LPL Geology Field Trip Practicum PTYS 594A
Canyonlands, Spring 1999

Table of Contents– Canyonlands, Spring 1999

Page	What	Who
i	Table of Contents	
ii	Itinerary	H. J. Melosh
v	Maps of Dubious Usefulness	
viii	Editor's Note	Andrew Rivkin
1	*The Geometry of Graben Systems & Graben on Other Planets*	Ross Beyer
4	*Kimberlites and Minettes of Agathla Peak*	Mark T. Hutchison
10	*The Four Corners Region: A Glowing Testament to the Nuclear Age*	Mark T. Hutchison
16	*Cliff Recession: Toreva-block landslides*	Gareth S. Collins
21	*Sandstone: Wonders and Weathering in the State of Utah*	Jennifer Grier [1]
26	*Incised Meanders, or from whence the Goosenecks of the San Juan???*	Devon Burr
29	*Arches and Buttes*	the letter R[2]
33	*Faults and Folds on the Colorado Plateau*	"Paul"
39	*Geologic History of Southeast Utah– Plate Tectonics*	Josh Emery
43	*The Geological History of Utah– (Nevada), Sevier and Laramide Orögeny*	Werner Ertel
47	*Laccoliths*	Terry Hurford
51	*ČhAø§in the Entrada Sandstone*	Joseph Spitale
55	*Upheaval Dome: Impact Crater or Salt Dome?*	Jeannie Riley, Nancy Chabot, and Windy Jaeger,
71?	*Cosmogenic Rifting in the Canyonlands National Park*	James N. Head, conducto
74ish	*History of SouthEast Utah National Parks*	Jason Barnes
75	*Newspaper Rock Petroglyphs*	Dave O'Brien
≡77	*Paradox Basin– You're damned if you do and damned if you don't*	⋆*B*⋆ [3]
81	*Graben Formation in Canyonlands*	Fred Ciesla
83	*Controls on Gråben Width/Mechanisms of Formation*	Andreas Ekholm
88	*Graben Formation over Dike Intrusions*	Aileen Yingst and Laszlo Keszthelyi
92	*Early Geologic Exploration of the Colorado Plateau*	Erich Karkoschka

---

[1] Your hostess with neuroses

presumed Rachel Mastrapa

[3] presumed Barbara Cohen[4]

[4] part of the NYNEX family

PTYS 594a,
PLANETARY FIELD GEOLOGY PRACTICUM

Spring 1999 Canyonlands Itinerary

Before departure, **Ross Beyer** will give us a pre-trip exposition on grabens on the Moon, Mars, etc.

Wednesday, 28 April

8:00 am	Depart LPL loading dock. Drive N. on Cherry to Speedway, proceed West to I-10, drive North towards Phoenix. In Phoenix take I-17 North to Flagstaff. Drive E. through flagstaff, then N. on Route 89
12:00	Stop for lunch at Sunset/Wupatki national monument. Pull out on road to O'Leary peak, just before monument entrance.
1:00 pm	Continue North on Rte 89 to junction with Rte 160. Turn right onto Rte. 160 and drive toward Kayenta. At Kayenta proceed North on Rte 163 toward Monument Valley.
3:00 pm	Stop on Route 163 near Agathla Peak where **Mark Hutchison** will describe the diatremes of Monument Valley.
3:30 pm	Proceed North on Rte 163 through Monument Valley. Stop at Navajo Visitor center, where **Gareth Collins** will describe Cliff Retreat and **Jennifer Grier** will discuss the weathering of the sandstone we will be seeing so much of.
4:00 pm	Continue North on Rte 163 to Mexican Hat on the San Juan River. Turn left onto Rte 261 for 1.5 miles, then left again onto Rte 316 to overlook the Goosenecks of the San Juan. **Devon Burr** will discuss river incision at this inspiring overlook.
5:30 pm	Return on Rte 316 to Rte 261, turn left and proceed North on 261 toward Natural Bridges National Monument.
6:30 pm	Camp in vicinity of Natural Bridges National Monument. **Andy Rivkin** will give a fireside chat on the History of settlement of SE Utah.

Thursday, 29 April

7:00 am	Break camp, visit Natural Bridges National Monument. We may select a short hike to better observe one of the Bridges. **Rachal Mastrapa** will discuss the origin of Arches and Buttes.
10:00 am	Leave the monument, travel West on Rte 275 to Rte. 95. Turn left (East) on Rte. 95 and proceed to Blanding over Comb ridge. **Paul Withers** may find this an inspiring spot to discuss Plateau Structures before us, folds and faults especially. **Josh Emery** will discuss the general plate tectonic setting of the region around us and **Werner Ertel** will discuss the Sevier Orogeny that buckled the paleozoic and mesozoic rocks in this region.
11:30 am	Arrive in the town of Blanding. Turn North on Rte 191 toward Monticello
12:00	Lunch stop in the vicinity of Recapture Reservoir. . Note the Abajo mountains to the North. **Terry Hurford** will explain how they, and other laccoliths, form.

1:00 pm Continue North on Rte 191 through Monticello, La Sal Junction to Moab. Continue on Rte 191 through Moab

3:00 pm Stop briefly at the visitor center of Arches National Monument, where **Joe Spitale** will describe Mayhem in the Entrada Sandstone and whether these may be traces of an ancient impact.

3:30 pm Continue NW on Rte 191 to its junction with Rte 313. Proceed South on Rte 313 to the Upheaval Dome overlook.

4:30 pm Arrive at the Upheaval Dome over look. Ooh and Aah over the view, then listen to presentations by **Nancy Chabot**, **Windy Jaeger** and **Jeannie Riley** on the debate over its origin. **Jim Head** will discuss the Roberts Rift proposal.

6:00 pm Depart Upheaval Dome, proceed North. Exit park, camp in National Forest south of Rte. 191. Fireside chat by **Jason Barnes** on the history of parks in SE Utah.

Friday, 30 April

7:00 am Break camp, continue North on 313 to Rte 191. Return South through Moab, La Sal Junction to Rte 211, turn left (West) on Rte 211 to Newspaper Rock.

9:30 am Stop at Newspaper Rock, which will be interpreted for us by **David O'Brian**.

10:00 am Continue West on 211 to park headquarters. Pick up camping permits.

11:00 am Proceed over Elephant Hill (get those 4WD in gear, folks!) West to Confluence Overlook.

12:00 Lunch stop at Overlook. After lunch, **Barbara Cohen** will describe the Paradox Evaporites and how they came to be located near the river far below us.

1:30 pm Proceed South down Devil's lane "road" to Red Lake Canyon trailhead. Hike to top of horst to overlook grabens to West. At some appropriate site we will discuss the formation of these grabens: **Fred Cielsa** will discuss the specific aspects of graben formation here at Canyonlands, **Andreas Ekholm** will discuss what factors determine the width of a given graben, and **Laslo Keszthelyi** and **Eileen Yingst** will describe how grabens may form over dikes.

5:00 pm Turn East off Devil's lane, drive 1 mile and occupy campsites at Devil's Kitchen. Fireside chat (without the fire!) by **Erik Karkoschka** on the Geologic exploration of the Colorado Plateau by Powell, Gilbert and Dutton.

Saturday, 1 May

7:00 am Break camp, drive south on Devil's Lane to Joint Trail trailhead.

8:30 am Hike 1.5 miles through vertically jointed sandstones, return by same route.

12:00 Rejoin vehicles, eat lunch

1:00 pm Return North on Devil's lane, drive back over Elephant hill to Rte 211. Proceed East on 211 to Monticello. Rejoin Rte 191 at Monticello and proceed South through Blanding. Pick up Rte 163 at Blanding, continue South.

6:30 pm Camp on national forest between Blanding and Mexican Hat.

Sunday, 2 May

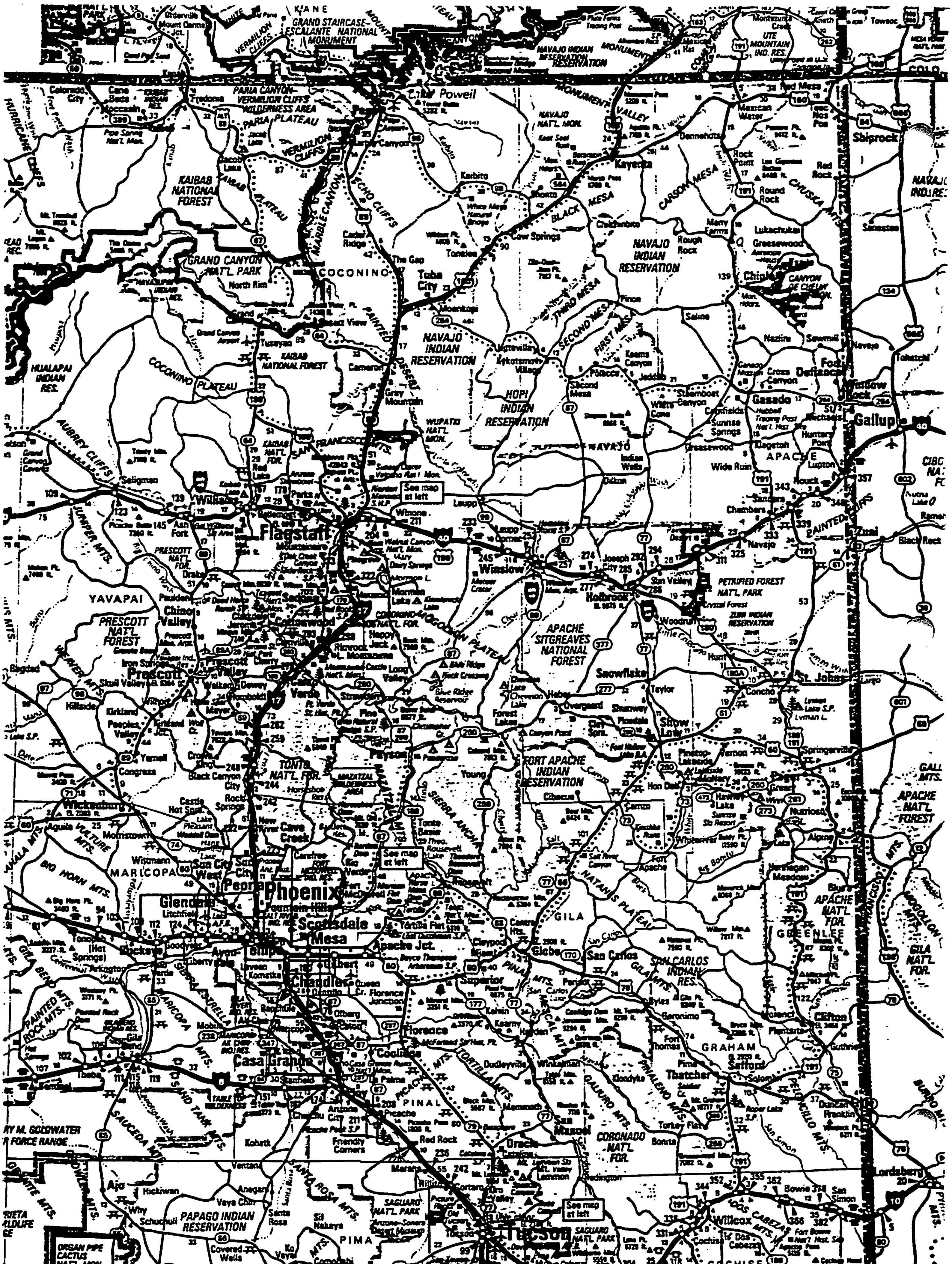
7:00 am Break camp, continue South on reverse route through Kayenta, Flagstaff, Phoenix to Tucson.

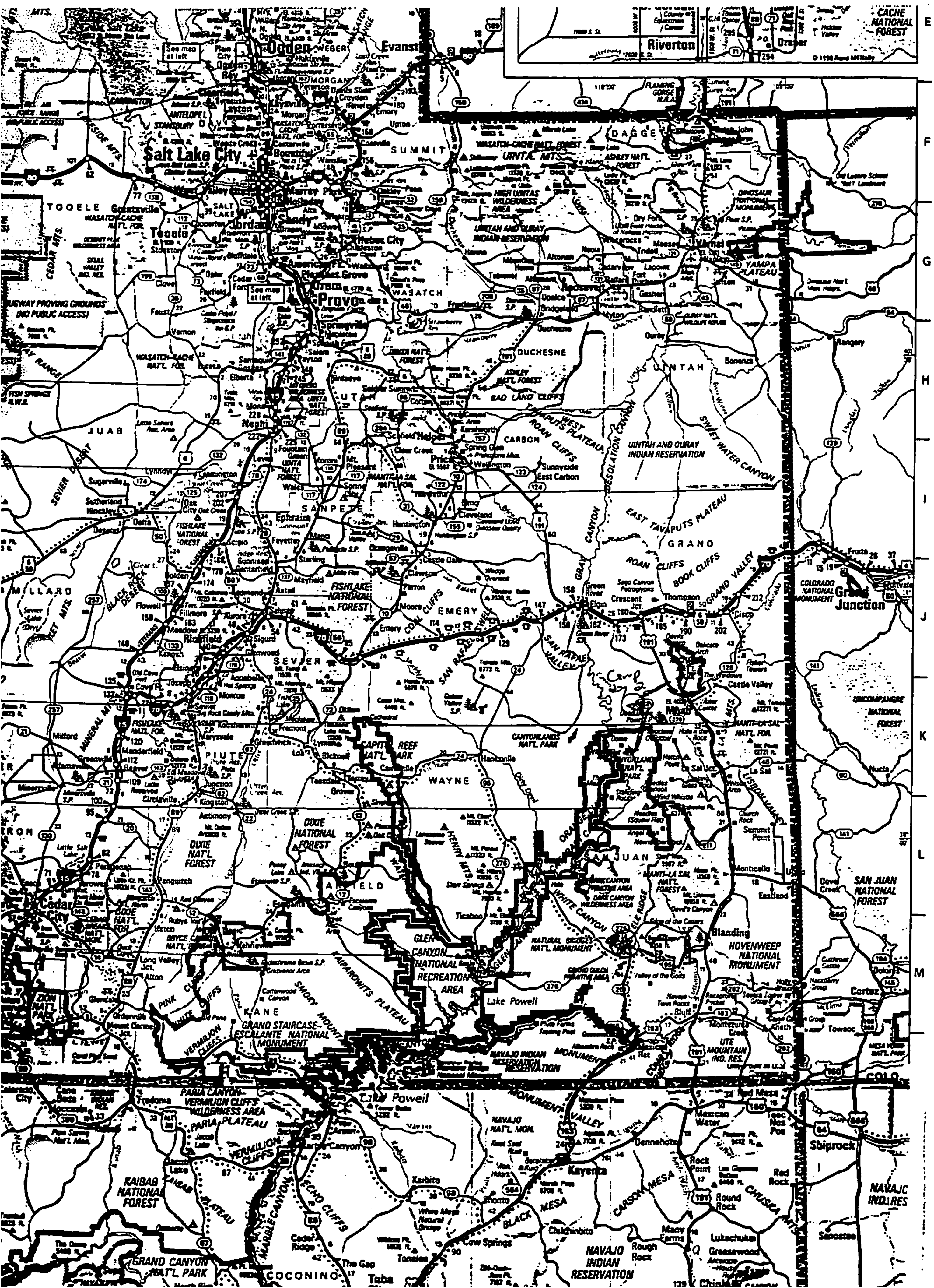
5:00 pm Arrive Tucson, unpack and clean vehicles, go home.

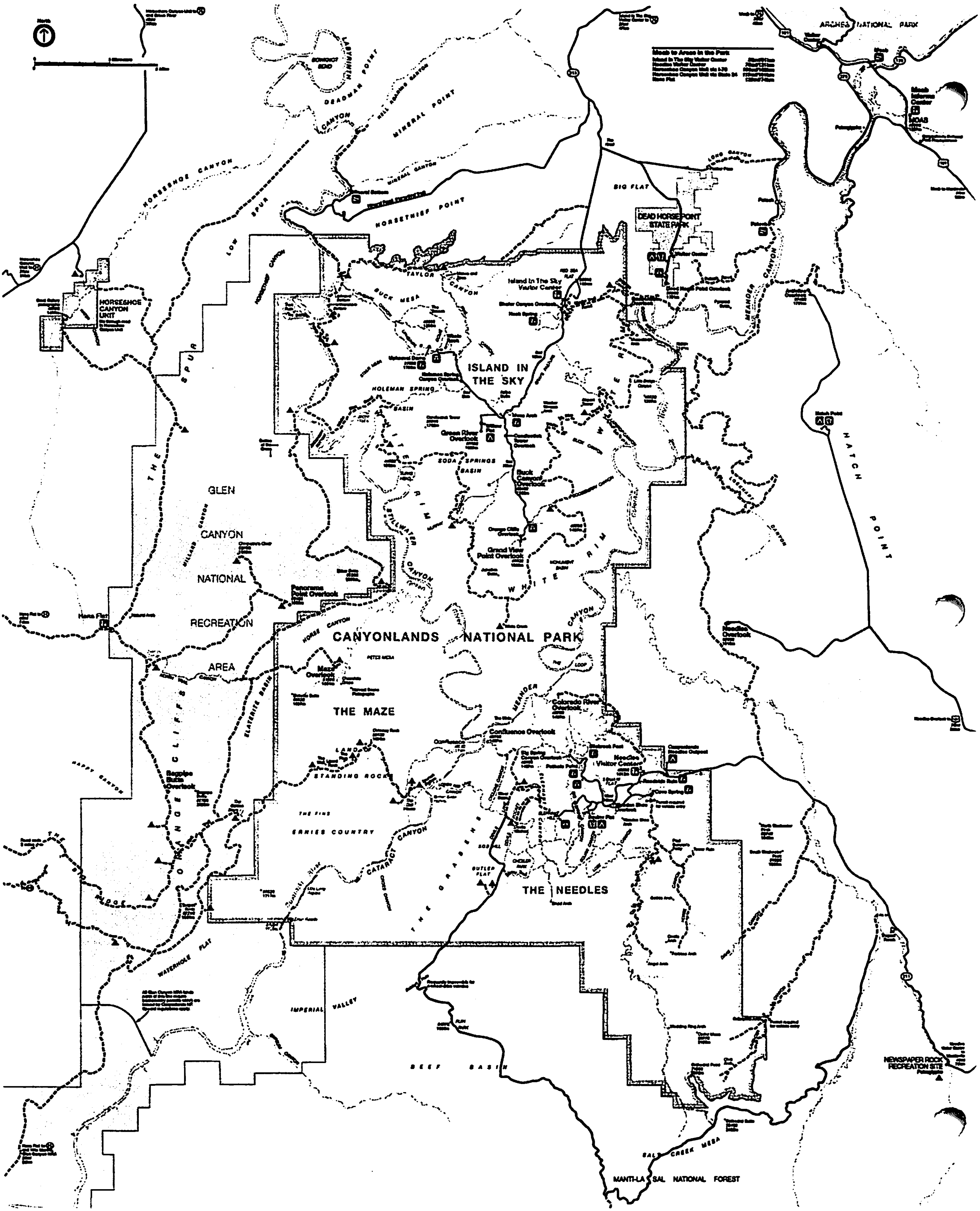
Drivers: Barnes, Beyer, Cohen, Emery, Ertel, Hutchinson, Karkoschka, Spitale

Particapants:

J. Barnes
R. Beyer
D. Burr
N. Chabot
F. Cielsa
B. Cohen
G. Collins
A. Ekholm
J. Emery
W. Ertel
J. Grier
J. Head
M. Hutchison
T. Hurford
W. Jaeger
E. Karkoschka
L. Keszthelyi
D. Kring
R. Mastrapa
J. Melosh
D. O'Brien
J. Riley
A. Rivkin
E. Roemer
J. Spitale
P. Withers
E. Yingst


KANE
GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT
VERMILION CLIFFS
NAVAJO INDIAN RESERVATION
MONUMENT VALLEY
UTE MOUNTAIN IND. RES.
COLO.
Lake Powell
Page
Colorado City
Fredonia
Moccasin
PARIA CANYON-VERMILION CLIFFS WILDERNESS AREA
PARIA PLATEAU
Jacob Lake
KAIBAB NATIONAL FOREST
KAIBAB PLATEAU
MARBLE CANYON
ECHO CLIFFS
NAVAJO NAT'L MON.
Kayenta
Mexican Water
Shiprock
CARSON MESA
CHUSKA MTS.
Round Rock
Red Rock
BLACK MESA
Kaibito
Shonto
Cow Springs
Tonalea
Chinle
CANYON DE CHELLY NAT'L MON.
Many Farms
Lukachukai
Rough Rock
GRAND CANYON NAT'L PARK
North Rim
COCONINO
The Gap
Cedar Ridge
Tuba City
Moenkopi
THIRD MESA
SECOND MESA
FIRST MESA
Pinon
Grand Canyon
Tusayan
Desert View
Cameron
PAINTED DESERT
HUALAPAI INDIAN RES.
COCONINO PLATEAU
KAIBAB NATIONAL FOREST
Kykotsmovi Village
Hotevilla
Second Mesa
Polacca
Keams Canyon
Jeddito
HOPI INDIAN RESERVATION
Ganado
Window Rock
Fort Defiance
Sawmill
Navajo
Gallup
Gray Mountain
WUPATKI NAT'L MON.
SAN FRANCISCO MTS.
AUBREY CLIFFS
Seligman
Williams
Valle
Red Lake
Parks
Ash Fork
JUNIPER MTS.
Flagstaff
Winona
Leupp
Two Guns
Winslow
Joseph City
Holbrook
Sun Valley
PETRIFIED FOREST NAT'L PARK
Chambers
Sanders
Navajo
Houck
Lupton
PAINTED CLIFFS
Zuni
Black Rock
Wide Ruin
Klagetoh
Indian Wells
Dilkon
Steamboat Canyon
Cornfields
Sunrise Springs
Greasewood
Hunters Point
St. Michaels
APACHE
NAVAJO
Meteor Crater
Munds Park
Mormon Lake
YAVAPAI
Chino Valley
Drake
Paulden
PRESCOTT NAT'L FOREST
Sedona
Cottonwood
Clarkdale
Jerome
Camp Verde
Rimrock
Happy Jack
MOGOLLON PLATEAU
APACHE-SITGREAVES NATIONAL FOREST
Woodruff
Snowflake
Taylor
St. Johns
Concho
ZUNI INDIAN RESERVATION
Bagdad
Prescott
Prescott Valley
Skull Valley
Hillside
Kirkland
Peeples Valley
Yarnell
Congress
Humboldt
Dewey
Mayer
Cordes
Strawberry
Pine
Payson
Heber
Overgaard
Show Low
Pinetop-Lakeside
Vernon
Springerville
Eagar
Forest Lakes
Clay Springs
Pinedale
Wickenburg
Aguila
Morristown
Wittmann
Black Canyon City
Rock Springs
New River
Cave Creek
Carefree
TONTO NAT'L FOR.
Young
SIERRA ANCHA
FORT APACHE INDIAN RESERVATION
Cibecue
Whiteriver
Hon Dah
McNary
Greer
Nutrioso
Alpine
VULTURE MTS.
BIG HORN MTS.
MARICOPA
Sun City West
Sun City
Peoria
Glendale
Phoenix
Scottsdale
Mesa
Fountain Hills
Tortilla Flat
Apache Jct.
Roosevelt
Tonto Basin
Litchfield Park
Goodyear
Buckeye
Tonopah
Avondale
Tempe
Chandler
Gilbert
Queen Creek
Florence Junction
Superior
Miami
Globe
GILA
San Carlos
SAN CARLOS INDIAN RES.
NATANES PLATEAU
Hannagan Meadow
APACHE NAT'L FOR.
GREENLEE
GILA NAT'L FOR.
Gila Bend
Arlington
Palo Verde
Maricopa
Mobile
Sacaton
Coolidge
Florence
Kelvin
Kearny
Hayden
Winkelman
Dudleyville
Peridot
Bylas
Geronimo
Fort Thomas
Pima
Thatcher
Safford
GRAHAM
Solomon
Clifton
Morenci
Duncan
Franklin
Casa Grande
Stanfield
Arizona City
Eloy
Picacho
Red Rock
Marana
PINAL
Mammoth
San Manuel
Oracle
CORONADO NAT'L FOR.
PINALENO MTS.
GALIURO MTS.
Bonita
Lordsburg
Rodeo
BARRY M. GOLDWATER AIR FORCE RANGE
SAUCEDA MTS.
SAND TANK MTS.
Ajo
Why
Kohatk
Ventana
Hickiwan
Vaya Chin
Santa Rosa
Sil Nakaya
PAPAGO INDIAN RESERVATION
PIMA
SAGUARO NAT'L PARK
Tucson
Oro Valley
Catalina
Mt. Lemmon
Redington
Willcox
Bowie
San Simon
DOS CABEZAS MTS.
Cochise
ORGAN PIPE CACTUS NAT'L MON.
Covered Wells
See map at left


Ogden
Evanston
Riverton
Draper
CACHE NATIONAL FOREST
© 1998 Rand McNally
See map at left
Salt Lake City
Great Salt Lake
TOOELE
Tooele
Grantsville
Stansbury
Kaysville
Layton
Clearfield
Bountiful
MORGAN
WEBER
SUMMIT
DAGGETT
FLAMING GORGE N.R.A.
UINTA MTS.
WASATCH-CACHE NAT'L FOREST
ASHLEY NAT'L FOREST
HIGH UINTAS WILDERNESS AREA
UINTAH AND OURAY INDIAN RESERVATION
DINOSAUR NATIONAL MONUMENT
YAMPA PLATEAU
Vernal
Roosevelt
Duchesne
DUCHESNE
Heber City
Park City
WASATCH
Sandy
Murray
Jordan
Orem
Provo
Springville
American Fork
Pleasant Grove
UTAH
Nephi
JUAB
CARBON
Price
Helper
Wellington
East Carbon
Sunnyside
WEST TAVAPUTS PLATEAU
ROAN CLIFFS
BAD LAND CLIFFS
DESOLATION CANYON
SWEET WATER CANYON
UINTAH
Rangely
Ouray
Bonanza
SEVIER DESERT
Delta
Fillmore
MILLARD
Ephraim
SANPETE
Manti
Gunnison
Salina
Richfield
SEVIER
FISHLAKE NATIONAL FOREST
EMERY
Castle Dale
Huntington
Green River
Crescent Jct.
Thompson
GRAND
EAST TAVAPUTS PLATEAU
BOOK CLIFFS
GRAND VALLEY
Grand Junction
Fruita
COLORADO NATIONAL MONUMENT
SAN RAFAEL VALLEY
Moab
Castle Valley
MANTI-LA SAL NAT'L FOR.
UNCOMPAHGRE NATIONAL FOREST
CANYONLANDS NAT'L PARK
CAPITOL REEF NAT'L PARK
Hanksville
WAYNE
Loa
Torrey
PIUTE
Marysvale
Beaver
Milford
Minersville
MINERAL MTS.
DIXIE NATIONAL FOREST
DIXIE NAT'L FOREST
HENRY MTS.
GARFIELD
Panguitch
Escalante
Boulder
Cedar City
Parowan
BRYCE CANYON NAT'L PARK
Tropic
SAN JUAN
Monticello
Blanding
La Sal
Nucla
NATURAL BRIDGES NAT'L MONUMENT
WHITE CANYON
GLEN CANYON NATIONAL RECREATION AREA
Lake Powell
KAIPAROWITS PLATEAU
GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT
KANE
ZION NAT'L PARK
Kanab
Orderville
Mount Carmel Jct.
Long Valley Jct.
Alton
PINK CLIFFS
WHITE CLIFFS
VERMILION CLIFFS
HOVENWEEP NATIONAL MONUMENT
SAN JUAN NATIONAL FOREST
Cortez
Dove Creek
Bluff
Mexican Hat
Montezuma Creek
UTE MOUNTAIN IND. RES.
NAVAJO INDIAN RESERVATION
MONUMENT VALLEY
COLO.
Red Mesa
Teec Nos Pos
Shiprock
Mexican Water
Dennehotso
Kayenta
Page
Lake Powell
PARIA CANYON-VERMILION CLIFFS WILDERNESS AREA
PARIA PLATEAU
Fredonia
Colorado City
Moccasin
Jacob Lake
KAIBAB NATIONAL FOREST
KAIBAB PLATEAU
MARBLE CANYON
ECHO CLIFFS
GRAND CANYON NAT'L PARK
COCONINO
Tuba City
The Gap
Cedar Ridge
Tonalea
Kaibito
Shonto
BLACK MESA
CARSON MESA
CHUSKA MTS.
Rock Point
Round Rock
Many Farms
Chinle
Lukachukai
NAVAJO INDIAN RESERVATION
E
F
G
H
I
J
K
L
M



North
Moab to Areas in the Park
Island In The Sky Visitor Center
Needles Visitor Center
Horseshoe Canyon Unit via I-70
Horseshoe Canyon Unit via State 24
Hans Flat
ARCHES NATIONAL PARK
MOAB
LABYRINTH
DEADMAN POINT
MINERAL POINT
MINERAL CANYON
HORSESHOE CANYON
LOW SPUR
HORSETHIEF POINT
BIG FLAT
LONG CANYON
DEAD HORSE POINT STATE PARK
TAYLOR CANYON
BUCK MESA
Island In The Sky Visitor Center
HORSESHOE CANYON UNIT
ISLAND IN THE SKY
HOLEMAN SPRING BASIN
Green River Overlook
SODA SPRINGS BASIN
Buck Canyon Overlook
Grand View Point Overlook
WHITE RIM
STILLWATER CANYON
MEANDER CANYON
HATCH POINT
GLEN CANYON NATIONAL RECREATION AREA
THE SPUR
Panorama Point Overlook
Hans Flat
HORSE CANYON
CANYONLANDS NATIONAL PARK
Needles Overlook
Maze Overlook
THE MAZE
ELATERITE BASIN
ORANGE CLIFFS
Colorado River Overlook
Confluence Overlook
Needles Visitor Center
LAND OF STANDING ROCK
Bagpipe Butte Overlook
HAPPY CANYON
THE FINS
ERNIES COUNTRY
CATARACT CANYON
THE GRABENS
BUTLER FLAT
THE NEEDLES
WATERHOLE FLAT
IMPERIAL VALLEY
BEEF BASIN
NEWSPAPER ROCK RECREATION SITE
SALT CREEK MESA
MANTI-LA SAL NATIONAL FOREST

Editor's Introduction

Gentle Readers,

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

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

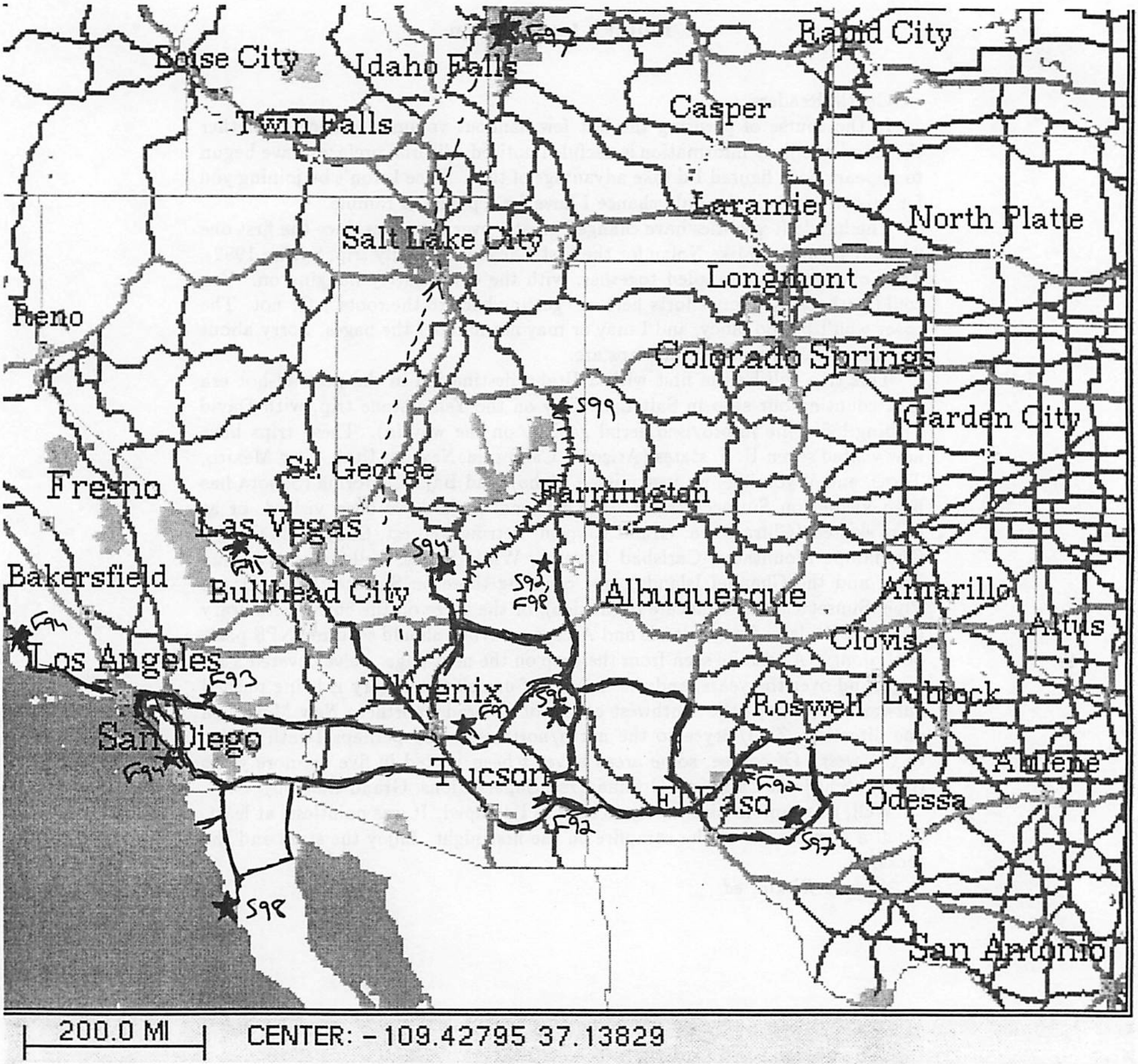
This trip will be the first with a Utahn destination in the post-ad-hoc era (not counting our stop in Salt Lake City on the Yellowstone trip, with David Trilling led some improvised aerial geology on the way in). These trips have now visited seven U. S. states (Arizona, California, Nevada, Utah, New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

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

Andrew Rivkin, ed.

