Lunar and Planetary Laboratory
Department of Planetary Sciences

Death Valley

Planetary Field Geology Practicum
PTYS 594a
7-10 October, 2000

The University of Arizona
Tucson, Arizona

Contents

Day 3:

Day 4:

PTYS 594a

PLANETARY FIELD GEOLOGY PRACTICUM

Fall 2000 Death Valley Itinerary

Friday, 6 October

4:00 pm Drivers pick up vehicles in preparation for early departure on Saturday.

Saturday, 7 October

8:00 am Depart Gould/Simpson loading dock. Drive W. on 6th to Euclid, turn N to Speedway, proceed West to I-10, drive West towards Phoenix. In Phoenix take I-17 North. Continue to Rte. 74 (Carefree Highway), proceed W. toward Lake Pleasant. Continue to join Rte. 93, turn North.

12:00 Stop for lunch at Hassayampa River Preserve. Observe possible pupfish in adjacent creek (if water is flowing).

1:00 pm Continue North on Rte 93 through Wickenberg.

2:00 pm Stop at Burro Creek overlook where **Celinda Kelsey** will describe Caliche formation in the basalts at this site.

2:30 pm Continue North on Rte 93 through Wikieup toward Kingman. Join I-40 at exit 71 and continue W to Kingman. At Kingman take Exit 52 onto Stockton Hill Road (dirt). Proceed N out of town toward Red Lake Playa.

4:30 pm Arrive at Red Lake Playa. Check condition of Playa before driving onto its surface. If there is time, observe giant polyons in low-angle sunlight. Presentations **by Jani Radebaugh** on playas and **Joe Spitale** on giant dessication polygons.

5:30 pm Continue North on Stockton Hill Road to paved Pierce Ferry Road. Turn right, drive 5 miles to sharp left bend in road, exit to right.

6:00 pm Camp in the Joshua Tree forest. Be careful to stay off the Hualapai Indian Reservation. **Jim Richardson** will give a fireside chat on the discovery of the Goldfields meteorite strewn field in this area.

Sunday, 8 October

8:00 am Break camp, **Andreas Eckholm** will describe Playas on Mars. Return W on Pierce Ferry Road. Visit Red Lake Playa if there was not time the previous day. Proceed to Arizona Rte. 93 and turn N toward Las Vegas.

10:00 am Arrive Hoover Dam. Park in lot on E side of the dam, walk out to overlook. **Erik Karkoschka** will describe the effect of the dam on the evolution of the Colorado River system.

10:30 am Continue on Rte. 93. Exit to Rte 146 W at Henderson. Proceed to I-15, exit 27, travel N to exit 33, turn W on Rte 160 toward Pahrump.

12:00 Lunch stop at Red Rock Canyon Park.

1:00 pm Continue West on Rte 160 through Pahrump, turn W onto Nevada Rte. 372. At the California border this becomes California Rte. 178.

Proceed to Shoshone. At Shoshone turn N on Rte 127, travel 2 miles then turn W on Rte 178. Proceed over Salisbury Pass (3315') descend to Jubilee Pass (1280') then into the southern end of Death Valley.

2:30 pm Stop at the overlook to Shoreline Butte, **Ferdinand Ip** will discuss Pleistocene lakes in this area and the history of Lake Manly.

3:00 pm Proceed N to Badwater. Several stops will be made where **Fred Ciesla** and **Devon Burr** will discuss the prominent gravel fans near Mormon Point, **Adina Alpert** will describe how they have been cut by recent fault scarps and **Andy Rivkin** will discuss desert varnish.

4:30 pm Continue North to Badwater where **Windy Jaeger** will describe the prominent turtlebacks.

5:00 pm Continue N to Furnace Creek, where we join Rte 190. Continue N to camp at Mesquite Spring Campground near Grapevine.

6:30 pm Camp. Fireside chats will be given by **Paul Withers** on the discovery and exploration of Death Valley, by **Curtis Cooper** on the Archeology of the valley and by **Yen Chamberlin** on the Aboriginal history of the valley.

Monday, 9 October

7:00 am Break camp, continue North 5 miles to Ubehebe Crater. **Ross Beyer** will lead us in viewing these spectacular examples of phreatic explosions.

8:30 am Continue on dirt road to Racetrack Playa. Along the way we will stop to view the Tin Mountian Landslide and the Chaos in the rocks of the Trucki mountains, hosted by **Joe Plassmann.**

10:00 am Continue south to Racetrack Playa, where **Abigail Wasserman** will describe the mysterious sliding stones.

10:30 am Return to Grapevine and turn south on Rte 190. Stop at Salt Creek where **Matt Chamberlin** will relate the amazing story of the Desert Pupfish.

11:00 Continue S on Rte 190 to the ruins of the Harmony Borax Works, where **Paul Withers** will describe the history of borax and salt mining in this area.

11:30 am Drive to Furnace Creek, continue on Rte 190 11 miles to exit for Dante's View, then drive 13 miles to overlook. This will be a lunch stop, after which **Laslo Keszthelyi** will describe how the Basin Range landscape evolved as the west widened and **Peter Lanagan** will discuss how Death Valley looks from space.

1:00 pm Return to Furnace Creek, turn S on Rte 178, drive 6 miles to Mushroom Rock, near the exit to Artist's drive, where **Rachel Mastrapa** will regale us on the subject of Salt Weathering.

2:30 pm Continue S on Rte 178 another 4 miles, park at the entrance to Artist's Drive, get out of the vehicles and stroll to Ventifact Ridge on the W side of Badwater Road. **Jennifer Grier** will lead us in examining the wind-sculpted rocks here.

3:00 pm Continue S to Devil's Golf course, walk out onto the salt flat. At this prime location **Matt Tiscareno** will describe how the evaporites in Death Valley were formed and **Terry Hurford** will tell us about the microbes that live in this apparently uninviting environment.

4:00 pm Continue S on 178 to the south end of Death Valley. If it is in good condition, take the dirt road 33 miles toward Baker, joining Rte 127. Rte 127 leads us past Silver Lake Playa and into the town of Baker.

	Continue through Baker on Kelbaker road and proceed towards Kelso. It is 44 miles to the Kelso dunes from here.
6:30 pm	Camp at a favorable spot near Kelso Dunes. **Jonathan Fortney** will give us a fireside chat on just how desert plants survive the inhospitable terrain we have been driving through.

Tuesday, 10 October

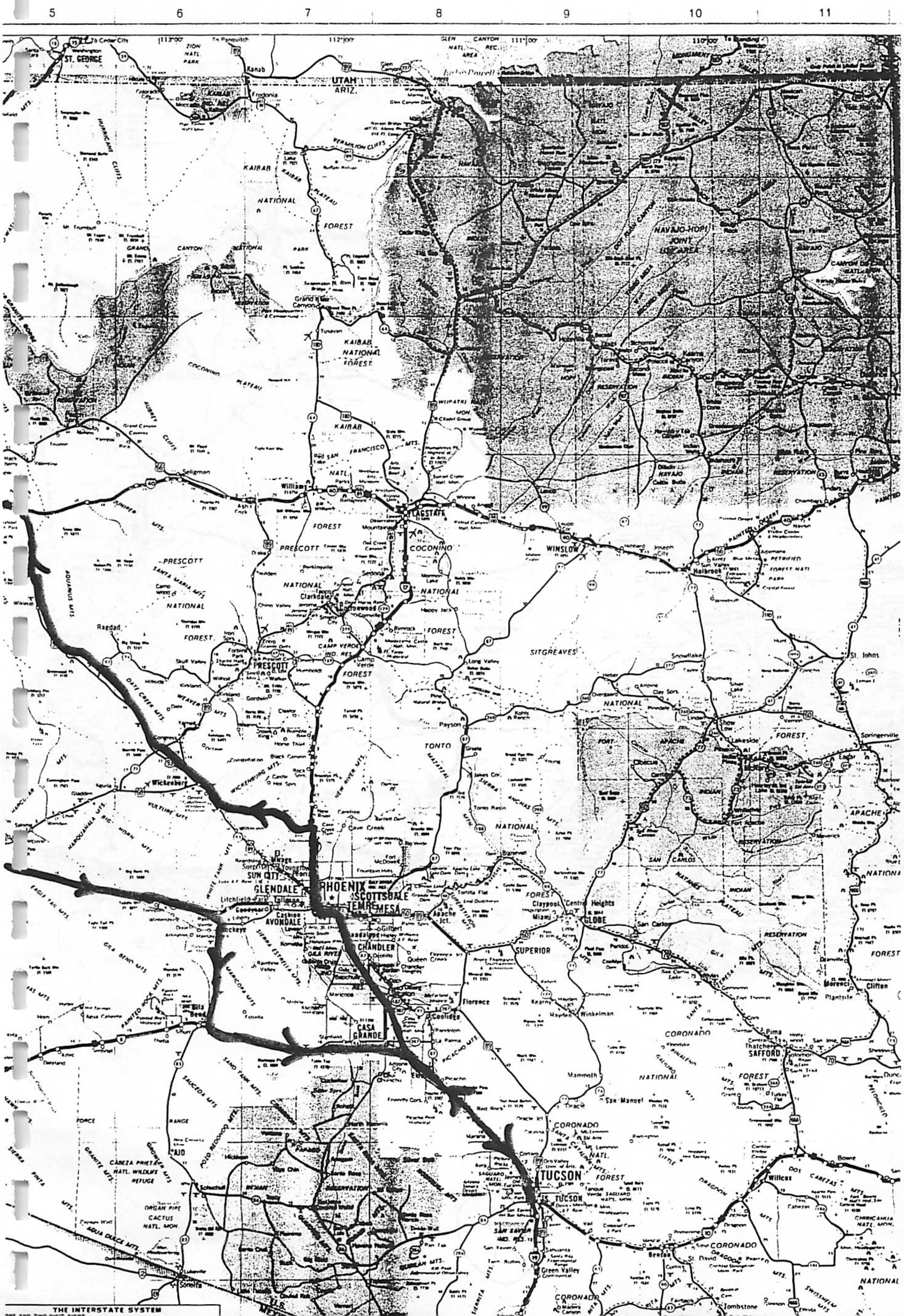
7:00 am	Break camp, continue S on Kelbaker road to a turnoff marked by a Bureau of Land Management sign a little N of a gas pipeline pumpstation. Drive W about 3.5 miles to the parking lot and climb into the dunes. **Gwen Bart** will describe the origin and shape of the Kelso Dunes. **Ingrid Daubar** will explain how some dunes (these in particular) make booming sounds when the sand flows. We will attempt to observe this phenomenon experimentally.
10:00 am	Depart Kelso Dunes, continue S on Kelbaker road another 12 miles to its intersection with I-40. Continue S on the road toward Amboy. Drive 10 miles to the National Trails Highway (old Rte 66) and proceed 2 miles W to Amboy Crater. Park and hike a short way over the lava field and ascend the cone. **David O'Brien** will describe what we see.
12:00	Rejoin vehicles, eat lunch
1:00 pm	Retrace our route on the National Trails Highway to the ghost town of Amboy, turn S on Amboy Road. In a few miles we cross Bristol Dry lake and perhaps **Paul Withers** will have a few additional words to say about the Sodium and Calcium Chlorides that are mined here.
2:00 pm	Join Rte 62 and proceed W to Twentynine Palms. Drive S from Twentynine Plams through Joshua Tree national monument, where Jason Barnes will describe the geology of "those cool white rocks".
3:00 pm	Join I-10 and proceed E toward Arizona. Continue E to Tucson (perhaps taking the Gila Bend "cutoff" to avoid driving in Phoenix).
7:00 pm	Arrive Tucson, unpack vehicles, go home. Drivers return vehicles to motor pool.

Drivers: R. Beyer, F. Ciesla, F. Ip, E. Karkoschka, P. Lanagan, J. Plassmann, M. Tiscareno.

Participants:

Alpert, A.
Barnes, J.
Bart, G.
Beyer, R.
Burr, D.
Chamberlin, Y.
Chamberlin, M.
Ciesla, F.
Cooper, C.
Daubar, I.
Eckholm, A.
Fortney, J.
Grier, J.
Hurford, T.
Ip, F.
Jaeger, W.
Karkoschka, E.
Kelsey, C.
Keszthelyi, L.
Lanagan, P.
Mastrapa, R.
Melosh, J.
O'Brien, D.
Plassmann, J.

Radebaugh, J.
Richardson, J.
Rivkin, A.
Spitale, J.
Tiscareno, M.
Wasserman, A.
Withers, P.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ST. GEORGE
Kanab
Fredonia
UTAH
ARIZ.
GLEN CANYON NATL. REC. AREA
ZION NATL. PARK
VERMILION CLIFFS
KAIBAB NATIONAL FOREST
KAIBAB PLATEAU
GRAND CANYON NATIONAL PARK
Grand Canyon
COCONINO PLATEAU
NAVAJO-HOPI JOINT USE AREA
HOPI
RESERVATION
NAVAJO
Seligman
Williams
FLAGSTAFF
COCONINO
WINSLOW
Holbrook
PAINTED DESERT
PETRIFIED FOREST NATL. PARK
PRESCOTT NATIONAL FOREST
Sedona
Cottonwood
Clarkdale
Camp Verde
PRESCOTT
Bagdad
Wickenburg
Payson
TONTO NATIONAL FOREST
SITGREAVES NATIONAL FOREST
Snowflake
Show Low
Lakeside
FORT APACHE
St. Johns
Springerville
APACHE
Sun City
GLENDALE
PHOENIX
SCOTTSDALE
TEMPE
MESA
AVONDALE
CHANDLER
Apache Jct.
SUPERIOR
Miami
GLOBE
SAN CARLOS
INDIAN
RESERVATION
Florence
Coolidge
CASA GRANDE
Gila Bend
Winkelman
Mammoth
CORONADO
SAFFORD
Clifton
San Manuel
TUCSON
S. TUCSON
Green Valley
Willcox
Benson
Tombstone
AJO
CABEZA PRIETA NATL. WILDLIFE REFUGE
ORGAN PIPE CACTUS NATL. MON.
Sonoita
CHIRICAHUA NATL. MON.
NATIONAL
THE INTERSTATE SYSTEM

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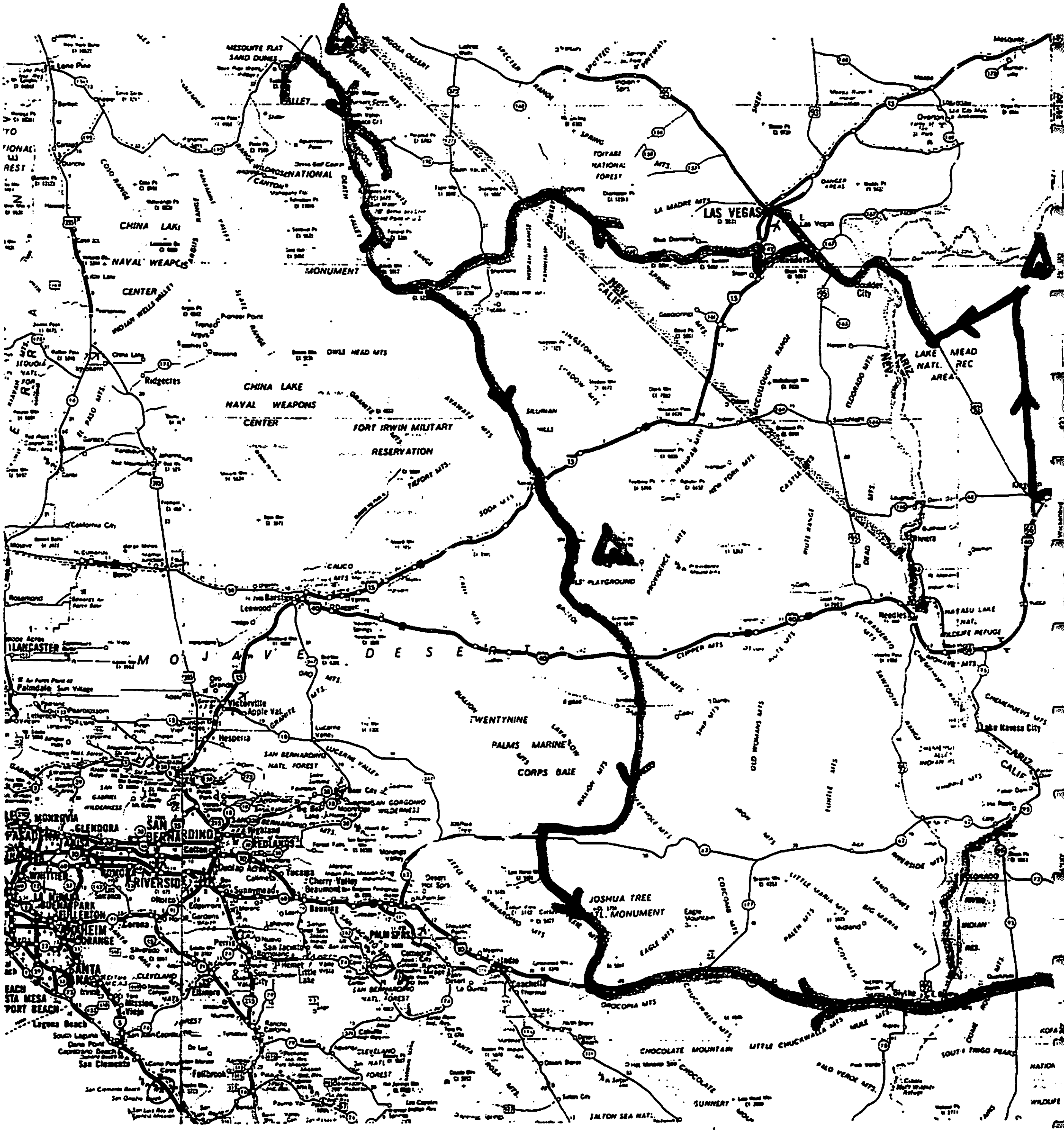
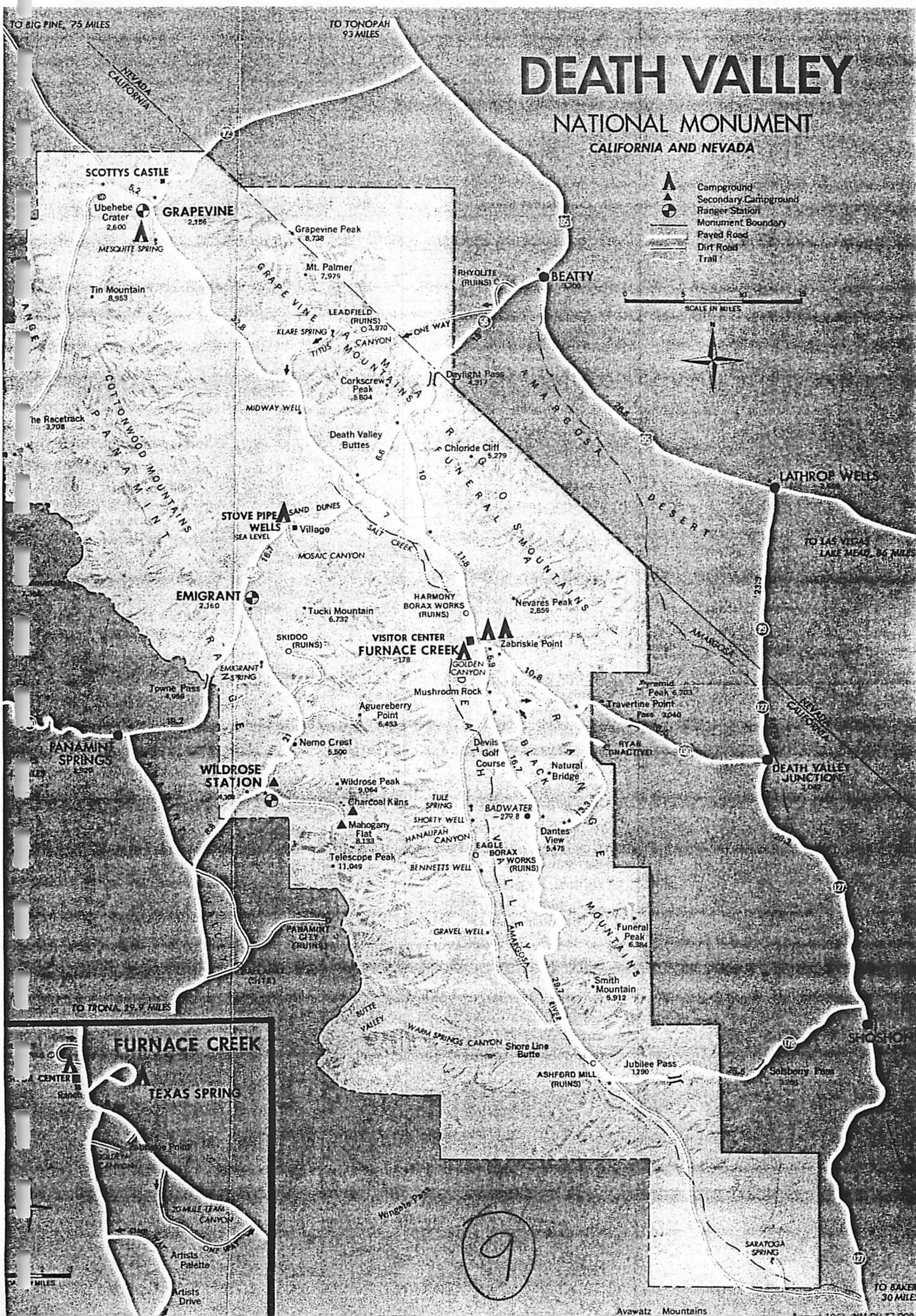

MESQUITE FLAT SAND DUNES
LAS VEGAS
Boulder City
LAKE MEAD NATL. REC AREA
CHINA LAKE NAVAL WEAPONS CENTER
FORT IRWIN MILITARY RESERVATION
OWLS HEAD MTS
Ridgecrest
Barstow
Needles
M O J A V E D E S E R T
LANCASTER
Palmdale
Victorville
TWENTYNINE PALMS MARINE CORPS BASE
SAN BERNARDINO NATL. FOREST
SAN BERNARDINO
REDLANDS
RIVERSIDE
GLENDORA
WHITTIER
ANAHEIM
ORANGE
JOSHUA TREE NTL. MONUMENT
PALM SPRS
Indio
Coachella
OROCOPIA MTS
Blythe
CHOCOLATE MOUNTAIN
SALTON SEA NATL.



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Ranger HQ (760) 786-2331

Uniform Time Scale	Subdivisions Based on Strata/*Time*: Eon	Era	Systems/*Periods*	Series/*Epochs*	Radiometric Dates (millions of years ago)	Outstanding Events: In Physical History	Outstanding Events: In Evolution of Living Things
0					0		
PHANEROZOIC	PHANEROZOIC	CENZOIC	Quaternary	Recent or Holocene Pleistocene	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
			Jurassic	Many	210		Climax of dinosaurs Birds
			Triassic	Many	250	Beginning of Atlantic Ocean	Conifers, cycads, primitive mammals Dinosaurs
		PALEOZOIC	Permian	Many	290	Climax of making of Appalachian Mountains	Mammal-like reptiles
			Pennsylvanian (Upper Carboniferous)	Many	340		Coal forests, insects, amphibians, reptiles
			Mississippian (Lower Carboniferous)	Many	365		
			Devonian	Many	415	Earliest economic coal deposits	Amphibians
			Silurian	Many	465		Land plants and land animals
			Ordovician	Many	510	Beginning of making of Appalachian Mountains	Primitive fishes
575			Cambrian	Many	575	Earliest oil and gas fields	Marine animals abundant
PRECAMBRIAN	PRECAMBRIAN (Mainly igneous and metamorphic rocks; no worldwide subdivisions.)				1,000		Primitive marine animals Green algae
					2,000		
					3,000	Oldest dated rocks	Bacteria, blue-green algae
~4,650	Birth of Planet Earth				4,650		

Flint + Skinner "Physical Geology" 2 ed (1977)

MINERAL NAMES

Mineral	Formula	Mineral	Formula
Åkermanite	$Ca_2MgSi_2O_7$	Hematite	Se_2O_3
Alabandite	$(Mn,Fe)S$	Hercynite	$(Fe,Mg)Al_2O_4$
Albite	$NaAlSi_3O_8$	Hibonite	$CaAl_{12}O_{19}$
Andradite	$Ca_3Fe_2Si_3O_{12}$	Ilmenite	$FeTiO_3$
Anorthite	$CaAl_2Si_2O_8$	Kaersutite	$Ca_2(Na,K)(Mg,Fe)_4TiSi_6$-
Apatite	$Ca_3(PO_4)_2$		$Al_2O_{22}F_2$
Aragonite	$CaCO_3$	Kamacite	α-(Fe,Ni)
Armalcolite	$FeMgTi_2O_5$	Krinovite	$NaMg_2CrSi_3O_{10}$
Augite	$Mg(Fe,Ca)Si_2O_6$	Lawrencite	$(Fe,Ni)Cl_2$
Awaruite	Ni_3Fe	Lonsdaleite	C
Baddeleyite	ZrO_2	Mackinawite	FeS_{1-x}
Barringerite	$(Fe,Ni)_2P$	Maghemite	Se_2O_3
Bassanite	$CaSO_4\cdot 1/2H_2O$	Magnesiochromite	$MgCr_2O_4$
Bloedite	$Na_2Mg(SO_4)_2\cdot 4H_20$	Magnesite	$(Mg,Fe)CO_3$
Brezinaite	Cr_3S_4	Magnetite	Fe_3O_4
Brianite	$CaNa_2Mg(PO_2)$	Majorite	$Mg_3(MgSi)Si_3O_{12}$
Buchwaldite	$NaCaPO_4$	Marcasite	FeS_2
Calcite	$CaCO_3$	Melilite solid solution	
Carlsbergite	CrN	åkermanite (Ak)	$Ca_2MgSi_2O_7$
Caswellsilverite	$NaCrS_2$	gehlenite (Ge)	$Ca_2Al_2SiO_7$
Chalcopyrite	$CuFeS_2$	Merrihueite	$(K,Na)_2Fe_5Si_{12}O_{30}$
Chamosite	$Fe_6Mg_3[(Si_4O_{10})(OH)_8]_2$	Merrillite	$Ca_9MgH(PO_4)_7$
Chaoite	C	Mica	$(K,Na,Ca)_2Al_4[Si_6Al_2O_{70}]$-
Clinopyroxene	$(Ca,Mg,Fe)SiO_3$		$(OH,F)_4$
Chlorapatite	$Ca_5(PO_4)_3Cl$	Molybdenite	MoS_2
Chromite	$FeCr_2O_4$	Monticellite	$Ca(Mg,Fe)SiO_4$
Cohenite	$(Fe,Ni)_3C$	Montmorillonite	$Al_4(Si,Al)_8O_{20}(OH)_4Mg_6$-
Copper	Cu		$(Si,Al)_8O_{20}(OH)_4$
Cordierite	$Mg_2Al_4Si_5O_{18}$	Nepheline	$NaAlSiO_4$
Corundum	Al_2O_3	Niningerite	$(Mg,Fe)S$
Cristobalite	SiO_2	Oldhamite	CaS
Cronstedtite	$(Mg,Fe)_2Al_3Si_5AlO_{18}$	Olivine	$(Mg,Fe)_2SiO_4$
Cubanite	$CuFe_2S_3$	Olivine solid solution	
Daubreelite	$FeCr_2S_4$	fayalite (Fa)	Fe_2SiO_4
Diamond	C	forsterite (Fo)	Mg_2SiO_4
Diopside	$CaMgSi_2O_6$	Orthoclase	$KAlSi_3O_8$
Djerfisherite	$K_3CuFe_{12}S_{14}$	Orthopyroxene	$(Mg,Fe)SiO_3$
Dolomite	$CaMg(CO_3)_2$	Osbornite	TiN
Enstatite	$MgSiO_3$	Panethite	$(Ca,Na)_2(Mg,Fe)_2(PO_4)_2$
Epsomite	$MgSO_4\cdot 7H_2O$	Pentlandite	$(Fe,Ni)_9S_8$
Farringtonite	$Mg_3(PO_4)_2$	Perovskite	$CaTiO_3$
Fassaite	$Ca(Mg,Ti,Al)(Al,Si)_2O_6$	Perryite	$(Ni,Fe)_5(Si,P)_2$
Fayalite	Fa_2SiO_4	Pigeonite	$(Fe,Mg,Ca)SiO_3$
Feldspar solid solution		Plagioclase	
albite (Ab)	$NaAlSi_3O_8$	albite	$NaAlSi_3O_8$
anorthite (An)	$CaAl_2Si_2O_8$	anorthite	$CaAl_2Si_2O_8$
orthoclase (Or)	$KAlSi_3O_8$	Portlandite	$Ca(OH)_2$
Ferrosilite	$FeSiO_3$	Potash feldspar	$(K,Na)AlSi_3O_8$
Forsterite	Mg_2SiO_4	Pyrite	FeS_2
Gehlenite	$Ca_2Al_2SiO_7$	Pyrope	$Mg_3Al_2(SiO_4)_3$
Gentnerite	$Cu_8Fe_3Cr_{11}S_{18}$	Pyroxene solid solution	
Graftonite	$(Fe,Mn)_3(PO_4)_2$	enstatite (En)	$MgSiO_3$
Graphite	C	ferrosilite (Fs)	$FeSiO_3$
Greigite	Fe_3S_4	wollastonite (Wo)	$CaSiO_3$
Grossular	$Ca_3Al_2Si_3O_{12}$	Pyrrhotite	$Fe_{1-x}S$
Gypsum	$CaSO_4\cdot 2H_2O$	Quartz	SiO_2
Haxonite	$Fe_{23}C_6$	Rhönite	$Ca_4(Mg,Al,Ti)_{12}(Si,Al)_{12}O_{40}$
Heazlewoodite	Ni_3S_2	Richterite	$Na_2CaMg_5Si_8O_{22}F_2$
Hedenbergite	$CaFeSi_2O_6$	Ringwoodite	$(Mg,Fe)_2SiO_4$
Heideite	$(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$	Roaldite	$(Fe,Ni)_4N$

Mineral	Formula	Mineral	Formula
Roedderite	$(K,Na)_2Mg_5Si_{12}O_{30}$	Stanfieldite	$Ca_4(Mg,Fe)_5(PO_4)_6$
Rutile	TiO_2	Suessite	Fe_3Si
Sanidine	$KAlSi_3O_8$	Sulfur	S
Sarcopside	$(Fe,Mn)_3(PO_4)_2$	Taenite	γ-(Fe,Ni)
Scheelite	$CaWO_4$	Tetrataenite	FeNi
Schöllhornite	$Na_{0.3}(H_2O)\ [CrS_2]$	Thorianite	ThO_2
Schreibersite	$(Fe,Ni)_3P$	Tridymite	SiO_2
Serpentine (or chlorite)	$(Mg,Fe)_6Si_4O_{10}(OH)_8$	Troilite	FeS
Sinoite	Si_2N_2O	Ureyite	$NaCrSi_2O_6$
Smythite	Fe_9S_{11}	V-rich magnetite	$(Fe,Mg)(Al,V)_2O_4$
Sodalite	$Na_8Al_6Si_6O_{24}Cl_2$	Valleriite	$CuFeS_2$
Sphalerite	(Zn,Fe)S	Vaterite	$CaCO_3$
Spinel	$MgAl_2O_4$	Whewellite	$CaC_2O_4 \cdot H_2O$
Spinel Solid Solution		Wollastonite	$CaSiO_3$
spinel	$MgAl_2O_4$	Yagiite	$(K,Na)_2(Mg,Al)_5(Si,Al)_{12}O_{30}$
hercynite	$FeAl_2O_4$	Zircon	$ZrSiO_4$
chromite	$FeCr_2O_4$		
magnesiochromite	$MgCr_2O_4$		
V-rich magnetite	$(Fe,Mg)(Al,V)_2O_4$		

"Meteorites and the Early Solar System"
Kerridge + Matthews, ed.
U of A Press (1988).

Igneous Rocks

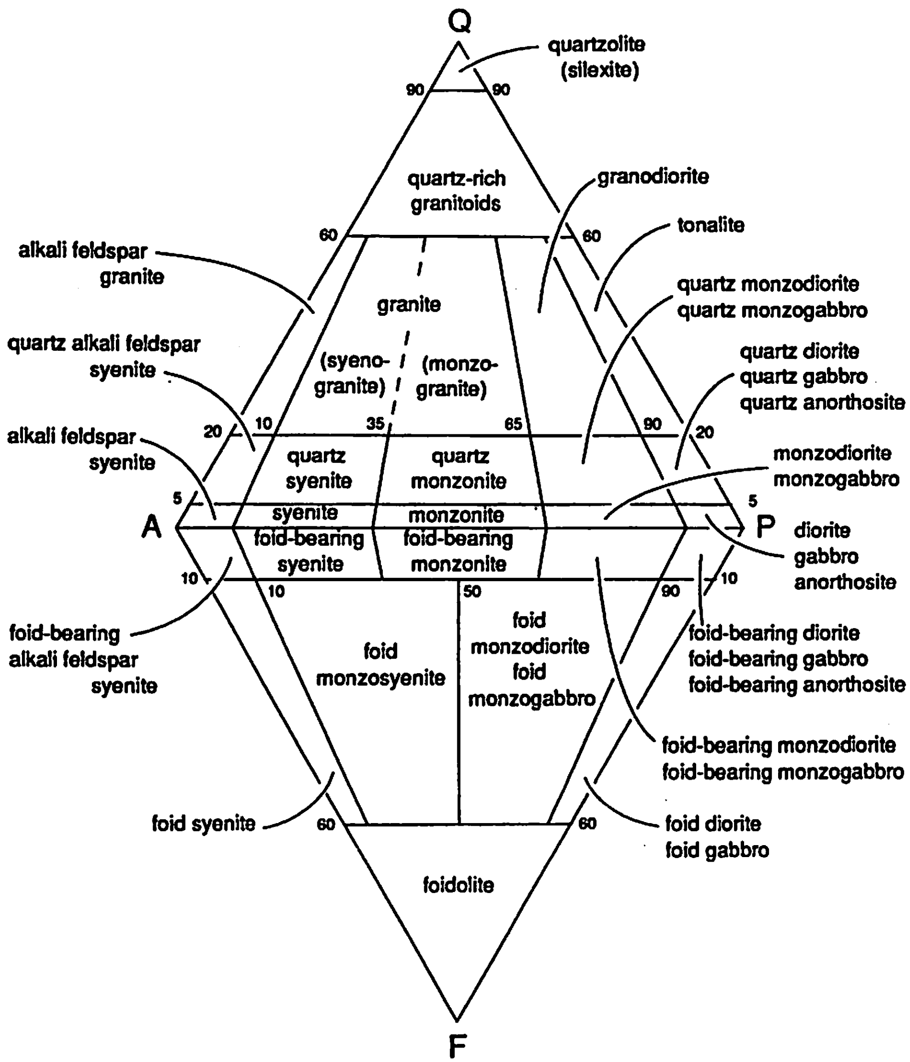

Fig. B.4. Classification and nomenclature of plutonic rocks according to their modal mineral contents using the QAPF diagram (based on Streckeisen, 1976, Fig. 1a). The corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid. However, for more detailed definitions refer to section B.2. This diagram must not be used for rocks in which the mafic mineral content, M, is greater than 90%.

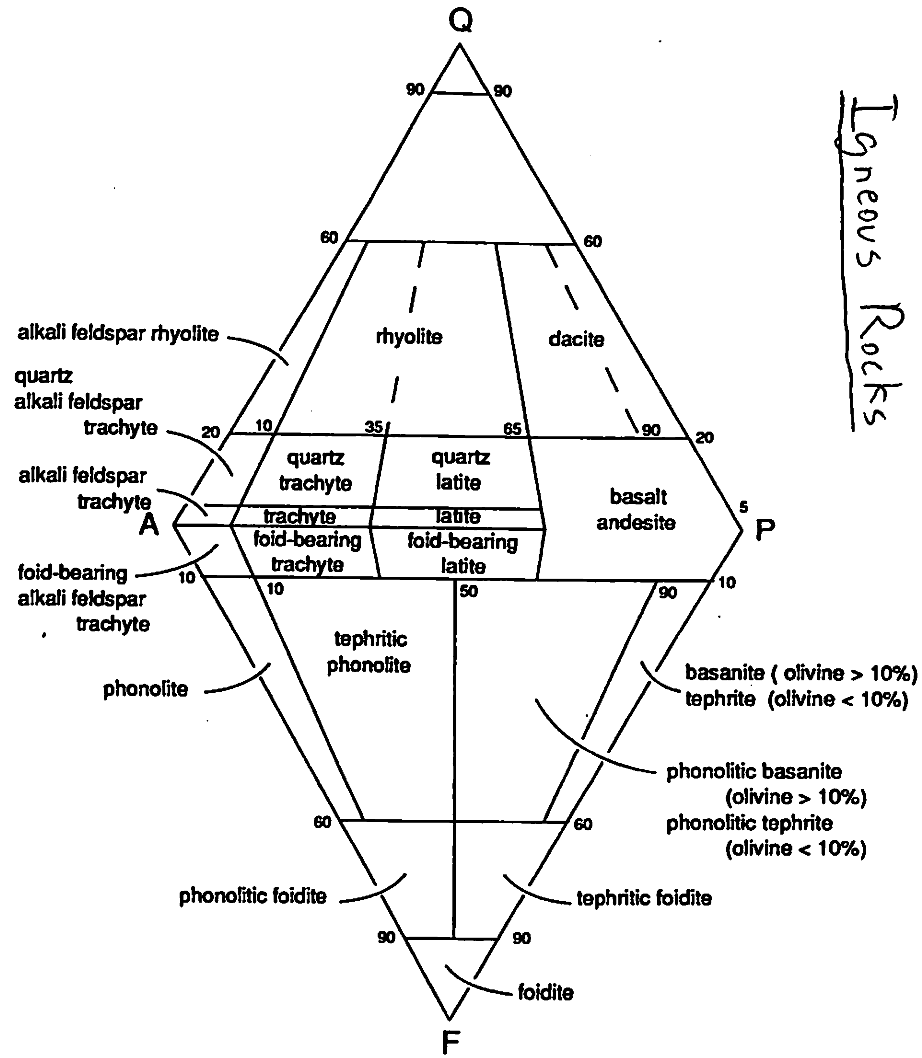

Fig. B.10. Classification and nomenclature of volcanic rocks according to their modal mineral contents using the QAPF diagram (based on Streckeisen, 1978, Fig. 1). The corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid. However, for more detailed definitions refer to section B.2.

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"Classification of Igneous Rocks and Glossary of Terms." Le Maitre, ed. Blackwell Scientific Publications (1989)

Caliche deposits at Burro Creek

Celinda Kelsey

Caliche is defined as a body resulting from the accumulation of calcium carbonate (calcite) and/or other carbonates in unconsolidated sediments, usually under conditions where moisture is deficient in all seasons.

Caliche is most often associated with carbonate sediments. These sediments partially dissolve into any ground water. In arid environments ground water is drawn upward through the vadose zone (rock and soil above water table level) by capillary action. The caliche is deposited within any type of soil or regolith within the vadose zone where evaporation occurs. Of interst for this field trip, caliche often forms crusts around the edges of playas. Caliche on earth preserves root stems and other life that have formed in the developing soil that is being calichified (I didn't make that word up.) The Burro Creek location has no limestone associated with it. Instead the surrounding lithology is basalt flows. How do we form calcite from basalt?

Basaltic minerals	Chemical formula	Comments
Clinopyroxene	$(Ca, Na)(Mg,Fe,Al)(Si,Al)_2O_6$	Augite
Olivine	$(Mg,Fe)_2SiO_4$	Fosterite-Mg rich, Fayalite-Fe rich
Orthpyroxene	$MgSiO_3$-$(Mg, Fe)SiO_3$	Enstatite
Feldspar-anorthite	$CaAl_2Si_20_8$	Plagioclase end member (50-90% of feldspar in basalt)

Probably anorthite is the best source of the calcium that is becoming caliche. Anorthite forms at very high temperatures within the basaltic magma or lava, indicating it is more stable at high temperatures and pressures. Therefore, it weathers quickly when exposed to surface temperatures and pressures. Magnesium also reacts to form carbonates (aragonite, dolomite) very easily. However, the literature on the caliche at Burro Creek indicates it is primarily calcite.

Isotope studies of the carbon and oxygen bound to caliche at Burro Creek indicate that they are coming from either the atmosphere, or respiration of microbes within the basalt. Calcite formed at the surface is in balance with atmospheric isotope abundances of 13C and 18O. However, calcite is also being formed in buried basaltic flows where carbon dioxide from microbes, which is deficient in the heavy isotopes of carbon and oxygen, is increasingly dominant with depth. The study of Burro Creek found this lighter calcite associated with older flows, which may have been buried and subsequently exposed. Paul Knauth and Jack Farmer of the Department of Geology at ASU performed this study.

Implications for Mars:

The martian surface would be ideal for forming a similar style of caliche, IF there has ever been rainfall at the surface. The rain water is needed to transport the calcium to locations rich in carbon dioxide (the surface and microbial communities) as well as speeding up the weathering process for the basaltic minerals. Some theories of martian climate do predict that rain has occurred. Detection of variation in the isotopes abundances, of caliche formed within a distinct time frame, would indicate microbial activity, without the need to know the exact atmospheric isotopic abundances of that time. Also, caliche on Mars would be valuable to study for fossil signs of life.

Resources:

Knauth, Paul and Jack Farmer, Biosignatures in calcite formed during the weathering of Basalt, GSA abs., 1999.

Scoffin, Terrence P., An Introduction to Carbonate Sediments and Rocks. A packet from the University of Texas at Austin, obtained in 1995.

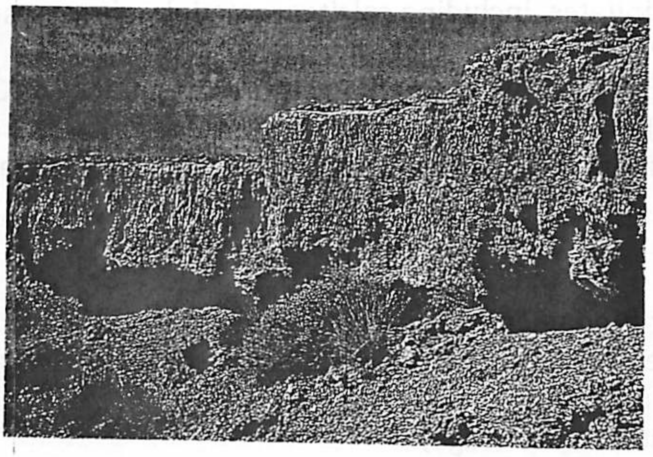


FIGURE 6-23 Caliche on Mormon Mesa in southern Nevada.

