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# SHORELINE PROCESSES



PTYS 594A - Planetary Geology Field Studies  
and  
PTYS 554 - Evolution of Planetary Surfaces

February 11- 14, 2011

QE40  
.P63  
B45  
2011

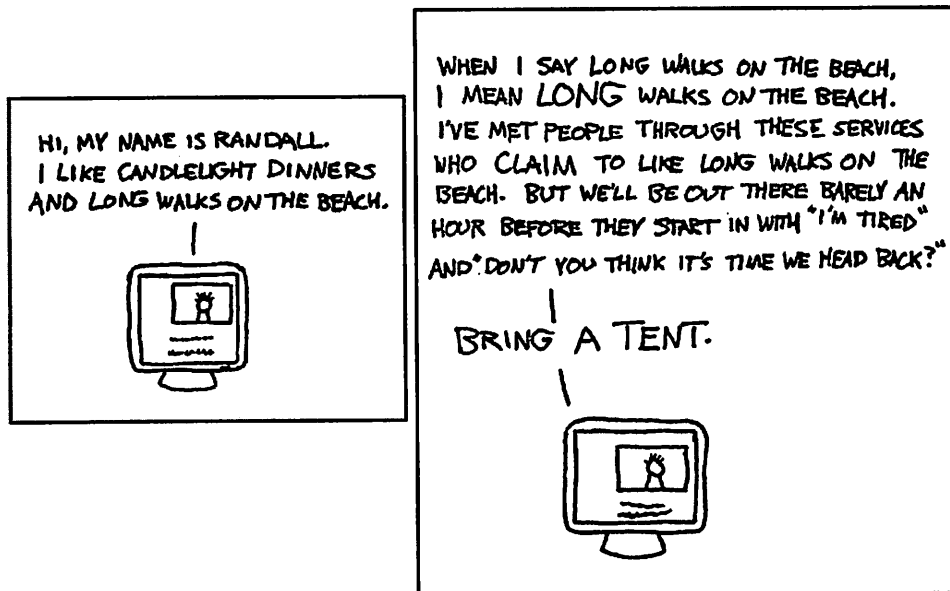
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Editor's note:

For the past two and a half years I've successfully avoided eye contact and slouched low in my chair when it was time for someone to volunteer to compile the field trip guide. After watching three students get tricked into the job during their first semester at LPL, I figured it was time for me to volunteer to take my turn at the job.

However, even after 5 field trips (7 including surfaces field trips), I am at a loss as to what I should write here. I liked that Rob included a comic from xkcd, so I googled "xkcd beaches," and found this:



We'll probably take some long walks on the beach on this field trip, so I hope you brought a tent.

*Catherine Elder, editor*

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## Road log for PTYS 594 – All times are AZ times

### FRIDAY 2/11/2011

- 7 AM Arrive at LPL loading dock bright-eyed and bushy-tailed with full ice chests, full stomachs and empty bladders.
- 8 AM Depart LPL for shoreline-based excitement!  
Drive north on Cherry, turn west on Speedway, enter interstate 10 westbound.  
After ~60 miles, transfer to interstate 8 westbound, drive 192 miles, stay awake.  
Exit the 8 at #159, go north on Ogilby road for 25 miles  
Turn left on CA-78, drive a few miles until we see a good spot overlooking the trough.
- 1PM **Lunch stop**  
Here, we'll hear talks from **Youngmin** on the formation of the Salton trough that graces the western vista. **Corey** will describe the origin of the Salton sea.
- 2 PM Depart lunch stop. Continue west on the 78 for about 60 miles.  
Continue straight on the 86 (the 78 veers off to the left), drive 22 miles.  
Left turn on Coolidge Springs Road, drive ~2/3 of a mile at the elbow in the road take a left turn, drive ~250m until the road peters out.
- 3.30PM Hike ~300m west to old shoreline contacts. Examine the former extent of Lake Cahuilla and hear all about it from the eminent **Dr. David Choi**.
- 4.15PM Back to Coolidge Springs Road, drive 1.5 miles further, then use dirt road that parallels the 86 to get to Travertine point (<1 mile). Listen to **Melissa** talking about tufa and travertine and try to find the tombolo that **Beary** will describe.
- 5.15PM Leave Travertine point, head south on the 86 for 11 miles. Turn right onto Borrego Salton Sea Way (AKA Co Hwy S22), drive 20 miles. Turn right onto dirt road, drive 4.5 miles, ignore at least three turnoffs until we hit a T-junction. Take a right turn here, after ~300m there's a side road that leads to an old well.
- 6.30PM Camp: Clark Dry Lake, elevation 560'. Sunset 6.17PM AZ time.

### SATURDAY 2/12/2011

- 8 AM Break Camp and backtrack to nearby clay dunes where **Katrina** will tell us all about them.
- 8.30 AM Drive 4.5 miles back to Borrego Salton Sea Way, turn right. Stay on this road as it turns into Pegleg Road and then Palm Canyon Drive drive 6 miles total. Left turn onto Borrego Valley Road, which turns into Rango Way and then Yaqui Pass, drive 11 miles total until we hit the 78. Take the 78 to Ramona (41 miles), stay straight to transition to the 67 and drive 9 more miles.  
Lots of closely spaced turns...  
Turn right at Poway Rd, 2.6 mi  
Turn right at Espola Rd 0.8 mi  
Take the 2nd left onto Twin Peaks Rd 2.3 mi  
Turn left at Ted Williams Pkwy 2.8 mi  
Continue onto CA-56 W 8.9 mi  
Take exit 1B for El Camino Real N 0.2 mi

Merge onto Carmel Valley Rd 1.8 mi  
Slight right at S Camino Del Mar 1.8 mi  
Slight left at Camino Del Mar 1.1 mi

- 11.30 When we cross over the estuary at this point we'll be on the wrong side of the road to stop so we'll go forward a bit and u-turn. Pull up at North Bluff Preserve, walk around the cliff corner to the north to see marine terraces and hear **Stephanie** talk about them. This seems like a good location to hear **Juan** talk about critters and tidal pools. Explore the cliffs and stop for **lunch** on the beach.
- 1PM Depart the beach. Do another U-Turn and head north on the 101 for 2.2 miles. We'll be driving across the San Elijo Lagoon, stop on the north side of the lagoon at Las Olas (Mexican restaurant). Their parking lot has good views of the lagoon that **Rob** will describe. There's a cross-walk to the beach at the restaurant. If there's time we can take a walk to the beach to look for sapping features related to drainage of the lagoon at low-tide. **Peng** will talk about sediment transport out onto the abyssal plains.
- 2 PM Depart Las Olas. South on the 101 for 1.5 miles, turn left on Lomas Santa Fe Drive for 1 mile and join interstate 5 southbound. Exit 9 miles later at La Jolla Village Dr, turn right onto that street, drive 1 mile. Turn left on Torrey Pines road, drive 2 miles south. Turn right at La Jolla Shores Dr and 0.5 miles later take a left on Calle Frescota. After 200m there's a beach-side parking lot on Camino Del Oro. Pray for parking spaces...
- 2.30 PM Walk out to LaJolla beach and hear from **Pat** about submarine canyons, one of which is just a few 100m off-shore.
- 3.30 PM Depart LaJolla and drive to campground (unfortunately not on the beach). Drive north on Camino Del Oro until LaJolla Shores Drive, take a right and drive to you hit La Jolla Parkway. Take a left here and drive until you hit interstate 5 (total <2 miles from the beach). We take the ramp to CA 52 East DON'T GET ON THE INTERSTATE. Drive 13 miles and exit on Mast Blvd. Take a left at the end of the off-ramp, drive 300m until West Hills Parkway and take a right onto that street. In Less than a mile it will terminate at Mission Gorge Rd. Take a right here and then a slight right soon after at Father Junipero Serra Trail.
- 4 PM Enter Kumeyaay campground on the right, our reserved sites are 20, 22, 24, 26. If anyone asks, then we have a maximum of 8 tents, 6 vehicles and 24 people (at least two of those are true).

This seems early, but I'm sure that traffic and beaches will delay us.  
Camp in Kumeyaay campground, elevation 300'. Sunset 6.30PM AZ time.

### **SUNDAY 2/13/2011**

- 8 AM Depart Kumeyaay campground the same way we entered. Go left on Mission Gorge Road and drive 2 miles. Rejoin the CA 52E/125S, drive 14 miles. Road becomes CA54, drive another 6 miles. Join interstate 5 south, drive 5 miles. Take exit 5A for CA-75/Palm Ave (right at the end of the off-ramp) drive 5 miles. Turn left at Coronado Cays Blvd and follow the road ~0.5 miles to the beach parking lot.
- 9 AM Arrive on Silver Strand Beach.

Beach cusps from **Cecilla**  
Beach profile from **Kat**  
Heavy metal laminae from **Ingrid**  
Ripple formation from **Tiffany**  
Tides from **Christa**.

We may go north to Coronado Beach, as the beach cusps look better there.

- 1 PM **Lunch** on the beach.
- 2 PM Leave the beach and start the long trek home.  
Go North on Silver Strand Blvd for 2.7 miles. It veers to the right and becomes Orange Avenue, go a further 1 mile. Turn right onto CA-75N and drive >2 miles, transition to interstate 5 south in a complex spaghetti junction.  
Exit 13A onto CA-15N go 1.8 miles, exit 2B onto the CA-94E, drive 6.4 miles. Exit 9B to merge onto CA-125N, and take exit 18A to merge onto interstate 8 eastbound. I hate city driving...  
Go 26 miles on the 8 and exit at CA-79N and drive north a few miles.
- 3 PM Pull up and hear **Dyer** clue us into the true nature of the peninsular ranges that we're standing in.  
Back into the vehicles and drive further north ~20 miles on the 79. Take a right onto CA-78 E, drive 34 miles. Turn right at split mountain road and drive 8 miles. The road forks here, take the left. Immediately afterwards a dirt road heads off to the left alongside a disused mining railway. Take this road and drive about 8 miles to find another very nice Lake Cahuilla Shoreline partly covered by an alluvial fan.
- 5.30PM Explore and camp at Cahuilla shoreline, elevation ~0'. Sunset ~6.30PM AZ time.

### **MONDAY 2/14/2011**

- 8 AM Break camp. Get back to CA-78 E via the way we came in and drive 32 miles east  
Turn left at Center Street/Forester Road, drive 2.5 miles. Veer right onto Walker Road and soon after left onto Gentry road, drive 7 miles.  
Turn right at Estelle Rd/W Sinclair Rd and drive 1 mile. Turn left onto Garst Rd and drive 1.5 miles. Turn right on Red Hill Road and drive 1 mile and then left into Davies road. Mud volcanoes are on the right.
- 10 AM Check out the mud volcanoes and hear **Jamie's** talk.  
Hop back in the vans and go 1 mile further west on W Schrimpf Rd. Turn left at Garst Rd and drive 3 mi south. Take a right turn on an unmade road to get to Cox road, turn right again on Cox and drive 2.6 miles north (yes, we are driving in a circle). Cox road turns in to Gentry road, turn right at Estelle Rd/W Sinclair Rd, drive 0.5 miles. Turn south onto Boyle Rd for 0.5 mi and west again on Mc Nerney Rd for 0.5 miles.
- 11AM Arrive at Obsidian Butte and hear about high-silica volcanism from **Chet**.  
Back in the vehicles and return to Estelle Rd/W Sinclair Rd and drive 5.5 miles east. Take the CA-111 south for 3.6 miles and then the CA-115S for 16.5 miles.

Transition to CA-78 E and drive another 16 miles to Osborne park road. Turn right there and we'll be in a parking area in the north end of the dunefield.

12.30 **Lunch** stop here.

When we're finished eating our fill **Catherine** will tell us about the Algodones dunes in front of us.

1.30PM Depart dunes. Keep going east on CA-78 for 16 miles. Turn right onto Ogilby road and drive 25 miles to interstate 8. Drive 192 miles to interstate 10 east, drive another 58 miles to Tucson. Exit Speedway to Cherry to LPL.

6.30PM Arrive back at the loading dock. I'll see most of you tomorrow morning in class.

## Participants

- 1 Corey Atwood-Stone
- 2 Patricio Becerra
- 3 Shane Byrne
- 4 David Choi
- 5 Ingrid Daubar-Spitale
- 6 Melissa Dykhuis
- 7 Catherine Elder
- 8 Katarina Jackson
- 9 Youngmin JeongAhn
- 10 Tiffany Kataria
- 11 Cecilla Leung
- 12 Juan Lora
- 13 Dyer Lytle
- 14 Chet Maleszewski
- 15 Stephanie Moats
- 16 Jamie Molaro
- 17 Dave O'Brien
- 18 Adam Showman
- 19 Joe Spitale
- 20 Peng Sun
- 21 Christa VanLaerhoven
- 22 Kat Volk
- 23 Zhiyong Xiao (Beary)
- 24 Rob Zelle

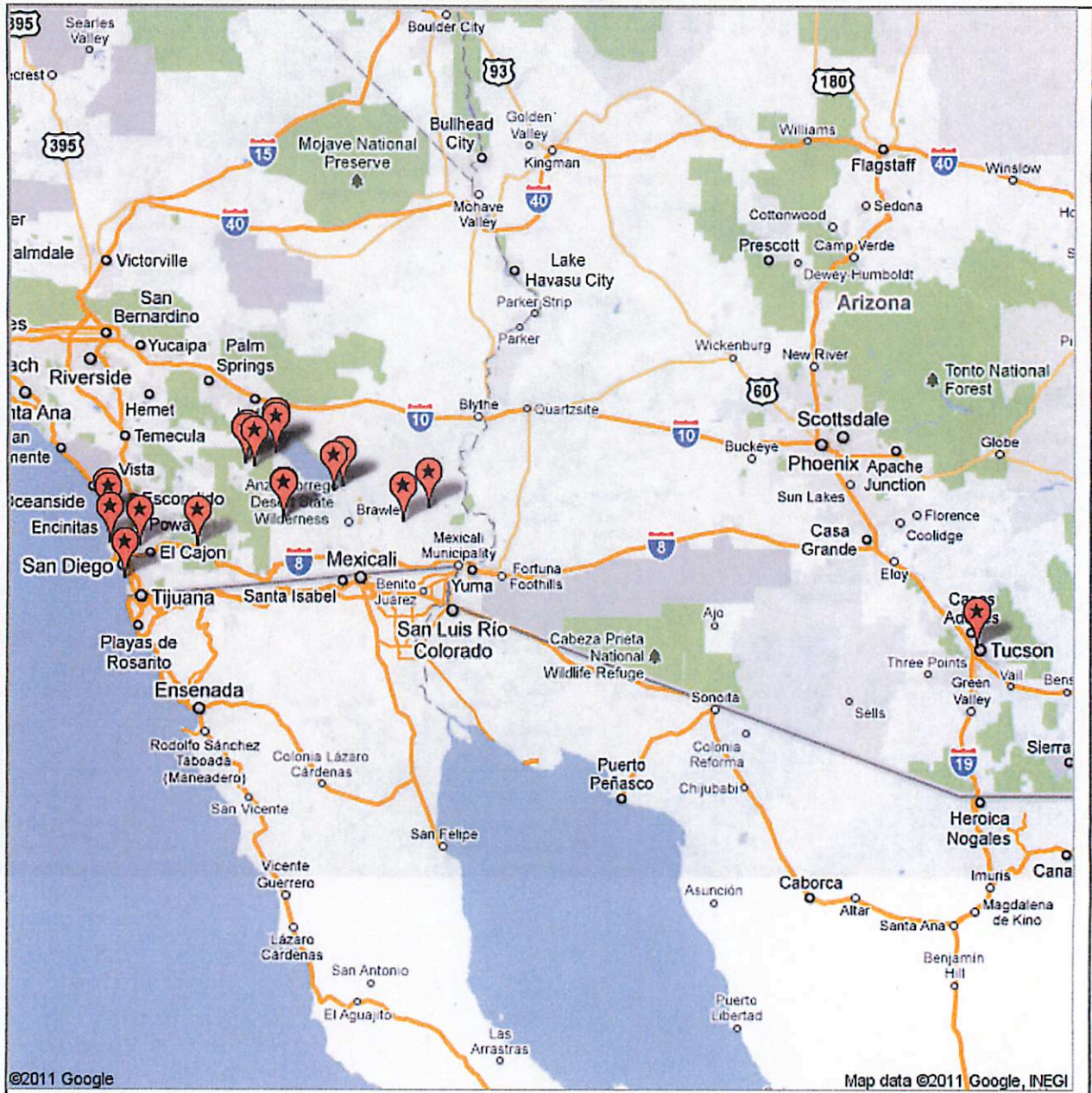








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**PTYS 594 Spring 2011**

LPL fieldtrip to the Salton Sea and Pacific coasts

1,337 views - Public


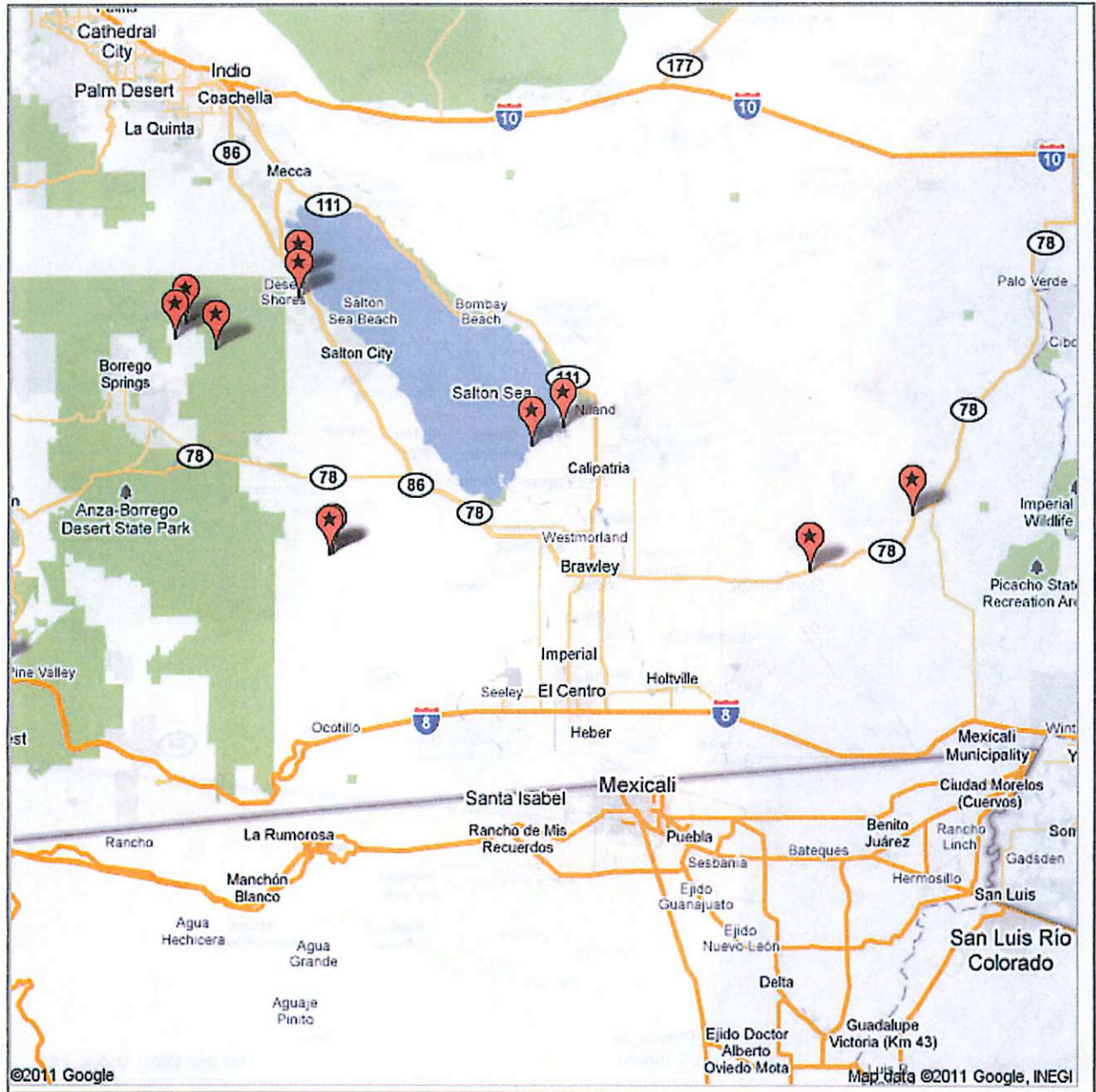
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### PTY5 594 Spring 2011

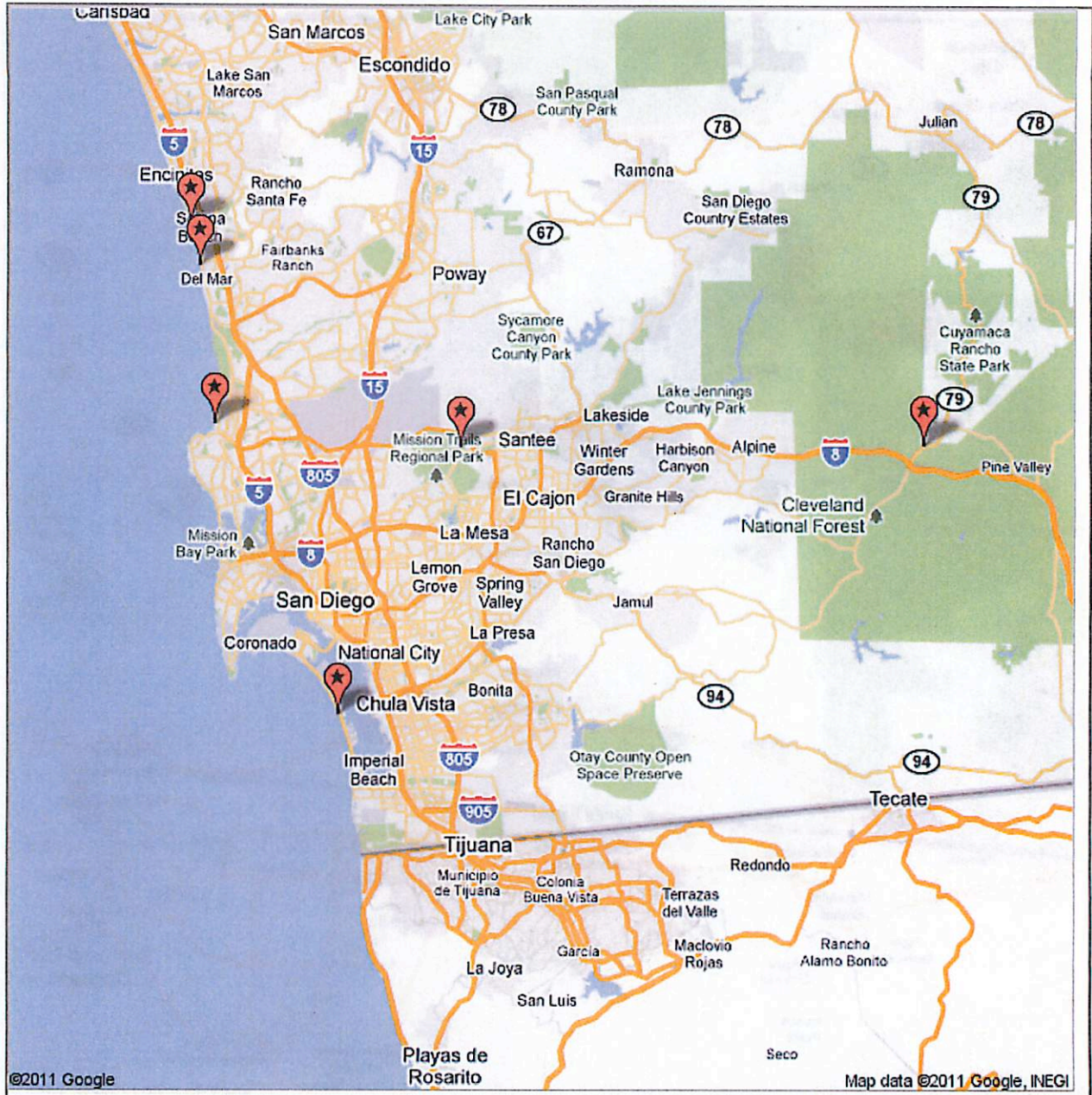
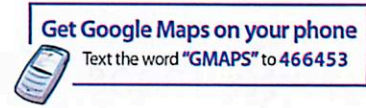
LPL fieldtrip to the Salton Sea and Pacific coasts

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**PTYS 594 Spring 2011**

LPL fieldtrip to the Salton Sea and Pacific coasts

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GEOLOGIC TIME SCALE						
Time Units of the Geologic Time Scale				Development of Plants and Animals		
Eon	Era	Period	Epoch			
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Earliest <i>Homo sapiens</i>	
			Pleistocene	1.6		
		Tertiary	Pliocene	5.3	Earliest hominids "Age of Mammals"	
			Miocene	23.8		
			Oligocene	33.7		
			Eocene	55		
			Palaeocene	65		
	Mesozoic	Cretaceous	145	"Age of Reptiles"	Extinction of dinosaurs and many other species First flowering plants First birds Dinosaurs dominant First mammals	
		Jurassic	208			
		Triassic	248			
	Palaeozoic	Carboniferous	Permian	286	"Age of Amphibians"	Extinction of trilobites and many other marine animals  First reptiles Large coal swamps Amphibians abundant
			Pennsylvanian	320		
			Mississippian	360		
		Devonian	410	"Age of Fishes"	First amphibians First insect fossils Fishes dominant	
Silurian		438	"Age of Invertebrates"	First land plants First fishes Trilobites dominant First organisms with shells		
Ordovician		505				
Cambrian		545				
Vendian		650	"Soft-bodied faunas"	Abundant Ediacaran faunas		
Proterozoic	2500	Collectively called Precambrian comprises about 87% of the geological time scale		First multicelled organisms		
Archean						
Hadean						
	4600 Ma			First one-celled organisms Age of oldest rocks  Origin of the earth		

(From <http://sci.waikato.ac.nz/evolution/geological.shtml>)

10 cm ruler



**ROCK DENSITIES**

Material type	Density range (Mg/m <sup>3</sup> )	Approximate weight of 1 cubic meter (Mg)
<i>Sedimentary rocks</i>		
Alluvium	1.90-2.00	1.90-2.00
Clay	2.00-2.60	2.00-2.60
Gravel	1.70-2.40	1.70-2.40
Lenses	1.40-1.70	1.40-1.70
Silt	1.80-2.20	1.80-2.20
Silt	1.20-2.40	1.20-2.40
Sand	1.70-2.60	1.70-2.60
Sandstone	1.60-2.70	1.60-2.70
Shale	1.70-2.70	1.70-2.70
Limestones	1.60-2.60	1.60-2.60
Dolomite	2.20-2.90	2.20-2.90
Chalk	1.80-2.60	1.80-2.60
Halite	2.10-2.60	2.10-2.60
Glauber's salt	1.88-1.97	1.88-1.97
<i>Igneous rocks</i>		
Rhyolite	2.35-2.70	2.35-2.70
Granite	2.50-2.80	2.50-2.80
Andesite	2.40-2.80	2.40-2.80
Basalt	2.60-3.00	2.60-3.00
Basalt	2.70-3.30	2.70-3.30
Gabbro	2.90-3.30	2.90-3.30
<i>Metamorphic rocks</i>		
Schist	2.30-2.70	2.30-2.70
Gneiss	2.50-2.80	2.50-2.80
Phanite	2.60-2.80	2.60-2.80
Slate	2.70-2.80	2.70-2.80
Quartzite	2.50-2.70	2.50-2.70
Amphibolite	2.90-3.00	2.90-3.00
Eclogite	3.20-3.50	3.20-3.50

**Udden-Wentworth Grain Size Scale**

Size Range	Name
>256 mm	Boulder
64-256 mm	Cobble
4-64 mm	Pebble (occasionally subdivided)
2-4 mm	Granule
1-2 mm	Very Coarse Sand
0.5-1 mm	Coarse Sand
0.25-0.5 mm	Medium Sand
125-250 μm	Fine Sand
62.5-125 μm	Very Fine Sand
31.25-62.5 μm	Silt
15.75-31.25 μm	Clay

**MOHS HARDNESS SCALE**

Index/Mineral	Scale	Common Objects
Diamond	10	
Corundum	9	
Topaz	8	
Quartz	7	Steel file (6.5)
Orthoclase	6	
Apatite	5	Glass (5.5) Knife blade (5.1)
Fluorite	4	Wire Nail (4.5)
Calcite	3	Penney (3.5) Fingernail (2.5)
Gypsum	2	
Talc	1	

