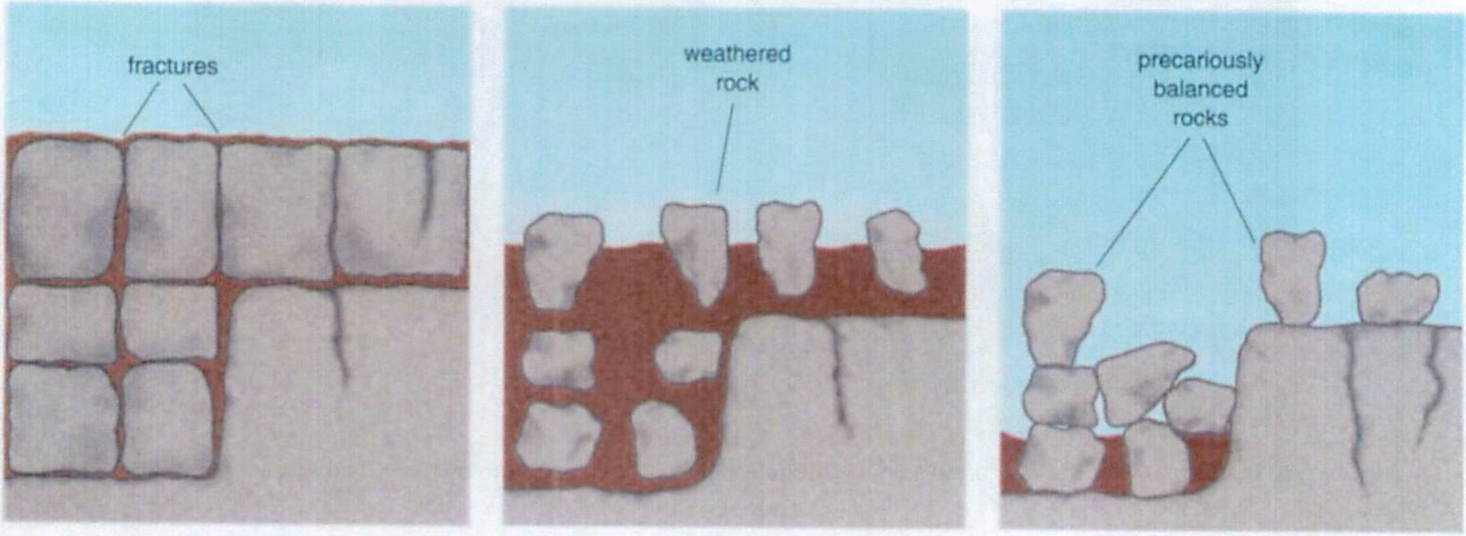
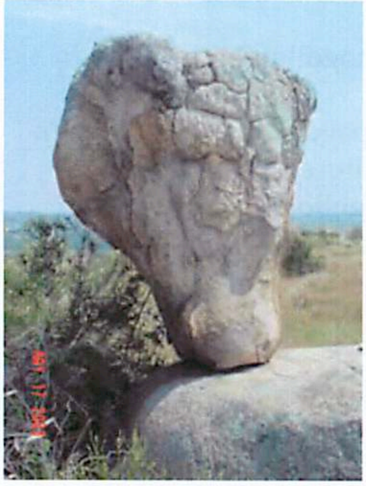
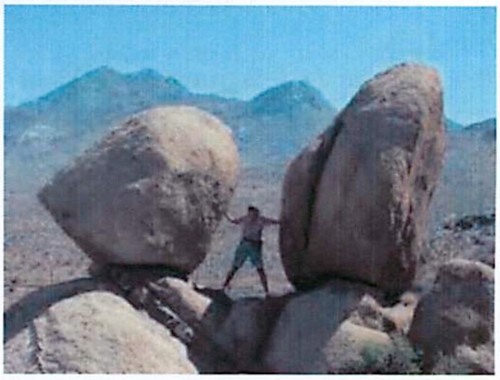


Figure 1. Formation of precariously balanced rocks. (Left) From fractured bedrock, erosion occurs when water permeates through the cracks and weathers the minerals. (Middle, brown) The grüs (loose material) resulting from the weathering begins to erode. (Right) Eventually, solid boulders settle on one another, possibly precariously balanced.

Examples

SE of Riverside, CA





outside Kelso, CA

Application

The study of PBRs is an opportunity to test seismic-risk hazard models and further refine their predictions about the risk and magnitude for such events. These models are important for building new structures and/or retro-fitting old structures in earthquake prone areas such as Southern California. PBRs can be thought of as long-term "witnesses" to the seismic history of an area, as modern seismograph measurements only extend to the past 100 years. PBRs can extend that history by 1-2 orders of magnitude, perhaps even more. PBRs can also be used to refine models of ground motion during earthquake events.