Obligatory pretty picture

We will not be seeing caliche anywhere near this thick at Burro Creek.
from Physical Geology by Monroe and Wicander (1992)

Playa Lakes

Jani Radebaugh

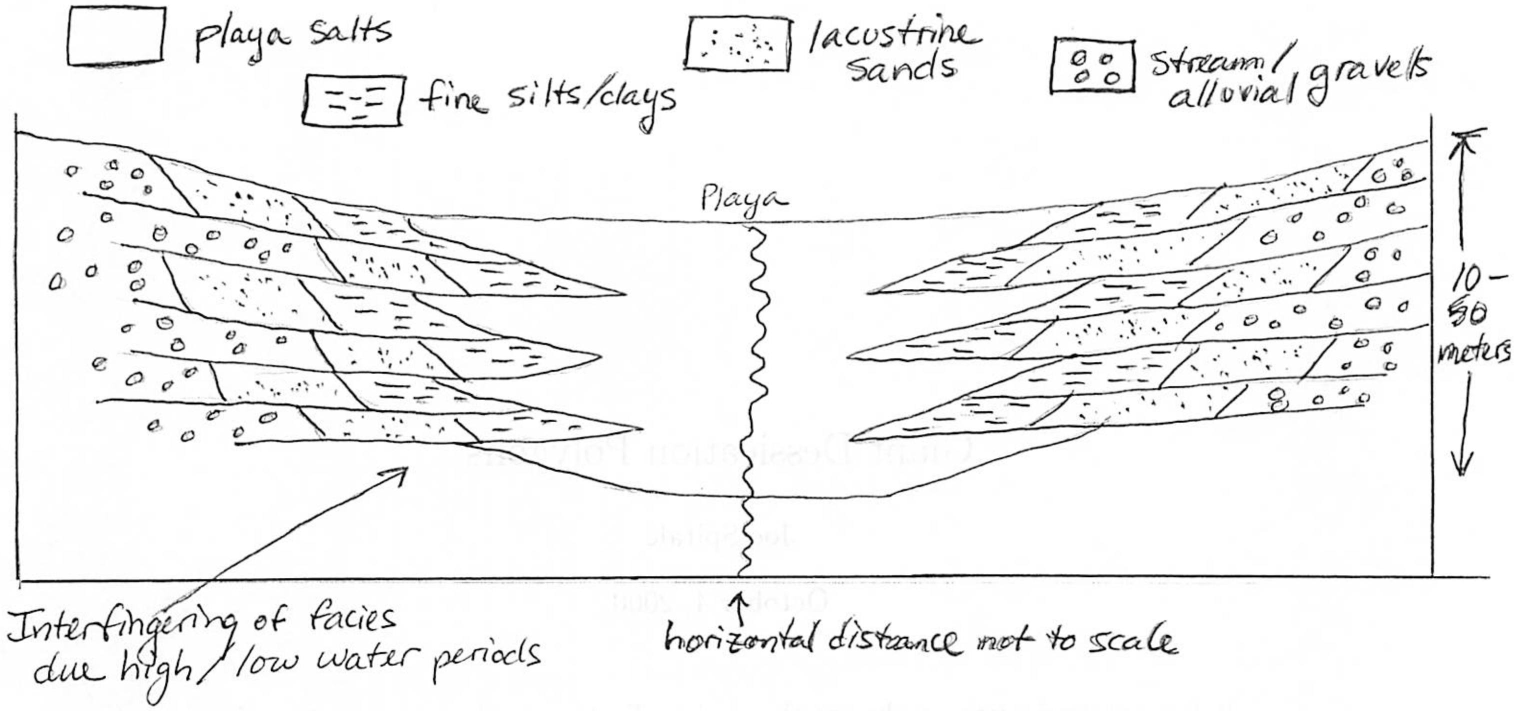
Pilot Valley Playa, Utah
An originally dry playa forms a lake during a 15-minute thunderstorm
From Penn State Dynamic Hydrologic Systems, http://www.cee.psu.edu/dynsys/

Playa lakes occupy small, closed basins, and are ephemeral; cyclically they evaporate entirely, leaving only the basin and evaporites, or minerals that were in solution. As this cyclic process of flooding and dessication repeats, more minerals leached by runoff streams from surrounding regions are concentrated in the basin. This results in formation of salt crusts, efflorescent crusts, solution pits and chimneys. Winds blow uninterrupted across playas, displacing brines and depositing sediments, adding to the dynamic nature of the depositional environment (Last, 1984).

The sediments associated with playa lakes consist, in order from the center outward, of:
1) very soluble salts of Na, Mg sulfates and carbonates
  –halite NaCl
2) sparingly soluble precipitates, including calcite, protodolomite, gypsum and mixed layer clays
  –gypsum $CaSO_4(H_2O)_2$, anhydrite $CaSO_4$, calcite/aragonite $CaCO_3$, dolomite $CaMg(CO_3)_2$
3) detrital minerals dominantly of quartz, carbonates, feldspars and clays
4) organic matter
(Last, 1984).

In a playa, there are four fundamental sedimentary facies. (Bodies of sediment, that were deposited in slightly different environments, each having a distinctive set of physical, chemical, and biological attributes, are **facies**).
These are (from lake center to lake edge):
1. lake
2. saline mudflat
3. dry mudflat
4. sandflat

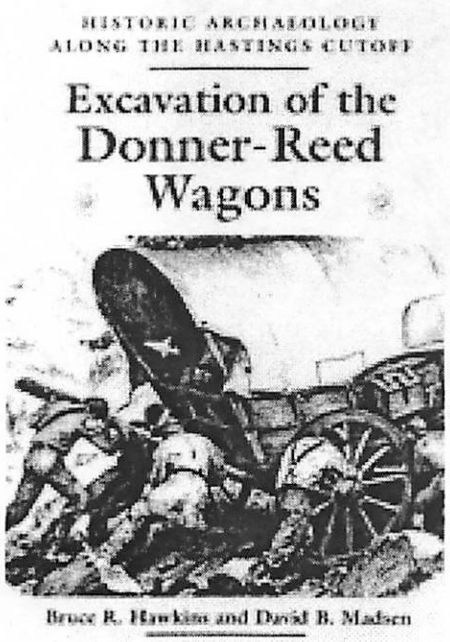
These facies occur in cycles of tens of meters thickness that record the gradual expansion and contraction of the playa. Smaller cycles of tens of centimeters thickness are superimposed on the large cycle, and record minor oscillations in the playa shoreline (Southgate et al., 1989).



A rough cross section of the playa at the foot of Pilot Range, Utah, with geology that may be similar to that of the salt pan in Death Valley. (Death Valley is a large, closed basin, so is technically a playa, that covers more than 200 square miles. The salt pan is what remains of a Pleistocene lake (Hunt, 1975)).

Playas can be challenging driving! Don't let the smooth, seemingly endless flat surface deceive you...there are pockets of wet, sticky clay, patches of water good for hydroplaning, and scattered sagebrush to thwart your path...

In 1847, the ill-fated Donner-Reed party of emigrants to California chose an alternate route out of Salt Lake City and became bogged down in the mud and playa of the Great Salt Lake Desert. Losing at least four wagons and numerous oxen, and a lot of valuable time, the delay contributed to their late attempt to cross the Sierra Nevada and the famous efforts by party members to endure a winter in the mountains.



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Giant Dessication Polygons

Joe Spitale

October 4, 2000

Polygonal dessication cracks are observed on Earth in arid environments and form non-sorted polygonal patterns. Typical horizontal scales for dessication polygons tend to be on the order of meters or less, but much larger examples on the order of 100m have been observed on playa in the deserts of the southwestern United States(Willden and Mabey, 1961). Polygonal features have also been observed on Mars at varying size scales. The largest features, observed by the Viking orbiter, are believed to be ice wedges. Mars Global Surveyor observed smaller polygonal features, similar in size to large terrestrial dessication polygons and their origin is not understood.

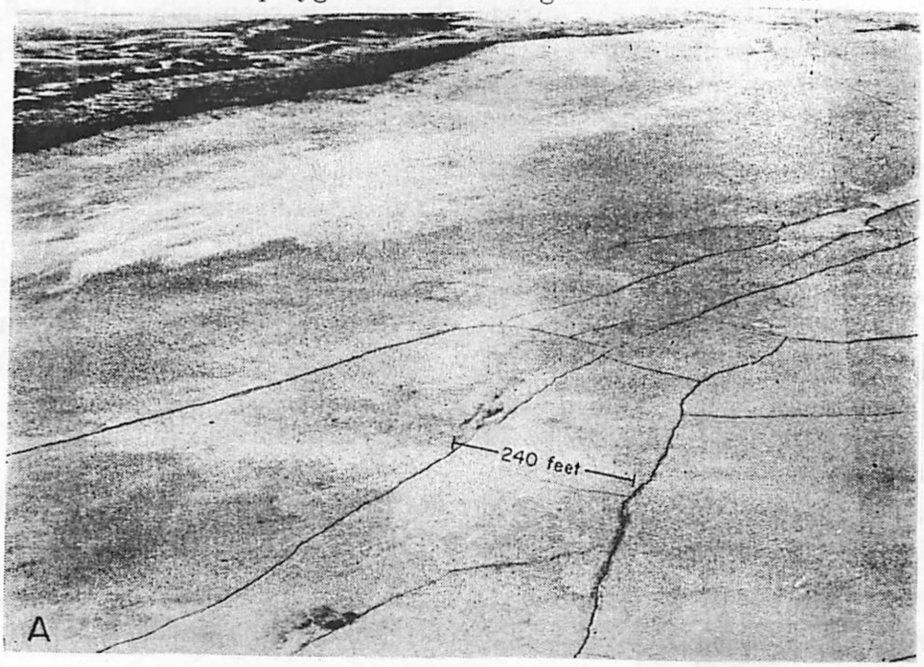

Figure 1: Arial photographs of giant dessication polygons on the Black Rock desert. *From Willden and Mabey (1961)*

18

Dessication cracking results from tensile stresses associated with contraction of lake bed sediments upon drying. The horizontal spacing of the cracks is associated with their depth, so it is necessary to dessicate a sediment bed to considerable depth to form the largest observed polygons.

Figure 2: Ground-level view of dessication fissure on the Black Rock desert. *From Willden and Mabey (1961)*

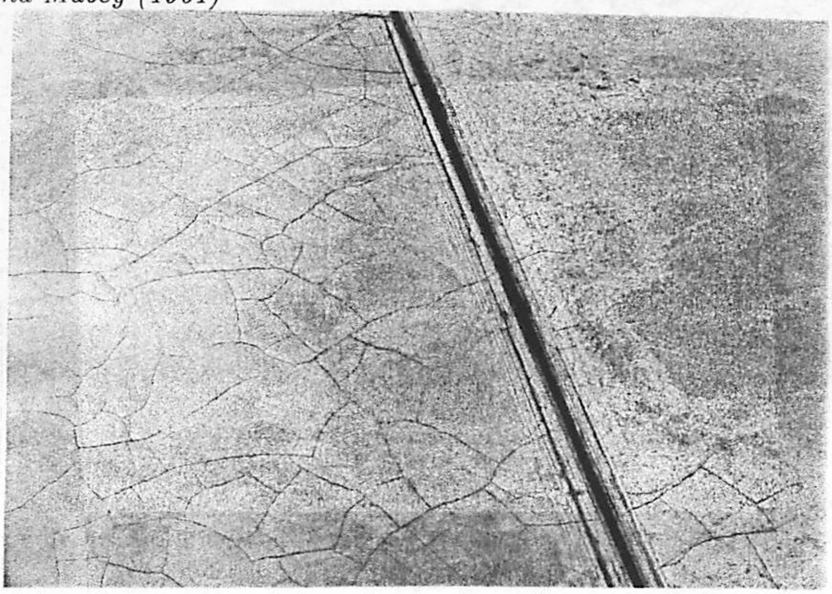

Figure 3: Arial photographs of giant dessication polygons on Lucerne Dry Lake. *From Shelton* et. al *(1978))*

Figure 4: Mars Orbiter camera image showing 100m-scale polygonal features on Mars. The image is intriguing, but ice-wedging seems more likely than dessication of lakebed sediments.

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The Gold Basin Meteorite Strewn Field

James Richardson
Fall 2000 PTYS Field Trip

Figure 1: *Location of the Gold Basin area, in northern Mohave County, Arizona. The strewn field is roughly located north of county road No. 25 (connecting Dolan Springs and Meadview), along the valley formed by the Hualapai Wash (connecting Red Lake to the Colorado River). [Courtesy of http:/maps.yahoo.com]*

Gold Basin Strewn Field Discovery

On November 24, 1995, James D. Kriegh, a retired civil engineering professor from the University of Arizona (UA), was prospecting in the Mohave Desert southwest of Meadview, Arizona. As a member of the Desert Gold Diggers organization, he had heard a talk a few years before, given by David Kring of the UA Lunar and Planetary Laboratory (LPL), on the field recognition of meteorites, thus giving him one more thing to keep an eye out for during his desert explorations. Utilizing a metal detector on that day, Kriegh found a odd rock which looked rather typical for the region, but which also displayed strong ferromagnetic properties – something which is decidedly *not* typical of normal desert rocks, but which *is* typical of meteoritic material. Within a few hours, Kriegh had located a second fragment of the same material.

Returning to the Tucson area, Kriegh brought the samples to David Kring for analysis, and within a short amount of time the meteoritic nature of both fragments was verified. Further investigation shown the fragments to be Ordinary (olivine–hypersthene) Chondrites, of the L4 (low iron content) variety. The stones showed the effects of having lain in the desert for hundreds, if not thousands of years, with "desert varnishing" evident on their exposed surfaces. Nonetheless, evidence still remained of the initial ablation created fusion crust on portions of the stones. The next question to be answered was: where there more?

***Figure 2**: A small Gold Basin meteorite, found by meteorite hunter "Bolide*Chaser." His description reads: "Approximately 35mm in length, this 20g L4 meteorite was found on the surface and shows evidence of being desert varnished and then of having been transported a short distance. Note broadly ablated top surface with relict primary fusion crust." [Courtesy of http://members.tripod.com/~bolidechaser/trip2/gbfinds.htm]*

Kriegh and Kring immediately set about organizing further expeditions to the Gold Basin region, with a team primarily composed of Jim Kriegh, John Blennert, and Ingrid Monrad. Over the course of the next few years, this team recovered more than 3000 meteorites from the area, indicating that Kriegh had discovered much more than an isolated meteorite fall, but had instead found an ancient meteorite strewn field – the fallen remains of a rather large meteoroid, which had disintegrated during its flight through the atmosphere and pelted the ground below with a huge shower of small stones. The significance of this find, beyond the number of meteorites and the initial size of the meteoroid, was that this was the *only* strewn field found to date of an ancient, or "fossil" nature; that is, this was the only strewn field to have been found which was *NOT* associated with a witnessed fireball sighting. This included Arizona's own Holbrook fall and meteorite strewn field, which had been witnessed in July of 1912.

Gold Basin Meteorite Analysis

The Gold Basin meteorites are L4 Ordinary Chondrites, dominated by olivine, pyroxene, and a metal–sulfide assemblage that has been clearly weathered. The samples are found lying on the desert surface, partially buried, or sometimes completely buried up to 10 inches deep in the fine–grained loose soil. The samples are sometimes partially or wholly encased in caliche, and may or may not have portions of their original fusion crust present. Rare stones have a complete fusion crust. The fusion crust range from a vivid black to a rusty red in color. Those which are found fully exposed on the surface may be covered with "desert varnish." The weathered state of the stones is classified as W2 to W3, depending upon the individual landing location, and is indicative of several thousand years in the desert environment.

Dating of the fall was accomplished using a combination of Carbon–14 and Berhillium–10 techniques, and yield an age of 14.3 +/– 0.8 ka (13,500 to 15,100 years) – dating the fall to the Late Pinedale portion of the Wisconsin Glaciation. This period would have placed the fall in a wetter and cooler environment than exists in this Mohave region today. The parent body of the fall is currently believed to be of asteroidal origin, having a bulk density of ~3500 kg/m^3, a radius of about 0.5 – 0.8 *m*, and would have entered the atmosphere with a velocity of 11 – 20 *km/sec*.

To date, ~3000 samples have been found over a roughly 225 square kilometer area. The full extent of the strewn field is not yet known: in fact, none of the strewn field boundaries have been located in more than just a very general fashion. Samples have been found in the foothills of the neighboring mountain ridges, and it is possible that the full strewn field extends over these ridges and into the neighboring valleys as well. Further investigation is underway.

Creation of a Meteorite Strewn Field

Criteria for Meteorite Occurrence

The primary criteria for a meteoroid entering the Earth's atmosphere to reach the ground as a meteorite are that it must have:

1. Sufficient mass to survive atmospheric passage. As a minimum, this equates to a visible fireball magnitude of roughly –8 to –10, and a mass of several kilograms.
2. Sufficient structural strength and density to survive atmospheric passage. As a crude minimum, the meteoroid must be of Carbonaceous Chondrite density (~1900–2100 kg/m^3) or greater to survive atmospheric passage. Volatile rich cometary material, termed friable material, will generally not survive.
3. Sufficiently slow meteor geocentric speed. Although meteor geocentric speeds can range from 11.2 to 72 *km/sec*, only the slowest speeds, those <~16–17 *km/sec*, have been shown by photographic fireball networks to have enough atmospheric penetration to potentially produce meteorite falls (this does not include the very largest, impact crater generating events).
4. Appropriate angle of atmospheric entry. As with reentering space vehicles, those meteoroids with too steep an entry angle into the atmosphere are more likely to be destroyed in the process due to high internal stresses and high ablation rates, while

those meteoroids with too shallow an entry angle are more likely to be "skipped" back out of the atmosphere again.

Note that if the mass of the meteoroid is great enough, more than a few thousand kilograms, then the remaining three criteria decrease in importance until the large impact events are reached – in which case a collision with the surface is imminent regardless of the other criteria. Looking only at the smaller, much more common events, it is interesting to explore criterion 2 and 3 in more detail, especially with regard to (1) the types of material striking the Earth's upper atmosphere as compared to that material which actually reaches the ground, and (2) the types of meteoroid orbits which are more likely to cause meteorite falls.

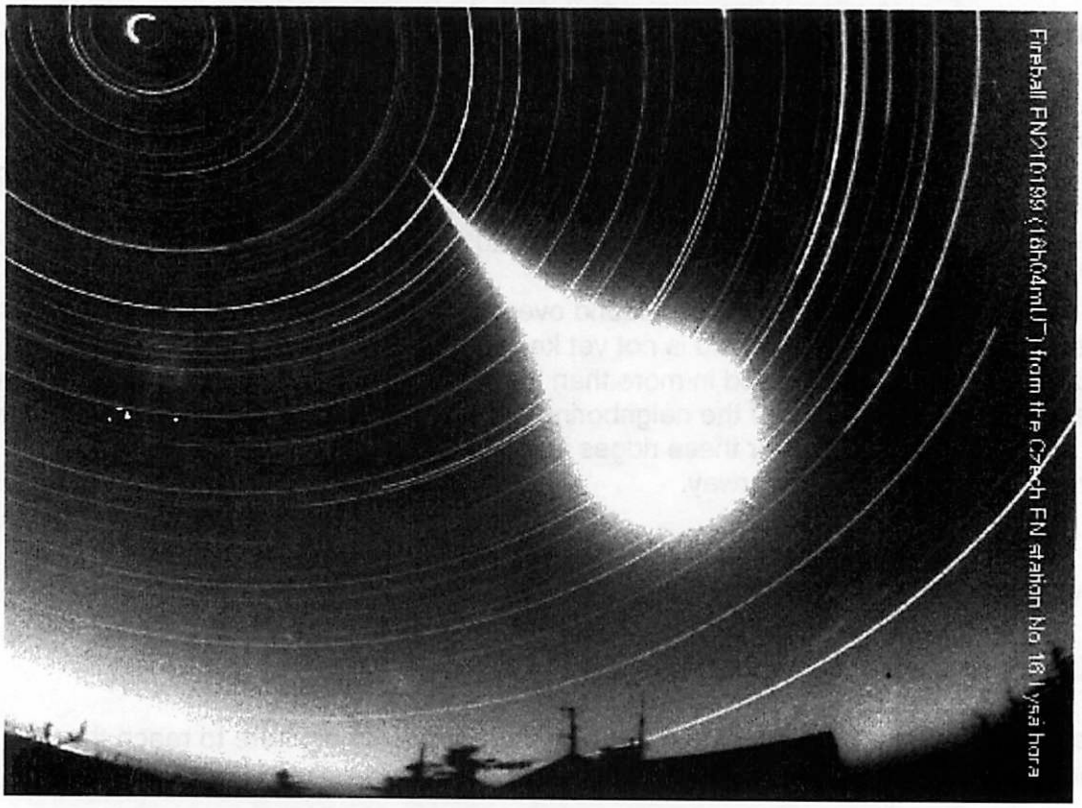

Figure 3: *Perhaps the brightest fireball every recorded at night, this sporadic meteor (estimated at magnitude −18 to −20) was caught on film by Dr. Pavel Spurny of the Czech Fireball Patrol at 18:04 Universal Time on January 21, 1999. [From: Cover, AMS Meteor Trails, No. 3, March 1999]*

Effects of Meteoroid Density on Atmospheric Survivability

The most illustrative way to explore the effect of meteoroid density on the survival chances of the meteoroid during atmospheric passage is to investigate the currently understood population makeup of (1) the observed meteor population, (2) the observed fireball population, (3) the observed fall population, and (4) the meteorite find population. The differences in these populations are surprising:

Overall Meteor Population

As a general rule, the smaller (fainter) is the meteoroid population under consideration, the more likely it is to be of cometary origin. As a very rough estimation, the visible meteor population is composed of about 9 cometary meteors for every 1 asteroidal meteor. This yields the following crude breakdown:

a) Cometary meteoroids: ~90%
b) Chondritic meteoroids: ~10%
c) Non–chondritic meteoroids: <1%

Fireball Population

When only the population of meteors of > –4 magnitude are considered, the more sturdy asteroidal meteoroids begin to make up an increasingly higher percentage of the population as compared to the fainter magnitudes. There are four basic fireball classes which are divided as follows:

a) Cometary meteoroids: 38%
   - Type IIIb fireballs, low density comets (0.2 – 0.34 g/cm^3 density): 9%
   - Type IIIa fireballs, high density comets (0.6 – 0.9 g/cm^3 density): 29%
b) Chondritic meteoroids: 62%
   - Type II fireballs, carbonaceous chondrites (1.9 – 2.1 g/cm^3 density): 33%
   - Type I fireballs, ordinary chondrites (~3.7 g/cm^3 density): 29%
c) Non–chondritic meteoroids (~7.9 g/cm^3 density): <1%
   - No fireball class

Observed Meteorite Falls / Fresh Finds

When only very fresh meteorite falls are considered, it becomes instantly apparent how important the density and sturdiness of the meteoroid material is to its likelihood of reaching the ground. The cometary meteoroid population disappears, and the carbonaceous chondrite population is greatly reduced. Thus, the ordinary chondrites and non–chondritic meteorites become the primary constituents of this population:

a) cometary meteoroids: 0%
b) Chondritic meteoroids: 84%
   - Carbonaceous chondrites: 4%
   - Ordinary chondrites: 80%
c) Non–chondritic meteoroids: 16%
   - Achondrites: 8%
   - Siderolites: 2%
   - Siderites: 6%

Meteorite Finds:

Once they are on the ground, meteorites instantly begin to undergo mechanical and chemical weathering. Again, those meteorites which are more sturdy and dense tend to withstand these processes much better. In this case, the iron meteorites (siderites) fare the best, despite their very small proportion of the overall meteoroid population:

a) Cometary meteoroids: 0%
b) Chondritic meteoroids: 37%
   - Carbonaceous chondrites: <1%
   - Ordinary chondrites: 37%
c) Non–chondritic meteoroids: 63%
   - Achondrites: 3%
   - Siderolites: 6%
   - Siderites: 54%

The upshot of these numbers is that the vast majority of meteors which are seen in the sky are not very likely to reach the ground even if the meteor is of fireball magnitude, and that the majority of meteorites which are found on the ground make up on a very tiny percentage of the overall visible meteor population. It took scientists many years to realize this disparity, and published texts frequently seem to conflict with one another with regard to the percentile breakdown of meteorite types. This is especially true if the author has combined old meteorite finds with fresh, observed falls.

Effects of Meteor Speed on Atmospheric Survivability

Meteoroid *heliocentric* speeds in the vicinity of the Earth's orbit fall into a relatively narrow range: from about 25 *km/sec* for particles in very circular orbits and near aphelion in the vicinity of the Earth's orbit, up to 42 *km/sec* for particles in near parabolic orbits and near perihelion at in the vicinity of the Earth's orbit. However, when vectorally combined with the motion of the Earth to create a *geocentric* speed, the range of possible observed speeds increases dramatically: from 11.2 *km/sec* for prograde objects just barely catching up to the trailing edge of the Earth and "falling" into it, up to 72 *km/sec* for retrograde objects slamming into the leading edge of the Earth head–on.

The direction from which the meteoroid approaches the earth will thus have a dramatic effect on its final geocentric speed and its ultimate survivability in passing through the atmosphere. Because only the slowest geocentric speeds, from about 11 to 17 *km/sec* have a possibility of allowing the meteoroid to reach the ground as a meteorite (for typical meteorite sizes), the possible radiant directions from which such meteoroids can come are limited to the "trailing" portion of the celestial sphere; that is, that portion of the celestial sphere which is more than 90 degrees away from the Apex of the Earth's Way. This, in turn, tends to limit the time of day for meteorite dropping fireballs to: [most likely] the late afternoon and early evening hours, [less likely] the early afternoon or late evening hours, and [very unlikely] the morning hours between midnight and noon.

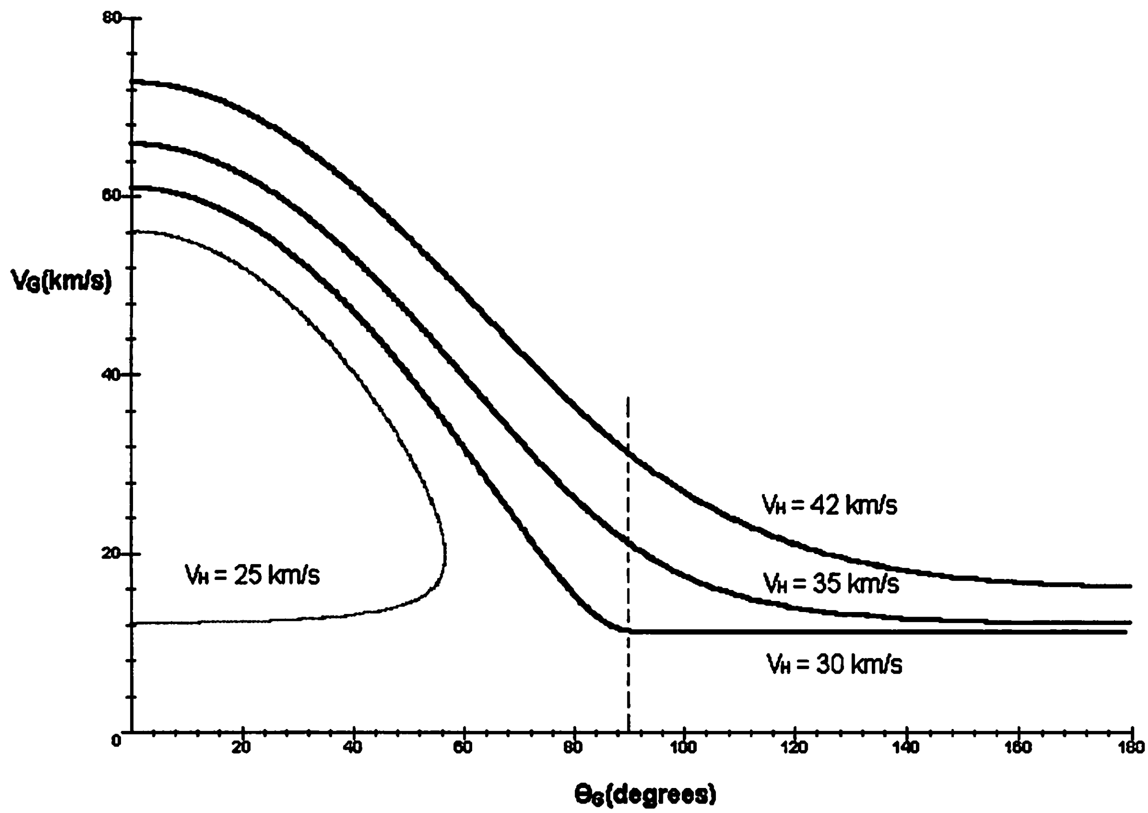

Figure 4: *Observed geocentric meteoroid speed (Vg) as a function of meteor radiant angular distance from the Apex of the Earth's Way (Theta_g); that is, angular distance from the point on the celestial sphere toward which the Earth appears to be moving in its orbit around the sun. Each line represents a different meteoroid heliocentric speed, running from 25 to 42 km/sec. The gray 25 km/sec line folds back on itself, indicating that meteoroids of this slow speed can only be seen in the general vicinity of the Apex point, either meeting the Earth head–on (retrograde), or being swept up by it (prograde). [From AMS Meteor Trails No. 3, March 1999]*

Meteoroid Disintegration and The Strewn Field

Most meteorite dropping fireballs will become visible at an altitude of about 70–90 *km*, which is below the normal band for most meteors of about 100–120 *km*, due to their very slow speeds (about 11–17 *km/sec*). As the meteoroid penetrates the atmosphere to more and more dense layers of the atmosphere, it will steadily lose kinetic energy and decelerate, while losing mass to the ablation process at the same time. The estimates on the amount of mass lost vary widely, depending upon the initial assumptions made, especially with regard to meteoroid density and structural strength. It is also not uncommon for fireballs to exhibit several flares in brightness over their paths, as smaller portions break off from the primary meteoroid due to the large differential stresses across the length of the body as it falls.

At about 15–20 *km* in altitude, most meteorite dropping fireballs will stop emitting visible light, as the body is decelerated down to about 2–4 *km/sec*. During the remainder of the meteorite's flight, the object will fall as a "dark body," continue to decelerate until it loses all of its initial cosmic velocity (the retardation point), and then silently and invisibly drops to the ground at the meteorite's terminal velocity. During the final deceleration phase of the fall to the retardation point, sonic booms may be emitted which will reach the ground a few minutes after the meteorite has landed.

More dramatically, some fireballs will end their visible track in a brilliant terminal flare, as the meteoroid catastrophically disintegrates into many smaller bodies. If this event occurs late enough in the meteoroid's flight, the resulting collection of bodies will rapidly decelerate until ablation stops, and then fall to the ground as a "meteorite shower." The area on the ground where this collection of meteorites from the same parent body are found is called a strewn field.

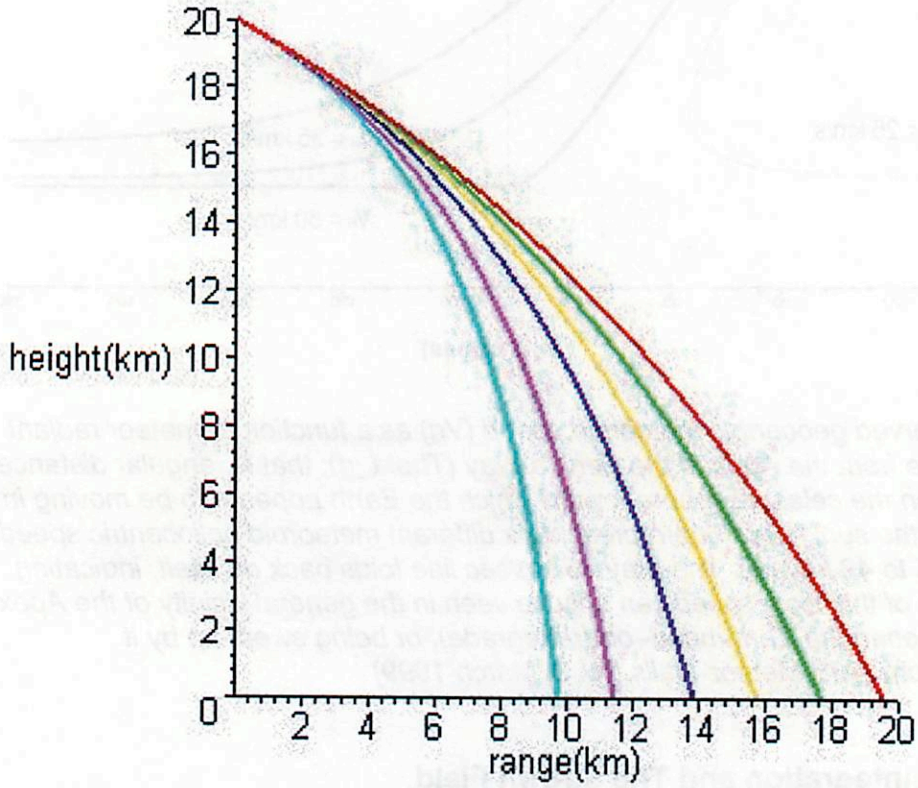

***Figure 5:** A simple model of mass sorting in meteorite strewn field creation. This plot shows the 2–dimensional atmospheric paths of meteorites from the parent body disintegration point (upper left) to meteorite land–fall (lower right). The parent body has an entry angle of 60 degrees CCW from the zenith, and breaks apart at an altitude of 20 km and a speed of 3 km/sec. The post–breakup particle sizes shown are 2 kg (red), 1 kg (green), 500 g (yellow), 250 g (blue), 100 g (purple), and 50 g (light blue).*

Strewn fields have a unique shape and mass distribution. The meteorites will fall to the ground in an elliptical pattern, with the long axis of the ellipse in line with an extension of the ground track of the initial fireball. An interesting aspect of the strewn field is that the more massive meteorites will be found at the far end of the ellipse (from the fireball track), while the least massive meteorites will be found at the near end. The reason for this sorting is that the drag force on each particle is proportional to the cross sectional area of the particle as seen from the direction of flight. Since the surface area to mass ratio is larger for smaller particles, these will experience a larger drag force and lose the horizontal and vertical components of their cosmic velocity faster than particles of larger mass – resulting in a differential sorting of the meteorite masses as they fall. An example of this sorting effect is shown in Figure 5, in which a simple model using an isobaric atmosphere and a drag force proportional to the particle's velocity and cross sectional surface area. The ellipsoidal shape of the strewn field is more difficult to explain, but is related to the distribution of kinetic energy and resulting vector velocities of the individual particles during the terminal blast (disintegration) of the parent object.

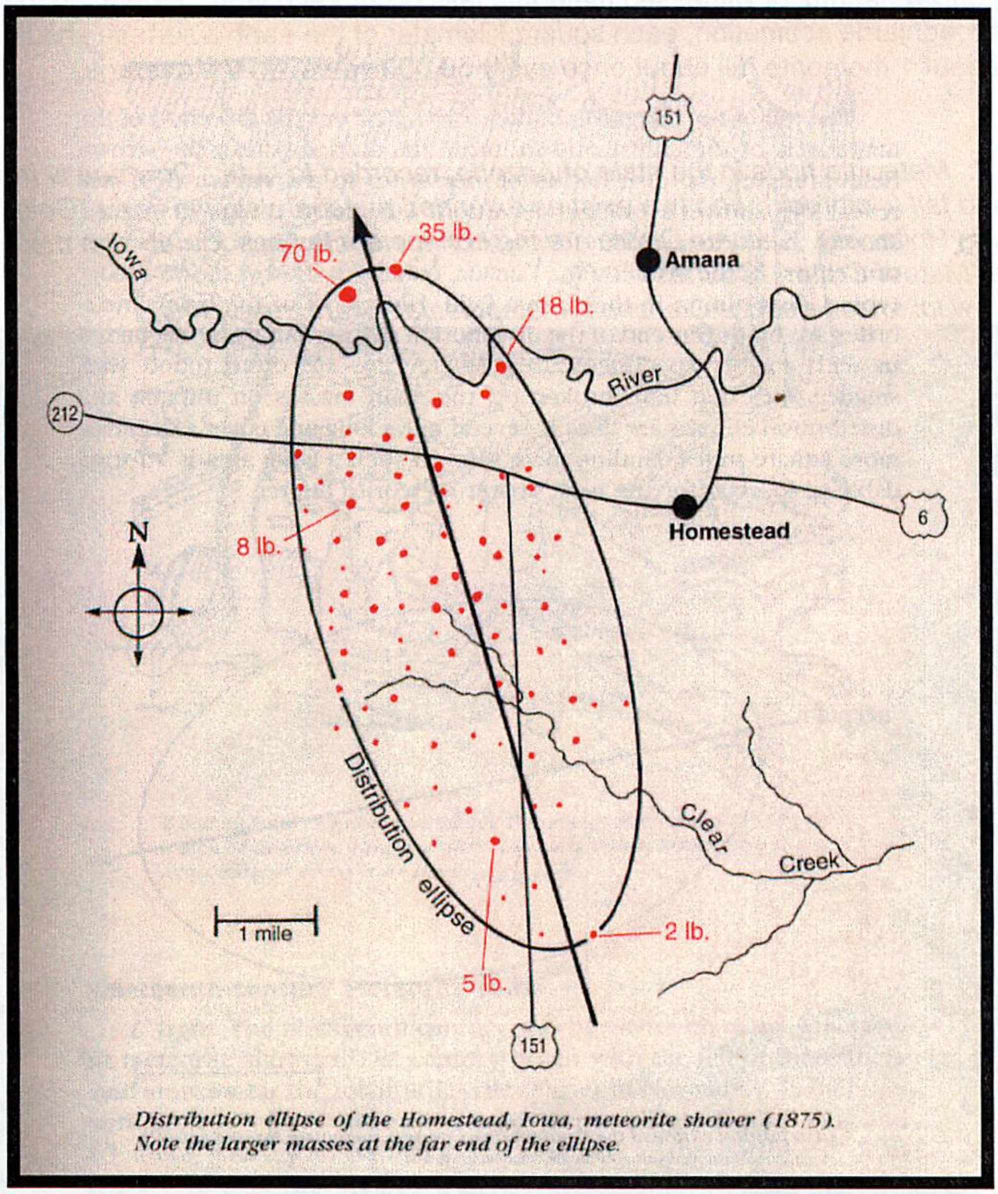

Figure 6: *Map of the Homestead, Iowa, meteorite strewn field, which fell in 1875. Note the characteristic elliptical shape of the field, with the long axis pointing in the direction of the ground track of the parent meteoroid/fireball. Also note the evidence of mass sorting in the field, with the more massive meteorites being found at the far end of the ellipse. [From Norton, R., "Rocks from Space," 1994]*

Frequency of Meteorite Falls in Arizona

As a rough order of magnitude estimation, approximately 5–50 meteorite dropping events occur over the entire surface of the Earth each day. It should be remembered, however, that 2/3 of these events will occur over ocean, while another 1/4 or so will occur over uninhabited land areas, leaving only about 1 to 10 events each day with the potential for discovery by people. Half of these again occur on the night side of the earth, with even less chance of being noticed. Due to the combination of all of these factors, only a handful of witnessed meteorite falls occur each year. Extending this order of magnitude estimation, each square kilometer of the earth's surface should collect about 1 meteorite fall about once every 50,000 years, on the average.

***Figure 7**: Meteorite finds in the state of Arizona, recorded to date. Only one is from a witnessed fall (Holbrook), and two exist as extended meteorite strewn fields (Gold Basin and Holbrook). Canyon Diablo are the iron meteorites associated with the Baringer Meteor Crater. [Courtesy http://www.lpl.arizona.edu/SIC/arizona_meteorites/az_stars_map.html]*

David Kring reports that over an area the size of the state of Arizona, about 2–3 meteorite dropping events can occur per year. This implies that since the time of Father Eusebio Francisco's initial entry into what is now Arizona in 1687 (the first recorded white man's exploration of the area), about 800 meteorite dropping events have occurred. By contrast, Arizona has only 39 recorded meteorite find sites (meteorites from 39 individual falls), many of which date back to before the entry of Europeans into the area. Due to Arizona's generally sparse population, only one of these finds resulted from a witnessed meteorite fall (Holbrook); however, due to Arizona's desert climate, unwitnessed falls are generally well preserved for thousands of years following the fall. This implies that there are many more meteorite finds yet to be made in this state.

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<u>Web Sites:</u>

Arizona Meteorites, http://www.lpl.arizona.edu/SIC/arizona_meteorites/

Gold Basin Meteorites, http://www.ctaz.com/~rvpark/Meteorites.htm

Gold Basin Meteorite Page, http://www.meteoriteimpact.com/goldbasin.htm

Gold Basin Meteorite Strewn Field, http://members.tripod.com/~bolidechaser/index2.htm

Andreas Ekholm presents:

PLAYAS

Playa: A term used in the southwestern US for a dry, vegetation-free, flat area at the lowest part of an undrained desert basin, underlain by stratified clay, silt, or sand, and commonly by soluble salts (Bates & Jackson, 1987).

ON MARS

Are there playas on Mars? How do we find them? If playas exist, where do we find them, and how old are they?

Playas form when streams empty into an undrained, closed basin, often forming temporary lakes. The sediments and salts contained in the water are deposited on the basin floor as the water evaporates, and form a flat, smooth surface.

Are there playas on Mars?

There are plenty of closed basins with smooth, flat floors on Mars. Many of the valley networks in the southern highlands drain into impact craters or other topographic depressions, and there is abundant evidence for the existence of at least temporary lakes throughout much of Martian history (Cabrol and Grin, 1999).

There have also been many reports of potential evaporite deposits on Mars, based on experiments as well as observations. E.g., Viking lander X-ray fluorescence measurements found considerable quantities of sulfates and chlorides in the Martian soil (Banin et al., 1992), and the Martian SNC meteorites have been found to contain traces of water precipitated minerals that include various combinations of carbonates, sulfates, halites, ferric oxides, and aluminosilicate clays, plausibly of Martian origin (Gooding, 1992). Also, Lee (1993) found several unusual intracrater high-albedo features in the southern highlands, which he interpreted as possible saline playas. Forsythe and Zimbelman (1995) drew the same conclusion from their observations, and Cabrol and Grin (1999) found depositional features that matched the location of bright albedo deposits in 6% of the impact crater lakes they studied, suggesting an evaporitic origin.

So it seems pretty safe to say that yes, there are indeed playas on Mars.

How do we find them?

So what reasons are there to suspect that a flat area in a closed basin is a playa and not a lava flow, impact melt, or something else?

The presence of channels leading into the basin is a good sign, because that indicates that it once contained water, at least for a short period of time. Since the basin is closed, the water could not escape other than by evaporation, sublimation, or infiltration. Thus, it would be forced to deposit its sediment load in the basin, as well as any dissolved salts (unless it infiltrated).

Another good sign is an unusual albedo pattern. Playas on Earth are often strongly zoned, and sharp contrasts in albedo are commonly found at the basin margins, where the albedo of salts stands in sharp contrast to that of the clastic materials composing the fringing alluvial fans, bahadas, or piedmonts. Several basins on Mars exhibit narrow curvilinear albedo patterns near their margins. Their analogs on Earth (in e.g. Death Valley and the Chilean Atacama desert) typically mark the location of groundwater seepage and/or paleoshorelines (Forsythe and Zimbelman, 1995).

