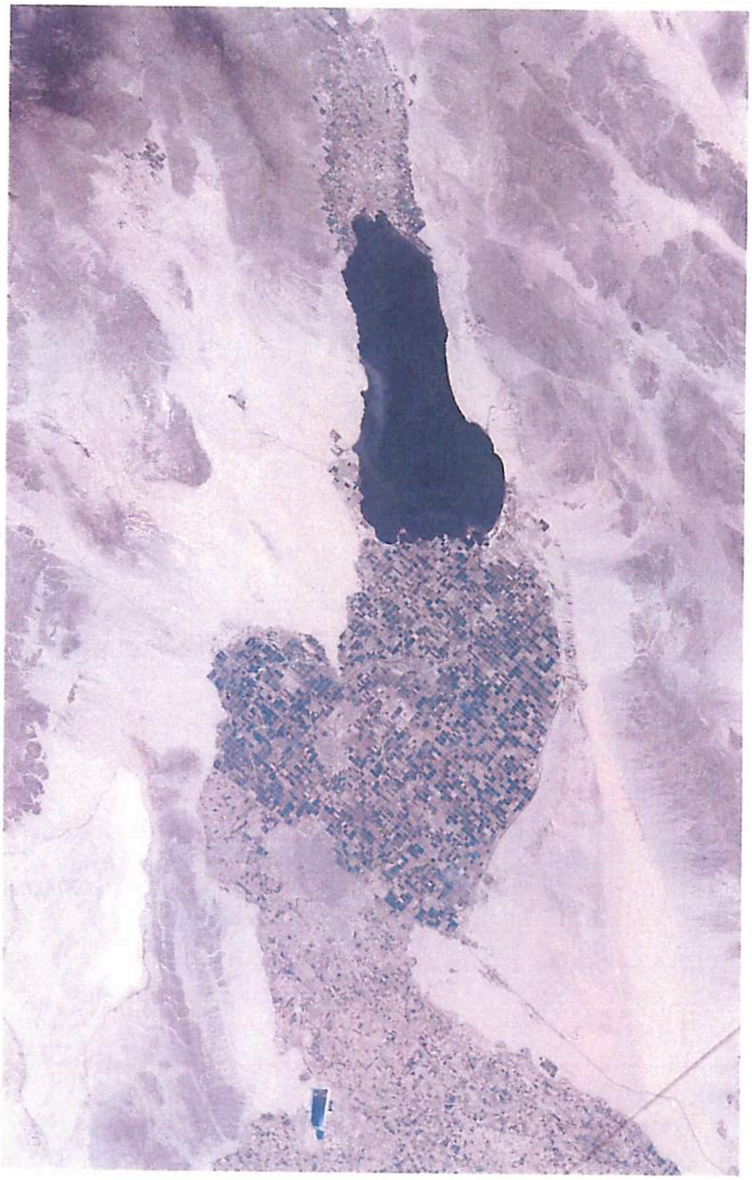
DEPARTMENT OF PLANETARY SCIENCES
LUNAR AND PLANETARY LABORATORY
The University of Arizona, Tucson AZ 85721

PTYS 594A: Planetary Geology Field Practicum

Beach Processes in Southern California



May 2 - 4, 2008

18/86

PTYS 594A: Planetary Geology Field Practicum

Beach Processes in Southern California

May 2-4, 2008
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The Salton Sea as seen from the International Space Station, courtesy of the Earth Sciences and Image Analysis Laboratory at JSC

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Editor's Note—

Beach geology—it's not all bikinis and sand in your socks. Indeed, as one erstwhile grad ruefully acknowledges in this very volume, studying beach processes can now be important for even the dynamicists and gas giant buffs out there, thanks to recent discovery of liquids on Titan. The processes we study as we venture to the Pacific coast may come in handy in learning what may have shaped Titan's surface. While previous handouts of this trip have given only passing mention of the planetary connection (see Abramov, O. (2002) Beaches on Mars?), this one boasts four explicitly extra-terrestrial topics (ok, one of them is still essentially Beaches on Mars?, but you catch my drift).

Our department has run a trip similar to this one twice before—once in the early years of fieldtrippery (1994, and boy, has the bar for these handouts been raised since then…rats) and again in 2002. The trip remains much the same, barring errors in this humble editor's Google Earth, cobbled-together route map. Real estate development has apparently made some of the previous trips' sites no longer as attractive or accessible; however, we soldier on, oranges, dyed sands and sunscreen in hand to learn what we may about our current and preserved coastlines.

As a first-time field trip editor, I'm not quite sure what's appropriate in this note. Given the examples of my predecessors, I should be windy, topical and yet wandering widely off-topic as far as science is concerned, and I should allude to my personal history with LPL field trips. As to the latter, this may be my last field trip with LPL, as I hope to have filed the last pieces of paperwork for my thesis by the time you hold this handout in your eager mitts. I have very much enjoyed driving oversize vehicles across sand dunes and burning various inflammables with my fellow grads, and I hope to be able to do so again in the future. Things look good for that—there are four LPL postgrads in attendance on this trip. Now the tangential (you mean we weren't there yet?): Wikipedia informs me that Silver Strand Beach, CA is the birthplace of the Nardcore style of hardcore punk rock. I'll make a s'more for the person who can tell me what that means.

Nicole Baugh, editor
April 2008

Approximate Route Map courtesy of Google Maps

A/J: Kuiper Space Sciences
B: Imperial Dunes
C: Travertine Rock
D: Night 1 Campsite
E: Silver Strand Beach
F: Solana Beach
G: Lucerne Valley
H: Night 2 Campsite
I: Amboy, CA

Total Distance: ~2000 km

PtyS 594a,

PLANETARY FIELD GEOLOGY PRACTICUM

Spring 2008: Beach Processes in Southern California

Approximate Itinerary

Friday, 2 May

8:00 AM	Depart LPL loading dock. Travel South on Campbell and Kino Parkway to I-10, proceed West to the intersection with I-8. Exit I-10, continue west toward Gila Bend.
9:30 AM	Rest stop at Sentinel Volcanic field west of Gila Bend. Continue west toward Yuma.
12:30 PM	Cross AZ/CA border at the Colorado River, then Exit I-8 in CA at Exit #156, Gray's Well road. Loop south over the Interstate, stop for lunch at Imperial Dunes turnoff. Following lunch, **Joe Spitale** will describe the dunes and the aeolian processes that have formed them.
1:30 PM	Continue west on I-8. Exit freeway at Exit #114, S. Imperial Avenue/Route 86 and proceed north to Brawley. Make a left to remain on Route 86 and continue north to Desert Shores.
3:30 PM	Exit Route 86 on Monterey Ave in Desert Shores (first exit on right), proceed east 1/3 mile, make a left at the T-intersection with Thomas Avenue and stop along the shore of the Salton Sea at Capri Lane. We will try to ignore the terrible stench of rotting fish and pesticides as **David Minton** acquaints us with the past and present history of the Salton Sea.
4:00 PM	Depart downtown Desert Shores, proceed north on Route 86 approximately one mile to left exit at the prominent landmark of Travertine Rock. Drive as close as possible to the rock, park the vehicles and explore the contact between the light and dark deposits on the rock. At this favored locality **Kat Volk** will describe the shorelines of ancient Lake Cahuilla. **Dave O'Brien** will describe the mighty San Andreas and San Jacinto fault that bounds the huge mountain masses to our east and west.
4:30 PM	Depart Travertine Rock. Turn south on Route 86, returning to Salton City. Make a right turn onto Route S22 and proceed west through the Anza-Borrego Desert Park. S22 joins S2 before reaching a T-intersection with

Route 79. Along this route, **Kevin Jones** will describe the formation of spheroidally weathered rocks. Proceed south on Route 79 (left turn) to the intersection with Route 76. Make a hard right turn onto Route 76 north, proceed past Lake Henshaw. Continue to the intersection with Route S-6 (AKA S. Grade Road), past the La Jolla Indian Reservation (*do not* take the intersection with Route S-7, which splits off from Route 76 just after Henshaw lake). Climb up a series of switchbacks until Route S-7 is reached near the mountaintop, make a left and proceed to the campground. We have reserved adjacent sites number 1, 2 and 3.

6:00 PM Make camp, eat dinner, sleep and dream of geologic processes in the geodynamically queasy core of the Peninsular ranges.

Saturday, 3 May

7:30 AM Break Camp, load up the vehicles and prepare for a day on the beach. Return to the intersection with S-6 and proceed south, first joining Route 76, traveling west, then make a hard left turn south, continuing to follow S-6. Make a left onto N. Lake Wholford Road, continue south. At the T-intersection, make a left onto Valley Center road, continue south. Join I-15 at San Pasqual Rd. and continue south. Merge onto I-5 and continue south to Palm Avenue, exit 5A, west toward Imperial Beach. Turn right onto Route 75, Silver Strand Blvd and proceed north. Pull into Silver Strand State Beach pay parking lot and prepare for sun, sand water and waves.

9:00 AM Arrive Silver Strand State Beach. Anoint ourselves with sunscreen, don our hats, bring along hand lenses, oranges (brightly colored floats), dyed sand, shovels, and binoculars and head for the beach face. Once there we will learn about the physics of wave breaking from **Mandy Proctor**. **Jade Bond** will describe the profile of the beach face, **Eric Palmer** will describe longshore drift and we will attempt to observe it directly with our oranges beyond the surf zone (binoculars will be useful here). **Nicole Baugh** will describe heavy metal laminae (no, this is not a musical genre), for which a small shovel will be useful. **John Weirich** will describe grain movement on the beach, which we will observe with dyed sand grains. Finally, **Keith Rogers** will enlighten us about the interface between fresh water, salt water and air in the beach face. Finally, **Catherine Neish** will discuss the origin of life in some warm, salty pond in some rocky setting.

12:00 AM Exhausted by this flood of beach science, we will take a much-needed break for lunch back at the vehicles.

1:00 PM Refreshed and invigorated, we will listen with rapt attention as **Brian Jackson** describes the tides that have been gradually moving water during the mornings researches. **David Choi** will describe rip currents (perhaps a swimmer or surfer will oblige us by finding one and riding it rapidly out beyond the surf zone—again, binoculars will be useful). **Lissa Ong** will describe beach cusps (hopefully we will see some good ones here). **Priyanka Sharma** will describe erosional and depositional processes on beaches, then **Doug Archer** will chime in on the nature of islands (unfortunately, theoretical at this site, but very important along other coasts).

2:30 PM Having sampled (but by no means exhausted) the wonders of Silver Strand Beach, we reluctantly return to the vehicles and return south on Route 75, rejoin I-5 and proceed north. Leave I-5 at Exit 29, Genesee Ave just past UCSD, and drive west as the road becomes Torrey Pines Rd (old Highway 101). Proceed, observing the estuaries and raised benches as we drive along them until we arrive at the pay parking lot for Solana beach overlooking the estuary of the San Dieguito river, just past the intersection with Ocean St.

3:30 PM Park vehicles, enjoy the view, and gather around **Tom Shad**, who will describe lagoons and estuaries, one of which we are overlooking. **Andrea Philipoff** will add her information on the marine terraces over which we have driven and over which we will shortly drive again.

4:00 PM We now have a long drive ahead of us to reach our campsite outside of Lucerne Valley. Return south along old highway 101, follow it after it becomes Camino Del Mar, then make a left onto Carmel Valley Road at the fork with N Torrey Pines Road. Drive under I-5 and join Ted Williams Parkway until it reaches I-15. Enter I-15 northbound toward Riverside. North of Temecula, I-15 splits off into I-215. Proceed north on I-215 toward San Bernardino. I-215 becomes I-15 north of San Bernardino. Continue north on I-15 to Bear Valley road, Exit #147 east toward Lucerne Valley. Join Route 18, continue east through the town of Lucerne Valley, where it becomes Route 247. After 12.6 miles turn left on Bessemer Mine road (unpaved and rough: Marked as Johnson Valley Off-Road Recreation Area). Drive 14 miles down this road to camp near the trace of the Johnson Valley segment of the Landers fault.

7:00 PM Arrive at our campsite off of Bessemer Mine road, near the fault scarp raised by the 1992 Landers earthquake. Make camp, eat, sleep and prepare for another day of geologic adventure.

Sunday, 4 May

7:30 AM Break camp, make a short walk to view the Landers fault scarp, then load up the vehicles and return to Route 247. Turn right and proceed back to

Lucerne Valley. On the left note the outline of the Blackhawk landslide. We may make a brief stop at the quarry near the toe of this enormous landslide. Just before Lucerne Valley Route 247 turns right (north) at a 4-way stop. Proceed north on Route 247 toward Barstow for 32 miles. Merge onto I-15 east via the ramp on the left. Drive 38 miles eastward on I-15 to the Afton Canyon Road exit. Exit there and drive about 300 yards south to stop at the gravel bar.

9:30 AM Standing on the now-dry gravel bar of fossil Manix Lake, **Josh Nelson** will describe the former lake and explain how this ridge of pebbles was formed by wind and waves. Stretching our imaginations far beyond Earth's pluvial period 11,000 years ago, **Colin Dundas** will describe possibly similar beach deposits on Mars and **Tamara Goldin** will do the same for Saturn's wetlands moon Titan. We will then return to the frontage road and drive a short 0.8 mile west to examine the clayey lake beds themselves, along with some interbedded fluvial sands and gravels. At this appropriate setting, **Ingrid Daubar-Spitale** will describe possibly similar sedimentary structures in Martian rocks.

11:00 AM Return to I-15 and return westward to Barstow. This begins our long drive back to Tucson (just 8 hours away, according to Mapquest!). At Exit #206, before reaching Barstow itself, drive south on Harvard Road. Make a jog westward onto Riverside Road, then south again on Newberry road to cross underneath I-40. Turn left onto National Trails Highway and drive to Fort Cady road, where we will pick up I-40 traveling east. Exit I-40 at Kelbaker Road and proceed south toward the now-extinct community of Amboy. At the T-intersection with National Trails Highway, make a right, turning westward toward Amboy. In the distance we can see the symmetrical cone of Amboy Cinder Cone and its lava field (which includes some of the best-marked wind streaks in this area). IF there is time we may make a foray into the lava field around the cone. Continue south on Amboy road. Note the evaporite deposits and mine in Bristol Dry Lake to the south.

12:00 Noon Stop for lunch in the vicinity of Amboy.

1:00 PM After lunch, return north to I-40 via Kelbaker road and proceed east to Needles. At Needles, drive south on Route 95 to join I-10 at Blythe. Turn east on I-10 and return to Tucson via I-10, using the Phoenix bypass at Buckeye, turning south on Route 85 to Gila Bend (a possible dinner stop if we are delayed), then east on I-8 to rejoin I-10 at Casa Grande.

8:00 PM Arrive Tucson, unload vehicles, go home.

==Finis==

Drivers:

Primary: Baugh, Bond, Dundas, Goldin, Minton,Proctor

Leaders: Jay Melosh, Adam Showman

Participants:

Archer, Doug
Baugh, Nicole
Bond, Jade
Choi, David
Daubar-Spitale, Ingrid
Dundas, Colin
Goldin, Tamara
Jackson, Brian
Jones, Kevin
Minton, David
Neish, Catherine
Nelson, Josh
O'Brien, David
Ong, Lissa
Palmer, Eric
Philippoff, Andrea
Proctor, Mandy
Rogers, Keith
Schad, Tom
Sharma, Priyanka
Spitale, Joe
Volk, Kat
Weirich, John

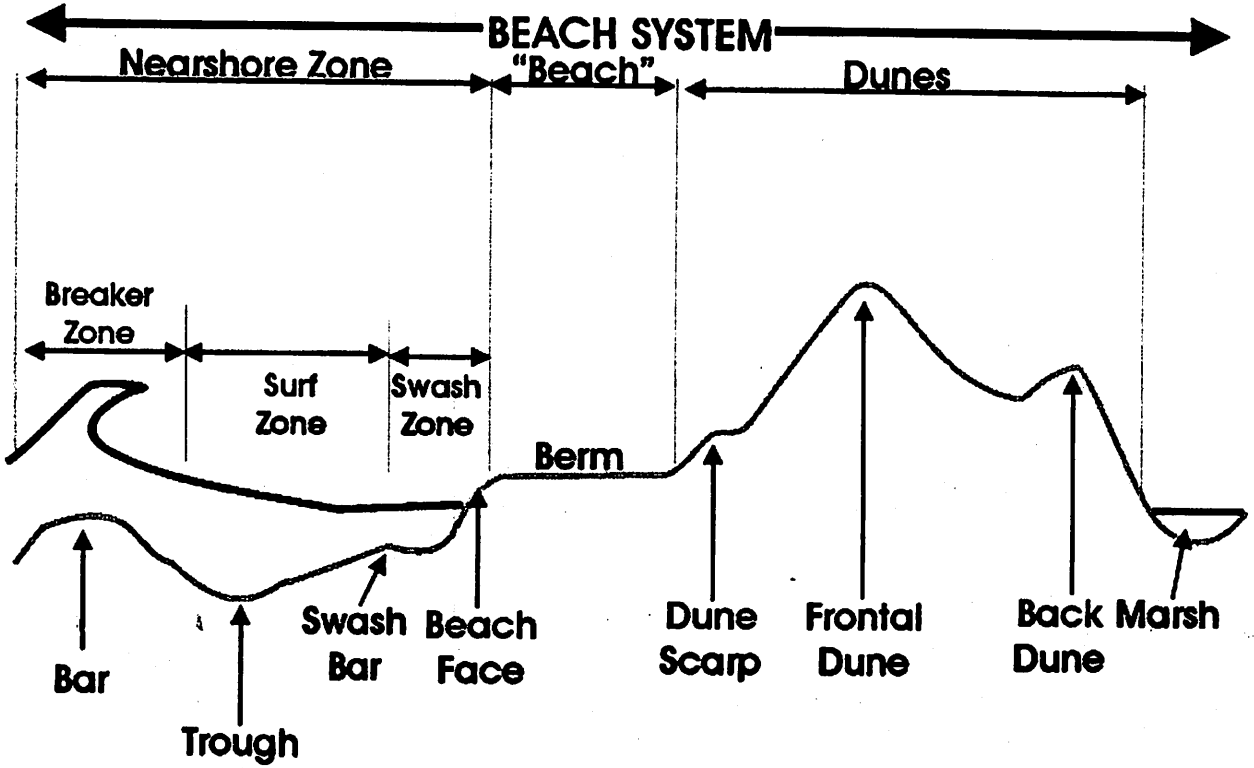
Field Guide Editor: Nicole Baugh

Tide Predictions for Silver Strand Beach, May 2-4

Date	Day	Time*	Height†	Time	Height	Time	Height	Time	Height
05/01/08	Thu	12:49AM	1.3 L	06:42AM	4.2 H	12:52PM	0.3 L	07:19PM	5.0 H
05/02/08	Fri	01:34AM	0.5 L	07:36AM	4.3 H	01:27PM	0.5 L	07:48PM	5.6 H
05/03/08	Sat	02:18AM	-0.3 L	08:28AM	4.4 H	02:01PM	0.7 L	08:21PM	6.1 H
05/04/08	Sun	03:03AM	-1.0 L	09:19AM	4.3 H	02:37PM	1.0 L	08:56PM	6.5 H

†All heights given in feet from Mean Lower Low Water level

*All times given in Local Daylight Time



Incomplete glossary of sea condition terms (Voigt, B. (1998) Glossary of Coastal Terminology Washington State Dept of Ecology Publication No. 98-105):

Mean lower low water (MLLW): Average height of the lower low waters over a 19-year period

Sea (as relates to weather): State of the ocean or lake surface with regard to waves

Sea breeze: A breeze that blows from the sea caused by unequal heating of land and water masses

Sea swell: Waves that have traveled a long distance from their generating area and have been sorted out into long waves of the same approximate period.

Wind waves: waves formed and growing in height under the influence of wind

Brief Glossary of Coastal Terms

Adapted from Komar, Paul Beach Processes and Sedimentation New Jersey: Prentice Hall 1976 pp 12-14

Backshore: The zone of the beach profile extending landward from the sloping foreshore to the point of development of vegetation or change in physiography

Beach face: The sloping section of the beach profile below the berm which is normally exposed to the action of the wave swash

Beach scarp: An almost vertical escarpment notched into the beach profile by wave erosion, commonly less than one meter in height.

Berm: A nearly horizontal portion of the beach or backshore formed by the deposition of sediment by the receding waves. Beaches may have more than one berm.

Berm crest: The seaward limit of a berm.

Breaker zone: The portion of the nearshore region in which the waves arriving from offshore become unstable and break.

Foreshore: The sloping portion of the beach profile lying between a berm crest and the low-water mark of the backrush of the wave swash at low tide.

Inshore: The zone of the beach profile extending seaward from the foreshore to just beyond the breaker zone.

Longshore bar: A ridge of sand running roughly parallel to the shoreline.

Longshore trough: An elongated depression extending parallel to the shoreline and any longshore bars that are present.

Offshore: The comparatively flat portion of the beach profile extending seaward from beyond the breaker zone to the edge of the continental shelf.

Shore: The strip of ground bordering any body of water, whether the ground is rock or loose sediment (beach).

Shoreline: The line of demarcation between the water and the exposed beach.

Surf zone: The portion of the nearshore region, extending from the inner breakers shoreward to the swash zone, in which borelike translation waves occur following wave breaking.

Swash zone: The portion of the nearshore region in which the beach face is alternately covered by the uprush of the wave swash and exposed by the backwash.

Uniform Time Scale
0
PHANEROZOIC
575
PRECAMBRIAN
~4,650

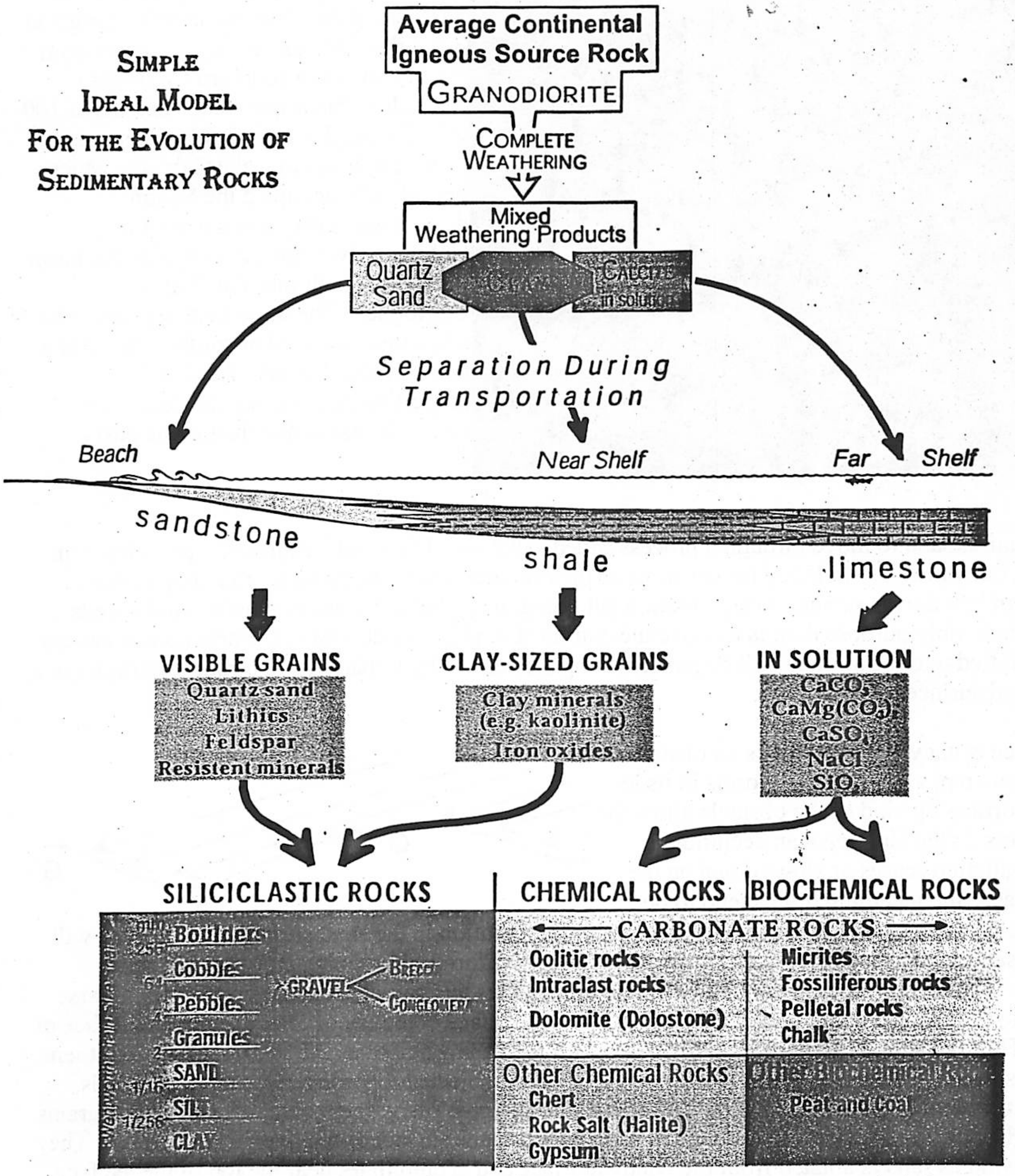
Subdivisions Based on Strata/*Time*				Radiometric Dates (millions of years ago)	Outstanding Events In Physical History	In Evolution of Living Things
		Systems/*Periods*	Series/*Epochs*			
PHANEROZOIC	CENZOIC	Quaternary	Recent or Holocene Pleistocene	0 2?	Several glacial ages Making of the Great Lakes; Missouri and Ohio Rivers	*Homo sapiens*
		Tertiary	Pliocene	6		Later hominids
			Miocene	22	Beginning of Colorado River Creation of mountain ranges and basins in Nevada	Primitive hominids Grasses; grazing mammals
			Oligocene	36		
			Eocene	58	Beginning of volcanic activity at Yellowstone Park	Primitive horses
			Paleocene	65	Beginning of making of Rocky Mountains	Spreading of mammals Dinosaurs extinct
	MESOZOIC	Cretaceous	Many	145	Beginning of lower Mississippi River	Flowering plants Climax of dinosaurs
		Jurassic		210		Birds
		Triassic		250	Beginning of Atlantic Ocean	Conifers, cycads, primitive mammals Dinosaurs
	PALEOZOIC	Permian		290	Climax of making of Appalachian Mountains	Mammal-like reptiles
		Pennsylvanian (Upper Carboniferous)		340		Coal forests, insects, amphibians, reptiles
		Mississippian (Lower Carboniferous)		365		
		Devonian		415	Earliest economic coal deposits	Amphibians
		Silurian		465		Land plants and land animals
		Ordovician		510	Beginning of making of Appalachian Mountains	Primitive fishes
		Cambrian		575	Earliest oil and gas fields	Marine animals abundant
PRECAMBRIAN (Mainly igneous and metamorphic rocks; no worldwide subdivisions.)				1,000 2,000 3,000		Primitive marine animals Green algae Bacteria, blue-green algae
Birth of Planet Earth				4,650	Oldest dated rocks	

Shamelessly stolen from Canyon de Chelly 2007 Handout

Flint and Skinner, 1977 "Physical Geology", 2nd ed.

SEDIMENTARY ROCK MODELS

SIMPLE IDEAL MODEL FOR THE EVOLUTION OF SEDIMENTARY ROCKS



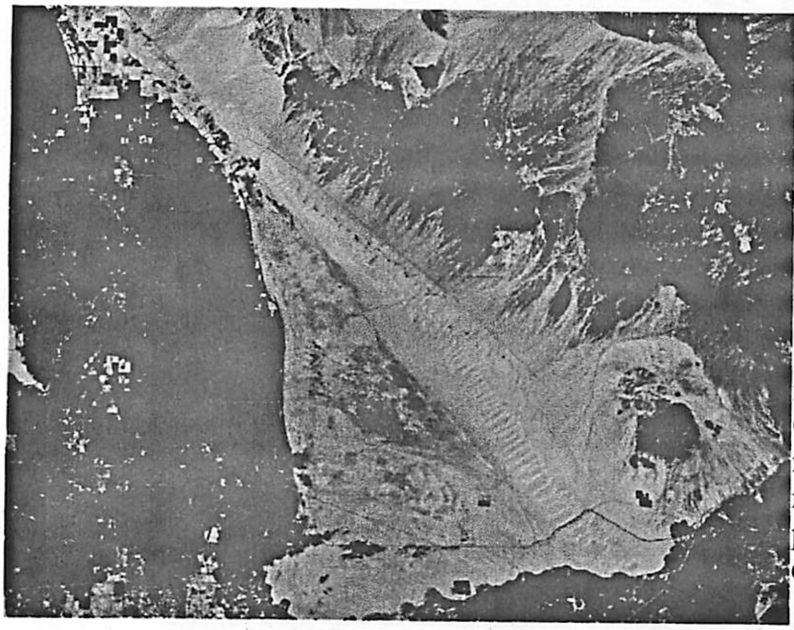
L.S. Fichter, 1993, 2000

http://geollab.jmu.edu/Fichter/SedRx/sedclass.html

Shamelessly stolen
from Canyon de Chelly
2007 Handout

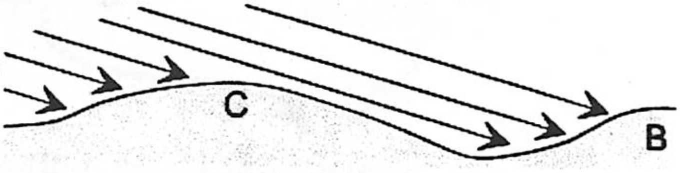
THE ALGODONES DUNE FIELD

Joe Spitale



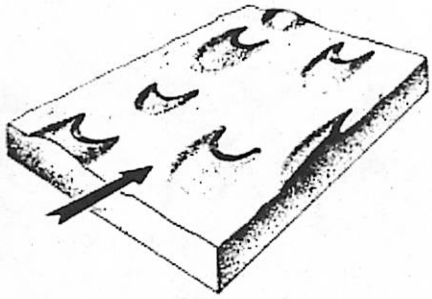
The Algodones dunes comprise a field of barchanoid dunes about 40 miles long and 3-6 miles wide extending southeast from the Salton sea in southern California. Individual dunes may reach heights of 100 m[1]. The sand was probably transported from the shores of Lake Cahuilla, which periodically occupied the Salton depression during times when the Colorado river flowed west into that basin instead of south into the Gulf of California[2]. The dune field appears to be migrating eastward or southeastward at a rate of about 1 ft/yr[2]. Sand grain properties indicate that the dunes are currently less active than in the past[1].

The wind causes sand to move through a process called saltation: The wind initially lifts particles from the surface, but when they fall they impart some of their momentum to the particles that they impact, ejecting them into the air stream. Once saltation get going, it can be sustained by slower wind speeds since the winds' only purpose then is to move the entrained sand grains downwind. Particles that are too large to be lofted into the air may still be pushed along the surface by impacts from airborne particles in a process called surface creep[3].

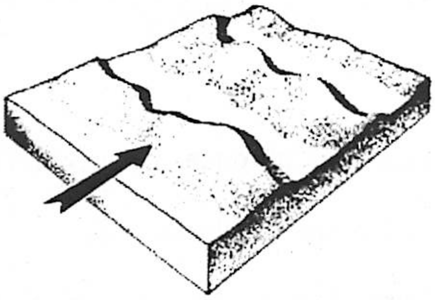


If the surface is uneven, or if there is an obstacle like a rock outcrop, a sand shadow forms in its lee. Turbulent vortices upwind of the obstacle allow the sand to fall out of the air stream an accumulate. Moreover, saltation ceases or slows down on the lee face because the incoming grains tend to be moving parallel to it. If the obstacle is just a topographic variation in the sand surface, then its face will continue to saltate or creep while sand accumulates in the lee, forming a ripple. Beyond the sand shadow, a new ripple forms from the hollow create by particles that saltate over the first ripple. Coarse grains tend to accumulate at the crest of the ripple because surface creep is not effective on the lee face of the ripple. The wavelength of the ripples increases with increasing height as the sand shadows lengthens. The height is limited because as the ripple grows, its crest is subjected to stronger and stronger winds, which blow the heavier grains accumulated there into the troughs, filling them. Because the heavy grains tend to stabilize the sand surface, dunes tend to emerge where the surface is relatively fine-grained. They move downwind as sand is ablated from the windward face and accumulates near the top of the lee face, causing slippage as the lee-face accumulation exceeds the angle of repose[3].

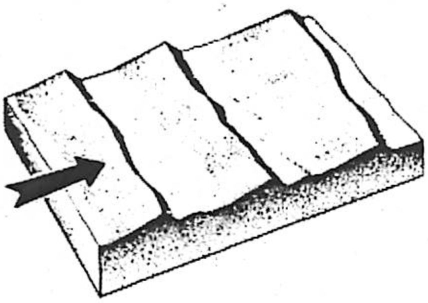
Single slip face: Barchanoid



BARCHAN DUNES. Arrow shows prevailing wind direction.

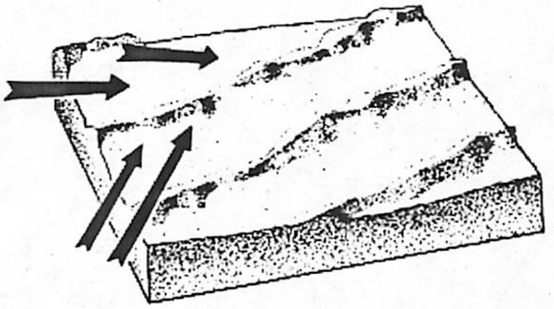


BARCHANOID RIDGE. Arrow shows prevailing wind direction.

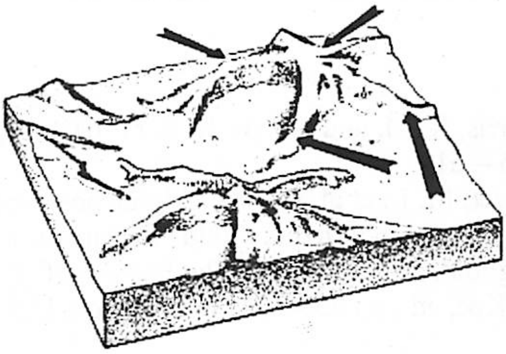


TRANSVERSE DUNE. Arrow shows prevailing wind direction

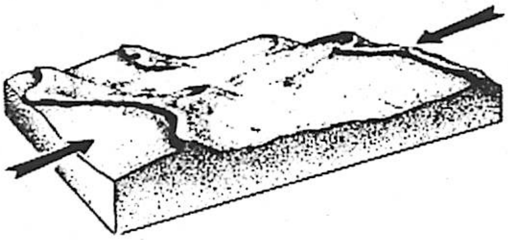
Mulitple slip faces:



LINEAR DUNES. Arrows show probable dominant winds.



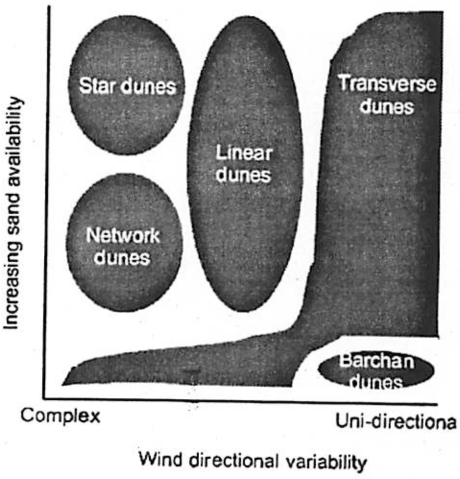
STAR DUNES. Arrows show effective wind directions.



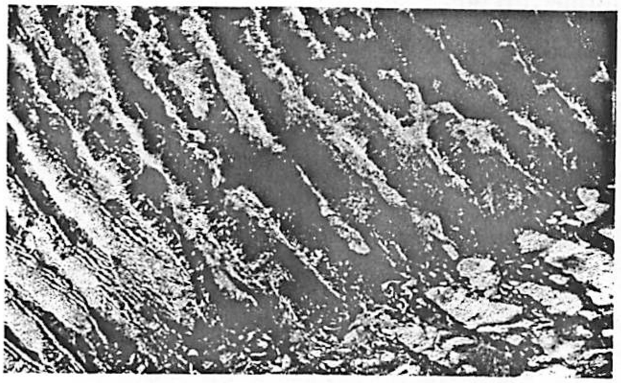
REVERSING DUNES. Arrows show wind directions.

Dunes can be classified based on the number of slip faces. Barchanoid dunes have a single slip face, and have axes perpendicular to the prevailing wind direction. The different types reflect the amount of sand available. Barchans can reach heights of about 30 m, with horizontal dimensions of about 400 m. Transverse dunes can reach heights of over 200 m and widths of many km[4].

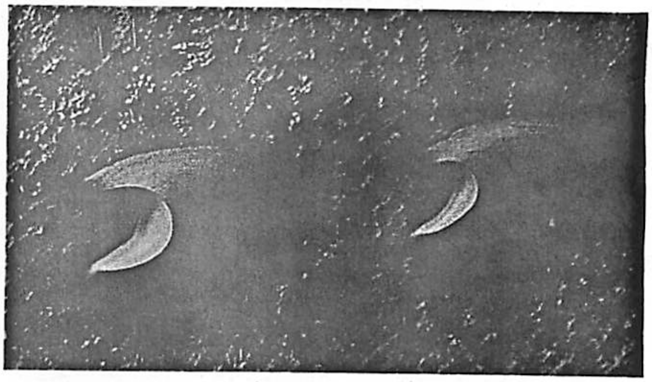
In regions with no single dominant prevailing wind, dunes can form with multiple slip faces. Linear dunes are not fully understood, but probably result from the action of winds from two directions. Star dunes are caused by winds from three or more directions, while reversing dunes form in ares of bimodal winds from opposing directions[4].



Courtesy R. Lorenz



Linear dunes on Titan. Courtesy R. Lorenz



Barchan dunes on Mars from HiRISE.

[1] Norris, R. M. and Norris, K. S. (1961). Algodones Dunes of Southeastern California. GSA Bull. 77, 605—619

[2] Sweet, M. L. et al. (1988). Algodones dune field of southeastern California: case history of a migrating modern dune field. Sedimentology 35, 939—952

[3] Bagnold, R. A., (1941). The Physics of Blown Sand and Desert Dunes. London, Chapman and Hall

[4] McKee, ed., pp 253-304. Washington, U.S. Geological Survey Paper 1052.

The Salton Sea

David A. Minton

History of the Salton Sea

The Salton Sea is an endorheic lake, that is it is a closed depression into which water enters but can only escape through evaporation or seepage. The modern Salton Sea was accidentally created in 1905 [1]. The Salton Sink, as the region was known prior to the 1905 flooding, had flooded many periodically throughout prehistoric times and into the 19th century, but without a continuous supply of water, the sink invariably returned to a dry state. [1].

In the late 19th century interest in the agricultural potential of the Salton Sink began to increase. Although several proposals had been made throughout the 1800's to reclaim the desert by diverting the flow of the Colorado river, none had succeeded in attracting adequate funding until George Chaffey, an experienced irrigation engineer from Los Angele took interest in the region [3]. At first he was skeptical that anyone would settle and farm land where the temperatures reached 120 degrees Fahrenheit in the shade, but after working in the interior of Australia where men regularly worked in temperatures of 125 degrees in the shade, he determined that a Salton Sink reclamation project was feasible [3].

In 1900 Chaffey became president and chief engineer of the California Development Company, and began to dig canals starting near Yuma, AZ that would redirect water from the Colorado River to the Salton Sink (renamed Imperial Valley so as not to scare away potential investors and settlers) [3]. From the very beginning, the Imperial Valley irrigation project encountered problems with silt. Silt carried by the turbulent Colorado river clogged up irrigation ditches and the canals leading to the Imperial Valley, leaving settlers with less water than they were promised [3].

