Canyonlands, 2nd Edition

Planetary Geology Field Practicum - PTYS 594A
September 8-12, 2004

pictures provided by National Park Service; top: arch and buttes, bottom: microbial mats

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Planetary Geology Field Practicum
PTYS 594a
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Presentations, cont.

Late Additions to Reference at the back:

PTYS 594a,
PLANETARY FIELD GEOLOGY PRACTICUM

Fall 2004 Canyonlands Itinerary

Wednesday, 8 September

8:00 am — Depart LPL loading dock. Drive North on Cherry to Speedway, proceed West to I-10, drive North towards Phoenix. In Phoenix take I-17 North to Flagstaff. **Celinda Marsh** will update us on the Basin and Range tectonic style at the Sunset Point overlook. At Flagstaff, exit to I-40 East, then proceed to Exit 201. Drive North to intersection with Route 89, then continue North toward Page.

12:30 pm — Stop for lunch at Sunset/Wupatki national monument. Pull out on road to O'Leary peak, just before monument entrance.

2:00 pm — Continue North on Rte. 89 to junction with Rte. 160. Turn right onto Rte. 160 and drive toward Kayenta. Possible stop at Tuba City to view dinosaur footprints, lead by **Jade Bond**. At Kayenta proceed North on Rte. 163 toward Monument Valley.

4:00 pm — Stop on Rte. 163 near Agathla Peak where **Colin Dundas** will describe the diatremes of Monument Valley.

4:30 pm — Proceed North on Rte. 163 through Monument Valley. Stop at Navajo Visitor center, where **John Moores** will describe the origin and weathering of the sandstone we will be seeing so much of, and **Stephanie Campbell** will discuss the formation of Buttes and Arches.

5:00 pm — Continue North on Rte. 163 to Mexican Hat on the San Juan River. Turn left onto Rte. 261 for 1.5 miles, then left again onto Rte. 316 to overlook the Goosenecks of the San Juan. **Kelly Kolb** will discuss river incision at this inspiring overlook.

6:30 pm — Camp in vicinity of the Goosenecks and the Valley of the Gods. **Brian Jackson** will give a fireside chat on the history of geologic exploration of the Colorado Plateau.

Thursday, 9 September

7:30 am — Break camp, return to Rte. 163. Stop at overlook of Comb Ridge, where **Jani Radabaugh** will describe this and other folds and monoclines of the Colorado Plateau. At Bluff, proceed North on Rte. 191.

9:30 am — Stop in the vicinity of Recapture Reservoir. Admire the (possibly snow-covered) Abajo mountains to the North. **Nicole Baugh** and **Eileen Chollet** will explain how they, and many other similar mountains in this region, form. At this location **Mike Bland** will acquaint us with the geologic history of SE Utah.

10:30 am — Continue North on Rte. 191 toward Monticello.

11:00 am — Stop South of Monticello. **Dave O'Brien** will electrify us with the hair-raising history of the atomic exploitation of this beautiful but deeply polluted countryside.

12:00 — Lunch stop in the vicinity of the Church Rock turnoff.

1:00 pm — Drive West on Rte. 211. Stop at Newspaper rock where **David Choi** will interpret the elaborate hieroglyphics of ancient American Indians.

1:30 pm Continue West on Rte. 211 to Needles district park headquarters. Stop to view displays, then listen to **John Keller** describe how the evaporites beneath our feet developed. Return East on Rte. 211.

4:00 pm Turn off on Beef Basin dirt road and proceed West 30 miles to campsite near the Ruins. Note that this is the beginning of our extreme 4WD transit. Care in driving is a must!

5:00 pm Camp near the Ruins. **Curtis Cooper** will describe the history of National Parks in SE Utah after dinner.

Friday, 10 September

7:30 am Break camp, drive North into Canyonlands park. Stop at Joint Trail.

8:30 am **Tamara Goldin** will explain the many theories that have been proposed to explain how rocks acquire joints like the ones we observe here. Hike 1.5 miles through vertically jointed sandstones, return by same route.

11:30 am Rejoin vehicles, eat lunch

12:30 pm Continue (if road conditions permit: if not, several other options will be explored) over SOB hill and proceed North down Devil's lane "road" to Red Lake Canyon trailhead. Hike to top of horst to overlook grabens to West. At this inspiring site we will discuss the formation of these grabens: **Mandy Proctor** will acquaint us with the mechanics of how these interesting structures form in the first place, **John Weirich** and **Yuan Lian** will discuss the specific aspects of graben formation here at Canyonlands, and **Maki Hattori** will discuss the planetary connection with grabens on Mars and elsewhere. Finally, **Moses Milazzo** will describe how grabens may form over dikes.

3:00 pm Continue North over the Silver Stairs to the overlook of the confluence of the Green and Colorado Rivers. Observe the Meander Anticline at river level and consider the mechanics of how the Canyonlands grabens formed.

4:00 pm Return South through Devil's Lane, down the Silver Stairs, and over SOB hill and return to the Ruins campsite in Beef Basin.

6:00 pm Camp near the Ruins site. **Miguel de Pablo** will make a fireside presentation on his Spanish dissertation topic, Geomorphology and hydrology of the Atlantis basin, Sirenum Terrae, Mars.

Saturday, 11 September

7:00 am Break camp, return to Rte. 211, proceed East to Rte. 191. Turn North toward Moab.

10:30 am Stop south of Moab in Spanish Valley, where **Carl Hergenrother** will discuss its formation as a consequence of salt tectonics. **Gwen Barnes** will discuss cliff recession by landslides and **Jim Richardson** will explain mathematical models of scarp modification.

12:00 Lunch under the trees in the public park in downtown Moab.

1:00 pm Continue NW on Rte. 191 to its junction with Rte. 313. Proceed South on Rte. 313 to the Upheaval Dome overlook.

2:30 pm Arrive at the Upheaval Dome overlook. Before we hike up the short trail, **Catherine Neish** will describe the lives of the microbes that form the ubiquitous soil encrustations near the parking lot. Hike up the trail to Upheaval Dome. Ooh and Aah over the view, then listen to presentations by **Jade Bond, Oleg Abramov** and **Brandon Preblich** on the debate over its origin. **Abby Sheffer** will discuss whether or not impact-metamorphosed rocks have been found at this site.

4:00 pm Depart Upheaval Dome, proceed North. Make a short stop near the junction with Rte. 191 where **Jason Barnes** will describe the Hematite concretions found in the Navajo Sandstone near this location, and their relevance to the similar concretions found on Mars. Proceed South on Rte. 191 through Moab, then South past Blanding.

6:30 pm Camp at "Jurassic Park" off Butlers Wash Road on Rte 191, 8 miles North of Bluff.

Sunday, 12 September

7:00 am Break camp, continue South on 191. Reverse route through Kayenta, Flagstaff, Phoenix to Tucson.

5:00 pm Arrive Tucson, unpack and clean vehicles, go home.

Primary Drivers: Barnes, Beyer, Bland, Bond, Goldin, Milazzo, O'Brien, Proctor.

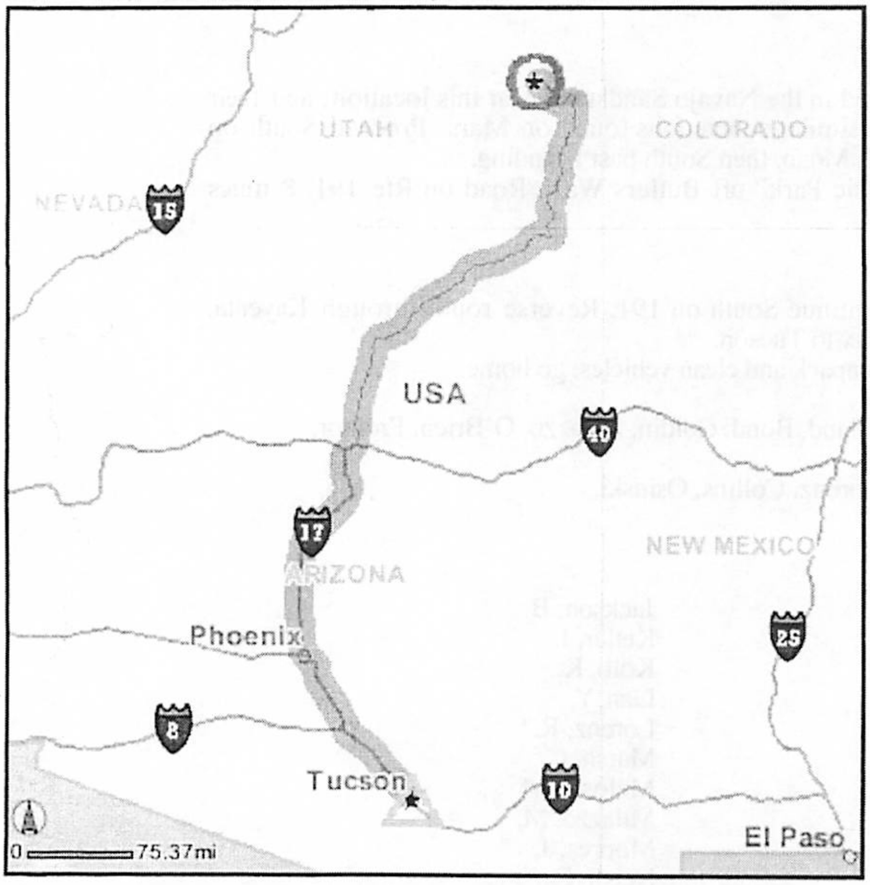
Faculty Co-Leaders: Showman, Lorenz, Collins, Osinski.

Participants:

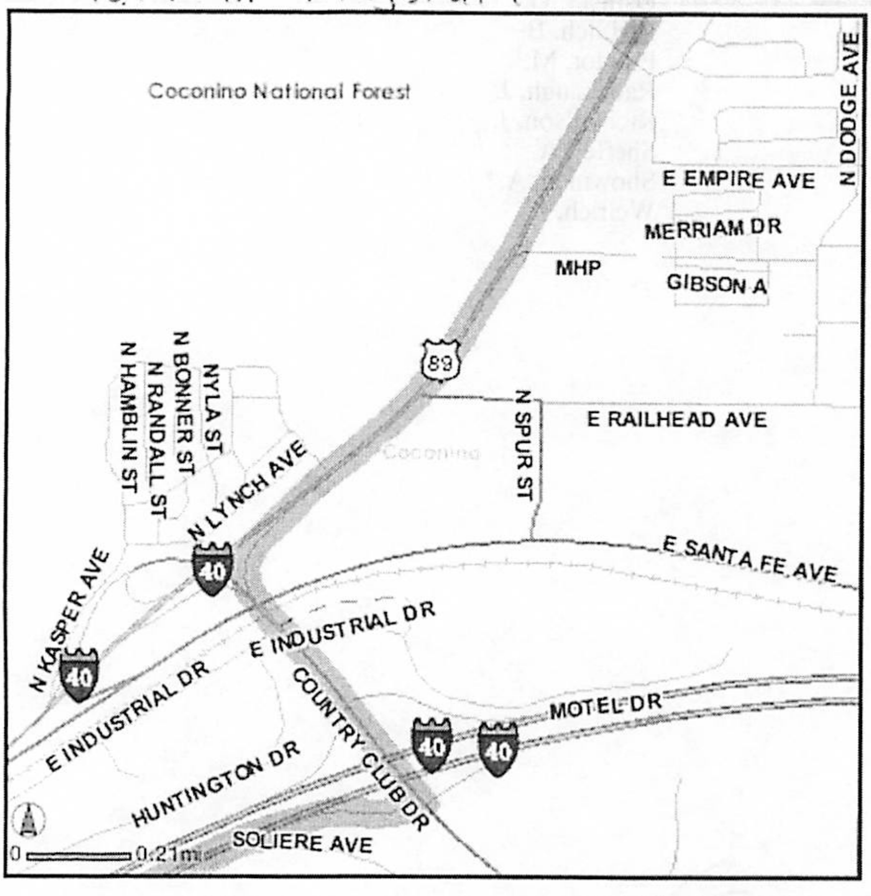
Abramov, O.
Archer, P.
Barnes, G.
Barnes, J.
Baugh, N.
Beyer, R.
Bland, M.
Bond, J.
Campbell, S.
Choi, D.
Chollet, E.
Collins, G.*
Cooper, C.
de Pablo, M.
Dundas, C.
Goldin, T.
Hattori, M.
Hergenrother, C.
Jackson, B.
Keller, J.
Kolb, K.
Lian, Y.
Lorenz, R.*
Marsh, C.
Melosh, J.*
Milazzo, M.
Moores, J.
Neish, C.
O'Brien, D.
Osinski, G.*
Preblich. B.
Proctor, M.
Radebaugh, J.
Richardson, J.
Sheffer, A.
Showman, A.*
Weirich, J.

Canyonlands, Fall 2004

Overview Map

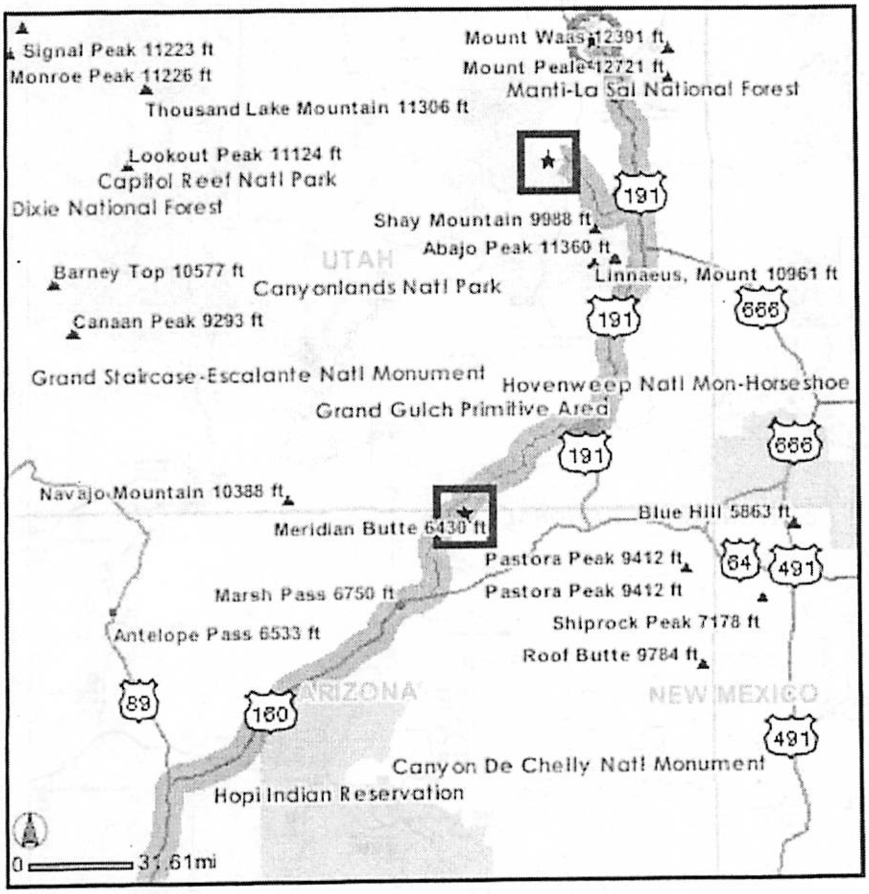


Turnoff in Flagstaff



Canyonlands, Fall 2004

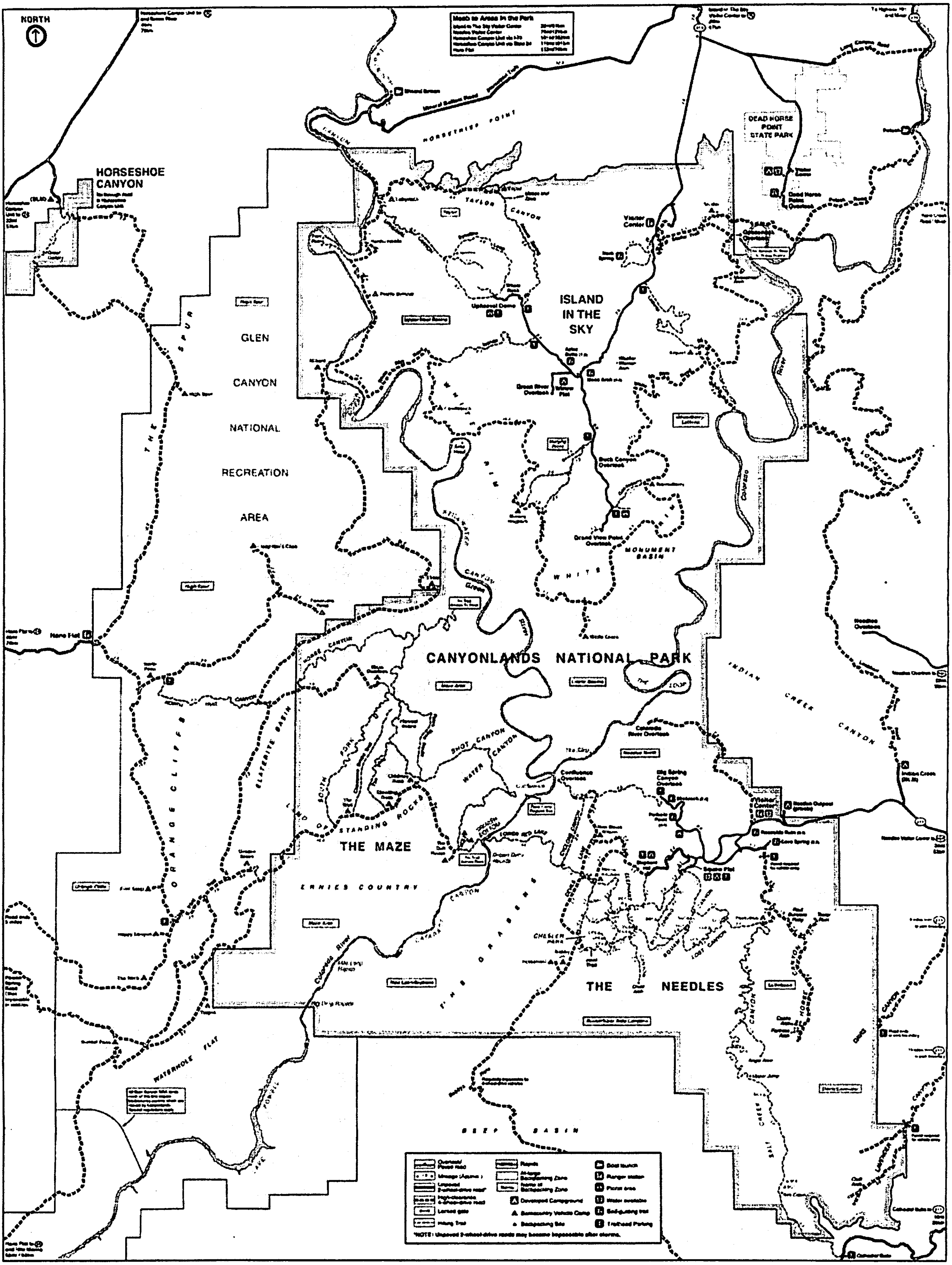
4 Corners Detail



S □ = Monument Valley on Rte. 163

N □ = Canyonlands, Needles District on Rte. 211

O = Moab, UT


NORTH
HORSESHOE CANYON
DEAD HORSE POINT STATE PARK
TAYLOR CANYON
Visitor Center
ISLAND IN THE SKY
Upheaval Dome
THE SPUR
GLEN CANYON NATIONAL RECREATION AREA
WHITE RIM
Grand View Point Overlook
MONUMENT BASIN
CANYONLANDS NATIONAL PARK
INDIAN CREEK CANYON
HORSE CANYON
SHOT CANYON
WATER CANYON
SOUTH FORK
ORANGE CLIFFS
LAND OF STANDING ROCKS
Confluence Overlook
THE MAZE
ERNIES COUNTRY
Squaw Flat
THE GRABENS
THE NEEDLES
WATERHOLE FLAT
BEEF BASIN

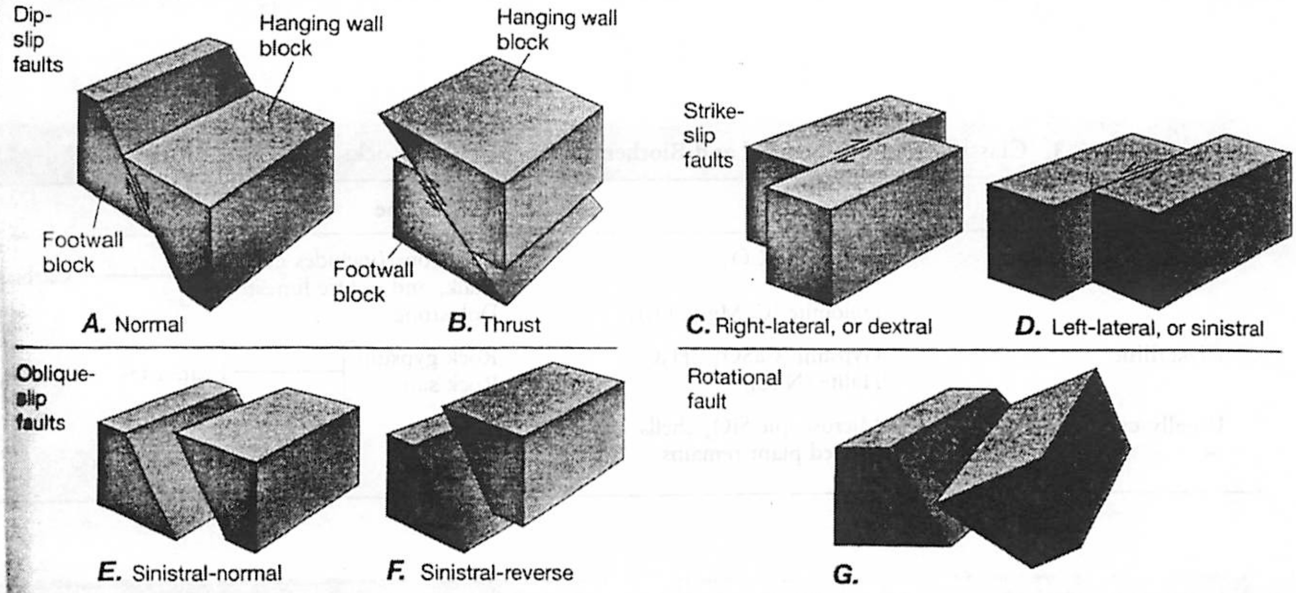


Figure 4.3 Faulted blocks showing the characteristic displacement for the different classes of faults.

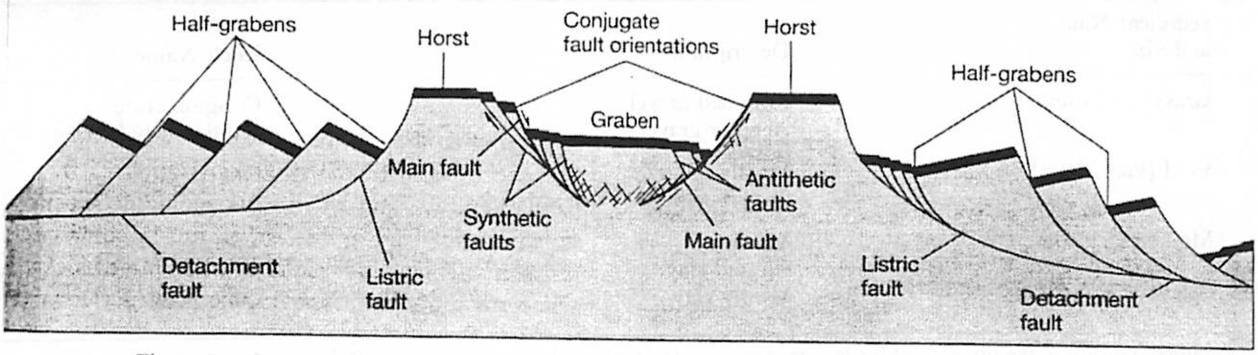


Figure 5.4 Systems of normal faults commonly are characterized by a main fault with associated subsidiary faults and by low-angle detachment faults with imbricate fault blocks in the hanging wall block.

Table 4.1 Fault Rock Terminology[a]

Cataclastic rocks					
Fabric	Texture	Name		Clasts	Matrix
Generally no preferred orientations	Cataclastic: sharp, angular fragments	Breccia series	Megabreccia	> 0.5 m	<30%
			Breccia	1–500 mm	<30%
			Microbreccia	<1 mm	<30%
		Gouge		<0.1 mm	<30%
		Cataclasite		Generally ≤ ~10 mm	>30%
		Pseudotachylite			Glass, or grain size ≤1 μm

Mylonitic rocks					
Fabric	Texture	Name		Matrix grain size	Matrix
Foliated and lineated	Metamorphic: Interlocking grain boundaries, sutured to polygonal	Mylonitic gneiss		>50 μm	
		Mylonite series	Protomylonite	<50 μm	<50%
			Mylonite	<50 μm	50%–90%
			Ultramylonite	<10 μm	>90%

[a] The terminology applied to fault rocks is by no means generally agreed upon. The definitions of the different categories, and the quantitative boundaries we have placed on them, should therefore be understood as guidelines to present usage, which can vary from one geologist to another. We believe, for example, that what we have defined as mylonite would fit anyone's definition, but other geologists use *mylonite* in a broader sense, even to include what we call mylonitic gneiss.

Structural Geology (1992) Twiss + Moores

TABLE 7-3 Classification of Chemical and Biochemical Sedimentary Rocks

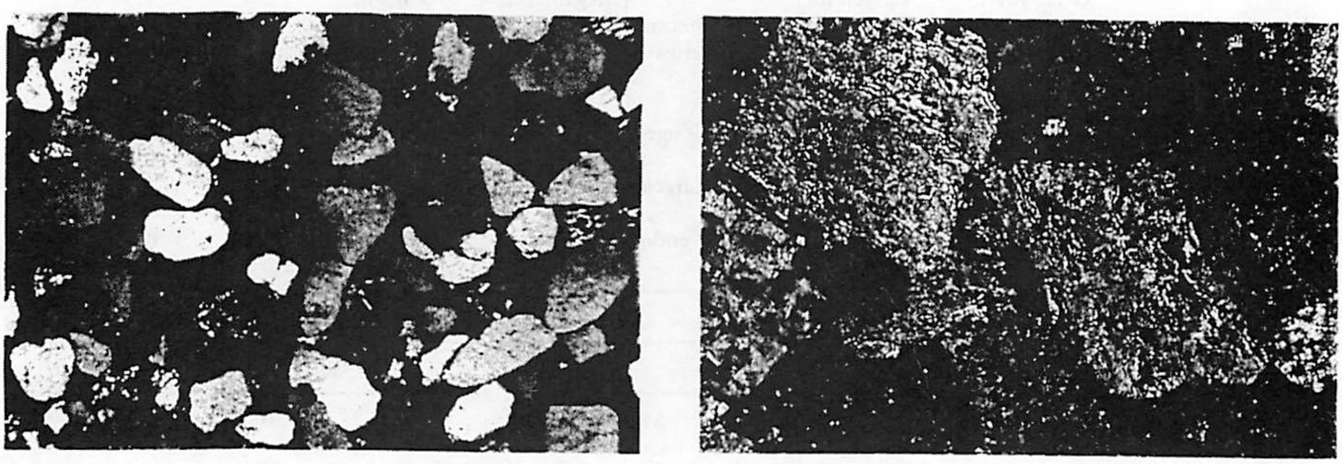
Texture	Composition	Rock Name	
Clastic or crystalline	Calcite ($CaCO_3$)	Limestone (includes coquina, chalk, and oolitic limestone)	Carbonates
	Dolomite [$CaMg(CO_3)_2$]	Dolostone	Carbonates
Crystalline	Gypsum ($CaSO_4 \cdot 2H_2O$)	Rock gypsum	Evaporites
	Halite (NaCl)	Rock salt	Evaporites
Usually crystalline	Microscopic SiO_2 shells	Chert	
—	Altered plant remains	Coal	

TABLE 7-2 Classification of Detrital Sedimentary Rocks

Sediment Name and Size	Description	Rock Name	
Gravel (>2 mm)	Rounded gravel	Conglomerate	
	Angular gravel	Sedimentary breccia	
Sand (1/16–2 mm)	Mostly quartz	Quartz sandstone	
	Quartz with >25% feldspar	Arkose	
Mud (<1/16 mm)	Mostly silt	Siltstone	Mudrocks
	Silt and clay	Mudstone*	Mudrocks
	Mostly clay	Claystone*	Mudrocks

*Mudrocks possessing the property of fissility, meaning they break along closely spaced, parallel planes, are commonly called *shale*.

FIGURE 7-9 (*a*) Photomicrograph of a sandstone showing a clastic texture consisting of fragments of minerals, mostly quartz in this case. (*b*) Photomicrograph of the crystalline texture of a limestone showing a mosaic of calcite crystals.



(a) (b)

Physical Geology
Monroe + Wicander (1992)

Uniform Time Scale	
0	
	PHANEROZOIC
575	
	PRECAMBRIAN
~4,650	

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

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

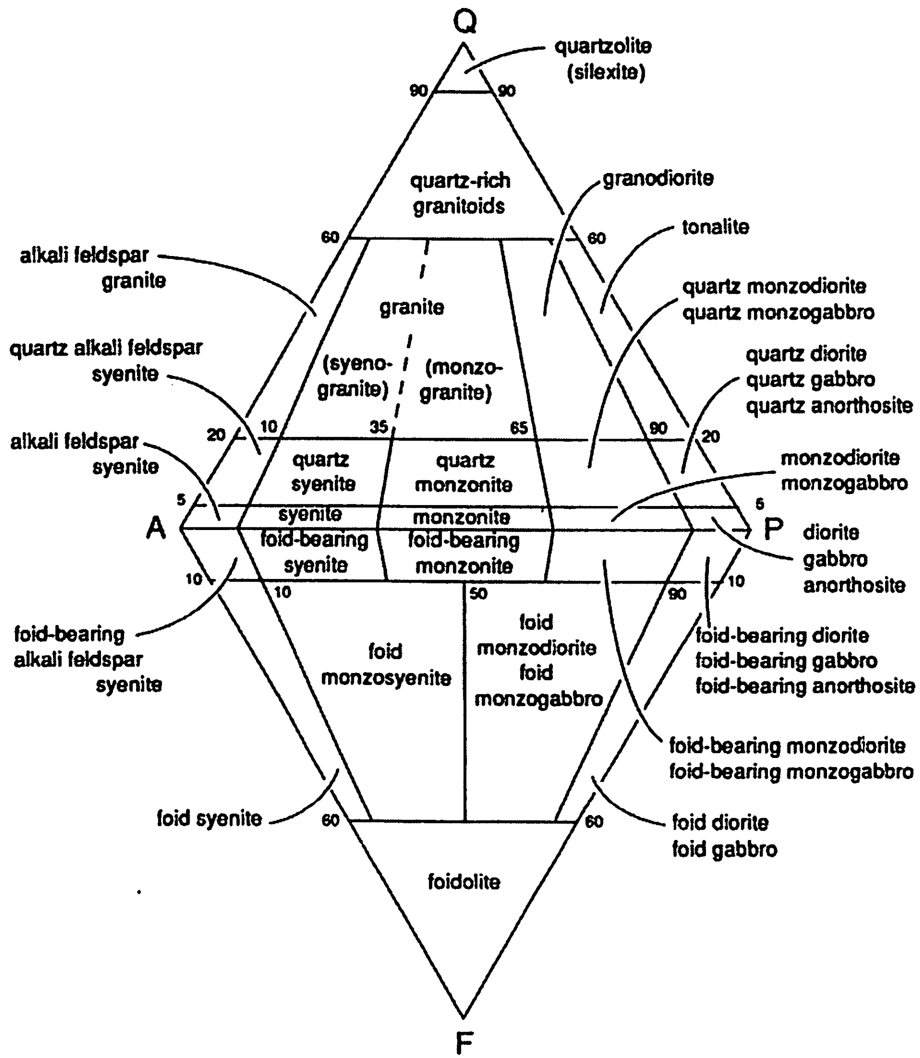


Fig. B.4. Classification and nomenclature of plutonic rocks according to their modal mineral contents using the QAPF diagram (based on Streckeisen, 1976, Fig. 1a). The corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid. However, for more detailed 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%.

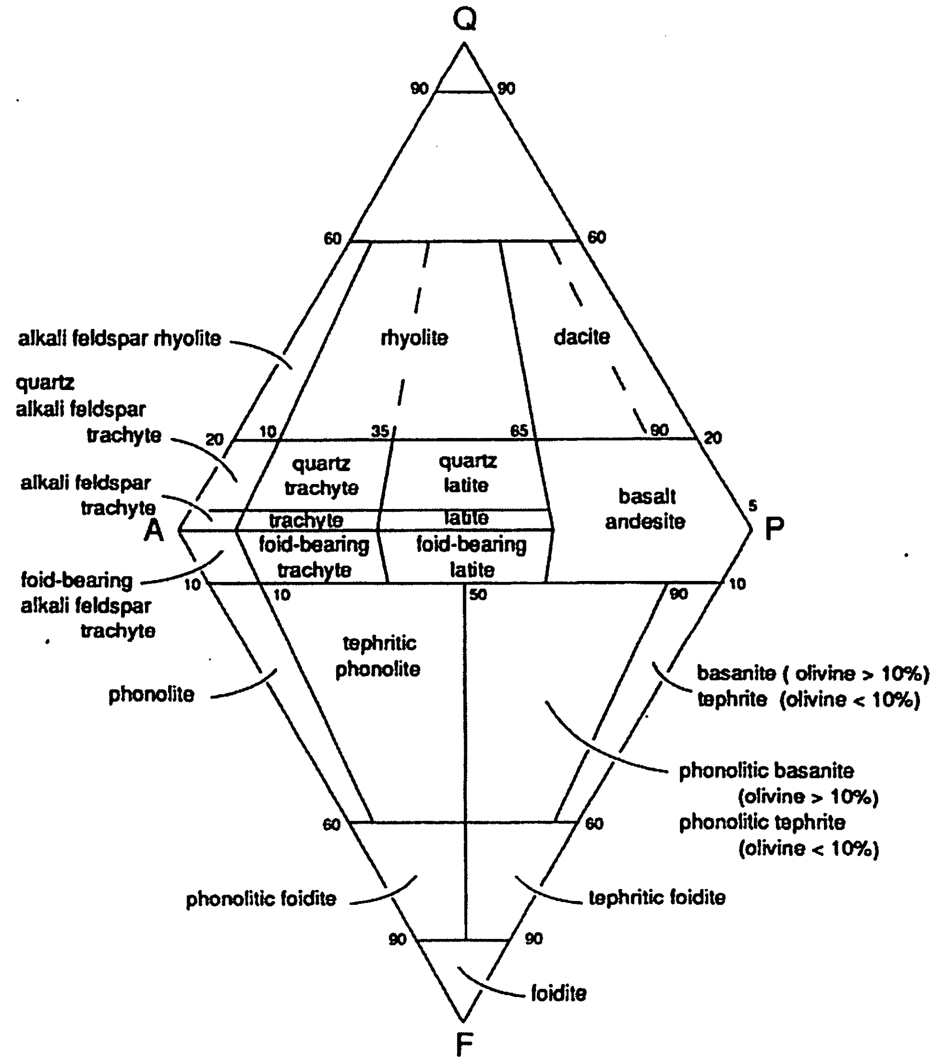


Fig. B.10. Classification and nomenclature of volcanic rocks according to their modal mineral contents using the QAPF diagram (based on Streckeisen, 1978, Fig. 1). The corners of the double triangle are Q = quartz, A = alkali feldspar, P = plagioclase and F = feldspathoid. However, for more detailed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

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

(10)

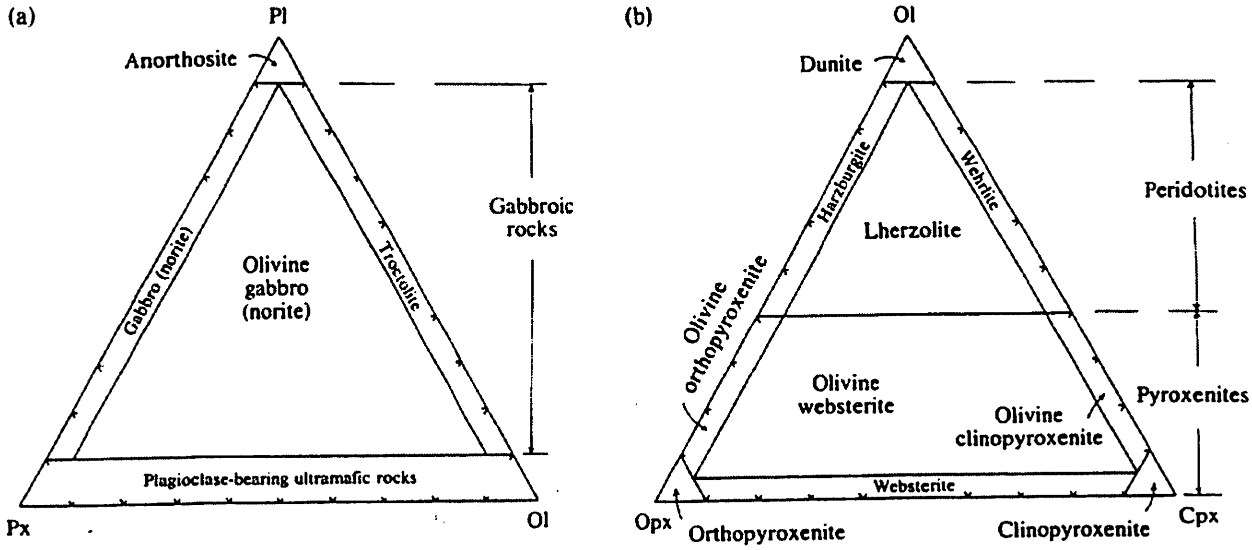
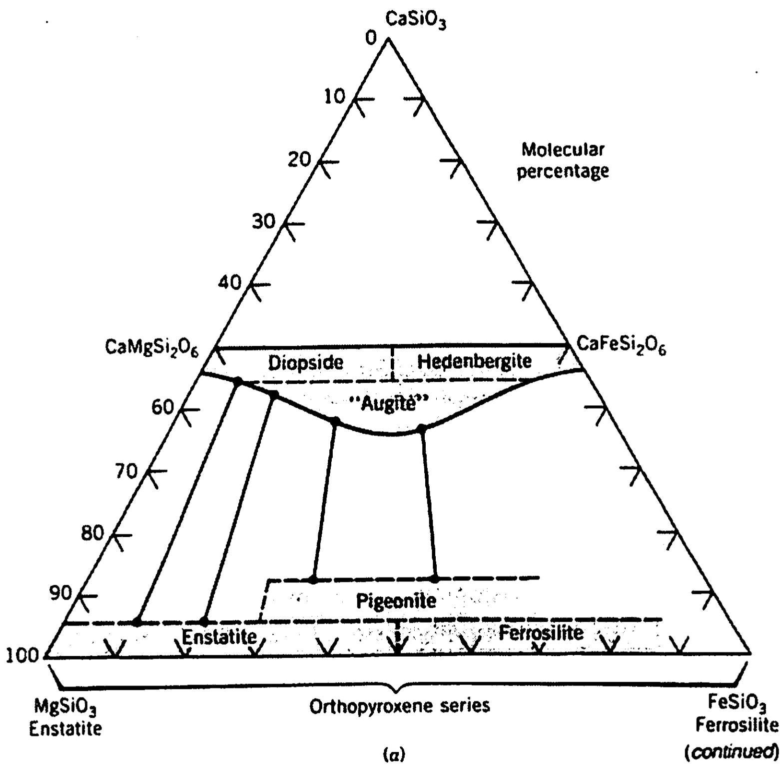


Figure 5-26 Classification of phaneritic rocks comprised of some combination of plagioclase, olivine, and pyroxene. (a) Rocks with major amounts of plagioclase (usually labradorite–bytownite). The field of gabbro is large and modifying prefixes are helpful, such as feldspathic gabbro, leuco-gabbro, olivine-rich gabbro, and so on. Gabbro in which the pyroxene is principally orthopyroxene can be called norite. (b) Classification of ultramafic phaneritic rocks comprised of olivine and pyroxenes. [After A. Streckeisen, 1979, Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites, and melilitic rocks: Recommendations and suggestions of the IUGS Subcommission on the Systematics of Igneous Rocks, *Geology* 7.]

Best, "Igneous + Metamorphic Petrology"

FIG. 13.47. *(a)* Pyroxene compositions in the system $CaSiO_3$-$MgSiO_3$-$FeSiO_3$. General compositional fields are outlined. Representative tielines across the miscibility gap between augite and more Mg-Fe-rich pyroxenes are shown. The "augite" field is labeled with quotation marks because all augite compositions contain considerable Al which is not considered in this triangular composition diagram.



Klein + Hurlbut, "Manual of Mineralogy"

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 & The Early Solar System" Kerridge & Matthews, ed.
U of A Press (1988)

Preface
to the
1st Edition
Spring 1999

Editor's Introduction

Gentle Readers,

In the course of perusing the last few handout volumes to decide whether the usual ancillary information is useful, I noticed editorial prefaces have begun to appear. So, I figured I'd take advantage of that. Since I won't be joining you for this trip, this is the only chance I have for a pointless ramble.

The handout volumes have changed greatly over the years since the first one was put together (Mike Nolan for the first Canyon de Chelly trip, Spring 1992). That one was sorta stapled together, with the cover barely hanging on. You could perhaps view my efforts here as "getting back to the roots". Or not. The cover won't be too fancy, and I may or may not number the pages. Sorry about how lame the Arizona/Utah maps are.

This trip will be the first with a Utahn destination in the post-ad-hoc era (not counting our stop in Salt Lake City on the Yellowstone trip, with David Trilling led some improvised aerial geology on the way in). These trips have now visited seven U. S. states (Arizona, California, Nevada, Utah, New Mexico, Texas, and Wyoming– we just missed Idaho), and Baja California (Sonora has been visited on Surfaces trips). Ten national parks have been visited, or at least skirted (Chiracahua, Grand Canyon, Petrified Forest, Canyon de Chelly, Guadalupe Mountains, Carlsbad Caverns, White Sands, Yellowstone, Joshua Tree, and the Channel Islands), not counting those on Surfaces trips (Organ Pipe, Sunset Crater, Pinacate of Mexico), or the three on the current itinerary (Natural Bridges, Canyonlands and Arches– maybe I should send my NPS passport along). As can be seen from the map on the next page, we've covered a lot of ground over the years, and the frontier of unvisited territory is being pushed outward to perhaps the southwest corner of Colorado/northern New Mexico in one direction, Zion/Bryce to the north/northwest, and perhaps Death Valley to the west. Of course, some areas haven't been visited in five or more years (inland Southern California/Joshua Tree, Superstitions, Grand Canyon).

Well, this ramble isn't nearly as long as I'd hoped. It was pointless, at least. Quaff a beer for me at the campfire on the first night. Enjoy the stars and the rocks.

Andrew Rivkin, ed.

Preface to the 2nd Edition

Fellow Students,

As I was looking over the last Canyonlands handbook, the editorial preface caught my eye, and I decided to revive the tradition, if only for this semester. The handout volumes have continued to change and evolve with time. There was the self-binding phase, the computer-intensive pdf phase, and my own editorial reign of benign neglect and Fast Copy. We've gone through the supply of classic Blue and Red covers and started using more color and graphics. Indeed, things have changed so much that the current generation of students can only wonder at what it would be like to participate in a field trip without a handbook, or the blessing/curse of University provided Excursions paid for by course registration fees and a generous department.

With this return to Canyonlands, we will have revisited all the Southwestern and Mexican states (Arizona, Utah, Nevada, California, New Mexico, Texas; Sonora) visited prior to the 1st Canyonlands. We've added Washington and a jaunt into Oregon on our Columbia River trip. The "unvisited territory" of Southwest Colorado was explored for the sake of K/T boundary deposits. We've been to the lowest point in North America in Death Valley, too. All this makes for a total of ten U.S. states visited by students on the Planetary Sciences Field Practicum.

Will this be the limit of our exploration? Certainly not. Surely there are planetary analogues in other states (Chihuahua, Idaho, Hawaii), at other altitudes (highest point in N.A. anyone?), and even in our own backyard that we haven't noticed before.

Like Andy before me, all my pointless rambling comes down to one simple piece of advice. Enjoy the stars and the rocks.

--Celinda Marsh, ed.

Basin and Range

By Celinda Marsh

What is the Basin and Range? The Basin and Range is a geologic province covering 10 % of the land area of North America, including all of Nevada, most of Arizona, and significant portions of Utah, California, and New Mexico (see Fig. 1). The region contains a series of ranges trending roughly north-south that are roughly 100 km long and ~15 km wide. The sediment filled basins that lie in between are of roughly the same size and orientation. The mountains are 1-3 km higher that the basins around them.