Field Trip Practicum Routes and Destinations

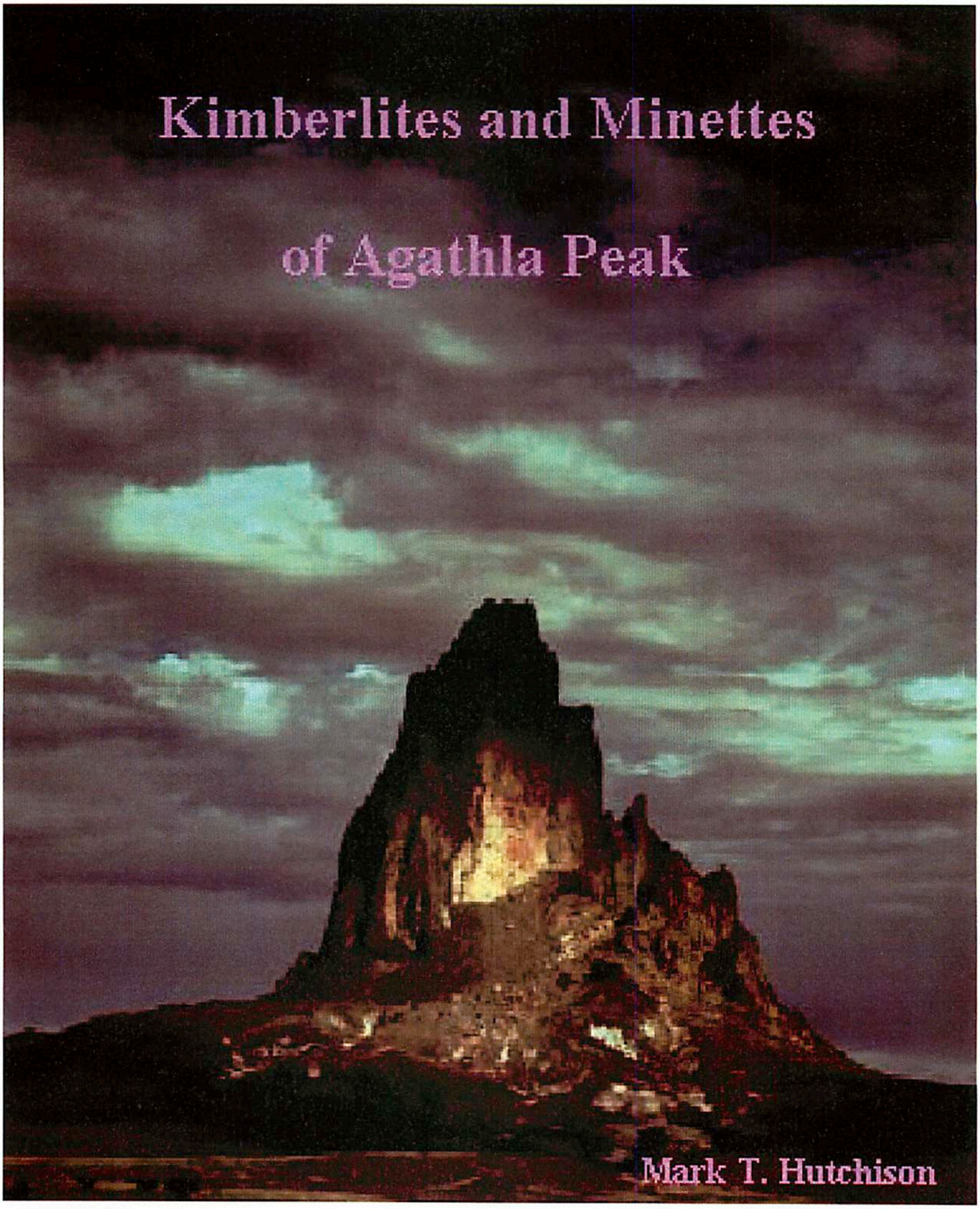
1992 – 1999



Map by Maps On Us (SM)
Map data Copyright Etak, Inc. 1984-1999. All rights reserved. Use subject to LICENSE.

Kimberlites and Minettes of Agathla Peak

Mark T. Hutchison



General geology

A large number of alkali-rich igneous bodies outcrop in the central part of the Colorado Plateau and are referred to collectively as the Navajo volcanics. Of these, perhaps one of the most striking is Agathla Peak (also known as El Capitan[1], Fig. 1). Agathla peak is one of six volcanic plugs and four extensive dykes lying within a 10 km^2 area of which the other most noteworthy is Church Rock to the South East (Fig. 2). Agathla rises 335 m above its surrounding Chinle formation sediments. It has been dated using the fission track method applied to apatite phenocrysts at 31 Ma[2]. Geologically, Agathla peak is unusual because it stands as a single volcanic plug which at the same time incorporates two very distinctive pyroclastic rocks: kimberlite and a tuff-breccia of crustal rocks and minette. Within both facies are to be found numerous clasts of country sedimentary and basement xenoliths up to 10 metres in diameter. The tuff-brecia is generally massive, however some crude saucer-shape layering is evident in the loftier reaches of the peak which suggests that both the diatreme and perhaps also the lower reaches of the crater zones are in evidence.

Fig. 1 Agathla Peak

Fig. 2 Church Rock

Definitions: Kimberlites, lamprophyres, minettes and lamproites

Kimberlites are essentially peridotites which include both carbonated and hydrated phases, typically phlogopite[3] and calcite. They are found exclusively in settings related to ancient cratonic regions, either in mobile belts or, more commonly, in the central parts of the cratons themselves. The belief that the Colorado plateau has behaved as a relatively stable, thick continental block for some 1200 m.y. is therefore consistent with observations of kimberlite outcrops within it. Dawson (1980)[4] proposed that kimberlites form by small degree partial melting of phlogopite carbonate garnet lherzolites[5] whereas more recent

---

[1] The term El Capitan was termed by Kit Carson. The Navajo name, Agathla, has been translated as meaning 'much wool' or 'the place of the scraping of hides' and refers to the annual sheep gathering conducted by the Navajo in its shadow.

[2] Naeser, C. W. (1970) *J. Geophys. Res.* **76**, 4978

[3] $K_2[Mg,Fe]_6[Si_6Al_2O_{20}][OH,F]_4$ mica, being similar to biotite with less Al and lacking in Fe^{3+}

[4] Dawson, B. (1980) *Kimberlites and their xenoliths* Springer Verlag, Berlin

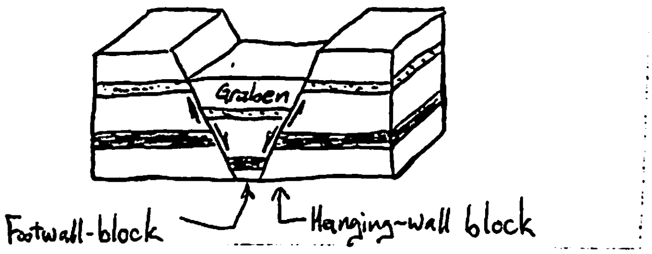
[5] Lherzolite is a peridotite characterised by an assemblage of olivine, orthopyroxene and clinopyroxene

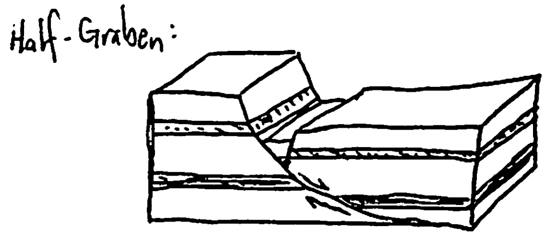
Geometry of Graben Systems & Graben on Other Planets

Ross Beyer

Graben – An elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides. It is a structural form, which may or may not be geomorphologically expressed as a *rift valley*.

Horst - An elongate, relatively uplifted crustal unit or block that is bounded by faults on its long sides. It is a structural form and may or may not be expressed geomorphologically.

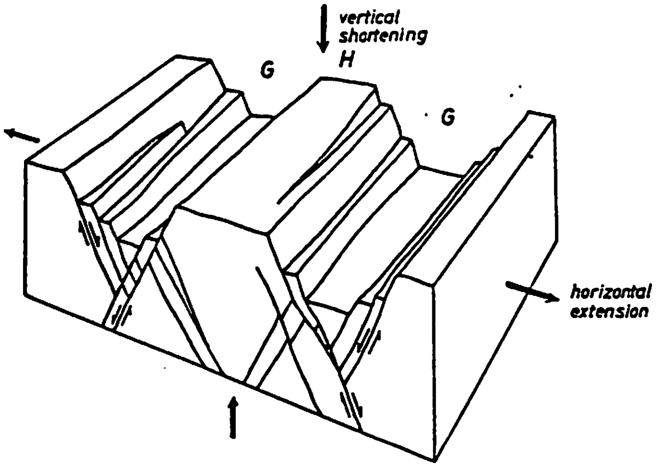




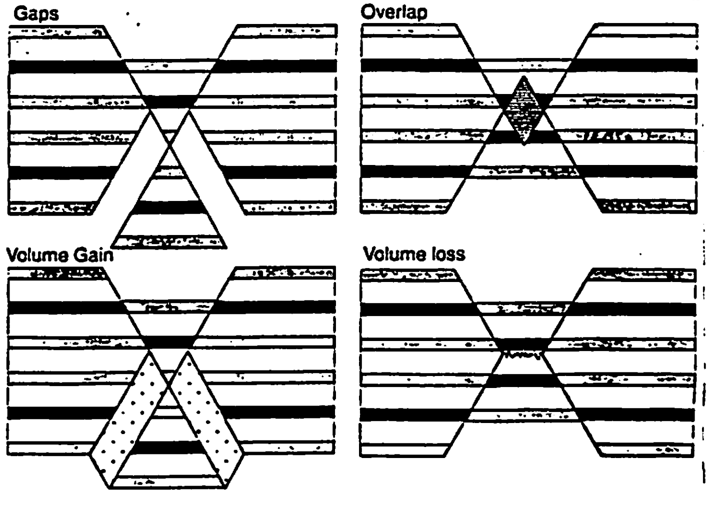
Graben are formed when the hanging-wall block that forms the trench floor moves downward relative to the footwall blocks. As such, graben are found in extensional environments. They can be formed either by a purley lateral motion of the crust away from the location of the graben or by intrusion from below that domes up the crust and causes the extension (see Yingst and Keszthelyi, this volume).

Half-graben occur when there is a single listric fault, such that as the hanging-wall block moves away from the footwall block, material from the hanging-wall block slumps down into the resulting depression.

The above diagrams are for the simple case, in reality, there are some volume problems at depth, and there are a number of ways do deal with them. One way is just to invoke a ductile region at depth, such that in the region where you would get a volume problem, you instead have your blocks fill in the spaces by ductile deformation. Another way is to have conjugate normal faulting, where the bounding faults of the graben alternate in their faulting activity.



Typical geometric features of horst (H) and graben (G) structures produced by the activity of conjugate normal fault systems.



That explains their cross-section, but all graben must come to an end (usually they have two) somehow. Depending on the local geology and state of regional stress, graben can terminate in a number of different ways. They can terminate in ramps that either connect the graben floor to the surrounding topography or ramps that bring the rift shoulders down to the surrounding topography. They may also widen out and terminate in a number of normal faults that splay out from the mouth of the graben. They can also intersect another graben at an angle and terminate that way.

Extraterrestrial Graben

Grabens are seen on almost all of the terrestrial bodies in the solar system. Their ubiquitousness is a little weird, considering that we believe only the Earth has plate tectonics, and therefore the main source of extension on the Earth cannot be used to explain these extensional features on other planets. The following is a list of the terrestrial bodies (that we have some surface data for, *e.g.*. not Pluto/Charon) that have graben or extensional features

Mercury
Venus
The Moon
Mars
Europa
Callisto
Ganymede
Io
Enceladus
Mimas
Tethys
Dione
Rhea
Miranda
Titania
Ariel
Triton

On worlds like Mercury, Callisto, and the Moon, the grabens are formed as the result of relaxation of the basin-forming impact craters. Over time, as these huge structures relax, material moves back towards the center, and forms concentric graben. On Venus, grabens are observed near coronae and other uplifted structures, indicating that they are the result of extension caused by intrusion from below. An additional cause of graben on the Moon is from the loading of the crust by the Maria. The basalt that poured out is a heavier load than the crust can support, and as the Mare lavas weigh down the crust, they cause extension and graben formation tangential to the boundaries of the Maria.

On Mars there are all kinds of graben, of a number of sizes, running all over the place. They range in size from a few kilometers across to the granddaddy of them all, the Valles Marineris, whose main graben is about 3000 km long, averages about 100 km across, and is about 5 km deep. It is thought that many of the graben on Mars are due to the effect of the creation of the Tharsis bulge which domed up a large section of the crust of the planet. However, we also see volcanic features like Alba Patera that have loaded the crust and have caused graben that way. Mars presents a rather difficult puzzle, because there are a number of places where graben seem to run at right angles to each other, indicating a significant change (if not a number of them) to the nature of extension in these regions.

I won't say much about the outer solar system satellites that I have listed. Many are icy bodies that show a large amount of extension that nobody can seem to satisfactorily explain.

So we think that explanations like crater relaxation and loading by lava are adequate answers to the reasons for some extension, but these are very local phenomenon and do not give us good answers for the more global tectonics that we see on Venus, Mars, and the outer satellites. Maybe upwelling mantle plumes are responsible, maybe some sort of global contraction is the culprit. Whatever the case, a lot more study and a lot more data (seismic data would be quite useful) are needed before an adequate answer can be given.

Instead of making this handout ten pages long to include a bunch of really pretty extraterrestrial graben pictures, I have just listed an awful lot of references, should you wish to take a look.

References

Baer, G., G. Schubert, D.L. Bindschadler, and E.R. Stofan. Spatial and temporal relations between coronae and extensional belts, northern Lada Terra, Venus. *J. Geophys. Res.* **99**, 8355-8369. 1994.

Banerdt, W. B., R. J. Phillips, N. H. Sleep, and R. S. Saunders. Thick Shell Tectonics on One-Plate Planets: Application to Mars. *J. Geophys. Res.* **87**, 9723-9733. 1982.

Banerdt, W. B., M. P. Golombek, and K. L. Tanaka. Stress and Tectonics on Mars. In: *Mars*. Tucson, AZ, University of Arizona Press, p. 249-297. 1992.

Davis, P.A., K.L. Tanaka, and M.P. Golombek. Topography of closed depressions, scarps, and grabens in the north Tharsis region of Mars: Implications for shallow crustal discontinuities and Graben formation. *Icarus* **114**, 403-422. 1995.

Hansen, V.L., and J.J. Willis. Ribbon Terrain Formation, Southwestern Fortuna Tessera, Venus: Implications for Lithosphere Evolution. *Icarus* **132**, 321-343. 1998.

Kargel, J.S., Pozio, S. The Volcanic and Tectonic History of Enceladus. *Icarus* **119**, 385-404. 1996.

Lucchitta, B.K., N.K. Isbell, and A. Howington-Kraus. Topography of Valles Marineris: Implications for Erosional and Structural History,. *J. Geophys. Res.* **99**, 3783-3798. 1994.

Morrison, N.D. A refined view of Miranda. *Mercury* **18**, 55-61. 1989.

Pappalardo, R.T., J.W. Head, G.C. Collins, R.L. Kirk, G. Neukum, J. Oberst, B. Giese, R. Greeley, C.R. Chapman, P. Helfenstein, J.M. Moore, A.S. McEwen, B.R. Tufts, D.A. Senske, H.H. Breneman, and K. Klaasen. Grooved Terrain on Ganymede: First Results from Galileo High-Resolution Imaging. *Icarus* **135**, 276-302. 1998.

Plescia, J.B. Geological terrains and crater frequencies on Ariel. *Nature* **327**, 201-204. 1987.

Thomas, P.G. The tectonic and volcanic history of Rhea as inferred from studies of scarps, ridges, troughs, and other lineaments. *Icarus* **74**, 554-567. 1988.

Thomas, P.G. and P. Allemand. Quantitative analysis of the extensional tectonics of Tharsis bulge, Mars – Geodynamic implications. *J. Geophys. Res.* **98**, 13,097-13,108. 1993.

Turtle, E.P. and H.J. Melosh. Stress and Flexural Modeling of the Martian Lithospheric Response to Alba Patera. *Icarus* **126**, 197-211. 1997.

References Jay wanted me to read:

Golombek, M.P. and G.E. McGill. Grabens, basin tectonics, and the maximum total expansion of the moon, *J. Geophys. Res.* **88**, 3563-3578. 1983.

Wise, D.U., M.P. Golombek, and G.E. McGill. Tectonic evolution of Mars. *J. Geophys. Res.* **84**, 7934-7939. 1979.

Wise, D.U., M.P. Golombek, and G.E. McGill. Tharsis Province of Mars - Geologic sequence, geometry, and a deformation mechanism. *Icarus*, **38**, 456-472. 1979.

theories[6] invoke more common depleted harzburgite[7] as the kimberlite protolith which has been metasomatised by deep seated CO_2-rich asthenospheric melts.

Lamprophyres are a group of dark porphyritic igneous rocks, rich in phenocrysts of mafic minerals, especially biotite, hornblende and pyroxenes, with a fine grained ground mass of the same minerals plus either feldspars or feldspathoids. They are commonly agpaitic, where Na+K/Al cations are greater than unity. Assemblages involving different dominant mafic and felsic minerals are assigned different names. Of these, the term minette refers to a lamprophyre characterised by phlogopite and K-feldspar where K is abundant and Na is poor (K_2O 3.3 - 7.3 wt% and Na_2O 1.3 - 2.9 wt%).

Lamprophyre should not be confused with the term lamproite which was introduced by the eminent petrologist, Niggli in 1920 and refers to a broadly similar rock which has a genetic similarity to kimberlites. He classified a group of rocks to which had previously been assigned a variety of names depending on their locality and which at the same time possessed the then unusual characteristic of having both very high K_2O and MgO contents. The terms lamproite comes from the Greek 'λαμπροσ' meaning 'glistening' and refers to the common presence of phlogopite phenocrysts in holocrystalline samples. Lamproites typically contain an assemblage of phlogopite, diopside, richterite, enstatite, sanidine, leucite, secondary serpentine phenocrysts in a glassy matrix.

Aghathla minette

The minette zone includes both aphanitic[8] and lamprophyric textured rocks where the lamprophyres are typical of those found throughout the region. The lamprophyres consist of euhedral phlogopite and diopside phenocrysts surrounded by Ti-magnetite, clinopyroxene with interstitial sanidine, analcime and calcite. The phlogopites are zoned with more Mg-poor rims typical of the evolution of a crystallising basic melt. The clinopyroxenes have spongy cores which could either represent initial orthopyroxene xenocrysts reacted with the minette liquid to form clinopyroxene and biotite intergrowths or else be due to the remelting of early formed phenocrysts due to rapid decompression on eruption up the pipe. The latter explanation concurs with the belief that related kimberlites travel through the crust extremely quickly (some authors suggest 70km/hour) as evidenced by the occasional occurrence of metastable diamond.

Agathla kimberlite

The circular cross section and neck-like morphology are typical of kimberlites from worldwide localities, however the mineralogy is a little unusual. Incompatible element phyric phlogopite and perovskite are not apparent crystallisation products of the kimberlite here and in particular, Ti, K and P contents from the more extensively studied Buell Park kimberlite are far lower than those for other kimberlites[9].

---

[6] Girnis, A. V. et al. (1995) *Earth Planet Sci Lett.* **134**, 283-296

[7] Harzburgite is a peridotite characterised by an assemblage of olivine and orthopyroxene

[8] Aphanitic rocks are volcanic rocks whose constituents cannot be discerned by the naked eye

[9] Schmitt, H. H. et al. (1974) *Geology of Northern Arizona*, G.S.A., 672-698

Xenoliths

The minette and tuff-breccia is found to contain dunitic peridotite, garnet granulite and various crustal metamorphic, granitic and sedimentary rocks. Interestingly, like many of the northern Navajo minettes, Agathla also incorporated garnet peridotite xenoliths unlike the more southerly, Arizonan minettes which only exhibit spinel peridotites. Evidently the sampled cratonic lithosphere was thicker towards the north in the mid-Tertiary.

Origin of the minettes and kimberlites

It is not altogether clear what the genetic relationship between the minette and kimberlite is, both from a temporal and from a regional point of view. However, clearly they are both rocks of similar provenance in that they are volatile and alkali rich and so it is possible it is likely that their emplacement is closely related. A popular theory for minette / kimberlite interrelation has been proposed following study of the Green Knobs diatremes, NM[10]. Accounting for crustal contamination, the peculiar mineralogy of a lack of incompatible element bearing phases suggests that the kimberlites are not partial melt products but were always in a gaseous-solid state. It is suggested that the kimberlite is essentially a conglomeration of water and CO_2 and relatively cool metasomatised garnet peridotite which reached equilibrium on ascent. This vapour phase is proposed to have formed on the intrusion of a minette melt into the mantle where deep seated deformation has occurred.

So where are the diamonds?

Kimberlites attract most of their interest due to the common presence of diamonds as an accessory mineral. Diamonds have been found in the U.S., although not in commercial quantities. The closest occurrences are in outcrops around the CO-WY border[11]. None of the Navajo kimberlites have yielded diamonds however, which can be explained by the particular characteristics of the stability of diamond (Fig. 3). In order for diamond to be found in a kimberlite (or for that matter any igneous rock); the magmatic source rock must contain significant atomic carbon at such a depth as to lie within the stability field of diamond (rather than graphite); the rate of ascent

---

[10] Smith, D. and Levy, S. (1976) *Earth Planet Sci. Letters* **29**, 107-125

[11] The largest U.S. diamond, of ~ 80 carats, was discovered here and is displayed in the New York headquarters of Tiffany's

must be rapid enough to preclude transformation to the low pressure polymorph and the oxygen fugacity must remain at such a state as to preclude the oxidation of carbon to CO_2 or its reduction to CH_4 even at low pressures (Fig. 4). Kimberlites and lamproites are the only igneous rocks which can maintain an oxygen fugacity at low pressure appropriate for preserving the chemical stability of diamond. In contrast, if deep mantle diamonds were entrained into ocean island basalts they would not be found as xenocrysts as they would have burned to form CO_2 during the last 20km of ascent to the Earth's surface (Fig. 4). Not all diamonds in kimberlite look pristine, however, which suggests that not all kimberlites don't burn their diamonds.

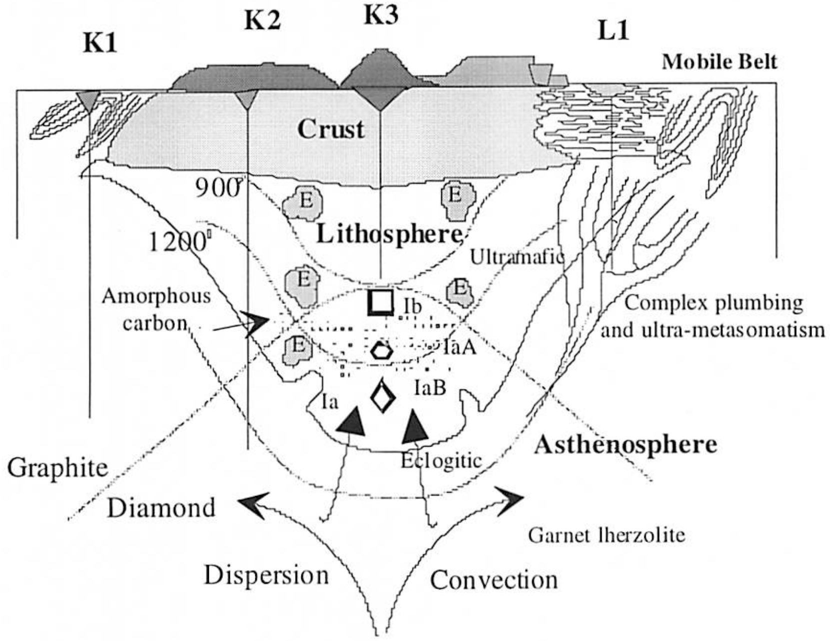


Figure 3 Kimberlites, lamproites and the formation of diamond in the cratonic lithosphere

From Figure 2 of Haggerty (1986).[12] K1 - K3 and L1 are typical kimberlite (K) and lamproite (L) sampling profiles. The range of diamond shapes and aggregation state with depth of formation are indicated by square, hexagon and diamond shapes and the terms Ib, Ia, IaA and IaB are as described in the text. Geotherm temperatures are in °C. The diagram is scaled to a lithosphere thickness of approximately 200 km.

Assemblages in xenoliths within the nearby Moses Rock dyke suggest that the Navajo kimberlites may have formed as deep as 200 km. As they also occur within the middle of the Colorado Plateau, corresponding to scenario K3 of Fig. 3, on this basis they could incorporate diamond. It is not clear what the oxygen fugacity of the Navajo kimberlites was, however it is quite possible that the volatile composition achieved from this present unusual source of volatilised minette associated peridotite is different from that achieved by the more typical partial melting of metasomatised host rock. It is concluded, therefore, that if free carbon is present in the host rock, any diamonds have been burned on ascent.

---

[12] Haggerty, S. E. (1986) *Nature*, **320**, 34-38

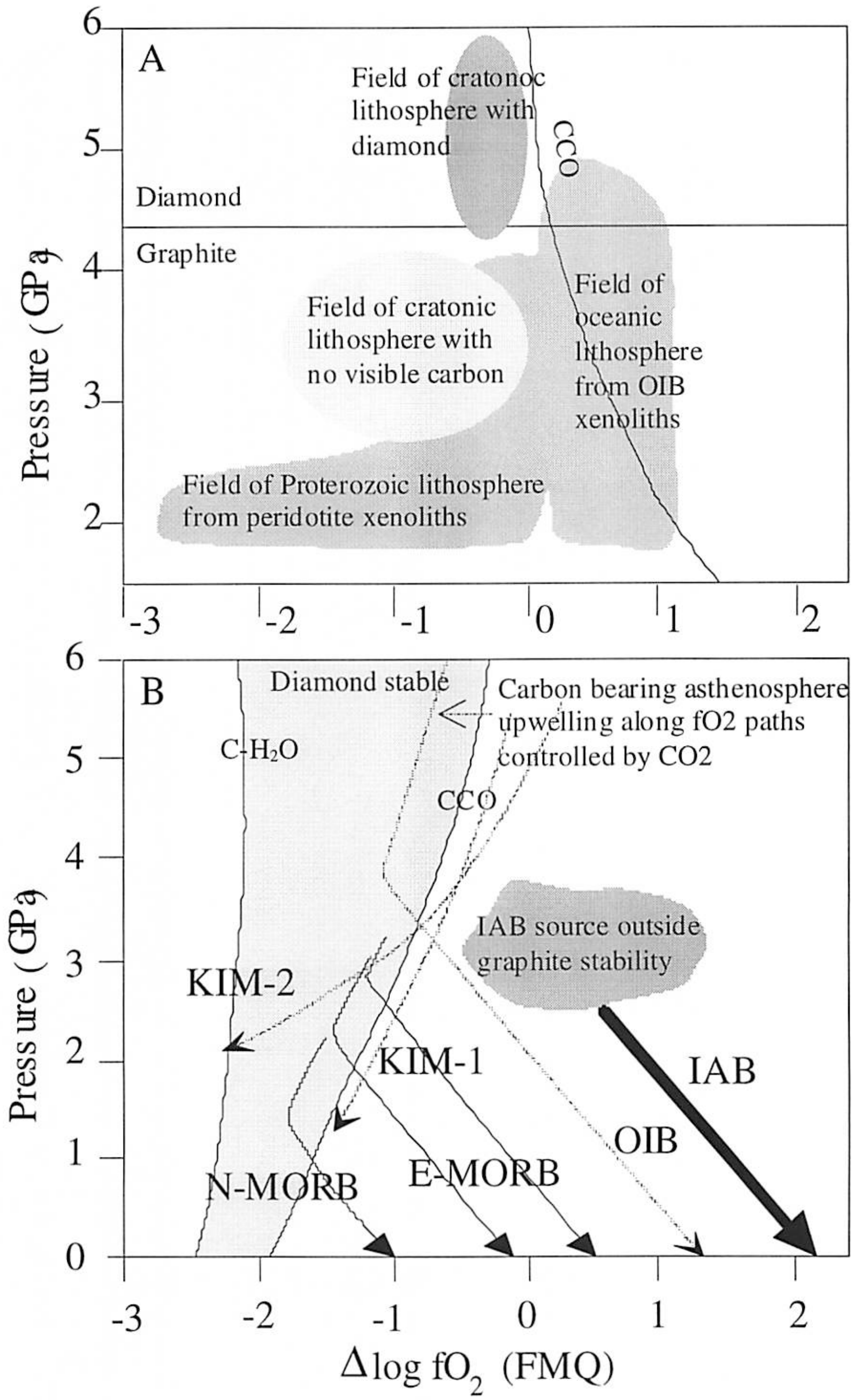


Figure 4 Pressure against fO_2 relative to FMQ.

A - CCO is calculated on the basis of a cratonic geotherm of 40mWm^{-2}. Fields of mantle lithospheric material are generally lie on the diamond stability side of CCO even at relatively shallow depth (~60 km). After Ballhaus (1993)[13].
B - CCO is calculated for an eruptive geotherm. On the final stages of magmatism, all oceanic basalts rapidly become too oxidised for diamond to remain stable. It is only kimberlite magma which, on ascent, remains predominantly within the stability field of diamond.

---

[13] Ballhaus, C. (1993) *Contrib. Mineral Petrol.* **114**, 331-348

The Four Corners Region: A Glowing Testament to the Nuclear Age

Mark T. Hutchison

Introduction

The four corners region comprising of the borders of Colorado, Utah, New Mexico and Arizona is inexorably linked with the nuclear age. The area has a wealth of uranium bearing mineral reserves and their inevitable enrichment facilities and has also been the playground of what may now seem a bizarre mix of gas reserves and nuclear explosives.

Mining, processing and other contaminated sites

The following statistics are available for the four states:

	AZ	NM	UT	CO
Uranium bearing mine	340	1311	1252	238
Uranium Mill *	1	10 (7) †	5 (0)	6 (1)
NPL Sites	6	8	5	2
Offsite Nuclear Tests	0	2	0	2

* Number of UMTRAP sites
† The Uravan Mill is quoted on the NPL
NPL stands for National Priorities List, these sites are the subjects of the implementation of immediate and extensive emergency containment and control measures.

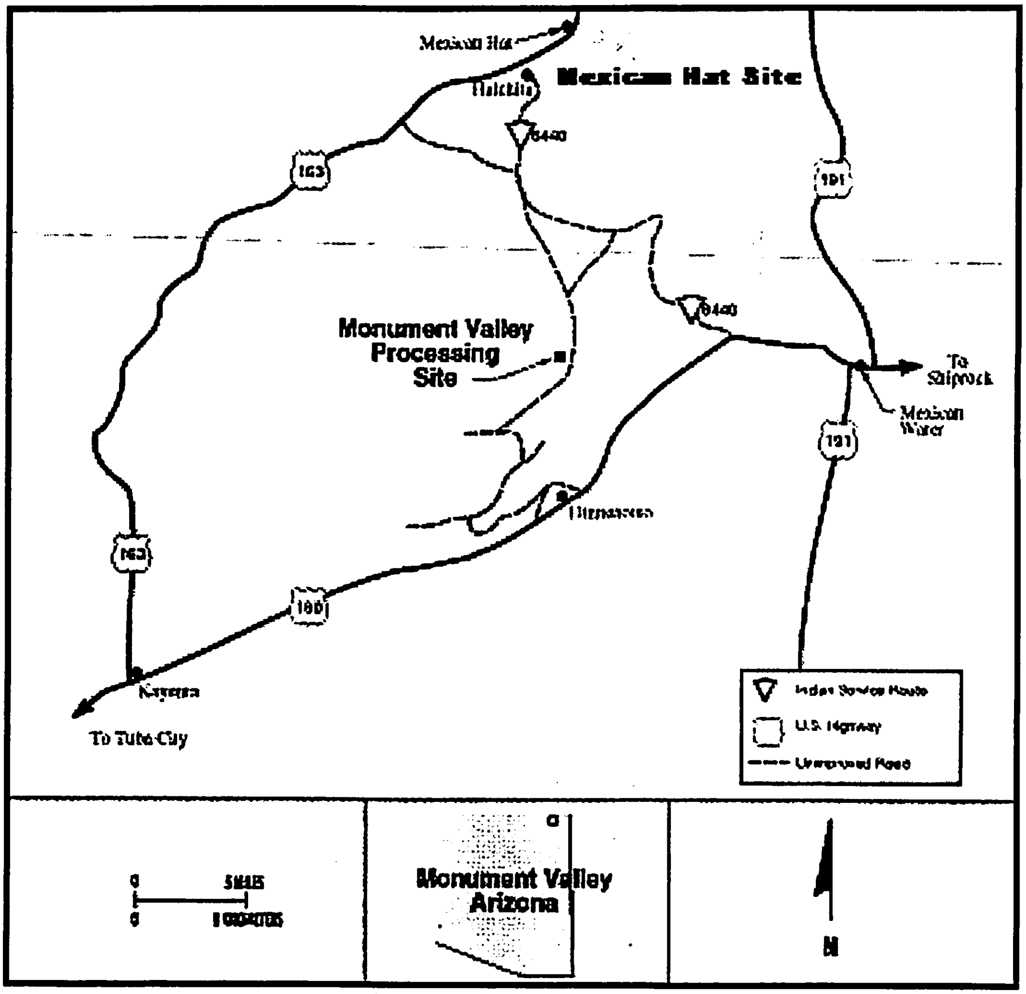
Of particular note concerning the route of this fieldtrip are the following sites:

Davis-Monthan AFB (NPL) Pipe/washdown contaminated site, Tucson AZ
Williams AFB (NPL) contaminated pipe site, Chandler, AZ
19th Ave. Landfill (NPL) Radioactive waste dump site, Phoenix, AZ
Monument Valley Mill (UMTRAP) Ongoing cleanup, Monument Valley, AZ
Monticello Tailings Site (NPL) Tailings landfill, Monticello, UT
Monticello Vicinity Properties (NPL) Radioactive non-federal site, Monticello, UT

Many mills are happily going about their business or have been spruced up for sale. Some however, have reached a point where they are the subject of the federal government's Uranium Mill Tailings Management Project (UMTRAP). The Monument Valley and Tuba City former processing sites are two of 24 uranium mill processing sites designated by the Uranium Mill Tailings Radiation Control Act for remediation by the Department of Energy. During the 1960's, private firms processed most uranium ore in the United States for the Atomic Energy Commission, a predecessor of the Department of Energy. Congress passed the Act in 1978 in response to public concern regarding potential health hazards from long-term exposure to uranium mill tailings. It authorized the Department of Energy to stabilize, dispose of, and control uranium mill tailings and other contaminated material at 24 uranium mill processing sites and vicinity properties.

The former **Monument Valley** mill and tailings site is on Navajo Nation land 21 kilometers (13 miles) east of Monument Valley Tribal Park in Arizona (Fig. 1). It is located

27 kilometers (17 miles) south of the Mexican Hat site and is about eight kilometers (five miles) south of the Utah-Arizona border. The site covered approximately 37 hectares (90 acres); tailings were located in two piles covering about 12 hectares (30 acres). The older heap-leach pile covered about four hectares (10 acres). The newer tailings pile was cone-shaped, about 17 meters 55-feet) high, covered about eight hectares (20 acres) and contained over two-thirds of the tailings at the site. The site also contained the old mill building foundations, contaminated soil, and wind-blown material. Surface remedial action has been completed and the source of contamination has been stabilized. However, residual milling-related contaminated ground water remains.



The former **Mexican Hat** mill and tailings site covered approximately 95 hectares (235 acres) and is located on Navajo Nation land at Halchita, Utah, about 2.4 kilometers (1.5 miles) southwest of Mexican Hat, Utah. Before remedial action, the site contained two adjacent piles of tailings. One covered 10 hectares (25 acres) and the other covered 19 hectares (48 acres). The site also contained seven mill buildings and associated debris, a concrete pad, contaminated soil, and wind-blown material. Residual milling-related contaminated ground water remains and although the disposal site is located on Navajo Nation land, the long-term surveillance of the disposal cell is the responsibility of the Department of Energy through a Custodial Access Agreement.

