Don't Panic

LPL Spring 2010 Field Trip to Southern New Mexico

LPL Spring (April 9-12) 2010 (AD) Field Trip Field Guide For Use In the Field During the Field Study at Some Interesting Places in Southern New Mexico

April 9-12, 2010

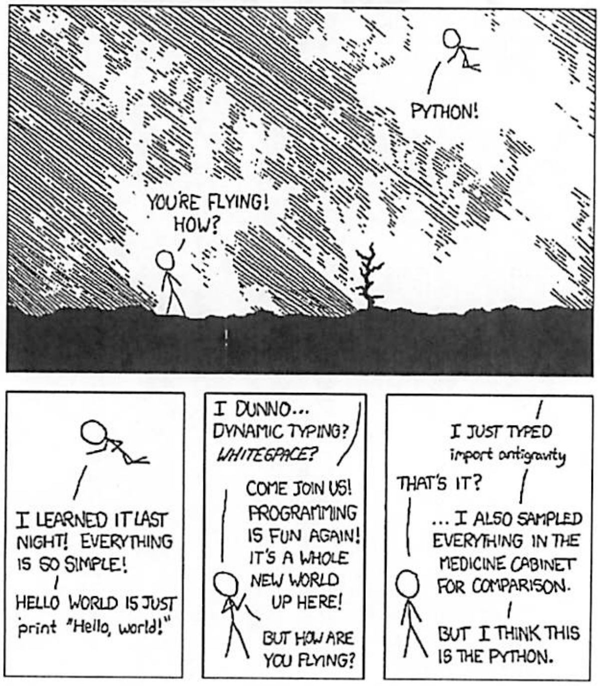
To whom it may concern,

Apparently, it has become a tradition for the editor to make a snarky comment[1] at the beginning of the field trip field guide for use in the field during the field study. Instead, I offer this one word of advice to future field trip participants: when the field trip organizer asks for volunteers to edit field trip field guide for use in the field during the field study, do not make some stupid joke along the lines of "Looks like you've volunteered to do it, <insert field trip organizer's name here>" when no one offers to volunteer. Rather, do what so many veterans have mastered:

1. Be absolutely quiet.
2. Shrink down into your seat to prevent being seen.
3. Pretend to work on something equally as important so that you won't be bothered.

Odds are, some stupid first year will speak up and be stuck with the job of field trip field guide for use in the field during the field study editor despite having a much larger workload than anyone else on the field trip.

And now I leave you with these seemingly unrelated words of wisdom from xkcd:



Field trip.

-Rob Zellem

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[1] Kat Volk, 2010

Itinerary for Spring 2010 LPL Fieldtrip

Friday 4/9

7:00 AM: Assemble at the LPL loading dock. All vehicles, people and luggage should be at LPL by 7:00 so that we can load everything and get equipment from the fieldtrip room.

8:00 AM: Depart loading dock. Drive east on I-10 towards New Mexico until bored, then take Exit 116. (Do not become bored before Exit 116, as this will lead to you taking the wrong exit). Follow the frontage road east for about a mile, then turn right on County Road B004. Follow this for about 20 miles to the Aden lava flow.

1:30 PM: Arrive Aden flow; lunch. **Christa Van Laerhoven** will talk about the human history of southern New Mexico. If hunger drives a mutiny in favor of an earlier lunch, there is a park in Deming close to the freeway exit. The aerial photos in Google Maps don't look all that attractive, though.

2:30 PM: Begin Aden flow exercise. **Huan Meng** will give an overview of the geologic history of southern New Mexico, and **Catherine Elder** will talk about lava flow inflation.

6:00 PM: Drive to Kilbourne Hole. Follow County Road B004 for a few miles further southeast. Eventually, B004 jogs left and moves away from the railroad tracks. Follow the road paralleling the tracks for a short distance, then turn right and proceed southwest on a network of anastomosing dirt roads. Camp near Kilbourne Hole.

Saturday 4/10

8:00 AM: Begin Kilbourne Hole exploration, with talks on volcanic surge deposits and physics by **Mike Borden** and **Eric Palmer**. **Youngmin JeongAhn** will talk about some proposed alternatives to the MER team theory of the Meridiani deposits on Mars. Watch out for rattlesnakes. (Seriously).

12:00 PM: Lunch at Kilbourne Hole. **Dyer Lytle** will describe the flora and fauna of the region.

1:00 PM: Depart Kilbourne Hole. We will extract ourselves from the maze of dirt roads, get to the freeway, and ultimately pass through Las Cruces and drive north on I-25. Nominal route: return to County Road B004 and go NW a few miles along the railroad tracks, then turn right on B007. Turn left on B008, which goes west for a few miles and then turns north and goes to the freeway, reaching I-10 near Las Cruces International Airport. We will drop off the aerial division along the way.
(Optional, depending on timing: Gravel deposits north of Las Cruces International Airport. Follow frontage road west from I-10 Exit 135 for about 1.4 miles, then turn right on a gravel road. After ~0.5 miles turn right and go north on Box Canyon Drive. Follow

this for about 3 miles. Park where the road descends into Box Canyon, unless road conditions look good. There are deposits of the Camp Rice Formation along the road into the canyon and along the arroyo.)
Follow I-10 into Las Cruces, then turn left and go north on I-25. Somewhere along the way, **Rob Zellem** will talk about alluvial fans and deltas. Take the Upham exit and go northwest for a few miles on County Road E071. Bear right at a Y junction, then go straight ahead through the intersection with E073. This should leave us heading NE on County Road E072. After ~4.9 miles, turn left and go west on E094 near the point where the road crosses a wash. Follow E094 as it curves north, then back west where it crosses the railroad. Bear right at another Y junction (stay on E094) and go north for several miles. The road drifts NW and eventually parallels the red fluvial deposits of the Abo Formation.

4:30 PM: Arrive near Caballo Mountains outcrops and camp.

Sunday 4/11

8:00 AM: Caballo Mountains stop, exploration. **Colin Dundas** will talk about a mishmash of fluvial bedforms, sandstone, and physics, **Tiffany Kataria** will discuss how to tell the difference between fluvial and eolian sandstone and **Jamie Molaro** will talk about lithification of sediments. Here and/or at White Sands, **Justin Wood** will show us how to take strike and dip measurements.

11:00 AM: Early lunch.

12:00 PM: Depart Caballo Mountains. We will extricate ourselves by the same route and go south towards Las Cruces on I-25. Take Exit 6 and go east on Highway 70. (Optional: Gravel deposits north of Las Cruces International Airport)

3:00 PM: Arrive at White Sands National Monument entrance. Explore this gypsum dune field, which is a Mars analog in several distinct ways. **Patricio Becerra** will describe the geomorphology of sand dunes, **Ingrid Daubar Spitale** will talk about determining dune migration rates remotely and **Serina Diniega** will talk about eolian sandstone deposits.

6:00 PM: Depart to camp. The site is TBD depending on our assessment of the weather. Options are the Lincoln National Forest (higher elevation and further away, but may be nicer and more sheltered from the wind) and BLM land just southeast of White Sands.

Monday 4/12

8:00 AM: Depart camp. We want to depart by 8:00 AM New Mexico Time. (The rest of this trip is run on Arizona time. Why bother changing?)

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8:30-9:00 AM: Meet ranger at White Sands National Monument, drive to Lake Lucero. **Priyanka Sharma** will explain the White Sands system (a good analog in many ways for the MER team model for sediments in Terra Meridiani on Mars) and **Kat Volk** will talk about the climate history of southern New Mexico.

12:00 PM: Return to Highway 70; lunch in this vicinity. There is an overlook and pullout in the Organ Mountains, a short distance west of White Sands. At lunch, **Chris Dietl** will talk about the White Sands Missile Range.

1:00 PM: Time to drive home. If you can no longer stand the sight of the other people in your truck, now is a good time to change vehicles. Drive west on Highway 70. Pass through Las Cruces. Highway 70 follows Main St. until it turns right on Picacho Ave., which ultimately leads to I-10. Drive west on I-10.

6:00 PM (Tucson time): Return to LPL. Unload vehicles. Disperse.

Human History of New Mexico

Christa Van Laerhoven, Spring 2010 LPL Fieldtrip

First Nations Peoples

The area now known as New Mexico was first appreciably populated starting in about 400 AD and by 500 AD settlements were both large and widespread. However, somewhere between 1100 and 1300 most of the area was abandoned, probably because of extended drought, and the populous moved to lands near the Rio Grande and its tributaries. These peoples were eventually named the "Pueblo" (meaning "town") by the Spaniards, with "Pueblo" referring to both the peoples and the towns they inhabited. Eventually, around 1500, the Navajo and Apache tribes migrated from the north and settled the areas the Pueblo had abandoned.

Arrival of the Spanish

Shortly after the appearance of the Navajo and Apache, the Spanish explorers arrived. In talking to the native people, the Spaniards heard of the wealth of the Pueblo cities. It was quickly assumed that this "wealth" was in the form of gold and numerous expeditions were launched which were largely unsuccessful.

The first attempt at organized colonization of New Mexico was undertaken by Juan de Onate. In return for using his family's wealth to fund the colonization, Onate was named Governor as well as Captain General. He founded the settlement of San Juan and used it as a base for further expeditions.

In 1958, Onate's nephew, Juan de Zaldivar, was on his way to meet his uncle for a large expedition when he stopped at the town of the Acoma tribe, from which he demanded food and blankets. He and his men were attacked and Zaldivar was killed. Upon learning of his nephew's death, Onate organized an army to gain revenge on the Acoma. The resulting conflict was won by the Spanish after three days of fighting. In the trials following the Spanish victory the Acoma were dealt brutal sentences. All adults were sentenced to 20 years of servitude and males over 25 were additionally subjected to having their left foot severed. The children of the tribe were placed with Spanish families. In 1606, Onate was forced to resign due to questions into his treatment of the native peoples.

Santa Fe was established in 1609 by Onate's replacement, Pedro de Peralta, and was made the seat of government for the area. Since Santa Fe has never ceased to be the seat of government of New Mexico, it is the oldest of the U.S. capitol cities.

The Pueblo revolt, Popé's Rule, and the "Bloodless" Reconquest

Eventually, the Pueblo and the Spanish developed a mutually beneficial, if uneasy, relationship. The market system was set up such that the Spanish would get the majority of the wealth derived from the labor done by the Pueblo people, but the Spanish would protect themselves and the Pueblo from raids from other native tribes. Around 1680 this changed. The area underwent a period of drought and while the Spanish coped well enough for food the Pueblo starved. Additionally, the Spanish soldiers were unable to protect the settlements from increased attacks from the surrounding native tribes. This unrest was harnessed by Popé who, in August 1680, organized a united revolt. Popé's intended date for the rebellion's start was August 18 but this date was moved up because the Spanish captured a couple messengers. The revolt began with the killing of a single Spaniard on August 9th and by the next day it was widespread. The Spanish were outnumbered and soon they retreated to Santa Fe and Isleta Pueblo, the one Pueblo tribe that didn't participate in the revolt. The Spanish that fled to Isleta, thinking they were the only survivors, soon left for El Paso del Norte. The Spanish in Santa Fe were besieged and eventually also fled to El Paso.

From this time until his death in 1688 Popé ruled the Pueblo peoples. He ordered the people to disavow anything introduced by the Spanish. This included destroying anything related to the Catholic Church, and the avoidance of any Spanish livestock, fruit trees, or crops. The independence of the native peoples from Spanish control was short lived. The nation suffered from internal power struggles among the various tribes and another extended drought made it ripe for reconquest by the Spanish.

In 1692, Diego de Vargas went to Santa Fe with an army and promised the Pueblo they would not come to harm if they agreed to be Spanish subjects and convert to Christianity. The Pueblo leaders agreed and the territory returned to Spanish rule. Due to this peaceful beginning, this is often referred to as the "bloodless" reconquest. Unfortunately, in the years following de Vargas lead many campaigns against resistive Pueblos.

Transition from New Spain to Mexico

In 1803 the United States of America bought all of the territory related to tributaries of the Mississippi River from the French in the Louisiana Purchase. This territory included some of the eastern part of what is now New Mexico. In 1819, Spain and the United States signed the Adams-Onís Treaty which left control of the south-east of North America (what is now Texas, New Mexico, California, etc) to the Spanish.

In September of 1810, Mexico claimed independence from the Spanish. After eleven years of war, the conflict ended with the Treaty of Cordoba in which the Spanish accepted Mexican independence. As a result of this victory and the Adams-Onís Treaty, claim to New Mexico now belonged to Mexico.

In 1836, The Republic of Texas seceded from Mexico and Texas claimed all territory east of the Rio Grande. To back this claim the president of Texas launched the Santa Fe Expedition: a trade expedition backed by about 300 troops. The expedition was badly supplied and, after losing their way and needing to backtrack, arrived in Santa Fe to find a displeased Mexican governor backed by 1500 troops. The Texans surrendered on the hope that they would be allowed to turn around and go home but they were made prisoner and marched to Mexico City. In the following year, after much diplomatic wrangling, they were released.

Mexican-American War

The Republic of Texas was annexed by the United States in 1846. Mexico, which viewed Texas as their own, broke diplomatic ties with the United States. Hostilities were further provoked by the U.S.'s President Polk claiming all territory east of the Rio Grande. The U.S. officially declared war in May 1846 after a most of a U.S. patrol was killed by Mexican cavalry while in disputed territory. The war did not go well for Mexico. Eventually most of Mexico's major cities were occupied and it had no choice but to surrender most territory presently part of the U.S. in the Treaty of Guadelupe Hidalgo.

America's New Mexico

Santa Fe was established as the capitol of the newly gained territory of New Mexico (which includes present day Arizona as well as New Mexico) in 1851. The southernmost portion of New Mexico was acquired in Gadsden Purchase of 1953 after it was realized that this territory would allow an easier route for a proposed transcontinental railway. New Mexico became the 47th state on January 6, 1912.

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Lava Flow Inflation
Catherine Elder

1 Background on Lava Flows

The lava's physical properties, the rate at which it is effused from the ground, topography, ground slope etc. all control how lava flows. However, there are only a few common types of lava and flow morphologies which can reveal the styles and rates of flow advancement (Houghton *et al.* 1999). The surface of lava flows solidifies to a solid crust within minutes of being exposed to the atmosphere, so flows initially form a small number of tubes or channels, but if the flow is strong enough, the roof constantly gets pulled apart into fragments and an open channel containing lava forms. Alternatively, if the flow is slower, a stable roof develops and forms a lava tube (Houghton *et al.* 1999). Similarly, the front of the flow either moves forward as a single unit, or if a crust is able to form, it advances by small tongues breaking through the front crust (Houghton *et al.* 1999).

1.1 Aa and Blocky Flows

The surface of aa flows are irregular, fractured, and covered by rough contorted centimeter to decimeter fragments (Houghton *et al.* 1999). Blocky flows are fractured like aa flows, but their fragments are smooth and angular (Houghton *et al.* 1999). Both aa and blocky flows move forward as a single unit. The fronts thicken as they advance to final thicknesses of $<$ 20 m for aa flows and several tens of meters for blocky flows (Houghton *et al.* 1999). Aa flows reach maximum lengths of tens of kilometers and blocky flows reach lengths of only kilometers. When the flow stops widening and moves downhill, channels form. Sometimes the front continues advancing until the source is exhausted, but other times the front comes to rest and lava piles up and thickens behind it which can sometimes breach the channel (Houghton *et al.* 1999). After a channel has become well established, a tube can form by gradually extending the overhang of the walls. In aa flows, tubes take several weeks to form, so they are only found in aa flows that remain active for long periods of time. Once a tube forms, the lave beneath is insulated and can flow further before solidifying, but they usually form near the end of a major flow, so they don't contribute significantly to extending the flow length (Houghton *et al.* 1999). If the lava drains from the tube at the end of effusion, it can leave a tunnel large enough to crawl or walk through and up to a few kilometers long (Houghton *et al.* 1999).

1.2 Pahoehoe

Pahoehoe flows advance at least 10 times more slowly than aa flows. This allows their surfaces to develop smooth and continuous crusts at the beginning of emplacement (Houghton *et al.* 1999). Early flows are thin, and get stopped by the crust. Spreading occurs by small tongues breaking through the crust, or by new lava slowly lifting up the front (Houghton *et al.* 1999). The resulting front is a series of tongues each 10-1000 times narrower than the width of the whole flow (Houghton *et al.* 1999). Tongues extend about 100 m before crusting

Figure 1: Left: An aa flow front advancing over pahoehoe on the coastal plain of Kilauea Volcano, Hawaii. Right: Pahoehoe toes fed by lava that broke out from a lava tube (out of view) also at Kilauea Volcano, Hawaii. Images are from USGS Volcano Hazards Program photo glossary of volcano terms.

over at which point small meter scale lava toes form. All tongues and toes are gradually uplifted when more lava arrives (Houghton *et al.* 1999). The lava tubes allow the flowing lava to stay at a temperature close to its initial value, and even though pahoehoe flows move much slower than aa flows, they are able to flow for a longer period of time and flow further distances than aa flows of similar volumes (Houghton *et al.* 1999).

2 Inflation

Inflation is the injection of molten lava underneath a solidified crust and is the process that forms pahoehoe flows. It can convert a 20 to 50 cm thick lobe into a sheet many meters thick in a period of weeks (Self *et al.* 1998). Flows emplaced by inflation can be identified by smooth, billowy, or ropey surfaces, the internal distribution of vesicles, crystallinity, and joints (Self *et al.* 1998). The smallest coherent package of lava in a pahoehoe flow is called a lobe. Lobes can coalesce laterally during inflation to produce sheets hundreds or thousands of meters wide. These sheets are also meters to tens of meters thick and can be hundreds of meters to several tens of kilometers long. The inflation of the lobe can last days, months, or years (Self *et al.* (1998) and references there in). Figure 2 shows the stages of flow development. Fresh bubble filled lava is continually brought into the lobe (Figure 2b, c). As the dense core crystallizes, incompatible elements concentrate in a residuum which can rise buoyantly as diapirs caused by secondary vesiculation (Self *et al.* 1998). These diapirs spread to form vesicle sheets when they hit the base of the upper crust (Figure 2d). Vesicle sheets mark the base of the upper crust at the end of inflation. Hon *et al.* (1994) developed an empirical cooling model that predicts the time in hours, t, required to grow a crust of thickness in meters, H:

$$t = 164.8H^2 \tag{1}$$

(Self *et al.* 1998, Hon *et al.* 1994). This cooling model sometimes overestimates cooling rates, but it is the only quantitative inflation model (Self *et al.* 1998). Inflation can often invert surface topography; high areas become inflation pits (Figures 3, 4).

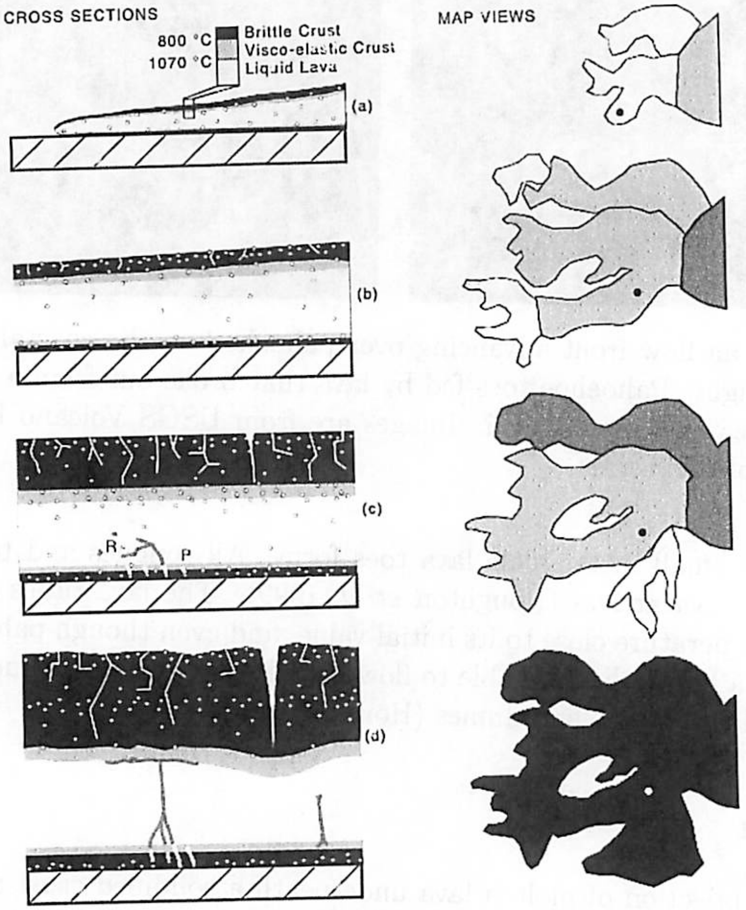

Figure 2: Cartoon of the development of an inflated pahoehoe sheet flow from Self *et al.* (1998). The left shows cross sections at a fixed location labeled by the dot in the concurrent flow field map on the right. In the cross section, shading darkens with cooling, and in the map view it darkens with age. a) A new lobe advances from left to right. b) The lobe thickens by inflation, and bubbles from the moving lava are trapped in the crust, forming vesicles. The lower crust grows much more slowly than the upper crust. c) Inflation continues. Buoyant, vesicular silicic residuum (R) that rises from the lower crystallization front is disrupted and mixed into the flowing lava. Some cracks in the upper crust reach the visco-elastic layer. d) Flow stagnates. The vesicular residuum (R) rises through the lava forming horizontal vesicular sheets at the base of the upper crust. Cooling is enhanced around deep cracks (Self *et al.* 1998).

3 Pahoehoe Flows in the Western United States

Pahoehoe flows are common in areas of crustal extension such as the Basin and Range province. The Basin and Range province has many small inflated hummocky pahoehoe flows fed from scoria cones like the Amboy and Pisgah flow fields in the Mojave Desert, California. The Colorado Plateau has many basaltic flow fields with inflated pahoehoe. The Taos volcanic field and the Potrillo maar field (including Kilburn Hole) in the Rio Grande

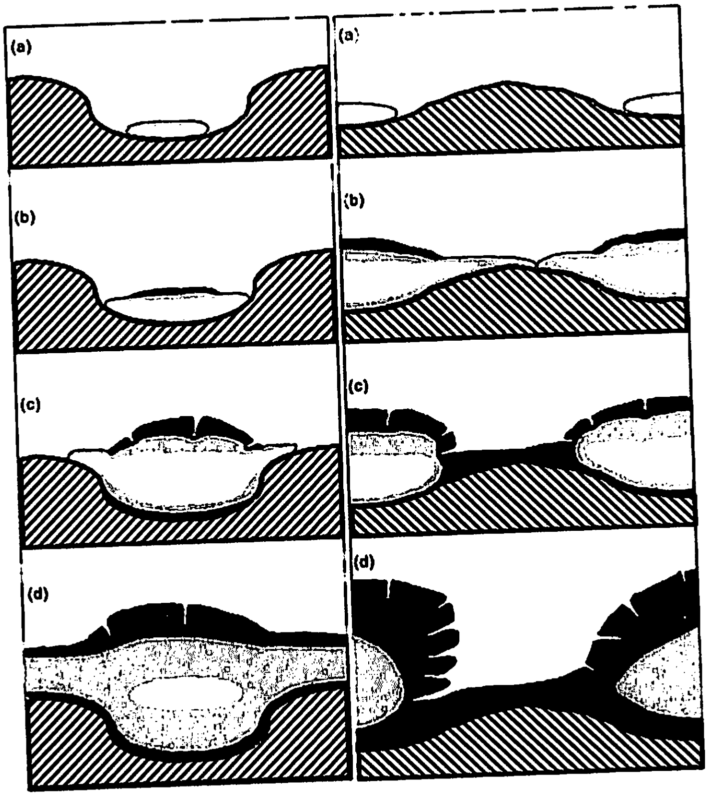

Figure 3: Cartoon of the inversion of topography during inflation from Self *et al.* (1998). a) The initial pahoehoe lobes are confined to the lowest areas. b,c) The flows advance, inflate and spread laterally filling the depressions. The thickest crust is on the oldest part of the sheet, so the highest inflation is over what was originally the lowest ground. Breakouts from the inflation features eventually cover the earlier higher ground. d) A continuous sheet or an inflation pit forms over the previous high points depending on the rate of inflation relative to the rate of crust growth (Self *et al.* 1998).