There are normal faults running north-south that have caused the majority of this topography. Transverse faults running generally east-west keep the basins and ranges to their roughtly 100 km length. With the exception of the East African rift system, this region has the highest continental heat flow on the Earth, which along with the abundant faults drives active hydrothermal systems. The lithosphere is very thin in this region, indicating that the lower regions of the crust are actually ductile from partial melting. The upper mantle below the Basin and Range is a region with anomalously slow seismic velocities. Once you tally up all the differences it is easy to see that the Basin and Range is a very unique region.

Why did the Basin and Range form? The easy answer is extension. The crust in the Basin and Range Province has expanded to cover over twice(!) the area it did prior to extension. The difficult part is why did it expand?

In the past there were massive compressional forces acting on the western edge of the North American continent. These compressional forces caused the Rockies to be formed (in the Laramide Orogeny), and earlier mountain ranges. They were due, in part to the fact that the Pacific plate used to be subducting underneath the North American plate. There is evidence that the Pacific plate was moving very shallowly underneath North America, until around the time that subduction stopped. The theory is that the hot mantle material rushed in underneath the North American crust. This made the crust itself hot and more buoyant, pushing it upward, about the same time that there was a void formed by the oblique movement of the San Andreas fault system to the west (also began as the subduction of the Pacific plate ended).

When did this extension happen? At the end of subduction of the Pacific plate. Oh, you want a number? The earliest evidence is from ~30 Ma, with things not really getting moving until 19-17 Ma. Take a look at the outstanding events listed during the Tertiary on the Geologic time scale (p. 9). There are still active faults in Nevada and western Utah, although everything has calmed down in the Southern Basin and Range (Arizona).

This is pretty recently on the geologic time scale, which opens up an interesting point when we think about planetary connections. Mars has been tectonically inactive for a pretty long time (4+Ga). If there had been a region with regular topography like the Basin and Range, it might have been obliterated by impacts by this point. Same goes for the Moon. However, we do see evidence of large extensional features on Mars (Valles Marinares). I'll leave as an exercise for the reader: What could we learn from the Basin and Range that would help us understand extension on other planets?

References:

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Fig. 1 & 3: Twiss and Moores (1992) Structural Geology

Fig. 2&4: Monroe and Wicander (1992) Physical Geology.

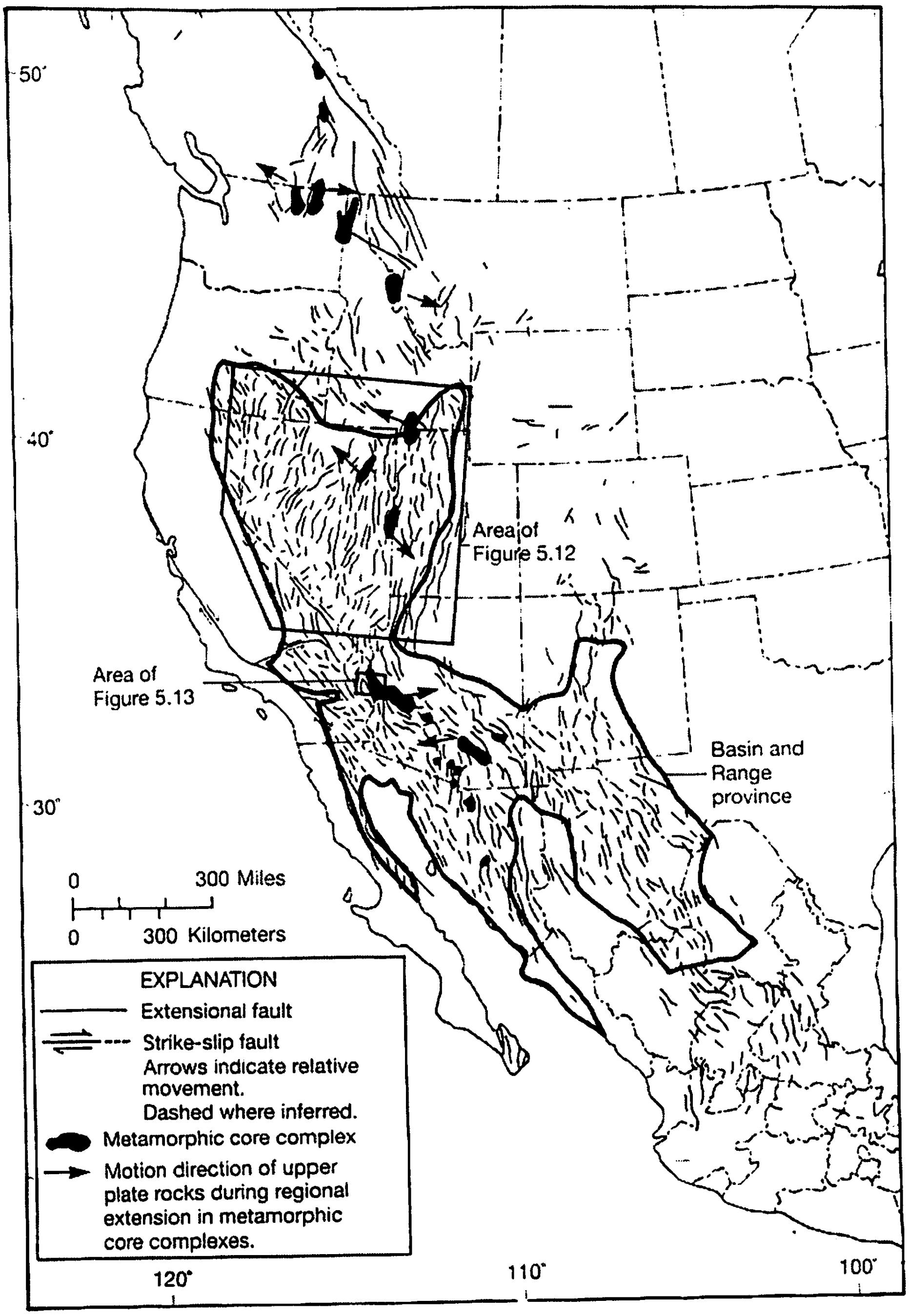
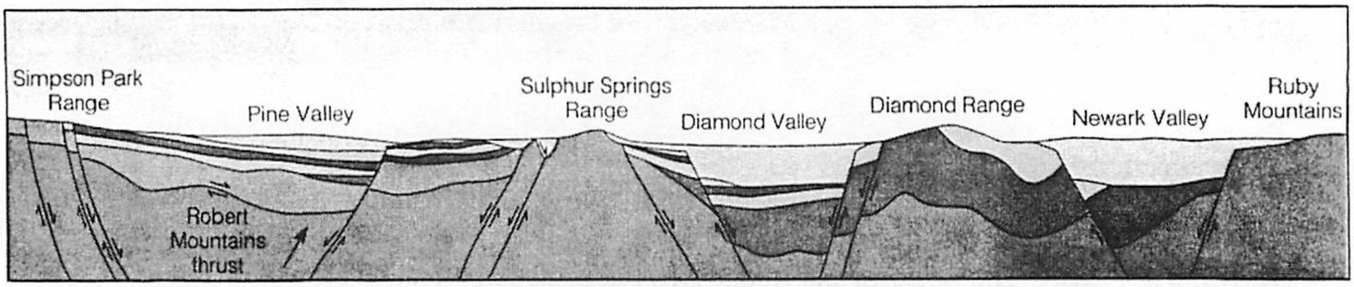


Fig. 1

The extensional province of the North American Cordillera, showing the boundaries of the Basin and Range province and the distribution of metamorphic core complexes with the slip direction of the hanging wall block on the detachment faults.



(a) Fig. 2

(*a*) Cross section of part of the Basin and Range Province in Nevada. The ranges and valleys are bounded by normal faults.

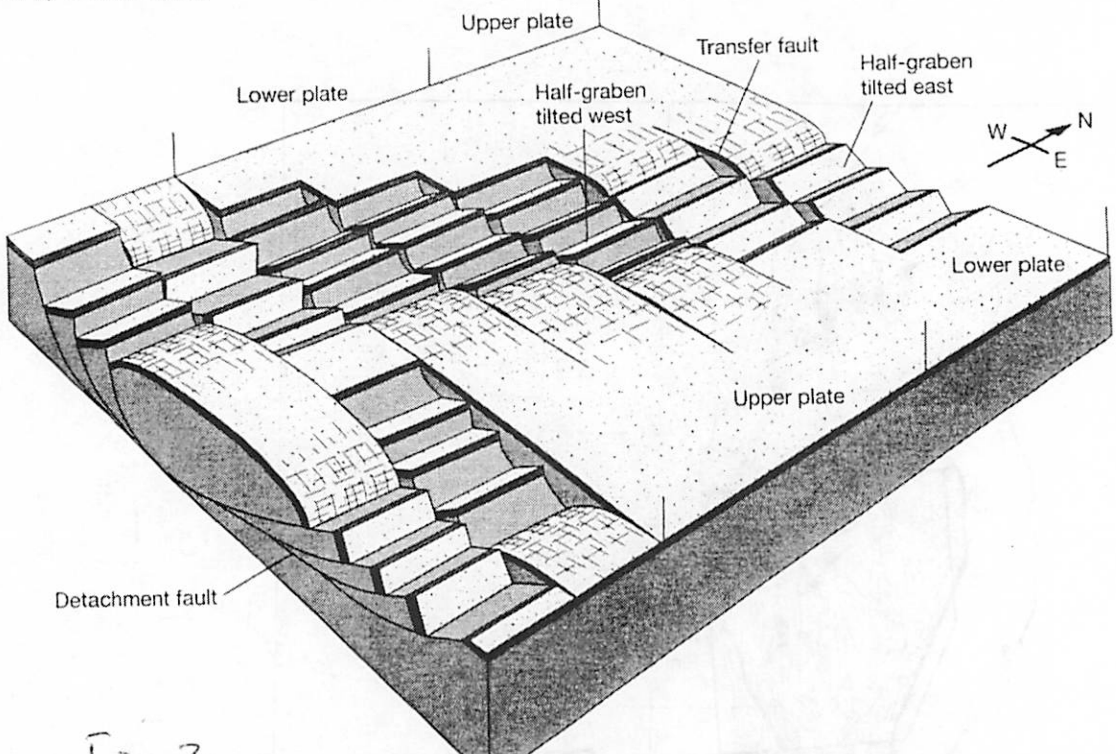
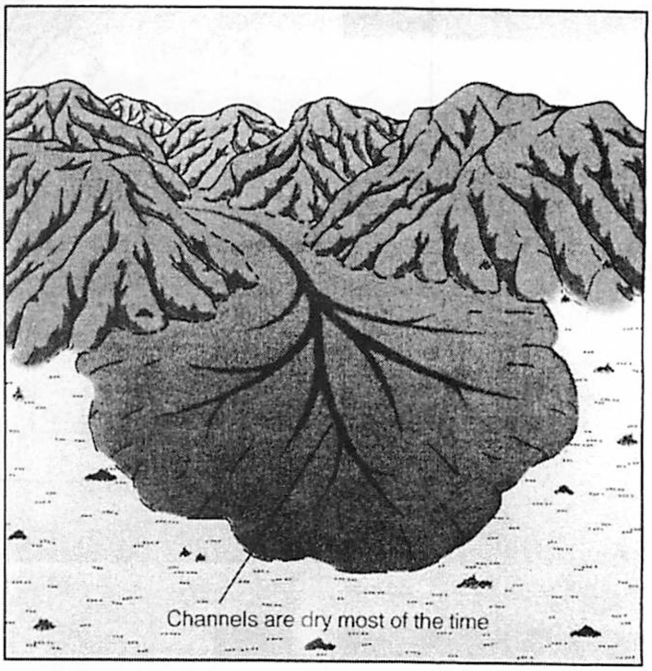


Fig. 3

Model of the fault geometry in basement rocks of a continental extensional province. Different domains of normal faulting are separated by transfer faults. Some domains, such as the two on the left, may contain sets of oppositely dipping normal faults separated by an unfaulted block.

Fig. 4: An alluvial fan forms where a stream discharges from a mountain canyon onto and adjacent lowland (common in the Basin and Range Province).



<u>Dinosaur Highway</u>

<u>Jade Bond</u>

Fossil Types

There are two main types of fossils commonly identified today – body fossils and trace fossils. Body fossils include bones, teeth and claws and are generally left behind by a dead animal (i.e. animal remains). Trace fossils are fossils left by living animals. They fall into three main subclasses:

- Locomotion traces (e.g. footprints, trails)
- Dwelling traces (e.g. burrows)
- Feeding traces (e.g. faeces, excreted sediment from worms)

Fossil Formation

Unsurprisingly, trace fossils are much more common than body fossils. However, to form a fossil footprint, a very specific environment is required. Generally, fossilized footprints are located in shallow marine deposited clastic sediments such as lakebeds, stream beds and flood plains. These sediments are soft enough to allow an impression to be made but also often have slow sedimentation rates, essential to fossil preservation. With the slow deposition rate, the footprint has time to dry and solidify before it is infilled, thus allowing it to retain its shape.

Due to the depositional nature of the environment, when deposition begins again on top of the footprint, it is the coarser grained material which fills the footprint first. The deposition then grades up towards the finest sediments at the top of the bed. This coarse infilling helps to preserve the fossil as when erosion occurs, differential erosion will result in the finer grained material being eroded away first, leaving just the coarser material behind in the shape of the footprint (i.e. a cast). Of course, there are some cases where the finer-grained material has survived erosion.

Arizona Fossils

The fossil site closest to where we are traveling is located approx. 5 miles west of Tuba City beside US160, on a Navajo Reservation. In the Navajo language, the tracks are called "Naasho'illbahitsho Biikee", translating to mean big lizard tracks (pretty logical!). The tracks themselves were discovered over 50 years ago and are now operated as a tourist site. Little scientific work has been done with them due to resistance from the Navajo. As the tracks are located in the Moenave formation, deposited in the early Jurassic, they are estimated to be approximately 200 million years old. Apart from footprints, several dinosaur eggs, claws, teeth and even a complete skeleton have been found in this region.

The vast majority of the tracks here have been identified as being therapod tracks. The term therapod means "beast-footed" (three toed) and this class of bipedal (two footed) carnivorous dinosaurs includes the Tyrannosaurus Rex. It also includes the Dilophosaurus, made famous as the poison spitting dinosaur in the movie "Jurassic Park", and is believed to be the dinosaur responsible for the majority of the tracks here.

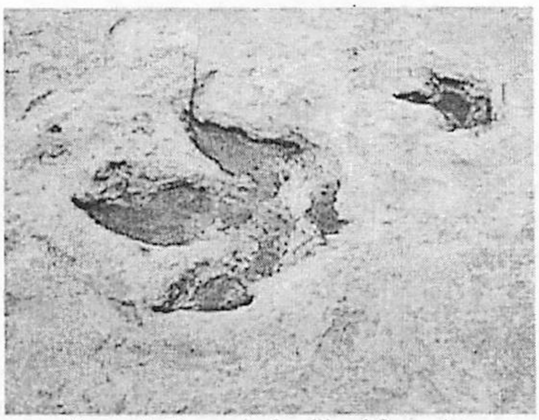


Figure 1: Example fossilized footprint.
Source: http://www.western.edu/faculty/jsowell/biol473/trip2003/

Dilophosaurus

The Dilophosaurus lived in the early Jurassic period, from 201 to 189 Mya and was a ceratosaur, the earliest form of a theropod. Growing to 20 feet long and 8 feet high, it weighed in at 650 to 1,000 lbs and was a carnivore, feeding on smaller herbivores. A fast moving dinosaur, it is believed to have hunted in groups (as several skeletons have been found together). It also had two crests located on its skull, the purpose of which is unknown but is believed to be either ornamental or sexual. Each hand had four fingers with one of them being reduced (similar to our thumb) and all fingers and toes had claws.

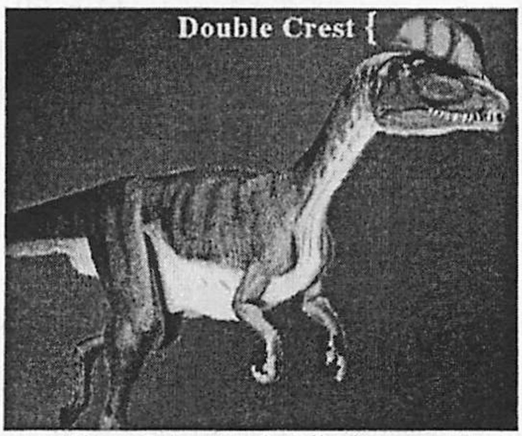


Figure 2: Image of a Dilophosaurus.
Source: http://www.ucmp.berkeley.edu/dilophosaur/details.html

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http://www.ucmp.berkeley.edu/dilophosaur/intro.html

Monument Valley Diatremes

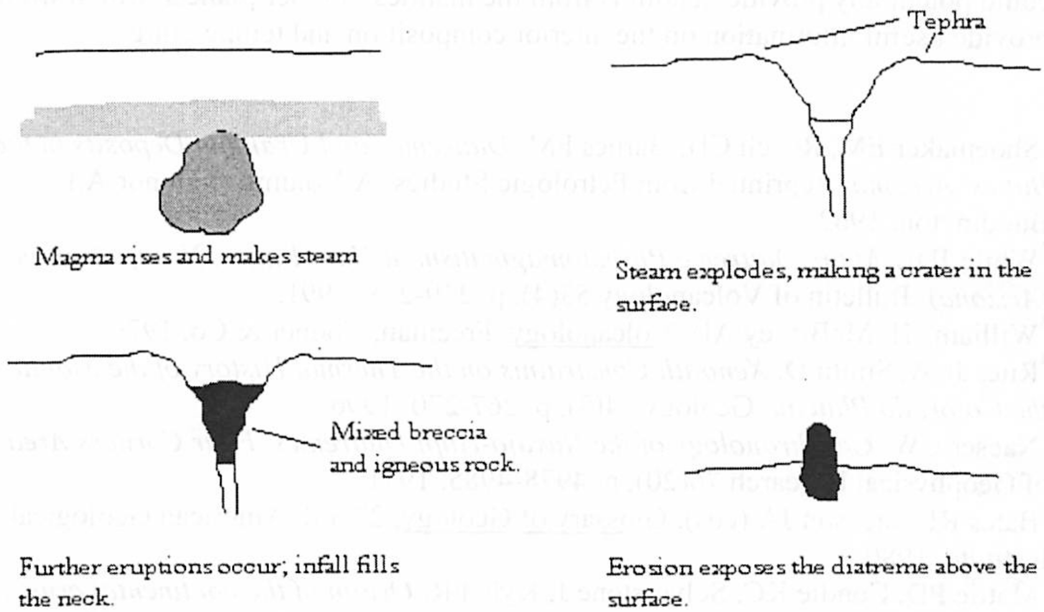
Colin Dundas

A **diatreme** is a column of volcanic material, composed of tephra which has fallen back into an eruption site and filled in the fissure.

Formation

Diatremes are thought to form as a result of **maar** volcanism, in which a volcanic explosion creates a crater and leaves debris around the cavity and in the pipe leading to the surface[1]. A common mechanism for this is **phreatomagmatism**[2]. In a phreatic eruption, upwelling magma encounters a layer of rock which is rich in groundwater, causing the water to evaporate. The resulting steam is under high pressure and ultimately explodes upwards, creating the initial crater and an ejected layer which contains a mix of lava and the underlying sediment. Alternatively, similar explosions may result from the rise of extremely volatile-rich magmas[1,3].

Collapse of the side walls and fallback from the eruption partly fills the cavity, setting up another explosive eruption. A particular volcano generally erupts multiple times on a very short timescale (potentially only a few months[1]) before shutting down. The diatreme forms in the pipe when it fills up with volcanic debris and sediment from the vent walls. This solidified remnant is covered by sedimentary rocks or occasionally **scoria cones**, volcanic cones formed by subsequent eruptions of lava. Erosion removes the softer surrounding rocks and leaves the diatremes we see.



Formation of a diatreme by phreatomagmatic eruption. Simplified from White (1991).

Monument Valley Diatremes

Several diatremes are exposed as outcrops in Monument Valley, as part of the larger Navajo volcanic field. The Hopi Buttes volcanic field, which is nearby, also exposes a large number of diatremes in various stages of erosion. The Navajo Volcanic field, which includes Agathla Peak, was emplaced beginning ~30 Ma[4] and contains around 50 diatremes or and other volcanic outcrops; several diatremes have been dated, by fission-track methods in apatite, to 31 Myr old[5]. Agathla, like many of the other diatremes, is a minette diatreme, which is rich in incompatible elements and appears to have come from partial melting in the lithosphere[5]. A minette is a type of dark igneous rock composed of biotite and feldspar[6]. Other diatreme rocks are classified as serpentinized ultramafic breccias[7]; these resemble kimberlites, which are peridotites with olivine and phlogopite phenocrysts[6].

Xenoliths

Diatremes and their magmas frequently contain xenoliths, fragments of rock included from the lower crust or the mantle. These appear both in the rock of the distreme and in the surrounding volcanic debris. This makes them useful for sampling portions of the earth which are normally inaccessible. A number of different xenolith types appear in the Navajo Volcanic Field, including peridotites and eclogites. These have been used to constrain the history and temperature of the mantle below the Colorado Plateau, which appears to have been relatively cool, possibly because of the subducted slab underneath[4].

Diatremes and the volcanic events that produce them may not be unique to Earth. Mars, with some amount of subsurface ice and groundwater, may potentially have phreatic eruptions as well, and similar processes could work elsewhere. Such diatremes could potentially provide xenoliths from the mantles of other planets, which would provide useful information on the interior composition and temperature[8].

[1]Shoemaker EM, Roach CH, Barnes FM. *Diatremes and Uranium Deposits in the Hopi Buttes, Arizona*. Reprinted from Petrologic Studies: A Volume to Honor A.F. Buddington. 1962.
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[6]Bates RL, Jackson JA (eds). Glossary of Geology, 2nd Ed. American Geological Institute, 1980.
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[8]McGetchin TR, Ullrich GW. *Xenoliths in Maars and Diatremes for Moon, Mars and Venus*. Journal of Geophysical Research 78(11), p. 1833-1853. 1973.

Formations in Sandstone

Implications of the Canyonlands for Planetary Science

By John Moores

What is Sandstone?

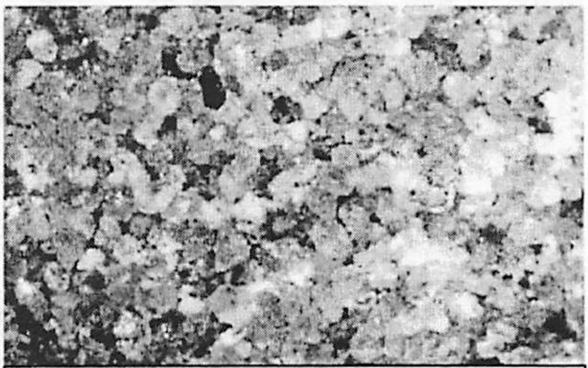


Figure 1 Closeup image of a sandstone matrix showing quartz clasts, note that the grains are well-sorted

- Porous form of Sedimentary rock formed from erosional debris in which the majority of clasts will pass through a screen with a mesh size of 0.0625mm to 2mm
- Typically composed of quartz grains (when used on its own to describe a rock, "sandstone" refers to a quartz content of 85-90%)
- May be derived from Fluvial or Aeolian (sand dunes) deposition
- Significant cross-bedding
- Grains may be recycled through multiple cycles of stone and erosion
- Grains are cemented together by smaller particles and held together by cementing minerals (typically one of silica, iron oxide, calcium carbonate)
- Presence of lithified sandstone implies ion transport mechanism for mineralization to occur: on earth this means water

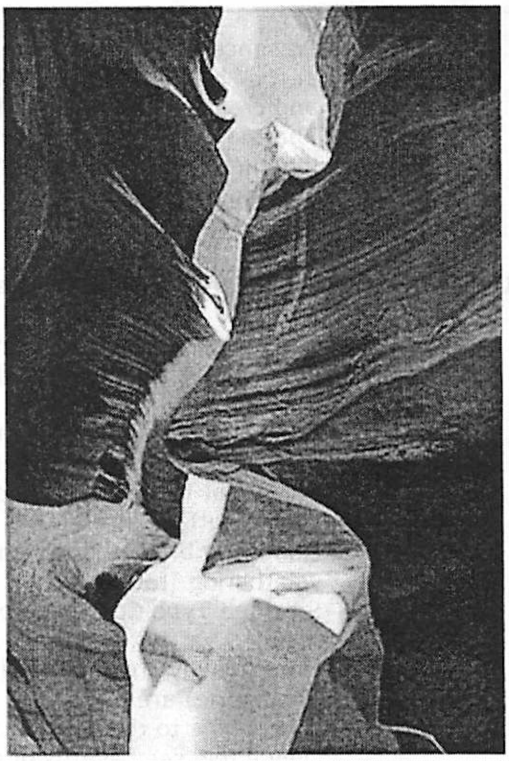


Figure 2 Slot Canyon in magic canyon, AZ

Weathering of Sandstone

- Over geologic timescales depositional areas become erosional with weathering breaking down the deposits
- Two major types of weathering: chemical and physical
- Chemical Weathering
    - Re-dissolution of cementing material due to ingress of water into pore spaces and subsequent release of clasts
    - Clasts not typically themselves dissolved due to low solubility of quartz in water (<0.5mmol/l)
    - Redistribution of ions within sandstone matrix, i.e. case hardening
    - Surprisingly resistant to chemical erosion compared to other rock types
    - Still karst-like topography including sink-holes and even stalactites and other cave-like features are sometimes observed
- Physical Weathering
    - Break down due to ice-wedging (freeze/thawing)

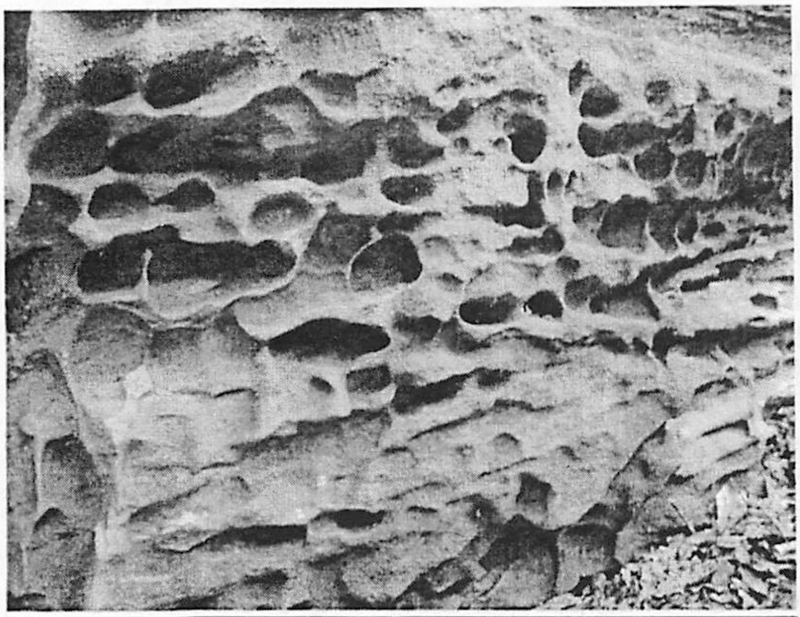
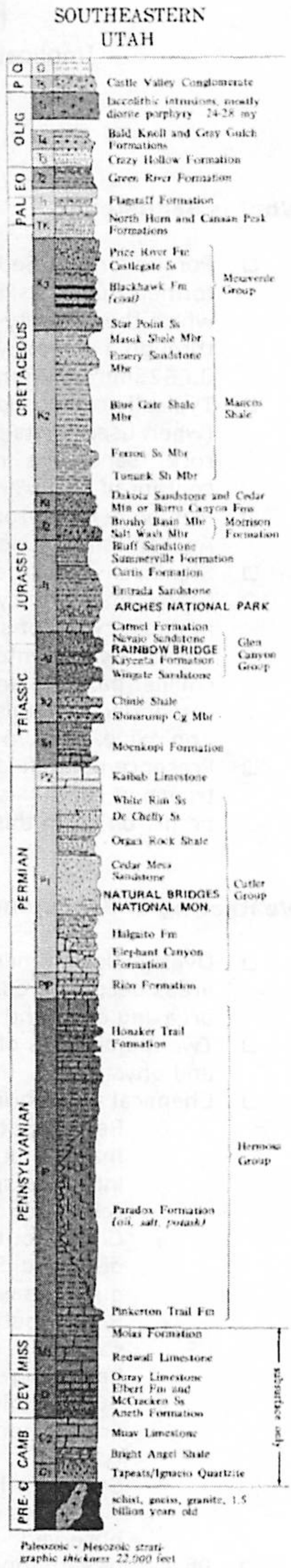


Figure 3 (top) Honeycomb Weathering in Sandstone; Figure 4 (side) Stratigraphic cross-section of Colorado Plateau in SE Utah



- Presence of water can alter mechanical strength of rock by up to 15% resulting in block failure and creation of shear cliff faces
- Thermal Cycling? Some evidence that inhomogeneous nature of "composite" sandstone may be significant.

Landforms in Sandstone seen in the Canyonlands

- Overview of a Stratigraphic section of the Colorado Plateau highlighting sandstone and other sedimentary units (see Figure 4)
- Small-Scale Landforms (< a few m)
  - water-pockets and weathering of joints
  - Polygonal Tesselation "elephant skin" possibly due to surface stress
  - Honeycomb-weathering and Cavernous weathering (tafoni)
  - Size and Type Controlled by moisture flow within rock
  - More heavily cross-bedded forms (i.e. Navajo Sandstone) are more
  - susceptible to this form of weathering
  - Only a few see caverns of any size, for instance the Aztek Sandstone
- Large-Scale Landforms (> a few m)
  - Often due to growth and merging of small-scale landforms
  - Merging water-pockets eventually form canyons with sharp cliffs
  - Spires, hoodoos, pinnacles due to gradual weathering along vertical fracture lines and

joints

- Deepening joints are aided by grit and larger clasts eroded out of the main beds
- Arches and Bridges formed from seepage of groundwater through porous sandstones such as Entrada and Cedar Mesa which weakens the rock causing block collapse

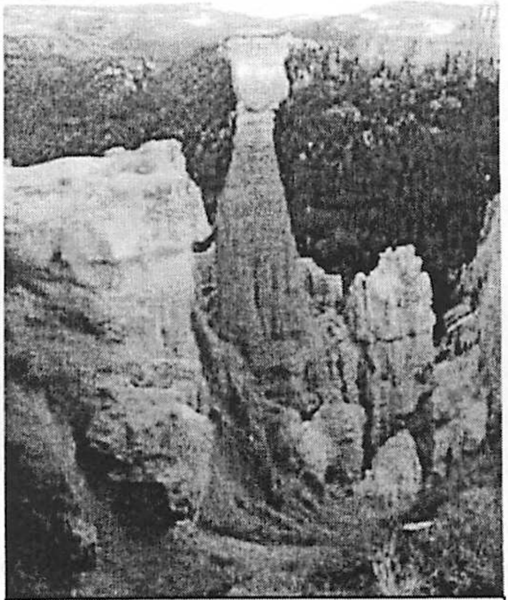


Figure 5 Hoodoo in Bryce Canyon

Implications for Planetary Science

- Often we are looking for water or evidence for the action of water in the past on planetary landscapes
- Recall that for lithification, sandstones require some type of mineral transport, i.e. a liquid solvent, typically water
- Thus Lithic Sandstones are very suggestive of past water and are very detectable in-situ (have been found on Mars by the MER rovers – see the talk by Jason Barnes)
- Additionally, small-scale weathering forms which are specific to sandstones often grow into distinctive large-scale geomorphologic features
- Potentially features such as spires, hoodoos, pinnacles, arches or bridges are of sufficient size to be detectable by remote sensing from orbital photographs

References

Figure 6 Natural Arch near Moab, Utah

[1] Young, Robert and Ann (1992) *Sandstone Landforms.* Springer-Verlag publishing.

[2] Steele, Brenda A. (1982) *Depositional Environments of the White Rim Sandstone Member of the Permian Cutler Formation, Canyonlands National Park, Utah.* U.S. Geological Survey Bulletin 1592.

[3] Scholle, Peter A (1979) *A Color Illustrated Guide to Constituents, Textures, Cements and Porosities of Sandstones and Associated Rocks.* Published by the American Association of Petroleum Geologists.

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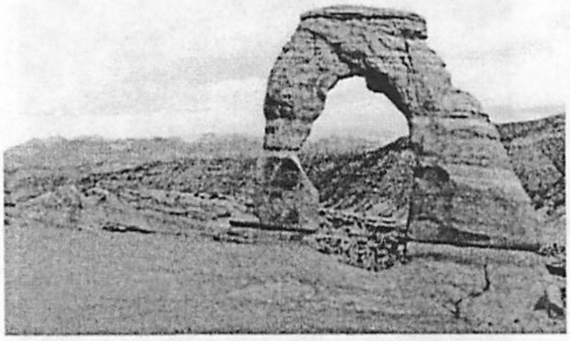
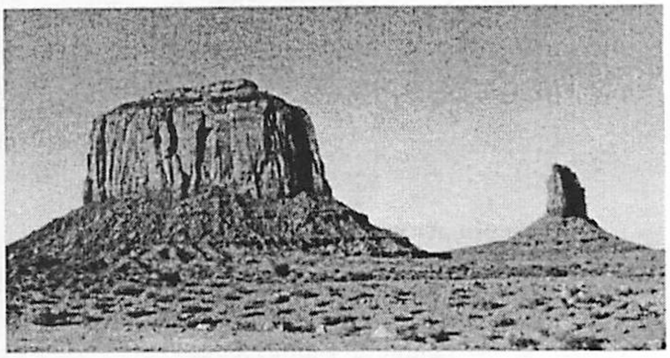
Arches and Buttes

Stephanie Campbell





Arches and Buttes are some of the most spectacular and unusual-looking landforms in arid climates. An arch can seem to be precariously balanced, leaving us to wonder how it formed and how it remains standing. A butte can tower nearly vertically far overhead. Both often rise out of seemingly flat terrain for no obvious reason. Why do they form where they do, and what can we learn from their formation?

What are they?

Arch

-Opening in a wall of rock formed by weathering and erosion

Butte

-Flat-topped, steep sided rock structure

-Often has talus pile at base, but weathering products are eventually carried away

What conditions promote their formation?

-Usually arid areas with little to no vegetation

-Cap rock more resistant than underlying rock. The cap rock is often sandstone, but can also be volcanic, such as basalt.

-Must be a way to transport weathered material away. The binding material of sandstone is often water-soluble.

-Arches often form in jointed rock, usually with closely spaced joints

-Buttes form on the edges of plateaus with steep sides

How do they form?

Arches

-2 closely spaced, parallel joints in a rock (few feet to few yards apart)

-Erosion leaves a fin of rock between the two joints. Formation is especially effective if this fin stands out beyond the mass of rock it protrudes from, so weathering can more easily sculpt the rock.

-Fin is weathered from both sides

-Sometimes, weathering creates a hole in the fin before the fin completely disappears. The hole is more easily created if lower rock is softer than overlying cap rock.

-Arch is formed, and is now weathered from all sides, so hole can expand relatively rapidly.

-Eventually collapses to form a spires or monuments

Buttes

-Start as plateau

-Weathering isolates a piece of the plateau from the main mass of rock. This is a mesa, and is characterized by a flat top with steep sides (often nearly vertical)

-Weathering continues on the edge of the mesa. Softer underlying rock is easily eroded once the cap rock is breached, so the sides remain nearly vertical.

-As the mesa shrinks, it is known as a butte. There is disagreement on when a mesa becomes a butte, but generally a mesa is wider than it is tall, while a butte is as tall or taller than it is wide.

-Eventually, butte shrinks to a spire and collapses.

Do arches or buttes exist elsewhere than Earth?

-Buttes seen on Mars

-Tells us something about conditions on Mars, but what?

Martian Landscape, SW of Cerberus region

Layered Terrain in Martian Crater

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Kelly Kolb

Incised Meanders in Southeastern Utah

What is an incised meander?

A meander is a bend or curve. An incised meander is "a meander in a stream carved downward into the surface of the valley in which it originally formed, suggesting rejuvenation of a meandering stream due to rapid vertical uplift or lowering of base level"[1]. Stream rejuvenation occurs when the base level of a stream lowers, forcing the stream's gradient, or slope, to increase. The stream cuts through the newly exposed rocks until it gets to its new lowest level.

Incised vs. Entrenched meanders

Incised meanders and entrenched meanders are often mistakenly considered synonymous. Entrenched meanders form similarly to incised meanders but have differently shaped cross sections. Entrenched meanders are symmetric, while incised, or ingrown, meanders are not[2]. The difference in symmetry results from the bedrock structure in which the meanders form.

How do incised meanders form?

Harden (1990) addresses the debate over whether incised meanders form by further erosion of an ancestral stream valley or during the process of canyon incision into a plateau by studying incised meanders in the Colorado Plateau[2]. Her results suggest that both occur. She determines that incised meanders often follow the paths of "ancestral streams," but that meander geometry originates from the bedrock structure of the region.

Factors affecting incised meander formation[2]

1. Channel gradient
   - Slightly correlated with bedrock type
   - Most significant variable in determining straight or meander

2. Drainage area
   - Ancestral streams
   - Regions

3. Bedrock structure & erodibility
   - easily erodible: asymmetric (incised)
   - sturdy, resistant: symmetric (entrenched)

4. meander shape
   - symmetric vs. asymmetric
   - partly determined by the gradient

Meanders of the Colorado Plateau

The San Juan, Colorado, and Green Rivers all flow through the Colorado Plateau, a formation of Paleozoic and Mesozoic age (~136-570 Ma)[3] that uplifted during the Laramide orogeny (~40-70 Ma)[4] as a response to eastward directed compression[2]. The Colorado and Green Rivers have incised meanders at locations where they flow upstream[5]. The San Juan River is famous for its region of pronounced incised meanders called the "Goosenecks." *Figure 1* is an aerial view of the Goosenecks. The lighter regions are locations of sediment pile-up, showing the asymmetrical shape of the meanders. *Figures 2* and *3* are close-up images of sections of the Goosenecks. *Figure 4* is another set of incised meanders along the San Juan.

A Depositional Age for the San Juan River[6]

Wolkowinsky and Granger (2004) determined a depositional age of 1.36 +0.20/-0.15 Ma for the San Juan River by examining ^{26}Al and ^{10}Be abundances in a region ~150m above the riverbed. The relative radioactive decay ratio, $^{26}Al/^{10}Be$, was used to establish the depositional age. They examined two sites, one at Bluff, Utah and the other at Mexican Hat, Utah. Wolkowinsky and Granger derived an age from only the Bluff site because of inadequate gravel depths at Mexican Hat. They found a bedrock incision rate of 110±14 m/Myr over the past 1.36 +0.20/-0.15 Myr, which is a little slower than that of the Colorado River near the Eastern Grand Canyon (~140 m/Myr over the past ~500 kyr). The difference in incision rates indicates "that the river system is not in equilibrium and may still be responding to drainage integration and incision."

Natural Bridges: an extension of incised meanders

As a stream flows over a relatively flat region, it winds itself around in curves, known as meanders. If a sudden flood develops, the torrent of water can break through a rock structure, connecting two meanders and forming a natural bridge (see *Figure 5*). Natural bridges, although similar to, are different from arches because they form from erosion rather than weathering[7].

References:

[1] "Golden Gate Photo: Glossary of Technical Terms." http://www.goldengatephoto.com/glossary.html#incisedmeander

[2] Harden, D.R. "Controlling factors in the distribution and development of incised meanders in the central Colorado Plateau." 1990, *Geology Society of America Bulletin*, v. 102, 233.

[3] Guccione, M.J. and Zachary, D.L. "Geology History of the Southeastern United States and Its Effects on Soils of the Region." http://soilphysics.okstate.edu/S257/book/geology/

[4] "Laramide orogeny." http://www.fact-index.com/l/la/laramide_orogeny.html

[5] "Colorado Plateau Mosaic." http://geoinfo.amu.edu.pl/wpk/geos/GEO_1/GEO_PLATE_I-1.HTML

[6] Wolkowinsky, A.J. and Granger, D.E. "Early Pleistocene incision of the San Juan River, Utah, dated with ^{26}Al and ^{10}Be." 2004, *Geology*, v. 32, 749.