The **Monticello** sites, which are included on the National Priorities List, are located near the City of Monticello in San Juan County, Utah. The Monticello Mill Tailings site comprises three operable units: the mill site, a 44-hectare (108-acre) tract located along Montezuma Creek, south of the City of Monticello; 25 peripheral properties located north and south of the mill site; and the surface (Montezuma Creek) and ground water located beneath and extending beyond the mill site. Although the milling process recovered about 93 percent of the uranium, the tailings that remain contain several radioactive elements, including uranium, thorium, radium, polonium, and radon. The total volume of tailings, process-related contaminated material, and tailings-contaminated soil is estimated at 2.0 million cubic meters (2.6 million cubic yards) throughout the Monticello sites. The tailings piles at the mill site were stabilized and covered with soil in 1961 to limit their dispersal or use. However, uranium mill tailings and byproduct materials, which were produced during uranium milling, contaminated the mill site, peripheral properties, and surface and ground water. Contamination also occurred in the City of Monticello from wind-blown materials and from the use of mill tailings as construction and fill materials. The whole cleanup operation for this site is estimated to cost in excess of $110 million.

Nuclear detonations for peacetime means

In the early 60s, following the test ban treaty which precluded atmospheric testing of nuclear explosives, the U.S. state department instigated a series of tests under the auspices of the Plowshare Program. The motivation of these tests was to utilise nuclear explosions for a variety of peaceful means and is summarised in a comment at the time by Dr. C. L. Dunham of the Federal Division of Biology and Medicine:

> *"As we learn more and more about how to control and reduce the amount of radioactivity released to the environment by a nuclear explosion their potential uses become tremendous. Today one can talk factually about digging a sea-level canal to connect the Pacific and Atlantic Oceans at a cost considerable less than that by conventional methods. One can talk seriously about using similar explosive techniques to cut passes through mountainous regions. The possibility of freeing natural gas trapped in rock has become so imminent that large private gas companies in the United States are pooling their resources with the Government to make such a development a reality. It has been estimated that natural gas resources may be very greatly increased in this manner. So you can see that nuclear energy is not only a source of power in itself but can be used indirectly to extended the fossil fuel supplies of the world.*
>
> *Another program in peaceful uses of nuclear explosives involves detonating them underground in appropriate relationship to target materials to produce transuranic elements. Exploration of the detailed chemistry of many of these awaits their production in usable quantities. Whether this approach is the answer to the question problem remains to be seen."*

Project Gnome was the first nuclear explosion of the Plowshare program. The 3.1 kiloton nuclear explosion was detonated on December 10, 1961 about 25 miles southeast of Carlsbad, New Mexico, in a salt formation 1200 feet beneath the earth's surface. The Gnome explosion produced a cavity with a total volume of about 960,000 cubic feet and melted about 2400 tons of rock. This melted rock was intimately mixed with about 13,000 tons of salt rock that was hurled into the cavity by implosion (steam pressure, produced from water in the rock, apparently was sufficient to blow off blocks of rock from the cavity walls). In addition, an estimated 15,000 tons of rock collapsed from the roof. After everything had settled, a dome-shaped chamber 134 to 196 feet in diameter, and about 75 feet high remained. Most of the non-gaseous radioactive residue was trapped in the mixture of rubble and once-molten salt below the chamber. The project did not provide a full measure of the experiment because of some unanticipated explosion outcomes and equipment delays. Although it had been planned as a contained explosion, GNOME vented to the atmosphere. A cloud of steam started to appear at the top of the shaft two to three minutes after the detonation. Gray smoke and steam, with associated radioactivity, emanated from the shaft opening about seven minutes after the detonation. Radioactive materials vented to the atmosphere about 340 meters southwest of ground zero. There were 48 subsurface experiments involved, making GNOME the most heavily instrumented seismic test in history.

Gnome was a precursor to further tests conducted in Colorado and New Mexico. More relevant to the geology of the four corners area these were conducted to stimulate the release of natural gas. On the 10th of December, 1967 a 26-kiloton detonation was performed at the **Gasbuggy** site, some 55 miles east of Farmington New Mexico. The canister (about 13-1/2 feet long by 18 inches in diameter) was lowered 4,240 feet underground and the hole was filled to within 50 feet of the surface with cement before the explosion. Subsequently, on September 10, 1969 a 43 kiloton fission-type nuclear explosion was detonated 8,426 feet underground at **Rulison** field, Garfield County, Colorado. The nuclear explosion produced a zone of fractured rock and a "chimney" of rock rubble around and above the detonation point. The void spaces produced provided a reservoir into which the natural gas flowed. A standard gas well was then drilled to the chimney, allowing recovery of the gas. The re-entry drilling operations were accomplished through a separate re-entry well located 300 feet southeast of the emplacement well. During production testing, the gas was burned, or "flared," at the surface and tests were done to check total radioactivity released; to identify the radionuclides likely to be of the greatest importance (radionuclides of primary interest were tritium and krypton-85); and to make judgements concerning the possible hazards of using such gas under commercial and domestic conditions. Projects Gasbuggy and Project Rulison were successful in that they indicated that gas flow in tight reservoirs can indeed be stimulated with nuclear explosives. A further test on May 17, 1973 involved three simultaneous detonation of 30-kiloton nuclear explosives at Fawn Creek, **Rio Blanco** County, in Northwestern Colorado. The three devices were placed at different depths (5840, 6230, and 6690 feet) in the same hole. analysis in mid-June, 1974, revealed that there was no communication between the top and the lower chimneys. As a result, drilling of a re-entry well to enter the middle chimney area was attempted, but without success. As an alternative the bottom chimney was entered instead. The bottom chimney reentry well was completed in early November 1974. A short flow test of the bottom chimney was conducted near mid-December 1974. During this flow test, Tritium, Krypton 85, Cesium 137 and Strontium 90 were detected.

Both the D.O.E. and the petroleum industry were encouraged by these tests and a number of papers appeared in the literature proposing actual production detonations. One of these articles, published in the 1973 Memoirs of the Four Corners Geological Society concerned the Wagon Wheel Project which proposed an exploitation of the gas reservoirs of the Pinedale Anticline, Sublette County, Wyoming[1]. The Wagon Wheel Information Committee was established in July, 1971, in Pinedale, Wyoming, after the local newspaper, the *Pinedale Roundup*, published a letter from the El Paso Natural Gas Company to Wyoming Congressman Teno Roncalio. This letter indicated that Congress would give twelve million dollars to El Paso Natural Gas to fund underground nuclear tests twenty miles south of Pinedale. Supported by the Atomic Energy Commission, the tests were intended to develop natural gas resources. However, the committee learned (partly

---

[1] Shaughnessy, J. and Butcher, R. H. (1973) Memoirs of the Four Corners Geol. Soc. 185-207

from similar tests in Colorado) that structural damage was certain to occur, that the air and ground water could be contaminated, and that major earthquakes and radiation poisoning could result. The Wagon Wheel Information Committee used a variety of strategies to prevent the nuclear detonations. These included public meetings, letters to newspapers, petitions, flyers, presentations, and political party platforms. The committee also sponsored school surveys, fund raising "blasts," a novel, picnics, lobbied Congress, and, perhaps most important, conducted a straw poll which indicated that the majority of voters were against the project. Members of Congress acknowledged that the committee was one of the best informed and hardest working citizens groups ever to lobby Washington. The Atomic Energy Commission and El Paso Natural Gas eventually abandoned Project Wagon Wheel. This was the last gasp of the US's involvement in the use of nuclear explosives for the extraction of gas.

Other interesting branches of the Plowshare program were the following:

Project Sedan was intended to provide safety data related to radioactivity, seismic effects, and air blast and was carried out at the Nevada Test Site. This was in addition to the objective of investigating excavation and cratering effects from explosions up to the 100-kiloton yield range. The detonation took place July 6, 1962, 635 feet below the surface. The event formed the largest excavation ever produced by a single human-made explosion. The crater measured 1200 feet in diameter and 300 feet deep. Biomedical studies of the Sedan test included: population studies of lizards, effects on close-in vegetation, food-chain relationships of radioiodine and of radiostrontium. Other studies were also done on: the neutron activated products in plants and soils and the concentrations of radionuclides in plants grown in ejecta.

Project Palanquin occurred on April 14, 1965 at the Nevada Test site. It was buried at a depth of 280 feet with a yield of 4.3 kilotons. The initial design depth was 200 feet but was changed to 280 feet as a safety precaution. The hole was let open an additional 320 feet below the device to test how much material could be trapped. The primary purpose of this event was to measure the effectiveness of trapping material during an explosion.
The Palanquin event did create a cloud 3200 above the surface. Radioactivity from this event was measured offsite. A second entrapment event named Bantam scheduled for October 1965 was canceled.

Row charge experiments, **Projects Buggy A-E**, conducted at the Nevada Test Site, were used to assess the possibilities for canal excavation.

Reference Sites

Department of Energy: *http://www.em.doe.gov/bemr96/*
Colorado Dept. of Public Health and the Environment: *http://www.cdphe.state.co.us/*
Project Plowshare: *http://www.fortlewis.edu/~jasobesk/Plowshare/*
World Information Service on Energy: *http://antenna.nl/wise/uranium/umtr.html*
American Heritage Center: *http://www.uwyo.edu/AHC/hh/fall97/page5.htm*
Proposition One Committee: *http://www.prop1.org/prop1/radiated/*
The Bureau of Atomic Tourism: *http://www.oz.net/~chrisp/atomic.html*
Office of Science and Technical Info.: *http://www.osti.gov/waisgate/opennet.new.html*

Cliff Recession: Toreva-block landslides

Gareth S. Collins
(April 1999)

ABSTRACT

This presentation will highlight a certain type of mass movement process, typical of this area, known as a Toreva-block landslide. The mechanics of this type of landslide will be discussed briefly, prior to an evaluation of planetary analogues.

THE ARCHETYPAL TOREVA-BLOCK LANDSLIDE

Toreva-blocks owe their name to an American Geologist Parry Reiche who, in 1937, proposed the following classification, a diagrammatic representation of which is provided in Figure 1A...

> *A Toreva-block is a landslide consisting essentially of a single large mass of unjostled material which, during descent, has undergone a backward rotation toward the parent cliff about a horizontal axis which roughly parallels it.*

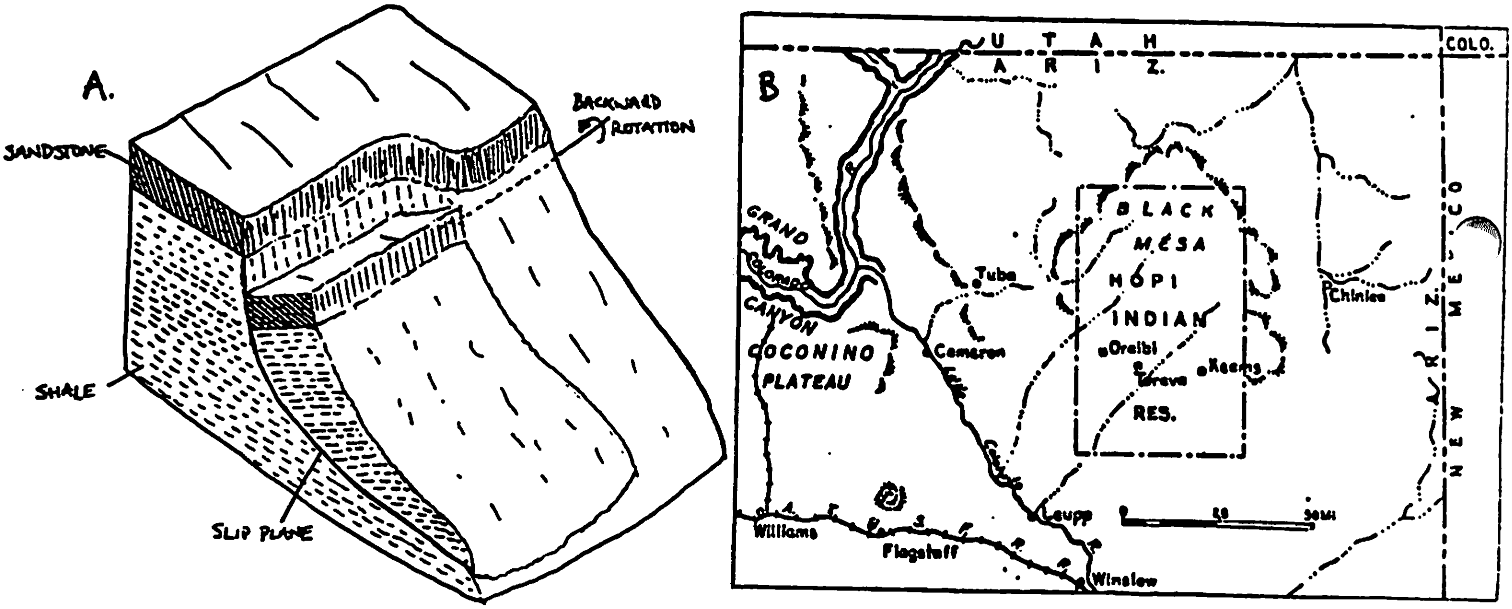


FIG. 1. A: Diagram representing the definition of a Toreva-block landslide. B: Map showing location of Toreva, after Reiche (1937)

These landslides are widely distributed in the southern part of the Colorado Plateau Province. However, it was their 'splendid development' near Toreva (see Figure 1B, for location map) that inspired Reiche to propose their name. In all cases the landslides *floor* in a shale layer underlying cap rocks of sandstone and/or limestone. The cap rocks are notoriously well jointed (Radbruch-Hall, 1977), that is they contain many "partings" formed by the release of tectonic or overburden stresses. Figure 2 shows a geological sketch map of the region through which we will be driving.

Although it seems likely, for reasons discussed later, that the majority of the Toreva blocks formed during the late–post-Pleistocene, there is evidence for much more recent activity: Indian occupation of the district has been intermittent for the past thousand years or more. This is most likely a reflection on the presence of mesa-foot springs which, in turn, owe their existence to the dip-slope surface and subsurface drainage of Toreva-blocks. In addition, two poor examples of Toreva-blocks are known to have formed in historic times. Consequently, a range of ages between a thousand and many thousands of years has been suggested for most of the Toreva-blocks in this area (Reiche, 1937).

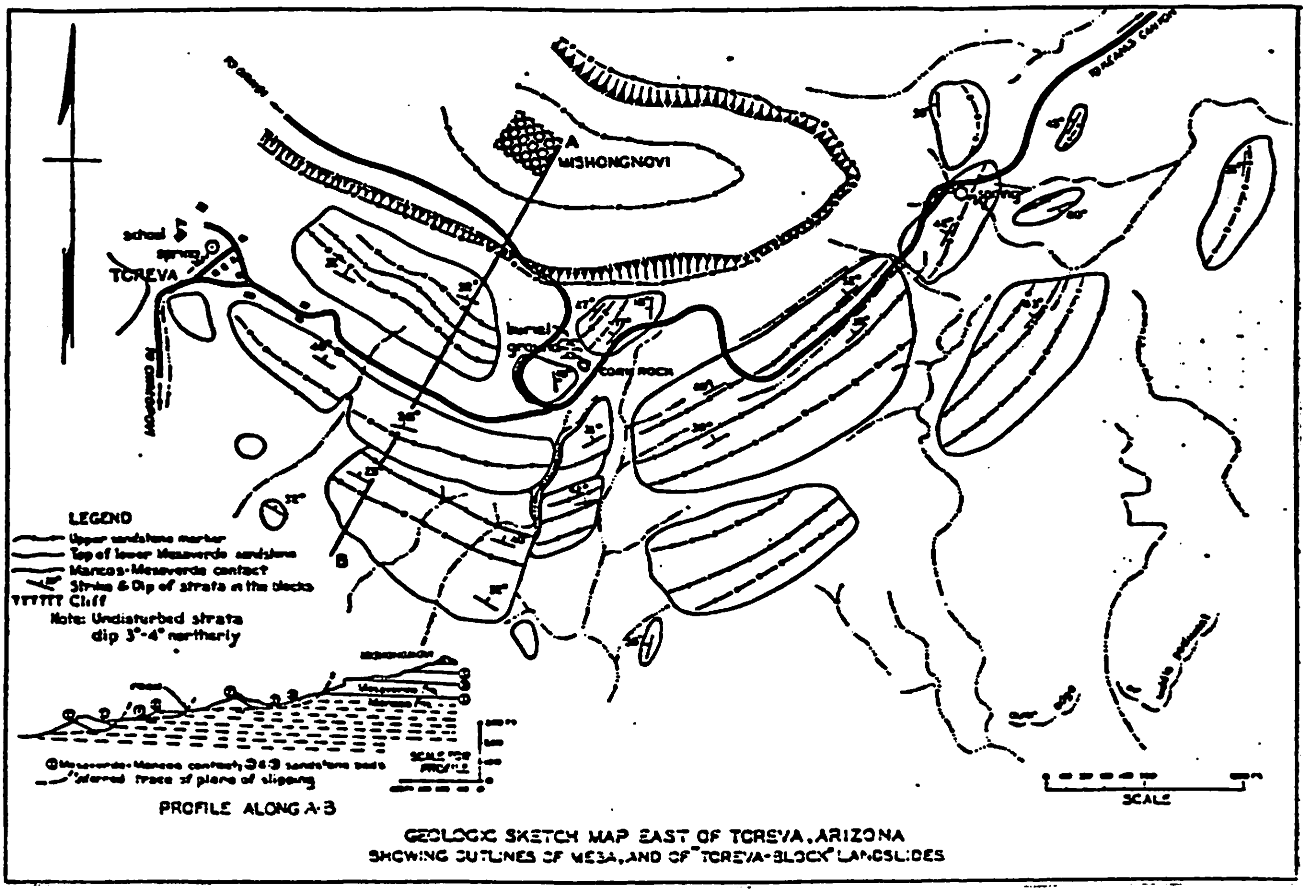


FIG. 2. Geological sketch map east of Toreva, after Reiche (1937)

THE MECHANICS

The mechanics of Toreva-block formation, like any geomorphological process, is a consequence of both the properties of the rocks involved, and the processes acting to modify them...

Material strength

Rocks may be characterized as *soft* or *hard*. Soft rocks such as mudstones and shales, have relatively low intact strength, which is dominated by internal cohesion. In contrast, hard rocks have such high strength, controlled by internal cohesion and frictional properties, that they fail almost exclusively along joints and fractures. Sandstone, limestone and basalt are examples of hard rocks. *In general*, therefore, bare rock slopes are formed on hard rocks, and slope failure occurs when the supporting rock is soft.

Slope Stability

Slope failure occurs when the driving force (shear stress, τ) tending to displace the material exceeds the resisting forces (resisting strength, s). Stability, therefore, represents some balance between shear stress and resisting strength and can be expressed as a safety ratio (Selby, 1982):

$$f = \frac{\textit{resisting strength}}{\textit{shear stress}} = \frac{s}{\tau} \tag{1}$$

Clearly, as f approaches 1 from above, a slope becomes less stable until $f = 1$ and failure is imminent.

Factors controlling the safety ratio

The shear stress τ is a function of: angle of slope (α); gravity (g); mass of sliding material (m)...

$$\tau = mg \sin\alpha \tag{2}$$

The resisting strength s is a function of: effective cohesion (c'), as reduced by the loss of surface tension; internal friction coefficient (ϕ); normal stress (σ) [controlled by angle of slope, mass of sliding material and gravity: $\sigma = mg\cos\alpha$]; pore water pressure (u)...

$$s = c' + (mg\cos\alpha - u)\tan\phi \tag{3}$$

[NB: This simple analysis neglects the presence of any vibrations]

Thus, Equation 1 can be re-written as:

$$f = \frac{c' + (mg\cos\alpha - u)\tan\phi}{mg\sin\alpha} \tag{4}$$

Hence, in order to promote failure, that is lower the safety ratio, f, one or more of the following must occur:

1. Loss of effective cohesion in the slope material: Due to increased pore water pressure.
2. Increase in angle of slope: Perhaps by toe removal.
3. Increase in pore pressure: Most commonly due to a rise in the water table.
4. Reduction in the coefficient of internal friction: Usually by fracturing and jointing.
5. Increase in the mass of the material above the slip plane: usually a result of heavy rainfall. [Note that an increase in mass doesn't necessarily result in a greater likelihood of failure as an increase in mass means an increase in both *normal* and *shear* stress.]

Landslides

Landslides are slope failures that are initiated by slippage along a well defined surface. This surface may be planar, or it may penetrate to some depth as a concave surface along which rotational slip may occur (see Figure 3). It is along this 'potential slip surface' that f must be ~ 1 for a slide to occur.

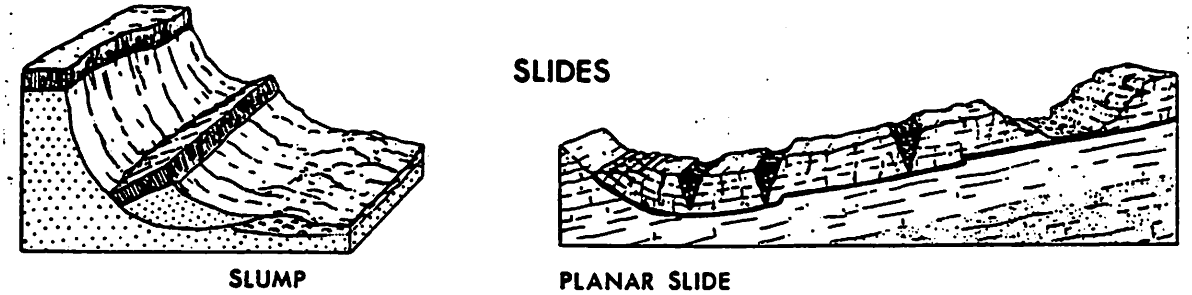


FIG. 3. Diagrams showing the two types of landslides. (a) Slump (Concave slip plane) (b) Planar slide

Whether a slope fails along a planar or concave surface is a function of the subsurface geology. Planar slides occur along planes of weakness, which may be an unconformity, a pre-existing fault, or a thin, underlying layer of weaker rock. Deep rotational slides, however, are confined to thick layers of *soft* rock, which may or may not be capped by harder rocks. Soft rocks have a resisting strength dominated by cohesion. As a result, shear stresses may increase with depth at a greater rate than the resisiting strength, thus allowing deep seated failure. In contrast, *hard* rocks have a resisting strength dominated by *friction*, which is proportional to the overburden pressure. Hence, in a sandstone, for example, the resisting strength increases with depth at a greater rate than the shear stresses and deep failures cannot occur.

Toreva-block Landslides

As mentioned above, the slump blocks at Toreva consist of hard cap rocks (sandstone and limestone) overlying soft shales. The slope failure, in all cases, occurs along a concave slip plane within the thick, underlying shale layer. The primary cause of failure is thought to be the weakening of the soft shale layer due to increased pore water pressure. This most probably occurred during the wetter climatic conditions of the Pleistocene Epoch. Indeed, Pleistocene age lakes appear to have repeatedly formed behind lava-flows in the area. This fact also potentially explains the fresh water emplacement of the travertine deposits found covering the feet of many of the Toreva-blocks (Rogers, 1991).

IN A PLANETARY CONTEXT

Processes similar to those that form Toreva-block landslides are operating on many other slope faces in the Canyon lands. For example, Ford et al. (1974), in their study of mass wastage in the Grand Canyon, state: "It appears that the major collapses of the sheer-walled overlying rocks begin a cycle of rapid cliff retreat shortly after the Bright Angel Shale is exhumed by the Colorado River or one of it's tributaries". Thus, although Toreva-blocks are not a ubiquitous feature, the processes involved in their formation are fundamental to cliff recession in the Canyonlands.

Large rotational slump blocks, analogous to the Toreva-blocks, are also present in contrasting geological settings on Earth. For example, one has been identified in a "new" caldera in Guatemala (Duffield et al., 1993). In this case the cap rock is the cooled, volcanic uppermost crust, and the weaker, underlying layer, is a ductile region of hotter igneous rock.

Landslides are present on other planets and satellites in the solar system, most notably the Moon (Howard, 1973), Mars (Lucchitta, 1979) and Io (Schenk and Bulmer, 1998). Of these, slump blocks similar to Toreva-blocks on Earth have been identified on Mars and Io (see Figure 4). Although detailed analysis is impossible, the study of landslides on these bodies has provided some interesting conclusions...

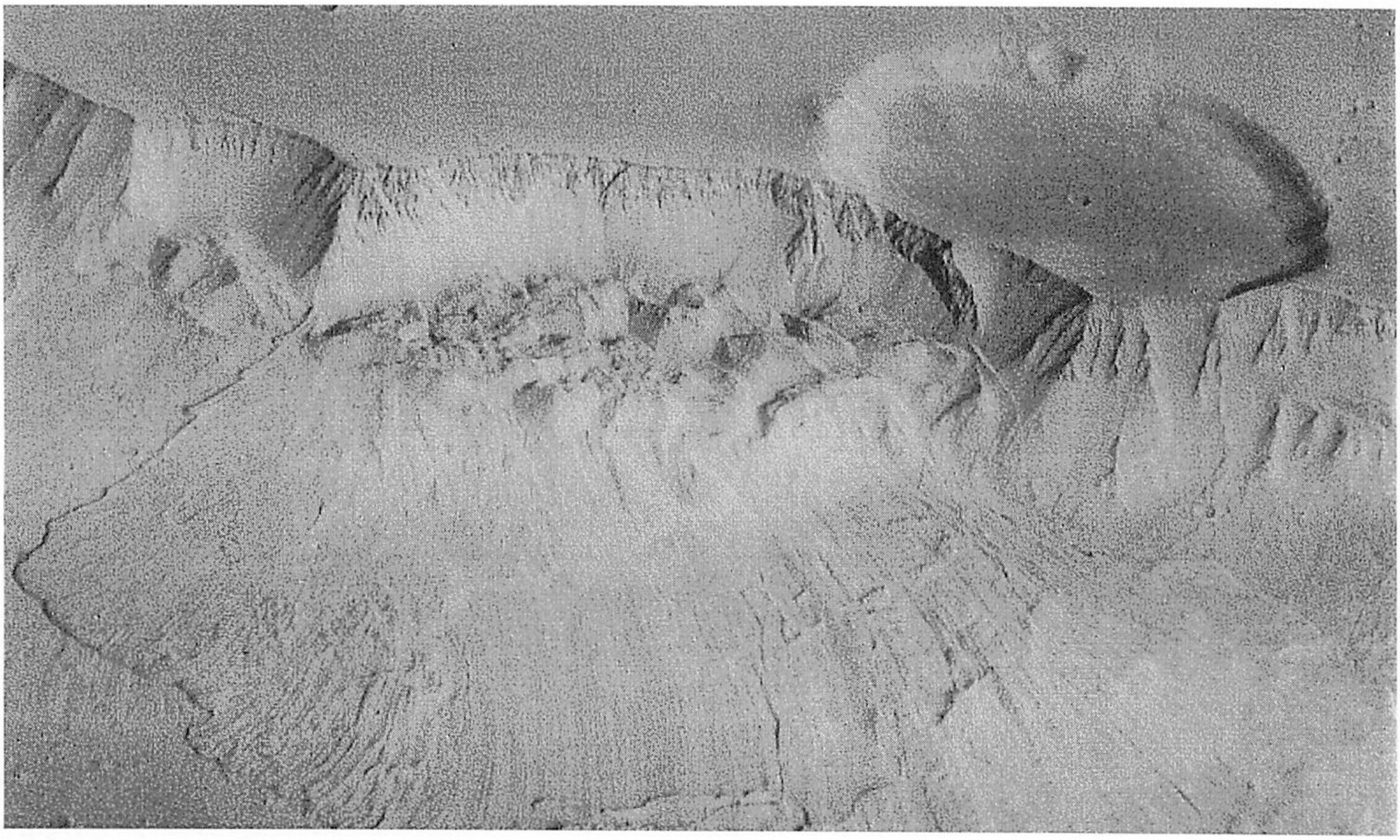


FIG. 4. Photo of slump blocks on Mars similar to those found at Toreva, courtesy of the Electronic Universe Project (www.zebu.uoregon.edu)

REFERENCES

Duffield, W., Heiken, G., Foley, D., and McEwen, A., 1993, Oblique synoptic images, produced from digital data, display strong evidence of a "new" caldera in southwestern Guatemala: Journal of Volcanology and Geothermal Research, **55**, 217–224.

Ford, T. D., Billingsley, G. H., Huntoon, P. W., and Breed, W. J., 1974, Geology of the Grand Canyon Museum of Northern Arizona, 116–128.

Howard, K. A., June 1973, Avalanche mode of motion: Implications from Lunar examples: Science, **180**, 1052–1055.

Lucchitta, B. K., December 1979, Landslides in Valles Marineris: Journal of Geophysical Research, **84**, no. B14, 8097–8113.

Radbruch-Hall, D. H., 1977, The systematic evaluation of landslide incidence and susceptiblity in the United States: Bulletin of the International Association of Engineering Geology, **16**, 82–86.

Reiche, P., 1937, The Toreva-block - a distinctive landslide type: Journal of Geology, **45**, 538–548.

Rogers, J. D., 1991, Toreva Block mega-landslides in the Colorado river channel, Grand Canyon, Arizona: Toreva Block mega-landslides in the Colorado river channel, Grand Canyon, Arizona:, Geological Society of America, 1991 annual meeting, 126.

Schenk, P. M., and Bulmer, M. H., March 1998, Origin of mountains on Io by thrust faulting and large-scale mass movements: Science, **279**, 1514–1517.

Selby, M. J., 1982, Hillslope materials and processes: Oxford University Press.

Sandstone: Wonders and Weathering in the State of Utah

with your hostess with neuroses, Jennifer Grier

> "Sandstone - A clastic sedimentary rock composed of sand-sized grains set in a matrix of silt or clay, and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent of sand. The sand particles usually consist of quartz, and the term "sandstone" when used without qualification indicates a rock containing about 85-90% quartz."

Introduction

The state of Utah is divided into three provinces, the *Plateau Country*, the *High Country* and the *Great Basin.* Since we will actually be visiting Plateau Country, and since it arguably has the most spectacular exposures of sandstone, this discussion will focus mostly on the sandstones of Canyonlands and the Plateau Country. The major geologic units with details on the sandstones are shown in Figure 1.

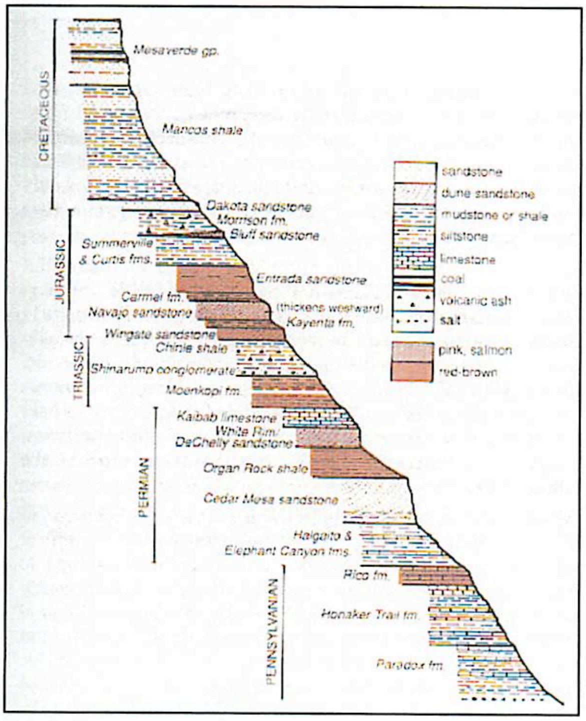


Figure 1 - Generalized stratigraphic section of important Paleozoic and Mesozoic sedimentary units of rock exposed in Utah Plateau Country.

Some sandstones carry abundant evidence of the environment in which they were deposited. In particular, some sandstones show cross-bedding, rippling, dune slumping, and interdune areas indicative of the environment prevailing at the time the sandstone was deposited. The Navajo sandstone was deposited when the large portion of Utah and the surrounding states were covered by a vast sand sea. Other sandstones, such as the White Rim, were laid down in the coastal environment which existed further in the past.

Figure 1 also shows which units of rock are "cliff formers" and which are "slope formers". Harder, more well consolidated units tend to form cliffs as they erode, which softer more friable units tend to crumble more quickly and form slopes. The sandstones in general are hard, strong cliff forming units.

A Closer Look at Regional Sandstones

The deep red Entrada Sandstone contains three major members of Jurassic age; the Moab, Slick Rock and Dewey Bridge members. The Glen Canyon Formation includes the Navajo Sandstone, Kayenta Formation, and Wingate Sandstone. These are triassic in age, except the Navajo. The Navajo Sandstone is a thick, cliff-forming, cross-bedded dune sandstone formation that underlies a large part of southern Utah and NE Arizona. The colorful cliffs, canyons, spires, and monoliths that have been eroded in this stone are responsible for much of the beauty of Zion, Glen Canyon and the Navajo Indian Reservation. The Navajo sandstone has two contrasting colors; various shades of red in the lower part and shades of light gray in the upper. The red Kayenta formation is composed of siltstones and shale laid down in an interlude between the sand dune advances of the Navajo and red Wingate sandstones. The Chinle formation (floodplains) and Moenkopi formations (floodplains and delta) underlie the Glen Canyon Group and are Triassic in age.

"Deposition - The laying down of rock forming material by any natural agent, e.g. mechanical settling."

The Cutler Formation of Permian age includes the White Rim Sandstone, Organ Rock Member and Cedar Mesa Sandstones. The White Rim Sandstone, deposited in a coastal aeolian environment of alternating marine and nonmarine conditions, is a light colored, cliff forming sandstone which overlays the reddish-brown sandstones and silty shales of the Organ Rock Member. The depositional environment for the Organ Rock Member is interpreted to be fluvial channel and related floodplain. The Cedar Mesa sandstone found beneath this member is also light colored, and shows evidence of a depositional regime including both fluvial and aeolian elements, and possibly mudflats.

Under this formation is the Rico Formation, underlain itself by the Hermosa Group of Pennsylvanian age. During the Pennsylvanian a shallow sea covered most of this area. The Hermosa Group includes the Honaker Trail and Paradox formations.

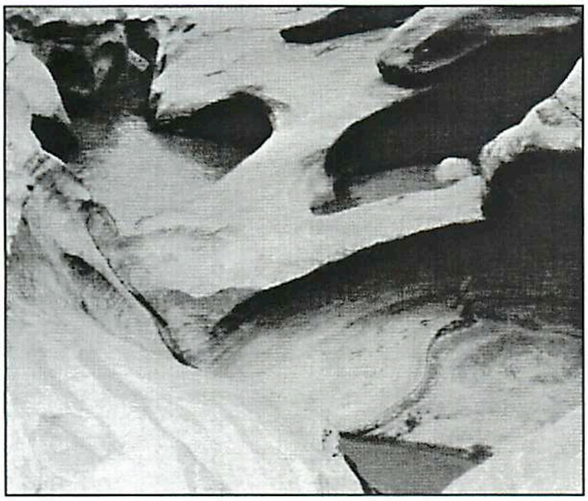


Figure 2 - Eroded pools in Sandstone.

The Provinces and Weathering

Based on climatic and other differences, the sandstone present in the three major provinces of Utah undergoes weathering characteristic of the region and the type of sandstone being weathered. The *Basin Province* of Utah is part of the Great Basin, a basin and range terrain. It is quite arid, and erosion and weathering is controlled predominantly by corrosion by windblown particulate matter and occasional catastrophic flooding. Vegetation is limited, so it does not contribute much to erosion in this area, neither does rainfall. Freeze/thaw cycles do help crack rocks, which allow wind and water to act more effectively. The *High Country* is a higher altitude hilly/mountain province. Here, vegetation and precipitation are much more of a factor in weathering. Also, the steep mountainsides are built of relatively weak rock, and landslides, triggered by heavy snowfalls and the occasional small earthquake, are not uncommon. The *Plateau Country* stands in the rain-shadow of the High Country to its west. The precipitation in this province is scanty, soils are thin and vegetation is sparse. River downcutting, freeze/thaw, occasional floods and most particularly wind, drive the weathering and erosion of sandstone in this region.