By 1904 the Imperial Valley had become a productive agricultural region, with ten thousand settlers living and farming the land. However, lawsuits surrounding lack of water due to the silt problem forced the cash-strapped California Development Company to take action. Engineers cut a new intake for the irrigation canal four miles south of the Mexican border, which would allow water to bypass the silt-clogged intake near Yuma. This proved to be a fatal mistake. During the winter and spring of 1905 the Colorado River experienced an unprecedented number of floods. The slope of the Colorado River river bed down to the Gulf of California was 15 inches per mile, while the slope leading to Imperial Valley was 48 inches per mile [3]. The swollen river began to divert its course away from the Gulf of California and flow through the newly-cut southern intake into Imperial Valley, and for two years all attempts made to block the river failed. The Salton Sea was born.

The Southern Pacific railroad company became involved, and later the federal government under Theodore Roosevelt, due to the destruction of railways in Imperial Valley and the fact that flood waters had created huge waterfalls that were cutting back toward Yuma and threatening to destroy dams and irrigation projects in southern Arizona. In the book *The Salton Sea, An Account of Harriman's Fight with the Colorado River*, by George Keenan (1917), Keenan describes the flooding of Imperial Valley:

> The most dangerous and alarming feature of the situation was the "cutting back" of the torrents as they rushed down the delta slope toward the Salton Sea. The fine silt of which the soil was composed washed out like powdered sugar, and wherever there happened to be a strong current, the flow soon produced a rapid. The rapid then became a cascade, the cascade grew into a fall, and the fall finally developed into a roaring cataract, which 'cut back,' upstream, at the rate sometimes of four thousand feet a day, widening as it receded, and leaving below

it a deep gorge with almost perpendicular walls. Some of the gorges were fifty to eighty feet deep and more than a thousand feet across. It was estimated that the channels thus formed during the floods of 1906 had an aggregate length of more than forty miles, and that the solid matter scoured out of them and came down into the Salton Sea was nearly four times as great as the whole amount excavated in the digging of the Panama Canal. The total of 400,000,000 to 450,000,000 cubic yards were moved. Mr Cory stated, "Very rarely, if ever before, has it been possible to see a geological agency effect in a few months a change which usually requires centuries."

Endorheic Lakes on Mars and Titan

While the current existence of the Salton Sea is largely due to human intervention, natural endorheic lakes are common on Earth and may have been common on Mars [2]. Evidence has accumulated for the existence of standing bodies of liquid hydrocarbon lakes at the poles of Titan containing at least hundreds of times more hydrocarbons than then entire known hydrocarbon deposits of Earth [4,8]. The lakes appear as very dark regions in images made from data taken by the RADAR instrument on the Cassini spacecraft. Measurements of the dielectic constant liquefied natural gas (LNG), a terrestrial analog to what is thought to fill Titan's lakes, suggest that the RADAR instrument is able to penetrate to a depth of 4–7 m below the lake surface [7]. Many of the lakes are bright near their margin, but dark in the middle, suggesting that they are shallow near the edge and have a depth $\gtrsim 7$ m in their middle.

Titan's polar lake regions appear to contain a wide variety of lake morphologies, with some clusters of steep-walled lakes possibly being karst-like [5,6]. Several lake-shaped but RADAR bright features in the lake regions of Titan suggest that some lakes periodically dry out, much like closed depressions in arid regions on Earth.

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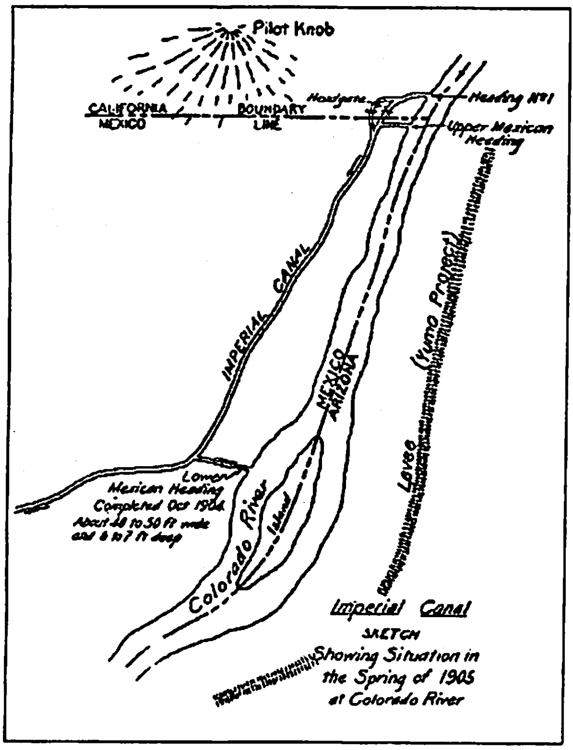
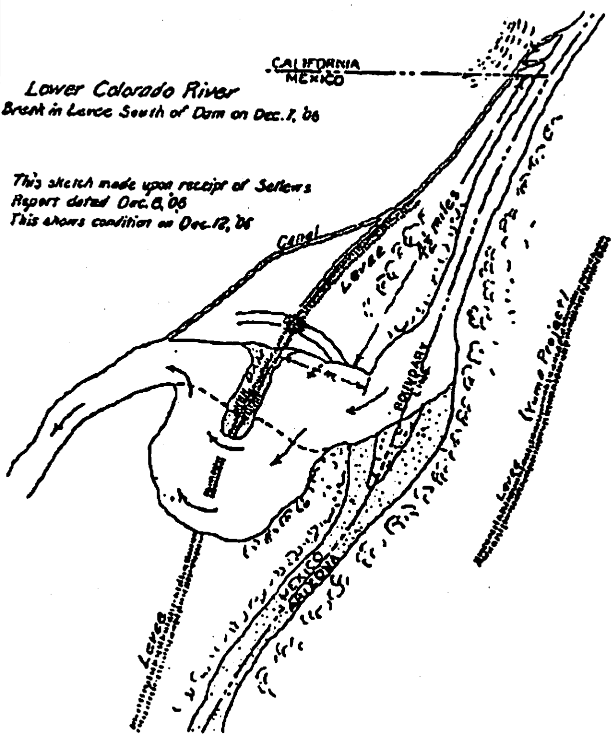
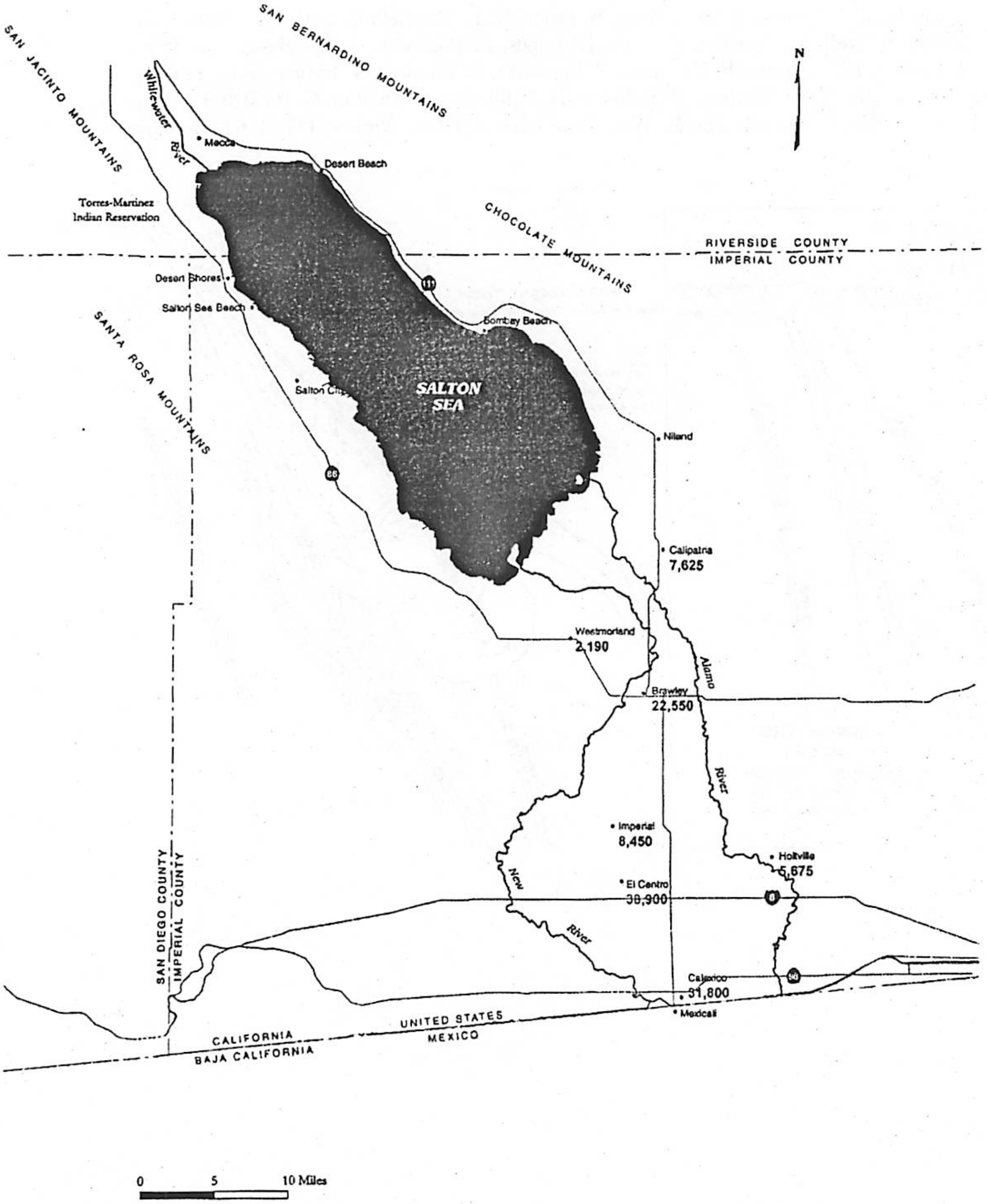






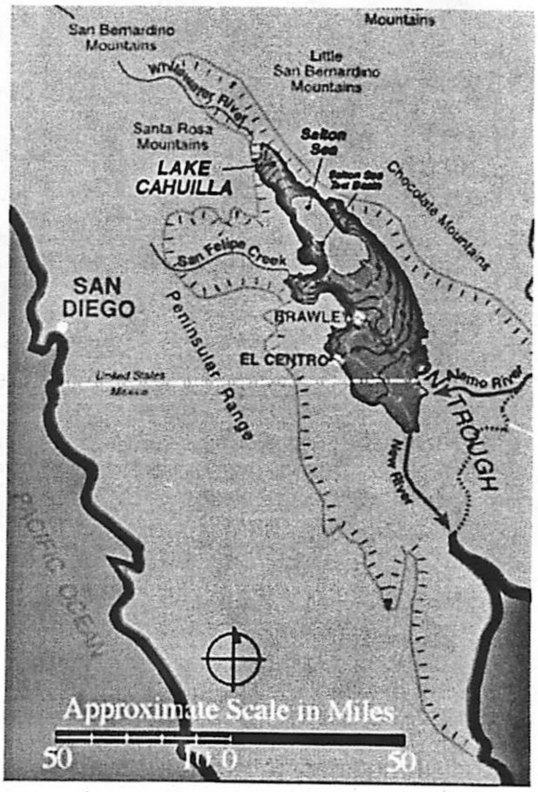
January 1, 2003 Population Estimate
California Department of Finance

The Shorelines of Ancient Lake Cahuilla

Kat Volk

Scope of the Ancient Lake:

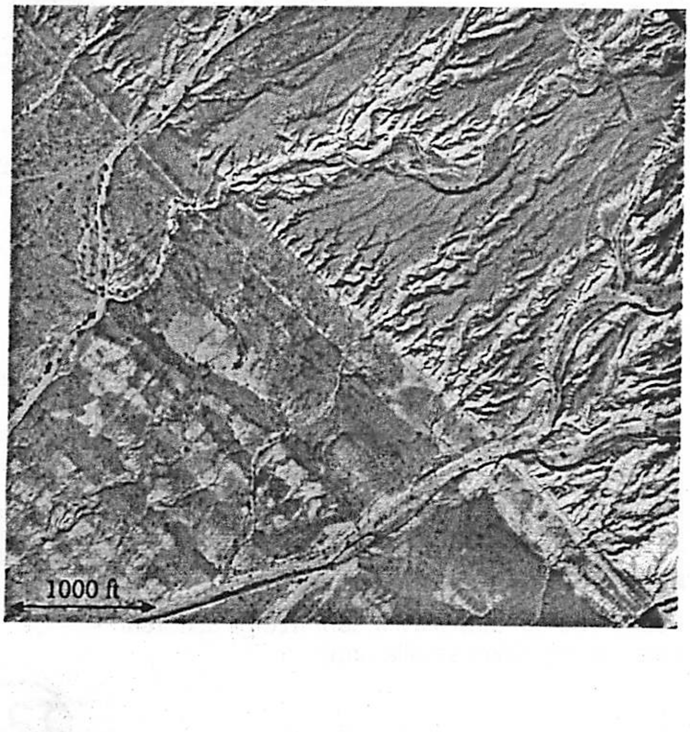
At 100 miles long and 35 miles wide at its widest point, Lake Cahuilla (also sometimes referred to as Lake Leconte) once covered roughly 2000 square miles of the Salton basin in southern California (this is about a quarter of the size of Lake Ontario or Lake Erie). Periodically in the region's history, sediments in the Colorado River Delta would build up and allow the river's course to change. This sometimes resulted in the river filling the Salton basin to create a huge lake. The lake would be sustained until the river again changed its course, leaving the lake to evaporate. It would have taken the Colorado roughly 20 years of continuous flow to fill the lake, and once the river was diverted, the lake would have taken about 50 years to disappear (Buckles et al. 2002). This cycle has repeated many times. Waters (1983) finds evidence for four major periods of lake activity over the last 2000 years alone.



The ancient lake shown in comparison to the present day Salton Sea. (The scale-bar at the bottom is 100 miles across.)
Image source:
http://gis.esri.com/library/userconf/proc00/professional/papers/PAP377/p377.htm)

Evidence for the Ancient Lake:

Many lines of evidence point to the intermittent presence of large freshwater bodies in the region. These include ancient shorelines visible on the ground and from the air, mineral deposits, shell fossils, as well as the oral traditions and archaeological evidence left by Native American cultures that utilized the lake.



Shorelines seen from above:

The image to the left is a Google Earth view of a section of ancient shoreline to the southeast of the Salton Sea. The upper right shows old streams that terminate when they reach the lake's high water mark. The streams seen cutting through the shoreline are all younger than the last iteration of the lake. (The scale-bar is 1000 feet.)

This image is a good analog for what we might see for an ancient lake on Mars or Titan from spacecraft images.

Image source:
http://epod.usra.edu/archive/epodviewer.php3?oid=384832

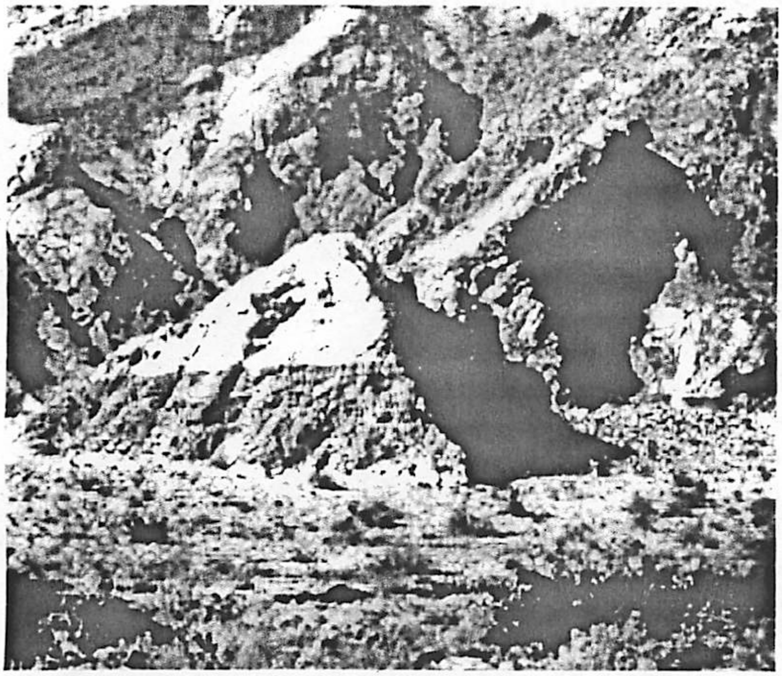


Image source: http://home.att.net/~amcimages/singer.html

Mineral Deposits:

The lake left behind freshwater lime deposits called travertine or tufa. It is deposited when algae remove CO_2 from water that has a large concentration of calcium carbonate, $CaCO_3$. The algae prefer shallow water and grow best on rocky surfaces, so the travertine deposits can often be found on the mountain sides in the region of the ancient lake.

The white colored travertine stands out against the dark desert varnish, as seen in the image to the left. This marks the high water point where the shore ran into the mountains.

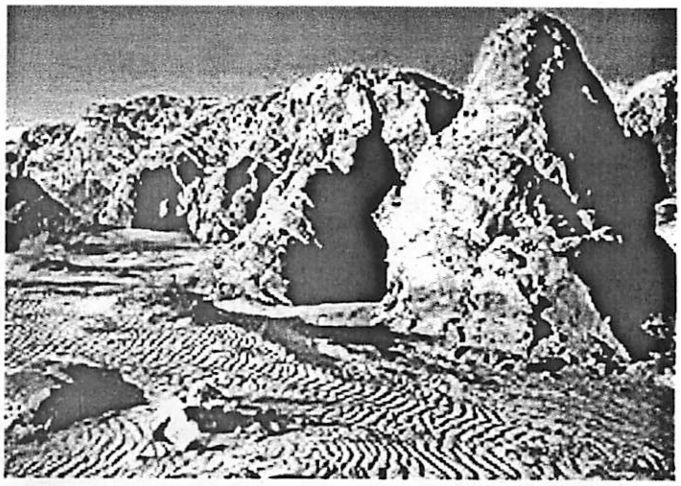
Shoreline Features:

The top image to the right shows erosion resistant sandstone cliffs along what was once an island in the ancient lake.

The bottom image to the right shows a cobble beach formed by the lake.

The image below shows another shoreline showing multiple water levels.

Image source: http://ca.water.usgs.gov/groundwater/gwatlas/basin/terminal.html



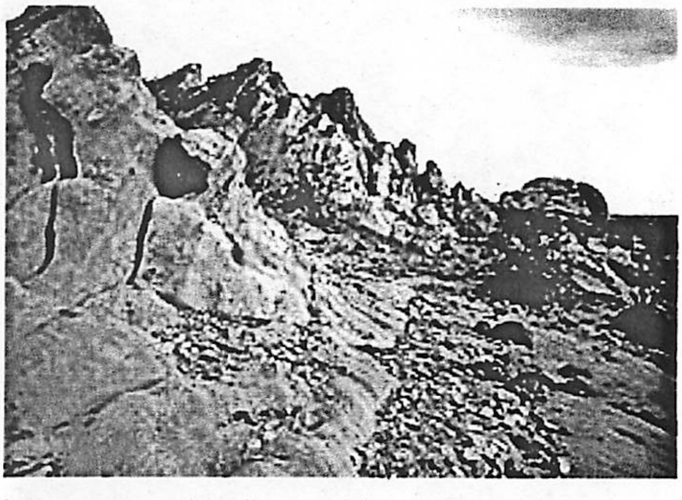
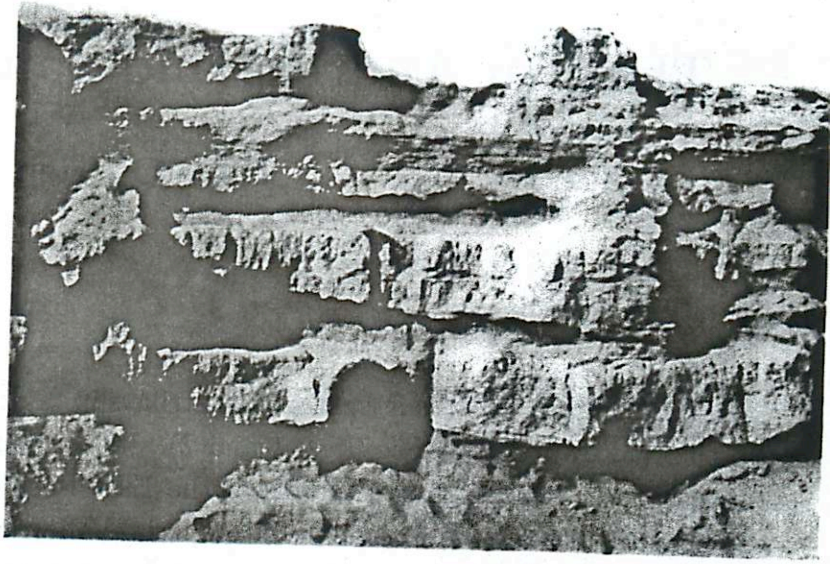


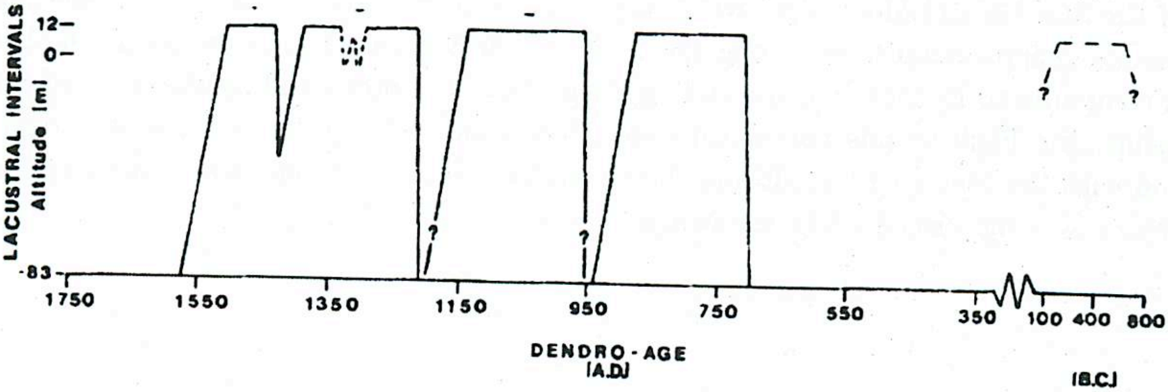
Image source: http://www.sdnhm.org/research/paleontology/lakecahuilla.html

Sedimentation:



The image to the right shows both fluvial and lake deposits. Notice the four distinct layers of lake deposits. These four layers have been radiocarbon dated using the embedded fossils of freshwater muscles to determine the recent history of the lake (shown in the graph below). The dates coincide well with the radiocarbon dates obtained from charcoal found at fishing sites along the lake.

Image and graph source: Waters (1983)



The graph above shows the altitude of the lake surface over time for the last few thousand years. The solid lines imply secure dating of the fossil record, while the dashed lines represent more questionable results.

Sources:

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The San Andreas and San Jacinto Faults

Dave O'Brien

Overview

The San Andreas Fault is a right-lateral strike-slip fault at the boundary of the Pacific and North American Plates (See Figs. 1 and 2). Its southern terminus is near the Salton Sea, which is also the northern terminus of the East Pacific Rise. This geophysical setting is responsible for the low elevation of the Imperial Valley area and the Salton Sea in particular, the bottom of which is only a few meters higher than the lowest point in Death Valley. The San Andreas runs along the southern side of the San Bernadino Mountains and the northern side of the San Gabriel Mountains, which together are part of the Transverse Ranges and are due to compressional forces along the fault, which is oriented more east-west in that region compared to its more north-trending segments to the north and south. West of the mountains, the Fault trends northward until Mendocino. Here it terminates at a triple junction with the Mendocino Fault and the Cascadia Subduction Zone, where the Juan de Fuca Plate is being pushed under the North American Plate.

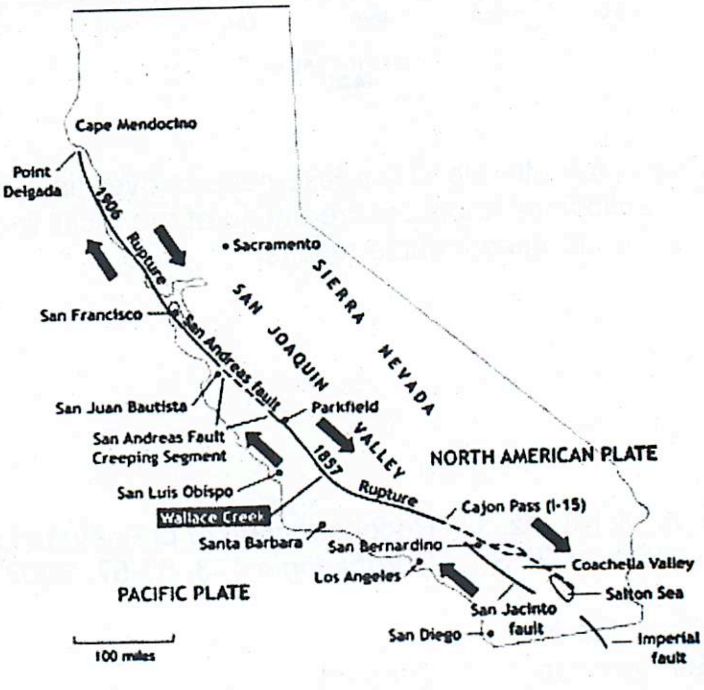

Figure 1: Map of the San Andreas, with sections that have experienced major surface ruptures shown as solid lines. From the *Southern California Earthquake Center* (http://www.scec.org/).

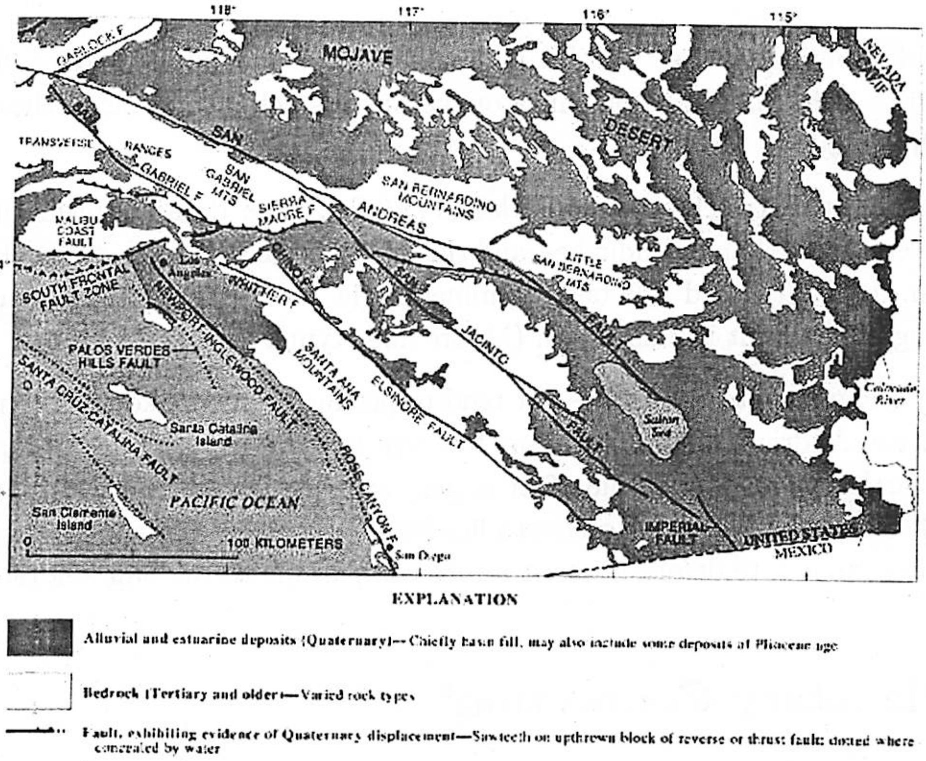

Figure 2: Map of major Southern California faults, from Brown (1991)

The San Jacinto Fault branches from the San Andreas near San Bernadino, and then runs roughly parallel to and westward of it (See Figs. 1 and 2). The Fault runs southwest of the San Jacinto and Santa Rosa Mountains, and like the San Andreas, is right-lateral strike-slip fault. It is more correctly termed a 'fault zone', since it consists of a number of closely related branches.

Seismicity

The San Andreas has been responsible for many small earthquakes and a number of well-known major earthquakes:

- 1857 Fort Tejon earthquake, with a magnitude of about 8.0.
- 1906 San Francisco Earthquake, with an estimated magnitude of 7.8.
- 1989 Loma Prieta earthquake with a magnitude of about 7.1 (seen live on TV during the World Series).

All of these earthquakes occurred in the central and northern sections of the Fault. The southern section of the Fault, in the San Bernadino and Imperial Valley area, has not experienced a comparable earthquake for over 300 years, giving worry that the 'next big one' is due in that area.

Parkfield experienced a series of earthquakes with a magnitude around 6.0 at roughly 20-24 year intervals, and based on this a quake was predicted to occur in the early 90s, but instead it hit in 2004.

Interestingly, the stretch between Parkfield and San Juan Bautista primarily experiences aseismic creep rather than earthquakes, and this is the subject of much study. Recent drilling studies near the fault found talc-bearing minerals (ie. baby powder) that could potentially aid in sliding of the fault in this region (Moore and Rymer 2007).

While the San Jacinto Fault does not tend to produce earthquakes as strong as the more well-known San Andreas, it produces more frequent earthquakes that are still quite powerful, with eight earthquakes of magnitude 6 or larger occurring since 1899, the most recent being a magnitude 6.6 quake in 1987. Recent studies (eg. Fialko 2006) suggest that the San Jactino Fault may accommodate deformation at a rate comparable to the San Andreas.

The 'Planetary Connection'

While Earth is the only planetary body known to experience plate tectonics, there is evidence for strike-slip faulting elsewhere in the Solar System. The most clear examples are on the icy satellites Europa and Ganymede, where offsets of tens of km or more can be directly seen by comparing features on either side of the faults (eg. Hoppa et al. 1999, DeRemer and Pappalardo 2003). The strike-slip movement on Europa is driven by tidal stresses, and this may be the case for Ganymede as well although it is not conclusive. Somewhat less direct evidence suggests that there has been strike-slip faulting on Mars (eg. Okubo and Schultz 2006, and references therein), driven for example by stresses induced during the evolution of Tharsis. Enceladus shows evidence for episodic venting from cracks near its south pole (the 'tiger stripes'), and a possible cause is shear heating due to tidally-driven displacement along those cracks (Nimmo et al. 2007). However, this displacement could be purely cyclical and there is no direct evidence that there has been accumulated displacement along those cracks such as that seen on Europa.

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Spheroidal weathering

Kevin Jones

What?

Spheroidal weathering is the subsurface production of concentric shells of weathered rock surrounding a corestone (Figures 1, 2). This is a subsurface chemical process, in contrast to exfoliation and spallation due to unloading as a rock is exhumed which may also produce spheroids.

Where?

Spheroidal weathering occurs in most rock types and in most climates on Earth. It is most common in coherent, homogeneous, strongly jointed rocks, particularly basalt and granite. Water is necessary for true spheroidal weathering (in contrast to exfoliation).

How?

The chemical weathering process that produces spheroidal shells must act on all sides simultaneously, and must therefore occur underground. Preexisting joint sets create initial planes of weakness. Weathering rates are greatest at corners where these joints intersect due to the higher surface-area per unit of rock there. The corners become rounded and the remnant corestones are reduced to spheroids. Spheroidally weathered rocks can then be exhumed as regolith is removed, producing boulder fields.

The chemical mechanism is probably hydrolysis, resulting in either dissolution or expansion of rock material. It remains unclear to what extent climate (temperature and moisture) and mineralogy (particularly biotite and feldspar content) contribute to spheroidal weathering. Water is required for true spheroidal weathering, although not for exfoliation, which can produce similarly spheroidal boulders.

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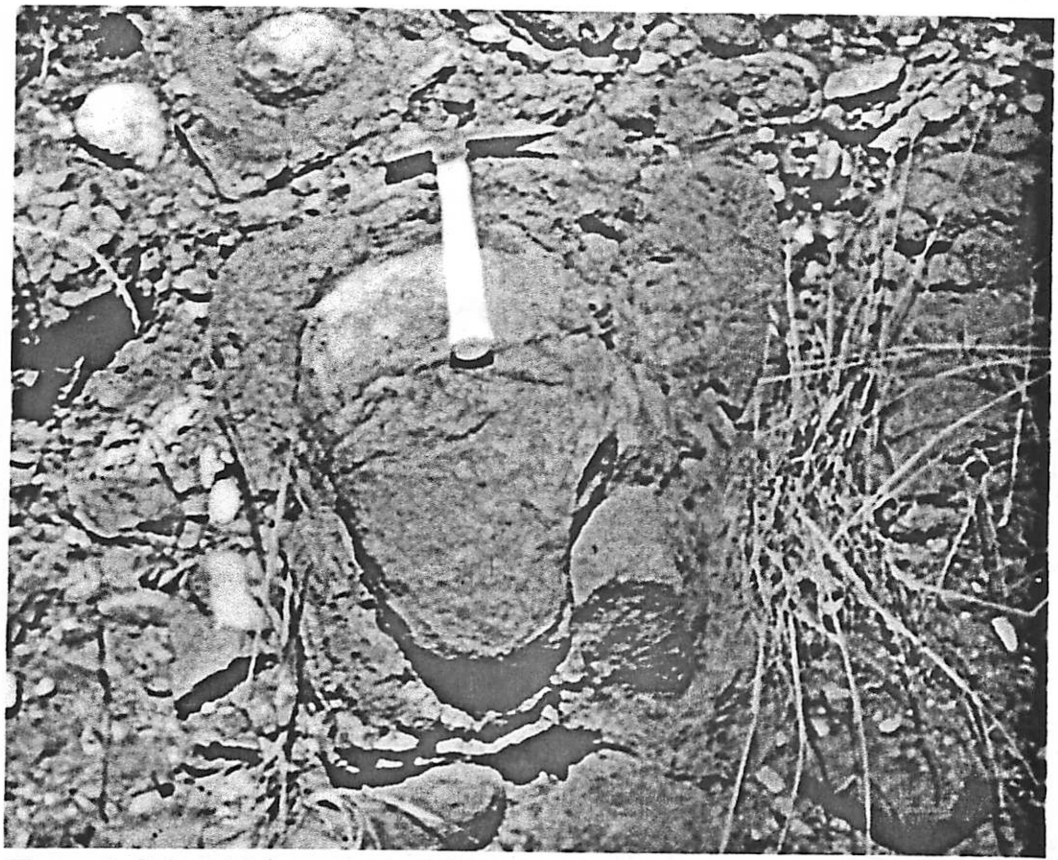


Figure 1. Spheroidal weathering of a basaltic boulder in Australia (from Ollier 1971).

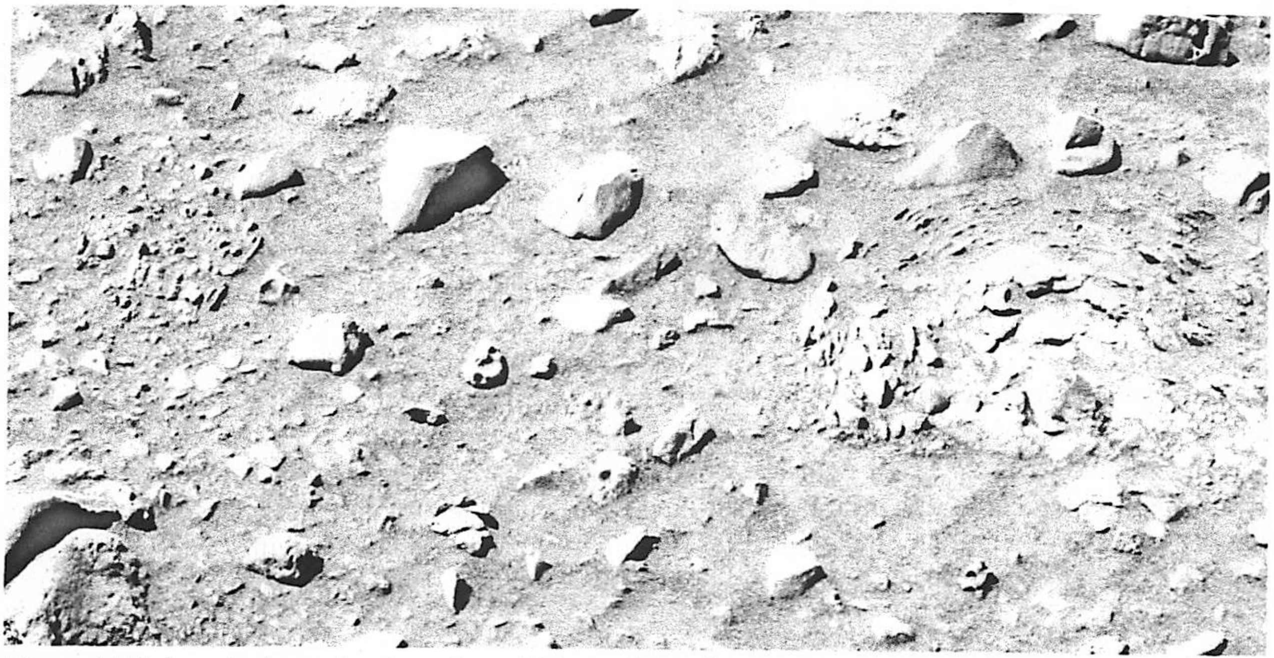


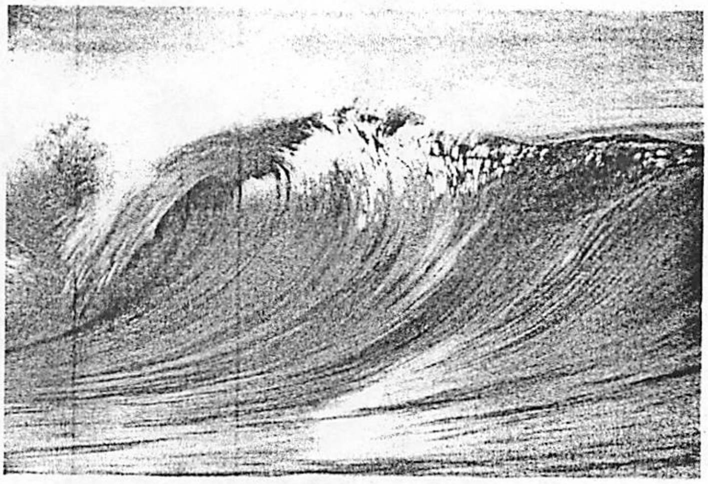
Figure 2. Spheroidal weathering of a cobble on Mars (at right). Image is approximately 60 cm across. Spirit panoramic camera image 2P135681340EFF3000P2387R1M1 from Sol 105.

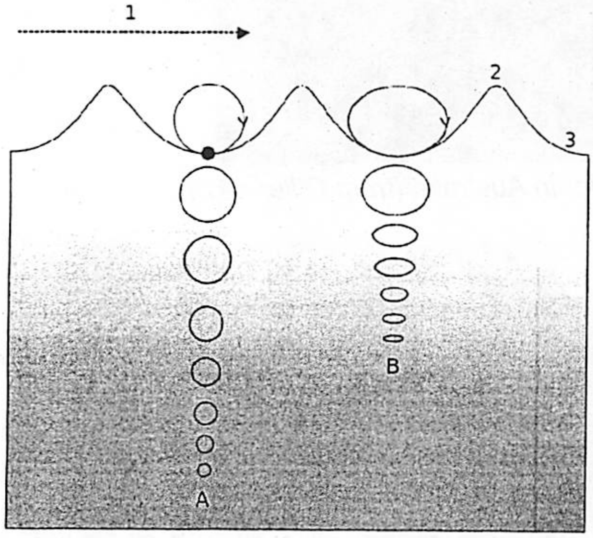
Physics of Wave Breaking

MANDY PR☺CT☺R

Waves:

Most ocean waves are generated through wind/water interactions. As the wind blows across the water surface, some fraction of the wind energy is transferred to the water through friction, which forms waves.