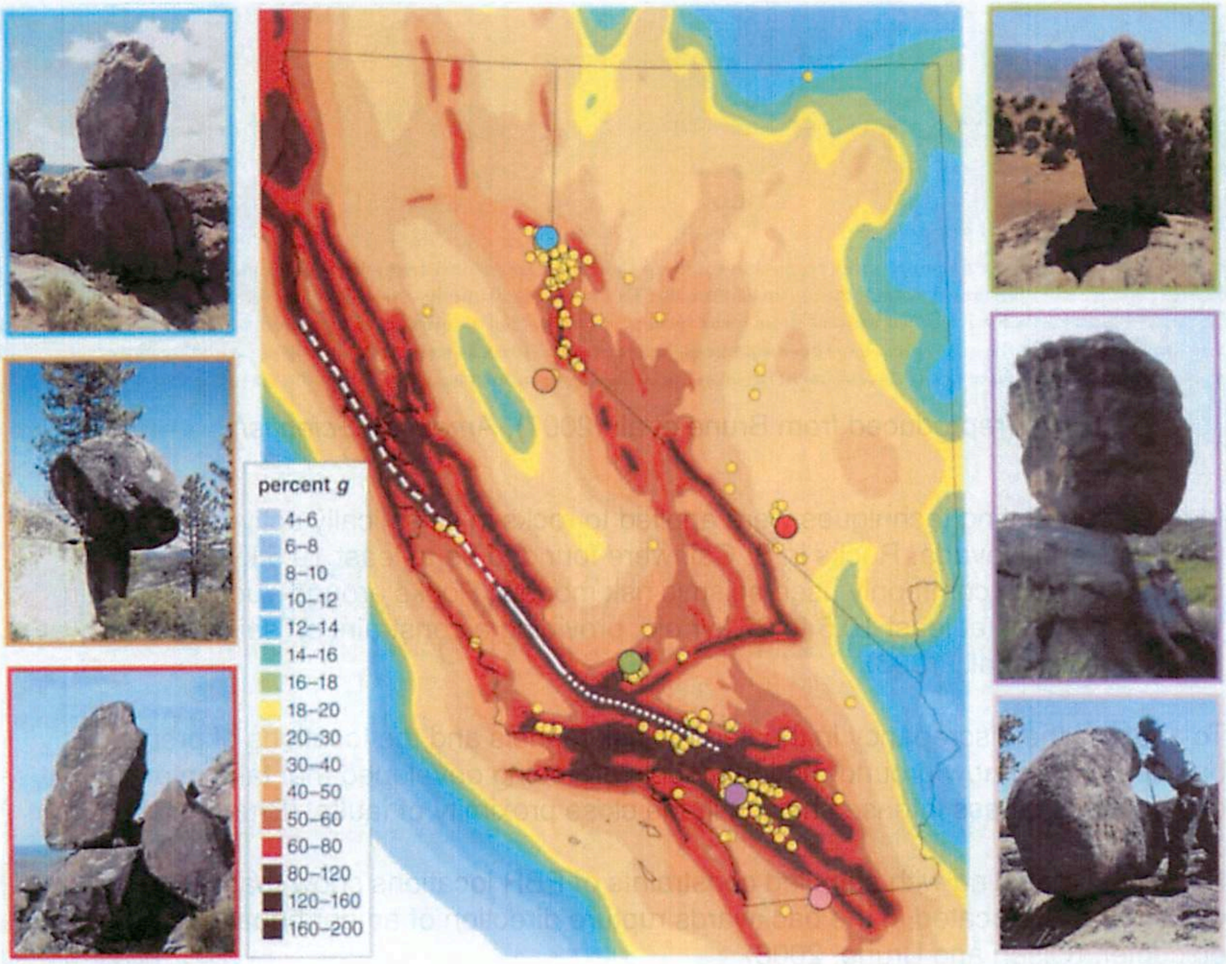


Figure 2. The authors have identified and studied precariously balanced rocks located throughout much of California and Nevada *(yellow dots)*, a region of considerable seismic activity. The background colors correspond to the peak ground acceleration that has a 2 percent probability of being exceeded in 50 years (expressed as a percentage of the acceleration of gravity, *g*), according to the U.S. Geological Survey. The most hazardous areas are close to geologic faults, such as the San Andreas Fault *(white)*, which runs most of the length of California. The dotted portion of this line shows where the fault slipped during the Fort Tejon event of 1857; the dashed portion, where it slipped during the San Francisco earthquake of 1906. Large dots denote the location of some of the more spectacular examples of precariously balanced rocks. The color of each of these dots matches the color of the frame in the corresponding photograph. (Seismic-hazard information from USGS Open-File Report 02-420-C.)