Rift contain many pahoehoe sheet flows (Self *et al.* 1998).

4 Lava Flows on Other Planets

Lava flows stretching hundreds of kilometers are commonplace on the Moon, Mars, and Venus and sometimes cover a larger area than the ancient flood basalts on the Earth (Houghton *et al.* 1999). Lava flows cover 90 % of the surface of Venus, 50 % of Mars, at least 20 % of the Moon, and 70 % of the Earth including the ocean floor (Houghton *et al.* 1999). The shape and size of extraterrestrial lava flows can provide insight into the properties of the crusts and mantles of other planets (Houghton *et al.* 1999). On Earth, pahoehoe lava flows are the dominant type of basaltic lavas in terms of both areal coverage and total volume (Self *et al.* 1998), and several large flows on other planets seem to be pahoehoe (Self *et al.* 1998, Theilig and Greeley 1986, Bruno *et al.* 1992, Campbell and Campbell 1992).

Figure 4: A hollow tree mold formed when lava from a pahoehoe sheet chilled and solidified around tree trunks and incinerated the trees on the Kilauea Volcano, Hawaii. The pahoehoe inflated to the highest point on the tree mold, and then deflated as lava drained out from beneath the solidified pahoehoe crust. Image from: www.geology.sdsu.edu/how_volcanoes_work/

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Mike Borden

THE PHYSICS OF VOLCANIC / PYROCLASTIC SURGES

Q: WHAT IS A PYROCLASTIC SURGE?

A fast moving current of hot gas and rock which results from certain explosive volcanic eruptions.

Also called: "Broken fire" (Greek)
Glowing cloud - Nuée ardente (French)

Figure 1: A Pyroclastic Surge

Q: WHAT HAPPENS DURING A PYROCLASITC SURGE?

Step 1: A volcanic eruption!

Either: <u>A Phreatomagmatic eruption</u> - an eruption in which magma comes into explosive contact with water (maars, marine volcanos , crater / caldera lakes, or aquifers

or: Direct frothing over at the vent of magma undergoing rapid gas loss

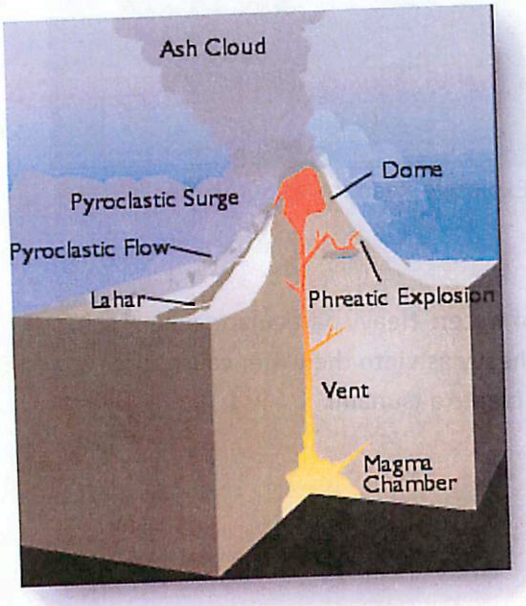
Step 2: Currents of hot gas and rock (tephra) are formed

Composed of: A <u>basal flow</u> which hugs the ground and contains larger, course boulders and rock fragments, and a hot <u>ash plume</u> which lofts above and is composed of gas and ash

Compositon depends on: Water to Magma ratio

High Ratio = <u>Wet Surge</u>: < 100° C, results in 3 phase suspension of solid particles, water droplets, and gas

Low Ratio = <u>Dry Surge</u>: > 100° C, result is same as wet surge except water vapor replaces water droplets



Step 3: Surges spread down the face of the volcano

Pyroclastic surges normally hug the ground and tend to follow valleys. As shown in Figure 2, they often accompany a pyroclastic flow (which is denser than a surge). Depending on the circumstance, they can also spread laterally under gravity.

Figure 2 (left): Anatomy of a Pyroclastic Surge Producing Volcanic Eruption
(Image from www.bbc.co.uk)

Turbulance: Pyroclastic surges are "very turbulant"! A figure of merit called the Reynolds Number is used to determine the level of turbulance experienced within a surge. *The* equation is as follows:

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

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

Speed: The speed of a surge, which can reach an upwards of 450 mph, is dependent on a number of factors. Among those are: Density of current, volcanic output rate, and gradient of slope.

Temperature: The temperature of a surge, which can reach an upwards of 1000° C, is a function the volume of water present during the eruption as well as distance from the source.

Step 4: Surge Meets Water

Although not every pyroclastic surge meets a body of water during its lifetime, many do. Two things happen when a surge meets water:

1) **Steam and Speed**

Hot ash from the surge causes water near the surface to boil and evaporate. This creates water vapor, which is about 1,600 times greater in volume than the water that produced it! Thus, the density of the surge decreases, which causes an increase in speed. This speed is further quickened as a very low friction bed of superheated steam now rests above the surface of the water. Aided by this speed, it has been found that surges can travel over 100 km over bodies of water.

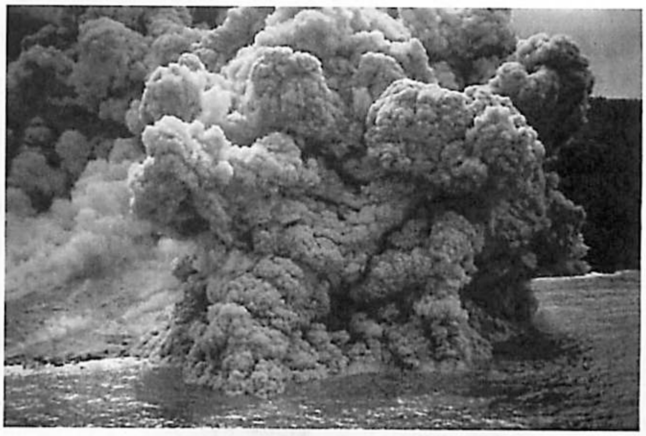


Figure 3: An Explosive Reaction as Surge meets Water

2) **Tsunamis**

A dangerous thing happens as the surge travels over a surface of water. Heavy particulate, mainly ash, drop out of the surge and into the water. This displacement of heavy ash into the water causes a similarly sized displacement of water. This displaced water can create a tsunami.

Mike Borden

Q: WHAT ARE THE POST-SURGE ENVIRONMENTAL IMPACTS?

Surge deposits are left behind after a surge has passed. These deposits are either laid down at the leading edge of the surge (ground surge) or by billowing ash clouds (ash-cloud surges) overriding them.

Figure 4: Surge Deposits at Laacher See volcano, Germany (Image from www.ucsb.edu)

Massive environmenal damage often results from regions which have experienced a pyroclastic surge. A surge can cause *scortching of the land*, the kinetic energy of moving boulders can *flatten trees and buildings* in their path, and a *layer of ash* is deposited across the land. In addition, *tsunamis* can cause devastate coastal ecosystems.

Runout distances as far as 100 km, though most reach only a few km from its source. Although surges tend to flow downhill, their low density occasionally enables them to climb obstacles as high as 5000' when topographic barriers are encountered.

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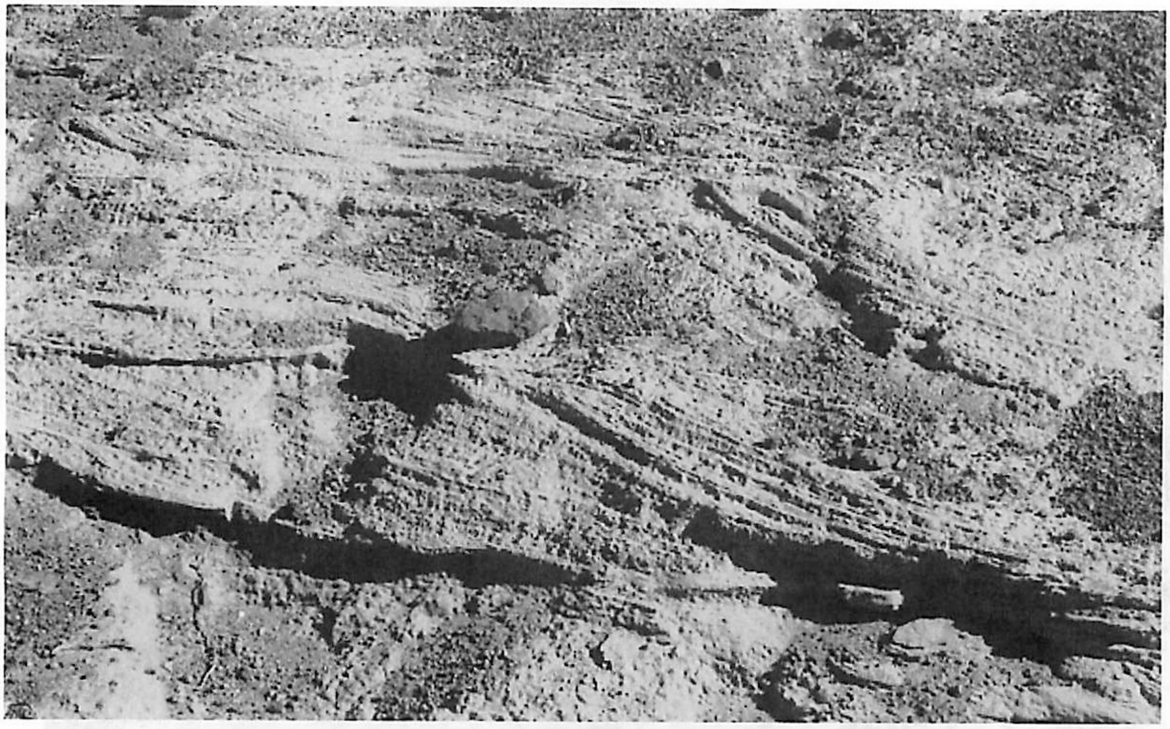
Expression of Surge Deposits

Eric E. Palmer



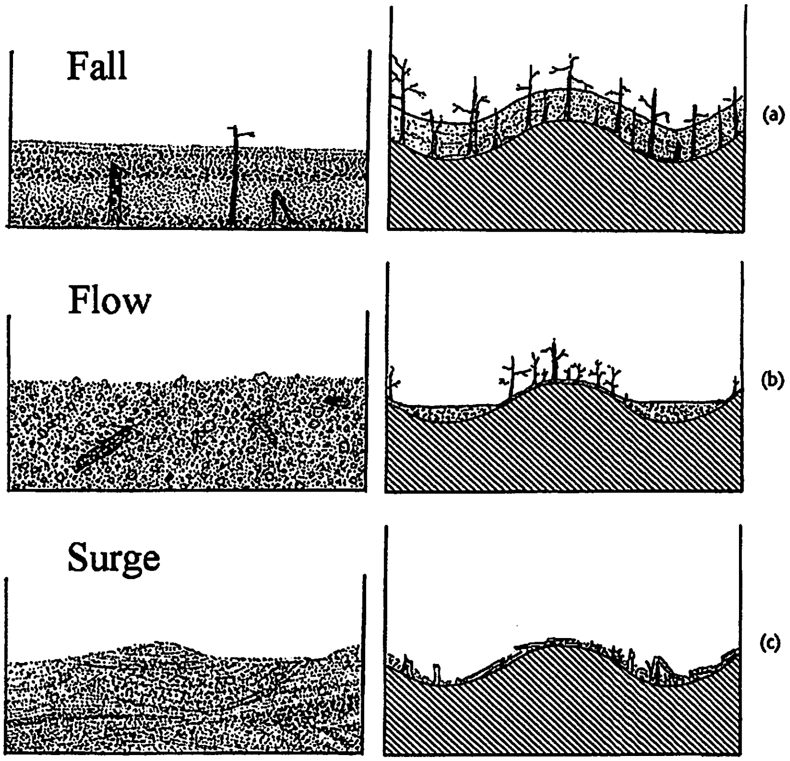
Cross bedding at Kilbourne Hole, NM.

Definitions

- **Pyroclastic** - fragmentation by explosive volcanism
- **Porphyritic** - igneous rock comprised of a glassy matrix and crystals (phenocrysts)
- **Vesicle** - bubbles of gas in a volcanic rock
- **Phreatic** - volcanic eruption with high water content (but not underwater)
- **Tephra** - Any fragmented material from an eruption that went into the atmosphere
  - **Ash** - 2 mm diameter or less, shattered vesicles
  - **Lapilli** - 2 to 64 mm diameter
    - **Cinders** - 1+ cm diameter, vesiculated (lots of holes)
      - **Scoria** - volcanic rock with large vesicles
      - **Pumice** - volcanic rock with small vesicles. Porosity of 90%, float
    - **Accretionary Lapilli** - spheroidal aggregates of ash, 3-4 mm. May have cores (Armoured)
  - **Volcanic bombs** - 64+ mm diameter, molten rock that cool in the air
  - **Volcanic blocks** - 64+ mm diameter, fractured rock thrown through the air
- **Tuff** - a rock formed of consolidated volcanic ash and lapilli
  - **Welded Tuff** - a hard and dense volcanic ash that was hot enough when it formed to "fuse" together. Consists of "Fiamme", which are squished nodules of lapilli (Fig)

- **Ignimbrite** - the material deposited by a pyroclastic flow, typically welded ash, lapilli and xenoliths from Si-rich eruptions (rhyolite, 68%+ SiO_2 and dacite, 63-68% SiO_2)
- **Nuée ardente** - a swiftly flowing cloud consisting of hot pyroclastic debris suspended in turbulent gas

Expression of Surge Deposits



Pyroclastic Fall - (a) Sedimentation of clasts through the atmosphere from an eruption jet, plume or laterally moving turbulent ash cloud during an explosive eruption

Pyroclastic Flow - (b) Flow (density current) of volcanic material consisting dominantly of vesiculated, low-density pumice and glass shards, which tends to follow topographic lows. Also includes flows consisting of poorly-vesiculated, dense lava clasts.

Pyroclastic Surge - (c) A turbulent, low-density, dilute high-velocity pyroclastic density current, commonly part of a pyroclastic flow. Can occur with pyroclastic flows (usually under) (Schmincke 2004)

General Process of Identification

- Pyroclastic eruptions will generate mostly ash & lapilli (juvenile volcanic material).
- When looking at an pyroclastic volcanic field, characterize different sets of juvenile volcanic material to establish different eruption sequences.
- Typically, magma will form some crystals when in the magma chamber. During eruption, the lava cools quickly, which leaves these crystals (phenocrysts) in a glassy matrix. The type and concentration of phenocrysts are a diagnostic characteristic of a volcanic eruption. By tracking the distribution of specific distributions of phenocrysts, it allows you to establish which rocks came from which volcanic vents. Using this data, you can identify if features have come from multiple eruptions of the same vent, different vents; and it helps to establish if features, such as cross bedding, come from pyroclastic surges or fluvial processes.

Pyroclastic Fall - Horizontal bedding. Because eruptions can last for days, the bedding provides a description of the amount of material, the rate and duration of each episode. Larger lapilli will land first, forming the base of the fall with smaller ash particles floating down more slowly. Material is almost always homogenous with the exception of xenoliths that may have come from the vent's walls.

Pyroclastic Flow - Volcanic material (lapilli and ash) are carried by very hot gas; however, the mixture of the material causes it to act like a fluid that has a density higher than air, in spite of the hot gas. This material will flow down mountains and hills, following topographic lows. During its movement across the surface, it will entrain country rock (not from that eruption). The key characteristic to discriminate a fall from a flow is the frequent occurrence of country rock in the mix. When deposited, they form a single cooling unit. They can have speeds up to 720 km/h.

Pyroclastic Surge - Similar to flows except more energetic and has more gas. They are more likely to contain rock scoured from the terrain it has traversed. It also has crossbedding features. As it travels, it will begin to form deposits (similar to sand dunes), which are built upon and/or eroded, forming crossbeds. It has speeds upto 1050 km/h. They can travel up to 10 km from the source.

12+3

Expression of Surge Deposits

1 Base surge - formed at initially eruption as the base of the eruption column collapses (base of a mushroom cloud). Base surge deposits are small volumes, less than 0.01 km^3, and within 3 to 5 km of the vent. Maximum thickness is generally less than 1 meter and thins to a few centimeters.
2 Ash cloud surge - material is neither buoying up (heat) or down (collapse)
3 Ground surge - formed at the base of a pyroclastic flow. Ground surge and ash cloud surge deposits are 1-2 m thick.

Planetary Connection - Mars

Sediment layers discovered by Opportunity at Meridiani Planum have been suggested to have formed by both aeolian and aqueous processes (Squyres et al., 2004).

Knauth et al. (2005), McCollom and Hynek (2005), Burt et al. (2008) counter with the suggestion that pyroclastic or impact surges can explain all sedimentary features without many of the mechanisms needed for aeolian and aqueous processes. These surges mechanism requires an atmosphere and water

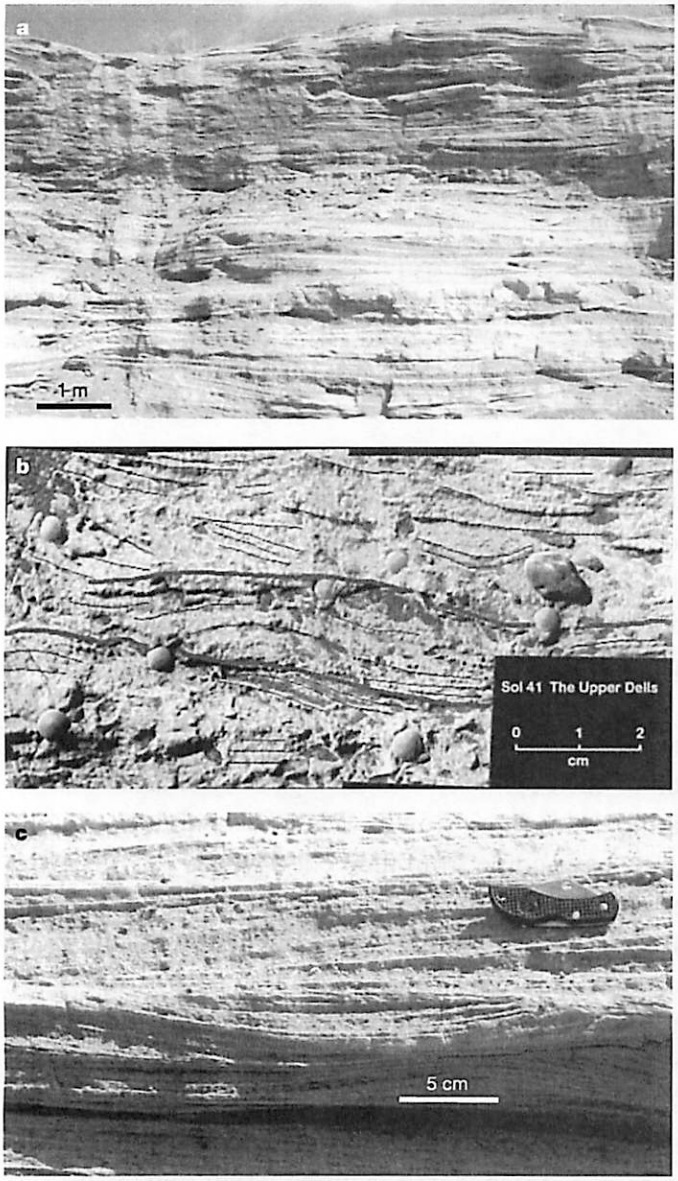


Figure 3 | Terrestrial surge deposits compared with cross-stratified martian deposits. **a,** Typical layered and cross-bedded aspect of a terrestrial deposit, Kilbourne Hole, New Mexico. **b,** Upper Dells mosaic taken on sol (martian day) 41. Lines added by the MER team to highlight cross-sets. **c,** Festoon cross-beds from Kilbourne Hole, New Mexico. Festoon cross-sets in terrestrial surges occur at the same scale as those observed on Mars and need not imply an aqueous origin.

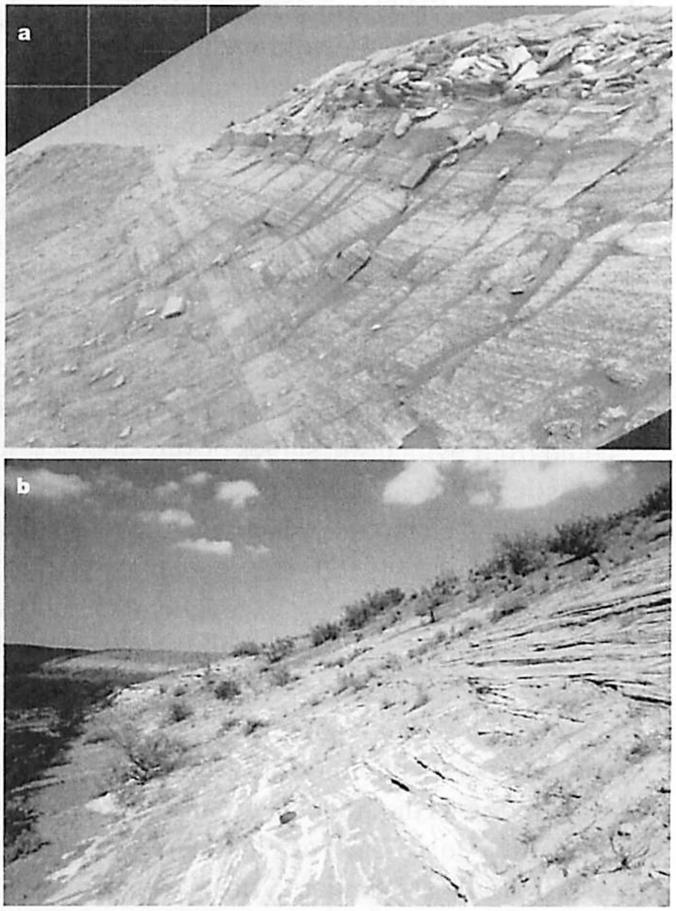
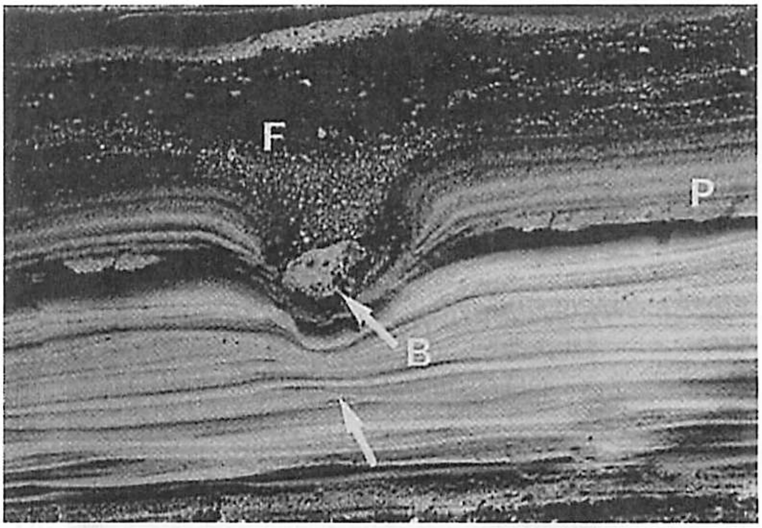


Figure 4 | Martian strata compared with terrestrial surge strata. **a,** Wall of Endurance crater on Mars, showing long, low-angle cross-sets overlying high-angle cross-sets (upper left part of photograph). The sloping straight line is an artefact of image stitching. The bedding displayed here is common in surge deposits. Impact surge explains all stratification in terms of only one process. **b,** Outcrop appearance of typical, layered surge deposits, Kilbourne Hole, New Mexico.