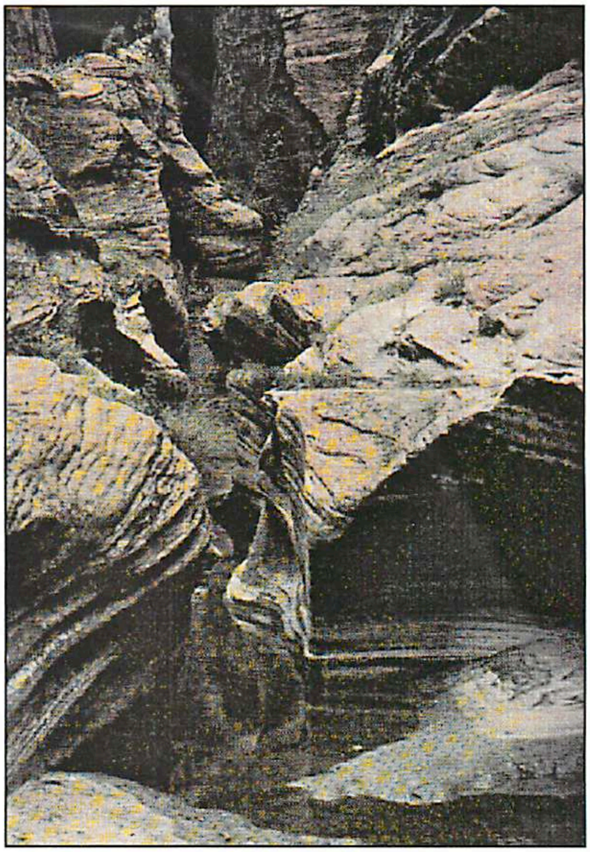


Figure 3 - A view from Echo Canyon, Zion National Park. Stones whirled by stream waters have ground "potholes", and gullies into the sandstone. Erosion allows for the details of cross-bedding to stand out in the Navajo Sandstone.

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

Some Details of Weathering Sandstone

Arches and buttes, which are a dominant feature of the weathering of rocks of the Plateau region, shall be discussed in by R. Mastrapa, this volume. But the details of general weathering and other features shall be discussed here.

The Navajo sandstone in particular is susceptible to the formation of water-pockets and potholes. These form along joints that serve as natural channels for running water. Most of them begin their development behind wind-etched depressions due to cross-bedding, where tiny, shallow pools collect after rainstorms. Therefore, these forms are most likely seen in heavily cross-bedded sandstones such as the Navajo found in environments which allow for a great deal of wind erosion, and occasional water. The standing water weakens the rock, and wind and more water eventually removes loosened sand grains, which slightly deepens the pools or pockets. As the pockets grow, tiny plants and animals come to inhabit them, and acids they secrete further erode the rock. Eventually, they can become large enough to hold water for a considerable length of time. Areas in which small streams can occasionally run further develop some areas into fluted pools (Figure 2).

A type of weathering called Honeycomb weathering is also common in the Wingate and Navajo sandstones. This is the development of fist sized holes called tafoni, which may be the result of solution of rock material and wind erosion.

Eventually, small rock depressions may string together, particularly along joints, guiding the flow of rainwater, inaugurating development of clefts, crevasses, and eventually deep narrow canyons. Water from sudden downpours churns through these passageways, scouring and smoothing their floors and walls. Figure 3 shows a water pool eroded deep into the sandstone by the additional assistance of stream-whirled stones. These deep, fluted canyons are typical of the Zion and Capitol Reef National Parks.

In both Monument Valley and Canyonlands National Parks are examples of the weathering of the vertically jointed Cedar Mesa Sandstone. Many of the sandstones of the Plateau region will eventually weather in this fashion. The vertical jointing of the sandstones allow for hoodoos, pinnacles and spires to form (see Jen's Superstitions handout on Hoodoos) as the rock cracks. The vertical cracks aid in erosion and weathering along the joints (Figure 4). Figure 5 also shows the effects of vertical jointing in the Wingate sandstone at Canyonlands.

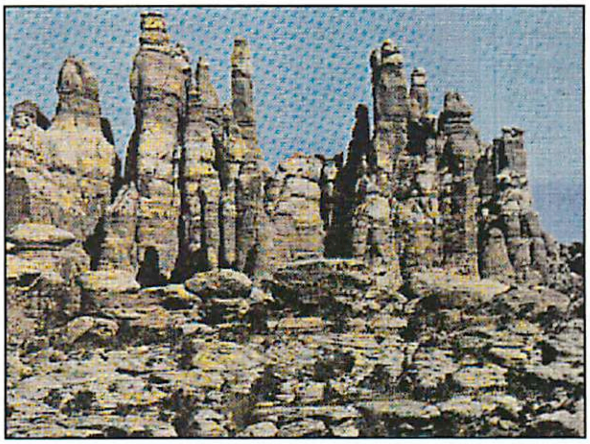


Figure 4 - Cutler Formation, Canyonlands National Park. Erosion continues to widen closely spaced joints creating red and white striped pinnacles (hoodoos) of the Needles District.

The action of wind and water is aided by the slow and steady working of the freeze/thaw cycle. Temperature contrasts that allow for freezing and thawing of small amounts of moisture either between sand grains or more effectively, in the joints of the rock are insignificant in the short term. But these cycles repeated over time eventually will loosen sand grains and break off rock flakes, initiating the breakdown of the solid rock, usually along the joints. Such frost wedging is especially effective in shady rock clefts where moisture is retained for longer periods.

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

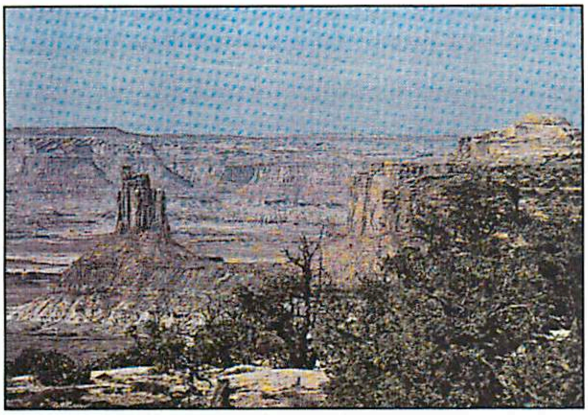


Figure 5 - A view across Canyonlands National Park. The peak on the left is Sixshooter Peak, formed as Wingate Sandstone broke away along vertical joints. The sandstone and siltstone of the Chinle Formation color the lower slopes.

A particularly interesting example of vertical jointing in sandstone is the weathered surface of Checkerboard Mesa, just outside of Zion National Park. The vertical jointing and crossbedding of the sandstone are at right angles to one another, and as the sloping surface of the mesa slowly weathers, a distinct checked pattern emerges.

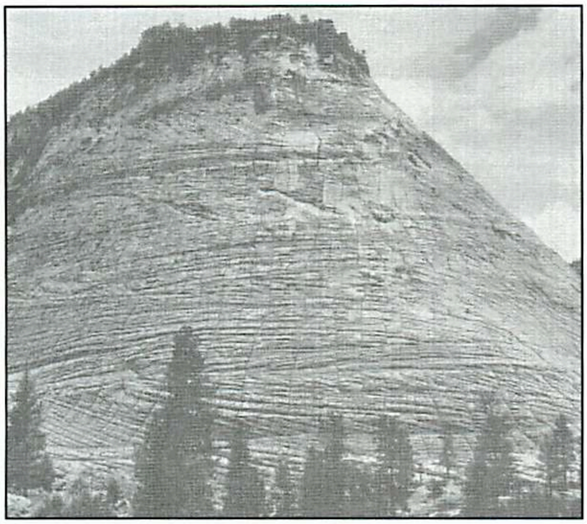


Figure 6 - Checkerboard Mesa just outside the entrance to Zion. Erosion along orthogonal joints and beds has produced this unusual checkered surface.

While both the Wingate and Navajo Sandstones are hard, cliff formers, the Wingate is rather more resistant to erosion. So while the Wingate formation can form the tall sharp peaks as seen in Figure 4, the Navajo sandstone will often weather into more gently sided dome formations. White dome formations just such as these are what give Capitol Reef National Park, in S. Central Utah, its name.

Particles weathered from sandstone in this area often get "recycled" in new aeolian environments. For example, Coral Pink Sand Dunes in SW Utah is formed by sand that has weathered out from local sandstones. The sand is entrained in the wind, and ends up getting trapped in a depression along a fault. Thus the sand once in dunes, then trapped in rocks, gets freed again by weathering and wind to reform dunes.

Conclusion

Sandstones in Utah weather into many amazing and beautiful formations. The vast exposures of sandstone, its tendency to be jointed and cliff forming, and the arid nature of the SE Utah climate are the major drivers in shaping these formations. Pools, fluted canyons, dunes, ripples, arches, buttes, pinnacles, spires, hoodoos, peaks and cliffs are all results of the weathering of sandstone in this area.

References

Bates and Jackson, eds. (1984) Dictionary of Geological Terms, 3rd Edition. American Geological Institute. Doubleday.

Chronic, H. (1990) Roadside Geology of Utah. Mountain Press Publishing Company.

Chronic, H. (1988) Pages of Stone 4: Grand Canyon and the Plateau Region. The Mountaineers, Seattle, WA.

Davis, G. (1984) Structural Geology of Rocks and Regions. John Wiley and Sons, New York.

Nations, J. and J. Eaton, eds. (1991) Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway. *GSA Special Paper 260.*

Peterson, F. and G. Peipiringos (1979) Stratigraphic Relations of the Navajo Sandstone to Middle Jurassic Formations, Southern Utah and Northern Arizona. *USGS Professional Paper 1035-B.*

Steele, B. (1987) Depositional Environments of the White Rim Sandstone Member of the Permian Cultlr Formation, Canyonlands National Park, Utah. *USGS Bulletin 1592.*

by Devon Burr

INCISED MEANDERS,
or
from whence the Goosenecks of the San Juan???

to take the two parts--incision and meandering--chronologically . . .

I. <u>Meanders</u> (from the name of a Turkish river that had 'em):

nearly ubiquitous in nature--found in rivers, in the atmosphere, in the Gulf Stream, etc

in rivers, part of a continuum of river planform geometry --

straight -> meandering -> braided -> compound

transition depends on energy and load, so that as slope, discharge, or sediment load increases, planform geometry shifts to the right

theories on formation (note the lack of agreement on this issue):
1) explanations based on oscillations as inherent properties of turbulent flow
    a) helical cells -> periodic reversals (Einstein and Shen 1964)
    b) secondary flow (Thompson 1986)
    c) turbulent flow and bursting (Yalin 1992)
  problem with these models is lack of data
2) explanations based on sediment transport
    a) bar theory (Callander 1978)
    b) bend theory
  problem with these theories is the presence of meanders in, say, the atmosphere
3) miscellaneous other explanations
    a) minimum variance of energy loss
    b) minimization of channel slope for given inpout (Chang 1988)

Despite the many competing theories for the initiation of meanders, the generally accepted explanation for their presence in rivers is differential erosion: greater flow velocity on the outside of bends causes greater erosion while slackwater on the inside of meanders causes depostion ===> outward migration and increasing radius of the meander.

. . . so much for meanders. . . what about the 'incised' part. . . ??

II. <u>Incision</u>

in general, incised rivers are one of two types (first discussed by Powell, 1875?):
a) super(im)posed = river cut down
(increased cutting power of river, usually produced by lowering of base level, resulted in downcutting into subsurface lithology/bedrock)
b) antecendent = land came up
(river course established previous to uplift, so that erosion of river into bedrock kept pace with the bedrock's uplift)
[c) consequent = river follows topography]

. . . so, if that's how meanders for, and that's how rivers incise, then it's simple to see how meandering rivers incise, right? . . . well, no.

III. The primary debate regarding the origin and evolution of incised meanders -- modification during incision?

Davis (1893) theorized that rivers established their meanders in a floodplain, then incised due to uplift and rejuvenation without modification
Winslow (1893) thought that the present pattern must have developed during incision, producing the observed slip-off slopes and undercut banks

Gardner (1975) offers a third alternative from flume work: incised meanders developed from alluvial meanders which deformed*prior* to incision
--meander incision, resulting from base level lowering, occurred upstream from structural axes and where orogenic movement decreased stream gradients;
--meanders were destroyed downstream from structural axes and where stream gradients steepened
in other words, "meander pattern . . . reflects responses. . . to continuing deformation" (Hunt, 1969).

The classic field example of this is. . . THE GOOSENECKS OF THE SAN JUAN!
The Goosenecks appear to be a combination of
1) superposed incision, due to lowering of baseleve when the Sea of California opened up, and
2) antecendent, with incision due to uplift.
The San Juan crosses the Monument Uplift; its sinuoisity is greatest on the top of the uplift, and less on the downstream/downdip side, in accord with Gardner's flume work. Further field studies by Harden (1990), which discuss variable rock resistances in a study of incised meanders on the CO Plateau, corroborate a more complex view of incision processes.

REFERENCES

Callander, R.A. 1978, River meandering, *in* Annual Review of Fluid Mechanics, 10, 129-158.

Chang, H.H. 1988, On the cause of river meandering, *in* White, W.R., ed, International conference on river regime, Wallingford, U.K., Hydaulics Research, 83-93

Davis, W.M., 1893, The topographic maps of the United States Geological Survey, *in* Science, 21, 225-227.

Einstein, H.A. and Shen, H.W. 1964, A study of meandering in straight alluvial channels, Journal of Geophysical Research, 69, 5239-47.

Gardner, T.W., 1975, The history of part of the Colorado River and its tributaries: An experimental study, *in* Fasset, J.E. ed, Four Corners Geological Society guidebook: Field Conference, 8th, Canyonlands, Utah, 87-95.

Harden, D.R., 1990, Controlling factors in the distribution and development aof incised meanders in the central Colorado Plateau, *in* Geological Society of America Bulletin, 102, 233-242.

Hunt, C.B., 1969, Geological history of the Colorado River, *in* The Colorado River region and John Wesley Powell, U.S. Geological Survey Prof. Paper 669-C, 59-130.

Thompson, A., 1986, Secondary flows and the pool-riffle unit: a case study of the process of meander development, *in* Earth Surface Processes and Landforms, 11, 631-641.

Winslow, A. 1893, The Osage River and its meanders, *in* Science, 22, 31-32.

Yalin, M.S. 1992, River mechanics, Oxford: Pergamon.

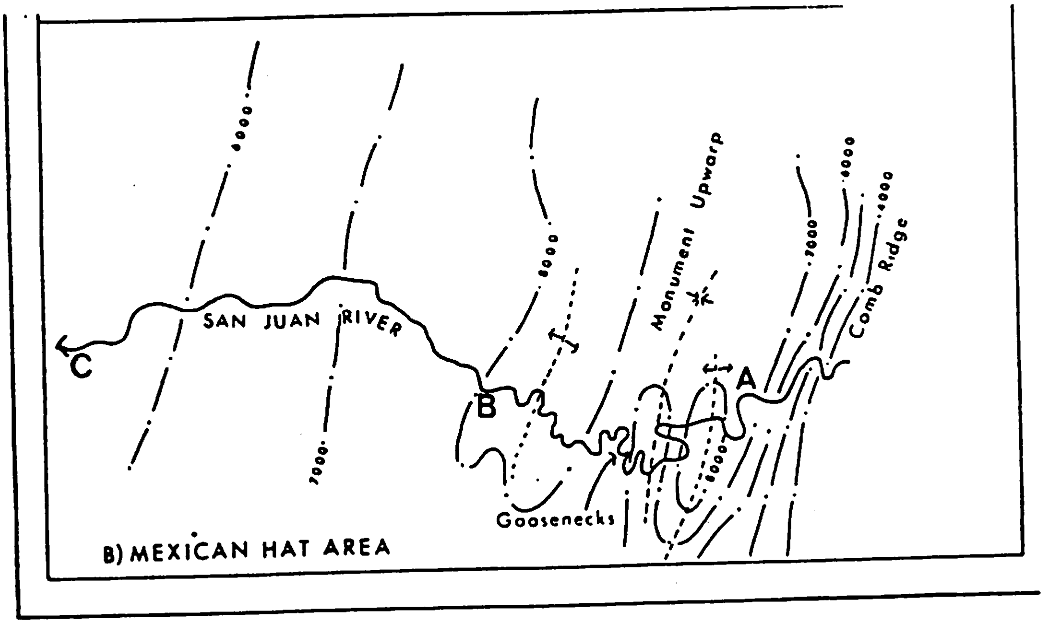


FIGURE 8—Sketch of (A) Canyonlands and (B) San Juan River, west Mexican Hat, Utah. Structural contours drawn on top of the Chir Formation are superimposed on the river course. Base map after Kell (1955).

from Gardner (1975)

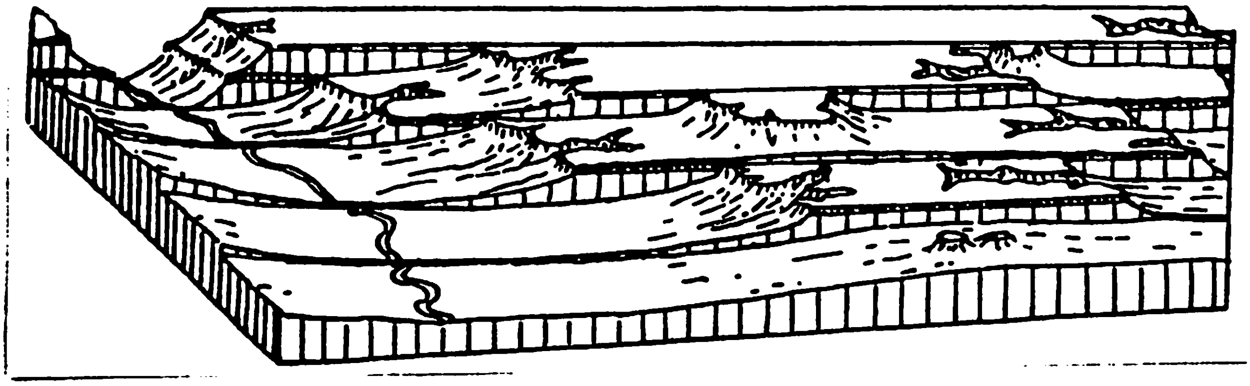
Arches and Buttes

Canyonlands April, 1999

Brought to you by the letter ®

Desert Weathering

The two main factors controlling erosion are rock type and local climate. I'll get into rock type in the next section. For now just keep in mind that we are looking at an area that does not see a lot of rain. When it does, it is usually in the form of a deluge that can change the surface on short timescales. Below is a diagram depicting the dissection of sedimentary layers in a dry environment.



Aeolian processes dominate the desert environment. Think of it as year round sand blasting. This process is extremely slow, but obvious in the rounded nature of most structures. Another product is layers of wind deposited sand. These layers are quite vulnerable to periodic flooding.

Resistance of Bedding

When looking at sedimentary layers you can classify them into two groups: *cliff forming* and *slope forming*. Cliff forming layers are more resistant to erosion because they hold together better. The reasons for this vary, but can depend the level of compression involved in deposition. Cliff forming layers are often referred to as layers of high *induration* (cohesion). Some examples are sandstone and limestone. Slope forming layers are the opposite. They have low induration and are generally found at the angle of repose. Some examples of slope forming rocks are mudstone and clay.

As the depositional environment changes, you can get alternating layers of slope forming and cliff forming materials. An example of this is shown in the next page.

Definitions of Desert Features

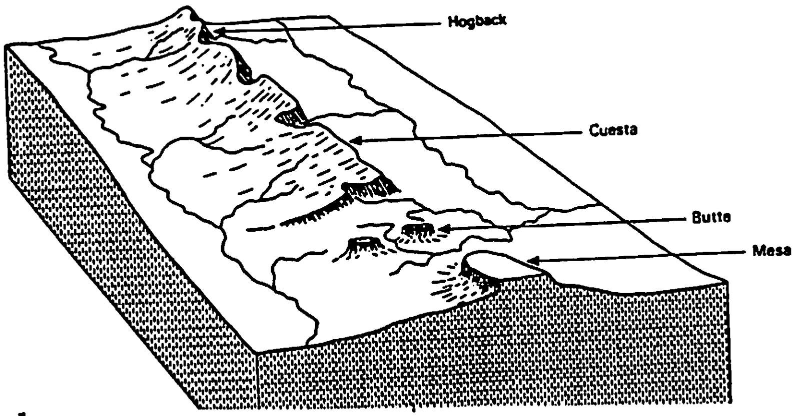
Mesa (table) – a flat topped plateau produced by fluvial erosion of flat-lying sedimentary layers in a desert environment.

Cuesta (hill, sloping ground) – An asymmetric ridge formed by erosion of slightly dipping layers.

Hogback (back of pig) – A symmetric ridge formed by erosion of steeply dipping layers.

Butte (knoll, hillock) – The remains of a dissected mesa, once the structure has become taller than it is wide.

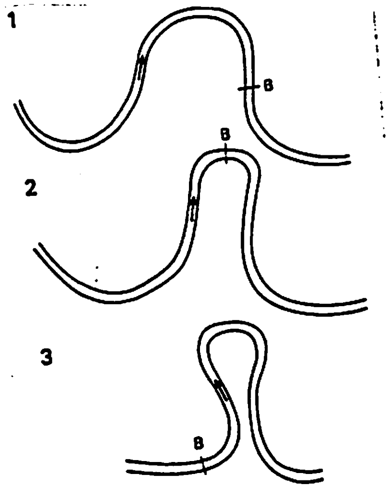
Arch – A bunch of rock that looks like an arch.



How to make an arch

There are many processes that can result in arch formation. The general recipe is to remove a weak bed from underneath a resistant bed. This can be done by fluvial or aeolian processes.

The picture on the last page is of a natural bridge that may one day become an arch. In this case the river cutting into the layers has formed a *meander*, or bend. The river cuts into the inside of the meander, resulting in a sharper and sharper turn. Eventually, the can tunnel through the cliff wall, abandoning the meander.

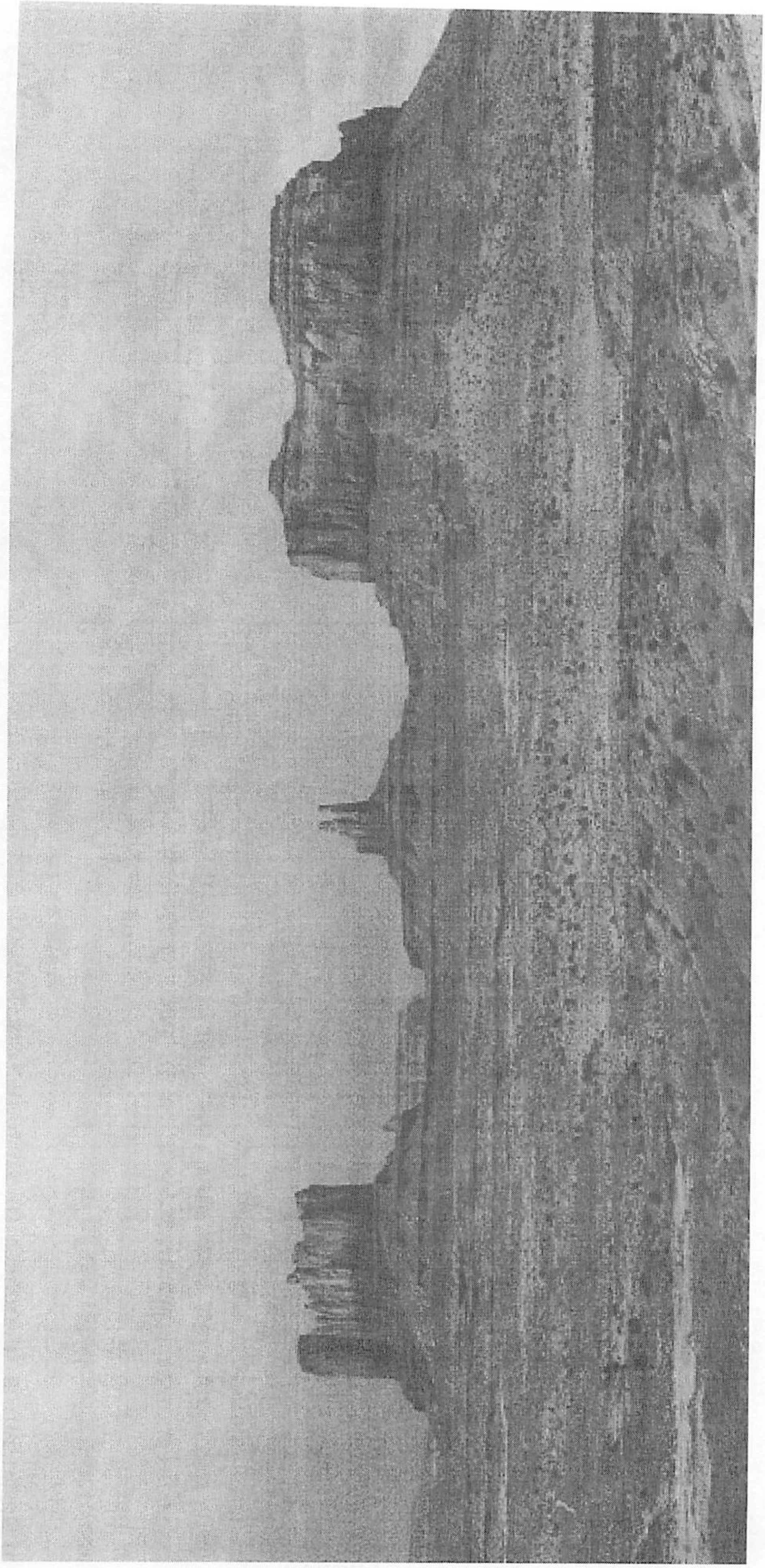


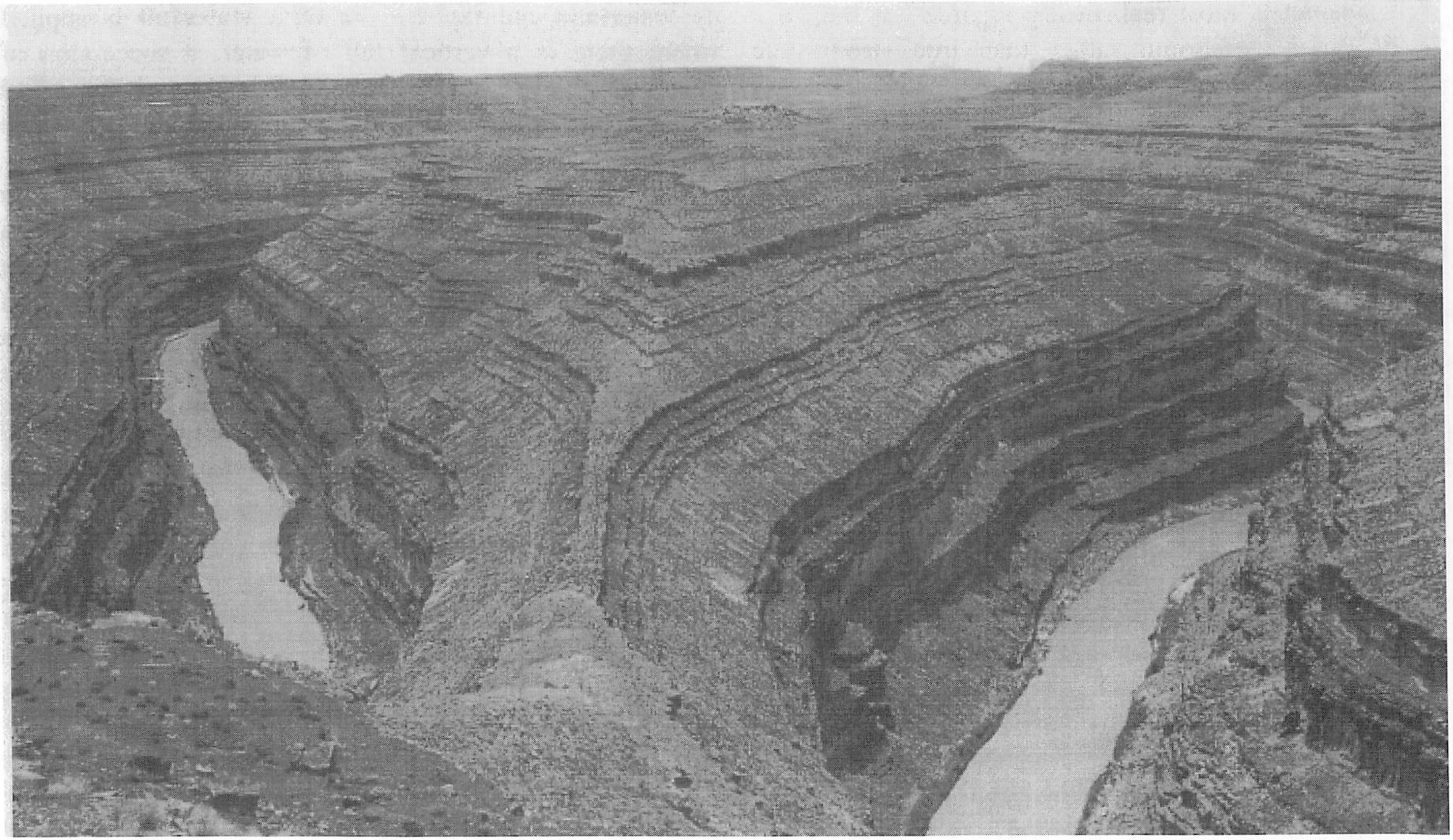
References

Chorley, R. J., S. A. Schumm, and D. E. Sugden, Geomorphology, Methuen and Co., New York, 1985.

Summerfield, M. A., Global Geomorphology, John Wiley and Sons, Inc., New York, 1991.

Twidale, C. R., Analysis of Landforms, John Wiley and Sons Australasia Pty. Ltd., New York, 1976.





Faults and Folds on the Colorado Plateau

Fault = planar fracture along which displacement of the two blocks has occurred

Fold = bend in usually planar strata
Monocline = local steepening in an otherwise uniform gentle dip
(Bates and Jackson, 1984)

Monoclines are regional, steplike folds in which otherwise horizontal or very shallowly dipping strata abruptly bend to a steeper inclination within a very narrow zone (Davis, 1984).

The Colorado Plateau (CP) is structurally very stable and was relatively unaffected by the Laramide orogeny (75 to 50 Ma ago) and other major events which shaped the rest of the southwest. The main features of the CP are basins, uplifts and monclines. Most of the monoclines are associated with uplifts and they commonly demarcate such uplifts and the adjoining basins. The modern concept for monoclines was derived by Powell, Gilbert, and Dutton from their studies of this region and in many respects monoclines are the principal structural features of the CP. Monoclines account for most of the vertical relief on the CP and a CP monocline typically has five to ten times the vertical relief of the uplift above it and of the basin below it (Kelley, 1955a).

CP monoclines have lengths ~ 10 – 100 miles, heights ~ 1000 – 10000 feet and dips ~ 10 – 80+ degrees. Many are sinuous (e.g Defiance, Hogback) and many have branches (e.g. East Kaibab).

The CP monoclines can be roughly divided into two groups. To the west the East Kaibab, Echo Cliffs, San Raphael-Waterpocket, Comb, and Defiance monoclines trend north-northwesterly and face eastwards. To the east and north the Uinta, Grand, Gunnison, Uncompahgre, Nacimiento, Nutria, and northeastern part of the Hogback face west to south. The Hogback might be better considered as related to the San Juan basin rather than fitting it in one of the two groups.

Monoclines are believed to be formed as near-surface strata are plastically deformed during the near-vertical movement of deep faults (Davis, 1978). Deep erosion in the Grand Canyon has exposed the "roots" of the West and East Kaibab monoclines, showing this relationship between fault and fold (Davis, 1984).

The inferred faults can be located by joining up bits of the monoclines (Davis, 1978). Geophysical evidence, including gravity highs and magnetic anomalies, is consistent with the proposed basement fracture zone (Case and Joesting, 1972; Davis, 1978)

Wherever a fault responsible for a monocline can be seen in the Grand Canyon exposures it is found to be a reactivated Precambrian fault. It is reasonable to suggest that this is true in the CP as a whole. The compressive forces which reactivated the faults and caused the monoclines were due to the Laramide uplift which occurred as the North American continental crust collided with oceanic plate to the west 75 to 50 Ma ago.

1 - The monoclines are upper-crustal expressions of near-vertical components of movements on reactivated, Precambrian, high-angle fault zones.
2 - The systematic distribution and orientation pattern of the monoclines reflects attributes of a rejuvenated basement-block mosaic partitioned by ancient, deep-seated faults.
3 – The reactivation of Precambrian fault and fracture zones to produce monoclines was caused by northeast-southwest regional compression during the Laramide orogeny.
(Davis, 1978)

Are similar features seen on other planets?

Seeing compressive features is reasonably easy, identifying folds without field geology is less so. The most similar features are wrinkle ridges, seen on lunar mare and the plains of Mars and Mercury (Banerdt et al, 1992; Golombeck et al, 1991; Melosh and McKinnon, 1988; Watters, 1991). A wrinkle ridge is a linear asymmetric topographic high, typically having considerable morphological complexity. The basic physiography of a wrinkle ridge is a broad rise with a superposed hill and a low relief wrinkle on top of the hill. Early hypotheses for the origin of these features centred on volcanism but evidence of vertical offsets across ridges, ridges extending into highland regions as fault scarps and offsets in pre-existing craters transected by ridges favours a tectonic origin. Plescia and Golombeck (1986) concluded that wrinkle ridges are anticlines overlying thrust faults, and Watters (1988) suggested that the best terrestrial analogues are anticlinal ridges in the Miocene flood basalts of the western Columbia Plateau.

Note that no lunar samples show the plastic deformation expected in folding (Heiken et al, 1991)

Venus, outer planet satellites?

There's got to be a morning after
If we can hold on through the night
We have a chance to find the sunshine
Let's keep on lookin' for the light

Oh, can't you see the morning after?
It's waiting right outside the storm
Why don't we cross the bridge together
And find a place that's safe and warm?
(South Park, after The Poseiden Adventure)

It's not too late, we should be giving
Only with love can we climb
It's not too late, not while we're living
Let's put our hands out in time

There's got to be a morning after
We're moving closer to the shore
I know we'll be there by tomorrow
And we'll escape the darkness
We won't be searchin' any more

References:

Banerdt, W. B., Golombeck, M. P., and Tanaka, K. L., 1992, Stress and tectonics on Mars, in "Mars", University of Arizona, eds Kieffer. H. H., Jakosky, B. M., Snyder, C. W., and Matthews, M. S.