[7] "Incised Meanders." http://www.dialspace.dial.pipex.com/town/close/kcb60/lith37.html

INCISED MEANDERS

Figure 1. Aerial View of Goosenecks of San Juan River, Utah
http://geoinfo.amu.edu.pl/wpk/geos/GEO_1/geo_images_I.1/FigI-1.2.jpeg

Figure 2. Close up view of incised meanders in San Juan River
http://geoinfo.amu.edu.pl/wpk/geos/GEO_1/geo_images_I.1/FigI-1.3.jpeg

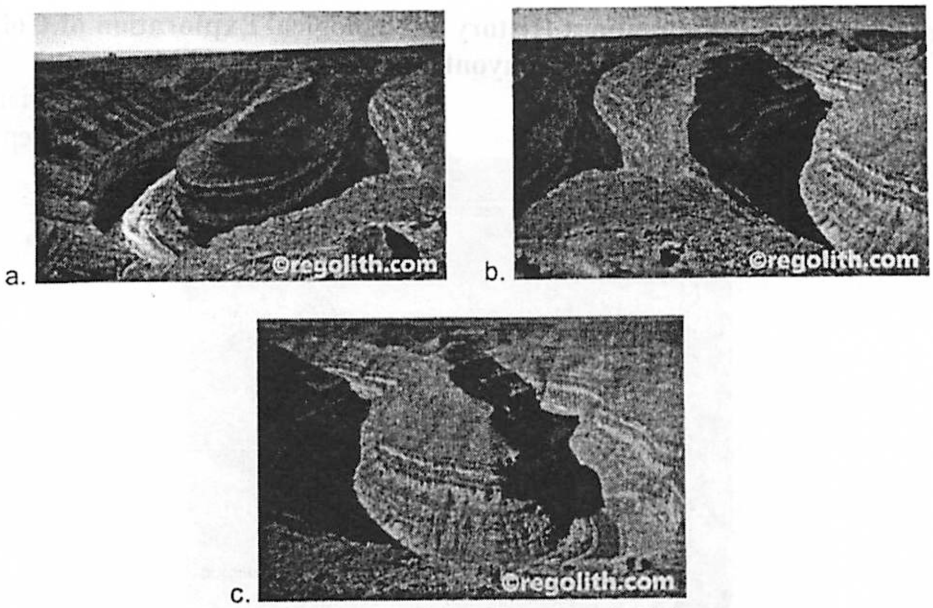


Figure 3. Other Gooseneck Pictures
http://www.dialspace.dial.pipex.com/town/close/kcb60/lith37.html

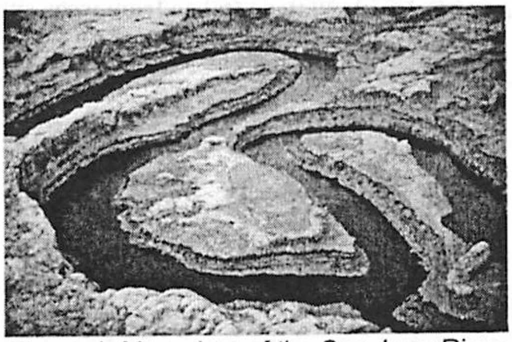


Figure 4. Meanders of the San Juan River
http://www.geology.wisc.edu/~maher/air/air04.htm


Figure 5. Natural bridge Sipapu at Natural Bridges National Monument, SE Utah
http://www.goldengatephoto.com/westus/natbridges.html

Figures for Fireside Chat about History of Geological Exploration of Colorado Plateau – LPL Canyonlands Field Trip, 2004

Brian Jackson
Sept. 8, 2004

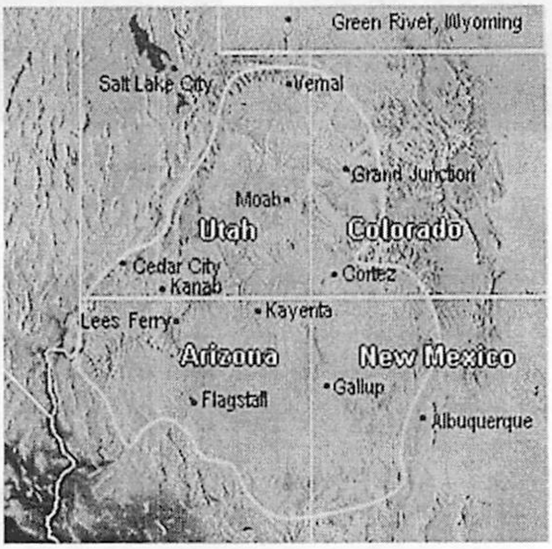


Figure 1: Map of Colorado Plateau (taken from www.cpluhna.nau.edu)

Figure 2: willow figure dating back to 1580 BC

May 10:
mended our canoes which had recd considerable injury yesterday, and proceeded down the river—at the distance of 2 miles the river became so verry bad that we were unable to proceed with our canoes loaded we discharged them and performed a portage of half mile which in consequence of the roughness of the side of the mountain along which we were obliged to pass made it extremely difficult and tedious—these may be well called the Rocky mountains for there is nothing but mountains of rocks to be seen partially covered with a dwarf groth of cedar & pines—violent wind with snow & rain

Figure 3: Entry from Ashley's expedition journal

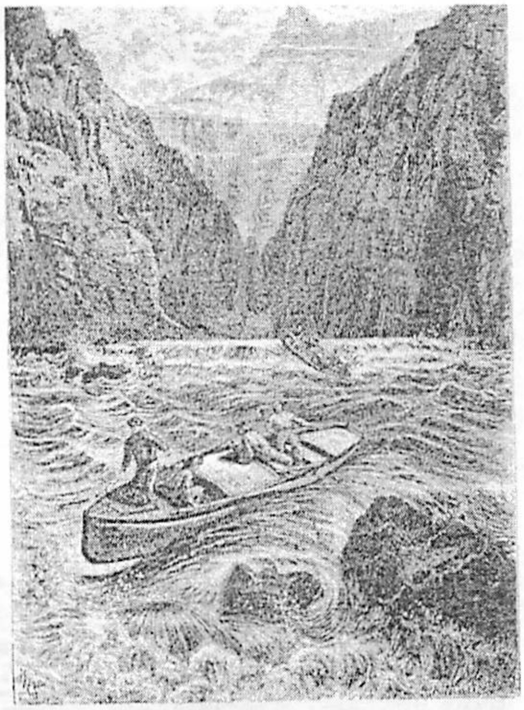


Figure 4: Drawing from Powell's *Exploration of Colorado and Its Canyons*, Cataract Canyon

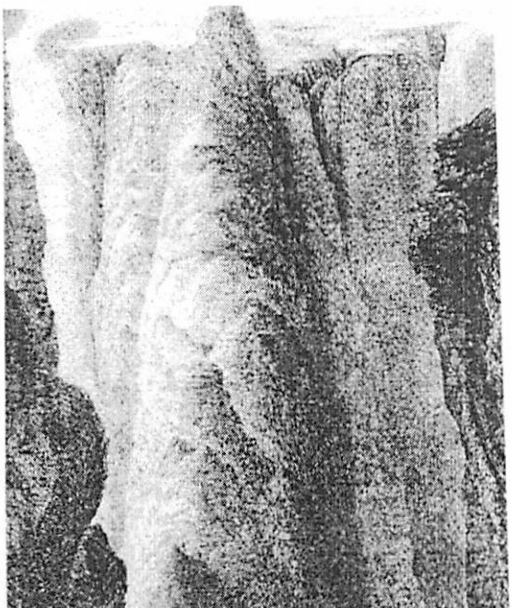


Figure 5: Drawing by Egloffstein accompanying J. C. Ives's expedition report

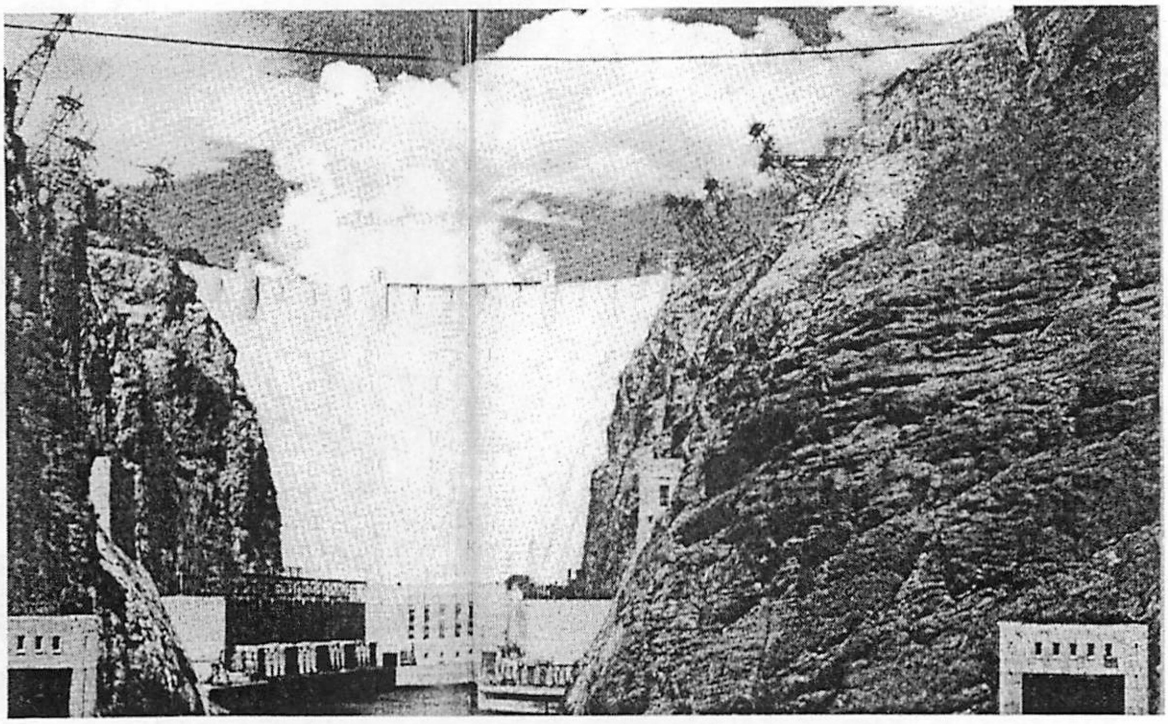


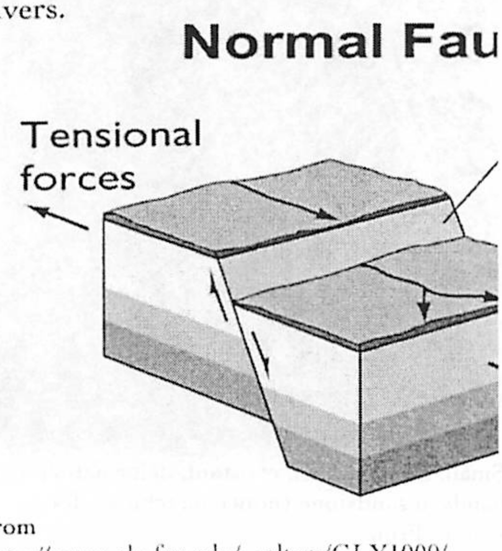
Figure 6: Boulder Dam on border of Nevada and Arizona

Faults and Folds of the Colorado Plateau

Jani "Warp Tour" Radebaugh

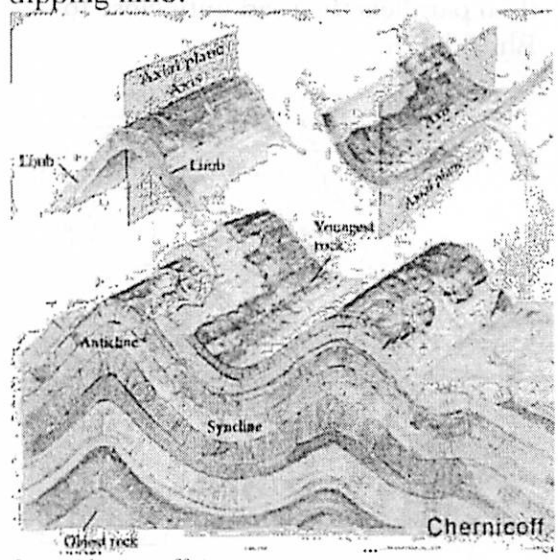
Between the folded, twisted Precambrian core complexes and downdropped basins of the Basin and Range province of Arizona and Utah and the massive folded belt of the Rocky Mountains lie the high, flat, nearly horizontal layers of the Colorado Plateau. Despite the remarkable flatness of this region, there are several prominent structural features that give us insights into the region's history. We will discuss faults and folds, leaving joints to Tamara.

Faults in this region are mainly normal faults, where one block has dropped down relative to another at a high angle (steep fault face). These are a result of tension in crustal blocks. There are many north-south trending faults (so in which direction were the forces??) in the Colorado Plateau. Many canyons follow faults lines, so you can see parallel canyons as tributaries to larger rivers.

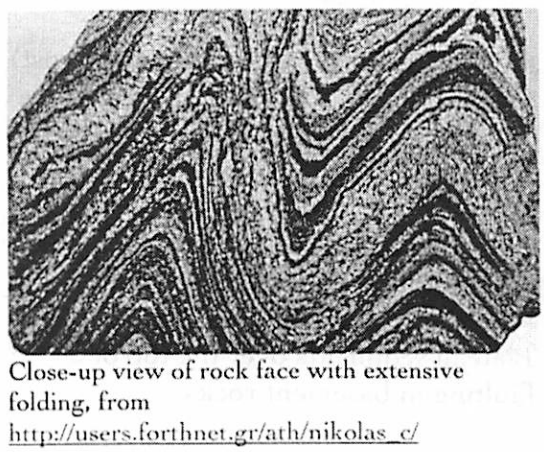


from
http://www.gly.fsu.edu/~salters/GLY1000/

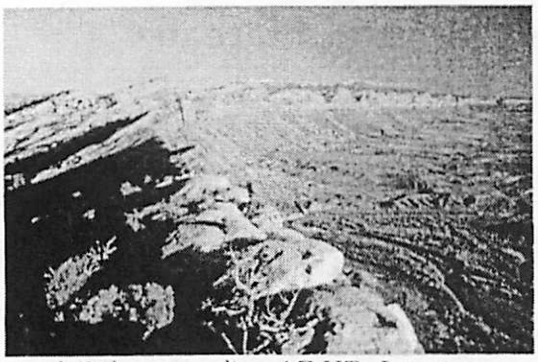
Folds in the Colorado Plateau are relatively gentle (compare the tight folds in the Rocky Mountains, Alps, and elsewhere), extensive (many are among the longest continuous folds on Earth) and are likely linked to major invisible regional faults in the underlying Precambrian basement rocks. Folds here are mainly expressed as **monoclines**, or anticlines (frowny face folds) that have one gently dipping limb (or side) and another steeply dipping limb.



from Chernicoff, in
http://users.forthnet.gr/ath/nikolas_c/

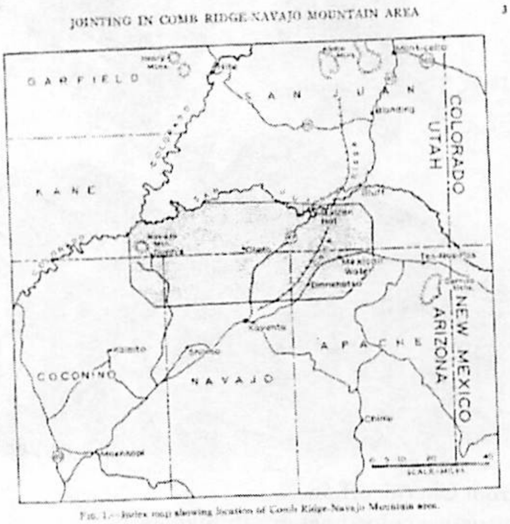


Close-up view of rock face with extensive folding, from
http://users.forthnet.gr/ath/nikolas_c/



Comb Ridge monocline, AZ-UT. Layers are dipping to the left. From http://www.suwa.org

Comb Ridge is an example of a monocline that we see during our trip. It is the eastern part of the Monument Uplift (so which way do the rocks dip?). It becomes visible at Kayenta, then parallels the road until close to Bluff, Utah.



Trace of Comb Ridge. From Hodgson, 1961.

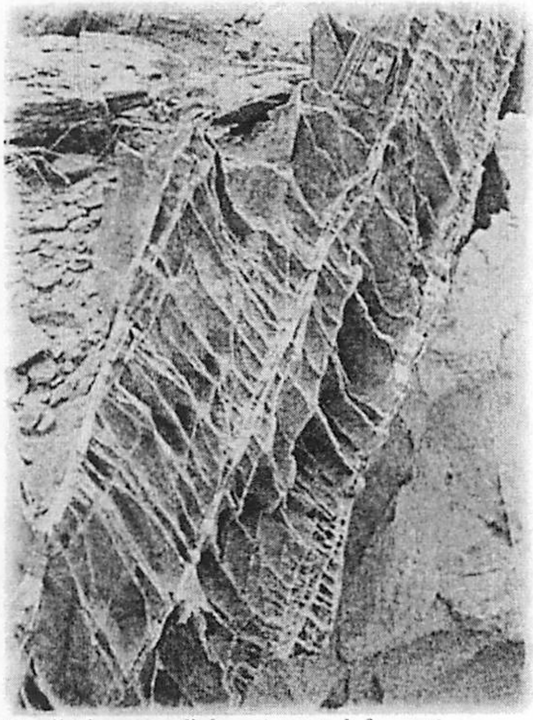
According to (our own Provost) George Davis (1999), there were three major regional tectonic deformations that have led to the features we see.

Laramide Orogeny - ~90-50 ma mountain building of the Rockies let to swells and monoclines in Colorado Plateau sediments over the top of faulting in basement rocks

Volcanism - ~25-19 ma, steep plate subduction led to volcanism in the large ash flow tuff deposits of the Marysvale volcanic field (west of Canyonlands), the weight of which led to deformation. Also large laccoliths, or volcanic swell-ups, such as the Henry Mountains, changed large regions.

Basin and Range - ~15 ma-present, large-scale extension led to formation of 3 major high-angle faults, all to the west of Canyonlands: Hurricane, Sevier, Paunsaugunt.

Folding, thrusting, faulting, and shearing in sandstones (like the Navajo Sandstone) led to **deformation bands**, or thin, brittle zones with little offset. These can be seen in many areas of the Colorado Plateau.



Small, thin, parallel, resistant, deformation bands in sandstone (notice matchbook for scale). From http://www.uib.no/people/nglhe/Utah.html

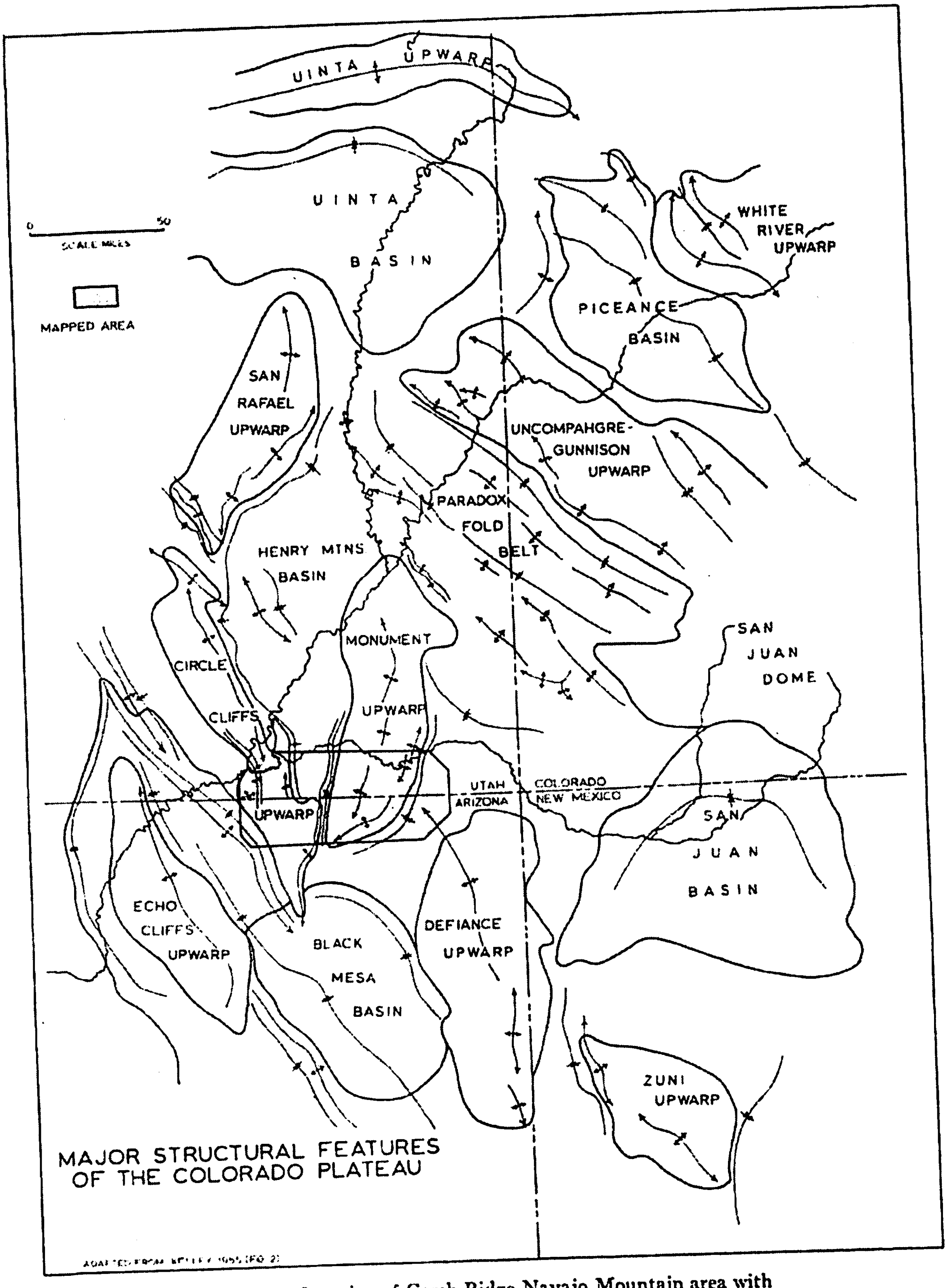
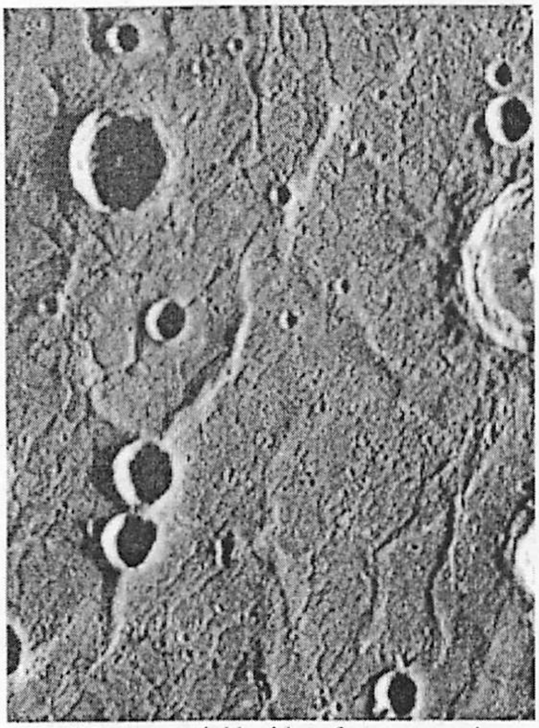


FIG. 3.—Location of Comb Ridge-Navajo Mountain area with respect to major structural features of Colorado Plateau.

(37)

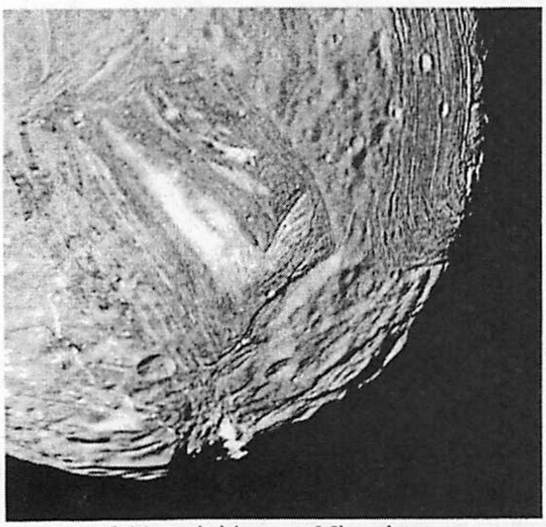
The planetary connection:

How do we get folds without plate tectonics? Are there any?



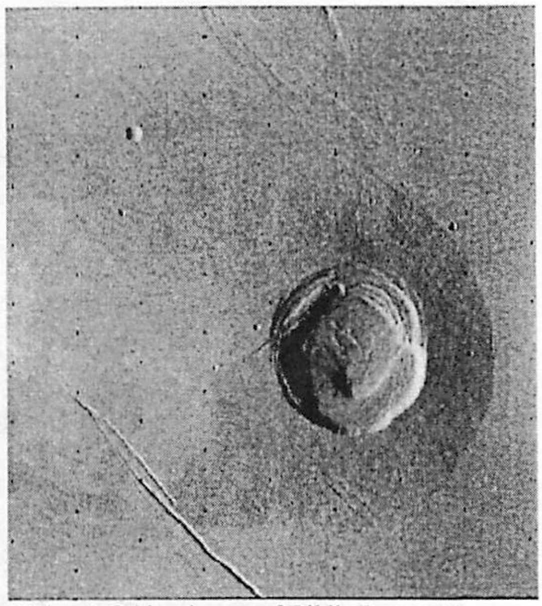
Lunar/Mercury wrinkle ridges from contraction of surface due to cooling.

Faulting on Mars (Valles Marinaris!), tiny moons Miranda, Ariel all seem to be related to global, or very large scale, tectonism, probably related to cooling.



Complex folds and ridges on Miranda

Regional faulting is related to volcanism and movement of crustal blocks.



Viking 2 Orbiter image of Biblis Patera, Mars. Concentric faults and downdropped blocks can be seen in the caldera walls, and NW-SE trending regional faulting that occurred in several episodes can also be seen. Image approx. 200 km across.

Citations not in figure captions:

Davis, G. H., 1999, Structural geology of the Colorado Plateau region of Southern Utah, with special emphasis on deformation bands, GSA Spec. Pap. 342, 157 pp.

Hodgson, R. A., 1961, Regional study of jointing in Comb Ridge-Navajo Mountain Area, Arizona and Utah, Bull, Am. Assoc. Petroleum Geologists, 45, 38 pp.

USGS Geology of the Colorado Plateau
http://wrgis.wr.usgs.gov/docs/usgsnps/province/coloplat.html

Geology of the Colorado Plateau by Annabelle Foos
http://www2.nature.nps.gov/geology/education/foos/plateau.pdf

Laccoliths: Blood-filled Tick Mountains

Nicole Baugh

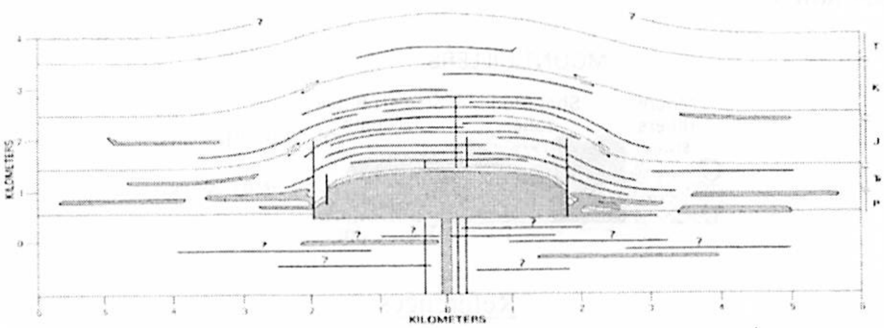
Introduction—A Study in Unfortunate Nomenclature

Laccoliths are a member of a generic class, the *domal tectonic landforms*. An intrusion of magma swells, uplifting the overlying rock to form a domed mountain[1]. This intrusion – in fact, all igneous intrusions—are referred to as *plutons*. Plutons may be subdivided into *tabular* and *non-tabular* bodies. These bodies, be they tabular or not, are further classified as *discordant* or *concordant*, depending on their orientation to the surrounding *country rock* (nonparallel and parallel, respectively)[2]. A laccolith results from a sill, a thin layer of magma between two layers of bedrock, that is fed by a dike, a cross-cutting sheet of magma, until the pressure of the inflowing magma forces the crust to dome. So:

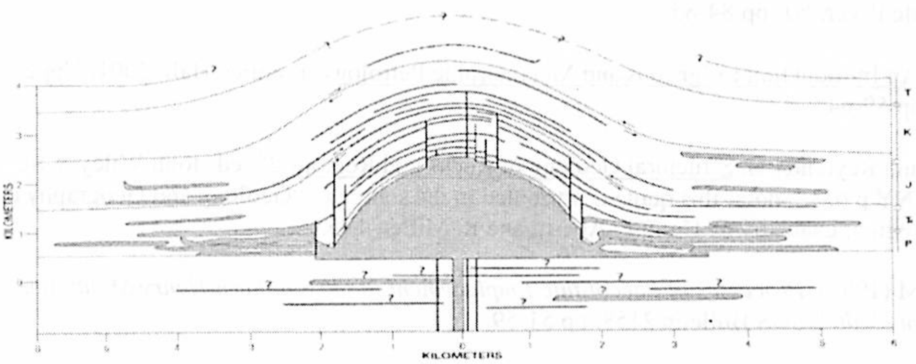
Laccolith=lens-shaped intrusion & deformation of county rock resulting from swelling of a concordant, tabular bodied pluton by a discordant, tabular bodied pluton. Hmm…

However, as intrusive contacts go, the laccolith got off lightly, as witness the following definition:

> Cactolith: A quasi-horizontal chonolith composed of anastomosing ductoliths, whose distal ends curl like a harpolith, thin like a sphenolith, or bulge discordantly like an akmolith or ethmolith[3].

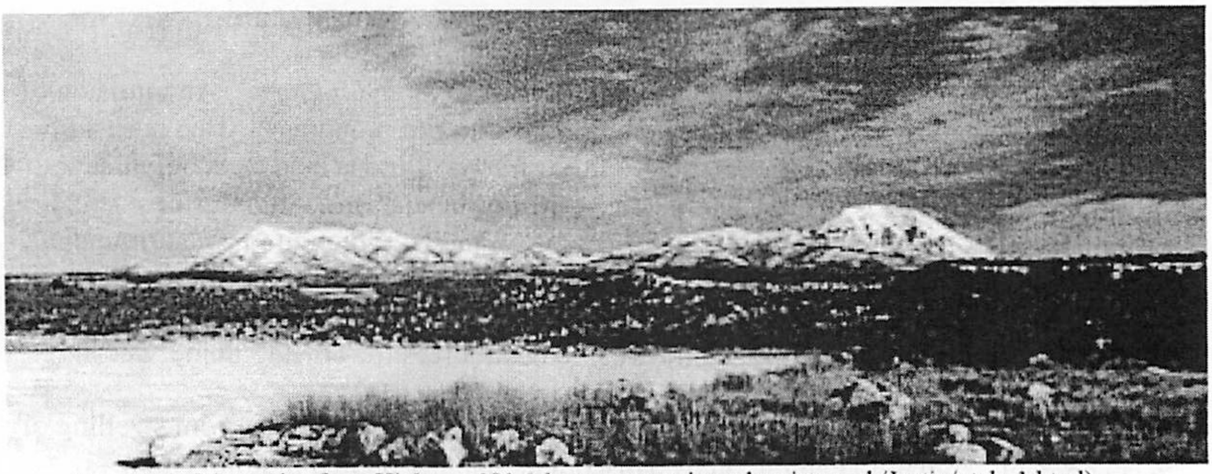


Sills and thin laccoliths, with central laccolith fed by dike[4]



Fully formed laccolith[4]

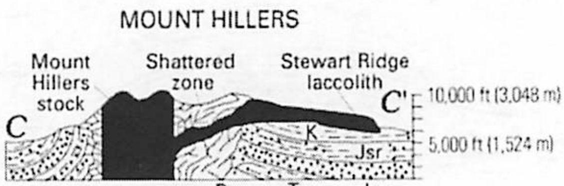
The Abajo Mountains



The Abajo Mountains from Highway 191 (photo:www.pointandsquirt.co.uk/Justin/utah_1.html)

Controversy!!

An alternate explanation for the formation of laccoliths, specifically those of the Henry Mountains (not far from the Abajo Mountains), is that, rather than forming from dike-fed sills, they may result from non-tabular plutons called stocks. Stocks do not have a local feeder. Instead they may extend to great depths. The geologic evidence has been used to support both claims.



References

[1]Bloom, A. Geomorphology A Systematic Analysis of Late Cenozoic Landforms 3rd ed. Prentice Hall,1998. Upper Saddle River, NJ. pp 84-85

[2]Winter, J. An Introduction to Igneous and Metamorphic Petrology. Prentice Hall, 2001. Upper Saddle River, NJ. pp 59-64

[3]Davis, G. and Reynolds, S. Structural Geology of Rocks and Regions 2nd ed. John Wiley & Sons, 1996. New York, NY p 651—note: this quote is attributed in the source to "Geology and Geography of the Henry Mountain Region, Utah" by C. Hunt, P. Aberitt and R. Miller, 1953

4Jackson , M (1997). *Processes of Laccolithic Emplacement in the Southern Henry Mountains, Southeastern Utah.* USGS Bulletin 2158. pp 51-59

[5]Ross, M (1997) *Geology of the Tertiary Intrusive Centers of the La Sal Mountains, Utah.* USGS Bulletin 2158. pp61-83

Name: Laccolith Complexes of Southeastern Utah

DOB: 25 Ma (Abajo Mountains)
25 Ma (Henry Mountains)
29 Ma (La Sal Mountains)
(from Sullivan)

Mug shot: See reverse

Physical Description:

1. Henry Mountains
   a. First surveyed in 1875 by Gilbert
   b. Too remote for industry, but famous to geologists because of Gilbert's treatise.
   c. Highest point: Mt. Ellen 11,520 ft.
2. Abajo Mountains
   a. Evidence of prehistoric Anasazi settlements.
   b. Highest point: Abajo Peak 11,360 ft.
3. La Sal Mountains
   a. Evidence of prehistoric settlements.
   b. Significantly damaged by mining and subsequent erosion.
   c. Highest point: Mt. Peale 12,720 ft.
   d. Elongated along salt-cored anticlines (Ross)
4. Geology (Nelson and Davidson)
   a. Magma emplaced in Phanerozoic sediments
   b. Mantle magma became plagioclase-hornblende porphyry (95% volume of Henry and La Sal, 100% of Abajo.)
   c. Syenite porphyry became 5% volume of Henry and La Sal
   d. Formed from a large east-west oriented late Oligocene magmatic belt stretching from Reno, Nev. to San Juan, Co.

Offences: Harboring dangerous fugitives from LPL.

Known Associates: Henry, La Sal and Abejo mountain ranges.

Known Enemies: Erosion. Over time, the softer stone on these laccoliths has eroded away, reavealing the hardened diorite cores.

References:

Grout, M.A., Verbeek, E.R., Relation Between Middle Tertiary Dike Intrusion, Regional Joint Formation, and Crustal Extension in the Southeastern Paradox Basin, Colorado, *USGSB, 2158,* 101-110

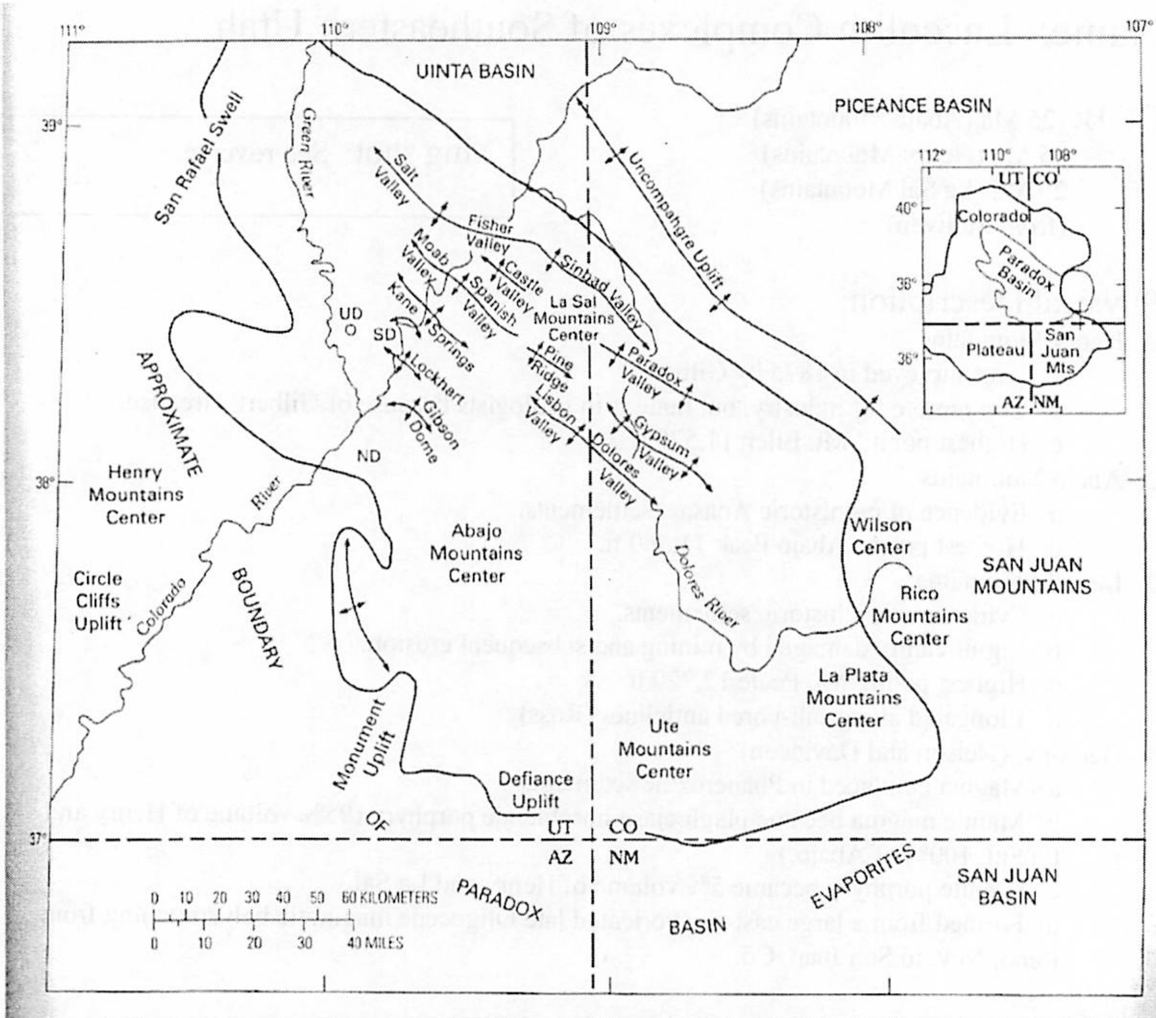
Nelson, S.T., Davidson, J.P., The Petrogenesis of the Colorado Plateau Laccoliths and Their Relationship to Regional Magmatism, *USGSB, 2158,* 85-100

OnlineUtah.com http://www.onlineutah.com/mountainsall.shtml

Ross, M.L., Geology of the Tertiary Intrusive Centers of the La Sal Mountains, Utah, *USGSB, 2158,* 61-83

Sullivan, K.R., Isotopic Ages of Igneous Intrusions in Southeastern Utah, *USGSB, 2158,* 33-35, 1998.

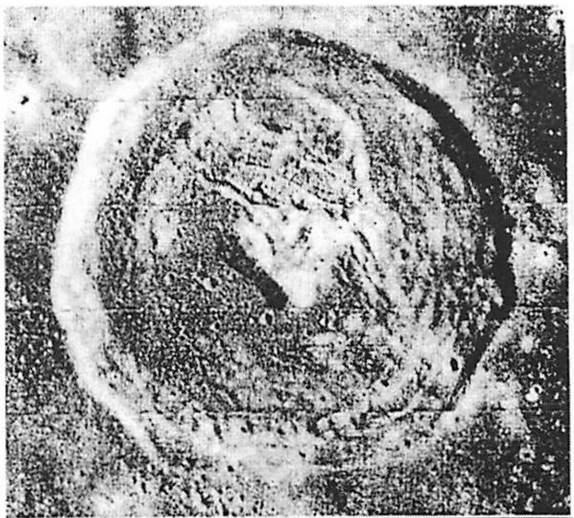
Utah! http://www.utah.com



Mug shot: From Grout and Verbeek, showing the location of the Henry, Abajo and La Sal mountains relative to other local geologic features.

Name: Laccolith Intrusion Model for Lunar Floor-Fractured Craters

DOB: 1976 (Schultz)



Mug shot: Lunar Orbiter 1 image (I-5-M) of the crater Doyle (2.0° N, 84.5° E; 32 km diameter). Adapted from Dombard and Gillis. 2001.

Physical Description:

1. Radial, concentric and polygonal fracture patterns.
2. Occurs in or near mare.
3. Modification during epoch of mare flooding.
4. Presence of basalt and pyroclastic deposits.
5. Uplift nearly entire floor of crater: craters generally shallow.
6. Ring faulting as approaches edge, creating "moat".
7. Unusually large, average diameter of 40 km (because of more fractures, lower gravity.)

Offences: Revealing confidential information about the lunar interior. Specifically:

1. Amount of uplift allows an estimate of the thickness of the intrusion.
2. Uplifted floor diameter indicates laccolith size.
3. Mantle depth can be estimated because the driving pressure is a function of column length. (Lunar magma is denser than the crust, so magma deposits must occur at the mantle.)

Known Associates: Craters in Mare Smythii and west of Oceanus Procellarum.

Known Enemies: The topographic relaxation model (acceleration of crater shallowing in high temperature, low viscosity region). Deceased (murder by simulation.)

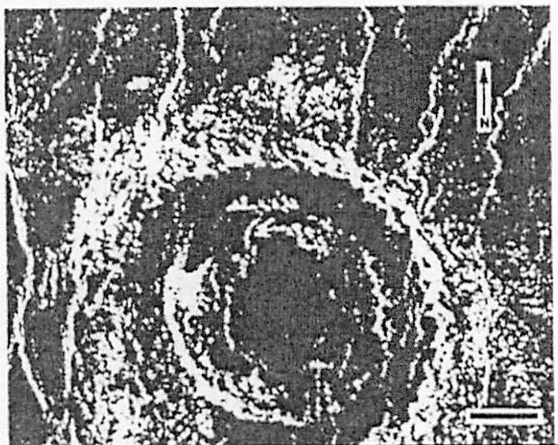
References:

Dombard, A.J., Gillis, J.J., Testing the viability of topographic relaxation as a mechanism for the formation of lunar floor-fractured craters, *JGR, 106,* 27,901-27,909, 2001

Schultz, P.H., Floor-fractured lunar craters, *Moon, 15,* 241-273, 1976.

Wichman, R.W., Schultz, P.H., Igneous intrusion models for floor fracturing in lunar craters, *Abstracts of the Lunar and Planetary Science Conference, 22,* 1501-1502, 1991

Name: Speculation on Laccolith Formation in Other Parts of the Solar System



Mug Shot: Volcanically modified crater centered at 52° S, 196° E, Venus. Adapted from Schultz, 1992.

DOB: 1992 (Venus)
1983 (Dione)
1996 (Mars)

Physical Description:

1. Laccoliths could possibly form anywhere with resurfacing.
2. Differences between moon and Venus:
    a. Unlike moon, crust denser than magma.
    b. Crust less fractured than moon because fewer impacts.
    c. Crust less fractured because melts together over time.
    c. Higher gravity limits height of any laccoliths
3. Uplift on Venus requires such high pressures that implies unreasonably long magma column.
4. Dione: Some ridges may be eroded laccoliths.
5. Laccolith-like shapes on Mars: possibly lava flows into subglacial voids?

Offences: Failure to show identification

References:

Lecinsky, D.T., Fink, J.H., Lava and Ice Interaction on Mars: Application of Terrestrial Observations and Laboratory Simulations, *LPI, 27,* 743-744, 1996

Moore, J.M., The Plains and Lineaments of Dione, *LPI, 14,* 511M, 1983.

Wichman, R.W., Schultz, P.H., Floor Fractured Crater Model for Igneous Crater Modification on Venus, LPICo., *789,* 131W, 1992.

All suspects processed by Eileen Chollet, LPL first year graduate student, 2004.

Geologic Overview of Southeastern Utah

Presented by: Mike Bland

The Precambrian:

(4.5 Ga – 550 Ma)

S.E. Utah

Utah (as we know it) does not exist. Crystalline basement resides quite deep. Rocks are most likely highly metamorphosed. No rocks of this period are exposed in SE Utah.

Globally

Earth Accretes and differentiates, Heavy Bombardment occurs, continental material slowly forms through subduction and partial melting of oceanic crust. Small terrains collide to form the North American Craton.

The Cambrian:

(550 – 500 Ma)

S.E. Utah

Subsidence of the cordilleran geosyncline (high topography west of Utah) occurs allowing a shallow sea to covered most of Utah. This period is known as the first major tansgression (Sauk). SE Utah is essentially on the cratonic shelf. No rocks are exposed from this period in SE. Utah

Globally

North American Craton is well established. Explosion of complex marine life (Cambrian Explosion). The equator runs across North America (from modern Mexico to modern Canada).

The Ordovician:

(500 - 440 Ma)

S.E. Utah

Tectonic uplift or a sea level drop causes most of Utah to be slightly above sea level at this time. The area seems to remain fairly stable throughout the period. No rocks from this period exist in SE Utah.

Globally

The second transgressive sequence begins (Tippecanoe). Proto-North America is still near the equator. Northern Appalachians form (Taconic Mnts.)

The Silurian:

(440 – 410 Ma)

S.E. Utah

Like the Ordovician, eastern Utah is still above sea level. Thus it is a period of substantial erosion. No rocks from this period are exposed in SE Utah.

Globally

Period of extensive reef and evaporite deposits due to the Tippecanoe transgression. North America is still near the Equator but drifting south. Most of continental material is south of the equator. Caledonian Mnts. form in collision between Europe and Greenland. Spore baring plants start to encroach on dry land.

The Devonian:

(410 – 360 Ma)

S.E. Utah

Devonian is a period of transition. In the early Devonian eastern Utah is still above sea level and is thus being eroded. By the end of the Devonian all of Utah is again covered by a shallow sea (period known as the 3rd transgression (kaskaskian)). No rocks from this period are found in SE Utah.

Globally

The Appalachians continue to form (specifically the Catskill) in a collision between proto-North America and Gondwanaland (Africa) that closes the proto-Atlantic ocean. The Devonian sees an explosion in fish varieties as well as the first amphibians on land and the earliest forests (seed plants).

The Mississippian:

(360 - 320 Ma)

S.E. Utah

Early, Utah is still covered by seas. These seas tend to be shallow in the SE. By the end of the period, however, Utah is again uplifted above sea level and eroded. No rocks from this period are found in SE Utah.

Globally

One word: limestone. Massive amounts deposited globally. End of Acadian and Antler orogenies.

The Pennsylvanian:

(320 - 285 Ma)

S.E. Utah

Period sees the uplift of the "ancestral Rockies" (Uncompahgre uplift). Creates a deep foreland basin (Paradox basin) in Utah which receives sediment from the uplift. Meanwhile, the 4th transgression (absaroka) covers all of Utah. Paradox salts and the Hermosa formation are deposited. **Earliest rocks that outcrop in SE Utah!!!**

Globally

Large increase in amount of land surface above sea-level (in North America) caused by continued collision of North America with Africa. Coal swamps dominate land surface. Insects flourish as the earliest reptiles prowl the land.

The Permian:

(285 - 245 Ma)

S.E. Utah

Lots of deposition is now occurring. The Paradox basin now seems to be above sea level. The ancestral Rockies continue to erode and deposit sediment (mostly sand) into the basin. However there are several marine incursions during this period. The Cedar Mesa and White Rim Sandstones of Canyonlands are from this period.

Globally

Period sees the final assembly of all of the continents into the super-continent Pangea as well as the end of the Appalachian orogeny. World famous "red beds" are deposited. Large synapsids and amphibians rule the land surface.

The Triassic:

(245 – 208 Ma)

SE Utah

Utah is still basically on the continental margin. Early in the period the area was covered by vast mud flats. The period then sees the rise of the Mesocordilleran high which cuts off SE Utah from the Pacific ocean (possibly related to subduction of Farallon plate). Meanwhile the west begins a period of extension adding 800 miles of dry land between Utah and the sea. The environment shifts from the mudflats to rivers, floodplains and swamps and finally to a desert environment where massive amounts of wind blown sand were deposited.

Globally

Pangea begins to rift apart Dinosaurs replace the synapsids. Earliest mammals.