Expression of Surge Deposits



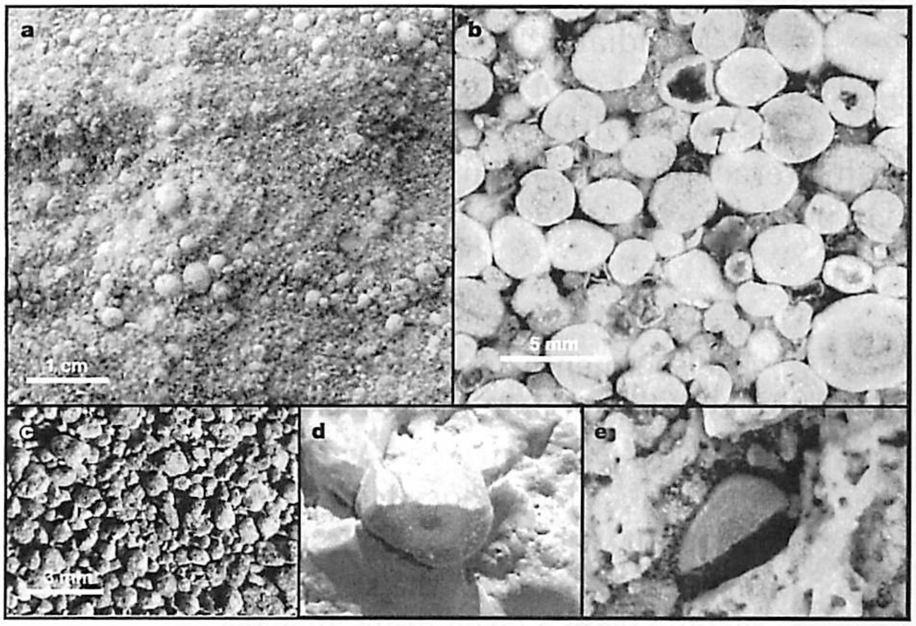
Features to look for

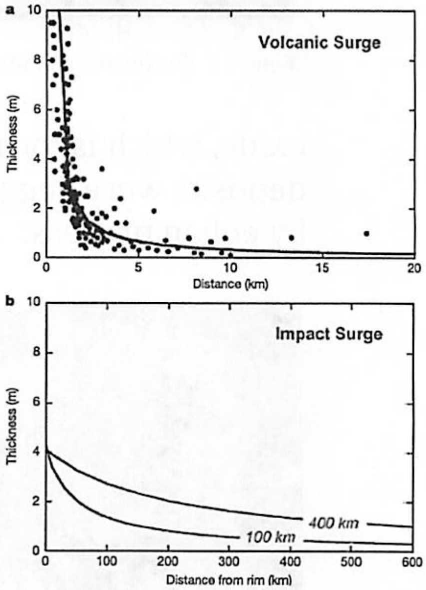
- Impact sags
- Shallow bedding
- Location of sources (vents/craters)
- Thin layers

Note: The clasts of pyroclastic flows reworked by water or wind are appreciably rounded or abraded. They can be a mixture of pyroclastic material and other sediments.

Water - Lack fine grained detritus (small rock pieces)

Wind - Lack very fine ash and the larger scoria





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Seven

Sediments at Meridiani Planum Formed Inside Massive Ice Deposits

Youngmin JeongAhn

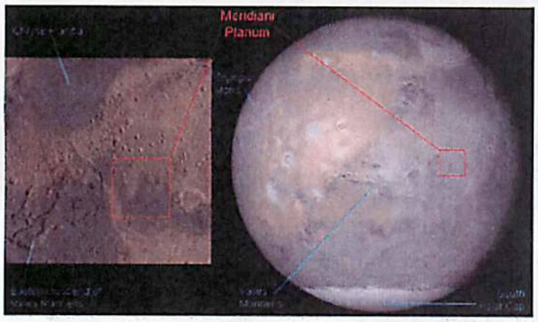


Figure 1 The location of Meridiani Planum

Meridiani Planum on Mars is the landing site of Opportunity. It is located near the equator and east of the Valles Marineris, which is a great rift system.

Meridiani Planum shows possible evidence of interaction with liquid water. It contains hematite, an iron oxide, which is formed with interaction of water on Earth. Sulphate-rich deposits were suggested to be playa evaporates that had been reworked by eolian process.

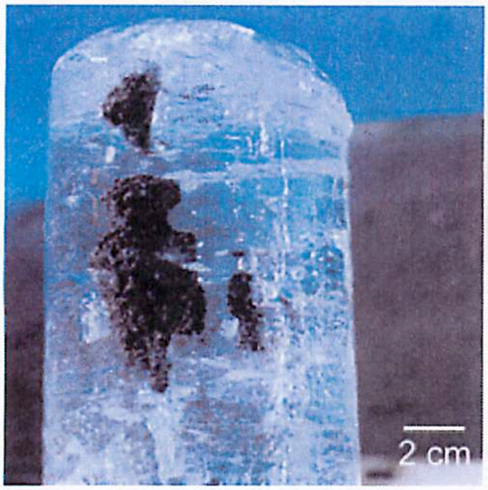


Figure 2 Ice core from Antarctica with an aggregation of soil grains.

The sediments on Meridiani Planum were also thought to be results of volcanic or impact-driven formation. Niles and Michalski proposed another possibility that it was made by eolian or impact-driven reworking of the sublimation residue from a large-scale dust-ice deposit.

This dust-ice deposit formed through precipitation of ice around dust grains and aerosols like the present the Martian polar regions. When the dust-ice deposit was heated by sunlight during summer, it reacted with volcanic aerosols though thin water film, which made highly acidic solution.

The massive ice deposit could have been formed when the poles were in different position or the obliquity had high value. Later climate shift made this deposit sublime, yielding sand-sized agglomerates of chemically weathered and hydrated siliciclastic material mixed with sulphate salts.

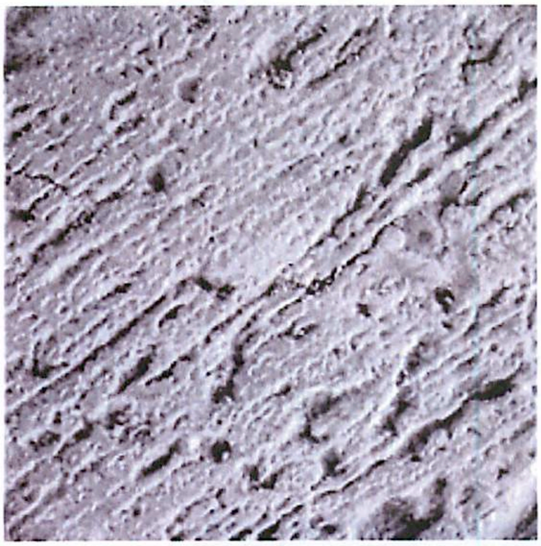


Figure 3 Outcrop image of sediments at Meridiani Planum inside Endurance crater.

The results of this study imply a possible common formation mechanism for other layered deposits having sulphate paired with hematite, including Aram Chaos, Aureum Chaos, Ioni Chaos and Valles Marineris. This theory dose not require a basin or the groundwater to be present.

However, there are also shortfalls in this theory. No model has allowed for the necessarily massive ice deposits at the Martian equator, for example, and it is curious how the dust and aerosols could aggregate into consistent sand-sized particles, as Brian Hynek said.

Dyer Lytle

Flora and Fauna of Southern New Mexico, and a Smidgen of History

The regions covered by this year's field trip lie mostly in the Lower Sonoran life zone, generally considered to lie below 4500 feet elevation. These areas also lie in the Chihuahuan desert which is the largest desert in North America covering an area of 175,000 square miles, most of which is south of the border in Mexico. This desert is characterized by receiving less then 10 inches of rain per year.

In these areas, at lower elevations, the plant life has much in common with the Sonoran desert around Tucson featuring Honey Mesquite bushes, Broom Snakeweed, and Coville Creosotebush. Some species that differ from the Sonoran desert are the American Tarbush in clay soils, and the Soaptree Yucca in sandy soils.

At higher elevations, in the grasslands, we see the Black Grama grass and Tubosa, which are also common in Arizona, and Burrograss. In the mountain foothills we find the Wright Mountain Mahogony, Wheeler Sotol, and Skeleton Goldeneye among the familiar Pinyon-Juniper forest.

Sotol cluster with towering bloom stalks, with flowers that attract hordes of insects.

Wildflowers we might see include Gold Poppies, Datura, Scarlet Penstemon, Indian Paintbrush, Lantana, Rock Nettle, Long-headed Coneflower, Scarlet Globe-mallow, Firewheel Blanketflower, as well as various cacti, Yucca and Sotal.

Some of the common animals in the area would be, for reptiles, the Trans-Pecos Rat Snake, the Western Hooknose Snake, the Grey-banded Kingsnake, the Western Diamondback Rattlesnake (and other rattlesnakes), the Horned Lizard ("horned toad"), the Trans-Pecos Striped Whiptail, the Texas Banded Gecko, the Crevice Spiny Lizard, the Bolson Tortoise, and the Collared Lizard.

Native Birds include the Greater Roadrunner (state bird on NM), the Lark and Painted Buntings, the Black-Chinned Hummingbird, the Chestnut-collared and McCown's Longspur, the Clark's Nutcracker, the Phainopepla (a silky flycatcher), the Mountain Plover, the Pyrrhuloxia (related to the cardinal), the Chihuahuan Raven, various Sparrows, the Curved-billed Thrasher, Bell's Verio, the Cactus Wren, the Great Horned Owl, the Red Tailed Hawk, the American Kestrel, and the Scaled Quail.

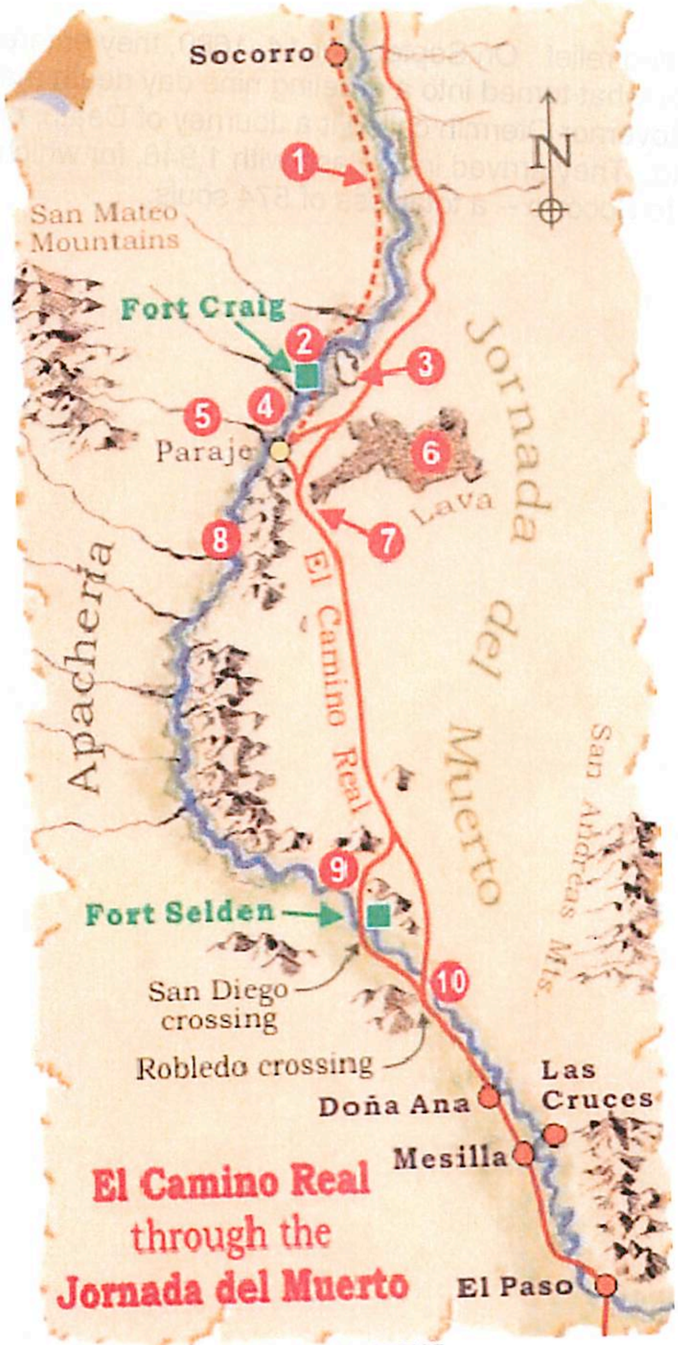
Mammals include the Round-tailed Ground Squirrel, Coyote, Mountain Lion, Mule Deer, Pronghorn Antelope, Bighorn Sheep, Wolves, Bear, Bats, and the Kangaroo Rat.

Jornada del Muerto

During the fieldtrip, when driving from Las Cruces to White Sands, we will cross the "El Camino Real del Tierra Adentro", "The Royal Road into the Interior Land", which the Spaniard Juan de Oñate established when he conducted a colonization expedition from Mexico City north starting in 1598, and reaching Santa Fe in 1603. The road was used as a major transportation corridor for nearly 300 years until the late 1800s when the railroad came through.

A part of this road, from north of Las Cruces to south of Socorro, was a shortcut across the desert that cut 30 miles off the trip and avoided many canyon crossings and quicksand traps along the Rio Grande. Because there was very little water available along this part of the route, caravans, which generally only made around 10 miles/day, often did a forced three day, all day and all night march to get across this stretch of El Camino Real.

II



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How Jornada del Muerto got its name:
(from http://www.caminorealheritage.org/jornada/jornada.htm)

In August 1680, Pueblo Indians discontent with Spanish rule erupted into what became known as the Pueblo Revolt, forcing a retreat of the Spanish. Governor Otermin found 2,520 refugees congregated at Paraje Fra Cristobal (see map #5). Most were suffering from exposure, starvation and sickness. Otermin had no choice except to order the continuation of the retreat to El Paso, 120 miles distant, the next inhabited settlement where they would find food and relief. On September 14, 1680, they entered the waterless desert passage for what turned into a grueling nine day death march. Over 500 perished on the trail. Governor Otermin called it a Journey of Death, or in Spanish, Jornada del Muerto. They arrived in El Paso with 1,946, for which 317 were Pueblo Indians from Isletta to Socorro -- a total loss of 574 souls.

TX.

Deltas and Alluvial Fans

Rob Zellem

Deltas

I. Introduction

A delta is a landform created when a river deposits sediment as it flows into a flat, arid area, or another body of water, such as a lake, ocean, or another river. The Greek historian Herodotus coined the term "delta" when he noted that the Nile River delta was in the shape of the Greek letter delta Δ (see Figure 1).

Figure 1: The Nile River delta. (http://visibleearth.nasa.gov/view_rec.php?id=1642)

II. Formation

Deltas form when a river flows into a slower body. As the river's velocity decreases, it's kinetic energy decreases, causing materials being carried by the river to be deposited. Heavier objects, such as boulders, will be deposited first near the river's mouth. Small particles, such as sand and silt, will be carried farther due to their relatively smaller mass. Such delta deposits are called *alluvium*. These deposits can also form a *deltaic lobe*, effectively creating and extending a long channel into the standing water. The Saskatchewan River delta has examples of both alluvia and a deltaic lobe (here, it is in the characteristic "bird's foot" shape; see Figure 2).

As a river forms a deltaic lobe, its overall gradient decreases because it's length increases while it's elevation change remains constant. However, as dictated by nature, water in the lobe will want to achieve the lowest energy state possible. Therefore if it can breach the lobe walls during a flood or particularly high tide, the river will favor this newly created path. The lower gradient of the deltaic lobe causes a decrease in the river's velocity and therefore an

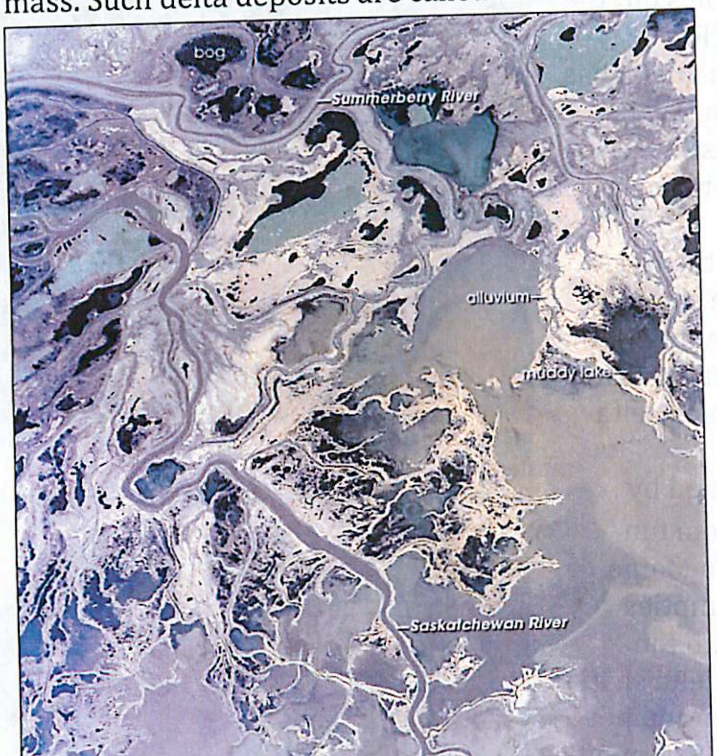

Figure 2: Saskatchewan River Delta, Manitoba, Canada. (http://earthobservatory.nasa.gov/IOTD/view.php?id=8167)

increase in sediment deposit, making it easier for the river to breach the walls of the lobe. This process, called *avulsion*, can occur repeatedly, resulting in the creation of many branches for a particular delta.

Material deposits at the mouth of a river can alternatively form deltas. The river will be forced to flow around the deposits and effectively split into two new branches.

III. Types

digitate delta – a river-dominated delta typically found on sediment-river rivers flowing into lakes resulting a main channel dividing itself into many channels. An example is the Mississippi River delta and the Saskatchewan River delta.

wave-dominated delta – as the name implies, the formation and hence shape of the delta is dominated by waves in the stationary body. These deltas tend to have the stereotypical Δ shape. Can be further described as a *cuspate* or *arcuate* delta. An arcuate delta is where the delta has many channels, but wave action smoothes out the coastline. An example is the Nile River delta. A cuspate delta is where the delta has typically only one distributary and wave action is stronger so that the coastline is pushed back around the delta, forming a "tooth" shape (see Figure 3).

tide-dominated delta – as the name implies, the formation and hence shape of the delta is dominated by tides in the stationary body. Typically exhibit dendritic structure. An example is the Ganges delta (see Figure 4).

Gilbert delta – a delta formed by course-grained sediments. Random fun fact: Gilbert deltas are frequent in Maine.

estuary delta – the river empties into an estuary which empties into the larger body of water so that the delta shape is due to the widening of the river and not as much the deposit of sediment. Sediment can be deposited in the estuary. An example is the Seine River as it empties into the English Channel (see Figure 5).

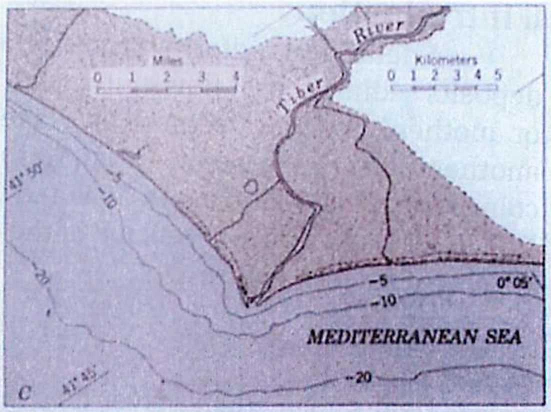

Figure 3: The Tiber River delta, a cuspate delta. (http://www.americaswetlandresources.com/background_facts/detailedstory/RiverDelta.html)

Figure 4: The Ganges River delta, a tide-dominated delta. (http://eol.jsc.nasa.gov/debrief/STS066/rep2.htm)

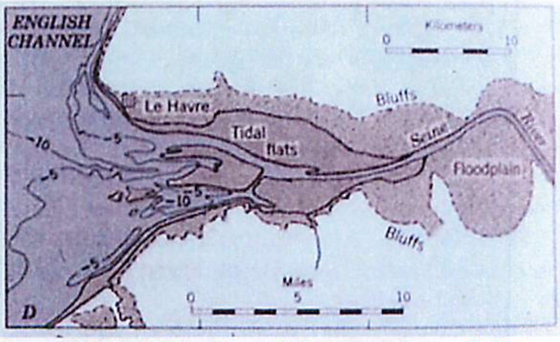

Figure 5: The Seine River delta, an estuary delta. (http://www.americaswetlandresources.com/background_facts/detailedstory/RiverDelta.html)

inland delta – when a river forms a delta on land and does not necessarily immediately flow into a larger body of water. The channels can rejoin prior to flowing into the larger body. Such deltas occur on the Amazon River.

IV. Sizes

There seems to be a rough correlation between a delta's size and its drainage basin. However, the strength of the delta's river relative to the strength of the larger body of water does factor into the delta's size.

IV. Sediment Divisons

Delta sediment is divided into three types:

bottomset – smaller grains that are carried the farthest by the river into the larger body of water

foreset/frontset – larger sediments that roll along the main channel; deposit on top of the bottomset as the delta advances

topset – smaller sediments that deposit when the foreset is no longer desposited; overlays the foreset

V. Deltas are Awesome because...

- The sand and gravel they deposit can be used for aggregate.
- Sources of water (deltas can reach aquifers and feed other bodies of water).
- Provide nutrient-rich farmland.

Alluvial Fans

I. Introduction

Alluvial fans are fan-shaped features created as a stream (which is typically fed by temporary sources, such as flash flooding in desert conditions) transitions from a steep slope (such as a canyon) onto a flat region (such as a plain; see Figure 6). They do not necessarily have running water in them all the time. Fun fact: a compound alluvial fan (where two alluvial fans merge into one) is called a *bajada*.

Figure 6: An alluvial fan in southern Iran. (http://earthobservatory.nasa.gov/IOTD/view.php?id=36041)

II. Formation

As a stream flows down a slope whose gradient is decreasing, the stream's velocity will decrease. The stream will thus have less energy to transport sediment, causing larger sediment to fall out. This sediment will divert the stream into many different paths, causing a fan shape.