Bates, R. L., and Jackson, J. A., 1984, "Dictionary of Geological Terms – 3rd ed.", Anchor

Case, J. E., and Joesting, H. E., 1972, Regional geophysical investigations in the central Colorado Plateau, U. S. Geol. Survey Prof. Paper 763

Crack, S. S. H., 1999, The Spitale tribute, Hawthorne House Productions

Davis, G. H., 1978, Monocline fold pattern of the Colorado Plateau, in "Laramide folding associated with basement block faulting in the western United States", Geological Society of America Memoir 151, ed. Matthews, V., pp 215-235

Davis, G. H., 1984, Structural geology of rocks and regions, J. Wiley

Golombeck, M. P., Plescia, J. B., and Franklin, B. J., 1991, Faulting and folding in the formation of planetary wrinkle ridges, Proc. Lunar Planet. Sci. Conf. 21st, pp 679-693

Kelley, V. C., 1955a, Monoclines of the Colorado Plateau, Geol. Soc. Am. Bull., v. 66, pp 789-804

Kelley, V. C., 1955b, Regional tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium, New Mexico Univ. Pubs. Geology, no. 5

Kelley, V. C., and Clinton, N. J., 1960, Fracture systems and tectonic elements of the Colorado Plateau, New Mexico Univ. Pubs. Geology, no. 6

Heiken, G. H., Vaniman, D. T., and French, B. M., 1991, "Lunar Sourcebook", CUP

Plescia, J. B., and Golombeck, M. P., 1986, Origin of planetary wrinkle ridges based on the study of terrestrial analogues, Geol. Soc. Am. Bull., v. 97, pp 1289-1299

Melosh, H. J., and McKinnon, W. B., 1988, Tectonic history of Mercury, in "Mercury", University of Arizona, eds Vilas, F., Chapman, C. R., and Mathews, M. S.

Plateau uplift: mode and mechanism, 1979, Tectonophysics special issue, v. 61, pp 1-336

Watters, T. R., 1986, Wrinkle ridge assemblages on the terrestrial planets, J. Geophys. Res., v. 93, pp 10236-10254

Watters, T. R., 1991, Origin of periodically spaced wrinkle ridges on the Tharsis Plateau of Mars, J. Geophys. Res., v. 96, pp 15599-15616

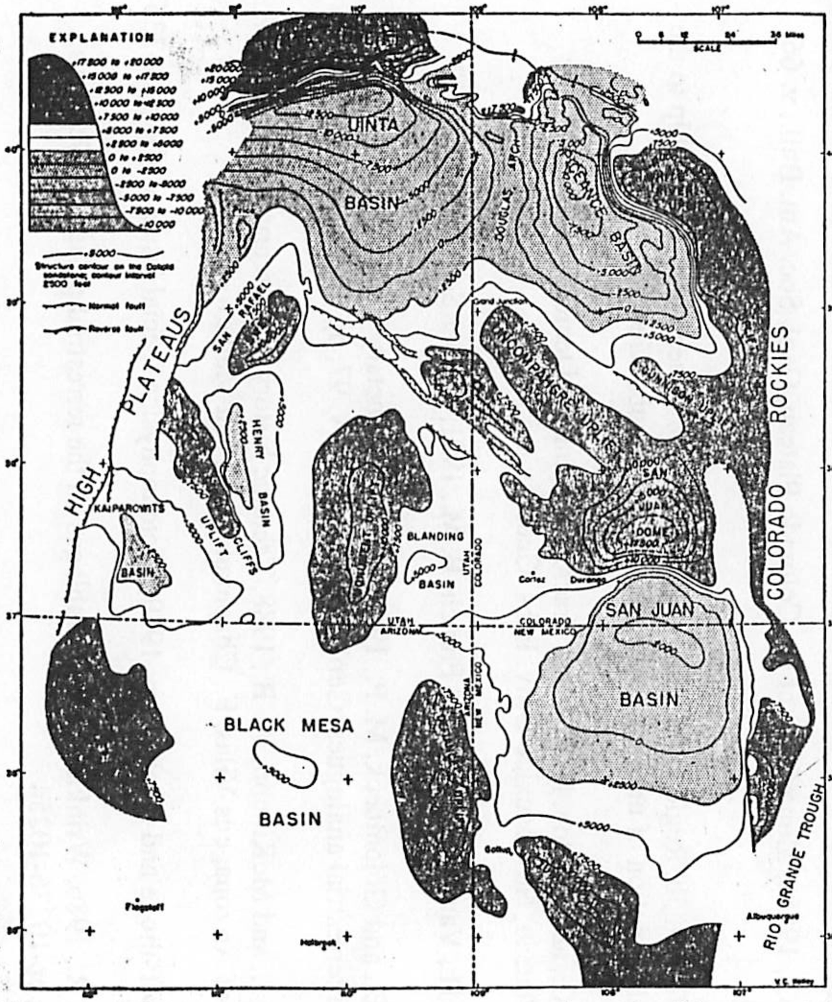


FIGURE 6. Structure-contour map of the Colorado Plateau.

Kelley 1955b

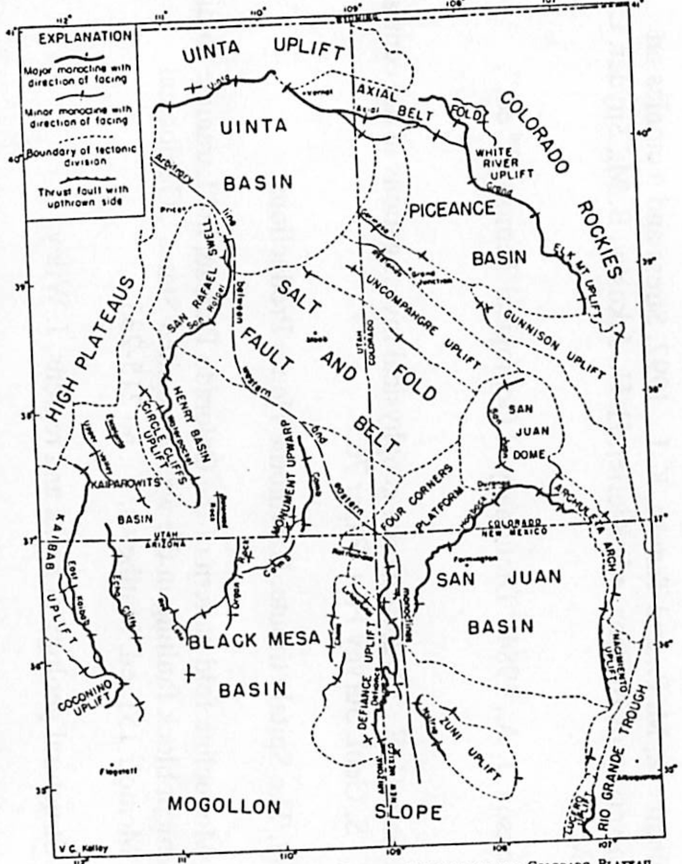


FIGURE 7.—MONOCLINES AND THE MAJOR TECTONIC DIVISIONS OF THE COLORADO PLATEAU STRUCTURAL PROVINCE

Some of the features are in whole or in part steep limbs of anticlines

southeast side of the Coconino uplift northeastward through the southwest fork of the Organ Rock monocline to the southern end of the Comb monocline. This Coconino lineament of monoclines may reflect a deep-seated tear that caused some right-lateral shift between

Kelley 1955a

der-
nd 6
nce,
that
vail-
it is
the
the
be-
ably
ixes.
ved,
ffer-
lifts
this
the
ion,
und
. In
for-
phic
tion
face
h of
has
may
950,
the

rests
d in
axes
trol
y or

sym-
ct is
enry
ing,

of emphasis of the relative role

vertical tectonics. Powell (1873, 1876), Gilbert (1877), Dutton (1880), Walcott (1890), Nevi[illegible]49), Prucha and other (1965), and Stearns (1970) have inte[illegible]ted monoclines as products of the draping of near-surface strata over fault-bounded basement blocks; vertical forces were considered to be responsible for the movements. Baker (1935) postulated that the monoclines formed above deep-seated thrust faults in a stress system characterized by horizontal compression. Kelley (1955a, 1955b) also favored the concept that horizontal compression was the "dominating action" in the formation of the large monoclines. Noble (1914), Maxson (1961), Huntoon (1969, 1971, 1974), and Huntoon and Sears (1975), on the basis of their work in the Grand Canyon, observed that the monoclinal folds in that region commonly

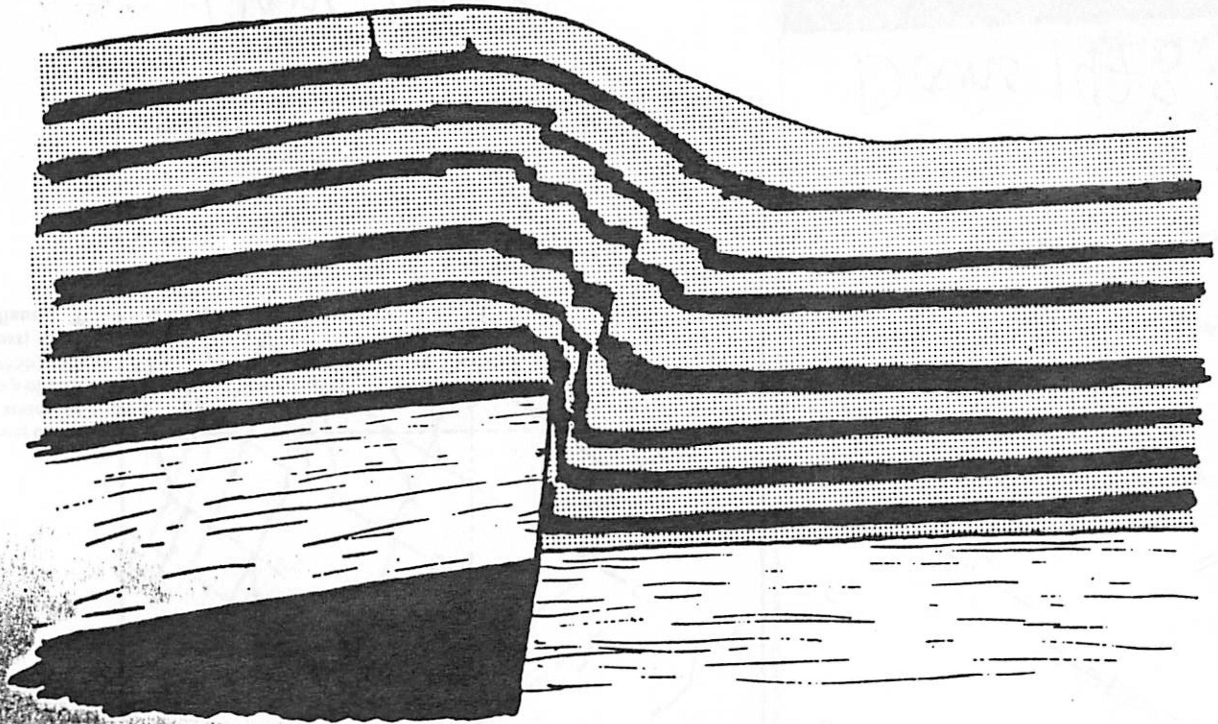
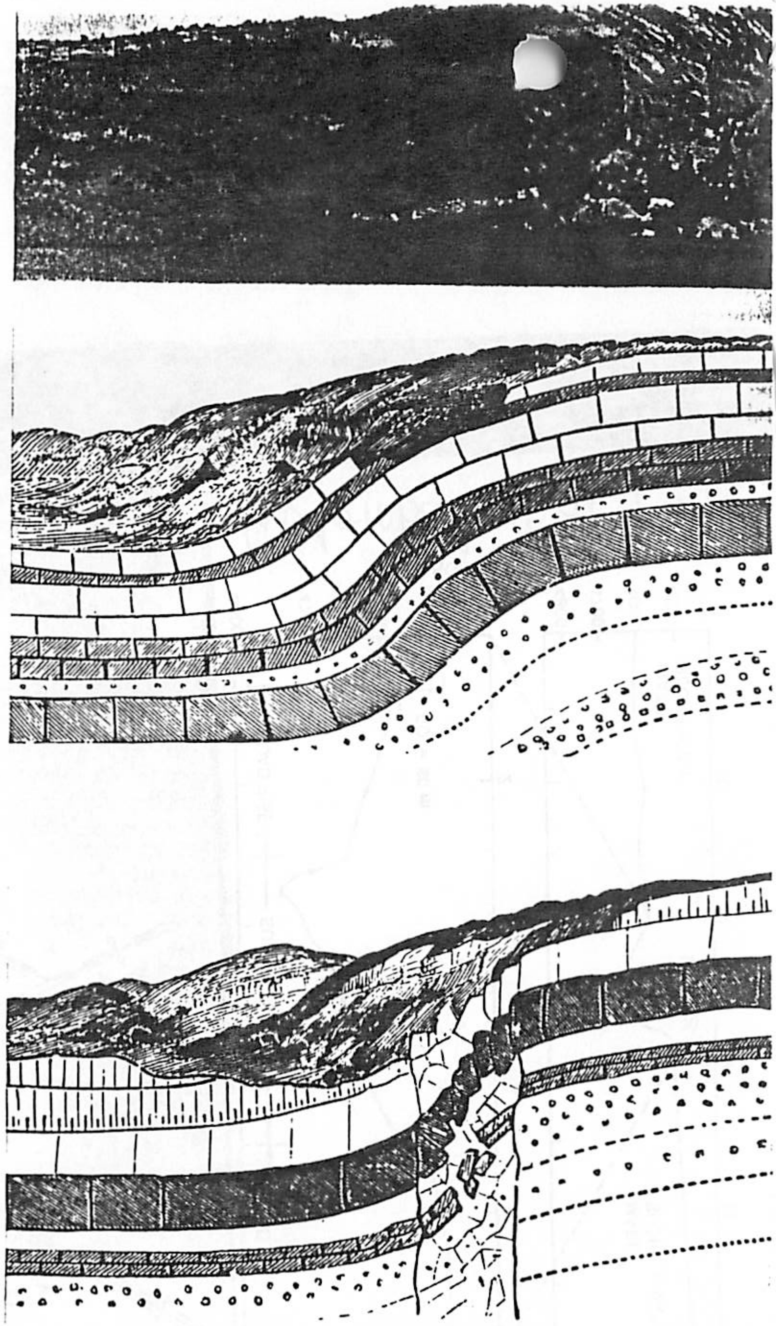


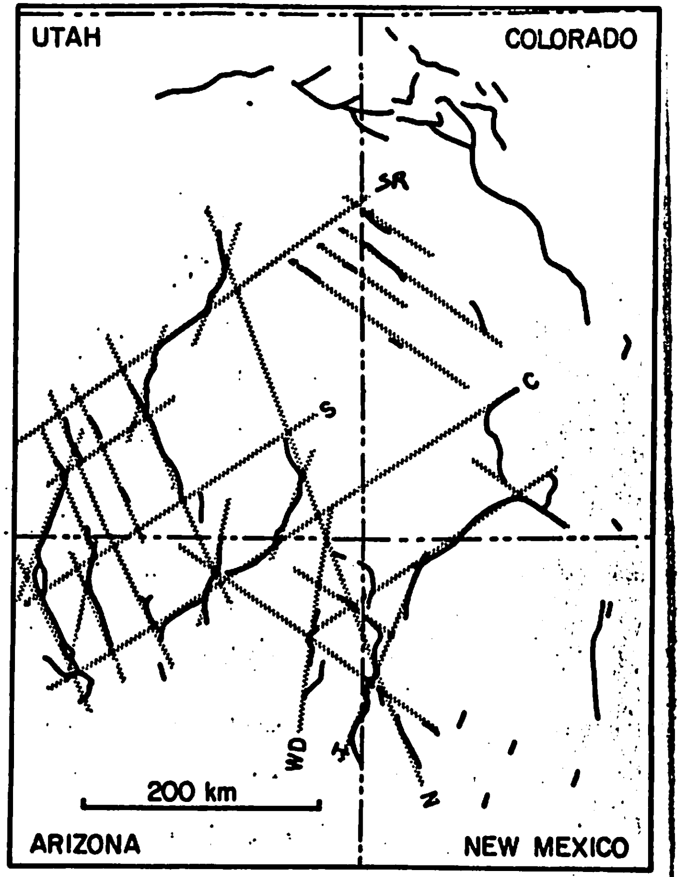
Figure 1. Photograph of experimental deformational model of "strata" of kaolinite and modeling clay resting on a rigid "basement" of pine board. High-angle faulting along pre-cut fault produces monoclinal fold in overlying thin layers.

Davis 1978



Davis 1984

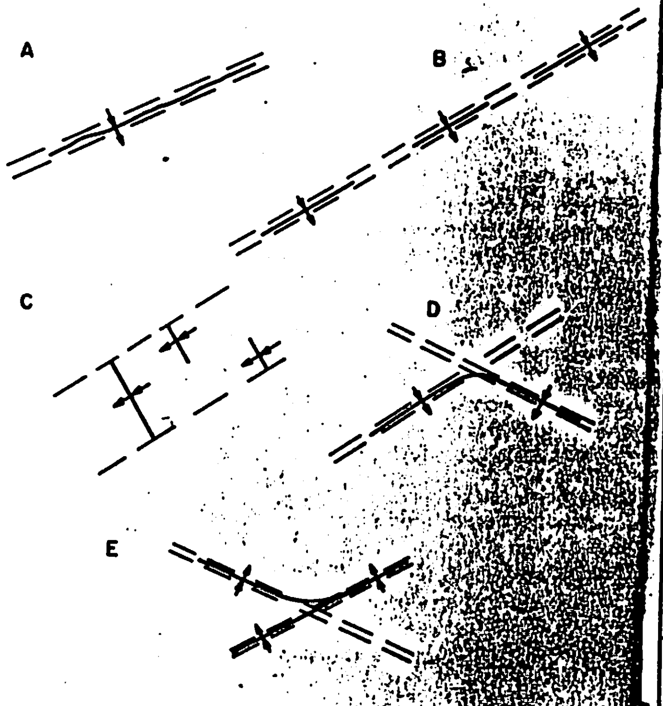
plifts are associated with gravity highs and high-amplitude magnetic anomalies ordered by relatively steep magnetic gradients. According to them (Case and esting, 1972, p. 10):



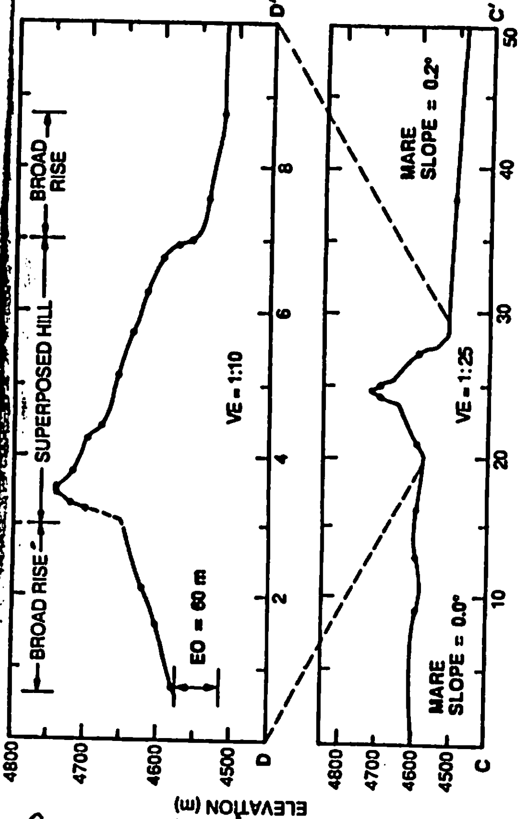
showing traces of the nt-fracture zones in teau. Base map of fold C. Kelley (1955b). SR = Snowmass; C = = West Defiance; T Nutria.

Davis 1978

to be restricted to the southwest portion of the 7). All are in part coincident with monoclinal segments (that *ble* vertical movement). The so-called Nutria fracture significant lineament cited by Kelley (1955b) as separating tw within the Plateau: a southwestern subprovince, dominate characterized by northeast-facing monoclines, and a no



Davis 1978



Golombeck et al 1991

① JE

Geologic History of Southeast Utah - Plate Tectonics

Josh Emery

This table gives a summary of important geologic and tectonic events in the history of Utah. The 'Notes' column contains interesting information which did not fit within the other categories. The figures which follow the table provide a diagrammatic representation of the Utah depositional environment through time.

Era	Period/Epoch		Time (Ma) Origin of Name	Rock Types	Environment	Plate Tectonics	Notes
Cenozoic	Quaternary	Holocene	11,000	Surficial Deposits - alluvium, colluvium, lake deposits (silts), dune fields, loess, glacial, soil	Lots of climatic oscillation Mostly Desert - Glaciers above 10K ft - Lakes (e.g. Bonneville) Change in Volc(bimodal) - ryolite/basalt	Regional Uplift (CO plateau) - incr. river flow energy Great Basin & Basin-Range These all due to high heat flow - reason for hhf is unknown (mantle upwelling?, plate collisions?)	Reflection Mojo ~30km below Great Basin ~45km below CO plateau High heat flow in Great Basin Low heat flow in CO plateau
		Pleistocene	1.6				
	Tertiary	Pliocene	5.3				
		Miocene	23.7	Igneous - ash-flow tuff - ryolite, andesite	Intense Igneous activity - voluminous ash flows West - extrusive East - intrusive	Subduction of Pac. Plate - esp. spreading center Change in rel. plate motion - activates San Andreas	Economic - lots of mineral deposits Henry, Abajo, La Sal Mts. (laccoliths)
		Oligocene	36.6				
		Eocene	57.8	Sandstone, shale, siltstone, limestone, conglomerate	Uinta Uprise and basin Deposition dominated by lake systems Eocene - Green River Paleocene - Flagstaff	Laramide Orogeny - structurally diff. than Sevier or Nevadan -shallow plate subd. ?? -change in int. w/ Pac. Plate?? -internal rot. of CO plateau??	Economic - Hydrocarb. (oil, gas, etc.) Uinta,San Rafael,Circle cliffs,Monument uplifts Topmost trend of Grand Staircase
		Paleocene	66.4				
Mesozoic	Cretaceous		From *creta*, latin word for chalk (cliffs of Dover) 144	Shale, limestone conglomerate, sandstone	End - oceans withdrew Mid - east UT flooded from N and S Early - like Jurassic (Morrison Basin)	Sevier Orogeny -Mesocordilleran high (west UT and NV) ~800 miles of crust added to western NA from Triassic to mid-Tertiary	Economic-bituminous coal Outcrops- Henry Mts. Lake Powell, Books Cliff 'Stomach Stones'
	Jurassic		From Jura Mts. between France and Switzerland 208	Sandstone, limestone, mudstone, conglomerate	Late - river flood-plains (Morrison Basin) Mid - Marine (shallow, from N) Early - desert-like	NA plate at ~ present Lat. Nevadan Orogeny - blocks sea from UT - collison w/ microplate? - subduction of Pac plate?	Lots of dinosaur fossils Economic-U,V,Ra,Cu construction mat. Navajo & Entrada SS
	Triassic		From 3-fold stratigraphic division in Germany 245	Late - windblown sand (sandstone) Early - shallow marine rocks (limestone,etc.)	Late - all above sealevel (desert-like in east) Mid - no rocks (erosion) Early - seas covered western ½ of UT	Atlantic Ocean opening as NA plate moves west	Kayenta, Wingate, Chinle formations Economic-Au,Ag,U,Ra builing stones, gas oil, asphalt Redbeds (all Earth)
Paleozoic	Permian		From Perm plains on west flank of Ural Mts 286	Sandstone, siltstone mudstone, dolomite limestone, chert, gypsum, phosphite	Wind erosion (1st time) Alluvial fans, shallow seasonal lakes, shifting dune fields in east Late - seas from north Mid - Gulf of Mexico Early - arm of Pacific	Ancestral Rockies Orogeny e.g. Uncompahgre uplift-Paradox basin (also Oquirrh basin) - UT at NW end of linked basin-uplifts - collision of another cont. (Africa?) with SE North America??	Redbeds Economic-phosphate, oil,gas,Pb-Zn-Ag ½ forms. in Canyonlands (Needles,Angel Arch white rim SS, upper walls of goosenecks)
	Pennsylvanian		From outcrops in Pennsylvania 320	Limestone,shale, sandstone,dolomite conglomerate, halite,sylvite,other minor salts	Mostly water covered -uplifted regions made lots of sediment Cycles of deposition in Paradox basin due to changing sea levels		Economic-K,N,P (potash, from salts) oil, some minerals CO and San Juan rivers cut into PA forms. (at goosenecks, ~150ft)
	Mississippian		From Mississippi river valley 360	Limestone, dolomite, shale, chert, sandstone	E. Utah emerged in late Mississippian UT entirely sea covered -shallowest in east	Western Utah continues general trend of regional subsidence	Economic - oil, gas, clay (bricks, tiles), lime products Lots of caves form in Miss. limestones
	Devonian		From Devonshire, England 408	Late - limestone, shale, sandstone Mid - limestone-dolomite mix Early - dolomite	Late Devonian seas most widespread of period Shoreline progressed eastward from early to late Devonian	Antler Orogeny - Stansbury uplift in W Utah - collision with a pacific microplate??	Economic - not much some oil, gas, quartzite Some unremarkable outcrops in west, none in east

@ JE

Era	Period/Epoch	Time (Ma) Origin of Name	Rock Types	Environment	Plate Tectonics	Notes
Paleozoic	Silurian	408 From Silures, ancient tribe inhabiting region between England and Wales	Marine - dolomite - limestone	Shallow seaway Shoreline uncertain - mid-Utah? - further east? (no rocks in east, erosion? or no deposition?)	North American plate moves N-S across the equator	Igneous intrusions in Uinta Mts. Economic-some ores in dolomite formation No outcrops in east
	Ordovician	438 From Ordovices, tribe in Wales when Romans arrived	Limestone, dolomite, sandstone, quartzite, shalestone, chert	West subsiding East stable, just above sea level Late - retreating seas Early - advancing seas		Economic-building stone, some mineral ore No outcrops in east Late - increasing coral Early - Trilobytes
	Cambrian	505 From *cambria*, the latin word for Wales	Quartzite-shale-carbonate sequences	UT completely covered in water - Deeper (up to 10x) in west	Rift opens in central NV Western chunk splits off Subsequent subsidence of NV and west UT - due to high heat loss from new hot trailing edge	Economic-host rocks fo minerals deposited in Tertiary, limestone & dolomite for cement Fossil stramatolites in north UT
Proterozoic		570	Quartzite, argillite, quartzitic conglomerate, diamicitite (glacial?), limestone, a few basaltic lavas (~80% mantle derived rocks, ~20% from Archean crust)	Western UT begins subsiding Growing North American craton	Adding to continent from ocean floor basalts, island-arc volcanic and sedimentary rocks, plus some sandstones eroded from Archean continental nucleus (Southern ⅔ of UT gained basement rocks in early Proterozoic)	Precambrian rocks exposed in Uinta Mts. A few isolated exposures around the state Possible glaciation between 900 and 800 Ma (Uinta exposures seem to be older than perio of glaciation)
Archean		2.5 Ga	Granitic gneiss, magmitite, schist, quartzite, gneiss	Continent included only northernmost Utah		Oldest dated rocks in Utah are in the Farmington Canyon Complex and are dated at 2.7 Ga Suggested that Farm. Complex began at ~3.6 Ga

Archean

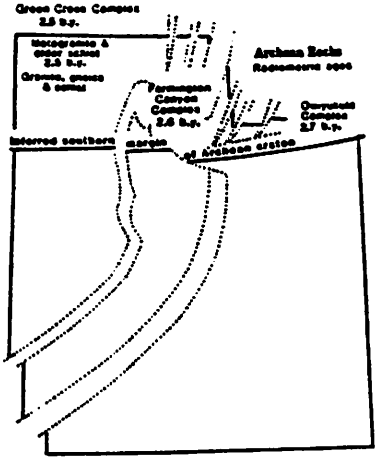


FIGURE 12 — Archean rocks (2.5 billion years and older) are preserved only north of an east-west line through Salt Lake City

Early Proterozoic

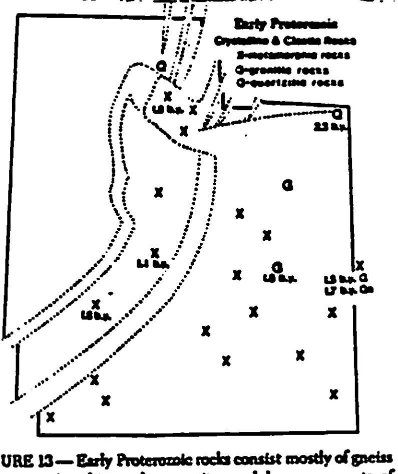


FIGURE 13 — Early Proterozoic rocks consist mostly of gneiss (Gn on map), schist and pegmatite, and lesser amounts of granitic and quartzitic rocks.

Late Proterozoic

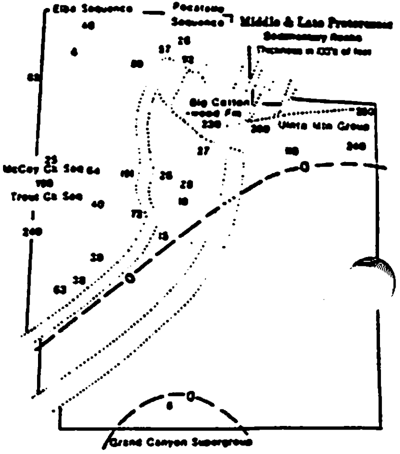


FIGURE 14 — Middle and Late Proterozoic sandstone, shale, and diamictite (now quartzite, argillite, and tillite)

8
JE

Cambrian

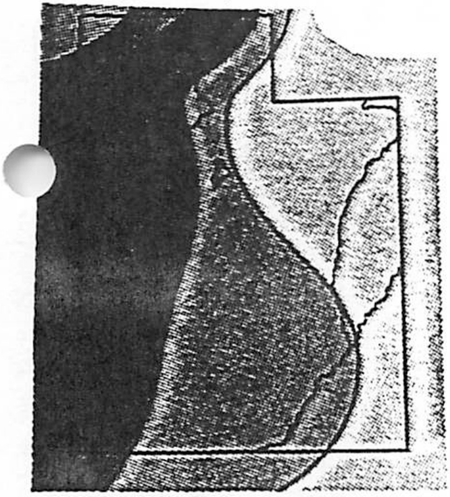


Figure 5-1. Generalized paleogeographic map of the Cambrian System. Relative darkness of patterns indicates the length of time represented and thickness of sediments preserved. Thus the darkest belt contains an almost complete record of Cambrian time.

Ordovician

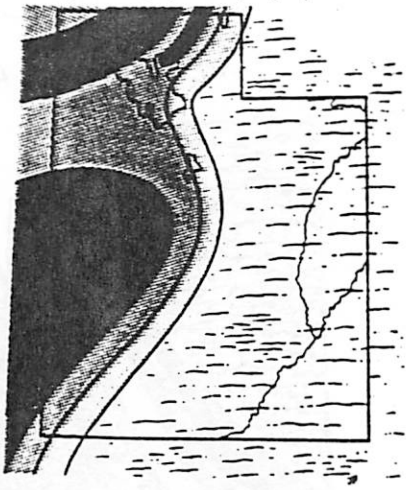


Figure 6-1. Generalized paleogeography of Utah during the Ordovician Period. Darker pattern indicates area covered by seas and receiving sediment during almost the entire period. Lighter zones show progressively thinner and less complete sedimentary record. Dry-land topography is shown diagrammatically.

Silurian

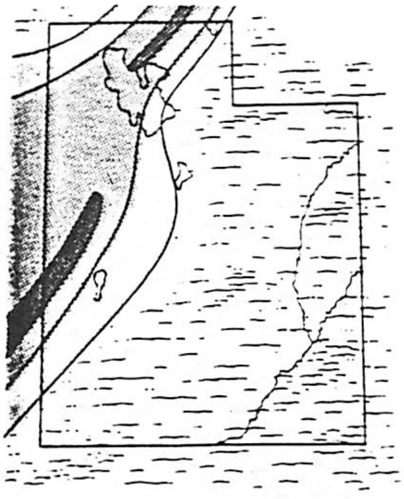


Figure 7-1. Two representations of the paleogeography of the
rian Period. Upper illustration shows by shaded
terns the distribution of thicker (darkest) to thin
(lightest) deposits. In general more time is represer
by sediments in the thicker sections.

Devonian

Early

Late

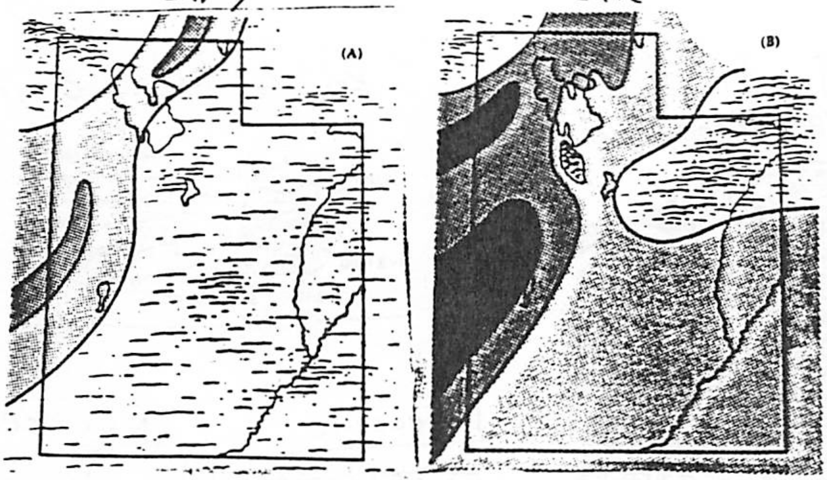


Figure 8-1. Generalized paleogeography of (A) Early Devonian time and (B) Late Devonian time. Relative darkness of patterns indicate length of time represented by preserved deposits. Darkest areas have the most complete record and greatest thickness of sediments. Topography of exposed land is shown diagrammatically. Note small uplift caused by the Stansbury disturbance near the southern end of Great Salt Lake.

Mississippian

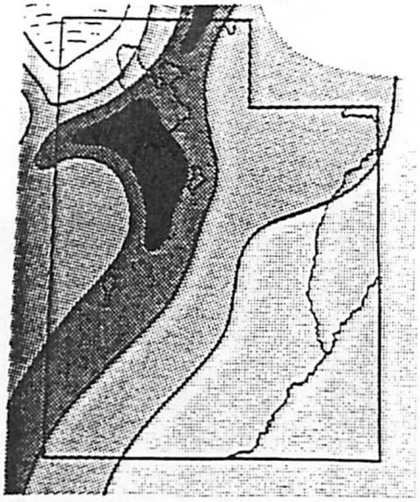


Figure 9-1. Simplified paleogeography of Utah for the Mississippian Period. Darkest shaded areas have thickest and most complete sedimentary sections. Lighter zones contain correspondingly less complete sections. Land area shown diagrammatically in the northwest corner is somewhat hypothetical.