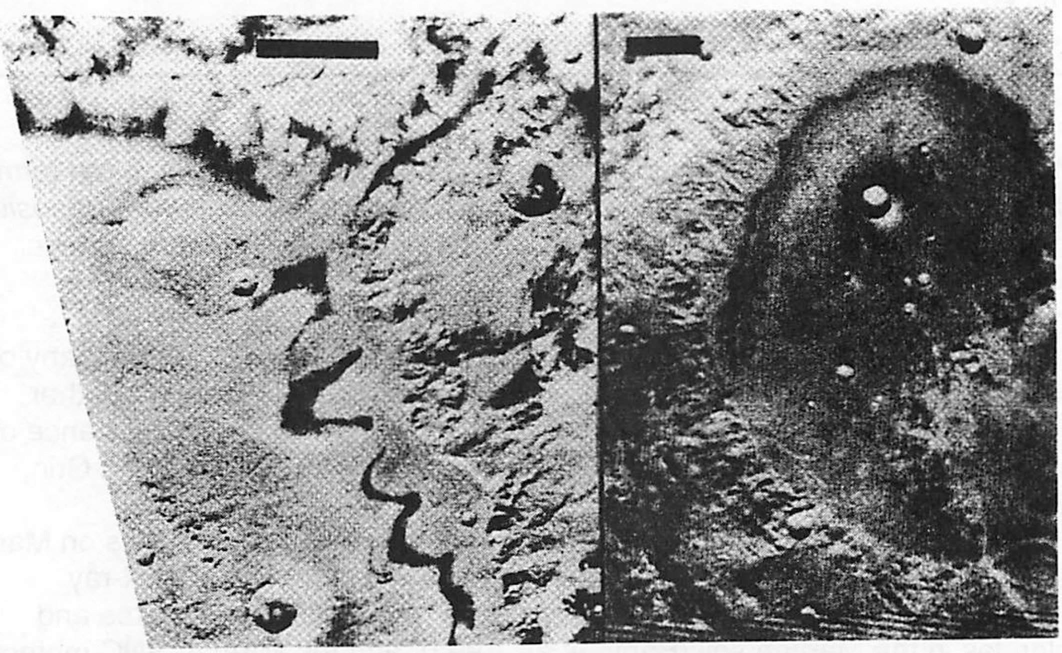

Figure 4. (Left) Margin of a Martian crater-basin with sharp albedo contrasts in the transition zone from the flat lying central facies to the marginal colluvial pediments. Scale bar is 25 km (Viking frame 321A38, centered at 341.8°W, 5.8°S). (Right) Martian crater-basin with a fine bright fringe developed approximately 1 km inward from the basin floor/crater wall margin. Scale bar is 5 km (Viking frame 212A05, centered at 10.2°W, 19°N).

MOC image of an unusual albedo feature in a Martian crater.

Where do we find them?

The majority of potential Martian playas are found in craters or other closed topographic depressions in the southern highlands, within 30 degrees from the equator. Goldspiel and Squyres (1991) identified 36 closed depressions which could have acted as local ponding basins for flow from the ancient valley networks.

While the majority of candidate playas are found in the south, the potentially largest playas are the great basins in the northern lowlands, such as Utopia, Amazonis, and Elysium (Scott et al., 1992). It may even be that the entire northern lowlands make up one gigantic playa if, as many researchers have suggested, they were once covered by an ocean.

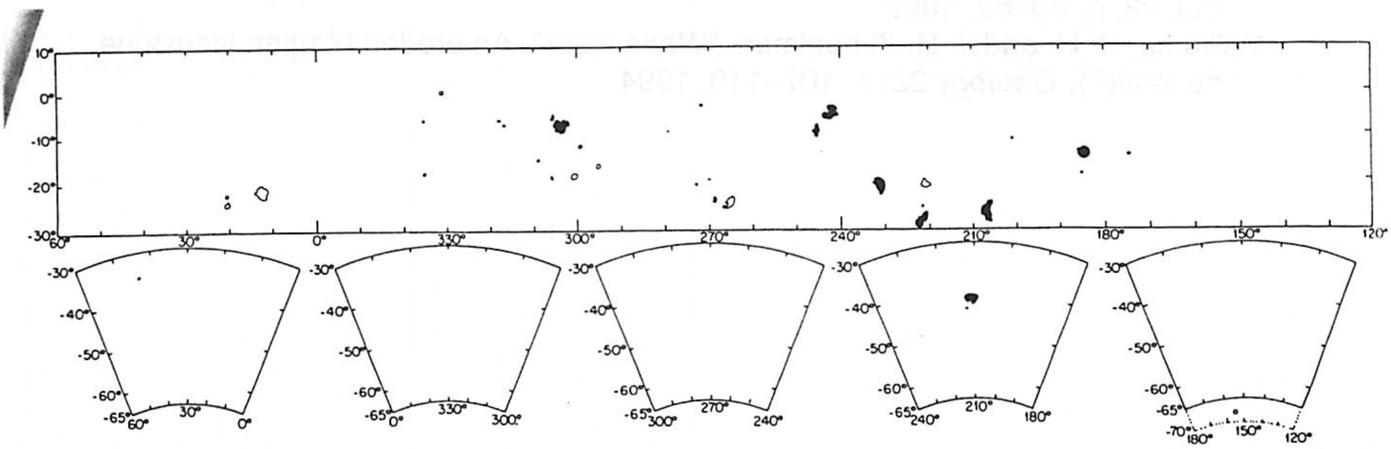

FIG. 9. Global distribution of observed ancient aqueous sedimentation basins on Mars. The basins shown as solid black exhibit evidence of volcanic modification subsequent to fluvial activity. Lateral dimensions of the larger basins are ~100 km.

How old are they?

Cabrol et al. (2000) report that Martian paleolake activity culminated in the Upper Hesperian (roughly 2–3 Gyr ago)—50% of all impact crater lakes they observed are of that age. Thereafter the activity decreases gradually, but is sustained until the Middle Amazonian (~600 Myr?). The youngest lakes observed are as young as 200–400 Myr. Assuming that playa formation is closely related to lake activity, we can then conclude that most playas are very old, that some may be relatively young, but that none are forming at present.

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The Hoover Dam

Erich Karkoschka

History: In the early 1900s, as the Los Angeles metropolitan area grew, an All-American canal was discussed diverting water from the Colorado river to the metropolitan area. It was designed as a small project paid locally. Before it was build, however, the idea of a large dam came up which would affect the water availability for much of southern California, Nevada, and Arizona. Such a project could only be carried out by the US. Government. This was approved in 1929. Construction of the Hoover dam occurred between 1930 and 1935.

Water, power, flood control: The water distribution of the lower Colorado river was the main incentive for building Hoover Dam. The dam also controls floods in the lower Colorado River. Part of the construction costs were paid by selling the electric power generated by the dam to nearby states. Arizona and Nevada asked for a major share of electricity although their populations could not use that much at that time.

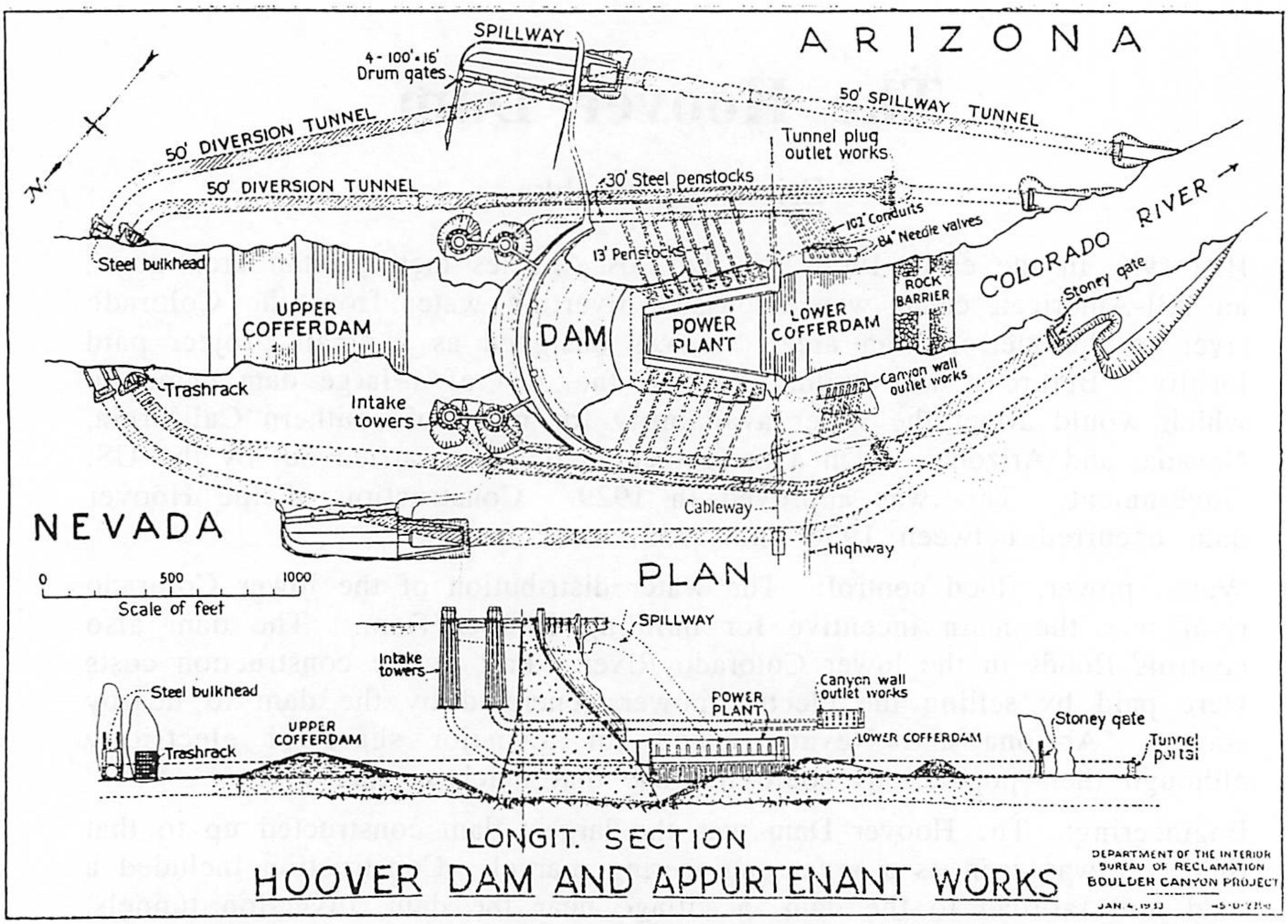
Engineering: The Hoover Dam was the largest dam constructed up to that time. It was seen as a great engineering marvel. Construction included a road and railroad to the dam, a village near the dam, diversion tunnels, coffer dams, the main dam, a power plant, intake towers, spillways, and finally the closure of diversion tunnels.

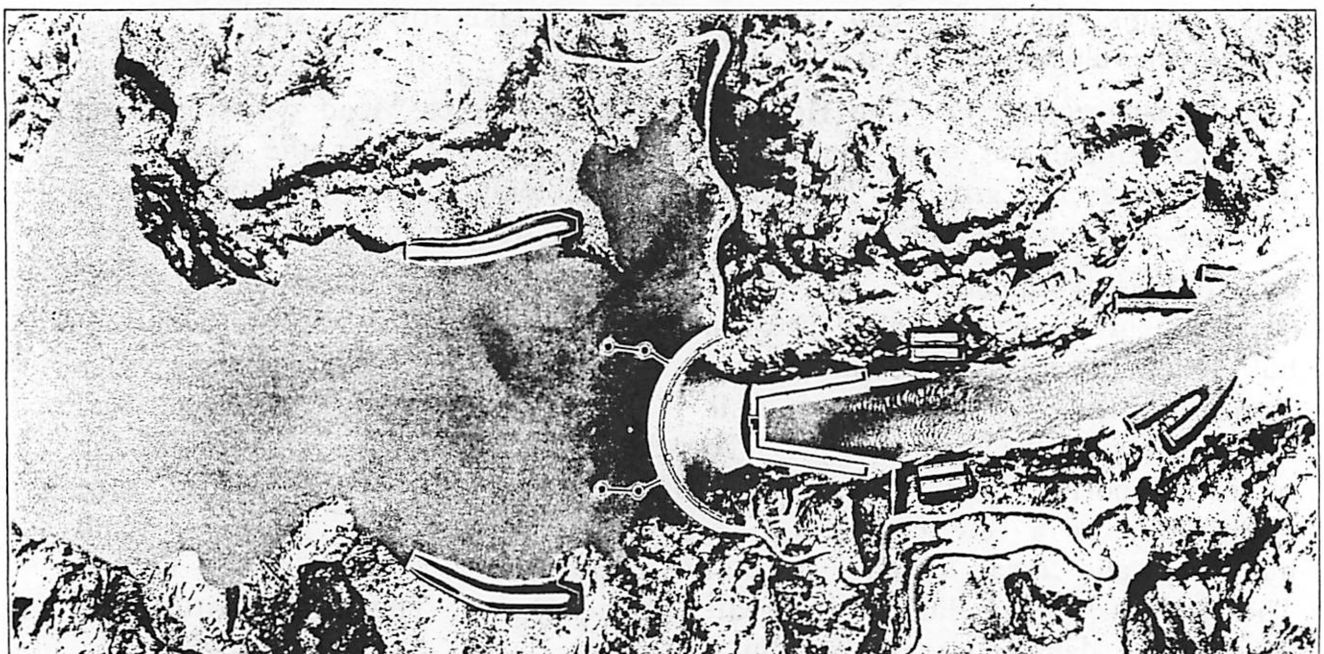
Lake Mead recreation: The Hoover dam created Lake Mead which is used for recreational purposes such as boating, especially after the population of Las Vegas has grown. That part of the Colorado River was hardly used by boats before, so that the dam as a barrier was no major disadvantage.

Environmental impacts: The Hoover dam, like other dams, affects the environment in ways which were not understood during its construction, but which have been become clearer in the meantime. The dam provides a barrier for the motion of fish. The dam changes the type and temperature of the river below. The dam blocks all rock and gravel the river transports. This erodes sand banks below while silting up the lake within one or a few centuries. Evaporation of the lake increases local humidity and local climate while reducing the available water below. The weight of the lake can create earthquakes. The probability of a catastrophic dam failure is low but not zero.

Fig. 1 (top): Final plan of the Hoover dam.

Fig. 2 (Bottom): Synthetic image of the dam at it would appear from the air.


ARIZONA
SPILLWAY
4 - 100' x 16' Drum gates
50' SPILLWAY TUNNEL
50' DIVERSION TUNNEL
50' DIVERSION TUNNEL
Tunnel plug outlet works
30' Steel penstocks
102" Conduits
84" Needle valves
COLORADO RIVER
Steel bulkhead
13' Penstocks
ROCK BARRIER
Stoney gate
UPPER COFFERDAM
DAM
POWER PLANT
LOWER COFFERDAM
Trashrack
Intake towers
Canyon wall outlet works
NEVADA
Cableway
Highway
0
500
1000
Scale of feet
PLAN
SPILLWAY
Intake towers
Steel bulkhead
POWER PLANT
Canyon wall outlet works
UPPER COFFERDAM
Trashrack
LOWER COFFERDAM
Stoney gate
Tunnel portal
LONGIT. SECTION
HOOVER DAM AND APPURTENANT WORKS
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BOULDER CANYON PROJECT
JAN. 4, 1933



Gravel Fans and Mudflows

Devon Burr
Fred Ciesla

Mudflows are highly concentrated water-clay-grain mixtures that flow in mountain streams after long or intense rainy periods. Often these flows will make their ways out of the defined stream channel, they may reach an area where they are not confined laterally. Here the flows will begin to spread out, and slow in the forward direction. Eventually the movement stops, and what remains is an alluvial fan.

The causes and movement of these mudflows has been studied in some detail because they can be an important factor in shaping terrain and they can also represent geologic hazards.

There are some particular conditions that are very conducive to allowing mudflows to begin. Those conditions of the source region are:

-poorly consolidated to unconsolidated material at the surface that becomes slippery when wet
-steep slopes
-abundant but intermittent supplies of water
-sparse vegetation

In addition, fans due to mudflows are also found in deserts due to sparse vegetation and though rains are infrequent, they can be torrential at times.

Much study has been done as to the factors that determine the distances and velocities at which individual flows will propagate. Obviously this is important in hazard planning. There have been two different methods used to model the mudflows: treating the flow as a Bingham fluid or treating it as a two-phase flow of water and entrained solids.

Bingham fluids are fluids that begin to flow once an initial stress, which exceeds the critical stress of the fluid, is applied. That is, once the applied stress exceeds the yield stress of the fluid, it behaves as a viscous fluid. The yield stress can be deduced from assuming a steady uniform, gravitationally driven flow, and equating the yield stress to the basal shear stress. For flow on a planar surface, the basal shear stress is:

$$\tau = \rho g h \theta$$

where ρ is the density of the mudflow at the time of emplacement, g is the acceleration due to gravity, h is the thickness of the flow, and θ is the local slope (assumed to be small) (Whipple and Dunne, 1992). The process of obtaining all of these original values is outlined in Johnson, 1984. And using an empirical formula, the viscosity of the flow is calculated using this yield stress.

A problem with this treatment rises when the fluid begins to spread laterally. Mudflows contain a wide variety of grain sizes, and sometimes boulders. The ability of a flow to carry material depends on the velocity of the flow. As the flow exits the channels and begins to fan out, its velocity and therefore its ability to carry sediments, decreases. Deposition will begin to take place, which will change the properties of the flow.

A secondary way of treating mudflows has only a little bit of work done on it (mostly in Russian, too, so I can't say too much on it –Fred). But this would consider the movement of a two-phase suspension: water with a high concentration of sediments in it. If you assume (incorrectly) that the sediments are uniform, the equations are easy, but in reality the sediments have a wide range of sizes and densities, etc., so things will get more complicated. This is work that is very much in progress. The nice thing, here, though is it easily allows for keeping track of the size of sediments that can be moved, and therefore the deposition process.

Studies such as that done by Whipple and Dunne in 1992 have shown that the morphologies of the resultant fans are dependent on the initial conditions of the mudflows specifically yield strength (and thus viscosity). These factors are controlled by sediment loading, the type of sediments (coarse versus fines) and the frequencies of the different types of flows.

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Gravel Fans and Mudflows
Part 2 (or Part 1, depending . . .)
Fred Ciesla
Devon Burr

Gravel flows and mudflows make alluvial fans (= "a low, gentlly sloping mass of loose rock material, shaped like an open fan"), deposited by a stream where they issue from narrow mountain valleys. The gradient in the mountains is usually similar to that at the top ("head") of the fan, so that deposition is initiated not by a decrease in slope but by
1) spreading out of the flow across the fan surface, and/or
2) infiltration of the water into the subsurface.
Fans are quite useful, since they provide evidence of mudflows and gravel flows. In fact, they are static mud/gravel flows, so to speak. So . . .

<u>Morphology of Arid–Region Alluvial Fans</u>

Slope:
–longitudinal slope generally decreases downfan, from =< 10 degrees near the head to .002 degrees near "toe";
–generally slope is gently convex upward, as are river channels regionally;
–however, segmented fans (such as those in Fresno County, CA) derive their "convex" slope from a series of straight segments, each representing climate? or tectonics?
–generally steeper on sides than down axis

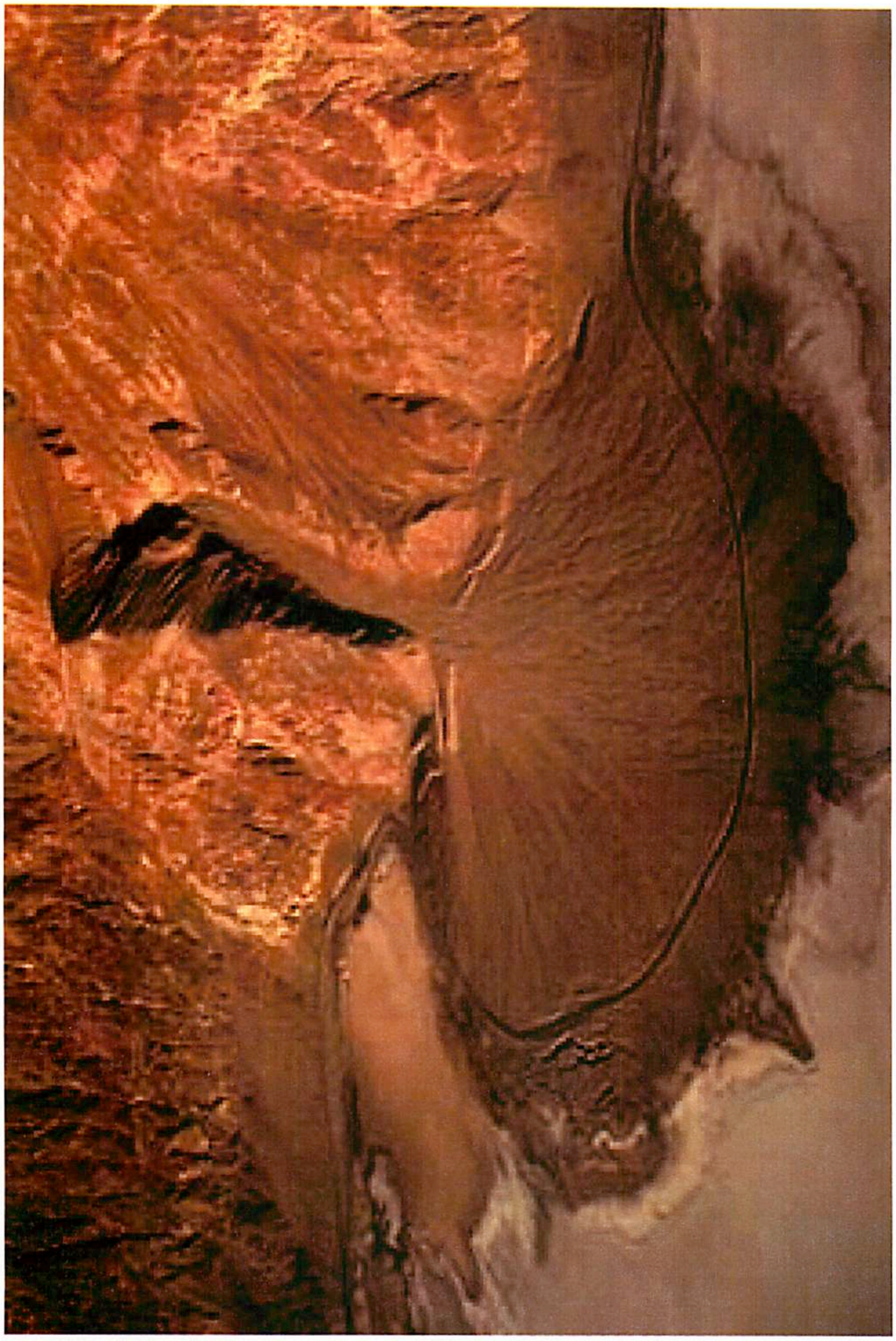
Surface units:
–generally three distinguishable (or distinguished?) types
1) modern washes = braided channels aned gravel bars with relief of <1 meter, widths of up to several hundred feet; no vegetation, desert varnish or other weathering.
2) abandoned washes = subdued remnants of modern channels, containing scattered vegetation, and varying degrees of varnish on gravel; in DV, mean particle size (7–25 mm) is slightly larger than for modern washed (connotes change in climate? also has slightly greater relief)
3) desert pavement = see A. Rivkin for details

Topography:
–shaped like part of a cone, although NOT a smooth surface (see above)
–incised or entrenched channels located close to head, several meters deep
–incision tends to enlarge fans, as flows that are not sufficientlybig to traverse the channel unconfined can when confined to a channel ==> downstream deposition

Area:

$$A_f = cA_b^{\,n}$$

–A_f is the fan area, and A_b is the area of the drainage basin feeding the fan
–*n* is the rate of change of the fan area with increasing drainage basin area, near 1 in a variety of environments
–*c* is 'how much the fan spreads out,' varies widely, reflects the effect on fan area of geomorphic factors other than drainage basin size, such as climate, lithology, tectonics, competition for depositional space



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

Adina Alpert

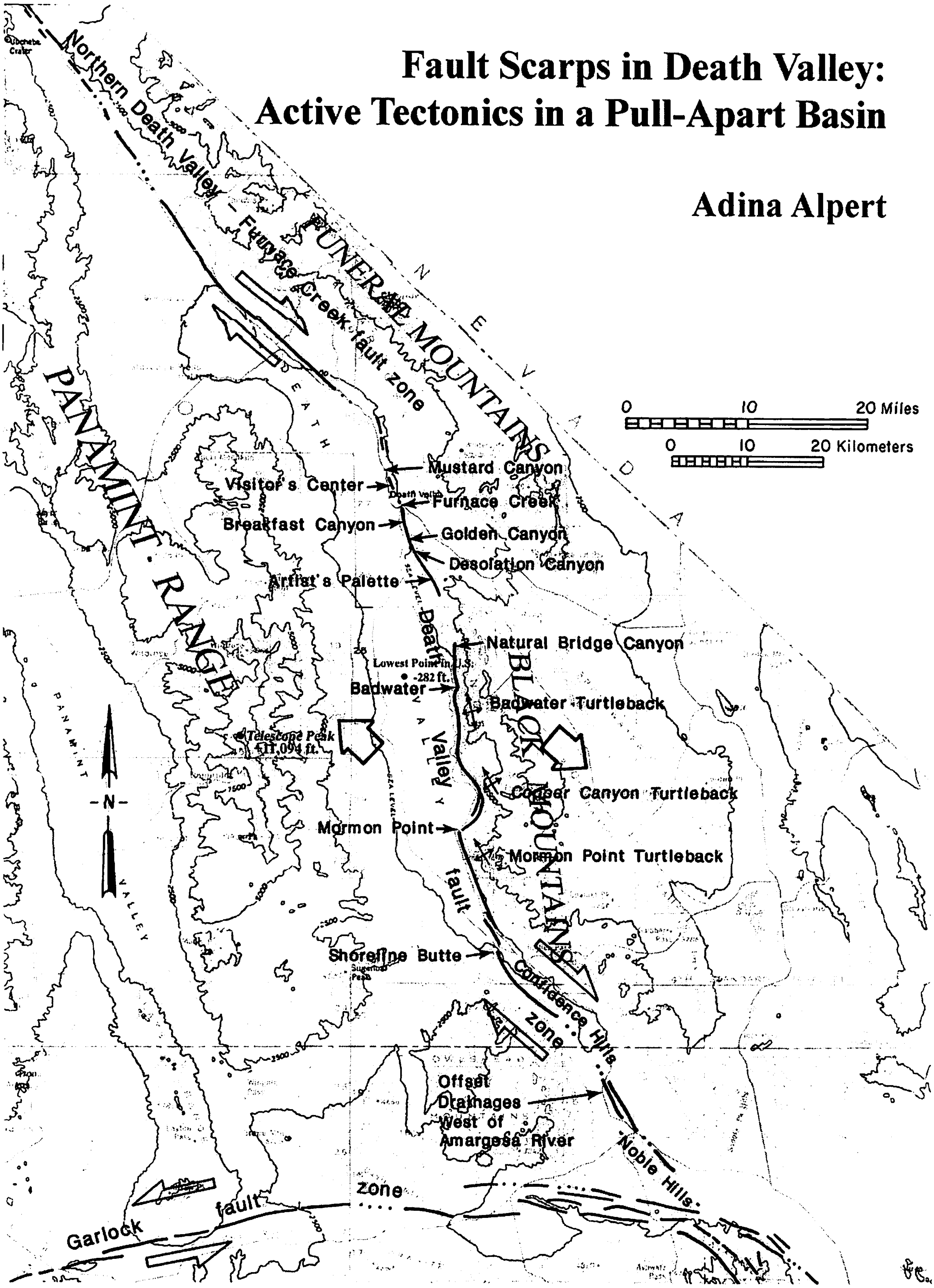


Fig. 1 (after Wills 1989)

The Death Valley – Furnace Creek – Garlock fault system

Geologic setting

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

"Pull-apart" basin formation

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

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

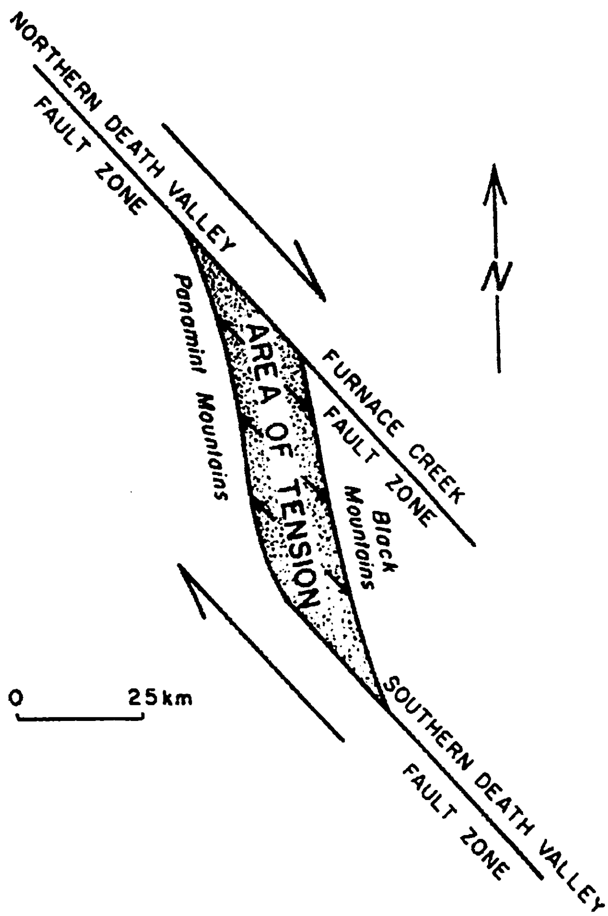


Fig. 2 – A model for the "pull-apart" basin in central Death Valley (after Burchfiel and Stewart 1966).

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

Present-day motion

Paleoseismological analyses of the Death Valley fault zone indicate that 4 to 6 separate moderate to large (M > 6.5) earthquakes have occurred along various segments of the fault since 10 ka (*Brogan et al.* 1991). Using GPS measurements taken between 1991 and 1996, *Bennett et al.* (1997) have estimated that the slip rate of the Death Valley fault is 3 to 5 mm/yr (in the strike-slip direction). This motion implies 30-50 m of strain accumulation over the next 10,000 years, which *Bennett et al.* project will result in 5 to10 M_W 6.5-7.5 earthquakes over that period. This finding is consistent with the paleo-seismological studies of the fault zone.

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

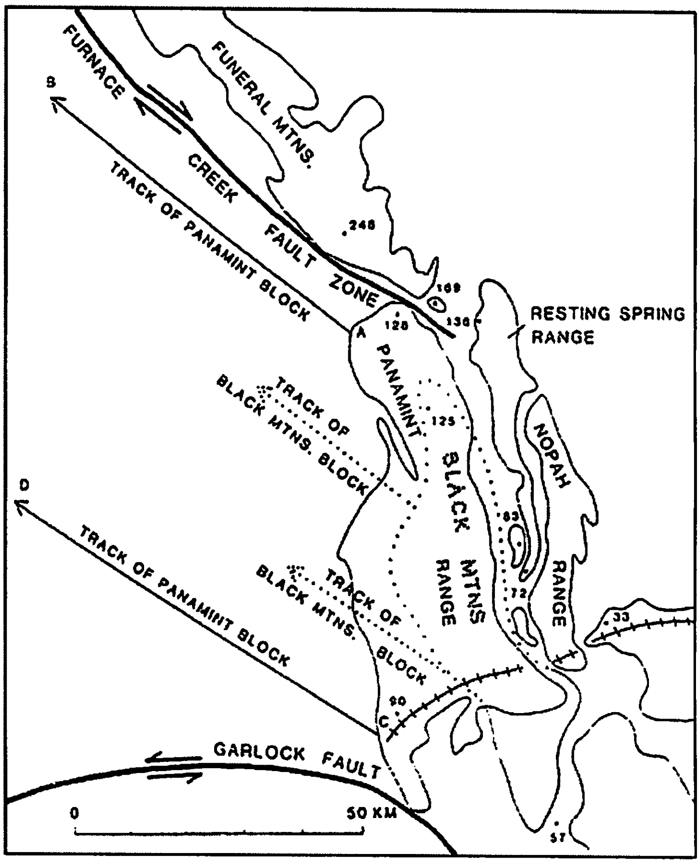


Fig. 3 – Reconstruction of Death Valley area prior to detachment faulting according to the Stewart model. Dotted pattern indicates prefaulting position of Black Mountains block below Panamint Range block. (from Stewart 1983).

Fault scarps in the Death Valley fault zone

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

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

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

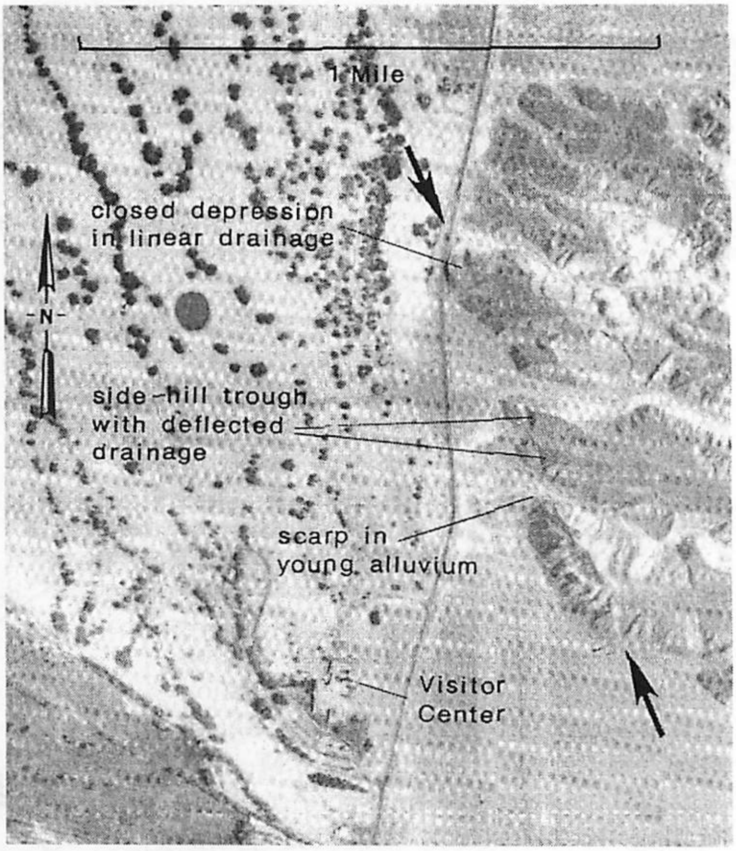


Fig. 4 – Aerial photo showing geomorphic features that identify the Death Valley fault zone northeast of the Visitor's Center. The trace of the fault is between the arrows. (From Wills 1989)

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

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

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

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

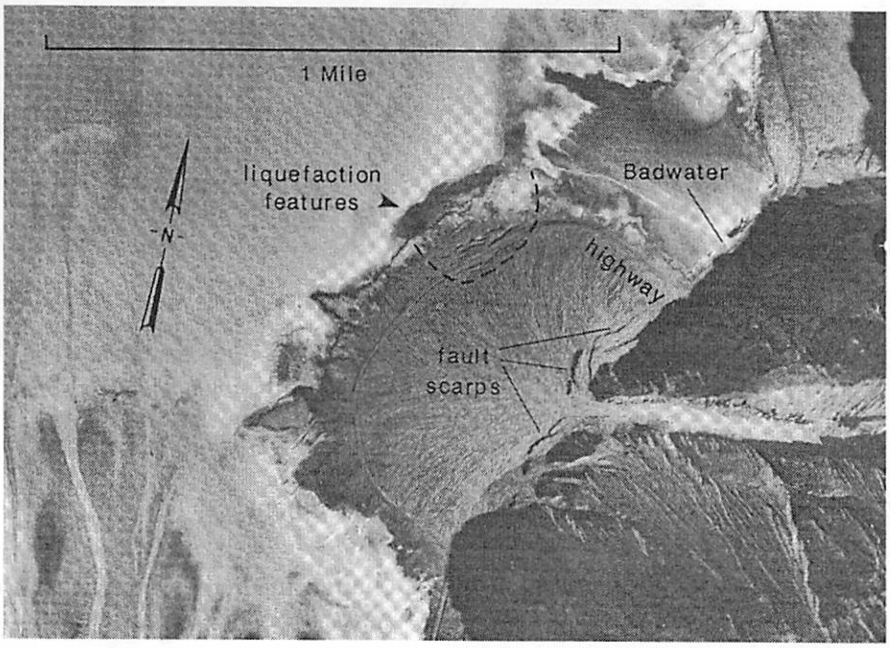


Fig. 6 – Aerial photo showing fault scarps at the apex of an alluvial fan in the lower center of photo. (From Wills 1989)

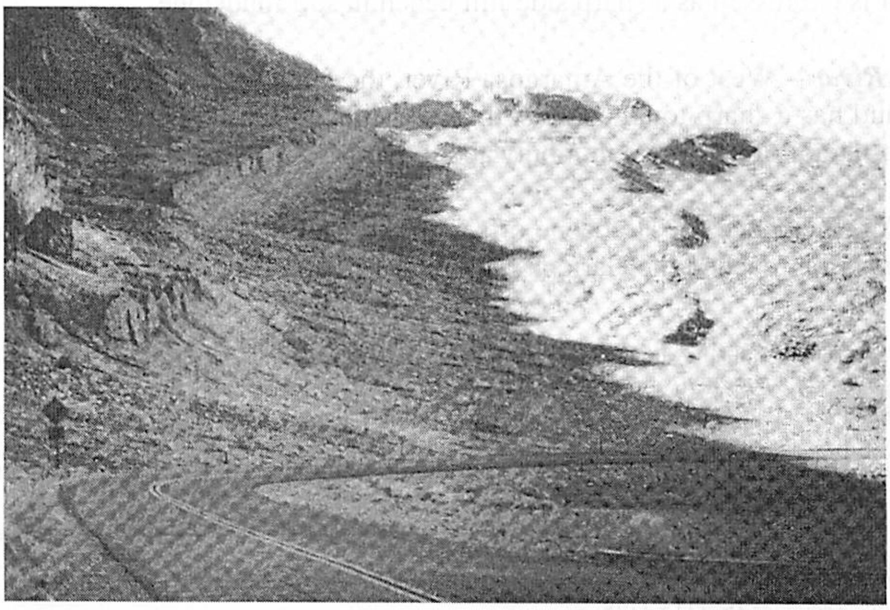


Fig. 7 – View to the southwest from Badwater showing fault scarps on the Badwater alluvial fan. Scarps that are erosionally enhanced identify the approximate location of the fault that has offset fan surface. Two fault scarps join to form a single scarp on the horizon. (From Wills 1989)

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

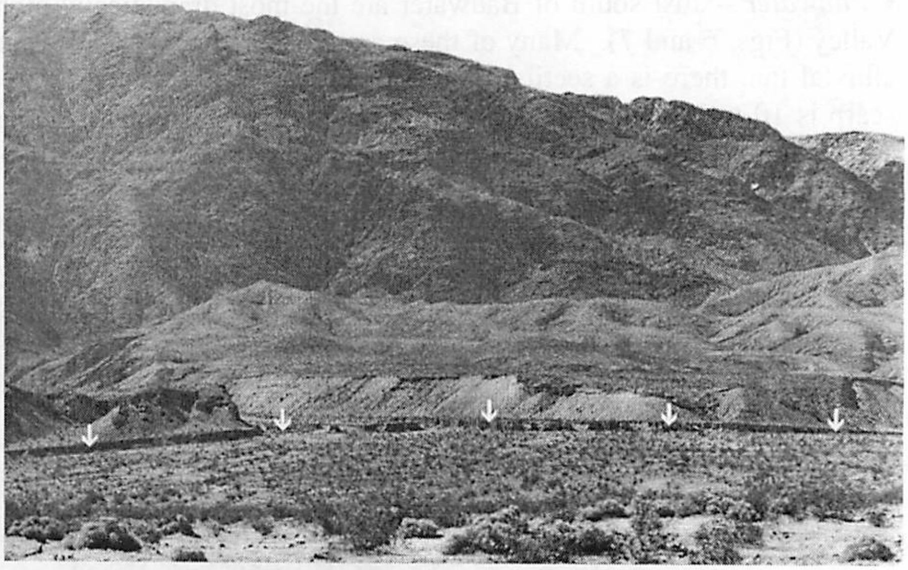


Fig. 8 – A low, young fault scarp crossing a wide arroyo, between alluvial fans, in Mormon Point cove. (From Sharp and Glazner 1997)

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

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

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

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Desert Pavements

a primer written at 3902 m and 616 mbar

-with your plausibly helpful host, Andy Rivkin

Desert pavements consist of a one- to two-particle-thick layter of closely packed gravel, shown in Figure 1 (McFadden et al. 1987). They are commonly found in arid areas, and have apparently been important to ancient caravan routes. Desert pavements have also been noted by the military as good transport routes for the same reason. Desert pavements have been suggested on Mars, as well.

Although desert pavements are ubiquitous features, the mechanism of their formation has been the matter of great debate, and is still not necessarily settled today. The three main theories, are *deflationary*, *wet/dry*, and *inflationary* theories.

Deflationary theory: The most commonly heard theory for the creation of desert pavements posits an initial mixture of particles of all sizes. Wind transport removes the smaller particles, and leaves behind a lag deposit of larger particles. This theory is touted by Halka Chronic in her entries in the *Roadside Geology* series, but is inconsistent with the physics of aeolian transport (see handout by Bart).

"Brazil nut" theory: An alternate view proposes that wet-dry cycles, although infrequent in the desert, are the main driver behind desert pavement formation. Often, clay minerals will swell when wet (and shrink when dry). When a wet-dry cycle occurs repeatedly, cracks can open up and void space is created. Smaller particles will preferentially fall into these voids, which has the effect of moving larger particles upward. Eventually, the largest particles are concentrated on the surface. This is similar to the so-called "Brazil nut problem", where the largest nuts in a can of mixed nuts are often found at the the top. In that case, however, it is shaking rather than wet-dry cycles which opens the void space (hopefully, anyhow). Jay Melosh has been the most passionate advocate of this theory (in my limited experience), and it was this theory that the experiments of Rivkin (1993, unpublished) were meant to test.

Inflationary theory: The most recent theory has been advanced by McFadden et al. (1987). Their work in the Cima volcanic field suggests that the cobbles comprising the pavements have *always* been at the surface. They propose a model by which windblown dust is washed underneath surface cobbles and soil is formed. The aeolian dust also accelerates mechanical weathering of rock, creating the cobbles in the first place. Wells et al. (1995), investigating the same field area, confirmed that a desert pavement comprised of pieces of a lava flow has been at the surface for the same amount of time as the lava flow itself.