The Jurassic:

(208 - 144 Ma)

SE Utah

SE Utah still remains a sandy desert with the Mesocordilleran high controlling the environment and preventing encroachment of the sea. Later in the period however, the sea encroaches from the north and eastern Utah again becomes a marginal mudflat. Late in the period the environment is dominated by river action as seen my deposition of the Morrison formation.

Globally

Western coastal mountains form in N. and S. America. Giant Dinosaurs dominate.

The Cretaceous:

(144 – 65 Ma)

SE Utah

Period is marked by the 5th transgression (Zuni). Seas flow in from the north and south flooding eastern Utah. By the end of the period however, the ocean has withdrawn and eastern Utah is once a near shore depositional zone. Two important orogenies occur: Sevier in the west and the Laramide in the East. The former produces a number of uplifts in eastern Utah including the Monument, San Rafeal Swell, and water pocket fold.

Globally

Rocky Mnts. form as continents head toward present locations. Dinosaurs dominate land.

The Tertiary:

(65 – 5 Ma)

SE Utah

This is generally a period of erosion with some deposition into fresh water lake environments. However two major events occur. First, in the mid-Tertiary igneous processes become important (form Henry, Abajo, LaSal, and Navajo Mnts.). Second, about 24 Ma region known as the Colorado plateau began uplifting to its present elevation of ~2km.

Globally

Geography as we know it begins to take shape. Laramide orogeny creates Rockies. Basin and range extension occurs. Mammals dominate the land surface.

Statigraphy of South Eastern Utah

Period	Age	Unit	Description	Locality
Precambrian - Mississipian	4.5 Ga - 320 Ma	No rocks exposed in S.E. Utah	4 billion years of Earth history and nothing to show for it.	
Pennsylvanian	320 - 285 Ma	Paradox Salts	Layered Evaporite Deposites interbedded with Limestones and shale	Base of San Juan River Colorado/Green river
		Upper Hermosa	Dark Grey thickly bedded limestone and Cherty limestone	Cliffs along San Juan River
Permian	285 - 245 Ma	Halgaito Shale (Cutler Group)	Redish-Brown/purple arkose S.S red siltstones, clays, and conglomerate	Near Mexican Hat and at the Col. Riv.
		Cedar Mesa S.S (Cutler Group)	White, reddish-brown, salmon S.S Massive, crossbedded, cliff forming	Canyonlands, esp. needles district Natural Bridges N.M.
		Organ Rock shale (Cutler Group)	Reddish-brown siltstone and sandy shale	Monument Valley with DeChelly S.S
		White Rim S.S (Cutler Group)	light grey to yellowish grey S.S Fine grained, crossbedded, Forms massive cliffs	Canyonlands esp. central portion. Forms light band in cliffs.
Triassic	245 - 208 Ma	Moenkopi Formation	limestones, siltstones, and sandstone generally reddish-brown, ripple-marks.	North Canyonlands San Rafael Swell
		Chinle Formation	Varigated red, yellow, purple, green clayey sandstone and siltstone	Petrified forest N.P. is most famous locality
		Wingate S.S	Reddish-brown, massive, crossbed, fine grained, well sorted. Forms prominent cliffs.	Forms wall surounding interior of Canyonlands. Orange cliff near Co. Riv.
		Kayenta S.S	Red-brown - lavender, fine-medium grained, interbedded w/ shale and L.S.	Caps Wingate Sandstone
Jurassic	208 - 144 Ma	Navajo S.S	Buff to pale orange, well sorted, fine grained, massive. Probably a wind blown deposit.	Famous S.S. of Zion, Capital Reef, Rainbow Bridge, Canyonlands.
		Entrada S.S	Pale-orange, fine-grained, massive, crossbedded, friable sandstone	Common in Arches N.P.
		Morrison Formation	vari-colored shales and fine grained sandstones, massive mudstones and shales. Famous for Dino fossiles	Famous in Dinosaur N.M. Seen here between Mexican Hat and Blanding
Cretaceous	144 - 65 Ma	Dakota S.S	Brown, massive to crossbedded conglomerate sandstone.	Exposed near the towns of Blanding and Monticello
		Mancos Shale	Dark-grey to black, fissile even bedded shale w/ fossiliforous sandstones.	Generally found near the town of Monticello
Tertiary	65 - 5 Ma	MesaVerde group		All are found North of Canyonlands near HWY 70.
		Wasatch Form.	Conglomerate to claystones	
		Green River Form.	Shale and Silt-stones	
Quaternary	5 Ma - Present	geomorphologic	River alluvium and Gravels, sand dune and landslide deposits	

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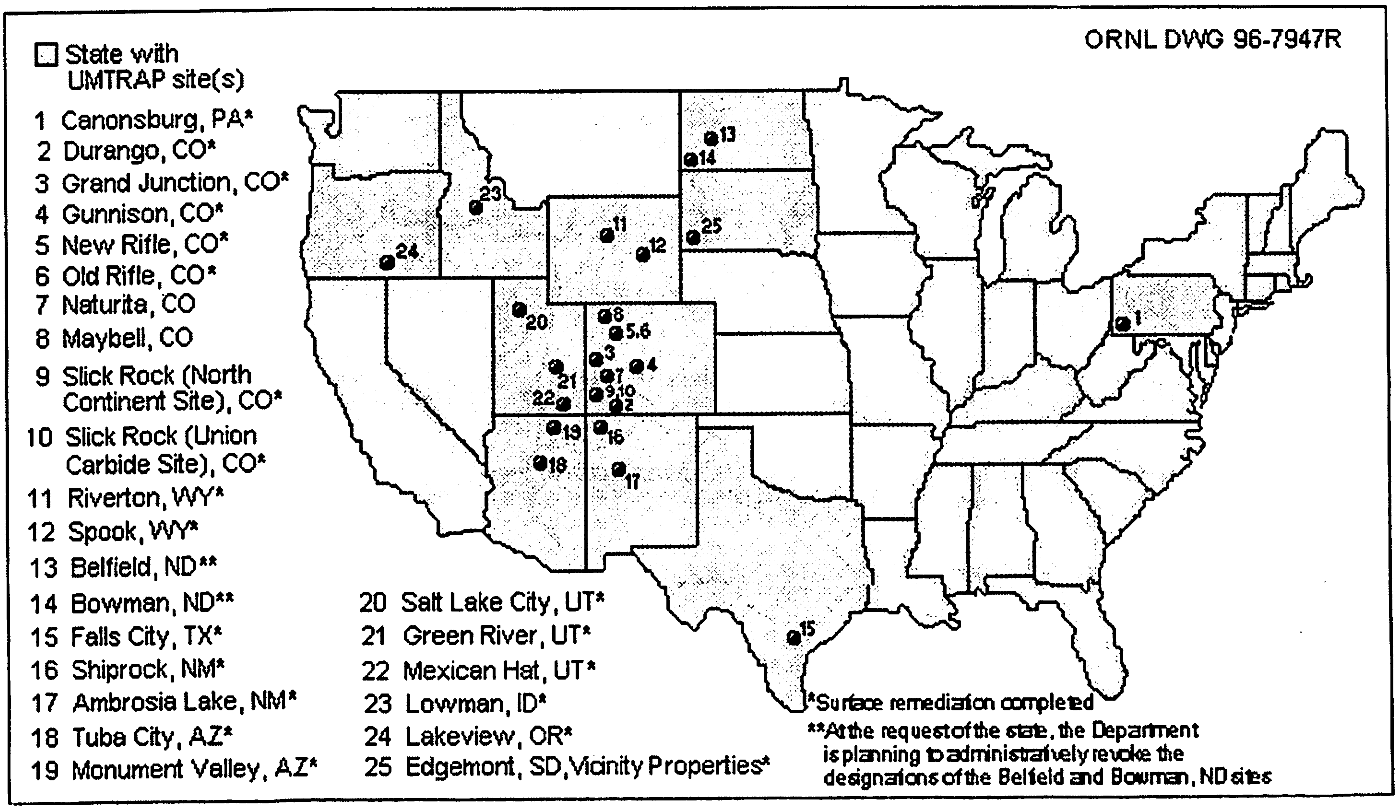
The Atomic History of the Four Corners

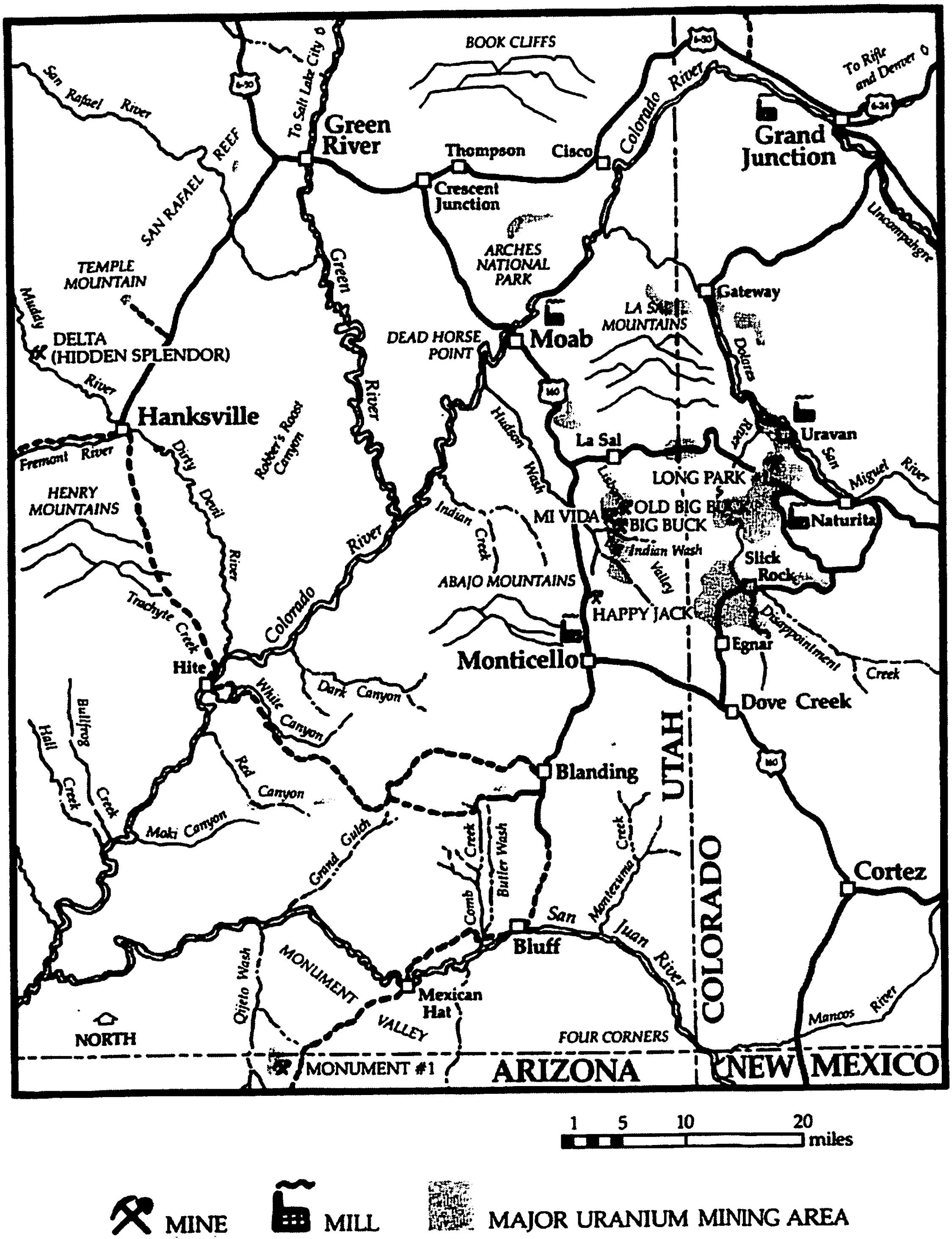
— Supporting Materials —

Dave O'Brien



UMTRAP = Uranium Mill Tailings Remedial Action Program

http://web.em.doe.gov/fig62.html



R.C. Ringholz, Uranium Frenzy; Saga of The Nuclear West

(50)

Petroglyphs at Newspaper Rock, Utah

by David Choi

> *The American desert was discovered by an unknown people. They tried its deepest secrets. Now they have vanished, extinct as the tapir and coryphodon. But the undeciphered message that they left us remains, written on the walls. A message preserved not in mere words and numbers, but in the durable images of line on stone:* We were here. --Edward Abbey, *The Serpents of Paradise*

Introduction to Petroglyphs

Petroglyphs are a form of artwork where pictures are directly carved or pecked onto a rock face. This differentiates them from pictographs, which essentially are paintings that use rock as a canvas. Petroglyphs are usually found exposed out into the environment, whereas pictographs are usually found in caves or under ledges for protection from the environment.

Most petroglyphs made in the United States were made by Native Americans. The state of Utah has over 7,500 documented petroglyph sites and may well be the region of N. America with the most petroglyphs. (Figure 1)

Petroglyphs are usually found on desert rocks with a patinated surface known as "desert varnish." This is a dark coating made up of clay minerals that accumulates over time. Chipping away at this outer varnish reveals the original, lighter rock underneath. Over time, petroglyphs will accumulate the varnish themselves and start to fade. This fact makes it useful for determining a relative age of petroglyphs, because calculating an absolute age (by radioisotopic measurements, for example) can be difficult.

Unlike hieroglyphics, petroglyphs in the Southwest most likely do not represent a written language. Instead, most archaeologists consider petroglyphs to have symbolic meaning at most. It is quite difficult to interpret these symbols without the cultural context of the Native American tribes that composed them. Nevertheless, archaeologists and others have made their best educational guesses as to what these symbols mean through contextual clues.

As for why ancient or historic Indian tribes made these petroglyphs, several reasons are given:

* To mark territory, to serve as a trail guide for hunting, or as a primitive map
* To record special events, such as rituals, dreams, or hunts
* To connect with spirits about harvests, rain, fertility, etc.
* To simply make art
* To state "we were here"

In the case of abstract petroglyphs, it is always a possibility that these drawings were made to reflect an altered state of consciousness or drug-induced state.

Newspaper Rock

Newspaper Rock is a petroglyph site located in southeastern Utah located near the head of Indian Creek and Canyonlands National Park. This site is one of many Newspaper Rocks, common in name only. There is, in fact, another Newspaper Rock at Fremont Indian State Park in Utah, and another one at the Petrified Forest State Park in Arizona.

Newspaper Rock was named by early settlers and explorers who considered the images as a form of writing that could be read like words on a newspaper. The Navajo name for Newspaper Rock is "Tse Hane," which means "rock that tells a story." However, due to the sheer density of images, it is difficult to determine if there is any logical progression to the petroglyphs.

Petroglyphs from a variety of time periods are found on Newspaper Rock. Some date as early as 900-1300 AD, when the Anasazi tribe inhabited the region. These early images can be seen at the top of the main panel of rock (Figure 2). However, most of the images are newer and fresher, and have been traced to the Ute tribe in the 19th century.

Many common petroglyphs are seen from the Utes. Several anthropomorphs (inanimate objects, forces of nature, or animals given human characteristics) with broad shoulders and horns or headdresses are seen. Petroglyphs depicting local wildlife such as deer, elk, bighorn sheep, and bison are also present. Human and animal footprints are also scattered throughout the rock face. However, it is the horse, and petroglyphs of horseback riding, that enable archaeologists to date these images. Native American historians know that the Utes acquired the horse around 1800. Note also the prominent depiction of hunting with a bow and arrow on horseback.

More on the Utes

The Utes have a distinct artistic style in their petroglyphs, but they also imitated other styles that are seen on the rock. It is unknown why they overlaid their petroglyphs on top of prehistoric petroglyphs made by ancient tribes. Perhaps an early attempt at erasing history?

The Ute tribe flourished in the Eastern Utah/Western Colorado region in the 19th century. Once they acquired the horse, they adopted a roaming and raiding lifestyle and raided Pueblo tribeland and Spanish settlements. By the latter part of the century, however, the opening of the West to exploration, settlement by Anglo-Europeans, and gold rushes meant the end of their dominance in the region.

It is interesting to note, however, that the opening of the West to settlers did not mean the end of the tribe. In fact, Anglo-European elements are seen in their petroglyphs. Note the interesting figure with a horned headdress with wavy lines emanating from its head. These represent traditional elements of Native American rock art, but also note the presence of chaps on the figure's legs, and a quirt-like object in the figure's hand. (A quirt is essentially a whip.) This may be a sign of the remarkable influence that Anglo-

European culture had on the Ute tribe. Also, see Figure 3 for a photograph showing Anglo-European fashion influence on the Utes.

Conclusion

Petroglyphs are a form of rock art that is found in numerous sites in the Southwestern United States. Although they have been neglected as a subject of academic studies in the past, more and more scholars are pursuing rock art studies in order to seek new knowledge of the Native American tribes that inhabited these regions many years ago. If you'd like to see more rock art, there are many opportunities in the Southwest, and in fact there are some in the Needles district of the Canyonlands. Sites are found near Devil's Lane, the Cave of 200 Hands near Devil's Lane, Salt Creek Canyon, and Horse Canyon. Various other petroglyph sites exist near Moab and Arches National Park. Please consult the text by Slifer for more details.

References

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Slifer, Dennis. *Guide to Rock Art of the Utah Region: Sites with Public Access*. Ancient City Press, 2000.

Wikipedia.org:
http://en.wikipedia.org/wiki/Petroglyphs
http://en.wikipedia.org/wiki/Newspaper_Rock_State_Historic_Monument

http://minerals.gps.caltech.edu/files/varnish/

Figure Sources:

(1) is from the text by Slifer, while (2) and (3) are from the text by Cole.

Figure 1. Map of the Four Corners region showing distribution of known rock art sites. (Adapted from Grant 1967, 17)

(1)

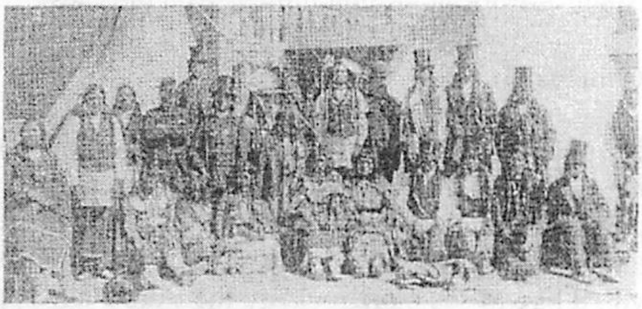


Plate 108. *Ute men wearing traditional and European style clothing, including top hats and capes at the Denver Expositions in 1882. A Ute with a top hat and cape may be represented in a petroglyph at site 5MN3446. William Henry Jackson photograph, courtesy of the Denver Public Library Western History Collection.*

(3)

Plate 110

Plate 111

Early and Late Historic Ute Indian Style petroglyphs at Newspaper Rock State Park, Utah. Plate 110 *is an overview of Newspaper Rock with its variety of elements. Note the heavily patinated figures at the top center of the panel that are probably Pueblo II-III Anasazi in origin and contrast with the more recent and lightly patinated Ute petroglyphs.* Plate 111 *shows a detail of an anthropomorph that appears to wear fringed leggings or chaps and holds a quirtlike object similar to those appearing in late Plains rock art.*

(2)

CANYONLANDS FIELDTRIP 2004
Evaporite Deposits in Paradox Basin
By John Keller

The Paradox Basin was formed during the Pennsylvanian epoch of the Carboniferous Period (320-292 Mya) in response to plate collisions between North America and the South American-African plate. The present basin, 11000 square miles in area, is defined by the extent of halite deposits of the Paradox Formation of the Hermosa Group. The deepest part of this assymetric basin was towards the northeast, adjacent to the Umcompahgre Uplift. Widespread evidence for 29 halite bearing evaporite cycles are found throughout the basin.

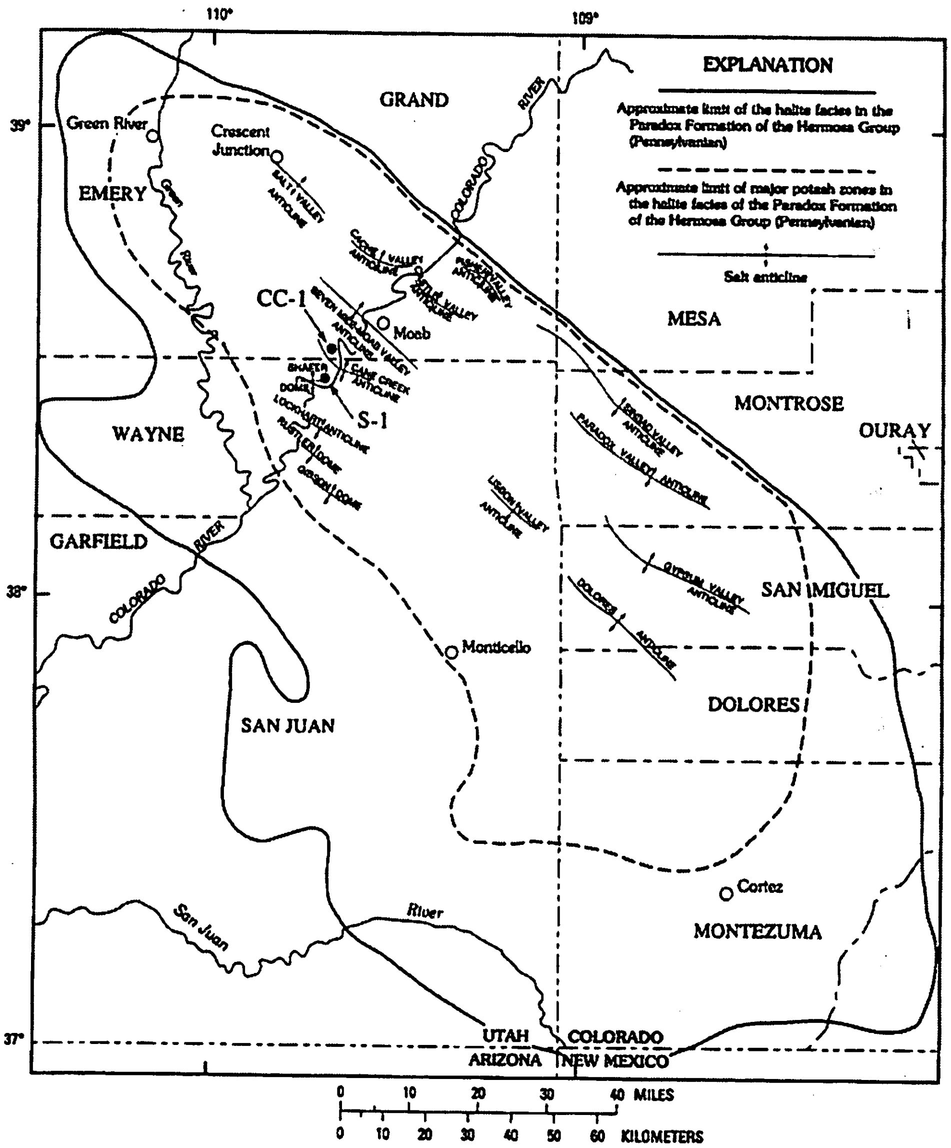


Figure 1. Limits of evaporite facies in the Paradox Formation of the Hermosa Group in the Paradox Basin, southwestern Colorado and southeastern Utah. Locations of Delhi-Taylor Oil Company Cane Creek No. 1 (CC-1) and Shafer No. 1 (S-1) core holes are also shown.

Evaporite Sequence (29 cycles identified in basin cores)

ANHYDRITE: Lower layers show mm-thick laminations that grade into a nodular texture above. Deposited after sudden rise in sea level and resulting influx of calcium and sulfate from the open ocean and mixing of saltier basin water and brine from the ocean. Nodular textures may have come from recrystallization of laminated anhydrite in muds.

SILTY DOLOMITE: Fine-grained, sugary texture; composed mostly of dolomite with quartz, calcite, anhydrite, clay, and mica. Sea level still rising and brines continue to decrease in salinity and increase in HCO_3 ions. Sorting of quartz in this layer may indicate transport by density currents or possibly eolian origin.

BLACK SHALE: Fine-silt to clay sized minerals of dolomite, calcite, quartz, clay minerals, and mica. Carbonate content reaches 30% and total organic content is a few to ten percent. Organic matter came from both marine and continental sources along with algae and bacteria. Quartz and such may have come from eolian origin. Upper part of black shale starts to show signs of sea level lowering.

DOLOMITE: Sugary texture again with blotchy texture from organic inclusions and pyrite clots. Somewhat less siliciclastic material perhaps because less silica rock was being available or because of lower rainfall rates and less flooding.

ANHYDRITE: Laminated texture either from precipitation directly out of the brine or anhydrite replacement of carbonate algal mats. If algal, was deposited in relatively shallow water allowing sunlight to support algae.

HALITE: Top sequence of evaporation deposited in highest salinity brine. Clear to slightly cloudy halite crystals with crystal sizes up to half a centimeter interspersed and laminations of anhydrite. Some laminae have "snow-on-the-roof" texture – layer of anhydrite draped like snow fallen on angular roof tops. Halite crystals underneath were in place when calcium sulfate rained down from above, indicating both halite and anhydrite were formed underwater. Laminations may have been caused by 1) yearly fluctuations in temperature and solubility of calcium sulfate (more soluble during winter months), or 2) annual storms carrying calcium bicarbonate into basin. Thickness of halite beds increases towards the top.

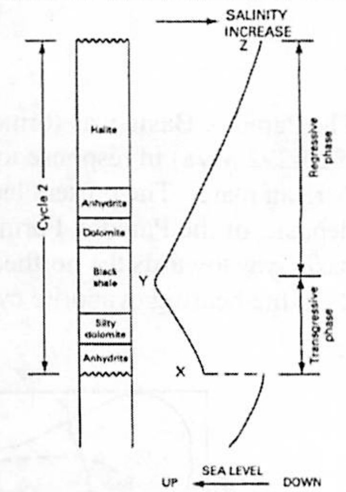


Figure 4. Stratigraphy of cycle 2 facies in Cane Creek No. 1 core. Curve shows relative sea level and salinity during deposition of each facies. Points X, Y, and Z (referred to in text) are important positions in the salinity cycle. Location of core hole shown in figure 1. Modified from Hite and Buckner (1981).

Figure 29. Photograph of segment of Shafer No. 1 core, depth 3,673 ft (1,119.5 m), illustrating snow-on-the-roof texture in halite bed of cycle 9. Location of core shown in figure 3.

Bromine

Bromine gets concentrated in brines through evaporation of sea-water. Small portion of bromine incorporated into halite and bromine content serves as indicator for salinity. Trend in bromine concentration shown below serves as evidence for continuous deposition of halites rather than sporatic episodes. Indicates deep basin with relatively large volume of brine.

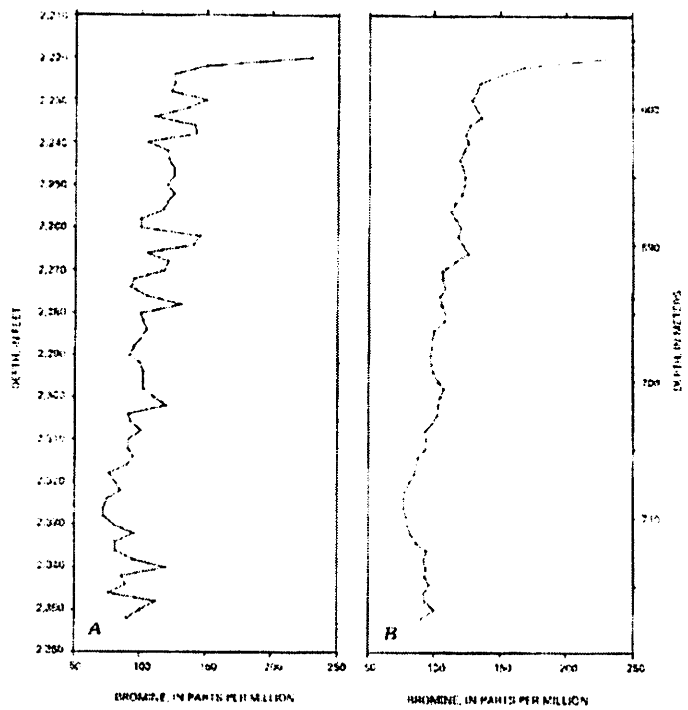


Figure 37. Bromine distribution in halite bed of cycle 3, Cane Creek No. 1 core. A, Analytical results. B, Smoothed profile using a moving average of five points

Glaciation in Gondwanaland

The repetitive nature of the 29 evaporitic cycles found in the Paradox Basin is possibly explained by episodes of glaciation in Gondwanaland. Melting of glaciers would cause a rise in sea level and influx of free ocean water into the Paradox Basin. Growth of Gondwanaland glaciers would decrease sea level, cutting off basin and allowing evaporation to increase salinity and deposition of anhydrite and halite beds.

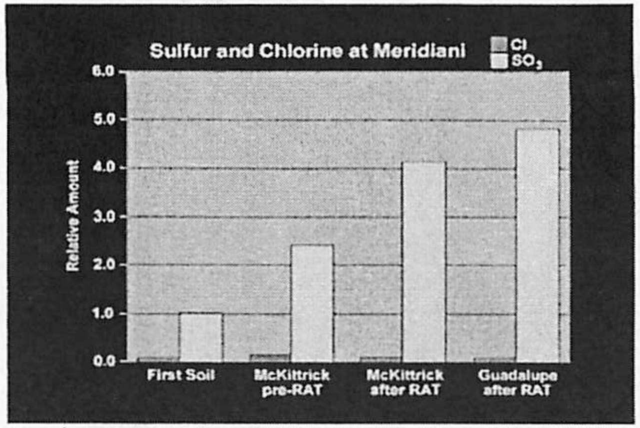
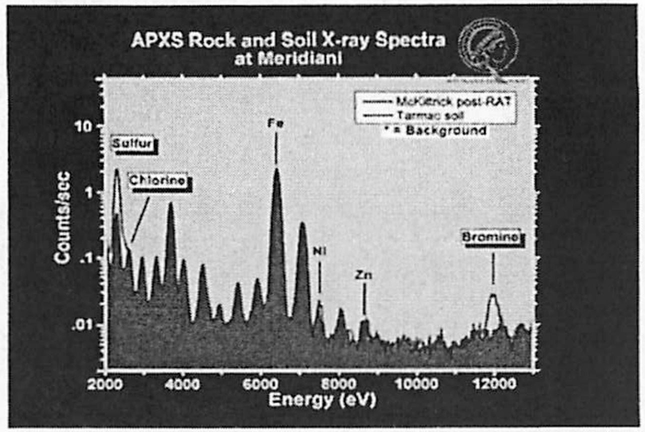
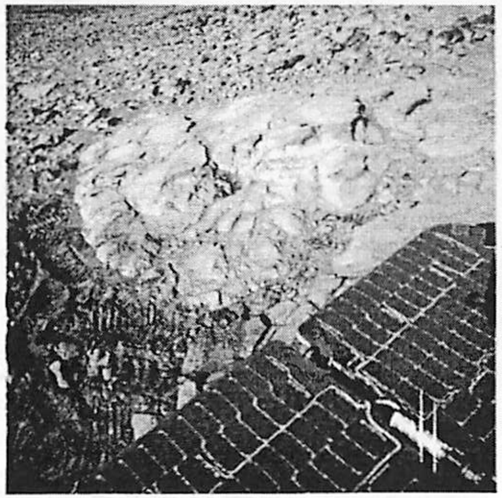
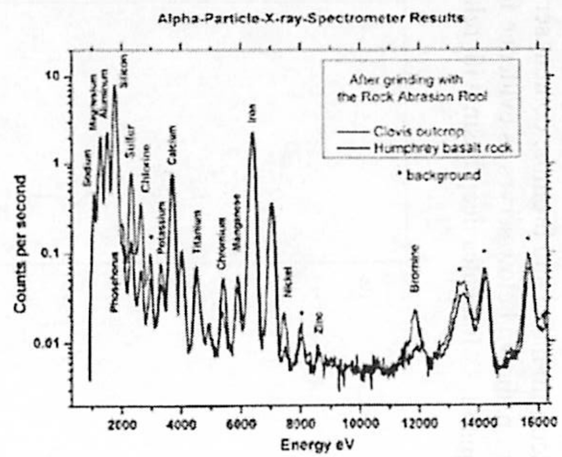
References:

Raup, O.B., & Hite, R.J., "Lithology of evaporite cycles and cycle boundaries in the upper part of the Paradox Formation," USGS Survey Bulletin 2000-B.

Raup, O.B., & Hite, R.J., "Bromine Geochemistry of Chloride Rocks of the Middle Pennsylvanian Paradox Formation," USGS Survey Bulletin 2000-M

http://marsrovers.jpl.nasa.gov/

MER Evidence for Evaporites on Mars

Rocks at Eagle Crater analyzed by Opportunity rover show evidence for evaporite deposits.		
Clovis Clovis outcrop in the Columbia Hills analyzed by Spirit rover shows evidence for water deposition of salt bearing rocks.		

58

History of the National Parks of Utah

by
Curtis S. Cooper

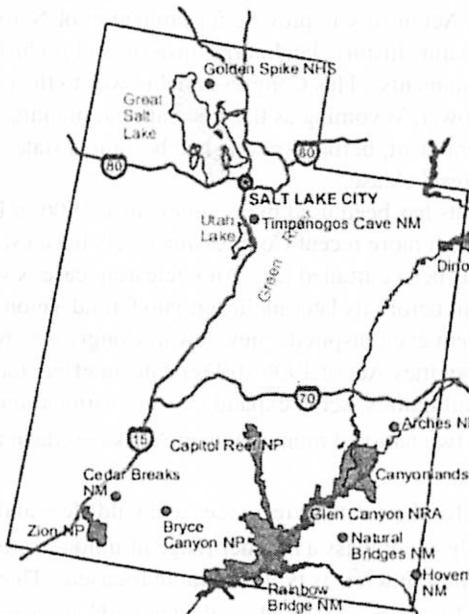


Figure 1: Shows the geographic locations of the National Parks and Monuments of Utah [4].

I. Introduction

The national parks of the state of Utah include *Zion* and *Bryce Canyon* in the southwest, *Capitol Reef* in the south-central part of the state, and *Arches* and *Canyonlands* in the southeast (see Figure 1). A number of national monuments are also shown in Figure 1. They each have unique histories, which in some cases date back thousands of years to the first human inhabitants of Utah.

Early European settlers encountered several tribes in Utah belonging to the Ute Nation, after which the state of Utah is named [1]. I have provided reference [1] in part for students who are interested in exploring further the ancient history of Utah.

In this discussion, however, I will concentrate primarily on the last hundred years of the histories of these national parks, especially with respect to their establishment, development, and administration by the National Park Service for the United States Department of the Interior. Note that the approach to maintaining and developing these sites, which by their designation as national parks identifies them as places of special geographic importance to the nation, has changed throughout the history of the National Park Service (NPS).

II. National Park Service

Founding the NPS—The bill to establish the NPS was held up about six years in Congress until it finally passed. It was signed by President Woodrow Wilson on August 25, 1916. The task of the NPS was to maintain and supervise the development of the 14 national parks and 21 national monuments existing at that time, all of them west of the Mississippi except for Acadia National Park in Maine: it was charged "to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." The interpretations of this charter vary greatly among NPS officials.

The NPS became truly national on August 10, 1933 by executive order following the request by Horace M. Albright, first assistant director of the NPS under director Stephen T. Mather, to President Franklin D. Roosevelt to also acquire the U.S.

Military Parks. Today, beyond the National Parks themselves, NPS administers the National Monuments, National Preserves, National Historic Parks, National Military Parks, Recreation Areas, and several other kinds of parks that have been established more recently. The NPS is consistently rated among the most popular federal agencies by public opinion poles [2].

National Monuments vs. National Parks—Many people (myself included before researching for this talk) are confused about the difference between national parks and national monuments. National parks and their boundaries are established by direct acts of Congress. I do not know if any national park foundation bills have ever been vetoed by a contemporaneous president. National monuments, on the other hand, can be quickly declared by the president without approval from Congress.

In 1906, Congress passed the Antiquities Act mostly to provide for protection of Native American artifacts on federal lands in the West. It authorized presidents to proclaim "historic landmarks, historic and prehistoric structures, and other objects of historic or scientific interest" as national monuments. This Congressional power to the president was first used by Theodore Roosevelt later that year to declare Devils Tower, Wyoming as the first national monument. He followed in 1908 with the proclamation of Grand Canyon National Monument, before Arizona had become a state. It is the second national monument to have been founded under the "scientific interest" clause.

The power to proclaim national monuments has been used many times since 1906 in U.S. presidential history, although in some states like Wyoming and Alaska, in which more recent Congressional acts have established vast regions of national park and national preserve territory, this power has been curtailed [3]. An interesting case is when President Franklin D. Roosevelt proclaimed Jackson Hole National Monument before its later inclusion into Grand Teton National Park, an action which sparked fiery scorn among locals. The incident even inspired a new law in Congress to repeal the Antiquities Act of 1906, which Roosevelt promptly vetoed! The Antiquities Act of 1906 still remains in effect today (except in Wyoming and Alaska).

Note that presidents have also used the Antiquities Act to expand existing national monuments. For example, Jimmy Carter in 1978 made substantial additions to two national monuments in Alaska—Glacier Bay and the Katmai—both of which have since been promoted into national parks.

National parks receive greater protection for their natural resources and wildlife—and usually better funding—than national monuments. The national parks also normally encompass a broader range of unique natural features than national monuments, whose scope in terms of historic and/or scientific interest is typically more focused. That being said, Congress has acknowledged the greatness of many national monuments—such as the Grand Canyon—and converted them into national parks after their original identification.

The first national park was Yellowstone, established in 1872. The largest is Wrangell-St. Elias National Park and Preserve, which boasts a grand 13.2 million acres (about the combined land area of Vermont and New Hampshire).

Administration Philosophy—It was the artist George Catlin who originally articulated the special national (and ultimately international) significance of certain western U.S. locations, which might be preserved "by some great protecting policy of government ... in a magnificent park ... A nation's park, containing man and beast, in all the wild and freshness of their nature's beauty!"

The essay by Dwight T. Pitcaithley [4], Chief Historian of the National Park Service, eloquently describes the founding of the national parks, which has been often called, in the words of Wallace Stegner, "the best idea we ever had." The philosophy espoused in the administration of the many national parks varies greatly, and the overall land management strategies of the NPS have evolved over time. These changes have greatly impacted the available activities and general accessibility of the parks nationwide. For example, the road through Denali National Park in Alaska, one of the crow jewels of the U.S. Park System, is only accessible to tourists by public bus. This is a long story that I won't delve into here in more detail, but **I strongly recommend you have a look at Pitcaithley's essay** (and associated references), if you have a chance on your own time. It is published on the WWW.

III. The Early Years in Utah's National Parks

In this discussion, I will briefly summarize the interesting and important events in the early histories of Utah's national parks. Although Zion National Park and Bryce Canyon National Park are furthest from our course on this trip, I will comment on several aspects of their histories briefly in my talk because they are considerably older than Arches, Canyonlands, and Capitol Reef in terms of the administration history of the National Park Service. These summaries are largely taken from the Utah History Encyclopedia, ed. by A.K. Powell [5]. Also, the article by Wayne K. Hinton [6] and Woodbury's well-written (though somewhat outdated) book [1] are invaluable references on the histories of Zion and Bryce Canyon. I have also referred extensively to the parks' own WWW pages [2].

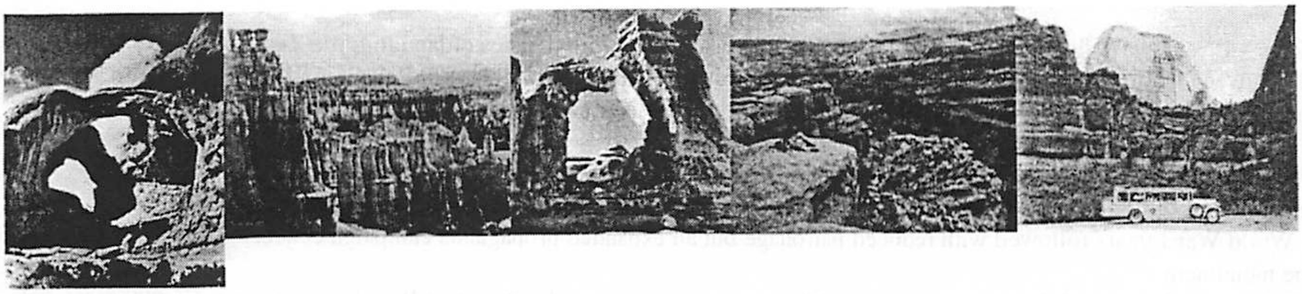


Figure 2: Spectacular views from each of Utah's national parks. From L to R: Arches, Bryce Canyon, Canyonlands, Capitol Reef, and Zion.

Arches—This national park has over 500 arches of Jurassic-era sandstone. The first Mormon settlers in the Moab area of southern Utah arrived in the 1850s but were driven out by the Utes. They returned in the 1880s to found the town of Moab. The first inhabitant of the park was John Wesley Wolfe, a Civil War veteran, who lived on the Salt Creek with his family in 1898.

The NPS learned of the area in the 1920s and petitioned for its inclusion in the national park system. Arches National Monument was thus created by President Herbert Hoover in 1929. A scientific expedition led by a local newspaper editor and amateur scientist named Frank Beckwith entered the monument from 1933-4 to study its geology, botany, wildlife, archeology, and paleontology. The highly successful publications of the Arches National Monument Scientific Expedition contributed to the growing popularity of the monument. The first paved road did not appear in Arches until 1958.

The boundaries of Arches National Monument were altered during the 1960s. The current national park currently includes 76,519 acres. Arches National Park was established by Congress and signed by President Richard Nixon on November 12, 1971. In 1955-56, a natural gas pipeline was built through the northern sections of the park, leaving a scar that is still visible.

Today, Arches National Park is among the most popular of the national parks and monuments in the southwest U.S., with thousands of tourists visiting it each year. The nearby town of Moab has become the center of a growing recreation area popular for hiking, biking, cross-country skiing, river running, and other outdoor activities. Like the system established in Canyonlands National Park, the NPS may someday restrict tourist traffic through Arches to preserve the park's natural wonders for the enjoyment of future generations.

Bryce Canyon—Bryce Canyon waited fairly long before promotion and development established its popularity. National Forest Supervisor J.W. Humphrey in 1915 visited Bryce Canyon and was amazed at its beauty and grandeur and sought to promote the area and improve its accessibility. Several pictorial articles appeared in tourist journals in 1916, and postcards featuring views like the one shown in Figure 2 began to circulate across the state. In 1919, the Utah state legislature asked Congress to create Bryce Canyon National Monument, which was done in 1923. Development was begun by the Union Pacific railroad, including campgrounds, cabins, a lodge, and improved access to the Canyon. In 1928, Bryce Canyon was promoted to Bryce Canyon National Park and placed under the administration of the NPS. Later, 12,000 additional acres were added to this magnificent southern Utah attraction.

Canyonlands—Located near the confluence of the Green and Colorado rivers, near the center of the park, the area had been promoted during the 1930s for inclusion into Escalante National Monument without success. Finally, after considerable opposition within the state of Utah, a bill establishing Canyonlands National Park—32nd in the national park system—made its way through Congress and was signed by President Lyndon B. Johnson on 12 September, 1964. With a total of 337,258, Canyonlands is the largest of Utah's national parks. Today, the park is divided into three districts, Island in the Sky, Needles, and Maze-Standing Rock, which are not connected by inner roads: visitors must leave the park to enter another district. The park is not developed in several areas, with access only to hikers.

Capitol Reef—Epraim Porter Pectol was the father of Capitol Reef National Monument. In 1933, a Pectol initiative in the Utah legislature failed to convince Congress to establish the park. The result was Capitol Reef National Monument, established by presidential decree (by FDR) on August 2, 1937. During the 1960s, the park received new facilities for entertaining the growing number of tourists to Capitol Reef. President Lyndon B. Johnson in 1968, just before he left office, was persuaded by preservationists to expand the monument an additional 216,056 acres, a controversial decision locally that also put great strain on the overworked staff of Capitol Reef. Still, the monument survived its growing pains and was eventually expanded to include most of the Waterpocket fold following the establishment of Lake Powell. After a number of failed bills, Congress finally voted to make Capitol Reef into a national park. The law was signed by President Nixon on December 18, 1971.

Zion—President William H. Taft on July 31, 1909 set aside some 15,840 acres of land in Little Zion Canyon as Mukuntuweep National Monument, the Indian name recorded by surveyor John Wesley Powell in 1872. The canyon was notoriously hard to get to, although its relatively few visitors were impressed that "nature seems to have made this canyon a fine gallery of stupendous proportions."