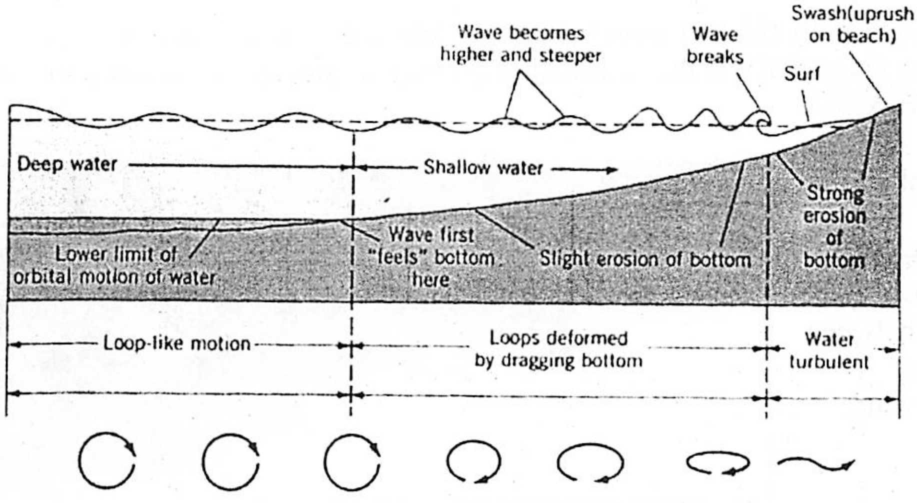


Although individual wave particles do not move forward with the wave, the energy and momentum propagate onward.

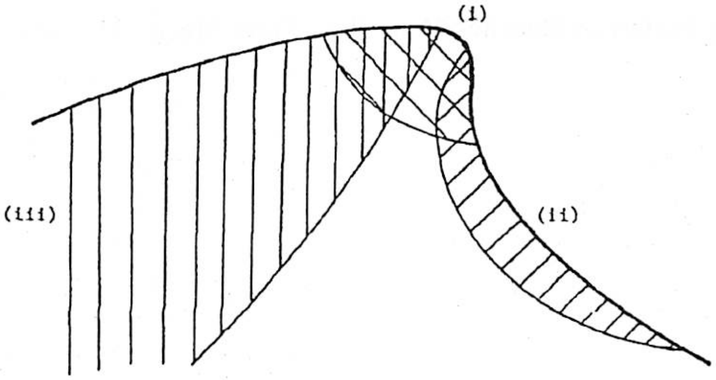
There are two regimes when considering waves:
In A (left) the waves are in the deep water regime. Particles in this situation move in circular paths as the waves move past them.

In B (left) the waves are in shallow water. Here the paths are flattened out do to interactions with the ocean floor.

As the wave moves toward the shore it transitions from a deep to a shallow water wave (shown below). Interactions with the ocean floor (friction) become important and the wavelength and amplitude of the surface wave changes. Particles in the wave are attempting to move in closed orbital paths (like above), but interaction with the sea floor slows the return of water along the bottom. The top of the wave is now moving faster than the bottom.



Change in orbital motion of water particles



As the wave nears breaking there are three important regions in the wave (shown left).

At (i) the crest of the wave, the particle velocity is greater than the phase velocity.

At (ii) the acceleration of the water here is greater than g.

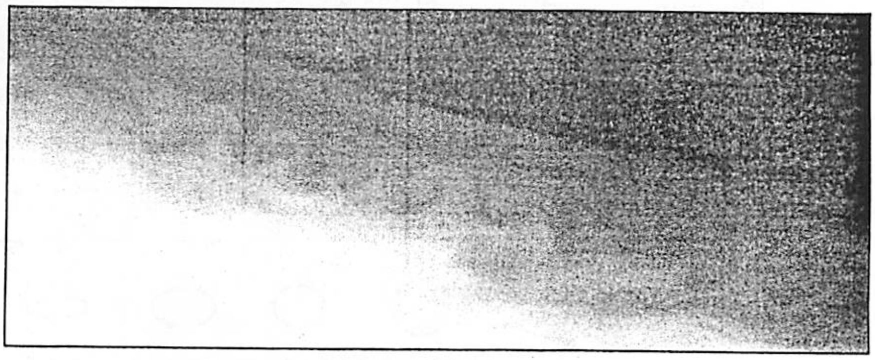
At (iii) the water accelerations are extremely low.

Since the water at (i) above is moving faster than the wave speed, the wave finally overturns. At this point a large amount of energy that had been stored in the wave is dissipated. This energy is responsible for erosion along the bottom and on the beach front.

Planetary Connection:

Wave breaking could erode the coastline of the proposed lakes on Titan and on ancient Martian coastlines.

Although we usually think of wave breaking solely in the context of water waves (which makes sense given that it is the easiest kind to observe) gravity waves can also "break" in the atmosphere.



Waves breaking in Saturn's atmosphere. Results from interaction between two layers of different density.

References:

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4) Astronomy.com

Beaches: A Profile
By Jade Bond

What is a beach?
Beaches are depositional geologic formations composed of lose sediments. They are located along the shoreline where a body of water and land meet. Beach sediments can vary greatly and often include sand, gravel, cobbles and pebbles.

What are the parts of a beach?

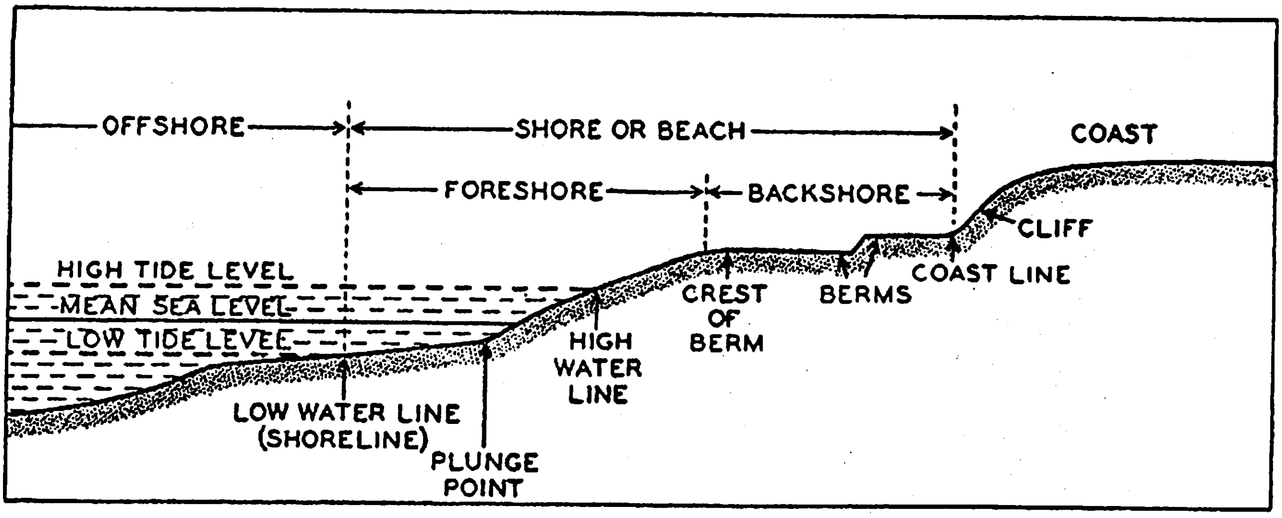

Figure 1: Schematic of a beach profile. Taken from: http://content.cdlib.org/xtf/data/13030/6r/kt167nb66r/figures/kt167nb66r_fig011.gif

Starting from the coast (the area with development, vegetation or permanent structures), the beach and shoreline area consists of three main zones:

1. Backshore
Generally flat, the backshore area is usually dry and is submerged only during high sea levels. As such, it is generally only eroded during storm events.

The backshore area is also where berms are found. A berm is a flat area formed by deposition of sediment by waves. Vertical berm growth is caused by the swash of a wave. Thus berm height is controlled (to some extent) by wave height. This means that berms on open ocean beaches are usually higher than those on sheltered beaches. Berms extend seaward to the berm crest which is generally located at or above the high water level. The berm crest migrates seawards during depositional periods and retreats during erosion periods.

2. Foreshore

This is the region located between the limits of the high and low tide swashes. This entire area is affected by wave action daily. The beach face is the innermost gently sloping region adjacent to the berm crest. Seaward of this is the flat low tide terrace. Exposed during low tides, this region is composed of fine grain sediments and the width of the terrace is controlled by the size of the tide (large tide = large terrace).

The beach face and low tide terrace are separated by the beach step or plunge point. This is the innermost region where waves break on the beach and as such is usually composed of coarse grained material.

3. Inshore

This region extends from the foreshore to just outside the breaker zone. This entire region remains constantly underwater.

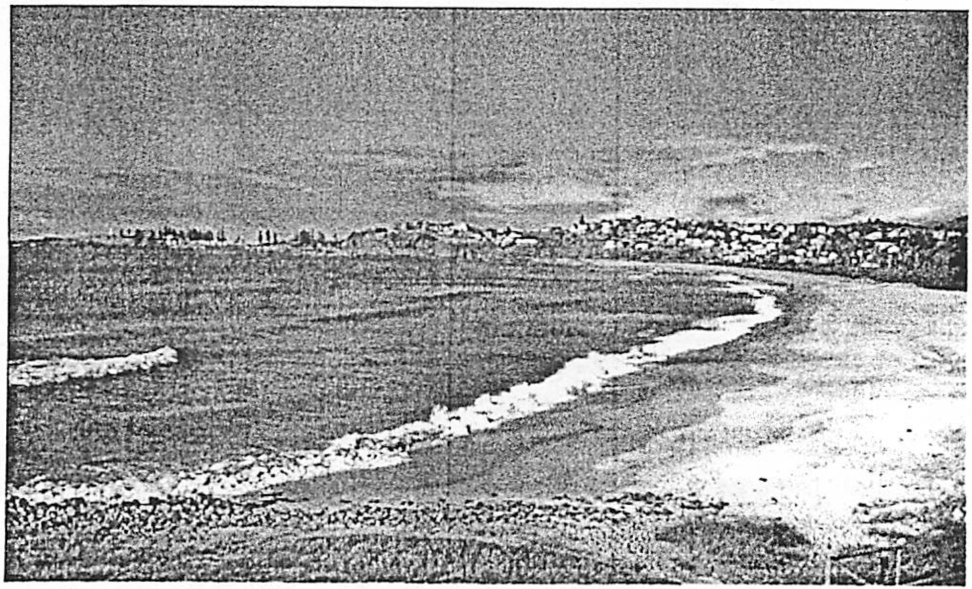

Figure 2: Typical beach displaying several common beach features
(Bombo Beach, South Coast NSW, Australia)
Image taken from:
http://www.kiama.nsw.gov.au/Corporate-Services/beach-lifeguard-service.html

How does a beach profile change?

The main way a beach profile changes is due to storm activity. During calm weather, waves have (relatively) low energy, resulting in the deposition of sediment on the foreshore region. This produces broad backshore region and is called a summer profile (see Fig. 3)

During storms, waves have more energy, meaning it is easier to remove sediment from the foreshore region. Additionally, strong winds often associated with storms can cause waves to extend further up a beach, thus removing more material. This produces a narrower backshore region and is often referred to as a winter profile.

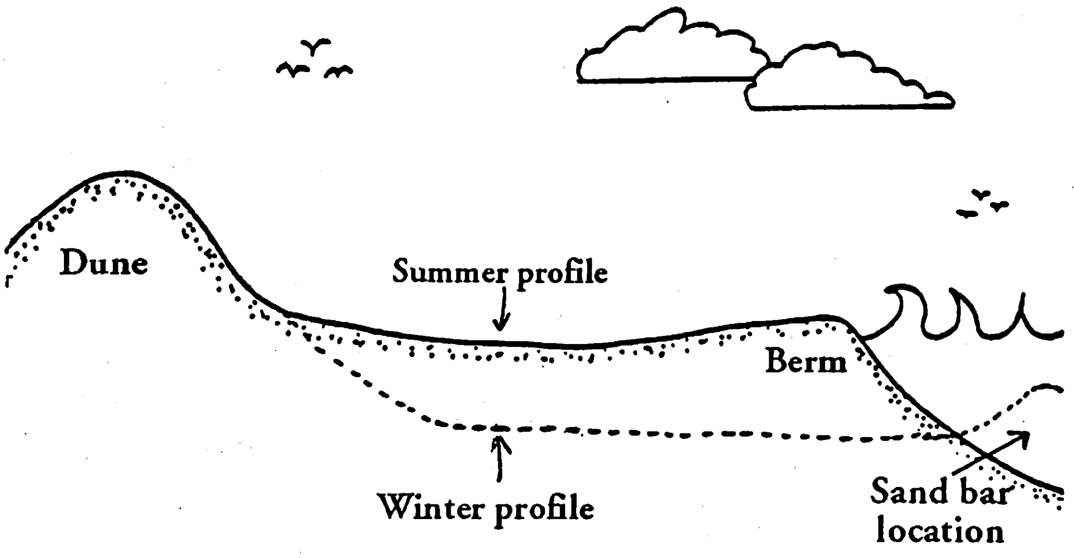

Figure 3: Schematic of a summer and winter beach profile. Taken from: http://ux.brookdalecc.edu/staff/sandyhook/tripdata/beaches/profile.html

Tides can also alter a beach profile. For example, on beaches with a small tidal range will have small low tide terraces and well developed beach steps de to their formation mechanisms.

Additionally, a small effect can be seen from the daily tidal cycle. High tides will tend to transport material onto a beach while low tides will tend to remove material in the backwash.

Winds can also potentially alter beach profiles by the saltation of particles and the induction of currents within the inshore region.

Is there a planetary connection?
Maybe. Possible shorelines have been observed on both Mars and Titan (see Fig. 4) so we may have shoreline features on other bodies. However, their morphologies and profiles are likely to be more like tidal flats than typical Earth beaches.

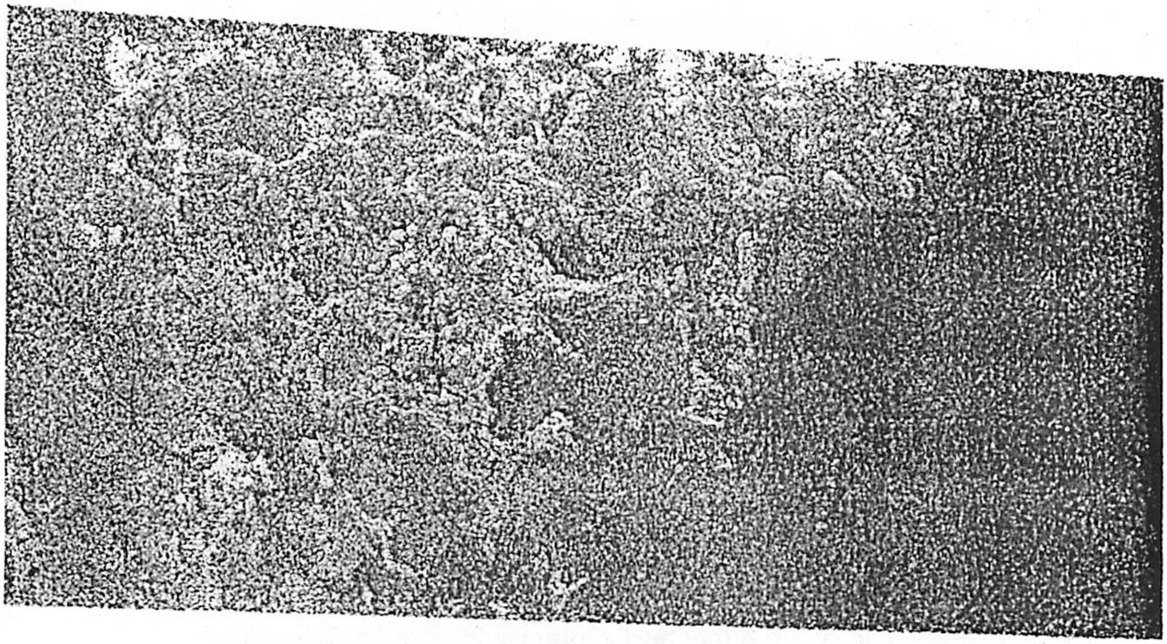

Figure 4: Cassini radar image of Titan showing a possible shoreline. Taken from: http://www.jpl.nasa.gov/images/cassini/2005-09-16/pia03563-browse.jpg

References:

Sverdrup, H. U., Johnson, M. W., & Fleming, R. H. *The Oceans, Their Physics, Chemistry, and General Biology.* New York: Prentice-Hall, 1942.
http://ark.cdlib.org/ark:/13030/kt167nb66r/

Beach Profile: Descriptive Terminology
http://w3.salemstate.edu/~lhanson/gls214/gls214_beach1.htm

Longshore Drift

Eric E. Palmer

Definition

Longshore drift is the movement of sand grains along the beach by waves. Waves that approach the shore at an angle rush diagonally up the beach. The water then returns directly down the beach under the force of gravity. Sand grains carried by the rush and backwash of the waves are moved along the beach in a sawtooth fashion

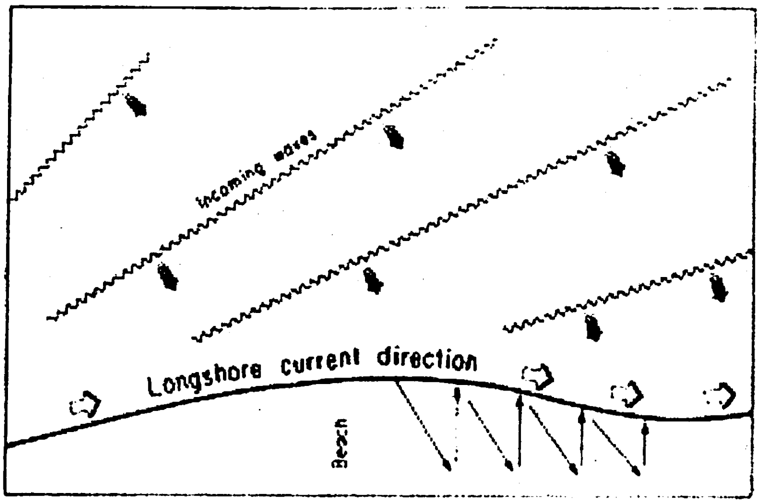

Figure 1 - Swash load - Courtesy of USGS

General Sediment Transport

Sediment is moved along the coastline under three possible actions.

1 - *Bedload transport.* Sediment is moved either in sheet flow or rolled along the bottom

2 - *Suspended load.* Sediment is carried up within the fluid column and moved by the currents.

Bedload and suspended load transport are most directly controlled by the currents in the local area, e.g. the Gulf Stream current will carry material from the tip of Florida towards Maine along its flow direction.

3 - *Swash load.* Sediment is moved on the beach face by the swash. This is the mechanism most commonly associated with longshore sediment transport. As the movie mentioned, waves typically are generated far out at sea without regard to a shoreline's direction. The waves will strike the shoreline at an angle. This results in sediment being pushed up the face of the beach at the angle the wave hit the beach. As the water retreats, aka backwash, it will pull sediment with it.

However, the backwash will move perpendicular to the beachfront (in the same direction as a rip-tide), thus giving a net movement of sediment that is proportional to the sin (wave angle).

Creation and Destruction

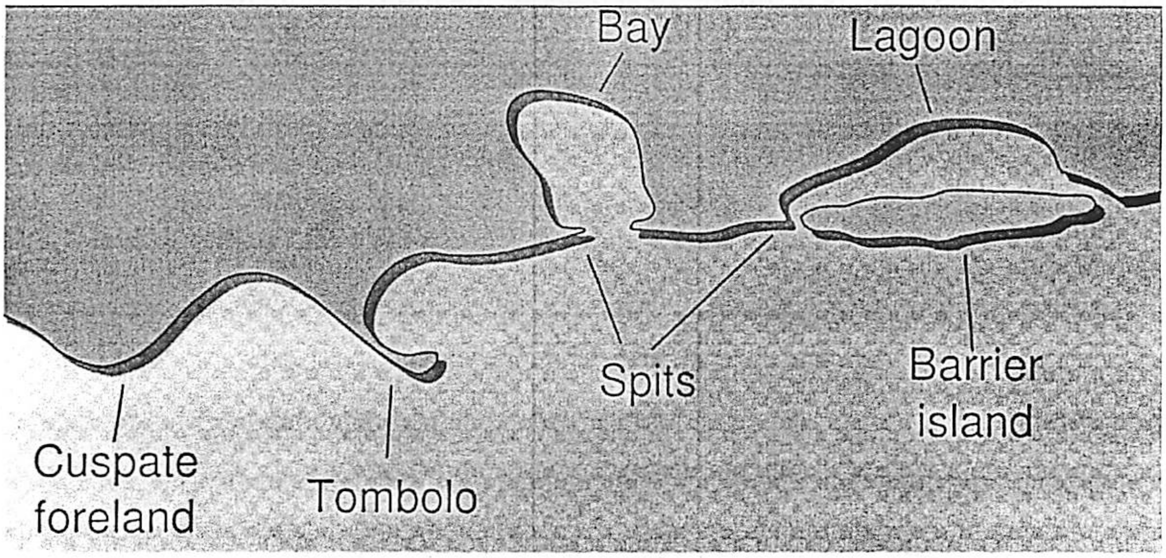

Figure 2 - Longshore drift generated landforms - Courtesy of wikipedia

Longshore drift move sand along the shore. It will transport material that deposited by rivers, as well as move detritus generated by wave action on foreland, e.g. sediment generated by wave action on rock cliffs.

In general, it attempts to smooth out the shoreline. However, other processes (such as fast moving river water or hurricanes) will stop the processes making outlets for water.

Beaches - This is just a temporary holding area for sediment as the longshore currents move it.

Spits - If the shoreline turns more than 30 degrees, the longshore drift's sediment will continue along it's original path and will be deposited. (See figure 3) It will continue to grow until the water currents (such as from a river reaching the ocean) remove it as fast as it is deposited. The spit can be stabilized if vegetation grows on it, slowing erosion. If the supply of sediment is decreased, an island can be formed as the sediment adjacent to the land is removed.

Barrier islands and lagoons - If the flow of water from the land, or wave action is not strong enough, the spit can grow until it touches or almost touches both ends of a bay. The spit would then be called a barrier island while the bay would be called a lagoon.

Tombolo - If a spit grows and reaches a pre-existing island, a tombolo is formed.

The Formation of a Spit

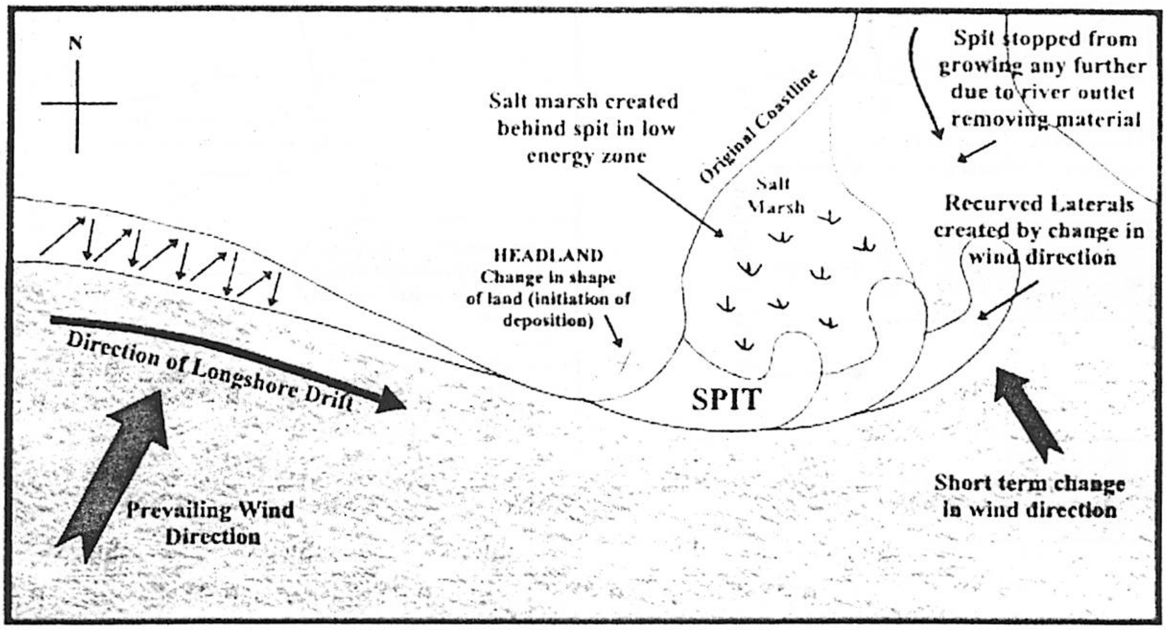

Figure 3 - Formation of a spit - Courtesy of geobytes

Source and sinks

One might expect that there would be little change in the shoreline because the wave action is somewhat similar along the coast. This is somewhat true if geologic structure is basically the same, e.g. the shore runs along a limestone layer. However, as shown in Figure 4, if the geology of the shoreline has different types of rocks, some more easily eroded than others, bays and headlands can be created.

Bays occur when the rock is less resistant to erosion. Both wave action and rainwater runoff will preferentially remove material, eroding faster, making an indent or a bay. The rock that is less erosive will become a promontory, land that is surrounded on three sides by water. Once formed, the headlands receive most of the ocean's concentrated wave erosion, but protect the bays.

A longshore drift will move the sediment from a headland and deposit it into the bays, either as a spit if the cut-in angle is large enough, or as large beaches. This is because the waves in the bay are not as strong, reducing the effectiveness of the longshore current.

The Formation of Headlands and Bays

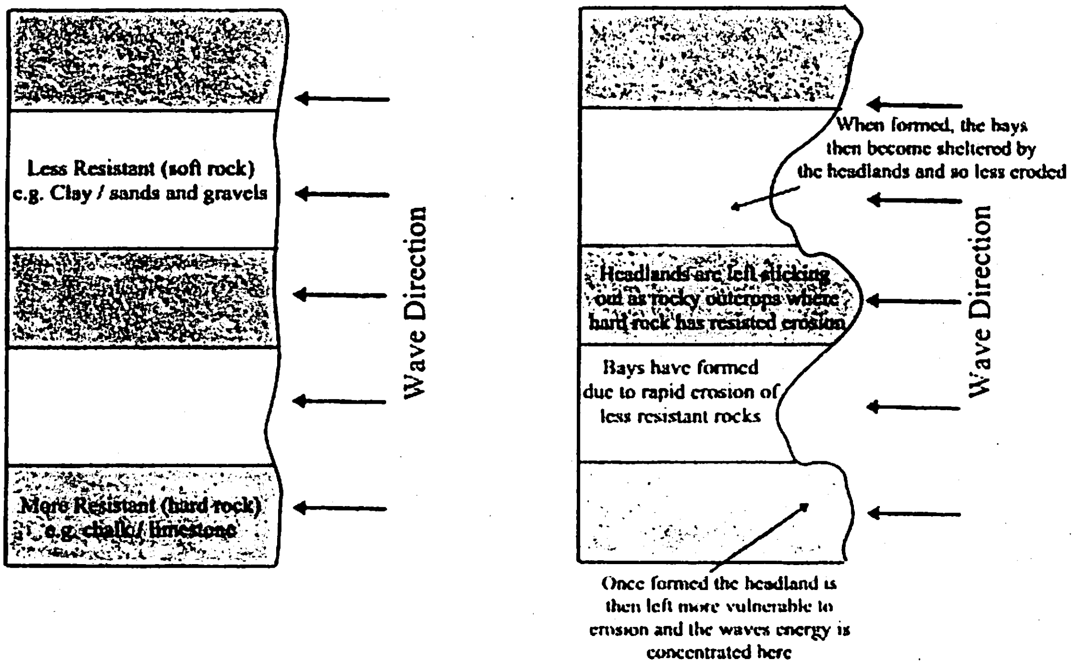

Figure 4 - Courtesy of geobytes

Amount of material

One way to estimate the amount of sediment is to calculate the amount of energy available to move material laterally. The energy flux per unit length is P_l. H is the wave height and Cg is group velocity.

$$P_l = \frac{1}{16}\rho g H^2 C_g \sin(2\theta)$$

Using this relation, we can find the volume of material that can be moved, Q, where C is a constant of proportionality which has been empirically found to be C=125, and n, the depth is usually considered to be n=1.

$$Q = CP_l^n \quad \text{units of } m^3\, s^{-1}$$

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HEAVY METAL CÖNCENTRATIÖN:

(Heavy Mineral Laminae)
Nicole Baugh

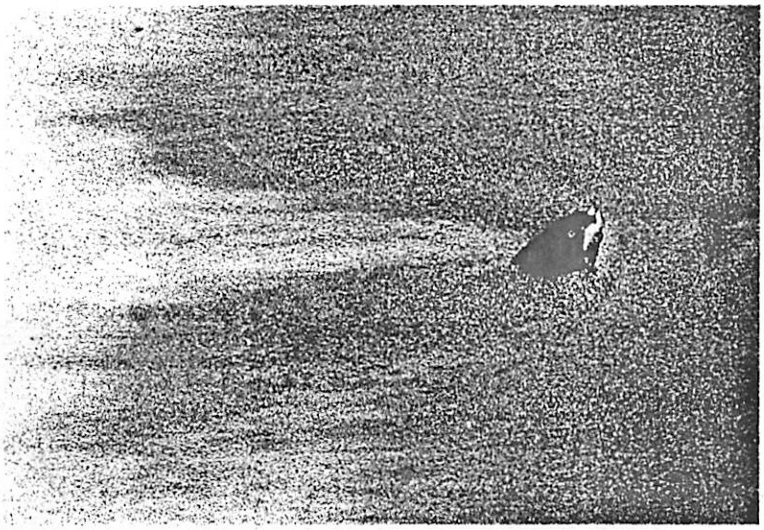


Image from http://web.uct.ac.za/depts/geolsci/dlr/hons1998/index.html

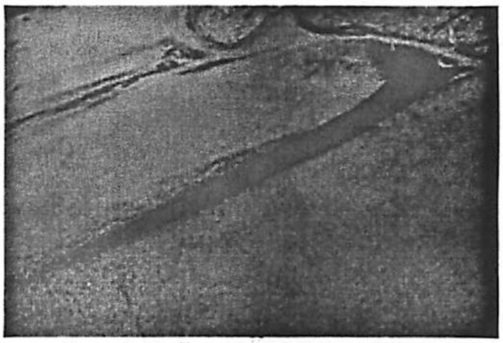


Image from http://pescaderomemories.com/category/invisible-beach/

Heavy mineral laminae (the dark streaks) on beaches. Note the "shadow" caused by the shell in the left image.

Introduction: What are heavy mineral placer deposits?

The erosion of mineral-rich rock by streams or waves can leave deposits of enriched heavy mineral grains in the form of water-laid placers. Running water concentrates these grains into deposits that can reach scales of 10^4 m.

These deposits can be made up of several different minerals:
Iron oxides (magnetite, hematite)
Titanium oxides (ilmenite, rutile)
Heavier silicate minerals (zircon, garnet)
Precious metals/diamond (rare)
Uranium/Thorium oxides (in monzanite, zircon, hematite-ilmanite—rare)

Placers, particularly those containing precious metals, can be exploited for their natural concentration of economically valuable materials (image to the left of gold placers in Sixtymile River area of Yukon

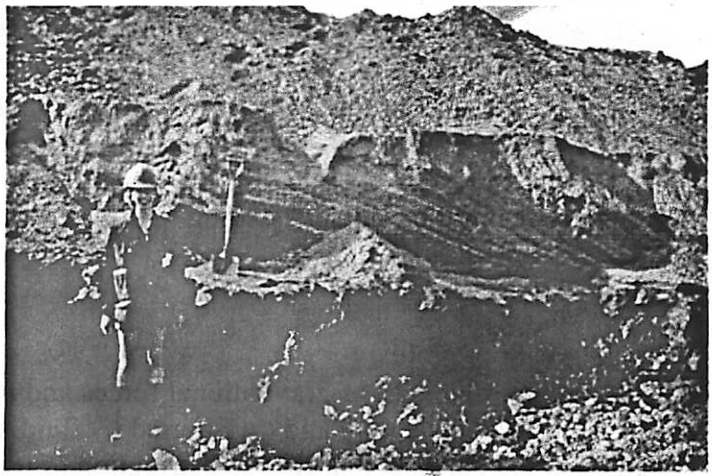


Image from http://www.igem.ru/igcp514/reports/report2006/report2006.htm

How are they formed?

Grains of heavy minerals are concentrated from the more abundant silicate sediment by some mechanical agent, usually running water. This concentration can happen in rivers, on the swash zones of beaches, and even in wind-formed dunes. For each of these sites, a source of sediment that has some heavy minerals must be present in order for placers to form. Furthermore, the rate at which this sediment is placed and the mechanisms for separating sediments by size and density must be appropriate in order to separate out the heavy grains and carry away the light grains. Four processes interact to accomplish this separation.

*note that heavy mineral grains have a smaller average grain size than lighter minerals

Settling of grains:

The velocity at which grains fall through fluid depends on size, density and shape and can be determined (see image at right) analytically for spherical particles at low concentrations in still water. Large grains (large particle Reynold's number) and turbulent flow requires approximations to the analytical solution, and additional complications arise for non-spherical grains and high sediment loads.

$$w_s = \left[\frac{4}{3}\frac{(\rho_s - \rho_f)gD}{\rho_f C_d}\right]^{\frac{1}{2}}$$

--smaller particles more effectively sorted by settling

--denser particles settle faster

--flattened particles settle more slowly

--turbulence can either increase or decrease settling velocity, depending on R_{ep}

--high concentration hinders settling

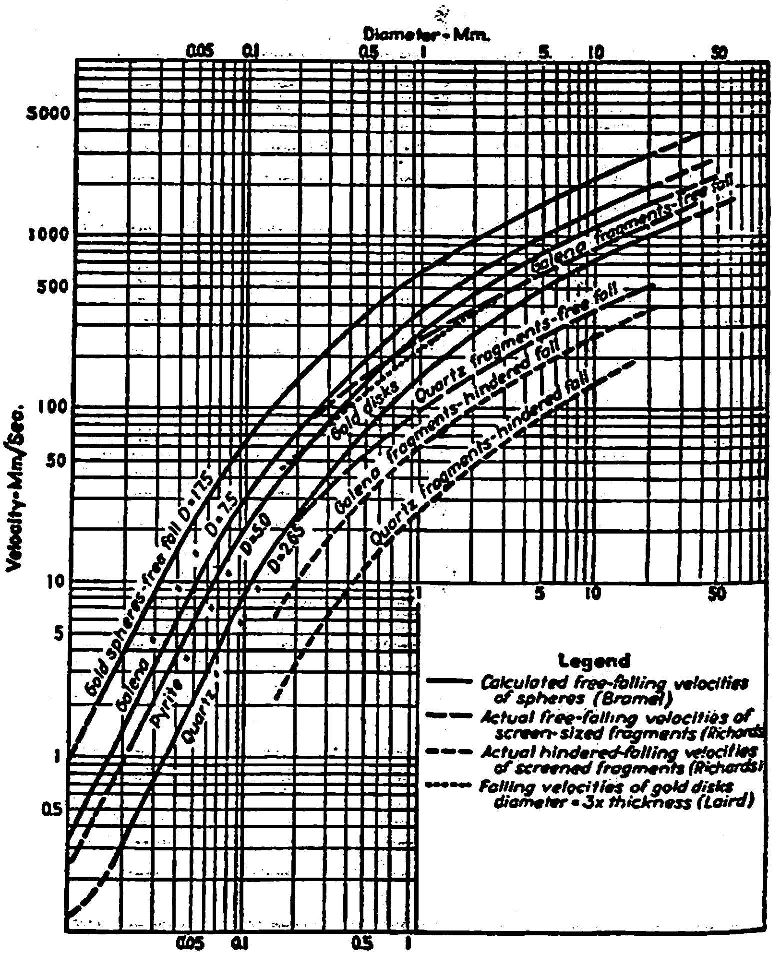
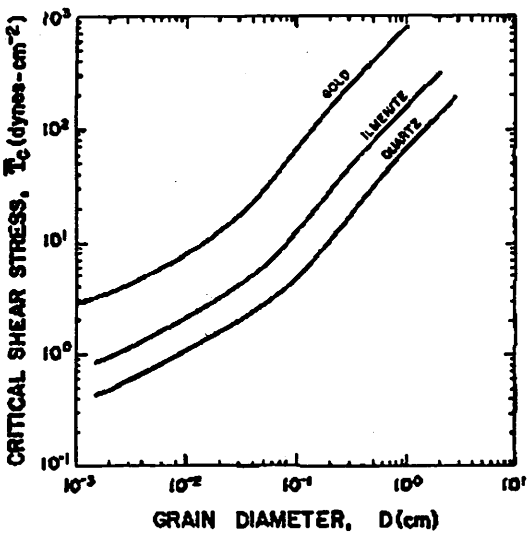


Image from http://24.69.64.171/mining/gold.htm

Entrainment of grains:

Competing influences of gravitational forces and fluid forces on grains determine whether a grain will be picked up and transported by fluid. Again, deviations from ideal cases (non-spherical grains, turbulent flows, distribution of particle sizes) play important roles in this process. A threshold shear stress, which depends on the densities of fluid and sediment, as well as particle size, must be exceeded in order for a grain to be picked up by flow.



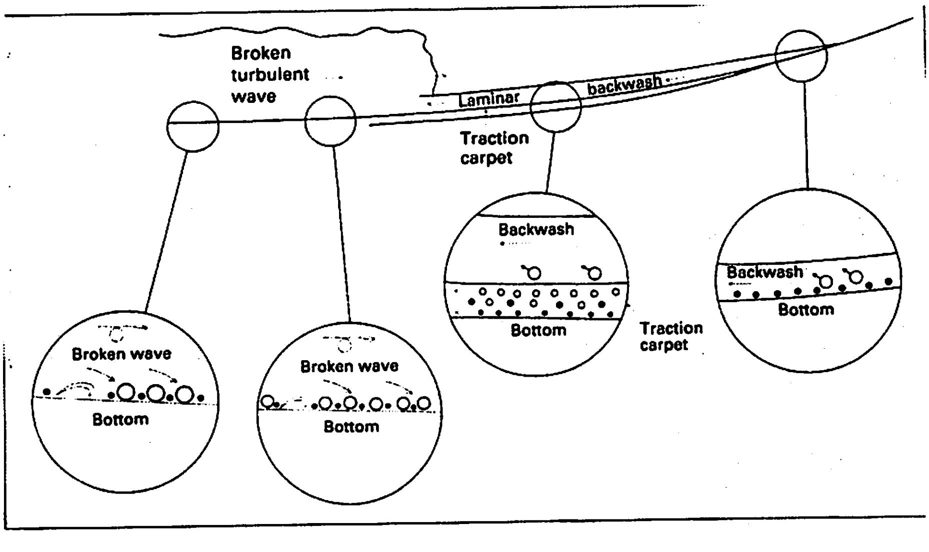
The image to the left shows the effect of density only on entrainment. However, when particles of different sizes are considered, larger grains are exposed to higher shear stresses and lift forces, while smaller grains are sheltered from flow and increased turbulence. Therefore, larger grains can be entrained at lower shear stresses. This adds a sorting mechanism based on size to the one based on density.