Pennsylvanian

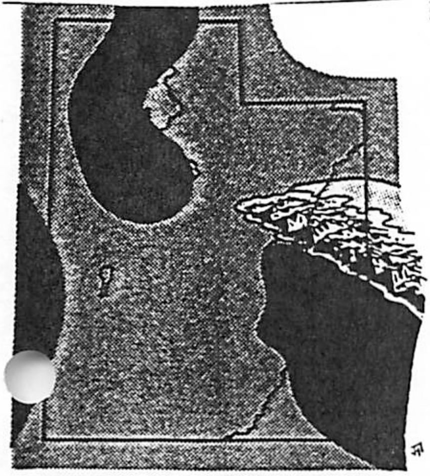


Figure 10-1. Generalized paleogeography of the Pennsylvanian Period. This view emphasizes the newly formed Uncompahgre Uplift in eastern Utah, the adjacent Paradox Basin and the Oquirrh Basin to the northwest. The darker the pattern the thicker and more complete the rock record of the period. Dry land topography is

Permian

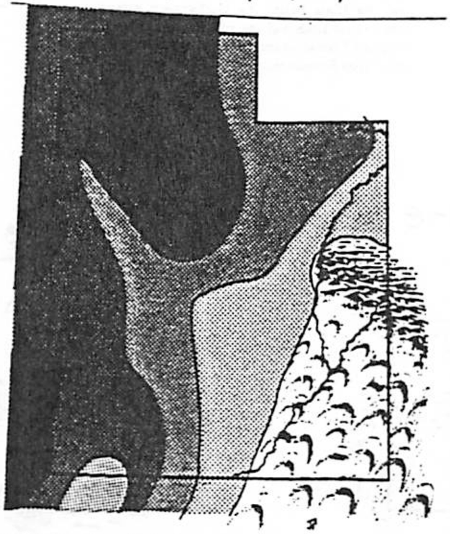


Figure 11-1. Generalized paleogeography of Utah for the Permian Period. Darkest patterns represent areas of thicker marine deposits; lighter patterns show relatively thinner, less complete sections. The Uncompahgre Uplift and dune-fields are shown diagrammatically

Early Triassic

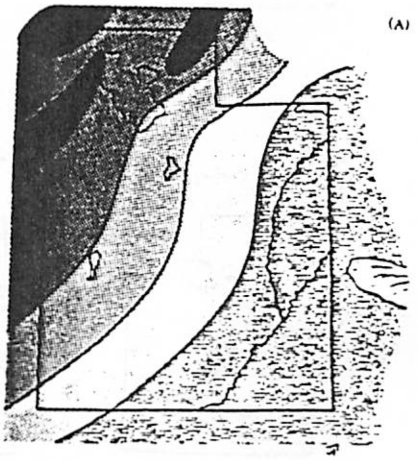


Figure 12-1. Generalized paleogeography of (A) Early Triassic time.

Jurassic

C
J.

Late Triassic/Early Jurassic

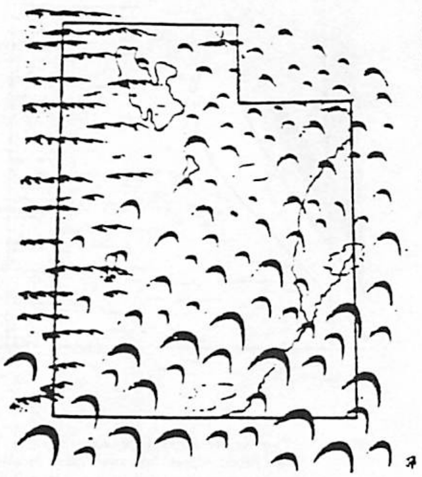


Figure 13-3a. Late Triassic-Early Jurassic, deposition was exclusively wind-deposited sand. A succession of barchane dunes crossing the region from north to southwest is diagrammatically represented.

Middle/Late

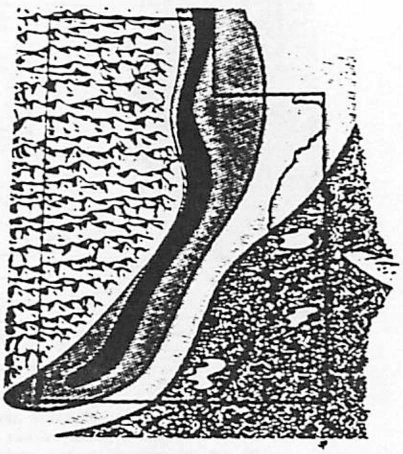


Figure 13-3b Paleogeography of Utah and vicinity during Middle and early Late Jurassic time. Darkest pattern indicates thickest and probably most complete sedimentary accumulation. Successively lighter belts have correspondingly thinner and less complete sections. Horizontal cross-lined pattern indicates chiefly marginal marine mud flats. Note the eroded remnant of the Uncompahgre Uplift in western Colorado.

End

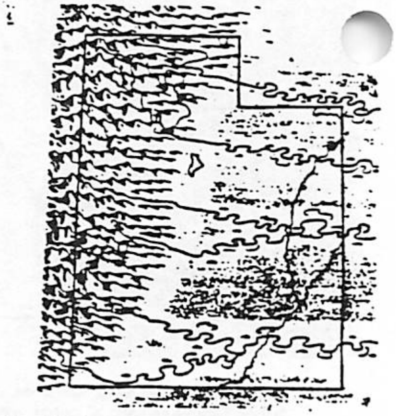


Figure 13-3c Paleogeography of Utah during deposition of the uppe part of the Morrison Formation. Rivers running fror the Mesocordilleran Highlands to the east deposite fine-grained sediment over most of the western interior At this time the remains of dinosaurs were buried her in large numbers.

Cretaceous

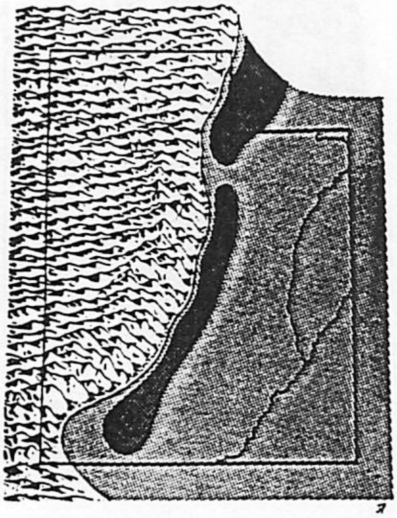


Figure 14-2. Generalized paleogeography of Late Cretaceous time in Utah. Darker pattern represents areas of thicker sediments in the transition belt between the Mesocordilleran Highland to the west and the interior of the continent to the east.

Early Tertiary
(Paleocene/Eocene)

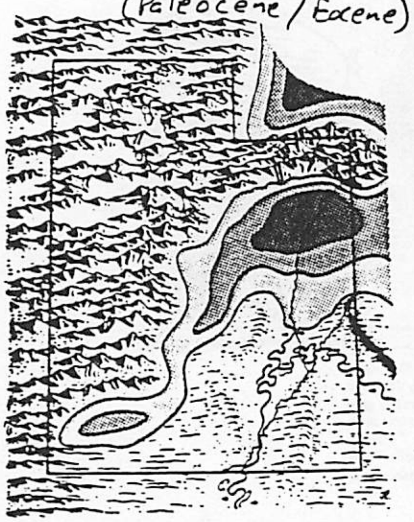
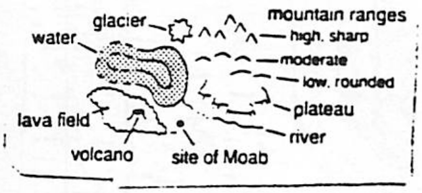
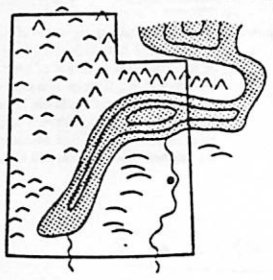


Figure 16-1. Generalized paleogeography of Utah during the Early Tertiary. The darker pattern the thicker the deposits of lake sediment. Chief site of deposition was the Uinta Basin; the southwestern extension into central Utah was the site of deposition of the Flagstaff Formation and southwestern Utah received the Claron Formation.

Key for last 6 diagrams



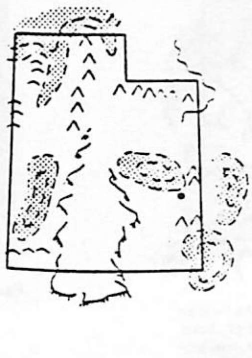
Paleocene



Eocene

Oligocene

Miocene



Pliocene

Pleistocene

The Geological History of Utah – (Nevada), Sevier and Laramide Orogeny

Introduction:

The Sevier and Laramide Orogeny are two major phases of Utah's geological history, which has to be seen in the major contents of plate tectonics, subduction and correlated volcanism, even if Utah is quite distant from the next plate border, and in consequence does not directly share the geological behavior of an active plate edge.

The following table supplies a general overview of Utah's geological and stratigraphical history, which consists of 6 major phases:

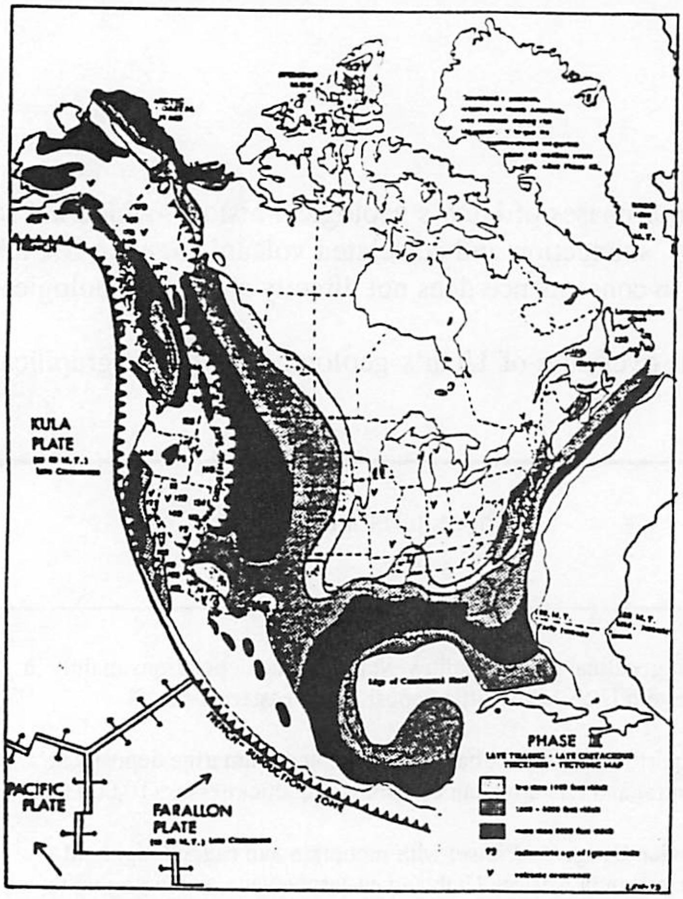
Phase	mill. Years ago	Geological time Interval	Characteristics
I	1200 – 350	Late Precambrian to Devonian	Miogeoclinal phase; shallow-water marine depositions mainly in western Utah, while little deposition in eastern Utah
II	350 – 200	Mississipian to Early Triassic	Oquirrh and Paradox basins; marine andnonmarine deposits in central and Eastern Utah of astonishing thicknesses (10,000 feet)
III	200 – 80	Late Triassic to early Cenozoic	**Sevier Orogenic Phase**; with mountain and rugged highland formation in western Utah and easternNevada, extending up to Alaska; thick marine and nonmarine depositions in eastern Utah down into coastal plains and shallow seas
IV	80 – 40	Latest Cretaceous to Eocene	**Laramide Orogeny** (Uinta Mountains, San Rafael Swell, Circle Cliffs and Monument) mark the end of marine deposition in Utah adjacent basins are filled with extensive continental stream and lake sediments
V	40 – 25	Oligocene	Volcanism, ash flow tüffs; lavas, stocks, and Laccoliths of the Henry, LaSal and Abajo mountains
VI	25 – 0	Miocene to recent	Regional uplifts; nonmarine sediments and basalts deposited in block fault basins; Lake Bonneville

The Sevier Orogeny represents the first event after tectonic activities started already in the late Jurassic along the west rim of the North American plate, parallel to changes in relative movements of the African plate and the opening of the Atlantic Ocean.

Phase III: Sevier Orogeny

Late Triassic to early Cenozoic (150 -80 Mill. Years ago)

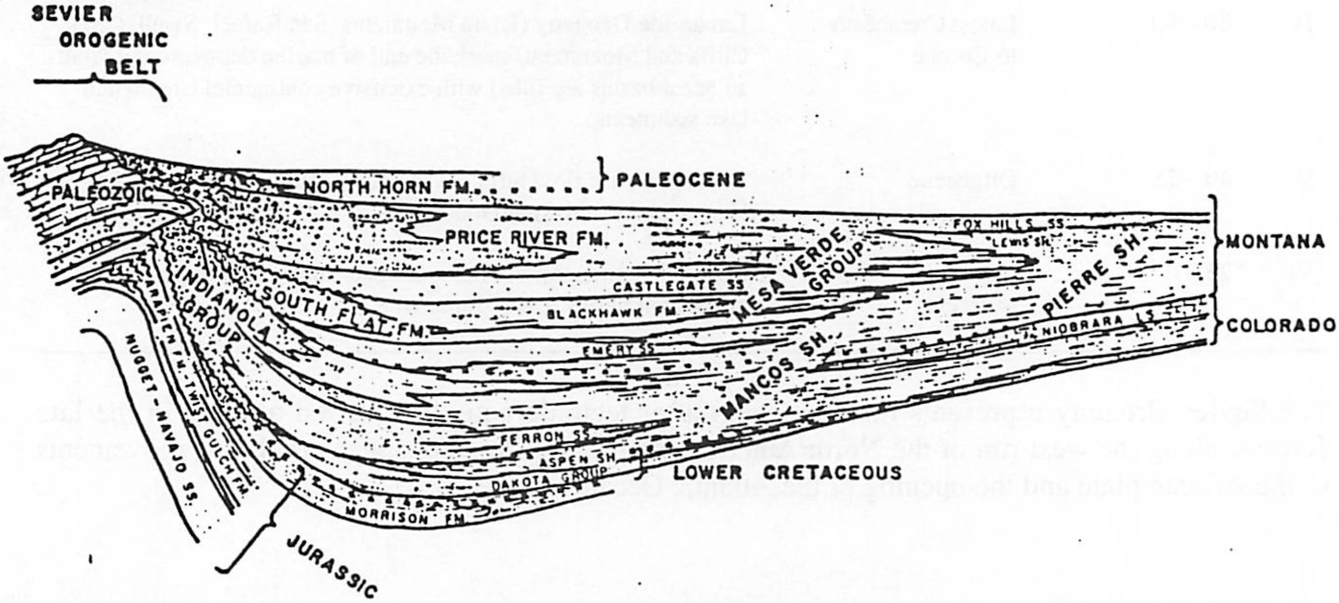
The Sevier Orogenic Belt formed during the latest Jurassic to early Cenozoic age running more or less North-south along eastern Nevada and western Utah, shedding clastics to the East. It extends in Utah along the Blue Mountains, Star Range, Pavant Range, Southern/Central Wasatch Mountains, and North-eastern Utah, but is part of a much bigger belt system extending even further north up to Alaska.



Phase III is a flip-lop of the main areas of deposition in earlier phases in Utah's geological history, with huge vertical uplifts in western parts of Nevada and eastern parts of Utah, originating from huge compressional thrust faulting, which shortened the surface area of the Sevier Orogenic Belt by 40 to 60 miles at least.

In consequence, huge depositions of eroded material took place in eastern parts of Utah along and into coastal plains and shallow seas. It was the period of the last epicontinental sea in Utah spreading from Texas in north-western direction, covering eastern Utah in the early upper Cretaceous.

Stratigraphy:



Diagrammatic section across Rocky Mountain geosyncline in central Utah (Gobban and Reeside, 1952; Fisher et al., 1960; Spieker, 1949)

Sevier orogenic structures are compressive and indicate foreshortening of crustal rocks. Two principal stratigraphies of the Sevier Orogeny are recognized: The Miogeosyncline in Nevada and Utah contains a thick section of Paleozoic rocks of carbonate assemblage (limestone, dolomite, clean sandstone, and little shale), and within and west of the Antler orogenic belt Paleozoic rocks of the siliceous assemblage (shale, dirty sandstone, chert, and volcanic rocks) of the eugeosyncline occurr.

Relationships between the Paleozoic sections in the eugeosyncline, the miogeosyncline, and the adjacent shelf are obscured by major thrust faults with displacements of tens of miles. Eugeosynclinal rocks have been thrust over miogeosynclinal rocks in western and central Nevada, and miogeosynclinal rocks have been thrust over thin shelf facies in southeastern Nevada and western Utah. Beside that the present day gepgraphic distribution of various rock assmeblages does not represent their distribution at the time of deposition.

Causes for the Sevier Orogeny

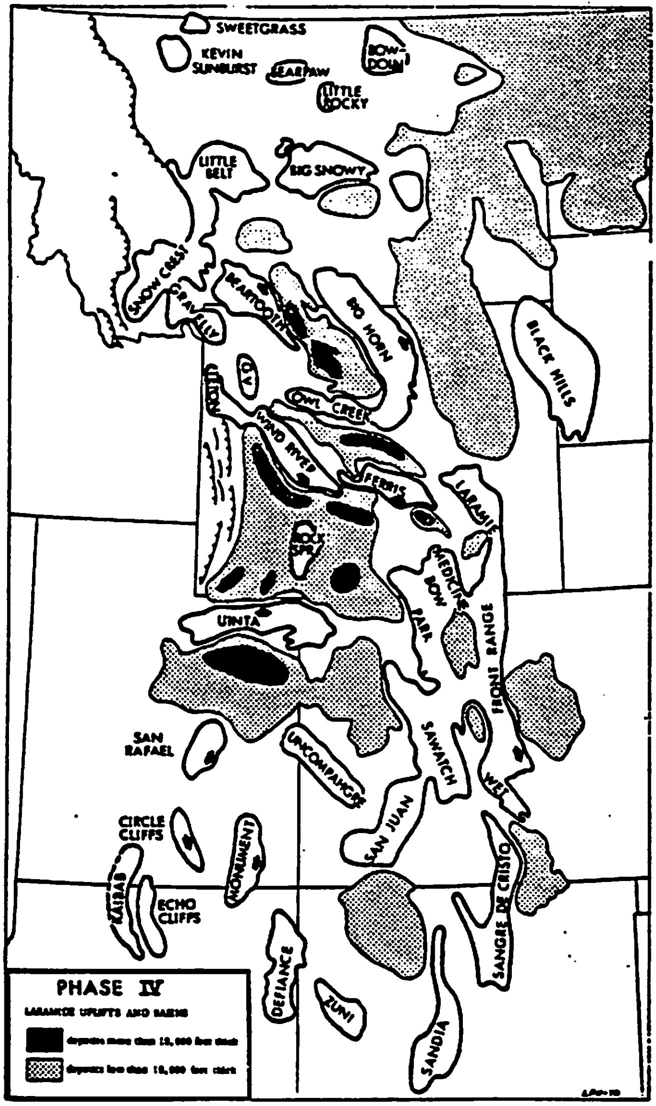
The reasons for the appearance of the Sevier Orogeny cannot be pinned down to one single reason or event. The "normal" product of a subduction zone would be the volcanic-magmatic rocks of the overlying arc. However, the coincidence between earlier arcs and later orogenic belts has long been noted in the Ordovician Taconic, the Devonian Acadian, and the Cretaceous Sevier Orogeny.
Therefore several theories are discussed in literature as possible causes for the Sevier Orogeny:

- Hamilton (1969): postulated rapid subduction of oceanic plates as the orogenic process
- Coney (1972): changing plate relationships in the Atlantic Ocean
- Pitman and Talwani's (1972): found indications for a decreased separation rate of North America from Africa in Phase III (in comparison to Phase IV)
- Burchfiel and Davis (1972): compressive stresses transmitted eastward through the crust from the zone of continental underthrusting
- Atwater (1970): restored the west coast plate relationships near the end of phase III, and found, that at that time the North American plate might have developped a San Andreas fault type boundary with the adjacent Kula plate

Phase IV: Laramide Orogeny

Latest Cretaceous to Eocene (75 -40 Mill. Years ago)

The Laramide Orogeny was characterized by the development of basement-cored overthrusts and adjacent synkinematic depositional basins in the just formed Cretaceous geosyncline and on its forelands to the east between Montana and New Mexico (see map below). It consists of the Uinta Mountains (biggest features), the San Rafael Swell, and the Cicle Cliffs and Monument, and marks the end of the marine deposition in Utah. The Uinta basin shows the thickest deposits, and consists of 13,000 feet of Paleocene-Eocene strata. 2 large lakes left extensive freshwater deposits in Utah: Lake Flaggstaff in the Paleocene created algal "bird's eye" limestone in the southern Wasatch Mountains, while Lake Green River later during the Eocene did not reach those big extentions to the South.



Laramide uplifts and basins. Basins are shaded, darker shade shows >10,000 feet of Early Tertiary deposition (after Haun and Kent, 1955)

The reasons for its appearance are not clear. The uplift started about 80 million years ago, while the Sevier Orogeny was still on its way. At the same time the North American plate changed direction with respect to the African plate, and the separation of Greenland and Europe from North America took place.

Pitman and Talwani (1972) found that the rate of opening of the North and South Atlantic were about twice as rapid between 81 and 63 mill. years ago (=Laramide ages) as during any period before.

The Laramide uplift found its end about 50 million years ago, again parallel to a change in plate tectonic behavior: The North American plate changed its direction of movement with respect to Europe.

All these events might be coincidence, however, heat must have been generated to power the uplift movements.

It is therefore not really astonishing that several authors have proposed various theories for the Laramide Orogeny.

Causes for the Laramide Orogeny:

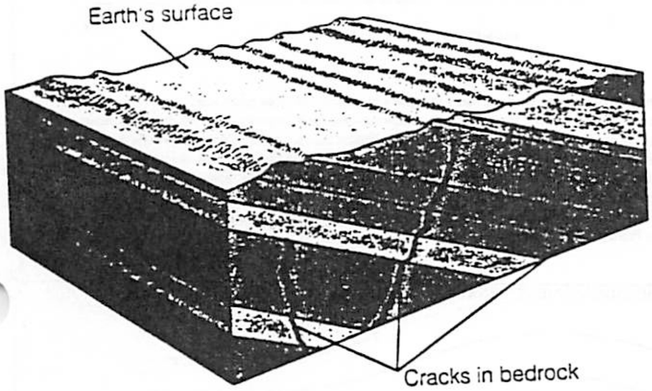
- Wise (1963): Laramide structures are maybe the results of northwesterly right-lateral mega-shear forces setup between Rocky Mountains and the west Coast
- Sales (1968): shear forces were left-lateral and directed more nearly east-west, in concordance with the movemnet of the Pacific plate
- Coney (1972): heat gained from overridden descending West Coast oceanic plate, but this area seems quite far away from the edge to be so affected
- Atwater (1970): reconstructed West Coast plate relationships between 80 and 60 mill. Years ago, showing north-migration of a trench subduction zone during that time. Maybe pressure release occasioned by changes in relative plate motion may have caused partial melting and uplift
- Livaccari et al (1980): low angle subduction of a Hess Rise twin boyuant ocean floor plateau, which are hard to subduct: Laramide uplift is riding on this low angle subducted ocean floor plateau

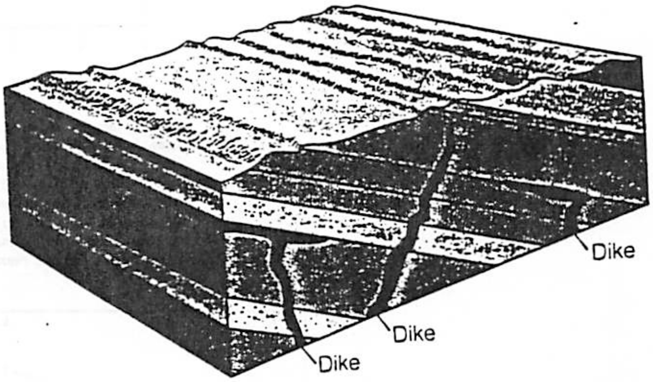
Laccoliths

Terry Hurford

The Basics of Intrusions:

Two basic structures of intrusions exist. They are classified by being cordant or discordant. A cordant structure is one which runs parallel with any layering in the where as a discordant structure cuts through these layers. A sill, an example of a cordant structure, forms when an intrusive magma squeezes into a crack between layers in a rock. Magma that intrudes into a crack discordant with any layering is called a dike.





After magma squeezes into a crack between layers forming a sill, continual flow of magma causes the sill to swell forming a laccolith. The sill intrudes in between two layers in the rock. Then as pressure of the magma below continues to push upward the layers directly above the sill are uplifted. New magma can then enter between the layers producing a dome of magma. This dome of magma when solidified is known as a laccolith.

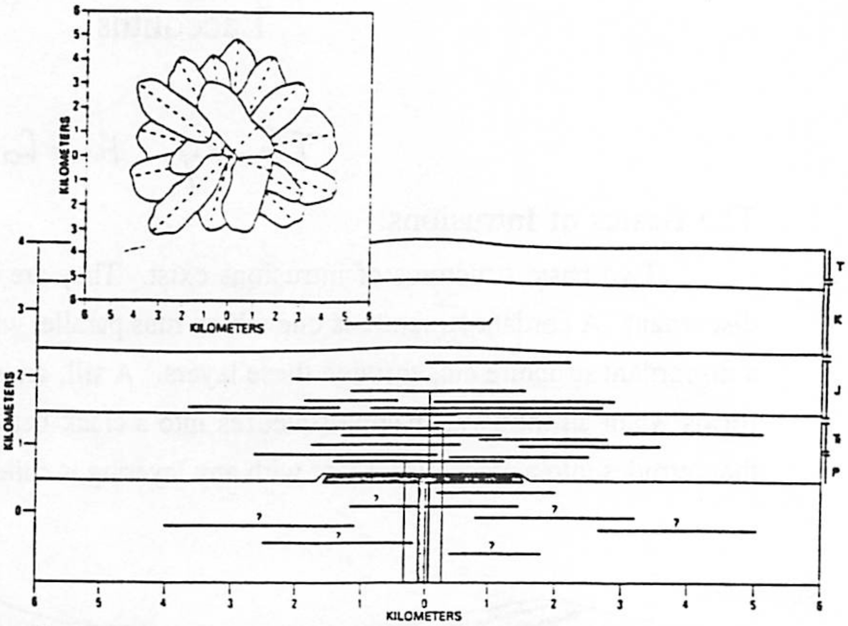
References

Jackson, M. Processes of Laccolithic Emplacement in the Southern Henry Mountains,
USGS Bulletin 2158. 1997 pg 51-57
Southeastern Utah.

Ross, M. Geology of the Tertiary Intrusive Centers of the La Sal
Mountains, Utah. USGS Bulletin 2158. pg 61-83. 1997

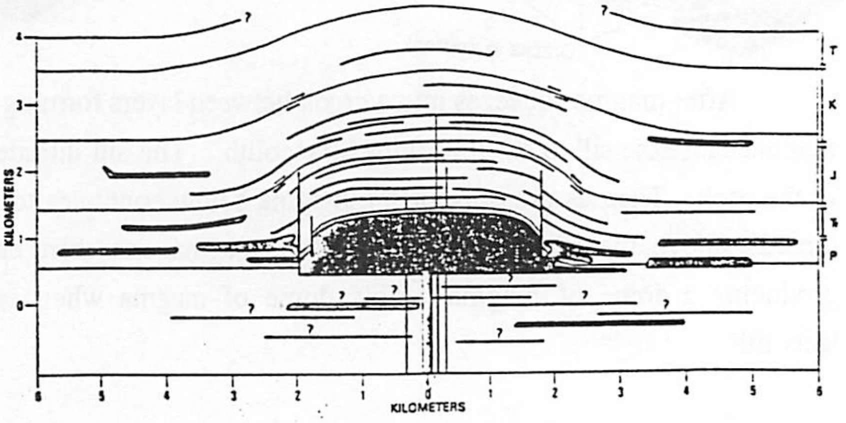
llivan K. Isotopic Ages of Igneous Intrusions in Southeastern Utah.
USGS Bulletin 2158. pg 33-35 1997

Plummer *Physical Geology Sixth Edition* 1991

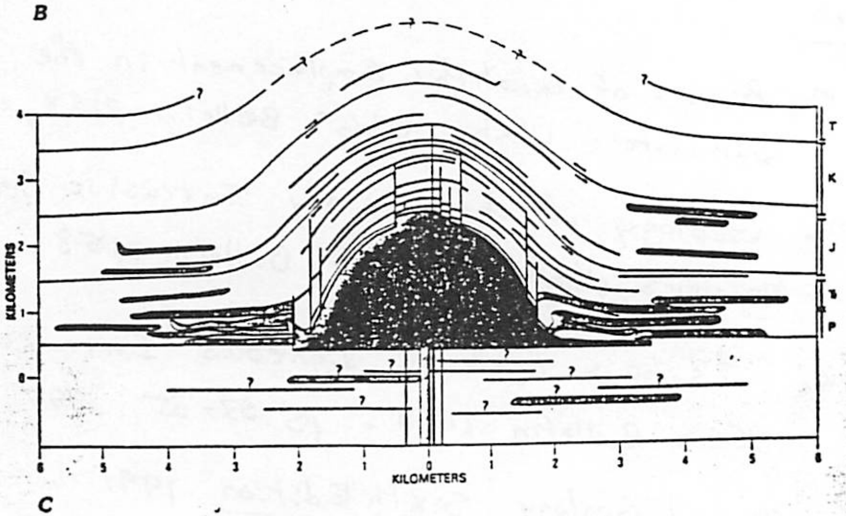


A

Figure 6 (above and facing page). Vertical cross sections showing states in growth of central intrusions and domes in the Henry Mountains. *A*, Emplacement of a stack of tongue-shaped sills and thin laccoliths fed by vertical dikes. Inset: plan view of early-formed intrusions, showing their tongue-like shape. The incipient major laccolith (supple pattern) has a circular plan shape. *B*, Thickening of the major laccolith induces bedding-plane faulting, and the overlying intrusions are faulted. Peripheral dikes and faults form as lateral growth of the laccolith stops. Some sills and thin laccoliths intrude laterally under the peripheral limb of the dome. *C*, The major laccolith continues to thicken as the dome grows in amplitude. Beds steepen and stretch on flanks of the dome, numerous faults lift the roof rock, zone of peripheral intrusion enlarges, and radial dikes cut upward through overburden. P, Ŧr, J, K, T: Permian, Triassic, Jurassic, Cretaceous, and Tertiary sedimentary host rocks. From Jackson and Pollard, 1988, figure 19.



B



C

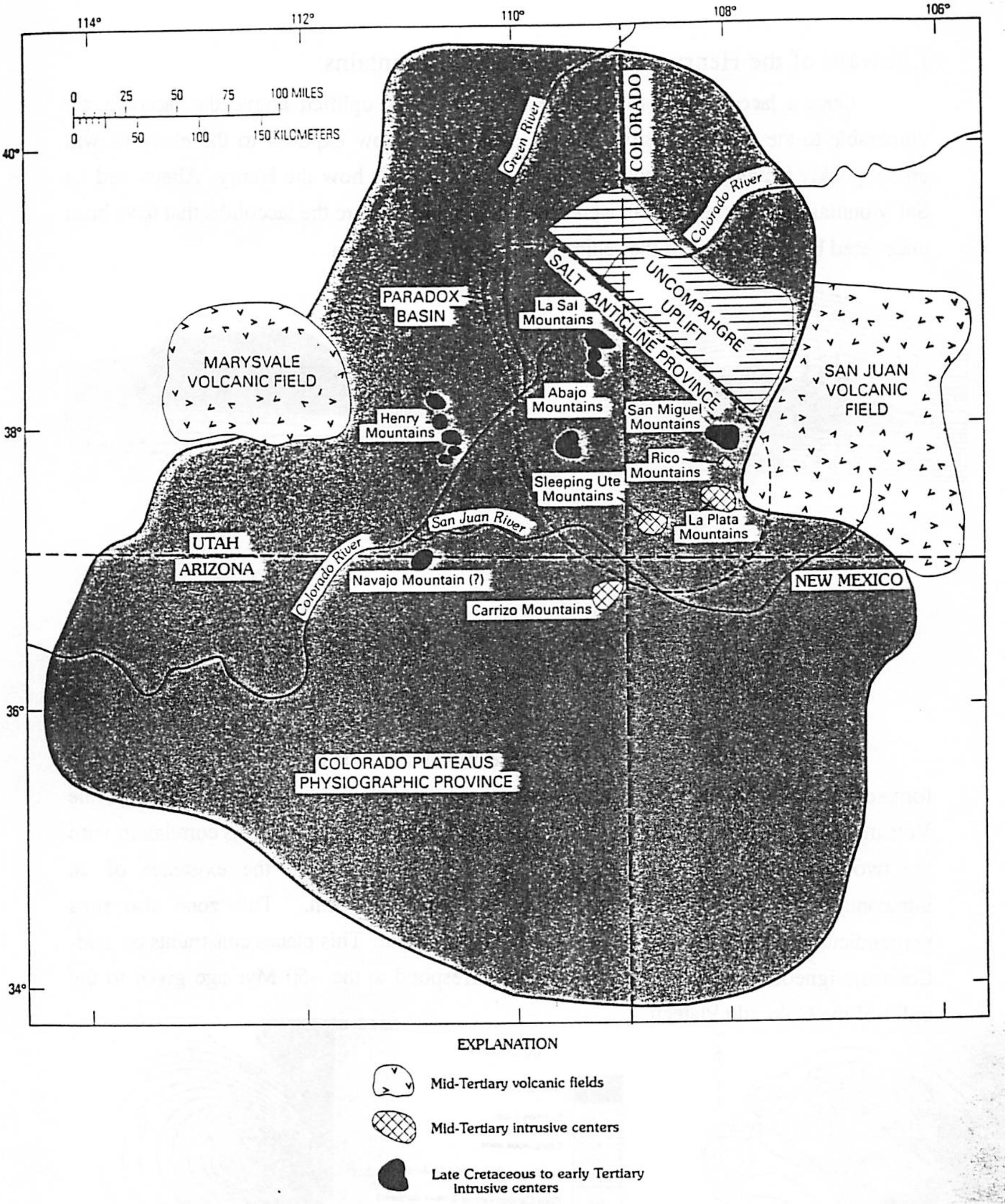
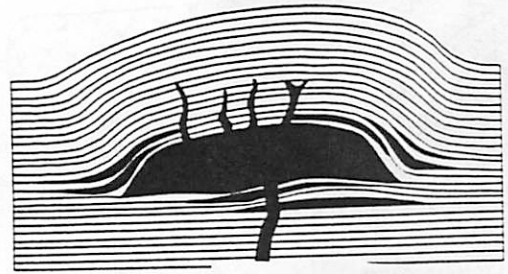


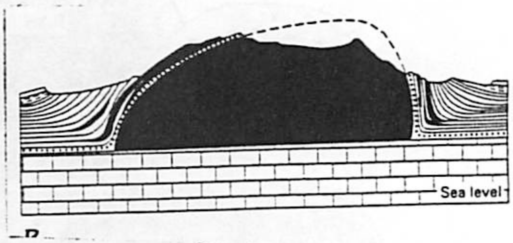
Figure 1. Selected magmatic and structural features of the Colorado Plateau (modified from Woodward-Clyde Consultants, 1983, figure 6–1, p. 136).