The Arrowhead Trails Association built the first road to Mukuntuweep National Monument, making the monument accessible to automobiles. On September 8, 1916, legislation passed to build a five mile road through Mukuntuweep Canyon. The World War I years followed with reduced patronage but an expanded propaganda campaign conceived to generate interest in the monument.

On March 18, 1918, Mukuntuweep National Monument was expanded by President Woodrow Wilson to 76,800 acres and renamed Zion National Monument. With the name change, officials in Utah now focused on obtaining national park status. Reed Smoot, a Mormon apostle and United States Senator, introduced the bill establishing Zion National Park, which eventually passed through the houses of Congress, and President Wilson signed it on November 20, 1919.

NPS director Stephen Mather returned to Zion regularly in its first years as a national park. Eviend T. Scoyen was appointed as the first superintendent of Zion National Park. During these years, the bridge across the Marble Gorge of the Grand Canyon was built, the first road into the canyon in 1917, and the first lodge in 1925. Scoyen also oversaw the construction of the Zion, Mt. Carmel Tunnel and Highway that seemed so necessary for expanding tourism in Zion. The project, which was finished in 1930, was a spectacular engineering feat in the history of road-building: "Five galleries from the tunnel to the canyon wall offer the motorist vantage points for viewing the awe-inspiring scenery" [1]. Tourism in the park gradually increased to 190,000 by 1941. Kolob Canyon National Monument, established in 1937 under FDR, was incorporated into Zion National Park in 1956.

Today, Zion is Utah's most visited national park, with over 3 million visitors in 1993. To reduce congestion, the NPS announced in the mid-90s plans to limit entry by private automobiles by constructing a public transportation system through the park. Nowadays, from April through October, the Zion Canyon Scenic Drive is accessible by shuttle bus only.

IV. Recent Developments under Clinton and Bush

Bill Clinton in 1996 used the authority granted by the Antiquities Act of 1906 to establish in south-central Utah a new huge national monument: Grand-Staircase Escalante National Monument. The monument extends 1.7 million acres, or 3% of the are of Utah, between Bryce Canyon and Capitol Reef national parks [7]. This action was widely unpopular in Utah and prompted the initiation of bills to further curtail presidential authority, none of which have been enacted. Grand-Staircase Escalante National Monument is unique in being the first national monument to be administered by the Bureau of Land Management rather than the NPS.

George W. Bush has come under intense criticism from environmentalists for policies adversely affecting the national parks. Environmental grievances against the present administration include [8]:

- **Oil and gas drilling.** In an effort to find oil and gas, 50,000-pound trucks are hammering the ground between Arches and Canyonlands National Parks (UT), sending shock waves into the earth and damaging fragile desert soils which may take decades to recover.
- **Drilling in protected wilderness.** In February 2004, the Bureau of Land Management sold drilling rights to 124 parcels of federal land in Utah and Colorado, 37 of which had been identified as suitable for wilderness protection.
- **More Roads in Protected Lands.** In January 2003, the Bush administration re-activated an antiquated 1866 law that granted states and localities rights-of-way across unreserved federal lands. That decision opens up for the first time millions of acres in national monuments, national forests, wilderness areas and other public lands to road building.
- **Water: Industry Over Wildlife.** The Administration is undermining a 100-year-old legal doctrine that grants the federal government water rights necessary to support public lands, whether they be Indian reservations, national forests, or national parks.
- **Privatizing Our Parks.** The Bush administration is attempting to "outsource" critical functions of the National Park Service, calling it a cost-cutting measure.

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The Joy of Joints

Tamara Goldin

What are Joints?

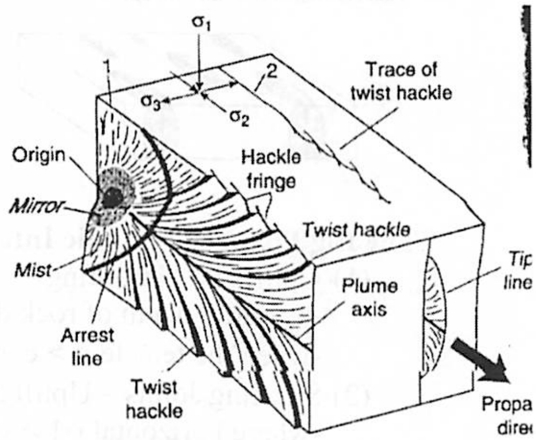
-Joints are natural fractures in rocks often occurring in regularly spaced and subparallel sets. Many geologists distinguish joints as fractures across which there have been no shear displacement (in contrast to faults).

-The term *joint* itself is nongenetic, but many contemporary geologists believe these joints showing no displacement are tensile fractures that form perpendicular to the minimum principal stress ($\sigma 3$) and parallel to the prinicipal plane of stress containing the $\sigma 1$ and $\sigma 2$ directions. Joints nucleate at tensile stress concentrations around Griffith cracks.

-Some geologists use the term *joint* to refer to shear fractures as well. These *shear joints* form close to the direction of maximum shear stress.

Why are joints worth studying?

-control landscape morphology (preferential erosion)
-affect rock strength and permeability
-provide stress and strain history



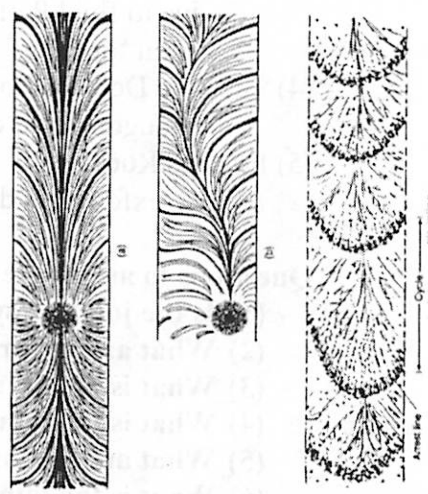
From van der Pluijm & Marshak 1997

Surface Morphology: Plumose Structure

-joint surfaces resemble a feather
-spreads outward from origin and consists of several zones
-*arrest lines* represent incremental growth
-Why isn't the joint surface smooth?

(1) real rocks are inhomogenous, anisotropic
 -inhomogeneities distort local stress field at joint tip
 -so principal stresses at tip not necessarily parallel to $\sigma 3$

(2) σ intensity at crack tip proportional to crack length
 - local tensile σ at crack tip proportional to σ intensity
 -velocity of propagation proportional to σ intensity
 -these parameters increase away from origin and reach a maximum
 -if σ at crack tip exceeds critical value, the excess energy forms additional off-plane cracks splaying off the main joint



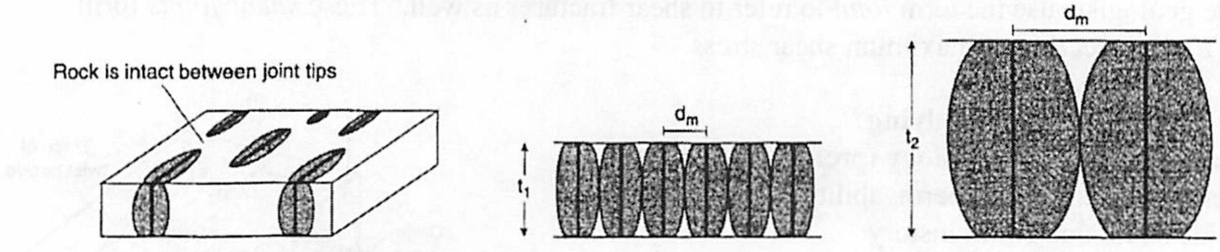
Other Theories of Joint Formation:

-shear, torsion, earthquakes, lineaments, cleavage, magnetic forces
-semi-diurnal tides (Hodgson 1961)

Joint Arrays

-*nonsystematic joints*—irregular spatial distribution
-*systematic joints*—parallel/subparallel, evenly spaced
 -*joint sets*—a group of systematic joints
 -*joint system*—2+ joint sets intersecting at a constant *dihedral angle*
 (1) *Orthogonal system* 90°
 (2) *Conjugate system* 30-60°

Joint Spacing (Sedimentary Rocks)
-joint formation relieves tensile σ for a critical distance d_m on either side
-this region of reduced stress is called the *stress shadow*
→ joint spacing controlled by the width of stress shadow
-the greater the cross-sectional length of the joint, the wider the stress shadow
→ joints more closely spaced in thinner beds and vice versa
-joint spacing also controlled by:
 -lithology (stiffer beds have smaller joint spacing)
 -*Hooke's Law*: $\sigma = E\varepsilon$ (E= *Young's Modulus*)
 -tensile strength (rocks with lower tensile strength have smaller joint spacing)
 -extensional strain magnitude (a bed that's been stretched more has more joints)



From van der Pluijm & Marshak 1997

The Big Picture: Tectonic Interpretation of Joints
(1) Uplift and Unroofing
 -as burial depth of rock decreases it cools and contracts→ horizontal tensile σ
 -when the tensile σ > compressive σ due to burial → vertical joints form
(2) Sheeting Joints—Uplift and Exhumation
 -where horizontal σ1 > vertical σ3 near the surface
 -joints parallel topography
 e.g. pluton that cools and contracts more than country rock
(3) Natural Hydraulic Fracturing
 -due to fluid P of water, oil, and gas in rock
 -when 'opening' tensile stress caused by fluid pressure exceeds 'closing' stresses
(4) Tectonic Deformation
 -orthogonal and conjugate joint systems
(5) Igneous Rocks
 e.g. exfoliation domes, columnar joints

Questions to ask in the Field? (from van der Pluijm & Marshak 1997)
(1) Is the jointing systematic or nonsystematic?
(2) What are the orientations of joint sets, dihedral angle?
(3) What is the nature of cross-cutting relationships, joint intersections?
(4) What is the joint surface morphology?
(5) What are the joint dimensions?
(6) What is the joint spacing and density?
(7) How is joint distribution affected by lithology?
(8) How are joints related to other structures/fabrics?

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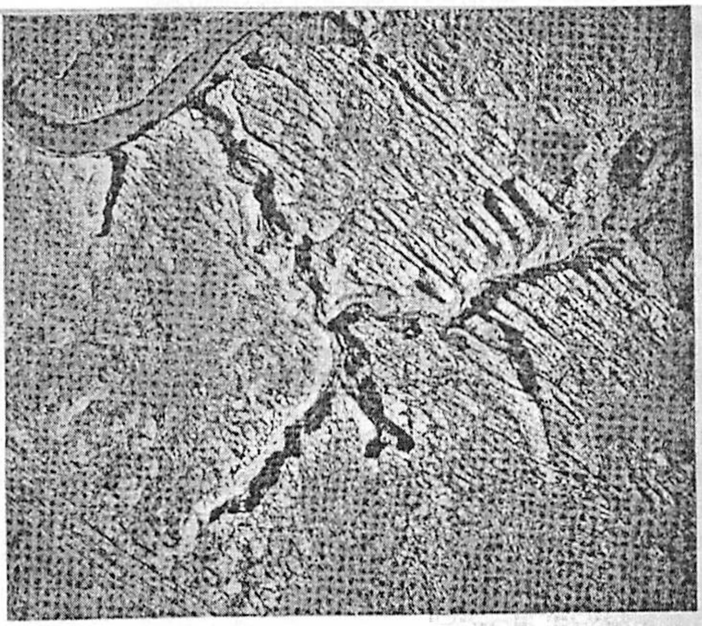
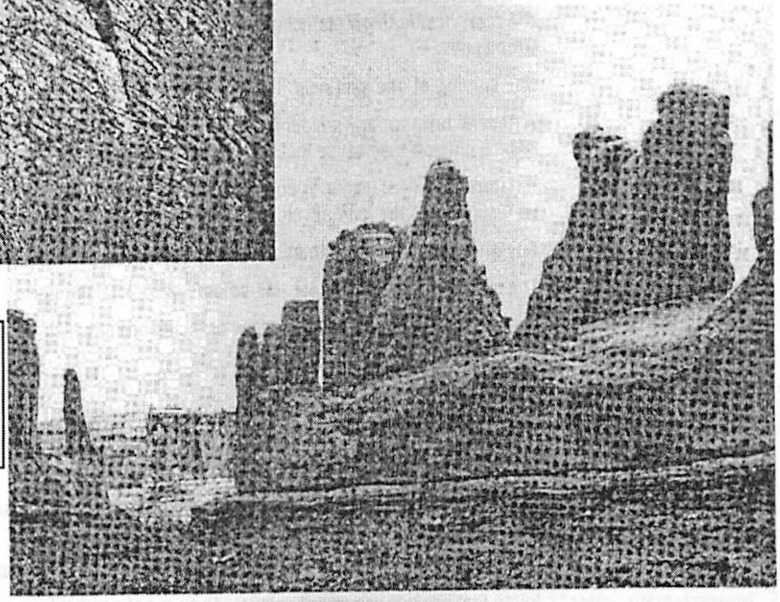


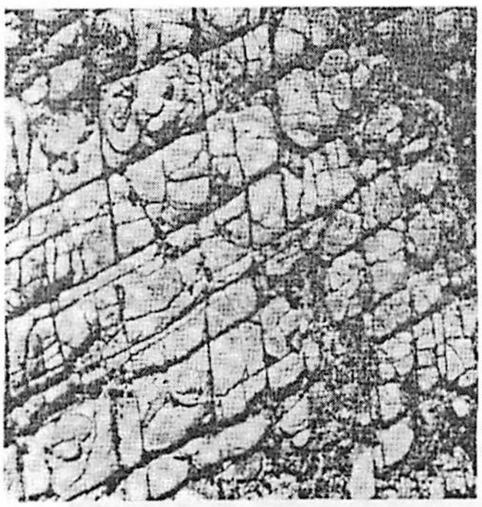
Arches National Park: regional joints in sandstone

(a)



Entrada Sandstone near Moab, Utah: large joint face

From van der Pluijm & Marshak



Cedar Mesa Formation, Canyonlands National Park: joint system

From Weijermars 1997

Table 7.1 Joint Terminology

Arrest line	An arcuate ridge on a joint surface, located at a distance from the origin, where the joint front stopped or paused during propagation of the joint; also called *rib marks*.
Columnar joints	Joints that break rock into generally hexagonal columns; they form during cooling and contraction in hypabyssal intrusions or lava flows.
Conjugate system	Two sets of joints oriented such that the dihedral angle between the sets is approximately 60°.
Continuous joints	Throughgoing joints that can be traced across an outcrop, and perhaps across the countryside.
Cross joints	Discontinuous joints that cut across the rock between two systematic joints, and are oriented at a high angle to the systematic joints.
Cross-strike joints	Joints that cut across the general trend of fold hinges in a region of folded rocks (i.e., the joints cut across regional bedding strike).
Desiccation cracks	Joints formed in a layer of mud when it dries and shrinks; desiccation cracks (or *mud cracks*) break the layer into roughly hexagonal plates.
Discontinuous joints	Short joints that terminate within an outcrop, generally at the intersection with another joint.
En echelon	An arrangement of parallel planes in a zone of fairly constant width; the planes are inclined to the borders of the zone and terminate at the borders of the zone. In an *en echelon* array, the component planes are of roughly equal length.
Hackle zone	The main part of a plumose structure, where the fracture surface is relatively rough due to microscopic irregularities in the joint surface formed when the crack surfaces get deflected in the neighborhood of grain-scale inclusions in the rock, or due to off-plane cracking (formation of small cracks adjacent to the main joint surface) as the fracture propagates.
Hooking	The curving of one joint near its intersection with an earlier formed joint.
Inclusion	A general term for any solid inhomogeneity (e.g., fossil, pebble, burrow, xenolith, amygdule, coarse grain, etc.) in a rock; inclusion may cause local stress concentrations.
Joint	A natural, unfilled, planar or curviplanar fracture that forms by tensile loading (i.e., the walls of a joint move apart very slightly as the joint develops). Joint formation does not involve shear displacement.
Joint array	Any group of joints (systematic or nonsystematic).
Joint density	The surface area of joints per unit volume of rock (also referred to as *joint intensity*).
Joint origin	The point on the joint (usually a flaw or inclusion) at which the fracture began to propagate; it is commonly marked by a dimple.
Joint set	A group of systematic joints.
Joint stress shadow	The region around a joint surface where joint-normal tensile stress is insufficient to cause new joints to form.
Joint system	Two or more geometrically related sets of joints in a region.
Mirror region	Portion of a joint surface adjacent to the joint origin where the surface is very smooth; mirrors do not occur if the rock contains many small-scale heterogeneities.
Mist region	A portion of a joint surface surrounding the mirror where the fracture surface begins to roughen.
Nonsystematic joints	Joints that are not necessarily planar, and are not parallel to nearby joints.
Orthogonal system	Two sets of joints that are at right angles to each other.
Plume axis	The axis of the plume in a plumose structure.
Plumose structure	A subtle roughness on the surface of some joints (particularly those in fine-grained rocks) that macroscopically resembles the imprint of a feather.
Sheeting joints	Joints formed near the ground surface that are roughly parallel to the ground surface; sheeting joints on domelike mountains make the mountains resemble delaminating onions.
Strike-parallel joints	Joints that parallel the general trend of fold hinges in a region of folded strata (i.e., the joints parallel regional bedding strikes).
Systematic joints	Roughly planar joints that occur as part of a set in which the joints parallel one another, and are relatively evenly spaced from one another.
Twist hackle	One of a set of small *en echelon* joints formed along the edge of a larger joint; a twist hackle is not parallel to the larger joint, and forms when the fracture surface twists into a different orientation and then breaks up into segments.

From van der Pluijm & Marshak

"Horst and Graben at the Chateau Godot"

(a.k.a. The Formation of Graben)

MANDY PR☺CT☺R

Graben: A crustal block that is downdropped. It is bounded on two sides by normal faults, and is the result of crustal extension

Horst: A crustal block that is upwarped. It is also bounded on two sides by normal faults, but results instead from compression.

Figure 1: Graben in the Elephant Hill area of Canyonlands National Park.
http://www.visi.com/~kghl/Photography/Descriptions/CL_Graben.html

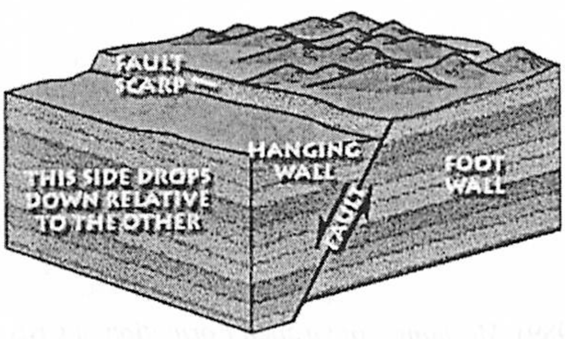


Figure 2: Normal faults form as the result of tensional stresses pulling the plate apart. One side of the wall then drops relative to the other.

http://wrgis.wr.usgs.gov/docs/parks/deform/gnormal.html

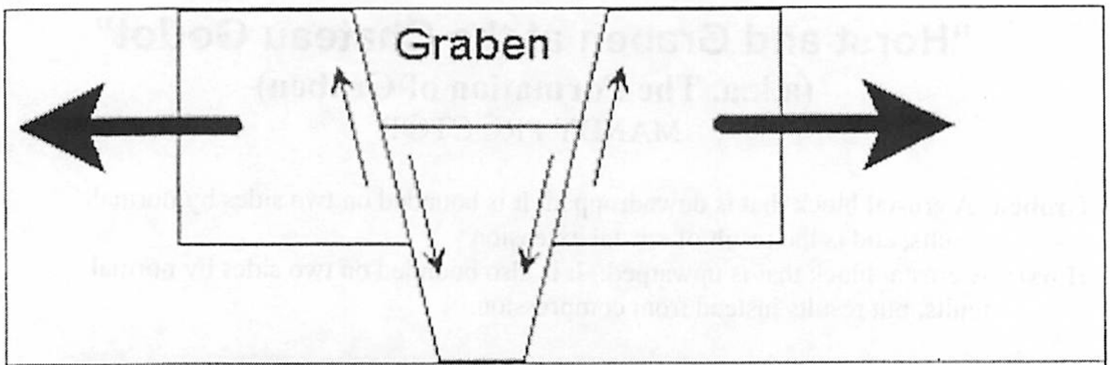


Figure 3: Cartoon of graben formation basics.
http://www.bhc.edu/academics/science/harwoodr/Geog102/study/tecton1.htm

Why two opposite (antithetic) faults?

1. Lower strain near the fault tip.
2. Bending stresses near original fault, allows for slip to relieve pressure.

Why the distance between graben?

Stresses are relieved at a large distance from the graben, hence the separation observed in nature.

Planetary Connection

Figure 4: Graben on Mars.

http://www.solarviews.com/eng/face.htm

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Graben Formation in Canyonlands

John Weirich
Fall 2004

Precursor to Graben Formation:

- 300 meter thick Paradox Formation (~68% halite) result of shallow inland sea ~300 million years ago

- Paradox Formation overlain by ~460 meter thick section of Pennsylvanian and Lower Permian sandstone and limestone

- Two to four degree northwestward regional dip caused by the Monument Upwarp

- Downcutting to the Paradox Formation by the Colorado River over the past half a million years

Previous Models:

- Salt dissolution (doesn't produce Meander Anticline) (Baars and Molenaar, 1971)

- Salt flow creating basal shear stress (creates level horsts, which are observed) (Stromquist, 1976)

- Gliding of overburden on a decollement (doesn't produce subsidence) (Fig. 3) (Huntoon, 1982)

Newest Model (Walsh and Schultz-Ela, 2003):

- Uses plain-strain finite-element models (Fig. 6)

- Salt flow causes up-warping near canyon, down-warping away from canyon (Fig. 7)

- Additional salt flow initiates further down-warping resulting in continued formation of grabens away from the canyon

- Grabens become more symmetric with time after younger graben forms, allowing horst blocks to rotate freely. This theory is untested! (Fig. 12)

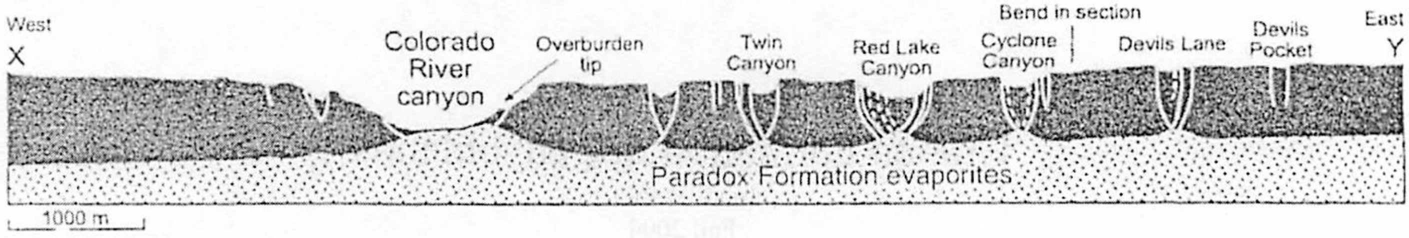


Figure 2.

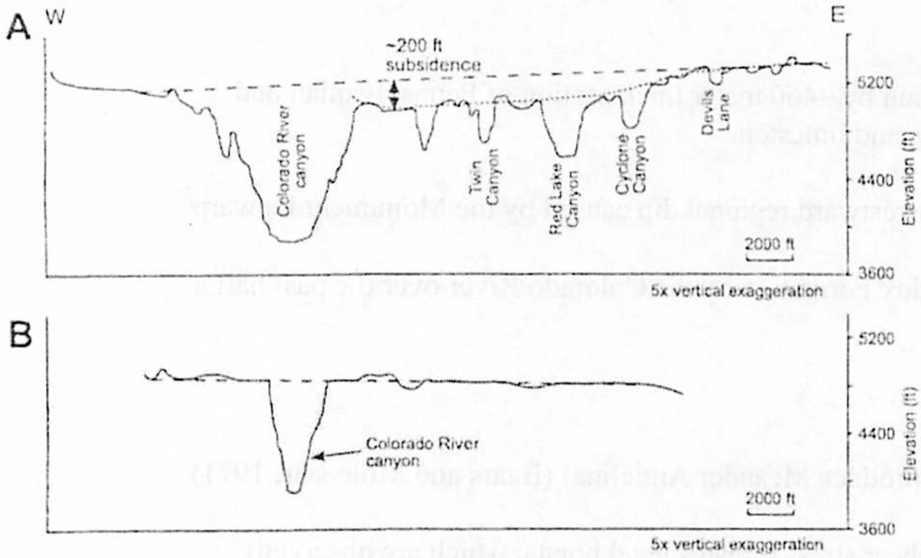


Figure 3.

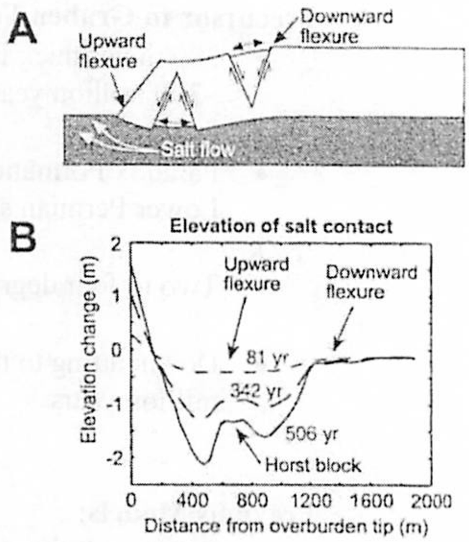


Figure 7.

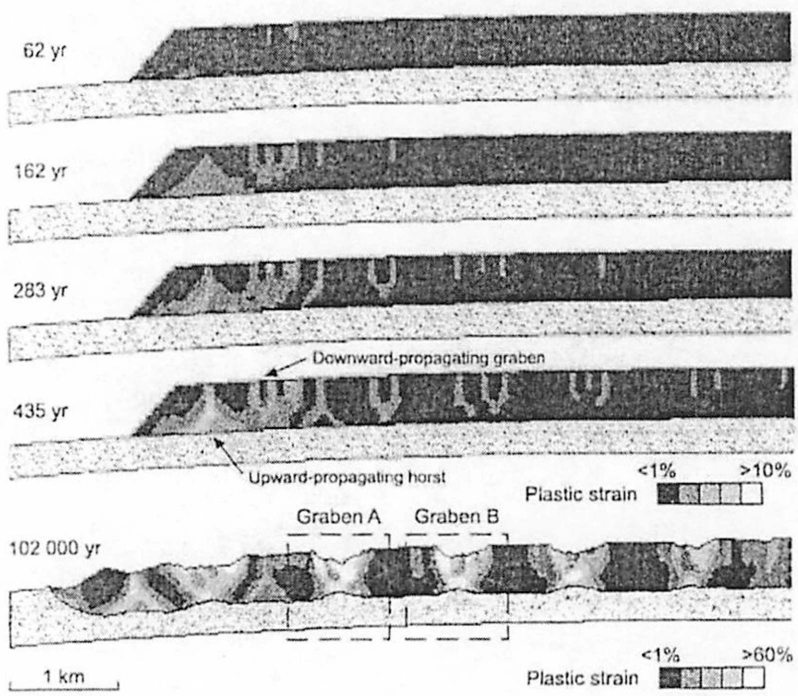


Figure 6.

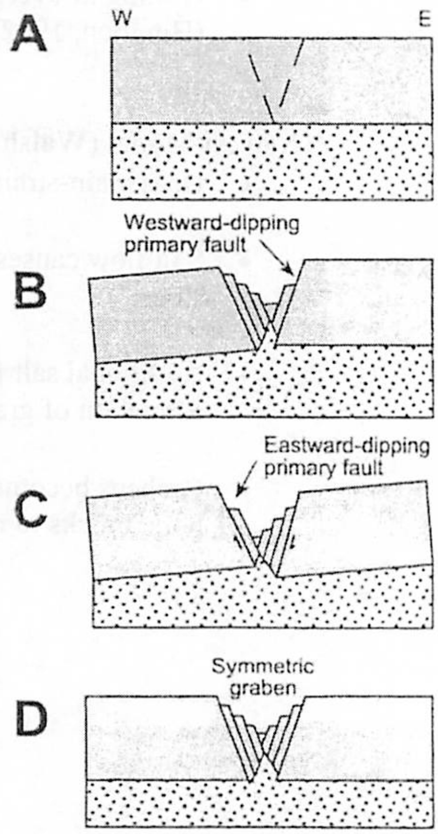
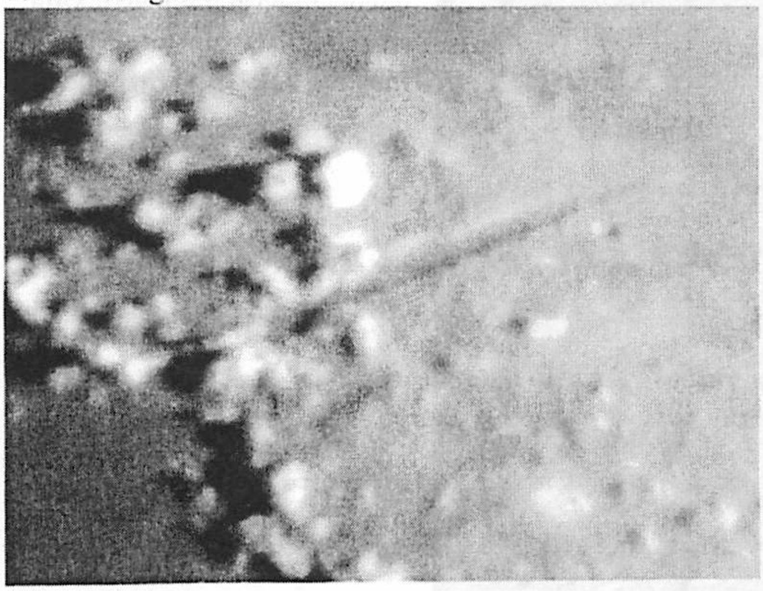


Figure 12.

Grabens on Extraterrestrial Bodies

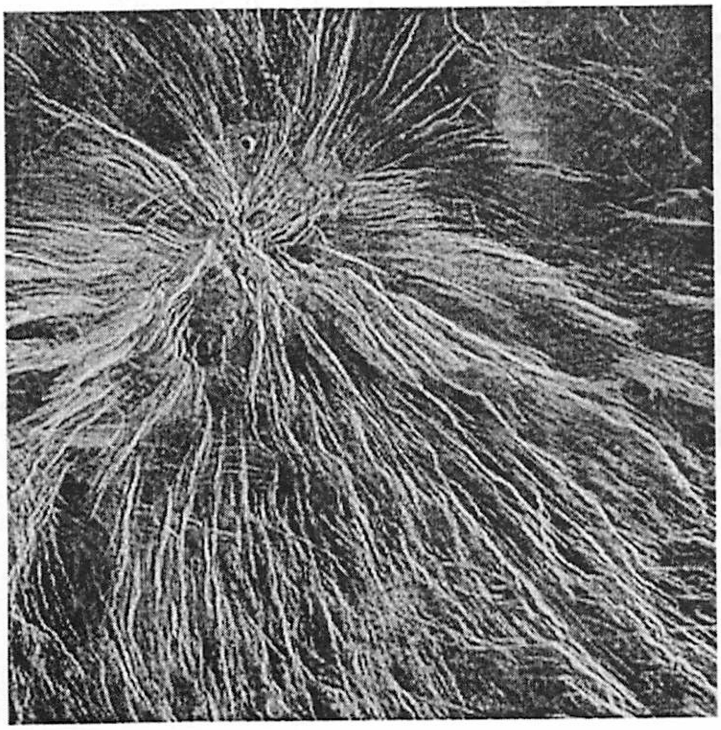
Maki Hattori

Grabens on the Moon: Usually formed from relaxation of impact craters often creating concentric grabens.



Alpine Valley
http://www.salzgeber.at/astro/moon/L100.html

Grabens on Venus: Many closely spaced radial grabens. Up to about 250km in diameter. Often caused by dome shaped uplifts.

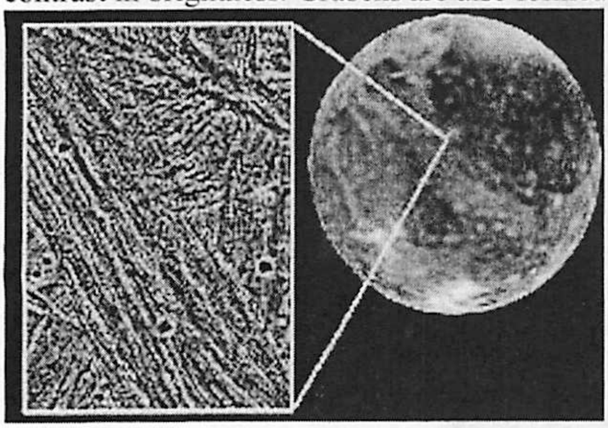


"Nova" in Themis Regio.
http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_c130s279_1.html

Grabens on Mars:
Below is a classical parallel graben ~3-5km in width. Most of the grabens are thought to have formed as a consequence of the creation of Tharsis. There are also volcanically induced grabens.

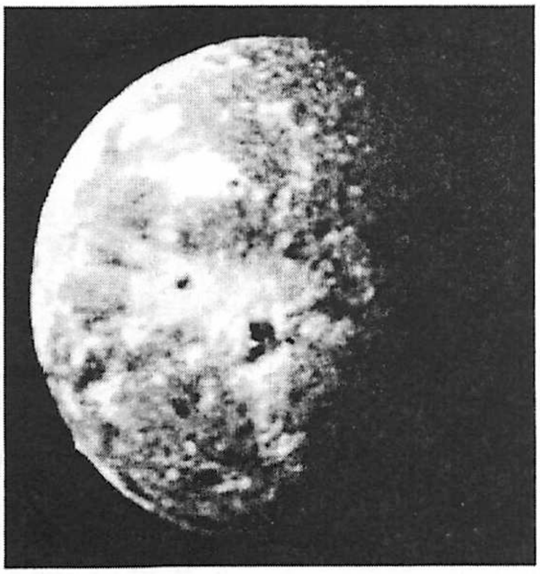
Acheron Fosse:
http://cmex-www.arc.nasa.gov/CMEX/data/catalog/TectonismonMars/Grabens.html

Grabens on Ganymede: Formed from global expansion and filled in with ice causing the contrast in brightness. Grabens are also formed from cryovolcanic activity.



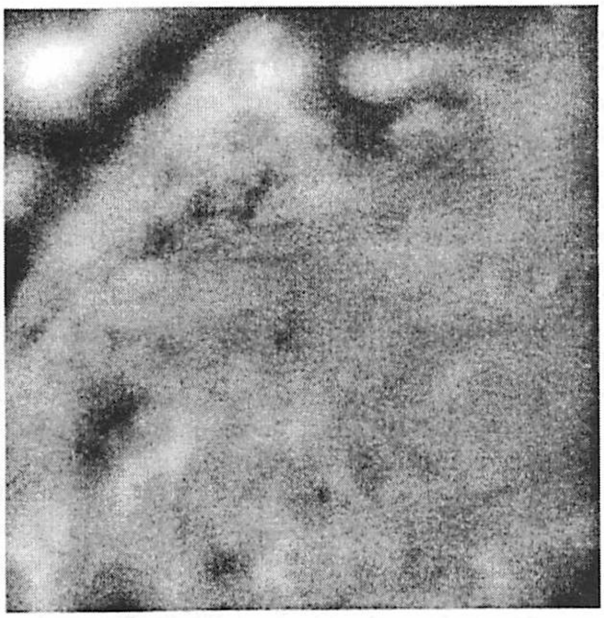
http://www.windows.ucar.edu/tour/link=/jupiter/moons/ganymede_grooves_2.html&edu=high

Grabens on Ariel: Result of Cryovolcanism similar to the icy moons of Jupiter.



http://geoinfo.amu.edu.pl/wpk/geos/GEO_10/GEO_PLATE_P-15.HTML

Grabens on Titan: ????



http://ciclops.lpl.arizona.edu/view.php?id=252

Graben Formation over Dike Intrusions

Moses P. Milazzo

September 8, 2004

1 Introduction

Magma is driven upwards by buoyancy forces resulting from lower density of the magma relative to the surrounding host rocks. This buoyancy force is usually low unless the magma contains some amount of gas. Exsolution of volatiles as the magma nears the surface causes the buoyancy to increase. On the Earth, at about 100 m depth massive amounts of water exsolve from the magma, causing a rapid increase in the ascent rate of the magma (11).

The propagation velocity and shape of an intrusion is controlled largely by its or the host rock's effective viscosity. Relatively fluid magmas propagate quickly through the host rock, cracking and pushing the rock aside, but only slightly or not at all altering its shape near the intrusion, but setting up stresses that allow graben formation. The ascent rate of a dike is largely controlled by the intruding material's viscosity. The ascent rate of basatic dikes has been measured as near 1 m/s. The host rock must be 10 to 14 orders of magnitude more viscous to behave elastically (9).

On the other hand, materials that are nearly as viscous as the host rock will propagate on time scales slow enough (cm/yr) that the host rock itself behaves viscously. This causes the host material to be highly deformed and to rise with the intrusion. This viscous flow of the host rock controls the propagation rate of, for example, a diapir, and causes uplift of the surface just above the diapir (9).

2 Dike Intrusion

Dike intrusion involves parting host rock along preexisting or magma generated fractures. While dikes can be of any composition, they usually have a much lower viscosity than the host rock. This is because more fluid materials can cause and move through and along thin cracks that are controlled by the regional stress field in the host rock. As a dike intrudes, the wall rock is pushed apart with relatively little deformation; the very fluid material moves quickly enough that the host behaves elastically. The thin cracks and elastic behavior of the rock through which the magma flows results in typical dike thickness:length aspect ratios of 1:1000 (Fig. 1) (5; 1).

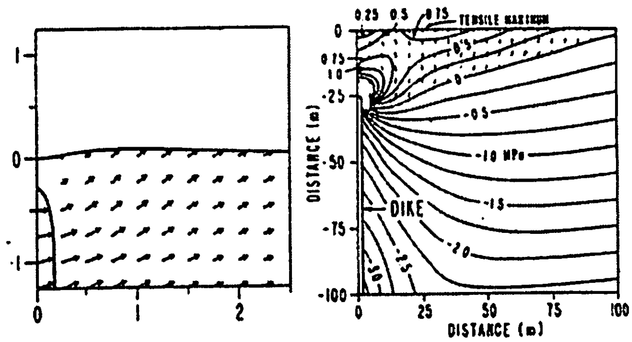


Figure 1: Left: Displacement vectors from a model in which a dike in a semi-infinite medium is subject to internal pressures. Displacements are near zero directly above the dike and reach a maximum some distance away. Right: Contours of maximum principal stress near a model dike. The tensile (positive) maximum at the surface is at a distance from the dike about equal to the depth to the dike top. (figure from (8))

3 Graben Formation

Figure (1) shows the deformation vectors and stress field of a model dike intruding near the surface. When a dike nears the surface, it causes horizontal, elastic displacements directed away from the dike. At the surface, the displacements are at their maximum some distance away from the point above the dike. This point experiences very little to no displacement. This difference in elastic displacements causes tension parallel to the surface between the zone just above the dike and the areas of maximal displacement on either side of it. This horizontal tension may lead to graben formation (Fig. 3). Grabens do not always form above dike intrusions, but when one does, this happens before the magma reaches the surface (due to the stress fields becoming compressive) (1).

The depth of the dike controls the distance between the two high strain areas, and this decreases as the dike nears the surface (Fig. 4); this distance is about twice the depth to the top of the dike. Thus, the width of a graben and amount of verticle subsidence give constraints on the depth to a dike and on its width. The thickness of a dike, T_d, can be estimated by measuring the amount of subsidence in the graben, S:

$$S \approx \frac{2}{3}T_d \quad (1)$$

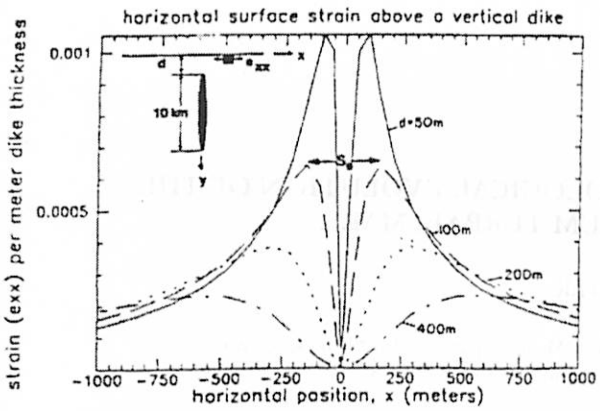


Figure 2: Model Strain parallel to Earth's surface. Curves are for different dike depths. From (5).

On the Earth, dike-induced subsidence of grabens ranges from a few centimeters to a few meters, and the widths range from a few meters to several kilometers (1).

4 Planetary Connections

The viscosity of a magma may be reduced by (a) reduced concentrations of network forming cations (Si and Al), (b) increased temperature, and (c) molecules that disrupt networks (OH). Thus, Mg-rich magmas often produce dikes and Si-rich magmas usually only form dikes at depths where temperatures are high or where the magmas contain high concentrations of water. Basaltic volcanism (48-55 wt.% SiO_2 is common on all terrestrial bodies, so dikes are expected to be common in the solar system (11). Dike-induced graben formation is likely to occur on other planets. Whether we can identify such grabens is not clear.

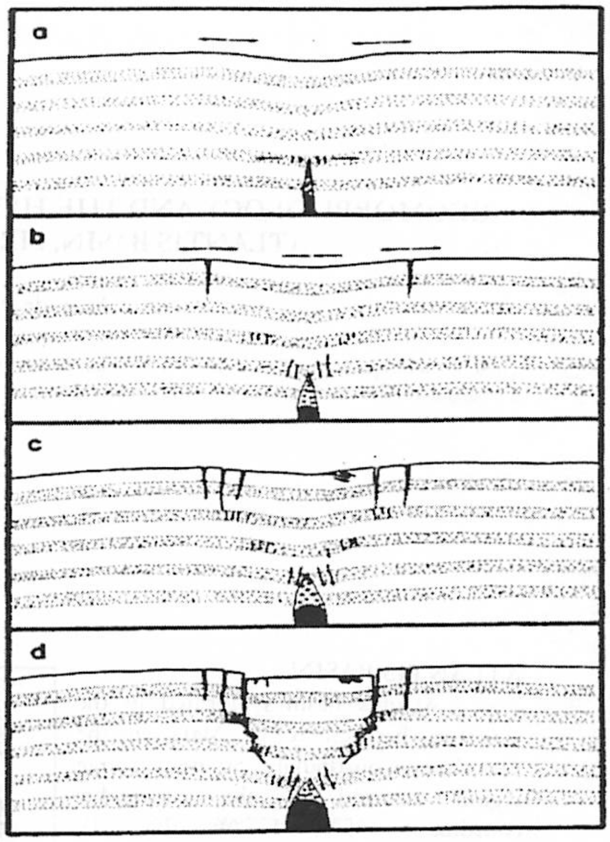


Figure 3: Schematic sequence of graben formation over a shallow dike, based on physical model experiments in a laboratory. From (8).

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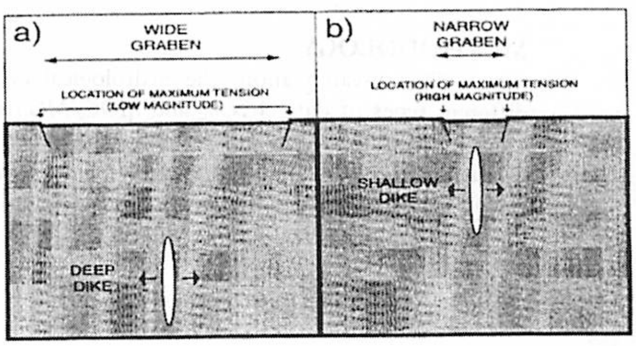

Figure 4: Schematic drawing showing the relationship between dike depth and graben width. From (1).

GEOMORPHOLOGY AND THE HYDROLOGICAL EVOLUTION OF THE ATLANTIS BASIN, SIRENUM TERRAE, MARS.

M.A. de Pablo Hdez.[1,2]

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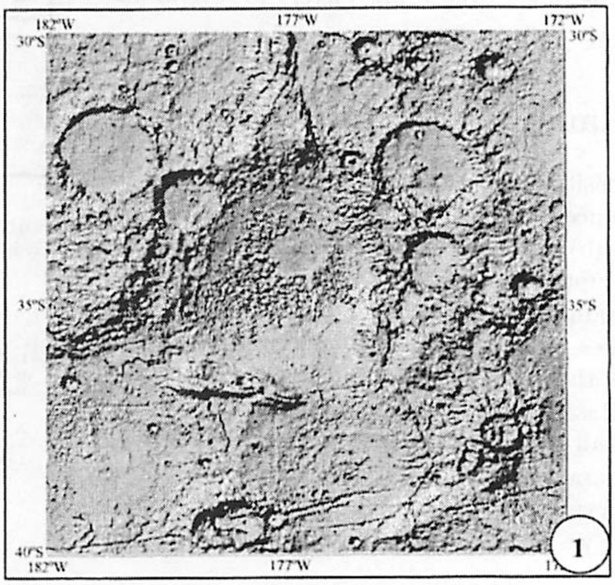
"When the investigator, having under consideration a fact or group of facts whose origin or cause in unknown, seeks to discover their origin, his first step is to make a guess"

G.K. Gilbert. "The origin of the hypothesis".