Differential Grain Transport:

If one size or density fraction is carried in a fluid at a different rate than another, then the two populations may come to rest at different locations, thus providing a sorting mechanism in a direction parallel to the flow. Experimental results show that for a given shear velocity, transport rates scaled with particle size (due to similar considerations as the entrainment of small grains).

Grain Shearing:

"Shear sorting" refers to the vertical fractionation of particles caused by dispersive pressures, as first described by Bagnold. Bagnold determined that if a concentrated flow of particles is subjected to shear, the granular mass expands away from the bed. He also showed that this dispersive pressure is greatest on large, dense grains.

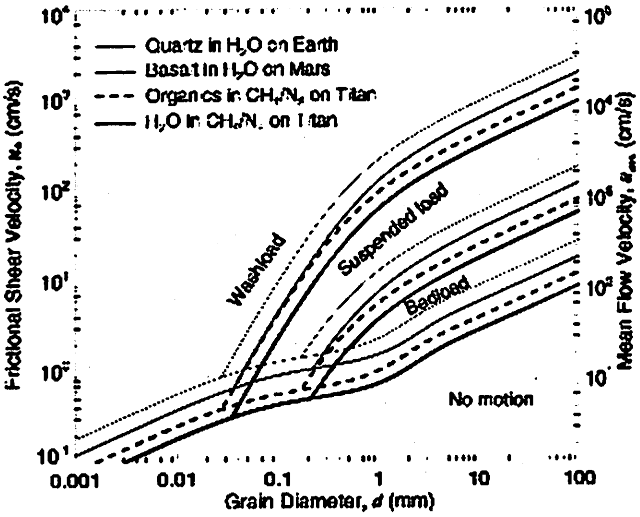


Placer Deposits on Beaches

The sorting process responsible for heavy mineral enrichment in the surf zone is a combination of grain settling, and entrainment and transport of grains (although grain sorting may also be expected in beach swash zones). A breaking wave carries sediment-laden water towards the swash zone (refer to above diagram, Force 1991). This wave slows as it creeps up the face, depositing grains that were in suspension, so grains with higher settling velocities settle first. The wave then retreats backward with a much lighter sediment load, thus increasing its erosive capacity. The larger grains are again preferentially carried away, and as a result of the differential settling above, these larger grains tend to be the lighter minerals. This leaves a lag deposit of heavy minerals on the beach sand.

Planetary Connection?

Heavy mineral laminates or placers can occur anywhere where the conditions of sediment supply and sorting mechanisms are met—and fluvial features are common to the surfaces of both Mars and Titan. Recent work by Burr, et al. shows that carrying capacity on Mars and Titan is similar to that on Earth. Lower gravity on Mars and particularly Titan result in overall lower settling velocities on those bodies. On Titan, this is partially compensated for by lower fluid viscosity of liquid methane and higher buoyancy of water ice in liquid methane. In either case, the same kind of process may be enriching mafic minerals on Mars or (possibly) heavy organics on Titan.



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Grain Movement on the Beach Face (± 1σ)

By: John Weirich

Terminology:

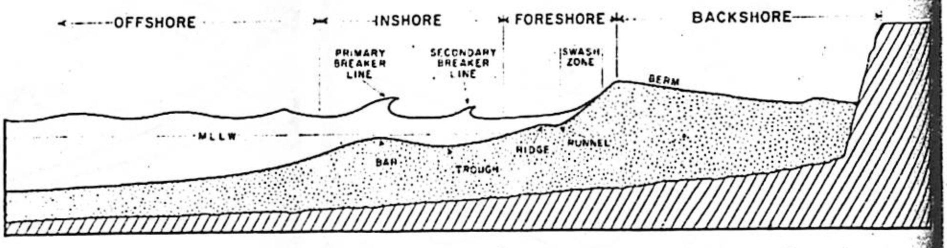


Fig.14. Terminology associated with the beach environment. M.L.L.W. = mean lower low water. (Modified after EMERY, 1960, p.168; BEACH EROSION BOARD, 1961, p.A-40.)

Beach face=Foreshore, **Shore face**=Inshore, **Longshore**= || to beach, **Cross-shore**= ⊥ to beach

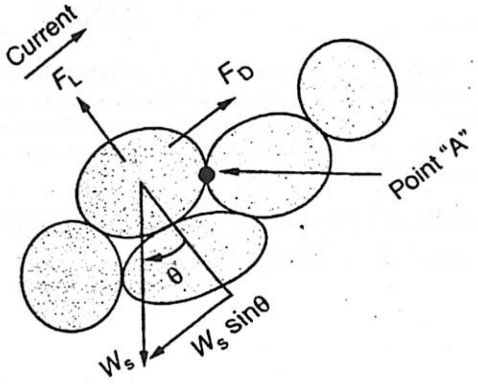
Transport Mechanism:

A. Suspended Load

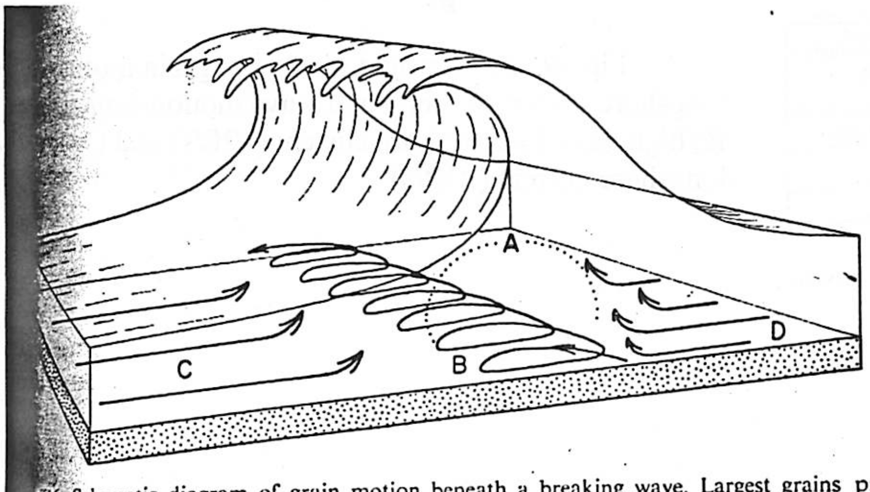
B. Bed Load (Saltation, rolling, etc.)

Current Speed ↑ - Easier to move

Grain size ↓ - Easier to move



Grain Movement of Inshore:



46. Schematic diagram of grain motion beneath a breaking wave. Largest grains present ate along the bottom at position *B*. Largest percentage of grains follows various horizontal flat-elliptical-alongshore paths during the collapse of each wave. Finest particles travel in pension at position *A*. Grains shoreward (*C*) and seaward (*D*) of the breaker zone move toward plunging wave essentially tracing water-particle motion. Diameter of grains at any position is marily a function of available wave energy or power.

Grain Movement of Foreshore:

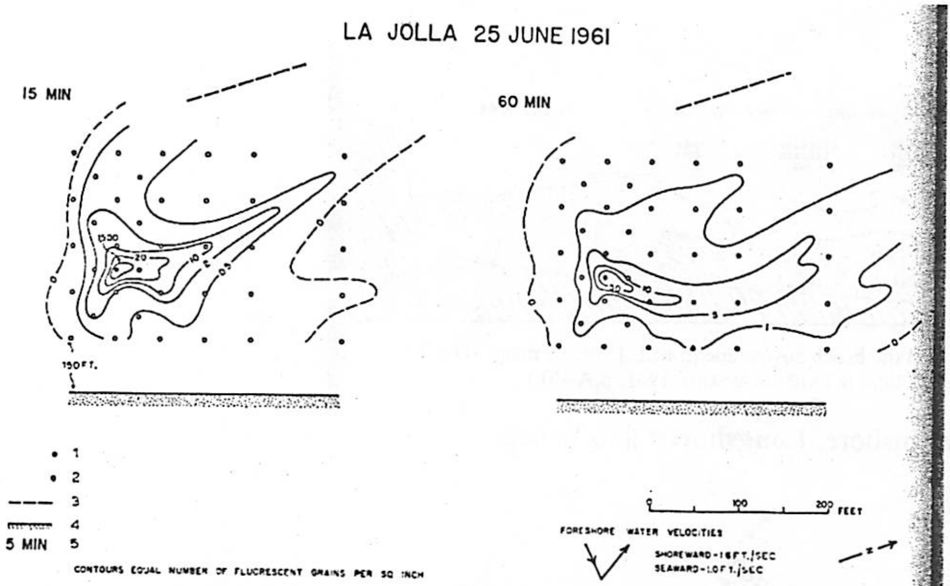


Fig.40. Typical diagonal offshore path of fluorescent sand under moderate wave and longshore-current action. Note that only a single release point was used during this test. Longshore-current velocity was 1.3 ft/sec to the north. *1* = Drop point, 20 lb. fluorescent sand was released at 3.53 h; *2* = sample station; *3* = breakers, average height 3.0 ft., period 14 sec; *4* = mean high-ide line in May 1961; *5* = time elapsed after sand released.

Note: Authors admit that large seaward component may be due to grain size disequilibrium

OVEMENT ON PLANAR FORESHORE–INSHORE SLOPES

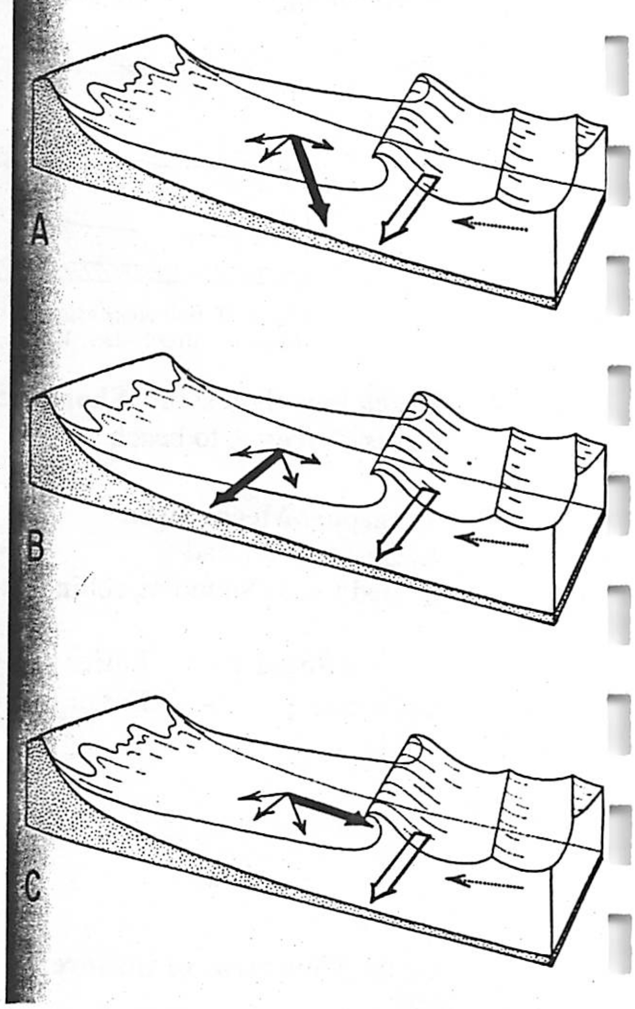


Fig 49. Primary and secondary grain motions for A) longshore current velocity and wave motion exert equal influence B) high velocity longshore current (>2ft/s) and C) low velocity longshore current (<1ft/s)

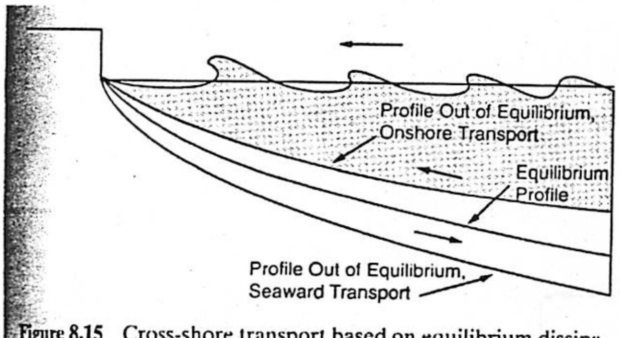


Figure 8.15 Cross-shore transport based on equilibrium dissipation model.

Grain Movement after Storm:

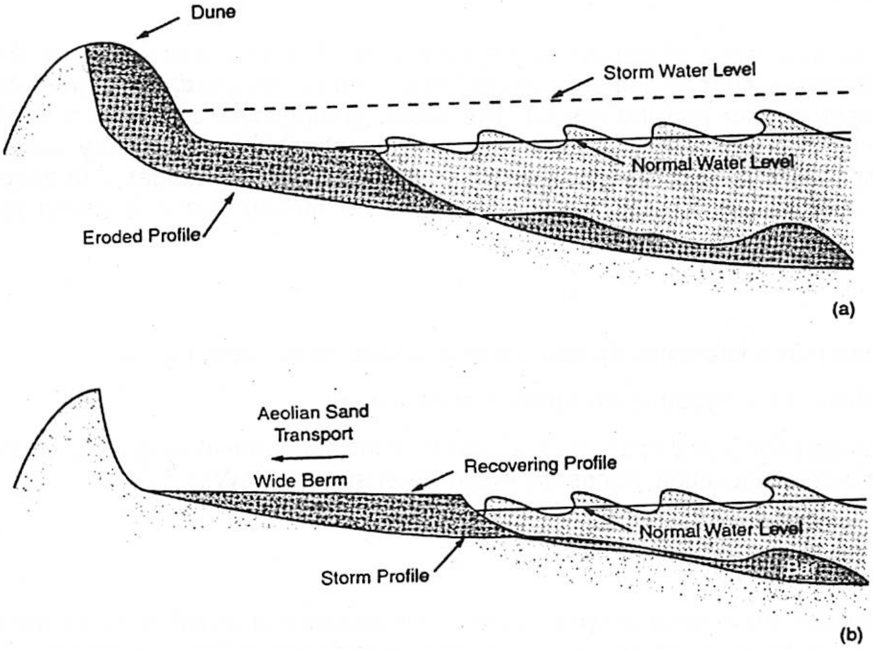


Figure 8.25 Dune erosion and profile recovery with wide berm leading to enhanced aeolian transport. (a) Dune erosion during elevated water levels and high waves; (b) profile recovery with wide berm.

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PTYS 594A: Planetary Geology Field Studies
Beach Processes
May 2-4, 2008

Hydrology on the Beach

"Indy" Keith Rodgers

Introduction

Beach groundwater can be considered at a range of scales: as a system in itself (subsurface flows), as a system that interacts with the swash (interaction between surface and subsurface flows), and as the interface between the land and the sea (interaction between the coastal aquifer and the ocean). The beach groundwater system is a *highly dynamic*, shallow, unconfined aquifer in which flows are driven though saturated and unsaturated sediments by tides, waves and swash, and to a lesser extent by atmospheric exchanges (evaporation and rainfall) and exchanges with deeper aquifers. The complex interaction of surface and subsurface water in the swash zone means that it is useful to define the terminology.

Definitions

Swash zone – the area of the nearshore that is intermittently covered and uncovered by wave run-up.

Still water level (SWL) – the water surface in the hypothetical situation of no waves.

Local mean water level (LMWL) - average over a time span much longer than incident and infragravity periods but shorter than the tidal period of the local water surface elevation. traces the mean water surface (MWS)

Set-up – a wave-induced increase in the MWS

Set-down – a wave-induced decrease in the MWS.

Watertable (phreatic surface) – the equilibrium surface at which pore water pressure is equal to atmospheric pressure.
Pore water pressure – the fluid pressure in the pores of a porous medium relative to atmospheric pressure.

Phreatic zone – the permanently saturated zone beneath the watertable.

Vadose zone (zone of aeration or the unsaturated zone) – the unsaturated region of a beach sand body extending from the watertable (or the capillary fringe, if one exists above the watertable) to the sand surface.

Capillary fringe (tension-saturated zone) - pore spaces are fully saturated, but pore water pressures are negative. thickness of the capillary fringe in sand beaches may vary between a few millimeters to nearly a meter, and it may extend to the sand surface.

Reverse Wieringermeer effect - when a curved interface forms under negative pressure (tension), water will be drawn into the pores until the radius of curvature is sufficiently small to produce a pressure difference across the air–water interface that will balance the applied negative pressure head. The addition of a very small amount of water will relieve the tension in the capillaries, resulting in a horizontal water surface. The pressure head at the surface will then be zero; in other words, the watertable will rise to the surface with a very small addition of water.

Submarine groundwater discharge (SGD) – all direct discharge of subsurface fluids across the aquifer-ocean interface, it comprises both terrestrially derived fresh groundwater flow (Qf) and seawater recirculating across the aquifer-ocean interface (SGR).

Observations

Beach groundwater response to tidal forcing – Observations of beach watertable behavior show that the watertable surface is generally not flat. The slope of the watertable changes with the tide, sloping seaward on a falling tide and landward on a rising tide and is generally steeper on a rising tide than on a falling tide. Watertable elevations with a humped shape, with the hump near the run-up limit have also been measured. This hump is generally attributed to infiltration from wave runup. Watertable fluctuations propagate landward as damped free waves, which are also referred to in the literature as groundwater waves or watertable waves. Field observations show that watertable fluctuations are asymmetrical, due to the fact that the sloping beachface acts as a highly nonlinear filter which causes the watertable to rise rapidly and drop off slowly compared to the tide. The beach fills more easily than it can drain under gravity, leading to a steeper rise than decline in water levels. For a given beach geometry, the lag in watertable response is due mainly to the hydraulic conductivity of the beach sediment. Measured watertable elevations are generally higher than the tidal elevation. This is often referred to in the literature as an overheight or superelevation. The overheight increases as the beachface slope and sediment size decrease and as tidal range and wave infiltration increase. In general, the elevation of the beach watertable increases as the permeability of the beach decreases.

PTYS 594A: Planetary Geology Field Studies
Beach Processes
May 2-4, 2008

Beach groundwater response to wave forcing – Wave forcing affects beach groundwater in a number of ways. Time-averaged wave effects contribute to watertable overheight, both by set-up raising the mean water surface at the shoreline and by run-up increasing the mean water surface through infiltration. Hydraulic gradients controlled by wave set-up also drive a general groundwater circulation in the beach. Run-up of individual waves generates high-frequency watertable and pore pressure fluctuations, which have been reported in a number of field experiments. High-frequency watertable oscillations exhibit a similar asymmetry to that of tidally induced watertable fluctuations, with a faster rate of rise than fall. The landward propagation of a swash-induced pore pressure wave has been shown to be similar to that of tidally induced groundwater waves, with the amplitude decaying exponentially and the phase lag increasing linearly in the landward direction. Some field evidence also suggests that wave effects can be observed over longer time periods. Waves can contribute to high-frequency watertable fluctuations through two mechanisms: the transmission of pressure forces through saturated sediment, and direct input of water through swash infiltration and the reverse Wieringermeer effect. It has been observed that a wave arriving at the base of the beachface induced an instantaneous rise in the beach watertable as a result of a mass pressure flux through the saturated sediment. Conversely, it has been found that the watertable elevation increased 4–5 s after maximum run-up, attributing this lag to the effects of frictional retardation on the input swash water. It is suggested that the relative importance of pressure vs. swash infiltration is controlled by the location of the exit point, with pressure forces dominating on the saturated beachface seaward of the exit point and infiltration dominating landward of the exit point. Many researchers have noted that the beach acts as a low-pass filter, only allowing the larger or longer period swashes to be transmitted through the beach matrix. Relatively few studies have reported simultaneous measurements of beach groundwater and swash. However, when run-up and groundwater spectra are compared, a considerable reduction in dominant energy and also a shift in dominant energy towards lower frequencies.

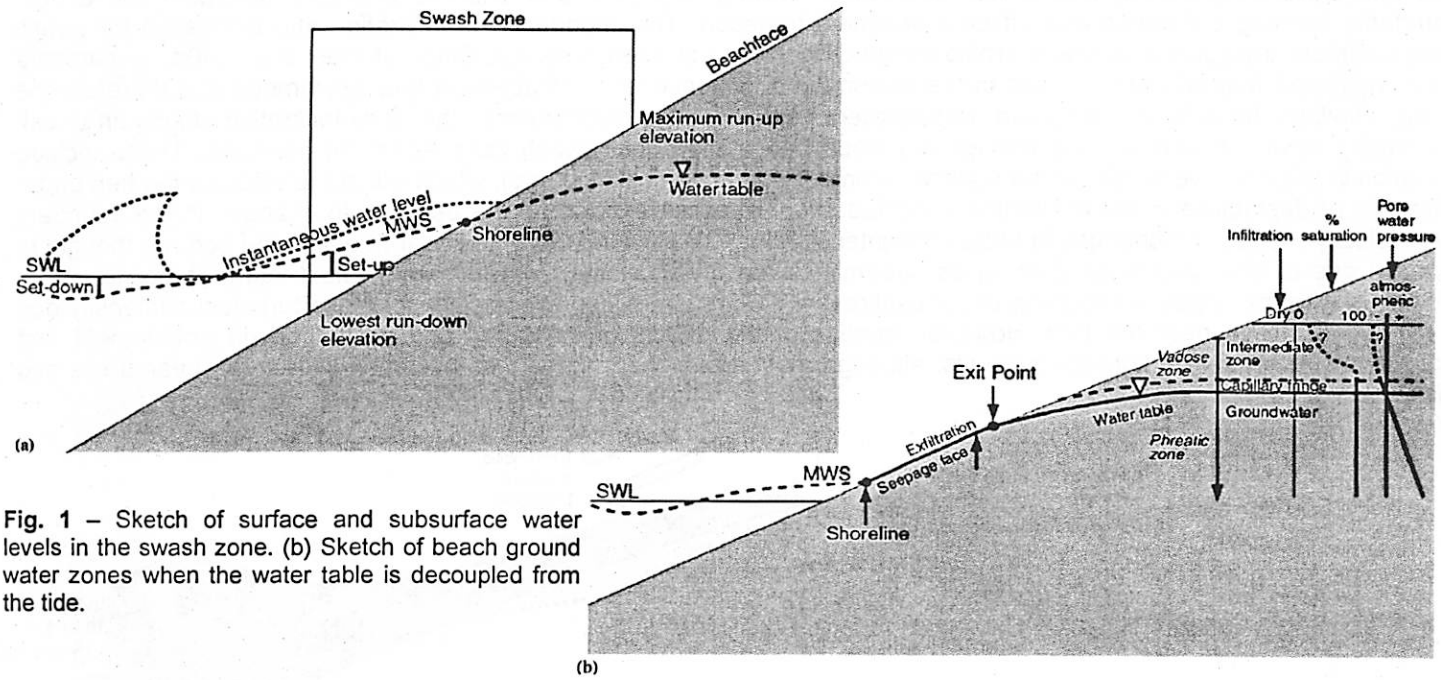


Fig. 1 – Sketch of surface and subsurface water levels in the swash zone. (b) Sketch of beach ground water zones when the water table is decoupled from the tide.

The capillary fringe – In unconfined aquifers, the dynamics of the watertable will be influenced by the capillary fringe for all but the coarsest sands and gravel. The presence of a capillary fringe can have a significant effect on the exchange of water between the ocean and the coastal aquifer, particularly in terms of the storage capacity of the aquifer. Specific yield has been observed to decrease with proximity of the watertable to the surface of the porous medium, with the amount of drainage occurring under a declining watertable reduced relative to that experienced for a deep watertable. Field and laboratory observations have shown that natural groundwater waves usually propagate faster and decay more slowly in aquifers with a capillary fringe. Capillary water does not rise to an even height above the watertable but instead forms an uneven fringe which is higher in fine-grained sediments because of the greater tensions created by smaller pore openings. An important effect of the capillary fringe on watertable dynamics is that shallow watertables frequently showed a disproportionate response to infiltration. When the capillary fringe extends from the watertable to the ground surface, the specific yield is close to zero and the application of a small amount of water will result in a rapid and large rise in the watertable. This is referred to as the reverse Wieringermeer effect. When the capillary fringe is close to the sand surface, the addition of a thin film of water can cause pore water pressure to increase as though tens of centimeters of water had been added, due to the elimination of meniscuses between the sand grains (Fig. 2). This disproportionate relationship between the moisture exchange and the corresponding change in pressure means that the amount of water required to cause the watertable to rise to the sand surface is in the order of a grain diameter (less than 1mm for beach sands), in comparison to the change in watertable elevation, which is on the order of the height of the capillary fringe. The reverse Wieringermeer effect, due to the appearance and disappearance of meniscuses between sand grains, is predominantly a swash zone mechanism when waves run up on the beachface and will lead to a significantly reduced storage term.

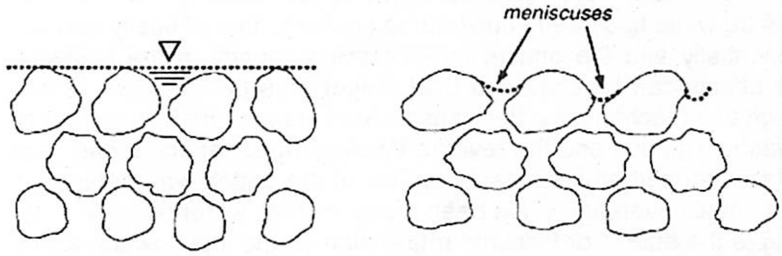
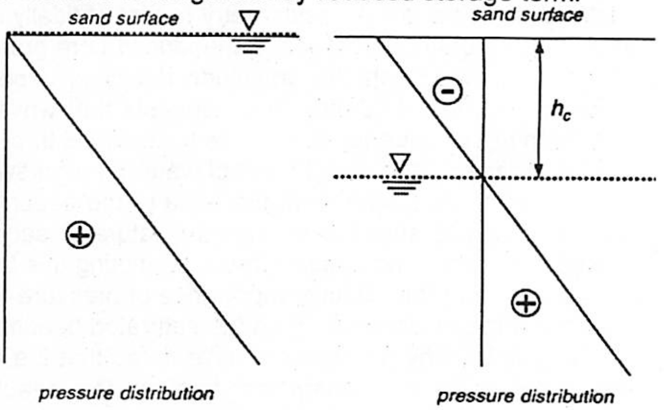


Fig. 2 – Sketch showing the appearance and disappearance of meniscuses between sand grains in the capillary fringe.



Infiltration/ exfiltration – The potential for infiltration or exfiltration has been linked to beach watertable elevation at both tidal and wave frequencies, with a low watertable favoring infiltration and onshore sediment transport and a high watertable favoring exfiltration and offshore sediment transport. The importance of infiltration and exfiltration for swash zone sediment transport and beach profile evolution has not yet been resolved. Since at least the 1940s, researchers have suggested that infiltration losses in the swash zone influence uprush/backwash flow asymmetry and therefore the energy available for sediment transport. Researchers have identified mechanisms other than infiltration effects on swash asymmetry by which vertical flow through a porous bed could affect swash zone sediment transport. These include alteration in the effective weight of the surface sediment due to vertical fluid drag, which will act to stabilize the bed under infiltration or destabilize under exfiltration; modified shear stresses exerted on the bed due to changes in the boundary layer velocity profile, and changes in turbulence intensity (Fig. 3). Flow velocity and shear stress at the bed are thought to increase due to boundary layer thinning as streamlines are drawn closer to the sediment–fluid interface occurs under infiltration, with the opposite occurring under exfiltration. Exfiltration is also expected to increase turbulence intensity due to enhanced mixing near the bed. However, studies of the effects of infiltration and exfiltration on entrainment and sediment transport exhibit conflicting results, although most researchers agree that infiltration increases shear stress and skin friction at the bed and

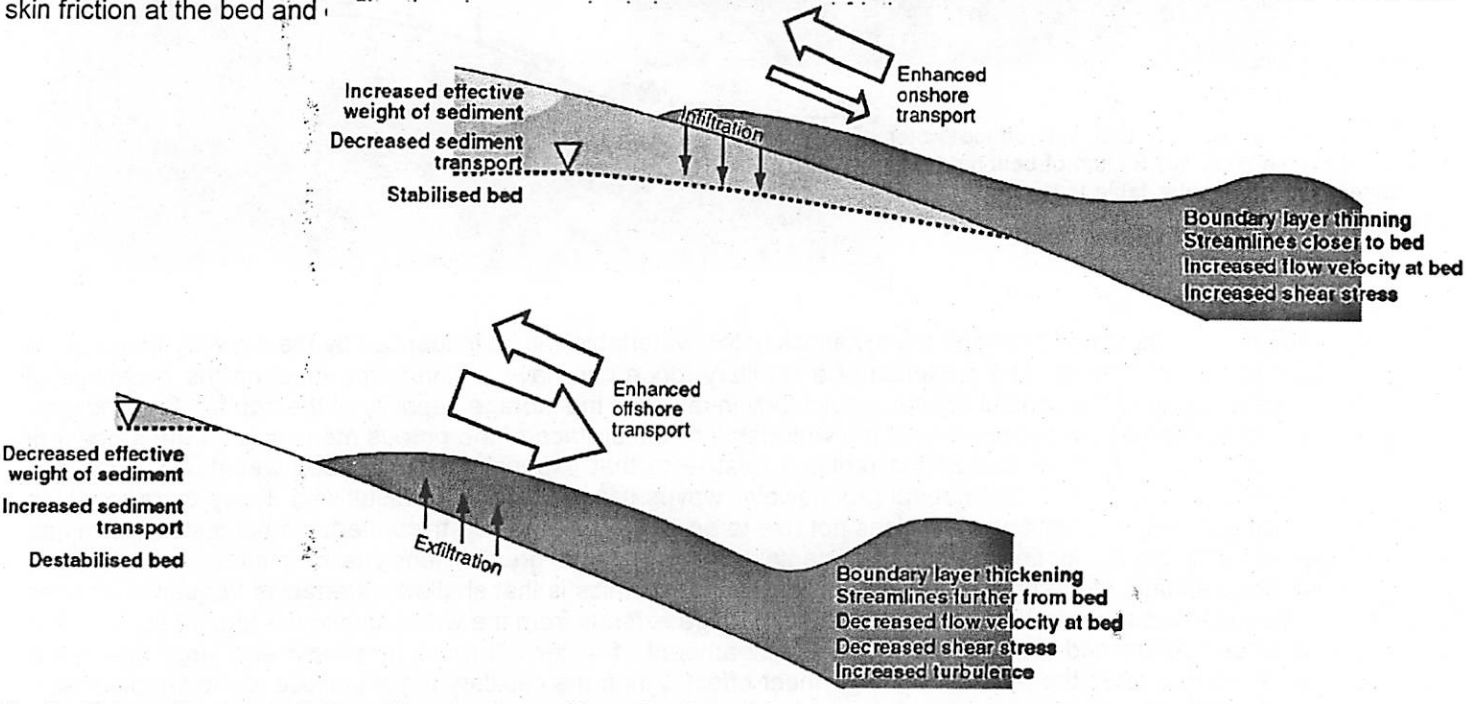


Fig. 3 – Schematic representation of the processes of boundary layer thinning and alteration of effective weight.

Submarine groundwater discharge – SGR is driven by a range of processes, but in the nearshore region the main mechanisms driving seawater recirculation are tides, waves and density-dependent flow (Fig. 4). Measurement techniques used to quantify SGD (e.g., seepage meters, piezometers, geochemical tracers) typically provide limited insight into the dynamics of the water exchange process. There is a need to identify conditions for which tide-, wave- and density-driven seawater recirculation are likely to be significant. The density gradients across the transition zone of the saltwater wedge drive convective circulation through the wedge which contributes to water exchange across the interface. Prediction of Qd is difficult due to the strong dependence of density-driven convection on the aquifer dispersivities which are typically uncertain and scale-dependent. Tidal forcing across a sloping beach face results in the movement of large quantities of water (Qt), relative to fresh groundwater discharge (Qf), across the aquifer-ocean interface. Water infiltration occurs when the instantaneous seawater level exceeds that of the beach water table causing input on the rising tide and discharge mainly on the ebbing tide. The nonlinearity associated with tidal forcing on a sloping beach boundary results in a tide-averaged asymmetric exchange pattern whereby infiltration dominates in the upper intertidal zone and exfiltration near the low-tide mark. This asymmetric exchange sets up a seawater circulation cell through the intertidal zone (Fig. 4). Tide-induced recirculation is a localized phenomenon characterized by high specific fluxes and relatively short residence times (order of 10^1 d). Tide-induced recirculation is typically confined to shallow intertidal sediments. Tidally driven recirculation is significant because recirculating seawater may mix with fresh groundwater discharging through the nearshore aquifer. The tide-induced seawater circulation cell which operates through the intertidal zone leads to the formation of an upper saline plume in addition to the classical saltwater wedge (Fig. 4). This upper saline plume represents an active and dynamic zone of mixing between the recirculating seawater (oxygenated) and fresh groundwater (anoxic), and thus an important biogeochemical reaction zone in the nearshore aquifer. The presence of the tidally driven circulation cell also results in fresh groundwater (Qf) discharging through a freshwater "tube" near the low-tide mark, rather than at the shoreline as is the case for nontidal conditions (Fig. 4). However, previous studies did not separate the "fresh" from the "recirculated" SGD components. It has been suggested that when fresh groundwater discharge is small, tidal oscillations significantly increase the magnitude of seawater recirculation across the aquifer-ocean interface. Such a tidal effect is reduced with increasing fresh groundwater discharge. SGD rates were found to be independent of site specifics.

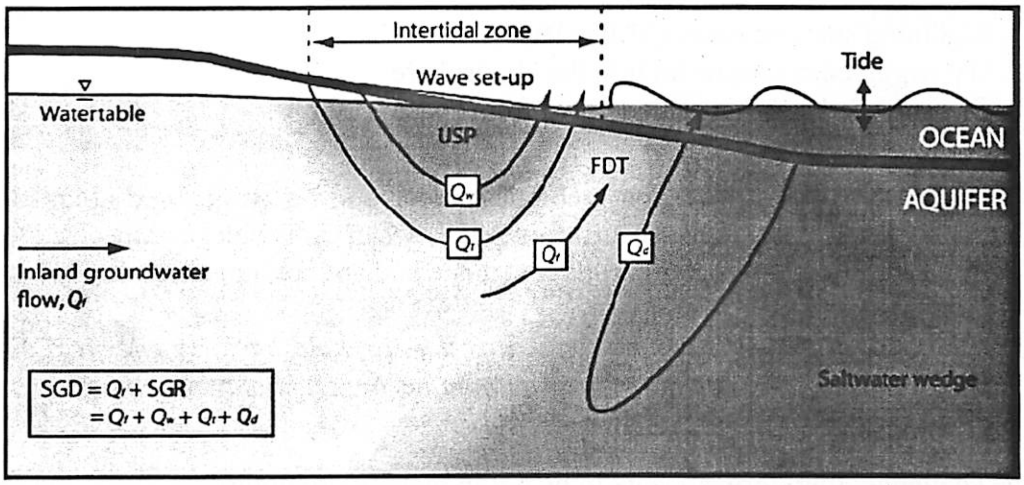


Fig. 4 – Conceptual model of a coastal groundwater system subject to oceanic oscillations. Qf-inland fresh groundwater flow, Qw-wave setup and runup, Qt-tides, and Qd-density-driven convection. Shading depicts typical salt distribution with an upper saline plume (USP) present in addition to the classical saltwater wedge. The two saline plumes confine a freshwater discharge "tube" (FDT) whereby fresh groundwater discharges around the low-tide mark.

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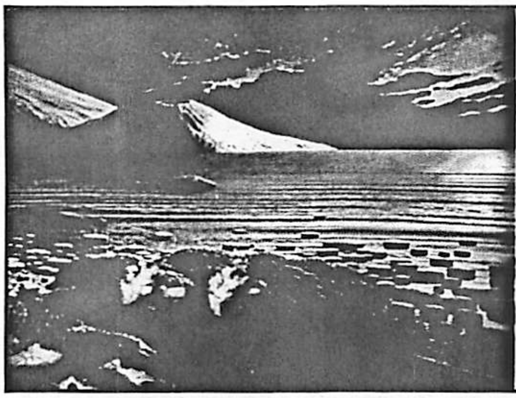


Tide Pools as a Location for the Origin of Life

by Catherine Neish

Beach Processes Field Trip
(Spring 2008)

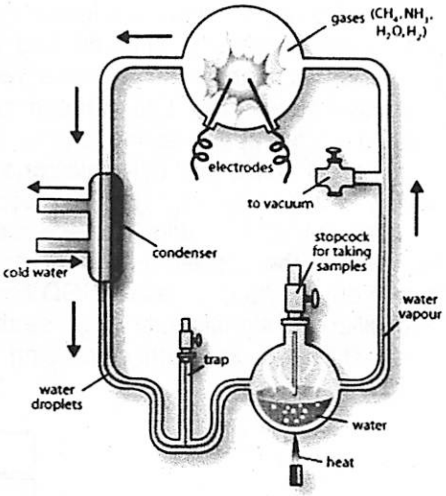
The Origin of Life

The origin of life (as we know it) appears to have relied on three key resources:

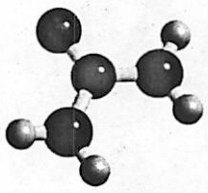
1. **Water** – the essential growth medium for all living things
2. **Chemical building blocks** – such as C, O, H, N, S, and P
3. **Energy** – to assemble the ingredients into a self-replicating entity

The first step towards the creation of life is the creation of its component molecules (amino acids, sugars, nucleic acids, etc.) from these resources. Many environments likely contributed to this inventory of prebiotic molecules on the early Earth, including:

1. Lightning sparked gases (Miller 1953)
2. UV triggered reactions high in the atmosphere
3. Organic products that rained down from space



The classic Miller-Urey experiment.



Urea (CH_4N_2O)

The first prebiotic molecule to be synthesized abiotically in the laboratory was **urea**. This occurred in 1828, when F. Wohler synthesized urea from the inorganic starting materials silver cyanate and ammonium chloride. In his words,

> *"I can no longer, as it were, hold back my chemical urine: and I have to let out that I can make urea without needing a kidney, whether of man or dog."*

The challenge, therefore, appears to be not in making prebiotic molecules, but in

(1) **selecting** the right ones[1] and
(2) **assembling** them into useful biological molecules.

Before biology, the raw materials Earth had to offer were the ocean, the atmosphere, and the rocks. Any "primordial soup" formed in an early ocean would have been far too dilute to foster selection or assembly. Surfaces, where molecules tend to concentrate, offer an alternative. Interesting chemistry tends to take place on surfaces where two different materials (like air and water, or water and rock) meet. Evaporating **tide pools**, where cycles of evaporation concentrate stranded chemicals, represents one appealing location for origins of life chemistry.

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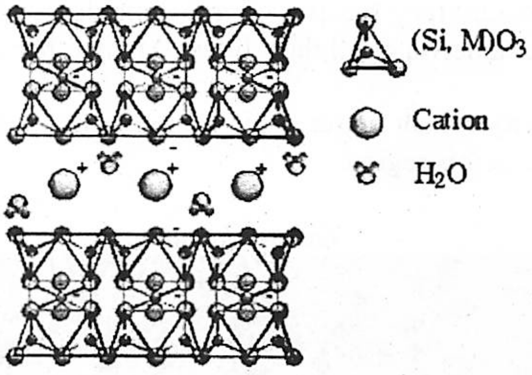
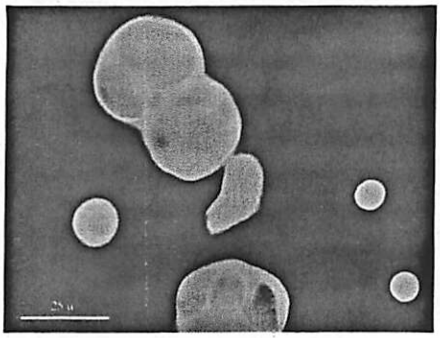
[1] It is possible to make many prebiotic molecules in the lab, but many other molecules with no biologic function appear as well. Biologic molecules also tend to have a particular "handedness" - only one stereoisomer is used, when two are possible.

