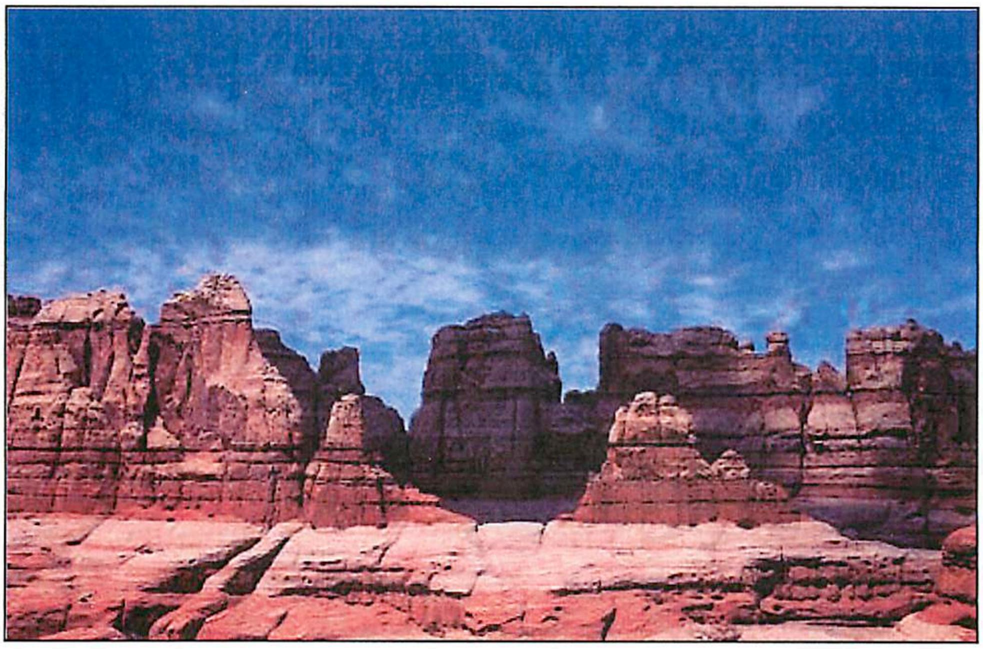
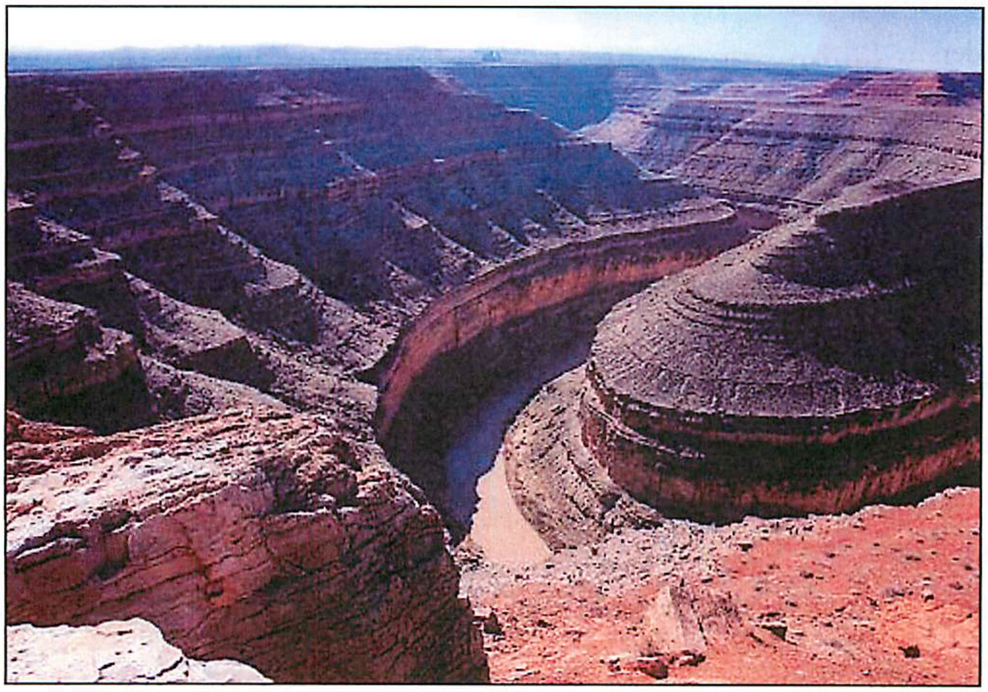
Canyonlands 2010





Planetary Geology Field Studies – PTYS 594A

September 3-7, 2010

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Presentations

Appendix

Canyonlands 2010 Itinerary

September 3

8:00 AM Depart LPL. **Joe Spitale** will give a CB commentary on the Basin and Range through which we will be driving.
12:30 PM Arrive Flagstaff. Lunch in this vicinity.
1:30: Depart lunch site.
4:15: Arrive Kayenta. Gas stop. Depart ~4:45.
5:00: Arrive at Agathla Peak. **Meghan Cassidy** will talk about diatremes.
5:15: Depart Agathla Peak.
5:30: Arrive Monument Valley. **Corwin Atwood-Stone** will tell us about the stratigraphy of the Colorado Plateau.
5:45: Depart Monument Valley.
6:00: Arrive in Mexican Hat
6:15: Camp on BLM land near Mexican Hat/Goosenecks

September 4

8:00 AM: Break camp
8:15 Arrive at Goosenecks overlook. **Christa Van Laerhoven** will explain these incised meanders, and **Jamie Molaro** will talk about the uplift of the Colorado Plateau.
9:00: Arrive at Comb Ridge overlook. **Dave O'Brien** will discuss monoclines.
9:15: Depart. Pass through Bluff at ~9:30.
12:30 PM: Arrive at Upheaval Dome. Lunch.
1:30 Talks and hiking at Upheaval Dome. **Shane Byrne** will present the impact theory, and **Catherine Elder** will discuss the older salt diapir model and salt tectonics in general. This will also be a good place for **Ingrid Daubar Spitale** to explain the formation of concretions, in the hopes that we might find a few somewhere
5:00: Depart Upheaval Dome.
5:30: Camp just outside Canyonlands NP.
(Option: After Upheaval Dome, drive south to Grand View Point, ~15 min from the crater. This place is a good overlook for most of the park., and where **Meghan Cassidy** will tell us about the history of Canyonlands National Park.)

September 5

8:00 AM: Break camp. Gas stop in Moab en route.
10:30: Newspaper Rock. **Dyer Lytle** will tell us about the native peoples of the area, who made these petroglyphs.
11:00: Reach turnoff to Beef Basin Road.
1:45 PM: Lunch near Joint Trail (or earlier, en route).
Afternoon: Joint trail. **Melissa Dykhuis** will tell us about jointing in rocks, and **Kat Volk** will give an overview of grabens, the features through which we have been driving. **Patricio Becerra** will tell us about the cross-bedding we've been seeing, and **Serina Diniega** will tell us about the local flora and fauna.
Camp: Bobby Jo campground (backcountry, unimproved), close to Joint Trail.

September 6
8:00 AM: Break camp
~9:00: Reach SOB Hill.
Hike, talks, lunch in some order. **Eric Palmer** will discuss the formation of sedimentary rocks like those around us, **Peng Sun** will explain how sedimentary rocks can be dated, **Colin Dundas** will talk about the details of the Canyonlands grabens, and **Youngmin JeongAhn** will discuss extensional tectonics in the Solar System.
3:00 PM: Depart SOB Hill.
~6:00: Return to pavement
6:30: Camp near Monticello. **Talk about laccoliths** near here.

September 7
Drive. (The route through Phoenix is slightly shorter, but we would hit Phoenix near rush hour. An alternate eastern route may be just as good and more scenic, with some interesting geology along the way). We hope to be back in Tucson at around 7:00-8:00 PM.

Contingency Plan
The road to the Joint Trail, SOB Hill and the Bobby Jo campground is not well-maintained and may be in bad shape after the monsoon storms. We will ask the park rangers for information about the road. If this route is not available to us, we will drive to Elephant Hill on day 3 and day-hike into the graben area; this would be a hike of 7-10 miles, depending on the route. (If it is clear by day 1 that we will have to take this route, some of the morning talks may be rescheduled from day 2 to day 4 to allow more time at Upheaval Dome.)

Sunrise/Sunset Times

Wed 09/01/2010	**Thurs 09/02/2010**	**Fri 09/03/2010**	**Sat 09/04/2010**
Sunrise: 5:58am Sunset: 6:49pm Moonrise: 11:31pm Moonset: 1:22pm Last Qtr: 10:22am	Sunrise: 5:59am Sunset: 6:47pm Moonrise: none Moonset: 2:19pm	Sunrise: 5:59am Sunset: 6:46pm Moonrise: 12:31am Moonset: 3:13pm	Sunrise: 6:00am Sunset: 6:45pm Moonrise: 1:36am Moonset: 4:01pm
Sun 09/05/2010	**Mon 09/06/2010**	**Tues 09/07/2010**	**Wed 09/08/2010**
Sunrise: 6:00am Sunset: 6:44pm Moonrise: 2:45am Moonset: 4:45pm	Sunrise: 6:01am Sunset: 6:42pm Moonrise: 3:56am Moonset: 5:25pm	Sunrise: 6:02am Sunset: 6:41pm Moonrise: 5:08am Moonset: 6:03pm	Sunrise: 6:02am Sunset: 6:40pm Moonrise: 6:19am Moonset: 6:39pm New Moon: 3:30am

This Week's Sky at a Glance

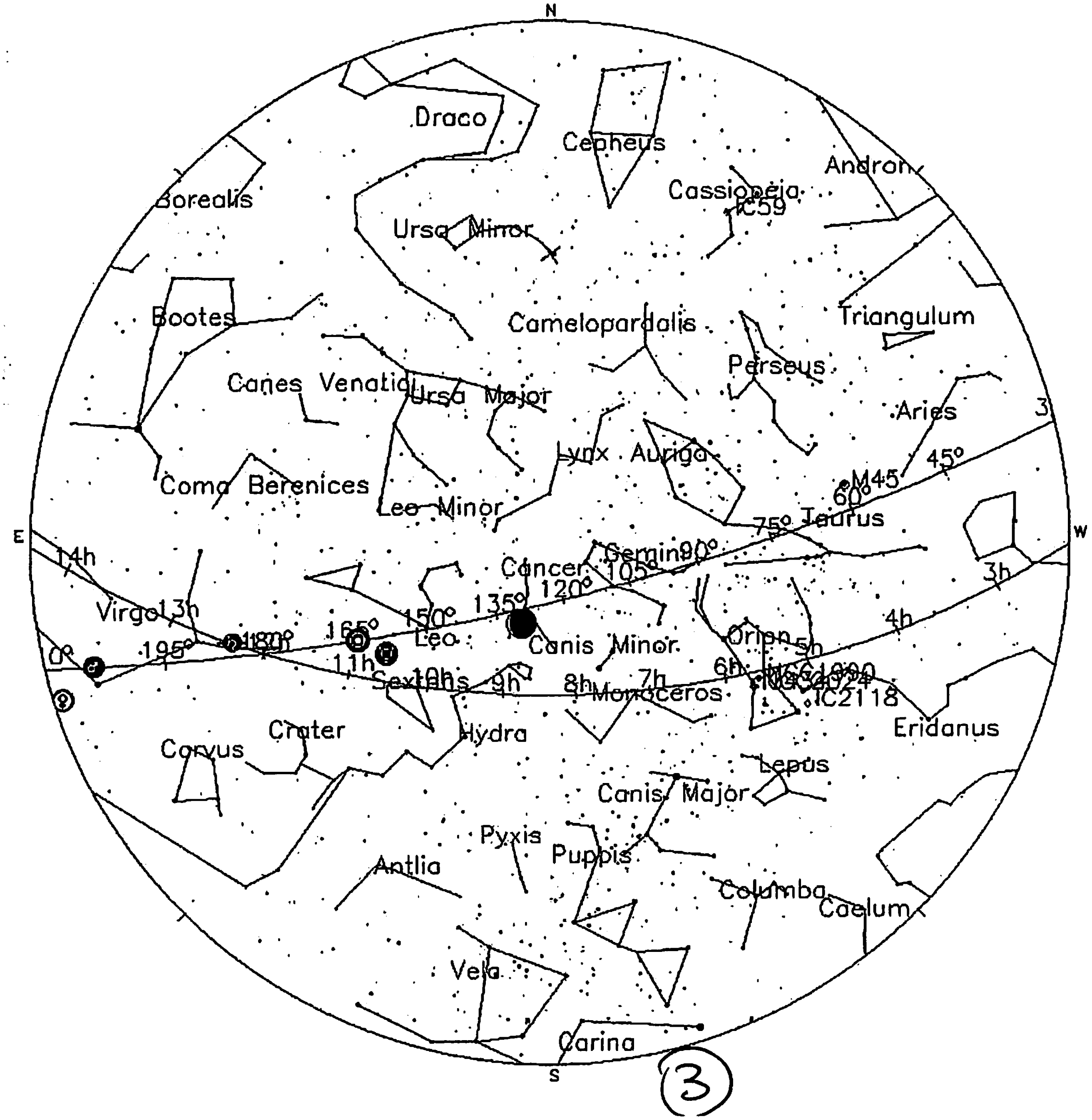
http://www.skyandtelescope.com/observing/ataglance

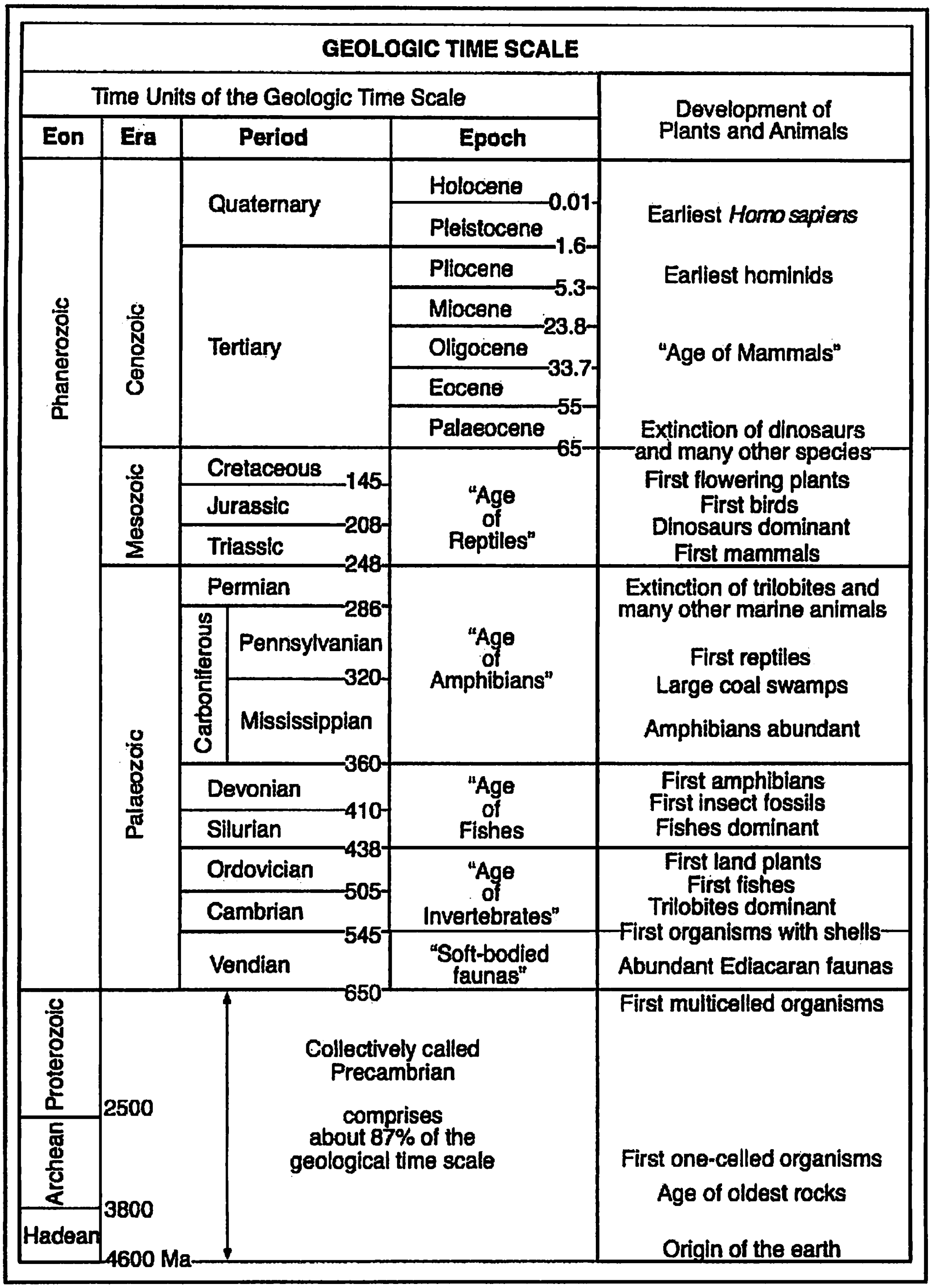
Sky Map

http://www.fourmilab.ch/cgi-bin/Yoursky

Sky above 32°N 110°E at Mon 2010 Sep 6 2:00 UTC

Explain symbols in the map.





GEOLOGIC TIME SCALE

Time Units of the Geologic Time Scale					Development of Plants and Animals
Eon	Era	Period	Epoch		
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Earliest *Homo sapiens*
			Pleistocene	1.6	
		Tertiary	Pliocene	5.3	Earliest hominids
			Miocene	23.8	
			Oligocene	33.7	"Age of Mammals"
			Eocene	55	
			Palaeocene	65	Extinction of dinosaurs and many other species
	Mesozoic	Cretaceous	"Age of Reptiles"	145	First flowering plants
		Jurassic		208	First birds Dinosaurs dominant
		Triassic		248	First mammals
	Palaeozoic	Permian	"Age of Amphibians"	286	Extinction of trilobites and many other marine animals
		Carboniferous: Pennsylvanian		320	First reptiles Large coal swamps
		Carboniferous: Mississippian		360	Amphibians abundant
		Devonian	"Age of Fishes"	410	First amphibians First insect fossils
		Silurian		438	Fishes dominant
		Ordovician	"Age of Invertebrates"	505	First land plants First fishes
		Cambrian		545	Trilobites dominant First organisms with shells
		Vendian	"Soft-bodied faunas"	650	Abundant Ediacaran faunas
Proterozoic	Collectively called Precambrian comprises about 87% of the geological time scale			2500	First multicelled organisms
Archean				3800	First one-celled organisms Age of oldest rocks
Hadean				4600 Ma	Origin of the earth

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

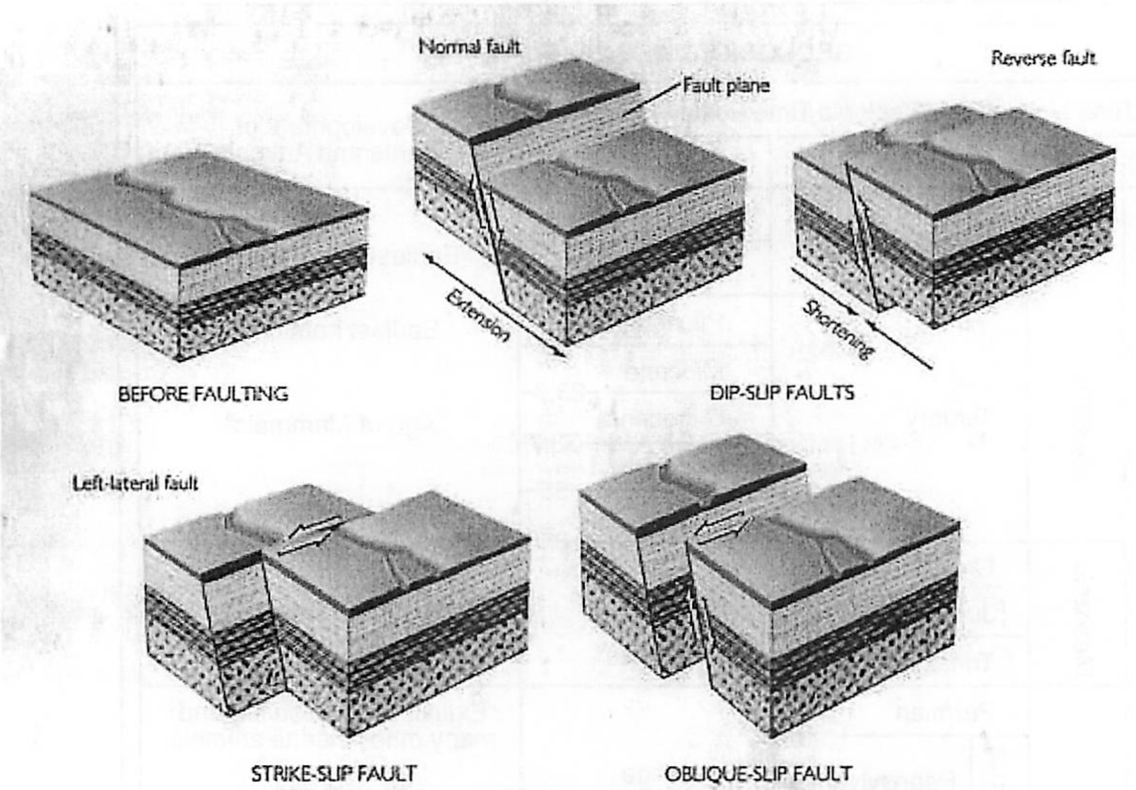
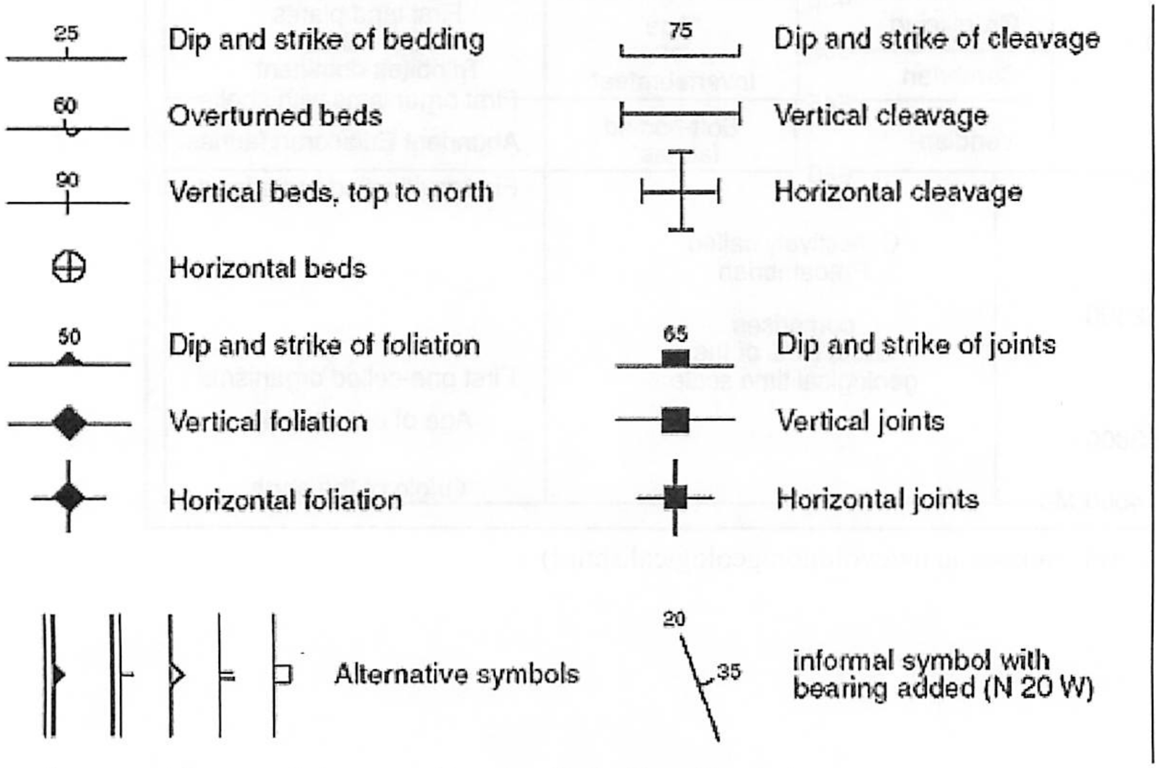


Figure 10.22
Press and Siever: *Understanding Earth*

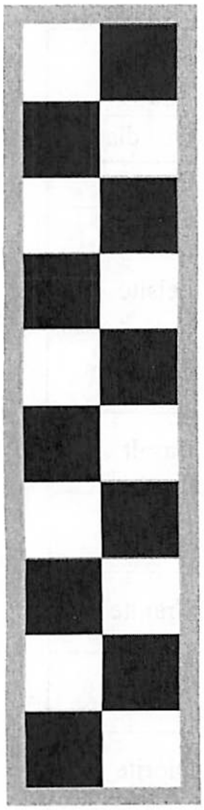
OHT 34

FAULT TYPES
http://www.geo.wvu.edu/~jtoro/Petroleum/Review%202.html



http://www.public.asu.edu/~arrows/structure/Labs/Geo_Blocks/

10 cm ruler



ROCK DENSITIES

Material type	Density range (Mg/m^3)	Approximate average density (Mg/m^3)
Sedimentary rocks		
Alluvium	1.96-2.00	1.98
Clay	1.63-2.60	2.21
Gravel	1.70-2.40	2.00
Loess	1.40-1.93	1.64
Silt	1.80-2.20	1.93
Soil	1.20-2.40	1.92
Sand	1.70-2.30	2.00
Sandstone	1.61-2.76	2.35
Shale	1.77-3.20	2.40
Limestone	1.93-2.90	2.55
Dolomite	2.28-2.90	2.70
Chalk	1.53-2.60	2.01
Halite	2.10-2.60	2.22
Glacier ice	0.88-0.92	0.90
Igneous rocks		
Rhyolite	2.35-2.70	2.52
Granite	2.50-2.81	2.64
Andesite	2.40-2.80	2.61
Syenite	2.60-2.95	2.77
Basalt	2.70-3.30	2.99
Gabbro	2.70-3.50	3.03
Metamorphic rocks		
Schist	2.39-2.90	2.64
Gneiss	2.59-3.00	2.80
Phylite	2.68-2.80	2.74
Slate	2.70-2.90	2.79
Granulite	2.52-2.73	2.65
Amphibolite	2.90-3.04	2.96
Eclogite	3.20-3.54	3.37

Udden-Wentworth Grain Size Scale

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

MOHS HARDNESS SCALE

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

IDENTIFICATION OF ROCKS AND ROCK FORMING MINERALS

Identification of Igneous Rocks

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

Identification of Sedimentary Rocks

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

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

Identification of Metamorphic Rocks

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

http://geology.about.com/library/bl/blrockident_tables.htm

Dark-Colored minerals

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

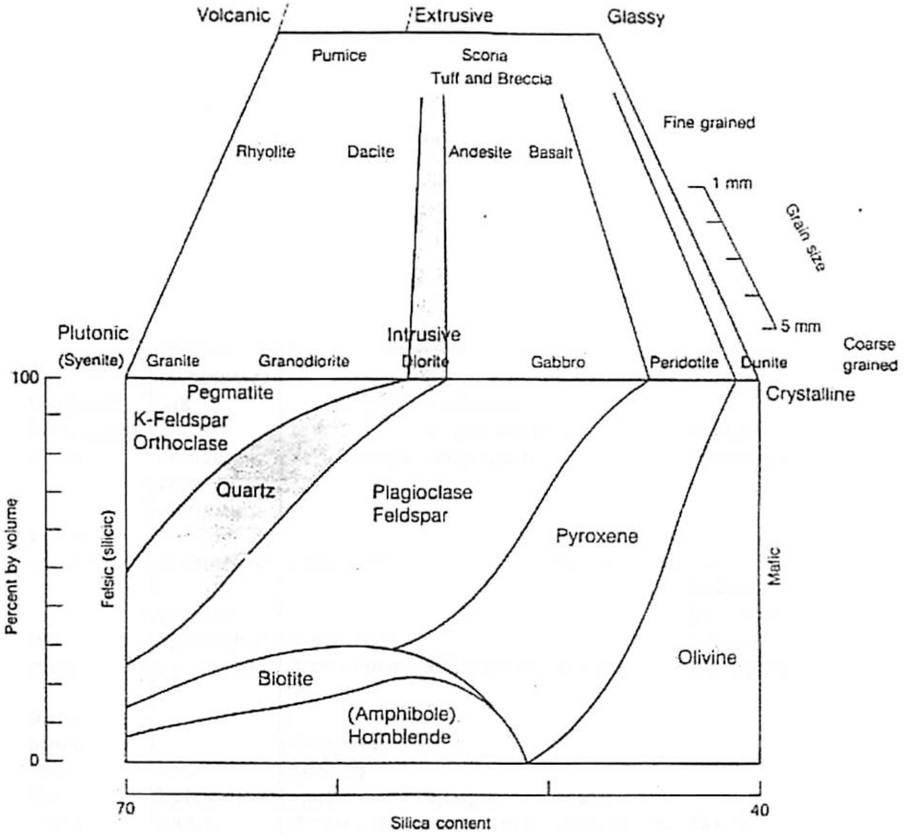
Light-colored minerals

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

Metallic			
	Streak	**Physical Properties**	**Name**
Hardness > 5	Dark Gray	Brass yellow	**Pyrite**
		Dark gray-black, attracted to magnet	**Magnetite**
	Brown	Silvery black to black tarnishes gray	**Chromite**
Harness < 5	Red-Red/Brown	Silvery gray, black, or brick red	**Hematite**
	Dark Gray	Brass yellow, tarnishes dark brown or purple	**Chalcopyrite**
		Iridescent blue, purple or copper red, tarnishes dark purple	**Bornite**
		Silvery gray, tarnishes dull gray Cleavage good to excellent	**Galena**
		Dark gray to black, can be scratched with fingernail	**Graphite**

http://www.thisoldearth.net/This_Old_Earth/Home.html

IGNEOUS ROCK TYPES

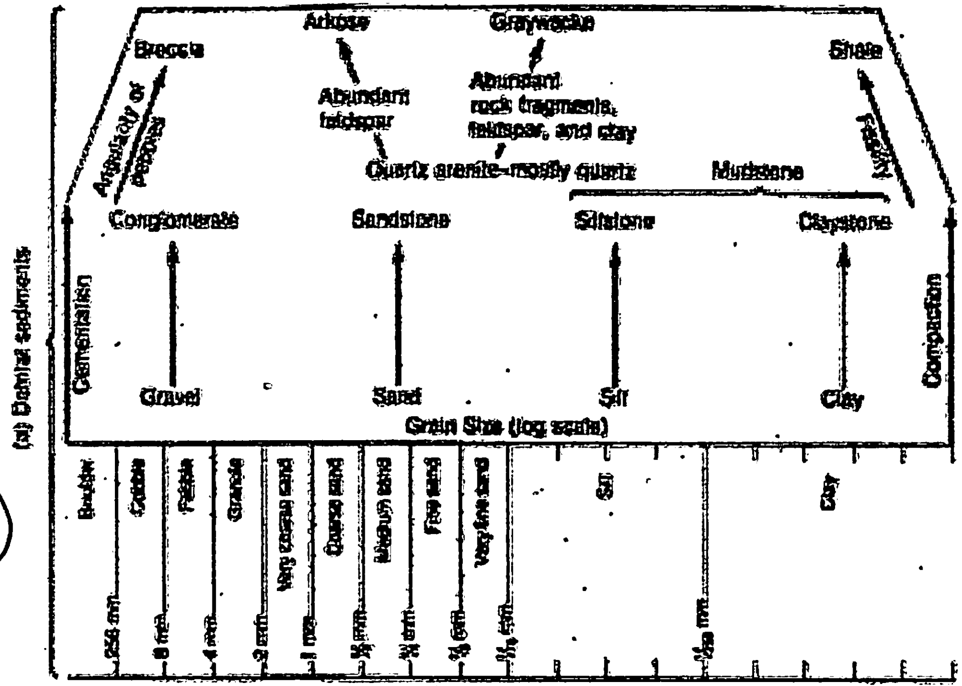


http://www2.ocean.washington.edu

MINERAL CHEMICAL CLASSIFICATIONS
http://www.appstate.edu/~abbottrn/mnrl-id/

CHEMICAL GROUP	ANIONIC SPECIES	EXAMPLES
OXIDES minerals	Oxygen, O^{-2}	Hematite, Fe_2O_3; Magnetite: Fe_3O_4
SULFIDE minerals	Sulfur, S^{-2}	Pyrite, FeS_2
CARBONATE minerals	Carbonate, CO_3^{-2}	Calcite, $CaCO_3$; Dolomite, $CaMg(CO_3)_2$
SILICATE minerals	Silicate, SiO_4^{-4}, "Tetrahedron"	
STRUCTURAL SUBGROUPS OF THE SILICATES	Isolated SiO_4^{-4} Tetrahedra	Olivine, $(Mg,Fe)_2SiO_4$; Garnet, $(Fe,Mg,Ca)_3Al_2Si_3O_{12}$
	Single Chains of Tetrahedra, $Si_2O_6^{-4}$	Pyroxene, e.g., Augite, $Ca(Mg,Fe)Si_2O_6$
	Double Chains of Tetrahedra, $(Si,Al)_8O_{22}^{-12\text{ to }-14}$	Amphibole, e.g., Hornblende, $NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$
	Sheets, $(Si,Al)_4O_{10}^{-4\text{ to }-6}$	Micas (phyllosilicates), e.g., Muscovite, $KAl_2(AlSi_3)O_{10}(OH)_2$, Biotite, $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$, Chlorite, $(Mg,Fe)_6Si_4O_{10}(OH)_8$
	Framework, SiO_2 or $(Al,Si)O_2^{-.25\text{ to }-0.5}$	Quartz, SiO_2 Feldspars K-Feldspar, $K(AlSi_3)O_8$ Plagioclase, $(Na,Ca)(Al,Si)_4O_8$

SEDIMENTARY ROCK TYPES
http://www2.ocean.washington.edu



(b) Chemical sediments

Rock	Limestone	Dolomite	Iron formation	Evaporite	Chert	Organics	Phosphate
Chemical composition	$CaCO_3$	$CaMg(CO_3)_2$	Fe-silicate -oxide carbonate	NaCl $CaSO_4$	SiO_2	Carbon	$Ca_3(PO_4)_2$
Minerals	Calcite (Aragonite)	Dolomite	Hematite Limonite Siderite	Gypsum Anhydrite Halite Other salts	Opal Chalcedony Quartz	Coal Oil Gas	Apatite

Figure 2-22
Sedimentary rock classification. (a) Detrital sediments, (b) Chemical sediments.

METAMORPHIC ROCK TYPES
http://www.dmtcalaska.org/course_dev/explogeo/class09/notes09.html

Primary igneous or sedimentary rock composition	*Main mineral groups present*	*Fine-grained < 0·1 mm*	*Medium-grained 0·1 mm – 1·0 mm*	*Course-grained > 1·0 mm homo-geneous*	*banded*
shale 'pelitic rocks'	phyllosilicates, quartz	slate	phyllite	schist	gneiss
sandstone 'psammitic rocks'	quartz		← quartzite →		banded quartzite quartzitic gneiss
limestone	calcite, dolomite		← marble →		banded marble
marl	phyllosilicates, calcite, dolomite	calcareous slate	calc-phyllite	calc-schist	calcareous gneiss
sandy shale 'semi-pelitic rocks'	quartz, phyllosilicates	quartzose slate, cleaved quartzite	semi-pelitic phyllite	semi-pelitic schist	gneiss
basalt, gabbro	amphiboles, plagioclase feldspar	greenschist greenstone	amphibolite	amphibolite	hornblende gneiss pyroxene gneiss
rhyolite, granite	K-feldspar, quartz, phyllosilicates	halleflinta		← granitic gneiss →	
dunite, pyroxenite, peridotite	serpentine, talc, Mg amphiboles	serpentinite	serpentinite ← talc schist → soapstone		ultramafic gneiss

Note from the Editor

As I browsed through the shelves of past field trip handbooks, I must admit that the editorial introductions were the segments that I read most thoroughly. My creativity cringes at the thought of such a spotlight.

I first learned of the planetary geology field trips while waiting two hours in a tropical thunderstorm for food that I inhaled and barely tasted. The current and past LPL students and faculty who had joined me for that ill-fated meal eagerly shared the joys and trials (mostly joys) of life as a grad student at LPL, assuring my as-yet-undecided undergraduate mind that LPL was the best place to be. Great research, great classes, great friendships, great everything. But the thing that struck me most was their mention of those "great field trips!" The trips turn the Southwest into a geological laboratory, and our *in situ* observations reveal the nature of planetary evolution.