ATLANTIS BASIN

Atlantis basin is located in the southern hemisphere of Mars, in the Phaethontis quadrangle, Sirenum Terrae region, centred in the geographic coordinates 35°S, 177°W (Fig. 1). Geographically, the Atlantis basin is located at the high cratered martian highlands of Mars, at the Cratered unit [1] [2] Geologically, the basin is excavated on volcanic and sedimentary plains of the Early Noachian epoch [3] [4]. Other units of the area are relatively featureless plains and ridged plains of the Early Hesperian. Inside the Atlantis basin and over the previously described units there is a region formed by chaotic material of the Middle and Later Hesperian, which seems to fill partially this basin.



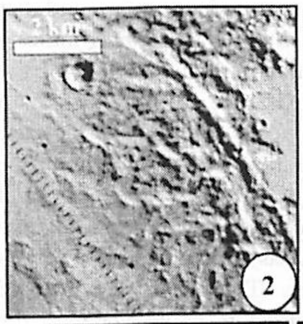
Atlantis lake [5] [6] is a putative small lake formed inside the Atlantis basin. This basin is also related to a great ancient lake (Eridania lake) [7] at the Eridania and Phaethontis martian quadrangles covering an area near of 3,000,000 km^2 and probably active until the Late Noachian [7]. The proposed hypothesis for the Eridania lake drying by the northward drainage through Ma'adim Vallis channel, only explains the partial drying of the Eridania lake, from the 1150 meters to the 950 meters of altitude of the water sheet. The Atlantis basin region is the objective of our study.

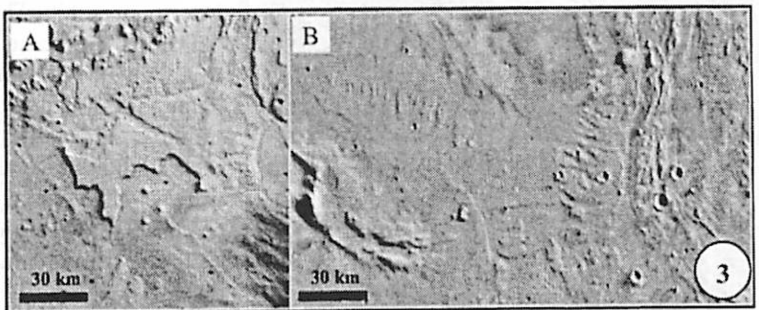
METHODOLOGY

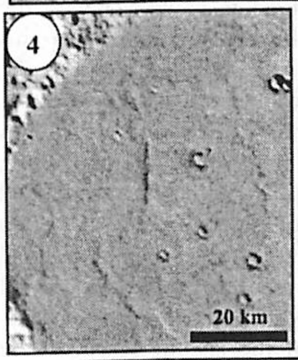
The research about the hydrological evolution of the Atlantis basin was developed with different types of data: *Viking* and *MOC/MGS* narrow images and *THEMIS/MO* diurnal infrared images. The different spatial resolution (between 180 m and 3 m) and spectral window (visible and thermal infrared) of the used data sets allow to us had a general and detailed point of view of the region and the different features of the studied area. Finally, the topographic analysis of the relief of the studied area was elaborated with MOLA data.

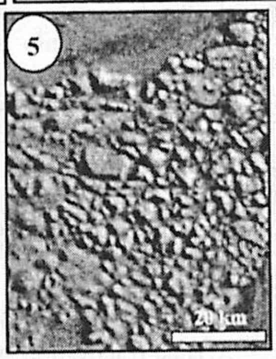
GEOMORPHOLOGY

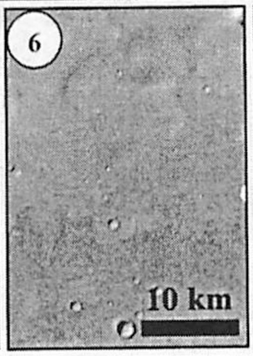
The general analysis of the images of the Atlantis basin region allow to made the first geomorphologic map of this area. The eight geomorphologic units mapped are related with different surface reliefs and morphologic features. On the other hand, a detailed analysis of the MOC and THEMIS images allow observe different water-related geomorphologic features: *Valley networks*: (Fig. 2), *Mesas* [8] (Fig. 3A) *and Serrated reliefs:* [8] (Fig. 3B), *Plain floor of impact craters and wrinkle ridges*: [7] (Fig. 4), *Chaotic terrains*: [9] [10] [11] (Fig. 5), *Mud-flows*: [11] [12] [13] (Fig. 6), *Collapse areas*: [11] (Fig. 7), *Iced-dust mantles*: [14] [15] [16] (Fig. 8), *Lobated eject*: [17] (Fig. 9), and *Gullies*: [18] [19] [20] [21] [22] [23] (Fig. 10).

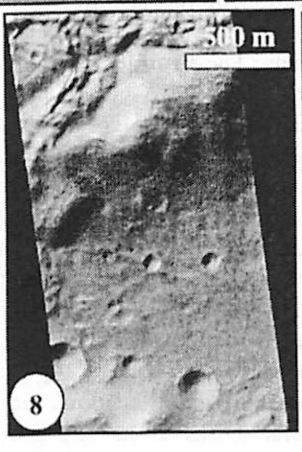


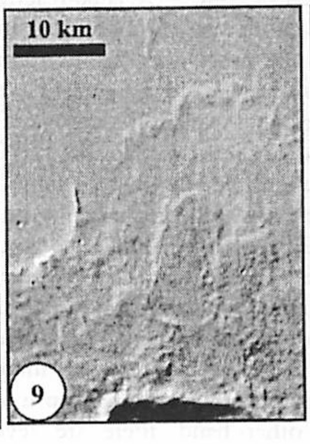


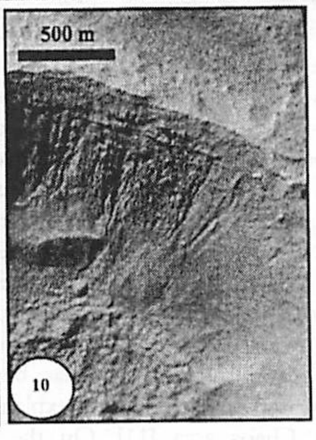






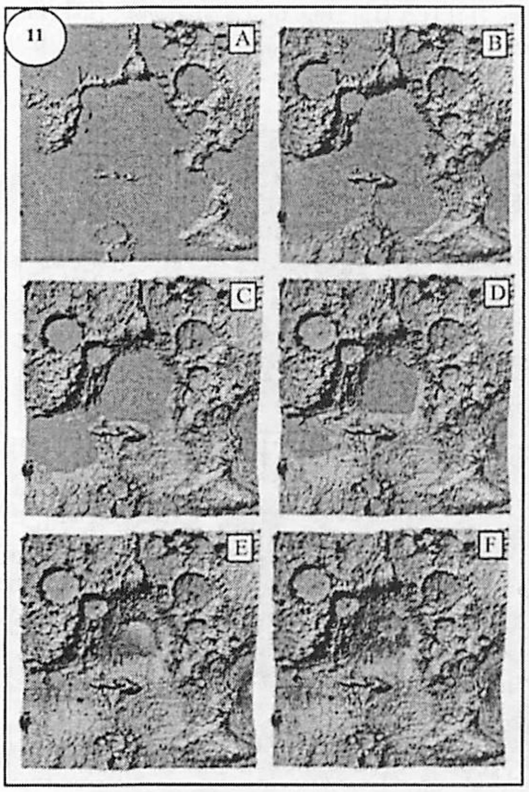






HYDROLOGICAL EVOLUTION

The MOC images have shown different geomorphologic features that indicate the existence of water in this region of Mars. Some of them are related with the existence of liquid water in the past (valley networks, mesas, serrated reliefs, chaotic terrains,...) while others indicate the existence of water (liquid and iced) in more recent times (mass-flows, gullies, dust-iced mantles,...), at the surface and subsurface.

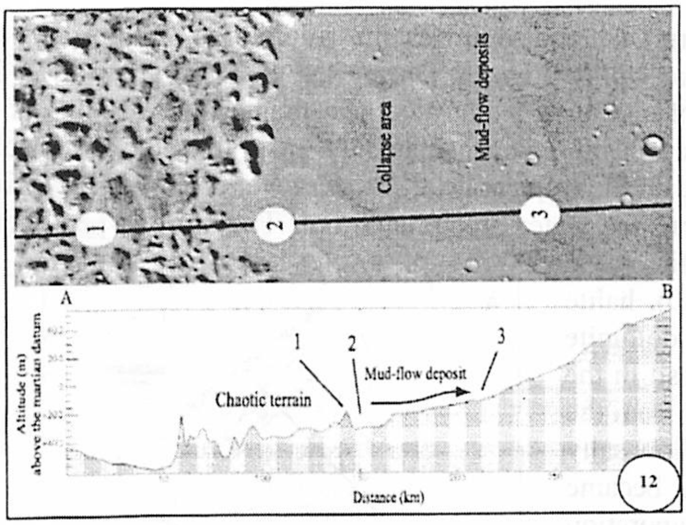


The Eridania great lake covered a big extension of Sirenum Terrae and Cimmeria Terrae ~3,500 million years ago [7], covering different basins of this area until an altitude of 1150 meters [7]. The abundant mesas and flat sedimentary deposits of this area could indicate an abundant sedimentation in the bottom of the basin during the existence of the lake. In addition, the inner edges of the basin were excavated by several flows generating drainage systems. The descent of the watersheet could produced the erosion of the previous lacustrine sediments forming mesas and serrated reliefs, and the incision of valleys. The autocompaction of the Eridania lake sediments could generate the ridges existing into the different basins of this region [7]. After the Atlantis lake disappear, the last ancient hydrological event inside the Atlantis basin was the Atlantis Chaos chaotic terrain formation by the melting of the permafrost [9] [10] [12] [13] [24] [25]. The iced water that could exist into the pores of the lacustrine sediments (permafrost) could melt due to a later thermal source. The thermal sources could be related both to volcanic [3] [5] [8] and tectonic processes. A later reactivation of the chaotic terrain relate with a possible dyke system reactivation was proposed [11] due to the mud flow deposits and collapse areas observed around this and other near chaotic terrains. The hydrological evolution of this basin in past geological times it is summarized in figure 11.

On the other hand, the models that explain the martian climatic changes [26] must be taking in account to explain the recent hydrological evolution of this basin where, theoretically [27], the present climatic conditions do not allow the existence of liquid water. But the gullies observation open the possibility that liquid water exists into the martian ground [18] [19] [20] [21] [22] [23] [28]. The groundwater that could generate the observed gullies could be related with the water that could infiltrate across the lacustrine sedimentary deposits at the bottom of the Eridania and Atlantis lakes millions of years before. Other possibility for the groundwater existence is the recharge of possible aquifer levels with the melted water of the ice-cemented dust mantels that covers part of the surface of this region, and which has been observed in other many places of Mars [14] [15]. The groundwater flow could also explain the presence of collapse areas in some locations around the Atlantis Chaos area [11]. On the other hand, there are several works about the ground ice distribution below the martian surface [29] and which proposed that the existence of lobated eject deposits in the Atlantis basin area would be a clear evidence for the existence of ground ice [17].

AN INCOMPLETE HISTORY

That hypothesis about the possible hydrological evolution of the Atlantis basin is not complete. The geomorphologic analysis show that the mud flow deposits around Atlantis Chaos flow from the chaotic terrain to the surrounding plains. However, a topographic profile of this area show that the central part of Atlantis Chaos is mainly located in the bottom of the basin while the mud flow deposits are located at the inner low slopes of the basin. Topographic profiles of this area shown that the mud flow front is located up to around 200 meters above the base of the chaotic terrain where it could be originated (Fig. 12). This observation rise up a question: did subsidence processes take place inside the Atlantis basin, or do some chaotic terrains have a different origin, or the tectonic activity could had an important role at the final evolution of this basin?.



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Salt Tectonics of the Paradox Basin

Carl Hergenrother
Canyonlands Field Trip
Fall 2004

The Paradox Basin of southeastern Utah and southwestern Colorado is 320-km long and lies adjacent to the Uncompahgre Uplift (Fig. 1). During the Pennsylvanian (323-290 Myr BP), the basin was the site of a shallow sea located near the equator. Sinking of the basin and the resulting uplift of peripheral regions isolated the basin from the surrounding sea. As the sea slowly evaporated in the tropical heat, the sea level dropped and various chemicals that were dissolved into the water precipitated out. The various precipitates included iron oxide (Fe_2O_3), limestone ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_20$), halite ($NaCl$), anhydrite ($CaSO_4$) and dolomite ($CaCO_3 \cdot MgCO_3$). The last deposit in the sequence was black shale formed from the ecosystem that thrived in the shallow salty marshland. The shale eventually became our precious fossil fuels. The evaporation and deposition of precipitates was not a solitary event. As many as 29 to 33 different episodes of flooding and evaporation are recorded. The total thickness of the evaporate beds is 1800-2100 meters.

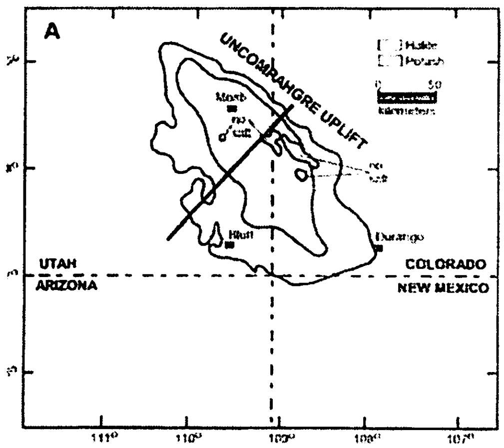

Fig. 1 – Map showing location of Paradox Basin (Baldridge 2004)

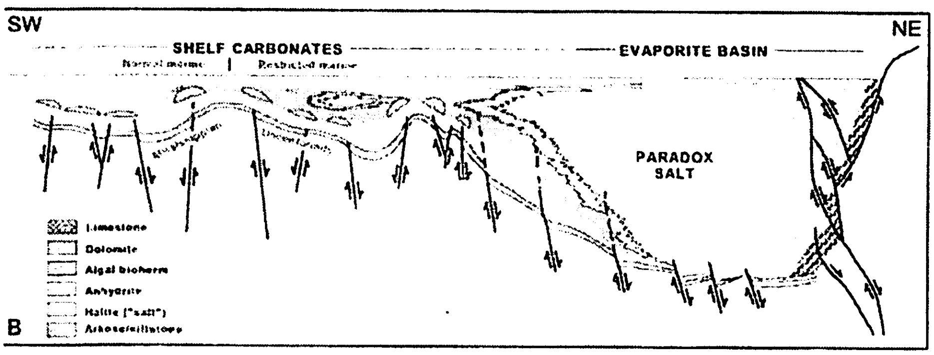

Fig. 2 – Cross section of Paradox Basin along line in Figure 1 (Baldridge 2004)

When the sinking of the Paradox Basin ceased, the basin filled in with deposits from the Uncompahgre and its tenure as an inland sea ended. As the deposits accumulated, the overburden caused the salt deposits to slowly flow. If the overlying deposits are of a greater density than the salt deposits, the salt will flow upwards. This process is called *diapirism*, the term *diapir* from the Greek meaning *to pierce* or *to penetrate*. Most salt movement can be caused by one of two processes. Halotectonism involves the application of tangential compressive stresses to the salt layer, while halokinesis is an isostatic process caused by the gravitationally unstable situation of a dense layer overlaying a layer of lesser density. In most cases, the two processes are both in play. Quite often, the movement of salt is initiated by halotectonic forces and then dominated by halokinetic forces during latter stages. As a result, salt diapirs are often aligned with local faults.

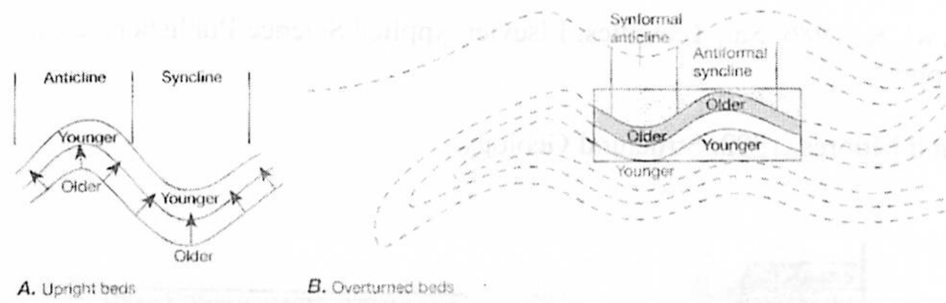

Fig. 3 – Distinction between an anticline and syncline (Twiss & Moores 1992)

The intrusion of salt into the upper rock layers caused these layers to heave upwards causing an anticline, which may be visible at the surface (Fig. 3). The removal of material from the salt layer around the diapir causes the area around the diapir to subside as a syncline (Fig. 3). The salt intrusions can take many forms such as walls, pillows, and bulbs with stems (Fig. 4). Water plays a large role in modifying salt diapirs as they rise. Slowly dissolving the salt, the water will create a cap rock of material at the leading edge of the diapir. The cap rock consists of insoluble material left behind by the dissolving water (usually anhydrite, gypsum, calcite and sulphur). Erosion of salt diapirs can result in the collapse of the overlaying layers. This manifests itself at the surface as sinkholes or valleys. An example is the cross section in Figure 5 where the salt has been progressively eroded away.

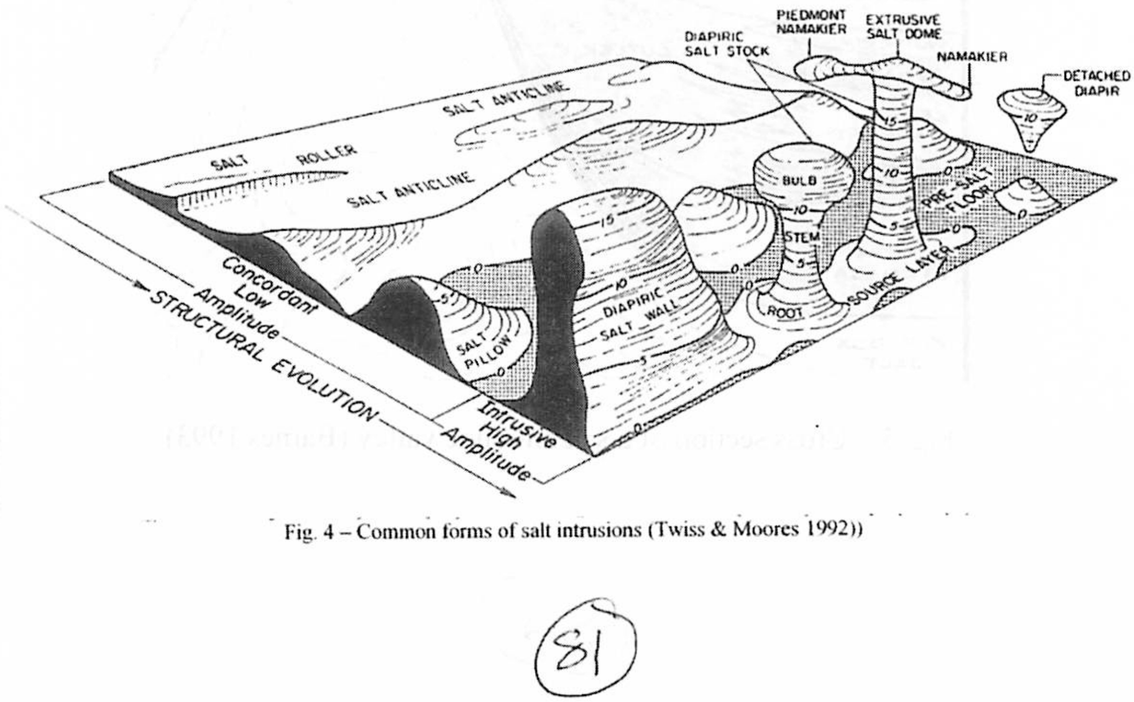

Fig. 4 – Common forms of salt intrusions (Twiss & Moores 1992))

The following books were ransacked for this handout::

Baldridge, W. S. 2004. Geology of the American Southwest. Cambridge University Press, Cambridge, 280 pps.

Barnes, F. A. 1993. Geology of the Moab Area. Canyon County Publications, Moab, 264 pps.

Jenyon, M. K. 1986. Salt Tectonics. Elsevier Applied Science Publishers, New York, 191 pps.

Twiss and Moores. 1992. Structural Geology.

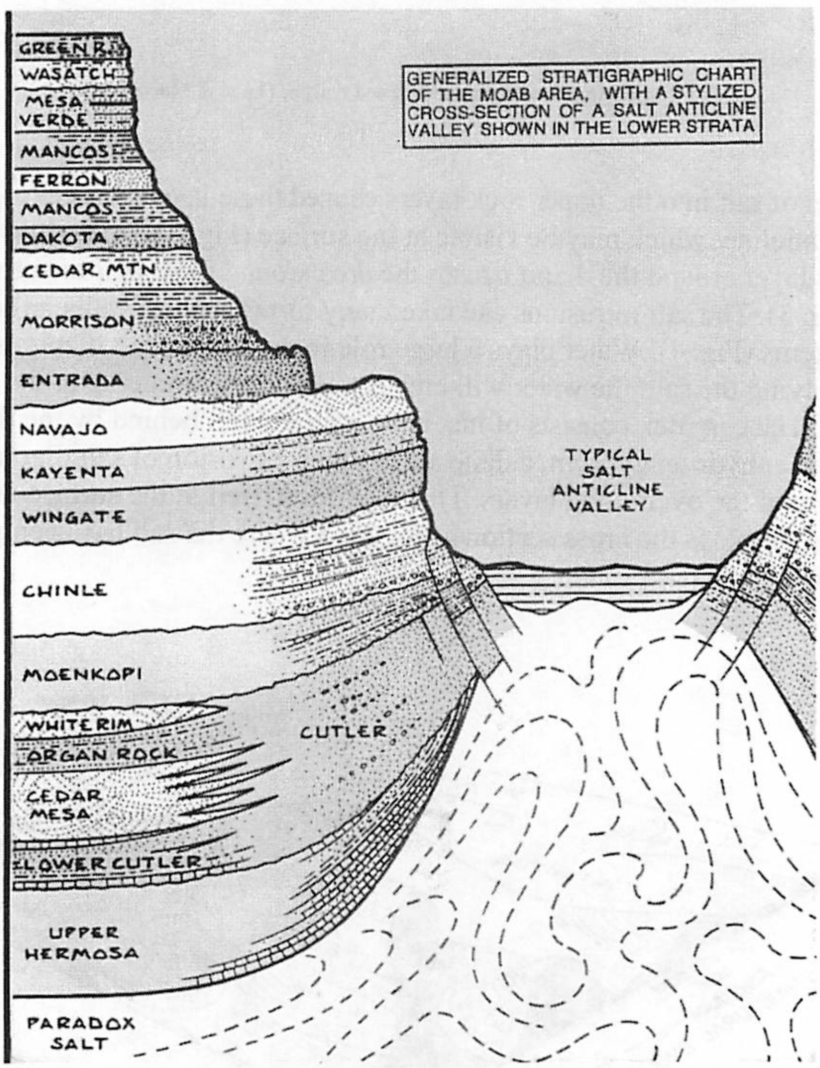

Fig. 5 – Cross section of a salt anticline valley (Barnes 1993)

Cliff Recession via Toreva-Block Landslides

Gwen Barnes

September 2, 2004

The first paper talking about these features, and calling them Toreva-blocks, was written by Parry Reiche in 1937 [1]. It is named for the city Toreva in the Hopi Indian Reservation, where there are some splendid examples of this kind of feature. Figure 3 shows where Toreva and Black Mesa are located with respect to the Grand Canyon and the surrounding states.

The Black Mesa area has harder rock overlying softer rock. The area of Black Mesa is floored by the sandstone of the Mesaverde formation, with the hardest sandstone overlying a weaker sandstone layer. Only the lower 170 feet of the Mesaverde formation is present near Toreva. Beneath the Mesaverde is the Mancos formation, which consists of soft, fissile shales with a thickness of about 300 feet. Both layers date to the Upper Cretaceous (90-65 Ma). Also, the unmoved rock strata has a northward dip of 3° - 4°.

A Toreva-block landslide is when an entire block slides down a hill intact. In the process, the block rotates "backward", along an axis parallel to that of the cliff. (See Figs. 1 and 2.) This kind of landslide is prevalent throughout the Colorado Plateau. Figure 2 shows a diagram of how this works. In the top part of the figure three areas of the Mesaverde Formation (sandstone) are shown, surrounded by plains of the Mancos Formation (mudstones and shales.) A cross section is shown across the trace. It appears that there used to be a flat layer of the Mesaverde sandstone above the weaker Mancos Formation. The center Mesaverde sandstone, in fact, appears to be unmoved. The figure shows how the two large blocks on either side of the central sandstone have slid down the hill, causing the strata to rotate backward. The dotted lines show a trace of the curved path that the blocks likely slid down. Vertical displacements of strata range from 70-220 feet. The blocks themselves range from 1100 feet to 1700 feet. The landslides occur when the softer, supporting material weakens and gives way.

The planetary connection is that Toreva-block landslides occur on other solid bodies too, such as the Moon and Mars [2] (Fig. 4.)

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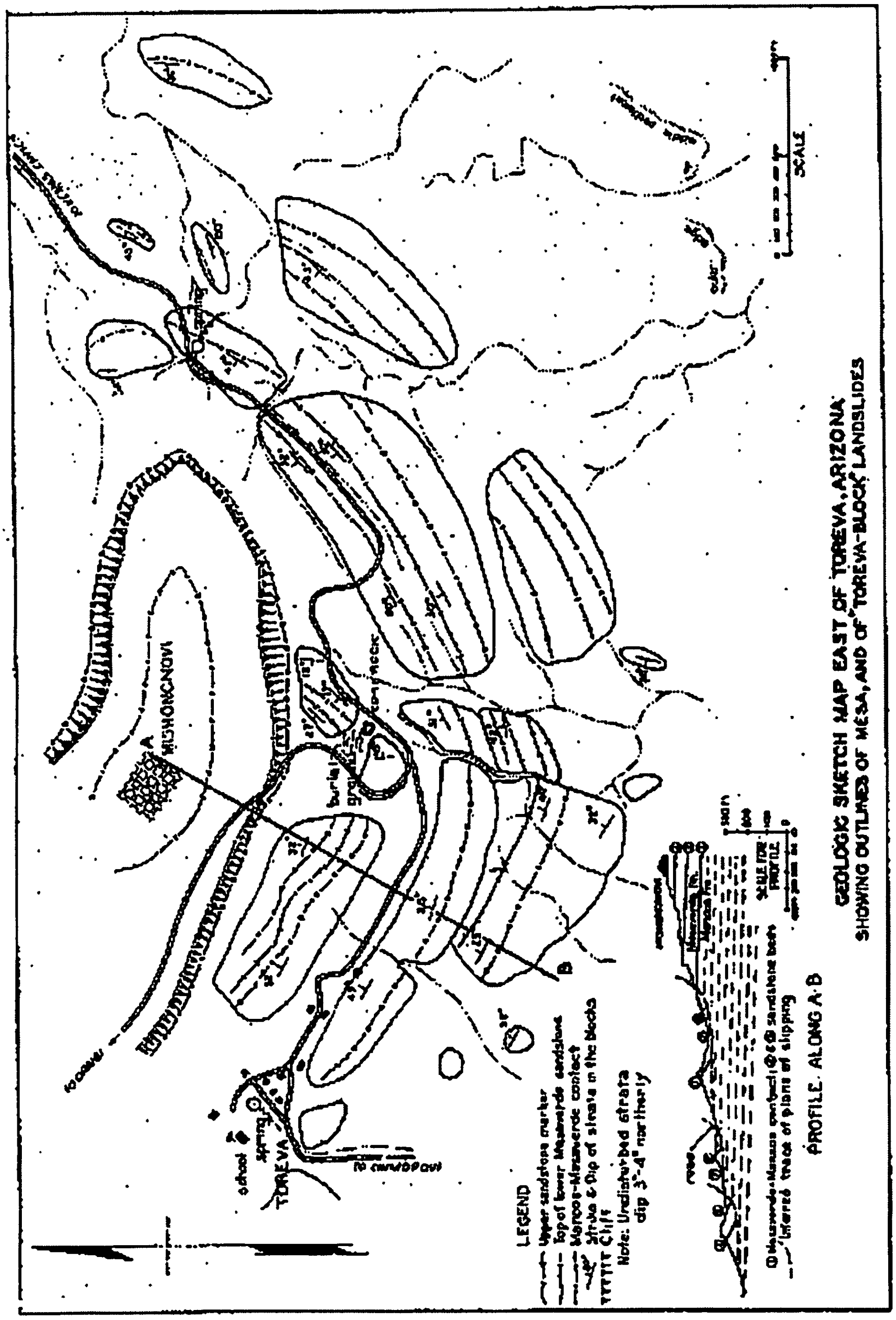


Figure 1: Geologic map of Toreva, AZ[1]

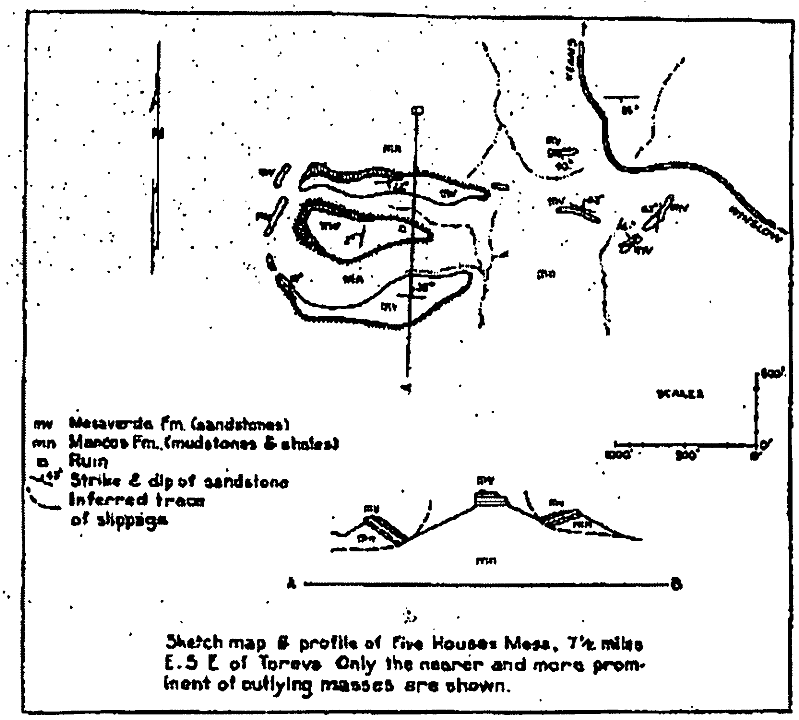


Figure 2: Geologic map of Five House Mesa, 7.5 miles ESE of Toreva, AZ [1]

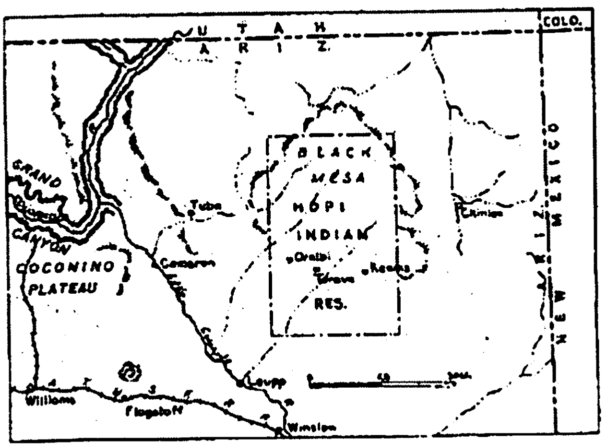


Figure 3: Location map of Toreva, AZ[1]

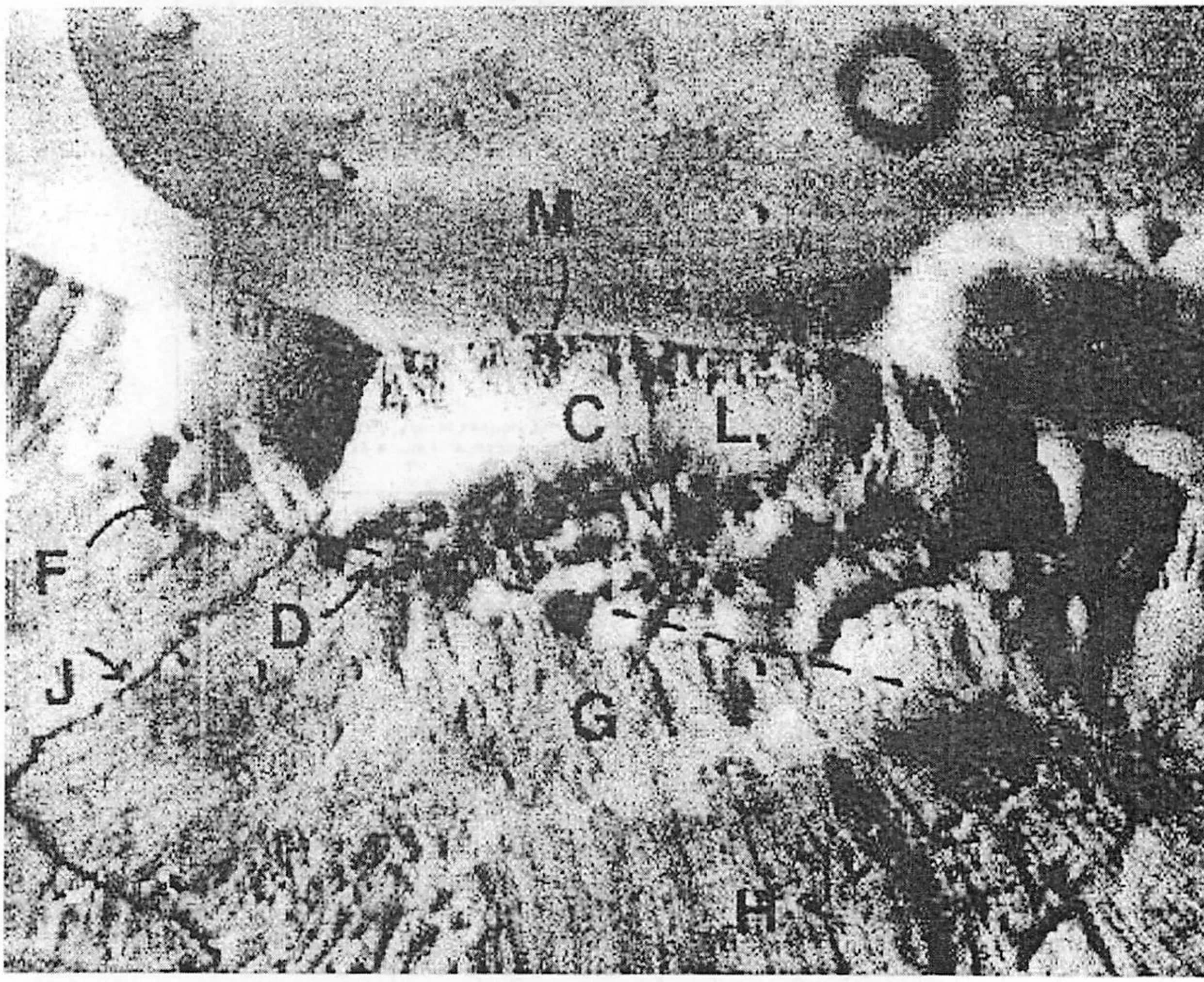


Figure 4: Landslide on south wall of Gangis Chasma.[2]

Dating Fault Scarps by Topographic Diffusion

or

Who the heck does equations on a field trip talk?!

Jim Richardson

Why date a fault scarp?

The primary reason is the need for more accurate and precise estimates of earthquake recurrence intervals. For most seismogenic areas of the world the principal uncertainty in earthquake risk analysis is the uncertainty in the recurrence intervals of potentially damaging or destructive earthquakes. On the outcome of such calculations (and their attendant uncertainties) ride enormous sums of human and financial commitments (from [1]).

The goal

The goal of this method is to ascertain the age of a fault scarp by mathematically modeling the degradation (erosional evolution) of a fault scarp from a fresh state to its current, observed state (Fig. 1 [2]).

Requirements for this method [2]

- The scarp is composed of an unconsolidated material (low material cohesion).
- The downslope flow of loose material is transport limited. That is, the downslope flow of soil is controlled by the transportation rate and not by the soil production rate (weathering limited).
- Although episodic or intermittent on short time-scales, erosion rates in the area have been relatively constant on the order of thousands of years (ka).
- The downslope flow rate of loose material is approximately proportional to the slope.

Downslope flow rates

Both field and theoretical studies suggest that the downslope flow rate of loose material on a hillslope is proportional to the gravitational shear stress ($g \sin \theta$) such that:

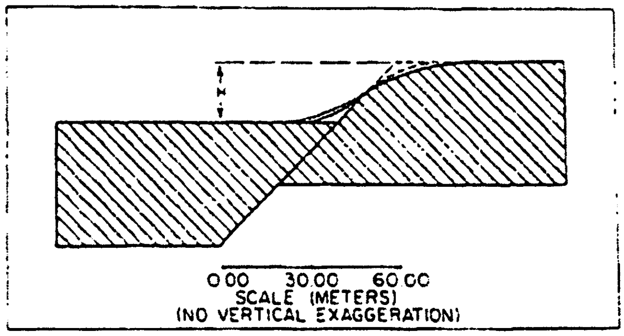


FIG. 1. -Idealized degradation of a normal fault scarp. The height of the scarp, *H*, remains unchanged if measured between the straight sections at the scarp base and crest (away from the scarp face).

$$f = \kappa \sin\theta \ , \qquad \text{Eq. 1}$$

where f is the downslope volumetric flow rate, κ is a constant, and θ is the slope angle above horizontal. At low values of θ this can be approximated by: [2]

$$f = \kappa \tan\theta = \kappa\nabla z \ , \qquad \text{Eq. 2}$$

where z is the elevation and ∇z is the slope.

In areas where the downslope flow rate of loose material on a hillslope is disturbance driven (landslide and seismic tremors, biological activity, etc.), f is given by: [3]

$$f = \frac{\kappa\nabla z}{1-\left(\frac{\nabla z}{\theta_c}\right)^2} \ , \qquad \text{Eq. 3}$$

where θ_c is the critical slope angle (angle of stability). Here too, when the slope angle is low, Eq. 3 can be approximated by $f = \kappa\nabla z$, Eq. 2: linearizing the downslope flow of loose material f, and making it a function of the slope ∇z and an unknown constant κ.

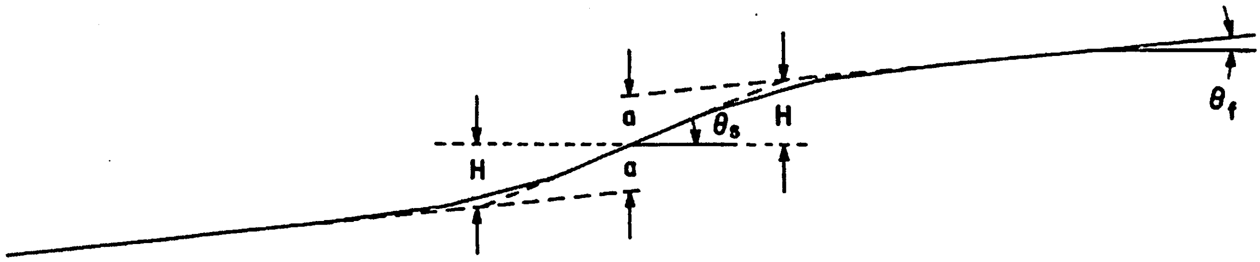


FIG. 2. Morphological measures of scarp-like landforms, from Hanks *et al.* (1984) as redrawn from Bucknam and Anderson (1979): $2a$, surface offset or vertical offset of the scarp at $x = 0$; $2H$, scarp height, the amplitude measure of Bucknam and Anderson (1979); θ_s, maximum scarp slope angle, $\tan\theta_s = \partial u/\partial x|_{x=0}$; θ_f, far-field or fan-slope angle, $\tan\theta_f = b$. Note that $2a$ and $2H$ are not the same, nor is their relationship ($2H = 2a/[1 - \tan\theta_f/\tan\theta_s]$) even a linear one.

Continuity equation on hillslopes

Assuming conservation of slope debris, if more debris enters than leaves a slope segment, debris will accumulate in that segment and the elevation of the segment must increase. Of course, the converse case also applies (from [2]). This leads to: [4]

$$\frac{\partial z}{\partial t} = -\left[\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y}\right], \qquad \text{Eq. 4}$$

defining the change in elevation per unit time, and where the downslope flow has been divided into x and y components: f_x and f_y respectively. Placing Eq. 2 in these terms yields:

$$f_x = -\kappa\frac{\partial z}{\partial x}\text{ , and } f_y = -\kappa\frac{\partial z}{\partial y}\text{ ,} \qquad \text{Eq. 5}$$

and combining these with Eq. 4 results in:

$$\frac{\partial z}{\partial t} = \kappa\left[\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2}\right] \text{ or } \frac{\partial z}{\partial t} = \kappa\nabla^2 z \text{ ,} \qquad \text{Eq. 6}$$

which is a form of the diffusion equation. Analytical solutions to this equation exist for a variety of initial and boundary conditions, including topography in the form of an eroding scarp.

Diffusion of scarp topography

The solution to Eq. 6 for a step of topography $2a$ in height, imposed at $x = 0$ and $t = 0$ upon a preexisting surface of slope $b = \tan\theta_f$ (for example, a single episode of vertical, dip-slip, block faulting of a fan surface of slope b) is given by: [1]

$$z(x,t) = a \cdot erf\left(\frac{x}{\sqrt{2(\kappa t)}}\right) + bx \text{ ,} \qquad \text{Eq. 7}$$

where only a cross-strike profile in (x,z) is considered and the error function $erf(\zeta)$ is given by:

$$erf(\zeta) = \frac{2}{\sqrt{\pi}}\int_0^{\zeta} e^{-\eta^2} d\eta \text{ .} \qquad \text{Eq. 8}$$

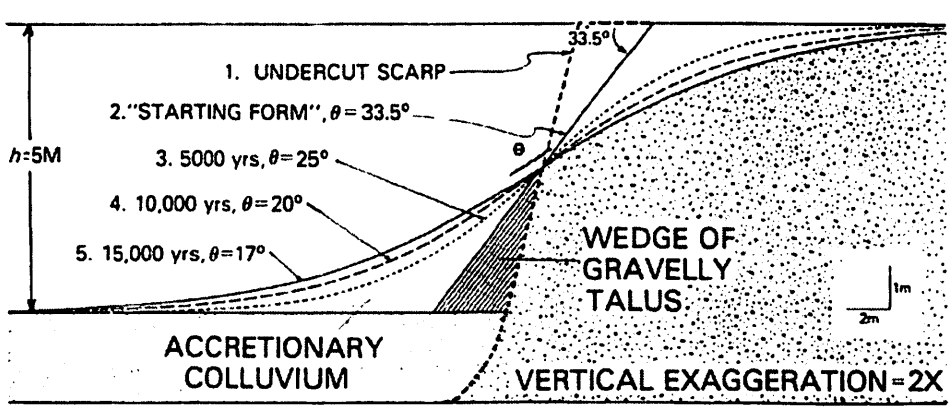
The maximum slope angle θ_s at some later time t (see Fig. 2) is expressed by:

$$\theta_s = \tan^{-1}\left[\frac{a}{\sqrt{\pi\kappa t}} + b\right]\text{ .} \qquad \text{Eq. 9}$$

Since θ_s, a, and b are measured quantities, Eq. 9 can be used to gain a first estimate of κt, the total downslope diffusion on the slope.

Fig. 3 [5] shows the evolution of a terrace slope over time, using (7) and (8) with $a = 2.5$ m and $b = 0$. Note that the desired starting form of the scarp for diffusive downslope flow is at $\theta_s = 33.5^\circ$ (the angle of repose θ_r), while the above model begins with a vertical scarp. In this instance, the model will not reach the desired starting point until $\kappa t = 4.541$ (Eq. 9), which must be subtracted out to obtain useful values for κt and t.