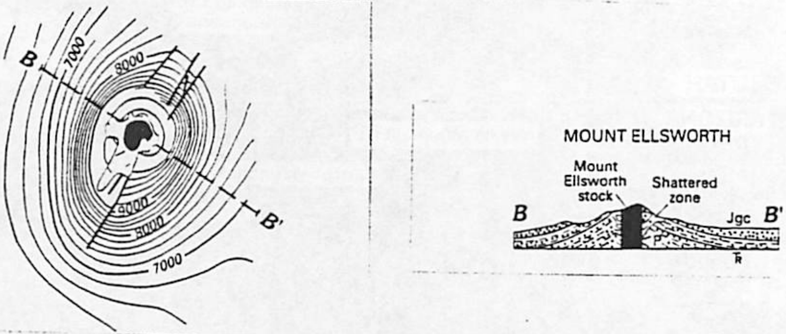
Uncompahgre Plateau, the basement rocks contain northwest-striking faults that show evidence of Proterozoic shearing (Case, 1991). Farther east, in the mountains of central Colorado, Proterozoic rocks contain both northwest-striking and northeast-striking fault zones that also show evidence of Proterozoic movement (Hedge and others, 1986; Tweto,

Lifeways of the Henry, Abajo, and La Sal Mountains:

Once a laccolith has formed the layers of rock uplifted above the laccolith are vulnerable to the effects erosion. These outer layers now exposed to the elements will erode quickly leaving the laccolith below exposed. This is how the Henry, Abajo, and La Sal Mountains in southeast Utah were formed. Their peaks are the laccoliths that have been uncovered by weathering of the sedimentary layers above them.







The cores of the laccoliths from these mountains can be dated to see when they formed. All show an age of 25-30 Myr making them contemporaneous with the Marysvale Volcanic Field to the west and the San Juan Volcanic field to the east. This correlation with the two fields on either side of the Colorado Plateau shows the existence of an intracontinental magmatic zone that is greater then 1000 km. This zone also runs perpendicular to the western coast and its subduction zone. This places constraints on mid-Cenozoic igneous activity. These ages also correspond to the ~50 Myr age given to the uplift of the Colorado Plateau.

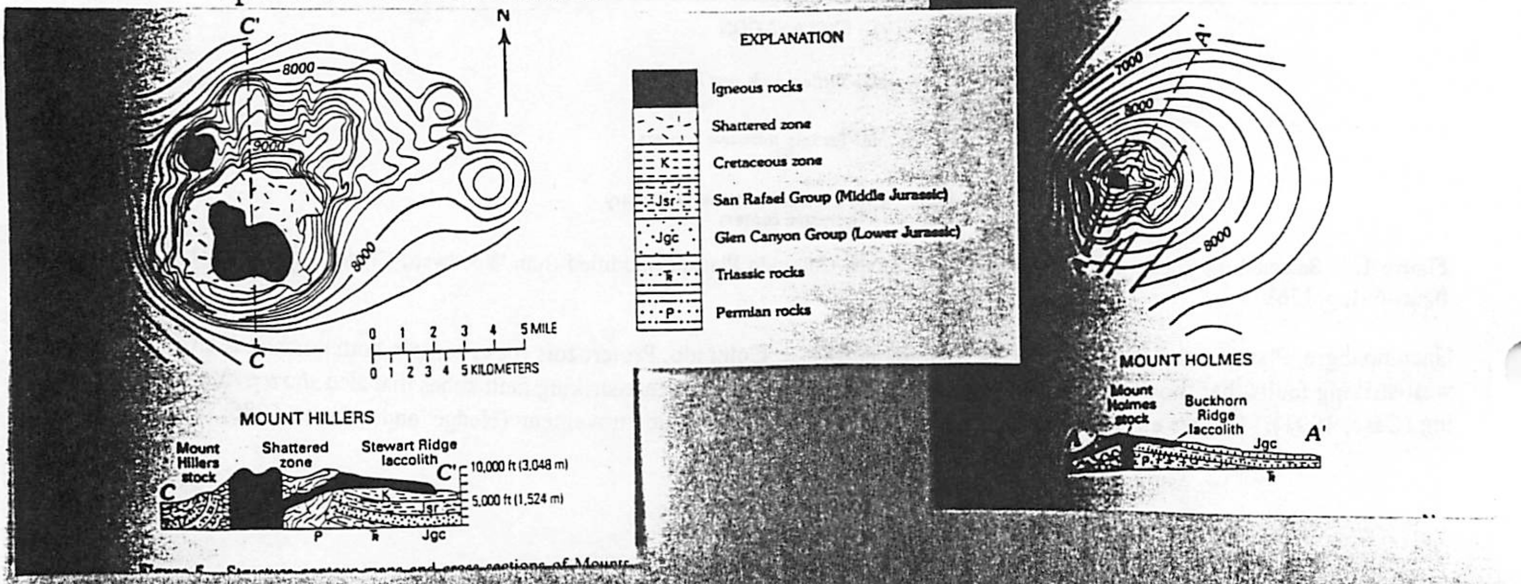


Figure 5. Structure-contour maps and cross sections of Mount

CHAOS in the Entrada Sandstone

Joseph Spitale

April 22, 1999

1 Introduction

A number of hypotheses (Alvarez *et al.*, 1998; Baars, 1972) have been proposed to explain the deformation seen in the Middle Jurassic Carmel formation and Slickrock member of the Entrada sandstone in southeast Utah. Most of these hypotheses can now be ruled out due to the newly recognized presence of liquefaction features which imply that the deformation occurred rapidly. It appears that the deformation must be seismogenic, resulting from either an earthquake or an impact. The proximity of Upheaval Dome and its tentative identification as an impact structure (Boon and Albritton, 1936) leads Alvarez *et al.* (1998) to propose that the deformation is an example of liquefaction caused by impact shaking. If the deformation was truly caused by the impact which putatively formed Upheaval Dome, then the impact must date to the Middle Jurassic. This interpretation is consistent with the current observational evidence, but more field observations will be necessary to resolve the question.

2 Geologic Setting

The Middle Jurassic Carmel Formation is widespread in southern Utah and lies atop the Lower Jurassic Navajo Sandstone. It consists of shallow marine and eolian deposits (Blakey *et al.*, 1983). In southeast Utah, it appears as an easily eroded series of red beds. The Carmel Formation is overlain by the Slickrock Entrada Sandstone, whose origin is primarily eolian. In Arches, it is a cliff-forming sandstone with white

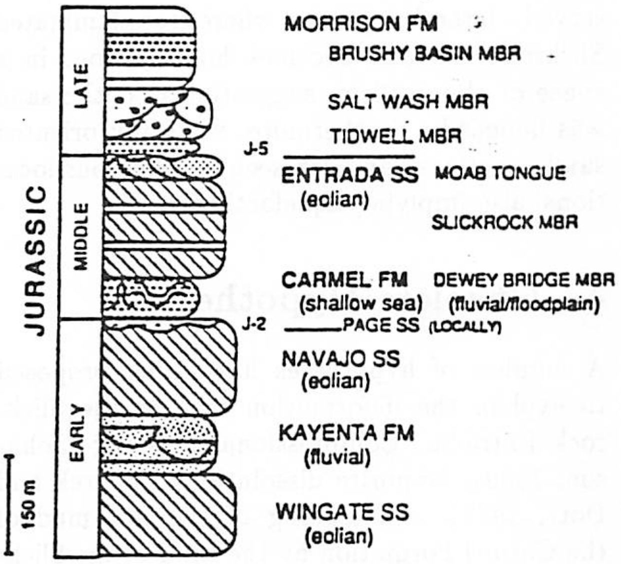


Figure 1: Stratigraphic context for the Carmel Formation and Slickrock Entrada Sandstone. *From Alvarez et al. (1998)*

cross-beds and pink planar beds. (Kocurek and Dott, 1983).

3 Deformational Features and Evidence of Liquefaction

Deformational features in the Entrada sandstone include folds with no apparent systematic axis orientation, displaced material, and liquefied or brecciated beds. Alvarez *et al.* (1998) observed a lateral transition where cross-laminated Slickrock Entrada becomes homogeneous in a space of about 10cm, suggesting that the sand was liquefied. Furthermore, vertically oriented sand injections can been seen in numerous locations, also implying liquefaction.

4 Obsolete Hypotheses

A number of hypotheses have been proposed to explain the deformation seen in the Slickrock Entrada. Compressional buckling (Johnson, 1969), evaporite dissolution (Kocurek and Dott, 1983), and loading of the soft mud of the Carmel Formation by the sand of the Slickrock Entrada (Peterson and Turner-Peterson, 1989) are ruled out by the liquefaction evidence, which requires the deformation to have occurred quickly. Baars (1972) suggested sliding of soft sediments down a paleoslope, but this should have resulted in basal shear, which is not observed (Alvarez *et al.*, 1998).

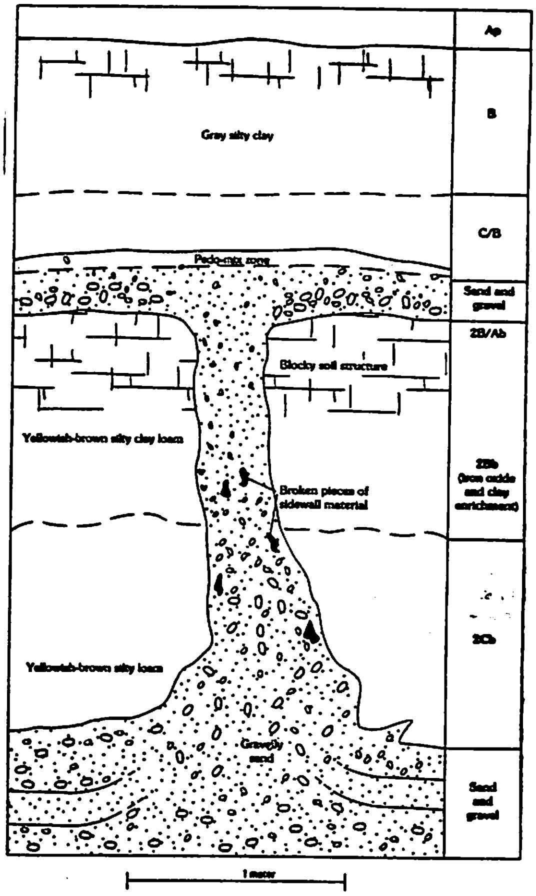


Figure 2: Illustration of a typical sand-filled dike. This example occurs in sediments along the Wabash River in the Wabash Valley of Southeran Indiana and Illinois.*From Obermeier et al. (1993)*

5 Impact versus Earthquake

The liquefaction evidence strongly suggests that the deformation was the result of a seismic process, but the cause of the disturbance remains unclear. It is uncommon, though not unheard of, for a large earthquake to occur in a region which is not seismically active. One generally expects to find evidence for a the quasiperiodic occurrence of earthquakes during the time which a region was active. Alvarez *et al.* (1998) see no evidence that southeast Utah was seismically active during the Middle Jurassic, although soft-sediment deformation does occur in some older horizons of the Carmel Formation in southwest Utah (Jones and Blakey, 1993).

The proximity of Upheaval Dome, a suspected impact structure, suggests that the disturbance may have been associated with a nearby impact (Alvarez *et al.*, 1998). Further field work is required to establish whether there is a physical connection between Upheaval Dome and the deformed Carmel and Slickrock Entrada. If Upheaval Dome is an impact structure, its age is very uncertain. The impact must postdate the formation of the Lower Jurassic Navajo Sandstone, but it has been suggested (Kriens, 1997) that the crater is as young as a few million years. The presence of possible ejecta on the current Navajo Sandstone land surface supports a greater age, such that the material would not need to be let down erosionally a large vertical distance. If the impact occurred during the deposition of the Slickrock Entrada, then the ejecta would need to be let down 100-200m, compared to 1-2km if the age were fairly young.

6 Discussion

The only reasonably firm conclusion which can be made regarding the cause of the deformation in the Carmel and Slickrock Entrada is that it was the result of a seismic disturbance. The cause of the disturbance remains in dispute. There is no morphological basis upon which to distinguish between an impact and a large earthquake. Circumstantial evidence would appear to support the impact hypothesis, but it is not even clear that Upheaval Dome was caused by an impact. If it was, it is still difficult to tie it to the deformation in the Carmel Formation and Slickrock Entrada Sandstone without further field study.

References

Alvarez, W., E. Staley, D. O'Connor, and M. A. Chan (1998). Synsedimentary deformation in the Jurassic of southeastern Utah – A case of impact shaking? *Geology 26*(7), 579–582.

Baars, D. (1972). *The Colorado plateau - A geologic history.* University of New Mexico Press.

Blakey, R., F. Peterson, M. Caputo, R. Geeseaman, and B. Vorhees (1983). *Paleography of Middle Jurassic continental, shoreline, and shallow marine sedimentation, southern Utah*, pp. 77–100. Society of economic paleontologists and mineralogists.

Boon, J. and C. Albritton (1936). Meteorite craters and their possible relationship to cryptovolcanic structures. *Field and Laboratory 5*, 1–9.

Johnson, A. (1969). Development of folds within the Carmel formation, Arches National Monument, Utah. *Tectonophysics 8*, 31–77.

Jones, L. and R. Blakey (1993). Erosional remnants and adjacent uncomformities along an eolian-marine boundary of the Page Sandstone and Carmel Formation, Middle Jurassic, south-central Utah. *Journal of Sedimentary Petrology 63*, 852–859.

Kocurek, G. and R. Dott (1983). *Jurassic paleography and paleoclimate of the Central and Southern Rocky Mountains region*, pp. 101–116. Society of economic paleontologists and mineralogists.

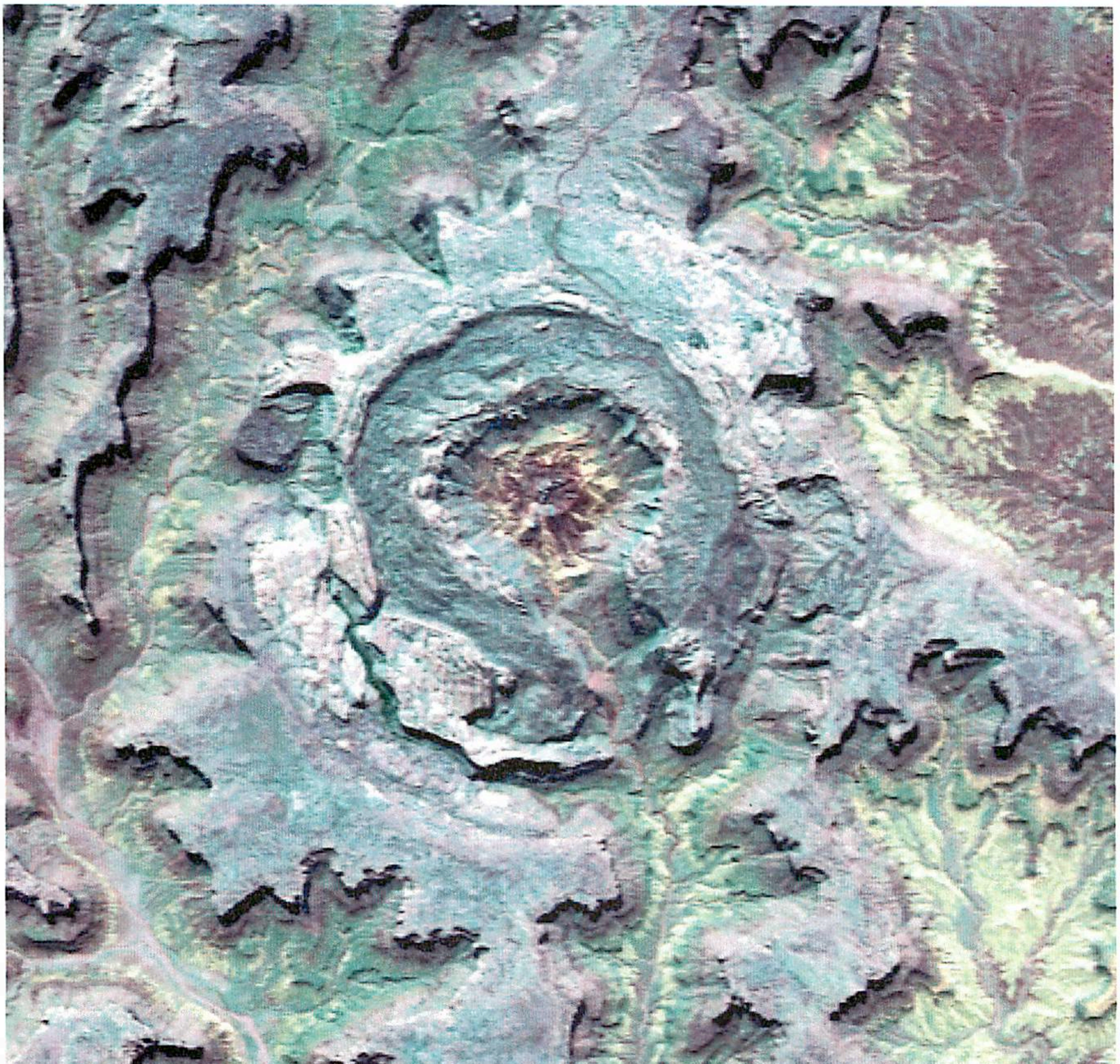
Kriens, B. (1997). Structure and kinematics of a complex impact crater, Upheaval Dome, southeast Utah. *Brigham Young University geology studies 42*, 19–31.

Obermeier, S., J. Martin, A. Frankel, T. Youd, P. Munson, C. Munson, and E. Pond (1993). Liquefaction evidence for one or more strong Holocene earthquakes in the Wabash Valley of Southern indiana and illinois, with a preliminary estimate of magnitude. U.S. Geological Survey Professional Paper 1536. 27 p.

Peterson, F. and C. Turner-Peterson (1989). Geology of the Colorado Plateau. In *Grand Junction to Denver*. American Geophysical Union.

Upheaval Dome:
Impact Crater or Salt Dome?

Jeannie Riley, Nancy Chabot and Windy Jaeger



INTRODUCTION

Upheaval Dome, located in the northern region of Canyonlands, Utah, is a structure that has created a great deal of controversy. Several different hypothesizes have been introduced; salt diapirs, salt doming, and meteoritic impact, to explain the origin of this geological structure.

Upheaval Dome is approximately 2.5 km in diameter and 1500 ft deep. It is characterized by a doming feature in the center; it then moves out to a rim syncline, and next into a rim monocline. Upheaval Dome is located in the western region of the Paradox Basin, which was formed in the Middle Pennsylvanian. Salt anticlines are present within the Paradox Basin and salt diapirs are found in the southern region of Canyonlands.

Visible rock layers in Upheaval Dome extend from the Navajo Sandstone (Middle Jurassic) to the Cutler Group (Permian). The Colorado Plateau was uplifted in the Miocene which helps conclude that around 1600m of rock layers must have been eroded over Upheaval Dome. The doming feature in the center of this structure contains two different rock units. The reddish-brown unit is the Organ Rock and the white unit is the White Rim Sandstone (see stratigraphic column). These beds lie approximately 250-350m above their levels in the surrounding area, they are also highly distorted. An overview of the stratigraphic setting can be see on the following geologic map.

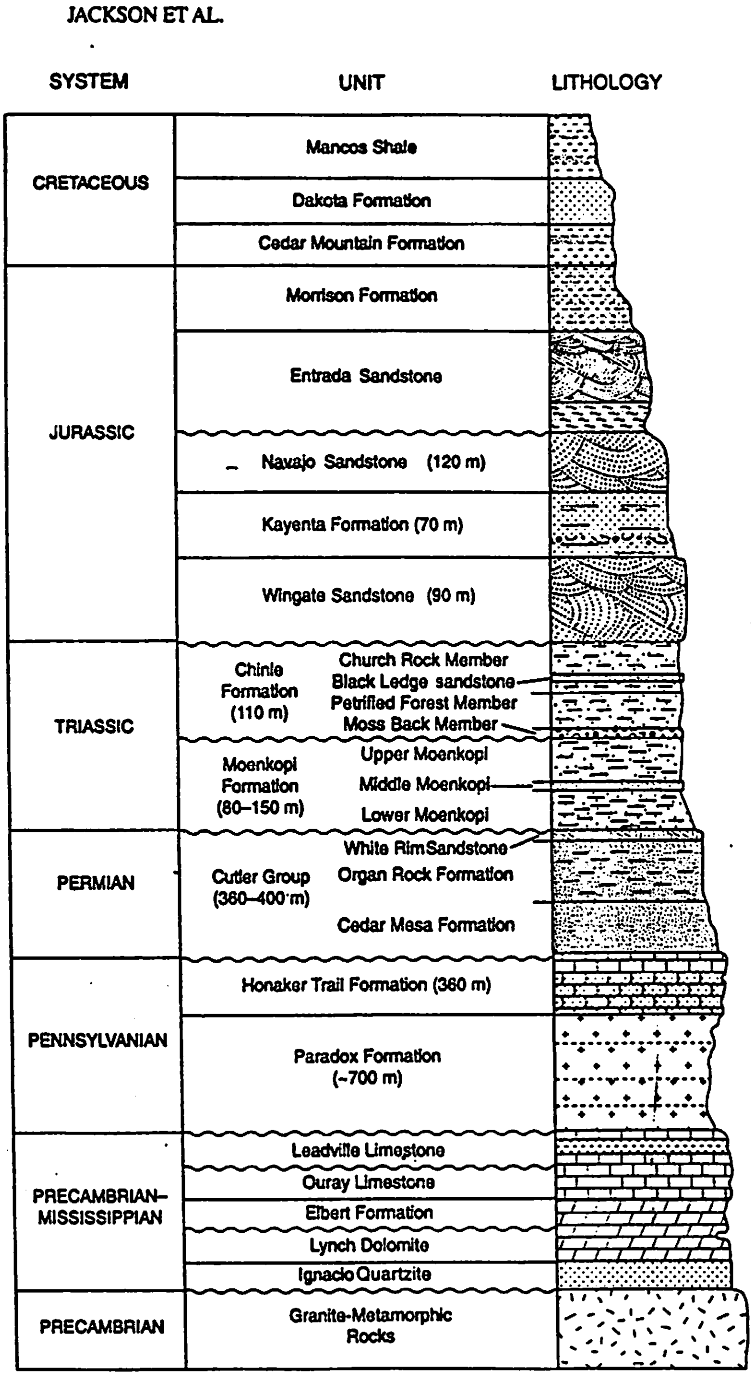


Figure 1: Stratigraphic Section

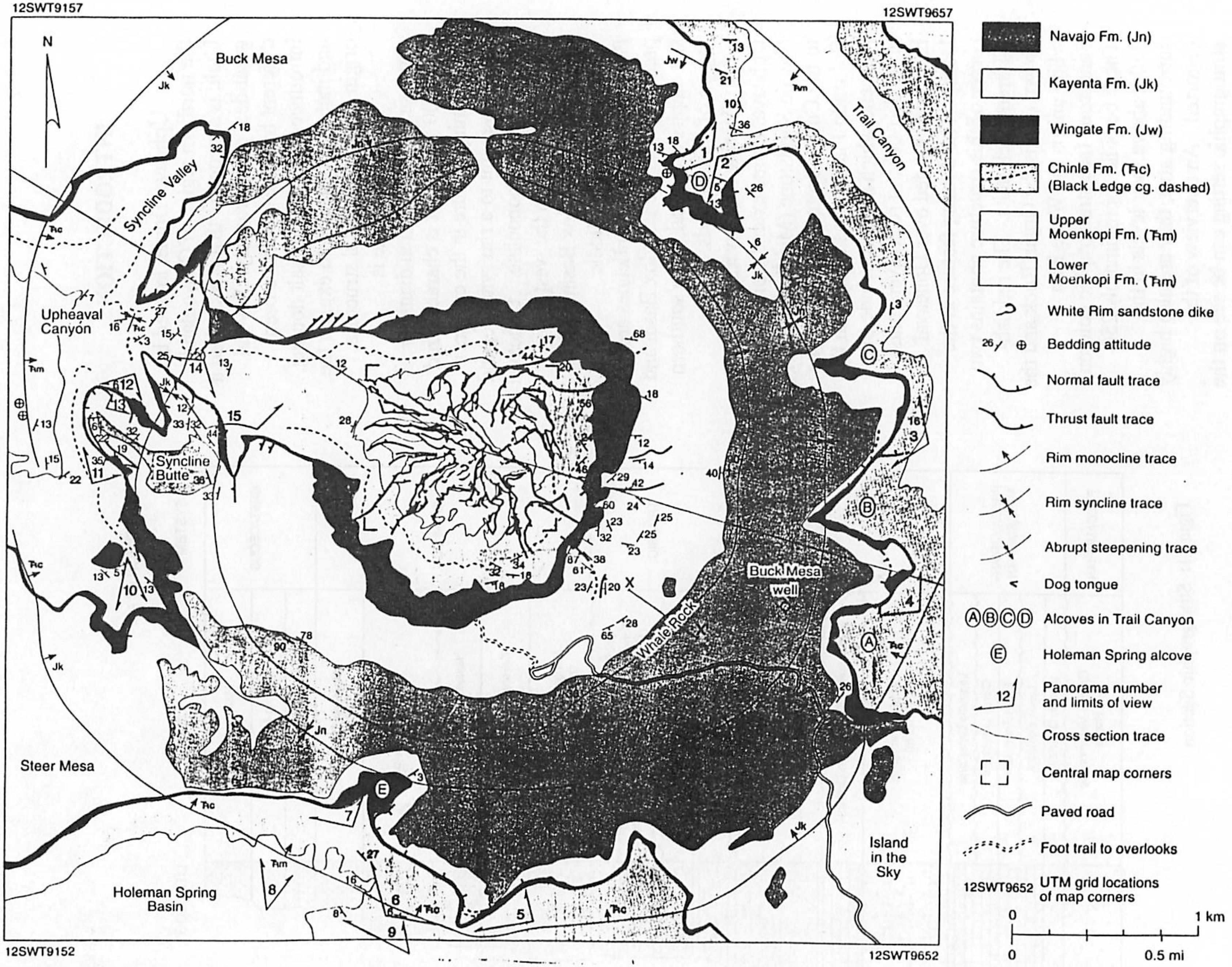
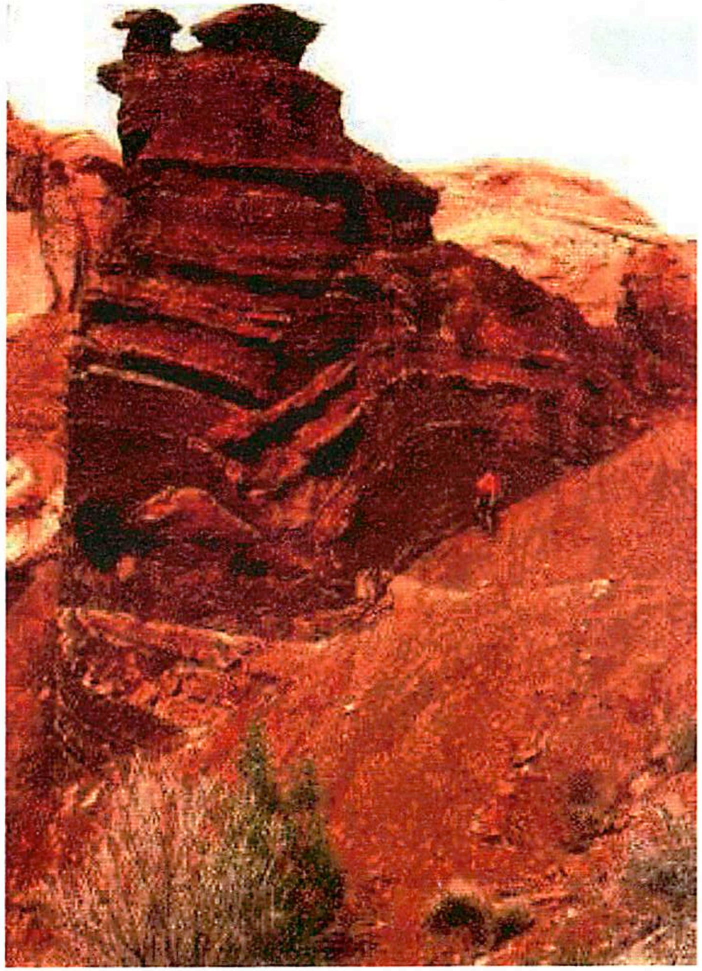
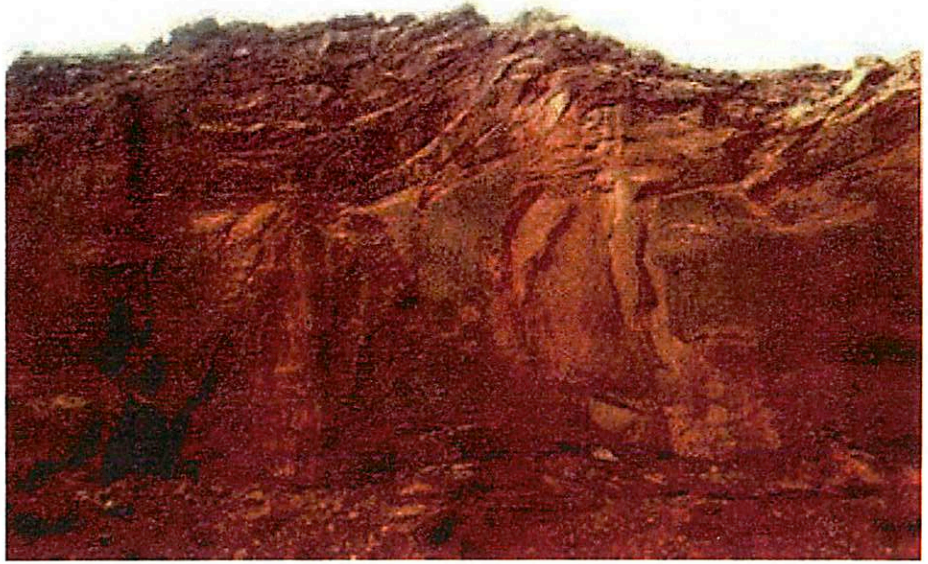
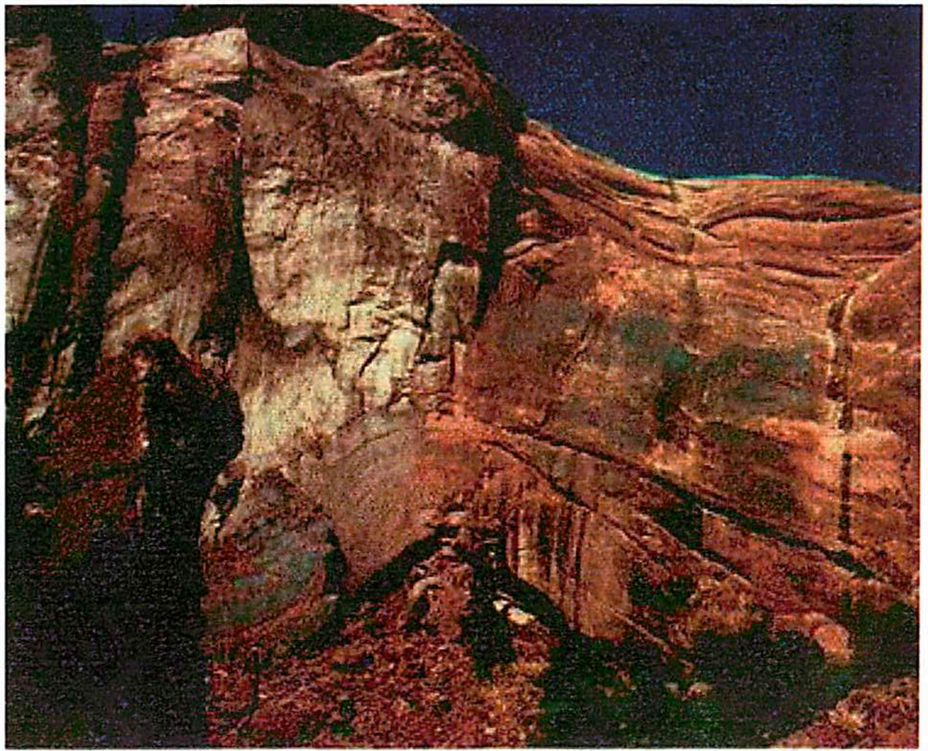


Figure 2: Geologic Map of Upheaval Dome



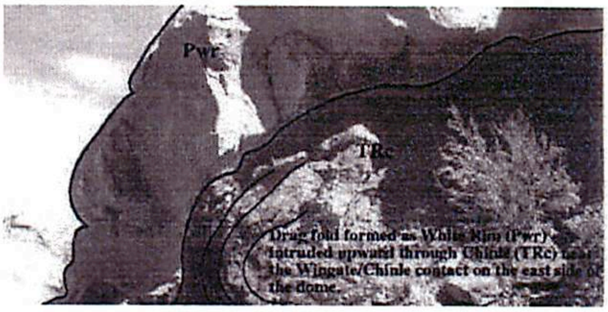
Above: Turret Rock in the central crater
Top Right: Kayenta over Wingate
Bottom Right: Wingate above Chinle
all photos from:
http://zephyr.rice.edu/department/students/munger/Comps/Comps.htm





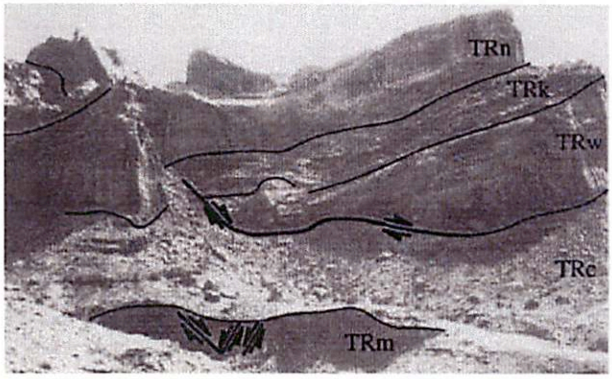
East side of Upheaval Dome:
Drag fold in the Triassic Chinle Formation.

P_{wr} = White Rim Sandstone
TR_c = Chinle Formation



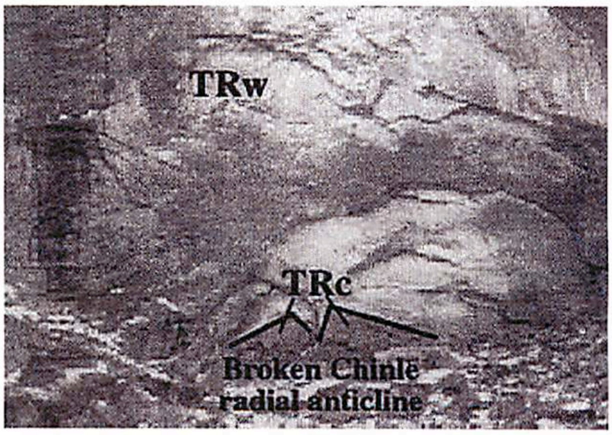
South of Upheaval Canyon:
Low angle normal fault between the Wingate and the Chinle.