III. Alluvial Fans vs. Deltas (and Mars)

Admittedly, the line between deltas and alluvial fans seems to be blurred. It appears that deltas typically are created by rivers that have a small gradient and empty into another body of water while alluvial fans are created by streams with a large gradient that empty out onto a plain. However, according to WaterWiki.net, alluvial fans can also be called inland deltas, adding much confusion to the whole situation.

Moore & Howard (2005) have found alluvial fans on Mars (see Figure 7). They define alluvial fans as "discrete landforms created by the deposition of loose, water-transported material forming broad, gently sloping ramps radiating from mountainous drainage outlets emerging into low-relief basins". However, if it can be proved that these structures actually once emptied into a larger body of water, they would likely be reclassified as deltas.

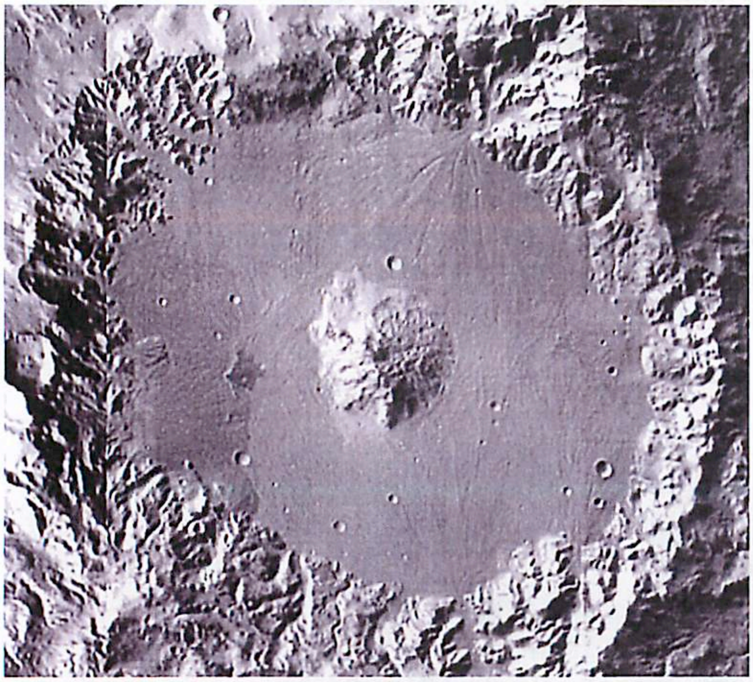

Figure 7: Martian crater containing alluvial fans. The central peak ~10 km. (Moore & Howard 2005)

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Fluvial Bedforms and Deposits

Colin Dundas

Figure 1: Sinuous and linguoid current ripples (Leeder, 1999)

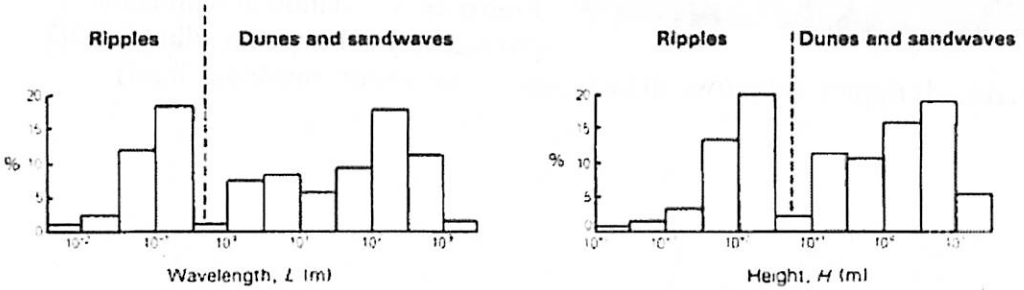

Figure 2: Aqueous dune and ripple morphometry (from Collinson and Thompson 1989, after Allen 1968)

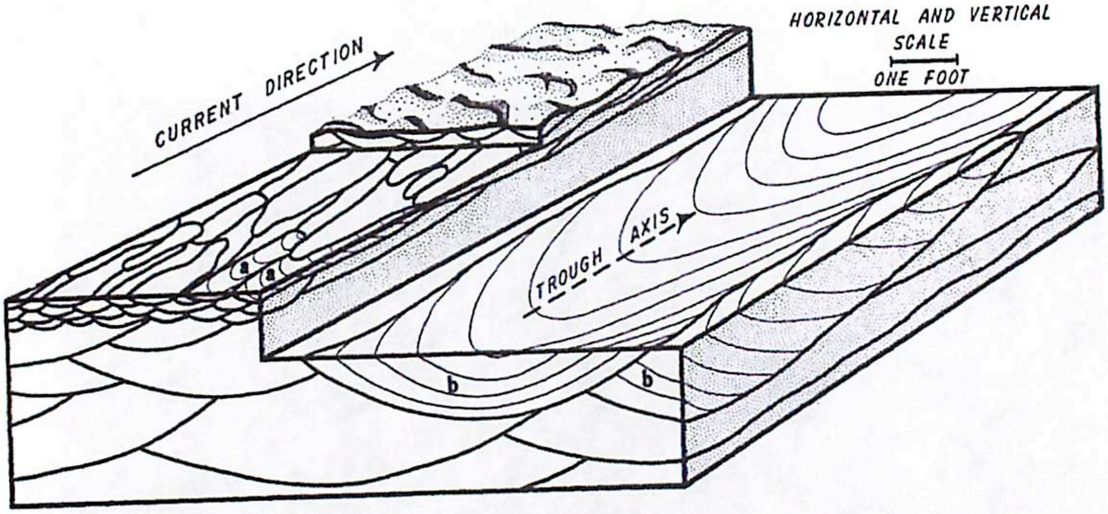

Figure 3: Block diagram of trough cross-bedding and cross-lamination at multiple scales, with cuspate ripples shown at the top. (Harms et al., 1963)

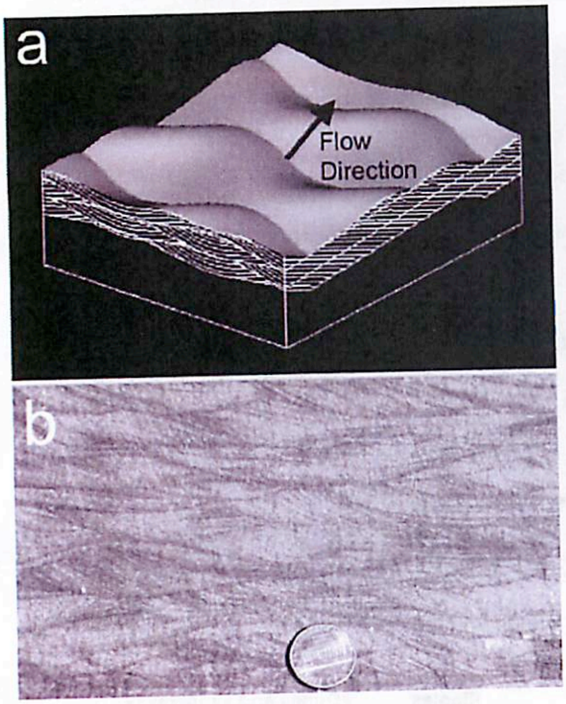

Figure 4: a) Computer simulation of lamination produced by migrating ripples with sinuous crests. b) Example of the lamination modeled in (a). (Grotzinger et al., 2005)

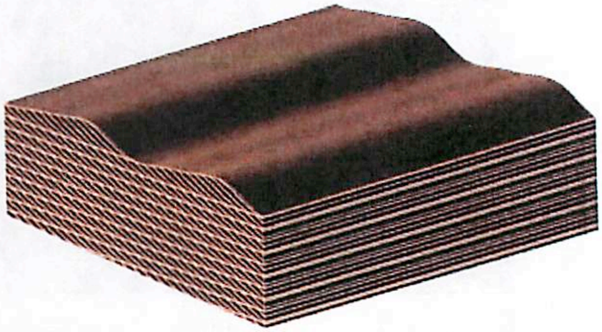

Figure 5: Simulation of lamination produced by subcritically climbing 2D (straight-crested) ripples. (http://walrus.wr.usgs.gov/seds/bedforms/index.html)

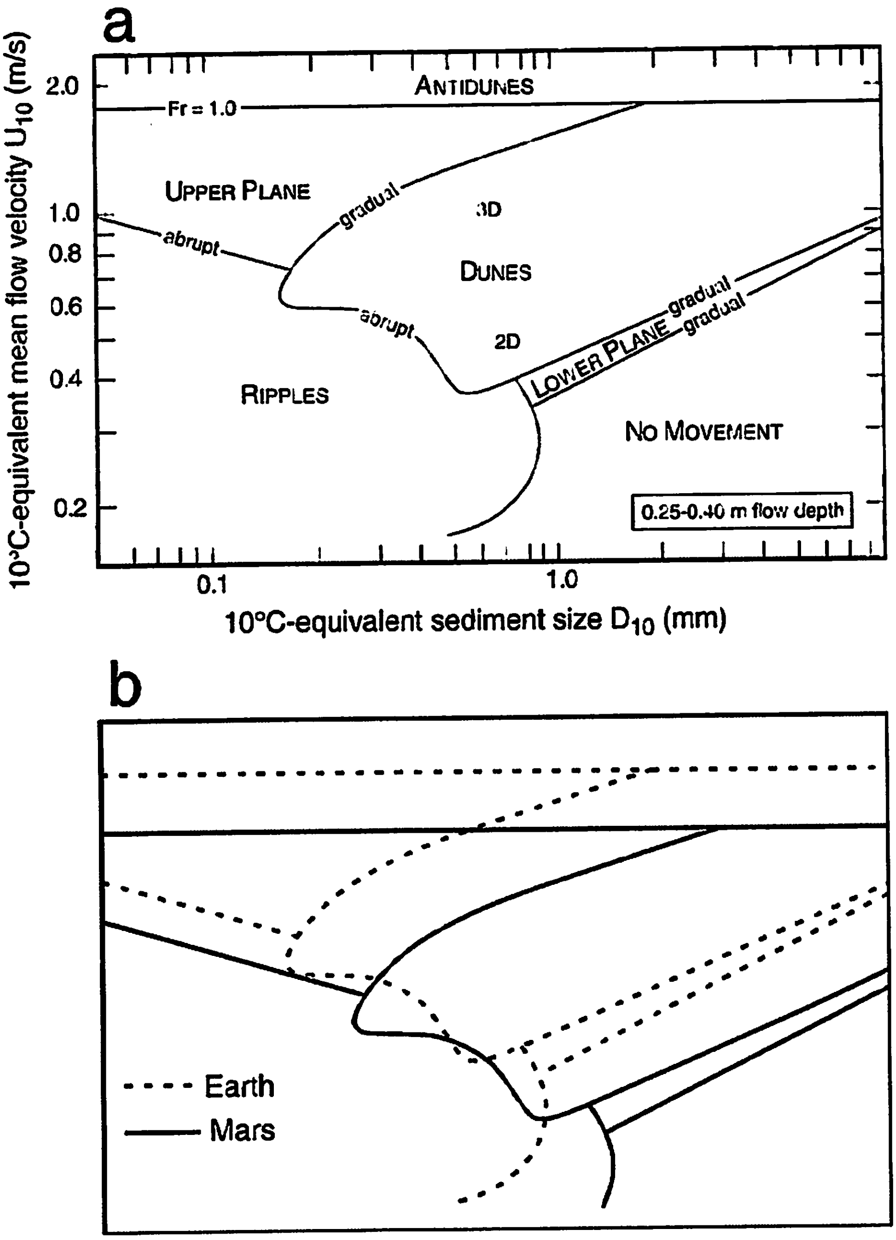

Figure 6: (From Grotzinger et al., 2005) a) Bedform phase diagram. The main (but not only) parameters affecting the type of bedform are the sediment size and the flow velocity. Viscosity (which is temperature-dependent) also matters, but let's not go into too much gory detail. b) Rescaled for Mars using dimensionless velocity and grain size and adjusting for reduced Martian gravity. The Froude number is $Fr = u/\sqrt{hg}$, where u is flow speed, g is gravitational acceleration and h is a length scale. This is effectively the ratio of inertial to gravitational forces. The basic point is that things are different on Mars, but not fundamentally so.

Some Concepts:

- Fluids move sediments when momentum is extracted from the fluid flow and imparted to sediment grains. This is fundamentally controlled by the shear stress at the surface of the sediment (the base of the fluid). Turbulent shear can loft particles away from the surface and into the main flow.
- Particle motion begins when the flow velocity exceeds some threshold, which varies depending on the grains.
- Grains move by rolling, saltating (hopping along more-or-less ballistic trajectories), or suspended in the flow.
- The loads transported by a flow can be divided into the bed load (rolling and saltating), the suspended load (held up by turbulent eddies) and the wash load (very fine suspended sediment).

Bedforms:

- The smallest bedforms in fluid flow are ripples, up to a few centimeters high and a few decimeters apart (Fig. 2). These can be straight, sinuous or linguoid (tongue-like). Coarse sediment forms planar beds rather than ripples.
- Dunes are similar to ripples in shape, but larger—discontinuously so.
- At high energy, "upper-stage" plane beds and antidunes form. Antidunes are symmetric, rounded, and migrate upstream. Antidune bedding is rarely preserved because high-energy-flow deposits tend to be reworked into lower-energy deposits when the flow wanes. They form when the Froude number Fr > 0.84.
- Why ripples and dunes at all? There is still active research on the formation and evolution of bedforms (for instance, see Raudkivi, 2006 and comment by Best and Robert). The basic story is that small defects on the surface lead to flow separation, forming hummocks and ridges that both propagate downstream and cause additional instabilities. The transition from ripples to dunes may be connected to the random formation of particularly large 'rogue' ripples able to form large-scale eddies.

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http://walrus.wr.usgs.gov/seds/bedforms/index.html
(This website has nice animations of the bedding structures produced by various bedform shapes, including movies where simulations are morphed to real sediments.)

$\frac{d}{dx}(32x)$

How to tell the difference between Aeolian and fluvial sandstone
by Tiffany Kataria

Eolian sandstone

Contain a smaller range of sediments. Quartz grains in air, for example, have a particle size/medium ratio greater than 2000:1 (Willett 1998).

Turbulent mixing lasts for thousands of km in air; sandstone grains tend to be more well-rounded

Tendency for laminae to dip in the direction opposite to dune movement

Laminae is mainly horizontal

Greater dispersion of dip directions of cross sets

For fine to medium sand cross strata with slipfaces less than 2 m high…
- Grain segregation is typically less distinct
- Cross-strata are more separated
- Cross-strata are thinner than the slipface height and have well-defined edges
- Dunes composed of coarse sand are rare

For fine to medium sand cross strata on relatively low slipfaces…
- Grainfall deposits (formed by settling out of suspended or saltating grains) are more common
- Cross-strata is narrower

Less likely to contain fossils

Both

Grains may saltate, roll and hop before being deposited, or remain in the medium for a prolonged amount of time by turbulent mixing before being deposited.

Sand flow cross strata form by the avalanching of non-cohesive sand down a slip face

Both possess “first dislodgement” grains that must overcome the stability of their weight in comparison with each other.

For fine to medium sand cross strata…
- Similar dip angles

Fluvial sandstone

Contain a larger ranger of sediments. Quartz grains in water, for example, have a particle size/medium ratio greater than 2.6:1 (Willett 1998).

Turbulent mixing lasts for hundreds of km in water; sandstone grains are less well-rounded

Upcurrent dip direction of laminae is not as pronounced

Laminae is rippled

Lesser dispersion of dip directions of cross sets

For fine to medium sand cross strata with slipfaces less than 2 m high…
- Grain segregation is typically more distinct (partly because of the greater size range of sediments transported by fluvial means)
- Cross-strata are in contact with one another, extending from the top to the bottom of the slip face
- Cross-strata are typically wider than the slipface height and have poorly defined edges
- Dunes composed of coarse sand are common

For fine to medium sand cross strata on relatively low slipfaces…
- Grainfall depositions are less common (avalanching is more continuous)
- Cross-strata is wider

May contain fossils (brachiopods, corals. Gastropods. algae. etc)

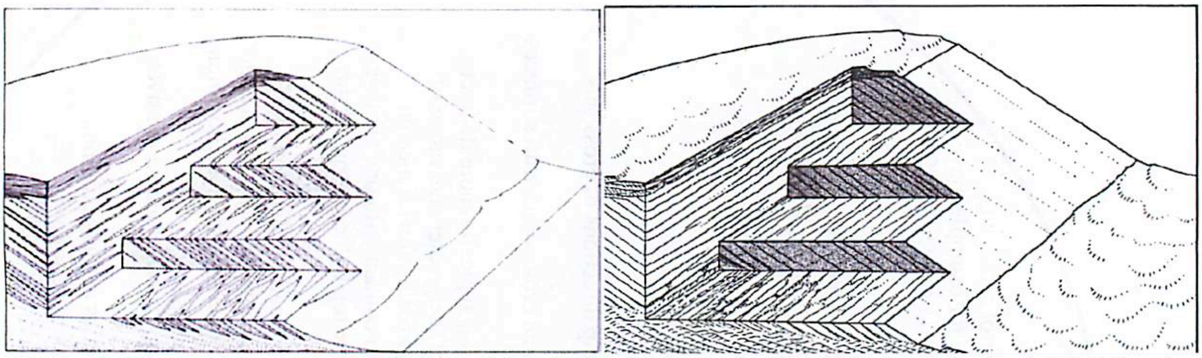

Figure 1: Comparison of eolian (left) and fluvial (right) cross bedding. Note that alluvial bedding is stippled, and has a distinct edge, while fluvial cross bedding is more rippled and has a poorly defined edge (Hunter 1977 and Hunter 1985).

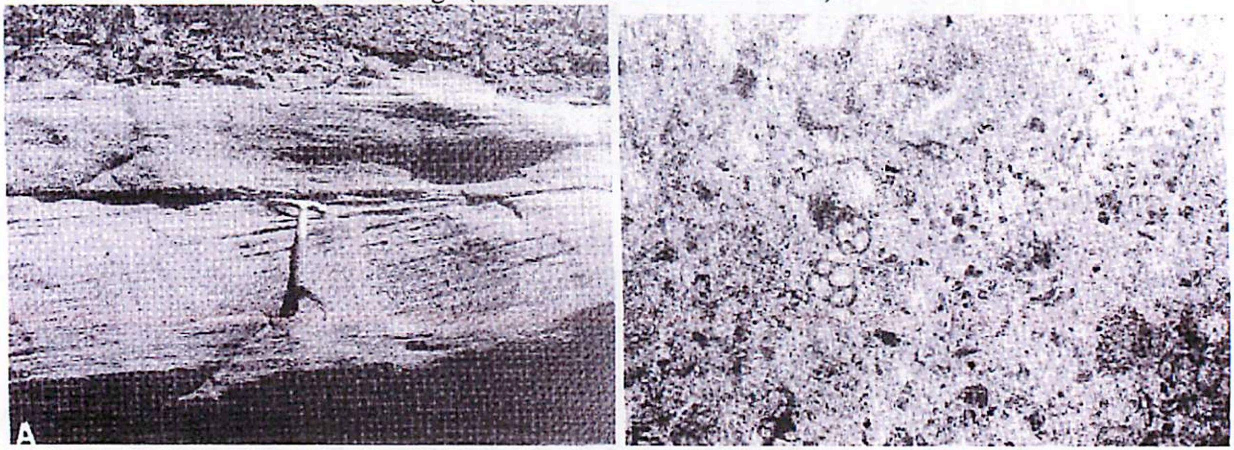

Figure 2: Comparison of eolian (left) vs fluvial (right) sandstone at Caballo Mountain. Note that the eolian sandstone has horizontal layering, and the fluvial sandstone contains diverse fauna.

Also: White Sands and its application to Mars stratigraphy

Gypsum sands at White Sands, New Mexico, are an excellent analog to eolian outcrops seen at Meridiani Planum on Mars. The MER Opportunity Rover identified polygonal cracks in the outcrop that crosscut bedding and extend along boulders; such features are also seen at White Sands (comparison below). Based on analyses at White Sands, the cracks seem to form after evaporation of water, which leads to the cementation of sand and shrinking of the sand volume (Chavdarian and Sumner, 2006). Such a process may be taking place on Mars.

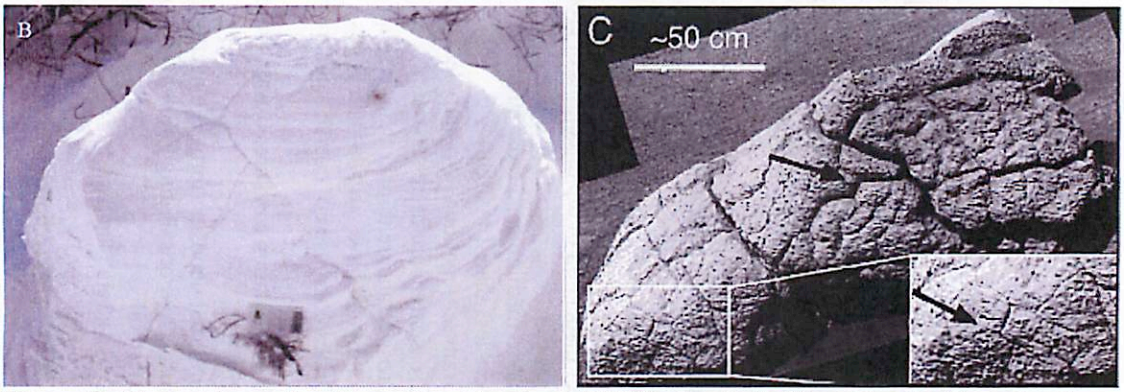

Figure 3: Comparison of polygonal cracks seen at White Sands (left) and by the Opportunity rover on Mars (right).

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Lithification

Jamie Molaro, Spring 2010

Lithification is the process by which sediments become rocks. When sediments are first deposited, they are unconsolidated and contain pore space. Lithification primarily involves compaction, the rearrangement of these sedimentary particles to reduce pore space. Larger grained materials such as sand and gravel are heavy enough to settle with minimum pore space. Finer grained materials such as clay and mud typically contain more pore space. Over time, if/as more material is accumulated, the thickness of the deposit, and thus the overburden weight, increases. The pressure on the buried sediments eventually causes the grains to be compressed together as tightly as possible.

As this occurs, connate fluids may be expelled from the consolidating sediments. Connate fluids are usually largely composed of water, but may contain dissolved minerals as well. Minerals in these fluids precipitate out, cementing the deposited grains together. Once cemented, the sediments are considered consolidated rock. In addition, some sediments may be in environments where external fluids may be circulated through the rock, either as a result of pressure and temperature conditions, unrelated groundwater flow, or underwater location. These fluids also carry dissolved mineral material that can be deposited into any remaining pore space within the sediments, helping the cementation process.

The most common cementing materials are calcium carbonate, silica, and iron oxides. Calcium carbonate cement is usually in the form of calcite. Silica cement is dominantly quartz but also can be chert or chalcedony. Iron oxide cements occur in the form of hematite or limonite. In many rocks, tiny inclusions of connate fluid may still be found. These inclusions provide direct information about the composition of the fluid and the pressure-temperature conditions that existed during diagenesis of the sediments.

Different types of deposited materials will become different consolidated rock types. The process of lithification can take on the order of hundreds of thousands of years, but will vary with the physics of a particular environment.