Experimental results: Rivkin (1993) attempted to test the "Brazil Nut theory" using pans roughly 50 cm × 20 cm × 5 cm in volume full of a gravel/sand/bentonite mix. Water was added to the mixture, and to facilitate rapid drying, the Hawthorne House Oven Facility was used. Unfortunately, the scale of the simulation was too small to allow a truly realistic experiment to occur, though dessication polygons and a playa-surface-in-miniature was created.

Planetary connection: As mentioned above, desert pavements have been proposed for Mars, though these suggestions depend upon the deflationary theory, currently in disfavor. Dust devils have been observed on Mars, and have also been proposed as a possible way for desert pavements to form on that planet. If desert pavements do exist on Mars, they imply that Mars may have had cyclic precipitation since the currently favored theories necessitate this.

References McFadden et al. (1987) *Geology*, Wells et al. (1995) *Geology*, Rivkin (unpublished).

Figure 1: An image of a desert pavement, stolen from Lisa Wells' Geomorphology page, http://www-geoimages.berkeley.edu/GeoImages/Wells/wells.html

TURTLEBACK FAULTS OF DEATH VALLEY, CALIFORNIA

Windy Jaeger

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

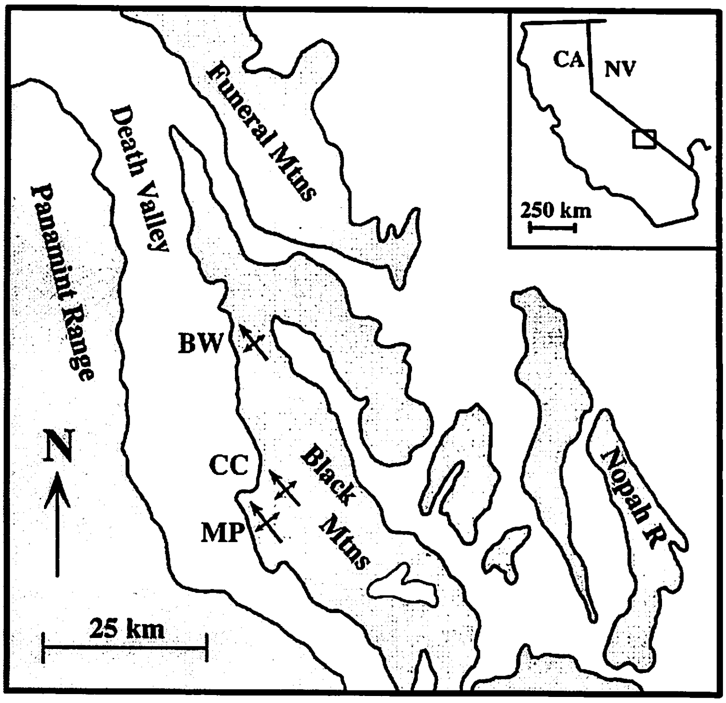

Figure 1. Map of the Death Valley region. Gray areas are pre-Quaternary (>1.6 Ma) highlands and white areas are Quaternary lowlands. Plunging antiform symbols mark the three turtlebacks: BW, Badwater Turtleback; CC, Copper Canyon Turtleback; MP, Mormon Point Turtleback [after Miller, 1992].

MODELS FOR THE FORMATION OF TURTLEBACK STRUCTURES:

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

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

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

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

- The relative motion of the hanging wall and the footwall of the turtleback faults is recorded in small- and large-scale features exposed on the footwall. For the three turtlebacks in the Death Valley region, these movement indicators show that the hanging walls were translated downward and northwest.

1. **slickenside** - a polished and striated rock surface that results from friction along a fault plane.
2. **fault mullion** - large grooves on a fault surface parallel to the direction of displacement.

- Fractures in the surrounding metasedimentary rocks are oriented perpendicular to the movement direction and to the long axes of the turtlebacks.

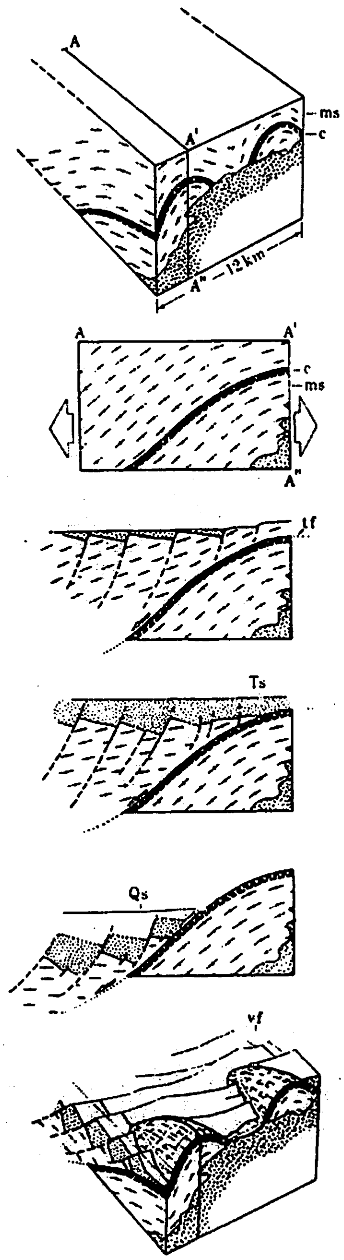

Figure 2. Block diagrams and cross-sections, illustrating the pull-apart model for turtleback formation; c = carbonate layers, ms = mixed metasedimentary rock, Qs = Quaternary sediments, tf = turtleback fault, Ts = tertiary sedimentary rock and vf = valley floor [from Wright *et al.*, 1974].

PALEOMAGNETISM OF THE BLACK MOUNTAINS:

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

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

TURTLEBACK (FOOTWALL) ROCKS:

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

  Mylonites (rocks that have strong flow texture)

  1. Quartzofeldspathic gneiss

     gneiss - a foliated rock formed by regional metamorphism
  2. Calcite ($CaCO_3$) marble
  3. Dolomite ($CaMg(CO_3)_2$) marble
  4. Pegmatite

     a coarse-grained igneous intrusive rock; roughly granitic in composition; the last and most hydrous portion of a magma to crystallize, thus it can have high concentrations of minerals present only in trace amounts in granites; generally occurs as dikes around the margins of batholiths

  Non-Mylonites

  1. Minor pelitic schist (i.e. metamorphosed mudstone)
  2. Rocks that post-date the foliation
     a. variably striking, highly altered mafic dikes
     b. N20°E striking latite dikes

        latite - a porphyritic extrusive rock with phenocrysts of plagioclase and potassium feldspar and little or no quartz

- The footwall mylonites vary in thickness due to ductile deformation such as folding and the formation of **boudinage structures** (i.e. pinches and swells formed by stretching a layer that was initially uniform in thickness).
- Both crosscutting relationships [Miller, 1992] and U/Pb dating of zircons [Asmerom *et al.*, 1990] indicate that the mylonitization was concurrent with early stages of brittle deformation in the Black Mountains (i.e. Upper Tertiary, <11.6 Ma).

CHARACTERISTICS OF A METAMORPHIC CORE COMPLEX:

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

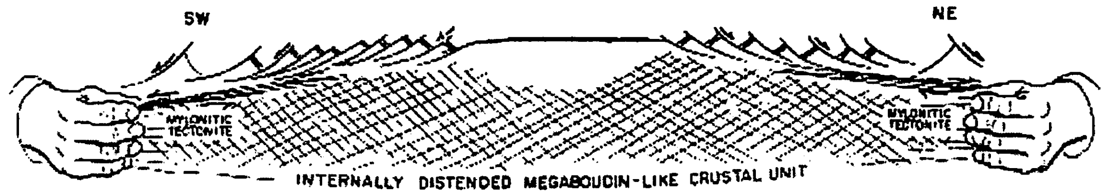

Figure 3. Schematic diagram of a metamorphic core complex [from Davis and Reynolds, 1996].

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Putting the "Death" in Death Valley
Paul Withers

In 1849, gold was discovered at Sutter's Mill in California and people from all over the United States packed their belongings and began to travel by wagon to what they hoped would be a new and better life. Since most of these pioneers began their exodus to California in 1849, they are generally referred to as 49ers. One of the supply points along the trail was Salt Lake City, where pioneers prepared for the long journey across the Great Basin desert before climbing over the High Sierra Mountains to the gold fields of California. It was important to leave Salt Lake City and cross the desert before snow began to fall on the Sierra Mountains, making them impassible. Only a couple of years before, a group of pioneers called the Donnor Party left late out of Salt Lake City and was trapped by a storm, an event that became one of the greatest human disasters of that day and age. The stories of the Donnor Party were still fresh on everyone's mind when a group of wagons arrived at Salt Lake City in September of 1849. This was much too late to try to cross the mountains safely, and it looked like these wagons were going to have to wait out the winter in Salt Lake City. It was then that they heard about the Old Spanish Trail, a route that went around the south end of the Sierras and was safe to travel in the winter. The only problems were that no pioneer wagon trains had ever tried to follow it and they could only find one person in town who knew the route and would agree to lead them. As this wagon train left Salt Lake City, some of these people would become part of a story of human suffering in a place they named Death Valley. [From here on, historical sources have a tendency to disagree on many details. Just enjoy the show.]

For $10 per wagon, Captain Jefferson Hunt of the Mormon Battalion led approximately 200 people, 110 wagons, and 500 horses and oxen south at ten miles per day. This slow pace (Hunt would only go as fast as the slowest wagon in the group) infuriated some of the more impatient gold seekers in the group. Remembering stories of a more direct route due west, and being overtaken by a party who had a rough map which showed such a route, many of the party swung west near Mountain Meadows in Nevada, confident that they could find Walker Pass, cutting 500 miles off their route. Since no Anglo had been that way before, the inevitable disasters followed. Cutting a long story short, most of the wagons decided to rejoin Captain Hunt and the well-travelled trail, though one jointly owned wagon was sawn in two as its two owners wished to go their separate ways. The bulk of the party eventually reached San Bernardino after an arduous journey. The remaining 50 people, not including the owner of the rough map, continued due west to discover Death Valley...

They were composed of three groups: thirty young men from Illinois, called the Jayhawkers; the Brier family, parents with their three young children; and the Bennett-Arcane group of thirteen men, two women, and four children. The three groups travelled in loose contact. They went west for weeks, struggling through the frequent mountain ranges. Springs and cattle feed were scarce. Around Christmas of 1849 they entered Death Valley. It had been two months since they had left the Spanish Trail. They spent Christmas at Furnace Creek, where, for the first and last time in many months, they found plentiful water. Their prospects were dismal. They were in uncharted territory, on an arid desert plain, with the Panamint mountains obstinate on the western horizon. The Jayhawkers abandoned their wagons, killed their oxen, divided their food and prepared to walk out, each man for himself. Several of them died in the mountains, though none in the Valley itself. The Briers were also on foot, having burned their broken wagons. They trudged after the Jayhawkers;

all survived. In the rear, the wagons of the Bennett-Arcane group struggled on. Many of their young men deserted them to race with the Jayhawkers, and one died from dehydration in the Valley. The wagons could not be dragged south over the salt flats to avoid the mountains, and no pass through the Panamints could be found. Exhausted, the group camped on the western floor of the Valley to decide their next move. Two young men, Rogers and Manly, were sent foward, with much of the food, to find a pass and bring food. They were expected to be gone for no more than fifteen days. Two families, with four young children, remained and waited to die.

When the men had been gone for twenty-five days, the families summoned up their last reserves of strength and prepared to attempt the walk out unguided. As they made ready their meagre supplies, a shot boomed out across the silent Valley. Their saviours, Rogers and Manly, had returned with supplies and a mule. They had travelled to within 30 miles of Los Angeles before finding the Rancho San Franciscito and the much needed supplies, including the first oranges the children had ever seen. The group fed and rested the next day, then began the slow journey across the Panamints. On the second day, they crested the range and turned to look back at the Valley that had been their prison for a month. "Goodbye, Death Valley," said one of the women, thus giving the Valley the name it still bears today.

It took three arduous weeks before they reached the end of the trail.

If you're still awake and interested, there now follow some tales of the wild borax days...

Borax was first found in Death Valley in 1873. Aaron and Rosie Winters were in their sixties and living near Las Vegas when a prospector stopped with them for the night. During the fireside conversation, the prospector told them about the rich borax deposits then being exploited in Nevada and how to recognise and test for borax. The next day Aaron and Rosie loaded up their burro and raced to Furnace Creek in Death Valley, where Aaron remembered seeing "cotton ball" deposits like those described by the prospector. They powdered the soft, white fluff, poured on sulphuric acid and alcohol, struck a match, and saw a green flame. "She burns green, Rosie! We're rich, by God!" exclaimed Aaron. Preoccupied with other deposits and the perennial problem of working in Death Valley, investors waited until 1881 before buying out their claims for $20,000.

The Pacific Coast Borax Company built the Harmony Borax Works a mile north of Furnace Creek in 1881. In traditional style, Chinese gathered the fluff from the floor of the Valley, Natives cut mesquite for the boilers, and the backers made fortunes. In winter at least. Summers were too hot for the refined product to crystallize and production shifted to other deposits at higher elevation. The refined borax was hauled out by twenty mule teams. A train of twenty mules pulled two huge wagons and a 1,200 gallon water tank, a total load of 36 1/2 tons. Each wagon, costing $900, was sixteen feet long, four wide, and six deep. The rear wheels were seven feet high, banded with iron tyres an inch think. Driving such a mule train was one of the most highly skilled jobs of the day. The 120 feet long mule train was controlled using a whip with a 6-foot handle and 22-foot lash. Only the railroads could beat them.

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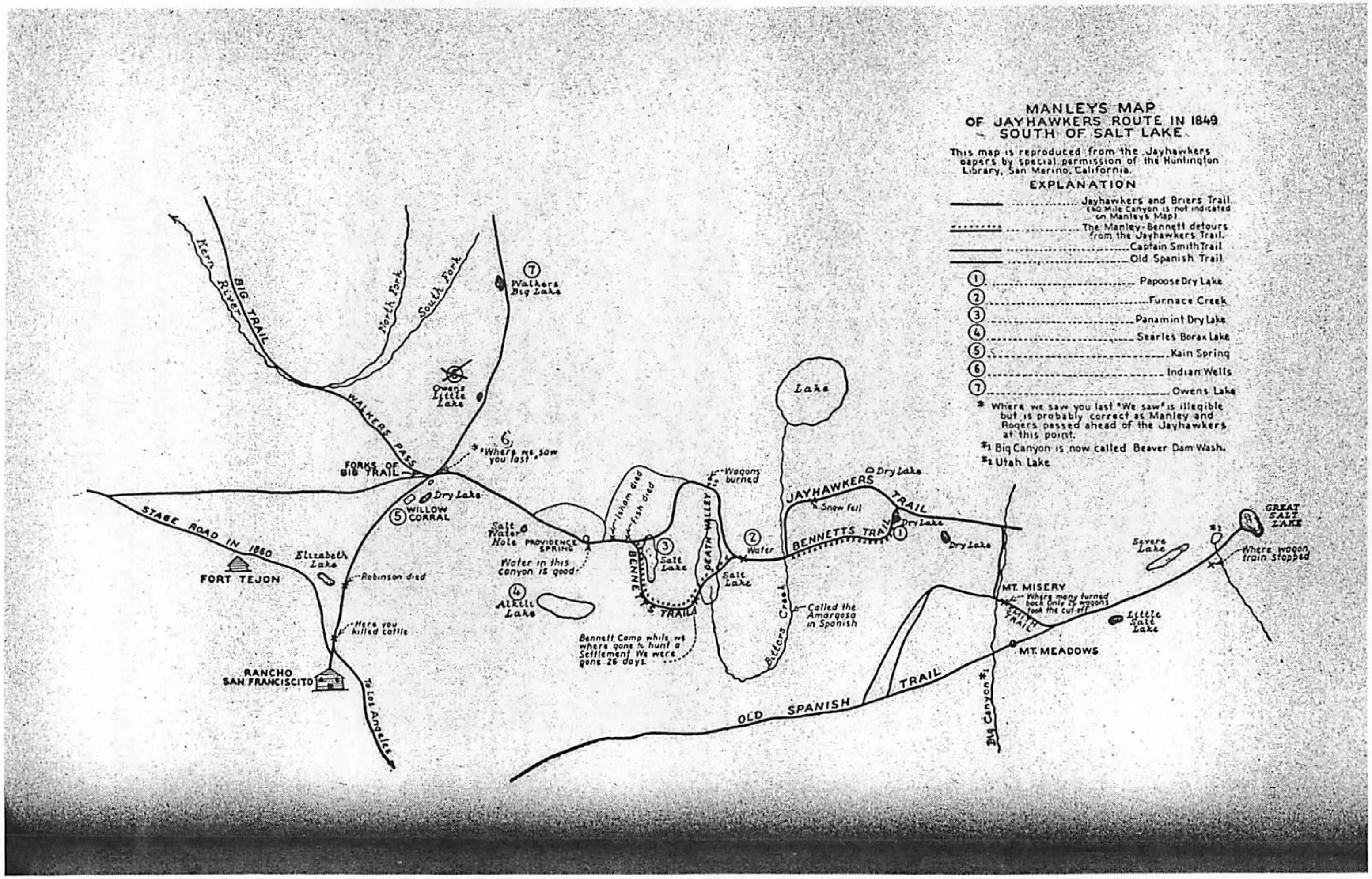
MANLEYS MAP
OF JAYHAWKERS ROUTE IN 1849
SOUTH OF SALT LAKE
This map is reproduced from the Jayhawkers papers by special permission of the Huntington Library, San Marino, California.
EXPLANATION
Jayhawkers and Briers Trail (40 Mile Canyon is not indicated on Manleys Map)
The Manley-Bennett detours from the Jayhawkers Trail.
Captain Smith Trail
Old Spanish Trail
1 Papoose Dry Lake
2 Furnace Creek
3 Panamint Dry Lake
4 Searles Borax Lake
5 Kain Spring
6 Indian Wells
7 Owens Lake
* Where we saw you last "We saw" is illegible but is probably correct as Manley and Rogers passed ahead of the Jayhawkers at this point.
#1 Big Canyon is now called Beaver Dam Wash.
#2 Utah Lake
Kern River
BIG TRAIL
North Fork
South Fork
Walkers Big Lake
Owens Little Lake
WALKERS PASS
FORKS OF BIG TRAIL
Where we saw you last
Dry Lake
WILLOW CORRAL
STAGE ROAD IN 1860
Elizabeth Lake
FORT TEJON
Robinson died
Here you killed cattle
RANCHO SAN FRANCISCITO
To Los Angeles
Salt Water Hole
PROVIDENCE SPRING
Water in this canyon is good
Atkili Lake
Isham died
Fish died
Salt Lake
BENNETTS TRAIL
DEATH VALLEY
Wagons burned
Water
Bennett Camp while we where gone to hunt a Settlement We were gone 26 days
Lake
Bitters Creek
Called the Amargosa in Spanish
JAYHAWKERS TRAIL
Snow fell
BENNETTS TRAIL
Dry Lake
MT. MISERY
SMITH TRAIL
MT. MEADOWS
OLD SPANISH TRAIL
Big Canyon #1
Severe Lake
Little Salt Lake
Where wagon train stopped
GREAT SALT LAKE

Archeology In Death Valley

By

Curtis Cooper

I will briefly discuss two interesting archeological endeavors within Death Valley National Monument, one pertaining to the ancient civilizations that once inhabited the Great Basin Desert region; the other concerning the excavation of Harmony Borax Works, a nineteenth-century borax mining community which includes a refinery, townsite, and Chinese quarters.

Before Death Valley dried up five or six thousand years ago, constant rains had maintained good-sized lakes and fertile soil. Pleistocene grazing mammals, including horses, camels, and bison roamed the valleys, pursued by saber-toothed tigers and jackal-like dogs. Ancient tribal peoples who had crossed the Bering Sea then flourished in Nevada and southeastern California. All that remain of their legacy are village trails, ancient tools, and mysterious rock paintings plastering desert canyon walls. Within the desert canyons of the Cosos Mountains of Eastern California, petroglyphs of vague origin can still be observed today. The images depict a variety of shapes and forms; several rock art forms are shown in Figure 1.

The most prevalent image is the Desert Bighorn Sheep. The paintings often depict sheep horns, sheep heads, two-headed sheep, and sheep-within-sheep (pregnant sheep). The animal is often shown being killed, as in the frame titled "Hunter with bow" in Figure 1. The repeated depiction of this animal obviously points to its cultural significance for the prehistoric people of the Great Basin. Clearly, the animal was a source of food; and the horns could have been used for crafting tools. What remains a mystery to modern anthropologists is the significance of the Bighorn paintings themselves. Was the painting of game a kind of "good-luck charm" for the prehistoric hunter? Were the petroglyphs associated with some form of shamanistic magic? Dr. David Whitley has proposed a new interpretation of the significance of the Bighorn petroglyphs that is quickly gaining support by anthropologists: "As is quite clear in the ethnographic record, the Coso petroglyphs were made by shamans; the sites themselves were shamans' vision quest locales; and the petroglyph motifs depicted the hallucinatory images seen by shamans when in the supernatural realm." Whitley furthermore connects the hunt of Bighorn Sheep with rainfall; thus, the Coso painters have been termed "rain shamans." Other anthropologists have rejected the shaman association, suggesting rather that the rock paintings were connected with mythology or astronomy.

It has been proposed, with the advent of modern dating techniques, that some of the drawings are between 10,000 and 19,000 years old, which would imply that the artists of these rock paintings settled the Cosos not long after the journey across the Bering Sea land bridge during the last Ice Age. If true, the extreme age of the petroglyphs could also mean that the style of rock painting found in other regions of the Great Basin originated in the Cosos of California. In any case, the drawings appear to span a succession of ages and styles, with well-documented works dating back to at least 7000 B.C. Figure 2 shows several of the competing chronologies proposed by anthropologists, based on the limited information available. As you can see, more modern results point to a much older chronology for the peoples of the Great Basin than had been originally conceived.

Sites from the Paleo-Indian Period (7000-5000 B.C.) are mainly associated with the relic shore of the ancient Lake Manly. This period seems to have been marked with the hunting of now extinct megafauna, or large animals; archaeologists have unveiled stemmed and shouldered spear and atlatl points, domed scrapers, crescents, gravers, and leaf-shaped knives from this period.

In the Pinto Period (3000 B.C. – A.D. 500), seed grinding implements have been unearthed. It is likely that the humans inhabiting the Cosos during this period began to shift toward plant food subsistence and away from a way of life focused purely on the hunt. Drills, gravers, scrapers, and scraper planes are found on Pinto Period sites. Mortars and pestles have also been found.

The Early Ceramic Period (A.D. 500-1000) appears to have been the age of bow and arrow for the Great Basin cultures. The projectile points unearthed from this period are smaller than those of earlier periods. Influence from the Anasazi areas of the Southwest is evident. Archeologists have found many artifacts originating from the Early Ceramic Period, including ceramics imported from the Anasazi, pendants, bone beads, unbaked clay figurines, and conical clay pipes.

From the Later Ceramic or Shoshonean Period (A.D. 1000-Ethnographic Present), archeologists have found knives, drills, gravers, scrapers, hammerstones, arrow shaft straighteners, and baked and unbaked figurines. Open-air and rock-shelter sites are found from this most recent occupational period of Death Valley. For example, open-air sites are found on gravel surfaces between the sand dunes; the most recent sites are found on top of dunes. The large base camps or villages of this period were located in valleys and along valley margins, whereas smaller campsites were located in particularly favorable locales in the foothills and mountains.

Many of the interesting artifacts of Harmony Borax Works are located in the Chinese quarters, for the Chinese immigrants from the Kwangtung Province of southwestern China who settled the Pacific Coast, in reaction to the discovery of gold in California in 1849 and the Taiping Rebellion of 1851-1864, essentially transplanted their cultural familiarities to their new locale. The excavation of this unique cultural facsimile permits the study of the culture and history of the Kwangtung Province in the most unlikely of places—Death Valley National Monument!

The borax industry is the business of producing and processing boron compounds. Borax is the chief product, the decahydrate of disodium tetraborate. The major uses of the compound today are much the same as they were in the nineteenth century: metalworking; brazing; detergent; disinfectant; and as an ingredient in glue, paint, and textiles. A community at Harmony developed around the borax industry towards the end of the nineteenth century. The Harmony Works is believed to have begun operations in 1883, producing three tons of refined borax per day by mid-1884.

The Chinese laborers employed by the Harmony Borax Works brought their civilization with them. The Borax Works excavation project therefore unearthed a rich collection of Chinaware and other artifacts of Chinese origin. Nearly 99% of the pottery sherds found at the site consist of Chinese ceramic wares. These artifacts include porcelain bowls, glazed pottery vessels, as well as flat-faced earthenware saucers. It is believed that these saucers were used as paraphernalia associated with opium smoking.

Various ceramic styles found at the Harmony site include blue-on-white, blue and green-on-white, celadon-type white, and unclassified white. The main distinguishing feature between them is the kind and color of the ornamentations on the glazed ceramic. Earthenware and stoneware have also been unearthed, though in smaller amounts, including glazed pottery vessels. The earthenware, in contrast to ceramic, is non-vitreous (not glassy) and porous. Stoneware, on the other hand, is not porous, just like glazed ceramics. However, because it is fired at high temperatures, it is usable for containing foodstuffs and wine without the need to be glazed. Figure 3 shows drawings of some of the Chinese porcelain bowls and an earthenware saucer that were excavated from the site.

Perhaps the most interesting conclusions made during the excavation of the works, however, arise from the relatively high proportion of artifacts of Anglo origin also found in the Chinese quarters. For example the personal items such as buttons, buckles, clothing rivets, and serving dishes were made in the United States. There also exists evidence that a substantial percentage of the meals taken by the Chinese miners were American canned and bottled food. Furthermore, although the earthenware saucer dishes were found as paraphernalia associated with opium smoking, relatively few opium-related artifacts were found. It appears that either opium usage was suppressed within the settlement or that its usage was far less prevalent there than in the Chinatowns of California's cities. These archeological discoveries have forced historians of nineteenth-century America to conclude, contrary to their prior expectations, that significant acculturation of the Chinese workers into the culture of California had occurred at Harmony. This process appears to have occurred more rapidly within the settlement than in the cities of California. Within San Francisco, in particular, Chinese integration into Anglo culture did not proceed effectively until the twentieth century. The reasons for the increased acculturation at the Harmony Borax Works and other similar settlements are not well-understood.

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Good Web URL:

http://www.desertusa.com/dv/du_dvpnearby.html

Figure 1: Petroglyphs of the Cosos

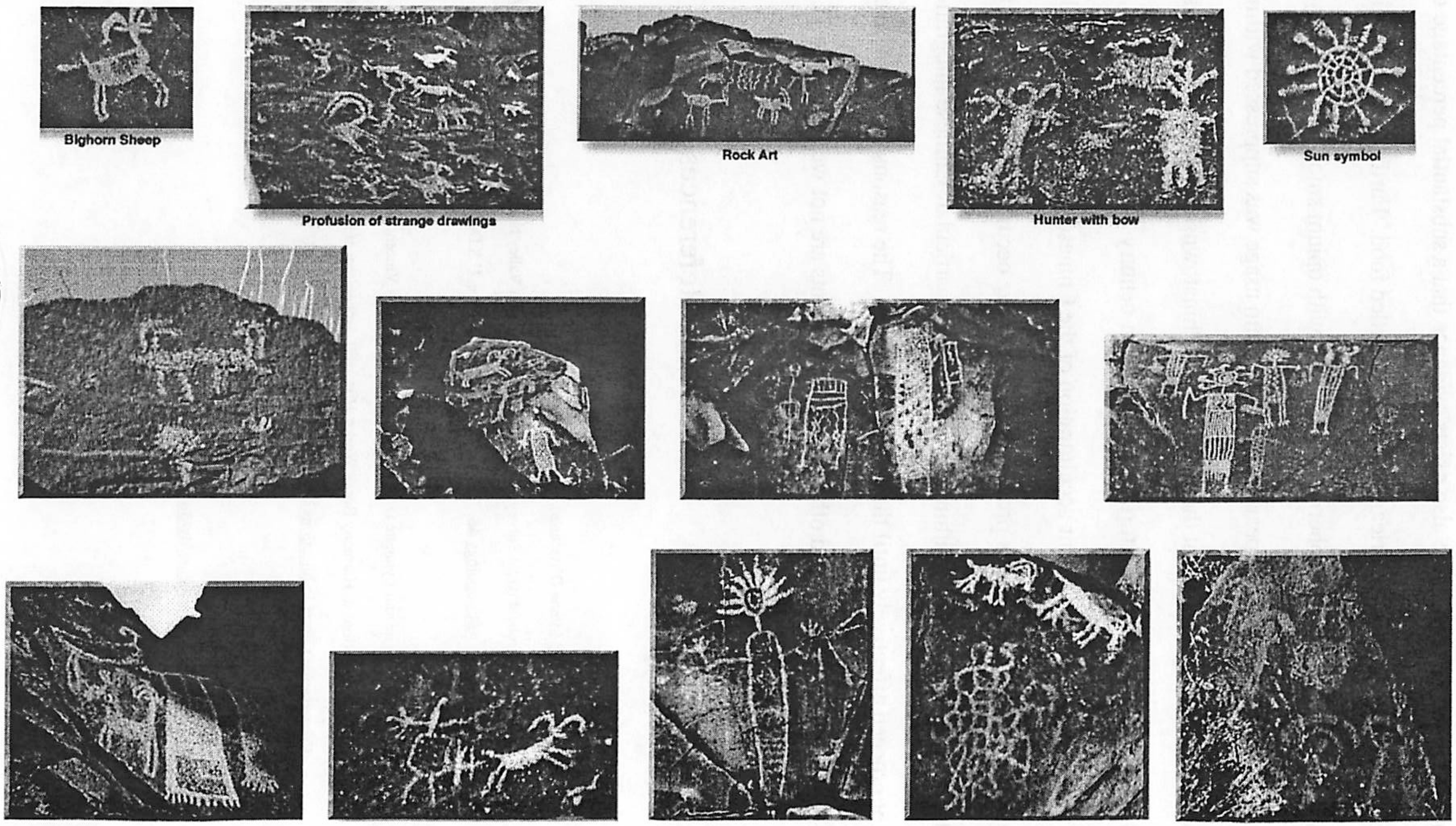

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Figure 2

[redacted]

CULTURAL CHRONOLOGIES PROPOSED FOR THE SOUTHWESTERN GREAT BASIN

	TAGG 1984:19-27	WARREN et al. 1980:18-22	CRAIB 1978:30	HESTER 1973:123-128	WALLACE 1977:141a
Present	Shoshonean (Ceramic Period)	Shoshonean	Shoshonean	Late Prehistoric	Death Valley IV Panamint (Shoshone)
AD 1000	Rose Spg/Eastgate (Ceramic Period)	Saratoga Springs	Rose Spring/Eastgate	Rose Spring/Eastgate	DVIII Saratoga Spgs
0			Elko/Gypsum		
1000 BC	Elko/Gypsum (Desert Archaic)	Gypsum		Great Basin Archaic	Death Valley II Mesquite Flat
3000 BC	Pinto (Desert Archaic)	Pinto	Pinto		Occupational Hiatus
5000 BC			?	Occupational Hiatus?	Death Valley I Nevares Spring
7000 BC	Paleo-Indian	Lake Mojave	San Dieguito	Western Pluvial Lakes Tradition	
9000 BC	Pre-Paleo-Indian		Paleo-Indian	Fluted Point Tradition	
11,000 BC		Pleistocene			

Modified from Tagg 1984:20.

Figure 3

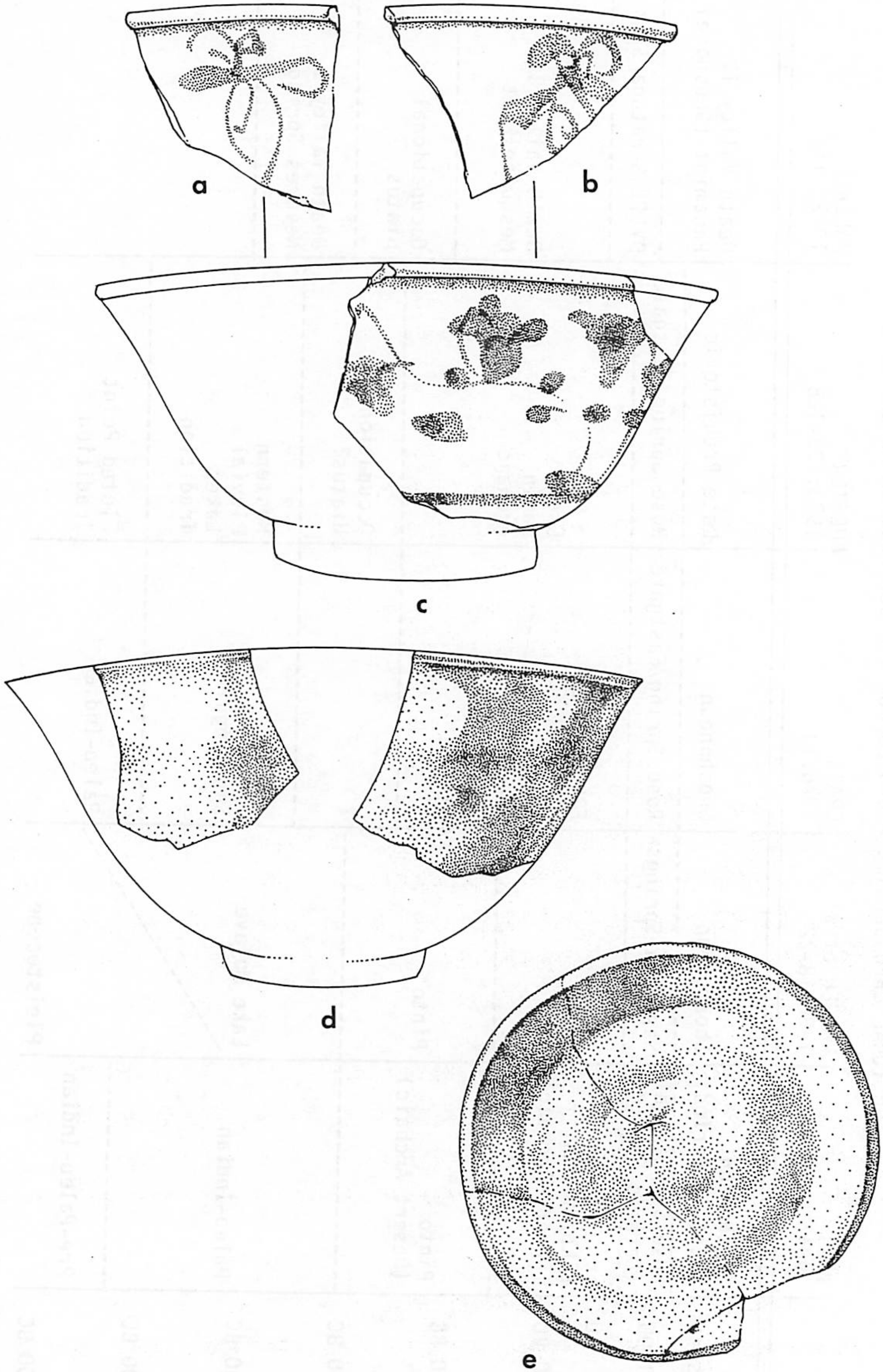

Figure 3. Chinese porcelain bowls and earthenware saucer.
Height of c is 2.5 in.; diameter of e is 3.5 in.

Ancient Peoples of Death Valley National Monument

Yen Chamberlain

Cultural Period	Climate/ Environment	Economy	Tools/Weapons	Site/Dwellings	Burial Practices	Art
Nevares Spring 7000BC – 5000BC	Cool; Moist Lush vegetation Plentiful game	Hunting large game	Dart Throwing stick	Sites located at flat gravel benches near springs. **Dwellings:** Unclear whether crude shelters or open air dwellings. Possible use of hearth. Small groups of no more than 6 persons. No traces of domestic debris Transient habitation of sites.	No evidence	No evidence
Mesquite Flat 3000BC – 1AD	Moderately warm; Moist Lush vegetation Plentiful game	**Early Phase:** Hunting large game **Late Phase:** Hunting and gathering wild food sources	**Early Phase:** Dart Throwing stick **Late Phase:** Dart Throwing stick Stone mortar & pestles	**Early phase:** Sites located on stone free ground near water source – between the sand dunes No evidence of dwellings. No evidence of hearths or cooking fires. Small groups of no more than 6 persons. Transient habitation of site. **Late Phase:** Sites located on silted ground along a section of the lake. Larger groups. No traces of domestic debris. Recurrent or extended stays at site – possible seasonal groupings.	**Early Phase:** Possible gravesite -Stone mound over shallow pit found with weapons and tools – no body found **Late Phase:** Flexed burial under stone mounds	**Early Phase:** No evidence **Late Phase:** Petroglyphs: broadline, geometric, curvilinear

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Ancient Peoples of Death Valley National Monument (cont'd)

Cultural Period	Climate/ Environment	Economy	Tools/Weapons	Site/Dwellings	Burial Practices	Art/ Ornaments
Saratoga Springs 1AD- 1000AD	Hot & Arid Desert Scant vegetation Few large game	Hunting (large and small game) & Gathering (Trade)	Bow & arrow Knife Blades Millingstones & Handstones Bone tools	Sites located throughout the valley and mountain slopes: -low rises near to Saratoga springs or overflow lake -low terraces parallel to Amargosa River -rock-free ground between Mesquite dunes -higher elevations – shallow caves and between rock overhangs **Dwellings:** Boulder rimmed circular clearings – 'sleeping circles' Possibly roofed over or fenced with brush and poles No evidence of hearths or domestic debris	Flexed burial- in living area or burial under stone mounds away from camp site	Petroglyphs – geometric, linear patterns, more elaborate (smooth flat faces of boulders or cliffsides) Pendants – green schist Trade items: Marine shell beads – (burial accompaniments) Puebolan clay pots
Panamint (Shoshone) 1000AD – ca 1870	Hot; Arid Desert	Primarily gathering & Some hunting	Bow & arrow Millingstones & handstones Wooden mortar & stone pestles Earthenware cooking pots (handcoiling similar to northern Californian desert) Basketry	Multiple sites located throughout the valley, valley floor and mountain slopes. Valley floor sites at mesquite covered sand dunes away from springs and water sources (seasonal sites) Mountain slopes – open sites near springs or rockshelters **Dwellings:** Conical /gabled houses constructed from mesquite log Circular structures of poles and brush Food storage pits Deadfall traps & hunting blinds	Cremation (traditional cremation grounds) or burial in rock covered graves	Pictographs naturalistic, geometric (bighorn sheep and some humans) – painting with red and white pigments Petroglyphs naturalistic, geometric shell beads glass beads pendants schist, talc, steatite – some with geometric designs clay figurines (nonfired)

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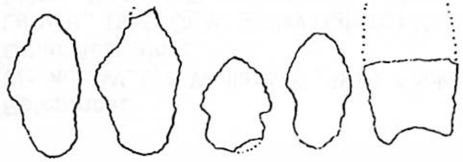
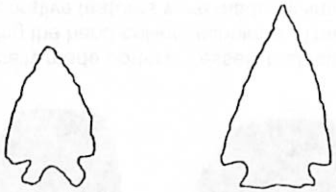
Ancient Peoples of Death Valley National Monument (cont'd)



Large heavy stone projectile points formed by crude flaking. These are likely to have been attached to sticks serving as weapon tips for darts and throwing sticks.
Nevares Spring Culture
page 3

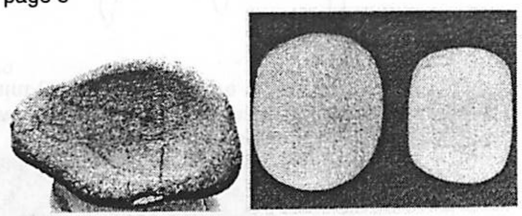
Large heavy crude stone chipped projectiles. Again due to weight and size it is likely that theses were used as weapon tips for darts or short spears.
Mesquite Flat Culture (Early Phase)
page 5



Finer more controlled stone chipping though still large and heavy stone projectiles indicating continued use of short spears and darts
Mesquite Flat Culture (Late Phase)
page7

Mortars made from coarse volcanic rock were also found during this period. Pestles were natural elongated cobblestones of volcanic rock. Such tools and their abundance give evidence to the introduction of a reliance on plant food for subsistence
Mesquite Flat Culture (Late Phase)
page 8

Skillfully made long-bladed and corner notched stone projectiles as well as more rounded unnotched (not shown). These are significantly smaller and lighter in weight which is indicative of their use as arrow tips.
Saratoga Springs Culture
page 12



Millingstone Handstone

The millingstone consists of a naturally flat rock with a slight depression. The handstones tended to have rounded ends and straight sides. They were used to grind seeds into meal.
Saratoga Springs Culture
Page 16

Wallace & Wallace (1978)

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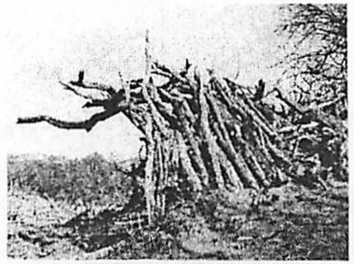
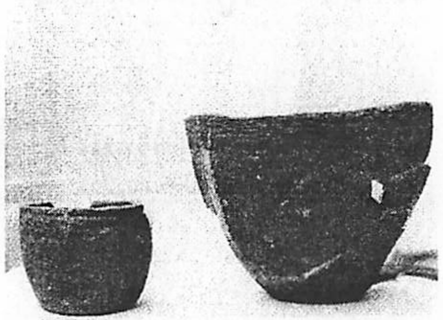
Ancient Peoples of Death Valley National Monument (cont'd)

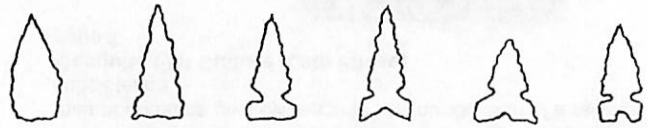
Framework of a conical shaped dwelling made from mesquite logs
Panamint (Shoshone) Culture
Page 29



Framework of gabled dwelling made from mesquite logs
Panamint (Shoshone) Culture
Page 29



Locally made pottery. Vessels had flat or partially rounded bottoms and were made by using the hand-coiling technique. The surfaces were finished by hand scrapping. Limited decorative features were made by small stick or fingernail indentations and consisted of simple patterns around the rim or upper section.
Panamint (Shoshone) Culture
Page 23-24



Projectiles of much smaller size and weight. Tend to be of triangular forms with squared or indented bases or with side and basal notches. Again would have been used as arrow tips.
Panamint(Shoshone) Culture
Page 23

Wallace &Wallace (1978)

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Ubehebejebes

The Ubehebe Phreatic Explosion Craters

Ross A. Beyer

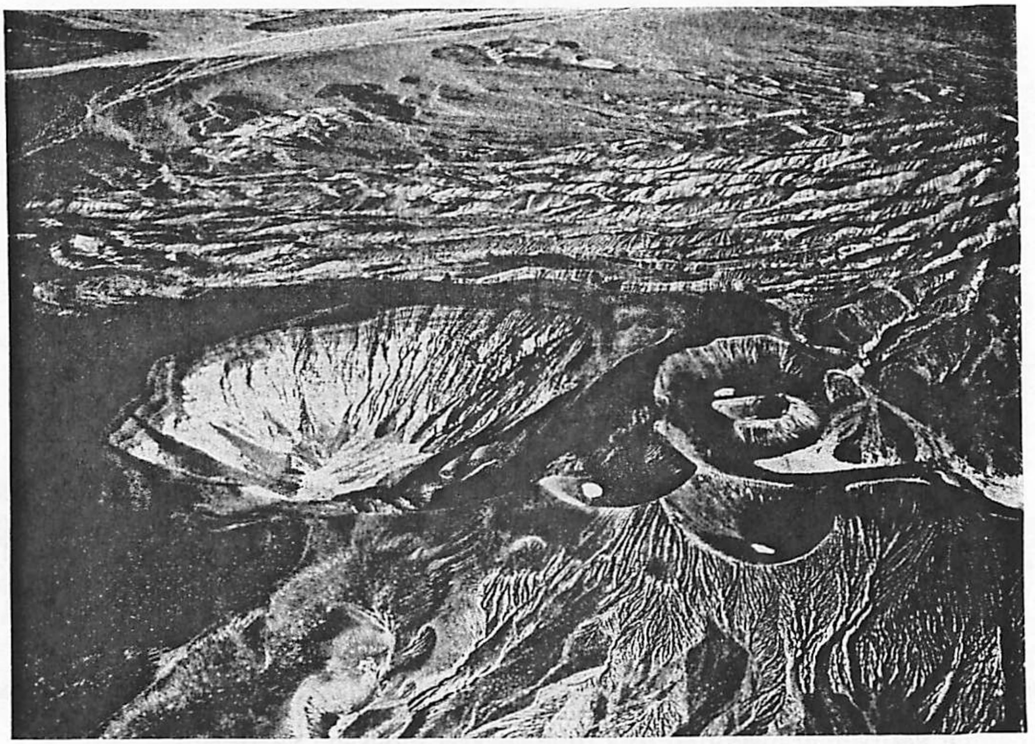
Phreatic eruption - Phreatic eruptions are steam-driven explosions that occur when water beneath the ground or on the surface is heated by magma, lava, hot rocks, or new volcanic deposits (for example, tephra and pyroclastic-flow deposits). The intense heat of such material (as high as 1,170° C for basaltic lava) may cause water to boil and flash to steam, thereby generating an explosion of steam, water, ash, blocks, and bombs.