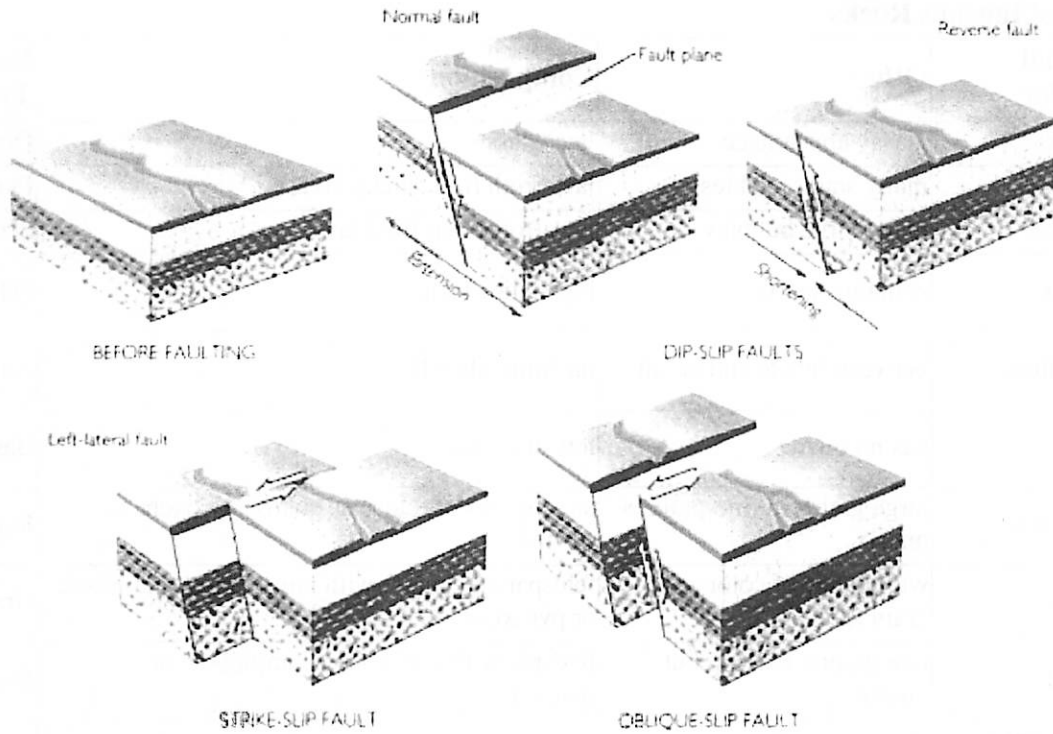
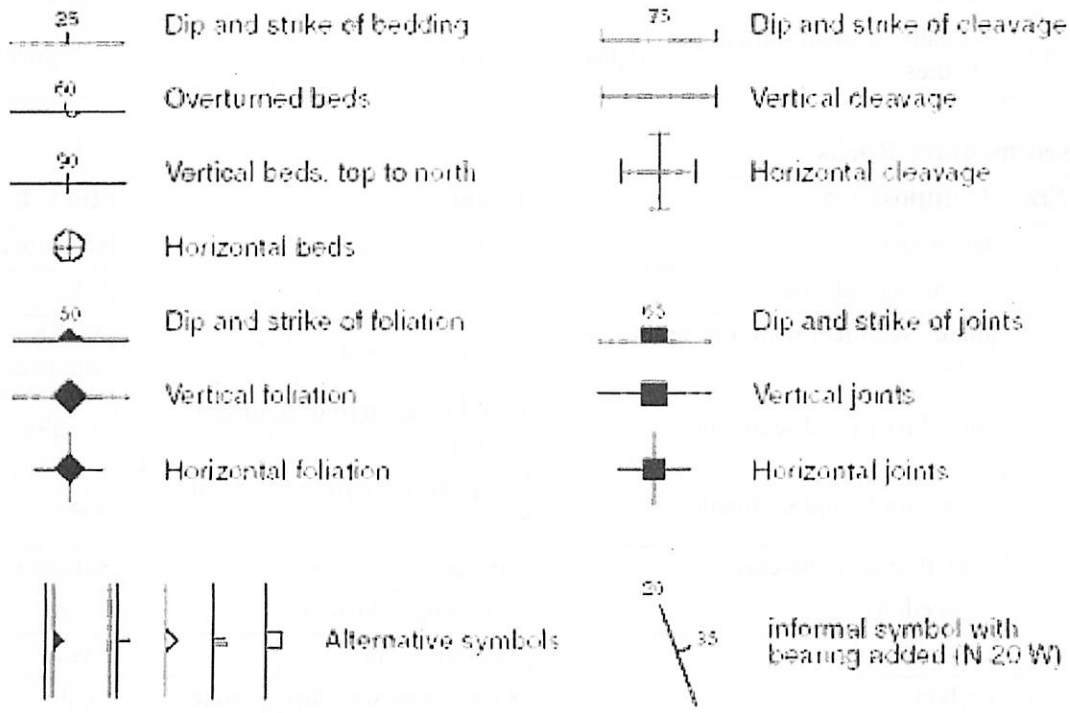


Figure 10.12  
 Wood and Sencer, *Understanding Earth*

GHT 54  
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**FAULT TYPES**

<http://www.geo.wvu.edu/~jtoro/Petroleum/Review%202.html>



[http://www.public.asu.edu/~arrows/structure/Labs/Geo\\_Blocks/](http://www.public.asu.edu/~arrows/structure/Labs/Geo_Blocks/)

## IDENTIFICATION OF ROCKS AND ROCK FORMING MINERALS

### Identification of Igneous Rocks

Grain Size	Usual Color	Other	Composition	Rock Type
fine	dark	glassy appearance	lava glass	Obsidian
fine	light	many small bubbles	lava froth from sticky lava	Pumice
fine	dark	many large bubbles	lava froth from fluid lava	Scoria
fine or mixed	light	contains quartz	high-silica lava	Felsite
fine or mixed	medium	between felsite and basalt	medium-silica lava	Andesite
fine or mixed	dark	has no quartz	low-silica lava	Basalt
mixed	any color	large grains in fine-grained matrix	large grains of feldspar, quartz, pyroxene or olivine	Porphyry
coarse	light	wide range of color and grain size	feldspar and quartz with minor mica, amphibole or pyroxene	Granite
coarse	light	like granite but without quartz	feldspar with minor mica, amphibole or pyroxene	Syenite
coarse	medium to dark	little or no quartz	low-calcium plagioclase and dark minerals	Diorite
coarse	medium to dark	no quartz; may have olivine	high-calcium plagioclase and dark minerals	Gabbro
coarse	dark	dense; always has olivine	olivine with amphibole and/or pyroxene	Peridotite
coarse	dark	dense	mostly pyroxene with olivine and amphibole	Pyroxenite
coarse	green	dense	at least 90% olivine	Dunite
very coarse	any color	usually in small intrusive bodies	typically granitic	Pegmatite

### Identification of Sedimentary Rocks

Hardness	Grain Size	Composition	Other	Rock Type
hard	coarse	clean quartz	white to brown	Sandstone
hard	coarse	quartz and feldspar	usually very coarse	Arkose
hard or soft	mixed	mixed sediment with rock grains and clay	gray or dark and "dirty"	Wacke/ Graywacke
hard or soft	mixed	mixed rocks and sediment	round rocks in finer sediment matrix	Conglomerate
hard or soft	mixed	mixed rocks and sediment	sharp pieces in finer sediment matrix	Breccia
hard	fine	very fine sand; no clay	feels gritty on teeth	Siltstone
hard	fine	chalcedony	no fizzing with acid	Chert
soft	fine	clay minerals	splits in layers	Shale
soft	fine	carbon	black; burns with tarry smoke	Coal
soft	fine	calcite	fizzes with acid	Limestone
soft	coarse or fine	dolomite	no fizzing with acid unless powdered	Dolomite rock

soft	coarse	fossil shells	mostly pieces	Coquina
very soft	coarse	halite	salt taste	Rock Salt
very soft	coarse	gypsum	white, tan or pink	Rock Gypsum

### Identification of Metamorphic Rocks

Foliation	Grain Size	Hardness	Usual Color	Other	Rock Type
foliated	fine	soft	dark	"tink" when struck	Slate
foliated	fine	soft	dark	shiny; crinkly foliation	Phyllite
foliated	coarse	hard	mixed dark and light	wrinkled foliation; often has large crystals	Schist
foliated	coarse	hard	mixed	banded	Gneiss
foliated	coarse	hard	mixed	distorted "melted" layers	Migmatite
foliated	coarse	hard	dark	mostly hornblende	Amphibolite
nonfoliated	fine	soft	greenish	shiny, mottled surface	Serpentinite
nonfoliated	fine or coarse	hard	dark	dull and opaque colors, found near intrusions	Hornfels
nonfoliated	coarse	hard	red and green	dense; garnet and pyroxene	Eclogite
nonfoliated	coarse	soft	light	calcite or dolomite by the acid test	Marble
nonfoliated	coarse	hard	light	quartz (no fizzing with acid)	Quartzite

[http://geology.about.com/library/bl/blockident\\_tables.htm](http://geology.about.com/library/bl/blockident_tables.htm)

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

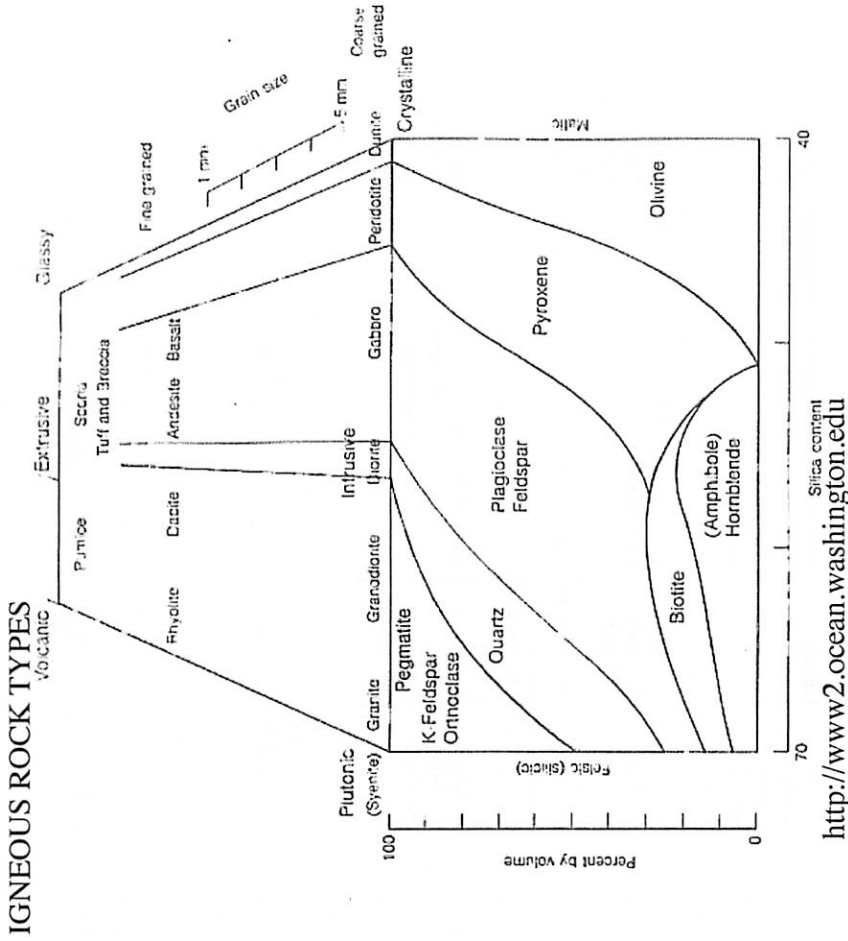
<b>Light-colored minerals</b>			
<b>Hardness</b>	<b>Cleavage</b>	<b>Physical Properties</b>	<b>Name</b>
<b>Hardness &gt;5</b>	<b>Excellent or good</b>	White or gray. Cleavage in 2 planes at nearly right angles. Striations. Hardness-6	<b>Plagioclase Feldspar</b>
		Orange, brown, white, gray, green or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

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

[http://www.thisoldearth.net/This\\_Old\\_Earth/Home.html](http://www.thisoldearth.net/This_Old_Earth/Home.html)

### MINERAL CHEMICAL CLASSIFICATIONS

<http://www.appstate.edu/~abbottrn/mnrl-id/>

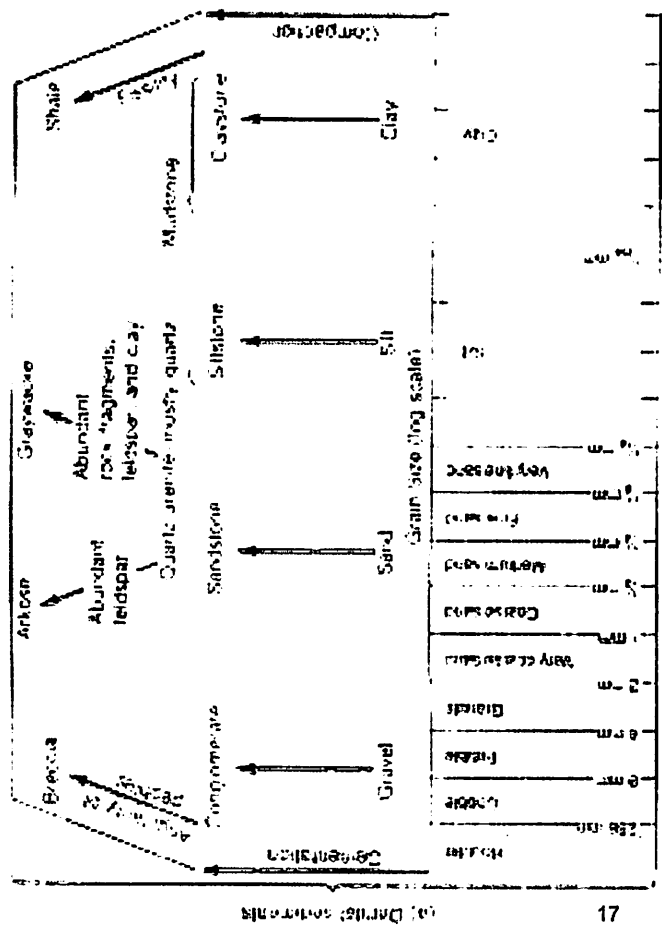


<http://www2.ocean.washington.edu>

CHEMICAL GROUP	ANIONIC SPECIES	EXAMPLES
OXIDES minerals	Oxygen, O <sup>2-</sup>	Hematite, Fe <sub>2</sub> O <sub>3</sub> ; Magnetite, Fe <sub>3</sub> O <sub>4</sub>
SULFIDE minerals	Sulfur, S <sup>2-</sup>	Pyrite, FeS <sub>2</sub>
CARBOXATE minerals	Carbonate, CO <sub>3</sub> <sup>2-</sup>	Calcite, CaCO <sub>3</sub> ; Dolomite, CaMg(CO <sub>3</sub> ) <sub>2</sub>
SILICATE minerals	Silicate, SiO <sub>4</sub> <sup>4-</sup> , Tetrahedra <sup>a</sup>	
	Isolated SiO <sub>4</sub> <sup>4-</sup> Tetrahedra	Olivine, (Mg,Fe)SiO <sub>4</sub> ; Garnet, (Fe,Mg,Ca)Al <sub>2</sub> Si <sub>2</sub> O <sub>12</sub>
	Single Chains of Tetrahedra, Si <sub>2</sub> O <sub>6</sub> <sup>4-</sup>	Pyroxene, e.g., Augite, CaMgFeSi <sub>2</sub> O <sub>6</sub>
	Double Chains of Tetrahedra, (Si <sub>2</sub> O <sub>7</sub> ) <sub>2</sub> <sup>4-</sup>	Amphibole, e.g., Hornblende, NaCa <sub>2</sub> (Mg,Fe,Al) <sub>3</sub> (Si <sub>7</sub> Al <sub>2</sub> )O <sub>22</sub> (OH) <sub>2</sub>
STRUCTURAL SUBGROUPS OF THE SILICATES		Micas (phyllosilicates), e.g., Muscovite, KAl <sub>3</sub> (AlSi <sub>3</sub> )O <sub>10</sub> (OH) <sub>2</sub>
		Biotite, K(Mg,Fe <sub>3</sub> )AlSi <sub>3</sub> O <sub>10</sub> (OH) <sub>2</sub>
		Claylike, (Mg,Fe) <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>
		Quartz, SiO <sub>2</sub>
	Framework, SiO <sub>2</sub> or Al <sub>2</sub> SiO <sub>5</sub> , <sup>25 to 0.5</sup>	Feldspars K-Feldspar, KAAlSi <sub>3</sub> O <sub>8</sub> Plagioclase, (Na,Ca)AlSi <sub>3</sub> O <sub>8</sub>



**SEDIMENTARY ROCK TYPES**  
<http://www2.ocean.washington.edu>



**METAMORPHIC ROCK TYPES**  
[http://www.dmtcalaska.org/course\\_dev/explogeo/class09/notes09.html](http://www.dmtcalaska.org/course_dev/explogeo/class09/notes09.html)

Primary igneous or sedimentary rock composition	Major mineral groups present	Typical conditions <math>P-T</math> range	Metamorphic grades <math>P-T</math> range	Commonly occurring rocks
shale, pelitic rocks, sandstone, 'psammite rocks'	phyllonites, calcite, quartz	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, phyllite
limestone	calcite, dolomite	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, marble
marl	calcite, dolomite, phyllosilicates	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, calc-schist
sandy shale, 'psammite rocks'	quartz, feldspar, calcite, dolomite, phyllosilicates	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, calc-schist
basalt, gabbro	amphiboles, plagioclase, feldspar	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, calc-schist
diabase, granite	K-feldspar, quartz, phyllosilicates	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, calc-schist
diabase, peridotite	serpentine, talc, Mg amphiboles	<math>P < 1 \text{ kbar}</math>, <math>T < 100 \text{ }^\circ\text{C}</math>	diagenesis, diagenetic schist	diagenetic schist, calc-schist

Rock	Chemical composition	Minerals	Dolomite	Iron formation	Evaporite	Chert	Organics	Phosphate
Chemical	$\text{CaCO}_3$	Calcite, Aragonite	$\text{CaMg}(\text{CO}_3)_2$	Fe-silicate oxide carbonate	$\text{NaCl}$ , $\text{CaSO}_4$	$\text{SiO}_2$ , Carbon	Coal, Oil, Gas	$\text{Ca}_3(\text{PO}_4)_2$
Minerals		Calcite, Aragonite	Dolomite	Hematite, Limonite, Siderite	Gypsum, Anhydrite, Halite, Other salts	Opal, Chalcedony, Quartz		Apatite

Figure 3-22 Sedimentary rock classification. (a) Detrital sediments, (b) Chemical sediments.

**Aa:** A blocky and fragmented form of lava occurring in flows with fissured and angular surfaces.

**Alkali metal:** A strongly basic metal like potassium or sodium.

**Alluvial fan:** A low, cone shaped deposit of terrestrial sediment formed where a stream undergoes an abrupt reduction of slope.

**Alluvium:** Unconsolidated terrestrial sediment composed of sorted or unsorted sand, gravel, and clay that has been deposited by water.

**Angle of repose:** The steepest slope angle in which particular sediment will lie without cascading down.

**Aquifer:** A permeable formation that stores and transmits groundwater in sufficient quantity to supply wells.

**Arroyo:** A steep-sided and flat-bottomed gully in an arid region that is occupied by a stream only intermittently, after rains.

**Artesian well:** A well that reaches an aquifer containing water under pressure. Thus water in the well rises above the surrounding water table.

**Barchan:** A crescent-shaped sand dune moving across a clean surface with its convex face upwind and its concave slip face downwind.

**Basalt:** A fine-grained, dark, mafic igneous rock composed largely of plagioclase feldspar and pyroxene.

**Basement:** The oldest rocks recognized in a given area, a complex of metamorphic and igneous rocks that underlies all the sedimentary formations.

**Basic rock:** Any igneous rock containing mafic minerals rich in iron and magnesium, but containing no quartz and little sodium rich plagioclase feldspar.

**Basin:** In tectonics, a circular, syncline-like depression of strata. In sedimentology, the site of accumulation of a large thickness of sediments.

**Batholith:** A great irregular mass of coarse-grained igneous rock which has either intruded the country rock or been derived from it through metamorphism.

**Bathymetry:** The study and mapping of sea-floor topography.

**Bedding:** A characteristic of sedimentary rocks in which parallel planar surfaces separating different grain sizes or compositions indicate successive depositional surfaces that existed at the time of sedimentation.

**Bolson:** In arid regions, a basin filled with alluvium and intermittent playa lakes and having no outlet.

**Butte:** A steep sided and flat topped hill formed by erosion of flat laying strata where remnants of a resistant layer protect the softer rocks underneath.

**Caldera:** A large, circular depression in a volcanic terrain, typically originating in collapse, explosion, or erosion.

**Carbonate rock:** A rock composed of carbonate minerals, especially limestone and dolomite.

**Cataclastic rock:** A breccia of powdered rock formed by crushing and shearing during tectonic movements.

**Chemical weathering:** The total set of all chemical reactions that act on rock exposed to water and atmosphere and so change its minerals to stable forms.

**Chert:** A sedimentary form of amorphous or extremely fine-grained silica, partially hydrous, found in concretions and beds.

**Cinder cone:** A steep, conical hill built up about a volcanic vent and composed of coarse pyroclasts expelled from the vent by escaping gases.

**Clastic rock:** A sedimentary rock formed from mineral particles (clasts) that were mechanically transported.

**Clay:** Any of a number of hydrous aluminosilicate minerals formed by weathering and hydration of other silicates.

**Composite cone:** The volcanic cone of a stratovolcano, composed of both cinders and lava flows.

**Deflation:** The removal of clay and dust from dry soil by strong winds.

**Delta:** A body of sediment deposited in an ocean or lake at the mouth of a stream.

**Deposition:** A general term for the accumulation of sediments by either physical or chemical sedimentation.

**Deposition remnant magnetization:** Magnetization created in sedimentary rocks by rotation of magnetic crystals into line with the ambient field during settling.

**Desert pavement:** A deposit produced by continued deflation, which removes the fine grains of a soil and leaves a surface covered with closely packed cobbles.

**Detrital sediment:** Sediment deposited by a physical process.

**Diagenesis:** The physical and chemical changes undergone by a sediment during lithification and compaction, excluding erosion and metamorphism.

**Diatreme:** A volcanic vent filled with breccia by the explosive escape of gases.

**Dip:** The angle by which a stratum or other planar feature deviates from the horizontal. The angle is measured in a plane perpendicular to the strike.

**Drainage basin:** A region of land surrounded by divides and crossed by streams that eventually converge to one river or lake.

**Drift (glacial):** A collective term for all the rock, sand, and clay that is transported and deposited by a glacier either as till or as outwash.

**Dune:** An elongated mound of sand formed by wind or water.

**Eolian:** Pertaining to or deposited by wind.

**Epicenter:** The point on the Earth's surface directly above the focus or hypocenter of an Earthquake.

**Erosion:** The set of all processes by which soil and rock are loosened and moved downhill or downwind.

**Evaporite:** A chemical sedimentary rock consisting of minerals precipitated by evaporating waters, especially salt and gypsum.

**Exfoliation:** A physical weathering process in which sheets of rock are fractured and detached from an outcrop.

**Fault:** A planar or gently curved fracture in the Earth's crust across which there has been relative displacement.

**Fault plane:** The plane that best approximates the fracture surface of a fault.

**Felsic:** An adjective used to describe a light-colored igneous rock poor in iron and magnesium content, abundant in feldspars and quartz.

**Fissure:** An extensive crack, break, or fracture in the rocks.

**Flood basalt:** A plateau basalt extending many kilometers in flat, layered flows originating in fissure eruptions.

**Flow cleavage:** In a metamorphic rock, the parallel arrangement of all planar or linear crystals as a result of rock flowage during metamorphism.

**Fluid inclusion:** A small body of fluid that is entrapped in a crystal and has the same composition as the fluid from which the crystal formed.

**Focus (earthquake):** The point at which the rupture occurs; synonymous with hypocenter.

**Fold:** A planar feature, such as a bedding plane, that has been strongly warped, presumably by deformation.

**Foliation:** Any planar set of minerals or banding of mineral concentrations including cleavage, found in a metamorphic rock.

**Forset bed:** One of the inclined beds found in crossbedding; also an inclined bed deposited on the outer front of a delta.

**Friction breccia:** A breccia formed in a fault zone or volcanic pipe by the relative motion of two rock bodies.

**Fumarole:** A small vent in the ground from which volcanic gases and heated groundwater emerge, but not lava.

**Geochronology:** The science of absolute dating and relative dating of geologic formations and events, primarily through the measurement of daughter elements produced by radioactive decay in minerals.

**Geomorphology:** The science of surface landforms and their interpretation on the basis of geology and climate.

**Geosyncline:** A major downwarp in the Earth's crust, usually more than 1000 kilometers in length, in which sediments accumulate to thicknesses of many kilometers. The sediments may eventually be deformed and metamorphosed during a mountain-building episode.

**Geotherm:** A curving surface within Earth along which the temperature is constant.

**Geyser:** A hot spring that throws hot water and steam into the air. The heat is thought to result from the contact of groundwater with magma bodies.

**Glacial rebound:** Epeirogenic uplift of crust that takes place after the retreat of a continental glacier in response to earlier subsidence under the weight of ice.

**Glacial striations:** Scratches left on bedrock and boulders by overriding ice, and showing the direction of motion.

**Glacial valley:** A valley occupied or formerly occupied by a glacier, typically with a U-shaped profile.

**Glacier:** A mass of ice and surficial snow that persists throughout the year and flows downhill under its own weight, of sizes 100 m – 10000 km.

**Glass:** A rock formed when magma is too rapidly cooled (quenched) to allow crystal growth.

**Graben:** A downthrown block between two normal faults of parallel strike but converging dips; hence a tensional feature. See also horst.

**Graded bedding:** A bed in which the coarsest particles are concentrated at the bottom and grade gradually upward into fine silt.

**Granite:** A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar, and micas.

**Gravity anomaly:** The value of gravity left after subtracting the reference value based on latitude, and possibly the free-air and Bouguer corrections.

**Gravity survey:** The measurement of gravity at regularly spaced grid points with repetitions to control instrument drift.

**Groundwater:** The mass of water in the ground below the phreatic zone occupying the total pore space in the rock.

**Horst:** An elongate, elevated block of crust forming a ridge or plateau, typically bounded by parallel, outward-dipping normal faults.

**Hydration:** A chemical reaction, usually in weathering, which adds water or OH to a mineral structure.

**Hydraulic conductivity:** A measure of the permeability of a rock or soil: the volume of flow through a unit surface in unit time with unit hydraulic pressure difference as the driving force.

**Hydrologic cycle:** The cyclical movement of water from the ocean to the atmosphere, through rain to the surface, through runoff and groundwater to streams, and back to the sea.

**Hydrology:** The science of that part of the hydrologic cycle between rain and return to the sea; the study of water on and within the land.

**Hydrothermal activity:** Any process involving high-temperature groundwaters, especially the alteration and emplacement of minerals and the formation of hot springs and geysers.

**Hydrothermal vein:** A cluster of minerals precipitated by hydrothermal activity in a rock cavity.

**Igneous rock:** A rock formed by congealing rapidly or slowly from a molten state.

**Inclination:** The angle between a line in the Earth's magnetic field and the horizontal plane; also a synonym for dip.

**Infiltration:** The movement of groundwater or hydrothermal water into rock or soil through joints and pores.

**Intrusion:** An igneous rock body that has forced its way in a molten state into surrounding country rock.

**Intrusive rock:** Igneous rock that is interpreted as a former intrusion from its cross-cutting contacts, chilled margins, or other field relations.

**Isograd:** A line or curved surface connecting rocks that have undergone an equivalent degree of metamorphism.

**Isostasy:** The mechanism whereby areas of the crust rise or subside until the mass of their topography is buoyantly supported or compensated by the thickness of crust below, which "floats" on the denser mantle. The theory that continents and mountains are supported by low-density crustal "roots."

**Isotope:** One of several forms of one element, all having the same number of protons in the nucleus but differing in number of neutrons and atomic weight.

**Joint:** A large and relatively planar fracture in a rock across which there is no relative displacement of the two sides.

**Laccolith:** A sill-like igneous intrusion that forces apart two strata and forms a round, lens-shaped body many times wider than it is thick.

**Lahar:** A mudflow of unconsolidated volcanic ash, dust, breccia, and boulders mixed with rain or the water of a lake displaced by a lava flow.