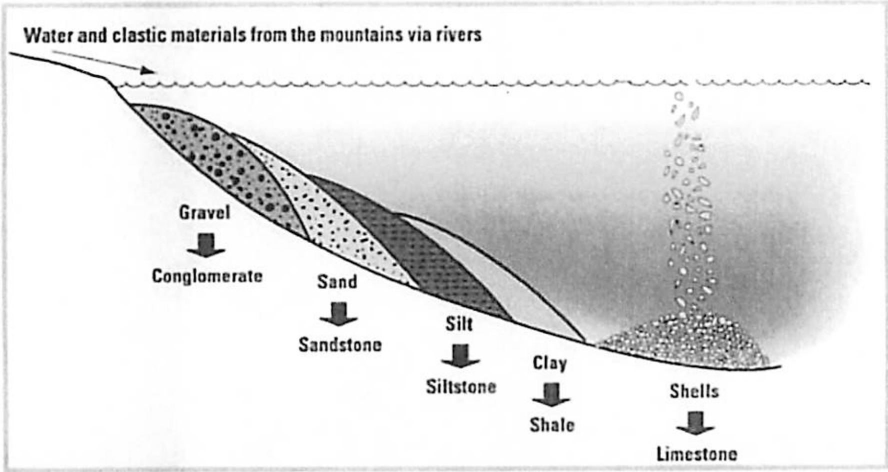
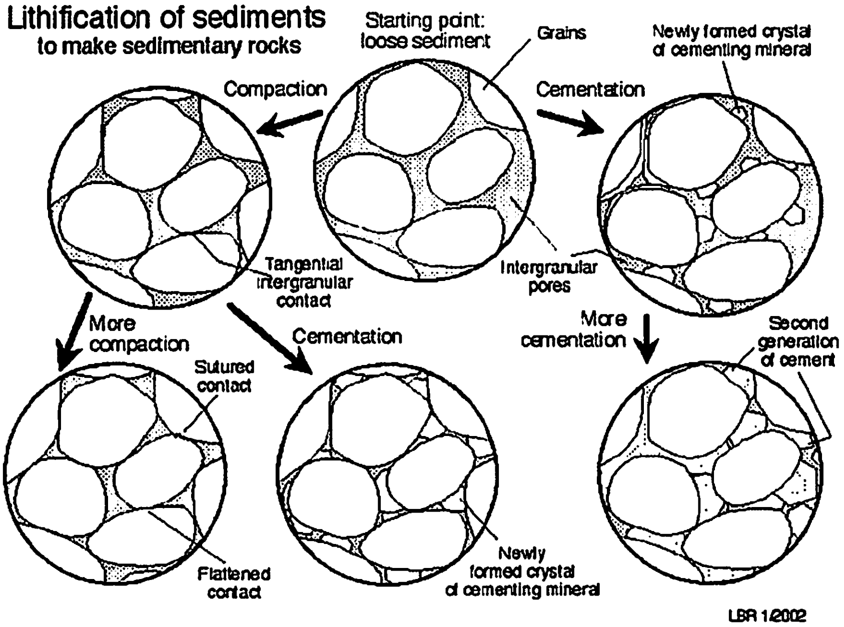


Fig. 2–9. Sediments to rock. Various size classes of sediments become different rocks after lithification.

Some sediments may also be lithified by recrystallization, rather than by cementation. This is important in the formation of limestone, and some shales. In this process, mineral grains will recrystallize in response to some change in their chemical environment, such as a rise in the pH level. As grains recrystallize and grow together, they form new interlocking grain boundaries binding the sediments into rock. Recrystallization can also occur due to a change in temperature, such as when lava cools and becomes solid.



Fossilization and petrification are often confused with lithification. These processes involve either the filling of pore space within an organism with mineral material continuously until the organism is completely dissolved, or the replacement of organic material itself with mineral material over time. These processes do not convert the organic material into rock, but simply provide a mold or cast for the minerals to precipitate into, forming the shape of the organism that died.

Due to Earth's plate tectonics and weather, deposition and lithification of material is happening constantly. If the deposition material (or geometry, or chemistry, etc) in an area changes over time, a layer of new material will overlay the original. Eventually both layers may be lithified but will become different rocks or have different structure. This lithologic stratigraphy in rocks can give us clues as to the history of a rock and the area where it came from and where it formed. Lithification can also occur on other terrestrial planets. On Venus, for example, volcanic activity causes layering of lava flows. If stratigraphy could be studied on Mars it could certainly be very enlightening. We see evidence of oceans and liquid water processes on Mars today. Those processes could have left behind a stratiographic record, as Earth has, giving clues to its history.

Sources:
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Geomorphology of Dunes

Patricio Becerra

Aeolian Sand Transport

Transport of sediment by the wind involves interactions between the wind and the surface of the ground. There are three modes of aeolian transport that depend primarily on the grain size of the available sediment (Fig. 1): Suspension (*<60-70* microns), saltation (60-500 microns, or sand-size), and reptation or creep (>500 microns).

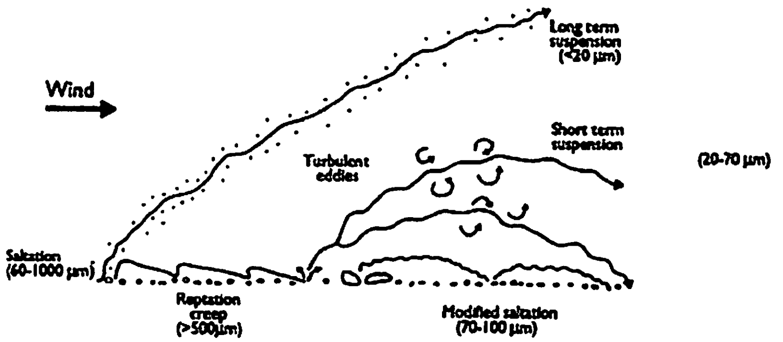


Figure 1. Modes of Aeolian sediment transport (from Lancaster 1995, after Pye 1987)

Two factors are necessary to accumulate sand into dunes: An adequate supply of sand, and winds that are strong and persistent enough to move the sand. Generally, sand will tend to accumulate in any site "where a sufficient reduction of wind energy exists along the direction of sand drift in an active system" (Fryberger and Ahlbrandt, 1979). Any obstacle that can lower wind speeds enough , can force sand accumulation. However, obstacles are not needed. According to Bagnold (1941), who published the single major work on dune formation and aeolian transport, sand "alone of all artificial solids has the power of self-accumulation". This "power" results from two processes: The difference between the saltating speed of sand over sandy and non-sandy surfaces, which produces a slower downwind movement of sand; and the drag effect of saltating sand grains on the wind velocity, which translates into strong winds favoring sand accumulation in already sandy areas.

Dune Morphology and Classification

The morphology of dunes reflects two primary environmental characteristics: The properties of the sediment (grain size), and the surface wind (shear stress and directional variability). The well known morphological classification of McKee (1979) groups dunes based on the number of slip faces, assuming that this number corresponds to the number of dominant wind directions:

1. Single Slip-Face or Crescentic: Simplest dune types. Their axes are perpendicular to a persistent unidirectional wind-regime. There are two sub-types:
    a. Barchanoid-type Dunes: Can be subdivided into barchan, barchanoid ridges, and transverse dunes (Fig. 2 A,B). Their primary difference is the amount of sand available for formation.
    b. Parabolic Dunes: Crescentic form opposite of barchan. Develop when vegetation anchors the "horns" of the dune (Fig. 2C)

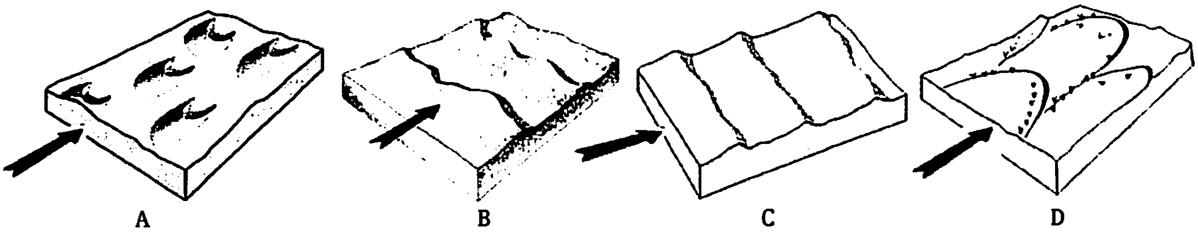


Fig. 2. Single slip-face dunes. Arrows indicate predominant wind direction A) Barchan. B) Barchanoid Ridges. C) Transverse. D) Parabolic

2. Two Slip-Faces: Dual slip-face structure due to winds from two different directions. There are two sub-types:
    a. Linear (Seif) Dunes: Most common type of dune on Earth. Characterized by their length, parallelism, regular spacing and high ratio of dune to interdune areas (Fig. 3A).
    b. Reversing Dunes: Found in areas of bimodal winds from opposite directions. Generally very short lived (Fig. 3B).

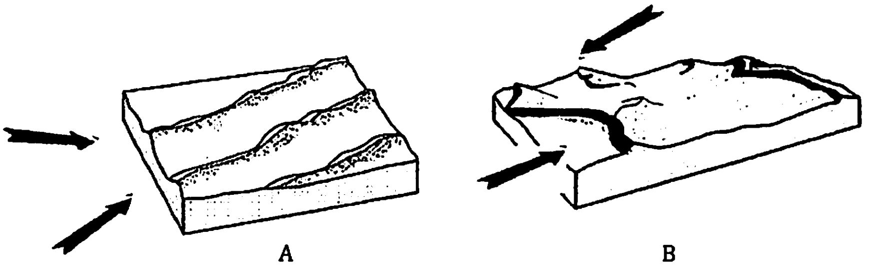


Fig. 3. Dual slip-face. A) Linear or seif dunes. B) Reversing dunes.

3. Multiple slip-faces (>2) or Star Dunes: Generally occur as a central peak with three or more radiating arms, each with a slip face in a different direction (Fig. 4).

4. Dome-shaped dunes: Low, circular dunes that form mounds on the upwind sides of the margins of sand deposits (Fig. 5).

McKee also discusses a second type of dune classification, by which each type of dune mentioned above can occur in three varieties: Simple dunes (basic form of each dune type), compound dunes (superposition of dunes of the same morphological type), and complex dunes (dunes of two types are superimposed or merged.

It is important to note that Lancaster (1995, p.197) concluded that sediment characteristics play a minor role in dune type formation and that the primary control of dune types is the local wind regime. Crescentic dunes occur in unimodal wind regimes, linear and reversing dunes in bimodal winds, and star dunes in complex wind regimes (dome-shaped dunes are rare, and occur only on the margins of sand seas).

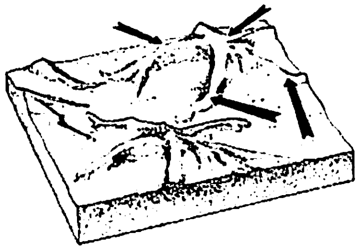


Fig. 4. Star Dunes

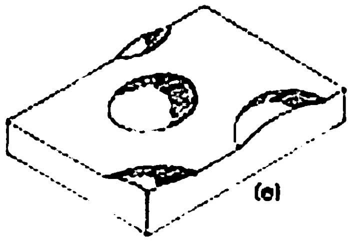
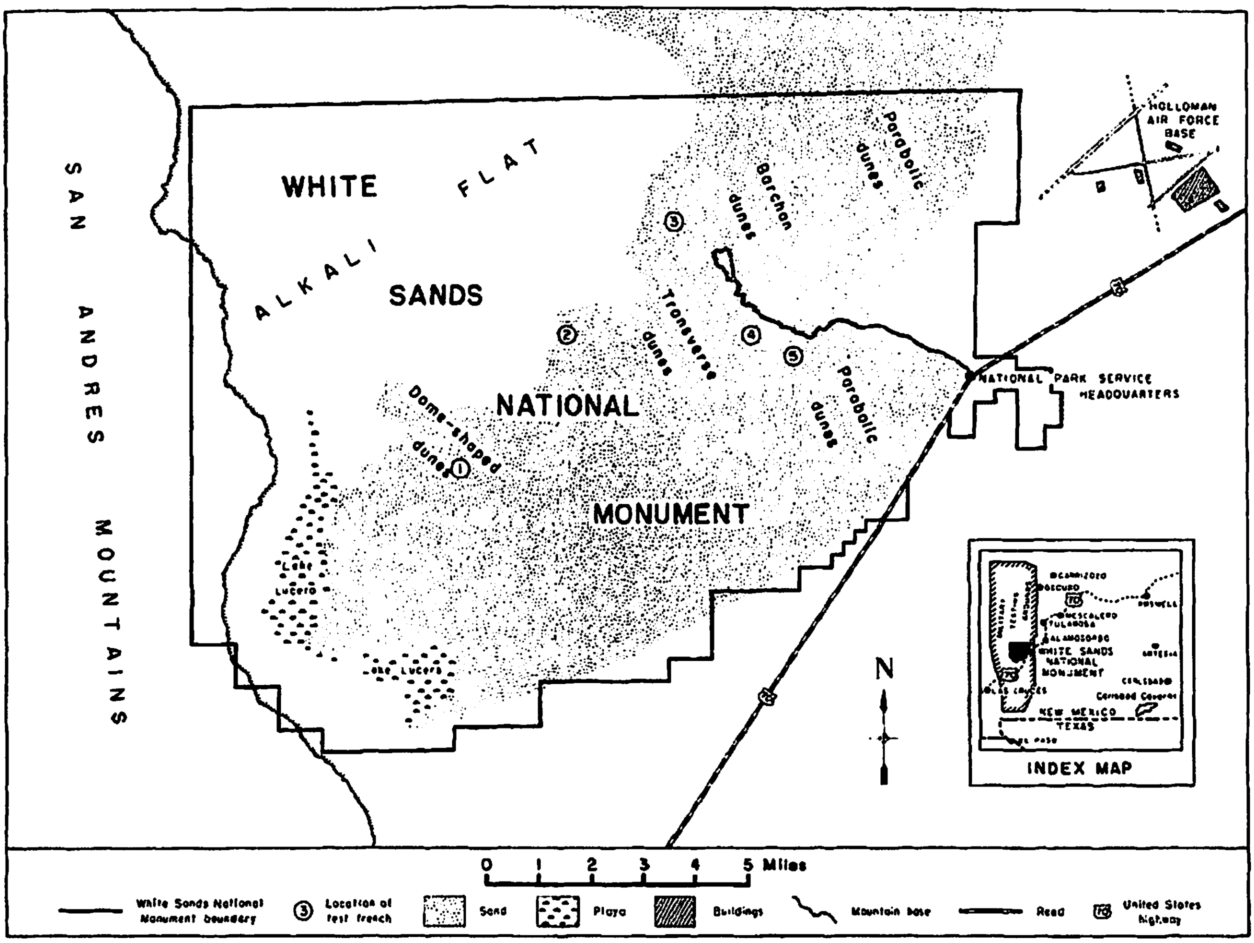


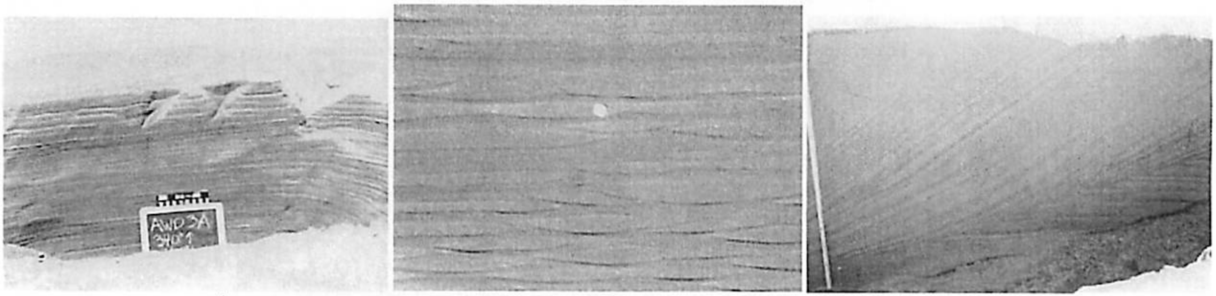
Fig. 5. Dome-shaped dunes

Distribution of Major dune types in White Sands National Monument (Map 1)



Sedimentary Structures of Major Dune Types

There are three primary modes of deposition on dunes, which form three types of Aeolian sedimentary structures: (1) Migration of wind ripples form climbing translatent strata (Fig. 6A). (2) Fallout from temporary suspension of grains on the brink of the dune forms grainfall laminae (Fig. 6B). (3) Lee slope avalanching forms grainflow cross-strata (Fig. 6C).



A B C

Fig. 6. Primary sedimentary structures in dunes. A) Wind ripple laminae or climbing translatent strata. B) Grainfall laminae. C) Grainflow cross-strata

1. Crescentic Dunes: Dominated by grainfall and grainflow cross-strata deposited on the lee side and preserved as the dune migrates downwind.
2. Linear Dunes: Composed of varying proportions of wind ripple and grainflow laminae. Dunes in areas where formative winds blow at a shallow angle to the dune have a higher percentage of wind ripple laminae
3. Star Dunes. Also composed of varying amounts of wind ripple and grainflow strata.

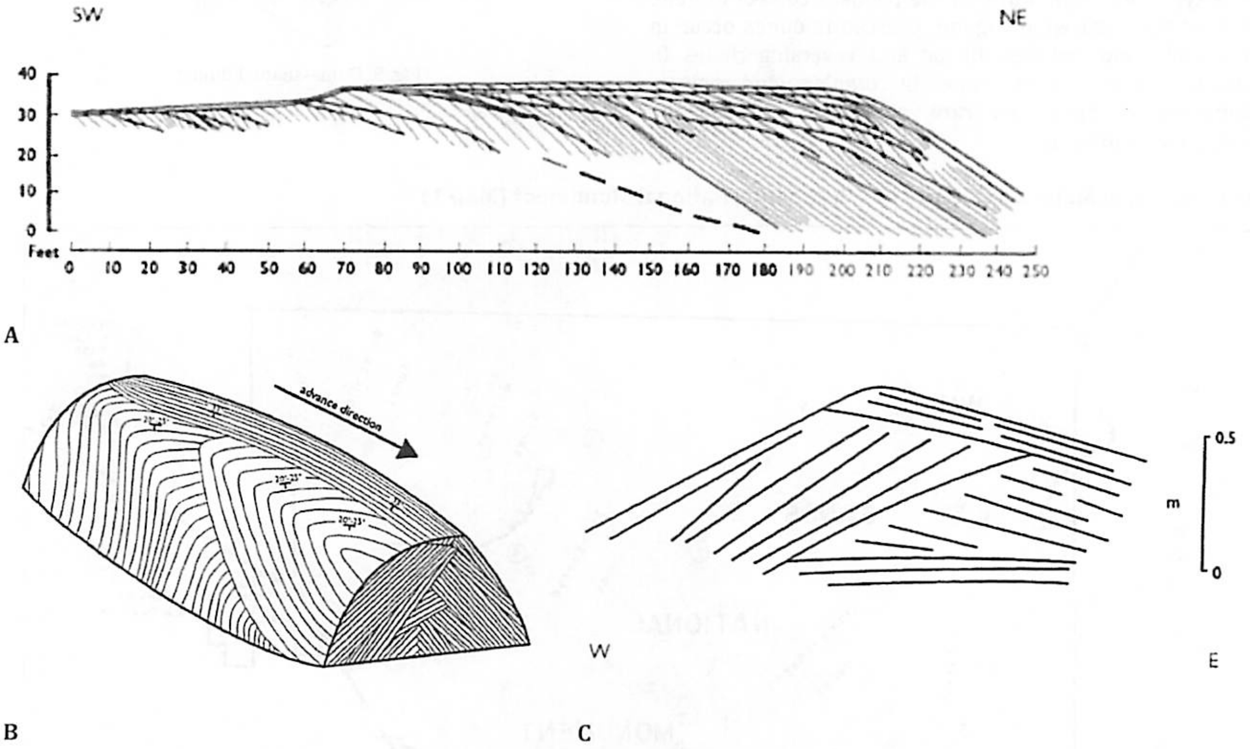


Fig. 7. Stratigraphic structure in the three major dune types. A) Crescentic dune in White Sands. B) Model for linear dune structures. C) Star dune in Namibia.

Planetary Connection

Most types of dunes are observed on all terrestrial bodies that posses a thick enough atmosphere, strong enough winds and a considerable supply of sand-sized sediments. i.e. all terrestrial bodies with an appreciable atmosphere: Venus, Earth, Mars, and Titan.

40!

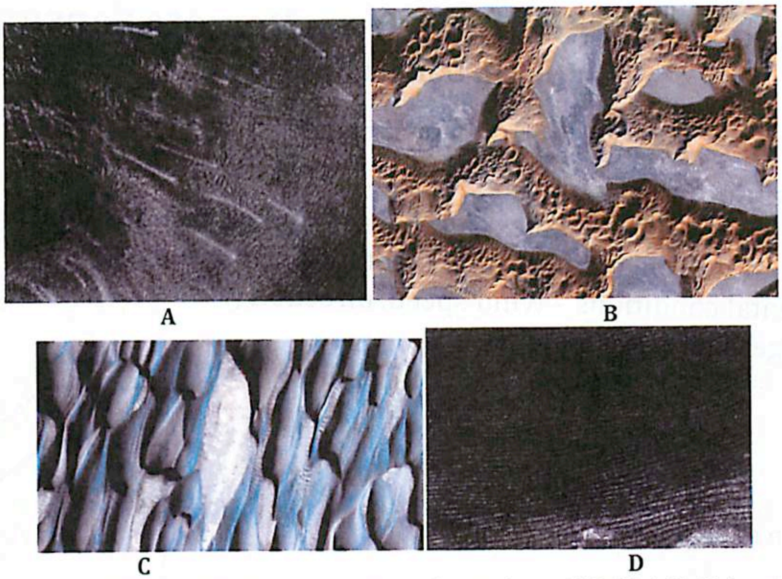


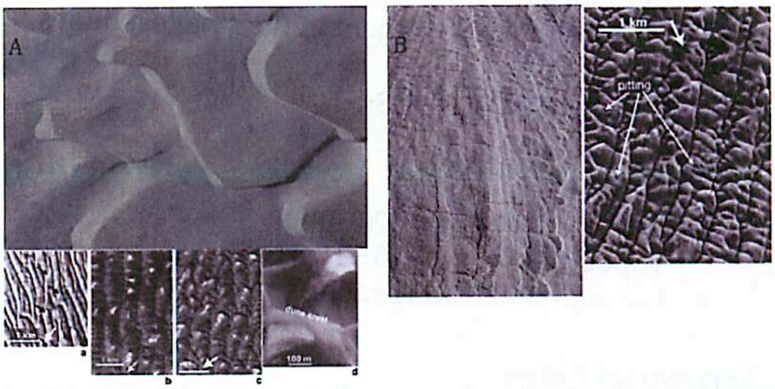
Fig. 8. Examples of dune fields on different planetary bodies. A) Venus' linear dunes. B) Rub' al Khali desert in the Arabian Peninsula (Earth). C) Dunes in Abalos Undae, Mars. D) Linear dune field on Titan.