At the edge of Ubehebe Crater, you'll be greeted by an eerie, surreal landscape. All is quiet now, but imagine yourself transported to a time several thousand years ago . . .

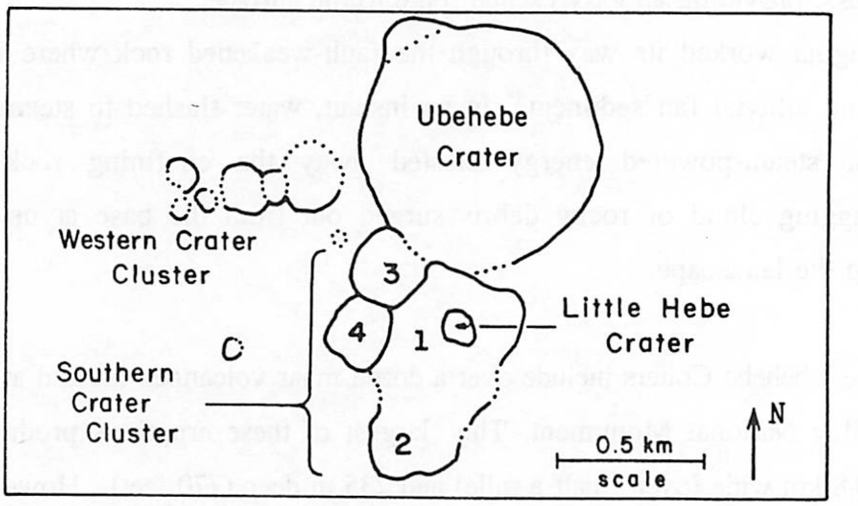
. . . Following weaknesses in the Earth's crust, searing magma rose upward. A fault along the base of Tin Mountain, responsible for uplift of the entire mountain range, lay in the path of the molten mass, providing an easy escape route to the surface.

Magma worked its way through the fault-weakened rock where it met water-soaked bedrock and alluvial fan sediments. In an instant, water flashed to steam. A sudden, violent release of steam-powered energy blasted away the confining rock above. A dense, ground-hugging cloud of rocky debris surged out from the base at up to 100 miles/hour, decimating the landscape.

The Ubehebe Craters include over a dozen maar volcanoes located at the northern end of Death Valley National Monument. The largest of these eruptions produced Ubehebe Crater which is 0.8 km wide (over a half a mile) and 235 m deep (770 feet). However, before Ubehebe crater exploded onto the scene, the area had a number of other volcanic eruptions. There is evidence of a cinder cone that was later destroyed by subsequent hydrovolcanic events. These phreatic eruptions created the smaller maars and tuff rings in the area. Ubehebe crater is the most recent eruption in this volcanic field, its ejecta blankets all the other craters, and stretches up to 4 km north to be found overlying the ancient lake beds of the Pleistocene Lake Rogers. The eruption of trachybasalt that created Ubehebe crater blasted through a 500 meter thick layer of fanglomerate and the ejecta is 50 meters thick at the crater's rim.



Ubehebe and Little Hebe craters, northern end of Tin Mountain on west side of northern Death Valley. Note that the material in the walls of Ubehebe is bedded sediment. (Photo by Spence Air Photos, courtesy of Department of Geography, University of California, Los Angeles).



PROBABLE SEQUENCE OF ERUPTIVE EVENTS OF THE UBEHEBE CRATERS

Nonphreatic vulcanian eruptions developed cinder cone located near crater no. 1; final stages of activity Strombolian. Vent area of cinder cone may have coincided with vent area of crater no. 1.

Phreatic eruptions formed crater no. 1 and destroyed cinder cone. Crater no. 2 developed approximately contemporaneously with crater no. 1—both are explosion craters with little rim ejecta. Crater nos. 3 and 4 developed after crater no. 1 and prior to Ubehebe Crater. Phreatic explosions of Western Crater Cluster may have been contemporaneous with activity from Southern Crater Cluster.

Mild volcanic activity from Little Hebe Crater developed small spatter cone which was disrupted by phreatic base-surge forming eruptions from same vent, greatly widening Little Hebe Crater.

Repeated, phreatic, base-surge forming eruptions formed Ubehebe Crater; ejecta from Ubehebe Crater covers all craters in volcanic field.

Index map showing crater designation and probable sequence of eruptive events.

It is thought that the fanglomerate acted as a permeable aquifer which was probably the source of the water and volatiles that interacted with the rising magma to produce the steam-driven volcanism in this area. Along the eastern section of Ubehebe crater there are exposures of the basement fanglomerate that have been intensely fractured and faulted due to explosive crater formation. The western portion of the crater has been modified from posteruption slumping. Finally, the flat floor of Ubehebe is often home to ephemeral lakes.

The deposits exposed along the rim include medium to well-bedded tuff, lapilli tuff, and tuff breccia. The lowermost beds contain agglomerate (from the early cinder cone) and tuff taht is thought to be derived from earlier phreatic eruptions. Ejecta from Ubehebe contains accidental material from the fanglomerate, ejecta from pre-Ubehebe volcanic activity, and juvenile sideromelane fragments with some bombs. Researchers have also found laminated cross-beds and other features which indicate that a massive base surge (a gas-charged debris flow) accompanied this eruption.

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Death Valley Geology Field Trip. This website is a cooperative endeavor of the US Geological Survey Western Earth Surface Processes Team and the National Park Service. http://www2.nature.nps.gov/grd/usgsnps/deva/ftube1.html

Geologic Chaos in Death Valley

Joe Plassmann
PTYS 594a Planetary Geology Field Practicum, Fall 2000

Introduction

The rocks in Death Valley clearly reflect the complex geologic history of the area. Nowhere is this history more difficult to interpret than in the so–called "Chaos" terrains of the valley. L.F. Noble first studied these rocks near the Virgin Spring area in the Black Mountains in the 1930's. Levi, like most geologists before and after him was at first completely at a loss to explain the complexly jumbled, faulted and folded strata he found there and through the rest of the area. He was also one of (if not) the first to cleverly group these rocks into a mappable unit. He called this unit the "Amargosa Chaos", named after the Amargosa mountain range in the southern end of the park. The challenge then of course was to describe the origin of the chaos.

Early Geology

Levi's original interpretation of genesis of the Death Valley Chaos terrains was that of regional thrust faulting occurring in Tertiary time. His conclusions were based on the ages of the rocks found in the chaos units, which range from Precambrian metamorphic, Cambrian sedimentary, and Tertiary volcanic, plutonic and sedimentary rocks, and the relatively intact overburden which consists of late Cenozoic basalts, conglomerates and alluvium. The main structural argument for his conclusion was a faulted contact between the underlying basement rocks and the chaos which he interpreted as part of a regional thrust complex, which he named the "Amargosa Thrust". He further mapped the chaos into three "phases", which he called the Virgin Spring, Calico, and Jubilee. The folding evident in this area – especially the "Desert Hound Anticline" he interpreted had occurred after the thrusting had ceased.

Later work

Many different views have been offered over the years to explain the chaos. All of these interpretations of course were compared and contrasted with the original Noble work. Curry (1954) considered the turtlebacks of the Black Mountain front as marking the northern extensions of the Amargosa Thrust, Hunt and Mabey (1966) agreed, adding that Paleozoic and late Precambrian rocks occur in the thrust plates, placing younger rocks over older ones. They added granitic intrusions along the thrust faults and some extrusive igneous activity, then they had the ends of the thrust plates moving into the basins. They also theorized that the Panamint Range, west of Death Valley, may also be an anticline in a thrust plate, concurring with Noble's theory for the Amargosa. Sears (1953) came up with a localized mechanism for extension that explained the chaos involving rising magma that cooled into the tertiary granites after forming the various anticlines and synclines in the area, then the chaos forming by gravity sliding off of the flanks of the anticlines. Bucher (1956) also theorized "gravity sliding" for the Virgin Spring phase of the chaos, but he favored a violent disruption hypothesis for the cause of the sliding. Drewes (1963) theorized that the chaos could be attributed to "repeated adjustments to large movements on the steep faults that bound the block", referring specifically to the chaos near the Black Mountain block east of Death Valley.

The most recent interpretations

Wright and Troxel (1969,1973,1984) have offered a different interpretation for the origins of the chaos. Revelations of the regional tectonics of the area during the time periods in question have made it clear that the chaos is unlikely to have originated from thrust faulting, and rather is more likely to have occurred from regional extensive forces. Further mapping of the area indicates that most of the faults in the chaos are normal or strike–slip. The faults also tend to flatten at depth, indicating a listric structure indicative of extension. Low–angle faults in the basement rocks accommodate the extension. Wright and Troxel's 1969 work first interpreted the chaos as forming on the underside of rotated fault blocks and near low angle detachment surfaces where normal faults flatten and join. By 1984, Wright and Troxel had separated the events that created the chaos into four major deformational episodes, the first occurring in Precambrian time (1.7 Ga) accompanying and following the metamorphism of the crystalline complex. The second started concurrently with the deposition of the arkoses and conglomerates low in the Crystal Spring formation, and continued for about 400 My in the late Precambrian. This phase included vertical crustal shifts, causing among other things the angular uncomformity beneath the dolomites and above the arkosic sandstones and conglomerates. The foldlike features in the late Precambrian and Cambrian rocks are interpreted to have been folded first, followed by intricate faulting in the Mesozoic or early Tertiary period. The final stage of chaos formation (Noble's Virgin Spring and Calico Phases) is attributable to extensional faulting in the Cenozoic. Troxel and Wright claim these later patterns of faulting lead to the illusion that there is a single Cenozoic dislocation surface, originally planar and then later folded.

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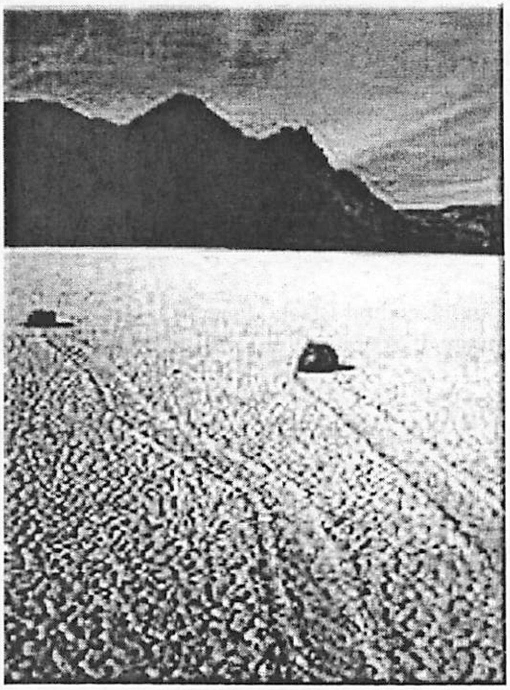
Gone Sailin'

The Mysterious Moving Stones of Racetrack Playa

Abigail Wasserman



The Mystery

It is a dark and stormy night on Racetrack Playa. A rare summer rainstorm floods the valley, stirring up a fine layer of clay that settles to cover the now viscous mud surface of the lakebed. The wind roars across the surface, howling as it whips through the natural topographic channels to the south. Ninety mile per hour gusts rake the playa surface. Rocks move.

They slide, scrape, and tumble before the wind, traveling uphill and northeast. The Grandstand would be alive with frenzied fans urging on their favorite racing stone… if anyone was ever present to witness these events. Apparently, when a rock moves in the desert and no one is there to see it, it still leaves a trail.

The Setting

- Racetrack Playa, a normally dry lakebed at 3,708' elevation between northern prongs of the Panamint Range
- Ubehebe Peak hulks in the west at 5,678'
- Width – 1.3 miles E-W, Length 2.8 miles N-S
- The north end is 1.5" higher than the south end
- Cobble to boulder-sized stones, mainly angular dolomites, with some smooth blocks of syenite
- Abundant mud and ever-present mud-cracks

The Evidence

- Trails up to 800 meters long, shallowly grooved or striated
- Rocks weighing up to 80 lbs
- Some trails show where rocks tumbled, slid, and then tumbled again
- Stones with rough bottoms travel the straightest paths, and smooth stones tend to wander
- Prevailing movement is to N-NE, the same as the wind direction, but trails often deviate 30° or more to either side of north and sometimes stones completely reverse direction
- Groups of tracks can be parallel, even through turns, while others cross or diverge
- Stones do not move every time the playa is wet
- In 1997 Paula Messina and Phil Stoffer mapped the entire playa using GIS (Geographic Information System) and 162 rocks and trails
    - Eastern trails are more linear on average than western trails

The Theories

- **Ice Sheets**
    - In 1955, George Stanley first proposed that the stones move with the assistance of wind-driven ice sheets forming after the playa is flooded.
    - In 1995, John Reid and other geologists from Hampshire College carefully mapped highly congruent trails and firmly concluded that some of the stones were moved by wind-driven ice.
- **Wind Alone**
    - In 1976, Robert Sharp and Dwight Carey contested the ice sheet theory by analyzing the stones that rolled rather than slid, as well as the criss-crossing tracks, and by corralling stones.
        - Two stones were placed inside an open, iron stake corral, and after the winter one had moved 28' to the northeast while the other did not move at all
- **Aliens**
    - Aliens in flying saucers attach tractor beams to the stones and pull them in varying patterns to conduct psychological experiments on humans.

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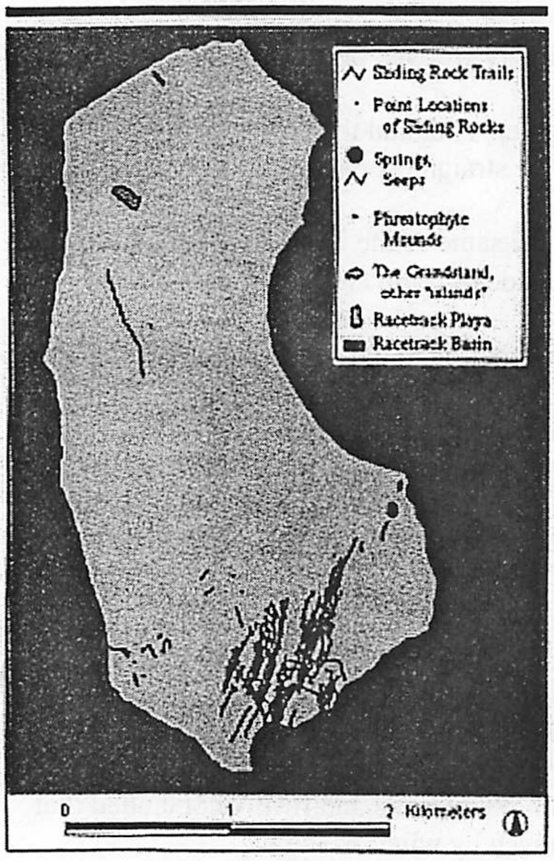
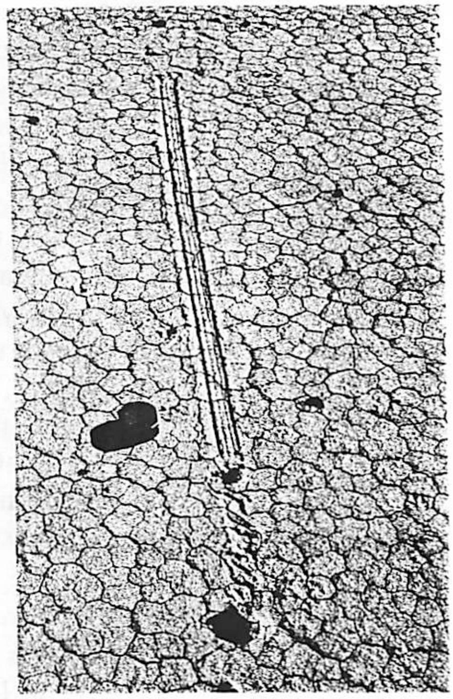


Map of the Racetrack, showing the rock trails. From Messina, et al. (1997)



A track made by a sliding cobble that hit another stone and then tumbled. Brunton compass is 2.75 inches across.

From Sharp and Glazner (1997)

A wide, striated track made by a pile of possibly frozen burro dung located beyond the dark glasses.

From Sharp and Glazner (1997)

Matt Chamberlain

DEATH VALLEY PUPFISH

The pupfish of Death Valley survive in populations that have been isolated recently in geological time. Assuming that the fish came from common ancestors while lakes and permanent water were present, the process of evolution can be studied by looking at the differences that have developed between the populations since their isolation from this parent genetic pool.

Hydrological History

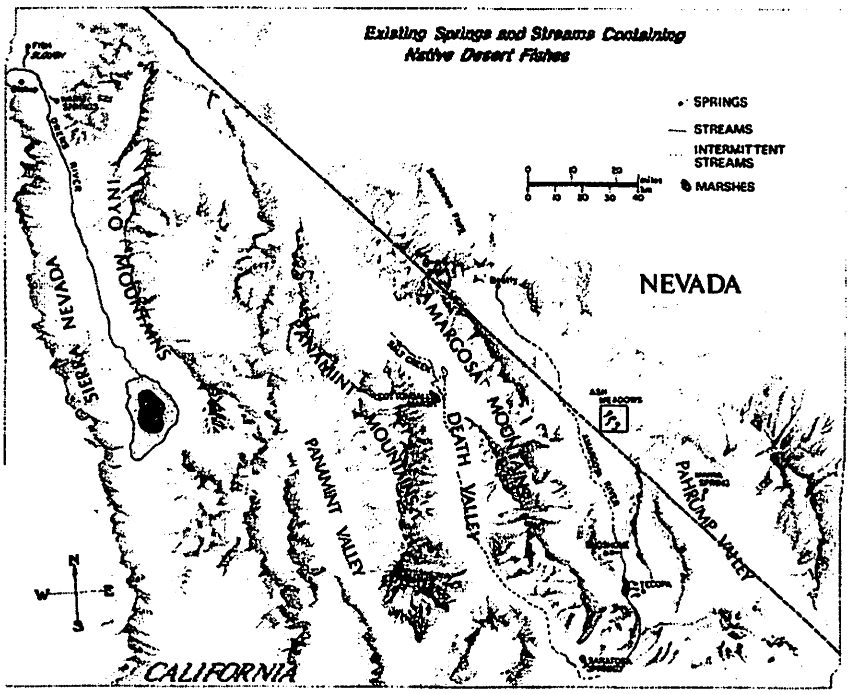


Figure 1: Location of pupfish habitats in the Death Valley system, taken from Soltz and Naiman 1978.

At present, pupfish populations within Death Valley cling to the life in water from springs scattered around the region. The fish got here during past ice ages while the climate was cooler and lakes were common in the valleys in the area. Death Valley itself had up to 150 meters of water. The fish ultimately came from the Colorado River (Soltz and Naiman 1978, and Miller 1950).

As ice ages receded and area dried out, the fish populations were left with diminishing habitats and ultimately forced into the springs where they are today. Some pupfish populations have been isolated for 10 to 20 thousand years while others have only been on their own for several hundred years. Water from the springs have been dated to 8 to 12 thousand years, indicating that the water has not only come from far away, but also it is from an old underground reservoir that is still draining times when water was more abundant.

Variations in Pupfish Populations

Morphology - The most obvious differences between the pupfish populations are morphological. These differences can be seen in overall size, fins, the number of scales, the patterns on the scales, teeth. Populations can also be differentiated by behavioral patterns, e.g. territorial tendencies and mating rituals.

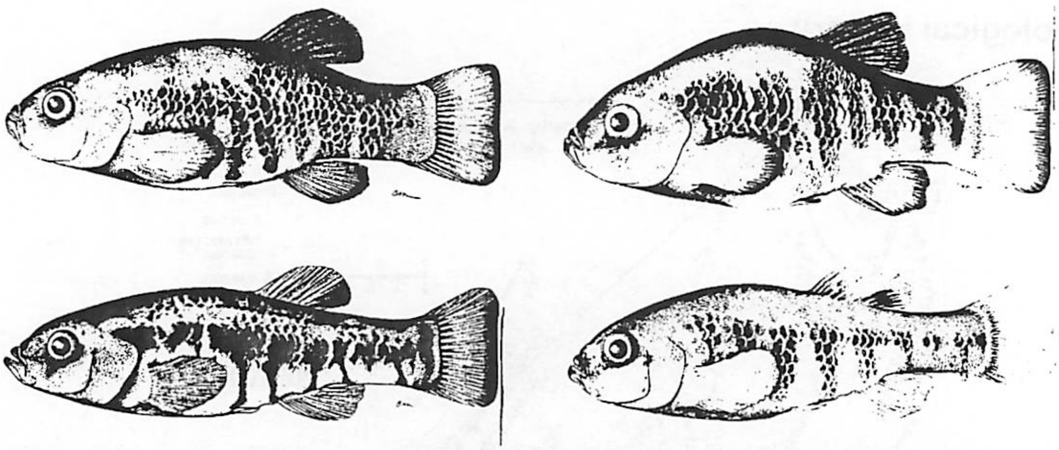


Figure 2: Examples of different pupfish found in Death Valley, taken from Soltz and Naiman 1978. *Cyrprinodon salinus* (left) and *Cyrprinodon milleri* (right) which are found in Salt Creek and Cottonball Marsh respectively are shown here.

Proteins - Turner 1974 did some experiments on proteins and was able to differentiate populations this way. Protein results were used to infer variations in the genetics of each population. When it came to comparing the similarity of the inferred genetics, very different relationships were found between populations than what would have been ascribed if using the morphology alone. See Figure 3 to see the different results using the these two methods to measure similarities between sets of populations.

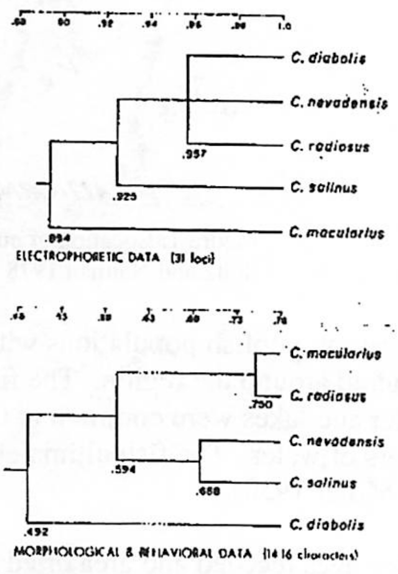


Figure 3: Dendrograms drawn using similarities based on morphology/behavior and biochemistry, from Turner 1974.

Thermal Tolerance - Brown and Feldmeth 1971 tested the different populations for variations in thermal tolerance. The procedure was along the lines of catching some fish, throw them into a cooking pot and see how long they can survive. The thermal regimes of the habitats of various pupfish vary dramatically. Shallow surface waters (rivers, ponds or marshes) have a wild range of temperatures while thermal springs that provide water of a constant temperature through out the year. The original idea was that evolution would soon 'deselect' any trait of the population that was unnecessary, which in this case would have been the ability to adapt to different temperatures. What was found however was pupfish from all populations (even the thermal stable ones) were able to adapt equally well to waters different temperature (hot or cold).

DNA - More detailed DNA analyses in the late 1990's (Duvernell and Turner 1999) have been able to differentiate between populations. Effects of genetic drift can be observed in small populations that have lost the genetic variability of larger parent population that is still present in other locations.

So, just how different are these populations?
Plastic Taxonomy - A way of reconciling the difference in the genetic similarities and morphological differences is by recognizing that pupfish have a plastic taxonomy. This is being studied by Wilcox in Colorado. Most elucidating is the observation that populations that have been separated (in the name of conservation) have changed physically and behaviorally on short time scales. even though genetically they are the same.

"Though these satellite populations may be genetically representative of their founding population, subtle changes between natural and artificial environments can elicit rapid changes in physical and behavioral attributes without a corresponding shift in genetic composition. Such a case exists in the management of the endangered Devil's Hole pupfish, Cyprinodon diabolis, where artificial populations of the species have changed so dramatically that managing biologists doubt most individuals could survive in their native environment." Wilcox.

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Economic Geology of Death Valley

Paul Withers

Death Valley has been a source of mineral wealth ever since Anglos first passed through the area on their way to the California goldfields. One of the original '49ers, the namers of Death Valley, picked up a glittering piece of rock during his ordeal, which a gunsmith later declared to be solidly veined with silver. No-one has ever found the whole hill of said rock, which the finder "remembered" seeing as he picked it up... By the 1870s Death Valley was part of the boom-and-bust Wild West, with gold, silver, copper, and lead deposits spawning what would soon become ghost towns.

Metals worth millions of dollars were soon excavated. However, unfashionable borate minerals soon became the economic driver. Estimates of the total value of the original borate deposits are on the order of billions, rather than millions of dollars. Death Valley and other regions in Southern California contain the major portion of the world's reserves of borates. Borates are oxides of boron (B), the fifth element in the periodic table, which lies between beryllium and carbon, and in the same chemical group as aluminium. Hence borates generally contain the component B_2O_3. Borates are industrially important, being used as a component of glass and pottery glazes in the ceramics industry, as a solvent for metal-oxide slags in metallurgy, as a flux in welding and soldering, and as a fertilizer additive, a soap supplement, a disinfectant, a mouthwash, and a water softener. Common borate minerals include colemanite ($Ca_2B_6O_{11}.5H_2O$), ulexite ($NaCaB_5O_9.8H_2O$), and borax ($Na_2B_4O_7.10H_2O$), which are all hydrated and all contain alkali metals. The usual apparatus of the chemical industry is used to refine the borates, though early companies were unable to get their refined product to crystallize from solution in summer temperatures exceeding 120F...

Historically, American borate mining can be divided into three phases: playa surface mining (1860 - 1890), underground mining (1890 - 1957), and open pit mining (1957 - present). The first phase gorged on surface deposits of those borates which were easiest to process, the second devoured large, concentrated subsurface deposits, and the third is in the process of finishing off the large volume, low grade deposits. Death Valley has played a major role in all three phases.

The economically important borates deposits in Death Valley were formed by precipitation from a permanent or semi-permanent lake. Large-scale borate formation in lakes requires several factors to be in operation simultaneously. Borates have relatively high solubilities, so an arid environment helps produce supersaturation in a lake and allows the borates to remain solid after precipitation. An interior drainage system with a relatively small drainage area (to reduce borate dilution by competing ions) are required. The boron source is usually a hot spring associated with volcanism. The arid environment is provided by the mountains to the west blocking marine moisture and basin and range topography forms the interior drainage. Add a dash of volcanism, et voila, borates.

Refining Borax

1) In the first step of refining, crushed ore is dissolved through steam addition and agitation. Insoluble rocks, sand and other solids are removed using screens.

2) Next, the saturated borax solution is pumped into large settling tanks called "thickeners" where remaining fine particles settle to the bottom of the tank leaving a clear, hot borax solution on top.

3) Crystals of borax pentahydrate and borax decahydrate form as this hot solution is cooled in the crystallizers.

4) The newly formed borax crystals pour out onto special fabric filters where they are also washed to ensure their purity. Water is drawn away from the crystals by a vacuum underneath the filter.

5) After this washing, the crystals are transferred to the dryers. These large rotating dryers use hot air to dry the borate crystals.

6) Dry borate crystals exit the dryer and drop onto a conveyor belt. The refining process is complete. The refined borates travel by conveyor to one of two places - storage or packing.

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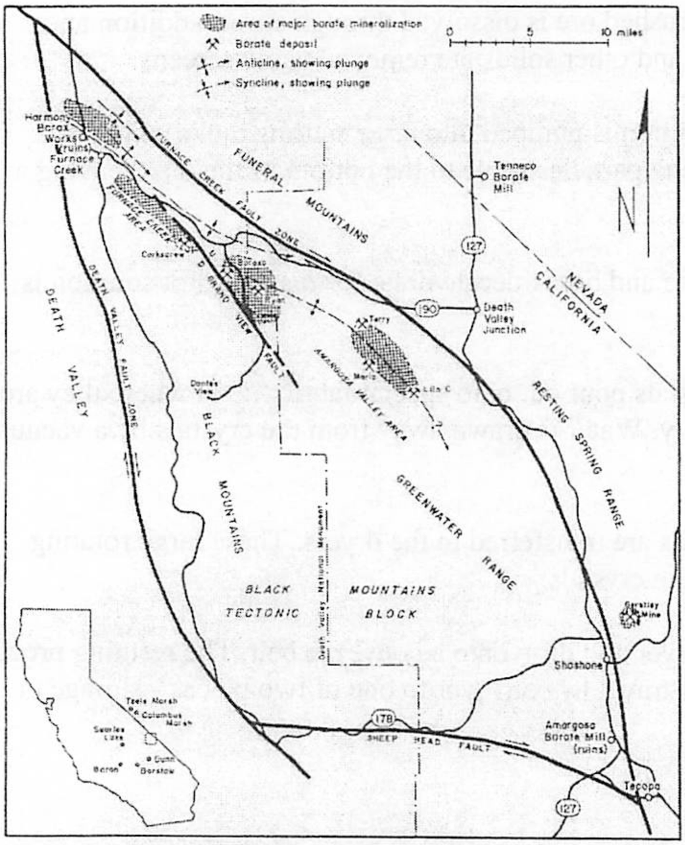

FIGURE 1. Map showing borate areas and structural features in the Death Valley area.

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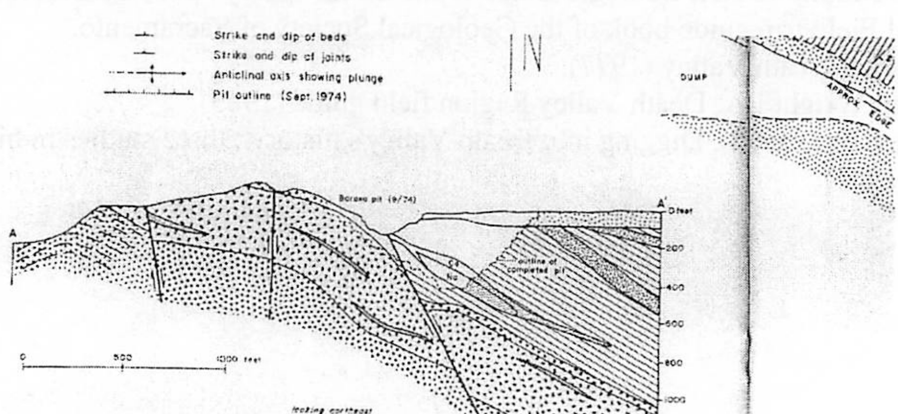

FIGURE 2. Geologic map and cross section of the Boraxo Pit area (S25 & 26, T26N, R2E SBM).

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TWENTY-MULE TEAM

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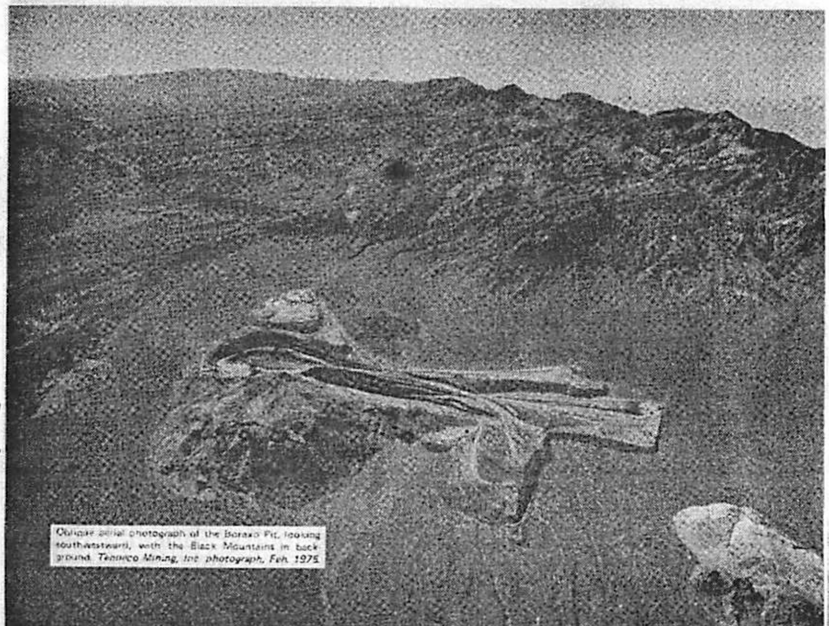

Oblique aerial photograph of the Boraxo Pit, looking southeastward, with the Black Mountains in background. *Tenneco Mining, Inc photograph, Feb. 1975.*

Basin and Range

aka The American West goes west

Laszlo Keszthelyi

What is the Basin and Range?

The Basin and Range <u>**is**</u> the American West. Imagine the setting from any "Western" movie and you are in the Basin and Range. Physiographically, it is a region characterized by rugged mountain ranges separated by sediment filled basins. Typically, both ranges and basins are on the order of 100 km long and ~15 km wide. The mountain peaks usually stand about a km above the surroundings, but in Death Valley the Panamint Range reaches 3 km above the valley floor. Most of the valleys have 3-8 km of sediment fill. The basins and ranges are all oriented roughly north-south. When looking at a geologic or topographic map of the western US, the image is one of an army of giant caterpillars advancing north from Mexico to the Canadian border (Dutton, 1880).

The Basin and Range Province covers $>1x10^6$ km^2, or more than 10% of the United States. The province itself has been subdivided into different regions by various workers. The subdivisions are not always consistent and Figure 1 shows what may be the simplest and most generally accepted scheme. What is important to note at this point is that while the entire Basin and Range shares the same general physiography, in detail the geology suggests that there are differences that become important when trying to understand how the Basin and Range formed.

The Basin and Range is also an area of active seismicity, anomalously high geothermal heat flow, and an extremely thin lithosphere. In fact, for much of the province, the lithosphere seems to be thinner than the continental crust. {Translation: the bottom of the continental crust is so hot it is gooey on the timescale of 1-10 Ma.}

How did the Basin and Range Form?

The series of basins and ranges we see are a flock of parallel horsts and graben. For those that don't know what horsts and graben are, they are ranges and basins, respectively, that form by extensional faulting. In order to drive physicists batty, extensional faults are called "normal" faults. The fault planes are not normal to anything relevant – in fact, most normal faults have dips of about 60° (note dips are always measured from the horizontal). The scarps cut by active normal faults can be seen running along the fronts of some of the ranges, but that is Adina's topic.

Note that this causes a problem at depth. A graben is bounded on both sides by faults dipping at ~60°. These should intersect at depth, causing a geometric nightmare. Two factors alleviate this problem in the Basin and Range. First, the rocks go gooey at a depth of only ~20 km. Over the timescales of interest, they flow like a liquid and will freely adjust to the shape of their "container." Second, the dips of the faults are not constant with depth – they usually become shallower (i.e., more horizontal) with depth. This would make the problem worse, except the faults on one side of the graben tend to be dominant. The result is what is called a "listric" normal fault (Figure 2).

What is stunning is the amount of extension inferred across the province: 250±50 km. That means that the narrower parts of the Basin and Range province have extended 250%!!! However, because it takes painstaking work across every basin and range on an East-West track, a well-constrained estimate of total extension is available only in one transect (in the central Basin and Range). But more limited studies to the north and south indicate that extension there is similar in extent, to within than a factor of 2. The one detailed transect shows that the amount of extension is very variable on the 10-km-scale, bouncing between 10% and >500%.

Why did the Basin and Range Form?

The formation of the Basin and Range Province is intimately tied to the formation of the Rocky Mountains, Colorado Plateau, Cascades, and San Andreas Fault system. It also interacted in a large way with the Columbia River Flood Basalt Province and the Yellowstone Hot Spot Track. In other words, to understand the formation of the Basin and Range, one must understand the geologic history of all of the Western US (and a bit of Canada and Mexico) over the past ~100 million years. Figure 3 is my crazy attempt at summarizing all that (trying to cram >>10^3 words into a little box). Note that the vertical axis is time and the horizontal axis is East-West. Some of the critical changes in the N-S axis I must describe in words… I will also provide a 1-sentence description of each of the events listed on Figure 3:

Arc and Back-Arc Volcanism: Arc volcanism = Cascades-type (Mt. St. Helens-type) volcanism. Back-arc volcanism = Long Valley (if you don't know the Long Valley Caldera, think of the Yellowstone Caldera and you will be wrong, but not in any way that matters for now). What is important about the location of this type of volcanism is that it is telling you where the subducting oceanic plate hits about 100 km depth.

Sevier "Orogeny": Orogeny = mountain formation. I put this orogeny in quotes because the faults of the Sevier Thrust Belt are all relatively shallow. Just how tall the resulting mountains were (as compared to today's Rockies) is still a bit unclear.

Laramide Orogeny: formation of the Rocky Mountains

Formation of the Mendocino and Rivera Triple Junctions: The "mid" Pacific Ocean ridge hits North America. We care because between the triple junctions there is no subducting oceanic plate. It is also the start of the San Andreas Fault system.

Opening of the Gulf of California: Baja decides to join the Pacific plate and wander to the NW.

Basin and Range Extension: the problem at hand!

What did all this activity do to western North America? The two orogenies are the result of massive compressional forces applied to the western boundary of the continent. It seems plausible that these forces are related to subduction along this margin of the North American Plate. It has been argued that forces that large make sense only if the subducting plate was rubbing directly against a substantial portion of the North American lithosphere with no lubricating hot mantle wedge. It is not clear if this is reasonable for the Sevier Orogeny, but at the time of the Laramide Orogeny, the volcanism moved all the way east to the middle of New Mexico and Colorado. This does *suggest* that there was no hot mantle wedge under California Arizona, Utah, Nevada, etc., at 70-40 Ma. There are a number of interesting studies of the temperature vs. time of exposed rocks from this age that suggest that the lower crust in the western USA was cooler than normal at this time.

The sudden sweep of volcanism back to the west at 30-40 Ma implies that hot mantle material came rushing into where previously there was thick, cold lithosphere. While the drag forces induced by runny mantle material can be shown to be negligible, the hot mantle is relatively buoyant, leading to large, broad uplifts. Two ideas compete for how this happened. In one, the dense bottom of the lithosphere detaches as a blob and sinks into the mantle. This seems to ignore the fact that there is a subducting slab sitting under the lithosphere. The other idea is that subduction decelerated, steepening the angle of the down-going slab, opening a void into which hot mantle material flowed. In detail, the volcanism did not sweep back straight E-W. Instead, it appears to roll back toward the central Basin and Range Province from the NE and SE corners. This could suggest that the northern and southern ends of the shallow slab were cooler and eventually dragged the warmer middle down. The details are still confusing… What we can confidently say is that the western US became both unusually thick and uplifted at the same time that its base become hot and soggy. Stuff wants to flow away, but where to?

Because subduction along the west coast of the US was somewhat oblique, a strike-slip fault like the San Andreas cannot take up all the relative motion between Pacific and North American Plates. Geometrically, a void opens where there is suddenly no subducting plate. This would give the North American continent the hole it needs to spread into. In detail, this does not explain Basin and Range extension because the extension started to the north of where the triple junctions formed. If the timing of the extension were governed by plate tectonic geometry alone, extension would have started in the middle and moved north and south with the two triple junctions. The opening of the Gulf of California also can make room for westward extension, at least near the southern end of the Basin and Range Province. Again, the details are remain confusing… But it is probably safe to say that, due to a combination of plate tectonically driven factors, it was easiest to push to rocks to the west. And so the work of the Sevier Orogeny is being reversed by the Basin and Range extension. The Rio Grande Rift appears to be have taken a less effective whack at the Laramide Orogeny, but that is another story. As is the story of why the Colorado Plateau is still sitting in one piece. And the story of how the Yellowstone plume interacted with the subducting slab and the northern part of the Basin and Range Province should be saved for the field trip to the Cascades and Columbia River Plateau…

I should note one old hypothesis that was popular in the literature for some time but is now quite ruled out. The idea was that the mid-ocean ridge was subducted and caused extension as it slid under the continent. Mid-ocean ridges are now shown to be *passive* upwelling caused by pulling the oceanic plate apart. Take away the subduction on one side and the ridge simply ceases to exist.