**Laminar flow:** A flow regime in which particle paths are straight or gently curved and parallel.

**Lapilli:** A fragment of volcanic rock formed when magma is ejected into the air by expanding gases.

**Lava:** Magma or molten rock that has reached the surface.

**Lava tube:** A sinuous, hollow tunnel formed when the outside of a lava flow cools and solidifies and the molten material passing through it is drained away.

**Leaching:** The removal of elements from a soil by dissolution in water moving downward in the ground.

**Left-lateral fault:** A strike-slip fault on which the displacement of the far block is to the left when viewed from either side.

**Levee:** A low ridge along a stream bank, formed by deposits left when floodwater decelerates on leaving the channel.

**Limb (fold):** The relatively planar part of a fold or of two adjacent folds (for example, the steeply dipping part of a stratum between an anticline and syncline).

**Limestone:** A sedimentary rock composed principally of calcium carbonate (CaCO<sub>2</sub>), usually as the mineral calcite.

**Lithification:** The processes that convert a sediment into a sedimentary rock.

**Lithology:** The systematic description of rocks, in terms of mineral composition and texture.

**Lithosphere:** The outer, rigid shell of the Earth, situated above the asthenosphere and containing the crust, continents, and plates.

**Lode:** An unusually large vein or set of veins containing ore minerals.

**Longitudinal dune:** A long dune parallel to the direction of the prevailing wind.

**Lopolith:** A large laccolith that is bowl-shaped and depressed in the center, possibly by subsidence of an emptied magma chamber beneath the intrusion.

**Maar volcano:** A volcanic crater without a cone, believed to have been formed by an explosive eruption of trapped gases.

**Mafic mineral:** A dark-colored mineral rich in iron and magnesium, especially a pyroxene, amphibole, or olivine.

**Magma:** Molten rock material that forms igneous rocks upon cooling. Magma that reaches the surface is referred to as lava.

**Magma chamber:** A magma-filled cavity within the lithosphere.

**Magnetic anomaly:** The value of the local magnetic field remaining after the subtraction of the dipole portion of the Earth's field.

**Magnetic north pole:** (1) The point where the Earth's surface intersects the axis of the dipole that best approximates the Earth's field. (2) The point where the Earth's magnetic field dips vertically downward.

**Magnetic stratigraphy:** The study and correlation of polarity epochs and events in the history of the Earth's magnetic field as contained in magnetic rocks.

**Magnetometer:** An instrument for measuring either one orthogonal component or the entire intensity of the Earth's magnetic field at various points.

**Mantle:** The main bulk of the Earth, between the crust and core, ranging from depths of about 40 to 3480 kilometers. It is composed of dense mafic silicates and divided into concentric layers by phase changes that are caused by the increase in pressure with depth.

**Mass spectrometer:** An instrument for separating ions of different mass but equal charge (mainly isotopes in geology) and measuring their relative quantities.

**Mechanical weathering:** The set of all physical processes by which an outcrop is broken up into small particles.

**Mesosphere:** The lower mantle.

**Metamorphism:** The changes of mineralogy and texture imposed on a rock by pressure and temperature in the Earth's interior.

**Meteorite:** A stony or metallic object from inter-planetary space that penetrates the atmosphere to impact on the surface.

**Micrometeorite:** A meteorite less than 1 millimeter in diameter.

**Microseism:** A weak vibration of the ground that can be detected by seismographs and which is caused by waves, wind, or human activity.

**Mineral:** A naturally occurring element or non-organic compound with a precise chemical formula and a regular internal lattice structure.

**Mohorovic discontinuity ("Moho"):** Boundary between crust and mantle, marked by a rapid increase in seismic wave velocity to > 8 km/s (depth 5-45 km).

**Mohs scale of hardness:** An empirical, ascending scale of mineral hardness.

**Monocline:** The S-shaped fold connecting two horizontal parts of the same stratum at different elevations. Its central limb is usually not overturned.

**Moraine:** A glacial deposit of till left at the margin of an ice sheet.

**Normal fault:** A dip-slip fault in which the block above the fault has moved downward relative to the block below.

**Oblique-slip fault:** A fault that combines some strike slip motion with some dip-slip motion.

**Ore:** A natural deposit in which a valuable metallic element occurs in high enough concentration to make mining economically feasible.

**Orogenic belt:** A linear region, often a former geo-syncline, that has been subjected to folding, and other deformation in a mountain-building episode.

**Orogeny:** The tectonic process in which large areas are folded, thrust-faulted, metamorphosed, and subjected to plutonism. The cycle ends with uplift and the formation of mountains.

**Outgassing:** The release of juvenile gases to the atmosphere and oceans by volcanism.

**Oxidation:** A chemical reaction in which electrons are lost from an atom and its charge becomes more positive.

**Pahoehoe:** A basaltic lava flow with a glassy, smooth, and undulating, or ropy, surface.

**Paleoclimate:** The average state or typical conditions of climate during some past geologic period.

**Paleomagnetism:** The science of the reconstruction of the Earth's ancient magnetic field and the positions of the continents from the evidence of remnant magnetization in ancient rocks.

**Paleowind:** A prevailing wind direction in an area, inferred from dune structure or the distribution of volcanic ash for one particular time in geologic history.

**Pangaea:** A great proto-continent from which all present continents have broken off by the mechanism of sea-floor spreading and continental drift.

**Pediment:** A planar, sloping rock surface forming a ramp up to the front of a mountain range in an arid region. It may be covered locally by thin alluvium.

**Preferred orientation:** Any deviation from randomness in the distribution of the crystallographic or grain shape axes of minerals of a rock produced by deformation and non-uniform stress during crystallization in metamorphic rocks or by depositional currents in sediments.

**P-wave:** The primary/fastest wave traveling away from a seismic event through the solid rock, consisting of a train of compressions/dilations of the material.

**Pyroclastic rock:** A rock formed by the accumulation of fragments of volcanic rock scattered by volcanic explosions.

**Radiative transfer:** One mechanism for the movement of heat, in which it takes the form of long-wavelength infrared radiation.

**Recrystallization:** The growth of new mineral grains in a rock at the expense of old grains, which supply the material.

**Recumbent fold:** An overturned fold with both limbs nearly horizontal.

**Regolith:** Any solid material lying on top of bedrock. Includes soil, alluvium, and rock fragments weathered from the bedrock.

**Relief:** The maximum regional difference in elevation.

**Remote sensing:** The study of Earth surface conditions and materials from airplanes and satellites by means of photography, spectroscopy, or radar.

**Rhyolite:** The fine-grained volcanic or extrusive equivalent of granite, light brown to gray and compact.

**Ridge (mid-ocean):** A major linear elevated landform of the ocean floor, from 200 to 20,000 kilometers in extent. It is not a single ridge, but resembles a mountain range and may have a central rift valley.

**Rift valley:** A fault trough formed in a divergence zone or other area of tension.

**Right-lateral fault:** A strike-slip fault on which the displacement of the far block is to the right when viewed from either side.

**Ripple:** A very small dune of sand or silt whose long dimension is formed at right angles to the current.

**Salination:** The movement of sand or fine sediment by short jumps above the ground or stream bed under the influence of a current too weak to keep it permanently suspended.

**Sandblasting:** A physical weathering process in which rock is eroded by the impact of sand grains carried by the wind, frequently leading to ventifact formation of pebbles and cobbles.

**Sandstone:** A detrital sedimentary rock composed of grains from 1/16 to 2 millimeters in diameter, dominated in most sandstones by quartz, feldspar, and rock fragments, bound together by a cement of silica, carbonate, or other minerals or a matrix of clay minerals.

**Sea-floor spreading:** The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room. This process may continue at 0.5 to 10 centimeters/year through many geologic periods.

**Secular variation:** Slow changes in orientation of the Earth's magnetic field that appear to be long lasting and internal in origin.

**Sedimentary rock:** A rock formed by the accumulation and cementation of mineral grains transported by wind, water, or ice to the site of deposition or chemically precipitated at the depositional site.

**Sedimentary structure:** Any structure of a sedimentary or weakly metamorphosed rock that was formed at the time of deposition.

**Sedimentation:** The process of deposition of mineral grains or precipitates in beds or other accumulations.

**Seismic reflection:** Mode of seismic prospecting in which a seismic profile is examined for waves that reflected from near-horizontal strata below the surface.

**Seismic refraction:** Mode of seismic prospecting in which the seismic profile is examined for waves that have been refracted upward from seismic discontinuities below the profile. Greater depths may be reached than through seismic reflection.

**Seismic surface wave:** A seismic wave that follows the earth's surface only, with a speed less than that of S-waves.

**Stratification:** A structure of sedimentary rocks, which have recognizable parallel beds of considerable lateral extent.

**Stratigraphic sequence:** A set of beds deposited that reflects the geologic history of a region.

**Stratigraphy:** The science of the description, correlation, and classification of strata in sedimentary rocks.

**Stratovolcano:** A volcanic cone consisting of both lava and pyroclastic rocks, often conical.

**Stress:** A quantity describing the forces acting on each part of a body in units of force per unit area. **Striation:** See Glacial striation.

**Strike:** The angle between true North and the horizontal line contained in any planar feature (inclined bed, dike, fault plane, etc.).

**Strike-slip fault:** A fault whose relative displacement is purely horizontal.

**Subduction zone:** A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.

**Sublimation:** A phase change from the solid to the gaseous state, without passing through the liquid state.

**Subsidence:** A gentle epeirogenic movement where a broad area of the crust sinks without appreciable deformation.

**Syncline:** A large fold whose limbs are higher than its center; a fold with the youngest strata in the center.

**Tectonics:** The study of the movements and deformation of the crust on a large scale, including epeirogeny, metamorphism, folding, faulting, plate tectonics.

**Thermal conductivity:** A measure of a rock's capacity for heat conduction.

**Thermal expansion:** The property of increasing in volume as a result of an increase in internal temperature.

**Thermomagnetic magnetization:** Permanent magnetization acquired by igneous rocks in the Earth's magnetic field as they cool through the Curie point.

**Thrust fault:** A dip-slip fault in which the upper block above the fault plane moves up and over the lower block, so that older strata are placed over younger.

**Till:** An unconsolidated sediment containing all sizes of fragments from clay to boulders deposited by glacial action, usually unbedded.

**Topography:** The shape of the Earth's surface, above and below sea level; the set of landforms in a region; the distribution of elevations.

**Topset bed:** A horizontal sedimentary bed formed at the top of a delta and overlying the foreset beds.

**Trace element:** An element that appears in minerals in a concentration of less than 1 percent (often less than 0.001 percent).

**Transform fault:** A strike-slip fault connecting the ends of an offset in a mid-ocean ridge. Some pairs of plates slide past each other along transform faults.

**Transverse dune:** A dune that has its axis transverse to the prevailing winds or to a current.

**Trench:** A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

**Tuff:** A consolidated rock composed of pyroclastic fragments and fine ash. If particles are melted slightly together from their own heat, it is a "welded tuff."

**Turbulent flow:** A high-velocity flow in which streamlines are neither parallel nor straight but curled into small tight eddies (compare Laminar flow).

**Ultramafic rock:** An igneous rock consisting dominantly of mafic minerals, containing less than 10 percent feldspar.

**Unconformity:** A surface that separates two strata.

**Unconsolidated material:** Nonlithified sediment that has no mineral cement or matrix binding its grains.

**Uplift:** A broad and gentle epeirogenic increase in the elevation of a region without a eustatic change of sea level.

**Vadose zone:** The region in the ground between the surface and the water table in which pores are not filled with water. Also called the unsaturated zone.

**Valley glacier:** A glacier that is smaller than a continental glacier or an icecap, and which flows mainly along well-defined valleys, many with tributaries.

**Vein:** A deposit of foreign minerals within a rock fracture or joint.

**Ventifact:** A rock that exhibits the effects of sand-blasting or "snowblasting" on its surfaces, which become flat with sharp edges in between.

**Vesicle:** A cavity in an igneous rock that was formerly occupied by a bubble of escaping gas.

**Viscosity:** A measure of resistance to flow in a liquid.

**Volcanic ash:** A volcanic sediment of rock fragments, usually glass, less than 4 mm in diameter, formed when escaping gases force out a fine spray of magma.

**Volcanic bomb:** A pyroclastic rock fragment that shows the effects of cooling in flight in its streamlined or "bread-crust" surface.

**Volcanic breccia:** A pyroclastic rock in which all fragments are more than 2 millimeters in diameter.

**Volcanic cone:** The deposit of lava and pyroclastic materials that has settled close to the volcano's central vent.

**Volcanic dome:** A rounded accumulation around a volcanic vent of congealed lava too viscous to flow away quickly; hence usually rhyolite lava.

**Volcanic ejecta blanket:** A collective term for all the pyroclastic rocks deposited around a volcano, especially by a volcanic explosion.

**Volcano:** Any opening through the crust that has allowed magma to reach the surface, including the deposits immediately surrounding this vent.

**Warping:** In tectonics, refers to the gentle, regional bending of the crust, which occurs in epeirogenic movements.

**Water table:** A curved surface below the ground at which the vadose zone ends and the phreatic zone begins; the level to which a well would fill with water.

**Weathering:** The set of all processes that decay and break up bedrock, by a combination of physically fracturing or chemical decomposition.

**Xenolith:** A piece of country rock found engulfed in an intrusion.



# Formation of the Salton Trough

Youngmin JeongAhn

The **Salton Trough**, also called the Salton Sink, is the long depressed area which stretches from Palm Springs to Mexicali. This region includes Coachella and Imperial Valleys in Southern California. The Salton Sea is located between the two valleys.

This place is the transitional area between the San Andreas fault system and the East Pacific Rise and contains two spreading centers, The Brawley seismic zone and the



Figure 1 Fault System of Salton Trough (from platetectonics.com)

Cerro Prieto geothermal fields, which are connected by Imperial fault. There is the largest geothermal power station in the Cerro Prieto fields.

The San Andreas system is right lateral and strike slip fault which passes San Francisco, runs along Santa Cruz Mountains, San Gabriel Mountains, and San Bernardino Mountains and reaches the Salton Sea on the south. The Pacific Plate on the west and the North American Plate meet along this fault.

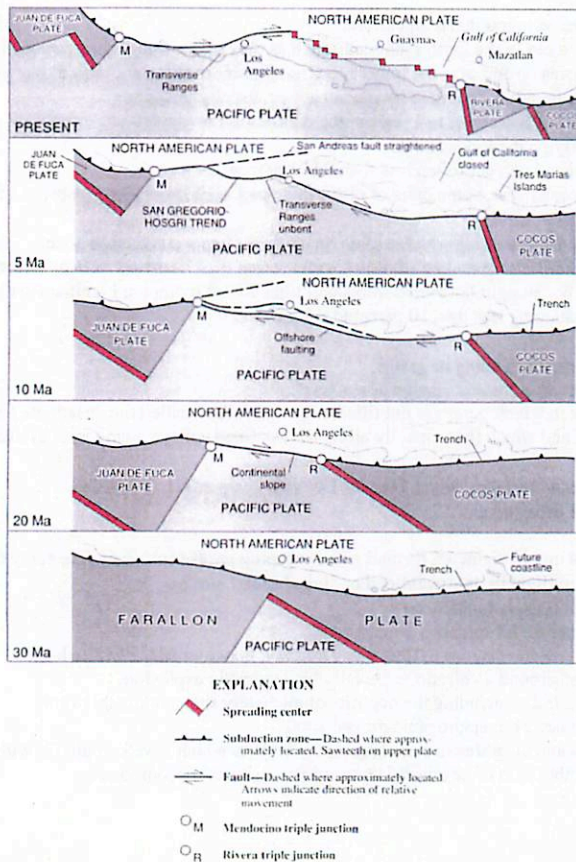


Figure 2 History of San Andreas Fault (from USGS)



This fault was induced by subduction of developed since 10-12.5 Myrs ago<sup>i</sup> and current relative movement rate of plates is about 33-37mm per year.<sup>ii</sup> Lots of earthquakes happen on this fault including the San Francisco earthquake of 1906.

The East Pacific Rise is an oceanic divergent plate boundary which extends from Antarctic plate to Salton Trough. This boundary entrapped Baja California and opened the Gulf of California around 5 Myrs ago during the East Pacific Rise subducted to the American plate. There might have been three marine incursions in the Salton Trough according to microfossil study.<sup>iii</sup>

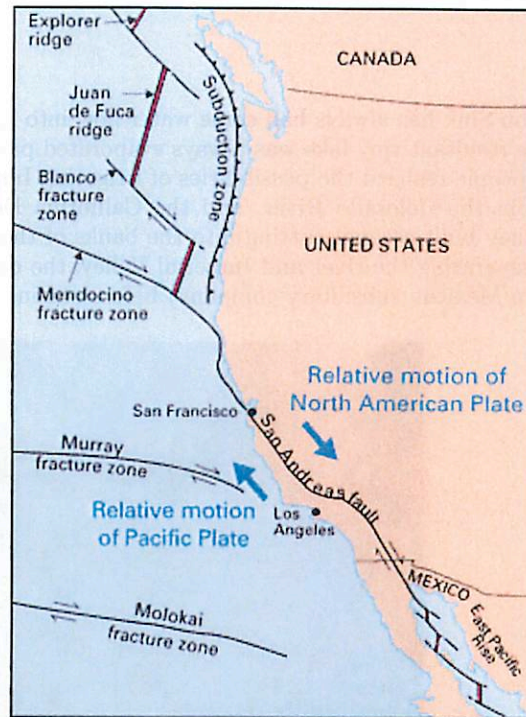


Figure 3 The San Andreas Fault System (from USGS)



The Salton trough experiences extensional stress and still sinks in the form of graben. Upheaval of the Colorado Plateau formed giant Colorado River and sediments were deposited 500 Myrs ago. The Salton Lake was formed occasionally and the recent one was half-manmade in 1905.

<sup>i</sup> Dickinson, W.R., and Snyder, W.S., 1979, "Geometry of triple junctions related to San Andreas transform". *Journal of Geophysical Research*, v. 84, no. B2, p. 561-572.

<sup>ii</sup> Wallace, R.E., 1993, "Present-Day Crustal Movements and the Mechanics of Cyclic Deformation". *The San Andreas Fault System, California*.

<sup>iii</sup> McDougall, K., 2006, "Late Neogene marine incursions and the ancestral Gulf of California". *MARGINS-RCL Workshop, Ensenada, Mexico*.



## Formation of the Salton Sea

Corwin Atwood-Stone

The Salton Sink has always had some water flow into it from rains and occasional flooding of the Colorado River, however the resultant tiny lake was always evaporated partway through the summer.

In 1901, people realized the possibilities of irrigating Imperial Valley (the area south of the Salton Sea) with water diverted from the Colorado River, and the California Development Company was formed to make this a reality. Therefore they built a canal cutting into the banks of the Colorado in southern California, however due to the hilly landscape separating the river and Imperial Valley, the canal had to swing south through Mexico (necessitating the creation of a Mexican subsidiary company) before coming into the valley.



FIG. 1 Overview showing the Salton Sea, Imperial Valley, The Colorado River, and surrounding areas. (2)

This canal brought more than 100,000 acres of Imperial Valley under cultivation by 1903, and in the process did dump some water into the Salton Sink, raising its lake level more than usual, but it was still small enough to mostly evaporate over the summer. However the new growing population was hungry for more arable land which the current

canal was unable to provide as its course was too long and its slope too shallow.

Thus several more cuts were made further south in southern California, however these were not a significant improvement. Finally the Mexican company was ordered to cut a new course south of the border which was able to supply all of the desired water. However due to their haste to have the project completed and their rather limited funds, they made this cut in loose alluvial soil, and installed only the barest hint of controlling devices.

Thus in 1905 the Colorado River entered the canal and quickly widened the channel to the point where it was carrying the flow of the entire river into Imperial Valley and flooded the Salton Sink, creating for the first time a true lake in the area.



FIG. 2 Flooding of the canal overwhelms the poorly built controls on the flow. (2)

The California Development Company made several desperate attempts to close the breach, however these proved ineffectual. Thus the Southern Pacific Railroad took control of the company and set about fixing it themselves, which they managed by late 1906. However in the spring of 1907 these new dams were overwhelmed as well and the flooding of the Salton Sea resumed. Late that year the Southern Pacific Railroad Company managed to close the canal for good.

By that time however the Salton Sea was fully formed with an extent 45 miles long by 20 miles wide. To this day the same sea remains filling the Salton Sink.

Subsequently new plans were made for a canal, termed the All American Canal, which would stay north of the border, to irrigate the Imperial Valley. The All American Canal was built from 1930-1942. This new canal is the largest irrigation canal in the world carrying 26,155 cubic feet per second at maximum and irrigating, through a series of smaller canals 630,000 acres.

The agricultural waste water from land supplied by this canal currently drains into the Salton Sea, keeping it at high levels. However this source is very variable and occasionally causes flooding of the surrounding towns. Also this turns out to be a fairly salty source, which combined with the fact that the only water leaving the lake does so by evaporation, leaving its salt behind, means that this is a highly saline lake. In fact the Salton Sea is currently >4% saline, and is thus saltier than the ocean which is only 3.5% saline. The result is that the Salton Sea is an ecological disaster with many species of fish dying. A number of solutions have been proposed to these issues however as of yet they all seem to be either ineffectual in the long run, or impractical to construct, or both.



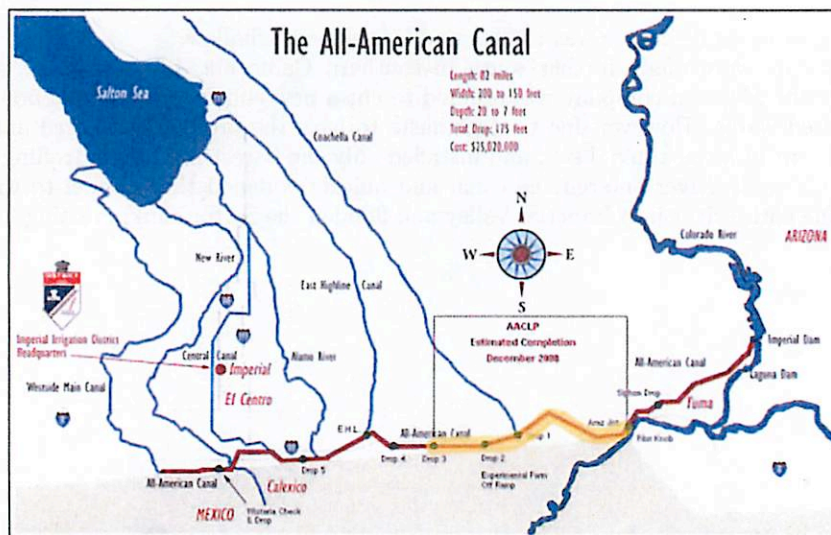


FIG. 3 A map overview of the course of the All American Canal. (2)

It should be noted that the Salton Sea is not the first instance of a major lake filling this area. Between about 1000 and 1500 AD what is now known as the Salton Trough was filled by a large body of water known as Lake Cahuilla, which measured 110 miles by 31 miles, dwarfing the modern Salton Sea. Lake Cahuilla was a result of a temporary change in the course of the Colorado River.

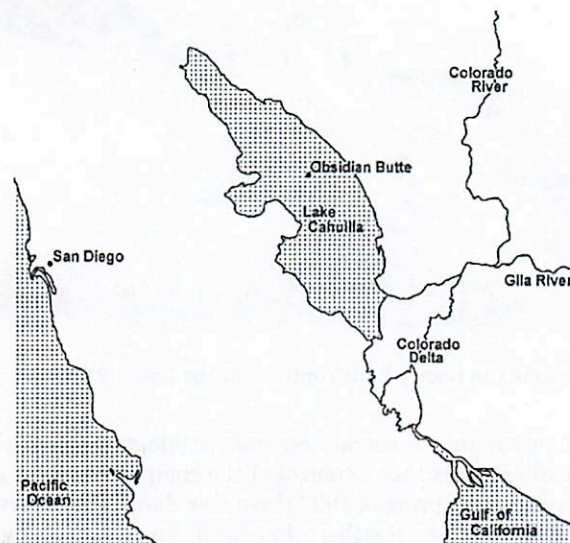


FIG. 4 The ancient lake Cahuilla which was the predecessor to the Salton Sea. (2)

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- [1] David Hornbeck, *The Salton Sink Before The Great Flood of 1905* (<http://www.imperialgroup.info/PDF/HornbeckSaltonBefore1905030>).
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- [4] Wikipedia, *Lake Cahuilla* ([http://en.wikipedia.org/wiki/Lake\\_Cahuilla](http://en.wikipedia.org/wiki/Lake_Cahuilla)).
- [5] Wikipedia, *All-American Canal* ([http://en.wikipedia.org/wiki/All-American\\_Canal](http://en.wikipedia.org/wiki/All-American_Canal)).

Lake Cahuilla and its Shorelines  
by David Choi  
(PTY5 594a) Spring 2011 Field Trip: Shoreline Processes

- Lake Cahuilla is a prehistoric lake located in the Salton Trough of Southern California.
- The lake at its maximum extent (~2,000 sq miles) would have been slightly larger than the present day Great Salt Lake, or ~6x the size of the Salton Sea.
- The depth of the lake may have reached 300 ft, though because most of the Salton Trough/Imperial Valley is below sea level, the maximum altitude of the shoreline reached 40-50 ft.
- The deposits comprising the floor of Lake Cahuilla (originating as silt from the Colorado river) support the rich agricultural activity of the area.
- The lake formed as a result of the Colorado River occasionally diverting its flow west and north away from the Gulf of California.
- Signatures of these prehistoric shorelines are seen in places along the present Salton Sea, usually in the form of travertine deposits.
- Geologic and archaeological evidence indicates that the lake existed up to an altitude of 12 m throughout the period of 750-1500 AD, with occasional dry periods.
- Sands comprising the current Algodones Dune Field may have originated from a glacial-era Lake Cahuilla.

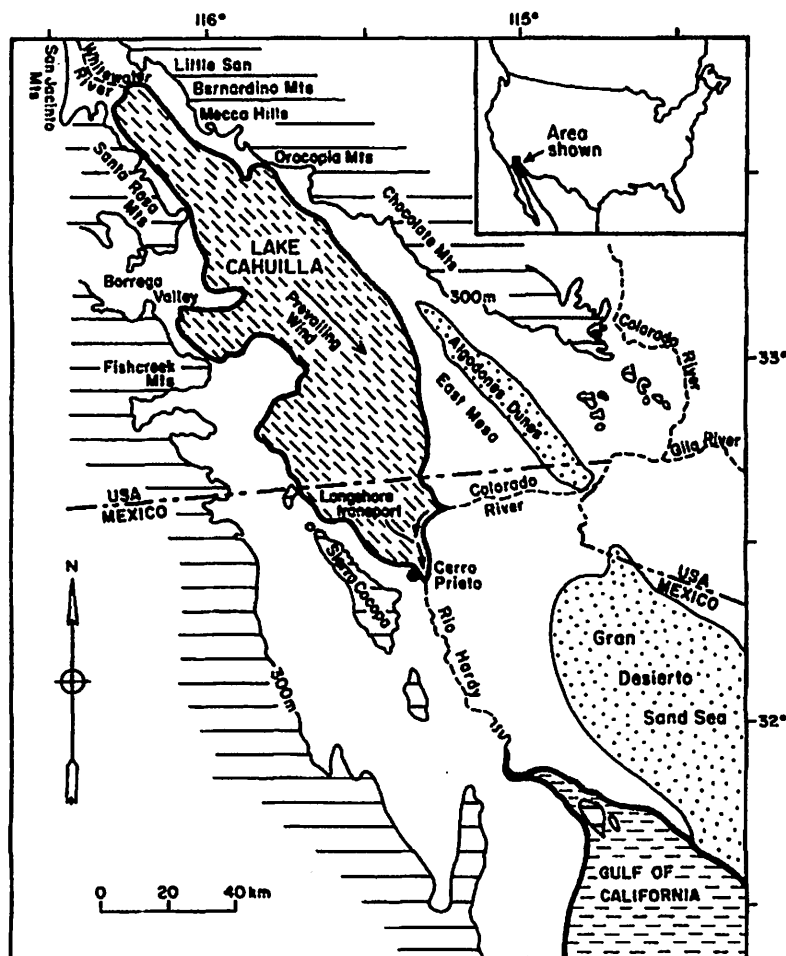


Figure is from Winspear and Pye, 1995

Fig. 6. The extent of Lake Cahuilla when filled to a maximum altitude of 12 m O.S.L. (after Waters, 1983) and the position of the entrance of the Colorado River to the lake. At this stage, the supply of sand to the south-eastern lake shoreline had diminished and Colorado-River-derived sands were instead transported southwards by longshore currents to a point where they could have been blown inland to accumulate in the north-western Gran Desierto.