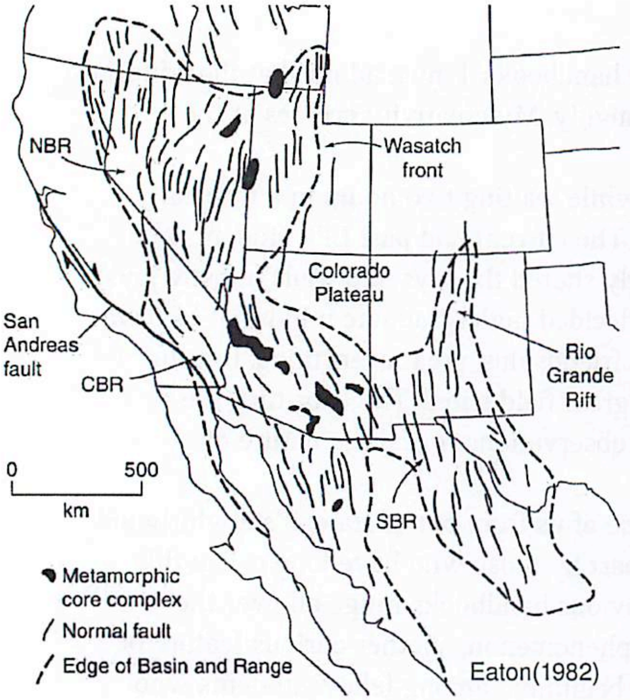
Canyonlands 2010 upholds the reputation. For those of us from out of state, it's a whirlwind tour of the geological history of the Southwest, led in part by those who have long called this area their backyard. The itineraries in the stacks of previous handbooks range all over the Southwest region, yet each field trip finds yet another phenomenon, another curious feature of the land to explore. This is my first field trip, a meager beginning among fellow students who have years of experience, but I hazard the guess that each layer of our understanding reveals a stratigraphy of secrets yet to be known.

As I am one of the newest to join LPL, timidity checks my verbosity. I'll leave with a much-repeated word of wisdom from Andrew Rivkin, editor of the 1999 edition: Enjoy the stars and the rocks.

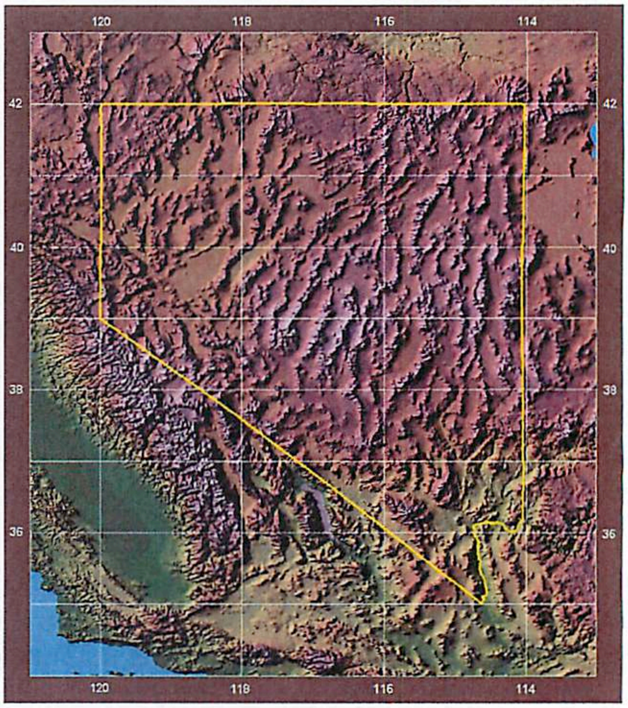
Melissa Dykhuis, ed.

Western U.S. Basin and Range Province

Joe Spitale

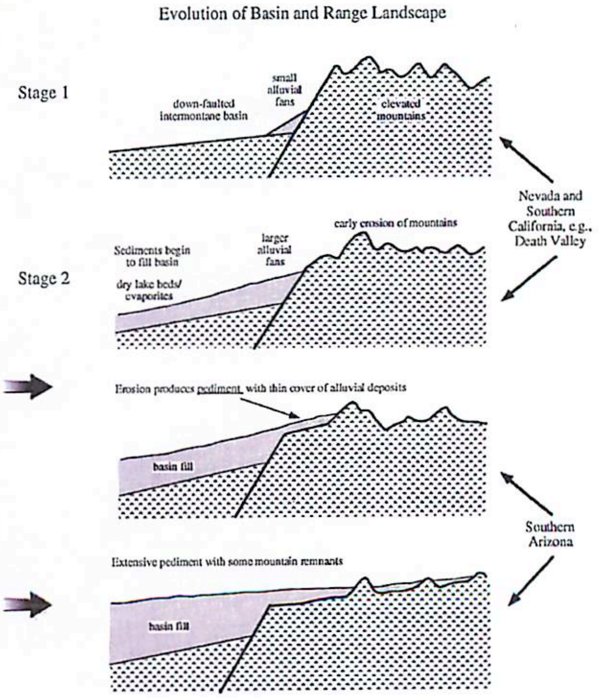


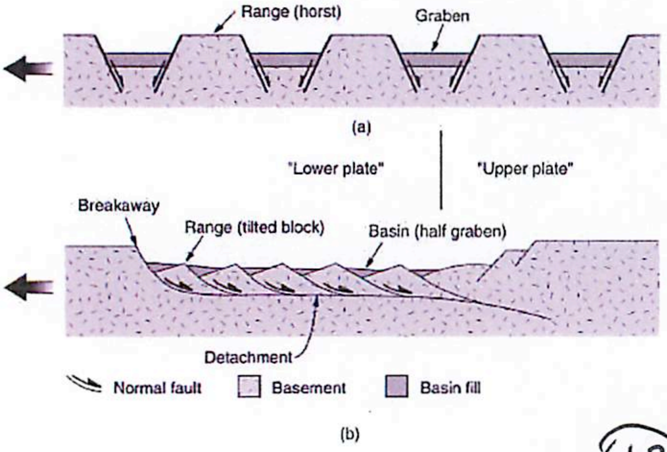
Eaton(1982)



Overview

- Basin-and-range province covers much of the western part of the U.S.
- Regularly spaced mountain ranges separated by flat basins.
- Typical spacings range from a few to tens of miles
- Southern regions tends to be more eroded and therefore less regular.
- Bilateral symmetry, high heat flow, thin lithosphere, episodic magmatism all reminiscent of oceanic spreading centers.
- Basin-and-range topography arises from regior
- Two broad types of deformation:
  - Block faulting: alternating horsts / grabens; occurs at relatively low strain rates.
  - Listric faulting: shallow concave-up faults overlaying a detachment; higher strain rates.





History

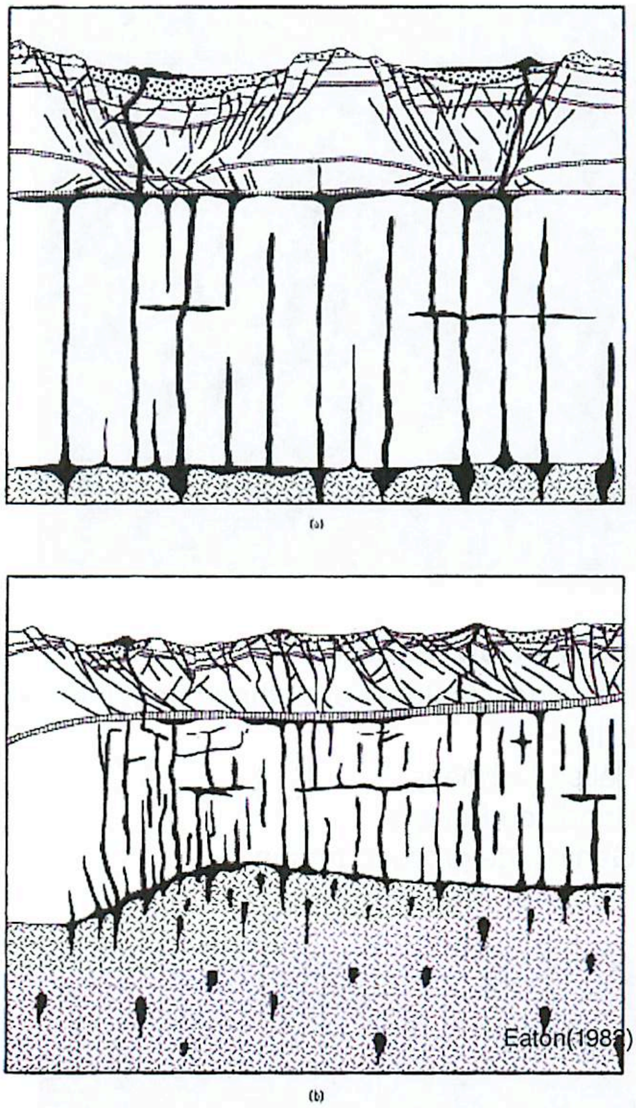
- Thrust-faulted terrain dates from prior orogenic events.
- Initial (>17 Mya) extension related to complicated boundaries at western edge of the North American plate.
  - High strain rates, detachments form, listric faulting
- Later transform motion of Pacific plate wrt NA plate.
  - Lower strain rates, block faulting.
- Total strain of ~100% over past 20 My.
- Current rates vary; up to ~ 1 cm/yr.

Basin structure

- Ranges erode back to form pediments.
- Normal faults typically buried.
- Basins fill up with alluvium.
- Playa are common.
- Local aquifers bounded by impermeable range blocks.

Volcanism

- Recurring magmatic episodes.
- Intrusions.
- Hot springs.
- May be diagnostc of stress history.


(a)

(b)

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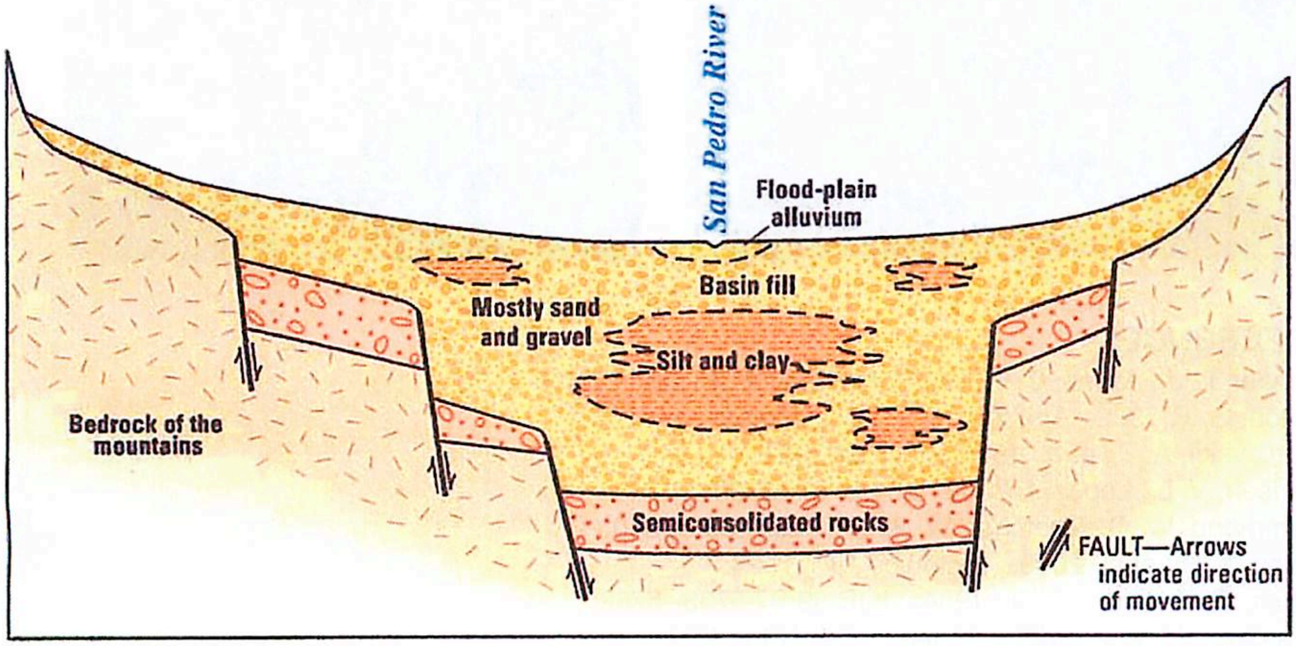
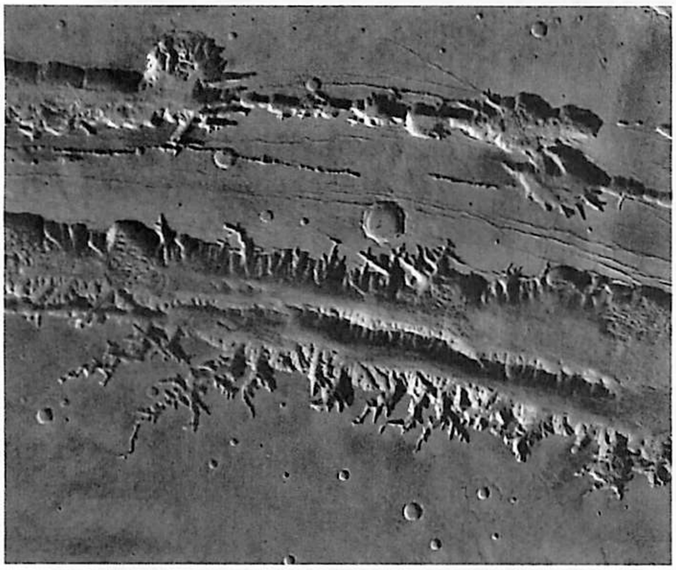
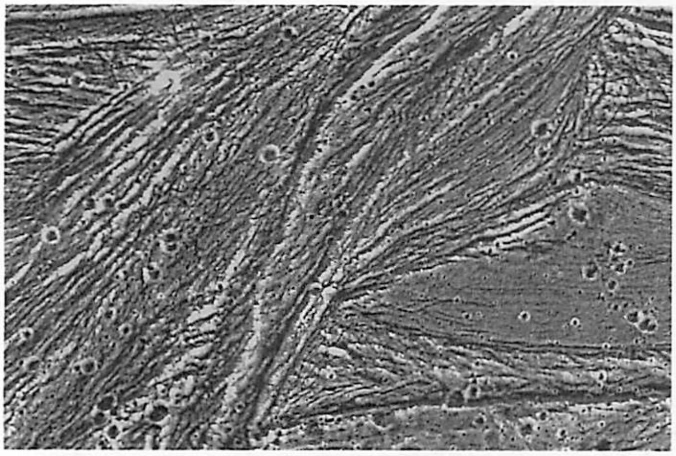


VERTICAL SCALE GREATLY EXAGGERATED



Planetary Connection

- Extensional features exist throughout the solar system, but basin and range unique to Earth.
  - Valles Marineris
  - Bands on Europa
  - Ganymede grooved terrain
  - Venusian Tesserae?



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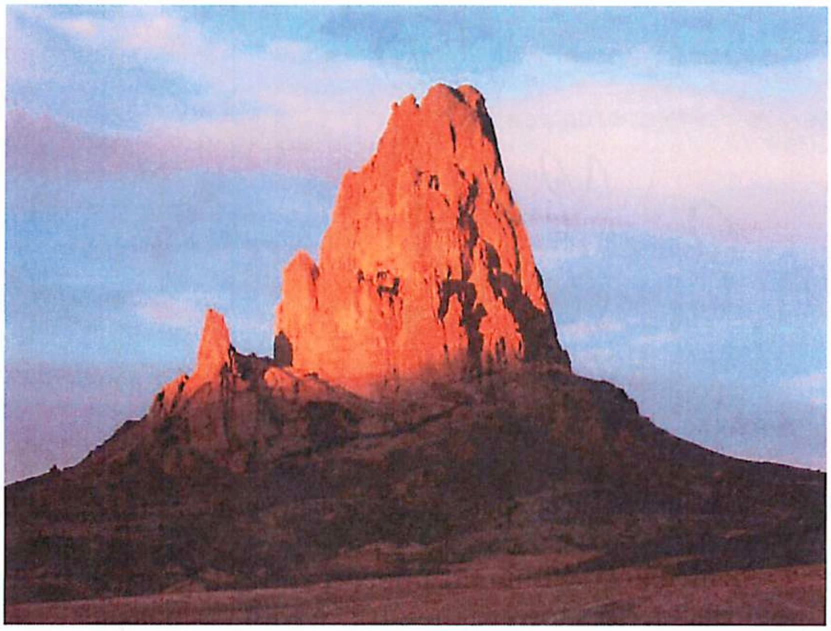
DIATREMES:
AGATHLA PEAK

Meghan Cassidy



A Little Volcanology

Igneous intrusions are formed when magma beneath the earth's surface solidifies. **Volcanic plugs** are a type of igneous intrusion formed when the central vent of a volcano becomes sealed due to the solidification of magma within it. When the rocks surrounding the volcanic plug are not resistant to weathering, they erode, exposing a **volcanic neck**, a cast of the volcanic pipe.

Diatremes are an igneous intrusion similar to volcanic necks and plugs, but with different composition and formation mechanisms. Unlike a volcanic plug or neck, which is comprised of roughly homogeneous igneous rock, "diatremes are composed of breccia [a mass of angular rock fragments] of volcanic rocks mixed with fragments of host rock, xenoliths of rocks that have been carried up from depth, and even surface sediments" (Mitchell, 1986). In volcanic necks and plugs, the magma in the vent calmly solidifies over time, but diatremes are formed by a much more violent process. There are two theories as to how diatremes are formed: the magmatic theory (also known as the fluidization theory) and the phreatomagmatic theory (also known as the hydrovolcanic theory). In the magmatic theory, the large volume of gas associated with the eruption originates in the magma itself. In the phreatomagmatic theory, the large volume of gas associated with the eruption is created when the magma comes in contact with water.

Diatreme Formation

Magmatic Theory

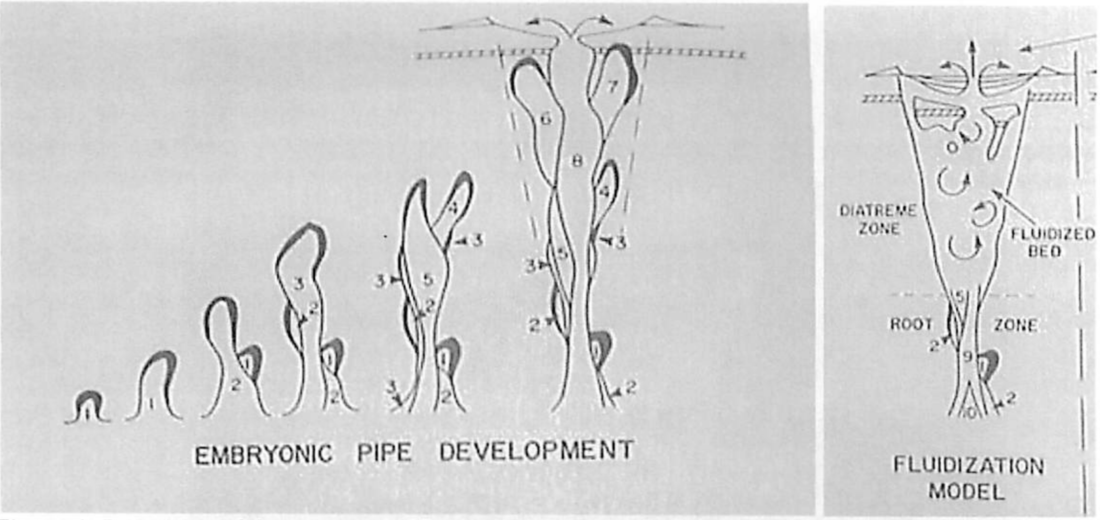


Figure 1: Depiction of the magmatic (fluidization) model for diatreme formation (Mitchell, 1986).

Kimberlite magma formed deep within the upper mantle of the earth (more than 150 km below the surface), rises toward the surface with various pulses building embryonic pipes (Mitchell, 1986). These embryonic pipes build on top of one another and overlap. $C0_2$ and H_20, volatiles present in high concentrations in kimberlite magmas, do not escape and remain dissolved in the magma at depth because of a high confining pressure. Eventually the as the magma reaches shallower depths (about 500 m), the pressure of the volatiles overcomes the pressure of the overlying rock. The rapid gas expansion forces the conduit to expand, and brecciates the surrounding rocks and any other solids entrained in the magma as the eruption reaches the earth's surface. As the erupting fluid transitions into this explosive phase, it reaches supersonic speeds and begins to swirl and churn. The fragments of rock in this mass of gas and magma scour out the funnel-shaped diatreme zone, which is eventually filled in with these fragments to form a cemented breccia after the eruption (Mitchell, 1986). This fluidization process would have to be relatively short lived since the fragments are often angular.

Phreatomagmatic Theory

Kimberlite magma rise through narrow fissures. The interaction of the rising hot magma with the cool water produces a short-lived phreatomagmatic explosion. The brecciated rock becomes recharged with water. Another pulse of kimberlite magma follows the same structural weaknesses in the rock to surface and again comes in contact with water producing another explosion. Subsequent pulses react with water in the same way while the contact front moves downwards (Lorenz, 1998).

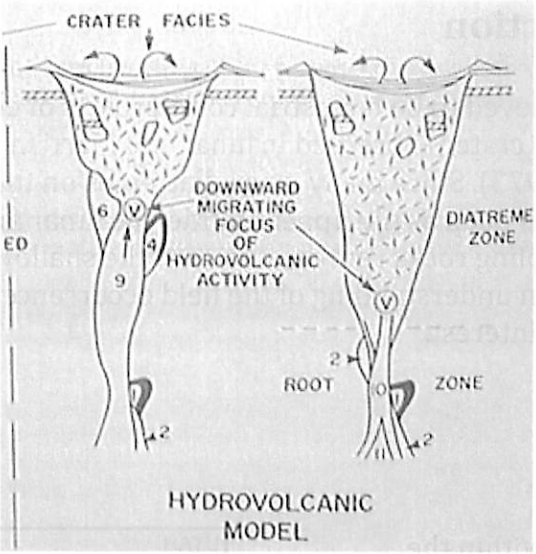


Figure 2: Depiction of the phreatomagnetic model for diatreme formation (Mitchell, 1986)

What about Maar-Diatremes?

Maars are interpreted as being formed by hydrovolcanic explosions, but have a distinctly different internal structure to kimberlites. Maars have an internal structure with a saucer-shape, and ring-faulting and upwarping of country rock is associated with the explosion.

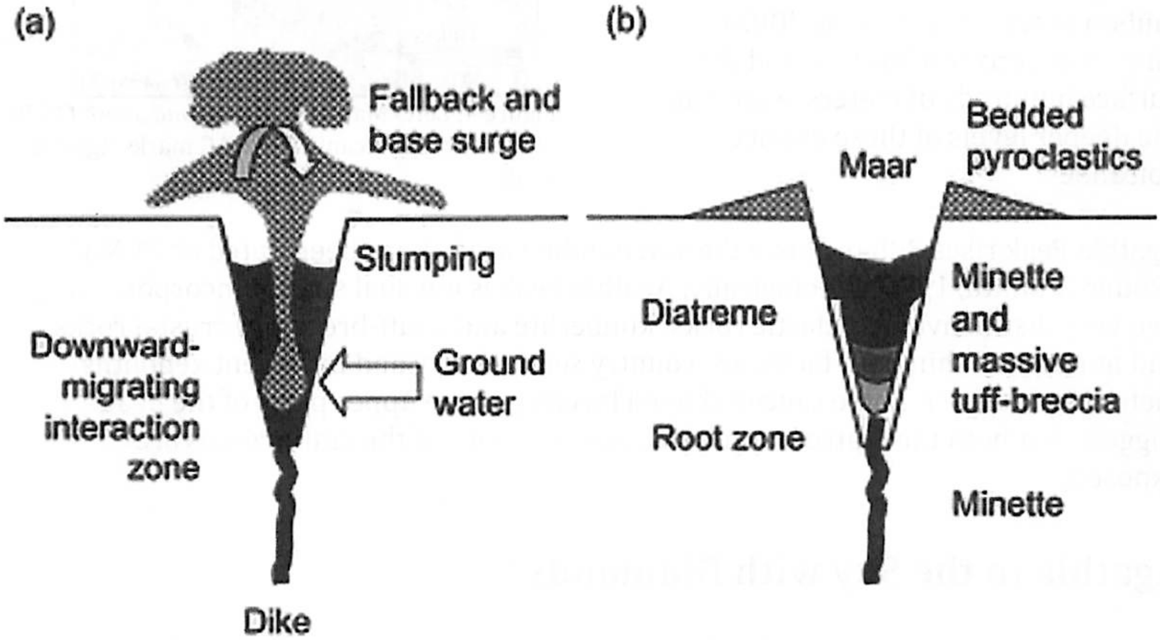


Figure 3: a) Hydrovolcanic eruption. b) Cross-section of resulting maar-diatreme structure (Ort, et.al, 1998)

Planetary Connection

Maar- diatremes are believed to be terrestrial counterparts of crater chain rilles and possibly of the dark halo craters observed in lunar and Martian photographs (McGetchen & Ullrich, 1973). Since many maar-diatremes on the Earth contain xenoliths derived from as deep as the upper mantle, the lunar and Martian examples provide a means of sampling rocks representative of the shallow interiors of planets. Consequently, an understanding of the field occurrence of xenoliths in these terrestrial features is of interest.

Agathla Peak

Agathla Peak is located within the Navajo Volcanic Field, which covers about 20,000 square kilometers in the four-corners area of Arizona, New Mexico, Colorado and Utah. It is made of dozens of intrusions, diatremes, tuff pipes, and dikes formed by phreatomagnetic eruptions. These maar-diatreme volcanoes erupted during the Oligocene, about 32 to 25 million years ago (Semken, 2003). Since then, erosion has lowered the surface hundreds of meters, exposing the deeper levels of these extinct volcanoes.

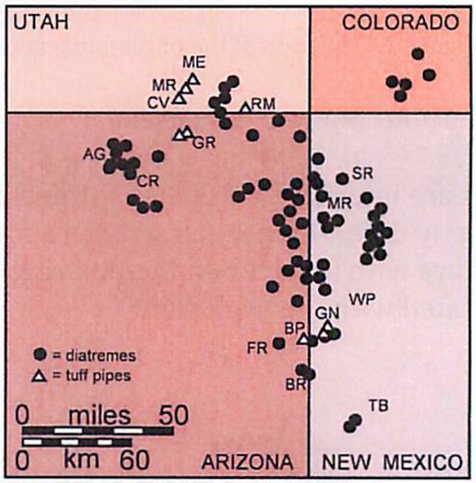


Figure 4: Left: Map from *Roden and Smith (1979)* of the Navajo Volcanic Field. AG marks Agathla Peak.

Agathla Peak rises 335 m above the surrounding area. It has been dated at 31 Ma[2] (Roden & Smith, 1979). Geologically, Agathla Peak is unusual since it incorporates two very distinctive pyroclastic rocks: kimberlite and a tuff-breccia of crustal rocks and minette. Within both facies are country sedimentary and basement xenoliths meters in diameter. Some saucer-shaped layering in the upper parts of the peak suggest that both the diatreme and the lower portions of the crater zones are exposed.

Agathla in the Sky with Diamonds?

Diatreme formation is not well understood since no one has ever observed a kimberlite eruption, but these geological features are economically viable (bling!). Magmas coming to the surface in kimberlite eruptions carry with them various minerals from the source regions deep in the mantle, such as gemstones, semi-precious stones, and diamonds.

None of the Navajo kimberlites have been found to have diamonds, so sadly your grad stipend will not exponentially increase this weekend if you so choose to wander off while I'm speaking and dig for diamonds. Only about 1 in 200 kimberlite pipes in the world contain marketable diamonds. However, significant amounts of olivine peridots and garnets have been found in the Navajo Volcanic Field. These are called "anthill" peridots and garnets. Since they are durable and can withstand rain, wind, and frost, ants collect them from the ground below the volcanic outcrops to build their shelters. Thus, they can be "mined" from anthills, preserving the igneous intrusions.

Figure 5: Ant carrying a garnet in the Navajo Volcanic Field

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Stratigraphy of the Colorado Plateau

Corwin Atwood-Stone

The stratigraphy of the Colorado Plateau is very diverse and was laid down under a variety of depositional environments. In Canyonlands National Park the oldest exposed stratigraphic layers are from the mid-Pennsylvanian and the youngest layers are from the late Cretaceous. The stratigraphic units of this area can be organized into the following categories from oldest to youngest: The Hermosa Group, The Cutler Group, Moenkopi & Chinle Formations, Glen Canyon Group, The San Rafael Group & The Morrison Formation, and the Cretaceous Strata. [See Fig. 1]

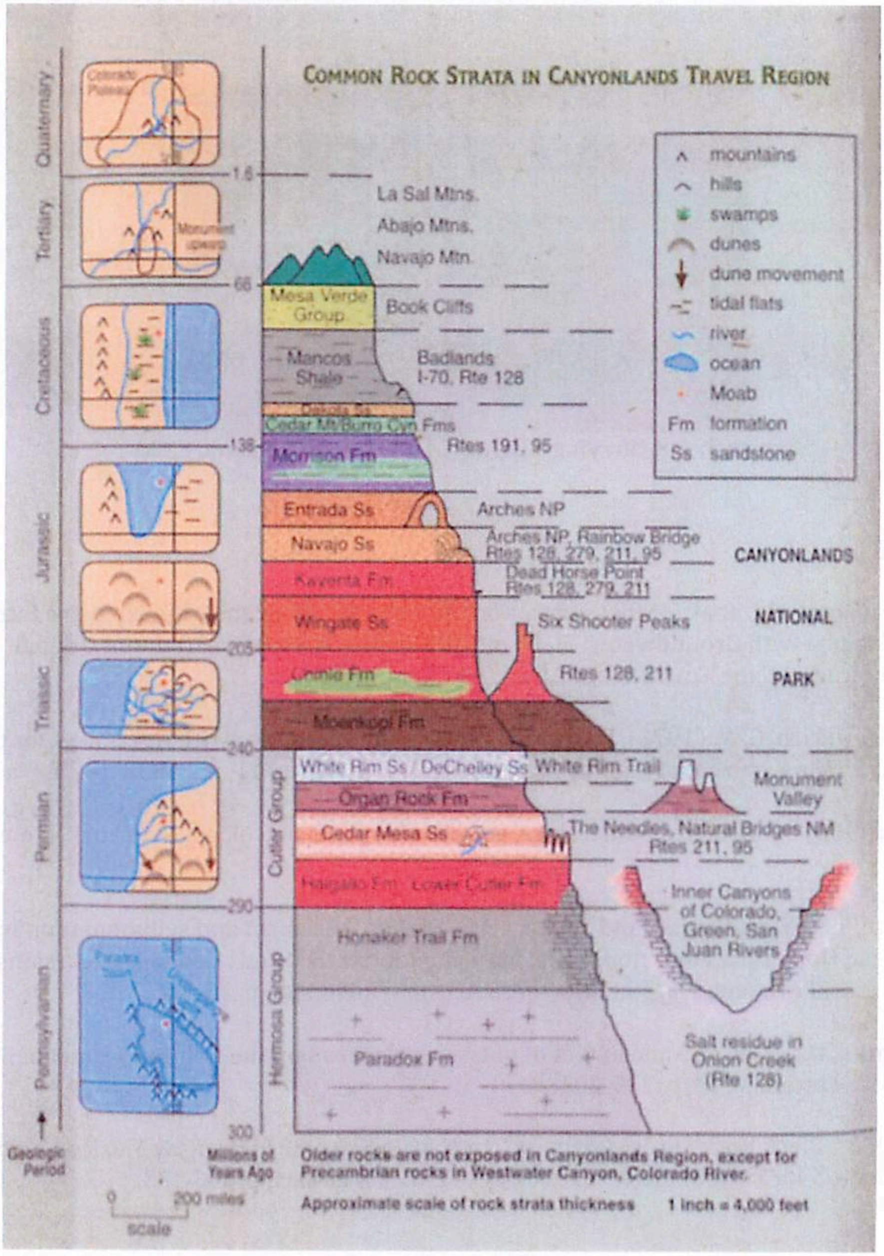

FIG. 1 This is a stratigraphic column of the Canyonlands area which shows the geography of the area during the period when each of the stratigraphic units was being deposited. (Canyon Country: A Geologic Guide to the Canyonlands Travel Region)

I. HERMOSA GROUP

During the Pennsylvanian the canyonlands area was covered by a vast sea, allowing a marine limestone layer, known as the Pinkerton Trail Formation to be deposited. Then in the mid-Pennsylvanian a large portion of the region sagged to form what is known as the Paradox Basin. The sea in the region was mostly stagnant, with occasional influxes of fresh seawater. The hot dry climate of the time evaporated this stagnant sea leaving an evaporite formation of salt and gypsum known as the Paradox Formation (which is the oldest formation exposed in the canyonlands). During the occasional influxes of fresh seawater thin layers of black shale were deposited atop the evaporites leaving an alternating pattern of evaporites and black shale. A rise in sea level in the later Pennsylvanian saw the paradox basin fully reconnected to the sea. This reconnection to the sea allowed the resumption of typical tropical marine deposition of fossiliferous limestone interbedded with marine sandstone and shale. This mostly gray layer in the stratigraphic history is known as the Honaker Trail Formation. In the late Pennsylvanian this sea began shallowing and retreating from the area towards the northwest.

II. CUTLER GROUP

During the Permian the canyonlands area was a costal plain bordered to the east by the Uncompahgre mountain chain. This area was covered with slow meandering streams carrying eroded sediment from the mountains to shallow seas. These arkosic sediments form the primary composition of the red beds of the Cutler Group. The lowest member of this group is the Halgaito Formation which is comprised of red siltstone and shale. Later in the Early Permian a white sandstone known as the Cedar Mesa Formation formed in the west as shallow coastal sand bars and costal sand dunes. Canyonlands National Park lies right where this marine depositional system meets the continental system, and in fact in the park the two systems are inter-fingered with each other producing alternating bands of red and white sediment. [See Fig. 2] Eventually the continental depositional system won out depositing a thick red layer of siltstone and shale known as the Organ Rock Formation overlying the white sandstone of Cedar Mesa. Later a final advance of the marine system laid down the White Rim Sandstone which was formed both as marine sand bars and costal dunes, as indicated by the presence of pristine cross-stratification, and in the marine areas, ripple marks. Afterwards the sea again retreated and the red Cutler sediments laid one last thin layer of shale over the White Rim Sandstone in the late Middle Permian. Then the advance of the Cutler sediments was halted as their source mountains, the Uncompahgre were finally eroded down to low hills.

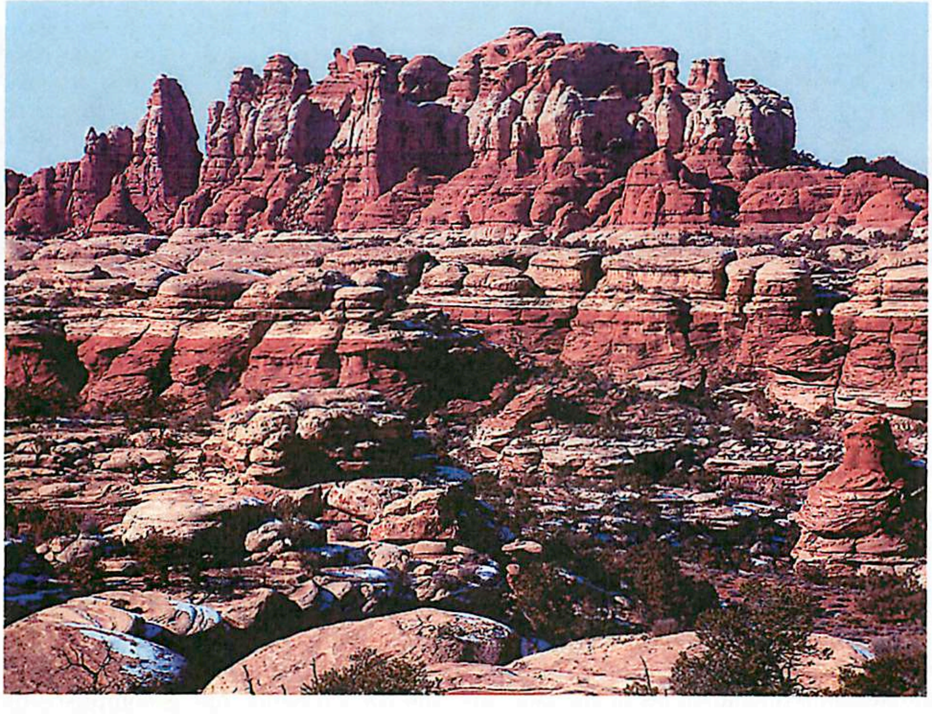

FIG. 2 The Needles in Canyonlands National Park shown here display the red and white banding of the Cedar Mesa Formation. (http://en.wikipedia.org/wiki/File:Canyonlands_Needles.jpg)

III. MOENKOPI & CHINLE FORMATIONS

In the Early Triassic the canyonlands region was primarily composed of brown tidal mudflats, with a sea to the west and low hills to the east. These brown sediments were transported down from the very low Uncompahgre hills to the flats and spread by tidal currents over the area. The resultant brown mudstone is known as the Moenkopi Formation. The presence of ripple marks and mud cracks in the horizontal bedding planes is what informs us that these are indeed tidal mudflats. As rivers began running over the canyonlands area and forming vast networked streams the Moenkopi deposition ceased and was overlain by the fluvial sediments of the Chinle Formation. The lowest members of the Chinle formation are lightly colored sandy conglomerates. Intermixed with these are also areas of point bar sedimentation where sand and debris is trapped and lithified in crescent shaped deposits. There are also thin flood plain deposits of shales from when the streams overflow. The upper portions of the Chinle Formation formed during the Middle-Late Triassic when the area was a very flat plain covered with rivers and lakes. These upper Chinle sediments manifest as colorful shales with a few isolated lake limestones. These shales are seen in varieties of reds, purples, grays, browns, and pale greens. [See Fig. 3] The Chinle Formation also contains a large abundance of brightly colored petrified logs.