It appears that rocks and minerals - as organizing templates, catalysts, chemical reactants, and protective containers - may have played a key role in life's origins. In particular, clays and mineral surfaces may have played an important role in providing a framework for life to organize.

Clays - ubiquitous minerals with regularly layered atomic structures - exhibit surface electrostatic charge that enhances their ability to adsorb organic molecules. And molecules adsorbed close to each other have a tendency to bond. Experiments have shown that RNA strands of more than 50 nucelotides can be assembled on clays. Researchers have also shown that amino acids tend to concentrate and polymerize on clays to form small, protein-like molecules. Such reactions occur when a solution containing amino acids evaporates in the presence of clays - a situation not unlike the evaporation that dries up a shallow pond or tidal pool.



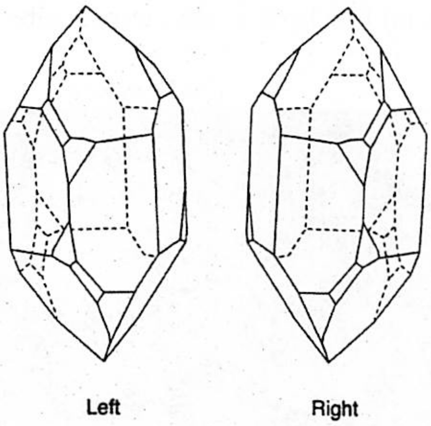
Right: Basic layer structure of a clay mineral.



As polymers get longer, though, the organic molecules tend to become more and more tightly bound to the mineral surface. And polymers cannot contribute to life if they are stuck to a rock. However, experiments have shown that **lipids** (fat-soluble molecules), when combined with clays and RNA nucleotides, incorporate RNA strands attached to clay into vesicles. The vesicles formed by lipids also provide one of the best ways to "isolate" life from a wet environment that tends to dissolve its component parts.

Left: Vesicles formed by the self-assembly of molecules formed in abiotic conditions (D. Deamer, R. Hazen).

Another problem mineral surfaces may help to resolve is that of homochirality. Many important biomolecules come in mirror-image pairs – like hands, they have the same structure, but cannot be superimposed. For reasons that are not well understood, life selects L-amino acids ("left-handed") and D-sugars ("right handed") almost exclusively over D-amino acids and L-sugars. Most researchers assume that this selection is a by-product of life's common ancestor having formed in a local "one-handed" or "homochiral" environment. Rocks may offer such a chiral environment, in the form of assymmetric mineral surfaces. A few minerals, most notably **quartz** (found in beach sand), occur in both right-handed and left-handed structural variants. In addition to offering a place to separate L from D molecules, mineral faces might also prove to be ideal templates for the assembly of life's molecules. And many different minerals – including clays and quartz – might be found in tidal zones.



Quartz forms both left-handed and right-handed crystals.

One author – Robert Hazen – speculates on the role tidal zones may have played in the origin of life:

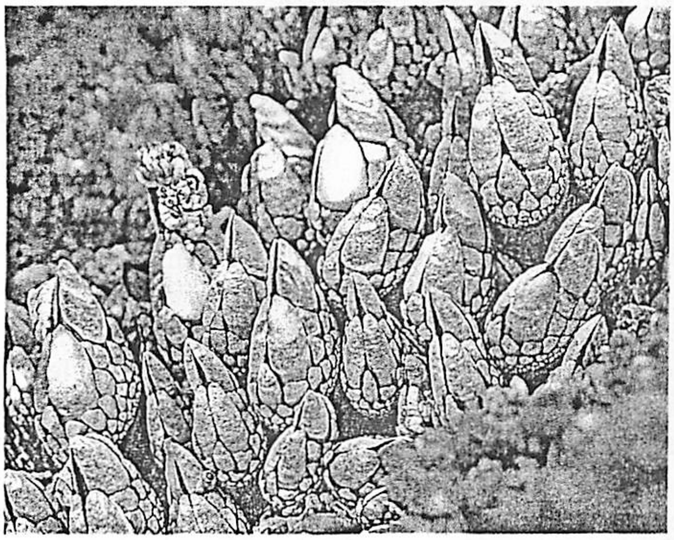
"Rocky outcrops and overhangs - especially in tidal zones, where seawater evaporates and thus concentrates organic molecules – might have promoted macromolecular formation. Imagine a shaded cove where increasingly concentrated mixtures of organic molecules accumulated and reacted, protected by a rocky ledge from the Sun's harmful radiation. Rocks might have served as Earth's earliest sunblock."

Current Tide Pool Fauna

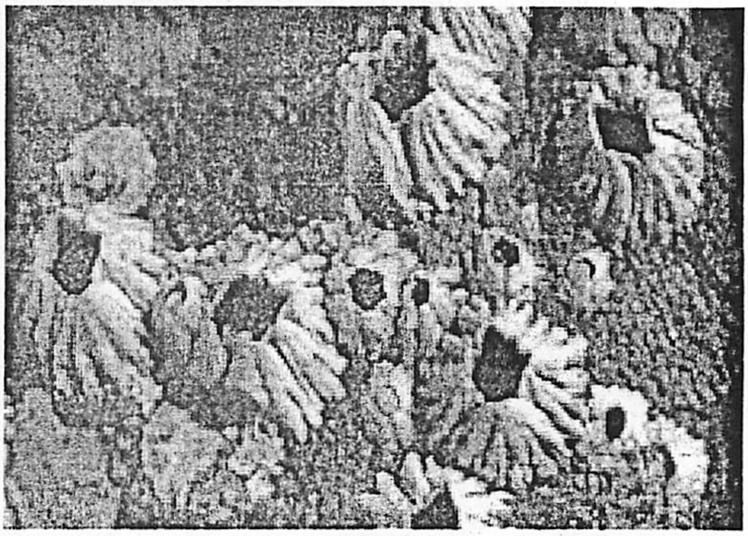
Current tide pool fauna live in one of four different zones, differentiated by the amount of water, sun, and air exposure they receive. Some animals live high above the water and only get wet occasionally. Other animals, live underwater all their lives. Many other animals, adapted to the tides, live in and out of the water each day.

Spray/splash zone: This region is flooded only by the highest tides and storm waves. Lichens and barnacles live in this region.

Goose Barnacle

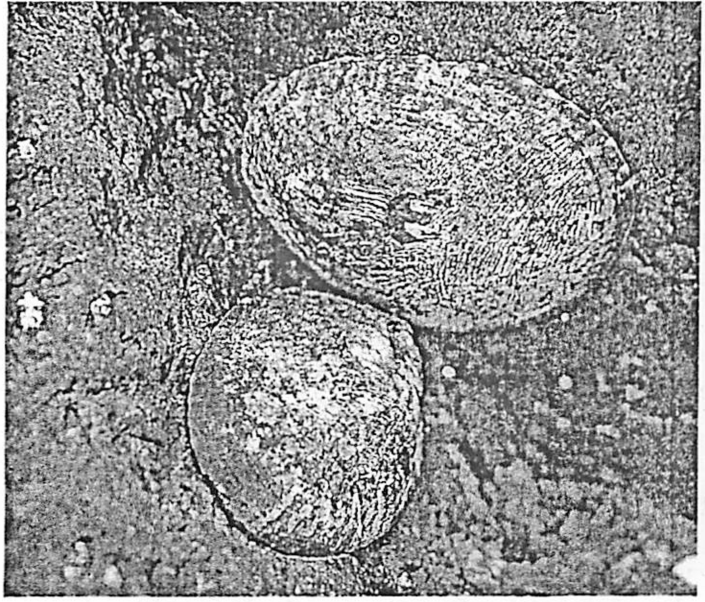


Acorn Barnacle

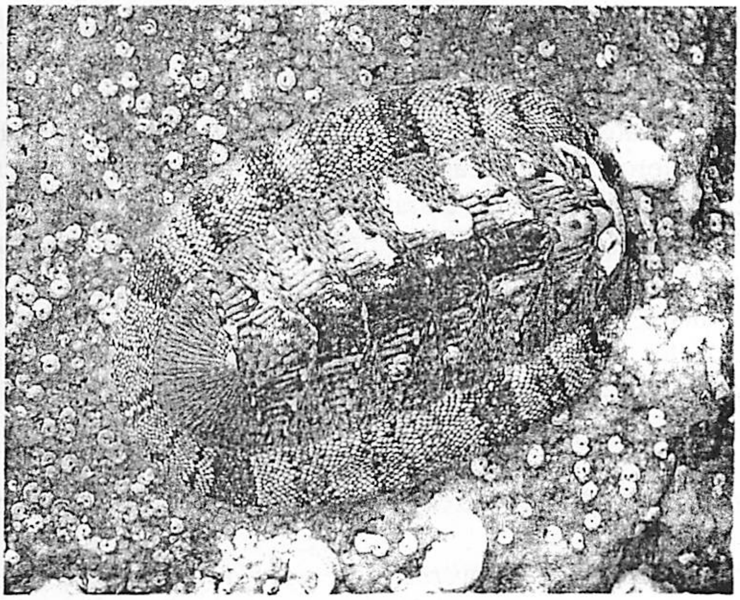


High tide zone: This region experiences rough waves and long exposure to air. Mollusks (limpets and mussels) live here, as do hermit crabs.

Owl Limpet

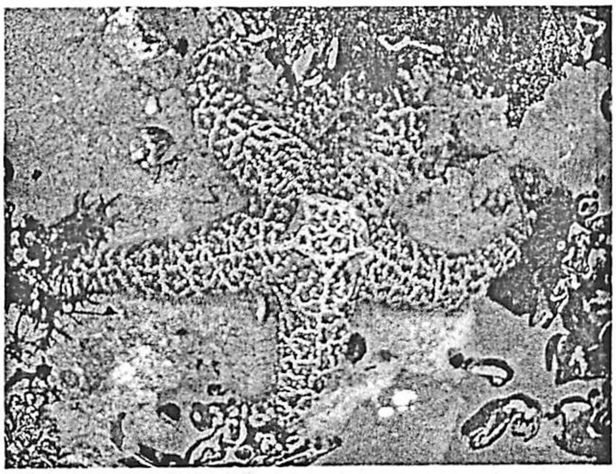


Scaled Chiton

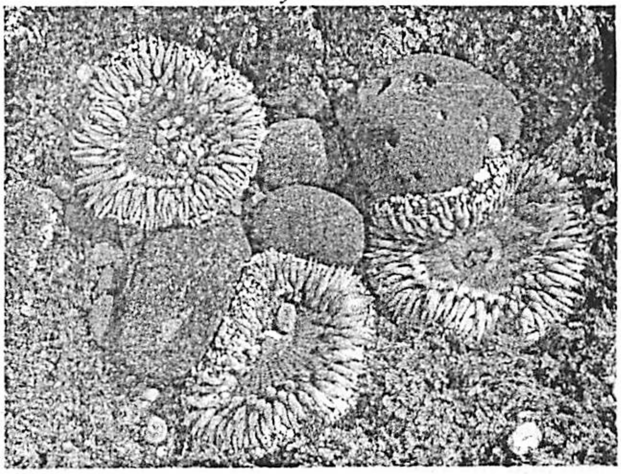


Mid-tide zone: This region is covered and uncovered twice a day by tides, so animals in this region must adapt to surviving in and out of water. Anemones, mussels, and sea stars live here.

Ochre Sea Star

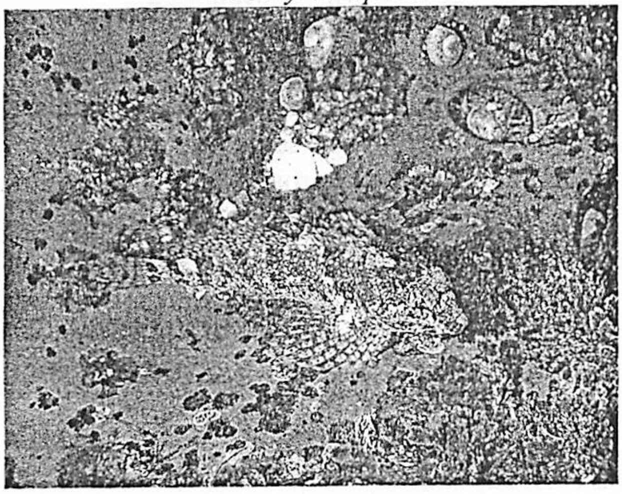


Solitary Anemone

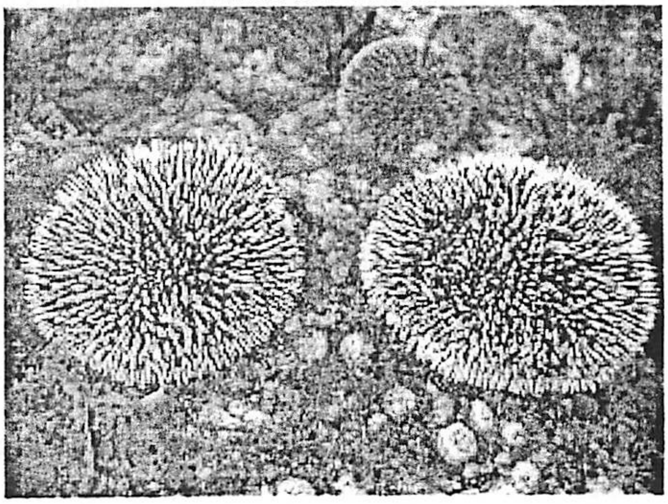


Low-tide zone: This region is usually covered by water. Animals that live in this region cannot tolerate much exposure to air or sun. Crabs, shrimp, small fish, sea slugs, and urchins live here.

Wooly Sculpin



White Sea Urchin



Planetary connection

Depending on how life formed on Earth, it may inform our ideas of how life might form elsewhere. If life formed on the surface, in small pools along an ocean or sea, life may be restricted to terrestrial planets like Venus, Earth, and Mars. If, however, life formed underground or underwater, other habitats - like the subsurface oceans seen in icy moons - could provide potential places for life to emerge.

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Spring 2008 LPL Field Trip, 2008 May 2-5
The Physics of Tides
Brian Jackson

I. Getting Old School

Humans have been aware of the ebb and flow of ocean tides on the Earth for a long time. For instance, around 2000 B.C., the ancient Indian mariners built a tidal dockyard in the Bay of Cambay (on the northwest coast of India). At times of high tide, the mariners sailed their boats into the dockyard and sealed it off, so that at low tide, their boats would remain afloat. They sailed out of the dockyard when the next high tide came.

In these early days, myths about the origins of tides abounded, but modern western ideas about the origins of tides began with Kepler. In working out the laws of celestial motion, Kepler was puzzled by the force that kept the planets in orbit around the sun and the Moon around the Earth, which he believed to be some form of magnetism. In 1609, Kepler speculated that the same force that held the Moon in orbit might also induce tides in the oceans. After reading about Galileo's discovery of Jupiter's moons, Kepler wrote a tract defending Galileo against his critics.

For his part, Galileo mocked Kepler's suggestion that the Moon was the cause of the Earth's tides. Galileo considered Kepler's idea of forces between widely separated bodies (action-at-a-distance) to be medieval mysticism. Instead, Galileo proposed a model of his own, inspired by his observations of barges bobbing in the docks of Venice, causing water in the dockyards to slosh back and forth. Galileo suggested that, as the Earth rotates, an ocean on the night side of the Earth would rotate into the same direction as the Earth revolves around the Sun. However, when that ocean rotates around to the other side of the Earth, twelve hours later, it would be rotating into the opposite direction as the Earth is revolving. Galileo argued that the acceleration would jar the water, which would then bob at its own natural frequency. According to Galileo, the acceleration would produce the classic pattern of semi-diurnal high tides. However, such a model fails to reproduce the semi-diurnal low tides (or much of the other complex behavior of ocean tides).

The origin of tides remained unclear until Newton published his Principia in 1687, in which he explained the laws of gravity and correctly attributed ocean tides to the gravitational attraction of the Moon. In his model (often called the equilibrium tide model), Newton imagined an Earth without continents, completely covered by the ocean. In this model, the Earth and the Moon both orbit the center of mass of the Earth-Moon system, the system barycenter. The ocean bulges at the sub-lunar point because of the Moon's gravity is strongest there. The ocean also bulges at the anti-lunar point because the revolution of the Earth about the system barycenter results in a centrifugal acceleration.

Newton also correctly realized that tides raised by the sun on the Earth were important. It was observed that when the Moon was either in opposition or conjunction with the Sun, the high tides were higher and the low tides were lower. When the moon was somewhere in-between, all the tides were lower. (By the way, when three heavenly bodies all lie on a straight line together, the bodies are said to be in *syzygy*.) Again, Newton was correct in attributing this effect to the gravitational attraction of the Sun, whose tidal gravity turns out to be about half as strong as the Moon's. Newton's model correctly explained the alternating semi-diurnal high and low tides and the semi-annual increase or decrease in the height of the tides. As successful as it was, however, Newton's model did not explain everything. In particular, the resonant behavior of some tidal bays cannot be explained by Newton's simple equilibrium tidal model.

II. S to the N, double O-P

By the mid-nineteenth century, great scientific minds like Laplace and Lord Kelvin began to apply the new technique of harmonic analysis to the problem of ocean tides, and their full, complex behavior began to be grasped. By breaking up the tide into component of differing periods and amplitudes, Lord Kelvin and his colleagues began the modern study of tides.

As applied to ocean tides, harmonic analysis essentially breaks the regular fluctuations of tides into several Fourier components resulting from gravitational interactions with either the Sun or Moon, each with a different period. Figure 1 (from the Naval Postgraduate School) shows how several periodic components combine to produce the daily tides near Los Angeles.

Each component has its own name and period and arises from a specific gravitational interaction. For example, the semi-diurnal (with a frequency of 2/day) from the Moon is called M2. The Sun's semi-diurnal tide is called S2. Other components have arbitrarily designated letters (K, O, P, N), but the number always stands for the daily frequency.

The harmonic analysis model worked well to predict the periodicity of the tide. In fact, Lord Kelvin invented a machine comprising a series of gears that calculated the height of the tide at a given bay by mechanically summing up to ten terms in the tidal Fourier expansion. The problem with this model, however, is that the size of each tidal component, essentially the Fourier coefficients, cannot be known *a priori*. The height of each tidal component depends in a complex and poorly understood way on local conditions at the tidal bay (such as bay depth, width, etc.). Observations of the daily tides must be made for several weeks in order to work out the contribution from each tidal component.

In some cases, the frequency of a particular tidal component may be commensurate with some natural frequency for the bay. In this case, that component drives tides into and out of that bay resonantly, and the tides can be quite large. The most famous example of a resonant bay is Canada's Bay of Fundy, whose particular shape gives rise to a resonance with the M2 tidal component and results in tides with a height greater than 5 m.

Naturally, though, even this complex model for tides doesn't tell the whole story.

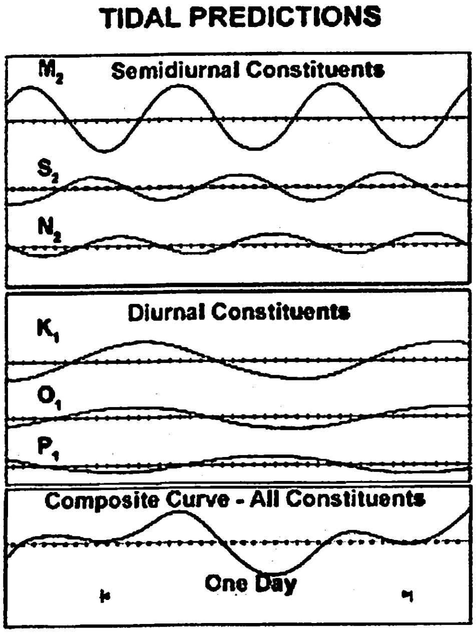

Figure 1: How the different tidal components add to give the daily tides.

III. Get the Friction On

If the Earth's oceans were perfectly fluid (i.e. if they responded instantly to tidal gravity), the tidal bulge raised by the Moon would point directly at the Moon. If you were standing on the beach, you would see the tide come in right as the moon passed overheard. However, friction with the ocean floor as well as ocean currents act to slow the rate at which a tidal bulge can follow the Moon (or the Sun). As a result, lunar tides lag the moon by several hours, and, in the rotating frame of the Earth's surface, the tidal bulge always lags the moon by an angle, α, of about 0.09 radians (5 degrees). In an inertial frame, this lag means the tidal bulge always points ahead of the moon (see Figure 2 from Wikipedia.com). This lag angle corresponds to a dissipation of tidal energy at a rate of about 4×10^{11} W, and most of the dissipation occurs in shallow ocean basins (Marchuk & Kagan 1989). Commonly the dissipation rate is parameterized as a quality factor, *Q*, which turns out to be $\sim 1/\alpha \sim 10$. It is noteworthy that the tidal dissipation rate depends sensitively on the arrangement of land masses on the Earth's surface, meaning in the past, when the continents were configured differently, the rate of tidal dissipation was probably different.

The Moon also raises tides in the solid body of the Earth as well, and the rate of energy dissipation in the Earth's solid body varies strongly as a function of depth. However, the rate of dissipation in the solid body is at least an order of magnitude less than in the ocean and so is usually negligible. However, this dissipation cannot be neglected for all planets.

Since the ocean tidal bulge points ahead of the Moon in an inertial frame, a torque results that transfers angular momentum from the Earth's rotation to the Moon's orbit. As a result, the Earth's rotation has been slowing over billions of years, and the Moon's orbit has been expanding, which means its orbit period has been slowing. Based upon historical astronomical observations, several authors have tried to estimate the rate of tidal dissipation necessary to produce the observed increase in the Moon's orbital period. Consistently, these estimates are a factor of 10 or more larger than the measured dissipation rate (Marchuk & Kagan 1989). This discrepancy has yet to be accounted for.

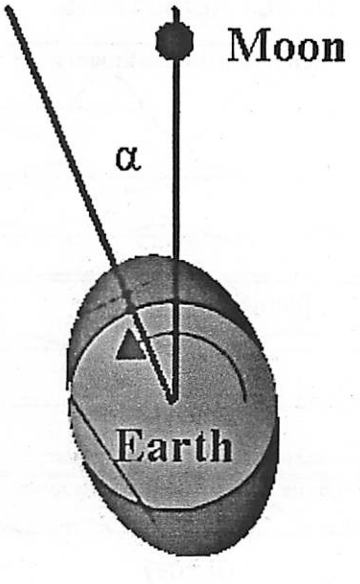

Figure 2: Tidal lag angle between the Earth's tide and the Moon.

IV. Pump Up the Bass

Having considered effects of tides on the Earth and Moon, we can now think about tides on other bodies in our solar system. Perhaps the most famous example of the effect of tides is Jupiter's moon Io. Due to resonant interactions with the other satellites in the jovian system, the eccentricity of Io's orbit is continually pumped up. Consequently, the size of the tide raised on Io by Jupiter changes over Io's orbit: it is largest at perijove and smallest at apojove. This tidal flexure dissipates a lot of energy in Io's interior and results in the spectacular volcanism with plumes ~ 100 km high (McEwen et al. 2004). Observations of Io's emitted heat flux give values ~ 2 W/m^2 (Schubert et al. 2004), which can be compared to the Earth's radiogenic heat flux of 0.08 W/m^2 (Davies 1999).

Jupiter's other satellite Europa also experiences significant tidal flexure and heating, which give rise to complex surface tectonics and probably a liquid ocean beneath a thin ice crust (Greenberg 2006).

The effects of tides have been considered for planets in other solar systems, so-called extra-solar planets. Many gas giant planets with masses comparable to Jupiter's have been found orbiting within a few hundredths of an AU of their host stars, close enough that tides raised on the planet probably have important effects. While there are many questions about the nature of these gas planets, one puzzle in particular may be solved by accounting for the effects of tidal heating: many of these planets seem to have radii that are too large.

For example, the planet uninspiringly named HD 209548 b, with a mass ~ 0.6 Jupiter masses, has a radius that is 30% larger than Jupiter's (Burrows et al. 2007). Since 209's orbit may be slightly eccentric (with an eccentricity ~ 0.01), tidal heating has been invoked to pump up the planet's radius by warming the planet's interior as it undergoes tidal flexure. Recent work suggests that, even though the tidal heating that planet is currently undergoing may be insufficient to pump its radius to the observed value, tidal heating in the past billions may be large enough (Jackson et al. 2008a).

Tidal heating may also be important for rocky extra-solar planets as well. Although no extra-solar planets with masses < 5 Earth masses have yet been detected, astronomers will likely detect the presence of rocky planets in other solar systems in the next few years. In fact, recent work suggests that the first such planets to be detected will be extremely volcanically active (Jackson et al. 2008b). In order to be detected, such small planets will have to have semi-major axes within a few hundredths of AU of their host star. Within such proximity to their star, rocky planets with even very small orbital eccentricities are likely to experience tidal heating comparable to or greater than Io's. Figure 2 shows the tidal heating for planets within 0.1 AU of an M dwarf host star (with a mass of 0.1 solar masses). For a wide range of orbital eccentricities and planetary masses, tidal heating rates exceed the heating of the Earth and even Io.

In short, tides affect the orbital and physical properties of planets in our solar system and in solar systems throughout the universe.

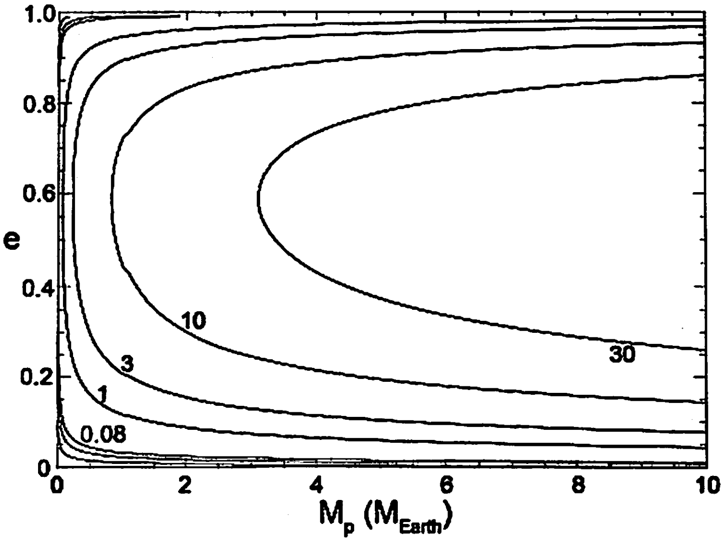

Figure 3: Tidal heating for a range of orbital eccentricity (e) and planetary mass (M_p) in Earth masses. The lines are labeled with tidal heating rates in W/m^2.

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Rip Currents

by David Choi

What is a rip current?

A rip current is a relatively strong flow of water directed away from the shoreline and out into the open sea. These currents are surface currents that do not flow underneath the surface to depth, like an undertow.

Why are rip currents important?

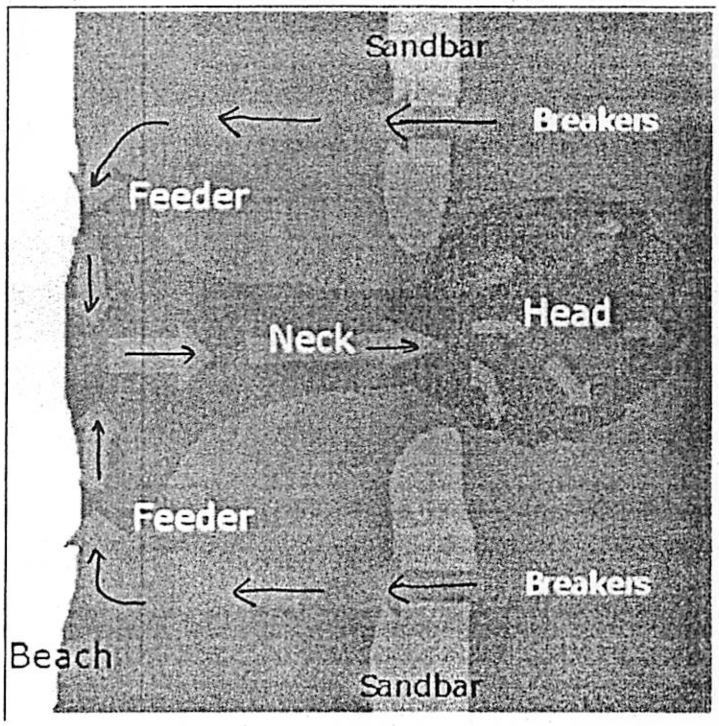
Because they can be deadly to swimmers or those wading in the water. The currents can be strong enough to pull even the strongest swimmers away from the shoreline, against their will. If people try to escape the rip current by swimming against the flow, they can quickly tire themselves out and drown. Over 100 die every year from rip currents, according to the US Lifesaving Association.

Where do rip currents form?

Rip currents are primarily seen along ocean shorelines, but can form wherever there is breaking wave action on a body of water. Typically they are located at or near a break or dip in a sandbar, or near any structure embedded along the shoreline (e.g. a pier).

How do rip currents form?

Essentially, rip currents form in order to establish a pressure and potential energy equilibrium between near-shore water parked in a channel between the beach and a sandbar, and the rest of the ocean.

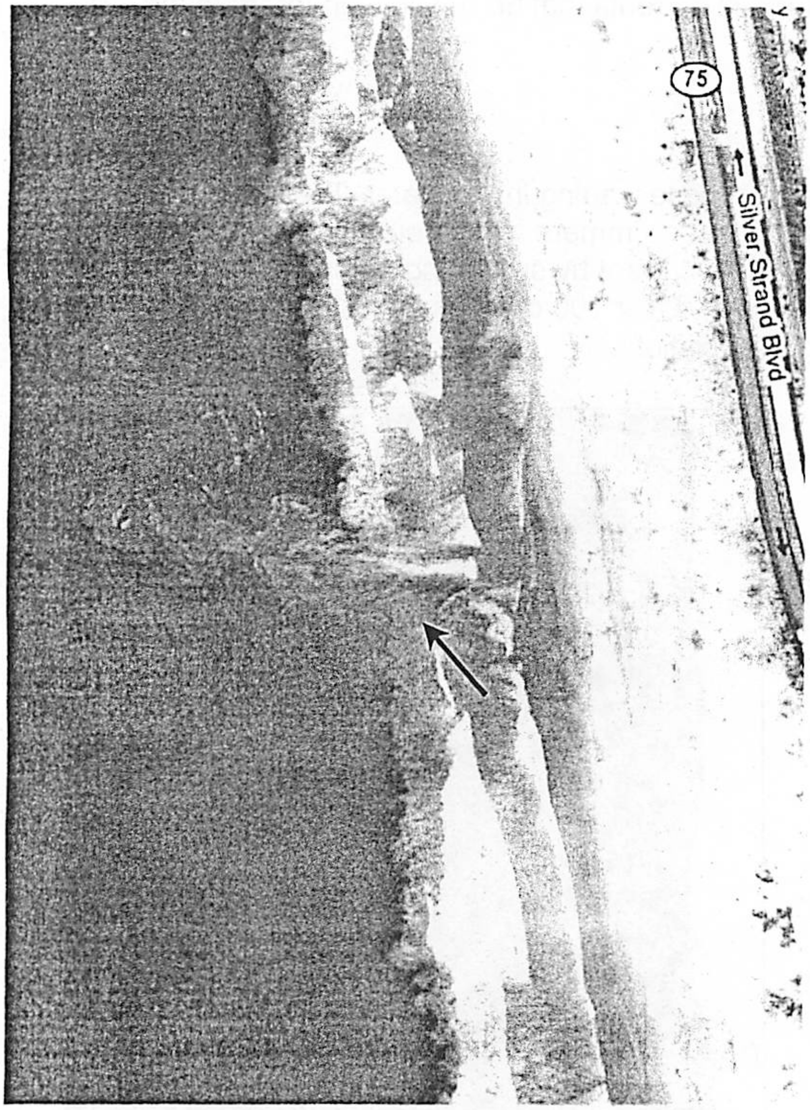


Schematic diagram for a typical rip current circulation pattern. Diagram courtesy of NOAA/NWS.

As incoming waves break over a sandbar, the water level in the channel (the area between the beach shore and the sandbar) increases, causing a pressure gradient. This pressure gradient drives a current parallel to the beach shore called a *feeder current*. Eventually, the feeder currents find a break in the sandbar, which is effectively an outlet for a release in the water pressure. Thus forming a rip current. However, rip currents can arise from complex circulation patterns created by variations in breaking wave activity.

What controls the intensity and spatial separation of rip currents?

Many factors: the tides, the wind, the direction and frequency of incoming breaking waves, the strength of these waves, the strength of the longshore current, the particular details of the near-shore topography (presence of sandbars, etc).



Satellite photo of Silver Strand Beach, California. The arrow indicates what appears to be a rip current. Note the nearly head-on direction of the incoming waves with the shore. Image courtesy of Google Maps.

Can we see rip currents without getting in the water?

Possibly. Look for a break in the incoming breaking wave pattern, as the outflow of the rip current acts to neutralize the waves. This break is typically accompanied by a narrow channel of foamy, but calmer water. Also look for a line of water that is a different color, or other debris that is caught in the current moving seaward. However, note that some rip currents don't exhibit any of these outward signs, so one should always be cautious.

What should I do if I'm caught in a rip current?

The important thing is DON'T PANIC. Another important thing is to not fight the current and try to swim against it directly towards the shore. You'll likely tire yourself out and increase your risk of drowning.

What you should do to get out of the current is either (a) **try to swim parallel to shore**, because the current is typically fairly narrow (10-20 feet), or (b) **drift with the current until it dies out in the open water, and then swim back**. Though keep in mind that the drift could take you tens, possibly hundreds of meters away from the beach before you try to start to swim back. However, the latest research (see below) indicates that drifting with the rip current could simply transport you back towards shallow water if you wait long enough, though it is too early to change the official advice.

Remember, a rip current is not an undertow -- rip currents are horizontal surface currents that flow outwards away from shore. They do not draw people deeper into the water.

What is some of the latest research on rip currents?

A team at the Naval Postgraduate School in Monterey, CA has mounted a campaign to deploy current sensors on the sea floor and GPS-enabled drifters in an effort to map rip currents and characterize their typical morphologies and velocities as a function of current and tide conditions. Their initial results indicate that there can be strong, persistent eddies that circulate in the surf zone (the area in between the shoreline and where waves begin to break), and that these eddies only rarely break and flow out into the open ocean. However, it is too early to tell whether this is a result of local beach conditions or could be a more universal picture.

Could there be rip currents elsewhere in the solar system?

Perhaps, but unlikely. It seems that in order to create a rip current, you need, for starters, waves on the body of liquid's surface, and typically this requires wind of sufficient strength for generation. The other factor that helps is sediment deposit (i.e. a sandbar) along a shoreline that would create an environment suitable for generating rip currents. In other words, a rip current depends on a pressure gradient by having a liquid at two different water levels. If there is no "potential well", per se, created by sediment deposit, then a rip current would be difficult, if not impossible, to form.

Mars and Titan are the only solar system bodies with probable past/present surface liquids. However, the case for rip currents on either body seems to be fairly weak. For Titan, the atmosphere/surface interaction environment (typical wind speed, liquid density, etc) do not appear conducive for surface and breaking waves on a surface of a polar lake/sea, as supported by evidence from *Cassini* RADAR and VIMS. An exception may be for rip currents induced by tides, though the exact velocity of the induced flow is difficult to constrain. Surface waves on a Martian sea/ocean are also unlikely, though the atmospheric conditions in the past are relatively unconstrained.

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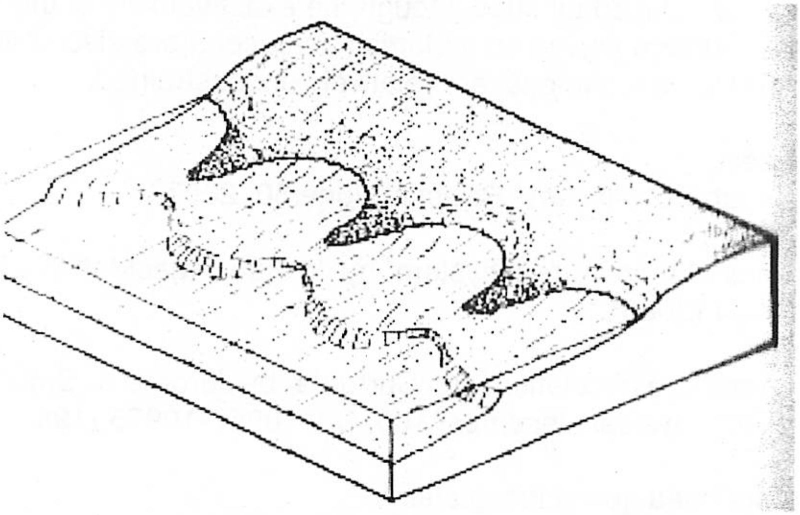
Beach Cusps

L. Ong

Observations and Morphology

- uniformly-spaced seaward-facing cusps (also called "swash cusps")
- wavelength 10 cm to ~20 m
- composed of ridges (perpendicular to shoreline) and bays (parallel to shoreline)
- Morphology dependent on:
    - o Sediment grain size
    - o Beach slope (also a function of grain size)
    - o Tidal range
- can form in any type of sediment (basaltic boulders, cobbles, sand, gravel, shingle beaches)
- sort sediment by grain size
    - o ridges/horns: coarser sediment
    - o bays: fine material
    - o creates differences in permeability: coarse material less erosive (high permeability dissipates energy)

Fig. 1: Image and schematic of beach cusps, illustrating bays and horns. From Komar (1998)



Observations of Formation

- cusps form within hours
- equilibrium spacing almost immediate
- alternating surge:
  - o water flows out of embayment, around horn, and into next embayment with successive surges
- uniform surge:
  - o water is divided into divergent streams by horns
  - o two streams join in center of embayment and recede
- formation from normal waves to beach? Wave direction disputed
- wave tank experiments show regular waves with long crest lengths best for formation

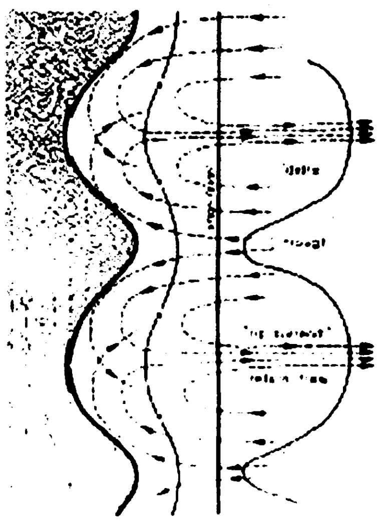


Fig. 2: Uniform surge motion observed by Bagnold (1940). From Komar 1998.