The ancient shoreline of Lake Cahuilla demarcates a change in surface texture. The linear feature also marks the cutoff for old creeks and streams that cut channels up to the shoreline. Now, only present-day streams cross the shoreline. Note also the weathered appearance of the older channels.

Scale: one side of the square agricultural fields at the bottom right is ~400m.

(Thanks to Kat V. for including the original source for this picture on her handout from 2008 [<http://epod.usra.edu/blog/2007/10/lake-cahuilla-shoreline.html>], from which I was able to find it on Google Maps.)

Another signature of Lake Cahuilla? Along a delta fan, are the lighter areas travertine deposits? Both the deposits(?) and parallel canal appear to follow height contours.

Feature is roughly 5 miles long, and is located about 15-20 miles NW of the linear feature above.



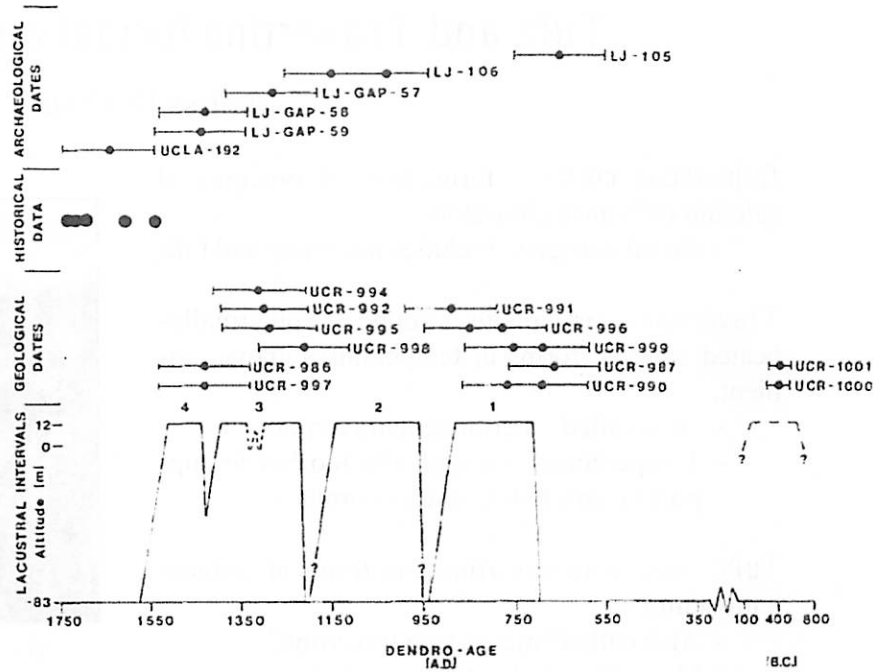


FIG. 6. Late Holocene lacustrine chronology of Lake Cahuilla. The trapezoidal-shaped outlines represent the lacustral intervals. The right line of the trapezoid represents the initial filling of Lake Cahuilla from -83 to +12 m. The top horizontal line represents the amount of time the lake stood at 12-m altitude. The left line of the trapezoid represents the recession of the lake from 12 to -83 m (complete desiccation). Solid lines represent firm chronologic placement of the lacustral interval; dashed lines represent tentative chronologic placement or duration of a lacustral interval. The large solid dots represent the time of Spanish reports on the position of the Colorado River.

**(left)** Several deposits of travertine, representing prehistoric shorelines of Lake Cahuilla, can be found near the coast of the present-day Salton Sea. Travertine is a form of limestone found in freshwaters with elevated levels of calcium carbonate.

Picture is from *Geology of the Imperial Valley* by Singer.

**(right)** Reconstructed timeline of Lake Cahuilla, using several lines of evidence.

Figure is from Waters (1983)

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Waters, M. (1983) Late Holocene Lacustrine Chronology and Archaeology of Ancient Lake Cahuilla, California. *Quaternary Research* **19**: 373-387.

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# Tufa and Travertine formations, Salton Basin

Melissa Dykhuis

Calcareous cinder: formations of precipitated calcium carbonate (limestone)

- Broad category, includes travertine and tufa

Travertine: precipitate around geothermally-heated springs, forms at temperatures above ambient.

- Also called “thermogene travertine”
- Temperatures are typically too hot to support macrophytes, so less porous

Tufa: similar to travertine, but forms at ambient temperatures

- Also called “meteogene travertine”
- More porous, due to macrophytes



Tufa formations, Mono Lake, CA (WikiCommons)



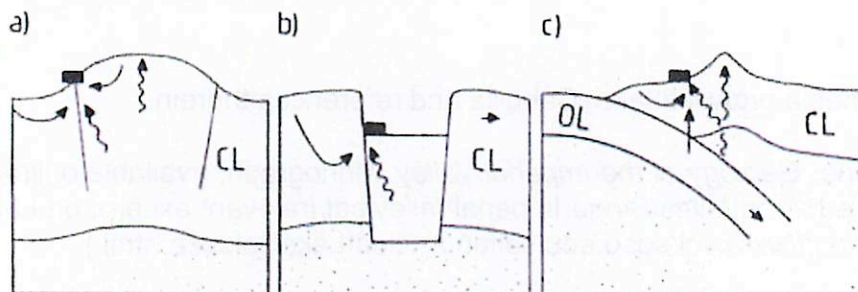
Travertine formations, Badab-e Surt, Iran (WikiCommons)

How do travertines form?

- Supersaturated, alkaline waters, with high  $\text{CO}_2$  partial pressure, flowing from vents
- This water degasses its  $\text{CO}_2$  upon exiting vents; this increases pH
- Increased pH results in lower solubility; precipitation occurs

Travertines in the Salton Basin

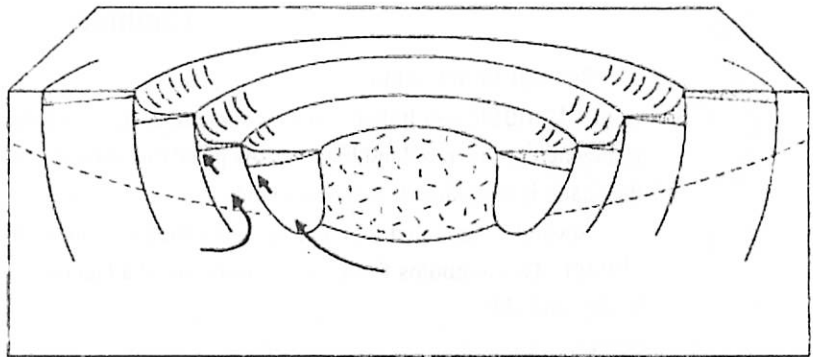
- Form underwater, not visible until waters have receded
- Age: a tufa slab from Travertine Point ranges in date from 1310 to 17840 yr before present (BP)



From Pentecost 2005: Methods of travertine formation via volcanism and tectonics. Travertine formations are depicted as black boxes; short arrows show plate movements; curly arrows show  $\text{CO}_2$  flux; long arrows show water flow. CL = continental lithosphere, OL = oceanic lithosphere.

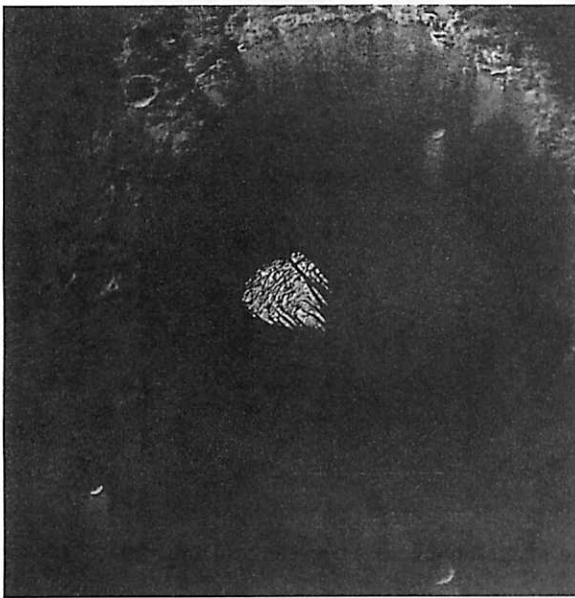
## Travertines on Mars?

Martian meteorites found in Antarctica contained carbonate globules similar to those found in Mono Lake tufa... and the search was on. Ever since, scientists have been studying California's travertines for species of extremophile life capable of surviving Martian conditions, while simultaneously searching Mars for evidence of travertines.



From Pentecost 2005: Formation of travertines as a result of meteor impact. Dotted line indicates water table. Vertical scale exaggerated.

The "White Rock" formation (below) found at the bottom of Pollack Crater on Mars is the best example found so far. It's thought to be a layer of magnesium carbonate or evaporated chloride/sulfate deposited from groundwater seepage.



Left: Mars Express image of "White Rock" in Pollack Crater.  
Top: HiRISE zoomed in on the white rock itself. Whiter material has been blown off of the crests to cover parts of the darker basins.

## References and further reading

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# Tombolo

## 1. General Information

A tombolo (an Italian term) or sometimes ayre is a **deposition landform** in which an island is attached to the mainland by a narrow piece of land such as a **spit or bar** (Fig. 1). Once attached, the island is then known as a tied island.

Several islands tied together by bars which rise above the water level are called a **tombolo cluster**. Two tombolos form an enclosure called a lagoon that might eventually fill with sediment by tide and ebb.



Fig.1 Tombolo near Paximadhi Eboea, Greece. The world's largest tombolo is between Sri Lanka and India.

## 2. Formation Mechanism

"True" tombolos are formed by **wave refraction**. As waves approaching an island, they are slowed down by the shallow water surrounding the island. These waves are then refracted or "bended" around the island to the **opposite side** as they approached. The wave pattern created by this water movement will cause a convergence of **long shore drifting** on the opposite side of the island. The beach sediments that are moving by lateral transport on the lee side of the island will accumulate there conforming to the shape of the wave pattern.

In other words, the waves sweep sediment together from both sides of the islands. Eventually, when enough sediment has built up the beach shoreline, known as a **spit**, it will connect with an island and form a tombolo.

Generally, there are two different ways to form a tombolo while both of them are formed by long shore drift (Fig.2 and Fig.3).



## Formation of a Tombolo

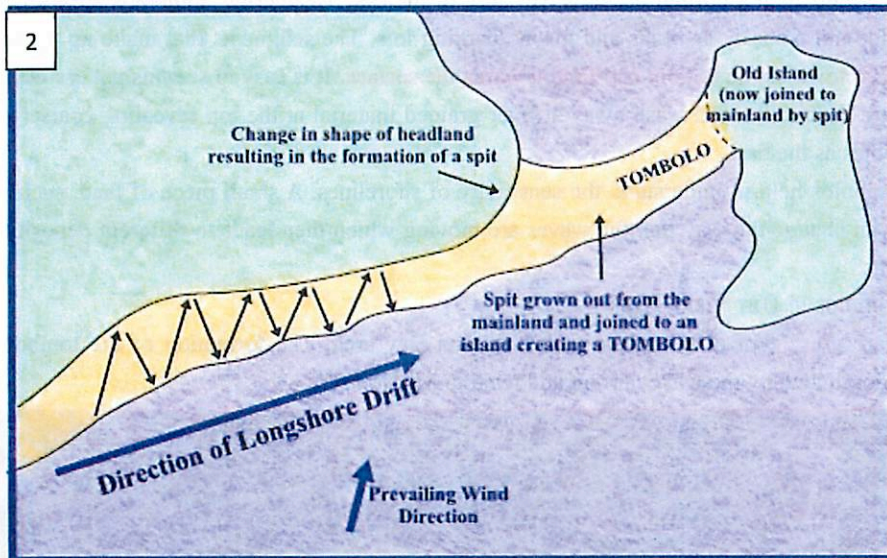


Fig.2 Tombolo formed by the longshore drifting on one side of the mainland coastlines.

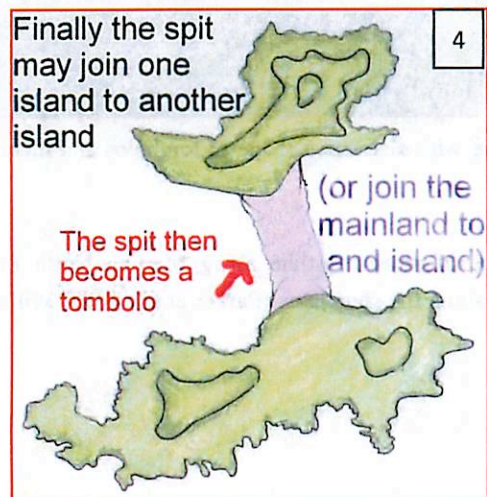
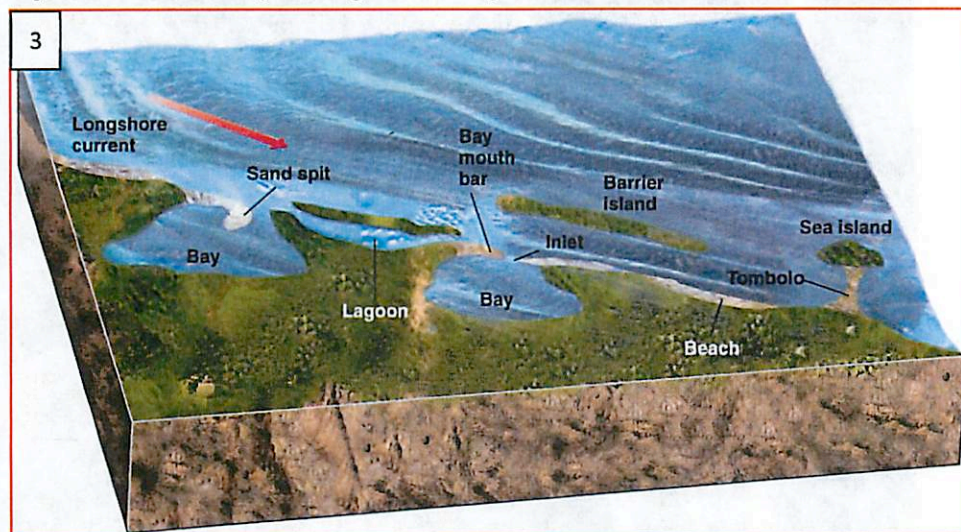


Fig.3 Coastal Formation (Jones Beach, <http://www3.ncc.edu/faculty/bio/fanellis/biosci119/COASTS1.htm>).

Fig.4 Tombolo formed between 2 islands. Longshore Drifting in Fig.3 and Fig.4 is happened around the islands.



Tombolos are more prone to natural fluctuations of profile and area as a result of tidal and weather events than a normal beach is. Because of the easy weathering, tombolos are sometimes man-made more sturdy as roads and maybe parking lots. The sediments that make up a tombolo are **coarser towards the bottom and finer towards the surface**. It is easy to see this pattern when the waves are destructive and wash away at finer grained material at the top revealing coarser sands and cobbles as the base.

Tombolos help to understand the sensitivity of shorelines. A small piece of land, such as an island, can change the way that the waves are moving which then leads to different deposition of sediments.

### 3. Tombolos in Our Field Trips

There are 2 typical tombolos in the Mission Bay area. The formation of the tombolos is mainly dominated by the wave current and wind in Mission Bay.

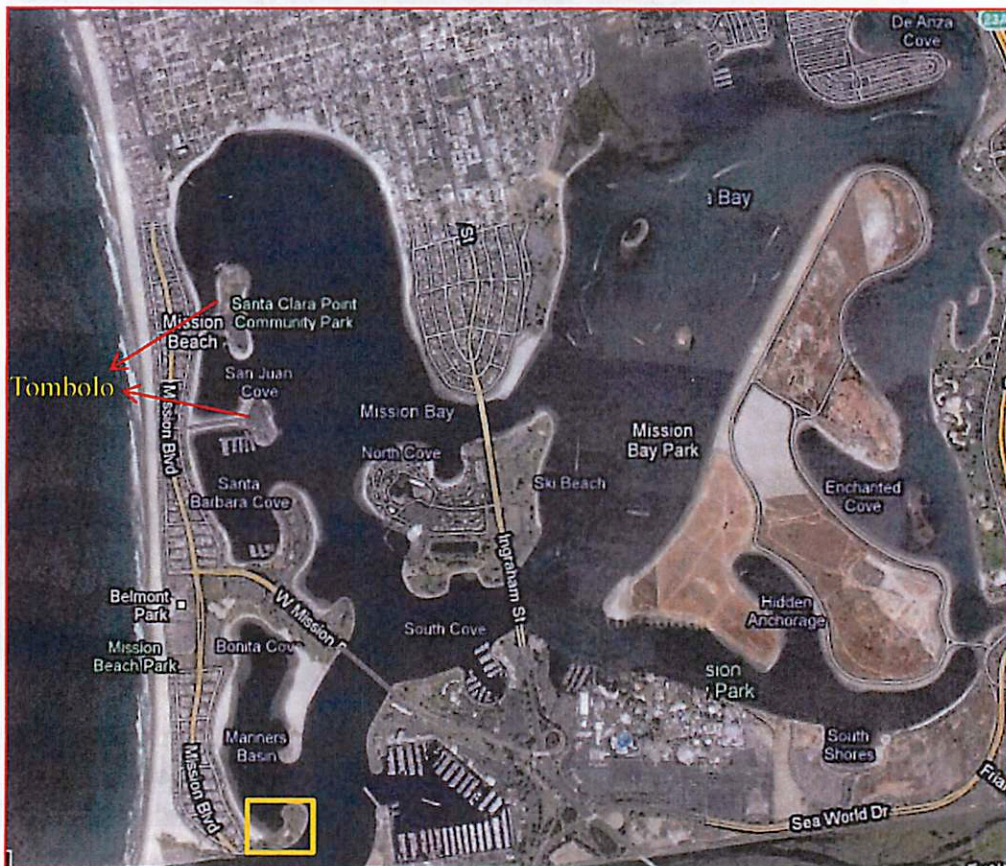


Fig. 5 Tombolos in our field trip area. They are with distinctive shape of tombolos and there are may be some other tombolos as well (square).

### 4. Tombolos on Mars

There are hypothesis about the existence of paleo-coastline along Martian North Plain. Tombolos-like terrains (Fig.5) were identified along the shorelines (Parker et al., 1993; Williams and Stice, 1991).

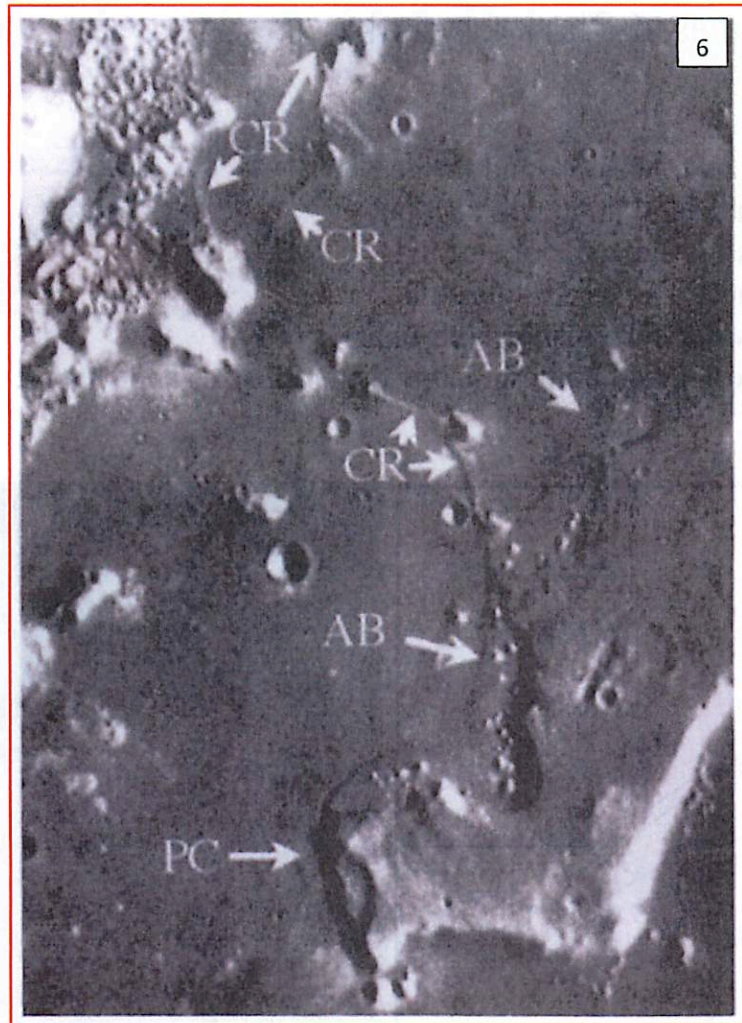


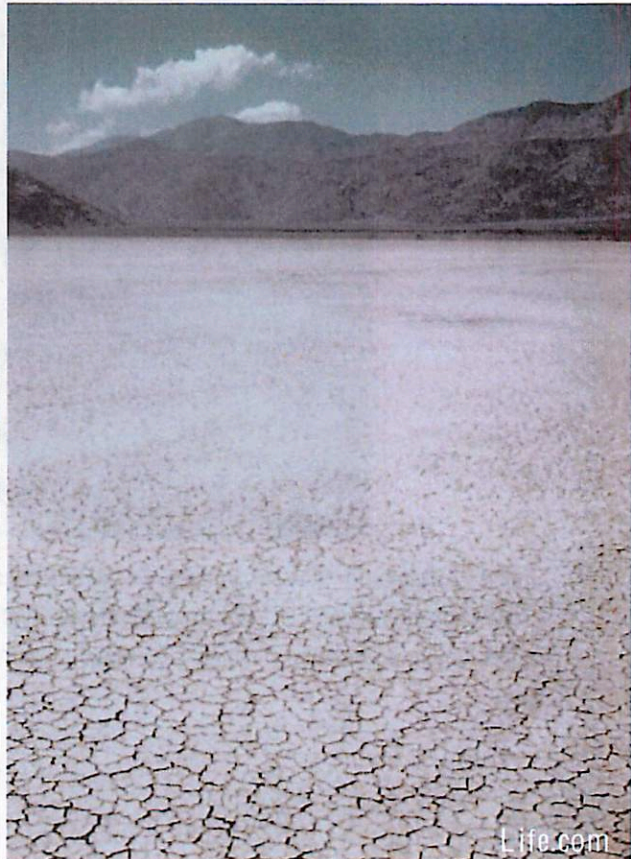
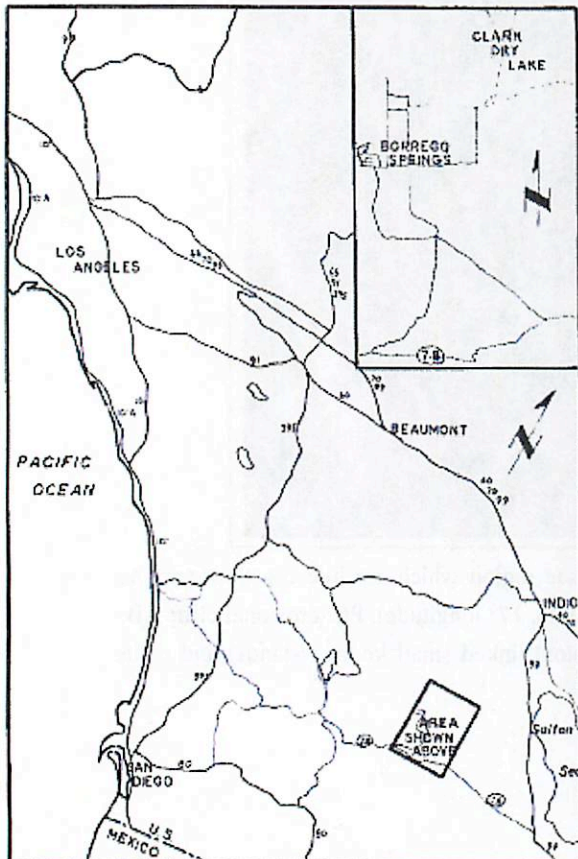
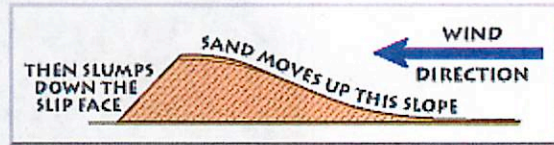
Fig. 6 Terrains on Mars at southwest Cydonia Mensae region which are like coastline terrains (Viking Orbiter images 227s04-1; centered at 32° latitude, 17° longitude). PC: erosional cliff; AB: small slopes around the plateau; CR: ridges (Tomboles) linked small knobs (islands) and main land.



# Silt-Clay Dunes of Clark Dry Lake

Katrina Jackson

Dunes are typically hills of sand formed by wind pushing sand up a gentle slope until it reaches the steeper slope of its leeward slip face. Dunes could also be formed from water currents, or with finer or coarser material, and come in many different sizes and shapes.



The Clark Dry Lake in California has dry, hard silt and clay material. The dunes on the southern side have surfaces composed of the same material as the surrounding playa.

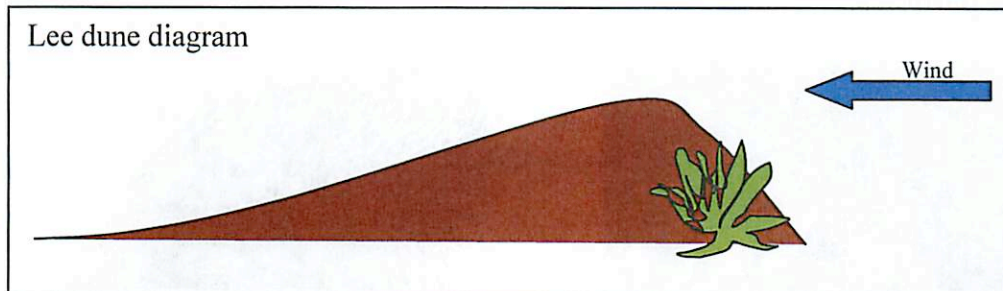
The dunes and wind are usually oriented north-northwest to south-southeast.





Their sizes range in height from six inches to five feet, in length from eighteen inches to thirty feet, and in width from one foot to twenty feet.

Unlike the diagram on the first page, these dunes have a steep windward side and a gentle-sloping leeward side. They form from vegetation near the upwind side, where a bush creates an eddy in the flow of wind-blown clay-silt particles.



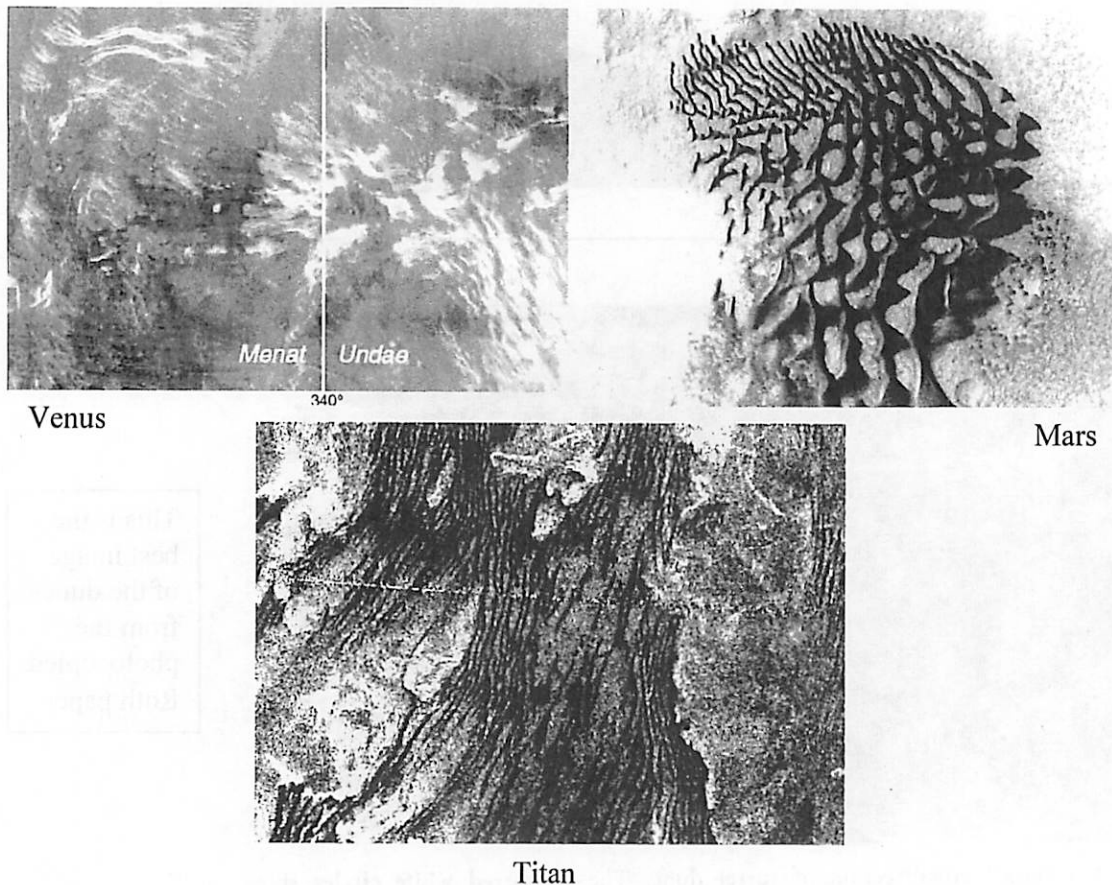
This is the best image of the dunes from the photocopied Roth paper.