White Sands as a Potential Terrestrial Analog to North Polar Dunes on Mars

Synkiewicz et al. (2008) compared morphological features of gypsum dunes in White Sands to those of the gypsum-rich dunes of Olimpia Undae (North Polar Erg). They found bright patches of new gypsum deposits in White Sands after a monsoon season in 2006 that closely resemble patches observed in the interdune deposits of many areas of the north polar erg. In addition, they found similarities between dessication cracks observed at White Sands after the 2007 summer, and examples of eroded and possibly indurated dunes within Olympia Undae.

Fig. 8. Comparison of White Sands Gypum Dunes to dunes in Olympia Undae.

A) Comparison of bright patches associated with new gypsum deposits.
B) Comparison of cross-cutting dessication cracks



Fun fact: Dunes on Earth are great for sandboarding. This sport is very similar to snowboarding, but in much hotter weather and with much more painful wipe-outs. It is very popular in my native Peru, where the largest dune in the world, the Cerro Blanco draa is located.

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Dune Migration Rates from Remote Sensing

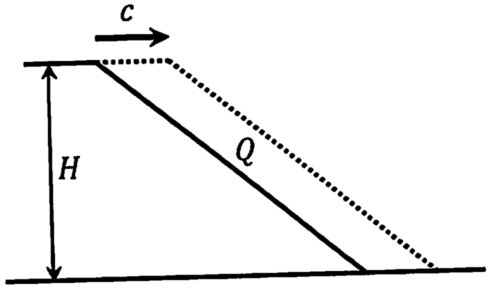
Ingrid Daubar Spitale

Why do we care about migration rates?

- Material properties & processes – grain size, sorting, composition, moisture/ice content, modification, induration/cementation, armoring…
- Environmental conditions – wind speed, direction (reversals), precipitation…
- History – age, sources, supply…

THEORY:

$$cH = Q/\gamma$$



After Bagnold (1941) Fig. 71d

c = rate of advance of slip face
H = dune height
Q = rate of sand flow at the crest
γ = specific weight of sand (gravity-dependent) = ρg

→ Rate of advance proportional to rate of sand movement at crest.
Inversely proportional to dune height, density of sand, & gravity.

All else being equal, higher (larger) dunes should move more slowly.
(Supported by terrestrial data.)
→ Look for the most movement in the smallest dunes.

MEASUREMENT METHODS:

Remote sensing

- Aerial (orbital) photography
- Topography e.g. LiDAR (Earth)
- Ground-penetrating radar

Ground truth

- Trenching → measure layer thicknesses
- Stakes at dune crests/toes
- Age dating of samples (time since burial)

Terrestrial Rates:

- Movement is sporadic, large day-to-day and spatial variations.
- Maximum: as much as several meters/day measured during storms.
- Averages: ~10-30 m/yr in warm deserts; ~0.05-3 m/year in cold deserts.

WHITE SANDS

McKee & Douglass (1971) used stakes and aerial photos spaced 6 months apart.
In aerial photos, fixed points between dunes & bushes were used for reference points.

Type of dune	*Rate of movement per year (range, in feet)*		
Embryonic (dome-shaped)	**24–38**	= 7.3-11.6 m	(western edge)
Transverse	**4–12**	= 1.2-3.7 m	
Barchan	**6–13**	= 2.8-4.0 m	
Parabolic	**2–8**	= 0.61-2.4 m	
Dunes of eastern margin	**0–5**	= 0-1.5 m	(eastern edge)

The answer to life, the universe, and everything.

- Rates for individual dunes vary a lot.
- **Fastest migration**: upwind (source) region – western edge of dune field.
- Slower toward east, until eastern edge, where no movement measured.
  - Possible causes: larger dunes, increasing vegetation, winds diminished by shielding from other dunes.
- → *Look for most movement near source.*

ANTARCTICA

- Better analog for Mars: cold & dry.
- Analog/testbed for GPR on ExoMars rover.
- Migration rates of individual dunes range from 0.05 m/yr to 3 m/yr.
- Averaged over longer time periods, migration is slower.
  - Due to increasing temperatures?
  - Or short-term rates are just more variable.
- Slower than migration in warm deserts – entrained ice, snow & reversing winds.

M.C. Bourke et al. / Geomorphology 109 (2009) 148–160

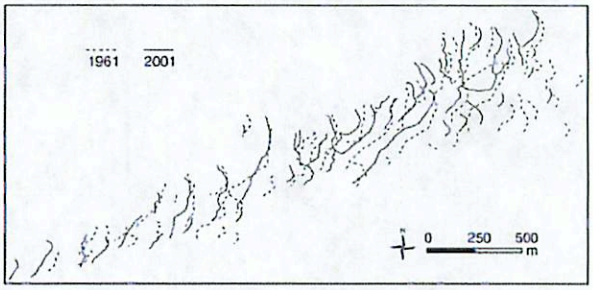


Fig. 7. Digitized crestlines from 1961 (dashed line) and 2001 (solid line).

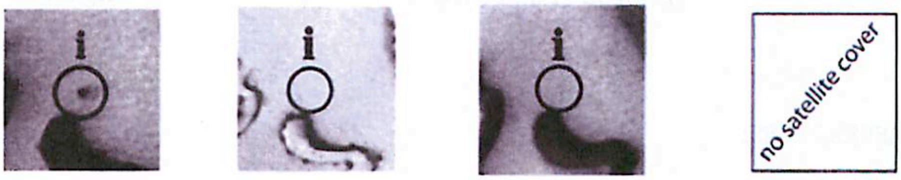
MARS

Didn't see any dune movement for many years….

- Dust raised regularly, which requires higher velocities than sand-sized particles.
- Sand grains on Spirit's deck after dust storms.
- Martian dunes *look* geologically young (sharp edges, few craters).
- So why so little movement seen?
  - Threshold wind speed to move sediment higher than on Earth; doesn't reach that speed very often.
  - Sediment is indurated/crusted? (ice, frost, precipitates, etc.)
  - High resolution + repeat imagery not available until recently.

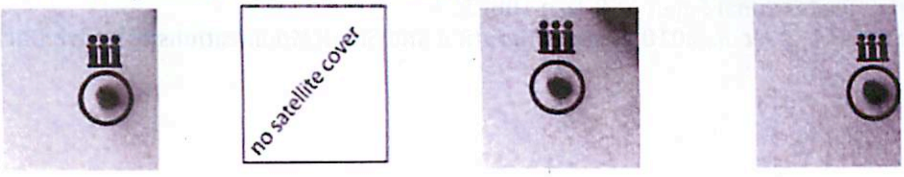
(right) MOC images showing dome dunes (~20 m wide) shrank & disappeared over 5.7 Earth years. *(Bourke et al. 2008)*

Panel 1: Change in dune i observed between 1999 and 2002



Panel 2: Change in dune ii observed between 1999 and 2004

Panel 3: Change in dune iii observed between 1999 and 2004



TITAN?

- Compositional difference – sticky organic grains?
- In order to detect movement, need high resolution & repeat imaging.

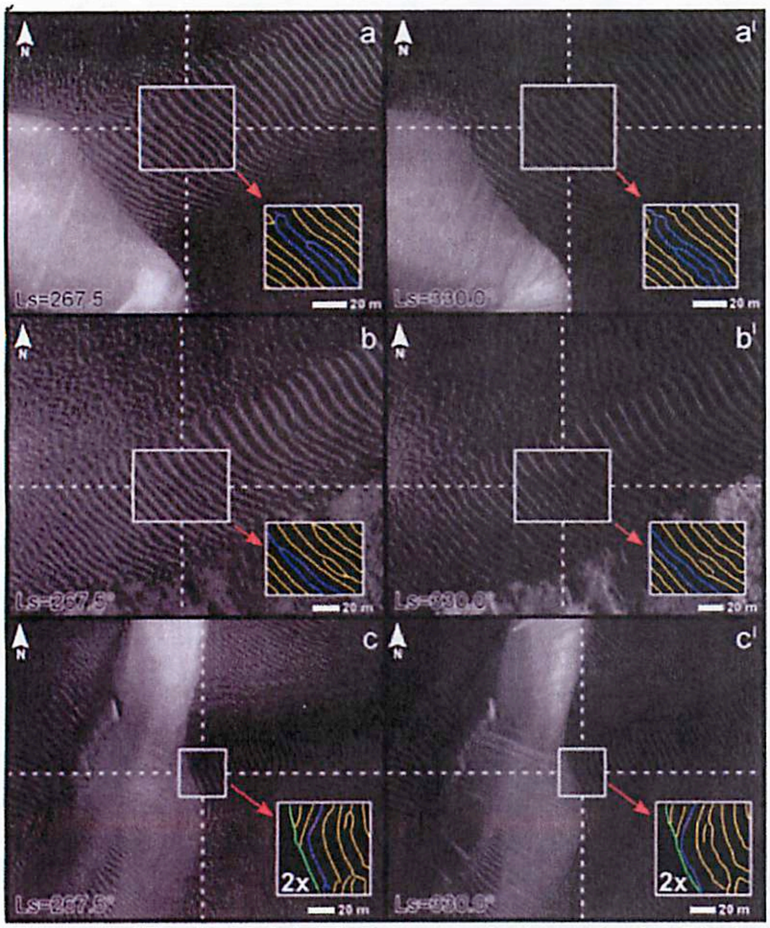


Fig. 3. Modifications of the ripple pattern in the study site. Ripples are outlined in yellow. Major changes in the ripple pattern are outlined in blue. c-c^{I}) dune crest is outlined in green. a, b, c) HiRISE PSP_004339_1890; a^{I}, b^{I}, c^{I}) HiRISE PSP_005684_1890.

(Silvestro et al. 2010)

(right) Dune movement due to gully activity (rather than saltation/normal migration) *(Diniega et al. 2010):*

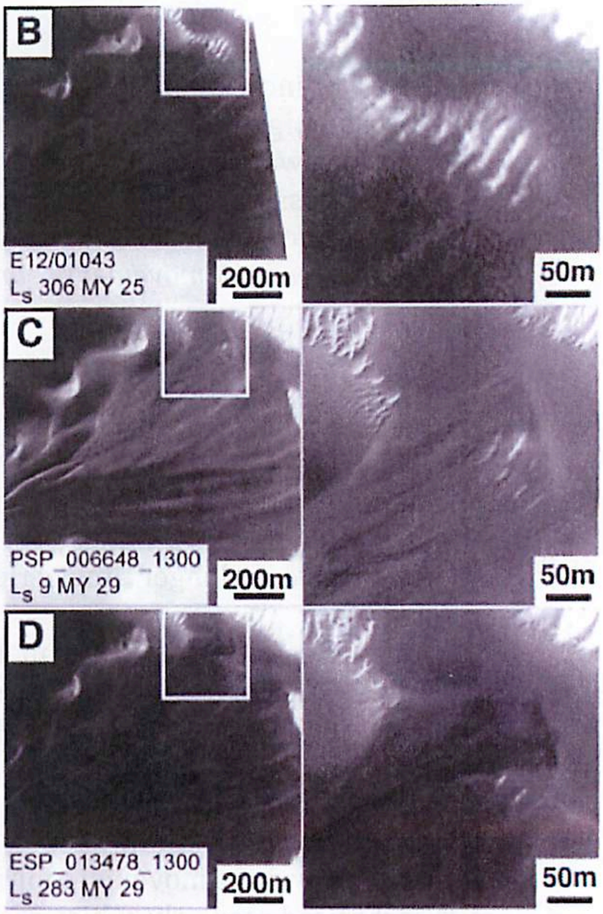


Figure 2: Portion of HiRISE image PSP_006648_1300 (A and C) containing two large classic gullies (with (i) alcove, (ii) channel, and (iii) apron) in Matara crater (49.5S, 34.9E). The bottom gully is heavily degraded, but the top gully is sharply-defined and currently active, as shown in insets: in 2002 (B), bright bedforms were visible at the foot of the debris apron. Those bedforms were increasingly covered in 2007 (C) and 2009 (D). The most recent deposit exhibits both the albedo and texture signatures of recent deposition.

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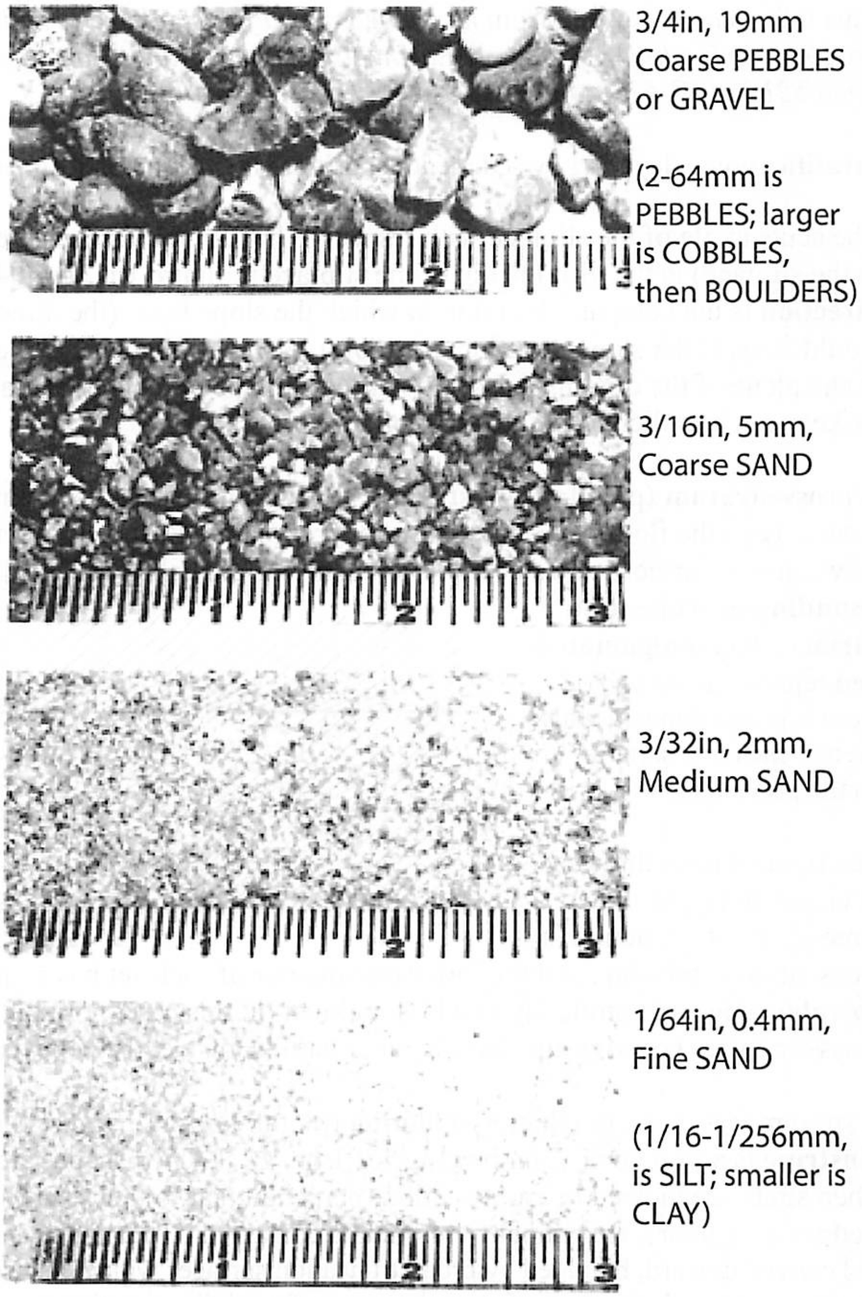
Sandstone, general information

by Serina Diniega

Sandstone is a sedimentary rock:

- *Clastic/detrital* in origin (as opposed to *organic* or *chemical*);
- composed mainly of sand-sized minerals or rock grains (Figure to right[i]), sediment that accumulates due to water or wind;
- compacted by pressure and cemented by precipitation of materials in pore-spaces (typical binding agents: calcite, clays and silica).[ii]



The existence of sandstone depends on[iii]:

Accumulation of sediment:

- mobile sand must be available, which can be affected by humidity levels and other conditions;
- sufficiently strong and consistent winds or currents that move sediment into a region;
- a drop in fluid-carrying capacity causes deposition of sediment (e.x., converging winds, topographic low);
- relatively low topography, to allow the formation of bedforms.

Preservation of deposits/stratigraphy:

- low levels of tectonic activity, deflation, or other erosion of region.
- water table variations.

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[i] *http://www.dot.state.tx.us/site_images/business/grain_size.jpg* (rulers are accurate (in))

[ii] *http://en.wikipedia.org/wiki/Sandstone*

[iii] Kocurek (1991), Interpretation of Ancient Eolian Sand Dunes, *Ann. Rev. Earth Planet. Sci.* **19**: 43-75.

Stratigraphy Terminology

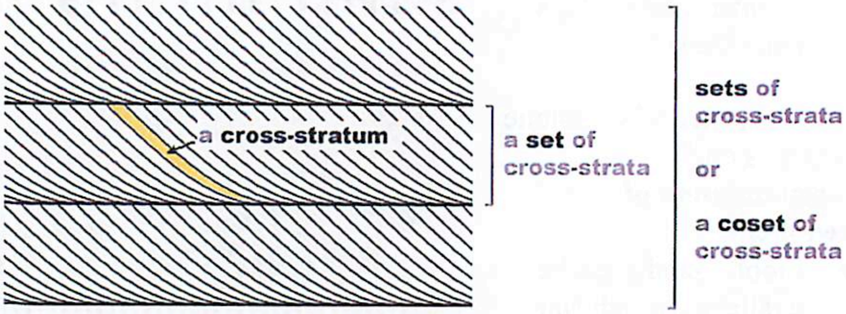
by Serina Diniega

This information is taken from *http://web.ncf.ca/jim/sand/overview/index.html* and *http://ocw.mit.edu/NR/rdonlyres/Earth--Atmospheric--and-Planetary-Sciences/12-090Fall-2006/52F3142C-6714-467D-B5D6-9BAD5E70EFBA/0/ch16.pdf.*

Stratification is layering by sediment deposition. It is a kind of sedimentary **structure.**

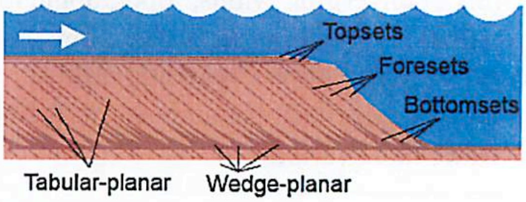
The acute angle of the slipface with respect to horizontal (as measured in a vertical plane normal to the slipface) is the **dip**; the dip of the slipface in figure 1 is about 40 degrees. The **dip direction** is the compass direction in which the slope faces (the direction toward which water would flow, if the slope were impermeable). A **line of strike** is a line formed by the intersection of the plane of the dipping surface (e.g., the slipface of a dune) and a horizontal plane. Lines of strike are perpendicular to the direction of dip.

A **cross-stratum** (plural: **cross-strata**) is a **layer** or **bed** that is inclined relative to a larger context (eg., the floor of a dune). A **set** of cross-strata is the entire series of adjacent cross-strata between two surfaces. Two or more adjacent sets are called **cosets**. The surface dividing sets is a **bounding** or **truncation surface.** An **amalgamated bed** represents but two or more separate depositional events, each one superimposed on the previous one.



The figure shows three sets of cross-strata; the upper three-quarters of each set's cross-strata is **tabular**, and the lower one-quarter of each set has a gradually decreasing dip, **downlapping** asymptotically to a less-inclined (in this case, horizontal) bounding surface; the cross-strata are **concave-up** (have a curve with its inside, the concave part, facing up).

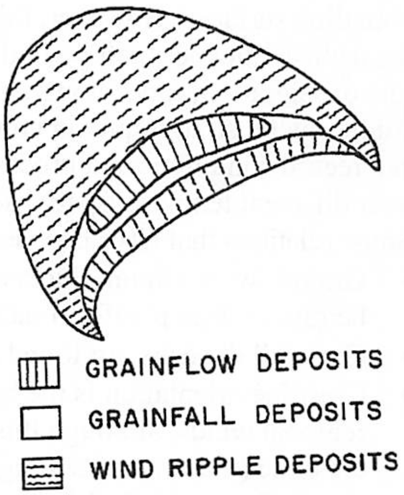
A stratum less than 1cm thick is a **lamina** (plural: **laminae**); more than 1cm is a **bed.** A **pinstripe** is a thin lamina, in the range of 1mm thick. Two shapes are commonly distinguished when strata are viewed in cross-section (perpendicular to their plane): **tabular** (rectangular) or **wedge** (triangular). **Hummocky** cross-strata contain sets of laminae that are both concave upward and convex upward, bounded by broad truncation surfaces which themselves may be either concave or convex upward; this type of strata has no preferred dip-direction (may form in oscillatory flow or refer specifically to terrain formed in large storms).



Within both **aeolian** (wind-formed) and **fluvial** (water formed) bedforms: layers left by material flowing along the top (of the delta, or of the dune) are **topset** strata. Layers left by material avalanching down the slipface, at the angle of repose, are **foreset** strata. Material caught at in the corner between the slipface and the interbedform area form **bottomset** strata.

Aeolian Stratigraphy and Connection to Dunes

by Serina Diniega

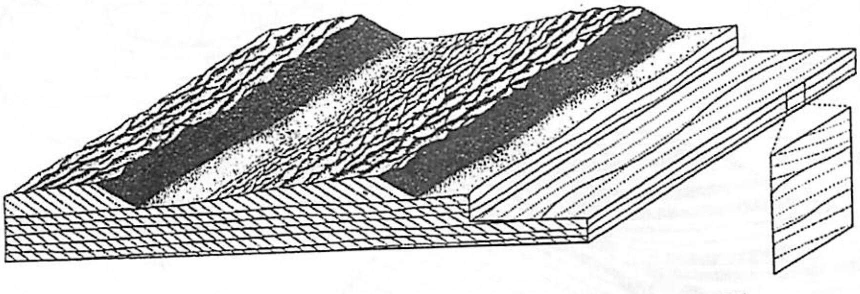


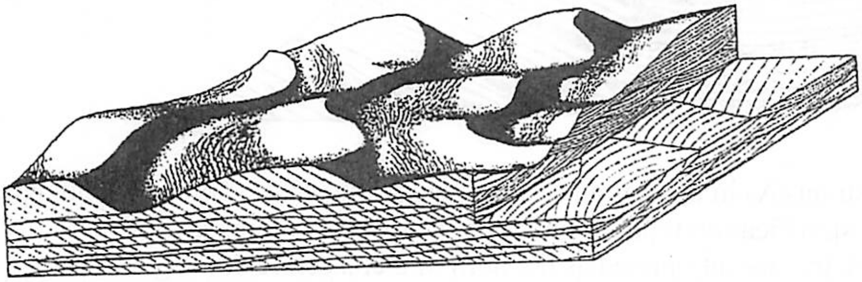
Grains within aeolian sandstone tends to be:

- well-rounded, as a result of long abrasion,
- well-sorted by size (sand grains are the easiest to move via wind, saltation).

Aeolian deposits form through three processes[i,ii], which are active on different surficial portions of a dune (Figure 4 from ref. i):

- *Climbing translatent strata* (a type of *tractional deposition*): formed by migrating wind ripples under conditions of net deposition. Thin, well-packed strata, with coarser grains concentrated in troughs.
- *Grainfall laminae* (also called *pin-stripe laminae*): tend to be a few grains thick and are poorly- sorted with intermediate packing.
- *Grainflow* (or *sandflow*) *cross-strata*: form due to avalanches of oversteepened slopes, so are at or near angle of repose (33°) and are loosely packed. They are internally structureless, except for coarser grains accumulating near the upper-surface and at the toe. On small dunes (<2m in height) grainflow cross-strata are narrow tongue-shaped bodies with well-defined edges, forming lenses. Compound grainflow cross-strata found on large dunes will be wide (several meters) and have diffuse boundaries, forming tabular cross-strata.