FIG. 3 On this cliff you can see the brightly colored Chinle Formation overling the reddish browns of the Moenkopi Formation. (http://3dparks.wr.usgs.gov/coloradoplateau/lexicon/chinle.htm)

IV. GLEN CANYON GROUP

By the beginning of the Jurassic the seas had retreated completely from the canyonlands area, and the rivers and lakes dried up leaving behind a vast dune field desert. At this time there is an abrupt unconformity separating the horizontally bedded shales of the Chinle from the cross-stratified red sandstones of the Jurassic formation known as the Wingate Sandstone. The Wingate Sandstone is the lowest member of what is known as the Glen Canyon Group. For a time after this rivers again flowed over the area, depositing the fluvial sandstones of the Kayenta Formation piecemeal atop the underling Wingate. Eventually these rivers gave way to the vast Navajo desert which formed the Navajo Sandstone. Unlike the red sandstones of the Wingate, the Navajo Sandstone is comprised of white quartzose sand, with occasional small limestone deposits intermixed indicating the presence of occasional ephemeral playa lakes. [See Fig. 4] In the Middle Jurassic there was then a period of erosional activity leaving behind an unconformity.

FIG. 4 This shows off a large section of the previously described strata. The upper cliff shows the three members of the Glen Canyon Group. The underling slope is comprised of the Chinle Formation with the Moenkopi Formation below that. Finally in the lower left corner one can see a small exposure of the White Rim Sandstone. (http://en.wikipedia.org/wiki/File:SEUtahStrat.JPG)

V. SAN RAFAEL GROUP & THE MORRISON FORMATION

In the Late Jurassic a new inland sea began forming from the north through the middle of the canyonlands area. Above the Middle Jurassic unconformity we find the sediments of the San Rafael Group, which primarily consists of red and brown mudstone and shale. The lowest member of this group is the Carmel Formation which depending on the area is either composed of limestone and shale, or red/brown mudstone. The mudstone facies of the Carmel is from a lowland mud-flat, with its red color possible being derived from the remnants of the Uncompahgre hills. As the sea rose a thick layer of pale-red sandstone and siltstone was laid down in the resultant aqueous environment in uniformly bedded layers. This layer, known as the Entrada Formation, is known for eroding into interesting structures called 'hoodoos'. The western portions of the Entrada Formation differ from the rest in that they were laid down as sand dunes. In a few areas this formation is overlain by a white marine sandstone known as the Curtis Sandstone. [See Fig. 5] After the inland sea retreated, fluvial systems brought deposits of green, gray and red mudstone and sandstone to the area, forming the Morrison Formation. Usually the lower portion of this formation consists of stream deposited sandstones and the upper portion includes floodplain and lake mudstones.

FIG. 5 This cliff exposure shows the reddish Entrada Formation capped by the white sandstone of the Curtis Formation. (http://en.wikipedia.org/wiki/File:Entrada_Sandstone_capped_by_Curtis_Formation_in_Cathedral_Valley.jpg)

VI. CRETACEOUS STRATA

The earliest Cretaceous formation in the area is a layer of conglomerate and sandstone with thin layers of green and purple shale interspersed. This formation alternately referred to as both the Burro Canyon and Cedar Mountain was formed by meandering streams running through flat lowlands and occasional lakes. Around halfway though the Cretaceous a vast inland sea formed in the east and moved westward across the canyonlands region. The initial deposits of this new sea show beaches and sand bars and lagoonal sediments moving steadily westward across the Colorado Plateau. The sediment from this westward march of the sea is known as the Dakota Sandstone. This formation is fairly thin, but is also very complex, exhibiting a range of rock types from conglomerates to carbonaceous shales to fine grain sands. Once the shoreline had passed an area a new formation of black organic rich shales was laid down known as the Mancos Shale. This layer was formed beneath fairly deep stagnant seas under anoxic conditions, which allows the organic material to be preservered and thus color the shales black. Then during periodic regressions of the sea, sandstone beds would be laid down atop this shale known as the Mesaverde Group. Sometimes these two formations cross back over one another several times as sea level fluctuated. Finally the sea retreated completely leaving a top layer of sandstone known as the Pictured Cliffs Formation. [See Fig. 6]

Around the end of the Cretaceous the Colorado Plateau ceased to be a depositional area as it was raised far above sea level by a series of orogenic events. For the duration of the Cenozoic the canyonlands area has been operating under an erosional regime and as such we do not see much in the way of Cenozoic stratigraphic units in this area.

FIG. 6 This cliff exposure shows the Mancos Shale interbedded with the sandstones of the Mesaverde Group and capped by the Pictured Cliff Formation. (http://www.geoexpro.com/geoscience/rich-petro/)

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Incised Meanders

Christa Van Laerhoven

Simply put, an incised meander is a meander that has become incised. That is, what was once a meandering river has cut itself down into canyons and the meanders can no longer move around as they once did. Sometimes called "entrenched meanders" or "goose-necks", they form when the rate at which the river downcuts is higher than the rate at which it can meander.

The "base level" of a river is the lowest possible level to which it can erode. For example, the base level of a river that empties into the sea is sea level. So, entrenching occurs when the base level drops relative to the elevation of the river bed. Either the base level drops or the elevation of the river is increased.

Incised Meanders in Southern Utah and Erosion-Uplift Feedback

On the early Colorado Plateau rivers were not connected to the sea, but instead drained into local depressions on the plateau. When the Basin and Range province to the west formed it was suddenly possible for rivers in the area to find the sea via the Colorado River, and therefore their base level decreased dramatically.

Erosion by rivers on the Colorado Plateau removes a lot of material, making the lithosphere in the region lighter. This in turn causes uplift, since the load is less than before, which causes further increase of the relative elevation of the river to the base level. This feedback is thought to have caused slightly less than one third of the region's total uplift in the last 65 million years.

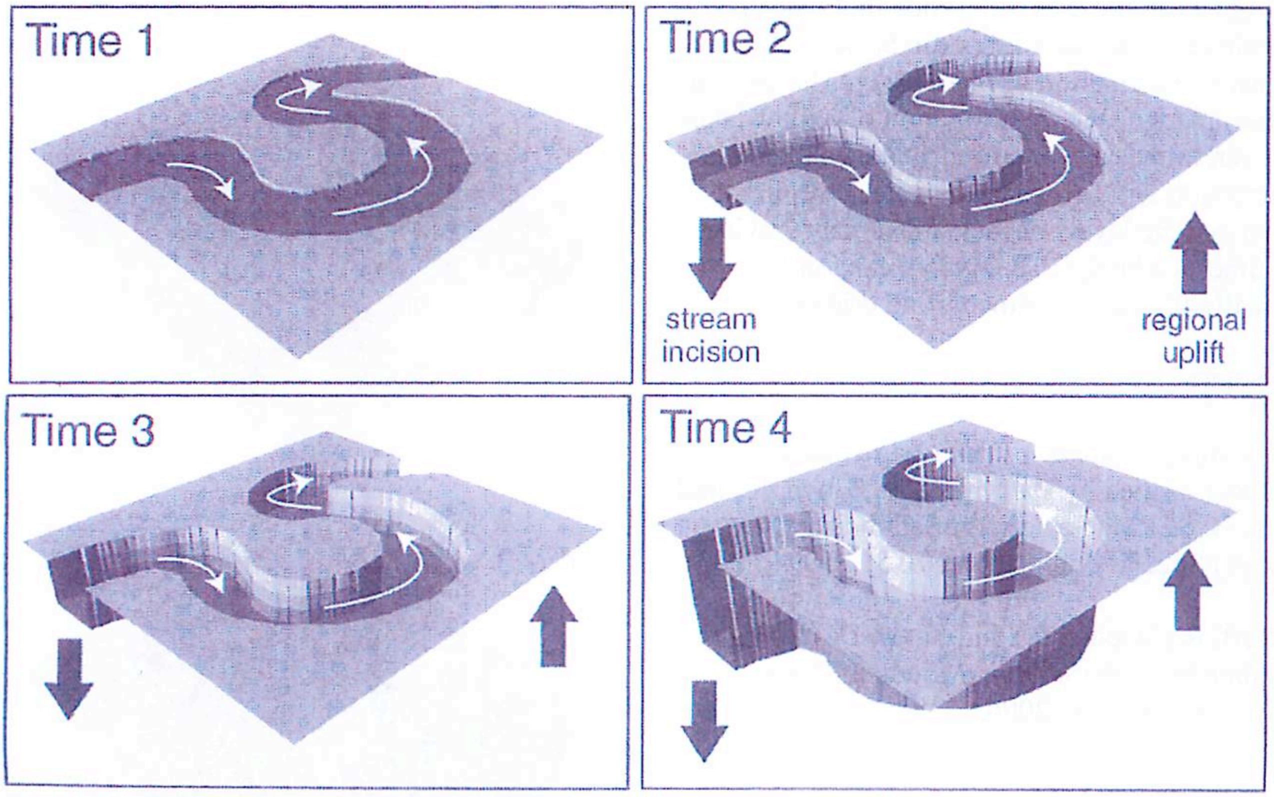

Figure 1: Schematic of erosion-uplift feedback. Image from Geology Underfoot in Southern Utah.

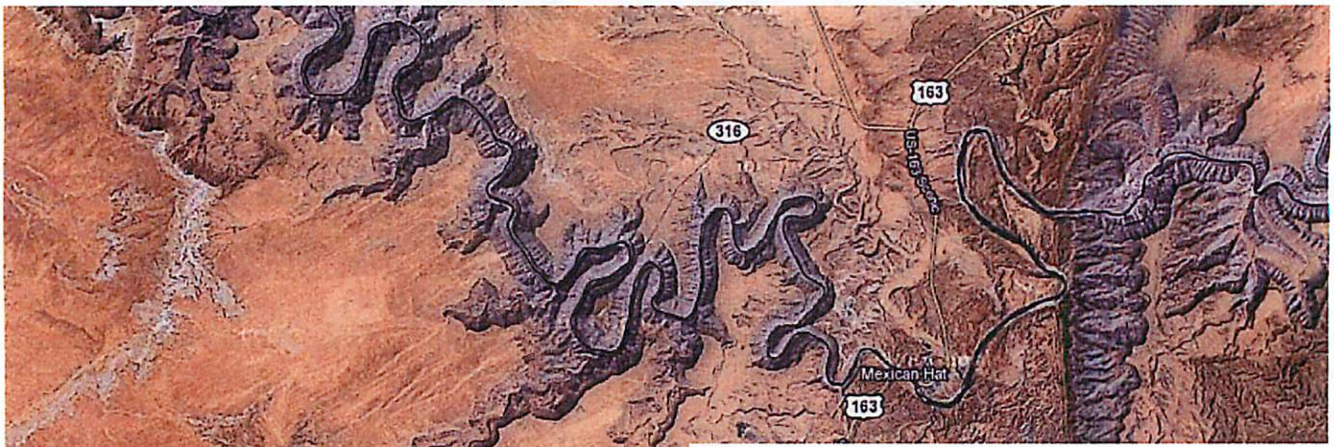

Figure 2: A satelite image of Gooseneck Overlook and surrounding area. Image from Google Maps.

Land Bridges

Even though the incised meanders are caught in a canyon they still erode their banks. A dramatic consequence of this can be seen as land bridges. The formation of these bridges happens in a process analogous to the formation of oxbow lakes. However, in the case of entrenched meanders the reconnection will take place at water level in the canyon and the layers of rock above may survive for a time as a bridge. The oxbow canyon eventually fills with sediments and dries up.

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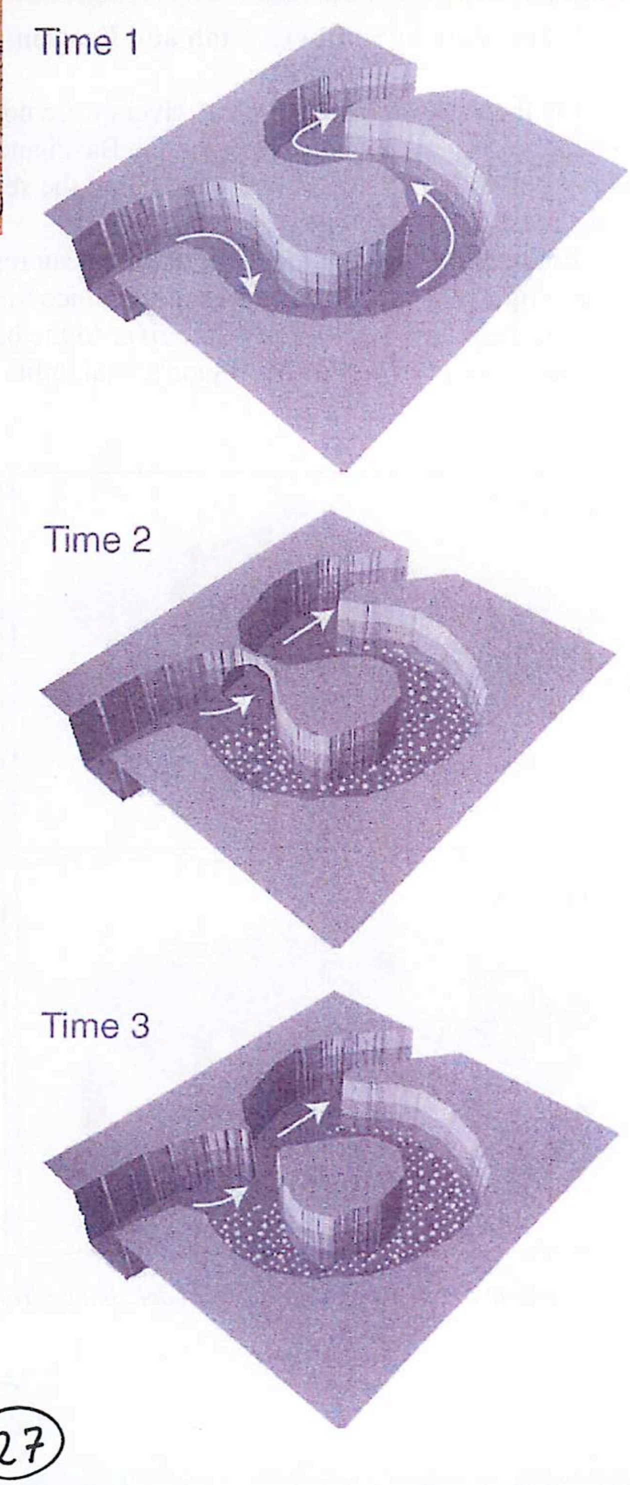


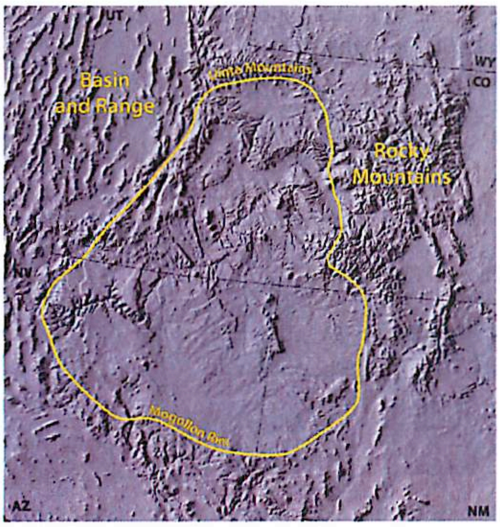
Figure 3: Schematic of the creation of a land bridge. Image from Geology Underfoot in Southern Utah.

Uplift of the Colorado Plateau

by Jamie Molaro

A Brief Geologic History

The Colorado Plateau is a region of flat-lying, largely undeformed crust between 3 highly deformed areas: the Rocky Mountains to the East, the Uinta Mountains to the North, and a large expanse of basin and range terrain to the West. The South edge of the plateau is the Mogollon Rim, as shown in the map below. The plateau is currently at an elevation of ~2 km or ~6500 ft and has a crustal thickness of 45 km (McQuarrie and Chase, 2000).



Throughout the Paleozoic Era tropical seas periodically submersed the Colorado Plateau Province and then receded, leaving behind layers of sediments that eventually lithified into limestone, sandstone, siltstone, and shale. This occurred over a period of ~300 million years. During the late Paleozoic and much of the Mesozoic era, upheaval accompanying the formation of Pangea caused series of mountain-building events that deformed western North America and caused a great deal of uplift. Eruptions from volcanic mountain ranges to the west buried vast regions beneath ashy debris. In the late Mesozoic era the Cretaceous Seaway opened up allowing for the area to once again be covered by a warm shallow sea.

A period of mountain building occurred in the late cretaceous (70-80 Ma) called the Laramide orogeny. This closed off the seaway and uplifted a large belt of crust from Montana to Mexico. The Colorado Plateau region acted as a rigid crustal block, the largest block to be raised in this event. Further tectonic activity occurred in the Mid Cenozoic and started to uplift the Colorado Plateau region again. This time, however, the uplift was uneven, resulting in a lift-and-tilt of the block (higher on the Eastern edge).

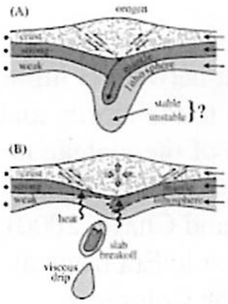
What caused the uplift? Here are three examples:

Thermal Expansion and Magmatic Crustal Thickening –

Morgan and Swanberg (1985) consider thermal expansion as a possible cause of uplift. Based on their calculations, they state that the Plateau is probably not in thermal equilibrium, though this is questionable. Assuming the mantle is dominated by olivine, then they assumed a corresponding range of coefficients of expansion controlling the process. In order for that expansion to cause 2 km of uplift, they found that the change in temperature should range from 1050-1400 °C. This could be cause either by lithospheric thinning or an equivalent heating of the mantle from a process such as convective instability.

Delamination of the Mantle Lithosphere –

Spencer (1996) suggested (though he was not the first) that delamination may have caused the uplift. If some lower portion of the lithosphere becomes more dense than the surrounding mantle it becomes unstable, detaches from the tectonic plate, and sinks into the mantle. This is called delamination. The result of delamination is uplift. Since a large chunk of dense lithosphere has just been removed the lithosphere left then rebounds upward in order return the system to isostatic equilibrium. Delamination is a very plausible explanation for many geologic events, though due to the nature of the event it can often not be proven.



This figure is not an example of delamination for the Colorado Plateau, I just wanted a small visual guide to what delamination is. This figure shows delamination due to plate convergence, but you can imagine a simpler situation where there is just a piece of material that happens to be more dense that sinks and "hangs off" the bottom of the lithosphere.

Intracrustal Flow –
McQuarrie and Chase (2000) proposed that intracrustal flow caused thickening of the crust which isostatically raised the Plateau. This flow would have been driven by a pressure gradient emplaced into the lithosphere from orogenic and tectonic activity just prior to the Colorado Plateau uplift. The required heat to initiate flow could have one or a combination of causes, such as depth of burial of the "flowing" material, removal of the lithospheric root due to convective instability, and/or radiogenic heating. McQuarrie and Chase calculate that 14.5 km of thickening would produce the 2 km uplift needed to explain the Colorado Plateau (see figure below).

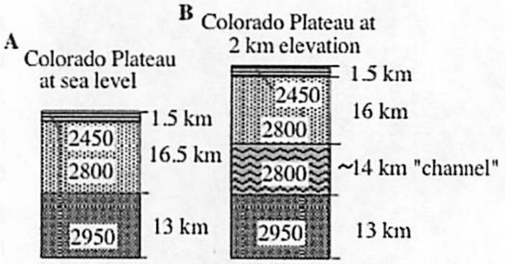


Figure 3. Crustal columns used in isostatic modeling. A: Proto–Colorado Plateau crust ~30 km thick and isostatically balanced at sea level. B: After addition of 14.5 km thickness of mobile crust (2800 km/m^3), column represents present crustal structure of Colorado Plateau balanced at 2 km elevation.

There are many theories out there to explain the uplift of the Colorado Plateau, and many variations on these theories as well. The effects of erosion can be extremely significant in the uplift process, but since that is a topic this trip I will not discuss it here. Several slab subduction theories have also been explored, but they are many, and often the required conditions are very specific. The thermal expansion theory is not very solidly founded, though perhaps still possible. Both of the latter theories are well supported by data and theory, and have been well studied. At this point, there is no way to say which is right or which is wrong.

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http://pangea.stanford.edu/~annegger/about_me/cp_geology.html
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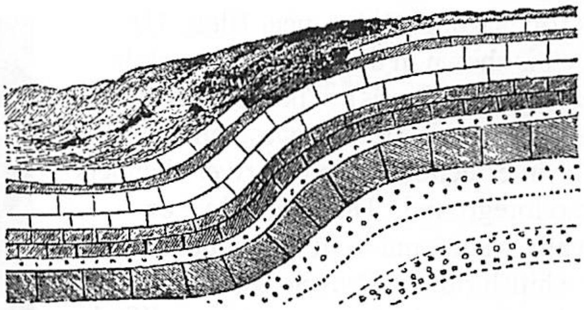
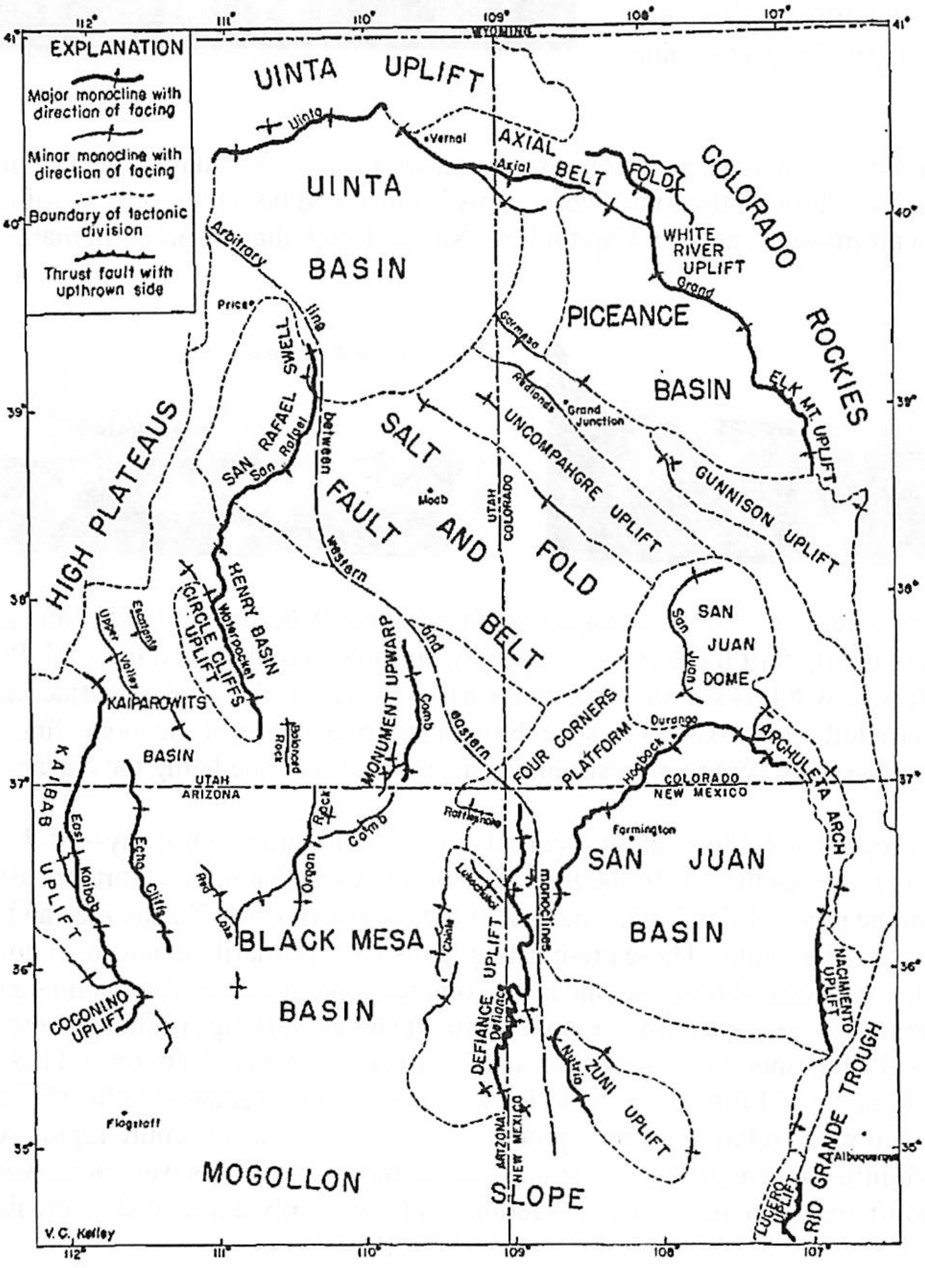
Monoclines of the Colorado Plateau

Dave O'Brien



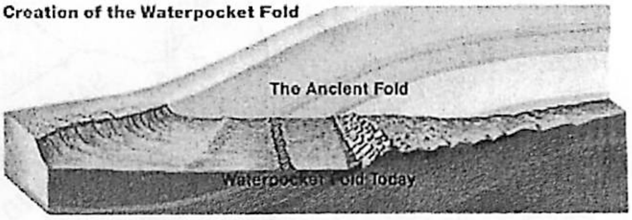
A monocline is a step-like fold in rock strata, as shown in the figure on the right (originally from Powell 1873). Monoclines are a dominant feature on the Colorado Plateau. As shown in the map below (from Kelley 1955), they define the boundaries of, and are responsible for creating, many of the basin and uplift subunits of the Plateau. They can have a length (perpendicular to the direction of increasing elevation) of hundreds of km, and are associated with uplifts of as much as several km.



In the map on the previous page, note that there are two general provinces: To the west, the monoclines trend north-south and face towards the east (ie. uplift towards the west); to the east and north, most monoclines face in a westerly to southernly direction.

A prominent monocline that we will see on this trip is Comb Ridge, near Bluff, UT, which is shown in the image on the right (courtesy Doc Searls). The photo is taken looking towards the northwest, and Bluff is at the intersection of the two river channels in the foreground. The monocline, or actually what remains of the monocline, is the whitish ridge of Navajo sandstone running across the image, and the uplifted region is towards the left of the image (west). This looks a lot different from the diagram on the last page! So what's going on here?

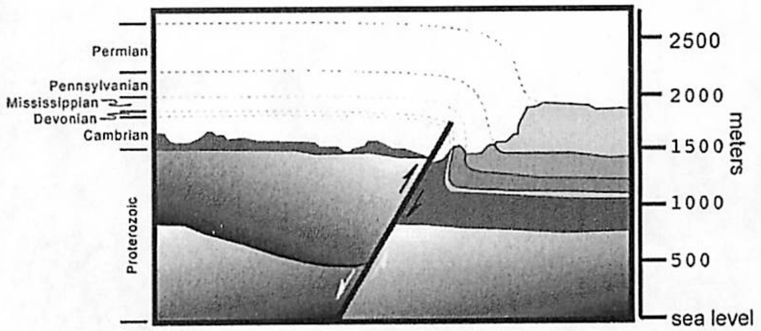
On the Colorado Plateau, most uplifted regions associated with monoclines have been heavily eroded, so what we're seeing is a cut through the folded zone. This is illustrated below for the case of the Waterpocket Fold, a prominent feature in Capitol Reef National Park that is similar in many ways to Comb Ridge.



The image on the left (courtesy USGS) is looking south along the Waterpocket Fold. Note the light-colored tilted rocks to the right of the image are Navajo sandstone, like that seen in Comb Ridge. The figure on the right (courtesy NPS) shows the current surface as well as the original surface and layers before erosion. What's left after erosion is a slice through the folded zone of the monocline, and the ridges seen on the surface represent more resistant layers, a prominent one being the Navajo Sandstone.

What causes the folding? The folding likely occurred during the Laramide Orogeny ~50-75 My ago, in which the compressive stresses that led to the formation of the Rocky Mountains further east reactivated pre-existing faults in the precambrian basement rock of the proto-Colorado Plateau area and caused deformation of the overlying strata. These pre-existing faults were primarily extensional normal faults associated with earlier tensional forces, but under the compressional forces of the Laramide Orogeny they became reverse faults. An especially good view into the inner workings of this process comes from studies of the East Kaibab monocline, which fortuitously crosses the Grand Canyon and has had a deep slice taken through it (described further on the following page). The subsequent uplift of the Colorado Plateau ~15-30 My ago was a relatively gentle process by comparison, as the entire region was uplifted fairly uniformly with little deformation of the strata—so the monoclinal folds were preserved through the Colorado Plateau uplift, and their subsequent evolution has been mainly dominated by erosion.

The East Kaibab monocline is responsible for the the Cockscomb feature in Grand Staircase-Escalante National Monument, which is similar to Comb Ridge and the Waterpocket Fold shown previously. It extends south from there, and crosses the far eastern part of the Grand Canyon, where it is exposed in cross section down to the basement rocks and is clearly associated with the Bluff fault. This figure (from Tindall 2000) shows what happened there.



In the earliest stage, normal faulting occurred (shown by the white arrows), which offset the precambrian strata. Additional precambrian sediments were then laid down in the western part (left), shown as the upper of the two proterozoic layers. Horizontal deposition of the subsequent layers followed. During the Laramide Orogeny, compressional forces reactivated the fault as a reverse fault (shown by black arrows), causing the formation of a monocline rising to the west (shown by the dashed lines). Finally, erosion cut away many of the raised layers, leaving the profile at the surface seen today. This is the likely mode of formation of most or all of the major monoclines on the Colorado Plateau. Note that for the case of the East Kaibab monocline shown here, the lowermost layers on either side of the fault are the same, and the leftmost one is lower then the right, indicating that the magnitude of reverse faulting that formed the monocline is less than the magnitude of the original normal faulting.

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Other References if you want to learn more!

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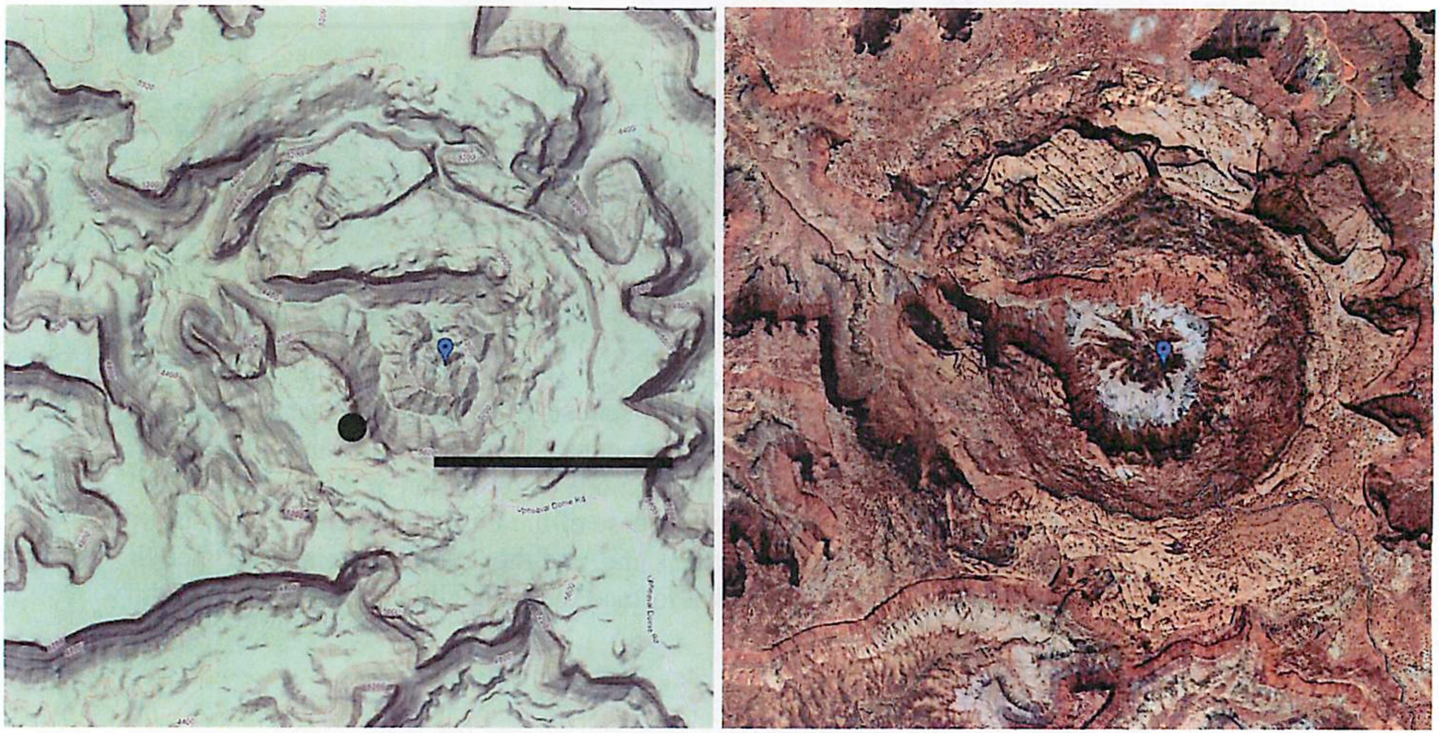
An impact origin for Upheaval Dome?

Shane Byrne – PTYS 594 – Fall 2010.



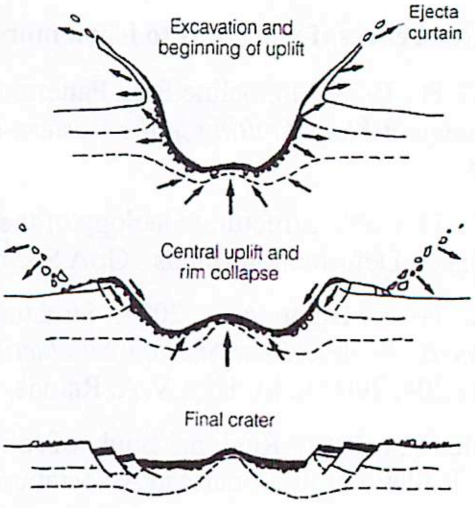
Dot marks deformation band location, line marks seismic profile.

Early theories suggested salt-driven or cryptovolcanic processes.
Given the area of the Colorado Plateau we expect one 10km crater to have formed during the Phanerozoic Eon.

So…. Are we looking at a crater?