There are also a couple of interesting side notes. Recent detailed geodetic studies of the current motions of different parts of the Western US have been compared to estimates of motion from the geologic record. In general, the correlation is good. However, in the south of the Garlock Fault things are less clear with the Mojave Block doing its own thing and possible outliers of the Colorado Plateau around Yuma. Life just gets messier the more you look at the details in both time and space. Another curiosity is that volcanic activity and fault activity are generally anti-correlated. When there is lots of volcanism in a region, the extension is taken up with intrusions and the formation of calderas (talk to Jani about those!). When there is little volcanism, the extension is taken up on brittle faults.

Planetary Analogs

While some extensional faulting can be found on many solid surfaces in the solar system, few things looks as well organized as the Basin and Range. The tectonic belts of Venus appear to be dominantly compressional. Extension on Mars has produced relatively few, but very large, canyons. The closest analog is probably the "tectonic resurfacing" of Ganymede. Perhaps plate tectonics provides a mechanism for large portions of the Earth to all behave in the same manner while the lack of plate tectonics on the other bodies leads to more chaotic surface features. The fact that we only see the last ~30 Ma of geologic history of North America preserved in the large-scale physiography also serves to simplify the picture. If we were looking at the results of everything since late-heavy bombardment without erosion, the Basin and Range would probably not look so orderly!

Just 3 references that have a lot of other references in them:

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Kearey, P., and F.J. Vine (1990) Global Tectonics, Blackwell Scientific Publications

Bally, A.W., and A.R. Palmer (editors) (1986) The Decade of North American Geology Project, Volume A: The Geology of North America -- An Overview, Geological Society of America, Inc., 619 pp.

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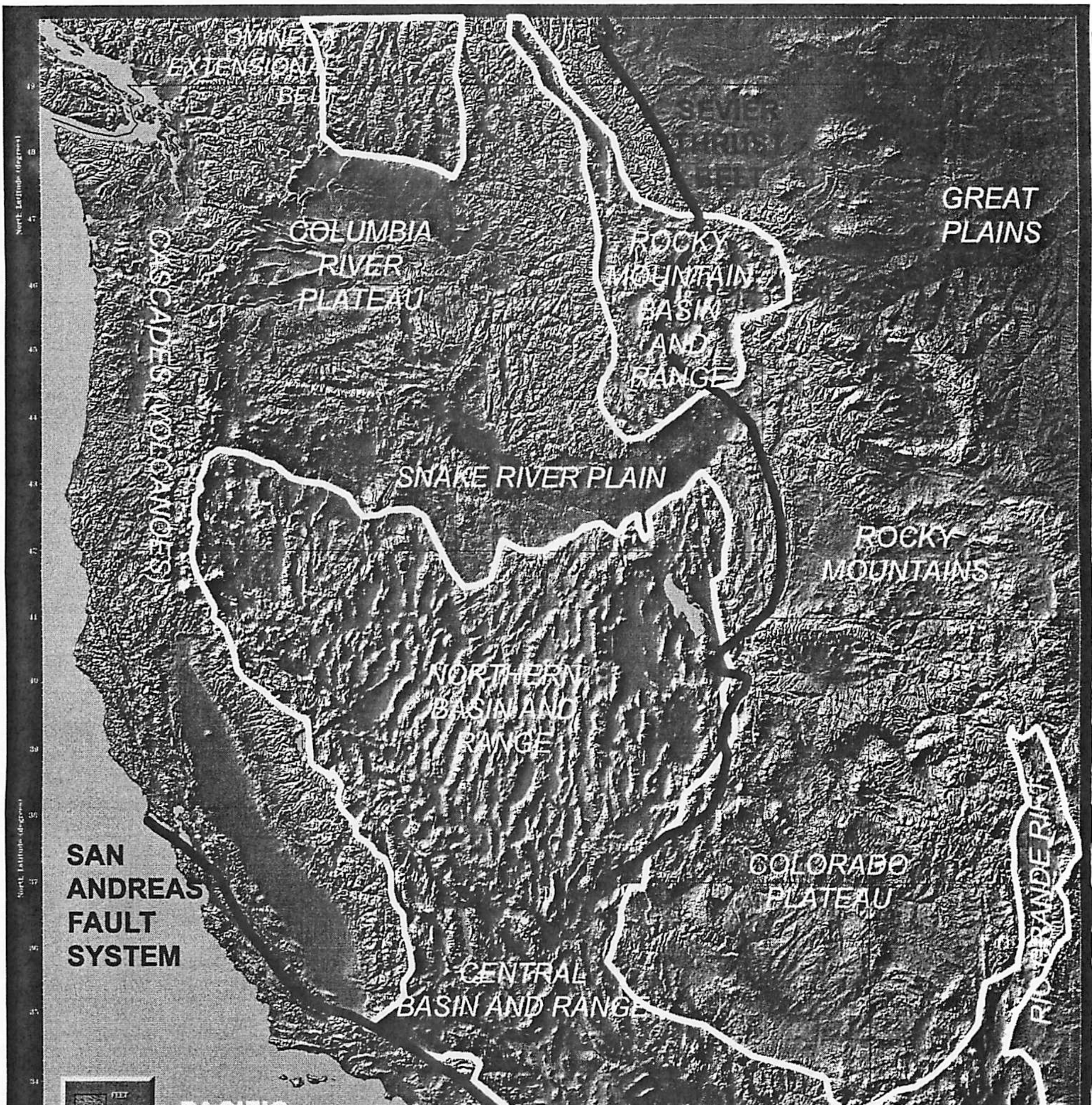
Figure 1. Shaded-relief map of the present-day western USA (and a bit of Canada and Mexico). Main physiographical provinces and some major structural features are labeled. From APL web page and Sonders and Jones (1999).

Figure 2. Progressively more realistic cartoons of large-scale extensional faulting in the Western US. From Kearey and Vine (1990), who copied it from Wernicke...).

Figure 3. Grossly oversimplified look at the Cenozoic geologic history of the western US. The earliest Basin and Range-type extension took place in Idaho, just after the Cretaceous. It has been difficult to date the start of extension in the main part of the Basin and Range, but it was probably around 30-35 Ma. However, the most dramatic extension began around 19 Ma with the most rapid motion somewhere around 17-10 Ma. The line with an arrow is supposed to represent the Mendocino Triple Junction. Note that the Rio Grande Rift actually started around 32 Ma.


OMINECA EXTENSIONAL BELT
COLUMBIA RIVER PLATEAU
CASCADES (VOLCANOES)
ROCKY MOUNTAIN BASIN AND RANGE
GREAT PLAINS
SNAKE RIVER PLAIN
ROCKY MOUNTAINS
NORTHERN BASIN AND RANGE
SAN ANDREAS FAULT SYSTEM
COLORADO PLATEAU
RIO GRANDE RIFT
CENTRAL BASIN AND RANGE
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The Map Projection is Cylindrical Equidistant with the shape corrected for 37.5 degrees north latitude.
Lighting is from the northwest.
The elevation data has a horizontal resolution of 1/2 arc minute in both dimensions and a vertical resolution of 20 feet.
The coastlines, rivers, and boundaries are from the World Vector database.
North Latitude (degrees)
West Longitude (degrees)

Fig 1

Fig 2

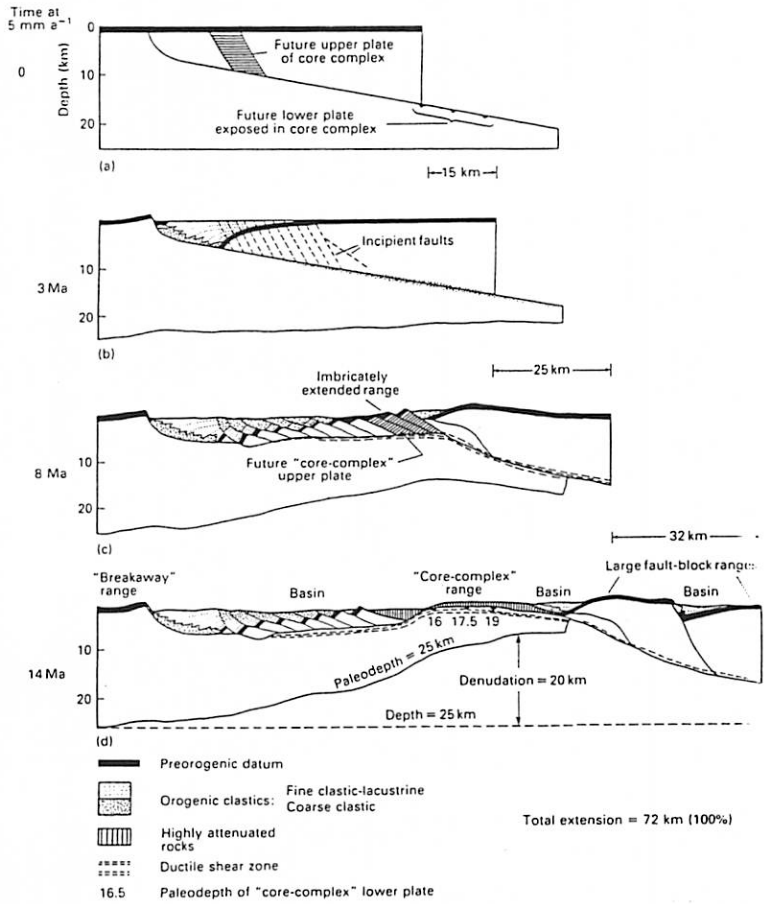
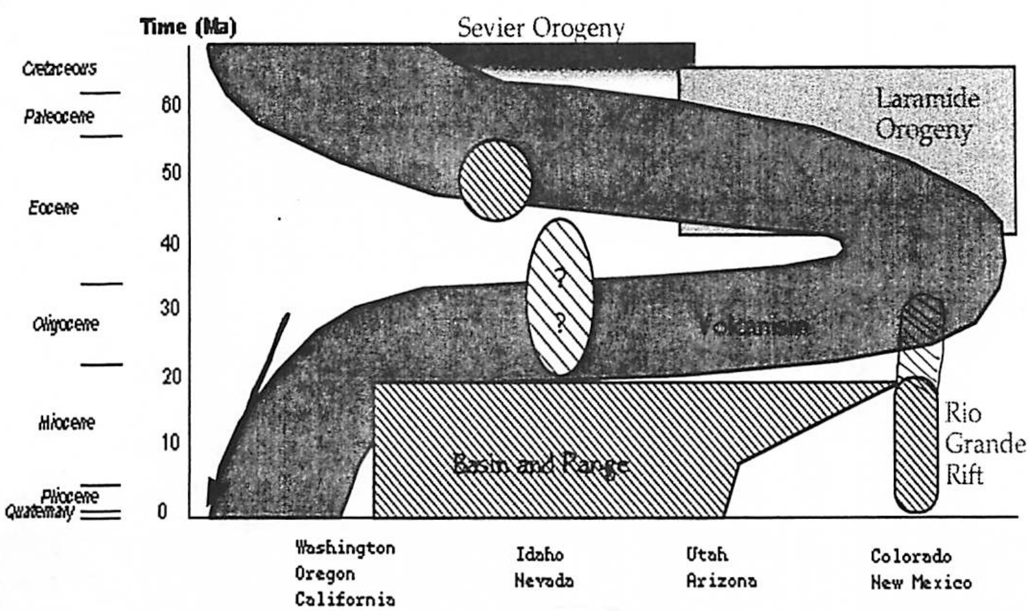


Fig. 11.19 Model of an extensional simple shear system in the upper and middle continental crust (redrawn from Wernicke, 1985, with permission from the National Research Council of Canada).

Fig 3



Death Valley

Remote Sensing of the ~~Martian~~ Surface Layer

Pete ("I have to think up a whole new title?") Lanagan

Introduction

Following the tradition of my highly acclaimed "Stratigraphy of the Colorado Plateau" talk, I will present monochromic images of Death Valley covering the electromagnetic spectrum from visible to radio wavelengths in wavelength increments of 1 nm. (Not really, but I just wanted to remind people how bad this talk could be.)

The Planetary Connection

We use remote sensing techniques to look at other planets....

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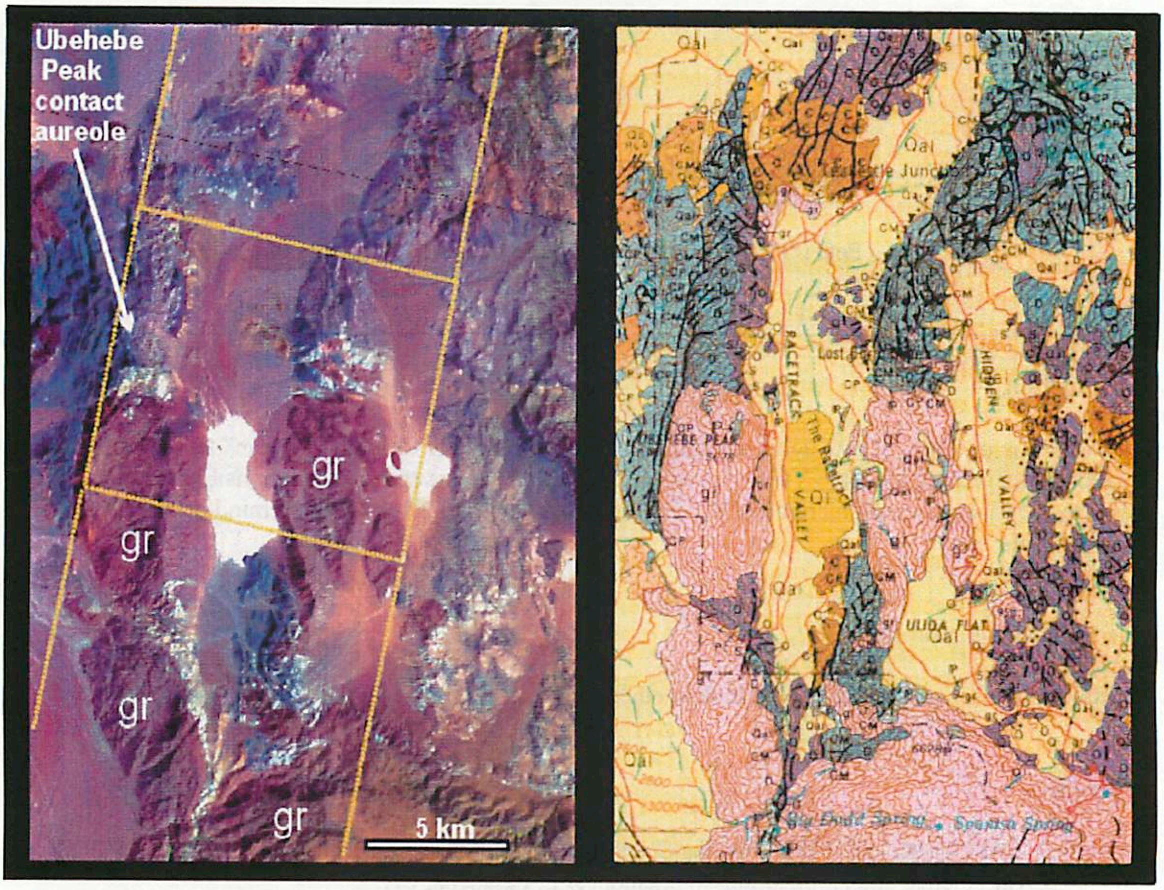
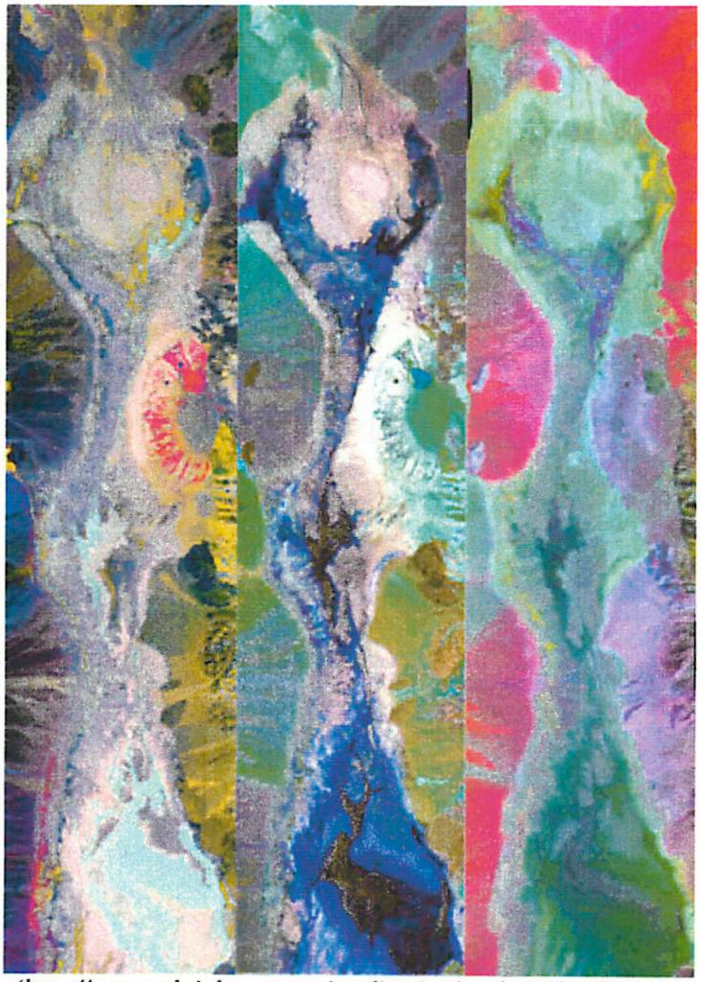


(http://www.sdsmt.edu/es/geology/specres/)

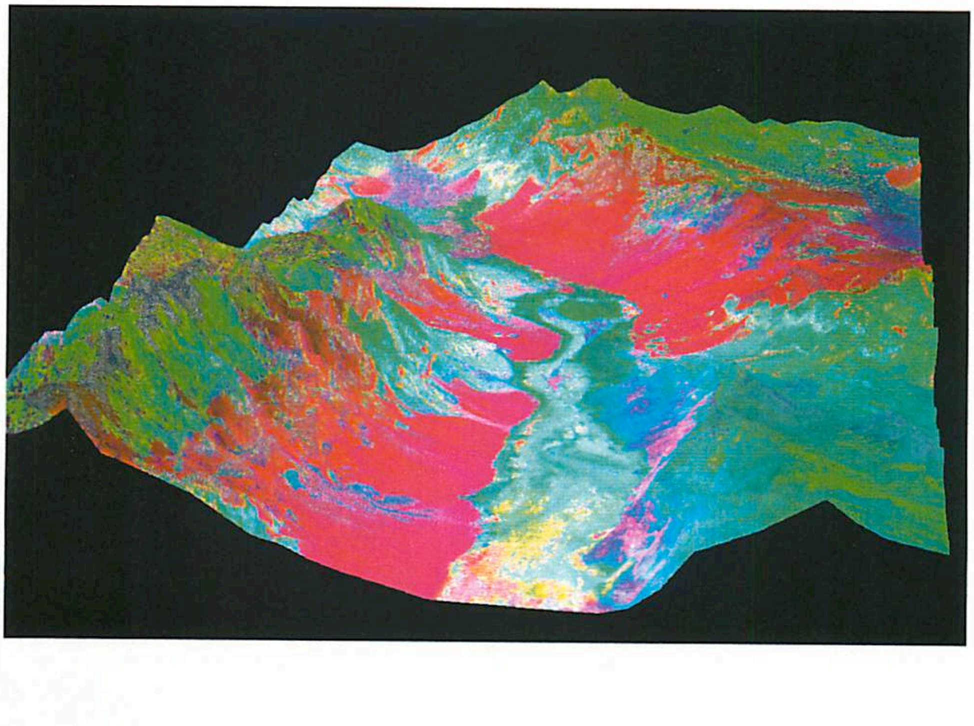
The Ubehebe Peak contact aureole is located in Death Valley National Park, California, at the southern end of the Last Chance Mountains. Figure 1 shows the location of the Ubehebe Peak contact aureole on a Landsat Thematic Mapper satellite image and on a generalized geologic map (Streitz and Stinson, 1977). The ground track of NASA's Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) flight f96050t01p02_r04 is shown by dotted yellow lines on the satellite image with the rectangular box outlining the specific AVIRIS scene used in this study.

(from Duke and Kozak, 2000)



(http://asterweb.jpl.nasa.gov/application/geology/death.htm)

(http://asterweb.jpl.nasa.gov/gallery/gallery.htm?name=DV)



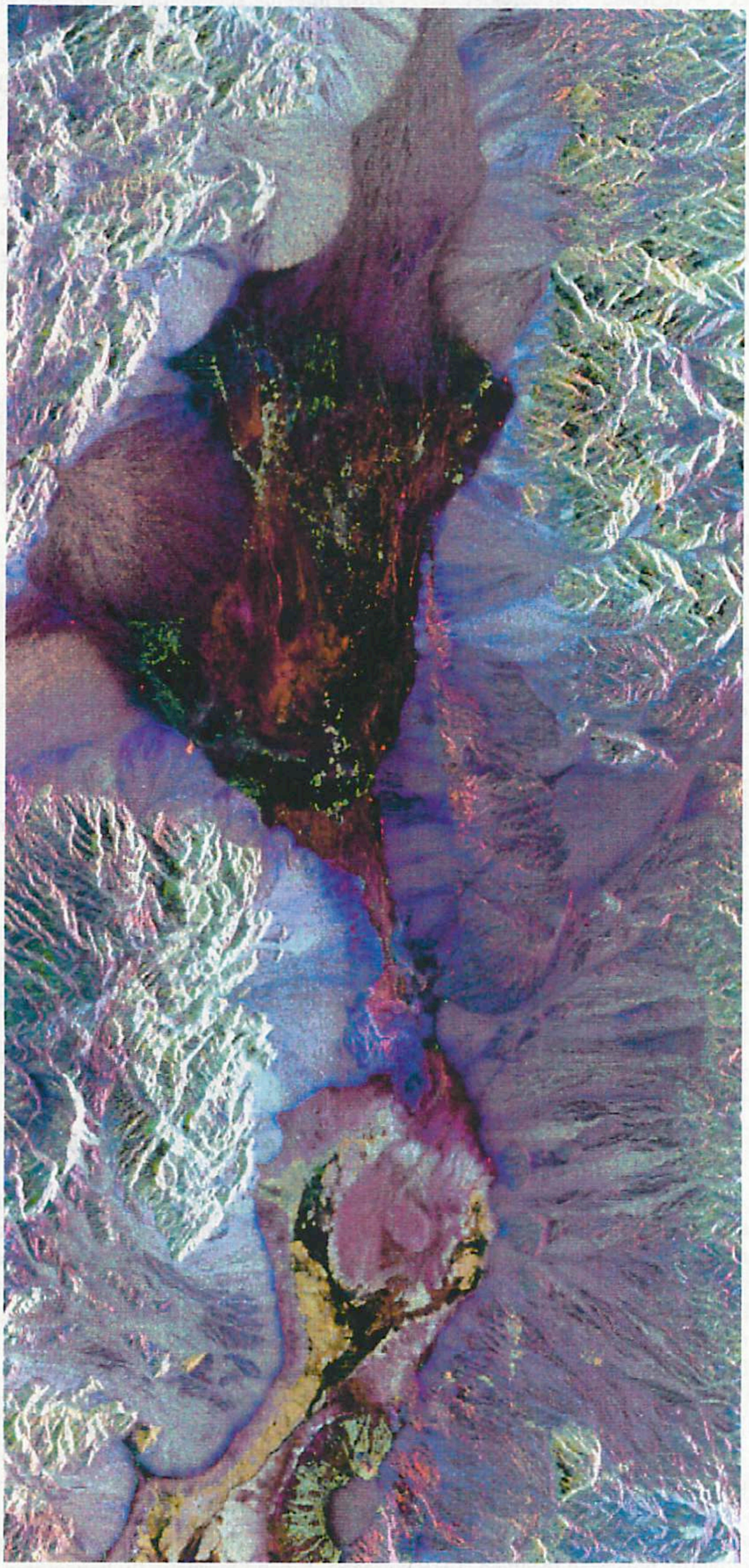
Previous page, top: The simulated ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images were made from coregistered AVIRIS imaging spectrometer data (the VNIR and the SWIR images), and Thermal Infrared Multispectral Scanner data (the TIR image). The VNIR image has a spatial resolution of 15 m, and combines ASTER bands 3, 2, and 1 in red, green, and blue (RGB). The SWIR image has a resolution of 30 m, and combines SWIR bands 8, 6 and 4 as RGB. The TIR image uses bands 14, 12 and 10 displayed as RGB, and has a resolution of 90 m. (Images displayed here are reduced in resolution.) The size of the area depicted is 12 x 50 km.
Bad Water in Death Valley is the lowest place in the United States. It is in the bottom middle of the image. The three versions of ASTER data illustrate the different compositional information available in various wavelength regions. For example, the bright red areas in the left image are vegetation patches at Furnace Creek Ranch and on the Furnace Creek Fan. The turquoise area in the upper left corner of the middle image depicts ground covered by limestone fragments. In the thermal image (right), surfaces with the mineral quartz present are depicted in red.
(from ASTER home page, CalTech, 2000; http://asterweb.jpl.nasa.gov/)

Previous page, bottom: This 3-D perspective view looking north over Death Valley, California, was produced by draping ASTER nighttime thermal infrared data over topographic data from the US Geological Survey. The ASTER data were acquired April 7, 2000 with the multi-spectral thermal infrared channels, and cover an area of 60 by 80 km (37 by 50 miles). Bands 13, 12, and 10 are displayed in red, green and blue respectively. The data have been computer enhanced to exaggerate the color variations that highlight differences in types of surface materials. Salt deposits on the floor of Death Valley appear in shades of yellow, green, purple, and pink, indicating presence of carbonate, sulfate, and chloride minerals. The Panamint Mtns. to the west, and the Black Mtns. to the east, are made up of sedimentary limestones, sandstones, shales, and metamorphic rocks. The bright red areas are dominated by the mineral quartz, such as is found in sandstones; green areas are limestones. In the lower center part of the image is Badwater, the lowest point in North America.
(from ASTER Images Gallery, NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team, 2000; http://asterweb.jpl.nasa.gov/gallery/gallery.htm?name=DV)

Characteristic	VNIR	SWIR	TIR
Spectral Range	Band 1: 0.52 - 0.60 μm Nadir looking	Band 4: 1.600 - 1.700 μm	Band 10: 8.125 - 8.475 μm
	Band 2: 0.63 - 0.69 μm Nadir looking	Band 5: 2.145 - 2.185 μm	Band 11: 8.475 - 8.825 μm
	Band 3: 0.76 - 0.86 μm Nadir looking	Band 6: 2.185 - 2.225 μm	Band 12: 8.925 - 9.275 μm
	Band 3: 0.76 - 0.86 μm Backward looking	Band 7: 2.235 - 2.285 μm	Band 13: 10.25 - 10.95 μm
		Band 8: 2.295 - 2.365 μm	Band 14: 10.95 - 11.65 μm
		Band 9: 2.360 - 2.430 μm	
Ground Res.	15 m	30 m	90 m

ASTER Spectral characteristics (http://asterweb.jpl.nasa.gov/instrument/character.htm)

Next page: This radar image shows the area of Death Valley, California and the different surface types in the area. Radar is sensitive to surface roughness with rough areas showing up brighter than smooth areas, which appear dark. This is seen in the contrast between the bright mountains that surround the dark, smooth basins and valleys of Death Valley. The image shows Furnace Creek alluvial fan (green crescent feature) at the far right, and the sand dunes near Stove Pipe Wells at the center. Alluvial fans are gravel deposits that wash down from the mountains over time. Several other alluvial fans (semicircular features) can be seen along the moutain fronts in this image. The dark wrench-shaped feature between Furnace Creek fan and the dunes is a smooth flood-plain which encloses Cottonball Basin. Elevations in the valley range from 70 meters (230 feet) below sea level, the lowest in the United States, to more than 3,300 meters (10,800 feet) above sea level. Scientists are using these radar data to help answer a number of different questions about Earth's geology including how alluvial fans form and change through time in response to climatic changes and earthquakes. The image is centered at 36.629 degrees north latitude, 117.069 degrees west longitude. Colors in the image represent different radar channels as follows: red = L-band horizontally polarized transmitted, horizontally polarized received (LHH); green = L-band horizontally transmitted, vertically received (LHV) and blue = CHV.
(Planetary Photojournal, JPL, http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA0134)



(http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA01349)

Salt Weathering
by ®

Glossary

Alluvial Fans: "A body of sediment whose surface form approximates to the segment of a cone which radiates downslope from a point on a mountain front, usually where a stream emerges." (Summerfield, 1991)

Deflation: "The removal of loose particles by the wind." (Summerfield, 1991)

Halide: A compound or ion containing fluorine, chlorine, bromine, iodine, or astatine.

Metal Chalcogenide: A sulfide of Cu, Zn, Sn, Pb, As, Sb, or Bi.

Erosion: The transport of material away from its place of origin.

Weathering: The breakdown of material prior to transportation.

Chemical Weathering: The breakdown of material by processes involving chemical reactions and the formation of new minerals.

Physical Weathering: The breakdown of material by breaking or fracturing

Background

Salt **weathering** is the process of breaking down rocks by the crystallization of salts within pores. This is a physical weathering process, similar in concept to frost wedging. Frost wedging involves the freezing of water within the cracks of rocks. When the water freezes and expands, it forces the crack wider. As the process repeats seasonally, the rock can be broken down into smaller pieces.

During salt weathering, salt is deposited in the pores of a rock. These salts can come from several sources, including air-borne salt particles, rain or snow, chemical breakdown of the rock itself, or ground water seeping through the rock (Wellman and Wilson, 1965).

As the salt crystals begin to form, larger crystals grow preferentially over small crystals, due to their increased surface area. Therefore, in a rock with a distribution of pore sizes, the large crystals in the large pores are favored over the small crystals in the small pores. The work necessary for a crystal to grow is balanced by the work needed to extend its surface. This relation is given by:

$$(P_l - P_s)dV = \sigma dA$$

where P_l is the pressure in the liquid, P_s is the pressure in the solid, dV is the increase in volume, σ is the interfacial tension between the liquid and the crystal face, and dA is the increase in surface area (Wellman and Wilson, 1965). The left side of the equation describes the work necessary during crystal growth on one face of the crystal. The right side is the work done to extend the surface of that face.

During salt weathering, the crystals growing in the largest pores grow until they fill the empty space. If the large crystal then grows into the smaller capillary pores adjacent to it, it will increase its surface area without significantly increasing its volume.

Energy is therefore minimized by the continued growth of the large crystal in the pore. This may result in rock fracture depending on σ and the strength of the rock (Wellman and Wilson, 1965).

Salt Weathering on Earth

Salt weathering is seen in many different environments on Earth, from arid deserts to sea cliffs to the dry valleys of Antartica. In Death Valley it has been noted as the major method of **alluvial fan** sediment breakdown where the fans encroach on salt laden areas. Goudie and Day made several traverses of alluvial fans consisting of Pre-Cambrian crystalline rocks and Teritary volcanics (1980). As the traverse approached the salt flats, the mean cobble size went from 41 cm to less than 6 cm. They also noticed an increase in the length to width ratio in the cobbles, which indicates splitting as a dominant process in breakdown. The end products of this weathering process are fine grained silts and clays that are subject to **deflation**.

The Planetary Connection

On Earth, the predominant force behind weathering and erosion is water. On other planets where water is scarce or non-existent other forces take over. On Mars, wind is an effective mechanism for erosion of small particles, but is not efficient at the weathering of larger material. How are the small particles produced? Malin proposed that salt weathering is presently active on Mars (1974). The present of salts in solution in water can depress the triple point of water so that it is stable as a liquid in the surface environment of Mars. When the water vaporizes, it leaves the salt behind and weathering occurs. Malin also suggested that the salt saturated liquid could also freeze seasonally, adding frost wedging as a possible weathering process.

Salt weathering may also be important on Venus where liquid water is non-existent. Since the process of salt weathering requires only the crystallization of a salt, water is not necessary. On Venus, it is possible for crystals to form from a supersaturated gas (Brackett, et al., 1995). Metal **halides** and **chalcogenides** could deposit on the highlands where the surface temperatures are lower, fracturing rocks and producing a fine soil layer. Observations of the emissivity of the Venusian surface predict bedrock and/or a well consolidated soil.

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The Ventifacts of Ventifact Ridge

(Or - How Wind and Sand Can Really Wear You Down)

With your Hostess Headed to the East Coast-ess – Jennifer A. Grier

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"*Ventifact* – A general term for any stone or pebble shaped, worn, faceted, cut, or polished by the abrasive or sandblast action of windblown sand, generally under desert conditions."

Introduction

Strong winds often blow in the desert and in the arid southwest in general. The overall lack of vegetation allows the wind to pick up large quantities of sand and silt. Sand entrained in high speed winds has proven to be an extremely powerful erosive agent, which works basically the same as commercial sandblasting. This form of erosion is the most effective in areas where the overall geology and local landforms serve to channel winds into only one or two prevalent directions. Such winds and the sand they carry can then continually and perpetually blast any surface features very effectively. Telephone poles left unprotected in some of these regions have been cut completely through in only a matter of decades by this natural sandblasting. Of course, the rocks in such areas also suffer from this constant sandblasting, and their surfaces are carved and fluted with erosional features. Any rock or pebble exhibiting such features is referred to as a ventifact. Ventifact Ridge is one of these places where the wind and local geology have conspired to make ventifacts ubiquitous features of the landscape.

Ventifact Ridge

The Death Valley trough acts as a wind channel or tunnel. Wind blows nearly uninhibited both up and down the Valley. Ventifact Ridge lies in the middle of this wind trough, and is unprotected by any other landforms or vegetation. Ventifact Ridge peaks at about 150 feet above the general surroundings, and about 80 feet above Badwater Road (see Figure 1). The north-west side of the Ridge is much steeper because it lies along a fault. The Ridge consists of a coarse conglomeration of stones and sand swept down from the mountains to the east. Most of the larger stones which litter the surface of the Ridge are chunks of black basalt, and vesicles are a common feature of these rocks. The wind which rips up and down the Valley, and the tiny particles entrained in that wind, have carved and sculpted the rocks of the Ridge. These carved and polished rocks are found all over the top of Ventifact Ridge. The sand and silt for such sandblasting is amply available from the alluvial fans found on both sides of the Ridge.

Note: It is illegal to collect rock samples on the Ridge, so leave the rocks, however cool, where you found them.

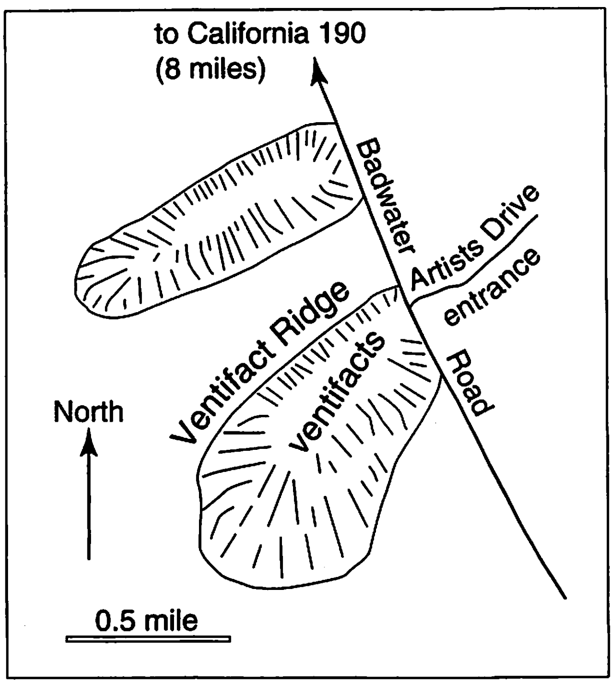

Figure 1. Schematic of the Ventifact Ridge (VR) area and surroundings. Illustrated are the major roads and the smaller, nearby ridge to the north.

"*Erosion* – The wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind and underground water."

The General Formation of Ventifacts

As mentioned, areas like Ventifact Ridge in Death Valley, and Garnet Hill in Southern California are covered with ventifacts for three basic reasons, (1) the local landforms conspire to create uni-directional or bi-directional winds, (2) they are in arid climates where sand and grit are readily available, and vegetation is sparse, and (3) they are otherwise unprotected highs with rocks exposed at the surface to be sculpted. Stones sculpted by sandblasting are called ventifacts, which means "wind made". Such rocks can possess a variety of wind eroded features including luster, grooves, flutes, pits, and facets. The types of erosional features formed generally depends on the wind direction and the nature of the rock. For example, heterogenous rocks become pitted as the soft components are eroded away preferentially. On the other hand, rocks with an even, fine grained texture will tend to polish and become lustrous, rather than pitted. A strong clast in a otherwise weak matrix will protect the material behind it, and "fingers" of uneroded material will be left behind the clast as the rest of the rock wears away.

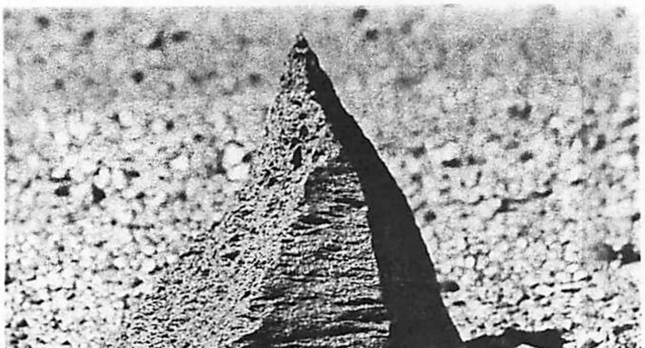

Figure 2. A grooved and pitted, vesicular basalt boulder with multiple wind-cut facets and a lee-side sand tail. About 50% of this rock has been eroded away, judging from basal dimensions, VR. (Tape measure 2.5 inches)

What To Do At The Ridge

Find the Stop: The entrance to Artists Drive is off Badwater Road, 8.5 miles south of California 190 and 7.8 miles north of Badwater. Directly west of that turnoff is a low, narrow ridge projecting about a mile southwest one the floor of Death Valley. Park west of Badwater Road just beyond the Artists Drive entrance. Do not confuse the site with the Artists Drive exit which is 3.7 miles to the north. Walk from the parking area to the top of the ridge (about 80 foot climb in elevation). Choose a spur of the ridge that appears to have many boulders, and walk about 300 yards down the crest to the southwest.

Orient Yourself: To the south of the Ridge is a vast white salt-pan flat, which extends east to the base of the Black Mountains. Also to the south, but much further away, is the peak of Mormon Point. To the east are the slopes of the Artists Drive formation, which appear variagated and colorful. Desert pavement is found in large expanses to the west, which have formed on the alluvial fans at the base of the Panamint Mountains. At the crest of those mountains is Telescope Peak, towards which the Ridge is almost directly oriented. Another, smaller ridge can be seen to the north, very close to Ventifact Ridge.

Check out the Ventifacts: Closely inspect a few of the stones on the ground and note that all exhibit some signs of wear. See if you can find examples of all the major categories of erosion forming ventifacts: luster, facets, Kanter, flutes, pits, grooves, and patterns.

Luster: Look for a polish on some stones somewhere between shiny and completely dull, especially on stones possessing a uniform, fine-grained texture.

Facets: The sides of some stones have been worn down so flat and so nearly perfectly planar, that these sides qualify as facets.

Kanter: This is the sharp edge formed by two or more facets which intersect.

Flutes: These small, shallow, dents are often an inch or so in length, and a small fraction of an inch wide and deep. These are U shaped in cross section, "*Vesicle* – A small cavity in an aphanitic or glassy igneous rock, formed by the expansion of a bubble of gas or steam during the solidification of the rock."

and are typically deeper at one end. Flutes are strongly lineated and parallel, and give ventifacts their characteristic look.

Pits: The wind eroded pits are more irregular, larger, and deeper than the original gas vesicles of the rock. If possible, locate a freshly broken chunk of basalt, and compare the size, shape and appearance of the vesicles with those on the surfaces of exposed rock. The eroded pits are larger, more rounded and often elongated or joined together.

Figure 3. Grooved and pitted basalt boulder, VR..

Grooves: Some surfaces will have several parallel grooves that are at least an inch long, U shaped in cross section, and a half an inch or more wide and deep. Grooves are much larger than flutes, and are often closed at the upwind end. If possible, find an eroded rock face that is nearly vertical, and see if there is a pattern of grooves radiating in a half circle upwards from the ground.

Patterns: Various patterns of flutes, pits and grooves can be seen on eroded surfaces. Some are like the half-circle grooves while other patterns are formed by flutes and pits alternating on highly vesiculated rocks.

Use Ventifacts to Find Prevailing Wind Direction: Notice that there are small accumulations of well-sorted windblown sand forming tails in the lee of the larger stones, and in other spots sheltered from the wind. This is the first clue to the direction from which the dominant winds blow. Note however that almost all the stones and rocks on the Ridge show evidence of sandblasting from two directions, both the north and the south. This should be obvious from the lineation of flutes, the direction of grooves (remember many are closed on the upwind end), and the directly of polished facets. You may see that many of the smaller stones seem to be eroded from many other directions in addition to north and south. This is due to those stone rotating or shifting positions. Recall that effective sandblasting is produced most readily in areas where the wind blows from one or two major directions. Other directional indicators come from pits. They are commonly formed on rock sides which face into the wind, inclined from 55 to 90 degrees to the wind direction. Flutes are often formed on rock edges oriented about 40 degrees from the wind direction. Grooves are generally located on the top surfaces of rocks.

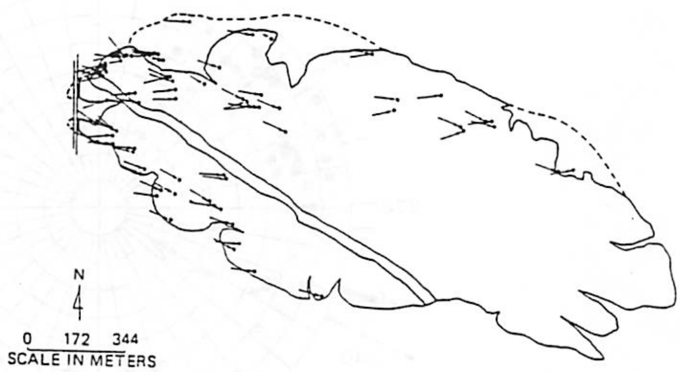

Figure 4. Wind Pattern around Garnet Hill, GH.

Ventifacts on Other Planets and What They Can Tell Us

One might expect that any planetary surface with rocks, wind, sand, and a relatively arid climate would produce ventifacts. This does, in fact, appear to be the case. Ventifacts were clearly imaged by IMP and

"*Weathering* – The destructive processes by which rocks are changed on exposure to atmospheric agents at or near the planet's surface, with little or no transport of the loosened or altered material; the physical disintegration and chemical decomposition of rock that produces an in-situ mantle of waste and prepares sediments for transportation."