Generally, the only preserved portion of dunes are basal portions of lee foresets[iii]. Dunes form *subcritically* climbing translatent strata as they migrate, as the rate of deposition is generally much less than the rate of bedform migration. Figures 18 & 19 from ref. iv, showing (essentially 2D) transverse dune system and barchanoid ridge system.

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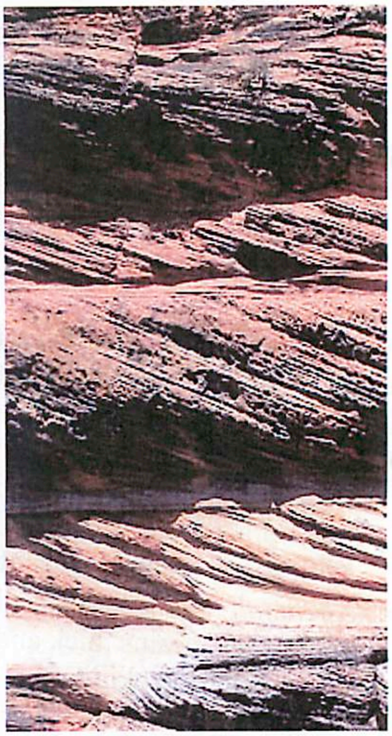
[i] Kocurek & Dott (1981) Distinctions and uses of stratification types in the interpretation of eolian sand. *J. Sediment. Petrol.* **51**(2): 579-595.

[ii] Hunter (1977), Basic types of stratification in small eolian dunes. *Sediment.* **24**: 361-387.

[iii] Kocurek (1991), Interpretation of Ancient Eolian Sand Dunes, *Ann. Rev. Earth Planet. Sci.* **19**: 43-75.

[iv] *http://ocw.mit.edu/NR/rdonlyres/Earth--Atmospheric--and-Planetary-Sciences/12-090Fall-2006/52F3142C-6714-467D-B5D6-9BAD5E70EFBA/0/ch16.pdf*

Studies have attempted to determine original dune type and migration (paleo-wind direction) from overall structure of cross-strata, foreset dip-direction and dispersion, and geometry of bounding surfaces. However, this can be highly complicated as the deposit thickness left behind by migrating dunes depends on rate of migration, sand supply, and rate of ground subsistence[i]. Additionally, stratigraphy in compound or complex dunes/draas can record conditions and processes from different times or valid over different temporal/spatial scales.



Some relations that have been empirically determined[iii]:

- Grainflow maximum thickness relates to minimum slipface height, as does planform radius of curvature of cross-strata.
- Grainfall deposits are found only near the tops of dunes.
- Crestline orientation is the best indicator of composite regional winds, although this requires knowing the type of crestline (transverse vs. longitudinal). Wind-ripple lamine also indicates wind direction.
- Type of crestline can be determined from the set style and relationship between bounding surfaces and cross-stratum orientations.

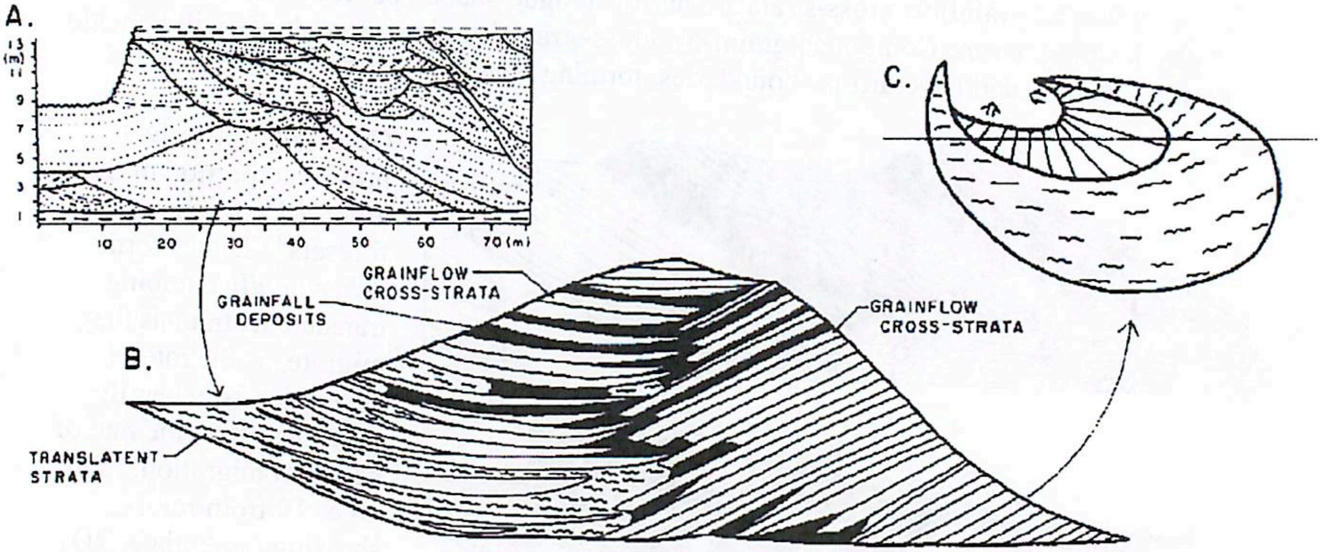


Figure 12 from ref. i. Cross-strata (A) in the Entrada Sandstone at Dinosaur National Monument. (B) shows the distribution of stratification types in one set of cross-strata: translatent strata occupy the left edge of the set and are interpreted as the horn of a crescentic dune; grainflow cross-strata and grainfall laminae in the center of the set indicate a central slipface with transport direction into the page, as determined by foreset dip direction; the right side of this set of cross-strata (intertongued with central cross-strata) also shows grainflow cross-strata and grainfall laminae, indicating an active slipface, but here transport direction was toward the left. The interpreted dune shape (C, line indicates where set would lie) is a crescentic dune with a very curved slipface.

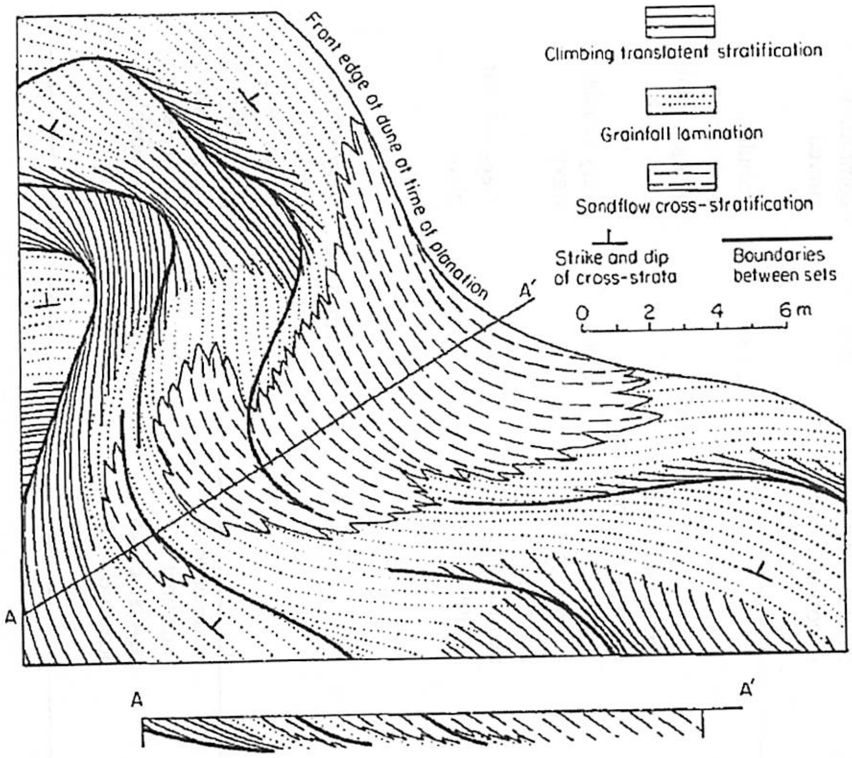


Figure 9 from ref. ii. Simplied cross-section of dune foreset cross-strata exposed from a planed-off barchanoid dune on Padre Island, TX, showing distribution of types of internal structure.

Small-scale deformation structures within cross-strata can be diagnostic of certain processes and environments[v]:

- Rotated blocks or plates within grainflow cross-strata are found in regions under tension (near the top of avalanche slopes) and areas of wet sand.
- Stairstep folds, normal faults, and break-apart laminae form only where cohesion is high, such as in sand crusts or wet sand. Generally these are limited to single laminae or a few sets of laminae.
- Stretched laminae form during a brief, high-wind storm.
- Small asymmetric folds form on the lower portions of slopes, due to compressive stresses where avalanches pile up against a flat base.

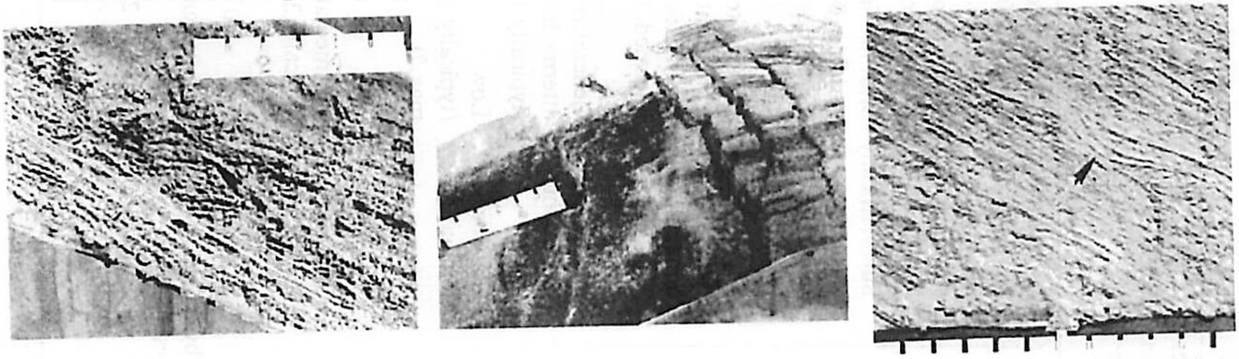


Figure 8 from ref. v. From left: rotated blocks formed in wet sand in laboratory specimen; high-angle, normal faults in surface of wet slipface in laboratory specimen; stairstep folds found in dry sand near base of barchan dune in White Sands, NM.

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[v] McKee, Douglas & Rittenhouse (1971), Deformation of lee-side laminae in eolian dunes. *Geo. Soc. Am. Bull.* **82**: 359-378.

Table 1. Characteristics of basic types of eolian stratification

Depositional process	Character of depositional surface	Type of stratification	Dip angle	Thickness of strata Sharpness of contacts	Segregation of grain types Size grading	Packing	Form of strata
Tractional deposition	Rippled	Subcritically climbing translatent stratification	Stratification: low (typically 0–20°, maximum ~30°) Depositional surface: similarly low	Thin (typically 1–10 mm, maximum ~5 cm) Sharp, erosional	Distinct Inverse	Close	Tabular, planar
		Supercritically climbing translatent stratification	Stratification: variable (0–90°) Depositional surface: intermed. (10–25°)	Intermediate (typically 5–15 mm) Gradational	Distinct Inverse except in contact zones	Close	Tabular, commonly curved
		Ripple-foreset cross-lamination	Relative to translatent stratification: intermed. (5–20°)	Individual laminae: Thin (typically 1–3 mm) Sharp or gradational, non-erosional	Individual laminae and sets of laminae: Indistinct Normal and inverse, neither greatly predominating	Close	Tabular, concave-up or sigmoidal
		Rippleform lamination	Generalized: intermediate (typically 10–25°)			Close	Very tabular, wavy
	Smooth	Planebed lamination	Low (typically 0–15°, max.?)	Sets of laminae: Intermediate (typically 1–10 cm) Sharp or gradational, nonerosional		Close	Very tabular, planar
Largely grainfall deposition	Smooth	Grainfall lamination	Intermediate (typically 20–30°, min. 0° max. ~40°)			Intermediate	Very tabular, follows pre-existent topography
Grainflow deposition	Marked by avalanches	Sandflow cross-stratification	High (angle of repose) (typically 28–34°)	Thick (typically 2–5 cm) Sharp, erosional or nonerosional	Distinct to indistinct Inverse except near toe	Open	Cone-shaped, tongue-shaped, or roughly tabular

$\frac{x}{100} = \frac{1}{2}$

Origin and sources of gypsum for the White Sands system

Priyanka Sharma

Introduction

The White Sands National Monument is located in the northern end of the Chihuahuan Desert in south-central New Mexico. It lies within an internally-drained, mountain-ringed valley called the Tularosa basin, which is a graben formed by extensional tectonics in the Rio Grande Rift. The basin is bordered on the east and west by the San Andres and Sacramento mountain ranges.

White Sands is the largest gypsum dune field in the world. There are approximately 275 total square miles of dune fields in the Chihuahuan desert, with 115 square miles (about 40%) located within White Sands National Monument. Using Landsat ETM+ data, four evaporite minerals have been identified in these dunes: gypsum ($CaSO_4$. $2H_2O$), halite ($NaCl$), calcite ($CaCO_3$) and thenardite (Na_2SO_4). The most common and abundant evaporite mineral in the area is gypsum, a hydrous form of calcium sulfate ($CaSO_4$. $2H_2O$), which gives the sand here its white color (Fig. 1).

Events leading upto formation of the White Sands

1) The Permian Sea

The gypsum that makes up White Sands is ultimately derived from marine rocks. Shallow seas covered much of New Mexico throughout the Paleozoic Era (570-245) million years ago). Marine deposits as old as 500 million years are present in the San Andres Mountains, but by far the most abundant sedimentary rocks in southern New Mexico are Permian in age (290-245 Ma). In the Permian Period, North America was part of a great megacontinent called Pangaea, and present day New Mexico was submerged in a tropical sea just south of the equator. In the middle of the Permian period, there was a major fall in sea level, causing vast stretches of water across southern New Mexico to nearly dry up. It was during this drying-up phase that large quantities of gypsum rock were deposited.

Gypsum is an evaporite mineral, i.e. it forms almost exclusively when dissolved ions become concentrated due to the evaporation of water. If sea water of normal salinity is reduced to about 20% of its original volume through evaporation, calcium (Ca^{2+}) and sulfate (SO_4^{2-}) ions will be concentrated enough for gypsum ($CaSO_4$. $2H_2O$) to begin to crystallize. The cycles of evaporation that took place in the middle Permian caused hundreds of feet of gypsum to settle out onto the sea floor.

2) The Laramide uplift

In the Jurassic and Cretaceous Periods, subduction beneath the North American plate resulted in uplift and volcanism along western North America. Towards the end of the Cretaceous, the angle of subduction beneath the United States became increasingly shallow, transferring compressive forces to the east. This eastward shift of compression is believed to be responsible for the formation of the Rocky Mountains. White Sands National Monument is about 200 miles south of the Rockies, but the same compressional forces that formed the Rocky Mountains also uplifted the marine rocks in southern New Mexico.

3) Formation of the Tularosa Basin

With time, the shallow subduction off the California coast ceased and a new, parallel-motion plate boundary formed (now represented by the San Andreas Fault). For reasons that remain unclear, this shift in tectonic regime caused enormous upwellings of magma from the Earth's mantle. These mantle upwellings stretched apart large portions of crust in the southwest, forming the Basin and Range province. A linear arm of the Basin and Range, known as the Rio Grande Rift, extends from southern New Mexico into central Colorado.

As the crust pulled apart in the Basin and Range, numerous fault zones developed. Large blocks of crust subsided thousands of feet along these faults, forming basins in between fault-bounded mountain ranges. The Tularosa Basin, at the southern end of the Rio Grande Rift, is just one of the many basins in the U.S. southwest that have formed due to crustal extension.

4) The Last Pleistocene Ice Age

The wet climate during last ice age (approximately 24,000 to 12,000 years ago) played a major role in the formation of White Sands. In the late Pleistocene Epoch, the Tularosa Basin (and much of the U.S. southwest) received substantially more rain than it does today. Heavy rainfall flushed large quantities of soluble gypsum from the San Andres and Sacramento Mountains down to the Lake Otero. The lake became saturated with dissolved gypsum. The wet ice age climate was critical in flushing large quantities of gypsum from the mountains down into the Tularosa Basin. As the ice age came to an end, the climate of the Tularosa Basin became increasingly more arid. Lake Otero slowly dried up, leaving behind enormous deposits of gypsum.

5) Dune formation

Gypsum is rarely found in the form of sand because it is soluble in water. Rain and snow that fall in the surrounding mountains dissolve gypsum from the rocks and carry it into the Tularosa Basin. Normally, dissolved gypsum would be carried by rivers to the sea. But no river drains the Tularosa Basin. The water, along with the gypsum and other sediments it contains, is trapped within the basin.

With no outlet to the sea, water flowing into the Tularosa Basin either sinks into the ground or pools up in low spots. One of the lowest points in the basin is a large playa called Lake Lucero. Occasionally, this dry lakebed fills with water. As the water evaporates, the dissolved gypsum is deposited on the surface.

Expansion and contraction caused by large temperature fluctuations and periodic freezing serve to break up selenite crystals along these planes. When crystals become small enough to be transported by wind, further breakdown, and rounding will occur. Gypsum is one of the softest minerals and gypsum sand will be broken down into smaller grains much more rapidly than quartz sand when transported by the wind.

Planetary connection

Since gypsum is a mineral that forms in the presence of water, the presence of gypsum dunes on any solar system object could be related to water-associated processes and could be used to study the interaction between hydrology and climate. The White Sands gypsum dunes in New Mexico may be a terrestrial analog to the gypsum-rich dunes of Olympia Undae detected in the north polar region of Mars (Fig. 2 shows a HiRISE image of these dunes). The material comprising these dunes is thought to have eroded from geologic units near the base of the polar deposits, but these units have poor to no gypsum content. Therefore, water likely affected these dunes after the sand had eroded out from the polar deposits. Several ideas have been proposed to explain the formation of gypsum, including hydrothermal (hot water) activity and melting of water-ice in the polar deposits. While the terrestrial gypsum dunes are white, these Martian dunes are dark due to the presence of basaltic grains that lower the brightness of the dunes. Another instrument on the MRO, CRISM, has found that the crests of the dunes are the most gypsum-rich.

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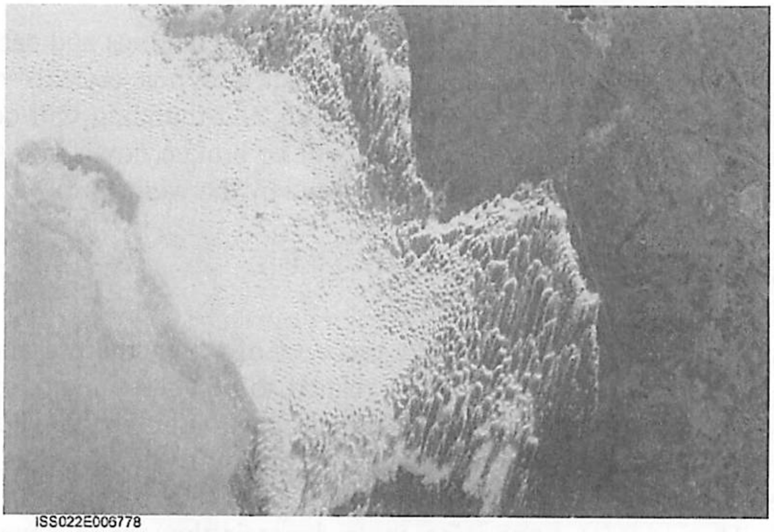

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Fig. 1. White Sands dunes (New Mexico) from International Space Station

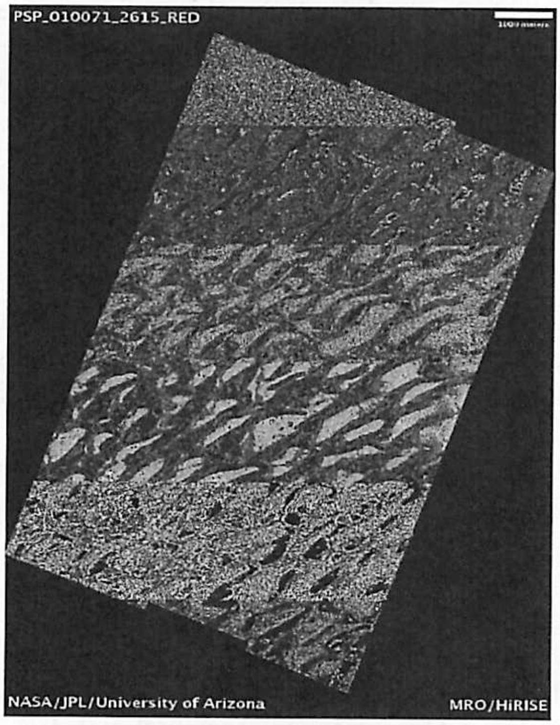
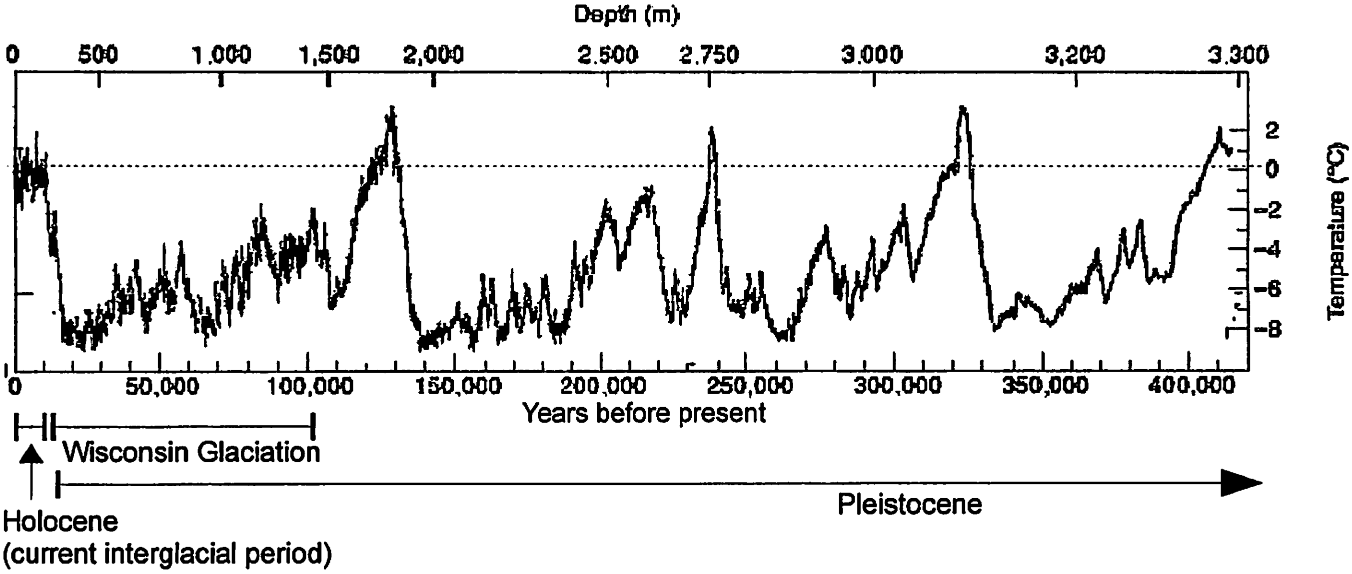


Fig. 2. Gypsum-rich dunes in Olympia Undae on Mars (HiRISE image: PSP_010071_2615)

Climate History of Southern New Mexico

Kat Volk

We'll start off with some Antarctic ice core data to put the discussion of New Mexico's climate in context. The past 1 Myr on Earth has been characterized by glacial-interglacial climate cycles with a period of about 100 kyr. The graph below shows the Antarctic air temperature over the last 420,000 years (taken from Petit et al. 1999). The temperature is calculated from oxygen isotope fractionation (which is linearly dependent on temperature) in the ice core samples.