Figure 1. Stages in the evolution of a terrace scarp. 1. Lateral undercutting of terrace gravels by stream to form a scarp steeper than the angle of repose. 2. This oversteepened slope rapidly ravels to form a rectilinear scarp at the angle of repose, here inferred to be 33.5° (see text), which is our starting form for diffusion-equation modeling. 3, 4, 5. Scarp profiles predicted by diffusion-equation model at stated time intervals (degradation rate coefficient, c, of 12×10^{-4} m²/yr).



Applications of the Diffusion Model

Fig. 4 on the following page shows an application of this model to the Drum Mountain fault scarps from [1]. Quoting the description: Some 30 km northwest of Delta, Utah, a swarm of normal fault scarps cuts a fan surface built on the east flank of the Drum Mountains. These scarps are presumably less than 12,000 years old, lying as they do beneath the Provo II level of Lake Bonneville. The scarps cut a bar formed at the Provo II level and are apparently unmodified by wave action. The fault scarps form a band some 30 km long and 5 km wide, pointing to a complicated near-surface faulting geometry.

The modeling gives nearly identical κt of 6.25 m for the three shorter scarps ($2a < 4$m) and larger κt for the two taller scarps. The larger scarp heights lead to larger θ_r model starting times (due to a in Eq. 9) and it is ambiguous as to whether they are actually older or not. This result points out the key weakness of this dating method: there is no analytical way to determine the diffusion constant κ independent of time t without outside information.

In actual practice, the age of one terrace or fault scarp in the geologic area is usually determined through some *other* means, the diffusion constant κ solved for in that instance, and then applied to all other scarps in the geologic area (provided that the alluvium / colluvium makeup of the scarp is similar). For the Drum Mountain scarps, Hanks used the diffusion constant determined from the Lake Bonneville terrace scarps (near Provo, Utah) where κ = 1.1-1.7 m² ka⁻¹, to obtain an age of 3500-5500 years.

Some typical values for downslope diffusion constant κ are listed below:

1.0	$m^2\,ka^{-1}$, common default value [1]
0.2-1.3	$m^2\,ka^{-1}$, central Idaho terraces [5]
1.1-1.7	$m^2\,ka^{-1}$, Lake Bonneville terraces [1]
8.3	$m^2\,ka^{-1}$, San Andreas Fault [6]
16	$m^2\,ka^{-1}$, Raymond Fault [1]

Other dating methods

In geomorphology, great care must be taken in the selection of a dating technique and in its application, because the desire is usually to date an *event* in preexisting strata, which has its own formation history. In the case of a fault scarp, trenching the base of the scarp to obtain the material that was quickly buried by tallus and colluvium following the formation of the fault is a common strategy. Available dating techniques include:

Relative Methods:
- "Clink vs. thump:" clast seismic velocity
- Weathering rinds
- Soil development
- Carbonate and other rock coatings
- Lichenometry

Absolute Methods:
- Tree rings
- Radiocarbon dating
- Uranium/Thorium dating
- Amino acid racemization
- Luminescence dating
- Cosmogenic radiomuclide dating

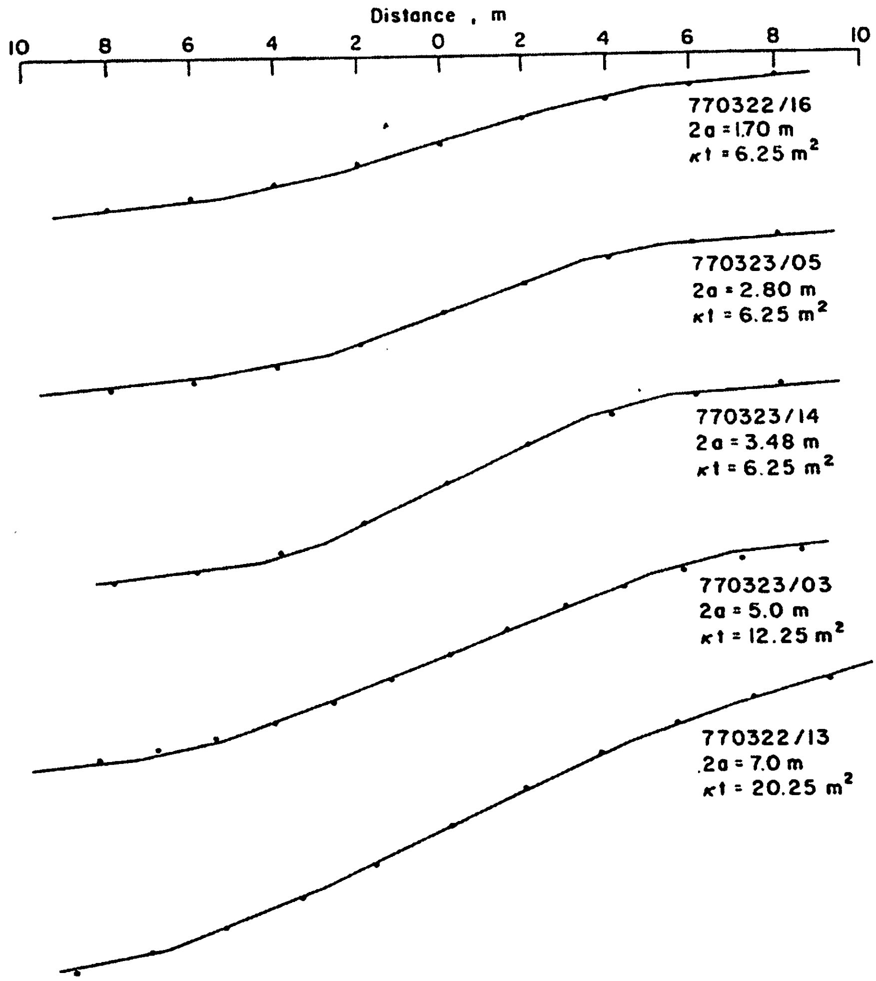


Fig. 4. Five elevation profiles of the Drum Mountains fault scarps. Topography, model calculations, profile identification, and model parameterizations are the same as in Figure 8.

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[6] J.R. Arrowsmith, D.D. Rhodes, & D.D. Pollard (1998). Morphologic dating of scarps formed by repeated slip events along the San Andreas Fault, Carrizo Plain, California, *J. Geophysical Res.*, **103-B5**, 10141-10160.

Don't bust the crust!

Biological soil crusts and their importance in arid regions

Ranger Catherine Neish

Introduction

Biological soil crusts are a vital part of desert ecosystems, covering up to 70% of the living cover in arid regions. Yet few people even realize they are there. What may look like dirt at first glance is actually a highly specialized community of cyanobacteria, mosses, and lichens (Figure 1). Forming a complex web of organic fibers, they bind the soil together into a thin mat. These crusts reduce erosion, increase soil fertility and help with water retention. Biological soil crusts take years to mature, but can be destroyed by one careless footstep. To maintain ecological diversity and the health of our deserts… don't bust the crust!

Figure 1: An arid landscape covered by biological soil crusts. Soil crusts are a highly specialized community of cyanobacteria, mosses, and lichens.

Structure and formation

Biological soil crusts – also known as crytogamic, microbiotic, and cryptobiotic crusts – are found in semiarid and arid environments around the world. In the US, the crusts are most common in the Great Basin, the inner Columbia Basin, the Sonoran Desert, and the Colorado Plateau.

The crusts are made predominantly of cyanobacteria, green and brown algae, mosses, and lichens. Cyanobacteria, the photosynthetic bacteria formerly known as blue-green algae, are one of the oldest known life forms. As the living component of stromatolites, they played an integral role in the early history of the Earth, converting the original CO_2 rich atmosphere into the current oxygen rich atmosphere. They were also among the first land colonizers, forming and stabilizing the early soils.

Biological soil crusts are formed by these living organisms and their by-products. The "knobby" topography characteristic of the crusts is created by the filamentous nature of cyanobacteria. When they become wet, cyanobacteria swell and move out of their sheaths into the surrounding soil (Figure 2a). The organism then grows new sheath material, extending its length. Repeated swellings leave behind a network of fibers, binding rock and soil particles together (Figure 2b). Amazingly, the soil-binding is not dependant on the presence of living filaments. The web is able to maintain soil structure even after the cyanobacteria have dehydrated and decreased in size. These networks provide cohesion and stability in sandy soils up to depths of 10cm.

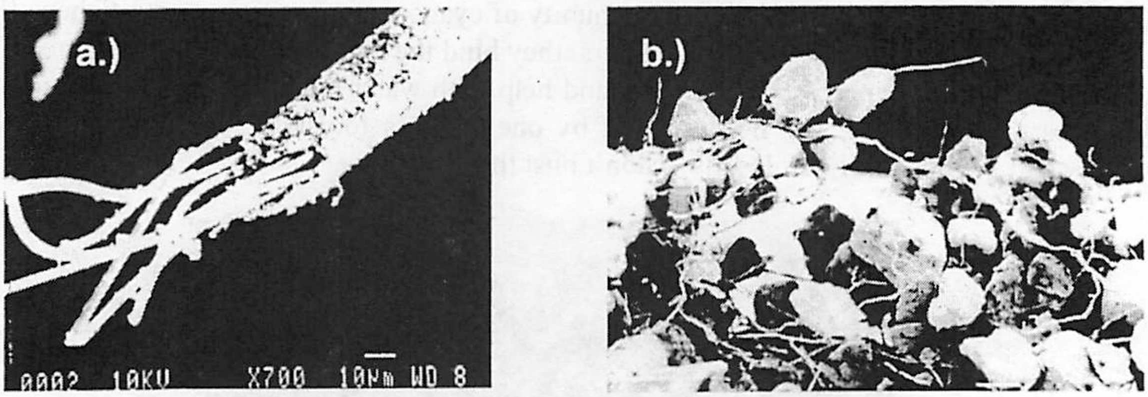


Figure 2: a.) Filamentous cyanobacteria migrating out of their sheaths. Scale bar is 10 micrometers. b.) Cyanobacterial sheath material, holding sand grains together, x 90.

The general appearance of the crusts varies from place to place. The colour of the crust is due partly to the density of organisms and partly to the often dark colour of cyanobacteria, lichens, and mosses. In the Great Basin and Colorado Plateau, where cyanobacteria composes the majority of the crust structure, the crust tends to be darker than the surrounding soil (Figure 3a). The cyanobacteria can either be on, or beneath, the soil surface.

Ecological Functions

Biological soil crusts contribute to a number of important ecological functions. They help to stabilize the soil, serve to intercept and store water, contribute to atmospheric nitrogen fixation, and aid in seedling germination and growth.

Soil stability: The filamentous sheaths exuded by cyanobacteria are extremely sticky, and help to cement soil particles together. In addition, the lichens and mosses in the crust bind the soil particles together with rhizines/rhizoids, the root-like structures they use for attachment. This soil binding increases the soil's resistance to wind and water action, and holds steep slopes in place.

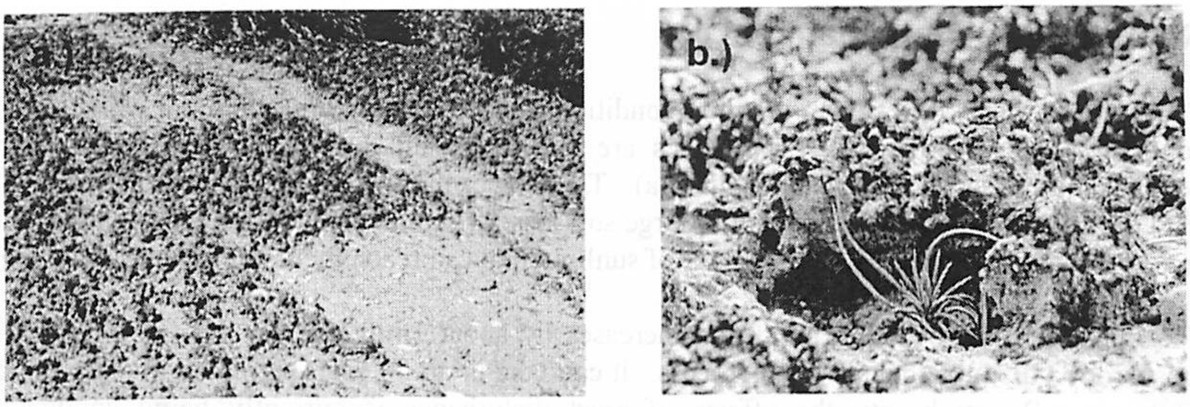


Figure 3: a.) Undisturbed crusts on the Colorado Plateau. These crusts are usually darker than the disturbed soils. Crusts generally cover all soil places not occupied by vascular plants. b.) Close-up of a seedling growing in the soil crust.

Water infiltration: The bumpy topography of the crusts helps intercept and store water, nutrients, and organic matter that might otherwise be unavailable to the plants growing in the soil. Rough soil surfaces (such as those created by the biological soil crusts) slow runoff water, increasing water infiltration into the soil.

Plant germination and growth: The crusts provide a safe, warm spot for seedlings to grow. The increased surface relief supplies safe sites for seeds to germinate. The dark surface colour increases the soil temperature, allowing germination earlier in the season, when conditions are wetter and more conducive to growth. The crusts also have increased nutrient content, as cyanobacteria are capable of fixing atmospheric nitrogen into a form vascular plants can use. This is an extremely important function, especially in desert ecosystems, where nitrogen levels are very low, and often limit plant growth.

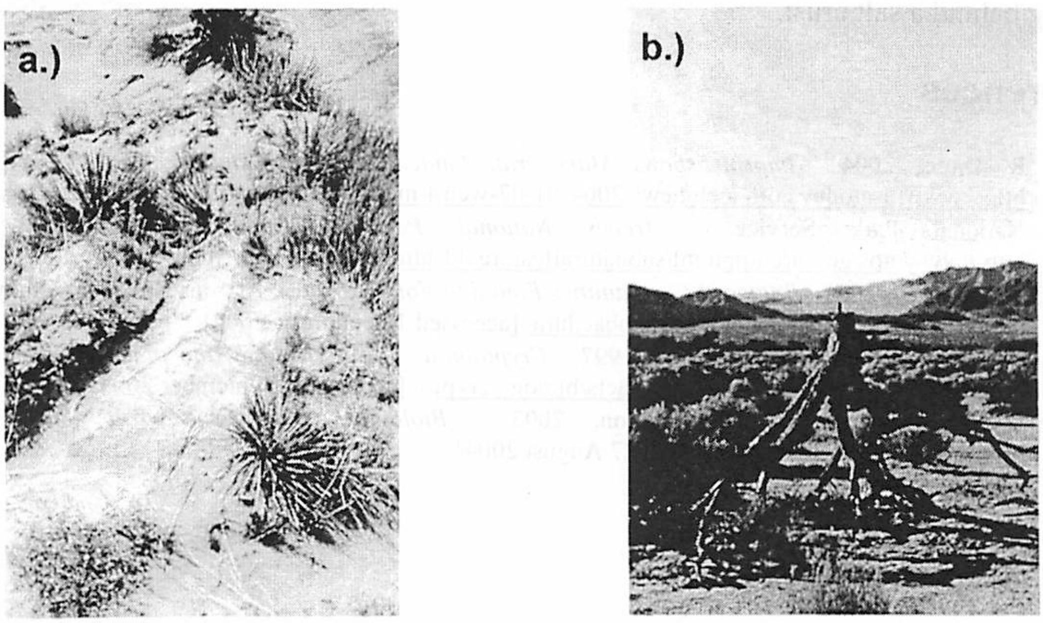


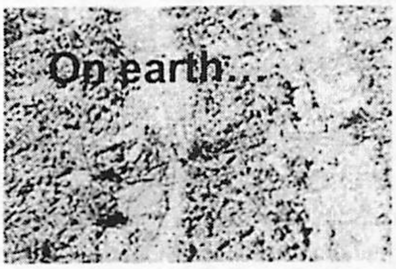
Figure 4: a.) A compressional disturbance crushes the crust, leaving soil unprotected from erosion. This can result in large amounts of soil loss. b.) In the photo on the right, soil levels are now several feet below what they were when the tree was alive.

Response to disturbances

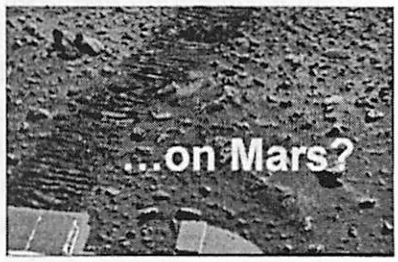
Though well adapted to severe growing conditions, biological soil crusts are not well adapted to compressional disturbances. The crusts are easily crushed by the wanderings of off-road vehicles, humans, and livestock (Figure 4a). This leaves the soil underneath exposed to erosion by wind and/or water, and can result in large soil losses (Figure 4b). The liberated sand can then cover nearby crusts, limiting the amount of sunlight that can reach them, thereby killing them.

The thickness of a cyanobacterial mat increases by about 1mm/year, so the full recovery of a crust from a disturbance is a slow process. It can take up to 50 years to regain the original crust thickness. Research into the effects of crust disturbance is currently being conducted at Canyonlands Park.

Planetary implications



Like the environments on Earth in which we find biological soil crusts, Mars is a desert. Thus, if life ever existed there, it seems possible that it might have been similar in form to the biological soil crusts, especially in its ability to resist dessication. Such an ecosystem might leave behind abandoned soil mats, allowing researchers to identify traces of past life. In fact, the recent Spirit landing on Mars found that the soil surrounding the landing craft was "strangely cohesive" and "weird", according to lead investigator Steve Squyres. These crusts are thought to be inorganic, however, perhaps created by moisture that made its way through the soil and evaporated, leaving behind a salt crust.



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"NASA: Big Meteorite Whacked Utah"[1]

Jade Bond

In addition to the salt dome theory so often applied to Upheaval Dome, the idea of the structure being produced by a meteorite impact has recently become more popular. The basic idea behind the theory is that an impact occurred here and produced a complex crater. Over the following millions of years, it has been eroded down by 0.1 – 2km to produce the structure that we see today.

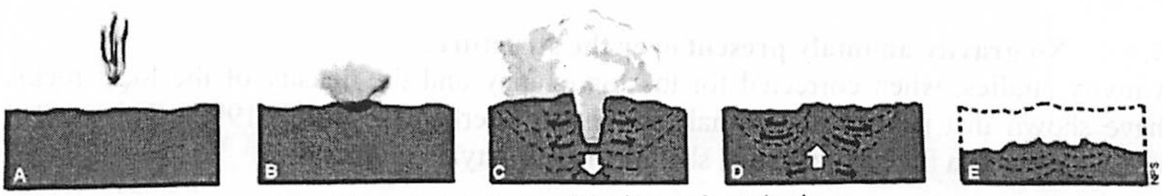

Figure 1: Schematic of the impact hypothesis.
Source: http://www.meteorite.com/impact/upheaval.htm

There are several different lines of evidence available that could possibly lead to the conclusion of an impact:

1. General morphology of site
The shape and structure of Upheaval Dome is similar to that of a complex crater (Fig. 2), considering erosion. The dome itself is also circular, not elongated like other salt domes present in the region (Kanbur et. al., 2000).

2. Listric faults.
These curved faults are observed on the rim of the structure to be dipping towards the center. They continue in to the central peak area, where they have reversed their dip. This is consistent with rock moving into the center of the dome (Fig. 3).

3. Complex and large folds.
Central peak strata are complexly folded on a large scale and are interpreted to indicate that the rock has moved in towards the center of the structure and been squeezed up (Herkenhoff et. al., 1999). Large radial plunging anticlines are also present through out the structure, also indicating compression of the strata.

4. Clastic Dikes.
These are dikes caused by hydraulic fracturing and are filled with rock fragments taken from the surrounding strata (Huntoon, 2001). The high pressures and energies needed to form this type of structure seem to imply that an impact occurred here. Roberts Rift, 22-32km northeast of Upheaval Dome, may also be another example of hydraulic fracturing, possibly also caused by the same impact (Huntoon and Shoemaker, 2001).

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[1] Siegel, Lee. 1995, Salt Lake Tribune. I kid you not; this was the title for a serious article!

5. **Flat salt layer.**

Both seismic refraction (Kanbur et. al., 2000, Louie et. al., 1995)) and seismic reflection (Herkenhoff et. al., 1999) studies have shown that the underlying salt layer is flat (Fig. 4 and 5). In addition to this, no salt outcrops are present and no bleaching of the core rocks has been observed (Huntoon, 2001). This suggests that salt diapirism was minimal in the structure.

6. **Deformation decreases with depth.**

This is consistent with the force required for the structure being provided from above, not below, i.e. an impact, not salt diapirism.

7. **No gravity anomaly present over the structure.**

Gravity studies, when corrected for the topography and the density of the local rocks, have shown that no gravity anomaly is present (Herkenhoff et. el, 1999). This is also consistent with a flat salt level and shallow, impact-style deformation.

8. **Possible identification of shatter cones and shocked quartz.**

These are associated with impacts, but Abby will be discussing them in more detail.

So . . . These various pieces of evidence can all be tied together if Upheaval Dome is an impact crater. Kanbur et. al. (2000) describe the development of a complex crater (via Jay's impact cratering book) as " . . . subsidence and radially inward transport of the walls of the transient cavity along listric faults, with the convergent flow raising the bottom of the transient cavity into a complex central uplift." (p. 9490). This strongly seems to agree with what we see in terms of faulting, folds and morphology (Fig. 6). The pressure and energy associated with the dikes is high enough that it is likely to have only been produced by something like an impact. The fact that salt domes or the effects of large scale salt movement can't be seen also lends weight to the idea of an impact. Also, the deformation pattern matches what you would expect to see at an impact crater.

So . . . it certainly is possible that Upheaval Dome is, in fact, an impact crater.

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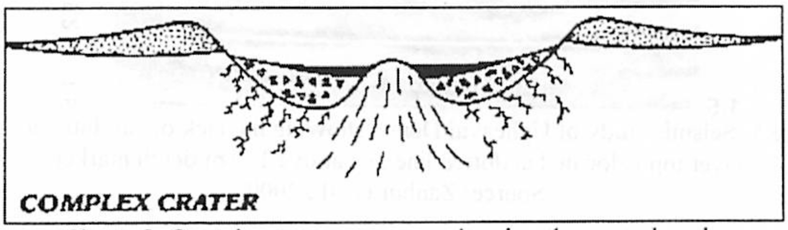


Figure 2: Complex crater structure, showing the central peak.
Source: http://www. eoascientific.com/prototype/newcampus/space/12/meteor/meteor5.html

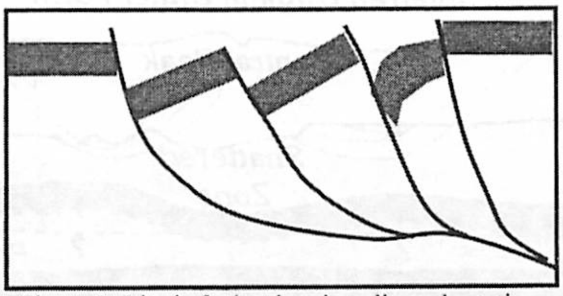


Figure 3: Listric faults showing slip and rotation.
Source: http://www.uwsp.edu/geo/faculty/hefferan/geol320/normalfaults.html

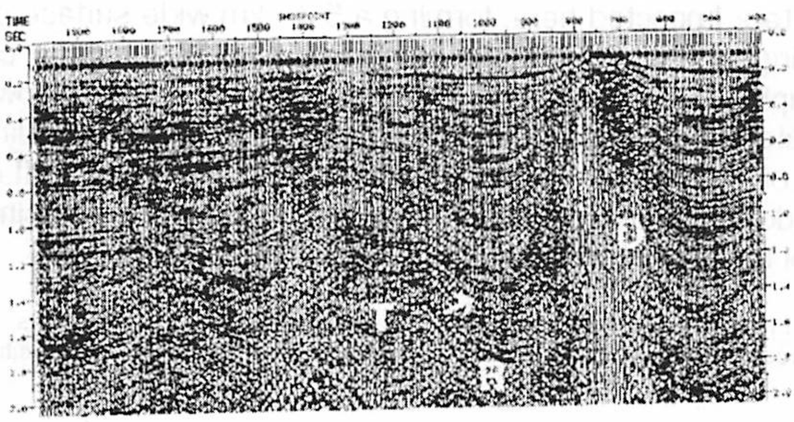


Figure 4: Seismic study of a salt dome (D), showing increasing deformation with depth.
http://www.seismo.unr.edu/ftp/pub/louie/dome/98seismo/impact.html

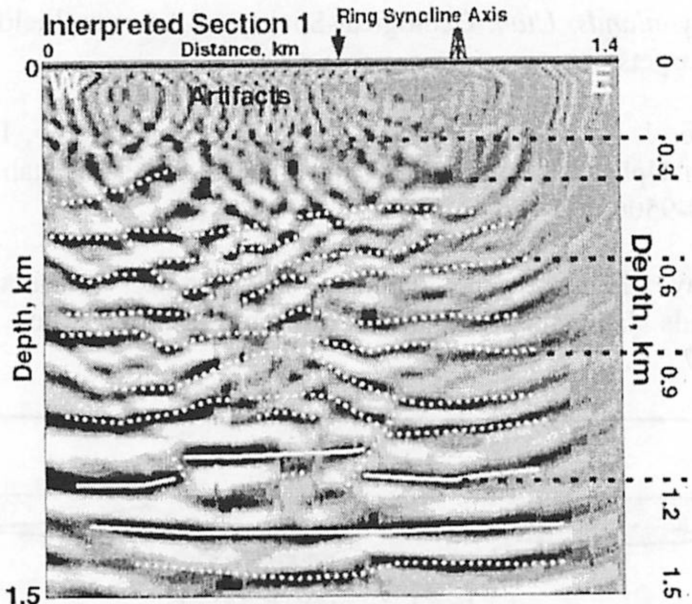
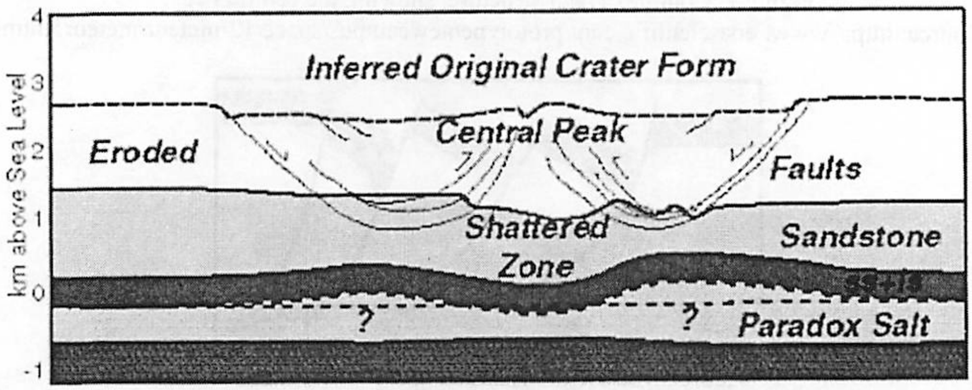


Figure 5: Seismic study of Upheaval Dome, showing the lack of salt intrusion. Salt layer top is located at dotted line just above 1.2km depth marker.
Source: Zanbur et. al., 2000



Section showing the **meteor impact hypothesis** for the origin of Upheaval Dome. Between 5 and 100 million years ago a 0.3 to 1.2 km meteor impacted here, forming a 5-10 km wide surface crater. Slumping of the crater walls along listric faults forced a central peak uplift in the shattered center of the structure. Salt flow may have later bulged the Paradox Formation in a ring surrounding the center of the impact, without significant salt diapirism. Uplift of the Colorado Plateau recently eroded 1 km of cover, exposing the roots of the impact structure.

Figure 6: Outline of the Impact hypothesis and the associated structures.
Source: http://www.seismo.unr.edu/ftp/pub/louie/dome/98seismo/refraction.html

Upheaval Dome, Utah: An Eroded Salt Dome?

By Oleg Abramov

I. A Quick Introduction to Upheaval Dome

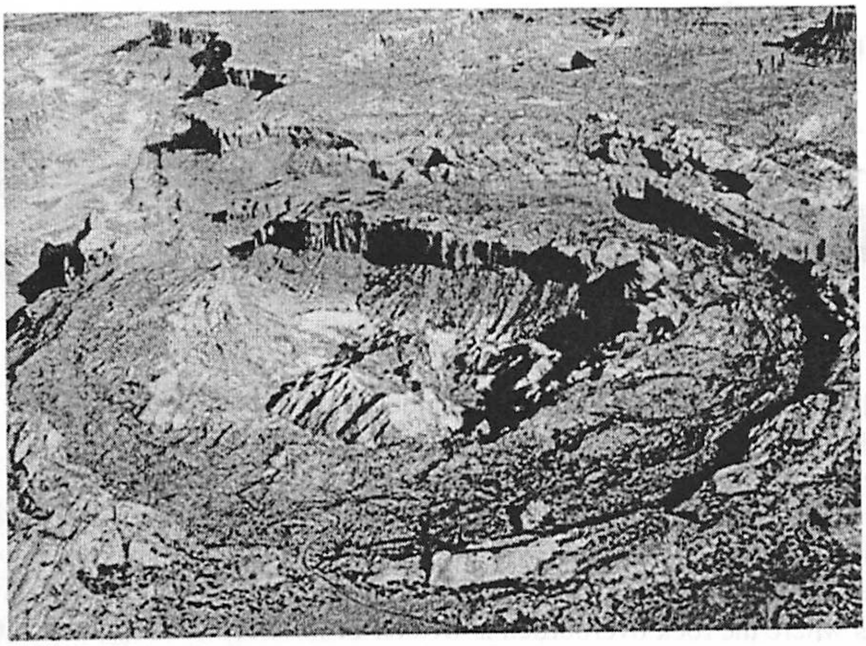


Figure 1. Oblique aerial photograph of Upheaval Dome, looking NW (from *Kriens et al.* [1999])

Upheaval Dome, a circular structure about 5 km in diameter, is located in the western part of the Colorado Plateau in the Canyonlands National Park. The structure consists of an outer annular, inward-dipping monocline, inside which there is a ~3.5 km circular syncline (Fig.1). Upheaval Dome is located in the western region of the Paradox Basin, which is underlain by vast salt deposits left by recurring seawater evaporation during the Pennsylvanian Period. For a detailed description of the geologic setting and a stratigraphic cross-section of the structure, please refer to Brandon Preblich's handout.

The origin of Upheaval Dome has been a subject of controversy for a considerable time. The early debates focused on an underlying salt dome [e.g. *McKnight*, 1940], cryptovolcanic [*Butcher*, 1936], and impact [*Boone and Albritton*, 1938] hypotheses. However, no igneous rocks have been found within 55 km of the dome, and the cryptovolcanic hypothesis currently has little support. The impact hypothesis was revived in 1983 by *Shoemaker and Herkenhoff*, and the two formation models presently debated are salt diapirism [e.g. *Jackson et al.*, 1998] and impact origin [e.g. *Kanbur et al.*, 2000; *Kenkmann*, 2003].

II. What is a Salt Dome?

Salt Dome. ***n.*** **[Geology]**

A mushroom-shaped or plug-shaped diapir made of salt, commonly having an overlying cap rock. Salt domes form as a consequence of the relative buoyancy of salt when buried beneath other types of sediment. The salt flows upward to form salt domes, sheets, pillars and other structures.

(*http://www.glossary.oilfield.slb.com/Display.cfm?Term=salt%20dome*)

Diapir. ***n.*** **[Geology]**

A relatively mobile mass that intrudes into preexisting rocks. Diapirs commonly intrude vertically through more dense rocks because of buoyancy forces associated with relatively low-density rock types, such as salt, shale and hot magma, which form diapirs. The process is known as diapirism. By pushing upward and piercing overlying rock layers, diapirs can form anticlines, salt domes and other structures.

(*http://www.glossary.oilfield.slb.com/Display.cfm?Term=diapir*)

III. Salt Dome Formation Mechanism

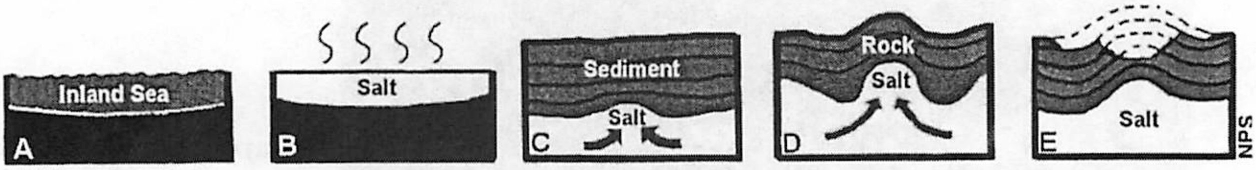
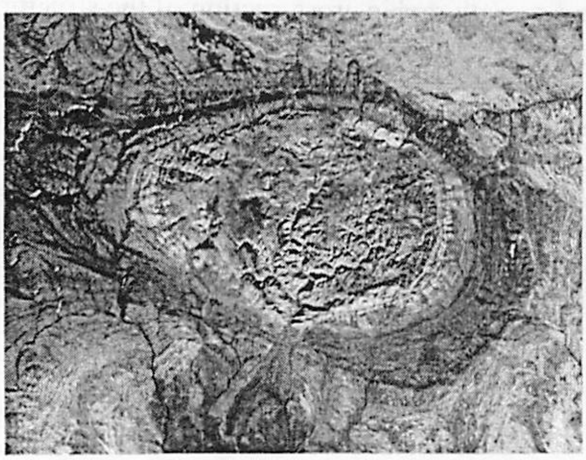


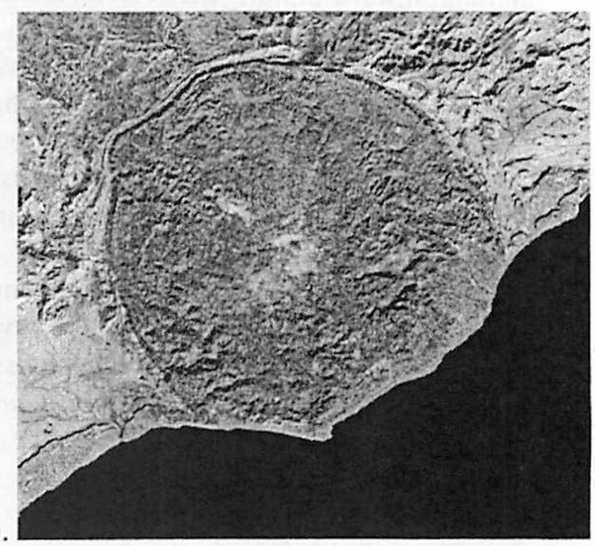
Figure 2. General mechanism of salt dome formation (National Park Service graphic).

The process usually begins with a large inland sea undergoing multiple episodes of evaporation and refilling(Fig. 2a). Over millions of years, this process produces a large salt deposit hundreds of meters thick, like the Paradox Formation in Utah (Fig. 2b). Over time, sediments are deposited over the salt, forming thick layers of rock overburden (Fig. 2c) which then push down on the salt below. Since the density of salt is significantly less than that of rock, it becomes buoyant. If the temperatures are sufficiently high to overcome its strength, the salt is then squeezed up in places where the rock overburden is weaker or thinner, forming a dome (Fig. 2d). In some cases, erosional processes remove the overlying layers of rock, forming a pseudo-crater (Fig. 2e). In other cases, the salt may intrude onto the surface.

IV. Examples of Other Salt Domes



a.



b.

C.

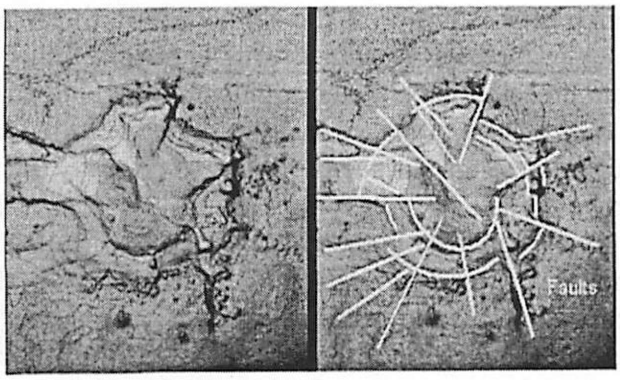


Figure 3. *a*) Salt dome in the Holmuz strait, Qeshm Island, Iran (ASTER image), *b*) Salt dome in the Arctic: Isachsen salt dome, Ellef Ringnes Island, NWT, Canada (ASTER image), *c*) Bright Bank, an underwater salt dome on the continental shelf of the Gulf of Mexico. Faults are indicated by yellow lines in the right-hand panel. (Image from *http://oceanexplorer.noaa.gov/explorations/03mex/logs/sept23/media/braton_image3.html*)

V. Proposed Upheaval Dome Formation Mechanism

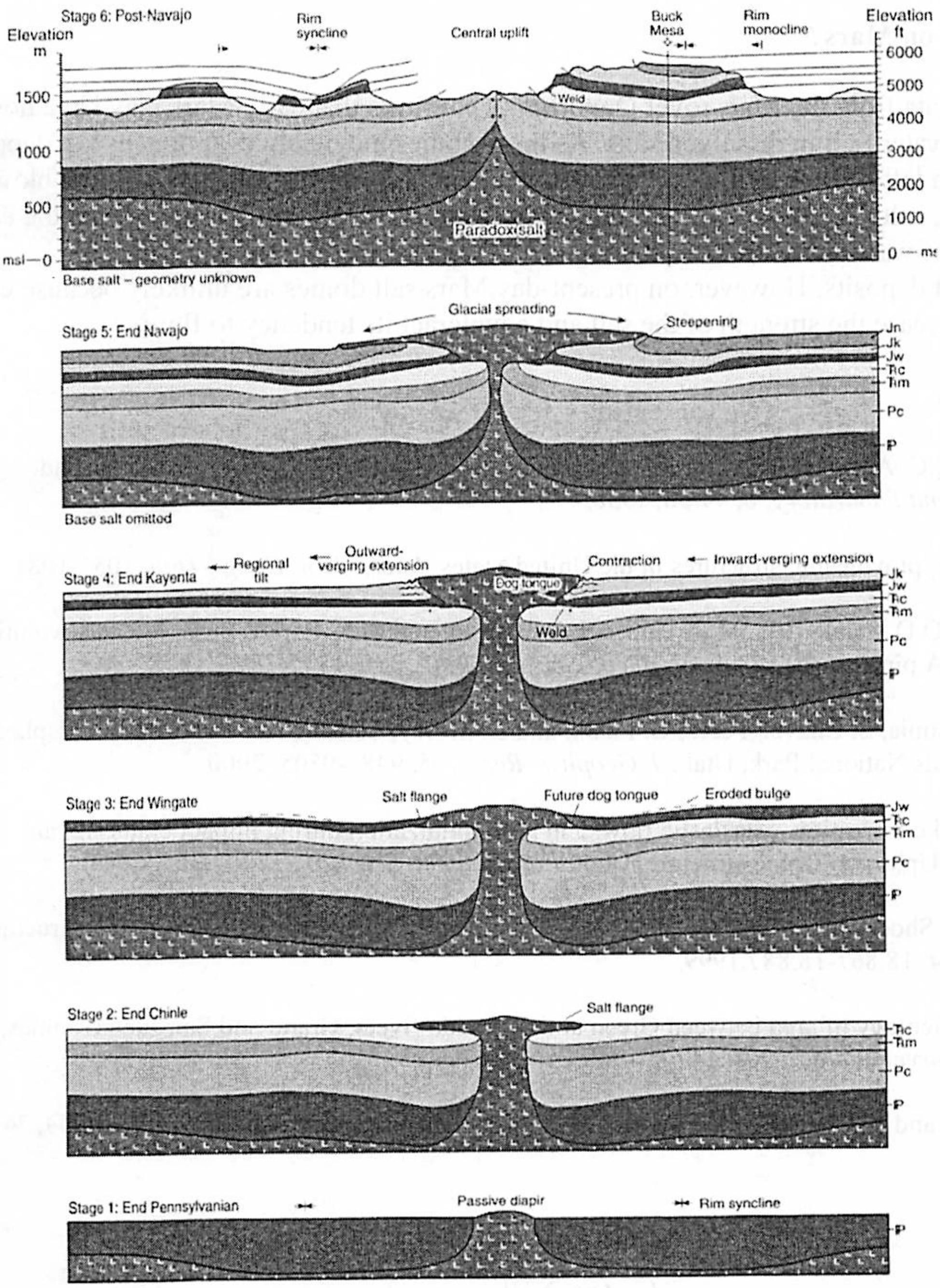


Figure 4. Salt-tectonic evolution of Upheaval Dome as proposed by *Jackson et al.* [1998].

Jackson et al. [1998] rejected the notion of an underlying salt dome due to strong evidence for lateral constriction rather than lateral extension in the dome center. The impact hypothesis was also rejected based on a lack of features associated with an impact crater (meteoritic material, melt fragments, in situ breccia, shock metamorphism, outer fault terracing, and overturned peripheral flap). *Jackson et al.* [1998] proposed that the Upheaval Dome is a pinched diapir, or a salt dome that has erupted onto the surface but was subsequently pinched off at the base (Fig. 4). The salt then would have eroded away, leaving a crater-like form. While such pinched-off diapirs are common below the sea floor in the Gulf of Mexico and other salt basins, the mechanism for pinch-off is unknown. *Jackson et al.* [1998] argued that the following features at Upheaval dome favor the pinched diapir hypothesis: rim syncline, rim monocline, steep zones in inner limb of rim syncline, outward-verging extension, radial synformal flaps (dog tongues), underlying salt deposits and nearby salt structures, multiple episodes of microfracturing and sealing, and postplacement microfracturing in the clastic dikes, and especially synsedimentary structures that indicate Jurassic growth of the dome over at least 20 Ma.

VI. Salt Domes on Mars?

Recent data from the Mars rover Opportunity confirms that early Mars may have hosted large bodies of water rich in dissolved salts. As these bodies inevitably evaporated, salt deposits would have been left behind, and in some cases would be subsequently buried by wind-blown sediments. Thus, salt domes were hypothetically possible on early Mars, provided that the early Martian bodies of water were sufficiently large and long-lived to produce substantial underground salt deposits. However, on present-day Mars salt domes are unlikely because cold temperatures increase the strength of the salt and counteract its tendency to flow.

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Impact Structure Exposed: Upheaval Dome

by Brandon Preblich

When did the impact occur?

-- The age has not been definitively determined. Somewhere in the Jurassic or Cretaceous periods (210 to 65 million years ago)

What was the surrounding area like before the impact?

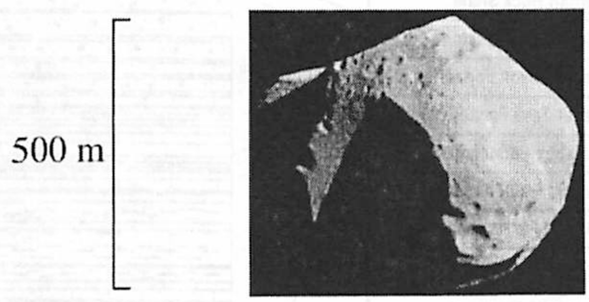
-- Jurassic: a desert, where sandstones formed. Shallow seaways then invade Utah. Brontosaurus, Stegosaurus

-- Cretaceous: the seas retreat. Swamps on edge of retreating area. Western Utah rises due to thrust faulting and folding. Tyrannosaurus

How big was the impacting object and how did it strike the ground?

-- 500 meters in diameter

-- Oblique impact from the WNW



Size of the impacting object. Godzilla and scale bar are both supplied for scale...

How did the crater form?

-- Impact occurs

-- Rapid flow of rock from the impact point as the transient crater forms

-- Transient crater collapses, and listric faults allow the rocks along the perimeter to move inward and upward to form the central peak

-- Erodes over millions of years

What is the nature of the resulting crater?