Proposed Formation Mechanisms:

Edge Waves

- rhythmic waves with wave fronts perpendicular to shoreline
- occur when a wave reflected by the shoreline is trapped by refraction and does not move on to deep water
- can travel with wave fronts perpendicular to coast ("progressive edge waves")
- "standing edge waves": superposition of two progressive edge waves moving in opposite directions, usually due to reflection off longshore boundaries

1. Standing Edge Wave Formation (Escher, 1937; Guza and Inman, 1975)

- cusps may form when edge waves and incident waves are superposed
- maximum swash run-up at antinodes of edge waves → bays due to erosion
- minimum swash run-up at nodes of edge waves → ridges due to deposition
- in most cases, periods: $T_{edge}=2T_{incident}$ (subharmonic edge wave)
- otherwise, $T_{edge}=T_{incident}$ (synchronous edge wave—usually when conditions for formation of subharmonic waves are unfavorable)

Subharmonic Edge Wave	Synchronous Edge Wave
$T_{edge}=2T_{incident}$	$T_{edge}=T_{incident}$
$\lambda_{cusp}=L_{edge}/2$	$\lambda_{cusp}=L_{edge}$

$$L_{edge}=\frac{g}{2\pi}T_{edge}^{\ 2}\tan\beta \text{ where } \tan\beta \text{ is the beach slope}$$

$\lambda_{cusp}=\frac{g}{\pi}T_{incident}^{\ 2}\tan\beta$	$\lambda_{cusp}=\frac{g}{2\pi}T_{incident}^{\ 2}\tan\beta$

- model fits observed cusp spacing (see plot below)
- but, cusps in this model do not grow after formation as observed

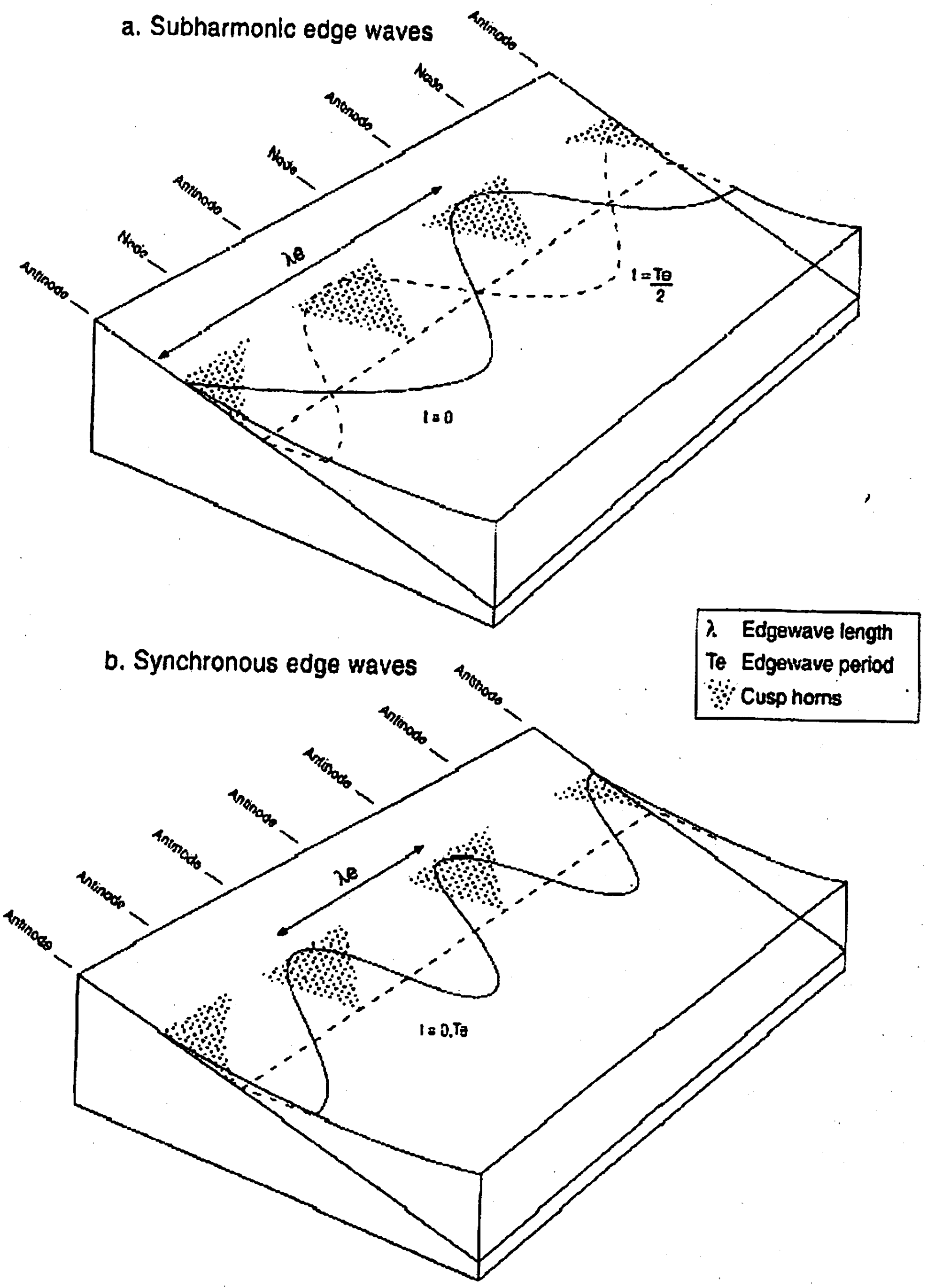


Fig. 3: Schematic of subharmonic and synchronous edge waves, and their effect on cusp formation. From Hughes and Turner (1999) after Komar and Holmes (1986)

2. Self-Organization Model (Werner and Fink, 1993)

- tested through simulations of wave swash, sediment transport, and morphological changes
- positive feedback mechanism: pre-existing topographic variations are sculpted by water flow
- erosion of depressions → bays
- water that moves over topographic highs is decelerated and deposits particles → horns

- if energy of the swells stays constant, a preferred cusp wavelength dominates
- "crash" analogy:
    - if bay is too small, wave crashes into wall, eroding particles
    - water slows and deposits particles to produce horns
    - when optimal wavelength is reached, wave does not crash into cusp, and system is stable
- wavelengths are similar to those predicted by standing-wave theory, and therefore also fit data
- predicts continued growth of cusps after initial formation time
- but, timescale is off: observed formation shows cusps form quickly and immediately have regular wavelengths

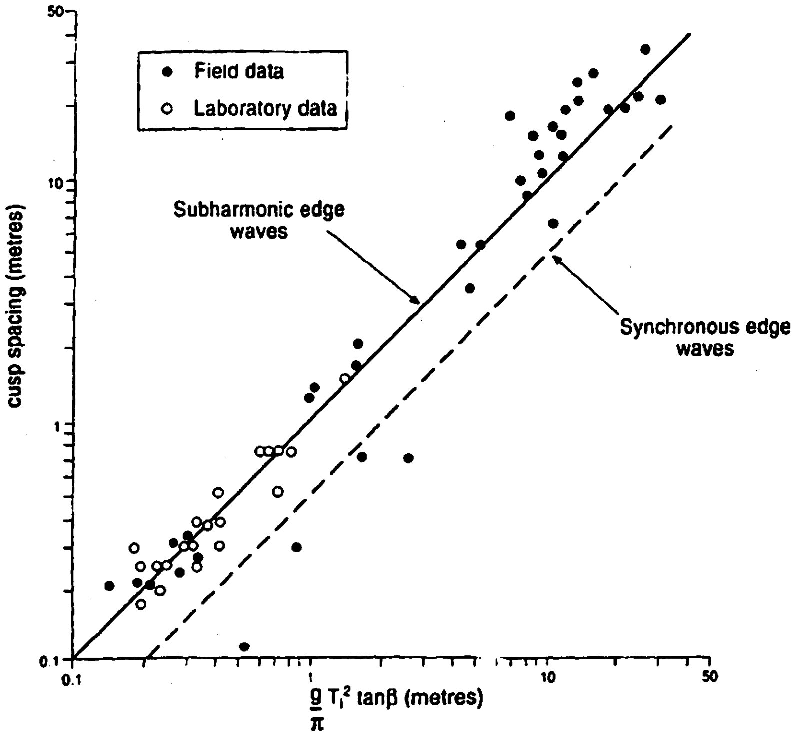


Fig. 4: Observed cusp spacing as a function of incident wavelength and beach slope. Observed field and laboratory data (circles) match predictions from the standing wave model for both synchronous and subharmonic waves.

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Beach migration: Erosion and Deposition

Priyanka Sharma

Beaches represent one of the most dynamic environments on Earth. A dynamic environment is one in which high levels of energy are expended over short periods of time, causing rapid change. For beaches, energy comes primarily from waves, wind, tides and currents.

Beach erosion is the wearing away of land or the removal of beach or dune sediments by wave action, tidal currents, wave currents, or drainage. Waves, generated by storms, wind, or fast moving motor craft, cause coastal erosion, which may take the form of long-term losses of sediment and rocks, or merely in the temporary redistribution of coastal sediments; erosion in one location may result in accretion nearby.

Important factors influencing beach movement/shape

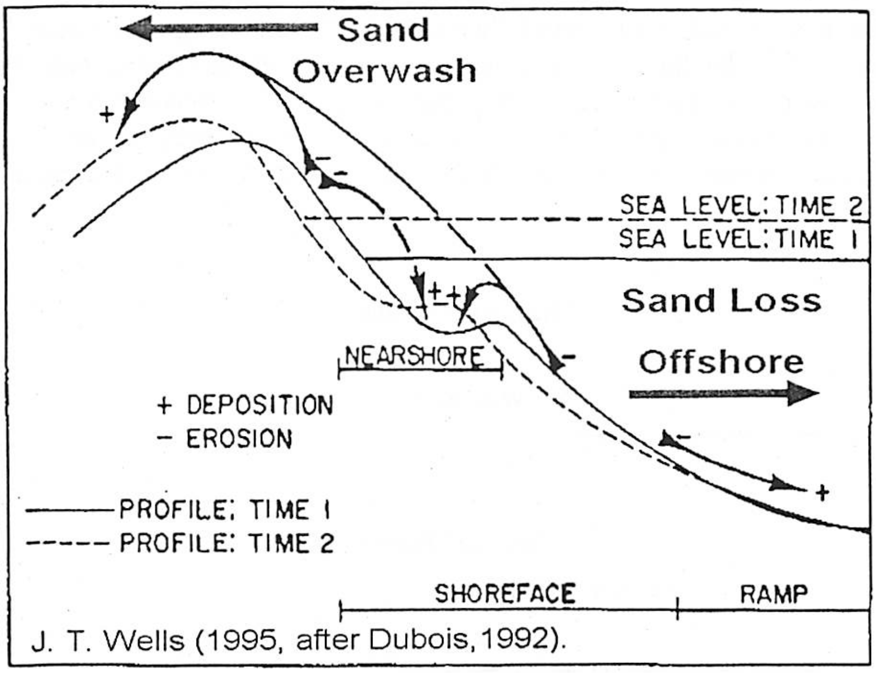
- **Sea-level rise:** Beaches transgress, or move landward, in response to sea-level rise. If sea level rises faster than sediment supply can keep up, beaches can disappear.
- **Seasonal effect:** Waves, currents, tides and winds are daily forces that influence the shape of our shorelines on time-scales that humans can plainly see.
- **Storms**
- **Underlying geology** can influence sediment supply, the pathways along which sediment may move, and where accretion or erosion takes place.
- **Sediment supply** is extremely important in determining whether a beach will erode or accrete
- **Development pressure** along beaches is usually very high because beaches are prime locations for living
- **Recreational usage** is also an important factor because of the popularity of beaches as tourist places

Beach movement in response to change in sea level

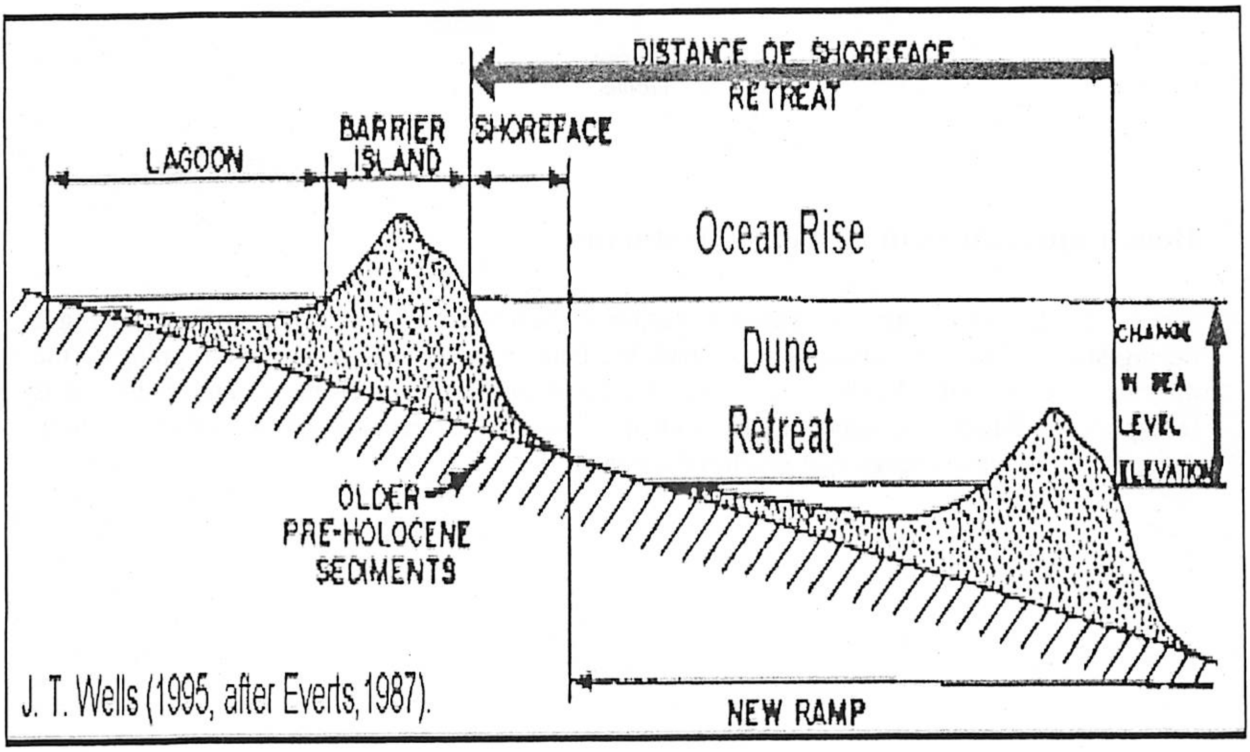
The greatest change in a beach is its response to the rise in sea level. As sea level rises, the beach must shift upward and landward, or be inundated. The latter is what happens to rocky shorelines like those of New England, which passively drown, although erosion may continually provide new material for continued beach formation. The rocks, however, have no ability to change their position or shape to accommodate the rising water. With time, the shoreline and beach position, the boundary between land and sea, will shift landward, or retreat.

Melting glaciers have had the most influence on sea level change during the past 20,000 years. Since reaching their maximum southern extent 20,000 years ago, most of the continental glaciers of the northern hemisphere, including those of North America, adding a huge volume of water to the ocean. The glaciers were more than a mile thick, over much of Northern America, northern Europe and northern Asia. The initial rate of ice melting and sea level rise was relatively rapid but has slowed significantly over the last five thousand years.

South of the glaciated areas, sea level generally rose as the glaciers melted, but in the areas that had been covered by thick ice, the wasting of the glaciers affected local sea level in a different way. During the Ice Age, land areas covered with ice were depressed due to the ice's mass. When the ice melted, the land surface rebounded and rose, resulting in a fall in sea level in these locales. Such global events have affected the ocean in the past several decades, and changes are taking place in the level of the sea now.



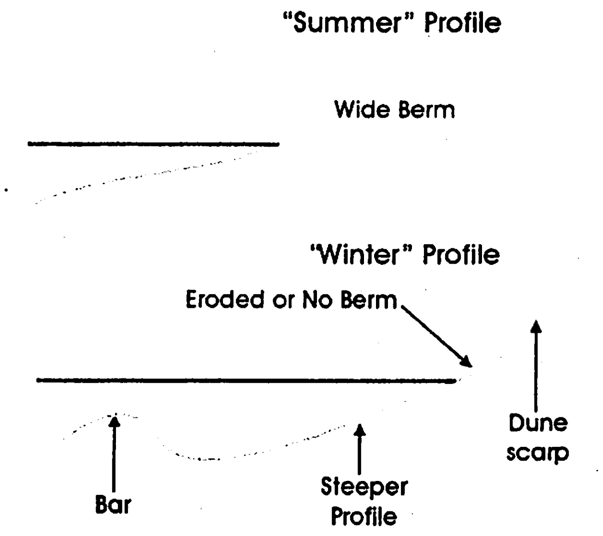
J. T. Wells (1995, after Dubois, 1992).



J. T. Wells (1995, after Everts, 1987).

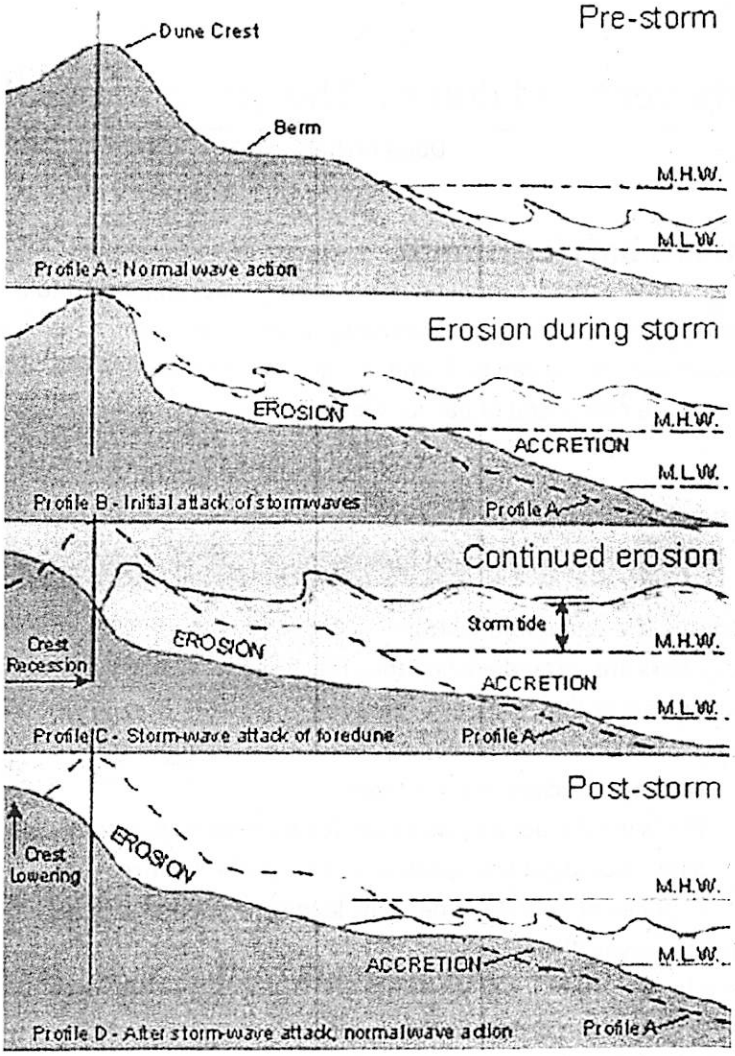
Seasonal beach movements

Beaches can have different shapes according to the season. Most beaches undergo seasonal variations from a lean, sediment-starved "winter" profile and a sediment-rich "summer" profile. Waves tend to be long and low in the summer and wash sand onto the beach, increasing the size of the backshore. During the winter, waves become higher and more closely spaced. They possess greater energy that erodes the backshore and carries sand away temporarily. Winter storms magnify the effect, as do tropical storms and hurricanes in the summer.



Beach movement in response to storms

Similar to the winter-summer shape variation in beach profiles, beaches undergo changes during storms. During storms, waves attack the berm and dunes, causing overtopping of the dunes and overwash. At the same time, the berm and dunes are eroded and sediment is transported offshore and deposited in sandbars. This causes waves to break farther offshore, decreasing the wave energy that reaches the beach.



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Beaches, washovers and dunes: The origin of barrier islands

Doug Archer

First of all, what is a barrier island?

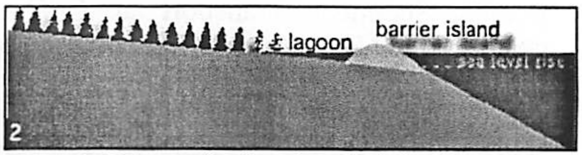
Barrier islands are long, thin islands of sand (and rarely gravel) that run parallel to a shoreline. They are wave and wind built and generally occur in mixed energy environments (tidal and wave motion). They are generally from 1-20km across and can be found along 15% of the world's shoreline. Most of the east and gulf coasts of the U.S. are comprised of barrier islands.

How are barrier islands formed?

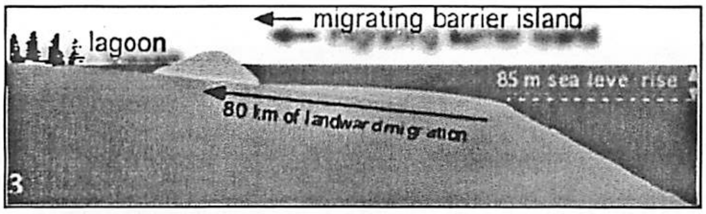
There are at least four theories for barrier island formation:

- Offshore bar theory (De Beaumont 1845):
    - Offshore bars are formed – when they reach sea level, aeolian processes build it up vertically and it is cemented by vegetation
    - There are problems with this theory
        - Not reproducible in wave tanks
        - If this were true, why don't we see their formation today?
        - Sand should get transported landward when bar reaches a certain height
        - Absence of nearshore deposits landward of barrier island
- Spit propagation theory (Gilbert 1885):
    - Spits are formed from longshore drift
    - Large storms cause a breach in the spit leaving a barrier island
    - This probably does occur but only explains a small fraction of barrier islands
- Higher Still Stand Theory (Leontyev and Nikiforov 1966):
    - Offshore bars are formed
    - Uplift or sea level drops exposes these bars which can then be cemented by vegetation.
    - Problems
        - Requires higher sea level than today – doesn't fit with most places based on climate record
        - Like above, the absence of nearshore deposits landward of barrier island
- Beach Ridge Submergence Theory (Hoyt 1967)
    - Dunes often form along beaches (think Pinacates and Baja)
    - Dune coalescence can create beach ridges that are higher than the surrounding terrain
    - Sea level rises and these dune ridges form barrier islands

Stage 1: Approximate 15, 000, when sea level was 85 meters below present beach ridges developed along the late Pleistocene shoreline which was much farther out along the continental shelf.



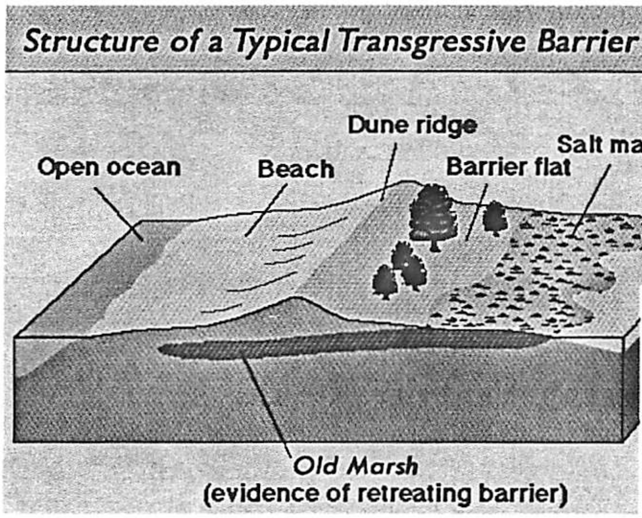
Stage 2. Rising sea level at the end of the Pleistocene results in breaching of the beach ridge and flooding of the region behind it. The beach ridge becomes a barrier island backed by a bay or lagoon.



Stage 3. The barrier system migrates landward across the shelf and sea level continues to rise.

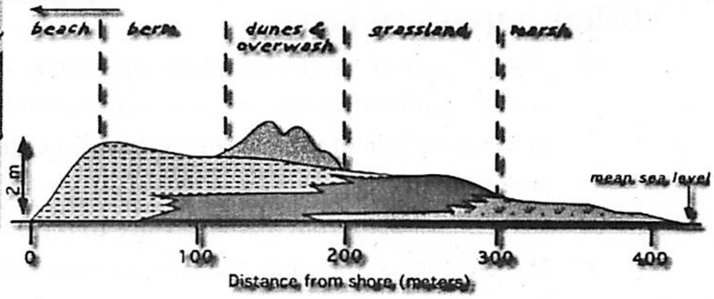
From : http://w3.salemstate.edu/~lhanson/gls214/gls214_barrier_isl.htm

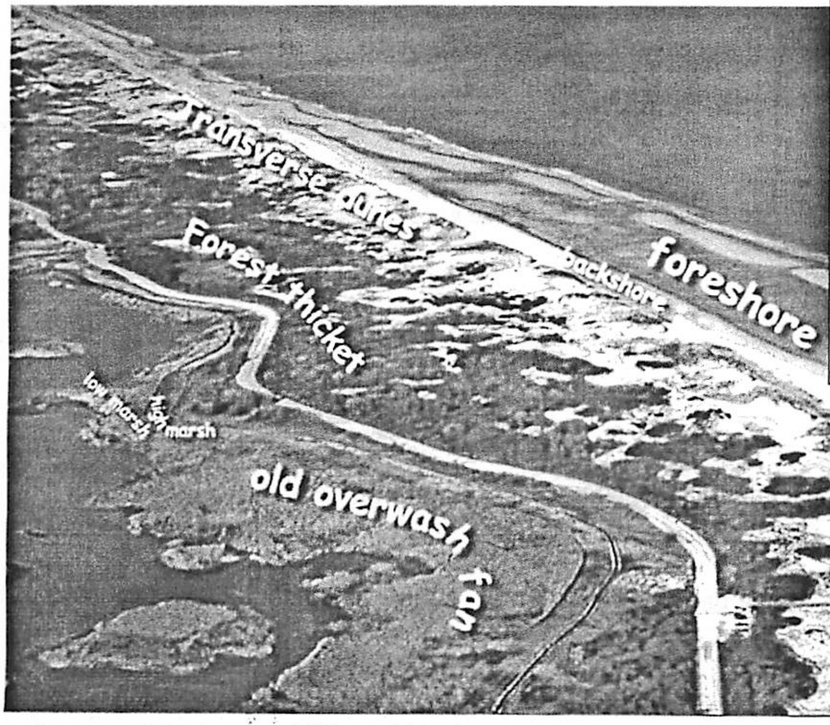
Anatomy of a Barrier Island



From : http://www.cofc.edu/CGOInquiry/Graphics/barris.jpg

From : http://w3.salemstate.edu/~lhanson/gls214/images2/barrier_x.jpg





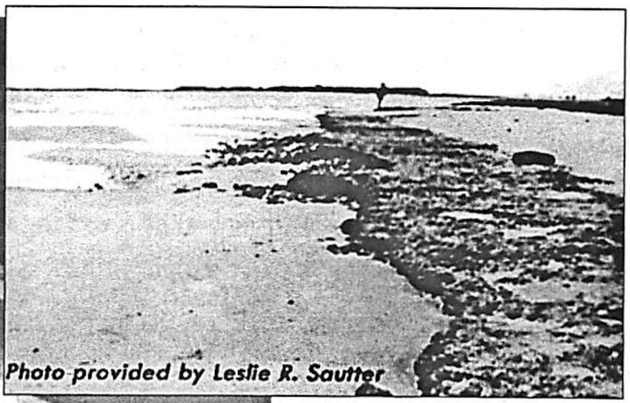
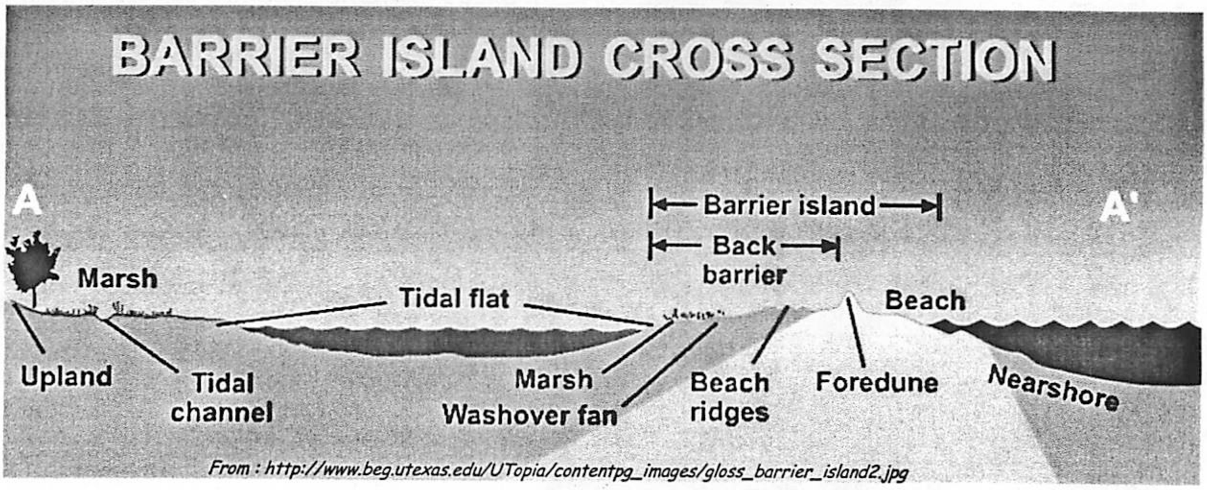


Photo provided by Leslie R. Sautter

From : http://www.cofc.edu/CGO Inquiry/Graphics/mud.jpg

From : http://w3.salemstate.edu/~lhanson/gls214/images2/plumismorph.jpg



From : http://www.beg.utexas.edu/UTopia/contentpg_images/gloss_barrier_island2.jpg

Other important facts:

- Washover /overwash – occurs during storms. An important process for transferring sediment into the back barrier region. Forms overwash fans from a breach in the dune face. This is the primary method of removing sand from a beach and results in a barrier island that, on average, conserves mass.
- Wind blows sand from the beach face to the back barrier region.
- The majority of barrier islands are less than 7,000 years old
- Transgressive island move shoreward. Net flux of sand is towards land.
- Regressive islands move seaward. Sand is supplied to the barrier islands faster than sea level rise.
- Many barrier islands along the coasts of the U.S. are in danger. There are three possible causes:
    - The rate of sea level increase causes island migration
    - Disruption of longshore movement by man-made structures
    - Lack of sand influx from the continental shelf to replenish the barrier islands
    - Moving islands is **bad** for developed islands. Oh no! there goes my house!

References:
NOAA website. http://www.csc.noaa.gov/beachnourishment/html/geo/barrier.htm

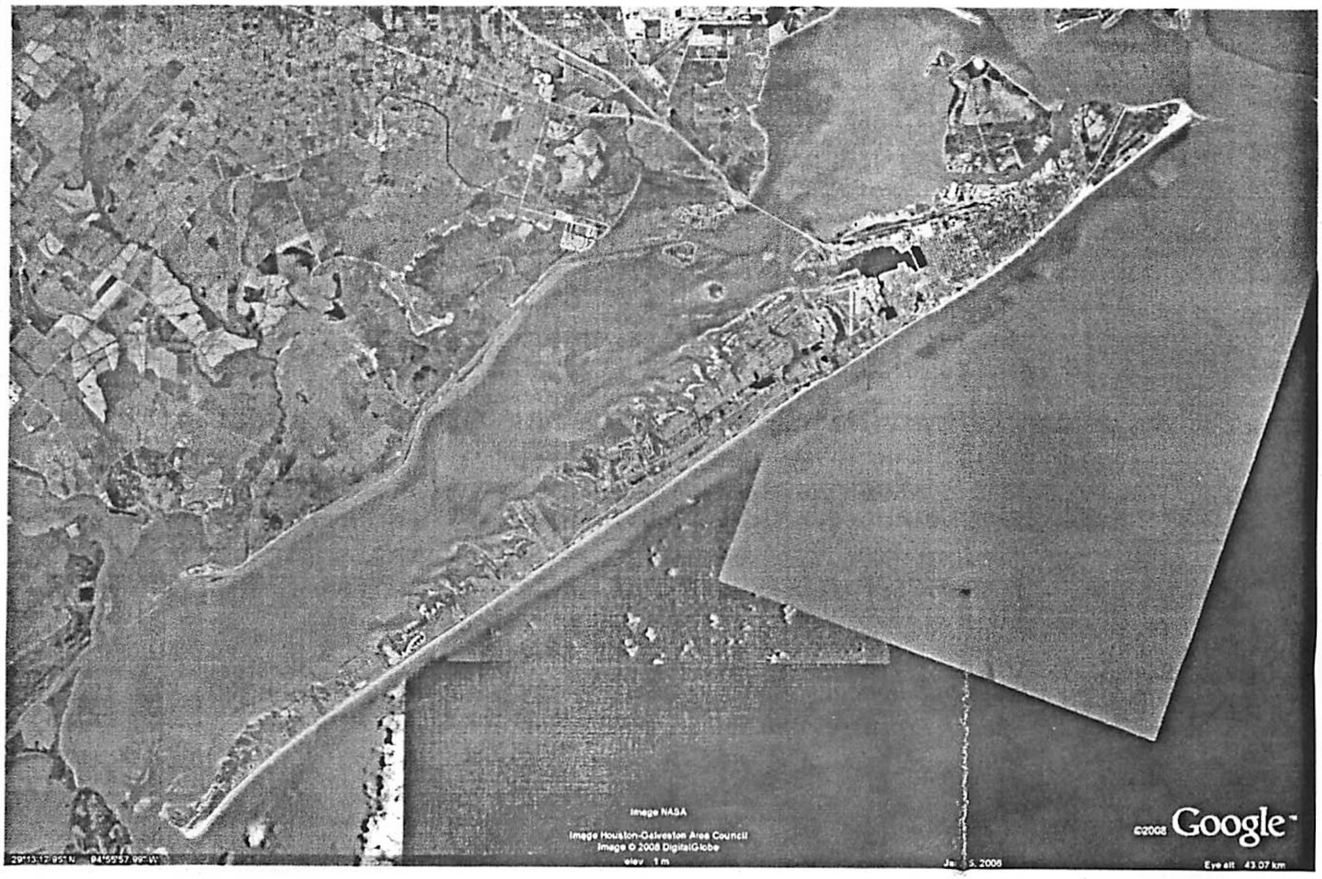
Salem State Geology Department website.
http://w3.salemstate.edu/~lhanson/gls214/gls214_barrier_isl.htm

Examples

http://www.erdc.usace.army.mil/pls/erdcpub/docs/erdc/images/estuary.jpg

http://bp3.blogger.com/_uxjGd2-aWiY/R0A_CLOl1zI/AAAAAAAAAx0/Ajq9BDOlcB0/s1600/National%2BSeashore.jpg

Taken of a barrier island in Cape Hatteras National Seashore, North Carolina

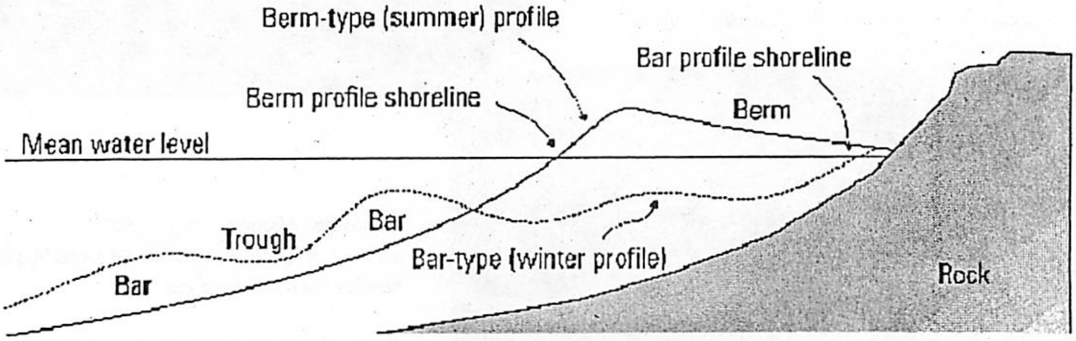


Bars, Spits, Lagoons and Estuaries:

An Introduction by Tom Schad
LPL Spring 2008 Geology Field Studies Trip

BARS

Sometimes referred to as shoals, bars are regions of sediment buildup usually exhibiting a linear formation near depositional coast lines and are most often parallel to the shore. Wave breaking against intermediate sloping beaches works through turbulence to carve out troughs. The eroded sediment forms large bars. Bars are also found in rivers and lakes.



Seasonal differences in sediment transport due to changes in wave energy generates a bar formation/destruction cycle. Sandbar formation is still actively studied through observations, modeling, and wave-pool experiments. These studies depend upon detailed studies of wave dynamics and boundary layer theory.

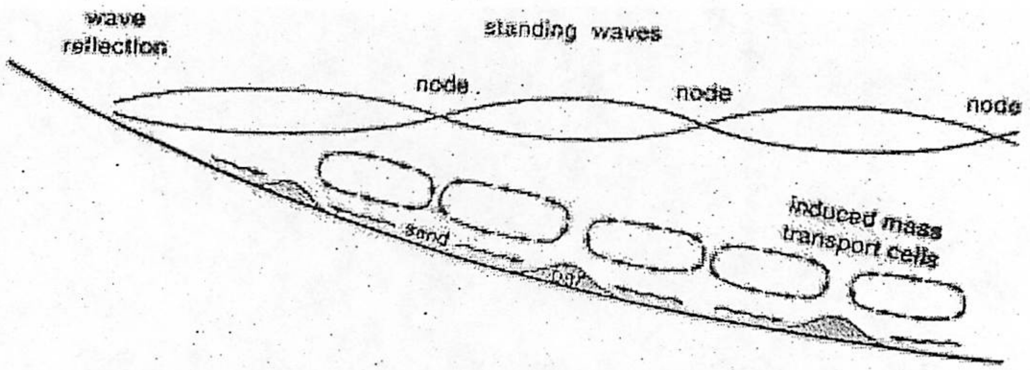
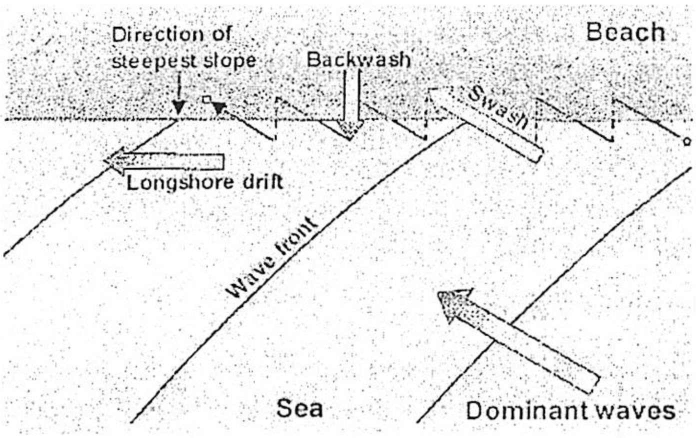


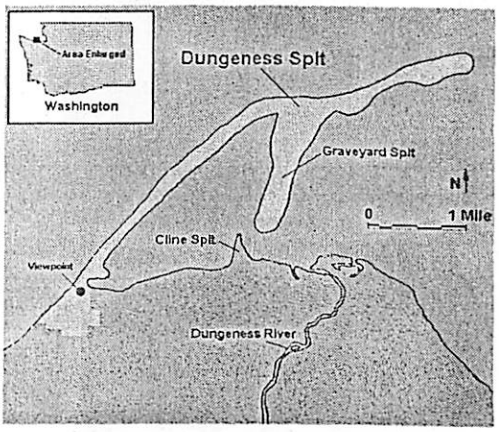
Figure 7-27 Schematic diagram illustrating bar formation associated with standing waves due to wave reflection from the beach. The standing waves form an envelope of surface-amplitude variations, with zero amplitudes at the nodes and maximum amplitudes at the antinodes. The mass transport of water associated with the standing waves forms a series of cells, with the bottom current flowing from node to antinode positions. Sediment carried by the mass-transport currents can be expected to accumulate as bars at the antinodes where the currents converge.

Bascom, W. *Waves and Beaches*. Anchor Press/Doubleday, Garden City, New York. 1980.
Komar, Paul D. *Beach Processes and Sedimentation*. Simon & Schuster, 1998.