(reproduced from Brune et al. (2007), *American Scientist*)

Some Significant Results

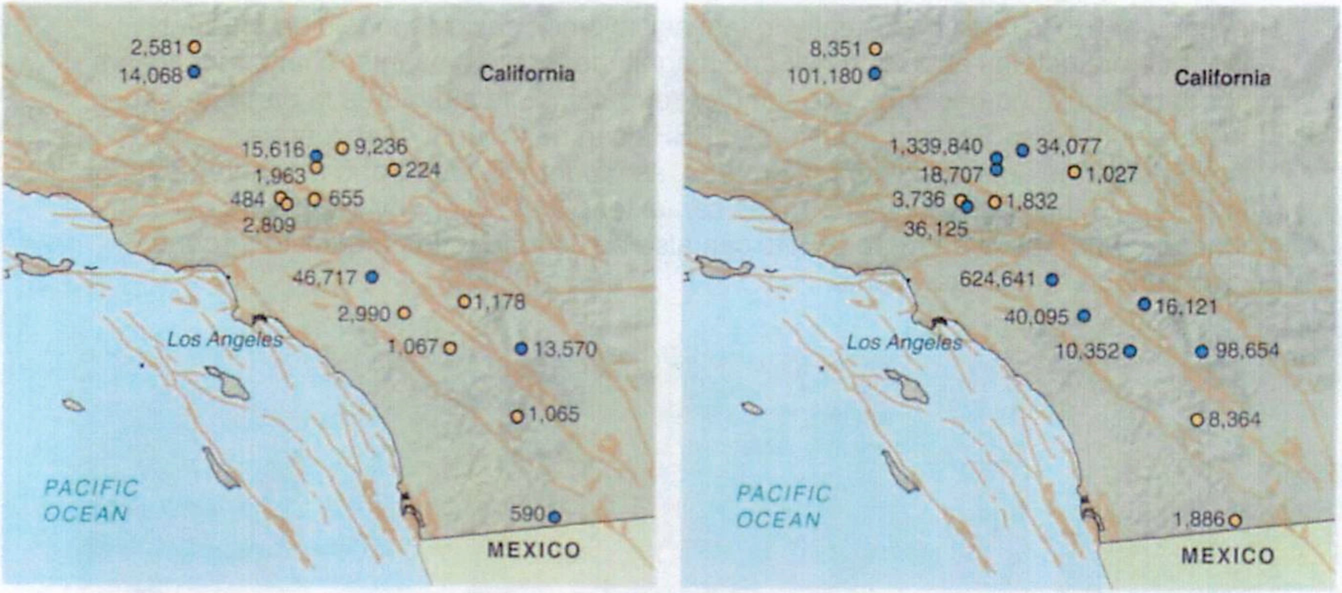


Figure 8. Most of the precariously balanced rocks studied in southern California are inconsistent with a 1997 model for how ground motion diminishes with distance from the causative fault during an earthquake. That model *(left)* implies that earthquakes from one or more of the regional faults *(tan)* would most likely have toppled most of these rocks *(yellow points)* within an interval of time *(indicated values)* that is smaller than 10,000 years (roughly the time these boulders have been standing). Just four of the 18 rocks studied are consistent with this model *(blue points)*. A revised ground-motion model now under development *(right)* reduces the degree of inconsistency, with only six rocks showing a mismatch.

(reproduced from Brune et al. (2007), *American Scientist*)

Independent dating techniques were applied to rocks in seismically active areas of California and Nevada. Rocks in S. Cal. were found to be at least 10.5 kyr old, inconsistent with commonly used seismic risk models. Rocks around Yucca Mountain were found to be at least 10.5 to 27 kyr old, providing a constraint on seismic activity at that site. (Bell et al., 1998)

To address the discrepancy in the seismic risk models and the locations of precariously balanced rocks, new ground-motion models are being developed that take into account observations of less intense shaking in the close proximity of faults. (Brune et al., 2007)

Numerical modeling with supplied constraints of PBR locations show that PBRs are expected to be located in the backwards rupture direction of an earthquake or near its epicenter. (Olsen and Brune, 2008)

Attenuation and dampening of strong ground motion from events along the Elsinore and San Jacinto faults in Southern California is most likely responsible for the existence of a band of PBRs located in between these two faults. The estimated acceleration required to topple these rocks is 0.3 +/- 0.1 g, somewhat lower than predicted from what would be expected in the area long-term from seismic risk maps. (Brune et al., 2006)

Related to PBR overturning, Purvance (2005) found that the chances of a precarious block overturning can be best obtained by examining the ratio of the peak ground velocity to the peak ground acceleration.

Planetary Connection?

No precariously balanced rocks have been definitively identified using from remote sensing of a solid body surface or from ground cameras. I speculate that great caution would have to be exercised in identifying PBRs from space, as the pixel resolution, lighting/shadow conditions, and nagging skepticism would affect the interpretation of the imaging results.

If a PBR on a solid solar system body was positively identified, however, one could use that to constrain a limit on the date of the last significant seismic shaking event. In the case for a body where plate tectonics is not expected to have taken place, one could conceivably use a PBR to place a constraint on the last significant impact event. However, the main barrier to PBR formation could be whether or not PBRs could form in the first place, especially if weathering is the main pathway to PBR formation.

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