Sojourner at the Pathfinder landing site. Mars, as one might think, appears to be an ideal place to form ventifacts. The morphology of ventifacts seen on Mars is very similar to that seen on Earth. Flutes, pits, facets and grooves have all be identified on Martian rocks.

Comparison of the ventifiacts at the Pathfinder site and at the Viking landing sites appears to indicate that ventifacts are much more common at the Pathfinder site. The exact reason for this is unknown, but it is possible that unidirectional or bidirectional winds were not channeled at the Viking sites. Also, there is evidence at the Pathfinder site for local supplies of abrading particles not seen at the Viking sites. Sediments deposited at the mouth of the Ares channel may be a source for such particles.

The direction and dip of flutes found on the rocks at the Pathfinder site are plotted in Plate 1a. The plot indicates that the wind which made these flutes blew predominently from the southeast to the northwest. The dip of the flutes is consistent with terrestrial work which indicates that flutes are inclined 40-90 degrees to the wind. This is strong evidence that the flutes are definitely wind carved, and not weathered out strictly by any chemical means.

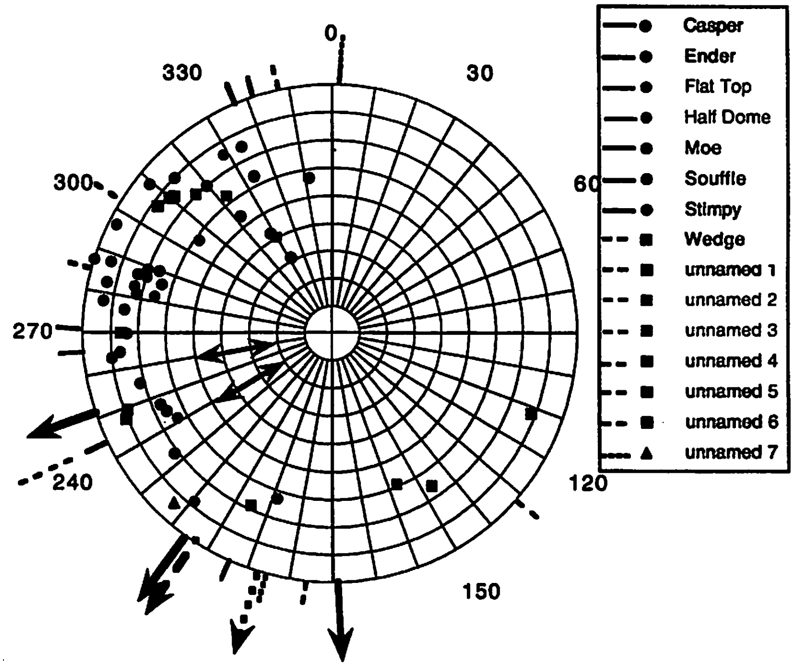

Plate 1a. Polar projection showing trends and plunges of flutes at the Pathfinder landing site. The circumferential axis represents trend and the radial axis plunge. Plunges are oriented downward toward the center of the plot and increase inward. Colored symbols correspond to the rocks upon which the flutes are located. Colored lines projecting outward from the edge of the plot show the direction the rover cameras were pointed when images used to derive flute orientations were taken (e.g., for the Moe observations, the rover had a heading of 271°). The association between the rock and rover orientation symbols is shown in the legend at right. The orange arrows represent the range of trends of groove-like features on the surface of Flat Top, as determined from IMP images projected to a bird's eye view using the Ames MarsMap virtual reality system [*Stoker et al.*, 1997]. Solid black arrows are minimum, average, and maximum values of local wind tail directions [*Greeley et al.*, 1997; *Smith et al.*, 1997a]. Arrow with large dashes represents the average trend of wind streaks as seen in orbital images [*Greeley et al.*, 1997; *Smith et al.*, 1997a]. Arrow with small dashes is the predominant wind direction predicted by the General Circulation Model [*Pollack et al.*, 1981; *Greeley et al.*, 1997; *Smith et al.*, 1997a].

"...Anyone who adjusts their fundamental orientation toward the universe so that it fits what university faculty members are currently writing simply has no notion of either the mutability of academic thought or its extreme limitations as a means of coping with reality"- *Andrew Greeley*

The SE to NW wind direction as determined from the ventifacts is exactly opposite that inferred from wind tails, wind streaks, and the general circulation model. However, it is likely that wind directions in ancient climatic regimes were different than those of the winds of today. Also, any sand supply would be likely to become reduced or exhaused over time. It this therefore likely that the ventifacts are witness to a different wind regime than that of the wind streaks. The tails and streaks would have been formed very recently, while the flutes may be very ancient in origin. The ventifacts are therefore a key to understanding past climate and climate change on Mars.

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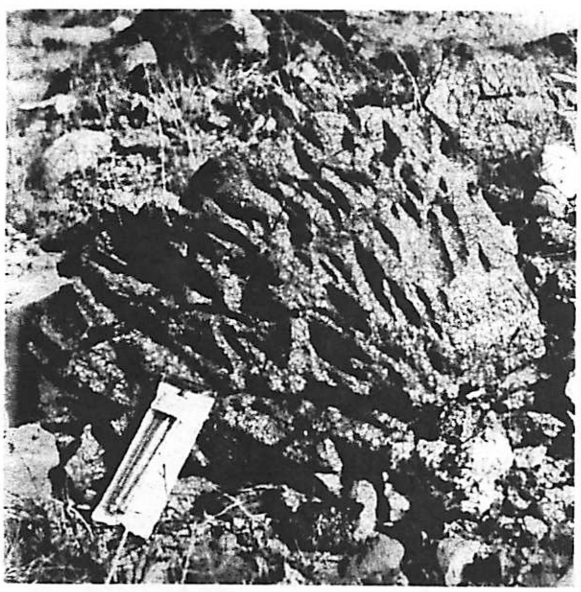



Figure 5: The left frame shows a fluted diorite at Garnet Hill. Note that the flutes cut across bands of aligned feldspars (white splotches) in the rock. The right frame is an image of the Mars rock Moe taken by the rover's left front camera. Moe is the most fluted rock seen at the landing site. This image clearly shows small flutes within larger flutes. The scale bar corresponds to a length of 10 cm at the back edge of the rock.

Evaporite Zonation

Matt Tiscareno

I. Introduction

- During the Pleistocene, Death Valley was covered by 600-foot-deep Lake Manly.
  - Dried up about 10,000 years ago.
- More recently, Death Valley had a 30-foot-deep lake (the "middle Holocene lake").
  - From 3,000 B.C. to the time of Christ (archaeological evidence).
  - Desiccation of this lake created the ***Death Valley salt pan*** (see Figure 22).

II. Formation

- Zonation of Death Valley salts can be compared to evaporating brine from a dish.
- Less soluble ions precipitate first.
  - Primary cations in order of decreasing solubility: Ca, Mg, Na
  - Primary anions in order of decreasing solubility: CO_3, SO_4, Cl
- As "middle Holocene lake" evaporates, salts become more concentrated, and precipitate in order of solubility.
  - First to precipitate are the carbonates, then sulfates, then chlorides.
  - Chlorides, by far most abundant, occupy the middle of the salt pan, since the lake level was lower by the time they began to precipitate.
  - Sulfates are on the edges of the salt pan, with carbonates even further out on the edges.
- Complications
  - Southern part of Death Valley was tilted eastward as evaporation progressed.
    - Eastern lakeshore is 20 feet lower in elevation than western lakeshore.
    - Salt rings are not concentric in the southern region, eastward edge is crowded up against the Black Mountains.
    - Similar asymmetry for similar reason found at Great Salt Lake in Utah.
  - In the 2,000 years since the lake vanished, fresh water (rains, floods) has reworked the salt deposits in some areas, particularly in the lower-lying chloride zone.

III. Chloride Zone

- By far the largest zone, covers three-quarters of the valley floor.
- Mostly halite (NaCl), with some sylvite (KCl).
- Four facies in the chloride zone.
  - 1) Massive Rock Salt
    - In center of the salt pan.
    - 2 to 6 feet thick, covering 7 or 8 square miles.
    - Nearly pure rock salt, less than 0.5 percent insoluble residue.
  - 2) Rough Silty Rock Salt
    - Example: Devil's Golf Course
    - As the lake dried, this location was alternately flooded and desiccated, and mud was incorporated in the salt.
    - Very rough upper surface, mantled with silt.
  - 3) Smooth Silty Rock Salt
    - Smoother surface due to more frequent flooding during deposition.

  - Salt layer contains about 15 percent insoluble residue, silt layer contains about 35 percent salt.
- 4) Eroded Rock Salt
  - Places where more recent flooding has occurred since desiccation of "middle Holocene lake" (most recent: flood of 1969), yet rock salt layer still distinguishable.
  - Not mapped separately from floodplain in Figure 22.

<u>IV. Sulfate Zone</u>

- At edges of the chloride zone.
- Sub-zones due to brine composition.
  - At north end of the salt pan, there is very little Ca, so thenardite (Na_2SO_4) and other Na-sulfates are common.
  - At south end of the salt pan, there is ample Ca and gypsum ($CaSO_4 \cdot 2H_2O$) is dominant, since Ca precipitates more easily than Na.
- Borates also appear in the sulfate zone, with similar sub-zonation:
  - Borax ($Na_2B_4O_7 \cdot 10H_2O$) and ulexite ($NaCaB_5O_9 \cdot 8H_2O$) in the north.
  - Meyerhofferite ($CaB_6O_{11} \cdot 7H_2O$) in the south.
  - At Cottonball Basin, evaporation leaves small pellets of borates, called "cottonballs", which were a focus of early borax work in the valley.
- Gypsum deposits
  - 2 to 5 feet thick, capped by about 6 inches of anhydrite (anhydrous gypsum).

<u>V. Carbonate Zone</u>

- Occurs at the outermost edges of the salt pan.
- Mostly sand or silt, with crystals of calcite ($CaCO_3$) that formed *in situ*.
  - Some Na-carbonates in the Ca-poor northern areas.
- There is actually more sulfate and in places more chloride than carbonate in what is called the carbonate zone.
- At panward edge of carbonate zone, groundwater forms hummocks of calcite-encrusted silt (crunchy when stepped on).

Source: Charles B. Hunt, *Death Valley: Geology, Ecology, Archaeology.* University of California Press (1975).

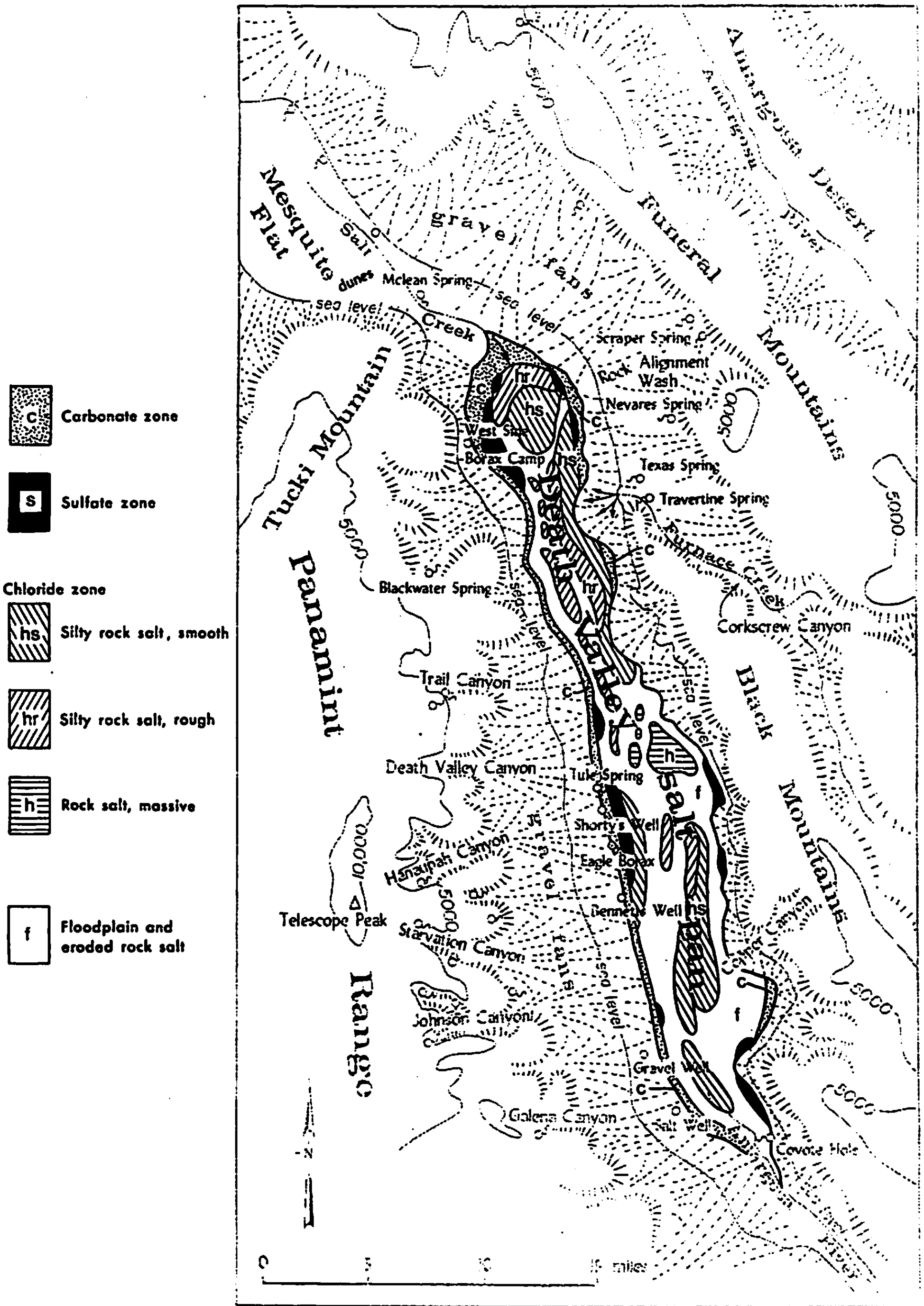


FIG. 22. Map of Death Valley salt pan.

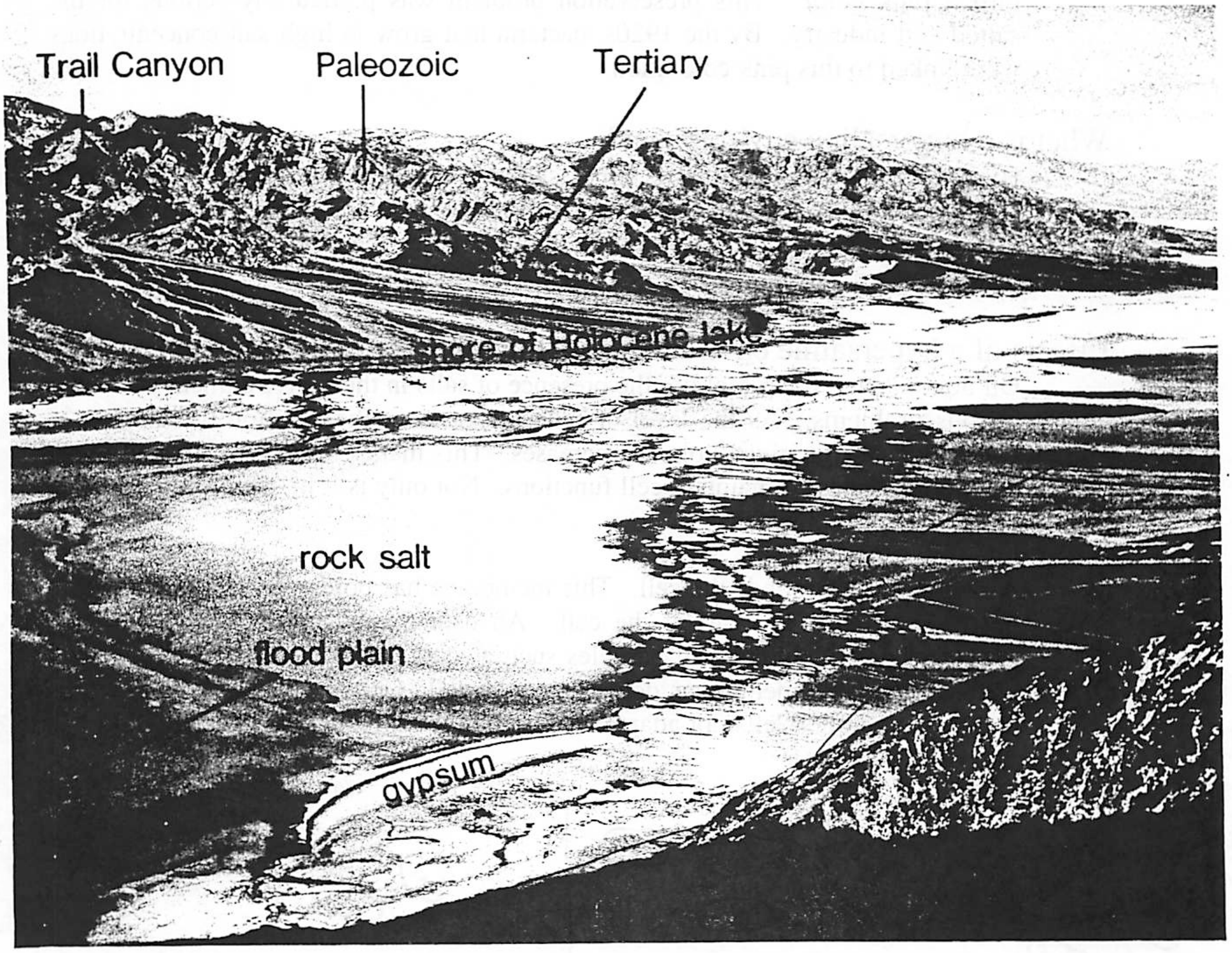


FIG. 23. Concentric rings on Death Valley salt pan, northwest from Dante's View. Badwater is at lower left corner. Gypsum in sulfate zone forms crescentic deposit in lower left center; rock salt of chloride zone extends over several square miles in left center. Shoreline features of Holocene lake which deposited the salts are plainly seen cutting across toes of fans on far side of valley.

Microbial Life in Hypersaline Environments

Introduction

Salt (NaCl) has long been used as a food preservative. An increased level of salt in food packaging removes moisture from the food, inhibiting microbial growth. In the early 1900s foods preserved with high levels of salt would occasionally turn a pink color. This preservation problem was particularly serious for the salted cod industry. By the 1920s, bacteria that grow in high-salt concentrations were linked to this pink coloration.

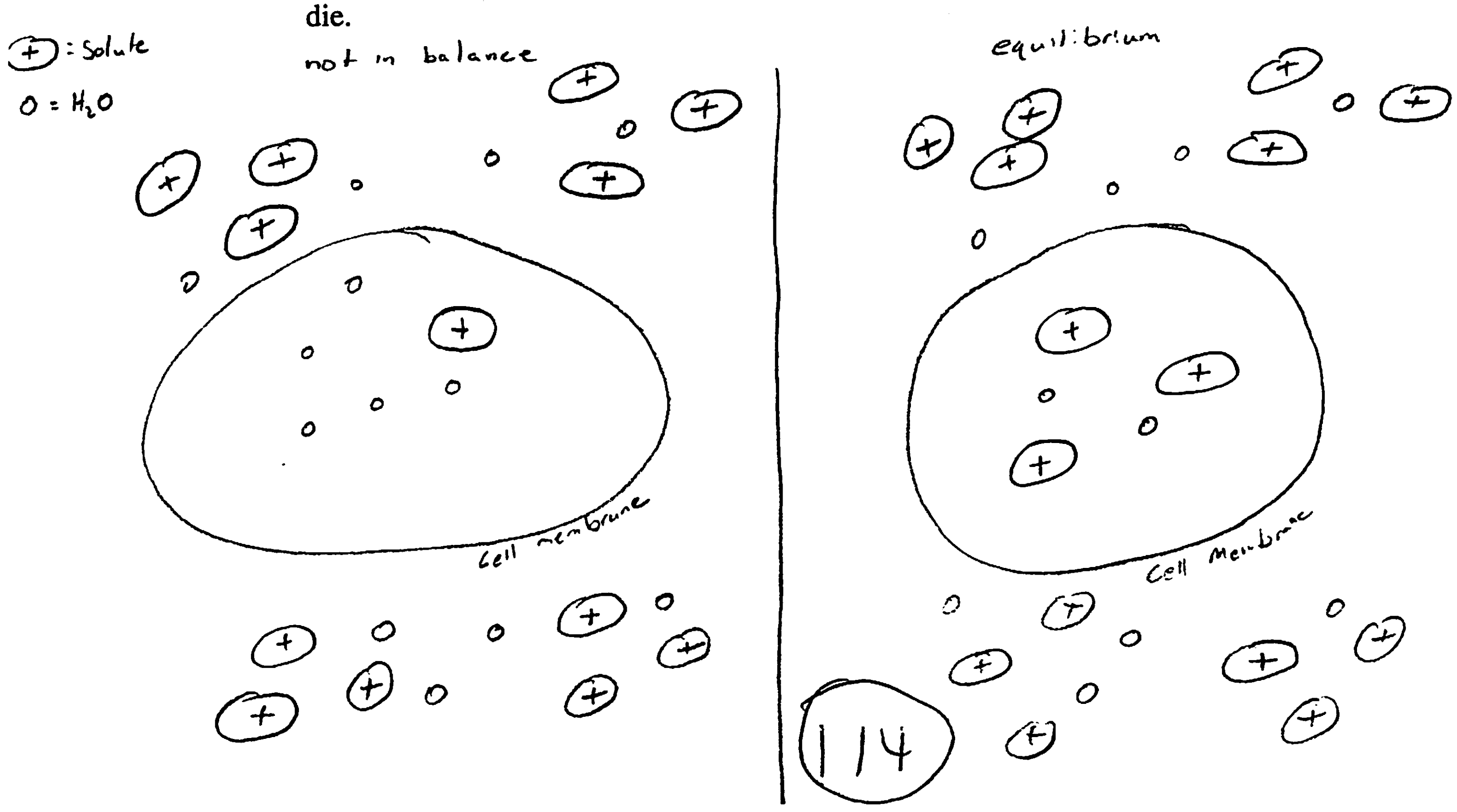
What is a hypersaline environment?

Hypersaline environments are either salt crystals or waters that contain >10% NaCl per volume (note the total salt content may be higher since NaCl is just one of many types of salts). As the salt level increases the amount of water present per unit volume decreases.

Effects of a hypersaline environment on microbes

On non-adapted microbial life the presence of salts in their environment can cause serious problems. As the level of salts increases in the solution the amount of water present in a given volume decreases. This makes it hard for the cell to get the water needed to maintain cell functions. Not only is it harder to get water the cell actually loses water.

A membrane surrounds the cell. This membrane has pores that allow material to be transported in and out of the cell. An osmotic pressure is generated if an excess of positively charged particles such as Na^+ surrounds the cell. Water will diffuse across the membrane, dehydrating the cell. Conversely, Na^+ will enter the cell by diffusion. Cells not adapted to handle the high Na^+ ion concentration will die.

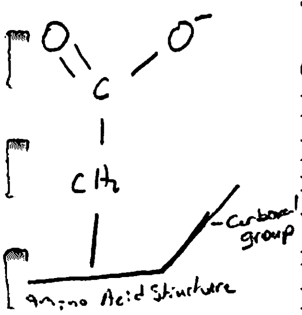


What is a halophile?

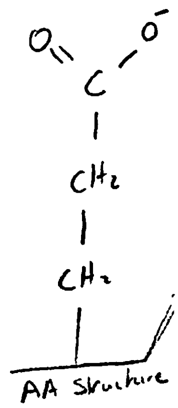
Some microbes need high saline environments in which to live. Halophile bacteria will grow in environments that are 10-34% NaCl. These bacteria have developed strategies to allow them to cope with the high saline levels.

How do microbes adjust to live in these environments?

In high saline environments the Na^+ outside the cell increases. Halophilic cells have developed a method of limiting the Na^+ interior to the cell membrane. Na^+ wants to diffuse through the membrane in order to equalize the electrochemical gradient. Halophilic cells instead actively increase the levels of K^+ ions internally in order to relieve the osmotic pressure. Na^+ is toxic to cells and so is K^+ but to a much lower extent. Even though levels of K^+ are increased within the cell, it can still function.



Cells utilize proteins to build the structures needed to carry out cell functions. Proteins are made from 20 different amino acids each having it own unique properties. Arranging the amino acids together builds a protein. The variability found in the amino acids allows the adaptability needed by the cell to function with increased K^+ levels. Two amino acids are negatively charged and attract K^+ ions to them. The K^+ ions bring much needed hydrated water molecules to the protein thus allowing it to continue to function.



How can these environments form?

One way to form a hypersaline environment is through evaporation. An isolated body of water will evaporate over time. During evaporation water is lost, concentrating the salts suspended in solution. This can increase the salinity of the environment. On the Earth this happens in places such as the Dead Sea and Salt Lake. In Death Valley the salt flats are all that remains of such an isolated lake.

A second method of salt concentration can occur in extremely cold environments. Ocean water near the South Pole begins to freeze as winter begins and temperatures decrease. Pure water is removed from the ocean increasing the salinity of the water under the large ice sheets.

Planetary Connections?

Mars may have had an ocean in the Northern Hemisphere at one time in its past. Floods that eroded the outflow channels emptied into the northern lowlands. Evaporation of water from this large ocean would have concentrated salts. If life existed in this water its ability to adapt to the higher saline content would be important for its survival. Adaptations would certainly be similar to those for terrestrial bacteria (provided Martian life is similar to terrestrial life).

Europa's ice shell removes pure water from the reservoir beneath it. If this ocean isn't very deep saline concentrations could be rather high.

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Desert Plant Adaptations

Jonathan Fortney

Fall 2000 Field Trip

Xerophytes

The physical and behavioral adaptations of desert plants are as numerous and innovative as those of desert animals. Xerophytes, plants that have altered their physical structure to survive extreme heat and lack of water, are the largest group of such plants living in the deserts of the American Southwest.

Each of the four southwestern deserts offers habitats in which most xerophytic plants survive. But each is characterized by specific plants that seem to thrive there. The Great Basin Desert is noted for vast rolling stands of Sagebrush and Saltbush, while in the Mojave Desert, Joshua Trees, Creosote Bush, and Burroweed predominate. The Sonoran Desert is home to an incredible variety of succulents, including the giant Saguaro Cactus, as well as shrubs and trees like mesquite, Paloverde, and Ironwood. The Chihuahuan Desert is noted for mesquite ground cover and shrubby undergrowth, such as Yucca and Prickly Pear Cactus.

Cactus, xerophytic adaptations of the rose family, are among the most drought-resistant plants on the planet due to their absence of leaves, shallow root systems, ability to store water in their stems, spines for shade and waxy skin to seal in moisture. Cacti originated in the West Indies and migrated to many parts of the New World, populating the deserts of the Southwest with hundreds of varieties, such as the Beavertail Cactus and Jumping Cholla.

Cacti depend on chlorophyll in the outer tissue of their skin and stems to conduct photosynthesis for the manufacture of food. Spines protect the plant from animals, shade it from the sun and also collect moisture. Extensive shallow root systems are usually radial, allowing for the quick acquisition of large quantities of water when it rains. Because they store water in the core of both stems and roots, cacti are well-suited to dry climates and can survive years of drought on the water collected from a single rainfall.

Many other desert trees and shrubs have also adapted by eliminating leaves -- replacing them with thorns, not spines—or by greatly reducing leaf size to eliminate transpiration (loss of water to the air). Such plants also usually have smooth, green bark on stems and trunks serving to both produce food and seal in moisture.

Phreatophytes

Phreatophytes, like the mesquite tree, have adapted to desert conditions by developing extremely long root systems to draw water from deep underground near the water table. The mesquite's roots are considered the longest of any desert plant and have been recorded as long as 80 feet. Botanists do not agree on the exact classification of the three mesquite trees: the Honey Mesquite, Screwbean Mesquite and the Velvet Mesquite, but no one disputes the success of their adaptation to the desert environment. Mesquites are abundant throughout all the southwestern deserts.

The Creosote Bush is one of the most successful of all desert species because it utilizes a combination of many adaptations. Instead of thorns, it relies for protection on a smell and taste wildlife find unpleasant. It has tiny leaves that close their stomata (pores) during the day to avoid water loss and open them at night to absorb moisture. Creosote has an extensive double root system— both radial and deep—to accumulate water from both surface and ground water.

Perennials

Some perennials, such as the Ocotillo, survive by becoming dormant during dry periods, then springing to life when water becomes available. After rain falls, the Ocotillo quickly grows a new suit of leaves to photosynthesize food. Flowers bloom within a few weeks, and when seeds become ripe and fall, the Ocotillo loses its leaves again and re-enters dormancy. This process may occur as many as five times a year. The Ocotillo also has a waxy coating on stems which serves to seal in moisture during periods of dormancy.

Another example of perennials that utilize dormancy as a means of evading drought are bulbs, members of the lily family. The tops of bulbs dry out completely and leave no trace of their existence above ground during dormant periods. They are able to store enough nourishment to survive for long periods in rocky or alluvial soils. The Desert Lily, also known as the Ajo, is found at a depth of 18 inches or more. Adequate winter rains can rouse it to life after years of dormancy.

Annuals (Ephemerals)

The term "annuals" implies blooming yearly, but since this is not always the case, desert annuals are more accurately referred to as "ephemerals." Many of them can complete an entire life cycle in a matter of months, some in just weeks.

Contrary to the usual idea that deserts are uniformly hot, dry and homogeneous in their lack of plant life, they are actually biologically diverse and comprise a multitude of micro-climates changing from year to year. Each season's unique precipitation pattern falls on a huge variety of mini-environments. And each year in each of these tiny eco-niches, a different medley of plants bloom as different species thrive.

Desert plants must act quickly when heat, moisture and light inform them it's time to bloom. Ephemerals are the sprinters of the plant world, sending flower stalks jetting out in a few days. The peak of this bloom may last for just days or many weeks, depending on the weather and difference in elevation. The higher one goes, the later blooms come. Different varieties of plants will be in bloom from day to day, and even hour to hour, since some open early and others later in the day.

Ephemerals such as the Desert Sand Verbena, Desert Paintbrush and Mojave Aster usually germinate in the spring following winter rains. They grow quickly, flower and produce seeds before dying and scattering their progeny to the desert floor. These seeds are extremely hardy. They remain dormant, resisting drought and heat, until the following spring—sometimes 2 or 3 springs— when they repeat the cycle, germinating after winter rains to bloom again in the spring. There are hundreds of species of ephemerals that thrive in the deserts of the American Southwest.

If you examine desert soils closely, you will dispel forever any notion you might have of the desert as a barren environment, for you will likely find dozens of both annual and perennial seeds in every handful of desert soil. In the Sonoran Desert, seed densities average between 5,000 and 10,000 per square meter. The world record is over 200,000 seeds per square meter.

This "seed bank" attests to the remarkable reproductive success of desert flora, made possible by their symbiotic relationship with desert fauna—birds, insects, reptiles and even mammals. Animals aid in both fertilization and dispersion of seeds, assuring the continued profusion and diversity of plant life throughout the deserts of the Southwest.

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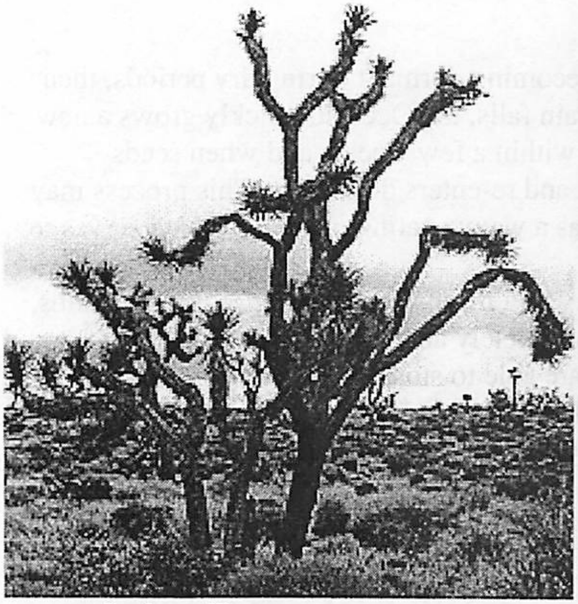
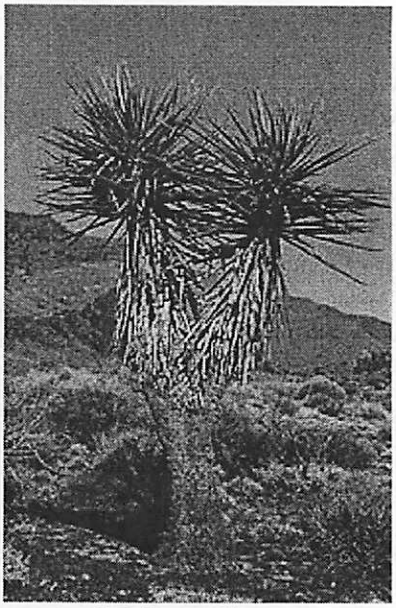
http://www.desertusa.com/du_plantsurv.html



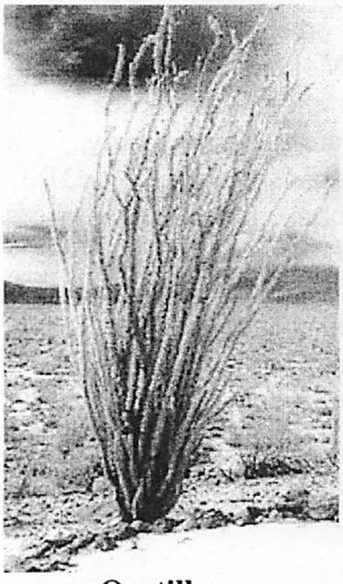
Joshua Tree



Mohave Yucca

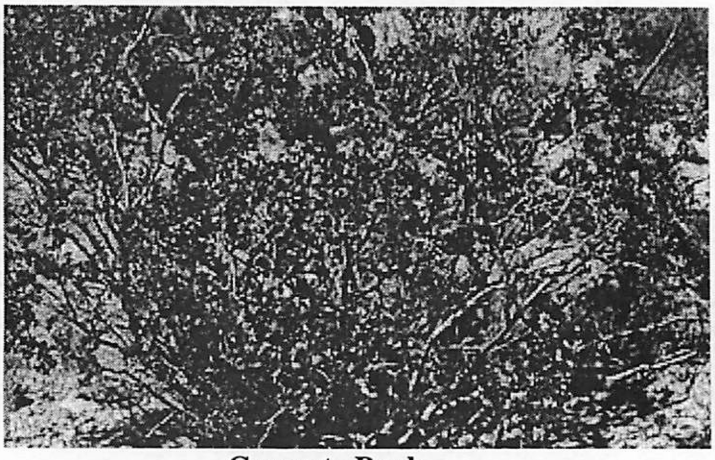
Joshua trees (and most other yuccas) rely on the female Pronuba Moth (*Tegeticula)* for pollination. No other animal visiting the blooms transfers the pollen from one flower to another. In fact, the female Yucca Moth has evolved special organs to collect and distribute the pollen onto the surface of the flower. She then lays her eggs in the flowers' ovaries, and when the larvae hatch, they feed on the yucca seeds.

Without the moth's pollination, the Joshua Tree could not reproduce, nor could the moth, whose larvae would have no seeds to eat. Although an old Joshua Trees can sprout new plants from its roots, only the seeds produced in pollinated flowers can scatter far enough to establish a new stand.



Ocotillo

See *Perennials* section



Creosote Bush

See *Phreatophytes* section for details

Fine Album

Kelso Dunes, California

Gwen Bart, fourth generation California native

The Kelso Dune field is one of the largest dune fields in the California desert. Dunes are formed by wind transport of sand. Air can move sand in two ways.

- **Saltation** occurs when a grain of sand is impacted in such a way as to cause it to bounce into the air. Then the air blows it along, and gravity soon returns it to the ground, impacting at an angle of about 10 degrees. The impact may cause additional grains of sand to bounce into the air and thus participate in saltation themselves.
- If the wind reaches a critical velocity, sand can also move by **surface creep**, where the wind is strong enough to cause grains of sand to slide or roll along the ground. Both of these processes are important to the formation of dunes.

Dunes originate where there is a disruption in wind flow sufficient to allow sand to settle in that area. This often occurs at the lee side of a rock or vegetation. The sand is blown into this area, its velocity decreases, and the sand is deposited.

Dunes have a gently inclined windward slope and a steeper downwind slope, also called the lee slope or slip face. Grains of sand are moved by surface creep and saltation up the windward slope. The wind continues up past the crest of the dune, and the sand drops off onto the lee slope. The dune itself moves downwind as sand from the windward slope is deposited on the lee slope.

There are several types of dunes. Four important types are described here.

- **Transverse** dunes require a large sand supply and a constant wind direction to form. They form ridges and troughs perpendicular to the prevailing wind.
- **Barchan** dunes are crescent shaped with the points of the crescent pointing downwind. They form where there is a constant wind direction but the sand supply is limited.
- **Longitudinal** dunes are linear dunes with lengths in kilometers and heights in the meters. They form in an area with limited sand supply where there are converging winds.
- **Star** dunes have a central peak with several arms coming off of the dune. This suggests that there was wind blowing in three or more directions when the dune was formed.

[Hamblin, 1989]

Kelso Dunes

Location:	east-central Mojave Desert
Sand source:	Mojave River Wash to the west - a broad alluvial apron periodically flooded by the Mojave River where it emerges from Afton Canyon
Distance from source area:	about 56 km
Prevailing dune form:	typical, small, irregular transverse dune ridges
Total surface area:	115 km^2
Active area [Lancaster]:	40 km^2
Net movement:	none
Maximum sand thickness:	215 m
Dune height:	about 10 m
Sand accumulation time:	10,000 - 20,000 years
Grain size:	90% between 0.25 and 0.50 mm
Sand composition [Ramsey]:	27.88% Plagioclase, 23.79% microcline, 40.40% quartz, 3.88% opaque, 4.03% other
Dune orientation:	in active areas, most dunes reflect prevailing westerly winds. However, dunes of other orientations due to northerly and southerly winds are not uncommon.

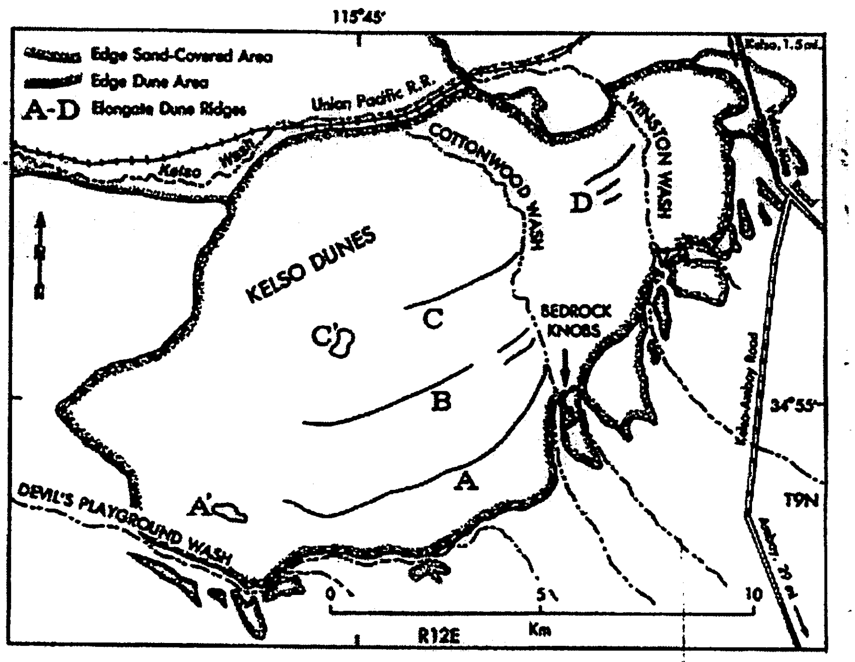


Figure 2. Geographic details of Kelso Dunes.

The modest sized dunes which are around 10 m in height are superimposed on four larger linear sand ridges, the largest of which (A) rises to 170 m above the south base of the dune mass.

[Sharp, 1982]

Although a large part of the dunes are still active, the dune field itself is not moving due to conflicting wind patterns. The crestal shape of the dunes in the active area is often changed as the winds shift back and forth. Measurements of the accumulation and removal of sand have been made at many points in this dune field. The results show that while the dune field is very active, there is no net transport of material. The orientations of the stabilized dunes to the north give a possible indication of past wind history in this area [Sharp, 1982].

In addition to the measurement of sand deposition and removal, remote sensing observations have been made of the dune field using both thermal IR and radar techniques.

Ramsey *et al.* used airborne thermal infrared multispectral scanner (TIMS) data and a newly developed linear spectral retrieval algorithm in conjunction with a spectral library of endmember minerals to see if the composition of the dune field could be determined remotely. 48 sand samples were also collected, and the results from the two methods were compared. The two methods showed general agreement.

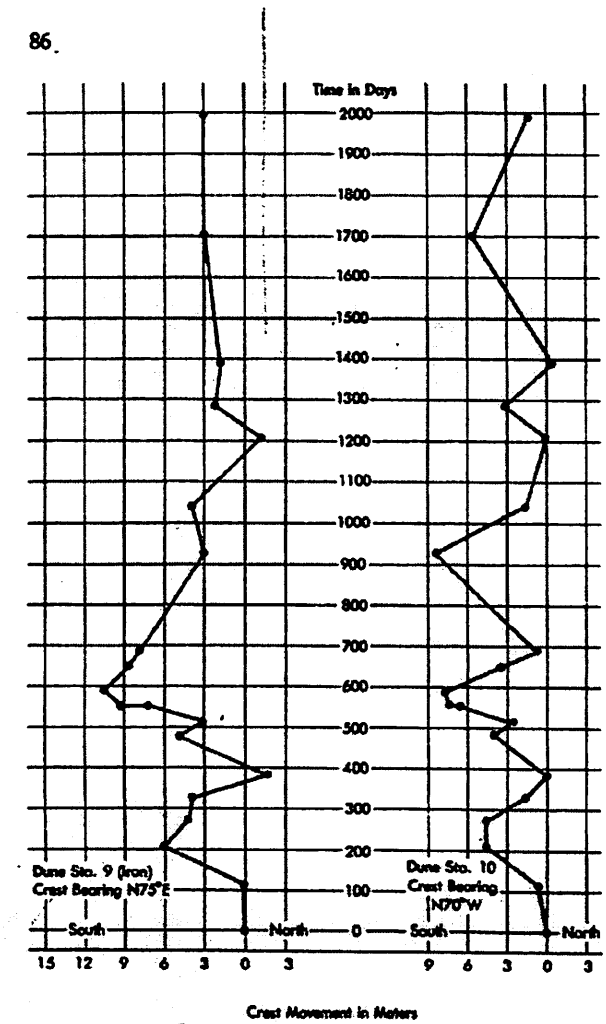


Figure 4. Plot of shifts in position of dune crests at stations 9(iron) and 10.