Structural Arguments:

- Complex craters characterized by central peaks
- Simple to complex transition on Earth at crater diameters of 2-4km

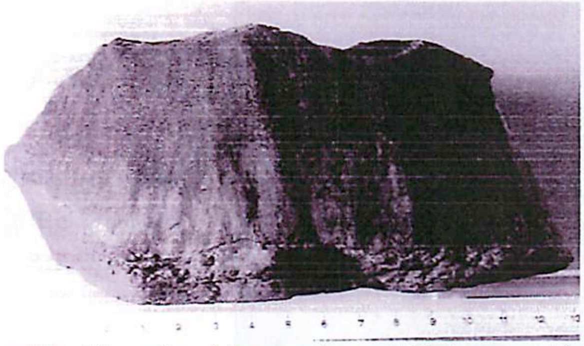


Making a complex crater:

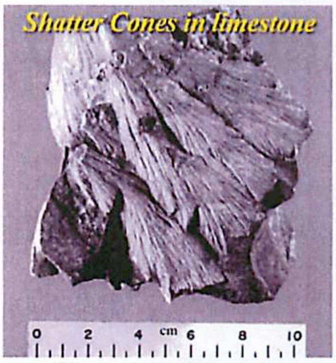
1. Bowl-shaped transient cavity created
2. Shatter cones and shocked minerals form
3. Slumping of wall material along listric faults
4. Moving material enlarges the diameter, fills in the cavity
5. Converging material and uplift create central peak

Kriens et al. (JGR, 104, 18,867-18,887,1999)

- Listric faults? YES
    - Outer bound at ~5km implies central peak of ~450m
- Outward dipping layers? YES
- Layer thickening in central peak? YES
- Shatter cones: YES (kind off… not well developed)

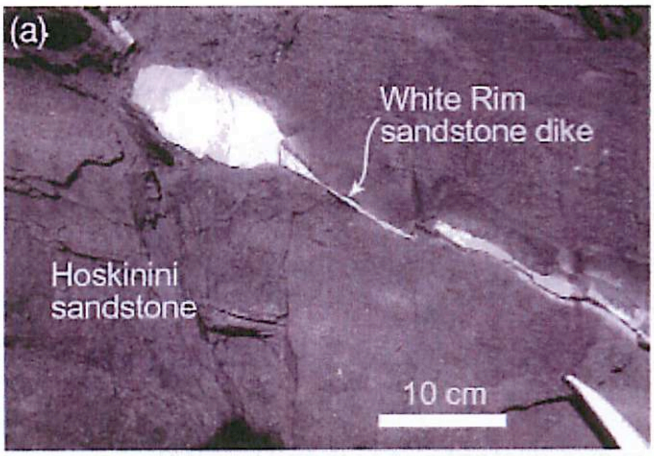


Found in Moenkopi formation at Upheaval Dome



Classic example

- Cataclastic dikes? YES (of white rim sandstone)
    - Requires pressures of >0.25 GPa to form.
    - **Kenkmann, Earth Planet Sci. Lett, 214, 2003.**

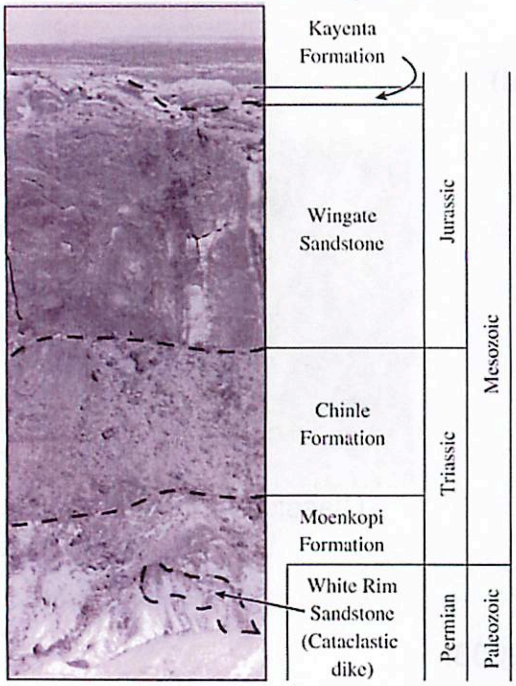


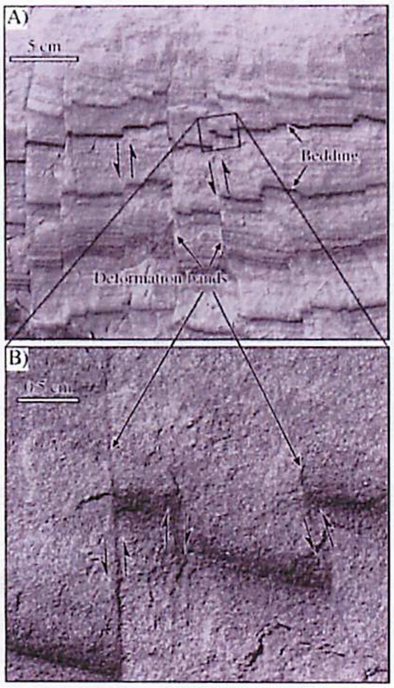
- Only sandstones provide dikes.
- High confining pressure stops strain nucleating into cracks.
- Highly porous rock responds to large pressures by collapsing pore-space.
- Rock becomes ductile by reverting to a granular fluid.

Shocked quartz? NO

- Planar microstructures exist in quartz within dikes, but they are either formed by arrays of dislocations or by open and healed microcracks.
- i.e. Hugoniot elastic limit (3.5-15 GPa) was not exceeded
- No high-pressure polymorphs
- Material has been weakly shocked

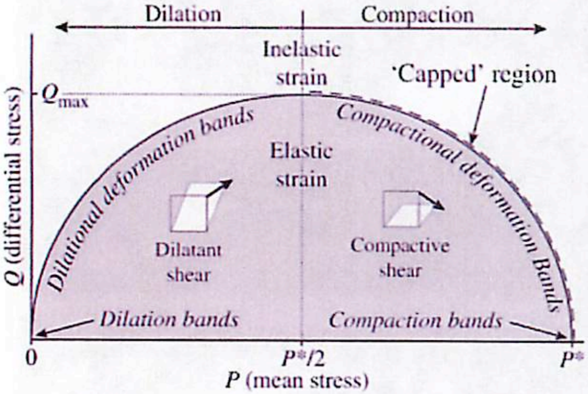
Deformation band argument:





Okubo and Schultz, Earth, Planet Sci. Lett., 256, 2007.

Deformation bands in Wingate Sandstone



Describe rock deformation in P-Q space:

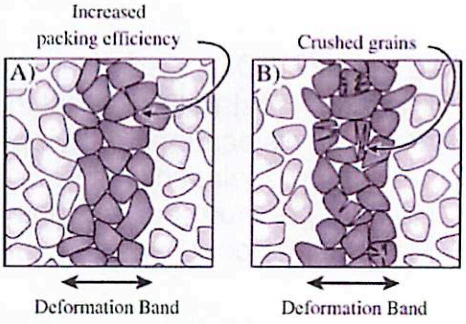
$$Q = \sigma_1 - \sigma_3$$

$$P = \frac{\sigma_1 - \sigma_2 - \sigma_3}{3} - p_i$$

P is effective mean stress
Q is differential stress
Q=0: P<0 is extension, P>P* (crushing strength) is compression.
Q <> 0: Shear can be dilational or compressional

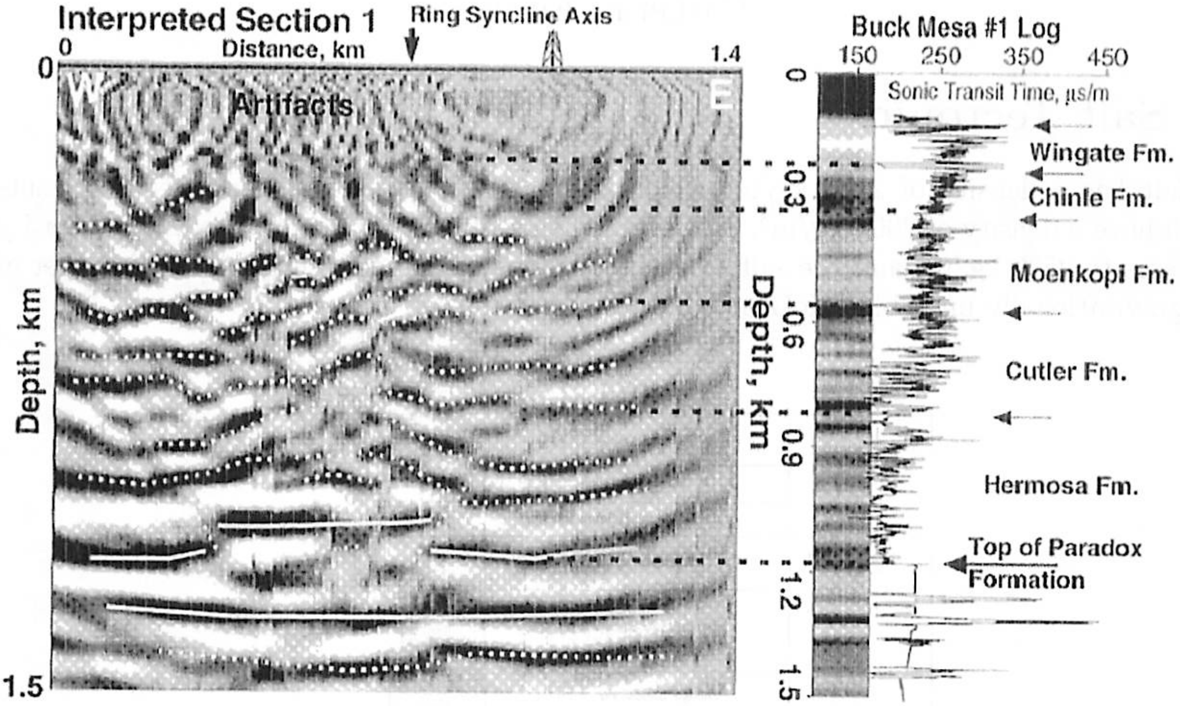
If we see dilatant shear then P < P*/2
If we see compactive shear then P > P*/2

- Okubo and Schultz see the latter in the Wingate Sandstone deformation bands
- P* is ~2.98±1.65 GPa for Wingate SS (calculated from grain size and porosity).
- Therefore mean stresses were >0.7Gpa at the time of deformation



- Maximum burial of 2.2km leads to lithospheric pressure of 0.52 MPa.
- In the most optimistic case inelastic strain will occur at P=0.2GPa (probably lower).
- So tectonics did not produce these deformation bands.

Seismic Arguments:



Kanbur et al. (JGR, 105(E4), 9489,9505, 2000)

- The seismic data look like crap, but acoustic data from nearby borehole are interesting.
- Bottom line is that the top of the paradox formation is not deflected upwards
  - i.e. no rising diapir

Recap

- Structurally consistent with an impact just larger than the simple to complex transition
  - Small central peak. Partly removed by erosion?
- Seismic/acoustic-borehole data show top of paradox formation is flat-ish.
  - No Salt Diapir

- Weak evidence for shatter cones
- Evidence for weak shocking of quartz (0.25 to 3 GPa) (in cataclastic dikes)
- Deformation bands show effective mean stresses >0.7 GPa
  - Pressures are much more than can be explained by overburden
- No shock mineralogy that would conclusively demonstrate an impact.
  - Removed by erosion?

Bottom line?

Impact scenario works well… but requires post-impact erosion to reduce the central peak in height and remove the heavily shocked minerals.

Upheaval Dome - Salt Diapir Theory

Catherine Elder

1 Salt Tectonics

Salt has a density of 2160 kg/m^3 which is greater than recently deposited sediments which have a density of 2000 kg/m^3. However, when sediments are compacted, their density increases to 2500 kg/m^3 and the salt's density remains unchanged. This makes the layer of salt gravitationally unstable (McGeary and Plummer 1992).

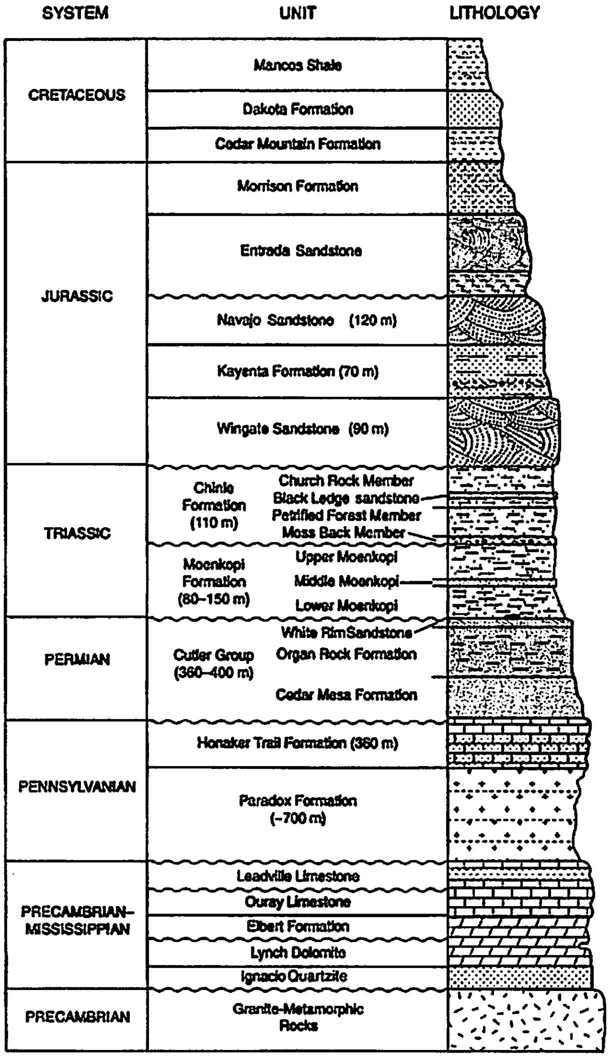


Figure 1: Figure from Jackson *et al.* (1998) showing a stratigraphic section through the formations at or below the surface of Upheaval Dome as determined from data taken at the Buck Mesa #1 well log. Figure also shows younger units that are now eroded.

2 Upheaval Dome - Salt Diapir Theory

The stratigraphic layers below Upheaval Dome include 900 m of salt below 300 m of limestone overlain by 1000 m of shales and sandstones (Kanbur *et al.* (2000), figure 1). Several authors have suggested a buried salt dome, but lateral constrictions instead of lateral extension in the center of the dome in addition to the lack of a large salt plug near the surface contradict this theory (Jackson *et al.* 1998). Jackson *et al.* (1998) suggests that Upheaval Dome formed when the stem of an extruded salt diapir was pinched off. Figure 2 illustrates

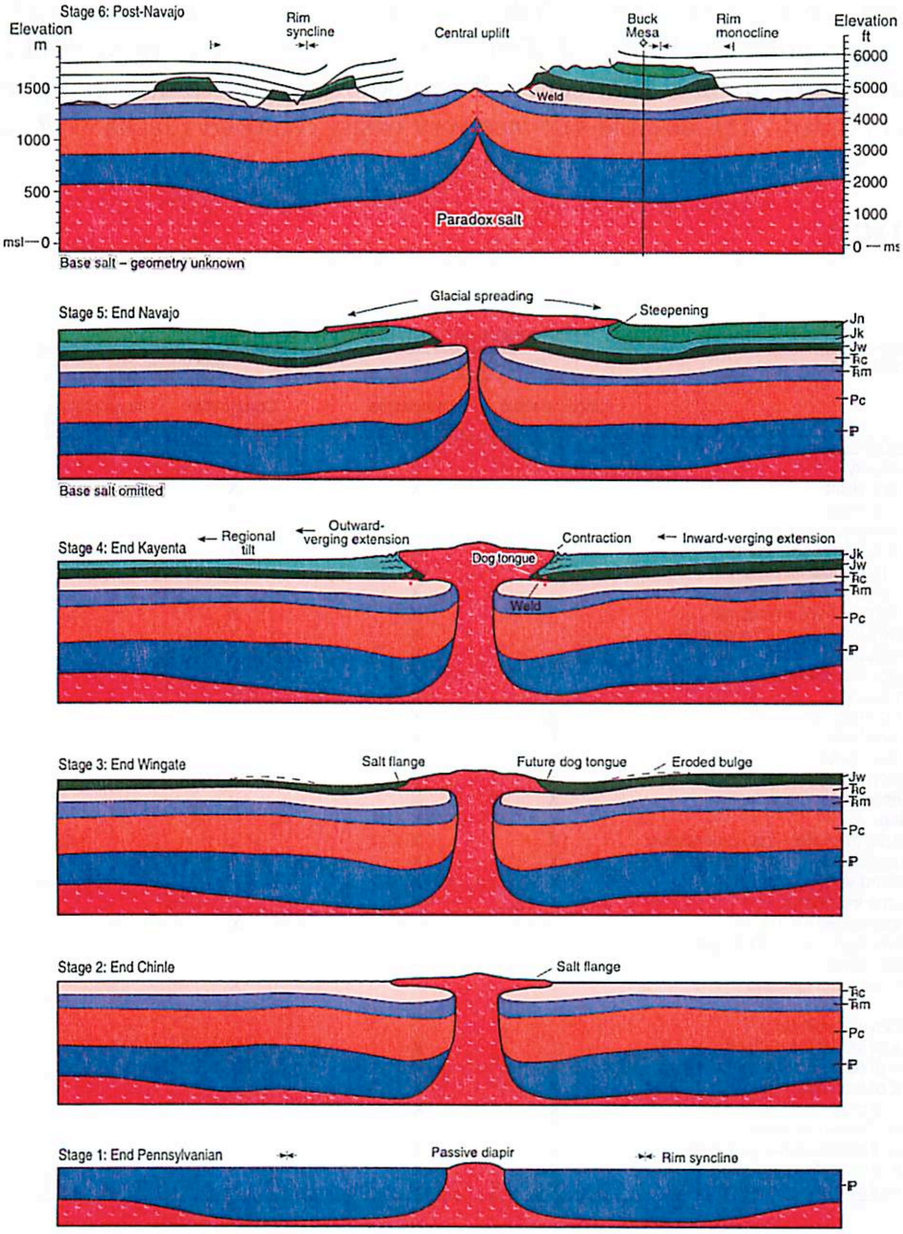


Figure 2: Illustration of the salt-tectonic evolution of Upheaval Dome (Jackson *et al.* 1998).

the stages which led to the formation of Upheaval Dome. First, a passive diapir emerged. It may have been periodically covered and then broken through the overburden to remain close to the surface. As the overburden thickened, the pressure on the salt layer increased which causes the salt to flow up the stock faster. A lot of the salt probably dissolved because the climate was wet at the time, but enough salt would remain to form a salt glacier which covers some of the surrounding strata. As more strata were deposited, the salt withdrawal may have caused fault growth. The presence of emergent salt may have prevented local accumulation of strata. A zone of abrupt steepening in the Navajo Sandstone suggests that the salt glacier spread outwards to a width of at least 3 km where it met the inward gliding strata. This rapid spread of the salt probably occurred because the feeder stock below was closing by lateral compression. Pinch-off of salt diapirs is common in the Gulf of Mexico and the Red Sea, but the mechanism that causes it is unknown. After pinch-off Upheaval Dome was uplifted and eroded. The soluble salt was very easily removed (Jackson *et al.* 1998).

3 Evidence

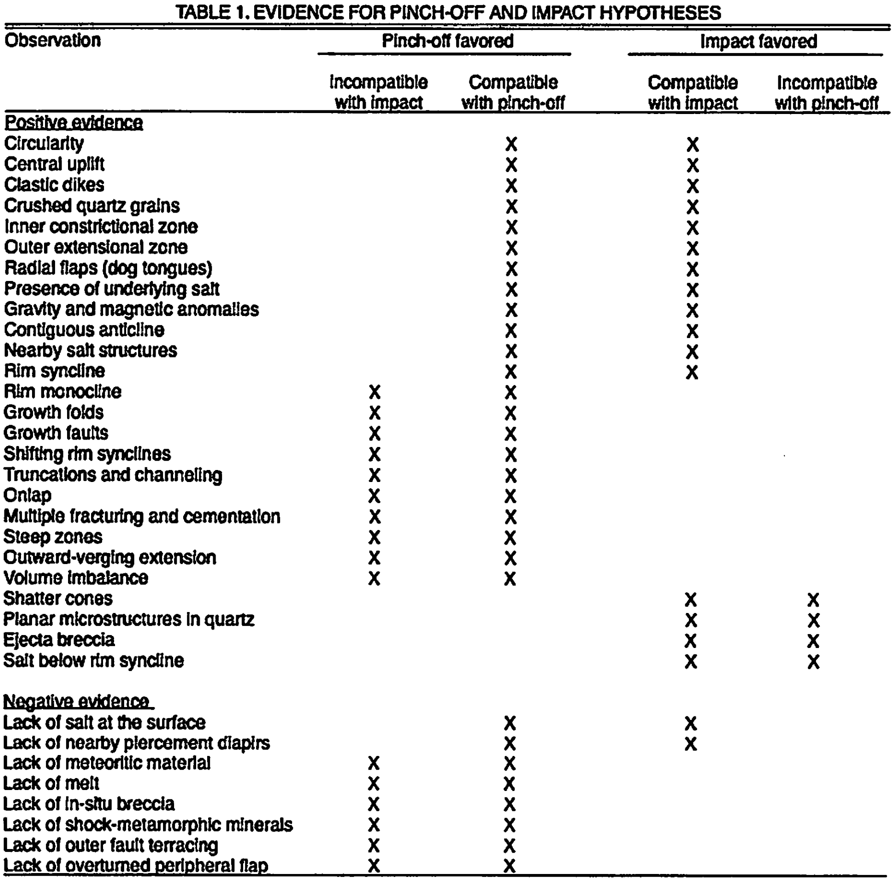


TABLE 1. EVIDENCE FOR PINCH-OFF AND IMPACT HYPOTHESES

Observation	Pinch-off favored		Impact favored	
	Incompatible with impact	Compatible with pinch-off	Compatible with impact	Incompatible with pinch-off
Positive evidence				
Circularity		X	X	
Central uplift		X	X	
Clastic dikes		X	X	
Crushed quartz grains		X	X	
Inner constrictional zone		X	X	
Outer extensional zone		X	X	
Radial flaps (dog tongues)		X	X	
Presence of underlying salt		X	X	
Gravity and magnetic anomalies		X	X	
Contiguous anticline		X	X	
Nearby salt structures		X	X	
Rim syncline		X	X	
Rim monocline	X	X		
Growth folds	X	X		
Growth faults	X	X		
Shifting rim synclines	X	X		
Truncations and channeling	X	X		
Onlap	X	X		
Multiple fracturing and cementation	X	X		
Steep zones	X	X		
Outward-verging extension	X	X		
Volume imbalance	X	X		
Shatter cones			X	X
Planar microstructures in quartz			X	X
Ejecta breccia			X	X
Salt below rim syncline			X	X
Negative evidence				
Lack of salt at the surface		X	X	
Lack of nearby piercement diapirs		X	X	
Lack of meteoritic material	X	X		
Lack of melt	X	X		
Lack of in-situ breccia	X	X		
Lack of shock-metamorphic minerals	X	X		
Lack of outer fault terracing	X	X		
Lack of overturned peripheral flap	X	X		

Figure 3: Table from Jackson *et al.* (1998) summarizing evidence for and against an impact origin or a diapiric pinch-off origin of Upheaval Dome.

The region surrounding Upheaval Dome is underlain by a large deposit of salt known as the Paradox Formation (Kanbur *et al.* 2000). This formation is a sufficient supply of salt for diapirism to occur (Jackson *et al.* 1998). Salt anticlines in the region are common, well studied, and salt definitely contributed to their formation (Kanbur *et al.* 2000). Shatter cones and planar deformation features, evidence of an impact, were observed near Upheaval Dome in the 1990s, but the observations were not conclusive (Jackson *et al.* 1998). Jackson *et al.* (1998), who argue for salt diapirism, compiled a table of types of evidence and mark the formation mechanism each piece of evidence favors (figure 3). More recent observations of the sandstones of Upheaval Dome revealed planar deformation features in quartz grains which only form when a shock wave travels through the quartz (Buchner and Kenkmann 2008). However, conclusive evidence of an impact does not rule out the possibility that salt tectonics also affected the feature. Daly and Kattenhorn (2010) argue that both slow forming and dynamic forming features observed at the dome indicates an impact event followed by a slowly evolving salt diapir. They also argue that differences in overburden created by an impact crater would promote movement of salt (Daly and Kattenhorn 2010).

4 Planetary Connection

Salt diapirism is seen in many places on the Earth. It has also been proposed to explain some features seen on Mars (Milliken *et al.* 2007). Diapirism in general is a process that could occur on icy satellites (Nimmo and Pappalardo 2006, Singer *et al.* 2010). One possible explanation of coronae on Venus is thermochemical diapirs (Golabek *et al.* 2009). Although salt tectonics probably only occur on Earth and Mars, similar processes occur on any terrestrial body where buoyant material rises through an overlying denser layer.

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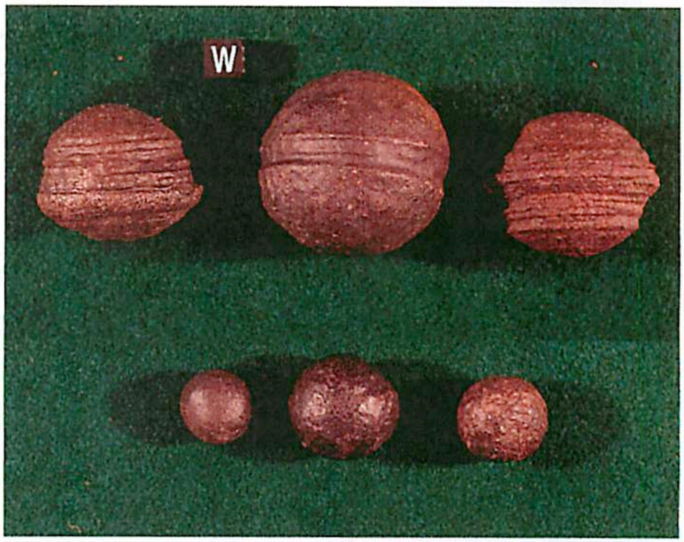
Moqui Marbles:
Terrestrial Analog for Martian Blueberries?

Ingrid Daubar Spitale

MOQUI (MOKI) MARBLES

Description:

- *Shape:* **spherical** (but also disks, buttons, cylinders, pipes, towers…)
    - Ridges - variations in porosity, permeability affect fluid flow.
- *Size:* pea- to baseball-sized
- *Color:* dark gray - black
- *Composition:* **hematite** (Fe_2O_3) & goethite (FeOOH). Some have sandstone interiors.
- *Distribution:*
    - More concretions in higher-albedo layers.
    - Spacing ∝ Size - determined by diffusion, density of nucleation sites.



Moqui Marbles, hematite concretions, from the Navajo Sandstone of southeast Utah. Scalecube with "W" is one centimeter square.
Paul Heinrich, 2008, Creative Commons

Formation:

~180 Ma:	Navajo sandstone deposited, lithified, buried.
~65-25 Ma:	Fe dissolved out of silicate minerals. • Hematite (Fe^{3+}) grain coatings → red sand. • Reducing fluids (hydrocarbons) remove Fe, reduce it to Fe^{2+} → bleaching.
~25-6 Ma:	Reduced fluids mix with oxidizing groundwater. Precipitate out Fe → concretions. • Nuclei catalyze precipitation? organic material? More likely "self-organizing" process of crystallization, precipitates from a given radius. • Multiple mineralization events → requires **episodic shallow groundwater, acidic saline brine** or other reducing fluid.
Since:	Concretions more cemented than host rock. Host rock weathers away, spherules left behind as a lag. Roll to gather in topographic lows.

Why here? Navajo sandstone highly permeable, high porosity.

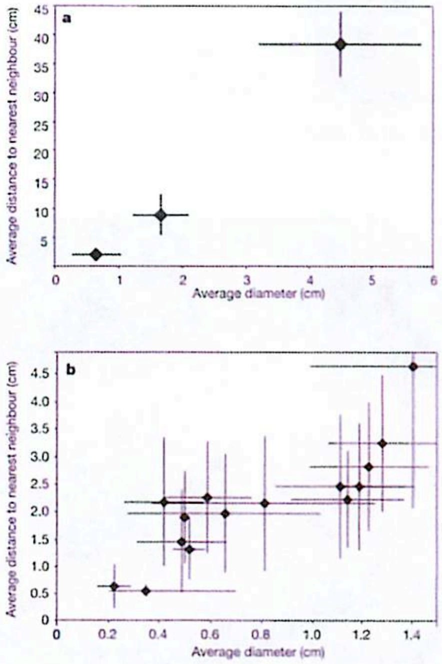
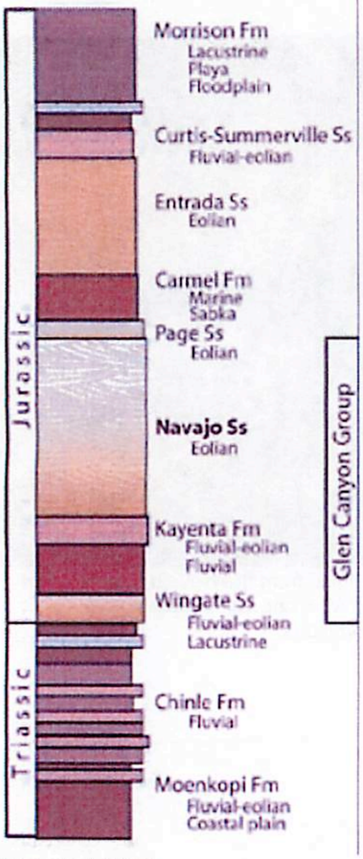


Figure 3 Navajo Sandstone statistics for haematite concretion size and spacing for select, small samples. The average diameter is plotted versus the average distance to the nearest neighbour for concretions. Error bars indicate one standard deviation. **a**, Linear trend between size and spacing for three populations of concretions at different portions of one reaction front ($n = 34$). Locality 2. **b**, Data from ten field sites. Small size populations from distinct reaction fronts ($n = 443$). Localities 1, 2, 3. *Chan et al. 2004*

Where are we likely to find them?



Stratigraphy of the Colorado Plateau

Chan et al. 2005

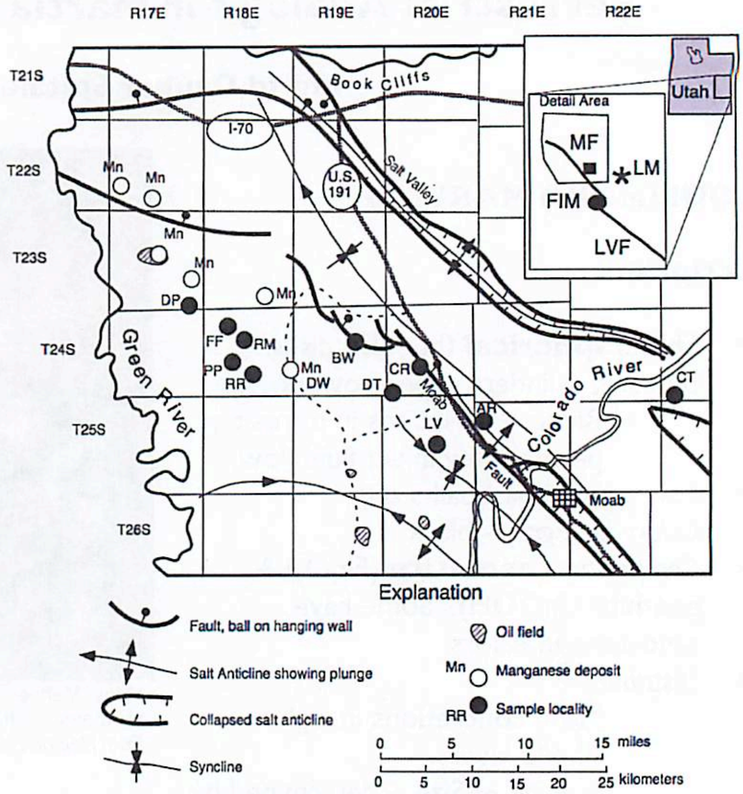
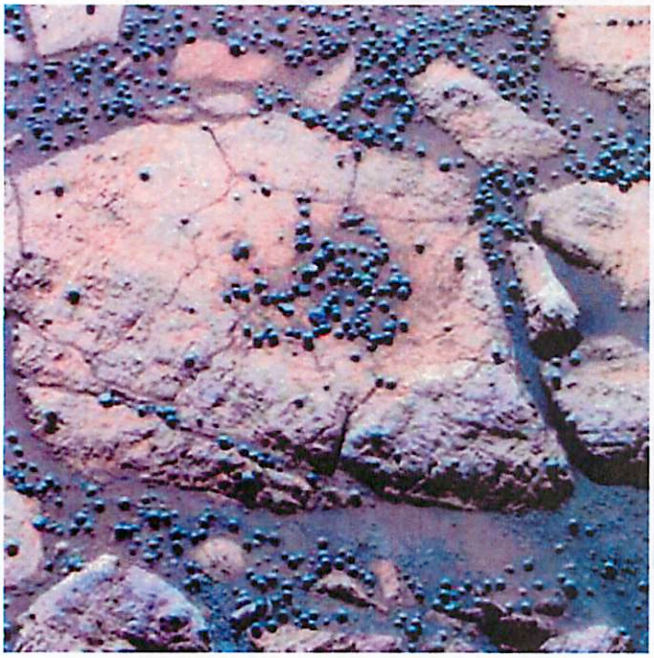


Figure 1—Location map and study area in Grand County, near Moab, Utah. Solid black circles show field localities of this study. Map modified after Doelling et al. (1987). GPS coordinates given in parentheses.

LM = LaSal Mountains,
MF = Moab fault,
LVF = Lisbon Valley fault,
RR = Rainbow Rocks (38°41′25N, 109°54′59W), back (northwest side) of Rainbow Rocks (38°41′51N, 109°54′33W),
RM = Redwall Mesa (38°43′10N, 109°55′28W),
PP = Pothole Point (38°41′38N, 109°55′07W),
BW = Bartlett Wash (38°42′50N, 109°47′ 6W),
DP = Duma Point (38°43′10N, 109°55′28W),
FF = Freckle Flat (38°44′04N, 109°56′43W),
DT = Determination Towers (~38°41′N, 109°45′W),
CR = Courthouse Rock (38°42′35N, 109°43′44W),
LV = Little Valley (38°36′04″N, 108°40′15W),
CT = Castleton Tower (38°40′07″N, 109°23′48″W),
AR = Arches (38°37′13″N, 109°38′10″W),
DW = Dubinky Well (38°42′18″N, 109°53′31″W),
FIM = Flat Iron Mesa (38°21′25N, 109°26′55W), approximately 25 km south of Moab.

Chan et al. 2000



(Left) "Berry Bowl" captured in a false-color composite image by Opportunity Rover.
Image credit: NASA/JPL/Cornell

BLUEBERRIES ON MARS

2000: TES detected crystalline hematite from orbit → decision to land in Meridiani.
2004: Opportunity landed in Eagle Crater, found "blueberries" everywhere:
Eroding out of bedrock, lag deposit on surface, settled between ripple crests.
Spherules are primary carrier of hematite detected from orbit.
General trend: fewer, smaller spherules as Opportunity drove southward – interpreted to reflect groundwater action.

Table 1 **Comparison between characteristics of the Utah analogue and proposed characteristics of the system on Mars.**

	Utah	**Mars**
Host rock	Fine- to medium-grained (0.06–0.65 mm) quartz arenite	Fine-grained sedimentary[9]
Fe source	Haematite grain coatings	Oxidized basalt (Fe^{3+})[23], orthopyroxene (Fe^{2+})[9], other?
Fe mobilizing fluids	Reducing (± hydrocarbons)	CO_2 (ref. 24), acidic brine[25], other?
Precipitating fluids	Oxidizing groundwater	Oxidizing groundwater
Concretion cements	Haematite (± goethite), carbonates (with no haematite)	Haematite[1]
Haematite characteristics		
In situ distribution	Internal within beds, along faults, fractures, joints	Internal[1]
Accumulations	Resistant surface concentrations, topographic lows	Surface layers, shallow depressions[1]
Geometry	Spherules + others based on host texture	Spherules[1]
Boundaries	Sharp to diffuse	Sharp[9], diffuse?
Crystals	Fine (<10 μm) to coarse (>10 μm) pore-fill cement	Pure and crystalline[2]

Similarities:

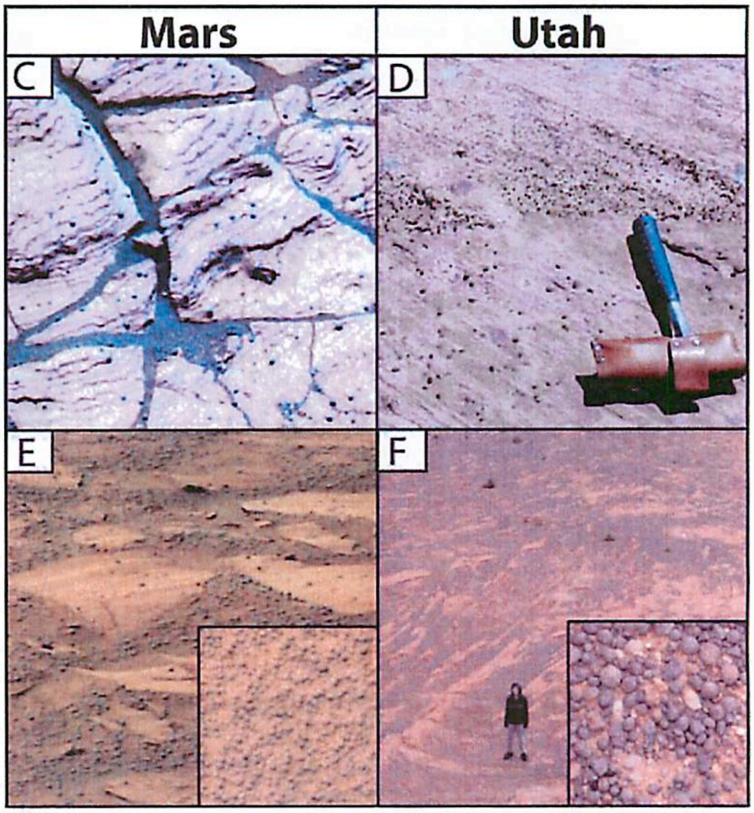
- Hematite mineralogy
- Sizes, spatial distribution
- Internal structure (no obvious nuclei, no internal structure)
  - Larger ones have shells/rinds
- Geometric forms (mostly spherical, with some doublets, triplets, equatorial ridges)

Differences:

- Utah spherules have higher SiO_2/Fe_2O_3 - Mars spherules ~pure hematite, terrestrial have more sandstone.
- Host rock is basaltic, not quartz sandstone. More soluble, less permeable?
- Evaporite cements, sulfate minerals instead of carbonates.
- Martian spherules are almost all perfectly spherical; terrestrial shapes more varied.

Alternate formation theories for Martian spherules:

- A*ccretionary lapilli*: grains adhere in surge cloud, concentric layers like hailstones
- Either volcanic or impact spherules. Impactor iron-nickel meteorite?