*Plate 3.* Over-all cross section of turret dune. The numbered white circles show the locations of samples taken. Notice the feather edge on the lee (left) side, and also vegetation that caused the dune.

The surface of these dunes is a one-to-three-inch layer of mud-cracked silt-clay aggregate particles. Below the surface is loose, dry sand-sized silt-clay, often with a few past surfaces characterized by more resistant and cohesive layers than the surrounding loose material. It is difficult to differentiate between the bottom of the dune and the lake surface.

The material in the dunes probably came from silt-clay blown off from mud curls, silt-clay broken up by human and animal activity, and sediments from the occasional flash flood.

Dunes have been found on Venus, Mars, and Titan. Extraterrestrial dunes can indicate an arid environment, and show the primary direction of the wind, and their shapes can reveal characteristics of the planetary body's aeolian processes. The dunes on Titan are near its equator and are thought to be mostly made of hydrocarbon particles.



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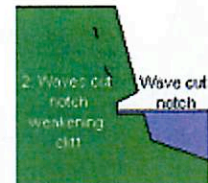
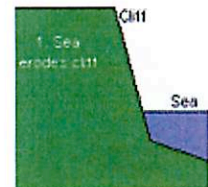
## Marine Terrace Formation



### Formation of Marine Terraces

#### Wave-cut platforms

- Destructive waves hit against the cliff face
- Causes undercutting (as a result of corrasion and hydraulic power)
- Undercutting creates a notch, which enlarges into a cave
- The cave ceiling collapses, creating a cliff face that retreats landward
- Base of cliff forms wave-cut platform
  - Attrition breaks cliff debris into smaller pieces
  - Other material washes out into sea at end of platform
  - The abrasion platform is composed of a veneer of sedimentary material (beach sand)

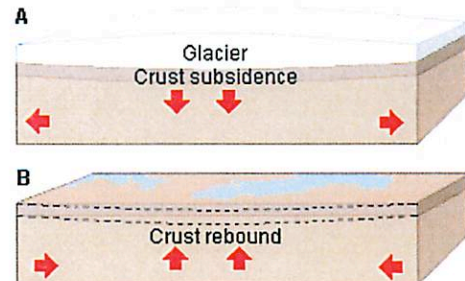


Creation of wave cut platform  
(taken from Wikipedia)

#### Vertical Uplift

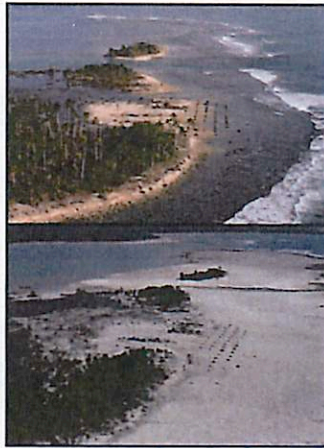
- changing global sea level
- tectonically raising the land mass
  - Glacial changes (isostatically supported crust rises with a decrease in glacial deposits)

Example of crustal rebound after the removal of glaciers. Taken from New World Encyclopedia.



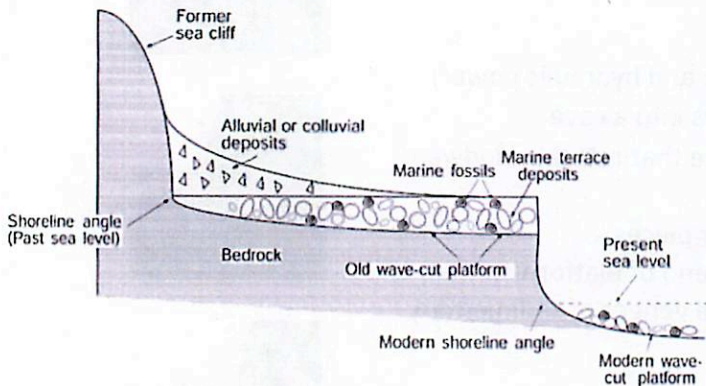


- Earthquakes (San Andreas fault line)

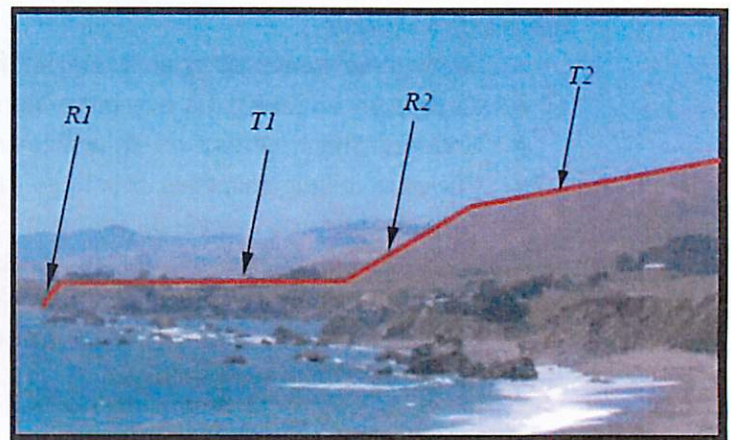


About 2.5 m of coastal uplift from the March 2005 Sumatran earthquake. Taken from Hinton, Anne.

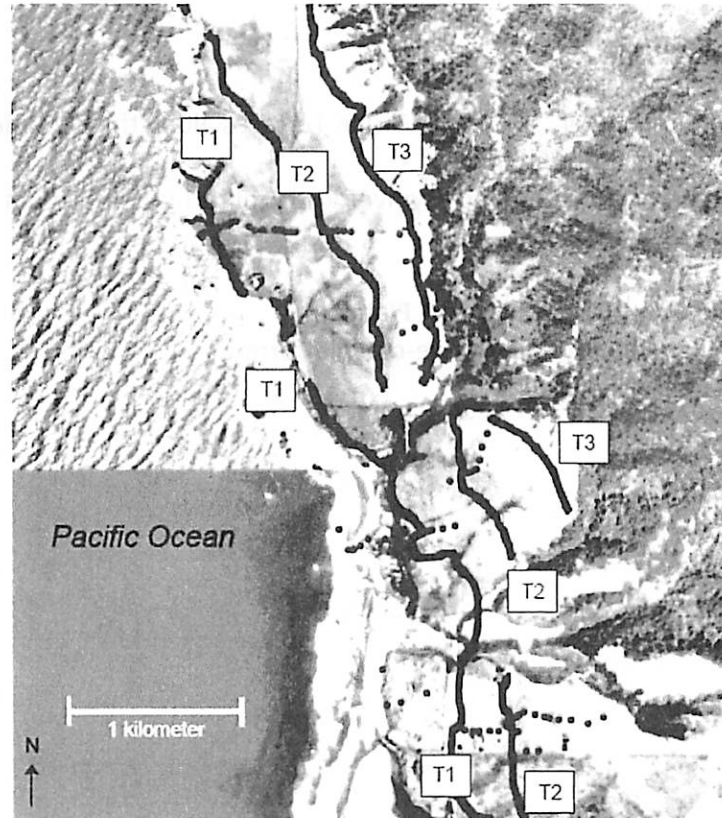
- After uplift, the terrace is removed from the high energy wave regime. Each successive terrace records past shorelines.



Cross section of a marine terrace after uplift. Note the formation of a new cliff edge at the modern shoreline. Taken from Clark, Alisha.



Marine terraces on the Californian coast (near Jenner, CA). The red line traces the stair step structure of multiple marine terraces. T1 and T2 represent shore platforms, and R1 and R2 represent sea cliffs. Taken from Leibson, Sarah.



Aerial photograph of the mouth of Ten Mile River. The marine terraces are marked. Taken from Leibson, Sarah.

#### Earth vs Mars

- Most large marine terraces probably need rapid vertical uplift to preserve their structure.
- Thus, Mars isn't expected to have marine terrace formation (no plate tectonics).

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## Tide Pools... and Astrobiology

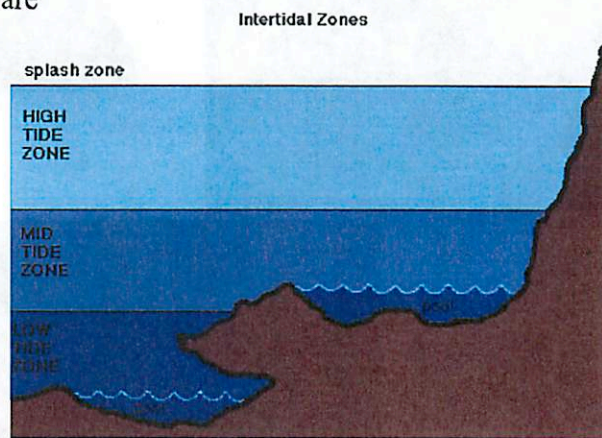
Juan Lora

**Tide Pools** are holes and crevices in rocky beach outcroppings that are periodically filled with seawater by tides. Despite their wildly varying environment, they provide a habitat for many organisms.

The tides bring in nutrients and oxygen, but also cause large oscillations in temperature, salinity, and cover for inhabitants.

### Tide Pool Zones:

- Low tide: Pools close to the sea that are continuously or nearly continuously filled with water. This is the most stable of the tide pool environments, and therefore often boasts the largest diversity of life.
- Mid tide: Pools that are periodically filled and drained by the tide. Organisms here must be adapted to living in and out of seawater.
- High tide: Pools that are filled only by high tides, and are therefore exposed to air, sunlight, and rough waves for long periods. Many of the animals here actively seek shelter to survive.
- Spray/splash: Regions that only receive seawater from storm waves and the highest tides. These are less pools than wet surfaces, and are home mostly to lichens and barnacles.



### Life

Tide pools are of particular interest to ecologists (and astrobiologists) because they provide harsh, reasonably isolated environments for which inhabitants must be well-adapted (and which are relatively easy to study). Tide pools are inhabited permanently by some species, but used as nursery or transitional habitats by others.

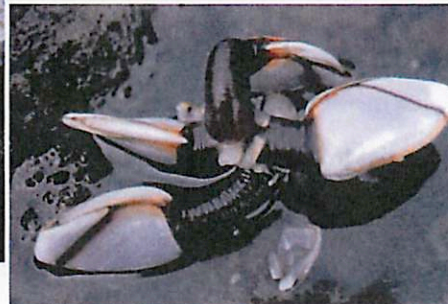
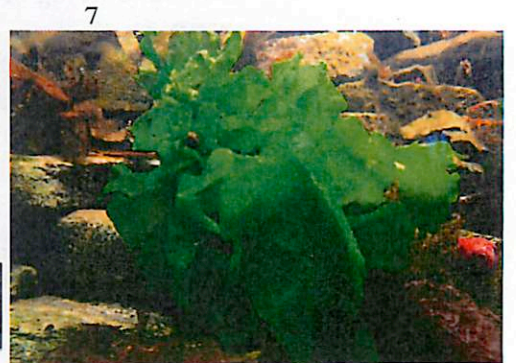
Organisms that live in tide pools include:

Low tide: Sculpins<sup>1</sup>, sea stars, sea urchins<sup>2</sup>, lobsters, crabs, barnacles<sup>9</sup>, abalones<sup>3</sup>, mussels<sup>4</sup>, anemones, kelp

Mid tide: killifish<sup>6</sup>, hermit crabs, barnacles<sup>9</sup>, mussels<sup>4</sup>, snails, limpets<sup>8</sup>, anemones, moss, rockweeds<sup>5</sup>

High tide and spray/splash: barnacles<sup>9</sup>, limpets<sup>8</sup>, snails, kelp, algae, lichen, sea lettuce<sup>7</sup>





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# Lagoons and Tidal Estuaries

Rob Zelle

## Lagoons

A **lagoon** is a body of shallow water that is partially or completely separated from the sea, and importantly, its waves, by a barrier. As a result, lagoons have calm waters, allowing for sedimentation that can cause a lagoon to become shallower with time. In addition, due to their shallow, typically calm waters, lagoons are abundant in highly productive plant life. **Coral lagoons** have barriers that are coral formations. **Coastal lagoons** have barriers that are formed by sand, such as a sand bar or barrier island. An example of a coastal lagoon is the San Elijo Lagoon (see



Figure 1: The San Elijo Lagoon (Google Maps)

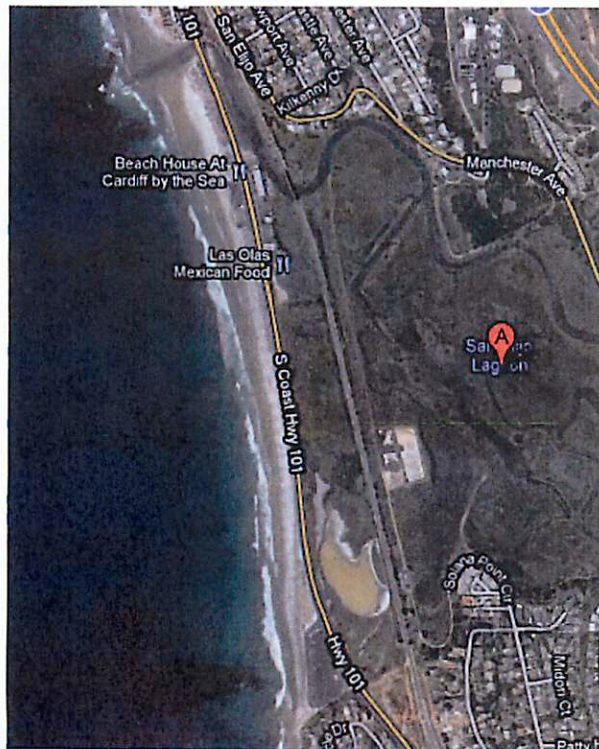


Figure 3: The San Elijo Lagoon (Google Maps)

Figures 1 and 2). A bad example is Disney's Typhoon Lagoon (see Figure 3).

Water circulation in coastal lagoons is extremely dependent upon land drainage. If drainage to the sea is limited, then the lagoon can actually become more saline than the sea due to evaporation. As a result, lagoons can have life not found in the sea.

Coastal lagoons are often associated with lower energy coasts where there is enough sediment to form a barrier. However, too much sediment from the mainland (such as from an estuary) can lead to the formation of a delta, rather than a lagoon, as sediment will be deposited when the faster moving waters from the river are slowed when it meets the ocean. (For more about deltas, see Zelle 2010.)



Figure 2: Disney's Typhoon Lagoon—not really a lagoon. (Disney)



Lagoons can be classified into three types based upon their flow into the sea (Hill 2001). **Leaky lagoons** easily exchange their water with the sea due to wide tidal channels and fast currents. **Choked lagoons** have restricted water flow between the lagoon and the sea due to long, narrow channels and high-energy coastlines. Here, circulation is dominated by wind patterns. **Restricted lagoons** have multiple channels with a net seaward transport, resulting in many of them being well mixed.

### Tidal Estuaries

An estuary is “a semi-enclosed coastal body of water, which has a free connection with the open sea, and within which sea water is measurably diluted with freshwater derived from land drainage” (Wolanski 2007). (Based on this definition, coastal lagoons can be regarded as estuaries.) An estuary essentially is where fresh water from a river or stream flows into the sea.

An estuary can flow directly into the open sea, such as the Seine River Delta (see Figure 4). An estuary can also flow into a lagoon, resulting in an **estuarine lagoon**. An example is the San Elijo Lagoon.

Estuaries can be classified into four types, based upon their mixing with the sea (see Figure 5). They can be **vertically mixed**, where the amount of salinity varies by the horizontal distance from the land to the sea. An example is the Delaware Bay. They can

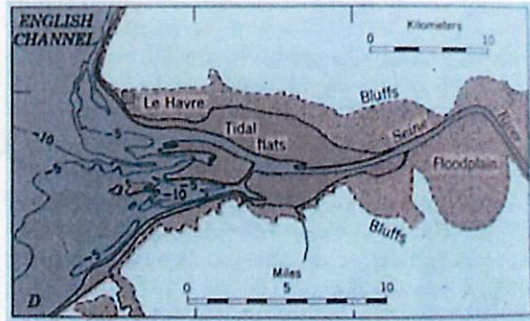


Figure 4: The Seine River delta, an estuary delta. ([http://www.americaswetlandresources.com/background\\_facts/detailedstory/RiverDelta.html](http://www.americaswetlandresources.com/background_facts/detailedstory/RiverDelta.html))

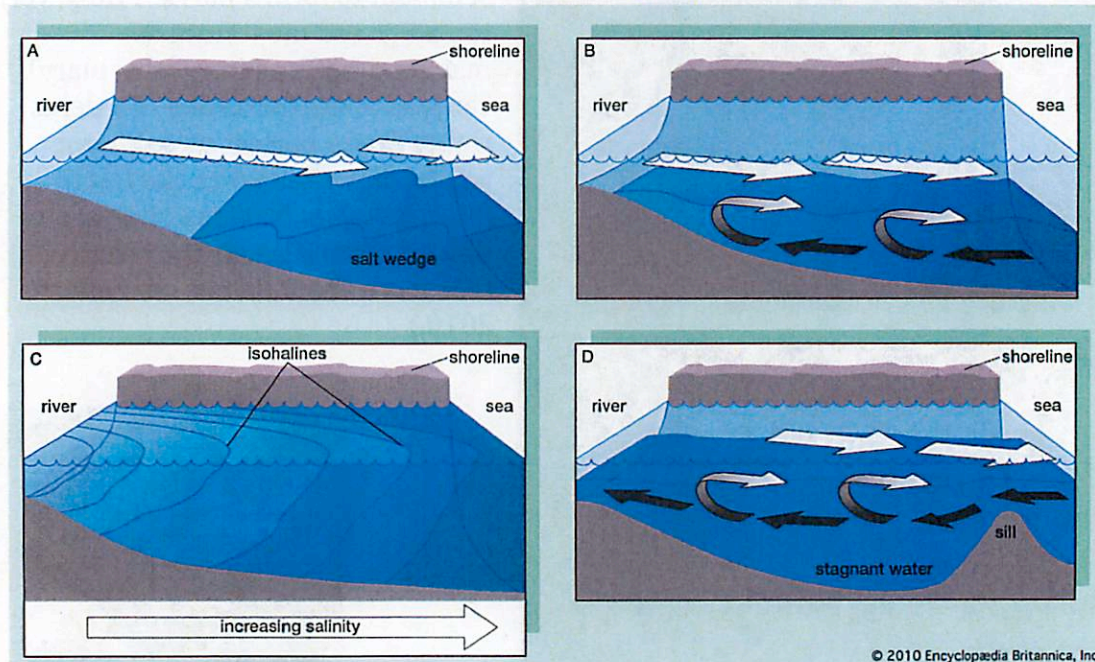


Figure 5: Four basic types of estuaries: salt wedge (A), slightly stratified (B), vertically mixed (C), and highly stratified (D). (Encyclopaedia Britannica)



be **slightly stratified** where salt water flows in from the bottom, mixes with fresh water, and then flows back out through the top. Thus, salinity varies with both horizontal and vertical distance. An example is the Chesapeake Bay. They can be **highly stratified**, which is similar to the slightly stratified, except mixing is limited to the top layers of water. Lastly, they can be a **salt wedge**, where the fresh water flows over a wedge of salt water. An example is the Mississippi River.

### The San Elijo Lagoon

The San Elijo Lagoon is actually a shallow-water estuary (or estuarine lagoon) fed by the Escondido Creek and Orilla Creek and a 77 square mile watershed ("San Elijo Lagoon Ecological Reserve"). The lagoon has served as hunting and gathering grounds for Native Americans since at least circa 6000 BC. It was named by the Portola Expedition in 1769 for St. Alexius, the patron saint of pilgrims and travellers. The 1800s and early 1900s saw the influx of European settlers who set up cattle ranches and farmed the rich land. They also constricted water flow in and out of the lagoon by constructing dikes and levees for duck hunting and salt harvesting and supports for the Santa Fe railroad and highways. In the 1960s, multiple developments, such as a theme park and condominiums, were proposed to cover the lagoon.

However, the Endangered Species Act in 1973 protected habitats in and adjacent to the lagoon, and with community support, the San Elijo Lagoon Ecological Reserve was dedicated in 1983. In 1993, the San Elijo Lagoon Conservancy dredged to open the lagoon inlet. However, the restoration of the lagoon's flow into the ocean and conservation in the face of increasing urbanization of the lagoon is still an ongoing effort.

As one of San Diego's largest coastal wetlands, the lagoon has more than 400 species of plants, 296 species of birds, 23 species of fish, 24 species of mammals, and 20 species of reptiles and amphibians (The San Elijo Lagoon Conservancy; see Figures 6 and 7).



Figure 6: Beach evening primrose (SELC)



Figure 7: Marsh Wren (SELC)

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# Sediment transport out onto abyssal plain

Peng Sun

**Sediment transport** is the movement of solid particles by the force of gravity or the flow passing through. Particles could be rocks of different size (such as dust, sand, boulder etc), mud, or clay. The flow could be air, fluid or ice. Transported Load could be bed load (particles

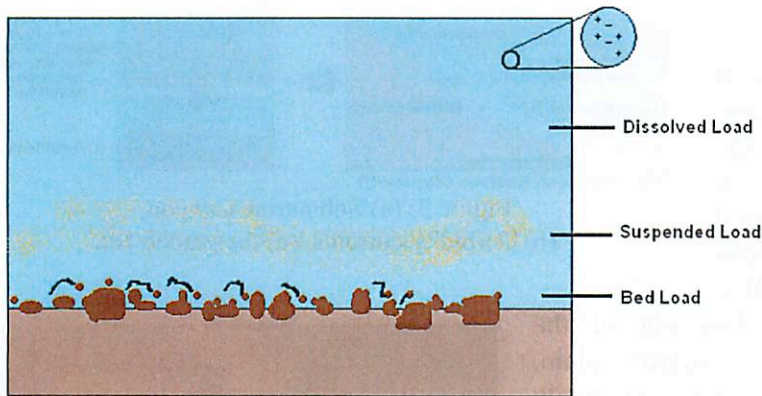


Figure 1: Sediment transport load classification

(particles bouncing or hopping along the flow), suspended load (particles move with the flow), dissolved load as shown in figure 1.

**Abyssal Plain's** base is formed when the lower oceanic crust (basaltic material) is melted and forced upwards by the asthenosphere layer of the upper mantle and reaches the surface at mid-ocean ridges to form new ocean

crust. Then fine-grained sediments cover this uneven surface. Shown in figure 2 is the abyssal plain and adjacent marine structure. It is suggested that much of this sediment is deposited from turbidity currents along the continental slope or submarine canyon on the slope down into deeper water.

**Turbidity Currents** is a current of sediment-loaded water moving rapidly down a slope through another fluid. The current moves because it has a higher density and turbidity than the fluid through which it flows. The driving force is gravity. Since the current contains sediments, the density is larger than the surrounding water. Figure 3 (b) shows the turbidity current along the continental slope. Figure 3 (c) shows that when the current slows down on fans on the continental rise and abyssal plain, the coarser-grained particles will settle down first and then will the lighter finer-grained ones. This renders a graded cross section for the sediments bed on the plain. The fans on the continental rise and the continental slope could be compared with alluvial fans, which are associated with mountains, basins and distributaries on the continent. And they both indicate fluvial features. The turbidity

currents

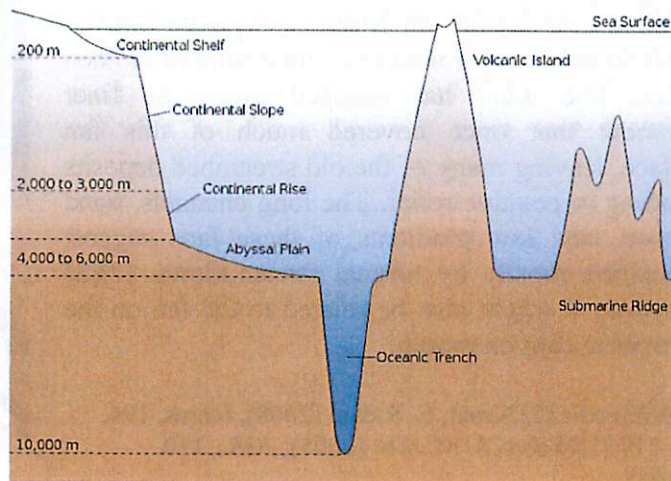


Figure 2 Abyssal plain



currents are also related to antidunes.

**Submarine Canyon** is a steep-sided valley on the sea floor of the continental slope. Submarine canyons could be extensions to large rivers or not. Powerful turbidity currents could form them and usually they have deep slopes.

**Alluvial Fan** is a fan-shaped deposit formed where a fast flowing stream slows down and spreads out at the exit of a canyon onto a flat plain as shown in Figure 4. It is often found in desert areas due to periodic floods from thunderstorms nearby. This could be compared with the flow out of the submarine canyons onto the abyssal plain. However, the alluvial fans would have relatively poorer sorted arrangement and coarser material at the mouth, as the flows are intermittent. While for the transported sediment along the submarine canyon, as they are travelling through the seawater, the driving force might be less than the alluvial fan's. So the entrained particle's size might be different from those on the alluvial fan. Also the coarsening upward feature of the alluvial fan materials needs to be checked for the fans on the mouth of submarine canyon.

**Planetary Connection:** Both Figure 3 shows a possible alluvial fan on Mars. A separate alluvial fan is found near the southwestern corner of Holden crater. The wind has stripped away the finer sediment that once covered much of this fan surface, leaving many of the old streambed deposits standing in positive relief. The long channels, wind erosion, and low gradients of these fans suggest deposition mostly by normal stream flows. [2][3] However, it might also be related to the fan on the submarine canyon mouth.

[1]Wikipedia [2] Kraal, E. R et al (2008), Icarus, 194, 101-110 [3]Moore, J. M. et al (2005), JGR., 110, E04005

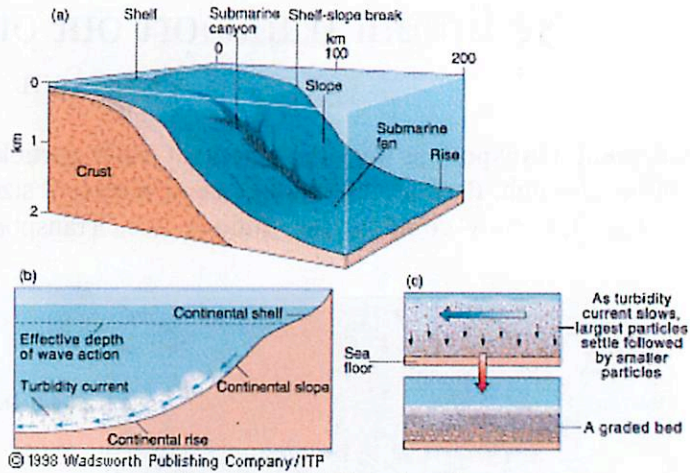


Figure 3: (a) Submarine Canyon; (b) Turbidity currents; (c) the graded bed



Figure 4: An alluvial fan

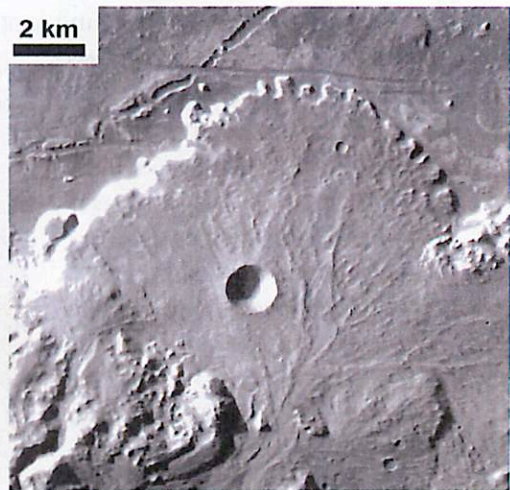


Figure 5: A large alluvial fan (?) in the southern floor of Holden crater, Mars.