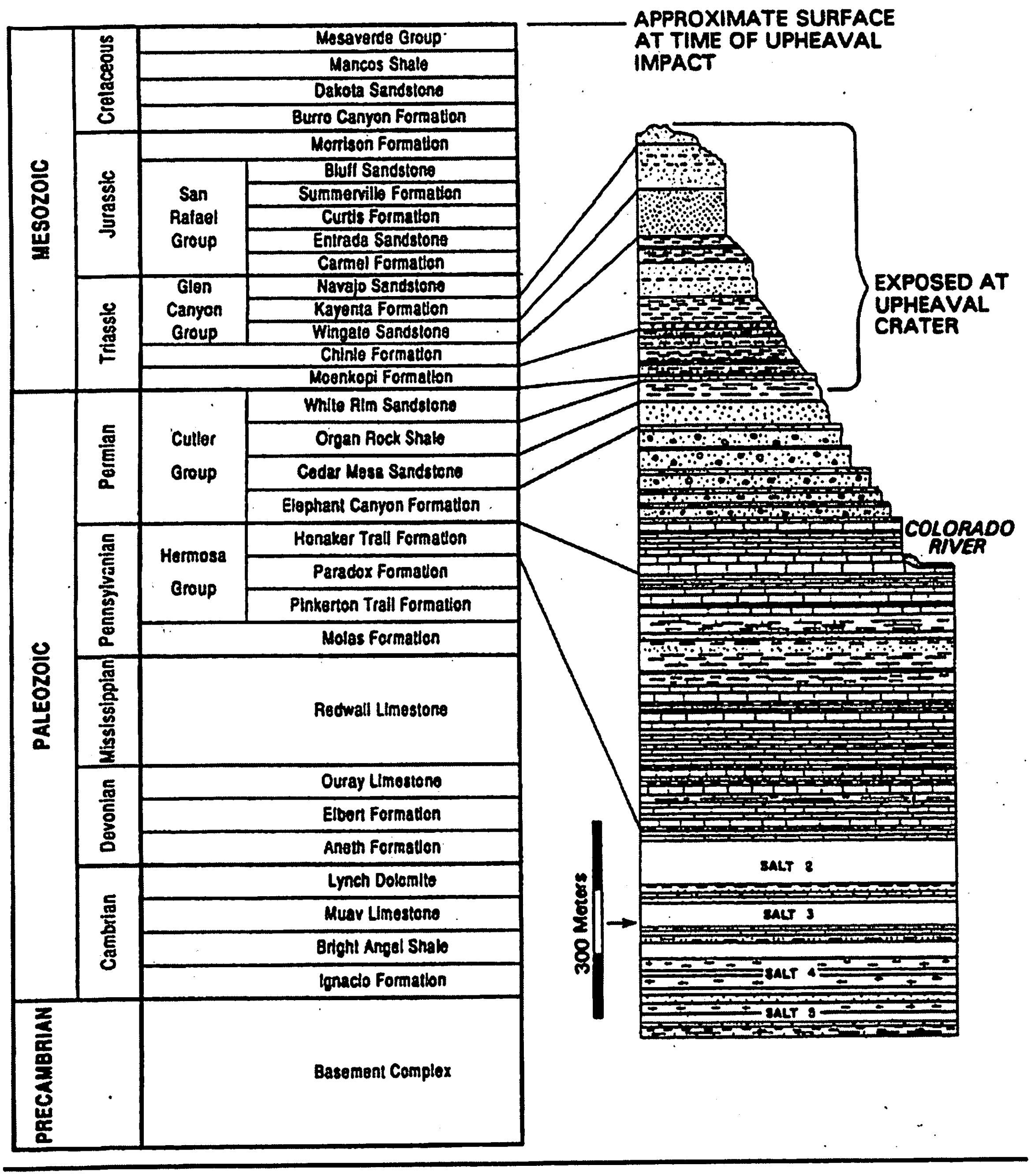
-- Complex impact crater

-- 5 km in diameter currently

-- Possibly 7-10 km in diameter originally

-- Central peak/"dome" in center, moving out to a rim syncline

-- Multiple rings



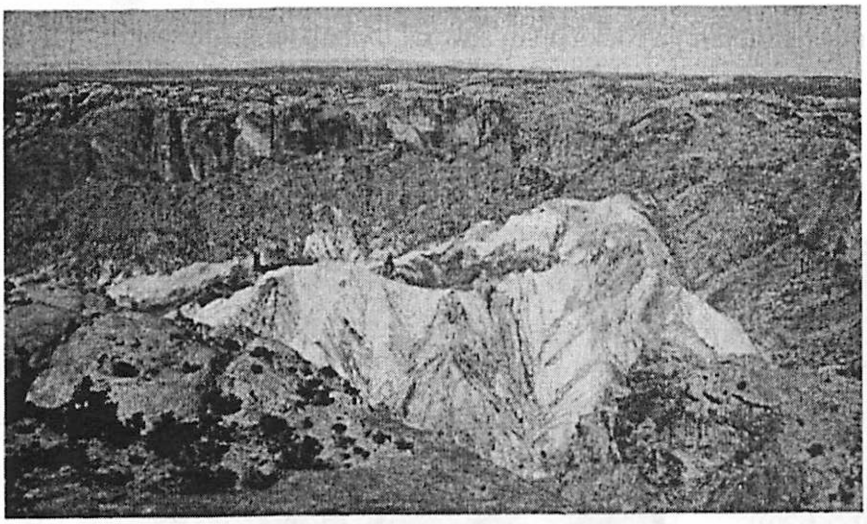
APPROXIMATE SURFACE AT TIME OF UPHEAVAL IMPACT
MESOZOIC
Cretaceous
Mesaverde Group
Mancos Shale
Dakota Sandstone
Burro Canyon Formation
Jurassic
Morrison Formation
San Rafael Group
Bluff Sandstone
Summerville Formation
Curtis Formation
Entrada Sandstone
Carmel Formation
Triassic
Glen Canyon Group
Navajo Sandstone
Kayenta Formation
Wingate Sandstone
Chinle Formation
Moenkopi Formation
PALEOZOIC
Permian
Cutler Group
White Rim Sandstone
Organ Rock Shale
Cedar Mesa Sandstone
Elephant Canyon Formation
Pennsylvanian
Hermosa Group
Honaker Trail Formation
Paradox Formation
Pinkerton Trail Formation
Molas Formation
Mississippian
Redwall Limestone
Devonian
Ouray Limestone
Elbert Formation
Aneth Formation
Cambrian
Lynch Dolomite
Muav Limestone
Bright Angel Shale
Ignacio Formation
PRECAMBRIAN
Basement Complex
EXPOSED AT UPHEAVAL CRATER
COLORADO RIVER
300 Meters
SALT 2
SALT 3
SALT 4
SALT 5

How did the dikes around the crater form?

-- Shock wave from impact hit aquifers and petroleum reservoirs nearby

-- Hydraulic fracturing occurs in strata above and below the reservoir

-- Fragments entrained in escaping fluids and remain as clastic dikes



What are the white and red rock units that make up the "dome" in the center?

-- White: White Rim Sandstone (Permian)

-- Red: Organ Rock (Permian)

Tell me something cool to leave me with a good feeling.

-- Shoemaker estimated that an impact of this magnitude would eject enough material to blanket the surrounding landscape for 6 miles! Beyond that, for another 6 miles there'd be rock missiles flying everywhere.

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Shocked Quartz, Shattercones, and Impactitites
Are they present at Upheaval Dome?

Abby Sheffer

Shocked Quartz – a form of quartz that has a microscopic structure that is different from normal quartz. Under intense pressure (but limited temperature), the crystalline structure of quartz will be deformed along planes inside the crystal. These are known as planar deformation features (PDFs) or shock lamellae.

Impactite - A vesicular (has bubbles), glassy to finely crystalline material produced by fusion of target rock by the heat generated from the impact of a large meteorite, and occurring in and around the resulting crater, typically as individual bodies composed of mixtures of melt and rock fragments, often with traces of meteoritic material.

Shattercone - A striated, conical structure in rocks up to several meters long. They are indicative of very high shock pressures (1-20 GPa) such as by nuclear explosion or large impact. The striations fan out from a central point and are often referred to as fan-tail or horsetail structures.

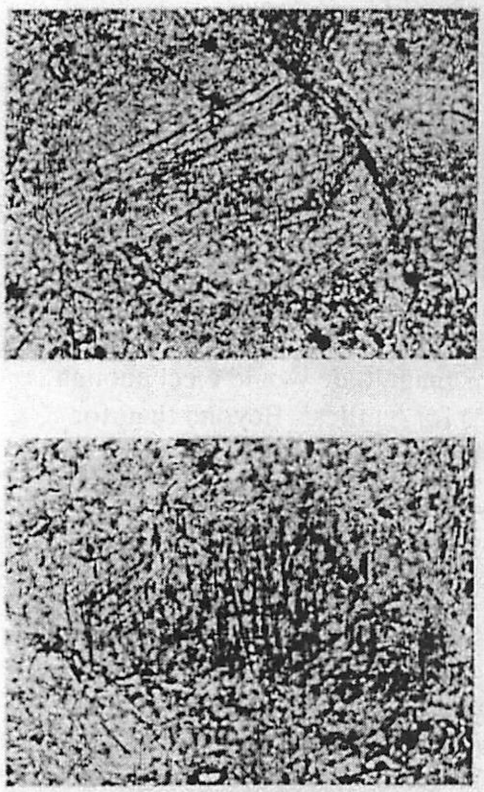
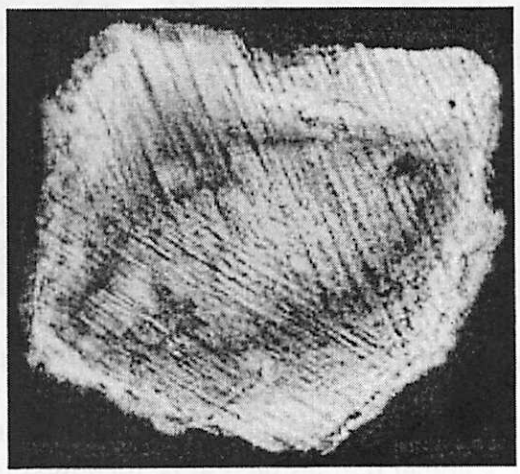


Figure 17. Planar microstructures in quartz grains from one sample of White Rim Sandstone dike near center of structure. Grains are ~0.3 mm across, with plane-polarized light, same scale in both photomicrographs. At least two sets of planar microstructures are visible in each grain.



Left: "Shocked quartz" from Upheaval Dome (Kriens, et al. 1999). PDFs are indistinct and not very parallel. They may indicate weak shock.

Above: Shocked quartz from the Chesapeake Bay impact structure. Note the very distinct sets of PDFs.

Koeberl et al. (1999) also looked for PDFs in quartz in the same dike as Kriens et al. (1999) but believed that the features seen were caused by low-strain deformation rather -- than by shock. They found no deformation that was characteristic of shock.

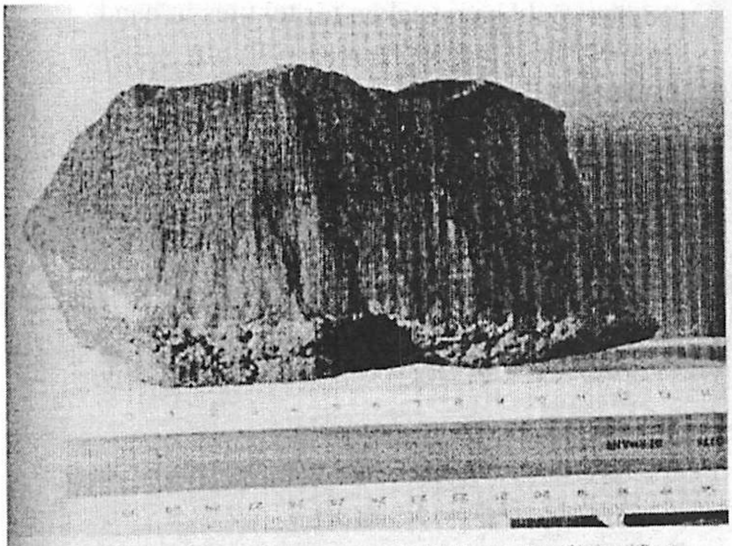
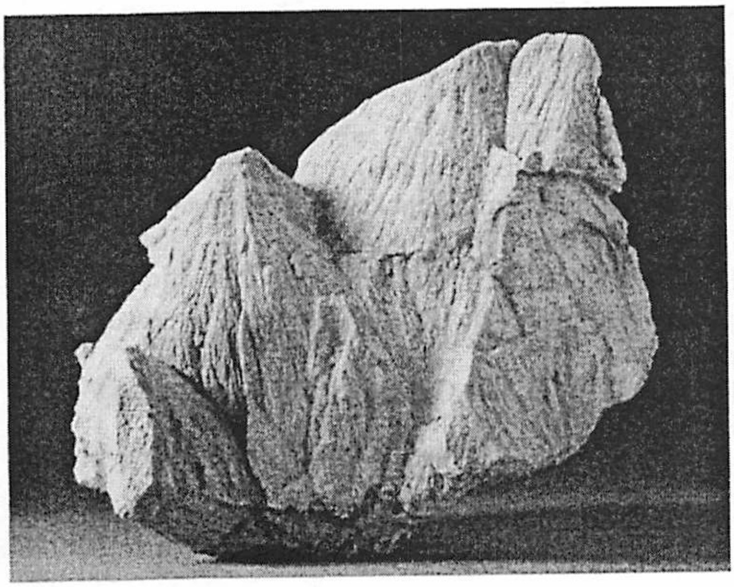


Figure 18. Shatter cone in sandstone of Moenkopi Formation found near the center of Upheaval Dome. Scale is in centimeters.

From Kriens et al. (1999). Shatter surfaces are not as finely decorated and grooved as at other impact structures, but show the characteristic fan-tailed pattern. Poorly lithified strata (sediment not completely converted into solid rock), porous rock, or low shock pressure could cause the striations to be less distinct.



Well-developed shattercone in limestone found at the Sierra Madera Crater on last semester's fieldtrip.

Impactites

Possible impactites found in a lag deposit (an area where loose soil or sand has been blown away, leaving behind larger rocks) by Kriens et al. (1997) have since been shown to be chert nodules weathering out of the Chert Pebble Unconformity layer above the Navajo sandstone. Since chert is microcrystalline or amorphous quartz, it was easily mistaken in hand sample for melted rock. However, upon further investigation, the nodules showed no evidence for melting and were enriched in elements associated with formation in hydrothermal processes – As, Sb, Ba and U.

Australite tektites (impactites). Rounded chert nodules could be mistaken for tektites in hand sample. These are very glassy with few vesicles inside.

Summary:

Shocked quartz – Maybe. If so, it's a good indicator of impact, but is not definitive.
Shattercones – Most likely yes. This is a very good indicator of impact.
Impactites – No. The presence of impactites would be a very good indicator of an impact event, but their absence does not rule it out.

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Terra Meridiutahni: Similiarities Between Southeastern Utah and Mars Rover *Opportunity*'s Landing Site

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ABSTRACT

Sandstone is ubiquitous in southeastern Utah, and there is reason to think that basaltic sandstone forms some of the stratigraphy underlaying *Opportunity*'s landing site in Terra Meridiani on Mars. The more concrete (pun intended) interplanetary connection involves the Blueberries that litter Eagle and Endurance craters. These hematite concretions form when iron compounds precipitate out of groundwater solution into small, usually spheroidal balls. In Utah they're sometimes known as Moqui Marbles, but on Mars they're Blueberries.

Subject headings:

PLANETARY SANDSTONES

You'll see a lot of sandstone in southeast Utah. Like, a lot. Locals and outdoors types call it 'slickrock'.

I thought it was rather pretty on my last fieldtrip to Canyonlands (Rivkin 1999). I remember asking the question, "so, is there sandstone on Mars?" The answer was: we don't know.

Sandstone is composed of sand particles cemented together. So, to form it you need: (1) sand and (2) a cementation mechanism.

Here in Utah, the sand is composed predominantly of silica (SiO_2) – a mature high-silica endmember chemical composition. Near as we can tell, formation of pure silica requires:

```
for(int n=0;n<MANY;n++) {
  partial melting(rock);
  eruption(rock);
  subduction(rock);
}
```

. Continental drift on Earth does this process quite well. It is not at all clear (despite those crappily-calibrated Mars Pathfinder APXS results) that rocks of higher silica content than basalt have ever formed on Mars, or any planet other than Earth for that matter. These high-silica rocks then have to be ground down by erosion into sizes suitable for long-range transport by either wind or water, and then deposited somewhere.

It may be possible that a sandstone-like rock could form from Mars' omnipresent dust grains: duststone. However, not all sand need be made of silica. Even here on Earth there is some sand made out of ground-up basalt, notably the stuff that makes up the black sand beaches in Hawaii (Figure 1.

The other element that goes into making sandstone is the cementing process. On Earth, this requires the burial

Fig. 1.— Black sand beach on the Big Island in Hawaii. The Kilauea eruption has buried this particular beach subsequent to when this image was taken during its present eruption.

and subsequent compaction of the sand layers in question, followed by the precipitation of cementing chemicals out of a groundwater solution. Here, the cement is frequently calcite (similar to in the caliche that is so hard to dig out of my front yard). Thus sandstone requires liquid, if not surface, water in order to form.

So, considering the briny remnant discoveries that *Opportunity* has made so far at Terra Meridiani, the chances that there is sandstone on Mars, though not like that here in Utah, has greatly increased. Stay tuned, the positive confirmation of sandstone in Endurance crater could happen any day.

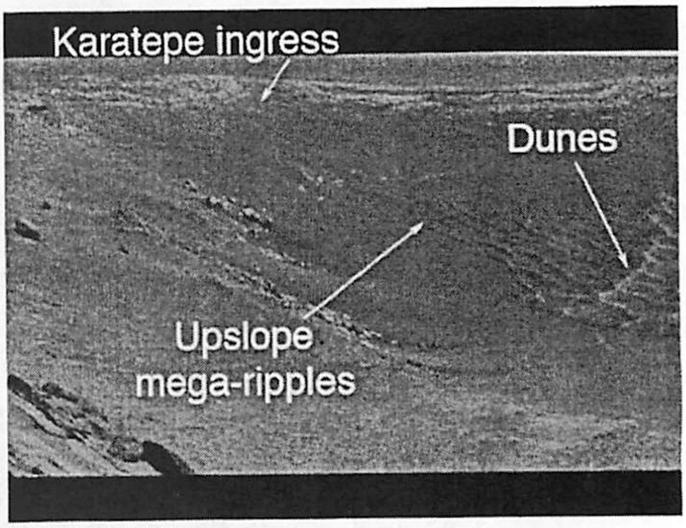

Fig. 2.— *Opportunity* rover view of the inside of Endurance crater. Some of the layered and cliff-forming units may be basaltic sandstone, though there is no positive confirmation of this from the rover after having driven past them. Also, note the dunes, possibly also made of basaltic sand, at the bottom of the crater.

BLUEBERRIES AND MOQUI MARBLES

Even after cementation, sandstones typically have up to 35% pore space. This makes them good for groundwater aquifers, but also allows for that same groundwater to perform subsequent aqueous alteration. In cases where the groundwater is able to leach iron from its environment, such as, say, where the sandstone is red, it can redeposit that iron in the form of Hematite (FeO_3) concretions. These concretions on Earth are sometimes nucleated by bacteria (Catling 2004), and can grow up to several centimeters in diameter.

Upon landing in Eagle crater in Terra Meridiani, a landing site chosen because of orbitally detected infrared spectral signatures of Hematite (and, of course, because the whole place is an utterly flat Oklahoma-sized parking lot that Ross Beyer (personal communication) calls, "an engineer's wet dream"), *Opportunity* found the crater floor to be covered in small, ~ 1 cm spherules whose spectra match that seen from orbit (Figures 3, 4, 5, 6). These Hematite balls were termed Blueberries due to their uniform distribution in the matrix in which they reside, *i.e.*, they don't form preferentially in layers or anything like that. Plus, they look blue in the false-color images the imaging team produces using Hematite absorption bands.

Chan et al. (2004) have recently (Nature, 2004 June 17) suggested that these Martian blueberries may be similar in both substance and formation mechanism to Moqui Marbles found in the Navajo Sandstone of Southeastern Utah (see Figure 7, 8).

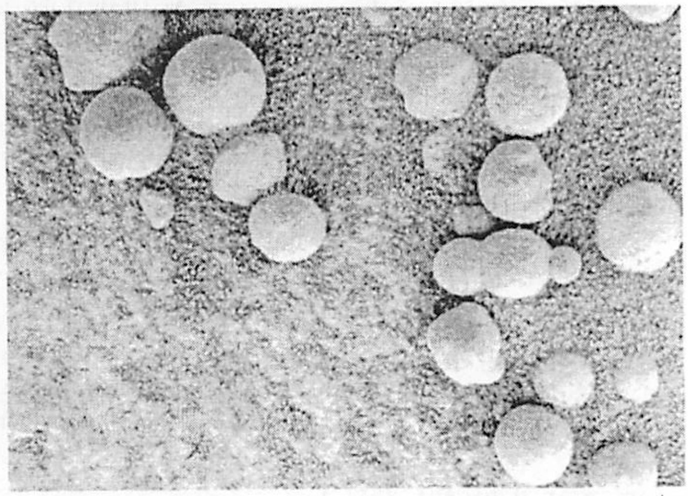

Fig. 3.— Blueberries in Eagle Crater, from *Opportunity*'s microscopic imager.

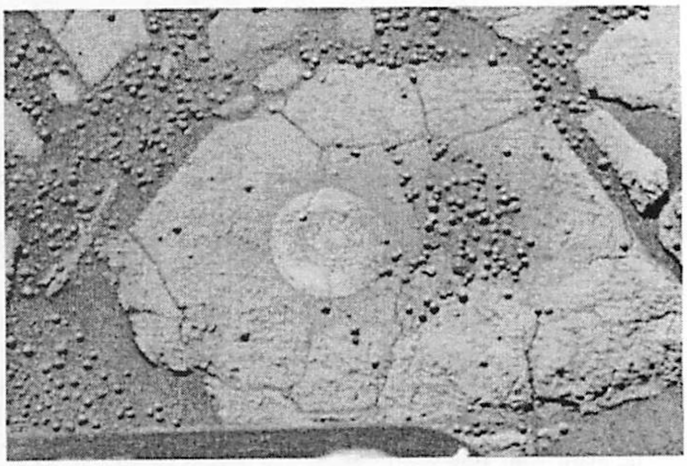

Fig. 4.— Berry Bowl, a small depression filled with blueberries that *Opportunity* used for spectral and APXS analysis.

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This 2-column preprint was prepared with the AAS LaTeX macros v5.0.

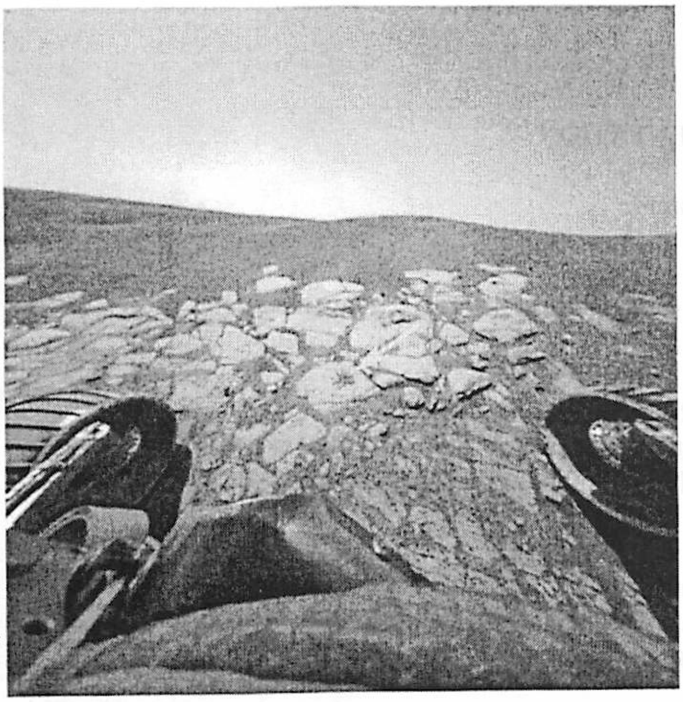


Fig. 5.— Berry Bowl in context.

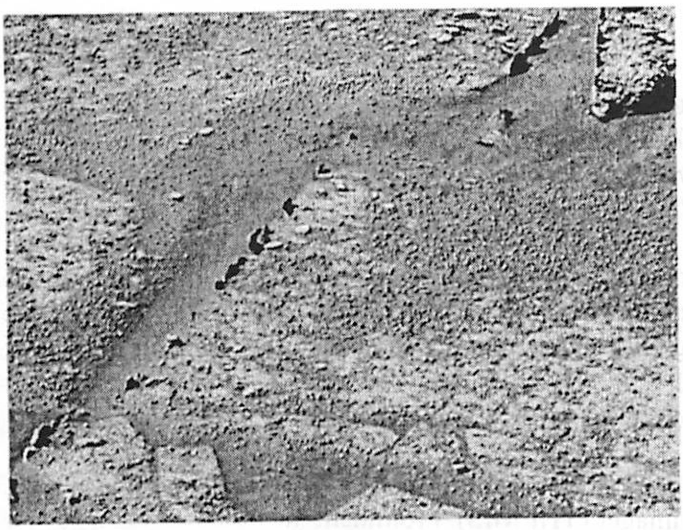


Fig. 6.— Blueberries all over Razorback, a small outcropping formation in Endurance Crater.

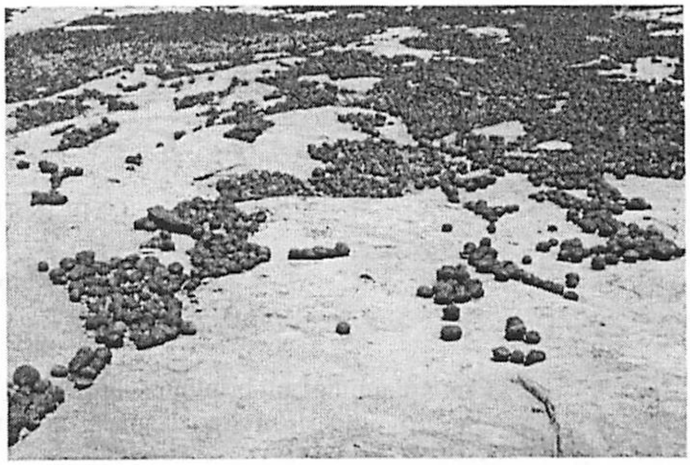


Fig. 7.— Moqui Marbles found in Southeastern Utah. Despite the lack of scale bar, these concretions are each several centimeters in diameter. Thanks to Matt Chamberlain for the photo.

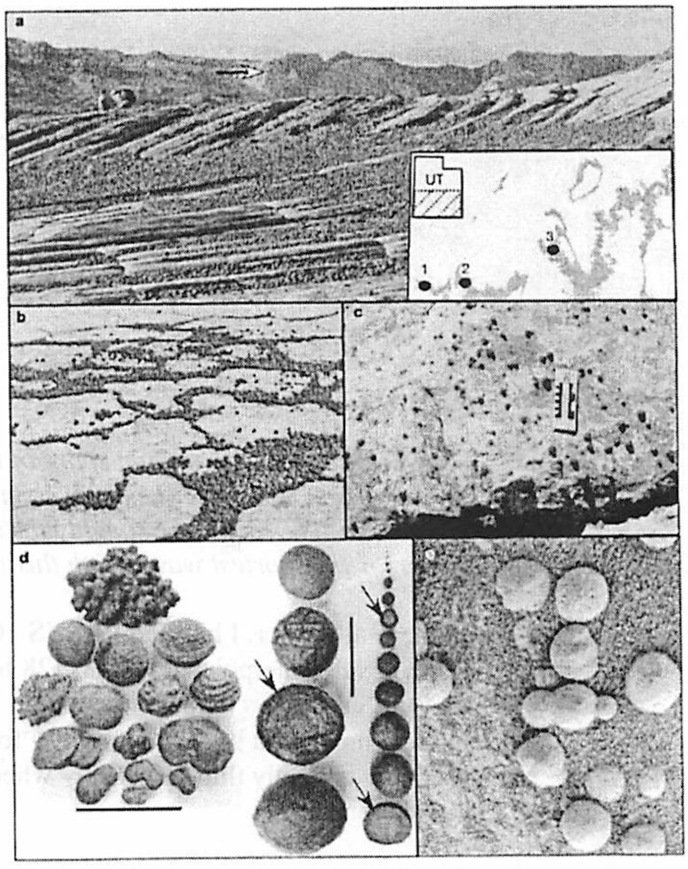


Fig. 8.— Chan et al. (2004)'s Figure 1, showing outcrop locations in Utah (a), a shot like Chamberlain's (b), concretions in matrix (c), and a comparison of shapes and textures of concretions on Earth and Mars.

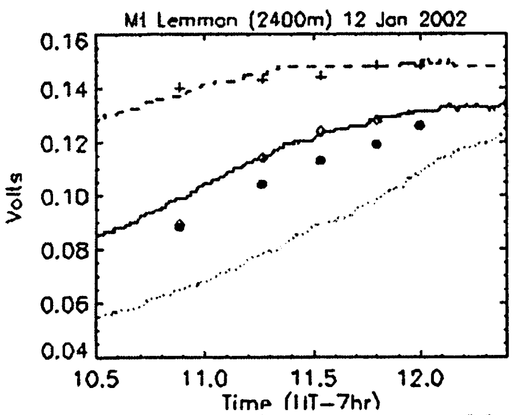
SOME INSTRUMENTATION

Ralph D Lorenz

I am *planning* on bringing along some 'toys' - some or all of the items below may not appear on the trip, due to technical malfunction, act of God, laziness on my part etc. etc.

1. UV Sensor. This is a photodiode array, with filtered diodes sensitive to various UV wavelengths. An amplifier converts the tiny photocurrent (which is proportional to the flux of light) into a voltage for readout. A similar photodiode array was carried on the Beagle 2 lander to Mars.

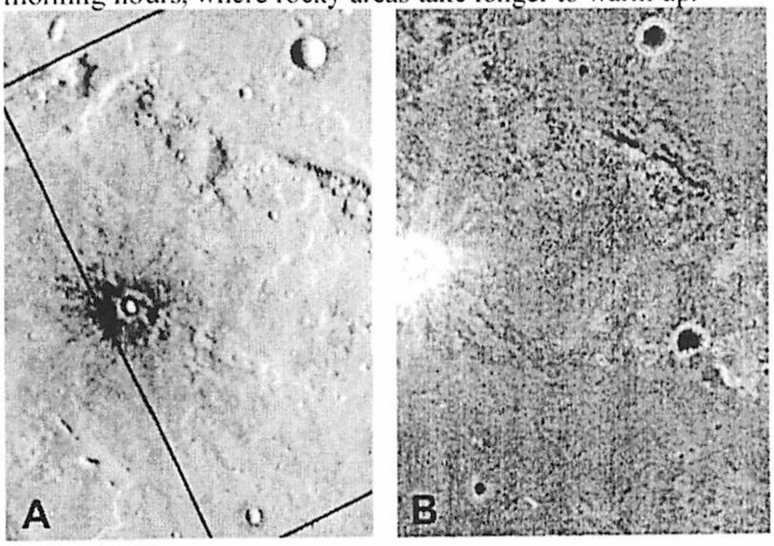
We will observe the increase in UV flux at higher altitudes (where there is less of an absorbing/scattering column of gas). The decrease in flux is not the same at all wavelengths. We can perhaps experiment with the UV shielding properties of different materials.



UV flux recorded with a flight spare of the Beagle 2 Environmental Sensor package in Tucson (lines) and on Mt Lemmon (symbols) The curves top to bottom decrease in wavelength. The fluxes are roughly the same for a given time of day (=solar zenith angle) except for the shortest wavelength flux (dotted line, solid circles)

2. Thermal imager. I have an IRISYS 1011 thermal imager for dust devil studies (a paltry 16x16 pixels, interpolated to 128x128 for display.) Field of view is 20° across, showing 8-14 μm brightness temperature in °C. The brightness temperature is the physical temperature scaled by an emissivity - for a black body the emissivity is unity. The sky is relatively optically thin (especially when dry) so the sky reads a low brightness temperature.

The Mars Odyssey spacecraft carries a thermal imager (THEMIS). Prominent in THEMIS nighttime images are the signatures of high thermal inertia (high density, thermal conductivity and specific heat). Rocks and boulders (being solid) retain the heat of the day far better than porous regolith or dust (which has low density and thermal conductivity) and thus show up as warm objects at night. The converse is true during the morning hours, where rocky areas take longer to warm up.



THEMIS day time image
(box denotes area covered in B)

THEMIS night time image

Themis day and night images : note the high thermal inertia of the ejecta blanket

3. Geiger Counter

I am not aware of any radioactive sources that we might encounter (radioactive minerals tend to be concentrated by hydrothermal and/or fluvial processes). However, it may be possible to sense the increase in cosmic ray flux (or rather, the secondaries from cosmic rays, mostly muons) as we increase our altitude. Perhaps someone has a gas lamp with a thoria mantle…

4. Bat Detector

Bats (as well as dolphins and a few other animals) use echolocation to identify and locate prey. They emit ultrasound pulses (25-150kHz, depending on the species of bat, usually a few milliseconds long, chirping down in frequency) and listen for the echo - obviously the echo time indicates the distance travelled by the pulse, and doppler shift indicates the range-rate. Bats perform sophisticated signal processing, to identify insect type form wingbeat doppler modulation, etc.

Human hearing peters out above 12 kHz or so (depends on age) and thus bat calls are inaudible. A bat detector uses an ultrasound microphone, amplifies the signal, and converts into a lower frequency sound audible to us. (Various methods are used - heterodyning, digital division etc., the latter being implemented in the unit I have.) [Planetary connection : the Huygens probe to Titan carries a small sonar]

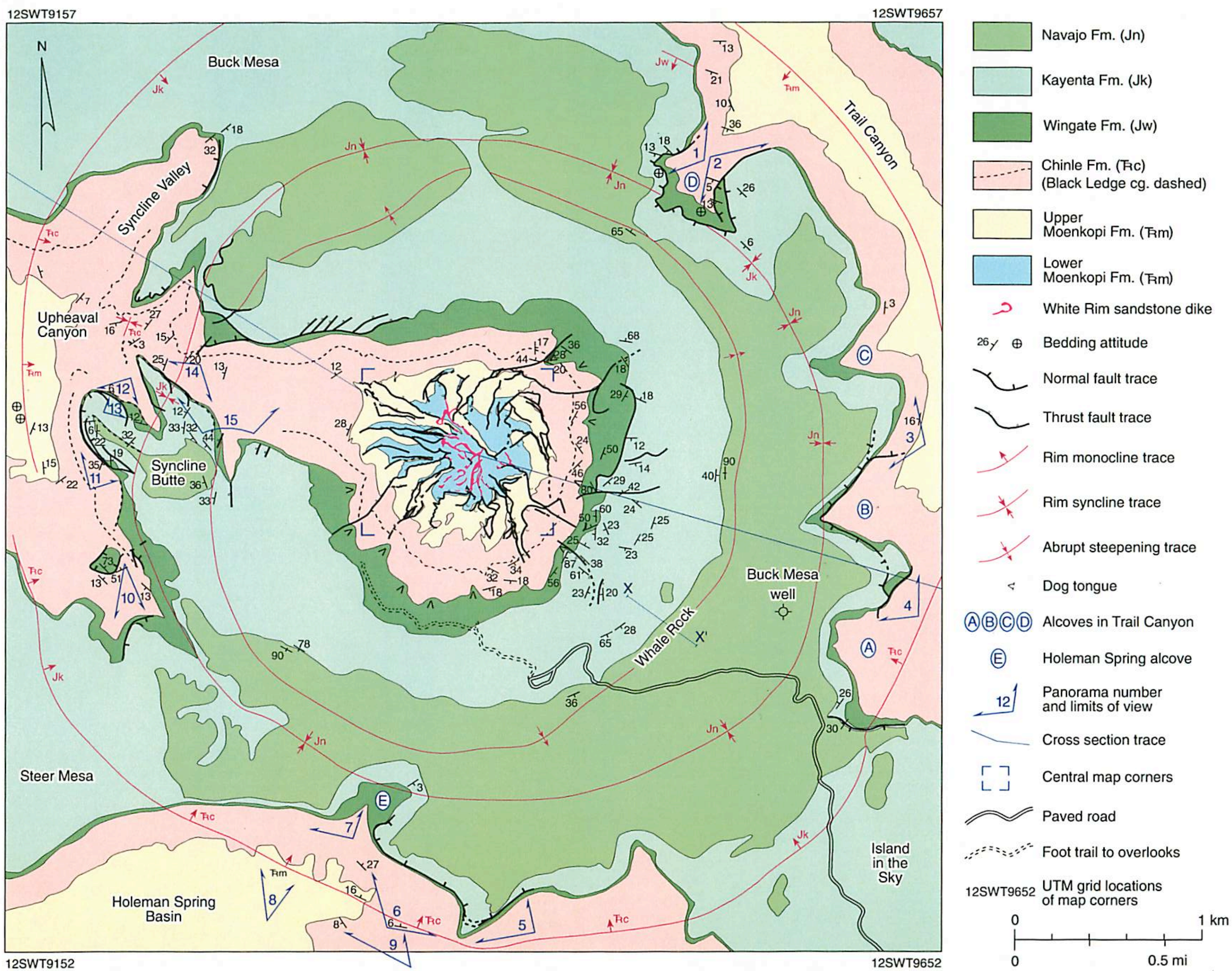


Figure 6. Geologic map of Upheaval Dome. The Chinle Formation is undifferentiated except for the Black Ledge member, and the middle and upper Moenkopi intervals are combined. Geologic details in the central depression appear in Figure 7; corners are marked by L brackets. Locations and view directions of panoramas in Figures 11, 13, and 14 are marked with large numbers and pairs of arrows; intersection point marks the observer's position.

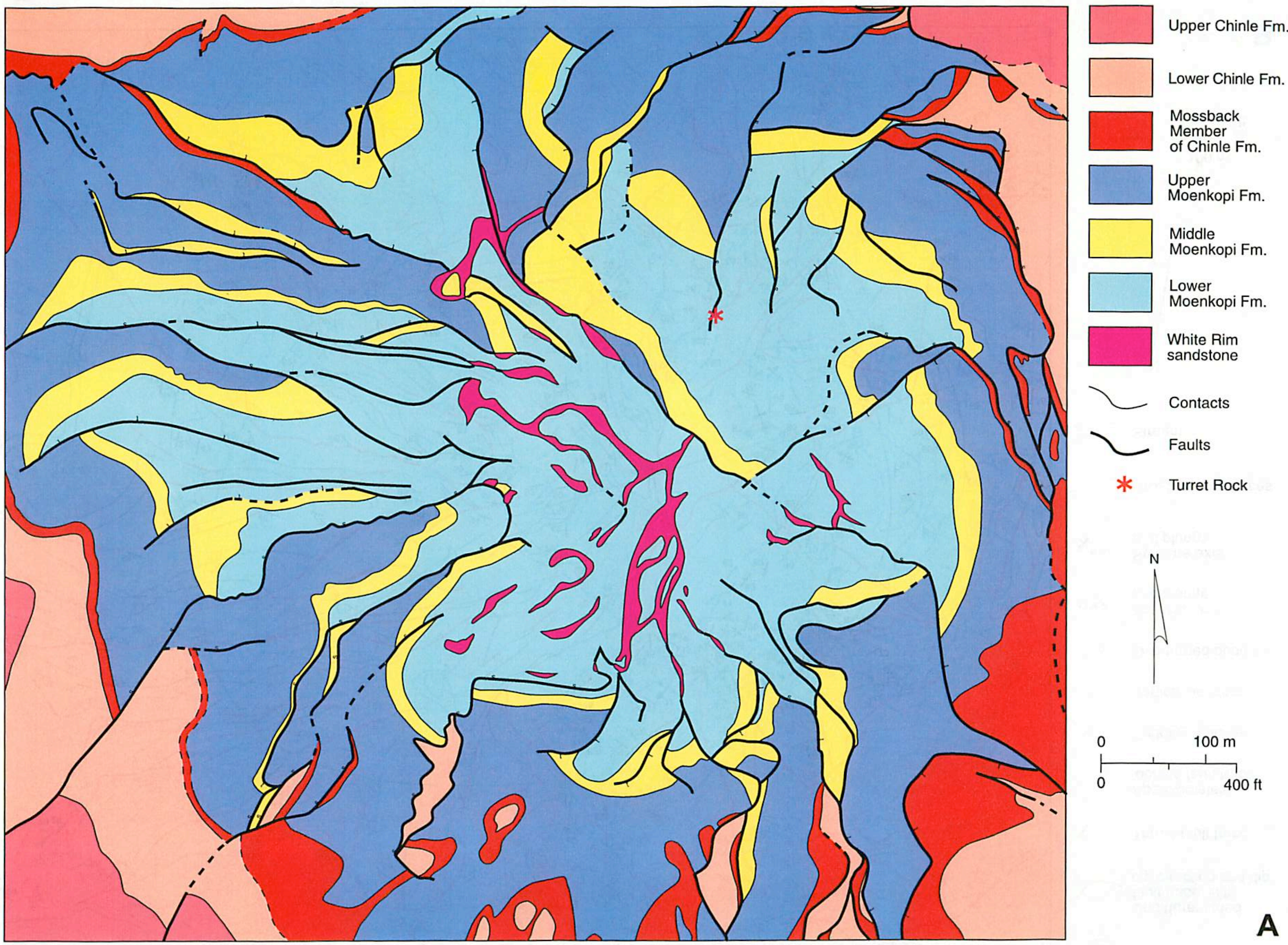


Figure 7. Geologic maps of the central depression, showing (A) stratigraphic units and faults, and (B) stratigraphic contacts, bedding attitudes, faults, fold axes, drainage network, and the linear and circular lines of sections in Figures 15 and 16.

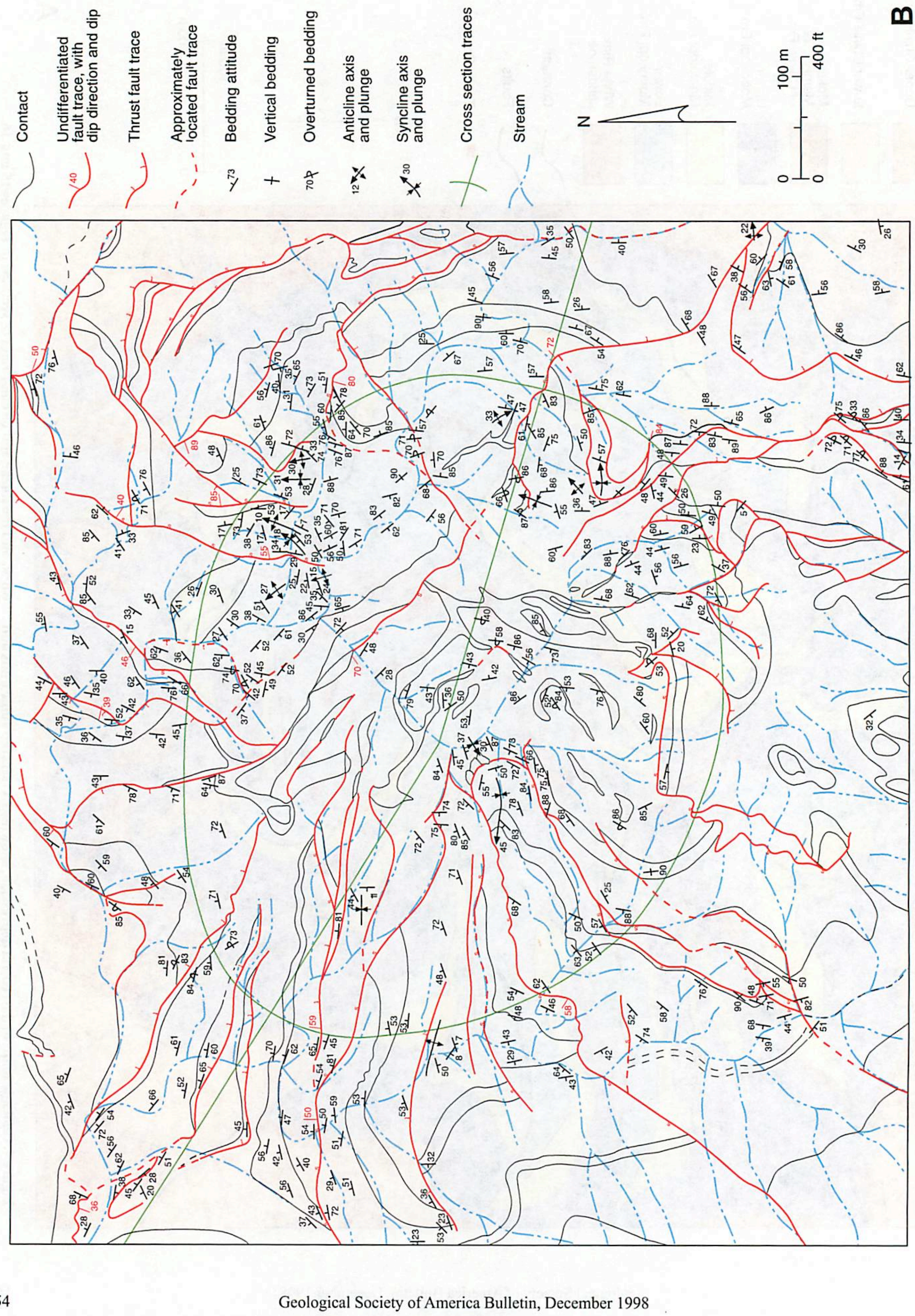


Figure 7. *(Continued).*