(C) Blueberries in Eagle Crater, Mars. Spherical, ~4mm diameter, embedded & regularly spaced within sedimentary rock. False-color composite. NASA/JPL/Cornell.
(D) Concretions embedded in Navajo Sandstone with similar spacing.
(E) Endurance Crater, Mars. False color panoramic. *Inset shows weathered accumulation of spherical forms.* NASA/JPL/Cornell
(F) Navajo Sandstone plains. Inset shows weathered concretion accumulation (up to 1 cm diam, most 3-6 mm).
Chan et al. 2005

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Unverifiable claims about Moqui Marbles:

- Provide protection from the evil eye.
- Improve fertility, happiness and life energy.
- Fortify your immune system.
- Link to extra-terrestrials.
- Relieve energy blockages.
- Bring the synthesis of the male/female duality, and the actualization of singularity.
- Vibrate to the number 4.

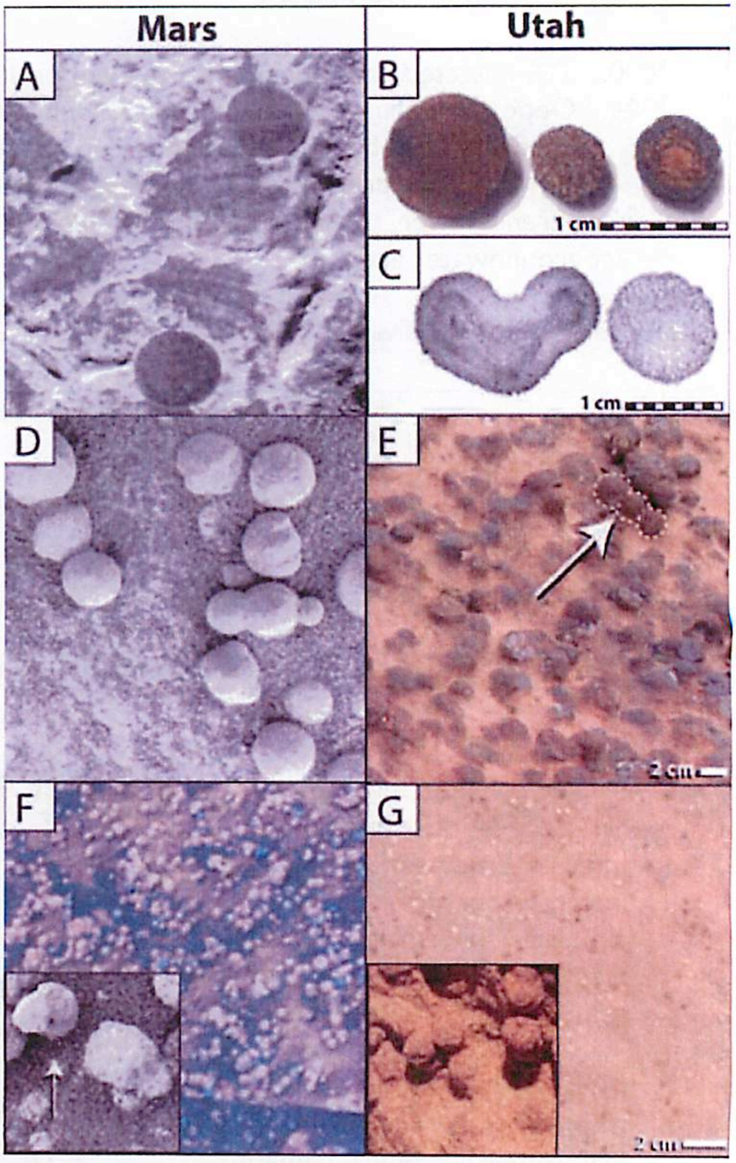


Figure 7. Comparison between internal structure and texture of Utah concretions and Mars "blueberries" (largest ones ~5 mm diameter). (A) Sliced Mars spherical forms showing relatively homogeneous internal structure. Image credit: National Aeronautics and Space Administration (NASA)–Jet Propulsion Laboratory (JPL)–Arizona State University–Cornell–U.S. Geological Survey (USGS). *(B) Sliced* (cross sectional) "blueberry"-sized Utah concretions showing relative homogeneous internal texture as well as concentric layered texture. (C) Microtomography displaying internal structure of Utah concretions. (D) Triplet of spherical forms from "Berry Bowl" in Eagle Crater, Mars. Image credit: NASA–JPL–Cornell–USGS. (E) Example of in situ concretion twins and triplets, Navajo Sandstone. (F) "Popcorn" texture coating associated with hematite-rich spherical forms in Endurance Crater, Mars. Image credit: NASA–JPL–Cornell. Inset: Detailed close-up showing hematite-rich spherical form embedded beneath the "popcorn" coating. Image credit: NASA–JPL–Cornell–USGS. (G) Weakly cemented Navajo concretions of both hematite (red) and carbonate (white) mineralogy. Inset: Weakly cemented terrestrial concretions with texture *similar to Mars "popcorn."*

Chan et al. 2005

Dyer Lytle
Fall 2010
LPL Field-trip
September 5, 2010

NATIVE PEOPLE OF SOUTH-EAST UTAH

Newspaper Rock contains petroglyphs drawn over the last 2000 or so years by the Fremont, Anasazi, Navajo, and modern cultures. This is one of the largest collections of petroglyphs anywhere. Native people have lived in this area for at least 10 thousand years.

Fremont Culture

The Fremont people were once thought to be a sub-culture of the Anasazi, they are now considered to be a distinct prehistoric culture that ranged over the western Colorado Plateau and the eastern Great Basin. It is believed that existing groups of hunter-gatherers and farmers developed into the Fremont between 2500 and 1500 years ago. Corn was in cultivation in this region 2000 years ago although the people were still nomadic at this time. By 750 years ago, settled village life had developed in the heart of the Fremont area, which included most of Utah. Their villages had timber and mud pit-houses and their farming lifestyle included irrigation using water diversion techniques.

The height of the Fremont culture is considered to range from 700 A.D. to 1250 A.D. The Fremont are distinguished from other pre-historic cultures of their time by the way they made baskets, moccasins, pictographs and petroglyphs, and thin-walled pottery. Other artifacts showing the complexity of their culture are the snare traps, rabbit nets, fur clothing, leather mittens, and bows and arrows found at the archeological sites.

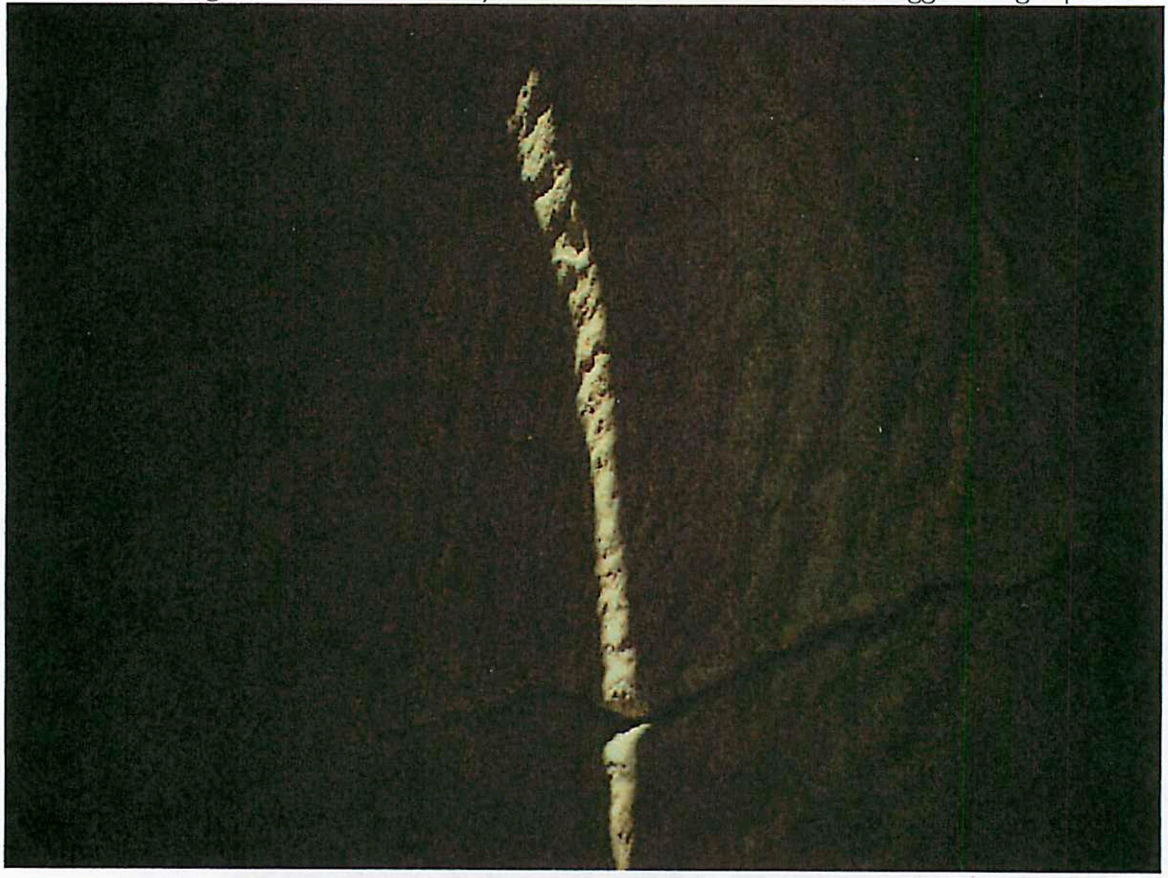
Fremont Pottery

Like some of the other cultures of the time, the Fremont disappeared between 1250 and 1500 A.D. This was probably due to climatic changes and the migration into the area of the ancestors of the Ute, Paiute and Shoshone.

Anasazi Culture

The Anasazi ranged across a wide area centered on the Four Corners region of the southwest. They disappeared at the height of their civilization towards the end of the 13th century. The Anasazi left behind a lot of physical evidence from which their lives can be understood. They were very good basket makers and started settled communities earlier than their archaic predecessors. Around 500 A.D., they began to build pit houses and farm corn, beans, and squash. Between 700 and 900 A.D. they began living above ground perhaps because they were able to store food for longer periods in places that were dry and rodent free and pueblos followed.

The Anasazi are known to have practiced archeo-astronomy, knowledge of celestial patterns and their attributions to various gods traveled along trade routes throughout the southwest. At the Chaco Canyon site in north-west New Mexico, several calendar systems have been documented. The best known of these is the "light-dagger" on top of Fajada Butte where a grove in the rock lets sunlight enter in such a way that at the summer solstice, a dagger of light pierces a spiral carved into the wall.



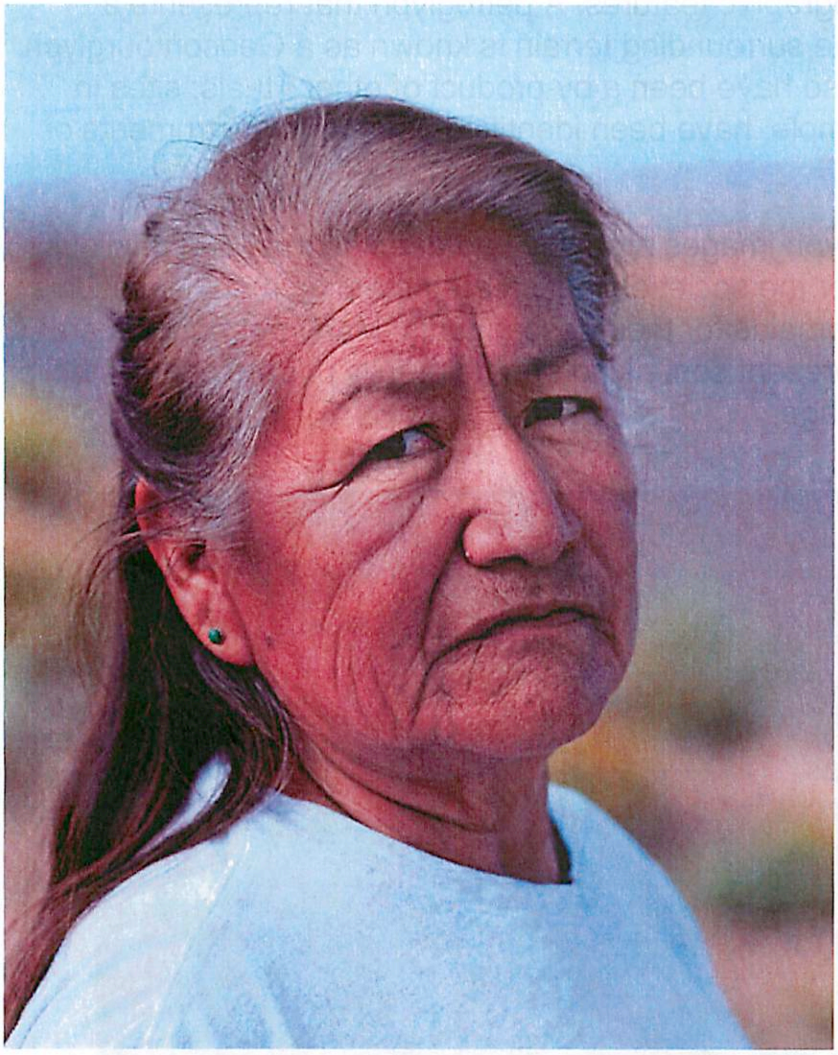
The downfall of the Anasazi empire in the late 1200's, once attributed to a long lasting drought is now considered to be a mystery. Some ideas for the cause of the fall now concern wars and/or religious upheavals.

Navajo (Diné)

The Navajo, Athabaskan speakers, originally lived in western Canada. When they arrived in on the Colorado Plateau is uncertain and they may very well have been coincident with the Anasazi. When the Spanish arrived in this area, the Navajo were found to be farming corn.

After the de Vargas reconquest of New Mexico in 1692-96 Pueblo refugees joined the Navajo communities and by 1754 Utes and Comanches from the north attacked them and drove them into the canyon-lands of north-west New Mexico and north-eastern Arizona. The shift to a dependance on livestock, particularly sheep, did not come until the early 19th century. This dependance on sheep and goats for their livelihood prompted increased raiding of Spanish-American herds leading to the Navajo War of 1863-64 and the four year imprisonment of the tribe at Bosque Redondo. This was the time of the "Long Walk" when 9000 Navajo were forced to walk 300 miles. The Navajo returned to their homeland in 1868 when a reservation was created for them in northwestern New Mexico and northeastern Arizona. This reservation has been expanded many times and now includes areas of southwest Colorado and southeast Utah.

The Navajo traditionally live in octagonal houses called "hogans". The door of a hogan faces east to welcome the sun each morning. The religious song, "The Blessingway", describes the first hogan as being built by Coyote with help from beavers to be a house for First Man, First Woman, and Talking God.

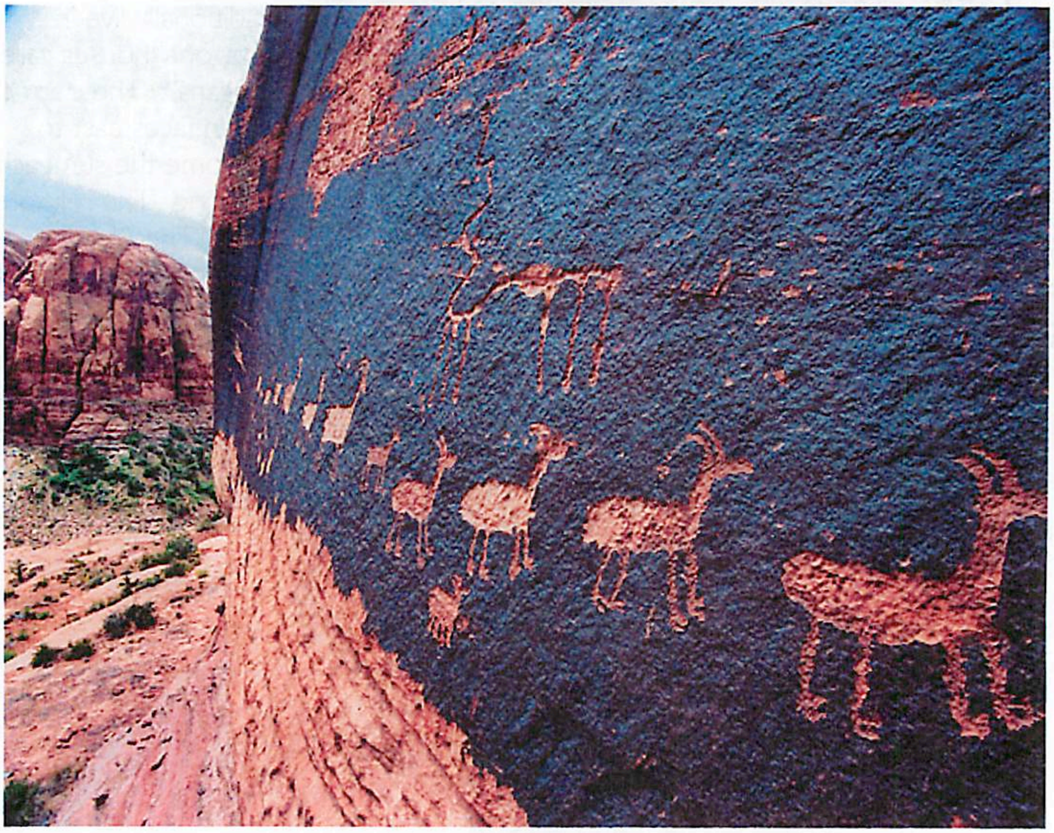


Pearl Joe, Canyon de Chelly, September, 2009

Petroglyphs

Petroglyphs are images made on rock by removing part of the rock surface by incising, pecking, and abrading. The term should not be confused with pictograph, which is an image drawn or painted on a rock surface. There is no known way to date petroglyphs. From Wikipedia:

> There are many theories to explain their purpose, depending on their location, age, and the type of image. Some petroglyphs are thought to be astronomical markers, maps, and other forms of symbolic communication, including a form of "pre-writing". Petroglyph maps may show trails, symbols communicating time and distances traveled, as well as the local terrain in the form of rivers, landforms and other geographic features. A petroglyph that represents a landform or the surrounding terrain is known as a Geocontourglyph. They might also have been a by-product of other rituals: sites in India, for example, have been identified as musical instruments or "rock gongs".
>
> Some petroglyph images probably had deep cultural and religious significance for the societies that created them; in many cases this significance remains for their descendants. Many petroglyphs are thought to represent some kind of not-yet-fully understood symbolic or ritual language.



Rock Jointing (Joint Trail)

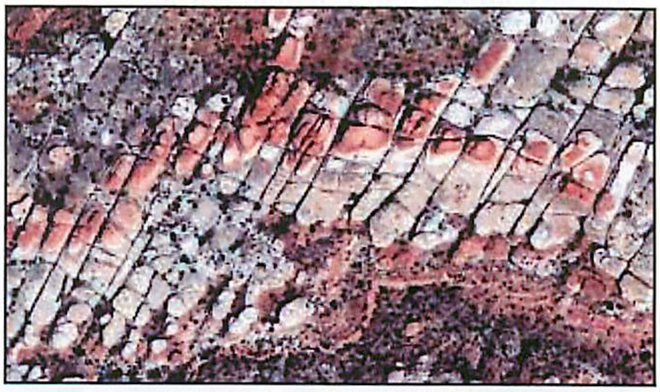
Melissa Dykhuis

Rock joints: fractures in rock, sometimes empty, sometimes filled with other material

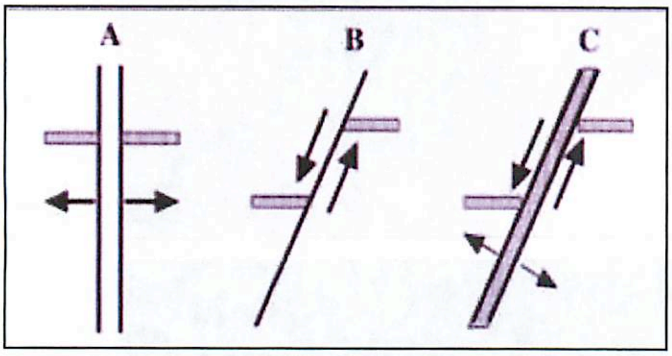
- Created by stresses on the rock, or by shrinkages due to cooling
- Occurs on all scales and timescales
- Joint trail is a macroscopic example (right)

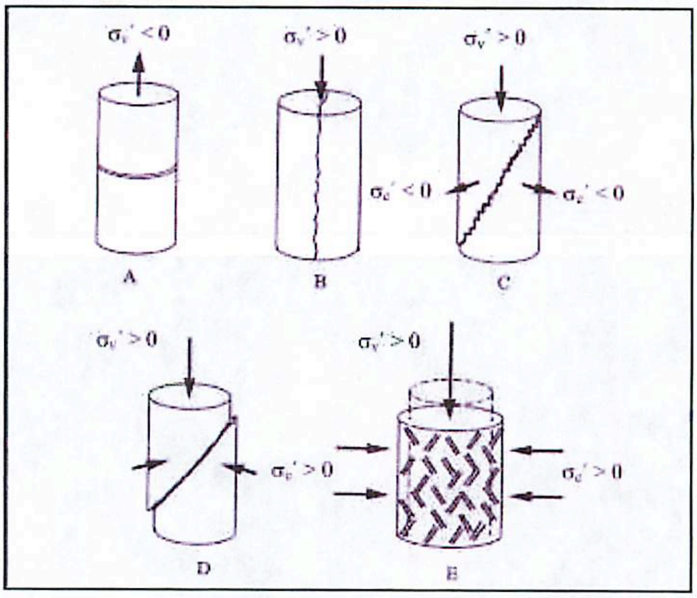
Joints vs. **faults**

- Faults require motion parallel to fracture (below)
- Joints can be created *either* by stresses on the rock *or* by cooling (e.g. drying mud)



Joint trail area, about 0.15 sq. mi.



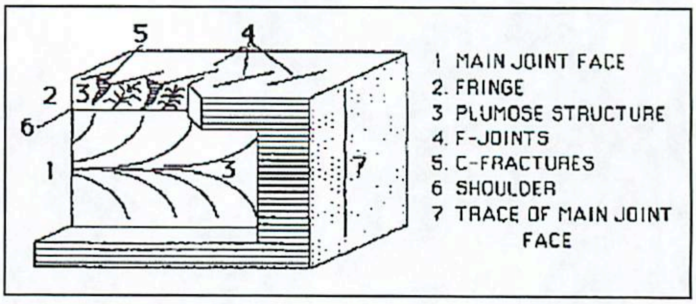


Figures from Mandl's *Rock Joints: The Mechanical Genesis*. **Left**: rock joint (A), rock fault (B), dilational fault (C). **Right**: tension fracture (A), extension or "cleavage" fracture (B), dilational or hybrid extension-shear fracture (C), shear fracture (D), multi-shear cataclasis (E).

How did the Canyonlands rock joints form?

Hodgson 1961: extensive study of jointing, covering 2,000 sq. mi. of Colorado Plateau.

- Noted plumose structure of some joint faces, suggesting propagation from inner structural inhomogeneity.
- Suggests preexisting early joint patterns propagated upward through new layers.
- Colorado Plateau criss-crossed with vast network of joints, crossing several folds.

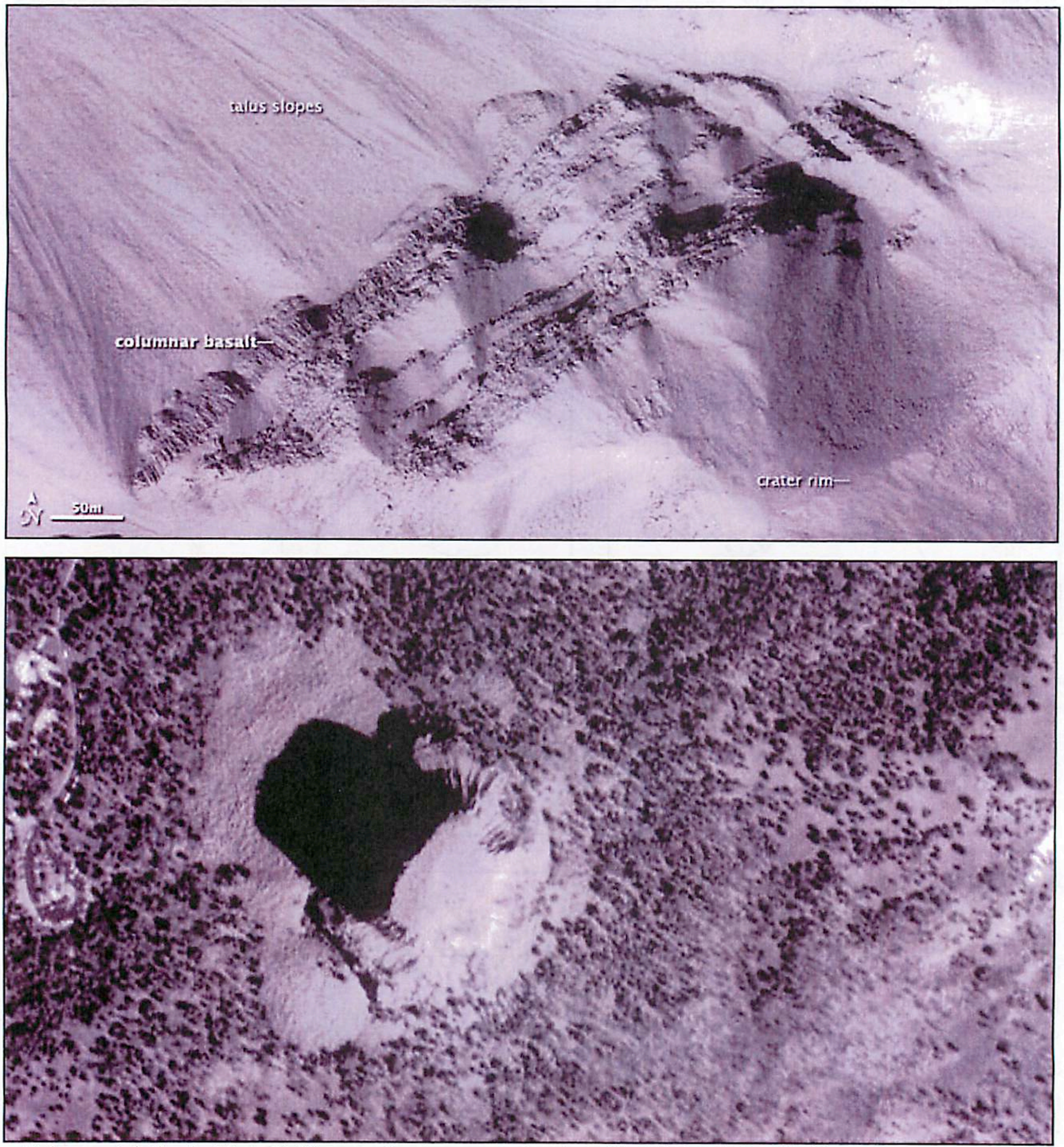


How did the Canyonlands rock joints form? (cont'd)

- Not genetically related to folding.
- Possible solution: tides.
- Conclusion: much more data needed to fully understand.

Jointing comparison: Earth and Mars

- HiRISE discovery in 2009: columnar jointing in the Marte Vallis crater on Mars.
- Evidence of cooling lava and liquid water.



Columnar jointing in Marte Vallis crater (top), contrasted with similar jointing in Devil's Tower (bottom).

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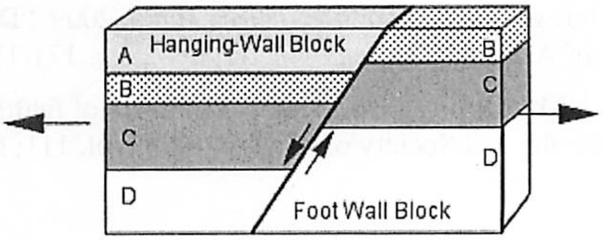
Graben Overview

Kat Volk

Graben occur as a result of tensional stresses in the crust. Graben form when two adjacent normal faults cause one block of crustal material to be depressed relative to two surrounding blocks.

Normal faults: When brittle crustal material is put under extensional stress, fractures will occur and allow one block of land to slide along the fracture or fault.



Normal Fault
Extensional Stress

The fracture will typically occur at a dip angle of 60° (the angle is measured relative to the horizontal). The exact dip angle depends on the coefficient of friction (for 60° the coefficient is ~0.85).

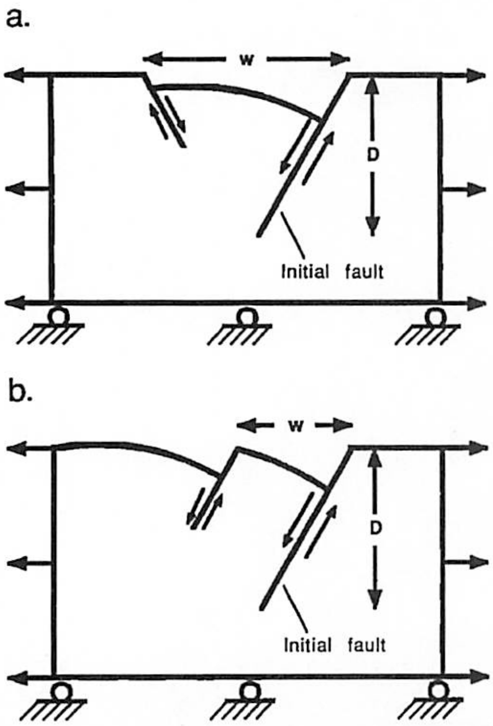


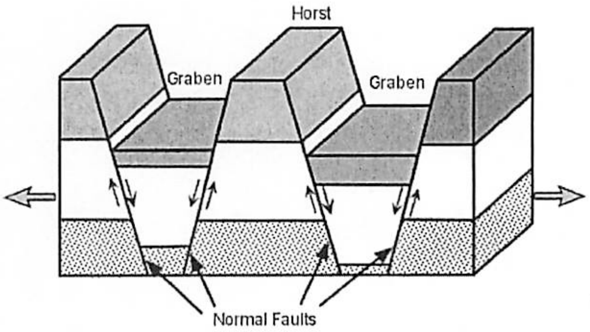
Fig. 8. Schematic representation of models in which slip occurs on (*a*) antithetic and (*b*) synthetic secondary fault segments. The distance *D* is the depth of the initial fault measured from the surface. The distance *w* is the surface distance from the initial normal fault to the surface expression of the secondary fault segment.

Figure 8 from Melosh & Williams 1989

Normal faults tend to occur in series. The two possible configurations are shown in the figure to the left.

The configuration in (a) is more common because this it tends to be the more efficient way to relieve sheer stress and therefore minimize the total strain energy.

A series of normal faults aligned as in (a) yields **Graben and Horst** terrain (shown in the diagram below).

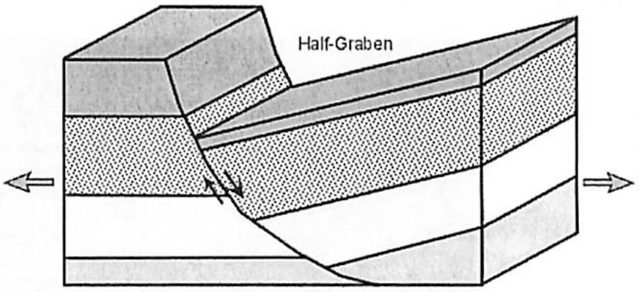


The width of a graben is determined by the depth that the original normal fault reaches. This depth may relate to some discontinuity in the layering of the crust (like a change in the strength properties of the material, etc), or it could be controlled by other factors.

If you know the width of a graben, you have a rough estimate of how deep the fault goes. If the dip angle can be measured, then you also have a good idea what the coefficient of friction is for the crustal material. These two pieces of information can be used to estimate the tectonic stress required to form the fault. On Earth, typical stresses required to form normal faults are a few tens of MPa. For comparison, a typical thrust fault (faults that form as a result of compressional stress) might require a few hundred MPa.

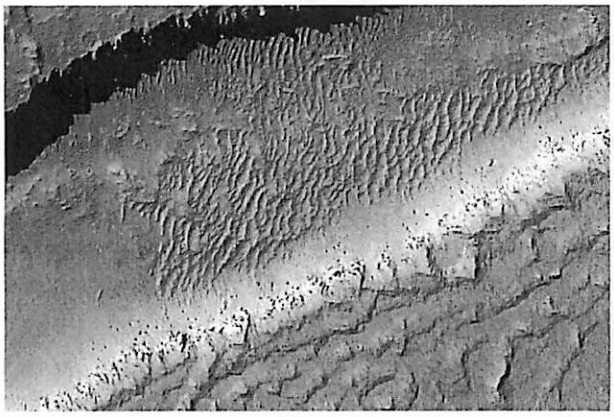
Variations on the theme of graben: If the normal fault plane is curved (which might be the case if the coefficient of friction varies with depth), you can get **half-graben** instead of typical graben.

In this case, the hanging wall block rotates as it is downwardly displaced along the fault (as shown to the left).

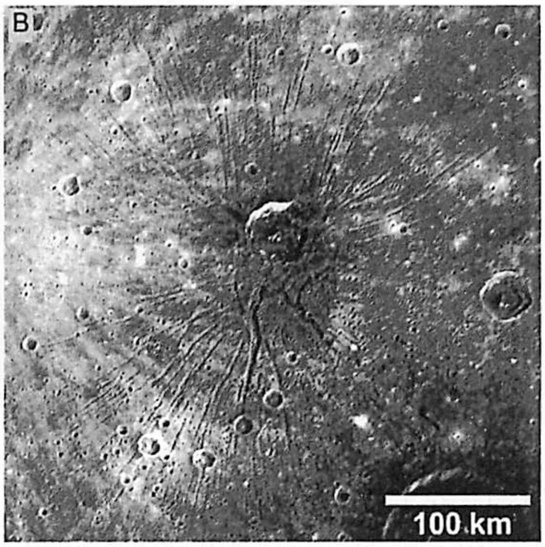


Possible causes for tensional stress: On Earth, graben can be a result of continental plate movement. Very large scale graben (also called rift valleys) can be an indication of continental splitting. On smaller scales, the extensional stress might come from an upwelling mantle plume or the flexure of the lithosphere under a load. Mass flow in a subsurface layer (such as occurs with glaciers) can also cause extensional stress.

Graben in the solar system: Graben have been observed on all the terrestrial planets as well as on a few of the outer solar system's icy moons. Below to the left is a HiRISE image of a graben on Mars. Below to the right is an image of graben associated with post-impact uplift of the Caloris basin on Mercury (figure 4b from Murchie et. al 2008).



http://hirise.lpl.arizona.edu/PSP_010346_1570



Sources:

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Melosh & Williams 1989. JGR, vol. 94, no. B10.

Murchie et al 2008. Science. Vol. 321. no. 5885.

The three generic images of graben and normal faults were borrowed from:
http://earthsci.org/education/teacher/basicgeol/deform/deform.html

Cross – Bedding

Patricio Becerra

Cross-bedding is a type of sedimentary structure that is formed when sediment is deposited by a flowing current like water or air. The most distinctive characteristic of cross-bedding, which is a direct result of the "flowing-formation-nature" of these structures, are the sets of thin strata that are preserved at an angle with respect to larger scale layers or beds, called bounding surfaces.

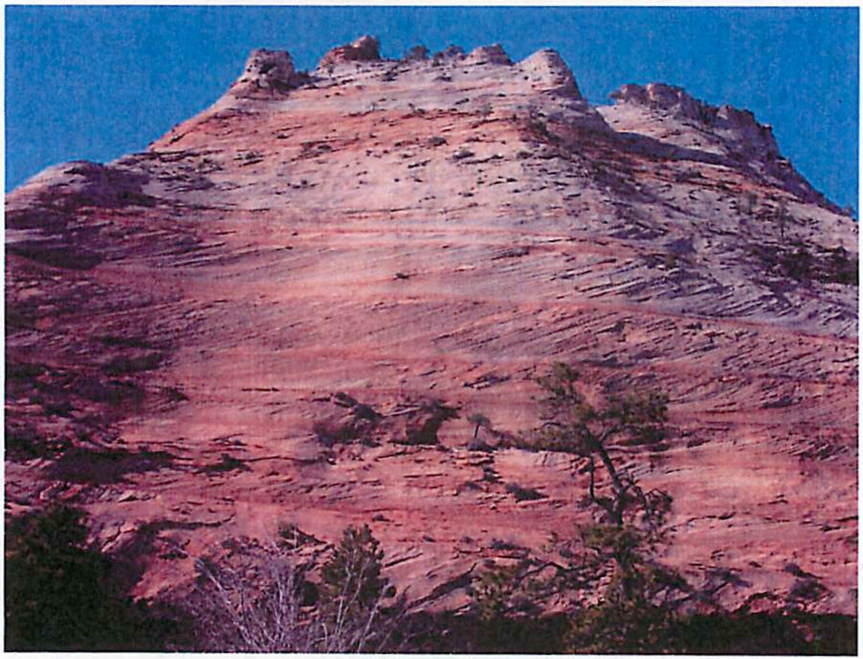

Fig. 1. Cross-bedding in Zion National Park

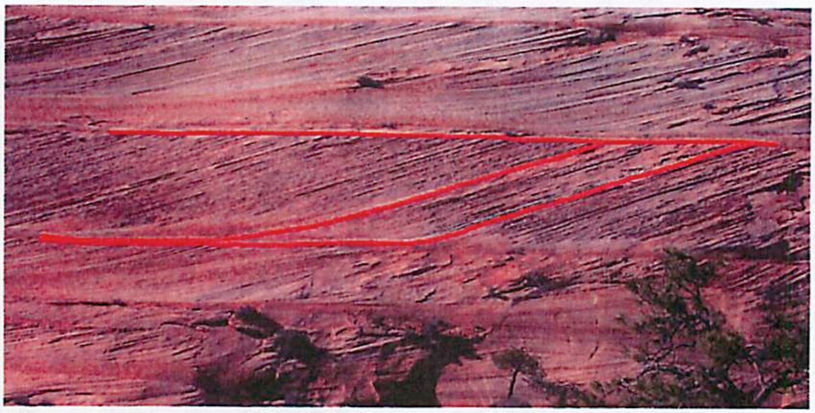

Fig. 2. Outlined inset of fig. 1.