SPITS

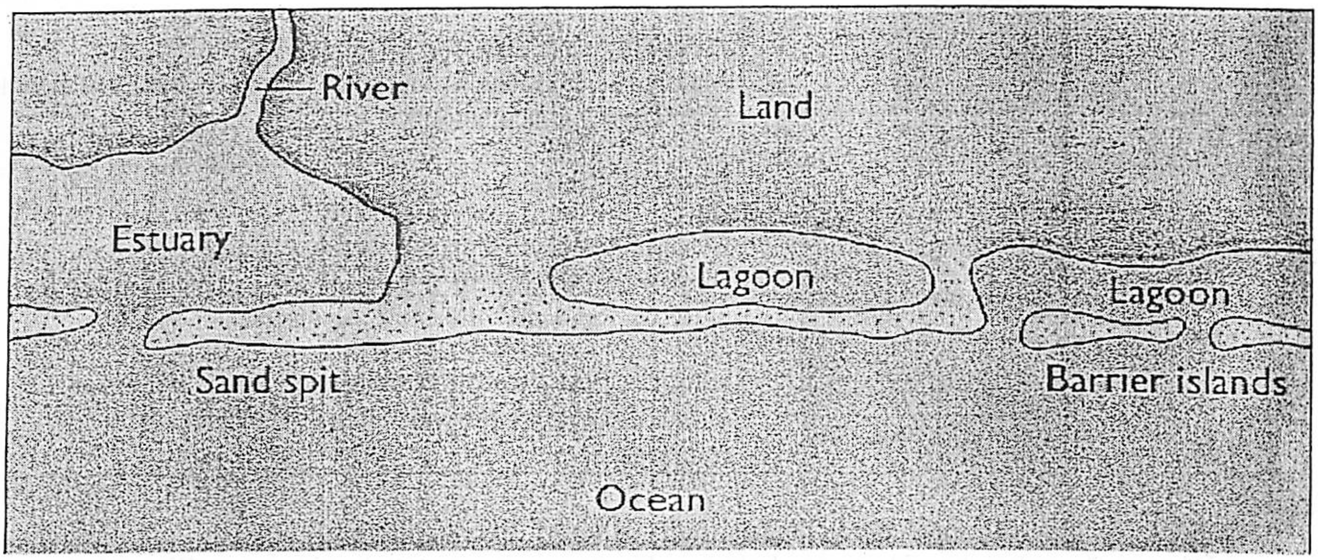
A spit is a particular type of bar that develops primarily through longshore drift deposit often at a prominent indentation in the coastline. Spits, as primarily linear type bars, are characteristically connected to the mainland at one end while terminating at the other in the open water.





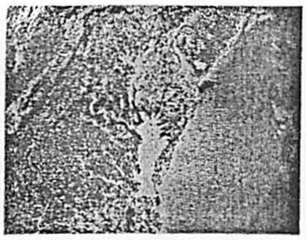
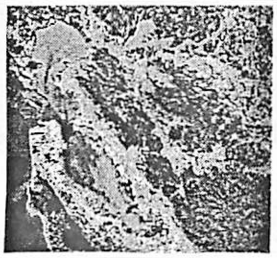
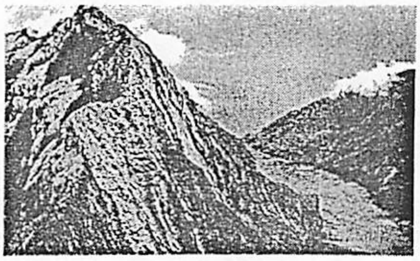
LAGOONS

A lagoon is an enclosed coastal body of water that is comparatively shallower than the sea it borders. Its water is salt or brackish in composition and is delineated from estuaries through the absence of a fresh water source. Coastal lagoons are often formed when a bar is formed across an indentation of the coastline through longshore drift. Lagoons are also formed in regions of coral grow when a reef separates a body of water from the sea or when the center of an atoll subsides.



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 fresh water derived from land drainage."
D.W. Pritchard (1967)

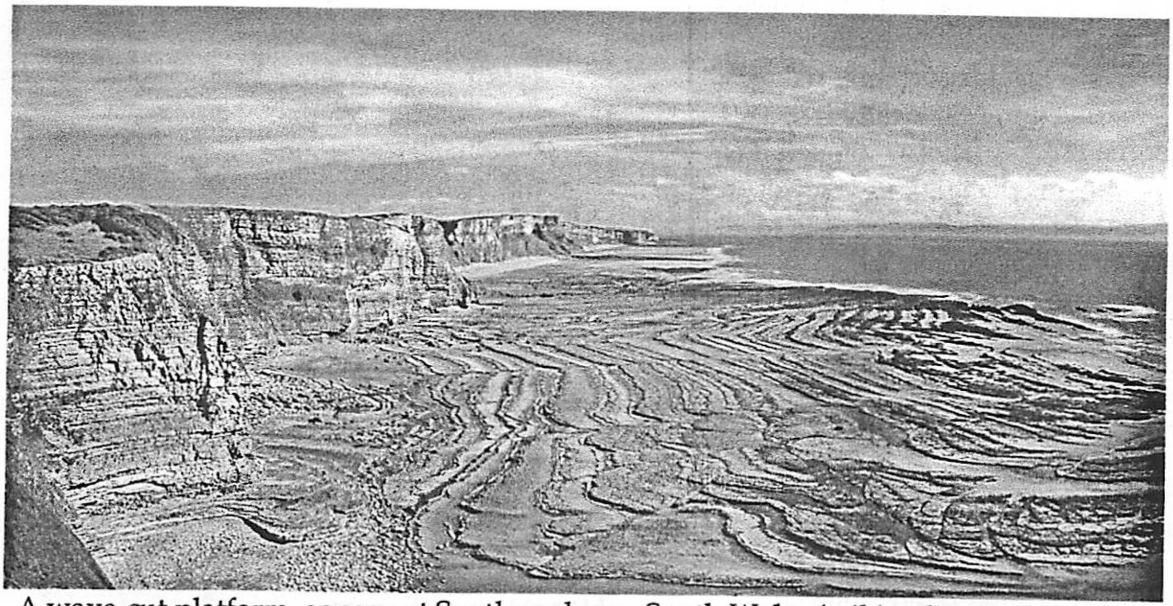
	**Coastal Plain Estuaries** Rising sea levels at the end of the last ice age, about 15,000 years ago, claimed low-lying coastal river valleys. *Locations (e.g.):* Narragansett Bay (RI), Chesapeake Bay (MD), Delaware Bay (DE), Thames River (England), Ems River (Germany), Seine River (France), Si-Kiang River (Hong Kong), and Murray River (Australia).
	**Tectonic Estuaries** Crustal faulting or folding can sometimes cause sinking of land near the coast below sea level allowing for tectonically formed estuaries. *Locations (e.g.):* San Francisco Bay
	**Bar Built Estuaries** Bar-built estuaries are formed when sandbars build up along the coastline. These sand bars partially cut off the waters behind them from the sea. Bar-built estuaries are usually shallow, with reduced tidal action. Wind is frequently the most important mixing tool for the fresh and salt water. This *Locations (e.g.):* Texas and Florida Gulf coasts (East Matagorda Bay), The Netherlands, North Carolina (Albemarle Sound and Pamlico Sound).
	**Fjords (Glacial)** Glacial cut valleys often can lead to estuary formation. A shallow mouth governs the mix of sea and fresh water between the ocean and what are often deep fjords. *Locations (e.g.):* coasts of Chile, New Zealand, Canada, Alaska, Greenland, Norway, Siberia, Scotland, and other countries.

Estuaries, being rather protected environments, support diverse habitats and are vital components of the marine ecosystem. They also help regulate toxics from continental rivers, filtering the water before flowing into the sea. Estuaries also provide helpful buffers from flooding.

"Estuarine Science." Narragansett Bay Commission. University of Rhode Island.

MARINE TERRACES

Andrea Philippoff



A wave-cut platform, as seen at Southerndown, South Wales (wikipedia.com).

What is a marine terrace?

-a flat area carved by wave action often seen at the base of sea cliffs

-also called a wave-cut platform or shore-platform

-(and, according to Peter Lanagan in the 2002 field trip guide, marine terraces are also exterior platforms on buildings useful to amphibious troops as sniper positions)

Formation

-when waves with enough energy continually crash into the base of a sea cliff, they begin to erode material away from the base of that cliff

-over time, they can form a "wave-cut notch", which can turn into a cave

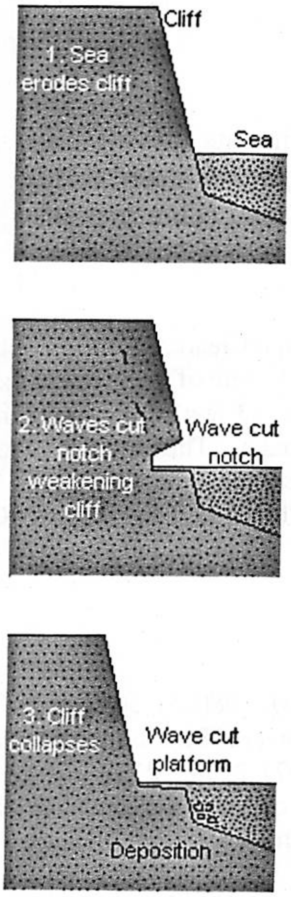
-if the cave gets too large (from continued wave action and freeze-thaw weathering, climate-permitting), it will collapse under the pressure of the over-lying rock

-results in landward cliff-retreat

-the base of the cliff becomes the roof of the terrace

-rubble from the collapsed cliff face may be washed out to sea to form an off-shore terrace

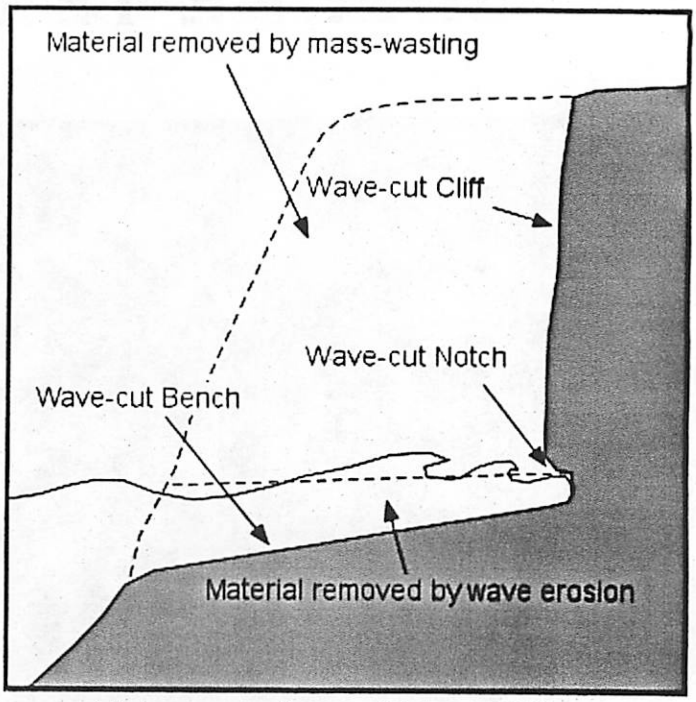
-step-like morphology results from repeated seismic events



Marine terrace formation.
wikipedia.com

Marine Terraces: Geologic Secretaries

-contain records of past sea levels
-document seismic activity from earthquakes and isostatic rebound along coastlines
-though global sea level is currently rising, in places with marine terraces, locally it appears that sea level is falling – though it is really the *land* that is rising, not sea level
-various dating techniques may be used to constrain the timing, as well as the magnitude, of these events

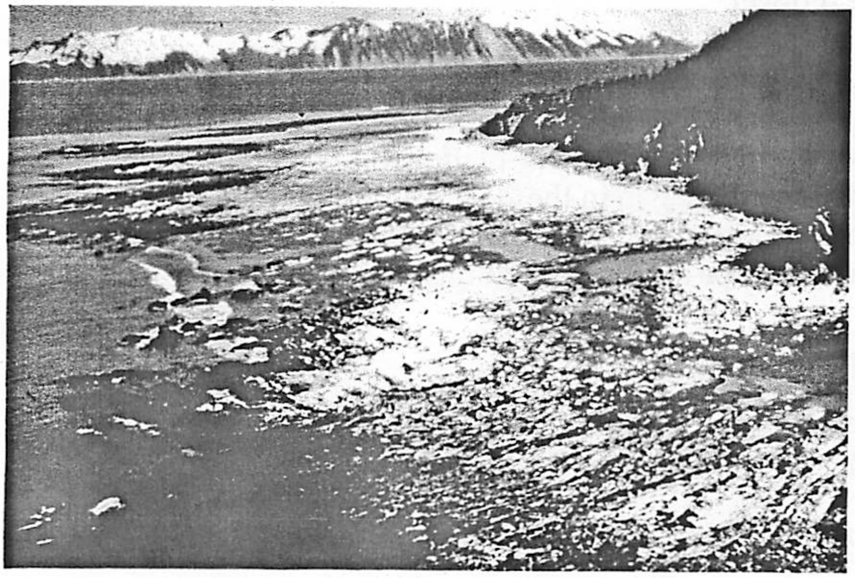


Marine terrace diagram (Nelson, 2003).

Planetary Connection

Mars
-ancient ocean?
-proposed (though highly contested) shorelines (Head et al., 1999; Withers and Neumann, 2001; Carr and Head, 2003; Perron et al., 2007)

Titan
-methane ocean
-marine terraces?
-wind tunnel experiments indicate that kerosene (an analogue for Titan) builds larger waves than water (Lorenz et al., 2004)



Uplifted sea floor, Cape Cleare, Montague Island in Prince William Sound. Site of the greatest recorded tectonic uplift on land (33 feet), from the March 27, 1964 Alaskan earthquake. The newly exposed surface is ~0.25 miles wide.
floorhtmllib/batch07/batch07j/batch07z/aeq00001.jpg

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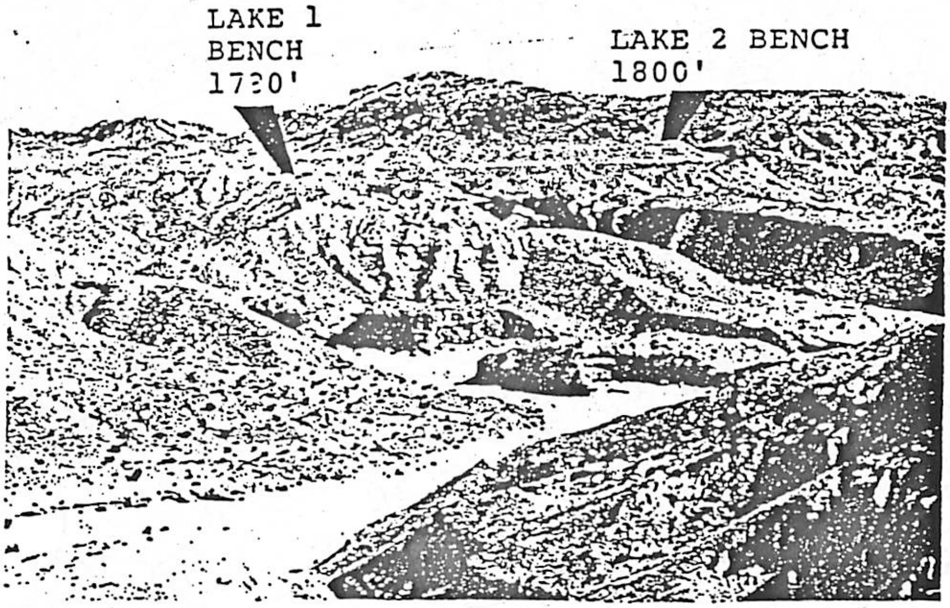
floorhtmllib/batch07/batch07j/batch07z/aeq00001.jpg

wikipedia.com

Reprinted from the LPL 2002 Beach Processes Field Guide

Manix Lake Gravel Bars
Felipe Ip

As Manix lake filled during one of the glacial stages, the surrounding rivers were forced to deposit their sediment in deltas around the edges of the lake and the center of the lake received only clay deposits. Above the lake deposits is another set of river deposits marking the draining or evaporation of the lake and the advancement of the surrounding rivers into the center of the playa. Gravel bars are found on shores attacked by the high energy of large waves. Waves action was generated by winds toward the shores. Some of the gravel beach bars can be observed at Stop #2 in Map No. 1 on the next page. Two well–developed wave–cut benches occur across the major drainage from the beach bar and elsewhere around the margin of the basin. See figure below.



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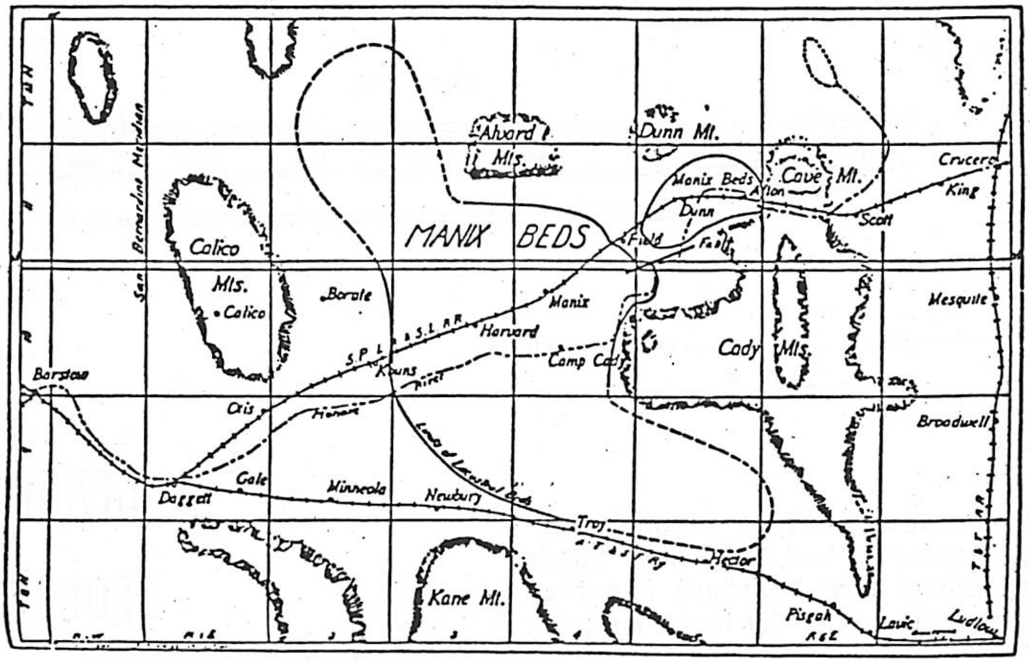
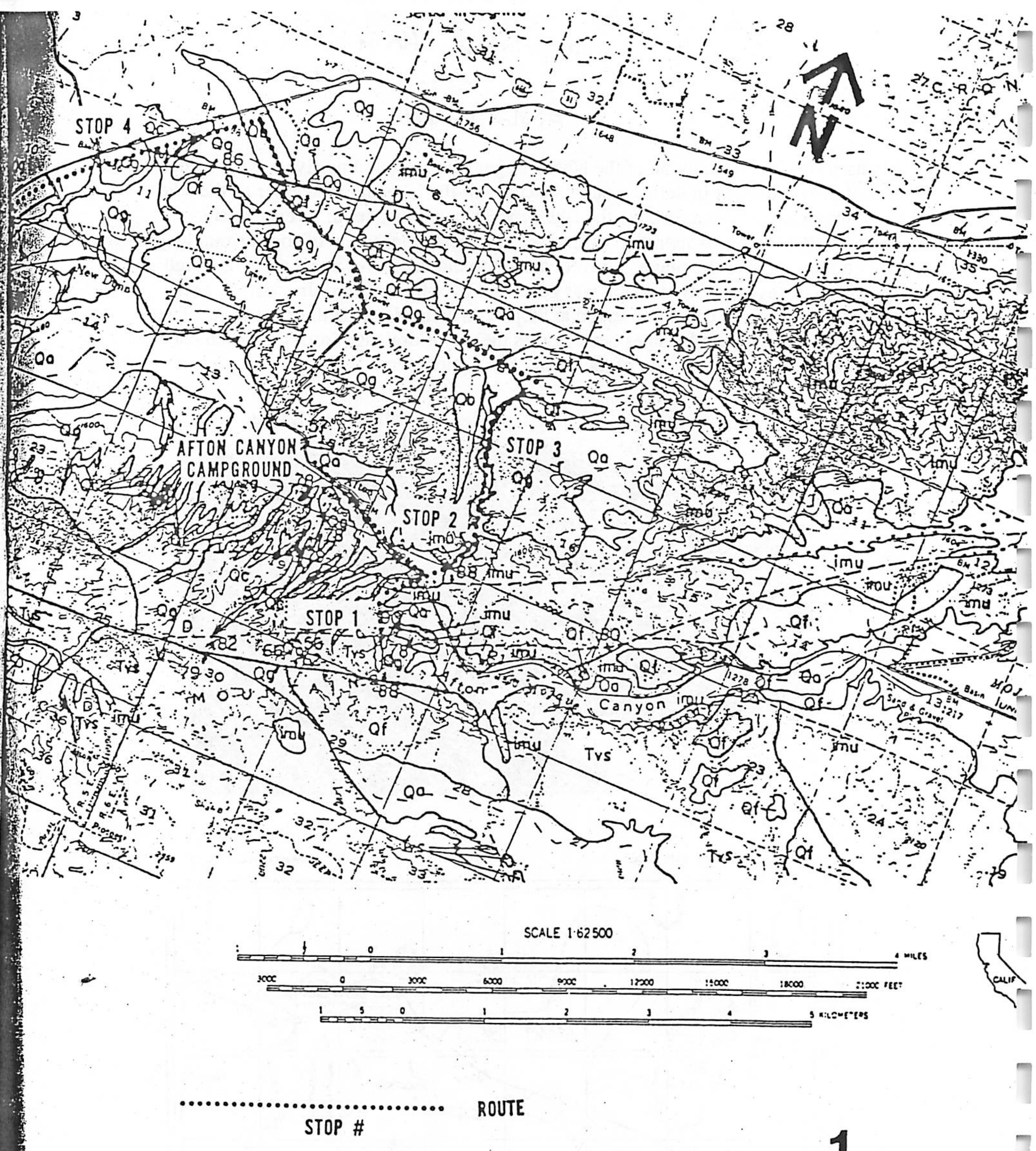


(From Buwalda, 1914)



Topographic base: parts of Alvord Mtn, Cave Mtn, Newberry, and Cady Mtns Quads. Geology modified from Southern Pacific Co 1958 Areal Economic Geologic mapping.

'02
75

1.

GENERALIZED GEOLOGIC MAP

MANIX FAULT ZONE

82

Ref: Keaton and Keaton, 1977

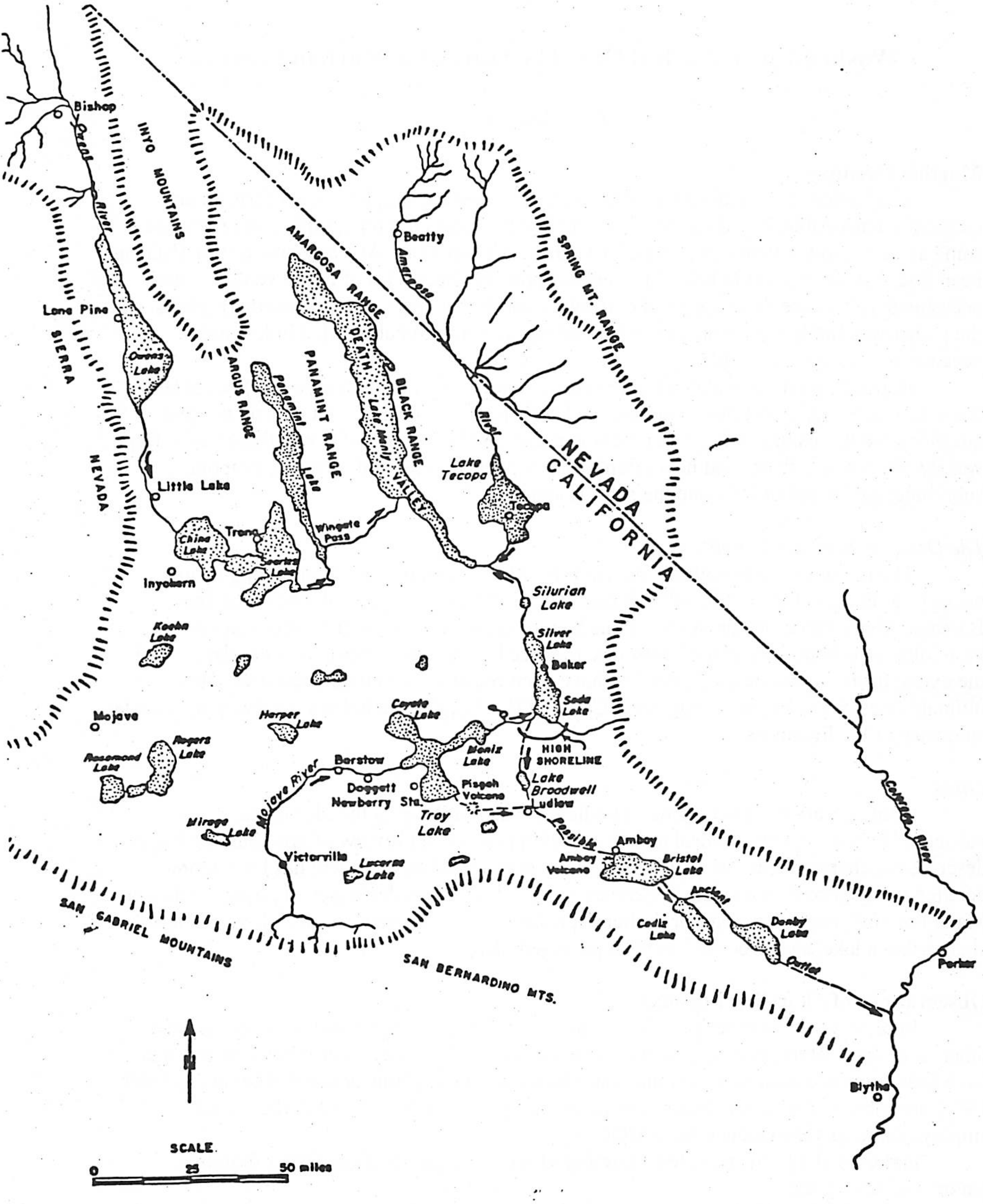


Figure 2. Pleistocene drainage in the Mojave Desert (modified from Blackwelder, 1954).

Figure 2.

Washed Up or Washed Out: The Search for Martian Beaches

Colin Dundas

Martian Oceans

The basics of the main Martian ocean hypotheses are simple, straightforward and eminently reasonable, based on the following logic: 1) Mars has topography, and therefore, some areas are lower than other areas. 2) There is H_2O on Mars. At least some of this H_2O has been liquid at some point in time. 3) There has probably been a lot of liquid water, at least occasionally, because there are giant outflow channels that empty into the northern plains, and the planet was likely once warmer. 4) All that liquid water probably filled in low areas, because it was, in fact, liquid.

Depending on the scale and your taste in terminology, the outcome of 4) could be described as "mud," "puddles," "ponds," "lakes," "seas" or "oceans." Of course, the real questions are things like: where was the water, exactly? how much of it was there? how deep was it? when was it there, and how often? what happened to it—did it freeze, evaporate, sublimate, get buried or infiltrate the subsurface?

The Oceanus Borealis Hypothesis

The major ocean hypothesis put forth for Mars is that of a northern-plains-filling ocean (e.g. Parker et al., 1989, 1993; Baker et al., 1991), occasionally dubbed Oceanus Borealis. Many variations or twists on this hypothesis are possible—it has been linked with past volcanic outbursts or glacial episodes, proposed at various scales (i.e. water depths and the extent of the shoreline), suggested to have occurred at various times, and a variety of ultimate fates have also been suggested. Carr and Head (2003) includes a relatively up-to-date summary of the literature.

Lakes

Another variant in the theme of bodies of water on Mars is the idea of lakes, particularly filling craters. Cabrol and Grin (1999) give a brief review of previous work and describe the characteristics of 179 possible former crater lakes, and there has been more detailed work since then as well. (There are many other papers dealing with possible lakes on Mars. For any given Hesperian-or-earlier depression on the Martian surface, there is a fair chance that a lake, sea or ocean has been proposed there).

Observations of Shoreline Features

In order to answer the specific questions posed above, observations of beaches and other shoreline features are needed in order to determine the water level. Shoreline features have been proposed mainly in conjunction with the northern plains ocean; Parker et al. (1989, 1993) are some of the major discussions of the subject, and Clifford and Parker (2001) employs some newer evidence from MOC.

Parker et al. (1993) reported a number of morphologies and suggested shoreline features as analogues:

- Plains unit boundaries suggested as strandlines.
- Stepped massifs with encircling aprons: possible wave-cut benches.

- Curvilinear ridges, up to 10s of km long and 2 km wide: possible spits and coastal barriers formed by transport of sediment parallel to a coast.

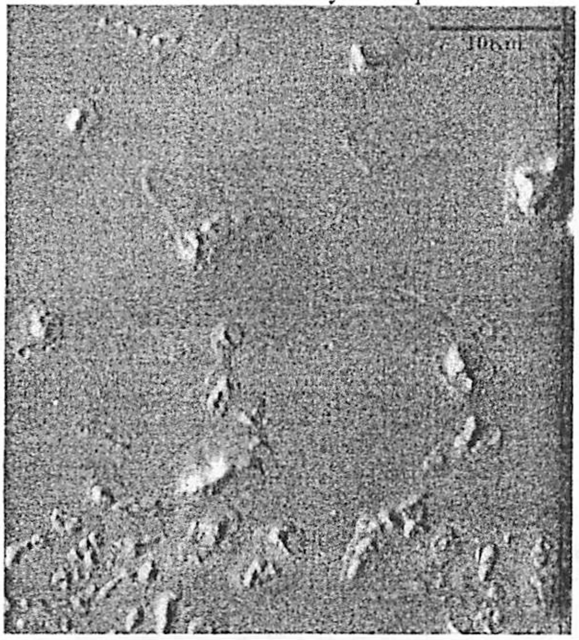


Figure 1: Stepped massifs in Cydonia (Parker et al., 1993)

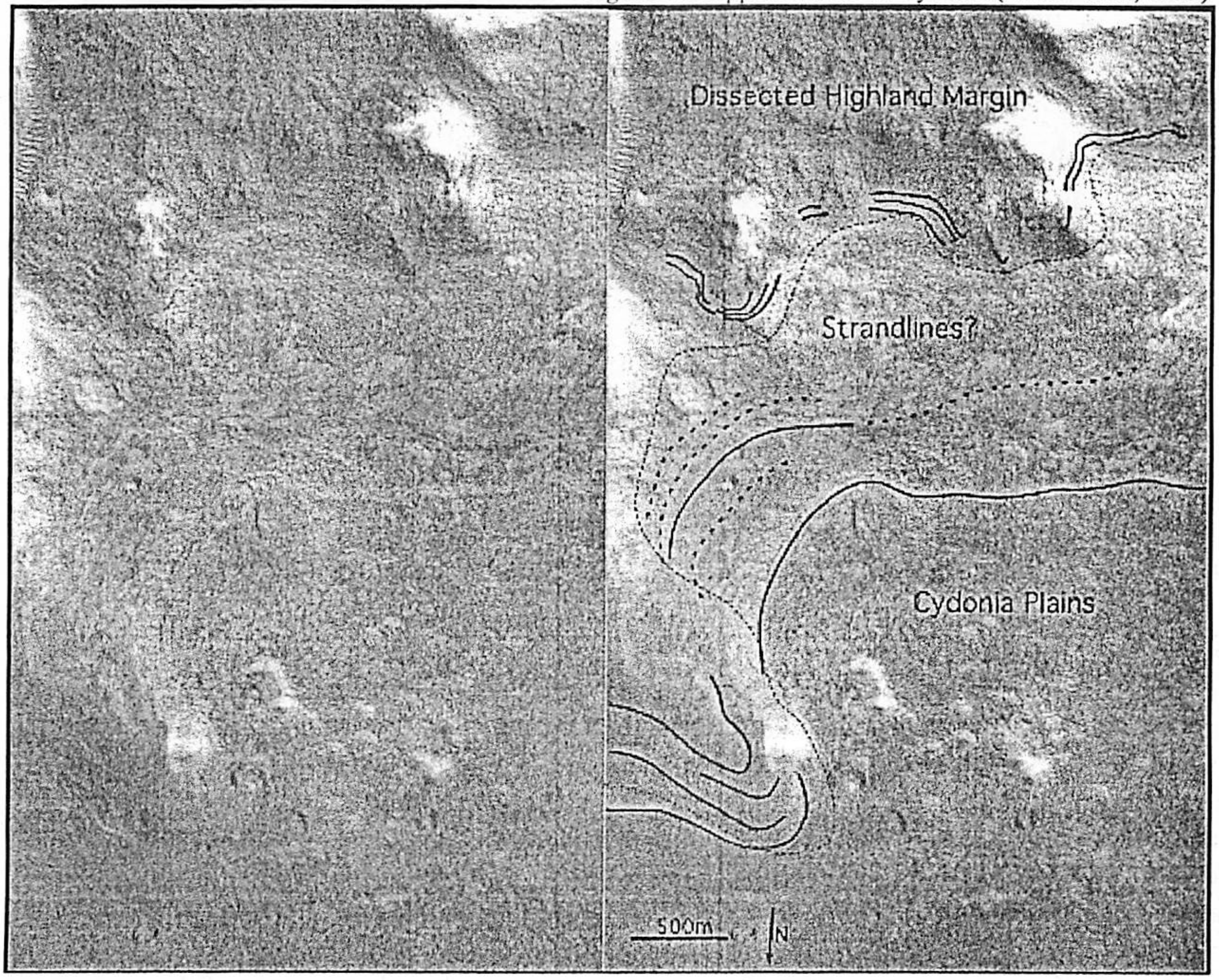


Figure 2: Proposed shoreline features (strandlines) on Mars from Clifford and Parker (2001).

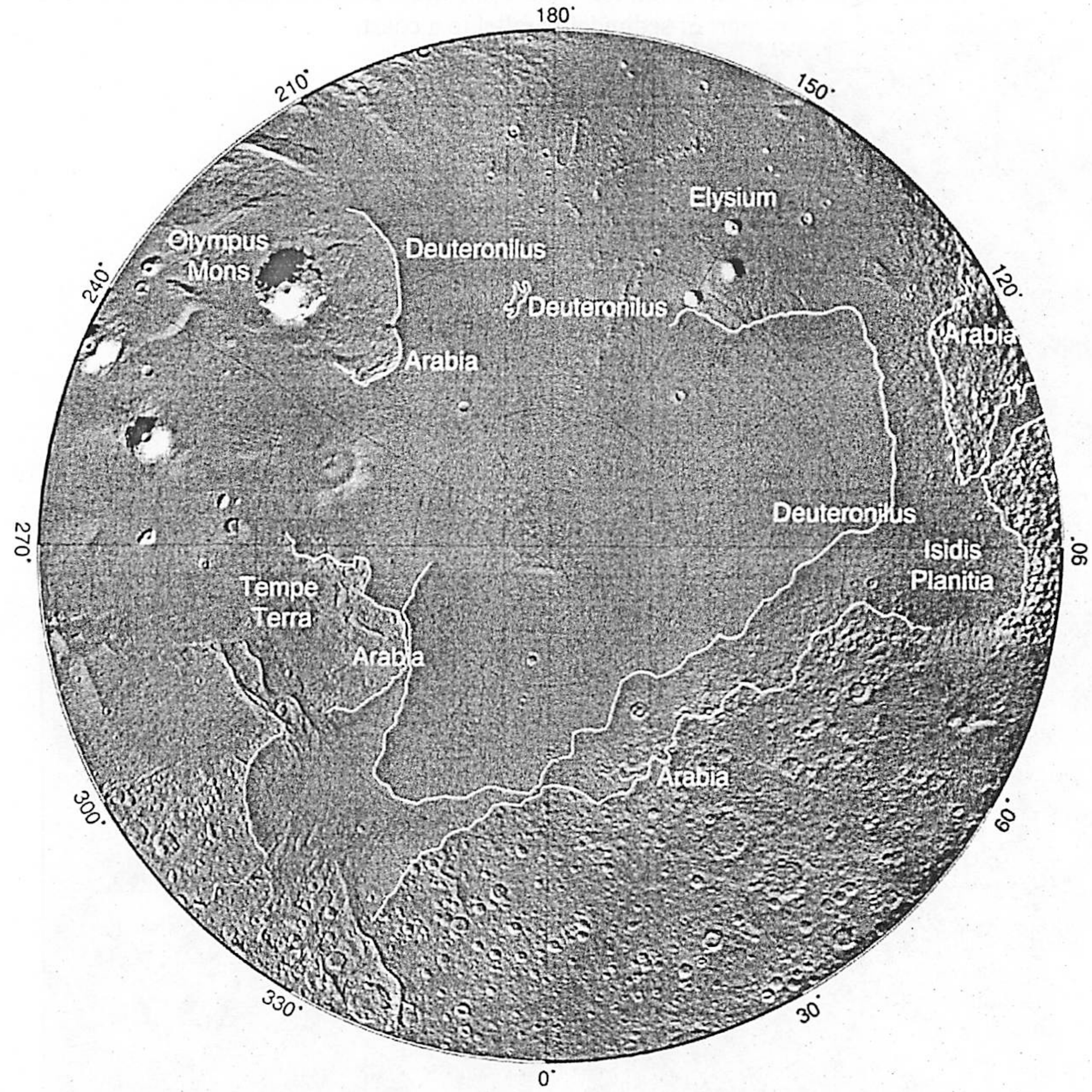


Figure 3: Proposed shorelines of Clifford and Parker (2001) as plotted by Carr and Head (2003).

Malin and Edgett (1999) used MOC images to assess many of the proposed coastal features, and concluded that while many of the contacts correspond to boundaries between geomorphic units, none was conclusively due to the occurrence of a shoreline. In many cases, coastal geomorphic hypotheses were refuted, as some of the contacts were in fact scarps facing in the wrong direction. Carr and Head (2003) and Tanaka et al. (2003), with a broader available data set, reached similar conclusions. Suggested spits appear to be deformational features, and proposed wave-cut benches look more like mass-wasting features. Ultimately, Parker (2008) has also concluded that the shoreline contacts more closely resemble the edges of lava or debris flows. While large volumes of water may have once ponded on Mars, current geomorphic features do not appear to preserve any fine-scale shoreline features.

One further intriguing set of analyses has used topographic observations of the shorelines. Head et al. (1998) found that while the outer Contact 1 of Parker et al. (1989) has elevation variations of order 6 km, the inner Contact 2 is close to an equipotential surface. However, Carr and Head (2003) note that the northern plains in general are quite flat, so many contacts running through them will also be near level. Perron et al. (2007) found that an appropriate polar wander event could bring the contacts closer to level, but in the absence of evidence that the contacts are actually shorelines, the relevance of this is uncertain.

Shoreline features have also been suggested around possible lakes. Most compelling is the observation of river deltas now preserved in inverted relief (e.g. Malin and Edgett, 2003). Additional shorelines have been suggested based on changes in valley morphology at consistent elevations (e.g. Irwin et al. 2002) or linear features at near-constant elevation (di Achille et al., 2007).

A further complication for potential Martian coastlines is the distinct possibility that bodies of water would have been ice-covered. This would result in different coastal landforms related to ice grounding along the shoreline.