# Submarine Canyons

Patricio Becerra

Submarine canyons are steep-sided valleys on the sea floor of the continental slope (fig. 1). Many have been found to reach depths greater than 3 km below sea level, making them some of the deepest canyons on Earth. There are many theories for their formation including glacial-era sub-aerial carving, erosion by turbidity currents, volcanic, and earthquake activity. Many submarine canyons continue as submarine channels across the continental rise and may extend for hundreds of kilometers.

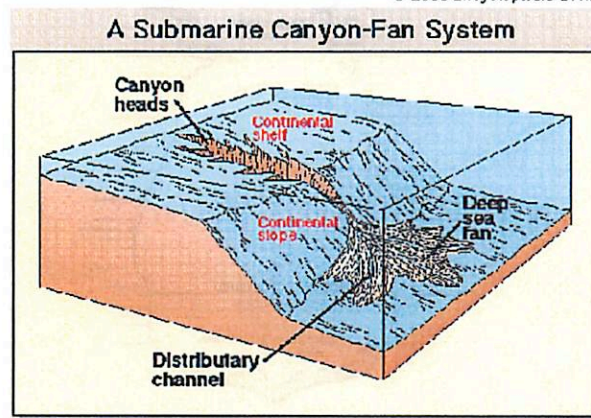
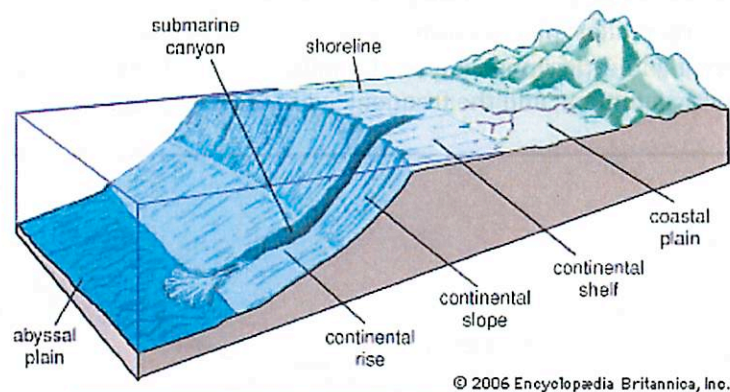


Fig. 1. (Top) Elements of the continental margin showing a submarine canyon. (Bottom) Elements of a submarine canyon.

## Characteristics

- Form on steep continental slope
- Steep walls up to thousands of meters high/deep (Great Bahama Canyon ~4,300 m)
- V-shaped gorges that extend all through the continental slope and even reach the ocean floor
- Canyon heads mostly located near the coast, or at the outer edge of the continental slope
- Walls are very steep and frequently include overhangs (fig. 2)
- Most have been cut in rock. Granite (Monterey, California, Baja). Quartzite (Trincomalee Bay, Ceylon). Soft shales (Fangliao Canyon, Taiwan)

- Channel patterns: Small tributaries at their heads, winding channels/lack of pronounced meandering.
- Canyon floors slope seaward
- Usually form deep-sea fans on the shallower continental rise
- Relation to adjacent land is uncertain, as many are found off river valleys, but many have no clear connection to land valleys

### Instability

- Sand and other materials build up in the head of the canyon
- Canyon heads fill rapidly, and the fill is carried seaward when it becomes unstable
- Analogous to landslide that becomes a turbulent, scouring flow (turbidity current)
- Interval between flows can be several months to a year
- Sediment creep takes place continuously in canyon heads
- Bottleneck profile (Scripps canyon, La Jolla) is caused by the partial filling of the canyon with sediment, and the frequent sediment creep (fig. 2)

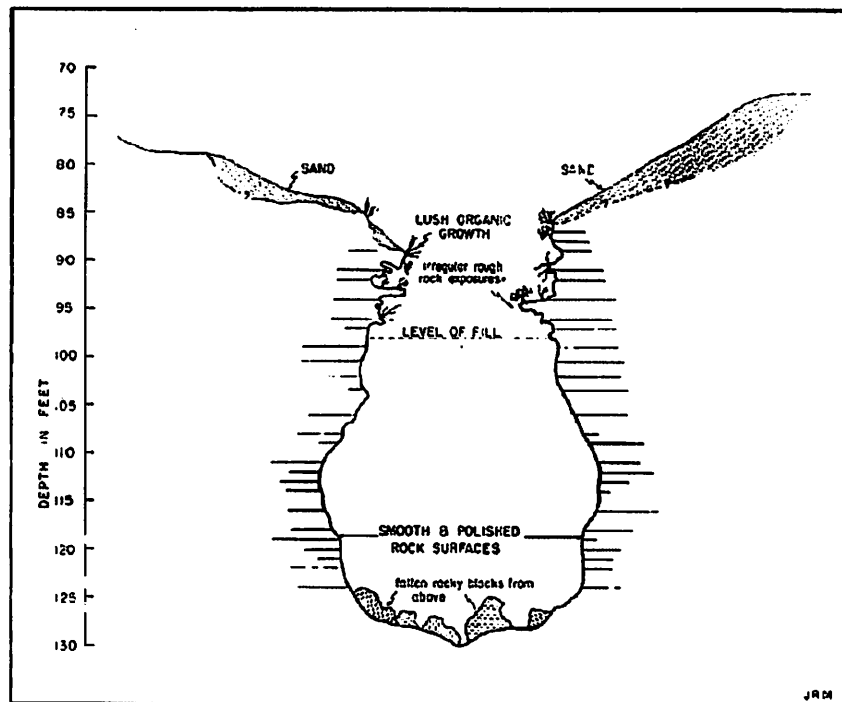


Fig. 2. Diagram of Scripps Canyon profile showing overhanging walls, smooth surfaces due to sediment creep, and irregular surfaces where organisms anchor. Dill (1964).

### Origin

- From resemblance to land canyons: submerged river valleys. But submarine canyons are too geographically widespread and occur at too great depths.
- Some upper parts of submarine canyons likely formed from sub-aerial river erosion during exposure of the continental slopes
- Turbidity currents: dense, sediment-laden currents that flow downslope when an unstable mass of sediment fails upslope. Could be triggered by earthquakes. Generally accepted theory for current erosion of submarine canyons



- Lobate deposits and deep sea fans along channels serve as evidence for turbidity currents as drivers (mudflows or muddy waters)
- Very few submarine canyon initiation models have been done:
  - o Pratson and Coakley (1996): "Seascape" evolution model for the incision of submarine canyons through downslope eroding sediment flows

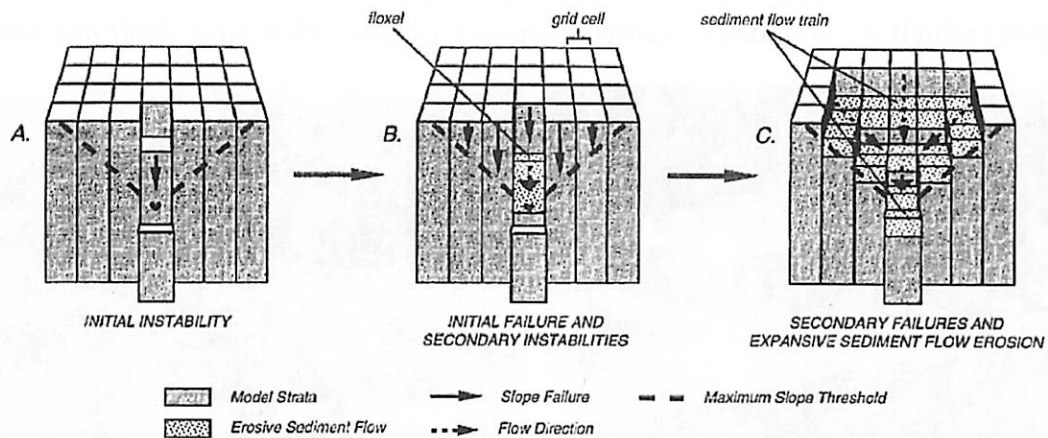


Fig. 3. Schematic of a sequence of possible slope failure from the Pratson and Coakley (1996) seascape evolution model

### Planetary Connection

- Deep-sea valleys that originate from submarine canyons have been compared to martian outflow channels (Komar, 1979)
- Repeated turbidity flows in submarine canyons form deep-sea channel networks similar in morphology to Martian outflow channels
- Catastrophic nature of turbidity flows points to similar formation mechanism for martian outflow channels

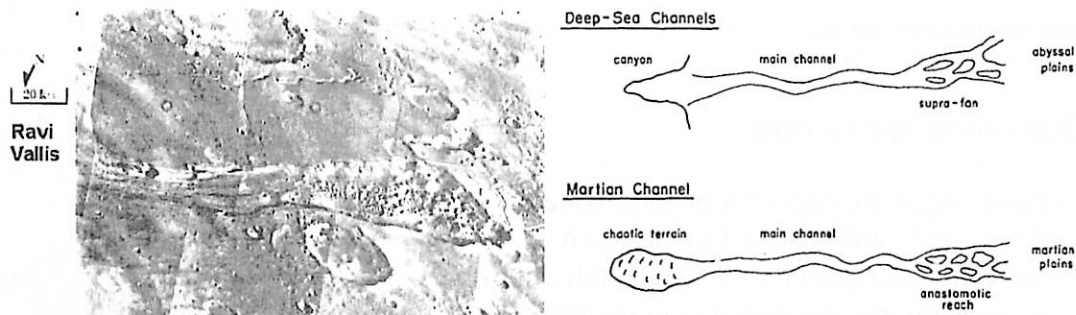


Fig. 4. Ravi Vallis on Mars. Schematic of analogy between martian outflow channels and terrestrial deep-sea valleys.

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# Beach Cusps

Cecilia Leung

Beach Cusps: a series of ~uniformly spaced arc-shaped scallops that form in the swash zone of a shoreline. The seaward pointing ridges are called *horns* (contain coarser sediment), which are bounded by crescent-shaped troughs called *bays* (finer grained).

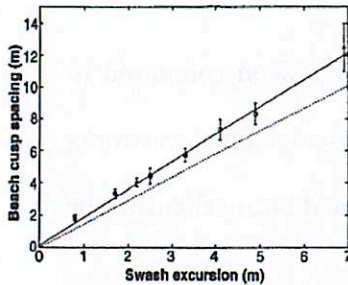
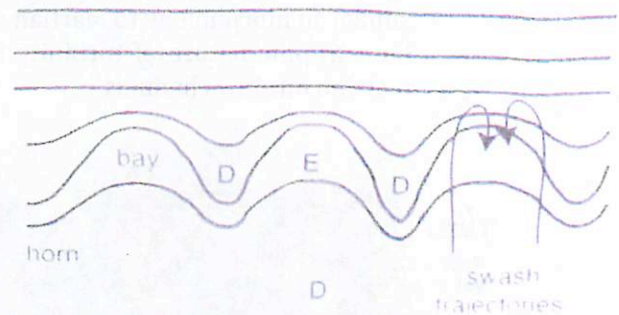


Fig 1. Linear correlation between cusp spacing and swash length. (Werner, 1993)

- Typical cusp spacing = 10 cm to 60 m apart.
- Spacing = function of swash length and beach gradient.
- Cusps tend to form when waves are at normal incidence



## Self-Sustaining Mechanism:

- Incoming wave encounters horn, water deflected to either side. Deceleration of wave causes coarser sediment to fall out of suspension and deposited onto the horn.
- Swash flow along curvature of bay until collide into one another in the middle.
- Convergence of water in the bay leads to erosion of the bay.
- Receding wave is met by new incoming wave. Deposition of eroded sand at the mouth of the bay and on submarine deltas.

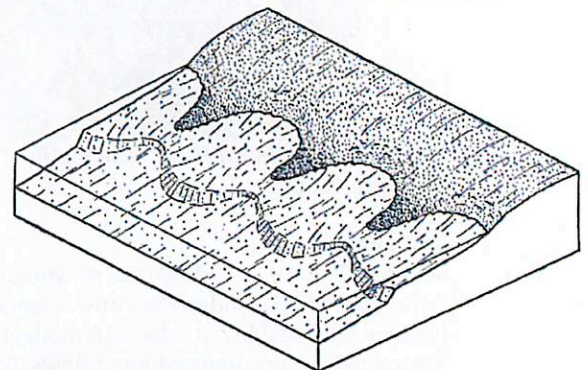


Fig 2. [top] Diagram showing swash trajectories & areas of erosion (E) in the bays, and deposition (D) at the horns and submarine deltas. [bottom] Block diagram of cusp features. (Kuenen, 1948)

## Origin of Beach Cusps (2 Models):

### I. Standing Edge Wave Model:

Trigger mechanism for beach cusps originate when an incident wave interact with a standing edge wave near the shore. The form & spacing of the edge wave drive the regular pattern of erosion and deposition giving rise to beach cusps.

A standing edge wave results when 2 edge waves with the same frequency travel in opposite directions along the shoreline.

a. subharmonic (half the freq of incident wave)- forms beach cusps with horns at every anti-node.

b. synchronous (same freq as incident wave)- forms beach cusps with horns at every other anti-node.

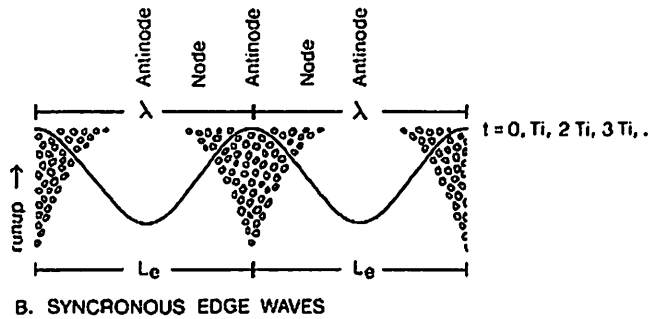
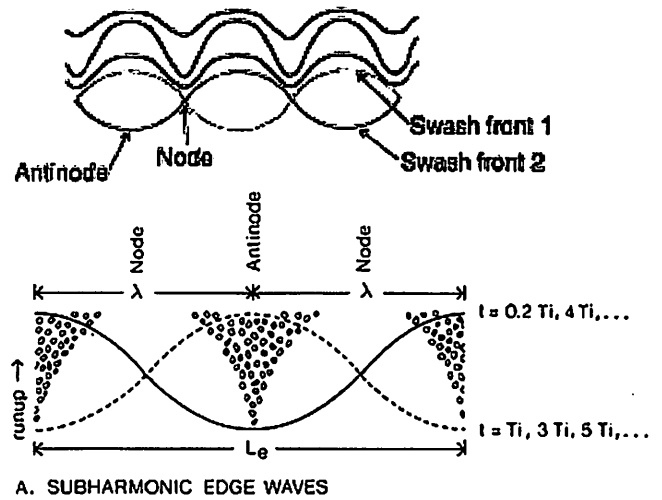


Fig 3. Cusp formation by standing edge waves (Aagaard, 1985)

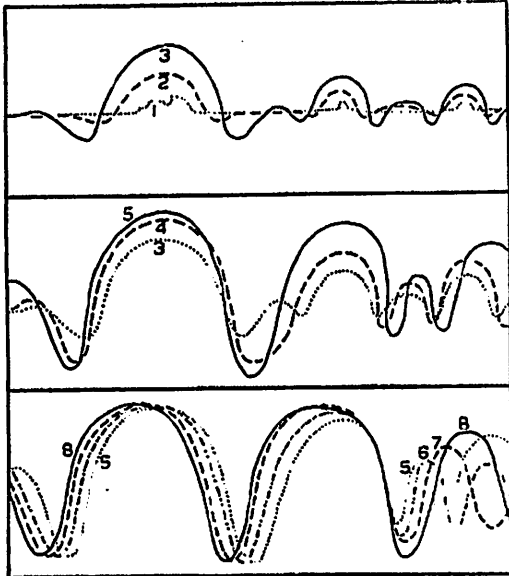


Fig 4. Simulated stages of cusp development from initial irregular indentures. (Kuenen, 1948)

### II. Self-Organization Model:

Rely on coupling between the morphology of the beach and the flow of the water to create relief.

-Incipient topographic depressions along the foreshore attract and accelerate water flow.

-Increased flow enhances erosion, further amplifies depression.

-Topographic lows may evolve into cusp bays, and topographic highs into cusp horns.

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# Beach Profiles

Kat Volk

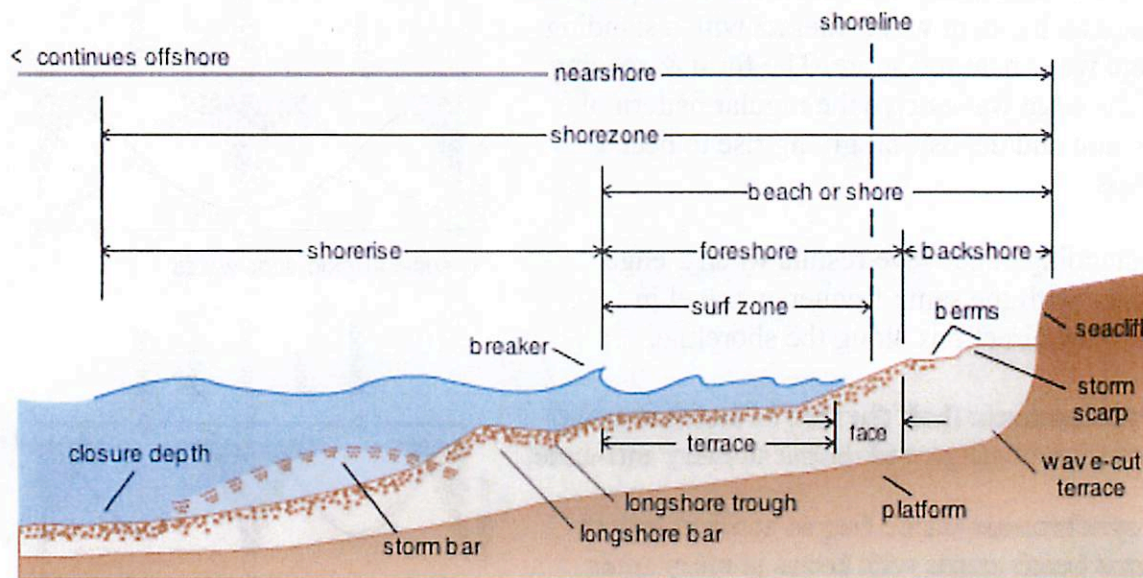


Image from: [http://coastalchange.ucsd.edu/st3\\_basics/beaches.html](http://coastalchange.ucsd.edu/st3_basics/beaches.html)

**Backshore:** The furthest landward part of the beach, which is generally dry except during storms. Characterized by **berms** (flat areas of sand and sediment deposited by low energy waves).

**Foreshore:** Ranges from the low-tide mark to the limit of swash from waves at high-tide.

The steeper, landward part of the foreshore is the **beach face** (generally the landward limit of the swash from high-tide waves). The flatter, seaward part of the foreshore is the low-tide **terrace** (the width of this is controlled by the size of the tides).

The slope of the beach face is related to sediment particle size (steep slopes tend to have larger grain sizes) as well as what kind of **breaker** waves collapse into as they reach the shore.

**spilling breaker:** breaks far offshore on flat-sloping beaches



**plunging breaker:** breaks closer to the shore on steeper beaches



images from: <http://kingfish.coastal.edu/biology/sgilman/7770Oceansinmotion.htm>

**Inshore / Shorerise:** From the low-tide water mark seaward out to the **closure depth** of the beach profile (the point at which seasonal changes do not affect the depth of the profile).

**Longshore troughs and bars** form at the location where waves typically break. The size, location, and depth of these troughs and bars is determined by wave height, steepness, and the type of breaker produced.

### Seasonal Beach Profiles

**Summer (calm) profile:** If the waves hitting the beach are generally low energy, then sand and sediment is deposited, creating wide, gently sloping berms.

**Winter (storm) profile:** High energy storm waves move sediment away from the beach face to form a larger offshore bar. This leads to a steeper profile without large berms.

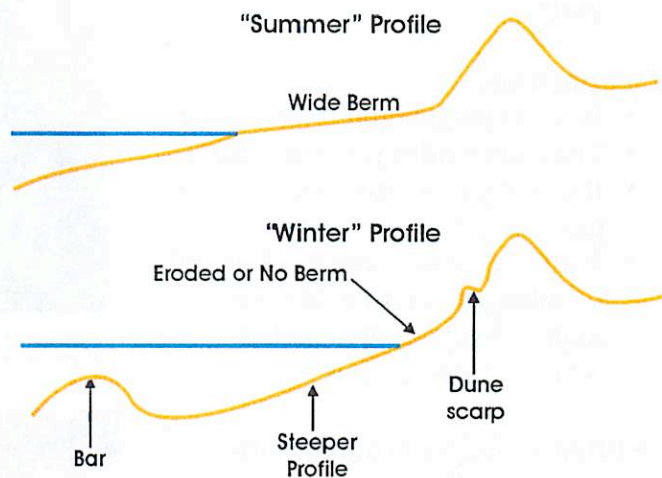


image from: <http://www.maine.gov/doc/nrimc/mgs/explore/marine/faq/shape.htm>

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[http://coastalchange.ucsd.edu/st3\\_basics/beaches.html](http://coastalchange.ucsd.edu/st3_basics/beaches.html)



# HĚAVY MĚTÁL LÁMÍNĚ

Ingrid Däubär Spítalė

Also called “placer deposits” or “strand-line deposits”.

## DESCRIPTION:

- Dark streaks on beaches, subsurface layers.
- Located in inner surf zone, also seen in swash zones.
- Often higher content of magnetic grains.

## Composition:

- Iron oxides (magnetite, hematite)
- Titanium oxides (ilmenite, rutile)
- Heavier silicate minerals (zircon, garnet)
- Precious metals, diamonds [rare]
- Uranium/thorium oxides (in monzanite, zircon, hematite, ilmenite) [rare]

→ Often mined for economic ore deposits, including precious gems and gold.

Note, heavy metal minerals have *smaller* average grain sizes.

## FORMATION:

Minerals sorted by density and size during selective entrainment, transport, and deposition.

Wave swash carries away lower-density, coarser-grained minerals (quartz & feldspar), and leaves behind higher-density, smaller-grained minerals as a lag deposit.



Dark layers containing magnetite in Lake Bonneville paleo-beaches, Utah.  
Photo credit: Clint Cox. <http://bit.ly/dJpKjk>



Small-scale placer deposit in Namakwa Sands, S. Africa.  
Photo credit: D.L. Reid. <http://bit.ly/dEzWTL>



- Most efficient in areas of high erosion → concentrations of heavy minerals correspond to topography, features that control erosion/deposition - e.g. sand bars.
- Common on beaches on the leeward (downwind) side of peninsulas – sediments trapped there from long shore drift.

Do *not* represent different sources or parent rocks – same source, sediments are just sorted.

### Processes that sort grains:

#### 1. Selective entrainment: Will particles be picked up by fluid?

- Gravity vs. fluid forces
- Threshold shear stress (depends on density of fluid & grains, gravity, grain size...)
- Larger grains have a lower threshold shear stress → size-based sorting mechanism

#### 2. Differential grain transport:

- Velocity, distance a grain is carried by fluid depends on grain size & density.
- → Sorting in direction of flow
- Experiment: transport rate ~ grain size (same as for entrainment)

#### 3. Settling velocities: Velocity of grains falling through a fluid

- Depends on size, density, shape of grains.
- Turbulence counteracts settling forces.
- Smaller particles settle faster.
- Denser particles settle faster.

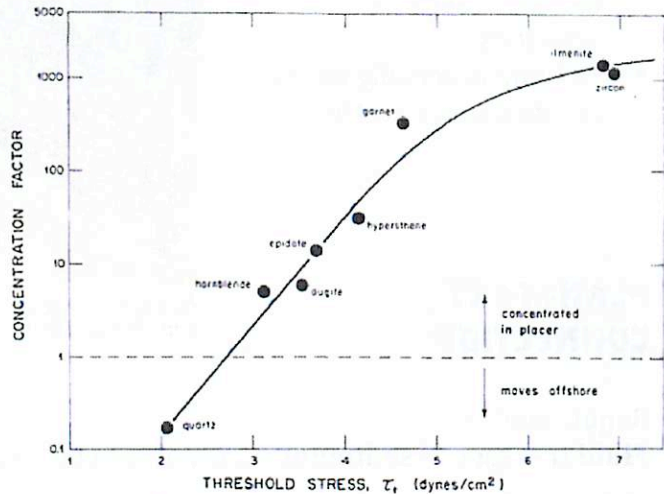
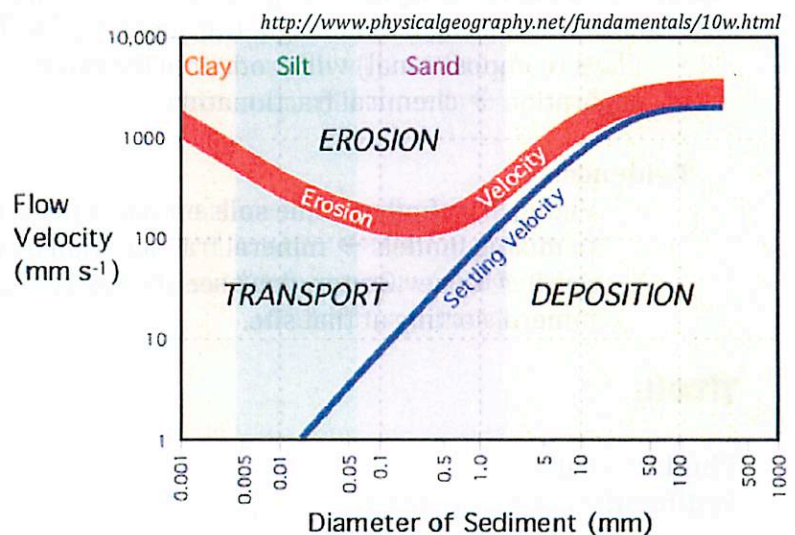


FIG. 7.—The concentration factors of the principal heavy minerals in the placer versus the threshold stress from figure 6 required for their entrainment, the systematic trend indicating that selective entrainment must have played an important role in forming the placer. (Komar & Wang 1984)



## COMPARISON TO AEOLIAN GRAIN SORTING

- Same processes, but: different dependencies, lower viscosity (→ less shear on beds → entrain smaller particles), increased settling velocities...
- → Wind is actually better at size-density sorting.



Aeolian grain sorting, Kelso Dunes, CA. Photo credit: Michael Welland  
<http://bit.ly/e4MkU8>

## PLANETARY CONNECTION

Requirements:

**Fluid** transport + **sediment** supply able to be sorted (i.e. variation in size/density)

### MARS:

**Fluid:** Wind obviously important now, water in the past (amount? persistence?)

**Sediment:** Global dust layer homogenized – derived from basalts with heavy metals, also resistant to weathering (titanomagnetite, ilmenite, Fe-, Ti-oxides)

- Clays (compositional) will erode into the finest grains. Then grain (physical) separation → chemical fractionation.

### Evidence:

- Viking, Pathfinder: some soils enriched in Fe, depleted in Ti & Al oxides compared to mixing models → mineral fractionation by (aeolian) sediment transport
- Spirit @ Gusev Crater: *don't* see chemistry ~ grain size → no evidence of heavy mineral sorting at that site.

### TITAN:

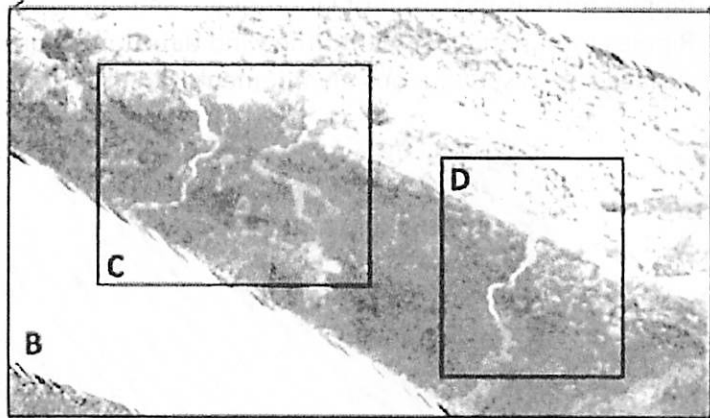
**Fluid:** Methane

**Sediment:** H<sub>2</sub>O ice, organics

- lower gravity → lower settling velocities
- lower fluid viscosity + higher buoyancy of grains, compensates for lower g. → amount of sediment transport ~2x Earth

### Evidence:

- Rounded cobbles at Huygens landing site are size that could be moved by bed load
- Gradual change in spectra & albedo across plains – thought to be due to systematic grain sorting across an outwash plain – larger grains nearest outflow, fines at farthest end.
- Radar-bright channels: brighter upstream than downstream – due to sediment sorting?