Water and air are capable of moving sand-sized sediment to form depositional structures known as ripples or dunes. When these structures reach an unstable height (which happens when the crest reaches the angle of repose), the grains will avalanche down the side of the pile and create a thin depositional layer of the grains that have fallen (Fig. 3). Over time, multiple avalanching episodes will result in many thin parallel layers next to one another. These are the cross bedded laminae, and as is evident from figures 1 and 2, they form at an angle to the horizontal nature of the main bed.

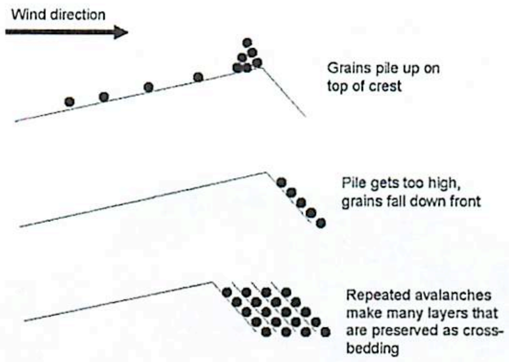

Fig. 3. Cartoon illustrating the migration of ripples and dunes.

Deposition by dunes or ripples is measured with respect to the depositional surface (Fig. 4.). Where bedforms migrate forward and leave a deposit, they climb upward with respect to this surface. The resultant sets of cross-strata are called climbing translatent strata.

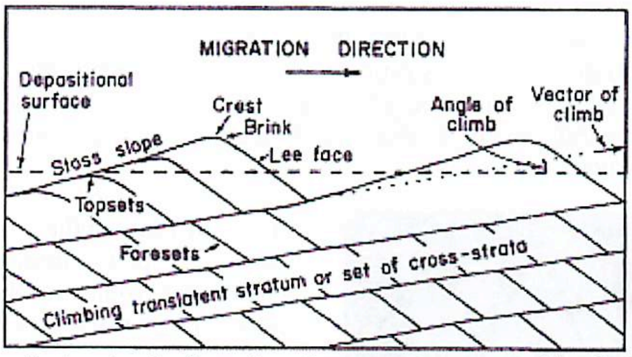

Fig. 4. Schematic showing the formation of cross-strata generated by climbing dunes.

The cross-laminae reflect the lee sides of ripples and dunes. These steep faces tilt down-current and thus indicate current flow direction. Because ripples and dunes move by erosion off the stoss slope and by deposition down the lee face, the crests of the dunes and ripples are frequently lost to erosion and the cross-beds show only the lower part of the original depositional structure.

In the case of eolian cross-bedding, there are three distinct stratification types: (1) Wind ripple deposits, in which migration of wind ripples form climbing translatent strata (Fig. 5A), (2) Grainfall or fallout from temporary suspension of grains on the brink of the dune that forms grainfall laminae (Fig. 5B), and (3) Grainflow, which forms grainflow cross-strata by way of lee slope avalanching from large dunes(Fig. 5C).

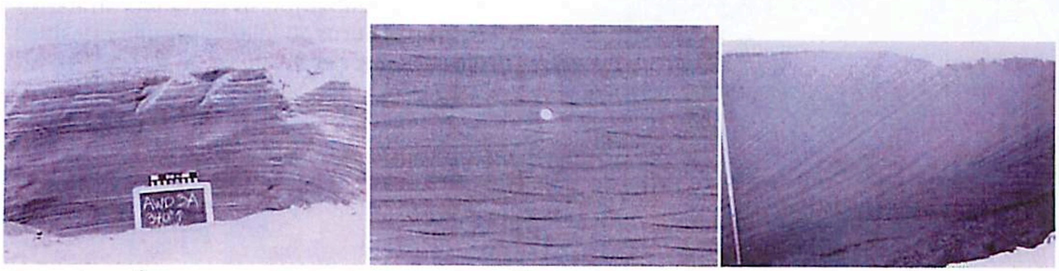
A B C

Fig. 5. Primary Aeolian sedimentary structures. A) Wind ripple laminae or climbing translatent strata. B) Grainfall laminae. C) Grainflow cross-strata

Canyonlands National Park

Many of the most interesting cross-bedding structures in Canyonlands National Park (Fig. 6) formed during the Jurassic Period. A vast dry desert existed here during that time and large sand dunes and their associated cross-beds accumulated to great thickness, forming the Navajo sandstone that exists today.

Fig. 6. Cross-bedding in Canyonalnds National Park

Planetary Connection: Burns Formation, Meridiani Planum, Mars

The most prominent example of cross – stratification in other planets is the outcrop exposure of sedimentary rocks near the MER Opportunity landing site, known as the Burns formation (Fig. 7). This formation exposes several units of stratification that represent eolian dune fields, sand sheets, and interdune material/playas.

The importance of the discovery of this formation is that it provides evidence for the influence of ground and surface water in controlling primary depositional processes.

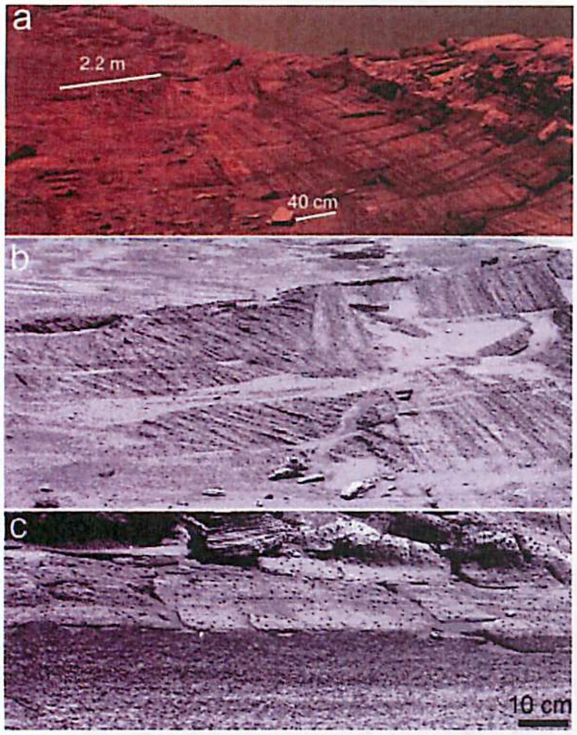

Fig. 7. Contact between stratigraphic units of the Burns formation. (a) Burns formation at eastern end of Burns Cliff. (b)Burns lower unit strata. (c) Close – up of Burns Middle/Upper unit transition (from Gratzinger et al. 2005).

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Flora and Fauna of the Canyonlands, Utah

Serina Diniega

The area is a 'cold desert' – water is sourced from the Green and Colorado rivers, a few springs, snow melt, and rain. Precipitation is infrequent and low (9in/yr); rapid evaporation (85in/yr) and runoff mean little of this water is retained.

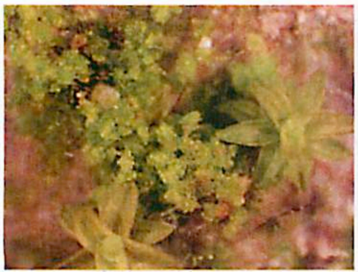
	low water	near ground water/sandy
moss/lichen/etc.	Syntrichia caninervis[1] (cryptobiotic soil*), Grimmia orbicularis[2] (rocks)	liverworts
cactus	prickly pear, 10 other species	
wildflowers	primrose[3], sacred datura, sand verbena[4], yucca	
grass	indian ricegrass, grama[5], needle and thread[6], galleta	monkey flower[7], easter flower, ferns, cattail[8]
shrub	blackbrush, shadscale[8], mormon-tea, cliffrose[9], four-wing saltbush	big sage, rabbit brush[10], greasewood[11]
trees	pinion pines, utah junipers[12], mountain mahogany, barberry[13], snowberry	cottonwood, willow, tamarisk, netleaf hackberry, russian olive[14]

*Cryptobiotic soil: blackish-gray, lumpy crust is actually a microscopic plant community made up of cyanobacteria, lichens, fungi and algae. BE CAREFUL as this is very fragile and will take years to redevelop. It plays an important role in stabilizing soil and retaining water/nutrients.

bugs: biting midges[15]
mammals: jackrabbit[16], desert cottontail[17], bighorn sheep, mule deer[18], coyote, bobcat, mountain lion, bats
avian: turkey vultures[19], golden eagles, ravens, white-throated swifts, violet-green swallows[20], owls
rodents: kangaroo rat[21], packrat, porcupine, rock and antelope squirrel, chipmunk[22]
reptiles: side-blotched, tree[23], leopard[24] and collared[24] lizard, snakes

Resources:
http://www.ohranger.com/canyonlands/flora-fauna
http://www.canyonlands.national-park.com/info.htm
http://www.protrails.com/area.php?areaID=13&subid=14
http://www.eveandersson.com/usa/ut/moab

1.



Protonemal gemmae
(Syntrichia)

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3.

4.

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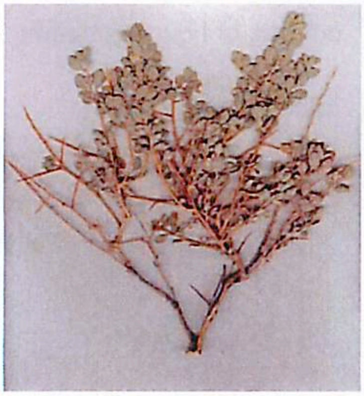

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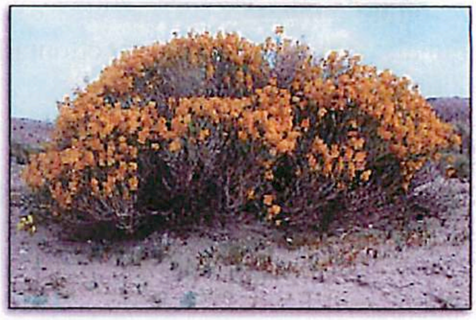

11.

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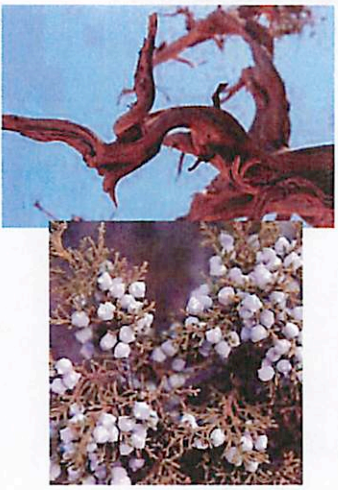

13.

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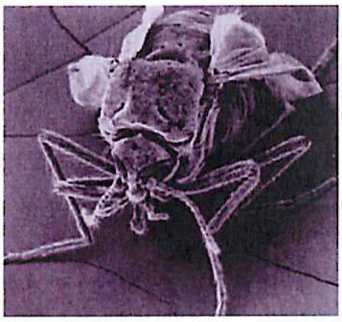

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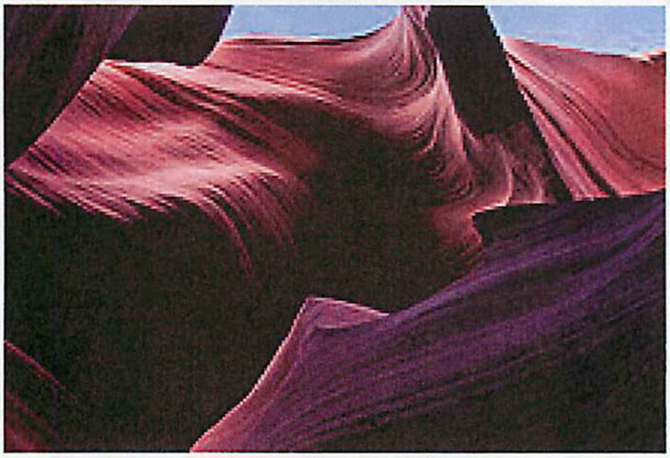
25.

Sandstone, Shale and Limestone

Eric E. Palmer

Broken and weathered rock pieces are called clastic sediments or detrital sediments. Shales, sandstones and conglomerates (clastic sediments) are much more abundant than rocks formed by chemical precipitation (limestones or evaporates such as rock salt, gypsum, anhydrite, borax, fluorite, etc.) Clastic sediments comprises more than 1/3 of all sedimentary rocks. Of this, shale comprises 75%, and sandstone is more common than conglomerates.

Sandstone



Classification	Grain Size (mm)
Very coarse sand	1.0-2.0
Coarse sand	0.5 - 1.0
Medium sand	0.25-0.5
Fine sand	0.125-0.25
Very fine sand	0.0625-0.125

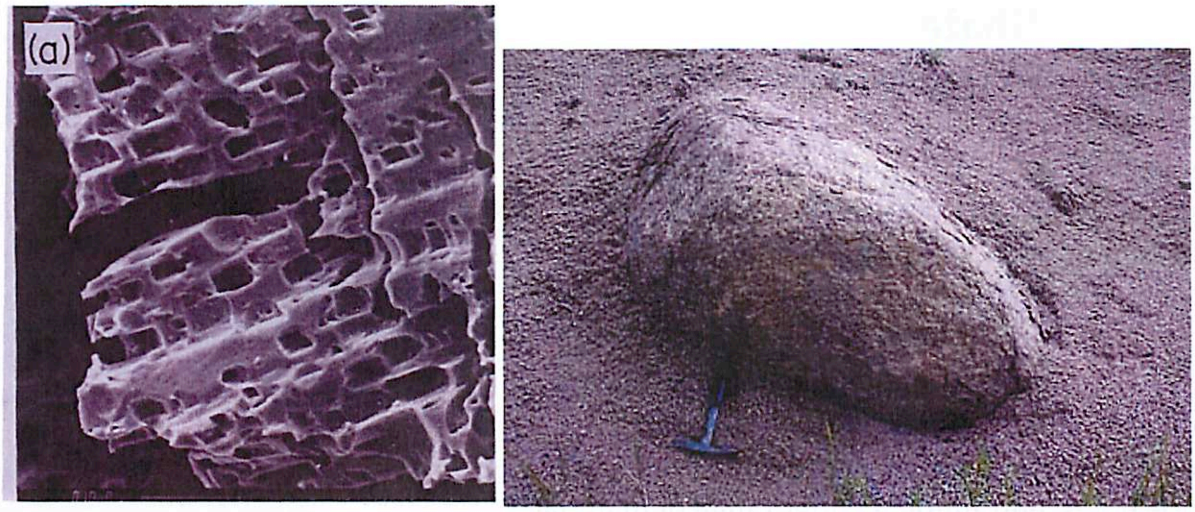
Sand is not a mineral (specific crystallographic and chemical formula) but describes the size of particles. You can have sand that is pure quartz (common), to olivine (the green sand in southern Hawaii), to volcanic rock (the black beaches near Hilo, Hawaii).

Sand is typically made up of quartz grains (SiO_2), which is one of the most weather-resistant minerals. The sand comes from chemical weathering of granite. Granite is made up of quarts (clear), two types of feldspar, K-feldspar (pink) and Na-plagioclase (white) and accessory minerals of biotite (black mica), amphibole (black) and muscovite (clear mica). Water, usually slightly acidic, breaks feldspar into kaolinite, a white clay. This chemical weather can occur with either HCl acid or H_2CO_3. The granite rocks break apart because the interlocking network of crystals no longer are held together.

$$2KAlSi_3O_8 + 2(H^+ + Cl^-) + H_2O \Rightarrow Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^+ + 2CL^-$$

Sandstone, Shale and Limestone

Eric E. Palmer

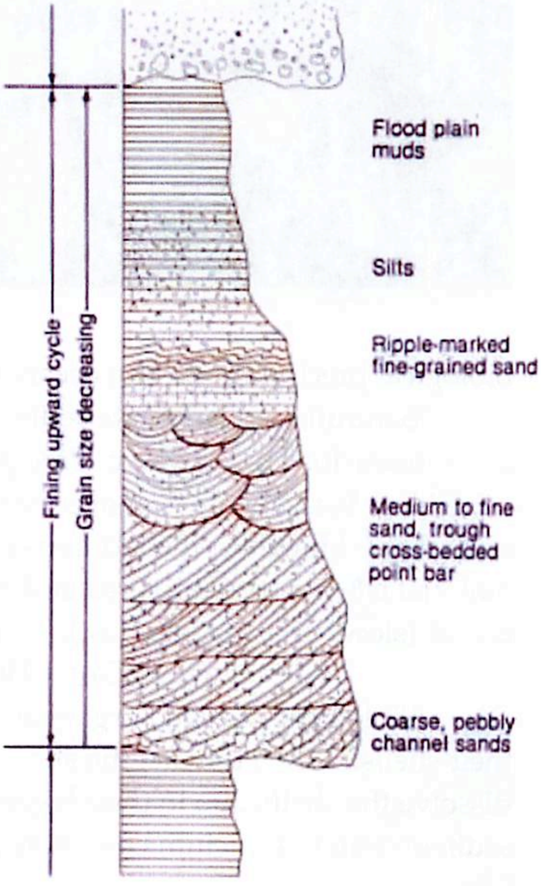


(left) SEM photomicrograph of prismatic etch pits of K-feldspar from Piedmont, NC. (Berner and Holdren 1979)
(right) Disintegrating boulder of granite. (http://www.uwsp.edu/geo/faculty/lemke/geomorphology)

Sand can be transported by fluvial or aeolian processes. Cross bedding can indicate the type of environment and the mechanics of sediment transport and deposition. The deposition due to fluvial processes are normally indicated by parallel bedding, while aeolian processes will typically be found in dune-like formations.

The size and shape of sand grains can indicate much in the way of their history. As sand is transported, edges are knocked off and their surfaces (rounded) and abraded (frosted). This can indicate the mechanism and length of time that the sand has been actively involved in transport (rivers, beaches, sand dunes, etc.)

Additionally, fluvial processes can show size sorting. Water speed controls sediment emplacement. Large sand grains are dropped quickly as a stream slows, while finer sand grains are deposited further downstream as the water current further decreases. Finally, silt and clays are carried further and are not dropped until water speed is greatly reduced (river delta or lakes). In turbid environments (major floods) much of the size sorting is lost to due turbulent mixing.



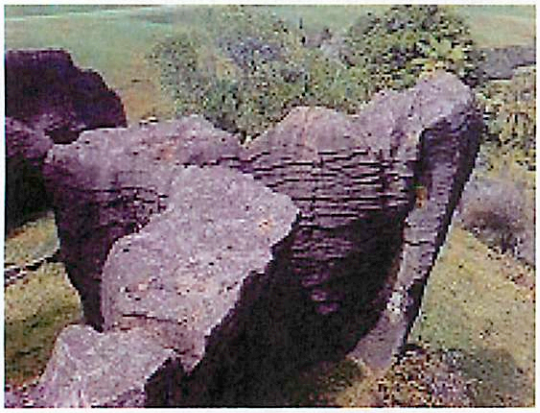
Sandstone, Shale and Limestone

Eric E. Palmer

Shale

Shale is a fine grained sediment and is the most common of the clastic sediments. They reveal less about their formation because of further weathering (soil formation, etc.) and erased those clues. Shale is highly variable in grain size and composition. The general description is: sedimentary rocks that have a large component of clay-size material (< 1/256 mm). They can contain larger clasts, making them more sandy, but most are silty having even smaller clastic grains. Some even are pebbly being the products of mud and debris flows, entraining a wider range of material.

Mud and silt are deposited on a river floodplain, river oxbow lakes, ebbing ties along tidal flats, and the deeper parts of the continental shelves and slopes. Their small grains make them idea for organisms, indicated by bioturbation (reworking and modification of sediment by organisms).



Limestone

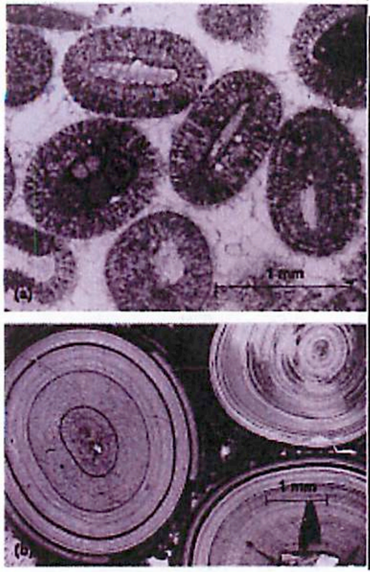
Limestone is a sedimentary rock composed mainly of calcium carbonate ($CaCO_3$), usually as the mineral calcite. Limestone can be confused with dolomite - $CaMg(CO_3)_2$. Dolomite is similar to limestone in structure, hardness (3.5 to 4) and color. Field diagnostic: limestone reactions to hydrochloric while dolomite does not.

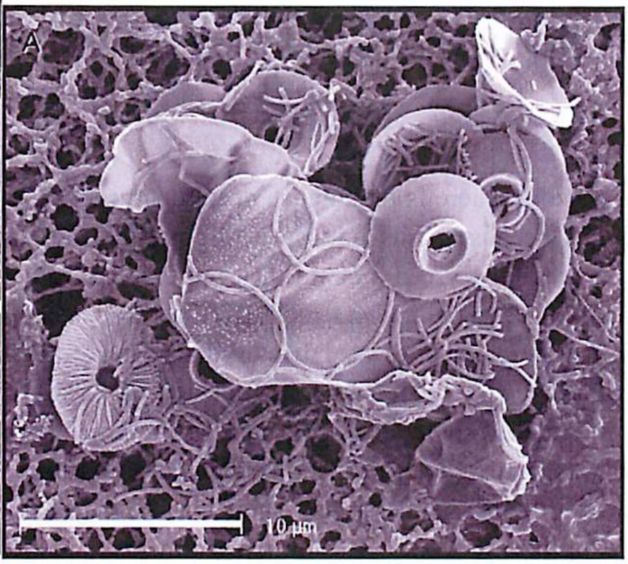
Limestone is the most common chemically precipitated sedimentary rock. It can be formed in one of two ways, by saturation of bicarbonate and by biological precipitation. The ocean is the primary place in which these rocks are formed.

Saturation - Carbonate sedimentation is based on the relative abundance of calcium and bicarbonate ions in seawater. Precipitation of $CaCO_3$ occurs when either the concentration of calcium or bicarbonate is above the saturation level, and seawater is usually fairly close to saturation. However, if conditions change, this carbonate can be dissolved again, usually as material is transported to greater depths in the ocean. The precipitated mineral can be either calcite (slow) or aragonite (fast). Over time, aragonite is usually turned into calcite.

$$Ca_2^+ + HCO_3^- \rightarrow CaCO_3 + H^+$$

Biological - Shelled organisms will extract calcium carbonate from the water to form their shells. When the die, the shells will form sediment on the sea floor. Colder waters will dissolve the shells due to their higher solubility, thus, in tropical seas there is the greatest sedimentation of calcium carbonate material. The biggest contributor to carbonate sediment is coral with many other organisms also contributing (foraminifera, ooids, and peloids, intraclasts and extraclasts).

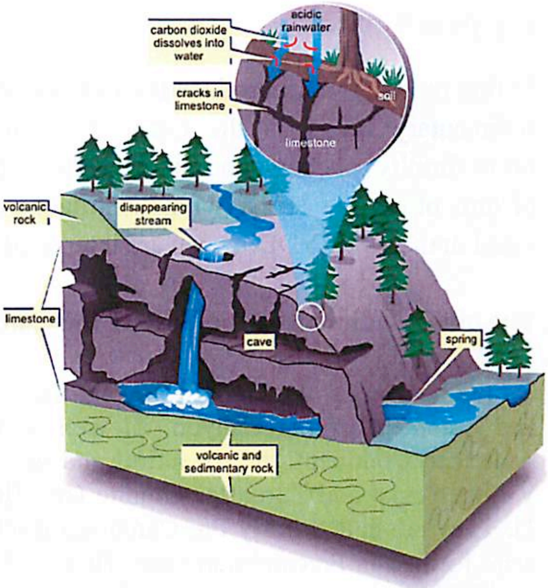




(left) Plain light micrographs of thin sections of ooids and pisoids. (a) Oolite of Mississippian age, southwestern Indiana. (b) Pisoids from the hot springs of Karlovy Vary (Carlsbad), Czech Republic.
(right) SEM images of shells of organisms that make up nannofossile oozes. *Ceratolithus cristatus* associations from the Canary Islands, Sample P233b-2.

Planetary Connection

- "Blueberries" on Mars bay be concretion of hematite (Fe_2O_3) from fluvial processes.
- Layered deposits on Mars (sand from aeolian, fluvial, impact).
- Meteorites (CM and CI) are aqueously altered and have formed calcite as a secondary process.
- Karst - suggested to have analog on Titan. Limestone is easily weathered by dissolution by carbonic acid, which is formed in the atmosphere from CO_2 gas. This acidic water will erode limestone forming underground rivers and caves. Thus, a karst topography may lack surface water because it is transported underground. This may be the liquid sink of titan



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C. Sprengela, J.R. Young . First direct documentation of associations of Ceratolithus cristatus ceratoliths, hoopcoccoliths and Neosphaera coccolithomorpha planoliths. Marine Micropaleontology 39 (2000) 39–41.
http://www.wikipedia.com

Fossil and Dating Sediment

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Overview:

Along the Colorado River of Arizona, there is the famous deeply carved Grand Canyon. It is frequently visited and studied by Geologist because of its intricate and colorful landscape. Throughout the long history, sediments and fossils naturally formed and are then preserved here very well to show us what happened in the remote past. Normally, the ancient rocks lay deeply beneath the surface of the earth. However, sediment rocks and fossils inside of the sedimentary layers here are exposed in the walls of the canyon because of the mountain formation movement long time ago which lift them up over thousands of feet together with the Colorado Plateau. There are almost 40 major sedimentary rock layers which can be observed by us now. By analyzing the sequence of the ancient rocks and the remains of animals, and plants and other organisms on the fossils, the researchers show that the major rock layers here are ranging from 2 billion years old to 230 million years old. Most of the sediments here are marine sediments which were deposited in seas and sea shores in the ancient western North America. Terrestrial sediments also exist here. The Great canyon formed during the tectonic movement. The clues are left on the very rocks. By dating and analyzing the fossils and sediments, we can somehow stitch together the geological history map piece by piece.

In this report, I will introduce the oldest and youngest sedimentary layers in the Grand Canyon, and the unconformity phenomenon here, while a detailed picture of all the layers with their dating history is listed in the APPENDIX if you are interested.

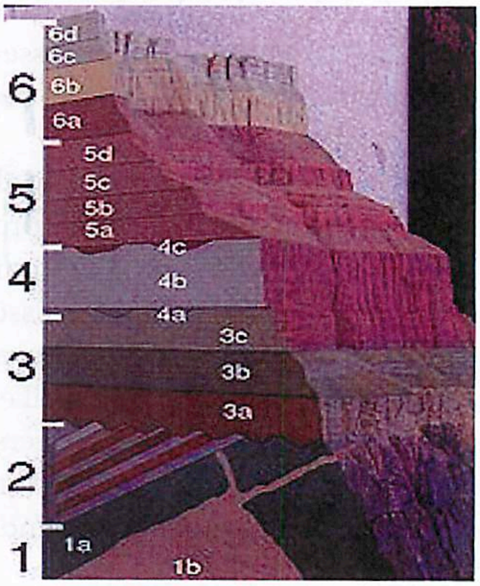


Figure1 A geologic cross section of the rock group of the Grand Canyon [1]

The oldest sediments---the Base of the Canyon

On the bottom of the Grand Canyon, there is the key and basement of the Canyon, as well as for North American Continent, the beautiful and twisted rocks, Vishnu Schist and Zoroaster Granite (see 1b in figure 1). They are called Early Pre-Cambrian Rocks as they were formed in Precambrian time. That is 1.75 billion to 1.73 billion years ago, nearly half the age of our earth mother. So, it is true they are the oldest rocks in the American Continent. However, 2 billion years ago, there were no plants or animals(So, no fossil exists in this layer.). But actually the earth was not silence but quite busy. The continent split, and the volcanic islands collided with the mainland. In the process, the rocks were pushed under the ground. They were melt, pressed, and re-cooked into these metamorphic rock. Evidence can be found on the surface of the grey and black rock even today. We can see the waves and belts as they were flowing in the old days. [1]

The mysteriously disappeared sediments---the Unconformity in the canyon

If looking upon the Early Pre-Cambrian Rocks, you will see some grayish color rocks. That is called bass formation with fossils consist of stromatolites in side of it (see the bottom of 2 in figure 1). They were around 1.25 billion years old. And they are the oldest sediment which contain fossils. So, here comes the question: *Where are the rocks whose age are ranging from 1.6 billion to 1.25 billion years old?*

Yes, we do lose around 400 million years of geologic history in the thick sequence of rocks here. This is called Pre-Cambrian Unconformity by geologists. There were very high mountains existed then. However, they were then completely removed by the power of the weathering and erosion. Mountains were changed into small hills, then plain and sands... Finally, there is no sedimentary layer left to represent a time.[1]

Figure2 Tonto Group is most easily seen as the broad Tonto Platform just above the Colorado River [1]

There is another great unconformity in the canyon. That is between the Chuar Group (see top of 2 in figure 1) from Late Pre-Cambrian Rocks and Tonto Group (see 3a in figure 1) from Paleozoic Strata. On the bottom of the Tonto Group(see figure 2), there are the Tapeats sandstones. They are dark brown and contain fossils of trilobites, brachiopods, and trilobite trails. The sediments formed during the Paleozoic era, around 545 million years ago. However, the layer below the Tapeats sandstones is called Sixty-mile Formation in Chuar Group. It is around 825 million years old. Another 400 million years of history is lost here. This is the major unconformity in the canyon.[2]

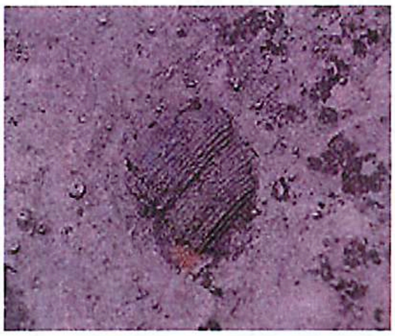


Figure3 Fossils, such as this brachiopod and fragments of crinoids, are common in the Toroweap and Kaibab formations [1]

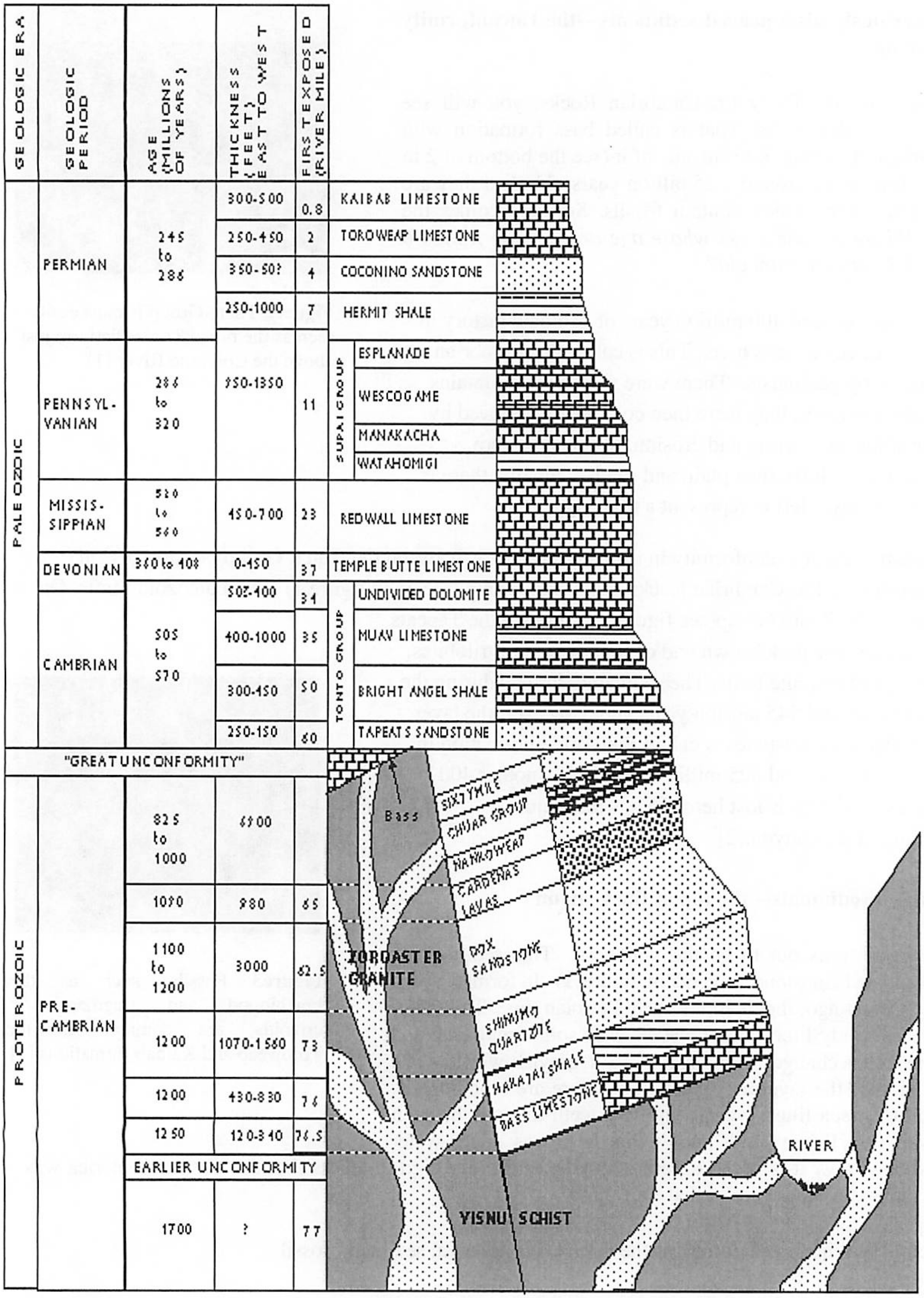
The youngest sediments---the top of the Canyon

The top layer turns out to be the youngest. This sedimentary layer is Kaibab Limestone (see 6d in figure 1). It formed about 270 million years ago, that is in the early Permian time. The major component is sandy limestone, together with some sandstone and shale. The color changes from cream to a greyish-white. The fossils in side of the layer are interesting. There are brachiopods, coral, mollusks, sea lilies, worms and fish teeth that can be seen on the wall (see figure 3). It shows that here was under water before although now it is in the desert. Actually, this is the sign to tell us that the western America was not even shown up off the sea at that time. [1]