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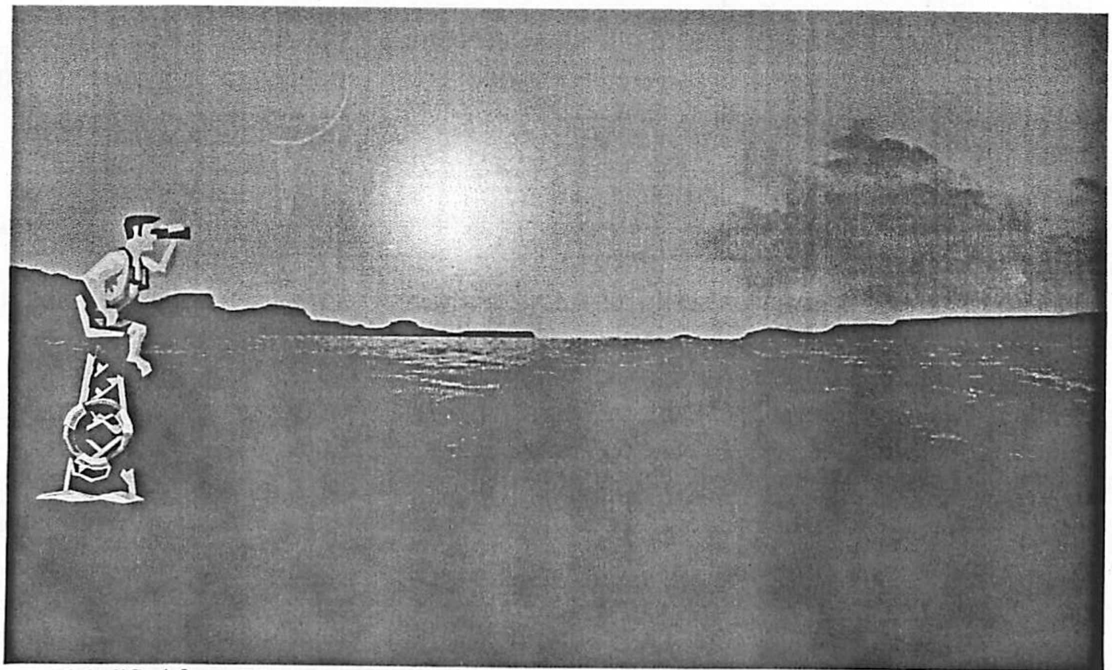
BAYWATCH TITAN

By Tamara Goldin

dense haze and goo lakes
running along methane shores
David Hasselhoff



Modified from artist's impression of Titan's beachfront by Mark Robertson-Tessi *(from Lorenz 2003).* Lifeguard may not be to scale or be of any scientific value…

THE HYDROLOGICAL CYCLE OF TITAN:

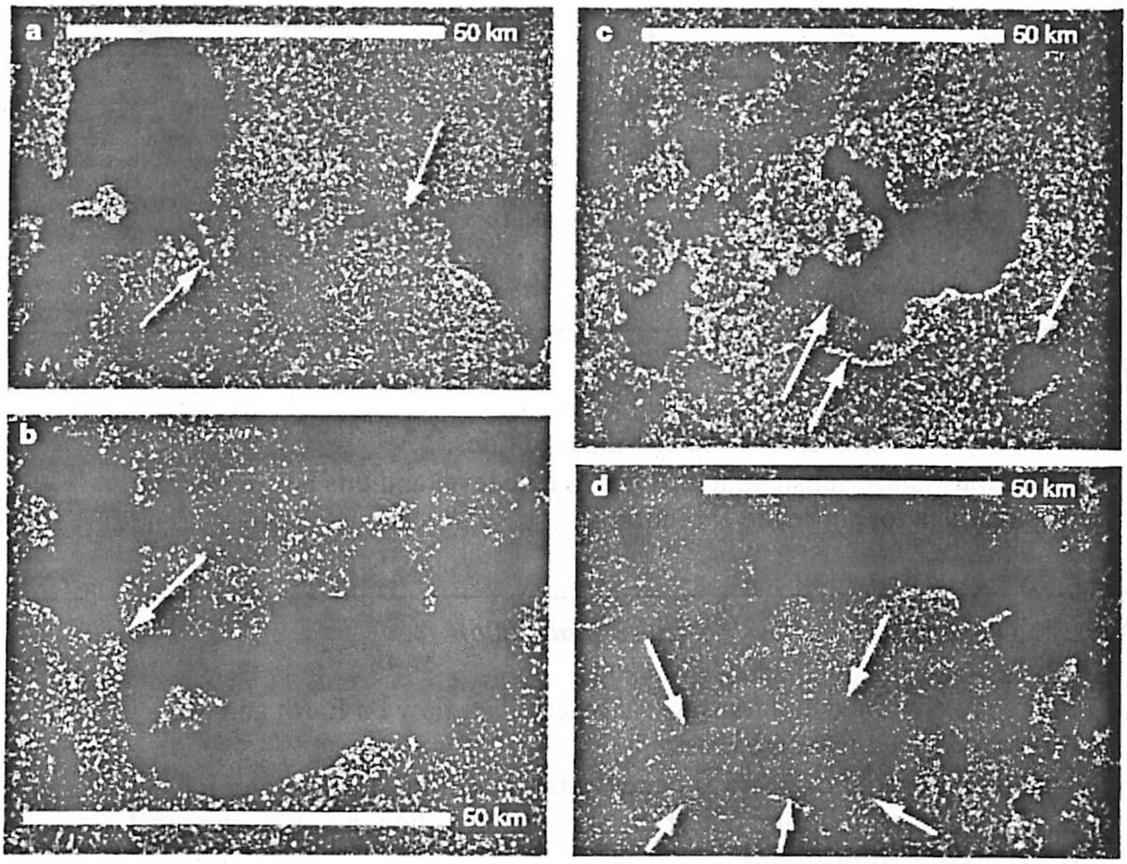
- Titan's dense atmosphere is dominated by nitrogen N_2 and methane CH_4 is the second most abundant component.
- Liquid methane is thermodynamically stable and condensation of methane in the atmosphere drives Titan's hydrological cycle.
  -Involatile ethane would be a component of lakes and depress the freezing point.
- Photolysis would rapidly dissociate the atmospheric methane quickly unless it is buffered by a surface reservoir.
- Oceans are not present → atmospheric methane abundance due to recent outgassing from interior?
- Methane humidity is highest near the poles and lakes stable only above 70 degrees latitude (at lower latitudes lakes would evaporate).
- Methane humidity of lower atmosphere can be buffered by evaporation from lakes covering only 0.002-0.02 of Titan's surface over timescales of centuries *(Mitri et al. 2007).*

SHORELINE MORPHOLOGY: *(Stofan et al. 2007)*

1) Steep margins and distinct edges suggesting confinement by topographic rim.
    → Seepage or groundwater drainage lakes intersecting the subsurface liquid-methane table?
2) Diffuse, scalloped edges often with associated channels.
    → Drainage lakes or groundwater drainage lakes?
3) More sinuous edges
    → Flooded river valley?

Other Notes:

- Lakes are ephemeral—some depressions appear to be partially filled with liquid or entirely dry suggesting evaporation of methane over time.
- Radar-bright edges seen images may be due to waves or a reflection of the lake bottom.



Cassini radar images of lakes from the T16 swath *(From Stofan et al. 2007)*. Note:

a) Channels leading into lakes
b) Channel between two lakes
c) Partially-filled lake, lake in nested depression
d) Possible dry lake

WIND AND WAVES: *(Lorenz et al. 2003, Ori et al. 1998)*

- Due to less solar heating, winds on Titan may be weak compared to Earth.
  -Wind speeds range between 0.1 to 1 m/s *(Mitri et al 2007)*.
- Low gravity, lower liquid density → waves (tidal, wind-generated) would be larger and less energetic with slower phase speeds compared to Earth.
- Erosion of shoreline by waves depends on land properties and slope of shore (tidal flat vs. steep crater rim).

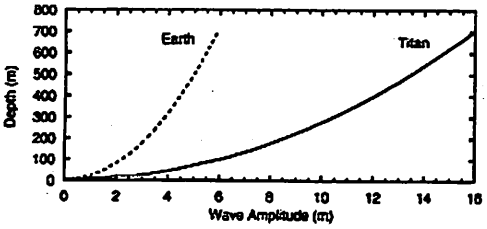


Fig. 1. Relationships between wave amplitude and liquid depth for progressive waves on Earth and Titan. At large depth, the tidal waves on Titan can reach larger amplitude than on Earth

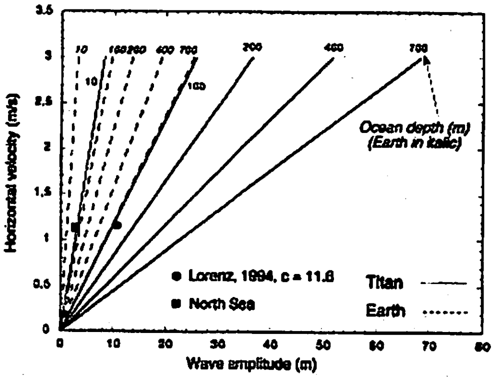


Fig. 2. Comparison for different ocean depths between wave amplitude and horizontal velocity in progressive waves for different depth of oceans. The waves on Titan can reach rather large amplitudes. Also positions of the North Sea and of reconstructed Titan ocean condition based on Lorenz (1994) with an orbital velocity (c) of the waves at 11.6 m s^{-1} are shown

(from Ori et al. 1998)

TIDES: *(Lorenz 1994)*

- Lakes may be modified by Saturn-induced tides.
- Tides may cause substantial changes in lake level and this has important implications for shoreline evolution.

SEDIMENT TRANSPORT: *(Burr et al. 2006)*

- Sediment entrained and transported by surficial flow on Earth and Mars is silicate material derived from the crust.
- Sediment material on Titan is either water ice (from Titan's water ice outer crust) or organic matter settling out of the atmosphere following photochemical reactions of hydrocarbons.
- Less liquid required to transport material of a given grain size on Titan (vs. Earth, Mars).
  -Precipitation of organic matter onto the surface would further enhance sediment transport.
- Understanding sediment transport is important for understanding the formation of channels (fluvial) and beaches (lacustrine).

Table 1. Parameters of Titan and Earth Surface Environments

		Titan	Earth
Planetary Radius	(km)	2575	6370
Surface Gravity	(ms^{-2})	1.35	9.81
Rotation Period	(s)	1.4×10^6	8.6×10^4
Atmosphere			
Composition		~95% N_2, ~5% CH_4	79% N_2, 20% O_2
Surface Temperature	(K)	94	288
Surface Pressure	(mbar)	1440	1013
Surface Density	(kgm^{-3})	5.3	1.25
Speed of Sound	(ms^{-1})	~200	~330
Scale Height	(km)	20	8
Typical Wind Speed	(ms^{-1})	<0.5	~10
Ocean			
Composition*		CH_4 (C_2H_6)	H_2O
Density	(kgm^{-3})	450 (650)	1000
Cubic Expansivity	(K^{-1})	1.3×10^{-3}(1.0×10^{-3})	2×10^{-4}
Viscosity	(Pa-s)	2×10^{-4} (1.2×10^{-3})	10^{-3}
Surface Tension	(Nm^{-1})	1.8×10^{-2} (1.8×10^{-2})	7.3×10^{-2}
Speed of Sound	(ms^{-1})	1500 (2000)	~1500
Specific Heat Capacity	($J\,kg^{-1}K^{-1}$)	~2000	4200
Latent Heat of Vaporization	($J\,kg^{-1}$)	~5×10^5	2.9×10^6
Boiling Point at Surface Pressure	(K)	115 (190)	373
Rossby Number Ro, Open Sea		0.1	0.1
Rossby Number Ro, Boundary		1.0	1.0
External Deformation Radius r_e	(km)	60	1000
Internal Deformation Radius r_i	(km)	- (?)	10

* strictly, the oceans are likely to be a ternary mixture of liquid ethane, methane and nitrogen, with the latter only a modest constituent (<10%). Propane and argon may be present at a level of a few percent or less, and dissolved traces of many other compounds may exist, together with insoluble suspended matter.

(From Lorenz et al. 2003)

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Sedimentary Structures on Mars

Ingrid Daubar Spitale

Basics of Sedimentary Rocks

★ Processes: weathering, transport, deposition, diagenesis (compaction, cementation and induration)

Particle Name	Sizes	Loose Sediment	Consolidated Rock
Boulder	>256 mm	Gravel	Conglomerate or Breccia (depending on rounding)
Cobble	64 - 256 mm		
Pebble	4 - 64 mm		
Granule	2 - 4 mm		
Very Coarse Sand	1 - 2 mm	Sand	Sandstone
Coarse Sand	0.5 - 1 mm		
Medium Sand	0.25 - 0.5 mm		
Fine Sand	0.125 - 0.25 mm		
Very Fine Sand	0.0625 - 0.125 mm		
Coarse Silt	0.031 - 0.625 mm	Silt	Siltstone
Medium Silt	0.016 - 0.031 mm		
Fine Silt	0.008 - 0.016 mm		
Very Fine Silt	0.004 - 0.008 mm		
Clay	<0.004 mm	Clay	Mudstone Shale Claystone

Sorting:

★ Based on size, density

★ Indicates energy of transporting medium: high-energy flows carry larger fragments.

  - *Beach & dune sands*: usually well-sorted because flows are ~ constant energy – coarser stuff not picked up, and fines remain in suspension
  - *Mountain streams*: usually poorly sorted – turbulent flows, eddies, velocity changing
  - *Glacial till*: poor sorting because deposited in place, not transported by liquid water.

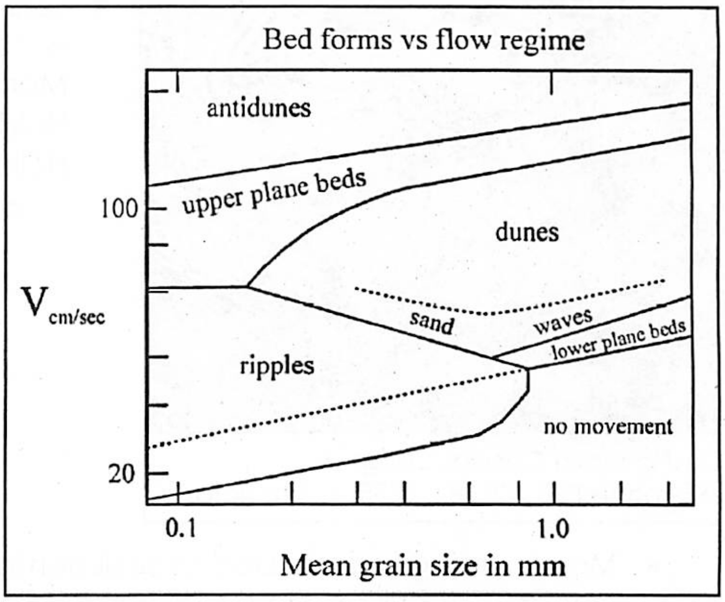
Rounding:

★ Random abrasion → rounds sharp corners

★ Amount of rounding indicates time spent in transport.

★ (not the same as sphericity)

Mars vs. Earth



- ★ Most Martian sediments result from impacts & aeolian weathering.
- ★ Same transport mechanisms (wind, water, ice), but different relative importance
- ★ Martian dust storms homogenize small particles planet-wide.
- ★ Early Mars sedimentation differed from present: more water, thicker atmosphere to weather & transport
- ★ Different gravity → affects only the transitions between bed forms, not the forms themselves.
    - o For same grain size & current depth, transitions occur at lower flow velocity on Mars.

Sedimentary Structures

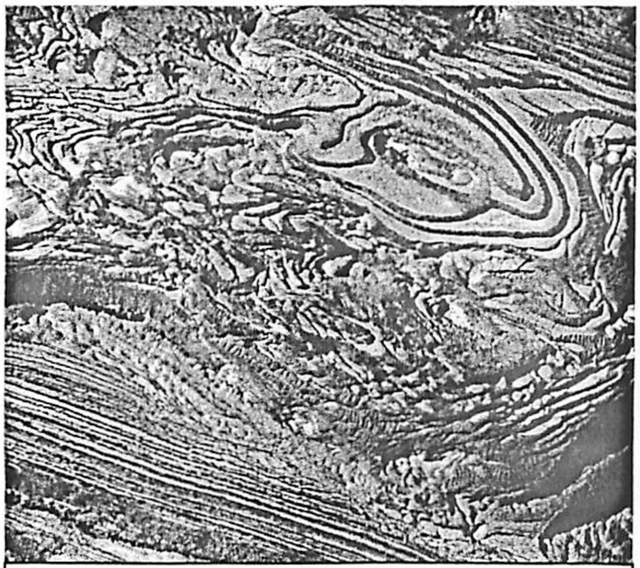
Important because structures are a record of the environment at time of deposition. Indicate flow medium (water, air), current velocity, direction.

Layering (bedding, stratification)

- ★ Beds laid down horizontally
- ★ Same lithology, textures, etc.
- ★ Bounded by planes of non-deposition

Layer Thickness	Name	
> 300 cm	Massive	↑
100-300 cm	Very thickly bedded	
30 - 100 cm	Thickly bedded	
10 - 30 cm	Mediumly bedded	
3 - 10 cm	Thinly bedded	bedding
1 - 3 cm	Very thinly bedded	
1 cm		
0.3 - 1 cm	Thickly laminated	laminae
<0.3 cm	Thinly laminated	↓

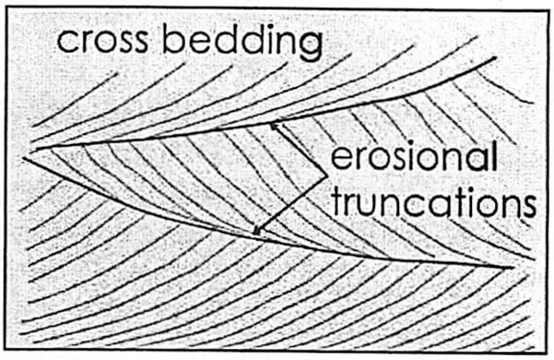
Layers in Arabia Terra at 8°N, 7°W. Subframe of MOC M14-01647



Folded layers in Candor Chasma.
HiRISE image PSP_001984_1735, ~2 km across

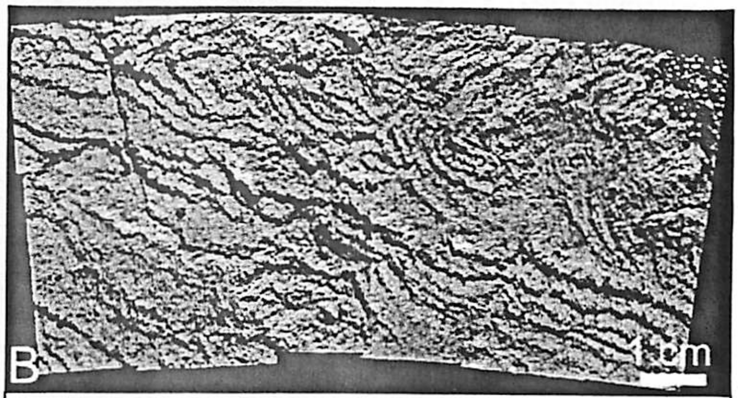
ON MARS:

- ★ Lots of layering seen from orbit in widespread regions of Mars (Valles Marineris, Mawrth Vallis, Candor Chasma, Holden Crater, Arabia Terra, Meridiani, Hellas basin, Gale Crater...).
    - o Steep cliff-forming layers + yardangs → indurated
    - o Lack of boulders at bases → fine-grained material
    - o High thermal intertia of layers → sedimentary rock (as opposed to indurated dust)
- ★ Most layering is described as sedimentary. Alternate theories include volcanic debris and layers of impact ejecta.
    - o Arguments against volcanism & ejecta: layers include cross-bedding, no lava flow fronts seen, no calderas seen, 100s of layers of ~same thickness across wide areas, geochemistry.
    - o If sedimentary, could still be aeolian or lacrustine.
- ★ See often within impact craters → lacrustine deposition?
- ★ Increased resolution from orbit shows thinner and thinner layers.
- ★ Landers saw fine laminae (e.g., Opportunity at Eagle Crater).



Cross-bedding

- ★ Sets of beds inclined to each other
- ★ Beds are asymptotic to lower surface upon which deposited
- ★ Boundaries between sets of beds are erosional surfaces
- ★ Very common in beach deposits, sand dunes & river deposits.
- ★ "Scoop-shaped" beds indicate what direction was "up" at time of deposition → reconstruct folding/faulting history
- ★ Some have suggested cross-bedding can be caused by volcanic debris flows or impact base surges.



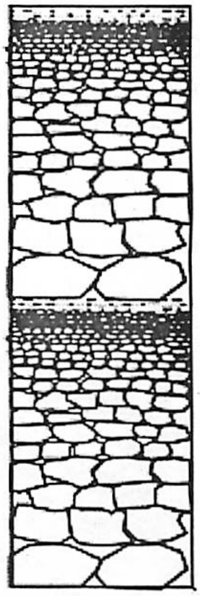
Trough ("festoon") cross-lamination seen by Opportunity near Erebus Crater.

ON MARS:

- ★ Opportunity saw "festoon" cross-lamination at Eagle Crater:
    - o Thought to be formed under water > 5 cm deep, currents ~10-50 cm/s

  - → Transient surface water ~playa or beach
  - Why is water more likely than wind? Trough shape rarely found in aeolian ripples + small scale (few cm)
- Also at Erebus Crater.
- More cross-bedding at Victoria – meter-scale → more likely aeolian.
- Also seen in walls of Valles Marineris.

Graded Bedding



- As current velocity decreases, larger grains are dropped first → grain size decreases towards top of bed
- Another indicator of top/bottom.
- See in submarine fans (repeated flows → turbidites), floodplains.

ON MARS:

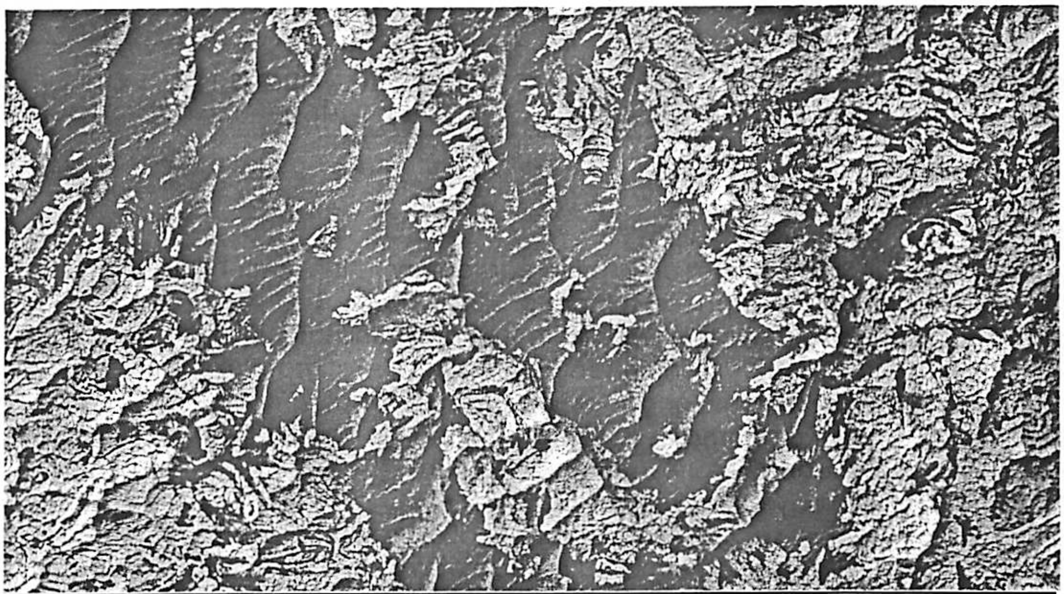
- Spirit saw graded bedding at Home Plate, but more likely volcaniclastic.

Ripple Marks

- Basically like dunes with smaller wavelengths
- Characteristic of shallow water deposition – can also be wind.
- Asymmetrical → indicate direction of current
- Symmetrical → oscillating flow, e.g. tidal action

ON MARS:

- Ripples seen from orbit at HiRISE resolution, but usually can't tell if indurated.



Possibly indurated ripples at different scales over light-toned layered deposits - Schiaparelli Crater, HiRISE observation PSP_006754_1790. ~100m across.

- Opportunity saw aeolian ripples of sand all over the place (not indurated – yet?), grain sorting

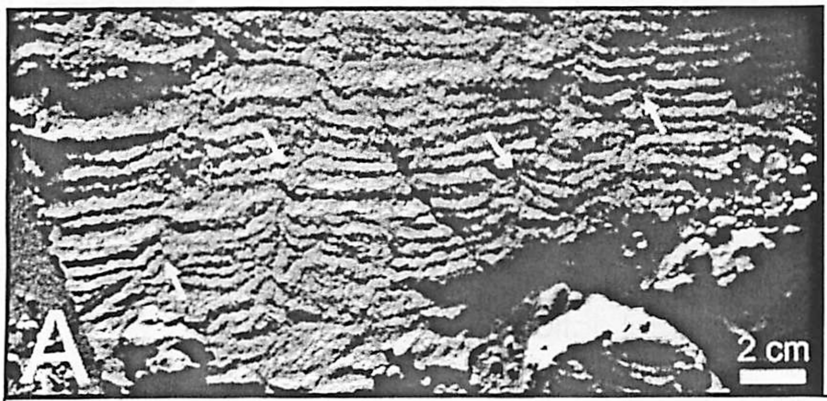
Mud/Desiccation Cracks

★ Result of drying wet sediment, shrinks as it dries
★ Requires alternating wet/dry cycle
★ Edges curl up → indicates top/bottom

ON MARS:

★ Lots of polygonal shaped fractures, "patterned ground" seen from orbit - some have been postulated to be desiccation cracks.
  - o Scale of those seen from orbit >> terrestrial mud cracks, though.
  - o Prevalence at high latitudes → ice-wedge polygons more likely.

★ Opportunity: desiccation cracks with "curl-up" shapes:



Desiccation cracks in lamination seen by Opportunity near Erebus Crater.

Awesome animated models of bed forms forming with various types of ripples, cross-bedding, etc.: http://walrus.wr.usgs.gov/seds/bedforms/

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Shoreline Features of Ontario Lacus, Titan

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ABSTRACT

I will discuss new results regarding the nature of shorelines around the south polar lake Ontario Lacus on Titan. The data stem from the T38 (2007 December 5) *Cassini* flyby of Titan. A series of 4 data cubes obtained by the VIMS instrument show two annuli surrounding the dark lake core. I suggest several possible sources for these annuli, eliminating some, and finally conclude that the inner and outer annulus respectively may represent tidal mudflats and perhaps a lag deposit indicitive of lake level change.

Subject headings: field trip — beaches — shorelines

1. HANDOUT

The LPL beaches field trip in spring of 2002 was the only one that I missed while I was a graduate student. I was bitter that the Owens Valley trip wasn't chosen, worried about studying mostly traffic jams, and thought that there was no way that I would ever need to know about beaches. Given that I studied gas giant planets exclusively at the time I thought that this was a safe bet. Now I'm writing the VIMS Ontario Lacus geomorphology paper. So, it just goes to show, never miss a field trip.

A quick overview of the observations themselves is shown in Figure 1. The rest of this handout is lifted directly from my in progress paper bound for *Icarus* entitled, "Shoreline Features of Titan's Ontario Lacus from *Cassini*/VIMS". Please do not distribute it past the immediate field trip environment. This handout will self-destruct in 5 seconds. Since this paper is still in progress, anything that you say on the field trip can and will be used to help me finish writing the paper :)

The concentric nature of the annuli surrounding the dark, central, liquid portion of Ontario Lacus implies that the rings and the lake are causally associated. Presumably the lake created Units 2 and 3 via lake level changes, shoreline processes, or some other phenomenon. Here we investigate several hypotheses regarding the formation of Unit 2 (the "shelf") and Unit 3 (the "bathtub ring").

1.1. Unit 2

Freeze/Thaw. Though Titan's polar temperatures are thought to drop to near the freezing point of both methane (91K) and ethane (90.3K), dissolved atmospheric nitrogen ought to depress the freezing point of lake-bourne liquids well below these values. If freezing is possible on Titan, we examine whether the morphology that we see might result from freezing and/or thawing. On Earth lakes freeze from the top down, and thaw from the bottom up, because H_2O solid is less dense than H_2O liquid, and thus floats on top

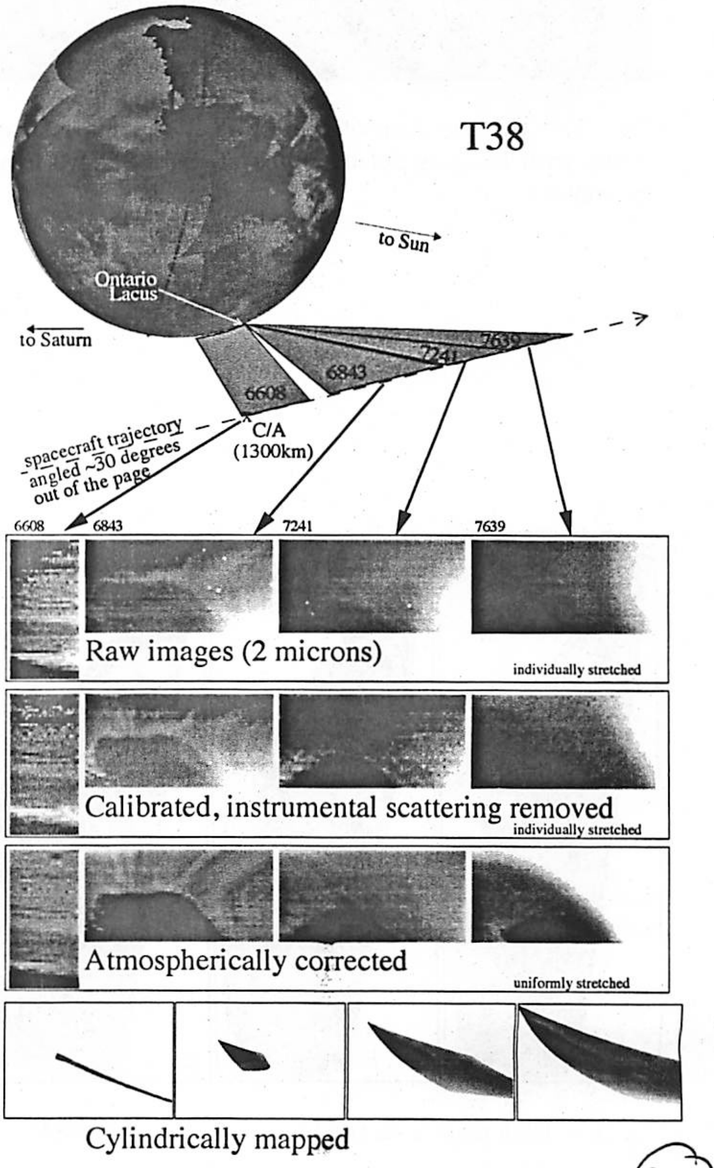

Fig. 1.— Geometry of the T38 VIMS observations.

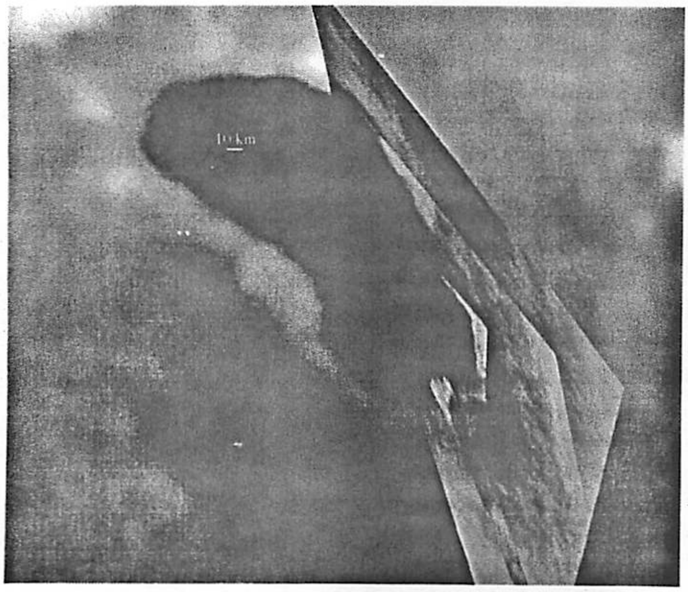

Fig. 2.— Combination of the VIMS T38 Ontario Lacus views, with Imaging Science Subsystem (ISS) rev9 image for context.

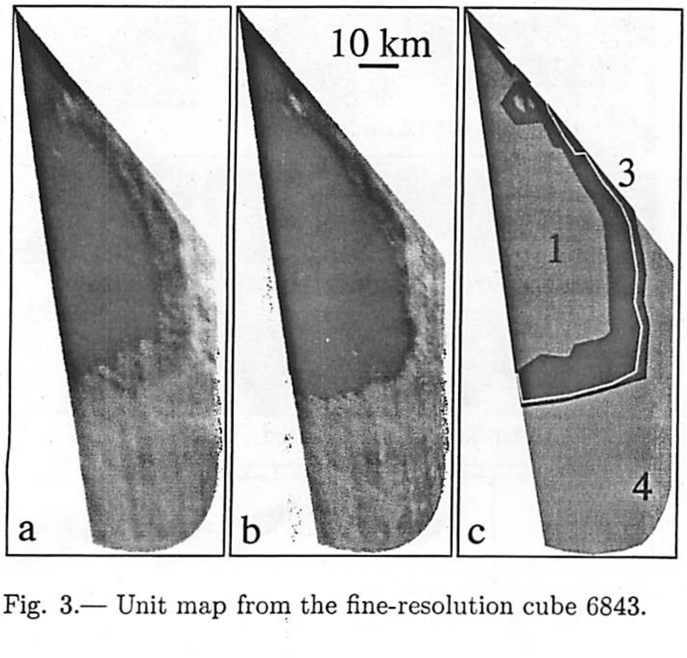

Fig. 3.— Unit map from the fine-resolution cube 6843.

of it. On Titan the lakes ought to freeze from the bottom up, and to thaw from the top down, as solid hydrocarbons are more dense than their liquids and should settle to the bottom of a lake. A previously frozen lake in the process of thawing might then be expected to transition relatively quickly from one with a solid surface to one with a liquid surface. At no time would a thawing lake, then, develop a ring around its margin. A lake in the midst of freezing might very well show a ring. As heat loss from the lake surface initiates freezing, the solids would fall to the lake bottom. As the freezing process depends on surface area, then, and not on depth, the freezing might be expected to proceed at the same rate (in units of grams per squate meter per day, perhaps) at the lake edges as at its center. Shallower areas would see their volumes fill with solid before deeper areas nearer the lake center. While the resulting solid-edged, creamy-center lake might resemble what VIMS sees in Figure 3, that cube was obtained near the end of Titan's south polar summer. Hence freezing is inconsistent with the seasonal phase at the time of T38, and we reject the hypothesis that the lake is in the midst of a freezing or thawing cycle.

Continental Shelf. In a body of liquid hydrocarbon sufficiently shallow, some light could penetrate to the lake-bottom, where it would be reflected and then detected by VIMS. However, we reject this hypothesis for several reasons. Because Unit 2 is spatially uniform in brightness, and because it has a sharp inner boundary with Unit 1, the inferred subaqueous topographic profile would be a stairstep – down at the outer edge of Unit 2, then of nearly uniform depth until the inner edge of Unit 2 where there would be a cliff-edge down to a liquid depth correcsponding to very high optical depth. This bathymetric profile seems unlikely, though it is not altogether unlike that of Earth's contentental shelves. Calculations of the mean free path for $2-\mu$m photons in liquid methane show that reflections off the lake bottom could only detected for very shallow depths: no greater than a few tens of centimeters.

Floating or Suspended Material. Unit 2 could result from scattering off of particles either floating on or suspended in liquid. In order to float, solid hydrocarbon material would need to be porous; in order to be suspended, it would need to have a small particle size. Both formation of a foam and the suspension of particles would require turbulent mixing of the lake's liquid, as could perhaps occur from tidal sloshing. The spatial uniformity and sharp inner boundary of Unit 2 are not easy to explain via this mechanism, however, but given present data we cannot rule it out entirely. RADAR altimetry over the area, presently planned for T49, could support or refute this hypothesis: if the all of Unit 2 is the same altitude as the lake center, then foam or suspension could be likely candidates. If, on the other hand, Unit 2 shows a nonzero slope or a different elevation than Unit 1, floating or suspended particles would be ruled out.

Beach. Another idea for the nature of Unit 2 is that it might be a beach. Beaches on Earth are created and maintained by wave action against a shoreline. Hence in order to form a beach around Ontario Lacus, the lake itself would have to show wave activity of sufficient energy. By analogy, Earth's Lake Ontario, of similar size to Ontario Lacus, does show beaches in some areas. Hence if the wind conditions near Titan's south pole are vaguely similar to those on Earth, generation of beach-forming waves may not be unreasonable. There is, however, a problem of scale. The widest beaches on Earth are a few hundred meters wide. Unit 2 is 10 km in extent. There are ocean shorelines on Earth that are many kilometers in width, however they form intertidal mudflats, and not beaches.

Tidal Mudflats. Some terrestrial shorelines are made of mud. The intertidal region is defined as that area of solid land that are exposed at the ocean's low tide and immersed at high tide. In cases where this slope is very low and the total tidal amplitude is high, wide intertidal zones filled with mud can result (see Figure 4). I'm still working on what the amplitude of tide might be at the edge of a 200-km long lake at Ontario's position would be, and on if Titan's in the right orbital phase for the lake-bourne liquids to have sloshed to the north. But right now this is my preferred interpratation for the identity of Unit 2.

1.2. Unit 3

Okay, I'm still working on this section. But I'll talk about these possibilities for what it could be.

Frost.

Beach.

Fine-grained Condensate.

Liquid-cleaned Area.

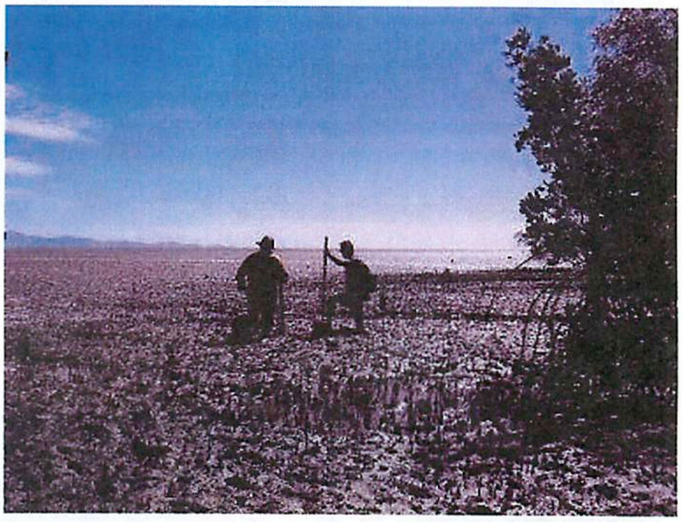

Fig. 4.— Three kilometer wide intertidal mudflat in Australia.

Current Tide Pool Fauna

Current tide pool fauna live in one of four different zones, differentiated by the amount of water, sun, and air exposure they receive. Some animals live high above the water and only get wet occasionally. Other animals, live underwater all their lives. Many other animals, adapted to the tides, live in and out of the water each day.

Spray/splash zone: This region is flooded only by the highest tides and storm waves. Lichens and barnacles live in this region.

Goose Barnacle

Acorn Barnacle

High tide zone: This region experiences rough waves and long exposure to air. Mollusks (limpets and mussels) live here, as do hermit crabs.

Owl Limpet

Scaled Chiton

Mid-tide zone: This region is covered and uncovered twice a day by tides, so animals in this region must adapt to surviving in and out of water. Anemones, mussels, and sea stars live here.

Ochre Sea Star

Solitary Anemone

Low-tide zone: This region is usually covered by water. Animals that live in this region cannot tolerate much exposure to air or sun. Crabs, shrimp, small fish, sea slugs, and urchins live here.

Wooly Sculpin

White Sea Urchin

Planetary connection

Depending on how life formed on Earth, it may inform our ideas of how life might form elsewhere. If life formed on the surface, in small pools along an ocean or sea, life may be restricted to terrestrial planets like Venus, Earth, and Mars. If, however, life formed underground or underwater, other habitats - like the subsurface oceans seen in icy moons - could provide potential places for life to emerge.

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