The temperature and climate record for New Mexico is not as easy to obtain for such long timescales, but looking at just the last ~50 kyr should give us a fairly good idea of what the climate was like during earlier interglacial and glacial periods.

The glaciers themselves did not extend down to NM, but the climate was colder and wetter than it is now. In northern NM, the temperature during the Wisconsin glaciation is estimated to have been 5 °C cooler than during the Holocene (Stute et al. 1995). Annual precipitation varied, but was perhaps twice the current value on average (Allen 2005).

As a result, NM had several large ice age lakes. The locations and extent of the lakes and drainage basins are shown to the right. A table showing current precipitation and evaporation rates at these locations is on the next page (figure and table from Allen 2005).

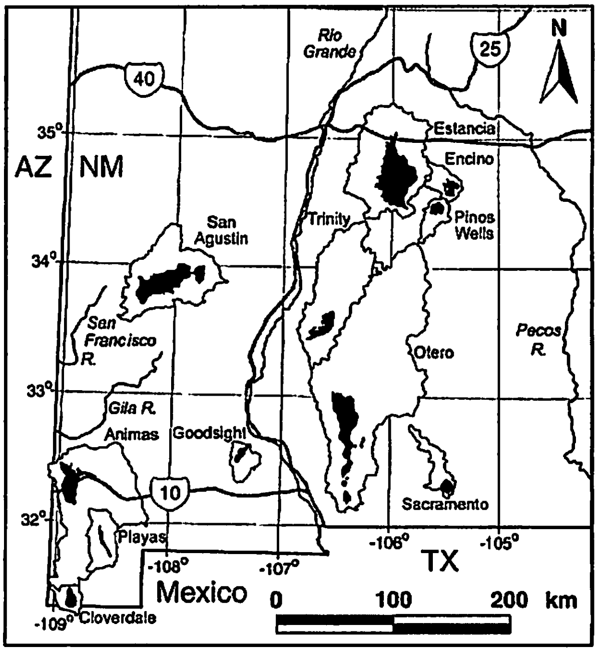


FIGURE 1. Distribution of ice-age lakes in New Mexico. Elevation and surface area of the ice-age lakes (black fill) and surrounding drainage basins (shaded) are listed in Table 1.

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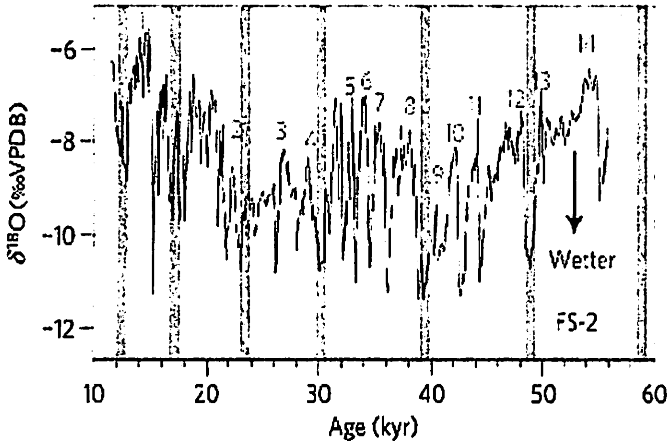
TABLE 1. Morphometric characteristics of late Wisconsinan lakes in New Mexico based on USGS 10 m digital elevation models and a geographic information system (GIS) delineation of the lake basins. Highstand lake elevations are from Hawley (1993, table 1). Values of mean annual precipitation and evaporation are the spatial average for the area covered by the highstand lakes. Precipitation and evaporation estimates were obtained from a GIS grid interpolated from contour maps compiled by the National Oceanic and Atmospheric Administration (the digital contour maps of precipitation and evaporation and associated metadata are available from the RGIS Clearinghouse at http://rgis.unm.edu/). Estimates of evaporation are for a free water surface (see Farnsworth et al., 1982 for a discussion of the evaporation data).

Lake	Lake Elevation m (ft)	Lake Area km²	Basin Area km²	Lake Area/Basin Area ratio	Modern Precipitation cm/yr	Modern Evaporation cm/yr
Animas	1279 (4195)	374	5670	.066	25	184
Cloverdale	1576 (5170)	102	460	.222	41	178
Encino	1882 (6175)	96	620	.155	35	137
Estancia	1890 (6200)	1125	5050	.223	31	127
Goodsight	1372 (4500)	65	590	.110	25	183
Otero	1204 (3950)	745	12,600	.059	25	166
Pinos Wells	1859 (6100)	82	560	.146	36	132
Playas	1311 (4300)	49	1120	.044	27	190
Sacramento	1347 (4418)	86	780	.116	25	165
San Agustin	2115 (6940)	786	3880	.203	29	115
Trinity	1431 (4695)	207	4240	.049	25	159

Precipitation levels varied significantly on thousand year timescales, even within a single glaciation. The plot on the lower left shows oxygen isotope data from stalagmites in Fort Stanton Cave in southeastern NM (from Asmerom et al. 2010). The plot on the lower right shows similar timescale variations in the shoreline elevation of one of NM's ice age lakes (from Allen 2005).



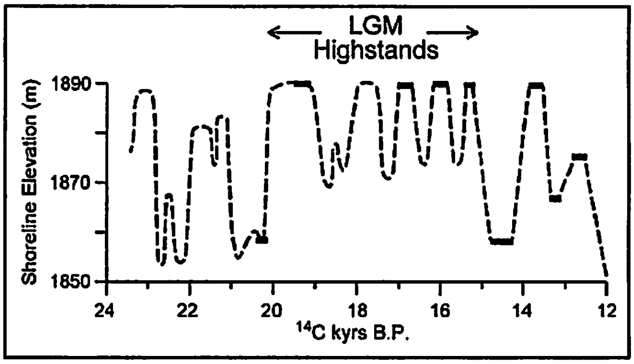


FIGURE 7. Reconstructed elevation of Lake Estancia during late Wisconsinan pluvial episodes, ca. 24 to 12 kyrs B.P (modified from Allen and Anderson, 2000). Solid lines indicate portions of curve constrained by shoreline evidence.

Summary: New Mexico's climate during the Wisconsin glaciation (and probably earlier ones too) was characterized by large fluctuations in both temperature and precipitation on kyr timescales, but it was generally colder and wetter than during the Holocene. The Holocene also shows kyr variations in moisture levels, but the wettest part of the Holocene is dry compared to the moisture levels during the Pleistocene (Polyak & Asmerom 2001).

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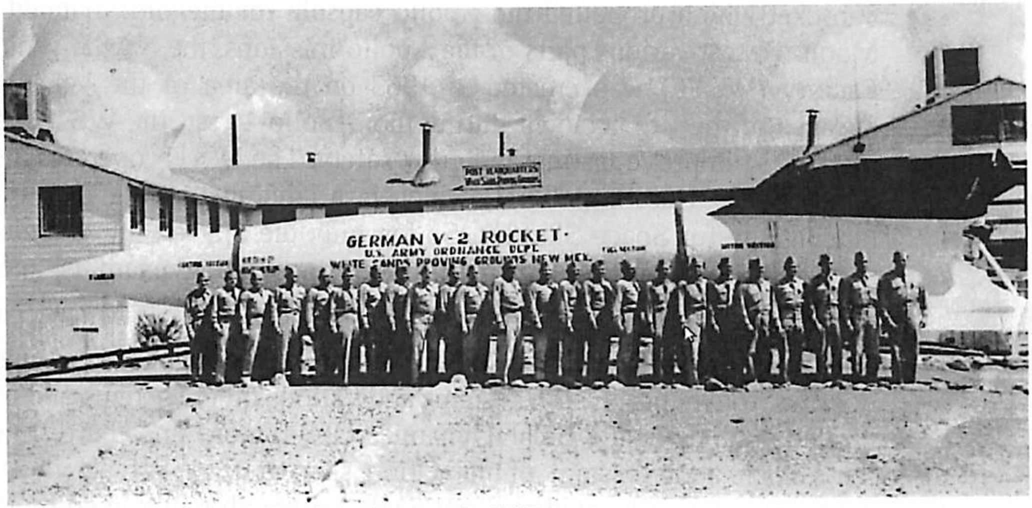
White Sands Missile Range

Christopher Dietl



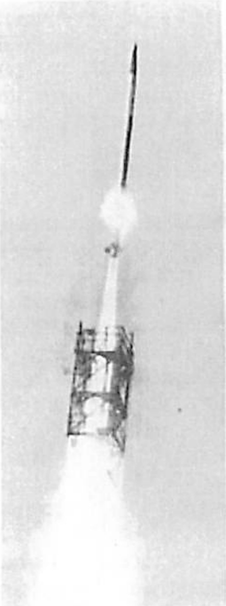
Leadership of the WSPG in front of a V-2

With its 3,200 square miles (8,300 km^2) the White Sands Missile Range (WSMR) is the largest military facility in the United States. It has been the testing ground for the first nuclear bomb, space technology and various weapon systems.

The history of missile testing in New Mexico started in 1930 with Robert Goddard, one of the pioneers of modern rocketry. He used the remoteness of Roswell to conduct rocket experiments until 1941. In 1944, the US Army declared the Tularosa Basin for military necessity in course of America's missile program and established the White Sands Proving Grounds (WSPG). On July 16, 1945, only two months after the end of World War II in Europe, the first nuclear bomb was detonated at the Trinity Site in the northern part of the WSPG. During the chaos after the surrender of Germany, all victorious forces tried to acquire German weaponry as quickly as possible to prevent the others from getting a military advantage. This was essentially true for the V-2 rocket ("Vergeltungswaffe 2", vengeance weapon 2). Although rather pointless as a weapon, it was the most advanced ballistic missile of its time and the first human artifact in space. The development was undergone by a group of scientists under the auspices of the famous Wernher von Braun at the rocket test facility in Peenemünde at the German Baltic Sea coastline. The US forces successfully secured 300 railroad freight cars of V-2 components which were subsequently send to the WSPG. The team of von Braun surrendered to the US army fearing either being killed by the SS or being captured by the Red Army. Despite their questionable activities in the Third Reich (more than 12,000 forced laborer died during the construction of the V-2 and ca. 8,000, mostly civilians, were killed by the V-2 as a weapon) von Braun and over 100 men of his crew were moved to Fort Bliss near El Paso, Texas, where they continued working on the V-2 together with American scientists at the WSPG. Besides military tests, the V-2 was also used by civilian scientists to conduct experiments. Among them were flights with fruit flies and monkeys which became the first animals intentionally sent into space. The knowledge gained with 67 launches of the V-2 led to the construction of many modern US-rockets like the Redstone and Aerobee rockets. The Aerobee was built for research of the higher atmosphere and cosmic radiation. Experiments with this rocket led to the discovery of cosmic X-rays and

New Mexico from a V-2

several of their sources in the 1950s. Although originally intended for military use, a modified Redstone rocket propelled the first US-American satellite (Explorer-1) in its orbit. The Redstone was also used for the Mercury program, during which the first US-American, Alan Shepard, was sent into space. WSPG was renamed to WSMR in 1958.



Flight test of an Aerobee rocket

Wernher von Braun and his colleague Arthur Rudolph designed also the Saturn-V-rocket which propelled the Apollo capsule for the first manned flight to the Moon. To test various parts of the Apollo-missions, the NASA White Sands Test Facility (WSTF) was created in 1963 on the area of the WSMR. Especially because of the fire accident during the Apollo-1 test, the WSTF was expanded in 1967 to improve testing and crew safety. The WSTF operates also the White Sands Space Harbor (WSSH) which is a landing training facility and backup landing site for Space Shuttles. So far, only the Space Shuttle Columbia landed at the WSSH Northrup Strip in 1982, since the gypsum is unfavorable for landing.

Today the WSMR and the WSTF continue serving as a testing facility for missiles, rocket propulsion systems and various other systems and materials. The ground station for the Solar Dynamics Observatory and the testing facility for the launch abort system of the Orion spacecraft, a part of the Constellation program, are also located at the WSMR. Although still owned by the US Army, the WSMR today can be seen as a service company also open for private companies and international customers.

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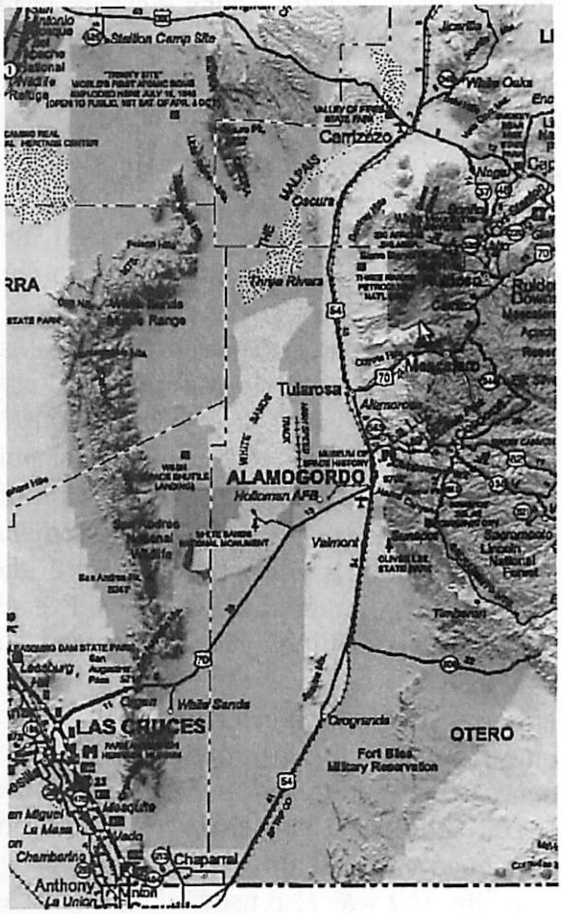

Map of the WSMR

Rio Grande Rift history

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The Rio Grande Rift is a rift valley extending north from Mexico, near El Paso, Texas through New Mexico into central Colorado, and is part of the Basin and Range Province. The upper Rio Grande flows south following the rift valley, but did not incise it.

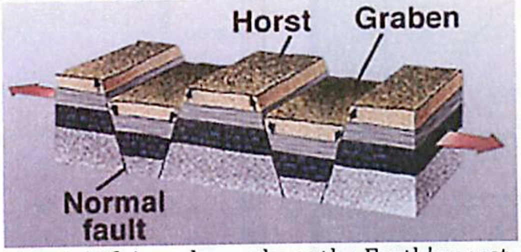

Fig 1. Rift is a place where the Earth's crust and lithosphere are being pulled apart and is an example of extensional tectonics.

The faulted western margin of the Rift lies along the Rio Puerco, about 20 miles west of the Civic Center. The eastern edge of the rift lies at the base of the Sandia Mountains. (As in Fig 2.)

The Rio Grande Rift represents the easternmost part of the widespread extension in the western U.S. during the past 35 million years. After the Farallon Plate subduction-associated compressive forces of the Laramide orogeny (The Farallon Plate was an ancient oceanic plate, which began subducting under the west coast of the North American Plate— then located in modern Utah— as Pangaea broke apart during the Jurassic period) ended during the Eocene Epoch (35 Ma), erosion of these uplands filled the area of the Raton Basin with abundant sediments. In the late Oligocene Epoch *regional* tensional forces became dominant and rifting was

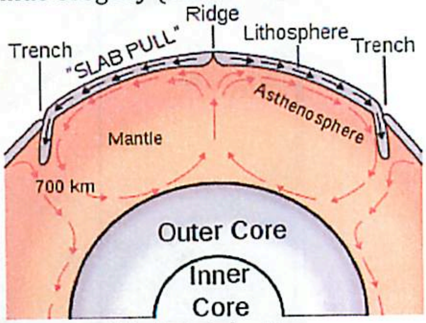

Fig 3. Subduction

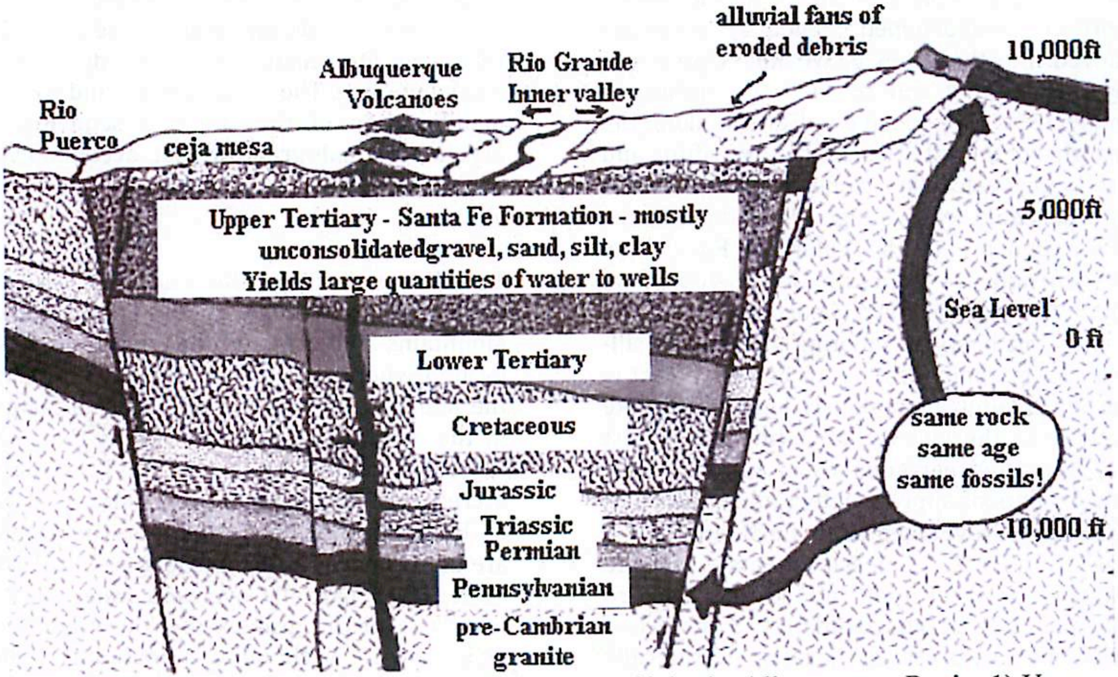

Fig 2. Three-Dimensional View of the Rio Grand Rift in the Albuquerque Region1) Upper Tertiary - Santa Fe Formation - mostly unconsolidated gravel, sand, silt, clay - Yeilds large quantities of water to wells. 2) Lower Tertiary; 3) Cretaceous; 4) Jurassic; 5) Triassic; 6) Permian; 7) Pennsylvanian; 8) Pre-Cambrian Granite

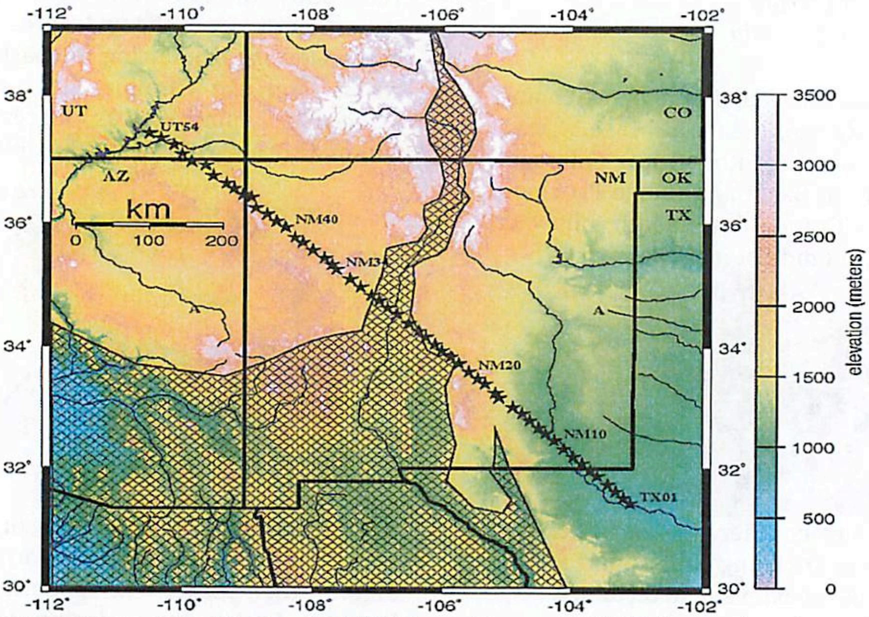

Fig 5. Seismic profile from the Rio Grande Rift Seismic Transect (RISTRA) experiment crossing the rift system

initiated as the crust and uppermost mantle began extending. The rifting produced fault zone-bounded valleys (grabens or half-grabens, as in Fig 1.). A graben consists of normal faulting on each flank with the central portion downdropped. Igneous intrusions moved into the zones of weakness produced by this faulting and reached the surface in many areas as extensive volcanism along the margins of the rift. The most active rifting and associated volcanism came to an end in the late Cenozoic. The youngest eruptions in the rift region are in the Valley of Fires, New Mexico and are approximately 5,400 years old. The Socorro, New Mexico region of the central rift hosts an inflating mid-crustal sill-like magma body at a depth of 19 km that is responsible for anomalously high earthquake activity in the vicinity, including the largest rift-associated earthquakes in historic times (two events of approximately magnitude 5.8) in July and November 1906. Earth and space-based geodetic measurements indicate ongoing surface uplift above the Socorro Magma Body at approximately 2 mm/year. The rift is presently nearly tectonically quiescent, but significant deformation and faulting with offsets of many kilometers was responsible for its formation starting about 35 million years ago. The largest-scale manifestation of rifting involves a pure-shear rifting mechanism, in which both sides of the rift pull apart evenly and slowly, with the lower crust and upper mantle (the lithosphere) stretching like taffy. This extension is associated with very low seismic velocities in the upper mantle above approximately 400 km depth associated with relatively hot mantle and low degrees of partial melting. The upper crustal and surface manifestation of the rift is a sequence of asymmetric half-grabens that accommodate deep basins that are substantially filled with alluvium.

The Valles Caldera National Preserve is dominated by a huge caldera in the Jemez Mountains (Volcanic group of mountains), located where the Rio Grande Rift intersects the Jemez Lineament, a linear crustal feature in the southwestern United States that may represent a suture zone from the Proterozoic accretion of North America (as shown in Fig 5). However, the Jemez Mountains themselves are not primarily a tectonic feature of the rift; rather, they partially overlie a range on the west side of the graben, the lower and less well-known Nacimiento Mountains. The Colorado Plateau, to the west, includes the San Juan Volcanic Field and the San Juan Mountains.