Reference:[1]Wikipedia / Geology of the Grand Canyon area, sediment, fossil

[2] http://www.bobspixels.com/kaibab.org/geology/gc_layer.htm#rocks

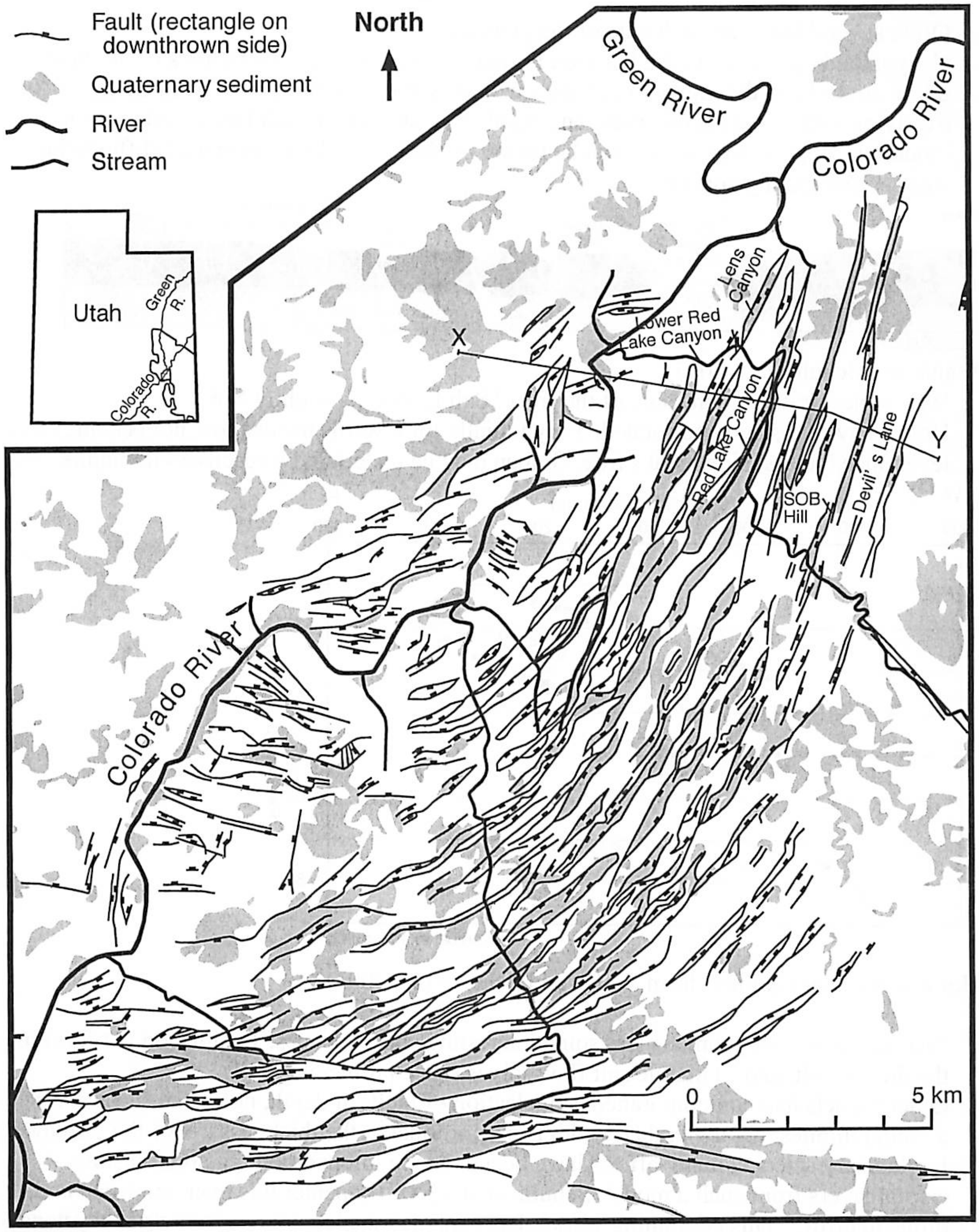
Appendix: The picture shows the sedimentary layer names and ages. [2]



GEOLOGIC ERA	GEOLOGIC PERIOD	AGE (MILLIONS OF YEARS)	THICKNESS (FEET) EAST TO WEST	FIRST EXPOSED (RIVER MILE)		
PALEOZOIC	PERMIAN	245 to 286	300-500	0.8	KAIBAB LIMESTONE	
			250-450	2	TOROWEAP LIMESTONE	
			350-50?	4	COCONINO SANDSTONE	
			250-1000	7	HERMIT SHALE	
	PENNSYL-VANIAN	286 to 320	950-1350	11	SUPAI GROUP	ESPLANADE WESCOGAME MANAKACHA WATAHOMIGI
	MISSIS-SIPPIAN	520 to 560	450-700	23	REDWALL LIMESTONE	
	DEVONIAN	360 to 408	0-450	37	TEMPLE BUTTE LIMESTONE	
	CAMBRIAN	505 to 570	50?-400	34	TONTO GROUP	UNDIVIDED DOLOMITE
			400-1000	35		MUAV LIMESTONE
			300-450	50		BRIGHT ANGEL SHALE
			250-150	60		TAPEATS SANDSTONE
"GREAT UNCONFORMITY"						
PROTEROZOIC	PRE-CAMBRIAN	825 to 1000	6900			
		1090	980	65		
		1100 to 1200	3000	62.5		
		1200	1070-1560	73		
		1200	430-830	76		
		1250	120-340	76.5		
		EARLIER UNCONFORMITY				
		1700	?	77		

Canyonlands grabens, and some planetary implications

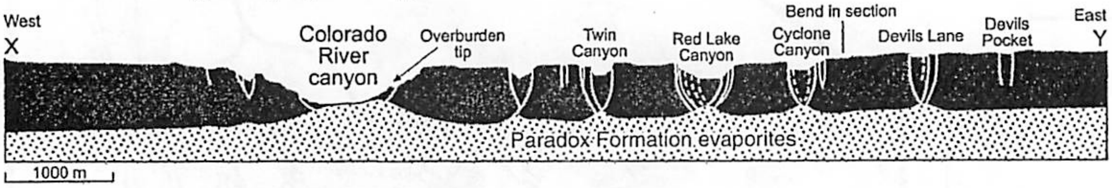
Colin Dundas



(Schultz-Ela and Walsh, 2002)

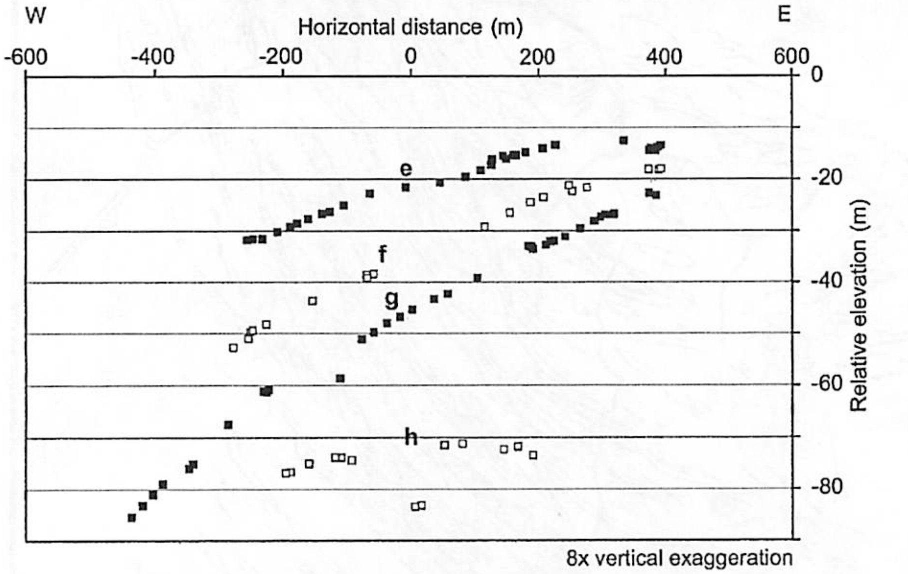
Key Points:

- Canyonlands grabens: arcuate system cutting ~460 m sequence of sedimentary rock.
- Graben widths up to 400 m, lengths up to 6 km, depths up to 100+ m. Graben walls are nearly vertical at the surface, but dip inwards below ~100 m depth. Deformation began 60-85 ka.
- Often several faults on each side of the grabens.
- Canyonlands grabens overlie Paradox Formation evaporites (~300 m thick). Old theories of the controls on the graben mechanics include salt dissolution, movement of the overlying rocks on a decollement, and basal shear stress from salt flow, while recent modeling supports a model in which erosion by the Colorado River caused differential stresses and gravity spreading.



(Walsh and Schultz-Ela, 2003)

- Why concentrated on one side of the river? Salt layer dips slightly NW.
- Horsts have subsided and rotated. They initially tilt towards the canyon, but become more level once the east side breaks free. Graben may be underlain by reactive salt diapirs.



(Horst surface topography: from Walsh and Schultz-Ela, 2003)

- The rock-over-salt geometry has some interesting consequences: 1) faults do not form in the ductile salt, and 2) ductile salt flow solves space problems.
- Older models had contemporaneous nucleation of faults at depth, not at the surface. Such a model implies that the graben width is proportional to the thickness above the salt layer.
- In planetary science, many efforts have been made to infer something about distinct crustal layers from such a model. Schultz et al. (2007) consider this oversimplified and prone to error: "This continuing work…has exploded the legend of symmetric, keystone-

collapse grabens in Canyonlands."

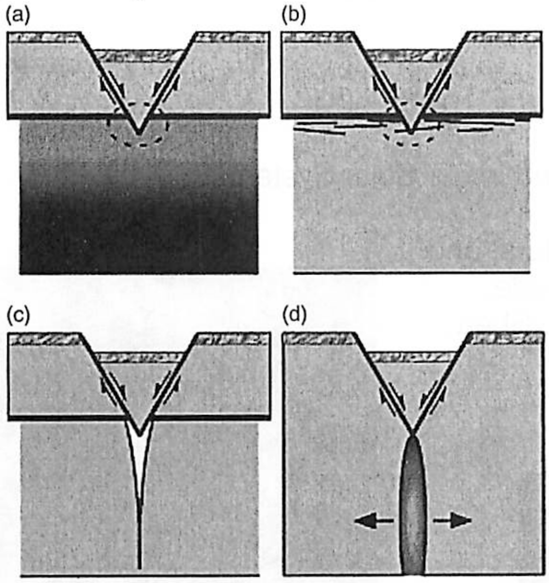


Figure 15.1. Previously proposed hypotheses for extrapolating planetary grabens to depth (after Tanaka *et al.* [1991]). (a) Faulting at bimaterial interface (e.g., brittle over quasiplastic rheology, megaregolith over basalt, dessicated ground over icy ground), (b) Faulted upper layer separated by sills or detachment zones from undeformed substrate, (c) Graben wedge falling into space-accommodating tensile crack in substrate, (d) Graben faults nucleated by dike dilation at depth. Dashed circles in (a) and (b) indicate areas of kinematic incompatibility; extension in (d) due to dike is subequal to that accommodated by superjacent graben. All these ideas imply a thin-skinned upper faulted layer that is uncoupled from subjacent strata.

(Schultz et al., 2007)

- Canyonlands grabens are instead asymmetric, with distinct master and antithetic faults.

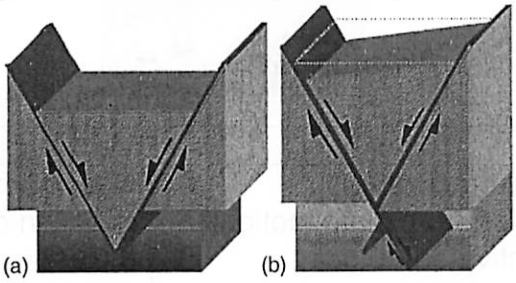


Figure 15.4. Comparison of symmetric "simple" graben (a) with asymmetric graben (b). Note variable offset along graben-bounding normal fault in (b). (Schultz et al., 2007)

- "Hourglass" model is better than classic models, and casts doubt on many planetary science papers that attempt to infer subsurface interface depths from graben widths.

References

[1] Grosfils et al., 2003. Journal of Structural Geology 25, 455-467. [2] Schultz et al., 2007. In: The Geology of Mars: Evidence from Earth-Based Analogs (ed.: Mary Chapman), 371-399. [3] Schultz-Ela and Walsh, 2002. Journal of Structural Geology 24, 247-275. [4] Walsh and Schultz-Ela, 2003. GSA Bulletin 115, 259-270. [2] includes many older references for those interested.

Graben/extensional tectonics in the Solar System

Youngmin JeongAhn

Normal faults and graben found in our Solar System :

Mercury, Venus, the Moon, Mars, and icy satellites (Europa, Ganymede, Miranda, Ariel, Dione, Tethys, Rhea, and Titania).

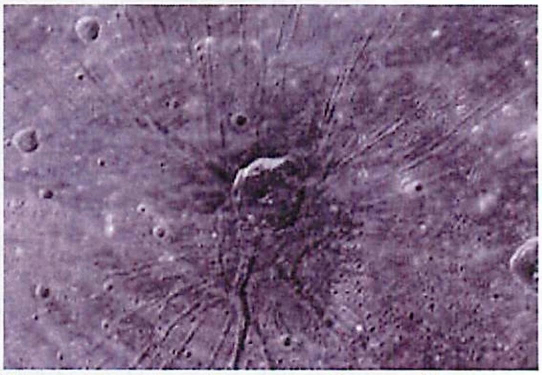


Figure 1 Pantheon Fossae on Mercury from volcanic activity or rebounded surface after impacts

Figure 2 Rima Ariadaeus on the Moon

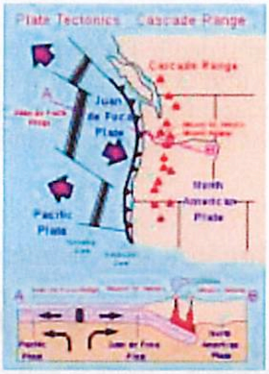


Figure 3 Juan de Fuca Ridge

Planet	Earth	Venus	Mars
Origin	Lithosphere-activated <- extension from plate motion Mantle-activated <- doming above magma plume	Near-horizontal injection of magma in dykes	
Size of dyke-induced graben	~ km wide, less than 1 m deep. Juan de Fuca Ridge – 10-100 m wide, 15 m deep	1-2 km wide, 10's of m deep	1-5 km wide, 10's-100's of m deep

Narrow dyke to the surface -> big horizontal extension

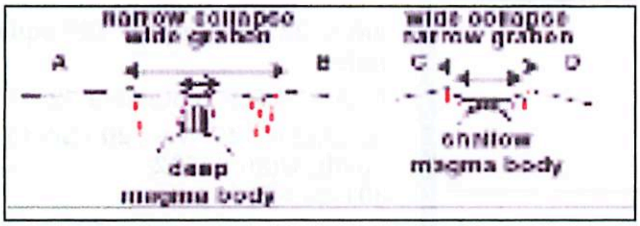


Figure 4 The effect of the depth of magma body

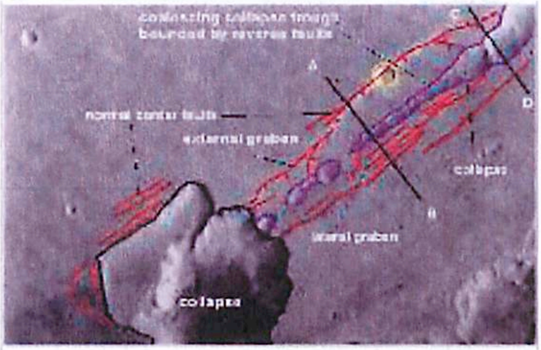


Figure 5 Noctis Labyrinthus on Mars

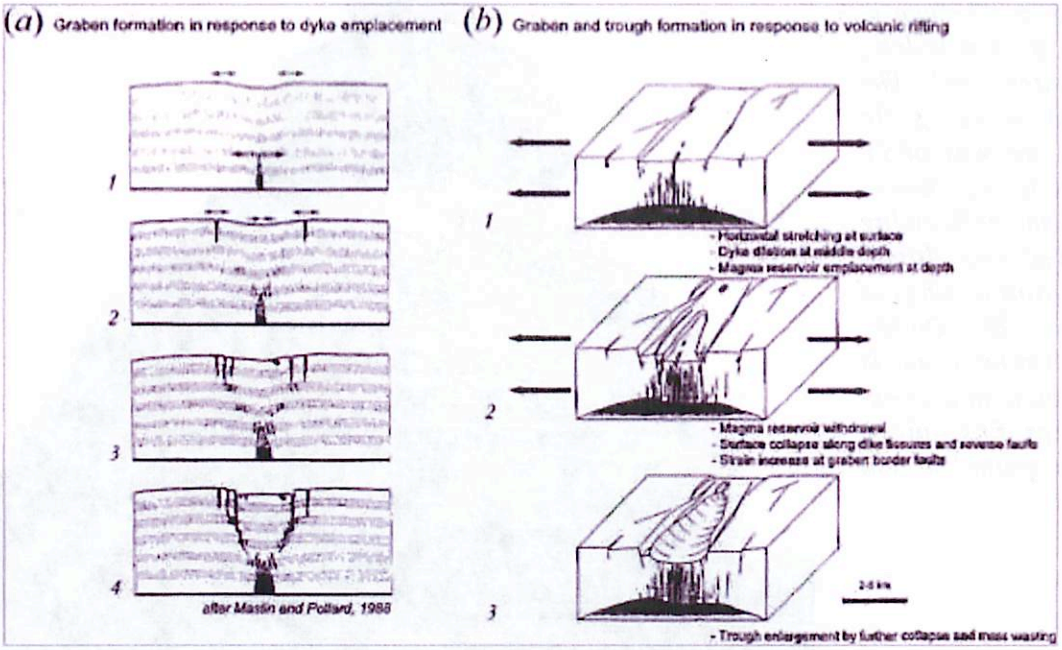


Figure 6 Mechanism of graben formation

References

Aspler, L. B., and Ernst, R. E. (2003) LPSC XXXIV, #1711.
Ernst, R. E. et al. (2001) AREPS, vol. 29, pp. 489-534.
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Chapter 5

Canyonlands National Park

Southeast Utah

AREA: **337,570 acres; 559 square miles**

ESTABLISHED: **September 12, 1964**

ADDRESS: **125 West 200 South,**
Moab, Utah 84532
801-259-7164

Utah's largest national park is a geological wonderland of spires and mesas rising to more than 7800 feet. A large triangular plateau, called Island in the Sky, stands high above the confluence of the Green and Colorado Rivers. The two rivers come together through deep, sheer-walled, meandering canyons; below their confluence is Cataract Canyon, a 14-mile-long stretch of white-water rapids. The Maze, an almost inaccessible jumble of canyons, lies west of the rivers; beyond are the red towers and walls of the Land of Standing Rocks. An eroded salt dome, Upheaval Dome, exposes rings of colorful Mesozoic rocks. On the Colorado River's southeast side is the Needles district, a natural exhibit area of arches, fins, spires, grabens, canyons, potholes, and Indian ruins.

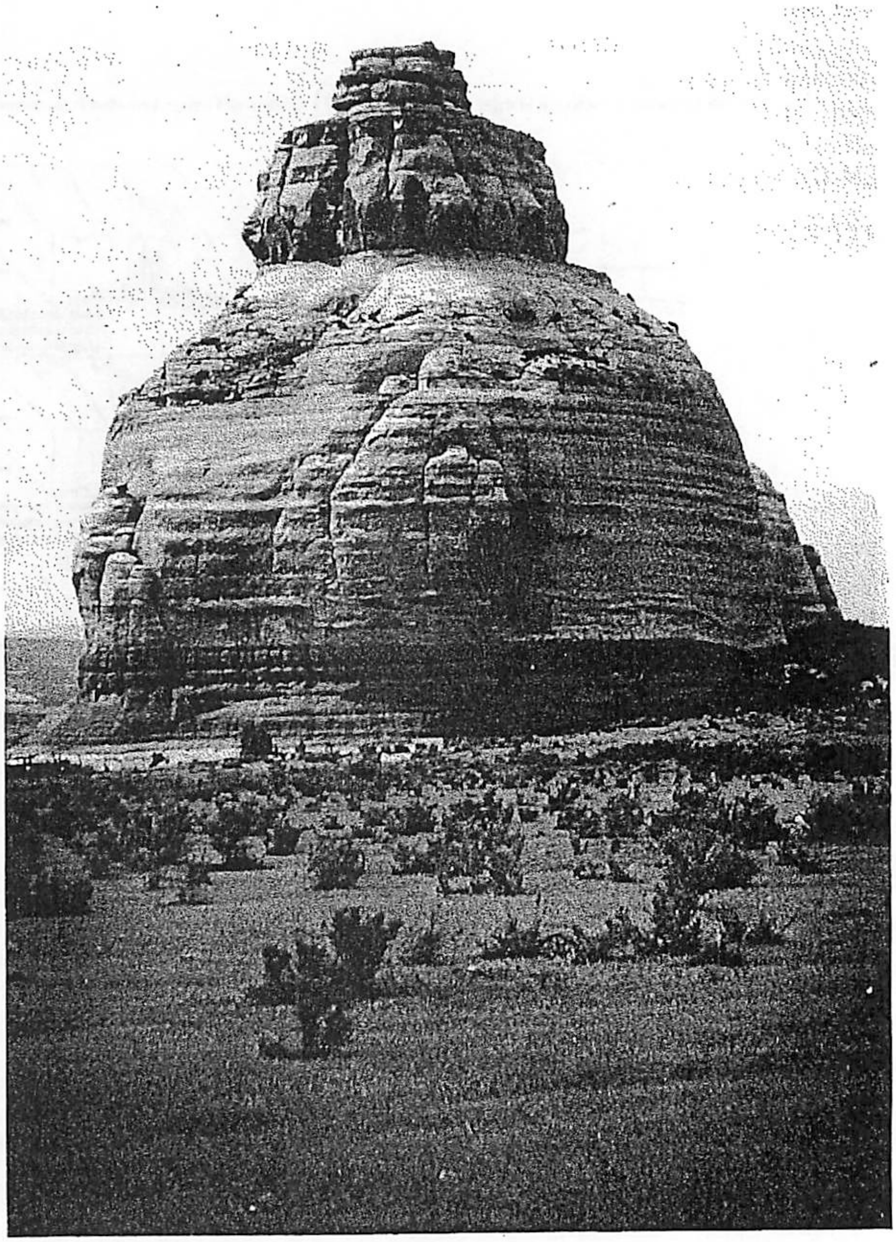

Figure 5.1 Church Rock, beside the entrance road to the Needles section of Canyonlands National Park. This huge sandstone monolith looks as though it had been "turned on a lathe." Photo by J.W. Kusiak.

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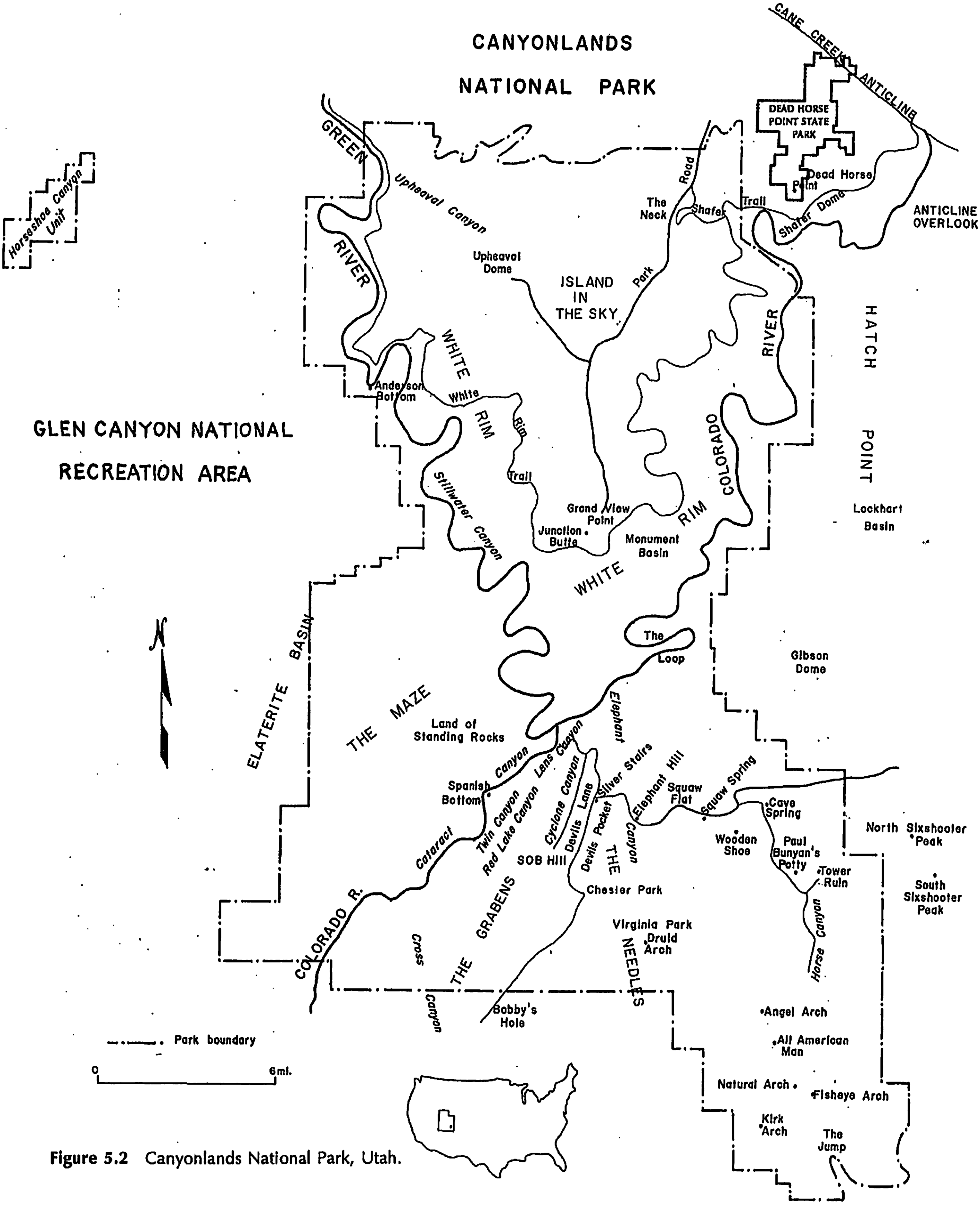

Figure 5.2 Canyonlands National Park, Utah.

Canyonlands National Park is a wild and primitive desert region between Capitol Reef and Arches National Parks in the heart of the Colorado Plateaus. The Green and Colorado Rivers, which join in the park, and much of the surrounding wilderness are little changed from when Major John W. Powell first explored the canyons in 1869. He entered what is now the park from the north, through the Green River's Labyrinth Canyon. He described the landscape between Labyrinth Canyon and the confluence of the Green and Colorado Rivers as

> "... naked rock with giant forms carved on it, cathedral-shaped buttes towering thousands of feet, cliffs that cannot be scaled, and canyon walls that make the river shrink into significance, with vast hollow domes, tall pinnacles, and shafts set on the verge overhead, and all the rocks, tinted with buff, gray, red, brown, and chocolate, never lichened, never moss-covered, but bare, and sometimes even polished." (Powell 1981 reprint)

After resting several days at the confluence in order to dry out gear and provisions, the intrepid explorers started out again through a stretch of white water that Powell named "Cataract Canyon," because of "bad rapids in close succession." (In parts of the canyon, huge blocks of rock that have fallen from the cliffs impede the water, producing turbulence.) One of Powell's boats swamped, three oars were lost, and all the boats were damaged and leaked badly from banging against rocks. After a narrow escape from being trapped in the gorge near the foot of Cataract Canyon by a flash flood, the party emerged safely in an open area of the river beside deserted Indian dwellings.

Being as interested in archaeology as geology, Powell carefully described the ruins, flint chips, arrowheads, broken pottery, and what he called "etchings" (pictographs) on the cliffs. He was excited to find stairsteps cut into a cliff leading up to a watchtower. "I stood," he wrote, "where a lost

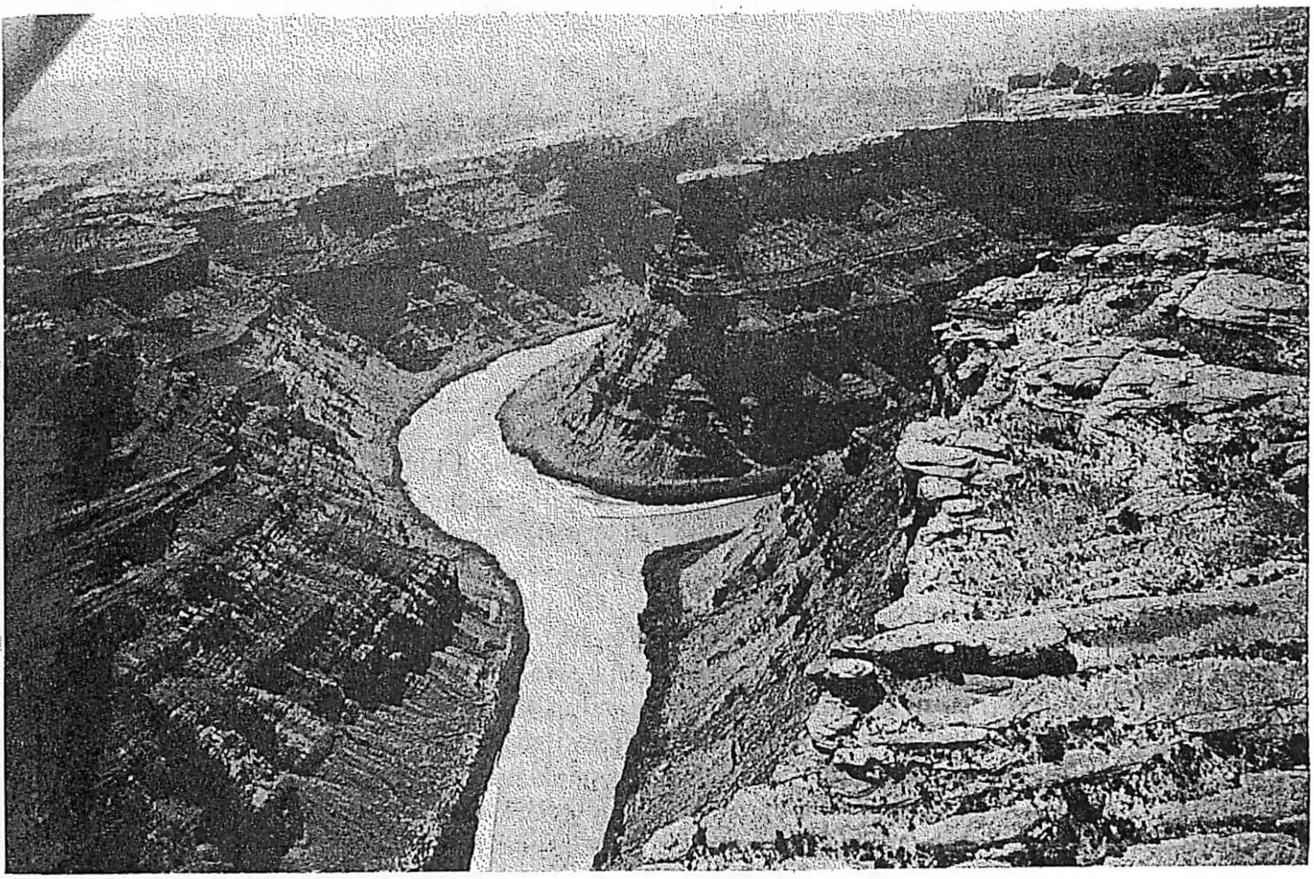

Figure 5.3 The confluence of the Colorado and Green Rivers, where Major Powell and his men camped in 1869. In this view, looking downstream (south), the Green River comes in from the right. The mesa top in the right foreground is the south end of Island in the Sky. Photo by M. Agnew.

people had lived centuries ago, and looked over the same strange country."

Powell's "lost people" may have been Indians of the Fremont Culture, who lived in this area until A.D. 900. Or they could have been a later group, the Anasazis, who arrived around A.D. 1075 and left during the twelfth century. The pictographs and camp sites of these early people can be seen in numerous places in the park. The Indians made pictures on the rock by scratching through the coating of desert varnish to the lighter-colored, unweathered rock beneath. *Desert varnish* is a thin dark film of iron and manganese oxides that forms on the surface of rocks.

Since this is desert country (only 5 to 9 inches of precipitation per year), water is precious and water holes are few and far between. Settlers were not attracted to the region, but in the late 1800s and early 1900s, cowboys and sheepherders passed through the area from time to time. Butch Cassidy and his "Wild Bunch" knew the region well and used their knowledge to evade posses of lawmen. The area was ideal for outlaws and cattle rustlers who knew the location of water holes and could come and go without getting lost in the jumble of canyons, cliffs, and rough terrain.

Canyonlands National Park was established in 1964 in order to preserve its outstanding scenic, scientific, and archeological resources. As the Colorado River leaves Cataract Canyon and crosses the park's southern boundary, the river flows into the head of Lake Powell at the northern end of Glen Canyon National Recreational Area. A strip of Glen Canyon National Recreational Area also extends along the western boundary of Canyonlands National Park (fig. 5.2).

Geologic Features

Island in the Sky

Island in the Sky is the best observation tower from which to gain perspective on the geological processes that have created the "architecture" of Canyonlands. This broad, level, roughly triangular mesa is wedged between the Green and Colorado Rivers and stands over 2000 feet above the two streams that come together at the foot of the mesa point. Views from the overlooks encompass canyon after canyon, stretching off to mountains ringing the horizon a hundred miles distant. Within the park, the Maze is to the west and the Needles is to the south. Closer to the mesa edge, about 1200 feet down, is the White Rim Sandstone bench, the habitat of desert bighorn sheep. The rivers are another 1000 feet down (fig. 5.3).

Red sandstones are the dominant rock of the Canyonlands landscape; but a rich variety of sedimentary rocks in hues ranging from near-white through orange, brown, or near-black provides contrast and diversity to individual landforms, as well as the overall panorama. The sandstones consist mainly of uniformly sized, clear quartz grains. The red rocks are cemented with iron oxide, which gives them their color. During and after the uplifting of these sedimentary rocks, differential weathering along joints and erosion by wind and water dissected the flat layers into hundreds of brightly colored canyons, mesas, buttes, fins, arches, and spires, and thousands of smaller features.

Upheaval Dome

Upheaval Dome, located in the northwest corner of Island in the Sky, is a circular feature about three miles across. From the air it looks like a bull's-eye (fig. 5.4). The view from the top of Whale Rock (elevation 5820 feet), a smooth, whale-shaped monolith of Navajo Sandstone, gives an idea of Upheaval Dome's enormous size. From the Wingate Sandstone rim (5700 feet), you can look down into Upheaval Dome's core more than 1000 feet below. Concentric rings of sedimentary beds are exposed between the core and the rim. The more resistant layers jut up in ridges and the less resistant layers form valleys. Upheaval Canyon breaches the western wall and provides a flume for runoff to carry away erosional debris. The canyon drains to the Green River five miles downslope (fig. 5.5 A,B).

Geophysical studies indicate that a *salt dome* forcing its way through sedimentary beds pushed up Upheaval Dome. The salt is from the Paradox Formation (a unit of the Hermosa Group) that was deposited during the Pennsylvanian Period. The Paradox salt beds evaporated from the brine of a landlocked ancient sea, trapped by a rising mountain block (the Uncompahgre Uplift). In this particular location, a rise in the granite floor deep below the sea bottom caused a slight thinning of salt layers above the crest, creating a weak zone.

Figure 5.4 Upheaval Dome, in the northwest part of Canyonlands National Park, was formed by the intrusion and subsequent collapse of a salt dome. The feature is three miles across and almost 1600 feet deep. National Park Service photo.

Eventually, many feet of sediment washed down from highlands, filled the basin, and covered the salt beds. The pressure of about a mile of sediment weighing down the salt caused it to become *plastic* (i.e., able to flow without rupture). Salt flowing upward over the hump as a huge plug (not unlike toothpaste oozing from a tube) arched the overlying beds into a dome, or circular anticline. As the beds were pushed up almost 1000 feet and turned almost on edge, they became cracked and severely deformed. This made them more susceptible to weathering and erosion and the top beds were stripped off. Since the beds exposed in the center of Upheaval Dome are softer than those forming the rims, the less resistant rock eroded more rapidly, creating the depression that resembles an open-pit mine.

The Maze, the Land of Standing Rocks, and the Fins

West of the Colorado and Green Rivers is the Maze, the wildest section of Canyonlands, described in the park brochure as a "30-square-mile puzzle in sandstone." Outstanding examples of prehistoric rock art are hidden in some of the deepest canyons. Beyond the jumbled canyons of the Maze is the Land of Standing Rocks, where weirdly shaped pinnacles, buttes, and mesas display sandstone layers.