Radar-bright channels in Cassini SAR radar. (Le Gall et al. 2010)

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## Ripple Formation

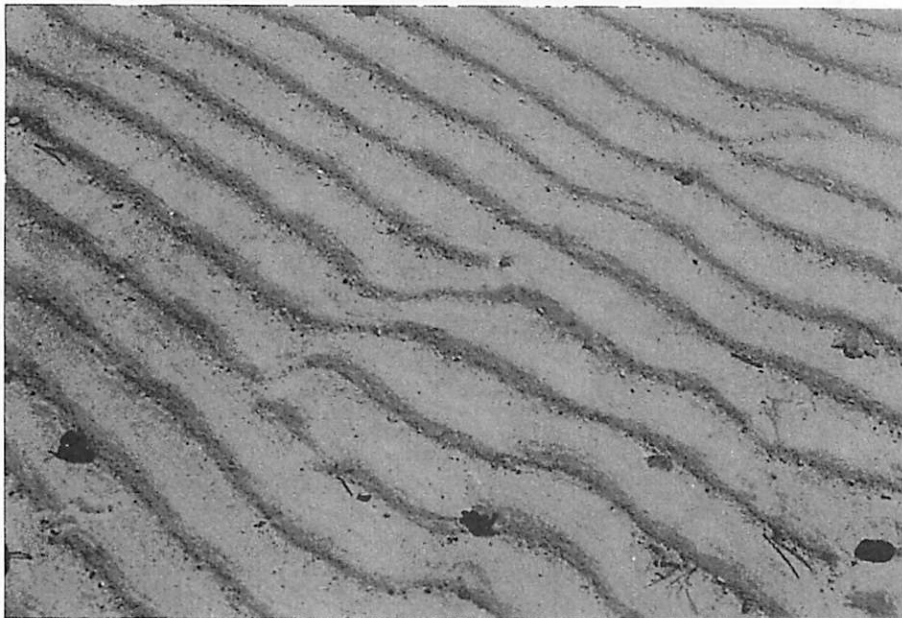
Tiffany Kataria

### *What are ripples?*

Ripples form as the result of larger grains settling as smaller grains are transported away. Ripples form perpendicular to the wind direction (Bagnold 1941). Ripples are seen on the surface and in subaqueous environments (**Figures 1 and 2**).



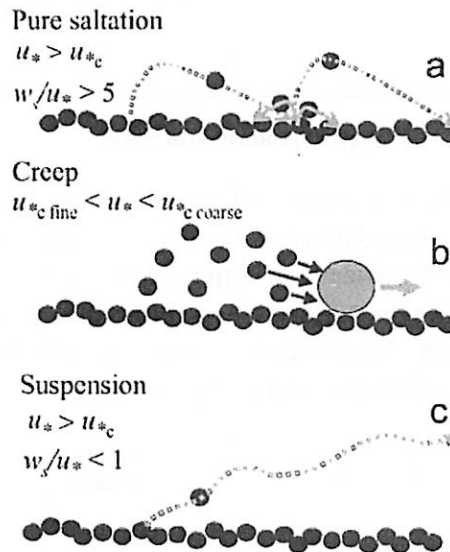
**Figure 1: Sand ripples seen at White Sands, NM.**



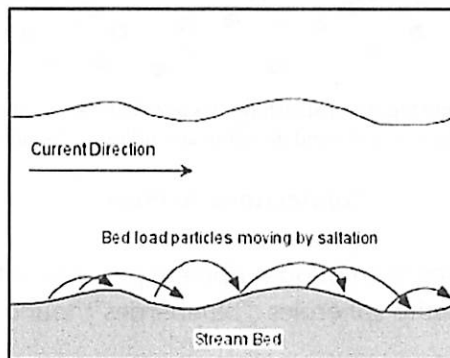
**Figure 2: Underwater sand ripples near Oxtongue Lake Ontario.**

### How do ripples form?

Ripples form from wind-blown sediment, commonly transported in three ways: saltation, creep and suspension (Bagnold 1941). These motions are mainly constrained by three parameters: the mean shear velocity,  $u_*$ , the critical shear velocity at which static grains are mobilized,  $u_{*c}$  and the settling velocity,  $w_s$ . *Saltation* occurs if the shear stress of the wind is greater than the critical value to initiate motion of the grains. In this case, the grains hop in ballistic trajectories, colliding with the bed (**Figure 3a**). This collision is semi-elastic, and thus some of the particles that collide with the saltating grains may become dislodged and either travel short distances ("splash" or reptation) or become part of the saltating population. If these grains are too large to be mobilized by the shear wind velocity itself, but instead can be moved by the collisions of saltating particles, these particles are part of the *creep* population. Creep particles move close to the ground (**Figure 3b**). If some particles have velocities smaller than the turbulent velocity and can be advected along with the saltating particles, it is said to be in *suspension* (**Figure 3c**). Sediment transport is similar in subaqueous environments (**Figure 4**).



**Figure 3:** Methods of sediment transport by aeolian processes. (a) Saltation; here, dotted lines indicate ballistic trajectories, while solid lines denote those grains that are "splashed" (reptated). (b) Creep. (c) Suspension, where the dotted line shows the grain that is uplifted and advected with the flow (Jerolmack et al. 2006).



**Figure 4:** Sediment transport in subaqueous environments.

When surface unevenness occurs due to differences in grain size, a hollow is created and thus less saltation impacts will form on the upwind side of the hollow than the downwind side (**Figure 5**, C vs. A). Therefore, more grains will be transported along AB than along CA. In this way, sand is removed from A to B, forming a ripple. This forms a new hollow downwind of the ripple, and thus the process continues. This type of ripple is commonly called "splash ripples", because they are formed from grains "splashed" by saltation (**Fig. 6a**). The wavelength of the ripples increase with increasing wind speed, but eventually flatten out as the wind is strong enough to transport all grain sizes. The height of the ripple depends on grain sorting. If the sand is more uniformly sized, the ripple amplitude will be smaller because of the reduced differential motion. Bagnold (1941) claims as a general rule that ripple height cannot be more than one-tenth the wavelength of the ripples.

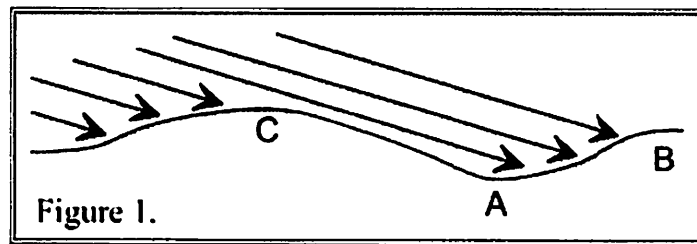


Figure 5: Formation of ripples.

A second group of ripples can form if there is a bimodal distribution of small grains, where coarse-grained ripples exceed 1 mm diameter, a coarse-grained version of a ripple can form, commonly called "granule ripples", where the larger grains settle at the crest of the ripple (**Fig. 6b**). Unlike "splash ripples", however, surface creep comes into play, as the coarser grains creep along by the finer saltating grains. These ripples are generally higher, as the coarser grains can build up upwind, and the movement of granule ripples is slow.

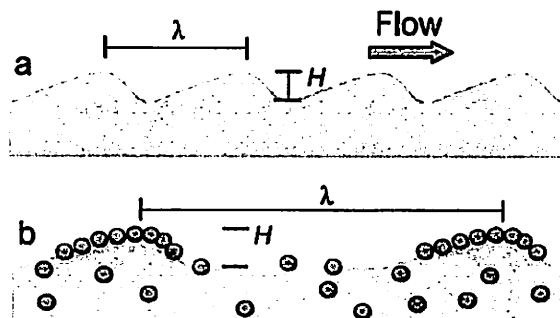


Figure 6: Cross section of two basic ripple types: (a) Splash ripples and (b) Coarse-grained ripples. Here, ripple wavelength, lambda, ripple height, H, and wind direction are indicated (Jerolmack et al. 2010).

### Connections to Mars

Ripples seen at Meridiani Planum been of both ripple types, where the large sediments of coarse-grained ripples are hematite spherules ("blueberries") found in Meridiani Planum (Jerolmack et al. 2010).



Young, fresh craters found in conjunction with ripples at Meridiani Planum have been used as an age dating method for the ripples themselves. In the case of Rayleigh crater (**Figure 7**), the crater overlies the ripples, and hence the crater is younger than the ripples. The size frequency distribution of these small craters indicate that the last phase of ripple activity likely occurred between ~50 ka and ~200 ka (Golombek et al. 2010). This estimate is consistent with the lack of eolian bed forms in craters that formed in the past 20 years, the little evidence for dune migration in the past 30 years, and the very slow erosion rates estimated during the Amazonian and Late Amazonian. Other authors contest that ripple and dune migration are occurring in the present day (Silvestro et al. 2010).



**Figure 7:** Navcam mosaic looking toward the south of Rayleigh crater. The Crater exposes layering beneath the ripples. Note the ripples on the rim and at the bottom of the crater.

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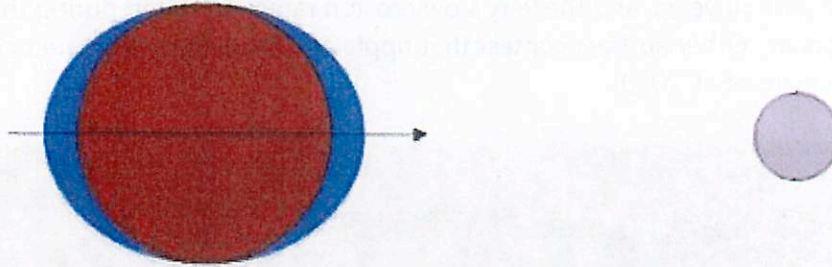


# Tides

Christa Van Laerhoven

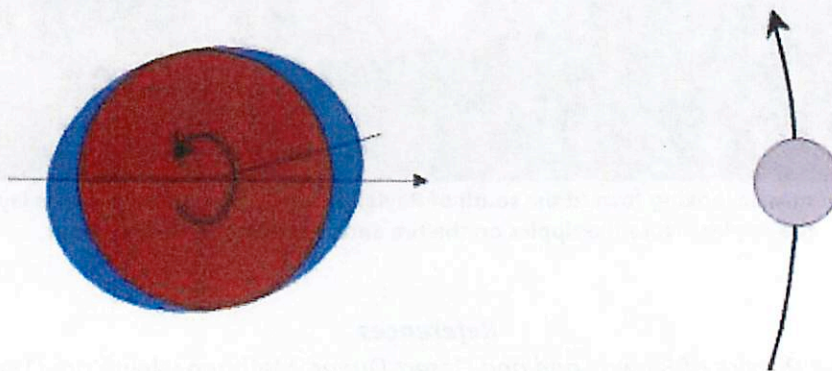
Because the Earth has a non-zero size, the gravitational force due to a perturber will be stronger on the side of the Earth facing the perturber and weaker on the opposite side. This mismatch causes tides. The Moon is the primary cause of tides on the Earth, but the Sun also has some influence.

If the Earth were able to deform freely it would fill out an equipotential surface. There would be a bulge both towards and away from the Moon.



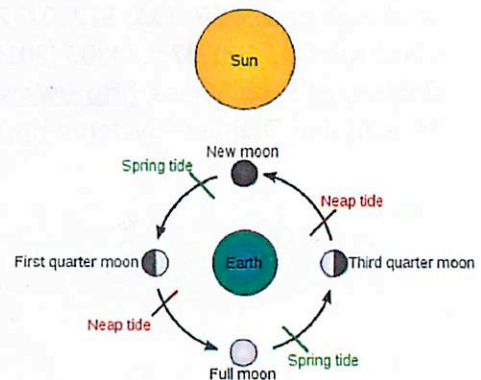
Since water is much more deformable than land, most of the tidal deformation of the Earth is the result of water movement, with amplitudes ranging up to ~1.5 m. The response of the “solid” Earth has a much smaller amplitude of centimeters. The atmosphere will also deform (the altitude of a given pressure can vary by kilometers), but it is much less massive than the oceans and so it doesn't represent that much mass movement.

Because the Earth cannot deform instantaneously the tidal bulge does not point directly at the Moon. Since the Earth rotates faster than the Moon orbits around it, the bulge leads the Moon. Another effect of the Earth's rotation is that it takes slightly longer than 24 hours for the Moon to cycle back to the same location on the sky, so the time between high tides is slightly longer than 12 hours (since there are two high tides in a day).



## Complications

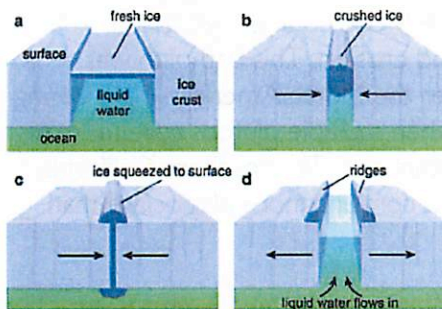
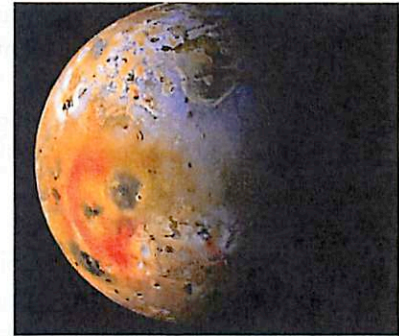
- The influence of the Sun can add or detract from the influence of the Moon depending on how they are aligned with respect to the Earth
  - Spring tide: When the Earth, Moon, and Sun align the mismatch in force felt on opposite sides of the Earth is higher, causing higher high tides and lower low tides than normal.
  - Neap tide: When the Sun-Earth-Moon angle is 90 degrees the mismatch is less, resulting in lower tidal amplitudes.



- Land gets in the way of water movement. The continents are big obstacles.
- Undersea topography near the shoreline can greatly effect the timing and amplitude of tides.
- The Earth-Moon distance changes over a lunar orbit. Tidal amplitudes are larger when the Moon is at perigee and smaller when the Moon is at apogee. (Likewise, the changing Earth-Sun distance will effect tidal amplitudes.)
- Where the Moon is with respect to the Earth's equatorial plane will shift the latitude of the peak of the bulge. (Similarly, the Earth's obliquity effects where overhead or underfoot the Sun is.)

### The planetary connection

- The heating caused by tides is the cause of Io's volcanic activity [2], and possibly contributes to Enceladus' geyser activity [3].



- Europa's ridges may be caused by repeated opening and closing of cracks from tidal movement. Tidal stresses can also cause cracks propagate in a particular scalloped fashion. [4]

- Tides can cause orbital evolution. Both the semi-major axis and the eccentricity can be effected. Examples:
  - the Moon: the orbit is expanding
  - Io: may have evolved or be evolving into or out of 4:2:1 resonance with Europa and Ganymede
  - Triton: the orbit is shrinking and has been circularized
  - various extra-solar planets

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Dyer Lytle  
Field trip, Spring, 2011  
February 7, 2011

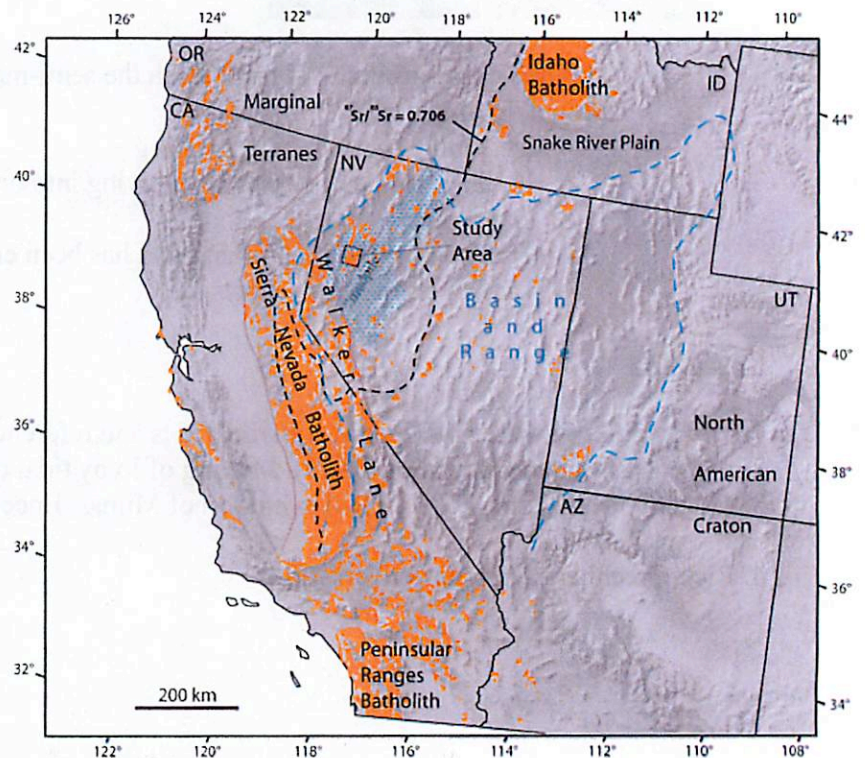


## PENINSULAR RANGES AND THE SOUTHERN CALIFORNIA BATHOLITH

The peninsular mountain ranges are Pacific coast ranges in southern California and Baja. They include the Santa Ana, San Jacinto, Palomar, and Laguna mountains in California, and the Sierra Juarez, Sierra San Pedro Mártir, Sierra de la Giganta, and Sierra de la Laguna in Baja California, Mexico. Mount Palomar, the highest point in the Palomar mountain range, is the home of the 200" Hale telescope (first light, 1949). 85% of the peninsular ranges lie in Mexico.

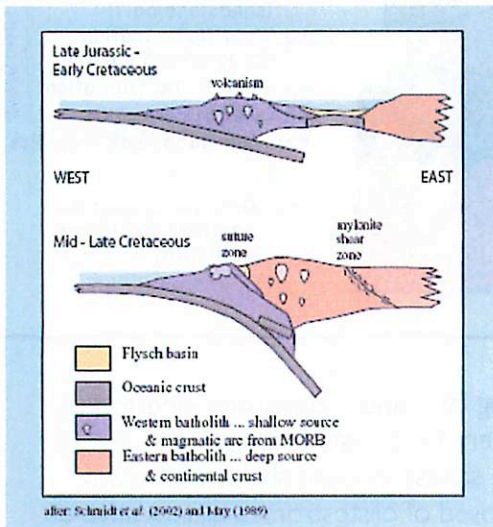
These mountain ranges are formed from the Peninsular Range batholith which is part of the large batholith that forms the Sierra Nevada range. A batholith is a large mass of igneous intrusive rock which formed underground as a huge body of magma slowly cooled and crystallized. This rock is exposed at the surface by extended periods of uplift and erosion. This batholith was formed as a result of the subduction of the Farallon Plate under the North American Plate during the Jurassic and Cretaceous periods. The peak of plutonism, when multiple plutons rose to form the batholiths in the area, happened about 100 to 80 million years ago. The southern California batholith is made of granodiorite, which is similar to granite, but contains more plagioclase than potassium feldspar.

History: In early triassic time (250 to 200 MYA), Pangaea, the most recent supercontinent, began splitting apart along places like the mid-atlantic ridge. This began shrinking the Pacific ocean and volcanic activity began around the ocean's edge due to the compression and collision of the tectonic plates in these areas. An extensive volcanic arc system formed during this period along the western margin of the north American continent. This is called the Sierran Arc and developed, throughout the Mesozoic Era (250 to 65 MYA), into the Sierra Nevada Batholith, the Southern California Batholith, and other plutonic and volcanic centers throughout the greater Mojave Desert region. Uplift and erosion of the Southern California Batholith formed the Peninsular mountain ranges.





Based on strontium ratios and geophysical anomalies, Langenheim, et. al. (2004) has shown that the Peninsular Ranges Batholith (PRB) is divided into two distinct parts. The western part, characterized by mafic, dense, magnetic rocks, and the eastern part by more felsic, less dense, weakly magnetic rocks. The differences seen indicate that the western part of the batholith is underlain by oceanic crust while the eastern part of the PRB is underlain by transitional to continental crust.



The suture zone between the east and west parts of the batholith is considered to be the origin of the San Jacinto fault. This fault has been the site of seven large earthquakes within the peninsular ranges since 1899. This fault is thought to be relatively recent (1.0 -1.5 m.y.) and is a good candidate for studying factors that influence the development of a strike-slip fault.

The Salton Trough, which includes the Salton Sea and the Imperial Valley, is a pull-apart basin on the east side of the peninsular ranges. This means the

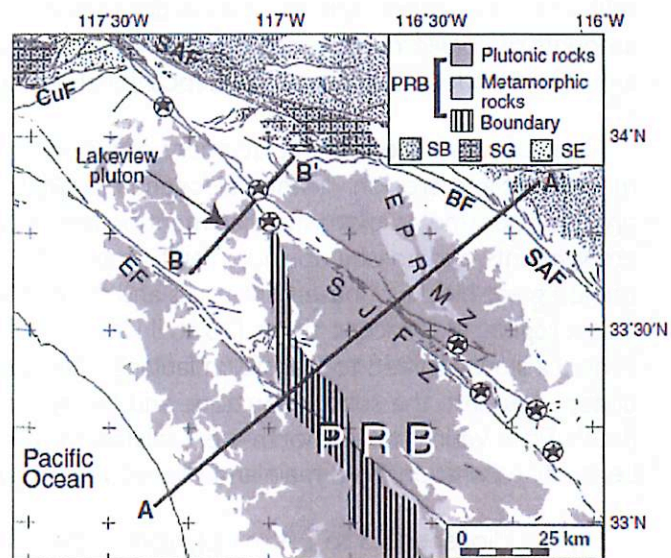
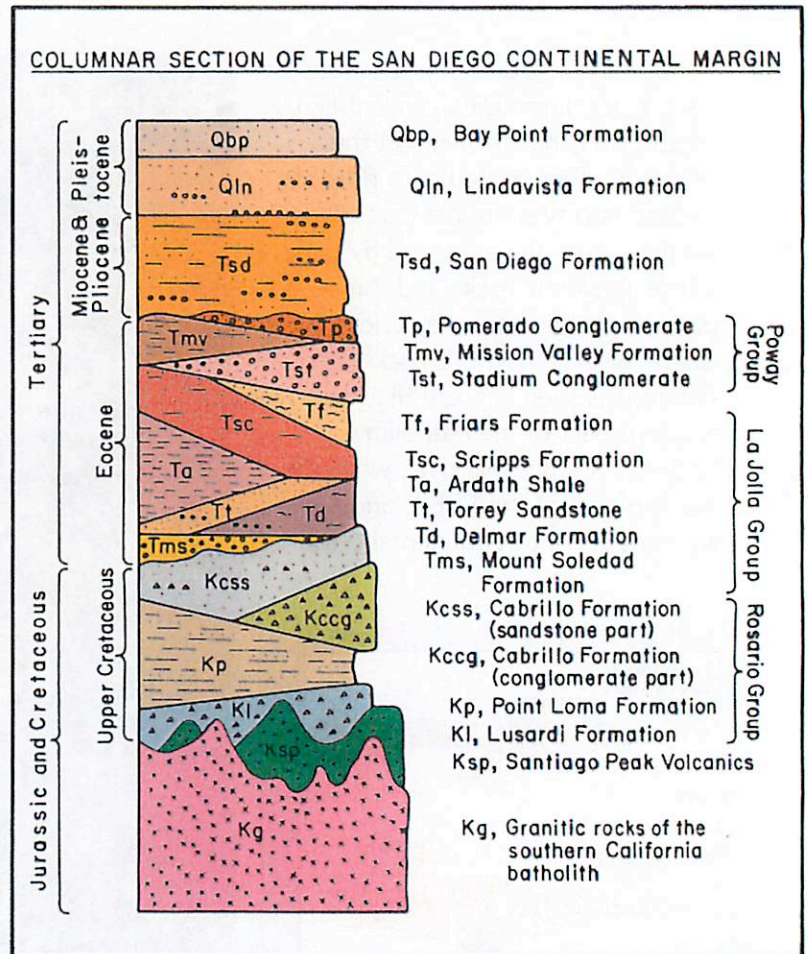


Figure 2. Simplified geologic index map of the Peninsular Ranges batholith (PRB), which lies south of the Banning (BF), Cucamonga (CuF), and San Andreas faults (SAF). Peninsular Ranges batholith rocks are juxtaposed against rocks of the San Bernardino (SB), San Gabriel (SG), and southeast San Gabriel (SE) basement type. Stars show epicenters of large earthquakes along the San Jacinto fault zone (SJFZ) (from Table 1 of Sanders, 1993). Models across profiles A-A' and B-B' are shown in Figures 4 and 5. EF—Elsinore fault; EPRMZ—eastern Peninsular Ranges mylonite zone.



southern California and Baja California peninsular ranges are pulling apart from the rest of North America.

The composition of the rocks that were present in pre-batholithic times include such formations as the Julian Schist. The metasediments (somewhat metamorphosed sediments) of the Julian Schist were intruded by plutons of the Peninsular Ranges batholith. The batholith intruded regionally metamorphosed volcanic and volcanoclastic rocks of Upper Jurassic to Cretaceous age, and nonvolcanic, clastic sedimentary sequences of late Paleozoic to Mesozoic age. The deep erosion of the central portion of the batholith has left only isolated screens of the host rocks. Other metasedimentary formations in the area are the French Valley Formation and the Bedford Canyon Formation.



The Bedford Canyon Formation is dominated by alternating lithic and feldspar-rich sandstones and shales, with lesser amounts of limestone, conglomerate, chert, pebbly mudstones, and tuffaceous sequences. French Valley is dominated by immature sandstones and shales with lesser amounts of conglomerate and chert as well as horizons composed of olistostromes, all indicative of a medium to deep submarine fan depositional setting.

In the years since the emplacement of the southern California batholith, the area underwent much uplift and erosion. In the Paleogene era (65 to 23 m.y.a.), the landscape wore down and probably became an extensive pediment bordered on the west by a coastal plain, shallow embayments, and coastal uplands. Fault systems predating the modern San Andreas Fault system carried great blocks of basement rocks and their sedimentary overburden north to the Central Coast region. In Miocene times (23 to 11 m.y.a.), subduction along the western coast of north America slowly shifted to transform faulting. This happened as the ancient Farallon Plate disappeared into the subduction zone and the North American Plate came in contact with the Pacific Plate which moves north-west relative to the NAP. During this time, the Baja Peninsula began its separation from mainland Mexico and began its northward migration.

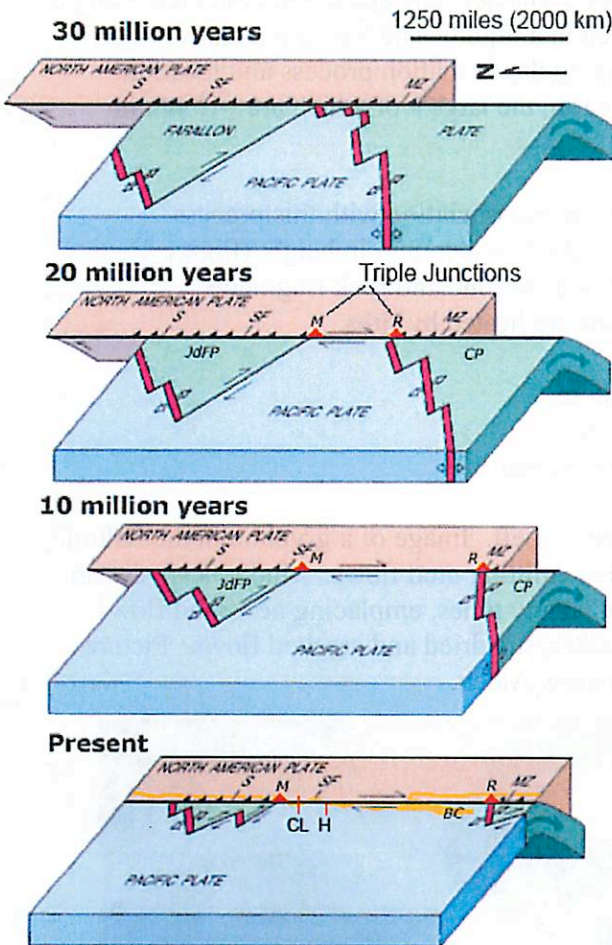
In the Pliocene (5.3 to 2.4 m.y.a.), uplift in the Peninsular, Transverse, Coastal Ranges, and the Sierra Nevada started to shape the height and extent of the mountain ranges visible today. Later,







in the Pleistocene, ice ages caused the rise and fall of sea level as well as changes in precipitation patterns. During low sea level times, streams carved downward into their valleys and during high sea level periods, valleys became flooded and back-filled with sediments. Continuing tectonic forces (faulting and folding) help shape the uplifts and basins visible on the landscape as they appear today.