Mineral images showed high concentrations of microcline and magnetite in the dune fields as well as in the surrounding mountains. This may suggest that a percentage of these minerals are locally derived. This relation has never been noted in the past. Both the images and sample results indicated that there was only about 42% quartz whereas previous studies have reported 70-90%. For the quartz, there is no evidence of a direct near field source, and most of this mineral is likely from the Mojave River Wash [Ramsey, 1999].

Radar has also been used to image the dunes in an attempt to remotely determine location of active or inactive sand. Active units of sand showed up brighter on the radar images than the inactive units [Paisley, 1991].

Dunes on Mars

The planetary connection is, of course, that there's no reason there couldn't also be dunes on other planets. In fact, Viking Orbiter 2 revealed a large sand sea (erg) around the northern polar cap of Mars . From Viking images, both transverse and barchan dunes were observed. The barchan dunes are located near the southern edge of the erg, likely produced due to having less available sand or due to deflation of that region by high speed winds. Some complex dunes are observed, and are thought to be due to the collision of barchan dunes. This would indicate that dunes on Mars migrate at different rates just as they do on Earth. However, the present activity of the dunes on Mars is unknown.

Just like the Kelso Dunes, the dunes on Mars provide insight into the wind history of the region. There is evidence in the dunes that more that one wind direction prevails in certain areas. Also, winds of speeds greater than 75 m/s are required to form the observed transverse dunes on Mars.

The dunes on Mars seem to be fairly young due to the lack of well developed longitudinal dunes. They also appear to have formed after the north polar cap formed.

The location of the dunes suggests that most of the sand has been removed from the Martian plains into the northern erg or to crater floors [Breed, 1979],[Tsoar, 1979].

Undoubtedly, MGS data and future Mars missions will enhance our knowledge of dunes on Mars.

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Booming Dunes!

by Ingrid "Boom-Boom" Daubar

What are Booming Dunes?

The phenomenon of booming dunes has been known for thousands of years. Desert legends include underground ghosts and gods groaning, subterranean orchestras, buried cathedrals ringing bells, or chanting monks buried with their monasteries. The sounds these people heard are still largely unexplained.

Booming dunes emit low-frequency (less than 100 Hz) **noises when the sand is moved**. They are usually of short duration, but can last for tens of seconds. They can be as loud as thunder and be heard from distances over 10 km.

Booming dunes are not to be confused with "squeaking," "singing," "barking," or "whistling" dunes, although these are more common. These emit high-frequency tones (500-2500 Hz) of very short duration (less than a quarter of a second) when the sand is sharply sheared. The sound is very similar to the sound produced when a wet finger is rubbed over the rim of a crystal glass. As Criswell et al. (1975) say, "*booming sand never squeaks, and squeaking sand never booms.*"

Which dunes boom?

Dunes that boom have been reported **all over the world**: the Sahara desert, South Africa, China, Hawaii, Afghanistan, throughout the Middle East, Baja, California, Nevada, Chile.... Some of these have been stable for more than 1500 years. The Kelso dunes, which we will be visiting, are among dunes that have been heard to boom.

Booming dunes are visually and mineralogically **identical to "silent" dunes**. The mean sand size is the same (~ 309 μm), with the same standard deviation. Most booming dunes are quartz sand, except two back-beach dunes in Hawaii, which are calcite sand, indicating that booming is not limited to quartz sand dunes. The booming itself most often happens in drifts of sand that form on the **lee** (downwind) side of isolated mountains or cliffs. **Desert** dunes are the usual site for booming, rather than beach dunes.

However, there are some important differences between booming and silent dunes. Booming seems to require **well-sorted** sand. The sands are also skewed toward the **fine** end of size distribution, i.e. there are more fines in booming sands. Booming sands are more polished; they are **smooth** on the scale of 1 μm. It is unclear whether this is a result of initial selection by their location (smoother grains drop into the lee of a dune, while rougher ones are carried past by winds), or subsequent polishing by the higher velocity winds found in dunes' lees.

One important observation is that booming sands are **dry** sands. Any humidity in the air will prevent booming. Rain within weeks prior will silence any previously booming dune. The smoothness of booming sand grains might be related to rapid drying.

How do Booming Dunes Boom?

Booming events are normally caused by **spontaneous slumping** of sand at or near the angle of repose (~ 30°-35°). These events are more dramatic, involving meter-size areas of the dune, and lasting a few seconds to 15 minutes. Booming can also be **forced**: by pushing sand downhill, shearing it by digging, or even just by walking on it. This produces booms in short bursts (< 2 sec). Either of these mechanisms produce **shearing forces in the vertical direction**. This sets the top layer of sand into **coherent vibration**, which converts sliding kinetic energy into vibrational energy.

The booming is oddly pure: a given "boom" has a **narrow frequency range**, with very little noise. Strong "**beats**," or harmonic frequencies (~ 1-10 Hz) are heard in prolonged booms. The acoustic signal is accompanied by a **seismic** signal. Both signals correlate exactly to the movement of the sand: they start when the sand begins to move, and stop when the sand ceases moving. The seismic spectrum has an even more sharply defined frequency range, one which matches the acoustic spectral shape exactly. These vibrations can by felt in the sand, and if they are forced by hand, they can be felt in the hand like a mild electric shock.

The mechanical to seismic energy **conversion efficiency** is estimated to be ~ 0.1-1%, i.e. less than one percent of the mechanical energy put into the sand's slide is converted to seismic energy. This process is 400 times more efficient than the conversion of mechanical energy to acoustic energy. In other words, there is 400 times more energy in the seismic signal than in the one you can hear.

The frequency of booming can be estimated by

$$\mathbf{f \sim (\lambda g/8D)^{1/2}}$$

(Bagnold 1966), where $\lambda \sim 14$, g is the local acceleration of gravity, and D is the average sand grain diameter. This predicts frequencies ~ 240 Hz, which is in the range of those observed. This was obtained using a theory involving dilation of dry sand while slumping and shearing it.

Where *Else* Might Booming Dunes Boom?
(or, The Planetary Connection)

Thousands of short-period seismic events were recorded at the Apollo 15 site. They had frequencies 2-20 Hz, and amplitudes ~ 0.6 nm. When analyzed, they were found to be of 154 distinct "types." The same types were repeated at the same time each lunar day. One hypothesis is thermally triggered landslides or slumping. However, the age of the craters involved is inconsistent with the mass moved by these slumping events. Exposure ages of crater ejecta can be used to estimate a maximum rate of erosion, and the amount of slumping indicated by seismic events is vastly higher than that.

However, booming represents a fairly efficient conversion of slumping energy to vibrational seismic energy. If these "seismic events" were actually booms, it would reduce the inferred erosion rates by 10^6-10^9, because much less material would be needed to produce those seismic signals. Booming lunar dunes would explain the regular pattern of slumping, and is also consistent with the narrow bandwidth observed. Booming requires well-sorted soil, and one Apollo 16 soil shows the necessary degree of sorting.

And if the moon... Why not on Mars? Mars is dry, and has lots of fines...

BOOMING ↓ SILENT ↓

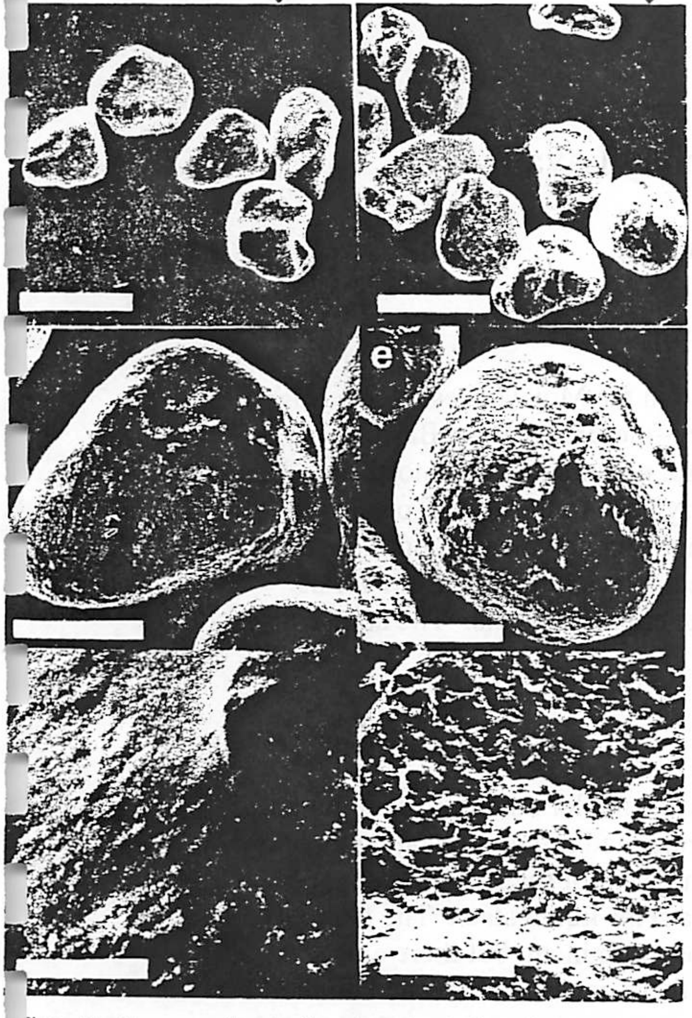

Figure 9. Quartz sand grains from booming (a through c) and silent (d through f) sand dunes. Scales on a and d, 500 μm; b and e, 200 μm; c and f, 40 μm. Note subdued surface relief of the booming sand grain in c compared to silent sand grain in f.

Lindsay et al. (1976)

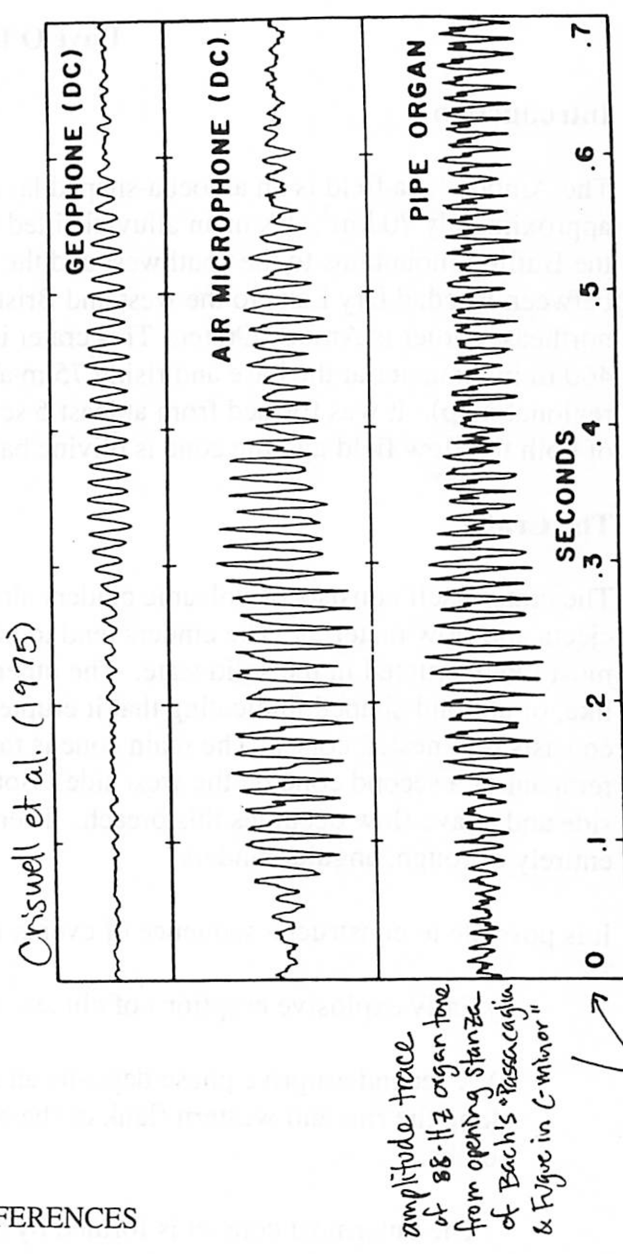

Fig. 7. Uncorrected seismic (top curve) and acoustic (middle curve) amplitude traces of event 2-1 (Figure 3) presented at high time resolution. The horizontal time scale is 0.7 s. The bottom curve is a short note from a pipe organ, as recorded on a 33⅓-rpm high-fidelity record.

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Amboy Crater and the Amboy Lava Field

Dave O'Brien

Introduction

The Amboy lava field is an amoeba-shaped lava field in the Mojave Desert covering approximately 70 km^2. It's in an alluvial-filled valley--the Bristol Lake Basin--between the Bullion mountains to the southwest and the Bristol mountains to the northeast. It lies between Bagdad Dry Lake to the west and Bristol Dry Lake to the east. Towards its northeast corner is Amboy Crater. This crater is a cinder cone volcano approximately 460 m in diameter at the base and rising 75 m above the lava field (see fig. 1 for a regional map). It was formed from at least 6 separate eruptive events. The composition of both the flow field and the cone is olivine basalt.

The Crater

The crater itself consists of volcanic cinders along with smaller amounts of agglutinated ejecta and flow material. The cinders tend to be angular and rough, indicating that they most likely erupted in the solid state. The other component of the ejecta is ropy, ribbon-like, or almond-shaped, indicating that it erupted in a semi-liquid state. The crater itself consists of 4 nested cones. The main cone is the most prominent, but there exists a remnant of a second cone on the west side. Both of these cones are breached on the west side and a lava flow occupies this breach. There are also two inner cones which consist entirely of rough, angular cinders.

It is possible to construct a sequence of events for the craters formation (fig. 2):

1) Early explosive eruptions of cinders and fluid bombs create the main cone.

2) A second eruptive phase deposits an agglutinated aggregate of basaltic rocks along the rim and western flank of the cone, probably by the eruption of pasty bombs.

3) The outermost conelet is formed by a mild explosive event

4) The two cone walls are breached on the western side by an outwardly directed explosion or by the flow that now occupies the breach.

5) An explosion creates another inner conelet.

6) Formation of the innermost conelet terminates the explosive eruption sequence

7) Subsequent eruptions, if they occur, are released from the base of the main cone.

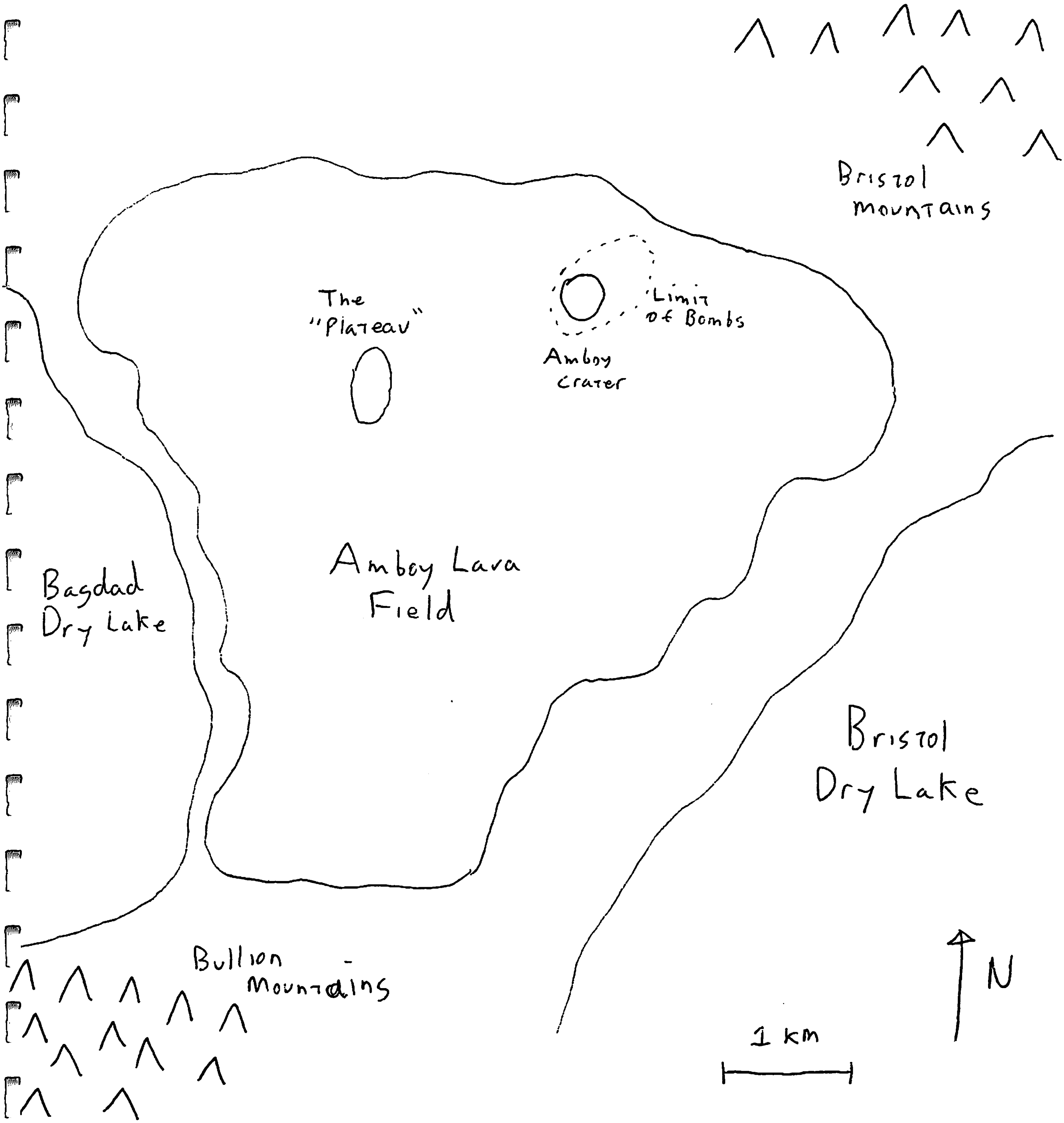

Figure 1: My attempt at a map of the Amboy lava field and the Surrounding geology (roughly to scale).

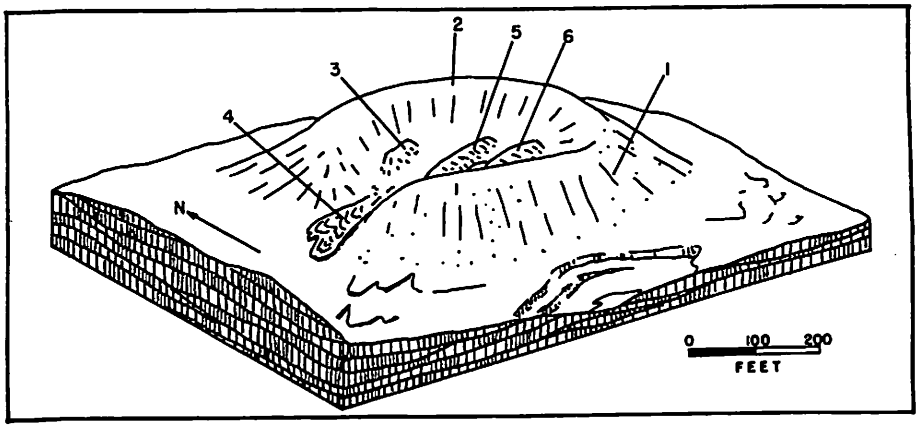

Figure 2: Stages in the development of Amboy Crater

The Lava Field

The lava field consists of many different flows, ranging in thickness form 1/2 to 5 m, which originated from multiple vents. Bombs are found in a region stretching about 1/2 km towards the northeast. Most of the flows are ropy pahoehoe, but blocky material also occurs, mainly at the snouts of some of the flows. The irregular nature of the flows and their uniform chemical composition, along with the sand which covers many parts of them, make it difficult to ascertain both the time sequence of the flows and the position of the vents from which they originate. The thickest flows occur near the crater itself and in the "Plateau" region about 2 km south-southwest of the crater, suggesting that they are the location some of the main source vents. The "Plateau" will be discussed in more detail later. The flows contain collapse features, pressure ridges, and basaltic blisters:

1) Pressure ridges (photo 8): There are dozens of features ranging from low wrinkles to large folds up to 15 m high and 50 m long. They are generally breached by a horizontal trough up to 6 m deep and 3 m wide. Their orientation is not correlated with the flow direction, suggesting that they were not formed by the convergence of two flows. They were more likely formed by the collapse of nearby lava crusts.

2) Collapse features (photo 9): These are most likely due to the drainage of lava from a large flow by secondary flows (fig. 3). Undisturbed lava tubes are not found, but their collapsed remnants are common.

3) Basaltic blisters (photo 10): There are several raised domes up to 10 m in height and 30 m across. They generally have a central depression about a meter across and one or more radial fractures. They appear to form by the inflation of a pre-existing flow from below either by intrusion or by a weak explosion (some of the basaltic blisters are somewhat disrupted in a manner consistent with explosion).

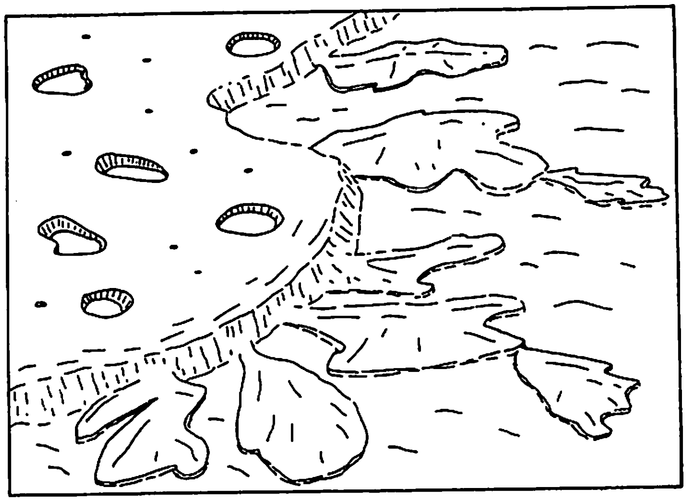

Figure 3: Flow units emerging from a parent flow, leading to Collapse depressions in the parent flow

The "Plateau" region mentioned before is about 1 km north to south and .3 km west to east. It contains two features which are not seen elsewhere (fig. 4):

1) "Jumbles" (photo 11): There are 14 piles of chaotically arranged blocks around the plateau region. They are up to 3 m high and 12 m across. The basalt blocks contain a reddish-brown alteration product containing ferric iron, which is not seen elsewhere in the flow. They tend to be concentrated in the northern part.

2) Depressions (photo 12): There are 12 bowl shaped depressions up to 80 m in diameter and 12 m in depth, some having raised rims of basaltic blocks. They tend to be concentrated in the southern part.

Both of these features seem to be explosive in origin. The two possible explanations are that the "Plateau" formed over a vent or vents which poured out a large amount of lava and produced numerous explosions. A second possibility is that lava flowed over a region of wet sand, producing explosions which caused these features. Steam would be present in either case, causing the ferrous to ferric alteration seen in the "jumbles." However, since the "Plateau" is a significant topographic high, the vent hypothesis seems more plausible than the wet sand hypothesis.

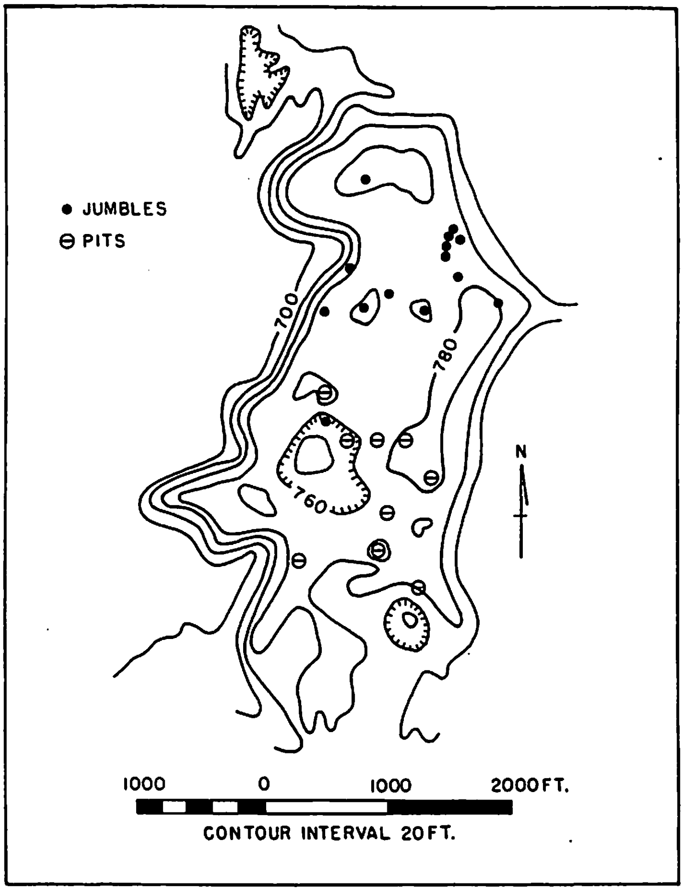

Figure 4: Map of the "Plateau" region

Age of the Volcanism

The cinders of the cone as well as the flows themselves have only been minimally affected by weathering. Cinders on the surface appear essentially the same as those less than a meter below the surface, and the flows themselves retain sharply defined features despite the abundance of wind-driven sand in the area. The end of the Tioga glaciation, the most recent stage of glaciation in California, ended approximately 6,000 years ago. If the crater and flows had formed before this, the flows would most likely be buried by a larger amount of lake bed sediment than is observed. Thus, the an upper limit for the age of the crater and flows is approximately 6,000 years.

Mars on Earth?

Numerous remote sensing instruments and rovers have been tested at the Amboy lava field both because of its (apparent) similarity to the Martian and Lunar surfaces and its proximity to JPL. Some notable examples are Mars Pathfinder's clone (the SIM rover) and the Russian-built Marsokhod rover prototype. There's probably more, and I could probably elaborate, but I stopped at these.

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This report (Parker) is the source of the figures and photographs I've included.

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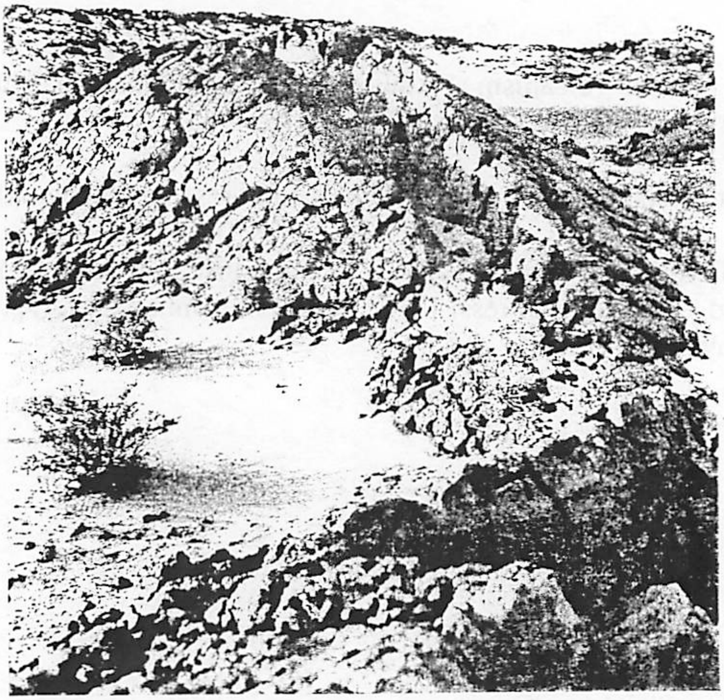


Photo 8. A breached pressure ridge. This arch was formed by the collapse of flows to either side. The figure of the man indicates the size of the ridge.

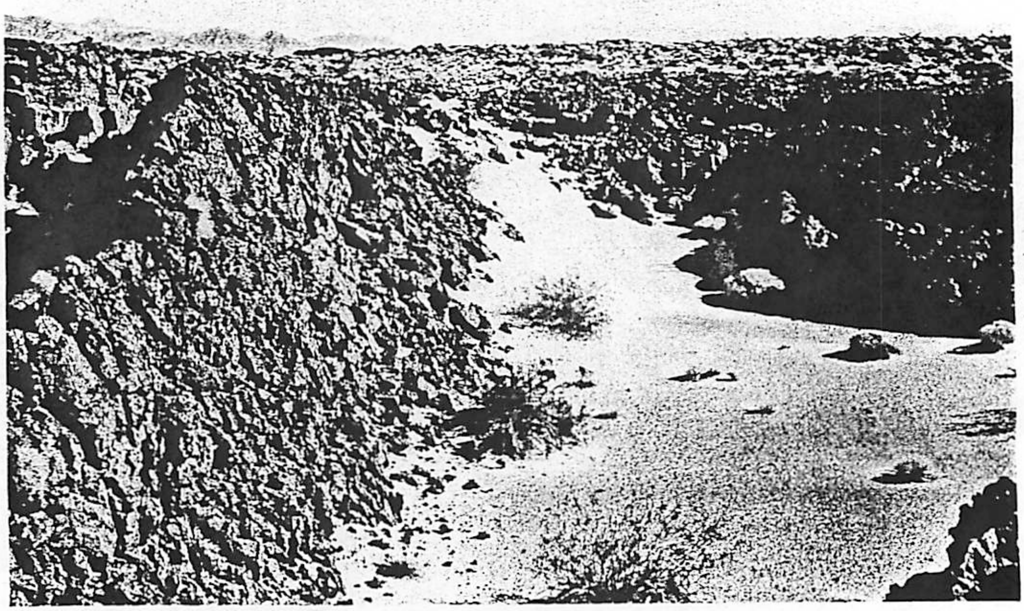


Photo 9. A collapse depression east of the cone, showing slumped lava slabs about its rim. The surface lava here solidified prior to the withdrawal of liquid lava from beneath it. The bottom of the depression is filled with drifted sand. The depression is approximately 100 feet in mean diameter.

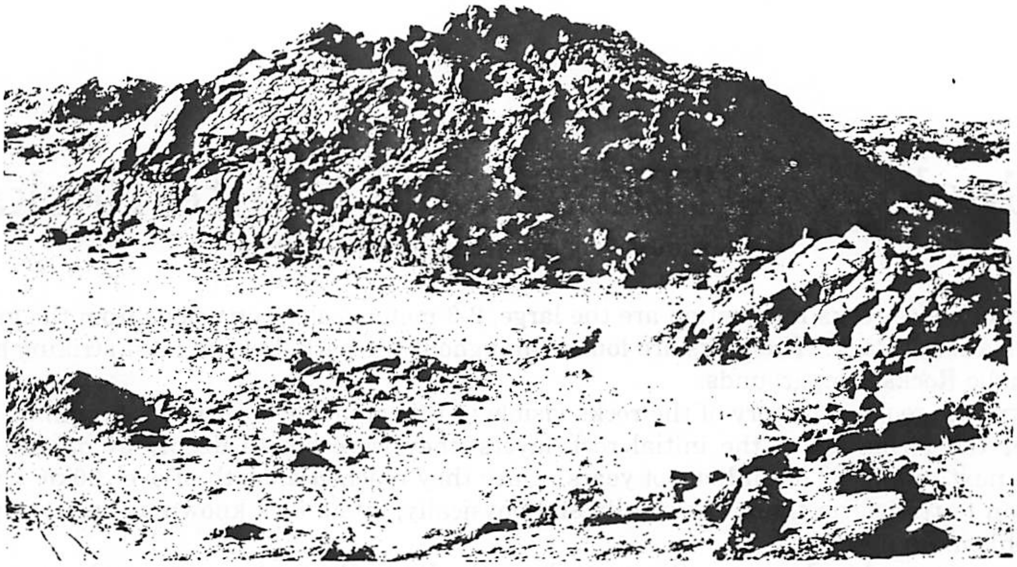


Photo 10. A large basalt blister (approximately 75 feet in basal diameter). The uplift and disruption of flows was caused by the intrusion beneath the surface of a lens-shaped laccolith of later basalt.

Photo 11. A typical jumble. The origin is ascribed to subsurface explosions that disrupted hardened lava flows.

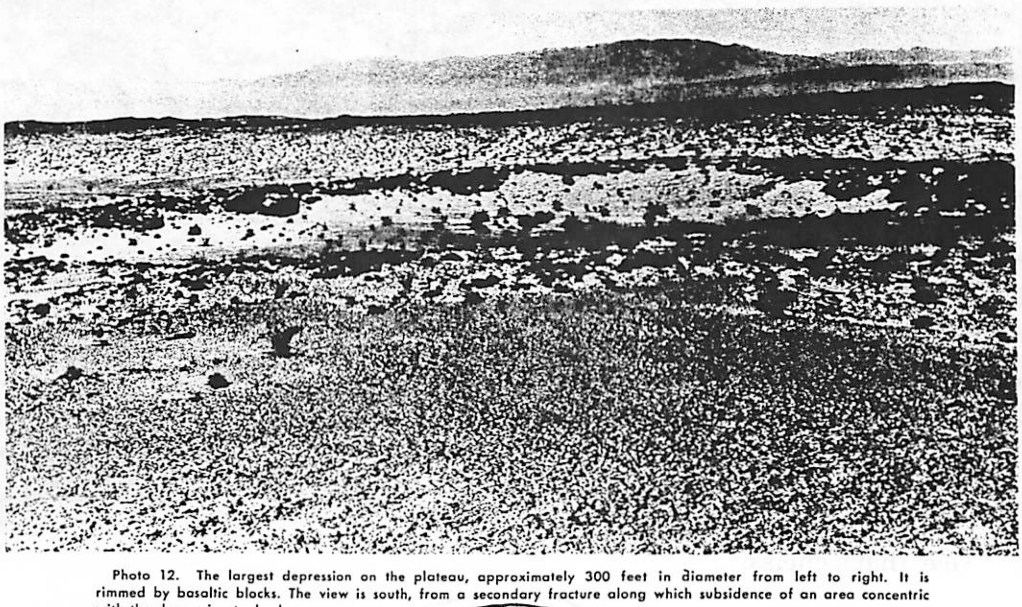


Photo 12. The largest depression on the plateau, approximately 300 feet in diameter from left to right. It is rimmed by basaltic blocks. The view is south, from a secondary fracture along which subsidence of an area concentric with the depression took place.

Geology of "Those Cool White Rocks"

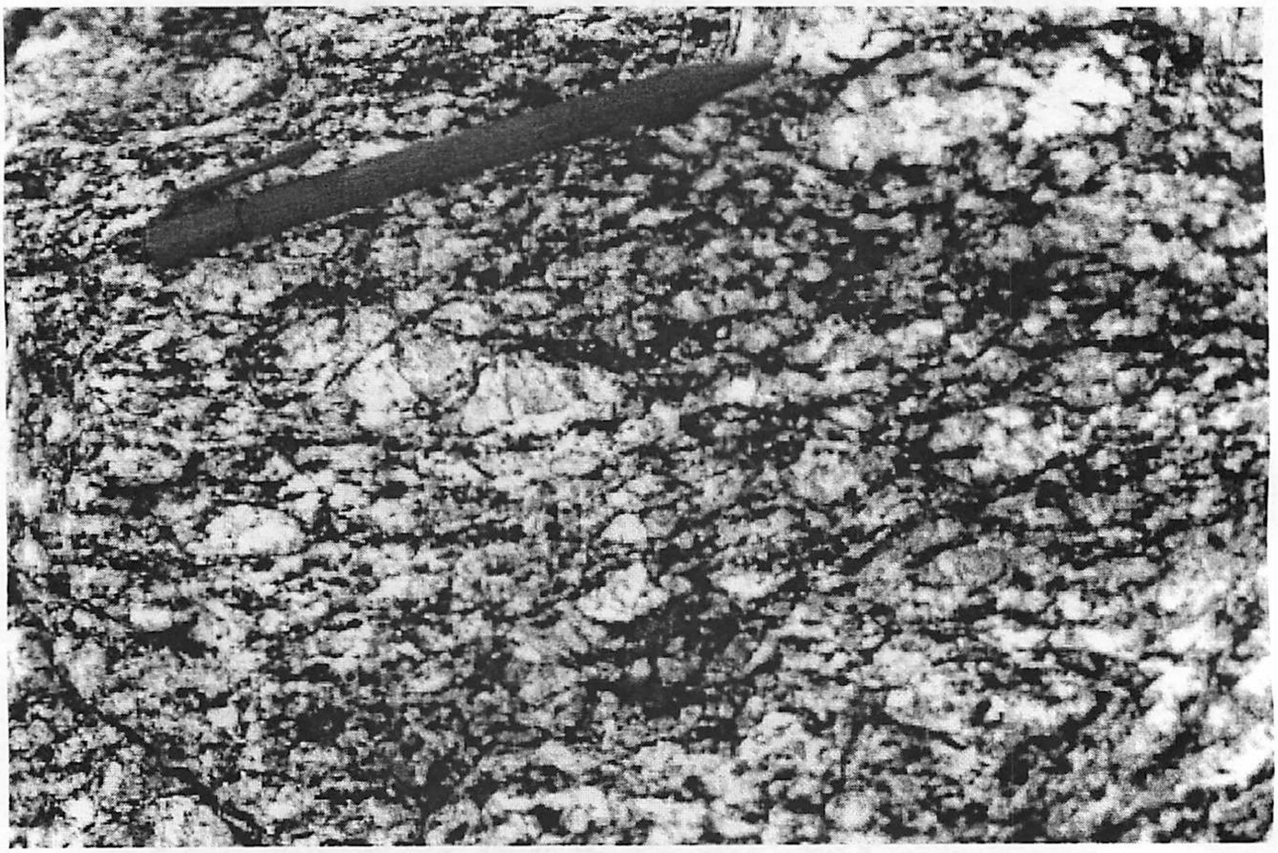
an exhaustively researched report by Jason

The cool white rocks in question are the large, 2-3 meter scale protrusions from the ground found in Joshua Tree National Park. The rocks are found throughout the park, but are most striking near the White Tank and Jumbo Rocks campgrounds.

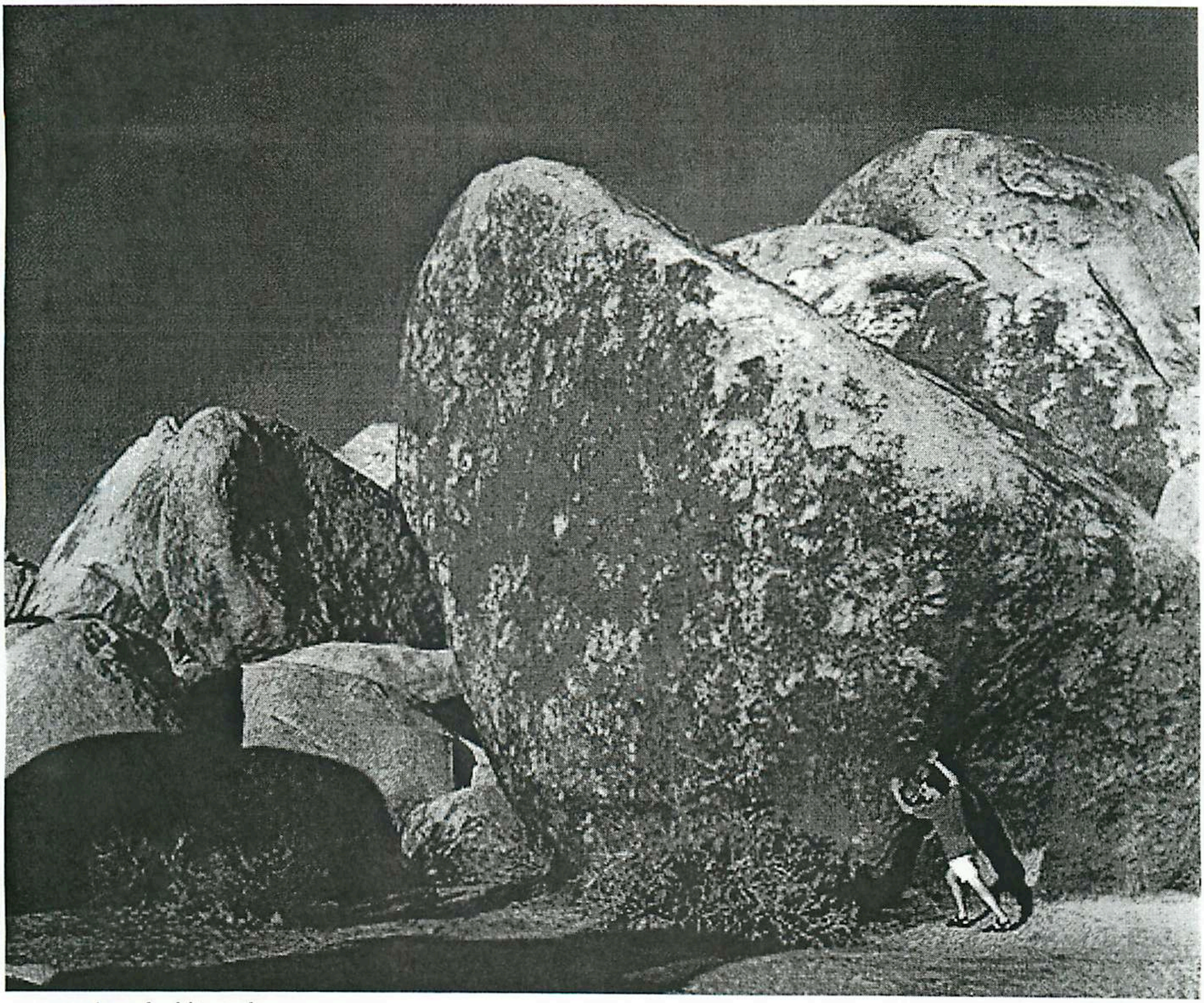
The known geologic history of the rocks visible in this area starts with the 1.5 billion year old Pinto Gneiss. After the formation of the initial rock layers, they were buried deeply by other layers over the course of the next hundreds of millions of years. Once they reached a depth of over 30km (!), the heat and pressure began to transform them, chemically and physically, into a rock known as *gneiss*, a process known as metamorphism.

Subsequent to this, however, the area above the Pinto Gneiss began to erode away, reducing the pressure from rocks above and raising the relative depth of the gneiss layer. 150 million years ago, molten magma was intruded into the gneiss at a depth of 20 km. The intruded material cooled very slowly at depth, creating large crystals in the new rock, called the White Tank Monzogranite. After the intrusive event, extensive erosion continued, erasing all geologic record of the conditions at the surface between 1.5 billion years ago and today.

Once the layer of gneiss with intruded granite was reached, differential erosion between the more cohesive gneiss and the more easily eroded monzogranite. The mountains on the western edge of the park are composed of the darker gneiss, while in this area the granite eroded more quickly. Horizontal cracks in the cool white rocks were formed when the pressure of overlying rocks was reduced, allowing the granite to expand in the vertical direction. The edges and corners of the rock are rounded as a result of *spherical weathering*.



Gee, that's gneiss.


A cool white rock