The Fins are narrow sandstone ridges, or walls, that are eroding along parallel joints. Cracks between closely spaced vertical joints become enlarged by chemical and physical weathering as water seeps down, dissolving iron oxide cement and loosening sand grains. Frost action, with its alternate freezing, expanding, and thawing, also breaks

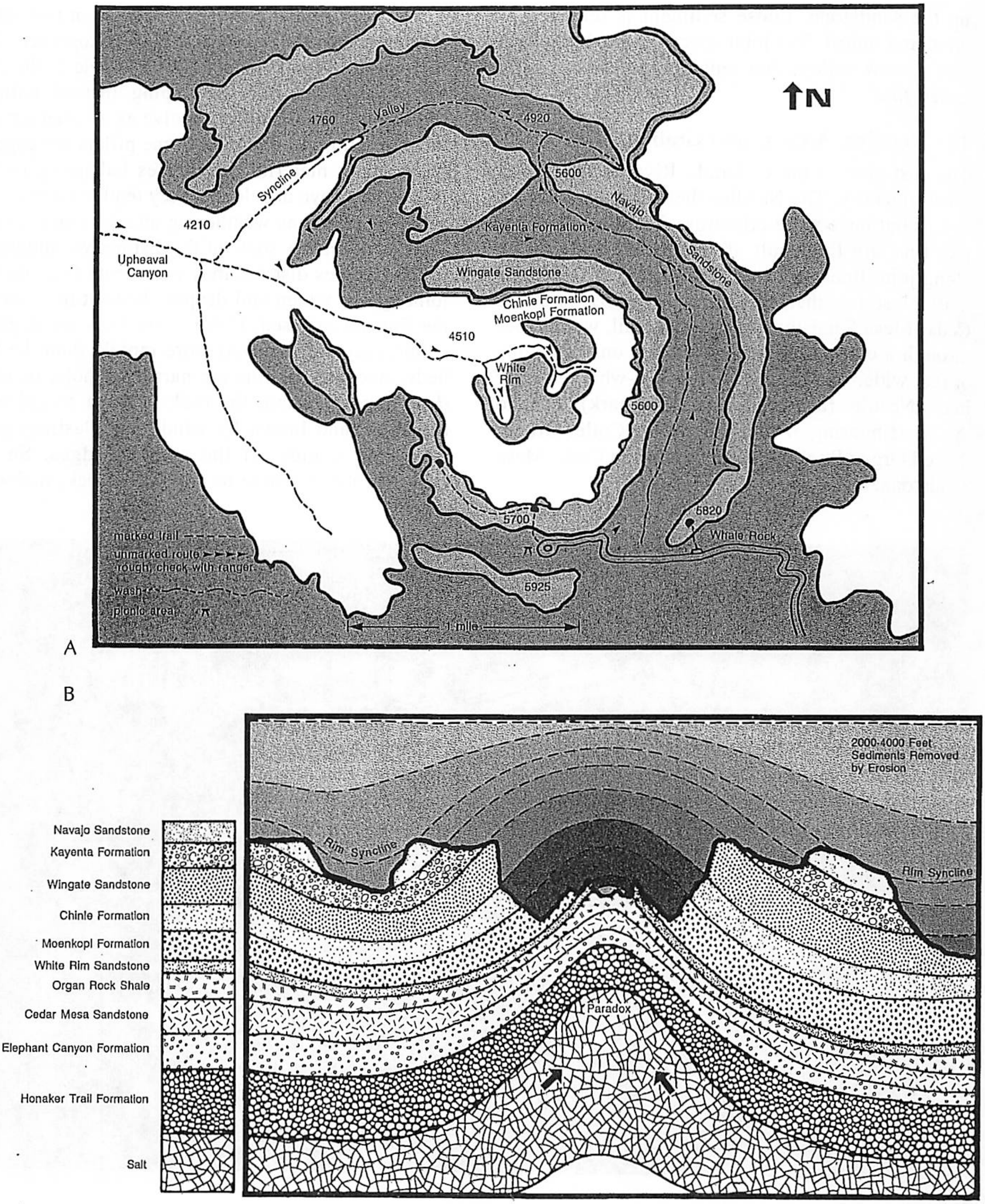

Figure 5.5 *A*. Upheaval Dome in map view. The topography is directly related to the rock formations, with the more resistant formations, such as the Wingate Sandstone. forming concentric walls. *B*. Cross section of Upheaval Dome, showing the salt dome at the core and the sedimentary layers that were arched up by pressure of the rising salt plug. Adapted from 1981 "Upheaval Dome." National Park Service and Canyonlands Natural History Association.

up the sandstone. Loose sediment is removed by wind and runoff. The joint spaces gradually enlarge into narrow valleys that separate the narrow walls, called *fins.*

The Needles, Arches, and Grabens

The east side of the Colorado River is an area of great diversity. The Needles themselves are similar to fins but have more crisscross fractures. Needles, like fins, are the result of weathering and erosion along joint lines and fault lines, some of which are quite close together, a feature characteristic of the Cedar Mesa Sandstone. The Joint Trail, which goes through a crack in this formation, is only a couple of feet wide. The distinctive red-and-white banding in the Needles (and elsewhere in the park) is due to the interfingering of two units of the Cutler Group: the red Organ Rock Shale and the white Cedar Mesa Sandstone.

The *needles* and *pillars* develop when two intersecting joint sets are spaced closely together. The second set of joints, which is at an angle to the first set, prevents fins from developing. Instead, pointed needles or rounded pillars evolve as weathering and erosion sculpture the rock. Some pillars are capped by resistant material that makes balancing rocks. Where fins have developed, they tend to evolve into a line of pillars as weathering attacks cross joints.

Natural arches, some of the distinctive landmarks in the Needles district, may form from fins. As the joint spaces widen and deepen, beds at the base of the fins are exposed. If the lower beds are slightly softer, they are removed more rapidly than the top beds. Because the fins are narrow, a hole, or *window,* appears where the rock is worn completely through. Sand blown by wind (sandblasting) polishes and rounds off the window edges. Snow, rain, and ice continue to attack the rock, dislodge

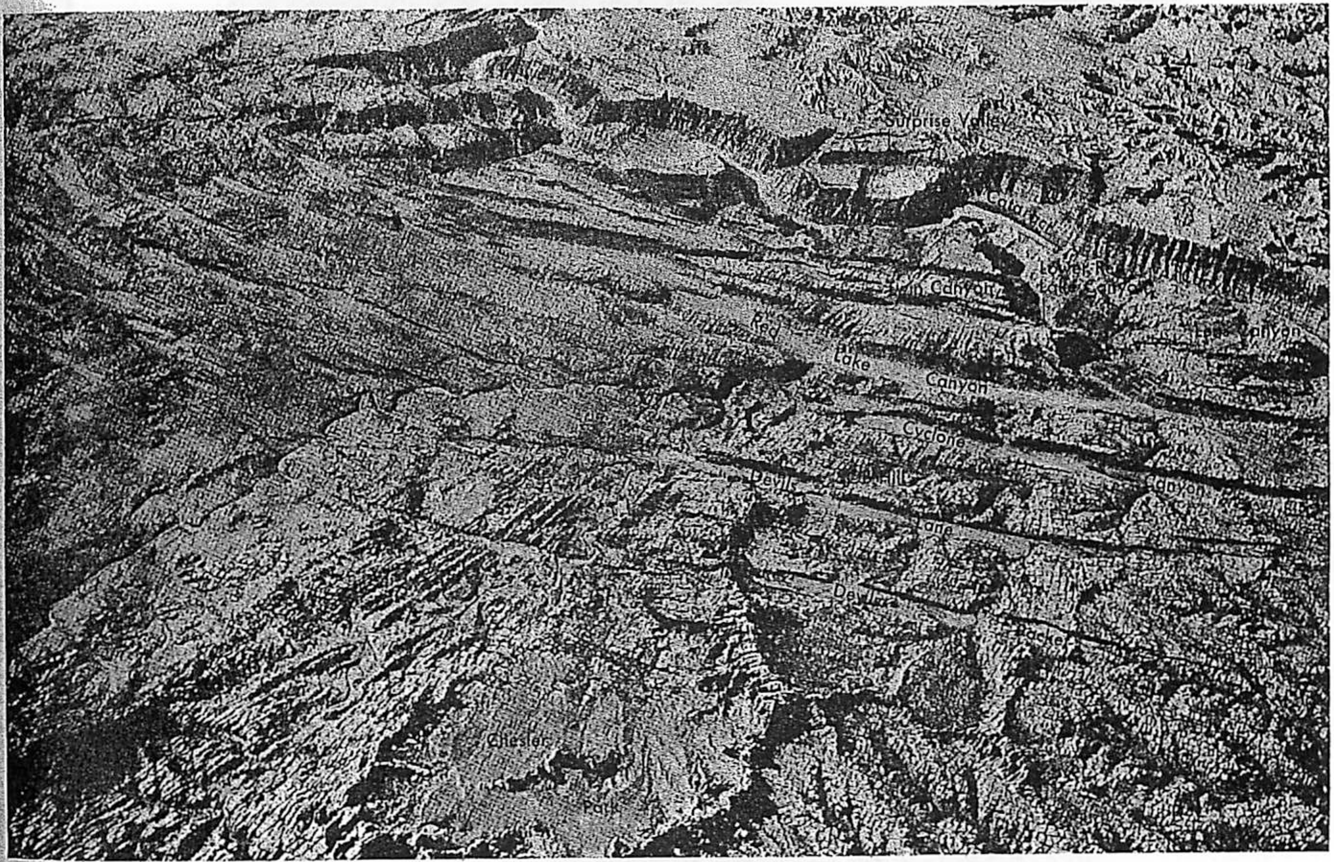

Figure 5.6 Needles and Grabens section, south central part of Canyonlands National Park, east of the Colorado River. Chesler Park (foreground) is a natural meadow, walled in by the Needles (left) and the Grabens, the parallel troughs beyond Chesler Park that run from left to right across the picture. Geologic structure controls the location and patterns of the canyons, mesas, and other erosional features. National Park Service photo.

fragments, and cause rockfalls (a process of mass wasting) until a window is enlarged to form a natural arch.

Because of their composition, type of cement, and structure, certain rock formations have a tendency to form arches. Canyonlands has 25 arches, mostly sculpted in Permian Cutler Group sandstones, which are more likely to form standing rocks than arches. In nearby Arches National Park (chapter 6), more than 300 arches have developed in Jurassic Entrada Sandstone.

"Potholes" form in Cedar Mesa Sandstone because the calcium carbonate that cements its sand grains is soluble in natural carbonic acid (carbon dioxide plus water). Carbonic acid attacks any weak spot or zone in the sandstone. Loosened sand grains fall, are washed, or blown away. Once a slight depression is started, more and more of the sandstone is exposed to the processes of weathering and: erosion. Potholes, caves, and sometimes arches develop in this way. Paul Bunyan's Potty is a well known example.

The name Chesler Park was given to an expanse of a thousand acres of flat, grassy land surrounded by pinnacles of the Cedar Mesa Sandstone. Chesler Park is east of the Grabens.

The Grabens is an area of elongate collapse troughs parallel to Cataract Canyon. As was the case in Upheaval Dome, the underlying salt deposits of the Paradox Formation acted as an unstable platform for the millions of tons of overlying shales and sandstones. Great thicknesses of salt accumulated in subsiding, elongate, valleys parallel to the rising, ranges of the Uncompahgre Uplift. As the weight of sedimentary overburden (washed down from the mountains) became ever greater, the salt flowed as a plastic mass toward the southwest, away from the source and greatest weight of sediment. When the flowing salt came against the ridges, it was deflected upward, forming salt walls and plugs that penetrated the overlying beds. In this way, the salt took the path of least resistance to reach areas where the pressure of overburden was lower.

When the Colorado Plateaus region was uplifted millions of years later, enough of the sedimentary cover was stripped off so that ground water seeped into the salt, dissolving some of the upper parts and causing the overlying sandstones and shales to collapse into the salt-valley grabens.

The Rivers

The Colorado River flows south through Canyonlands in a spectacular, deep, narrow-walled gorge. The Colorado is joined in the park by its largest tributary, the Green River, which also has a deep, narrow canyon (fig. 5.3). Together they flow quietly for about three miles until they enter Cataract Canyon at Spanish Bottom. The turbulent water in Cataract Canyon, which rushes through at a rate of around 40 million gallons per minute, is constantly boiling up as "white water" because of changes in the bedrock of the stream channel, slumping of the lower beds in canyon walls, and blocks of rock falling from the cliffs into the stream.

The Colorado River appears to follow a course through Cataract Canyon along the edge of the block-faulted area. The large faults on the east wall of the canyon do not appear on the western wall—nor do the intricate fracture patterns in the rocks on the southeast side of the Colorado, such as the lines of needles and their intervening, north-south, "racetrack" valleys, cross the river. Presumably, the path of salt-dissolving ground water terminates where it is diverted into the Colorado River drainage.

Both the Green River and the Colorado River have abrasive bedloads, a significant factor in their ability to cut down their channels to form *incised meanders* (fig. 5.7). These two rivers may have meandered back and forth on a fairly low, flat surface in the geologic past, and may have retained their meandering pattern as the region was raised. However, some geologists believe that during uplift, as base level was lowered, the streams began downcutting their flood plains so rapidly by headward erosion that they could do very little lateral eroding. In soft alluvial sediments, meanders migrate over a flood plain, but when meanders are trenched into resistant rock layers, as in Canyonlands, the meandering pattern becomes "trapped." The stream's energy, supplied by increased velocity, cuts its channel ever deeper but cannot widen it unless it encounters a zone of weak or easily erodible bedrock, as at Spanish Bottom, where gypsum beds have been eroded.

The water in the Green and Colorado Rivers is not potable because of the saline ground water that seeps into the rivers from the salt beds. People and animals in the park use water in potholes or rock depressions in the White Rim Sandstone and Cedar

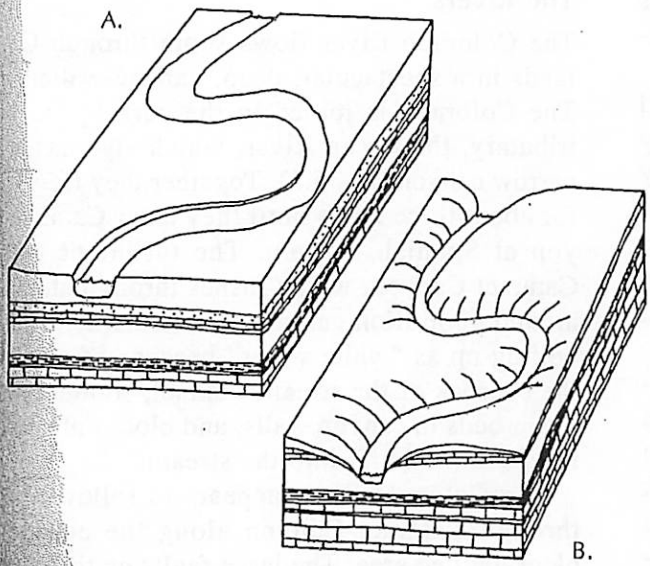

Figure 5.7 During and after regional uplift, a major stream that has developed meanders on a flood plain (A), may downcut its channel progressively lower, forming incised meanders (B).

Mesa Sandstone or depend on spring water that seeps from canyon walls along contacts between the Organ Rock Shale and the White Rim Sandstone. The hollows where water collects—locally referred to as "tanks" or "charcos"—are formed by the combined process of solution of calcium carbonate cement and removal of loose rock grains by wind (deflation). Tanks are found by Junction Butte near Grand View Point in the central portion of the park and also in the Needles district near Chesler Park.

Geologic History

1. **The development in Pennsylvanian time of the Paradox Basin and the Uncompahgre Uplift.**

The oldest rocks exposed in Canyonlands National Park are beds of the Paradox Formation of Pennsylvanian age in the bottom of Cataract Canyon. These exposures are of rock gypsum and interbedded black shale that are less soluble than the halite salt beds underneath Upheaval Dome and the Needles section. A gypsum plug, similar to a salt plug but more resistant, has been exposed by erosion at the mouth of Lower Red Lake Canyon, near the head of Cataract Canyon. The plug was pushed up into the overlying Honaker Trail Formation, the uppermost unit deposited in Pennsylvanian time. Both formations are units of the Hermosa Group.

The thousands of feet of evaporites that make up the Paradox Formation began to accumulate in Middle Pennsylvanian time when block-faulting caused the Paradox Basin to subside and the Uncompahgre ranges to be uplifted.

Water from a shallow sea that had covered the area early in the Pennsylvanian Period became landlocked in the sinking basin, and a system of interior drainage developed as mountains rose along the margin. In the *closed basin,* water escaped only by evaporation; and since the climate was hot and dry, water evaporated rapidly, concentrating salts and mineral matter in shallow lagoons.

When the salinity of a brine reaches a ratio of 10 parts salt per 1000 parts water (3 times the ratio of salt in seawater), the minerals anhydrite and gypsum begin to precipitate as crystals. If evaporation continues and no water is added to dilute the brine, the ratio of salt to water may reach 35 parts per 1000 parts water, or 10 times that of normal seawater. Under these conditions, halite (rock salt) precipitates. The heavier salt crystals tend to sink, accumulating over the bottom of the lagoon. This was what happened in the Paradox Basin.

From time to time, storms washed sediment down from the mountains. The coarser gravels accumulated in wedges along the base of the range, and the silts and muds spread over the salt flats. Occasionally fresh seawater breached the lagoons and moved into the basin over a shallow threshold in the margin. The salty brines were not flushed out because the fresh seawater acted as a barrier that prevented the escape of the dense bottom water. Thin black shale layers between some salt beds mark these incursions of seawater. For thousands of years, the layers of salt and clastic sediment accumulated, becoming ever thicker—up to 5000 feet in some places. The gypsum layers in the bottom of Cataract Canyon represent the last phases of the evaporite deposits.

Presumably, the weight of the accumulating overburden caused the salt beds to begin flowing plastically before the close of the Pennsylvanian Period, and this process continued

Table 5.1 Geologic Column, Canyonlands National Park

Time Units		Rock Units		Geologic Events
Era	Period	Group	Formation	
Cenozoic	Quaternary Tertiary	Alluvium Dune sand Landslide deposits		Arches and needles formed Entrenching of Green and Colorado Rivers Continuing uplift and block-faulting Forming of salt valleys by solution and collapse
Mesozoic	Cretaceous			Uplift and warping due to compression during Laramide orogeny Erosion
	Jurassic	San Rafael	Entrada Sandstone	Scattered patches exposed in park vicinity
			Carmel	Erosion
	? Triassic	Glen Canyon	Navajo Sandstone	Cross-bedded, white sands deposited by migrating dunes; forms cliffs, knobs, hummocks
			Kayenta	Deposited on flood plains and in lakes; slope-former
			Wingate Sandstone	Cross-bedded sands deposited by migrating dunes; forms red rimrock
			Chinle	Bright-colored shales; slope-former; contains petrified wood Erosion
			Moenkopi	Tidal flat deposits; shales with ripple marks, mud cracks Erosion
Paleozoic	Permian	Cutler	White Rim Sandstone Organ Rock Shale Cedar Mesa Sandstone Elephant Canyon Halgaito Shale	White, cross-bedded sandstone deposited in coastal dunes Reddish brown siltstones, sandy shales and sandstones deposited on oscillating shoreline and interfingered with deposits on beach dunes, in sand bars, and in arkosic alluvial fans. (Because formations thin and facies change from west to east, rocks are mapped as "Undivided Cutler" along the eastern margin.) Erosion
	Pennsylvanian	Hermosa	Honaker Trail	Shallow marine deposits
			Paradox	Gypsum and salt evaporites interbedded with shale and black limestone

Huntoon, Billingsley, and Breed, 1982

throughout the Permian and well into Mesozoic time. The migration of the salt beds had probably stopped by the end of the Jurassic Period.

Toward the end of Pennsylvanian time, a warm tropical sea spread over the region. About 1500 feet of fossiliferous limestones, shales, and sandstones blanketed the salt basin. These are the gray beds of the Honaker Trail Formation that crop out at lower elevations in the deep canyons of the park, especially along the Colorado River.

2. Permian deposition of the extensive, varied formations of the Cutler Group.

In some places the red, terrestrial Permian beds lie unconformably over gray, marine Pennsylvanian beds; but elsewhere the transition is more gradual. Early in Permian time, advancing seas deposited the Halgaito Shale, which grades into the Elephant Canyon Formation, a rock unit deposited in coastal lowlands. In Canyonlands, beds of these formations are exposed in Cataract Canyon, Elephant Canyon, and upriver from the confluence.

All during this time the Uncompahgre Mountains to the east were being severely eroded. Streams stripped sediment off the slopes and dropped it on enlarging alluvial fans that filled the basin at the foot of the range. The material in the fans lithified to iron-rich, red, arkose sandstones that are mapped as "undivided" rock units of the Cutler Group.

Interfingering with Cutler red beds are white Cedar Mesa Sandstone beds that were deposited in submarine bars and coastal dunes. The zone of facies change between these continental and marine rock units occurs as a 4- to 5-mile-wide belt across Canyonlands National Park from south of the Needles through the Maze and into the Elaterite Basin along the park's western boundary. Many of Canyonlands' most dramatic and colorful rock sculptures are in this zone where the two types of sedimentation shifted back and forth.

Muds that oxidized and became the *Organ Rock Shale* were laid down over the white sands of the Cedar Mesa. The Organ Rock beds make up brightly colored red, orange, and brown slopes that separate cliff-forming units above and below. Some of the most interesting exposures of the Organ Rock Shale are in the Land of Standing Rocks (fig. 5.8).

The "type locality" of the *White Rim Sandstone* is the topographic bench, mentioned earlier, about 1200 feet down from the surface of Island in the Sky. (A *type locality* is the location from which a stratigraphic unit takes its name.) The White Rim Sandstone that forms striking cliffs between Cutler and Organ Rock red beds includes ancient sand dunes as well as large marine sand bars. Interesting exposures of this rock unit can be examined along the White Rim Trail.

In the Elaterite Basin along the park's western boundary, the White Rim Sandstone displays a "fossil" offshore bar that may have been a barrier island late in Permian time. This structure contains petroleum that seeps out as a dark-brown, tarry substance called "elaterite." The oil probably migrated into the sandstone from a source rock and became trapped by the impermeable red shale beds along the east side of the sandbar. Because the structure has been exhumed by erosion and the gas has escaped, the oil is not recoverable.

3. Mesozoic Moenkopi and Chinle Formations

An unconformity between Paleozoic and Mesozoic beds represents withdrawal of seas and a lengthy period of erosion when the continent was high. The Triassic units in the Canyonlands area are red beds consisting of shallow-water clastic sediments deposited by streams on flood plains throughout a broad lowland that sloped gently toward a western ocean. The mudstones of the Moenkopi Formation, which accumulated on tidal flats, are exposed in the northern and western sections of the park. Mudcracks and ripple marks are visible on many of the outcrops.

An unconformity separates Moenkopi beds from brightly colored, overlying Chinle beds, which are mostly slope-forming shales. A geologist describes Chinle beds as showing up on canyon walls in the park like "a brilliant ring of fire" (Baars 1983, p. 167). In some places, pieces of petrified wood from the Petrified Forest Member of the Chinle Formation have weathered out of cliffs and collected around the base (fig. I.3A).

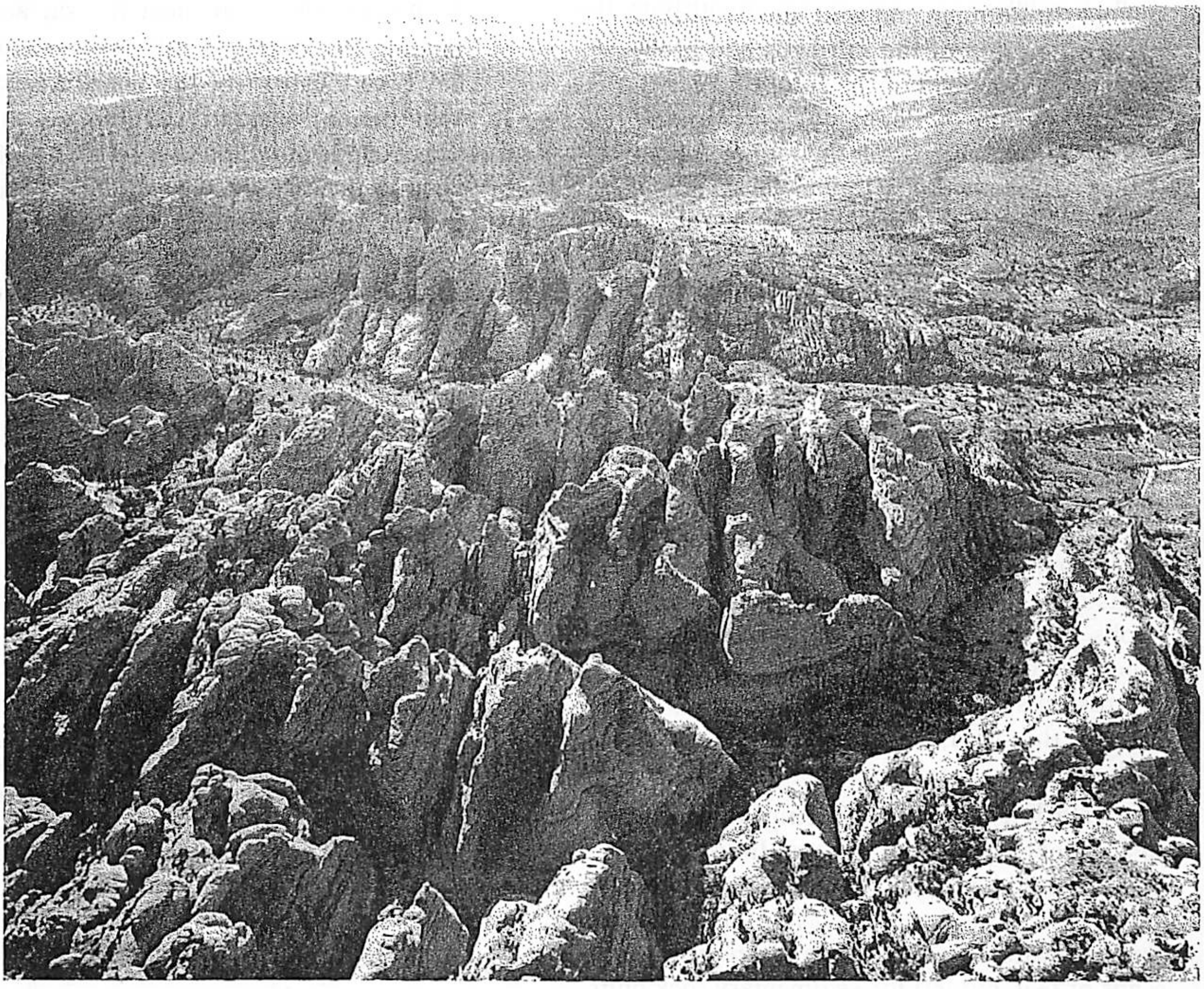

Figure 5.8 The Land of Standing Rocks, west side of the Colorado River, Canyonlands National Park. The location of the fins (closely spaced ridges) is controlled by the joint system of the Cedar Mesa Sandstone. National Park Service photo.

4. Sandstones of the Glen Canyon Group

The prominent cliffs of Wingate Sandstone, the cliffs and slopes of the Kayenta Formation, and the cliffs, knobs, and rounded monoliths of the Navajo Sandstone characterize Glen Canyon Group rock units in Canyonlands. Imposing outcrops of these strata encircle the western and northern sections of the park; and the cliffs, especially the red Wingate cliffs, form an effective barrier to travel across many parts of Canyonlands and vicinity. Much of the beauty and uniqueness of the Colorado Plateaus is due to the units of the Glen Canyon Group, which are well exposed in Canyonlands and other national parks and national monuments in the region.

As the Triassic climate became drier, sand dunes migrated across the region, burying the rivers and their flood plains. The dune sediment became the Wingate Sandstone. The Wingate cliffs rise several hundred feet throughout Canyonlands and run for hundreds of miles with very few breaks in their semicircular wall. Separating the Wingate dunes and the windblown desert deposits of the Jurassic Navajo Sandstone are the stream-deposited beds of the Kayenta Formation. Apparently a cycle of somewhat moister climate prevailed between the windy desert environments of the Wingate and Navajo. The Kayenta Formation, consisting of reddish brown to lavender sandstones with interbedded siltstones and shales, forms more gentle, ledgy slopes. The Navajo Sandstone, the top formation of the Glen Canyon Group, has well developed cross-bedding, and forms light-colored (buff to pale orange), steep, rounded cliffs, knobs, and hummocks. Some of the more striking ones resemble beehives, turbans, and temples in shape (fig. 5.1). Canyon View Point Arch and Millard Canyon Arch are also examples of Navajo Sandstone features.

5. **San Rafael Group deposition, ending the Jurassic Period.**
Rock units of the San Rafael Group unconformably overlie the Glen Canyon Group in the Canyonlands vicinity, mainly in scattered patches east and west of the park. In this area, the Carmel Formation beds accumulated on mud flats. The Entrada Sandstone, a massive sandstone; forms vertical cliffs and hummocky knobs that can be seen along some of the approaches to Canyonlands National Park.

Erosion stripped off most of the San Rafael beds in this area, along with any Cretaceous rock units that may have overlaid them.

6. **The relationship of the Laramide orogeny to the development of Canyonlands.**
The Laramide orogeny, which brought the Mesozoic Era to a close and lasted into Tertiary time, elevated the Canyonlands region thousands of feet, but left the sedimentary rock units essentially horizontal. The dip of the beds is so slight that they appear flat. However, the tectonic compressive forces that pushed up the surrounding mountains also produced joint systems and fractures that strongly influenced patterns of landform development in Canyonlands. Erosional processes, intensified by uplift, tended to follow the joint patterns while dissecting the flat-lying rocks.

The presence of the salt beds of the Paradox Formation, as explained earlier, complicated the fracturing and jointing. Sometime after uplift began, and as erosion stripped off the younger beds, ground water reached the buried salt beds. Some of the upper salt layers were dissolved, but the less soluble gypsum was left in place. In places where salt near the surface was reduced in volume—as it was under the grabens—the overlying beds collapsed.

7. **Quaternary erosion and deposition.**
The periods of cold and increased moisture that characterized Pleistocene climates increased the dissection and deepening of the canyons, especially the incising of the Green and Colorado River canyons. The volume of the two rivers was augmented by increases in runoff from glaciers in the Rocky Mountains and other highlands drained by these streams. Some of the dune deposits, landslide deposits, alluvial fans, and other unconsolidated sediments in the park accumulated—or at least began to form—in Pleistocene time. These processes continue today at a somewhat slower rate in the drier climate.

Geologic Map and Cross Section

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Aa: A blocky and fragmented form of lava occurring in flows with fissured and angular surfaces.
Alkali metal: A strongly basic metal like potassium or sodium.
Alluvial fan: A low, cone shaped deposit of terrestrial sediment formed where a stream undergoes an abrupt reduction of slope.
Alluvium: Unconsolidated terrestrial sediment composed of sorted or unsorted sand, gravel, and clay that has been deposited by water.
Angle of repose: The steepest slope angle in which particular sediment will lie without cascading down.
Aquifer: A permeable formation that stores and transmits groundwater in sufficient quantity to supply wells.
Arroyo: A steep-sided and flat-bottomed gulley in an arid region that is occupied by a stream only intermittently, after rains.
Artesian well: A well that reaches an aquifer containing water under pressure. Thus water in the well rises above the surrounding water table.
Barchan: A crescent-shaped sand dune moving across a clean surface with its convex face upwind and its concave slip face downwind.
Basalt: A fine-grained, dark, mafic igneous rock composed largely of plagioclase feldspar and pyroxene.
Basement: The oldest rocks recognized in a given area, a complex of metamorphic and igneous rocks that underlies all the sedimentary formations.
Basic rock: Any igneous rock containing mafic minerals rich in iron and magnesium, but containing no quartz and little sodium rich plagioclase feldspar.
Basin: In tectonics, a circular, syncline-like depression of strata. In sedimentology, the site of accumulation of a large thickness of sediments.
Batholith: A great irregular mass of coarse-grained igneous rock which has either intruded the country rock or been derived from it through metamorphism.
Bathymetry: The study and mapping of sea-floor topography.
Bedding: A characteristic of sedimentary rocks in which parallel planar surfaces separating different grain sizes or compositions indicate successive depositional surfaces that existed at the time of sedimentation.
Bolson: In arid regions, a basin filled with alluvium and intermittent playa lakes and having no outlet.
Butte: A steep sided and flat topped hill formed by erosion of flat laying strata where remnants of a resistant layer protect the softer rocks underneath.
Caldera: A large, circular depression in a volcanic terrain, typically originating in collapse, explosion, or erosion.
Carbonate rock: A rock composed of carbonate minerals, especially limestone and dolomite.
Cataclastic rock: A breccia of powdered rock formed by crushing and shearing during tectonic movements.
Chemical weathering: The total set of all chemical reactions that act on rock exposed to water and atmosphere and so change it minerals to stable forms.
Chert: A sedimetary form of amorphous or extremely fine-grained silica, partially hydrous, found in concretions and beds.
Cinder cone: A steep, conical hill built up about a volcanic vent and composed of coarse pyroclasts expelled from the vent by escaping gases.
Clastic rock: A sedimentary rock formed from mineral particles (clasts) that were mechanically transported.
Clay: Any of a number of hydrous aluminosilicate minerals formed by weathering and hydration of other silicates.
Composite cone: The volcanic cone of a stratovolcano, composed of both cinders and lava flows.
Deflation: The removal of clay and dust from dry soil by strong winds.
Delta: A body of sediment deposited in an ocean or lake at the mouth of a stream.
Deposition: A general term for the accumulation of sediments by either physical or chemical sedimentation.
Deposition remnant magnetization: Magnetization created in sedimentary rocks by rotation of magnetic crystals into line with the ambient field during settling.
Desert pavement: A deposit produced by continued deflation, which removes the fine grains of a soil and leaves a surface covered with closely packed cobbles.
Detrital sediment: Sediment deposited by a physical process.
Diagenesis: The physical and chemical changes undergone by a sediment during lithification and compaction, excluding erosion and metamorphism.
Diatreme: A volcanic vent filled with breccia by the explosive escape of gases.
Dip: The angle by which a stratum or other planar feature deviates from the horizontal. The angle is measured in a plane perpendicular to the strike.
Drainage basin: A region of land surrounded by divides and crossed by streams that eventually converge to one river or lake.
Drift (glacial): A collective term for all the rock, sand, and clay that is transported and deposited by a glacier either as till or as outwash.
Dune: An elongated mound of sand formed by wind or water.
Eolian: Pertaining to or deposited by wind.
Epicenter: The point on the Earth's surface directly above the focus or hypocenter of an Earthquake.
Erosion: The set of all processes by which soil and rock are loosened and moved downhill or downwind.
Evaporite: A chemical sedimentary rock consisting of minerals precipitated by evaporating waters, especially salt and gypsum.
Exfoliation: A physical weathering process in which sheets of rock are fractured and detached from an outcrop.
Fault: A planar or gently curved fracture in the Earth's crust across which there has been relative displacement.
Fault plane: The plane that best approximates the fracture surface of a fault.
Felsic: An adjective used to describe a light-colored igneous rock poor in iron and magnesium content, abundant in feldspars and quartz.
Fissure: An extensive crack, break, or fracture in the rocks.
Flood basalt: A plateau basalt extending many kilometers in flat, layered flows originating in fissure eruptions.
Flow cleavage: In a metamorphic rock, the parallel arrangement of all planar or linear crystals as a result of rock flowage during metamorphism.
Fluid inclusion: A small body of fluid that is entrapped in a crystal and has the same composition as the fluid from which the crystal formed.
Focus (earthquake): The point at which the rupture occurs; synonymous with hypocenter.
Fold: A planar feature, such as a bedding plane, that has been strongly warped, presumably by deformation.
Foliation: Any planar set of minerals or banding of mineral concentrations including cleavage, found in a metamorphic rock.
Forset bed: One of the inclined beds found in crossbedding; also an inclined bed deposited on the outer front of a delta.
Friction breccia: A breccia formed in a fault zone or volcanic pipe by the relative motion of two rock bodies.
Fumarole: A small vent in the ground from which volcanic gases and heated groundwater emerge, but not lava.
Geochronology: The science of absolute dating and relative dating of geologic formations and events, primarily through the measurement of daughter elements produced by radioactive decay in minerals.
Geomorphology: The science of surface landforms and their interpretation on the basis of geology and climate.
Geosyncline: A major downwarp in the Earth's crust, usually more than 1000 kilometers in length, in which sediments accumulate to thicknesses of many kilometers. The sediments may eventually be deformed and metamorphosed during a mountain-building episode.
Geotherm: A curving surface within Earth along which the temperature is constant.
Geyser: A hot spring that throws hot water and steam into the air. The heat is thought to result from the contact of groundwater with magma bodies.
Glacial rebound: Epeirogenic uplift of crust that takes place after the retreat of a continental glacier in response to earlier subsidence under the weight of ice.
Glacial striations: Scratches left on bedrock and boulders by overriding ice, and showing the direction of motion.
Glacial valley: A valley occupied or formerly occupied by a glacier, typically with a U-shaped profile.
Glacier: A mass of ice and surficial snow that persists throughout the year and flows downhill under its own weight, of sizes 100 m – 10000 km.
Glass: A rock formed when magma is too rapidly cooled (quenched) to allow crystal growth.
Graben: A downthrown block between two normal faults of parallel strike but converging dips; hence a tensional feature. See also horst.
Graded bedding: A bed in which the coarsest particles are concentrated at the bottom and grade gradually upward into fine silt.
Granite: A coarse-grained, intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar, and micas.
Gravity anomaly: The value of gravity left after subtracting the reference value based on latitude, and possibly the free-air and Bouguer corrections.
Gravity survey: The measurement of gravity at regularly spaced grid points with repetitions to control instrument drift.
Groundwater: The mass of water in the ground below the phreatic zone occupying the total pore space in the rock.
Horst: An elongate, elevated block of crust forming a ridge or plateau, typically bounded by parallel, outward-dipping normal faults.
Hydration: A chemical reaction, usually in weathering, which adds water or OH to a mineral structure.
Hydraulic conductivity: A measure of the permeability of a rock or soil: the volume of flow through a unit surface in unit time with unit hydraulic pressure difference as the driving force.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Limestone: A sedimentary rock composed principally of calcium carbonate ($\mathrm{CaCO2}$), usually as the mineral calcite.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Mesophere: The lower mantle.

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

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

Micrometeorite: A meteorite less than 1 millimeter in diameter.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Relief: The maximum regional difference in elevation.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Unconformity: A surface that separates two strata.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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