**Maximum extent of the Western Interior Seaway about 100 million years ago**



-  **Spreading center**—Arrows indicate direction of movement
-  **Subduction zone**—Sawtooth on upper plate
-  **Fault**—Arrows indicate direction of relative movement
-  **Triple Junction**

The San Andreas Fault system has gradually evolved since middle Tertiary time (beginning about 28 million years ago). The right-lateral offset that has occurred on the fault system since that time is about 282 miles (470 km); however, the fault system consists of many strands that have experienced different amounts of offset. This fault system is continuing to rearrange the peninsular ranges and the batholith that underlies them.

High points (feet) and lengths (miles) of peninsular mountain ranges:

Santa Ana range	5689 - 36
San Jacinto range	10834 - 30
Palomar mountain range	6140 - 20
Laguna range	6378 - 20

• Langenheim, V. E., et al. (2004). "Geophysical and isotopic mapping of preexisting crustal structures that influenced the location and

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## Mud Volcanoes and Seeps

Jamie Molaro

In general, the term mud volcano (also mud dome) refers to formations created by a pressurized mud diapir which breaches Earth's surface or the ocean floor. Because there is no magma involved, they can form at much cooler temperatures than actual igneous volcanoes. They are, however, often associated with lava volcanoes, forming in close proximity and emitting gases to relieve pressure. Lone mud volcanoes typically emit methane, CO<sub>2</sub>, and N. Their temperatures can be as low as the freezing point of the ejected material, particularly when venting is associated with clathrate hydrates (water based solids resembling ice with gases "trapped" inside). The ejected material is usually a slurry of fine dirt and rock particles suspended in a liquid. The liquid is usually water, though often is very salty or acidic depending on the formation process and location. Thousands have been identified all over the earth, the largest of which are ~10 km in diameter and ~700 m in height.

There are several features that form through and in association with this process:

*Gryphon*: Steep cone that extrudes mud, typically less than 3 m in height (Figure 1).

*Mud Cone*: High cone (shorter than 10 m) that emits mud and rock fragments.

*Scoria Cone*: Cone formed when mud deposits are heated by fires.

*Salse*: Water pools with gas seeps.

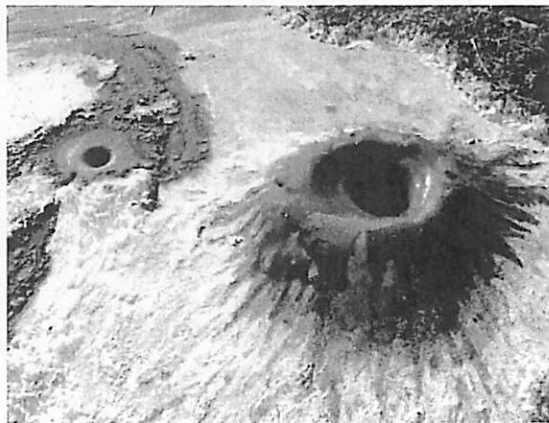
*Spring*: Water outlets, usually smaller than 0.5 m.

*Seep*: Spring without sufficient volume to flow.

*Mud Shield*: Mud extrusion that does not form a cone.



**Figure 1.** Left. Image of a gryphon in the Salton sea area emitting mud flows. Mud volcanoes can "erupt" many times, emplacing new mud flows over older, sun dried and cracked flows. Picture by Andrew Alden.



**Figure 2.** Right. Mud pot in Glenbair, CA. Mud pots form from springs. If the mud pot is particularly colorful, it is often called a paint pot. Picture by Mendo Mann.



The Davis-Schrimpf seep field in the Salton Sea is a large, very active area covered with seeps, gryphons, and many other features. The main driver for the formation of these features is carbonate metamorphism and CO<sub>2</sub> production, via the hydrothermal system, at depth. This seep field is also located above a shallow (depth 200 m) sandstone CO<sub>2</sub> reservoir. Buildup of gas increases the heat and pressure in the geothermal system, forcing diapers of mud and brine up to the surface forming what you see.

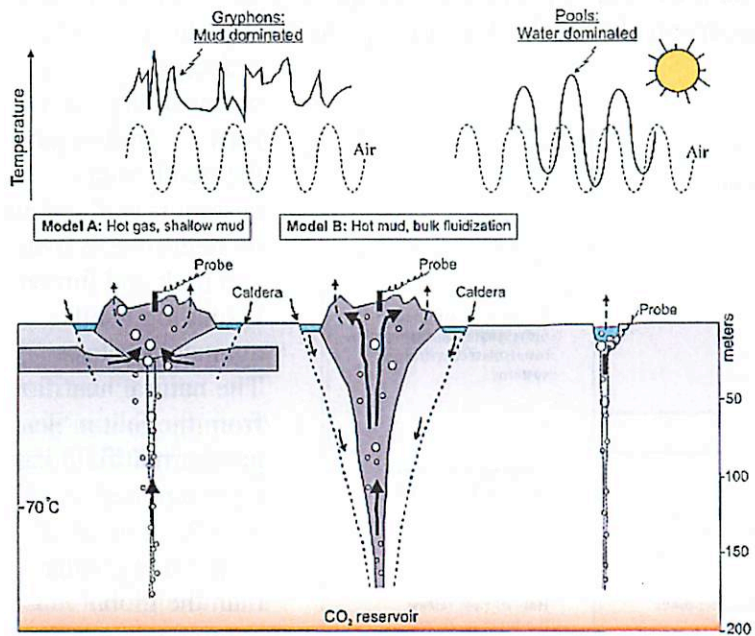


Figure 3. Schematic cross section of the near-surface part of the seeps showing the two different seepage modes (gryphons (left and middle) and pools (right)) and the interpreted subsurface fluid flow pattern. The gryphon has a temperature time series reflecting the interplay between the hydrothermal input (shown as arrows of heat input from below) and the local gryphon bubbling dynamics. The pool is more or less a stagnant body of water which cools the hydrothermal gas passing through. The temperature in the pool is strongly affected by diurnal variations in temperature. The two models to explain gryphon temperature are

presented. In the first case (model A), hot gas is migrating toward the surface and heating and mobilizing shallow mud (resulting in caldera formation). In the second case (model B), bulk fluidization of hot mud toward the surface is coupled with gradual subsidence of the caldera. Model B is favored due to the low mass, hence the limited capacity for heat increase, of the seeping gas.

## The Geothermal System

The geothermal field is a direct result of extension caused by the transform boundary between the North American and Pacific Plates. This transform plate boundary system makes up the San Andreas Fault system. The tectonic behavior of the fault system is dominated by strike-slip motion, but with small zones of extension between offset right-lateral faults. This extension results in magmatic intrusions (for example from the volcanic buttes on southeastern shore), providing a source of heat and causing heat-induced metamorphism in the lower sedimentary layers of the Salton Sea area. Surface gradients within the field are fairly constant, averaging 0.36 K/m.

A hydrothermal system transfers heat from the magmatic intrusions up to the surface. At depth are layers of highly hydrothermally altered rocks (Fig 4). These layers are very permeable and allow for the transport and circulation of hot water away from the intrusions. There is a large mass transfer of chemical constituents in these zones due to the high temperatures (~600 K) and flow. They can vary significantly in chemical

composition and pH, depending on the minerals in a given area. There is also evidence for a density interface between deep saline brines and less saline shallow waters. Hot water and brines move upward and pool beneath the very low permeability cap rock, which serves as a barrier for circulating water and convection currents, and as a thermal insulator, contributing to the increase in temperature in the geothermal system.

In the Salton Sea area, the cap rock thickness varies between 700 m in the northern region and 250 m in the southern region. Heat transfer through the caprock is characterized by conduction. The upper portion of the cap rock is made up primarily of clay, silt, and gravel, while the lower portion consists of evaporite layers. The hot water circulating in the system can deposit chemicals along flow paths through the cap rock,

reducing permeability even further. In this sense, the geothermal system is self-sealing by restoring its own cap rock and further insulating itself against heat loss. The natural heat flow from the Salton Sea geothermal field has been reported as  $\sim 0.3$  W/m<sup>2</sup>, an order of magnitude greater than the global mean continental heat flow.

Unit	Lithology	Heat transfer
Cap rock	Thick unconsolidated silt, sand, gravel, and anhydrite-rich deposits	Heat flow by conduction
Slightly altered reservoir	Shale and sand Small sand units	Enhanced conductivity resulting from presence of sand; still part of thermal cap
	Upper reservoir Shales, siltstone, and sandstone cemented by calcite or silica Major shale break	Convection within sand units; shales separate region into isolated hydrologic systems
	Lower reservoir	Fractures allow more extensive convection patterns
Highly altered reservoir	Reduced permeability results when altered by replacement of calcite with epidote; extensively fractured	
Zone of intrusion	Intrusion of small basaltic dikes and sills into sedimentary section; less than 20% intrusive bodies	Rate of heat release is a function of rate of intrusion

Fig. 20. The relationship between the lithology and the heat transfer characteristics at different zones from cap rock down to zone of intrusion.

Figure 4 (left)

## Planetary Connection

Oehler and Allen (2010) characterized high-albedo mounds near the Acidalia impact basin (Fig 5), which they claim have geologic, physical, mineralogic, and morphologic characteristics consistent with an origin from a sedimentary process similar to terrestrial mud volcanism. They propose that the occurrence of mounds in this area is a consequence of the basin being a depocenter for sediments delivered by the outflow channels from the highlands. This makes it an ideal setting for mud accumulation and for the development of sedimentary overpressure. The mechanism triggering mud volcanism could have been a basin-wide event, such as loss of overburden via sublimation of a body of water, and could have released a significant amount of gas. Potentially habitable environments could have also been established by regionally upwelling groundwater created by the mud volcanoes.



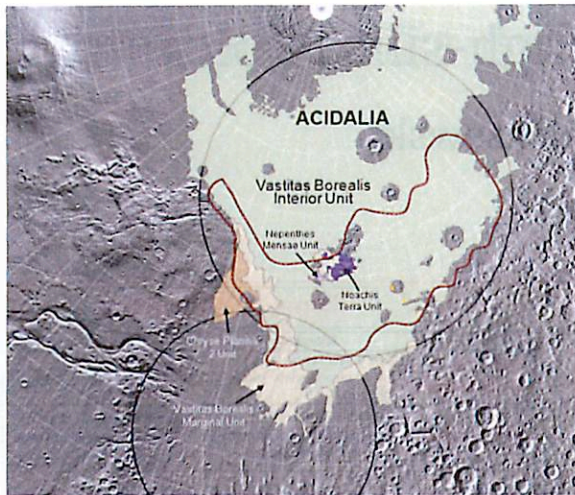


Fig. 5. The red outline is the "Generalized Area of Occurrence" of the mounds (red outline) where potential mud volcano mounds are found.



Fig. 6. Multiple mounds in region of prominent giant polygons. White arrows illustrate areas where material of the mounds appears to coalesce. The albedo of these mounds is similar to that of the plains, though the surface texture of the mounds is smoother than the knobby texture of the plains (black arrow). Well developed dunes can be seen in most of the troughs between polygons. North is up. Centerpoint of PSP\_003366\_2185 is 38.1°N, 347.2°E.

References: [www.wikipedia.com](http://www.wikipedia.com); Kasameyer et al. (1984), GSA Bulletin; Muffler and White (1969), GSA Bulletin; Oehler and Allen (2010), Icarus Svensen et al. (2011), Geology; Younger et al. (1982), Journal of Volcanology and Geothermal Research



# Salton Buttes and High-silica Volcanism

Chet Maleszewski







## High-silica magma content:

- Increased silica content in the magma increases its viscosity.
- Higher viscosities lead to more explosive eruptions.
- Structures made from high-silica magmas include volcanic domes and composite volcanoes.

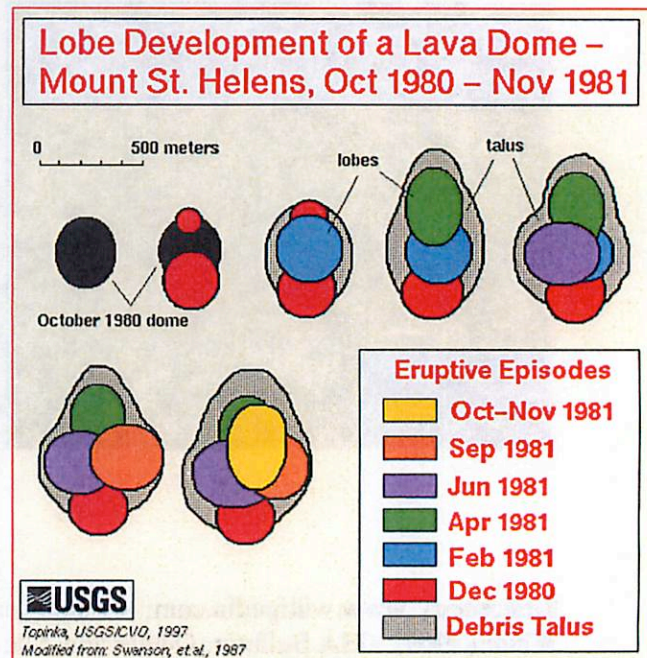
## Rhyolite Domes:

- Rhyolite is a felsic mineral composed of roughly 70% SiO<sub>2</sub> or greater.
- Given high viscosities of felsic magmas, material spreads too slowly from eruption center, crating a material buildup.
- Endogenic process: Material solidifies underneath previously existing solid rhyolite, pushing older material upward
- Exogenic: Magma reaches surface and accumulates on top of existing material.

## Salton Buttes:

Types of Volcanoes			
Volcano Type	Characteristics	Examples	Simplified Diagram
<b>Flood or Plateau Basalt</b>	Very liquid lava; flows very widespread; emitted from fractures	Columbia River Plateau	
<b>Shield Volcano</b>	Liquid lava emitted from a central vent; large, sometimes has a collapse caldera	Larch Mountain, Mount Sylvania, Highland Butte, Hawaiian volcanoes	
<b>Cinder Cone</b>	Explosive liquid lava; small; emitted from a central vent; if continued long enough, may build up a shield volcano	Mount Tabor, Mount Zion, Chamberlain Hill, Pilot Butte, Lava Butte, Craters of the Moon	
<b>Composite or Stratovolcano</b>	More viscous lavas, much explosive (pyroclastic) debris; large, emitted from a central vent	Mount Baker, Mount Rainier, Mount St. Helens, Mount Hood, Mount Shasta	
<b>Volcanic Dome</b>	Very viscous lava, relatively small; can be explosive; commonly occurs adjacent to craters of composite volcanoes	Novarupta, Mount St. Helens Lava Dome, Mount Lassen, Shastina, Mono Craters	
<b>Caldera</b>	Very large composite volcano collapsed after an explosive period; frequently associated with plug domes	Crater Lake, Newberry, Kilauea, Long Valley, Medicine Lake, Yellowstone	

USGS  
Topinka, USGS/CVO, 1997, Modified from Allen, 1975, Volcanoes of the Portland Area, Oregon, Ore-Six, v.37, no.9





- The Salton Buttes contains five rhyolite domes: Rock Hill, Mullet Island, Red Island (2 domes), and Obsidian Butte
- Obsidian Butte is surrounded by material thought to have come from a single volcanic flow. Material in the dome contains rhyolitic obsidian.
- Red Island (right): Both domes are covered by pyroclastic deposits from previous eruptions. Domes formed via endogenic processes.
- Mullet Island: extrusion of the dome spread radially outward, creating 'onion-skin' like foliation. Exogenic formation.
- Fluvial processes have eroded parts of the domes. These domes are partially covered by lacustrine and aeolian deposits.



References and Image Locations:

[http://vulcan.wr.usgs.gov/Volcanoes/California/SaltonButtes/description\\_salton\\_butttes.html](http://vulcan.wr.usgs.gov/Volcanoes/California/SaltonButtes/description_salton_butttes.html)

[http://vulcan.wr.usgs.gov/Glossary/Domes/description\\_dome\\_growth.html](http://vulcan.wr.usgs.gov/Glossary/Domes/description_dome_growth.html)

[http://en.wikipedia.org/wiki/File:Salton\\_Butttes\\_-\\_Red\\_Island\\_-\\_red\\_rocks\\_closeup.JPG](http://en.wikipedia.org/wiki/File:Salton_Butttes_-_Red_Island_-_red_rocks_closeup.JPG)

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# Alogondes Dunes

Catherine Elder

## 1 Introduction to Dunes

-Sand particles which are light enough to be lifted by the wind, but not so light that they become suspended in the wind travel by **saltation**.

-A dune forms by saltating grains hopping up the windward slope, and sand falling down the 'slip-face' which is at the angle of repose (Figure 1).

-The type of dune that forms depends on wind direction and sand supply (Figure 2).

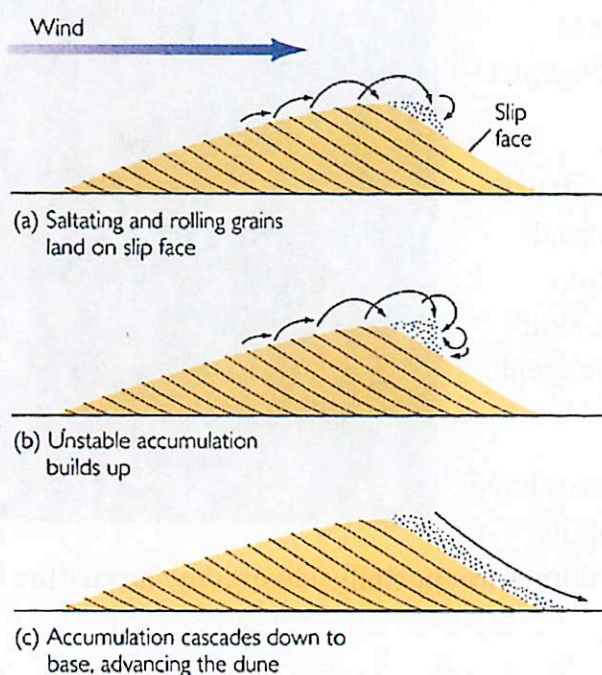


Figure 1: Formation of a dune. Figure stolen from Shane's PTYS 511 aeolian processes lecture.

## 2 Characteristics of Alogondes Dunes

-Located in the Imperial Valley in California along the southeastern border of the Cahuilla Basin (Figure 3). The Cahuilla Basin is at the northern end of a large structural trough that extends several hundred miles to the south and includes the Gulf of California. The Cahuilla Basin is now separated from the gulf by an alluvial divide deposited by the Colorado River (Norris and Norris 1961).

-40 miles long in a northwesterly direction and 3-6 miles wide (Norris and Norris 1961).

-Bordered to the east by alluvial fans that adjoin the Chocolate and Cargo Muchacho Mountains, and to the west by East Mesa and remnant shorelines of Lake Cahuilla (Ewing



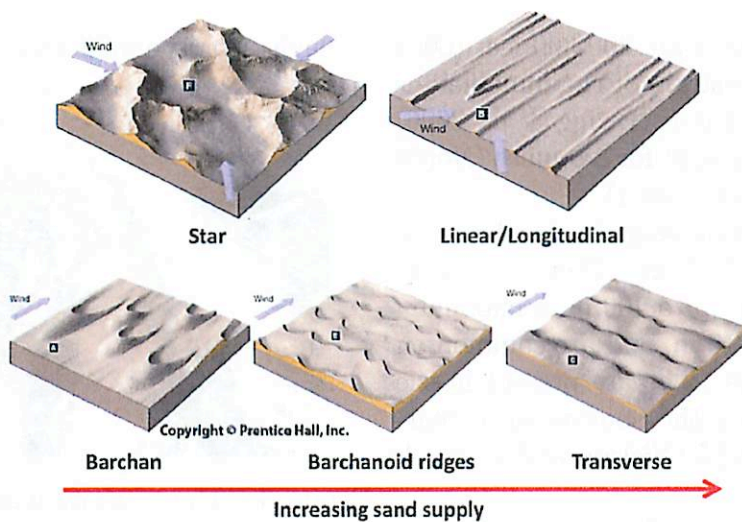


Figure 2: Types of Dunes. Figure stolen from Shane's PTYS 511 aeolian processes lecture.

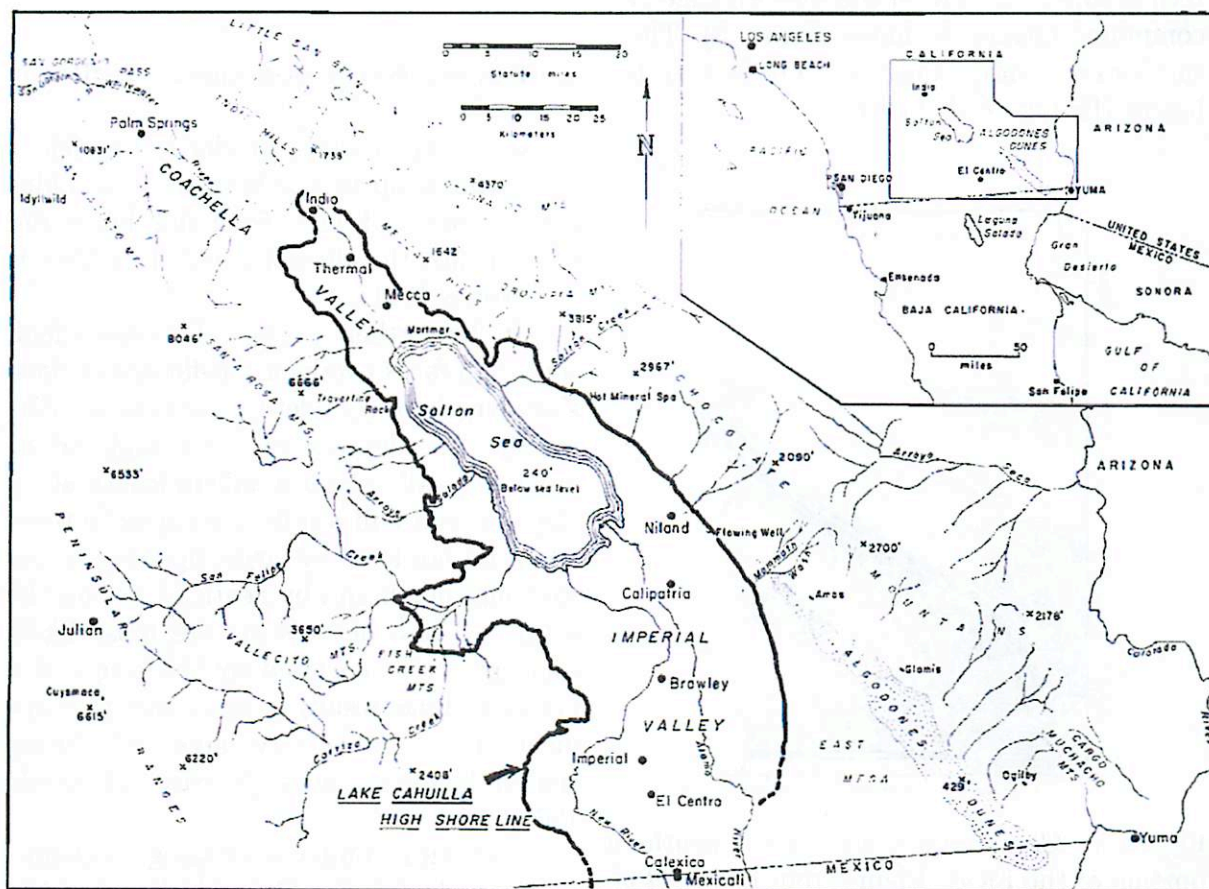


Figure 3: A map of the area from Norris and Norris (1961).

*et al.* 2006).

-Individual dunes are 200-300 feet (60-90 m) high (Norris and Norris 1961)

-The western margin of the dune field is an abrupt, linear ramp (Ewing *et al.* 2006) which is almost straight for 8-9 miles (Norris and Norris 1961) (Figure 4).

-**Zibars** are coarse-grained eolian features which lack slipfaces. They have fairly regular spacing of up to 400 m, a maximum relief of less than 10 m, and are common on dune field margins. They are present in the Algodones only on the southwestern margin of the dune field (Nielson and Kocurek 1986).

-Further east into the dune field crescentic dunes replace linear dunes. In the center of the field the crescentic dune pattern is superimposed on the western edge of compound crescentic dunes (Figure 5). The smaller crescentic dunes are up to 20 m in height, whereas the main bedforms reach 80 m in height (Ewing *et al.* 2006)



Figure 4: The western margin of the Algodones Dunes looking northwest showing parallel linear ridges. Figure from Norris and Norris (1961).

-Along the eastern border of the field a sandy apron up to a mile or more in width extends out and away from the dunes and ends against the alluvial desert floor (Norris and Norris 1961).

-In the southern portion of the dune field, some slip faces overlook flat-floored depressions largely or completely free of sand (Figure 6). The depressions are roughly triangular, typically about a mile in length along the base and half a mile from apex to base. They are bordered by large slip faces on the west and north and by gentle slopes on the south. These depressions are most likely sand-free areas enclosed by the wings of a barchan dune resulting from the development of a train of very large and closely spaced barchan dunes (Norris and Norris 1961).

-Statistical comparisons using geochemical data identify the Colorado River as the main source of the Algodones dune sands (Winspear and Pye 1995).

-Currently, the wind regime is dominated

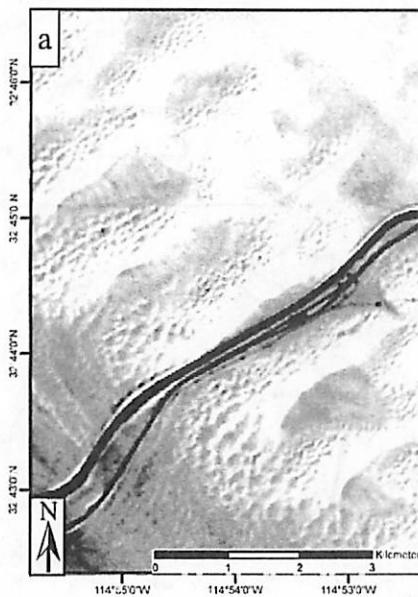


Figure 5: Compound dunes in the southern portion of the Field. Figure from Ewing *et al.* (2006).





Figure 6: Sand-free depressions and small barchan dunes advancing across the depressions in the southern portion of the dune field. Figure from Norris and Norris (1961).

by northwesterly, northerly and westerly winds (Winspear and Pye 1995).

### 3 Planetary Connection

#### 3.1 Fictional Planets

-Abydos - The scenes on the planet in the Stargate movie were filmed at Alogondes dunes.

-Tatooine - The home planet of Anakin and Luke Skywalker. Tatooine scenes in "Return of the Jedi" and scenes added in the special addition of "A New Hope" were filmed in Alogondes Dunes (Figure 7).

-A Jupiter sized planet orbiting HR 7162 was compared to Tatooine in some news articles, because HR7162 is in a binary star system, so planets around it would have a double sunset like Tatooine.

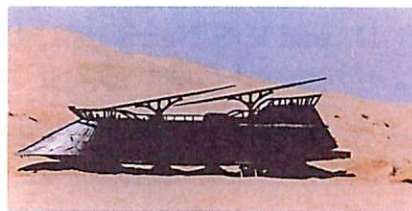


Figure 7: Jabba the Hut's Sail Barge in Alogondes dunes.

#### 3.2 Real Planets

Venus - The dense atmosphere should make it easier to move particles than on Earth. However, only two dune fields have been observed. There might be a lack of sand sized particles due to low erosion rates, or there may be dune fields not yet observed (Shane's PTYS 511 aeolian processes lecture).

Mars - Low atmospheric density, so it should be harder to form dunes on Mars than on Earth. Extensive dune fields have been observed (Figure 8). High wind speeds and lots of weathering lead to Mars having many dune fields (Shane's PTYS 511 aeolian processes lecture).

Titan - The atmospheric pressure is about the same as Earth's, but it is so much colder there that the atmosphere is about 5 times denser than Earth's. Titan also has lower gravity

and the dune material is less dense, so it is easier to form dunes on Titan than on Earth. A significant fraction of Titan is covered by dunes (Shane's PTYS 511 aeolian processes lecture).



Figure 8: An example of dunes on Mars. Figure stolen from Shane's PTYS 511 aeolian processes lecture.

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