TR_n = Navajo Sandstone
TR_k = Kayenta Formation
TR_w = Wingate Sandstone
TR_c = Chinle Formation
TR_m = Moenkopi Formation



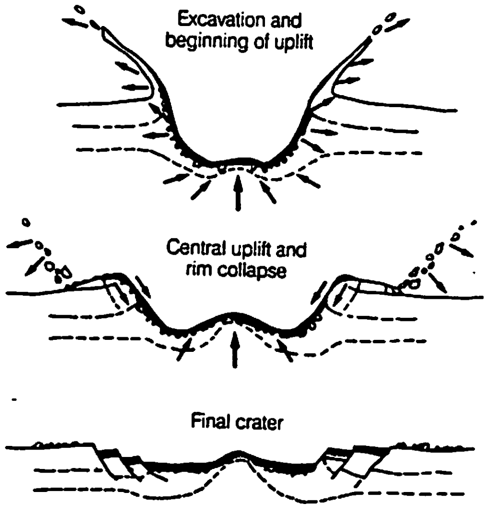
West wall of the crater:
Broken upper Chinle beds

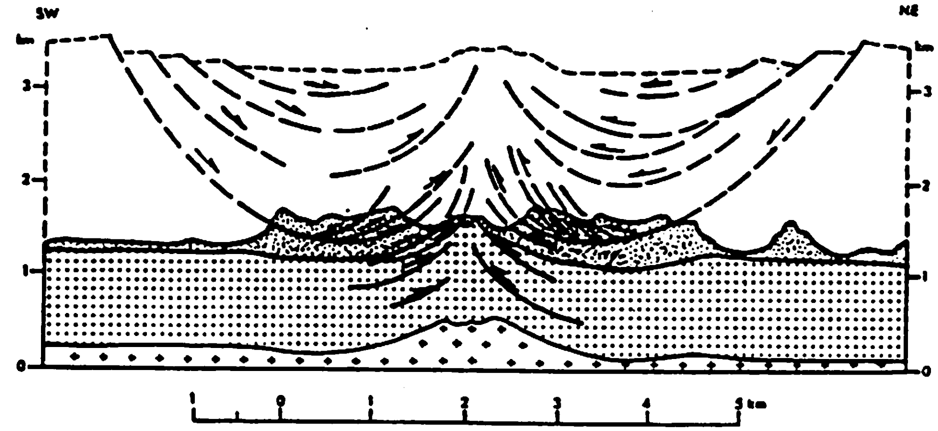
TR_w = Wingate Sandstone
TR_c = Chinle Formation

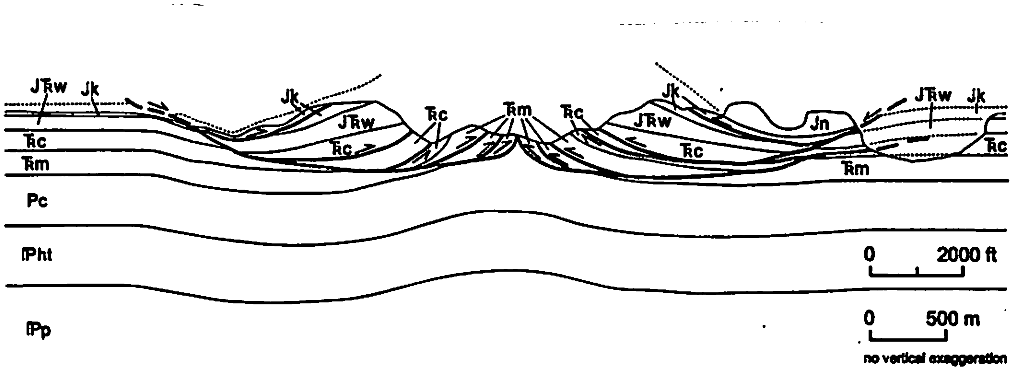


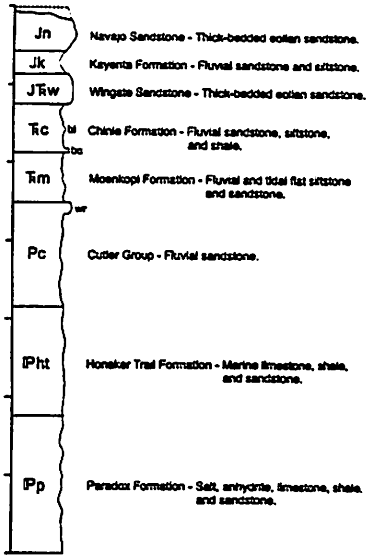
A Heavily Eroded Impact Crater?

The transition from simple to complex craters on the Earth occurs at diameters from 2 to 5 km. The collapse of a complex crater forms an uplifted central peak, whose height is comparable to the depth of excavation, as illustrated by the top left figure (Melosh, 1989). It has been proposed Upheaval Dome is a heavily eroded complex crater, and the actual crater rim was 1-2 km above the present day surface (under top left figure, from Shoemaker and Herkenhoff, 1984). This theory has been used to explain the observed outcropping of uplifted units in the center of Upheaval Dome (third figure from top, Kriens, Shoemaker, and Herkenhoff, 1997).

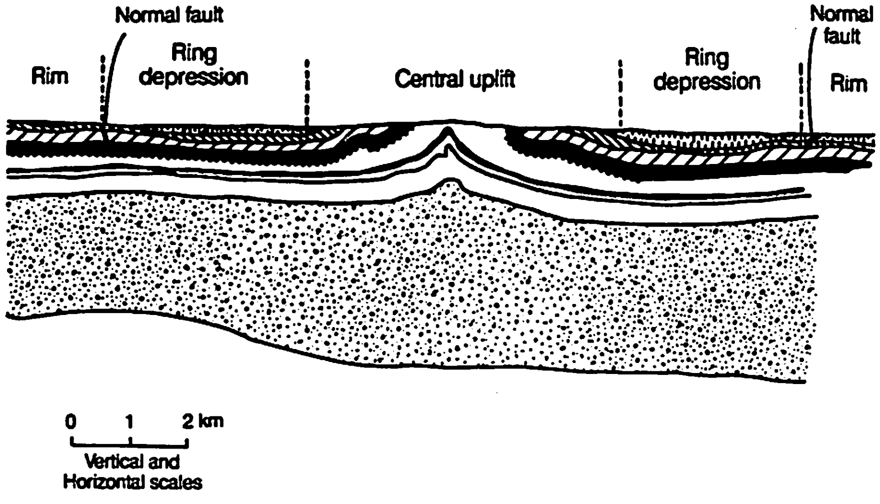






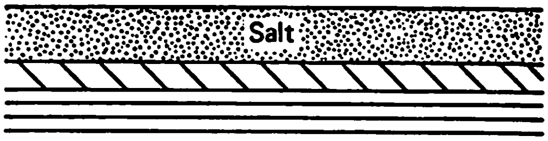


Jn	Navajo Sandstone - Thick-bedded eolian sandstone.
Jk	Kayenta Formation - Fluvial sandstone and siltstone.
JTw	Wingate Sandstone - Thick-bedded eolian sandstone.
Tc	Chinle Formation - Fluvial sandstone, siltstone, and shale.
Tm	Moenkopi Formation - Fluvial and tidal flat siltstone and sandstone.
Pc	Cutler Group - Fluvial sandstone.
IPht	Honaker Trail Formation - Marine limestone, shale, and sandstone.
IPp	Paradox Formation - Salt, anhydrite, limestone, shale, and sandstone.

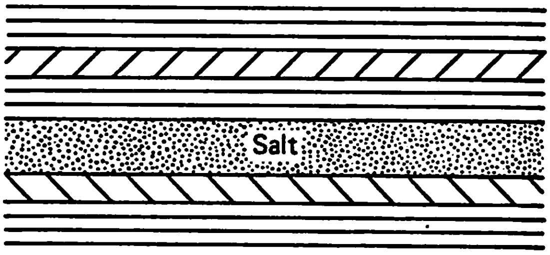


Bottom figure: Simplified geologic cross section of the Sierra Madera impact structure in west Texas. Sierra Madera appears to be a terrestrial complex crater. Although the surface rocks have been eroded away, the cross section shows a well-developed central uplift surrounded by a ring-shaped depression bounded by normal faults. (Figure and caption from Melosh, 1989).

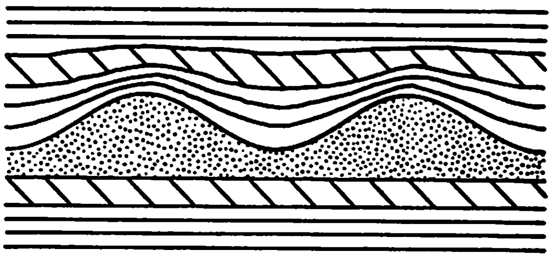
What is a Salt Dome?



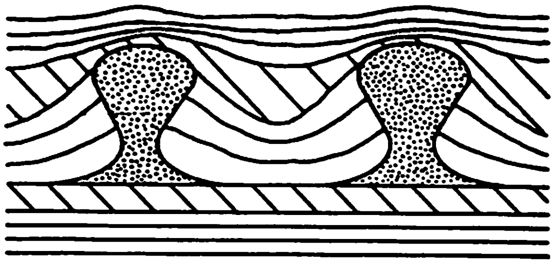
(a) Deposition of a salt layer



(b) Burial of the salt layer by additional sedimentation



(c) Growth of the instability of the salt layer



(d) Formation of salt domes

Recipe for a salt dome:

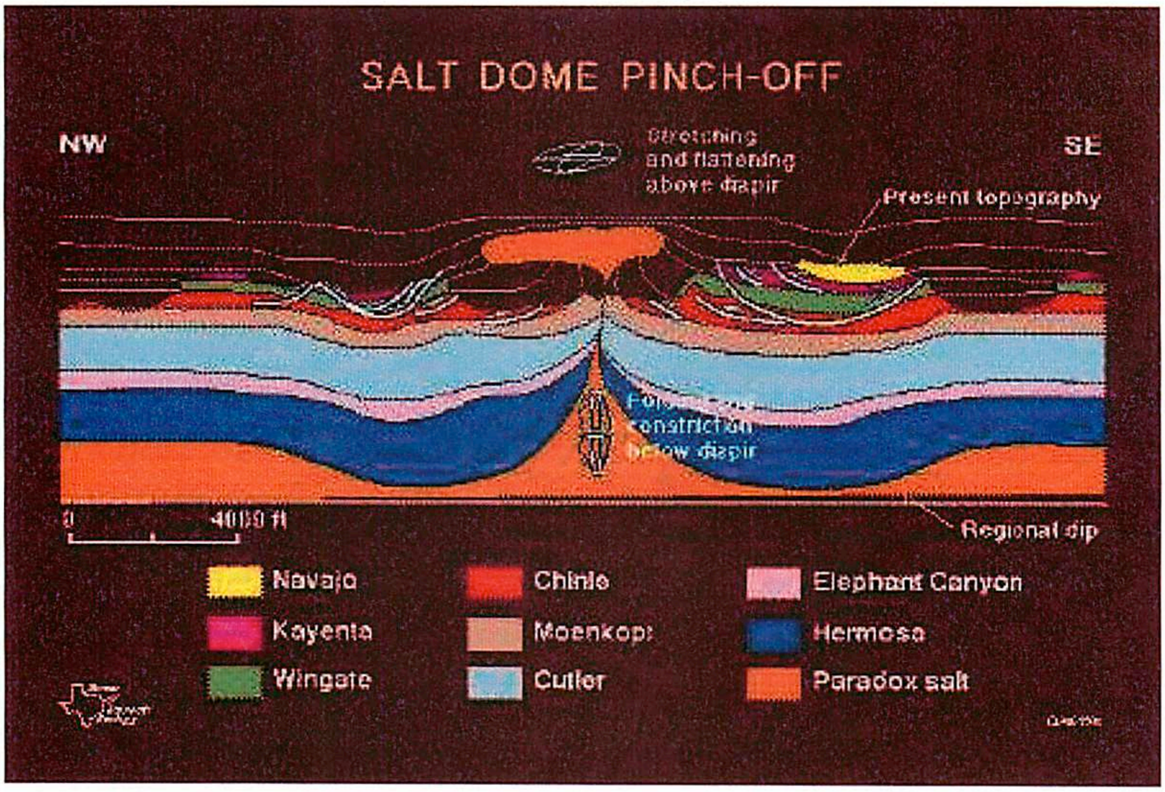
(a) Evaporate seawater leaving behind a large deposit of salt.

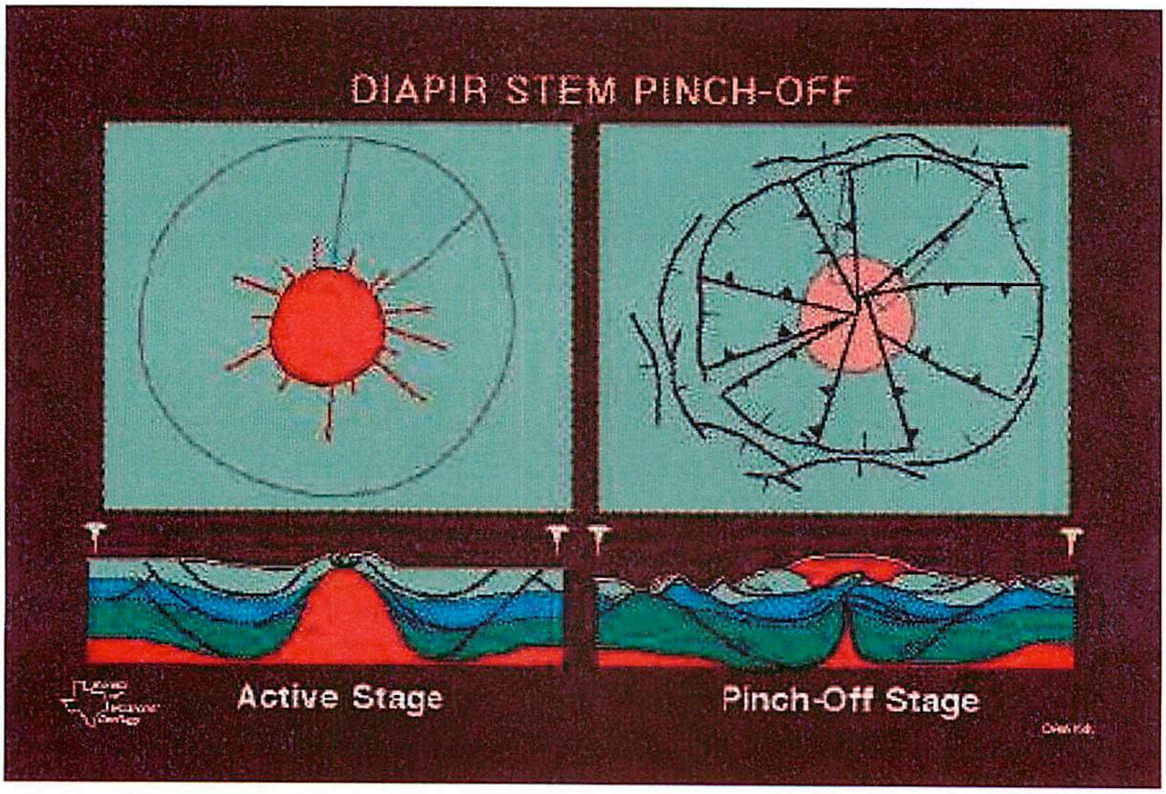
(b) Erode rocks from surrounding areas such as to deposit thick sediment layers on top of the salt. The salt is less dense than the overlying sediment, thus the arrangement is gravitationally unstable. However, at shallow depths of burial the strength of the salt layer counteracts its tendency to flow.

(c) With increasing depth of burial the temperature of the salt rises due to the geothermal gradient and the salt begins to creep upwards through the overlying sediment.

(d) These rising diapiric (plume-like) bodies of salt are the source of salt domes.

A PINCHED-OFF SALT DIAPIR?





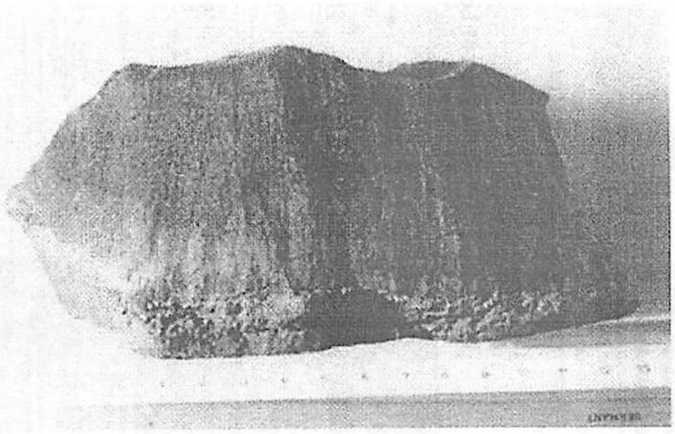
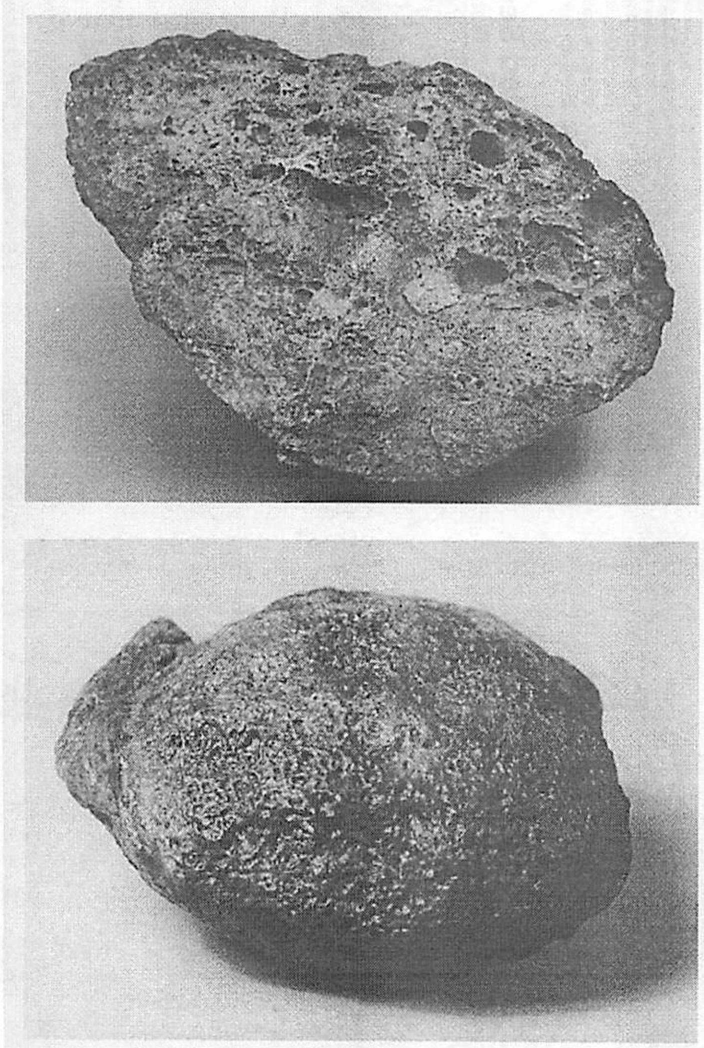


Figure 10. Shatter cone in sandstone of the Moenkopi Formation. Scale is in centimeters.



Eroded impactite bombs from lag deposit on Navajo Sandstone. Note vesicular interior in middle photo (dimensions: 10x15 cm) and "pull apart" tail in bottom photo (4x8 cm). Captions and photos from: Kriens, Shoemaker, and Herkenhoff, 1997.

Shatter cones & impactites?

Shatter cones contain a series of fractures and groves which appear to originate from a single point and are thought to be formed from propagation of a shock through the rock. The top left figure shows a proposed shatter cone found in the Moenkopi Formation near the center of Upheaval Dome (Kriens et al., 1997). Kriens et al.: "These cones are rare and not as finely decorated and grooved as shatter cones found at many other impact structures."

Shown in the middle and bottom photos are proposed impactites found at Upheaval Dome (Kriens et al., 1997). Impactites form from molten ejecta being thrown out during an impact. These samples were identified as impactites based on the vesicular textures, rounded shapes, and possible flow structures observed. They were determined to be dominantly quartz.

At LPSC '99 (Koeberl et al.), work was presented which concluded the identified "impactites" showed "no indication of being impact-derived." Instead, they suggest the source of the "impactites" is the Chert Pebble Unconformity which lies directly above the Navajo, the layer on which the impactites were found resting (chert = microcrystalline quartz). Furthermore, they were unable to identify any flow structures, and the cathodoluminescence of the samples indicated "normal metamorphic processes at moderate temperatures and pressures and do not show evidence of a high-temperature history." Also, the chemical composition of the "impactites" was found to show no similarity to possible target rocks.

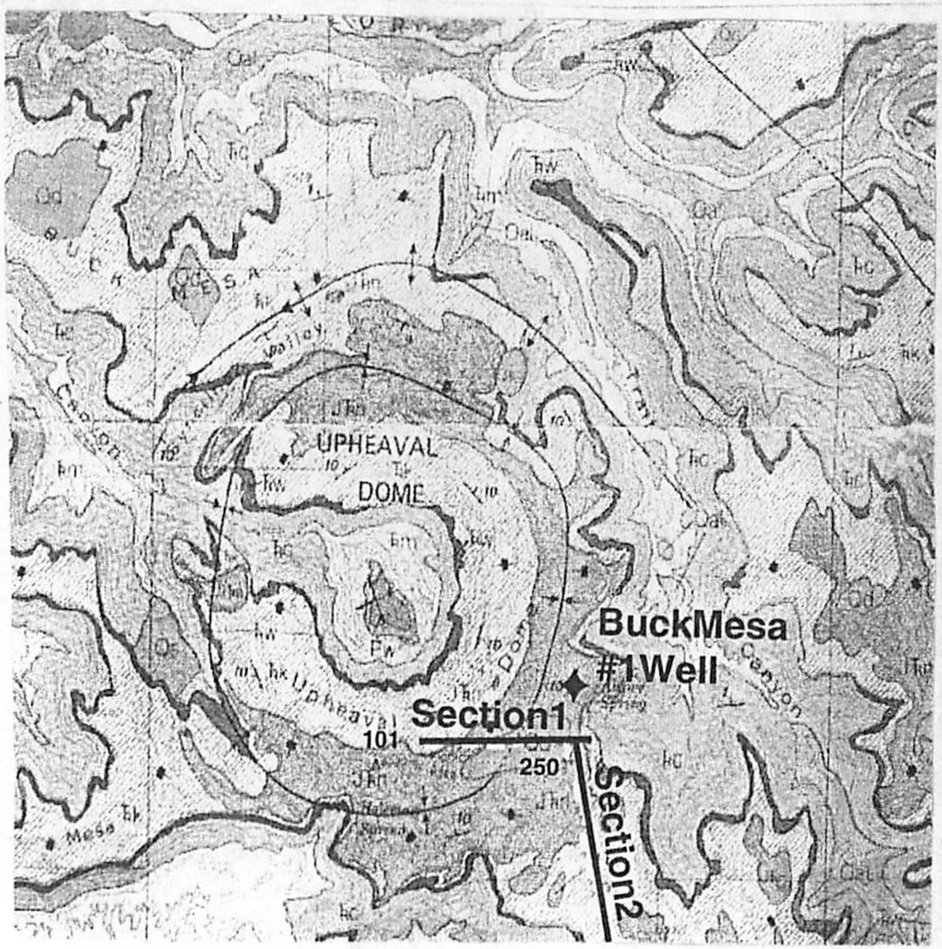
A NASA/JPL Seismic Study:

Seismic surveys recorded seismic waves generated by "repeatedly lifting and dropping a 700 lb, trailer mounted weight."

Look for evidence of salt doming. Deformation from a salt dome or diapir increases with depth. Deformation from an impact decreases with depth.

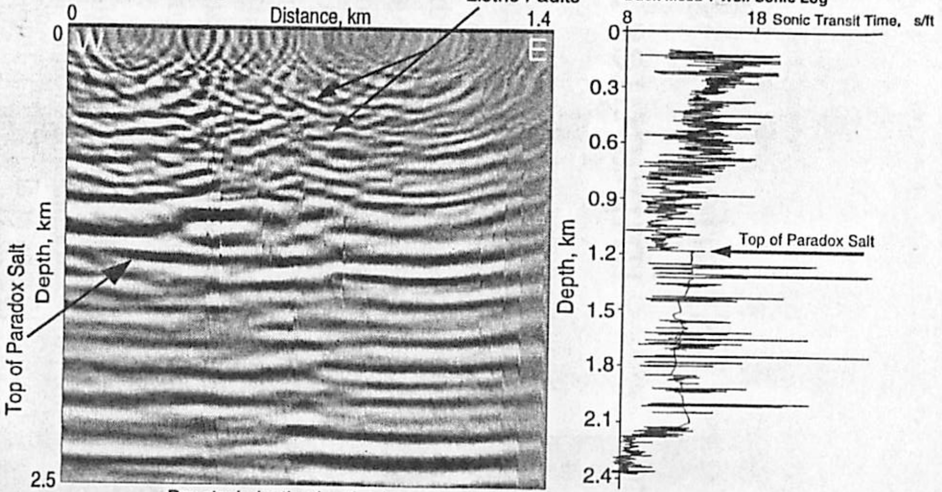
Reflection data sets show no evidence for salt doming.

Refraction data and subsequent modeling show no evidence for early arrivals due to passing through uplifted salt.



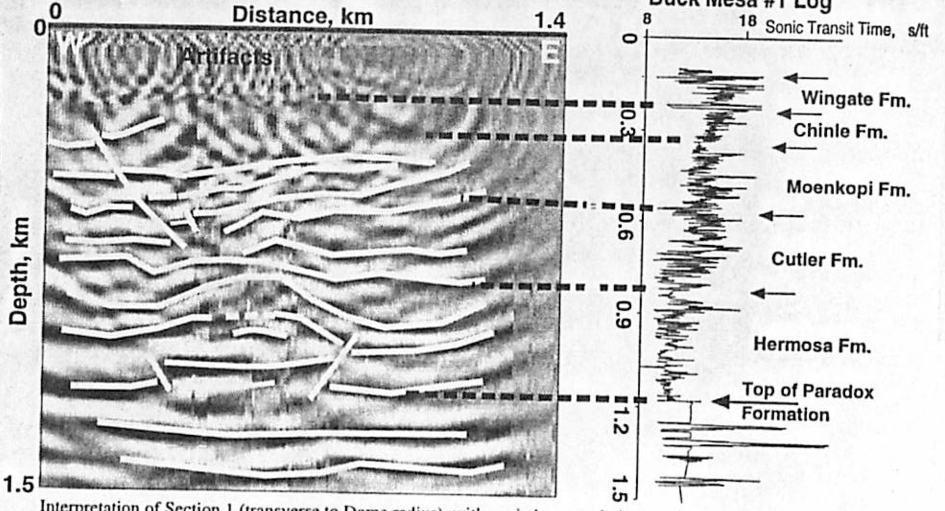
http://www.seismo.unr.edu/ftp/pub/louie/dome/

Pre-Stack Migrated Section 1



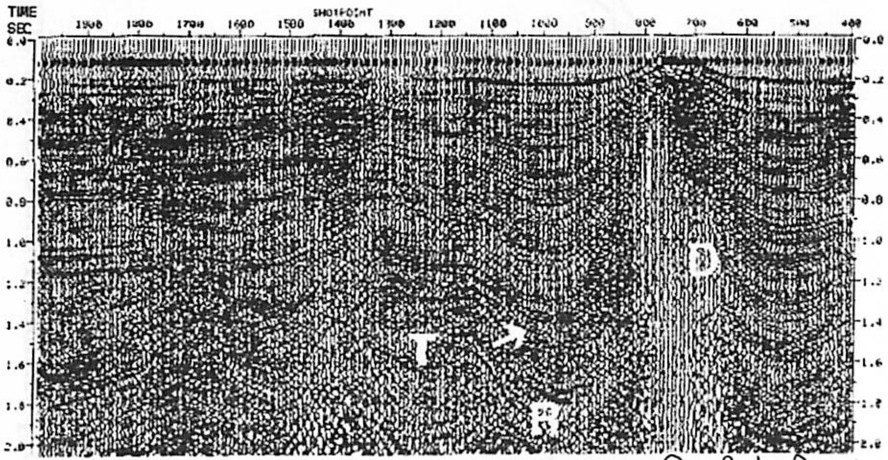
Pre-stack depth migration image for Section 1 (transverse direction), with Buck Mesa #1 well sonic log. The top and bottom of the Paradox salt correlate well with the log, despite migration artifact arcs. Images of listric faults appear above the salt.

Interpreted Section 1



Interpretation of Section 1 (transverse to Dome radius), with sonic log correlations to the top of the Paradox. White lines show interpreted faults as well as stratigraphy. The top of the Paradox has been deformed, but its uplift is limited to 100 m even within 500 m of the center of the Dome. The top of the Hermosa appears least disrupted, with listric fault blocks displacing stratigraphy above, in the central uplift.

Seismic reflection data from a salt dome, a salt diapir, and two impact craters:



D = Salt Dome

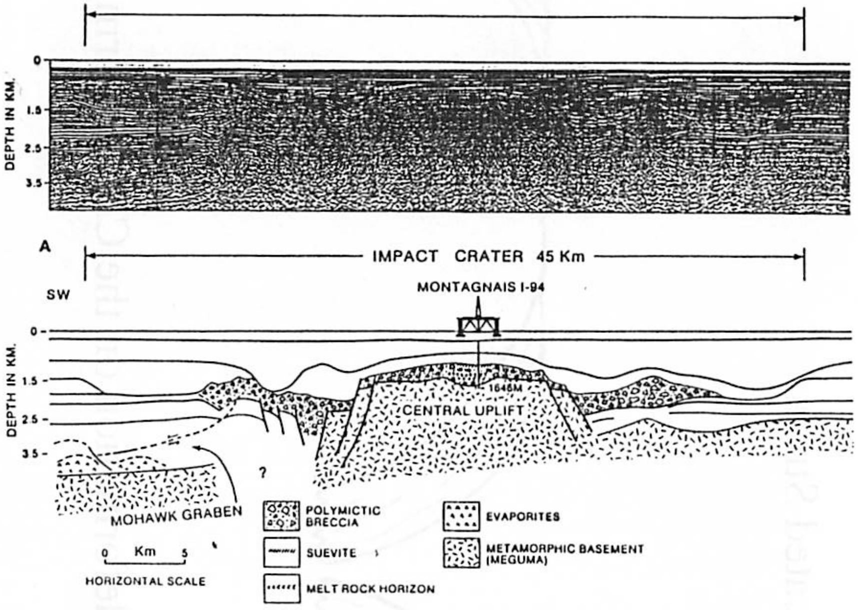


Figure 15. Sixtyfold reflection seismic section and corresponding interpretation across the Montagnais structure, Nova Scotia, Canada [after *Jansa et al.*, 1989].

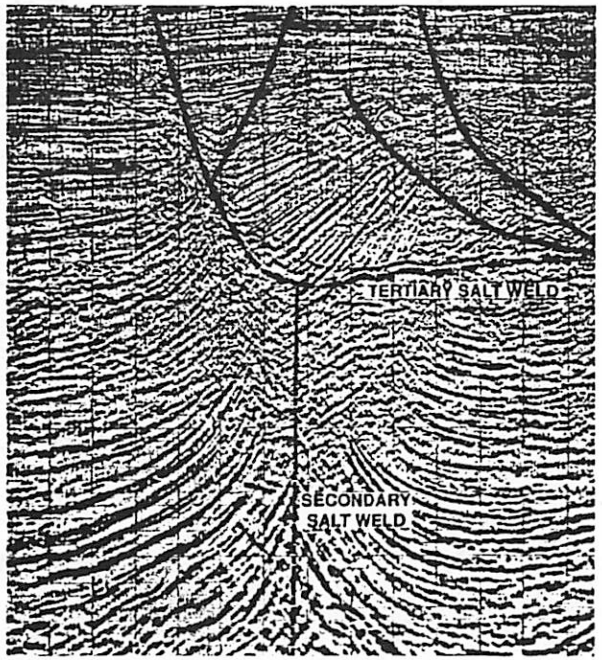


Figure 18. A pinched-off diapir shown by reflection seismic image in the Gulf of Mexico (from Hall and Thies, 1995, Fig. 4.3).

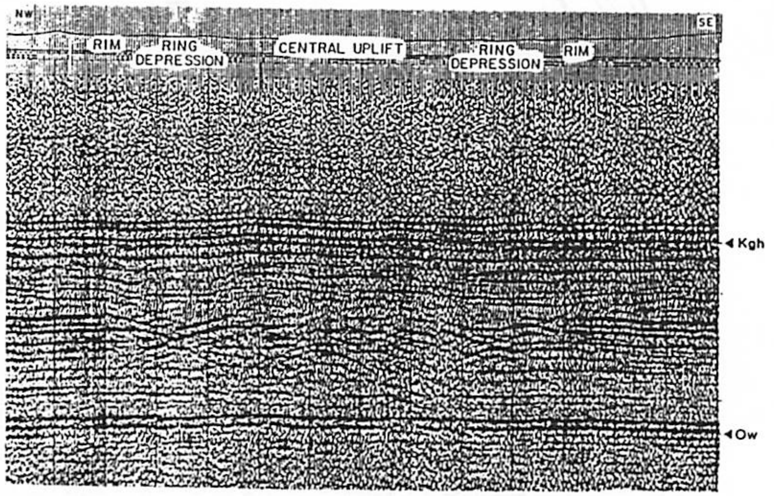
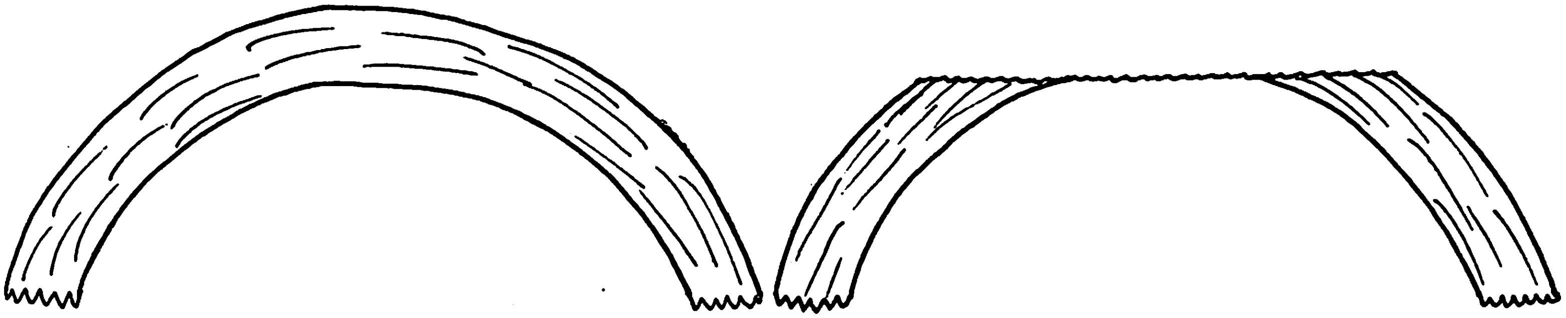


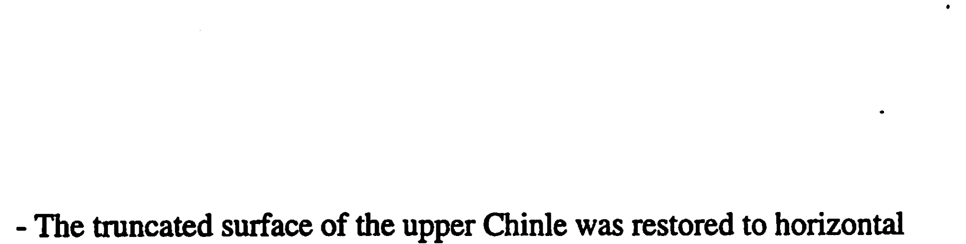
Figure 16. Reflection seismic section through the Red Wing Creek structure, North Dakota. Rim to rim distance is 9 km. The Cretaceous Greenhorn (Kgh) and Ordovician Winnipeg (Ow) reflectors are located at depths of ~715 and ~3625 m, respectively. Beneath the disrupted zone related to impact is the reappearance of coherent reflectors [after *Brenan et al.*, 1975].

Synsedimentary Features Observed at Upheaval Dome

Truncated Strata



Evidence for synsedimentary deformation on the Chinle Formation

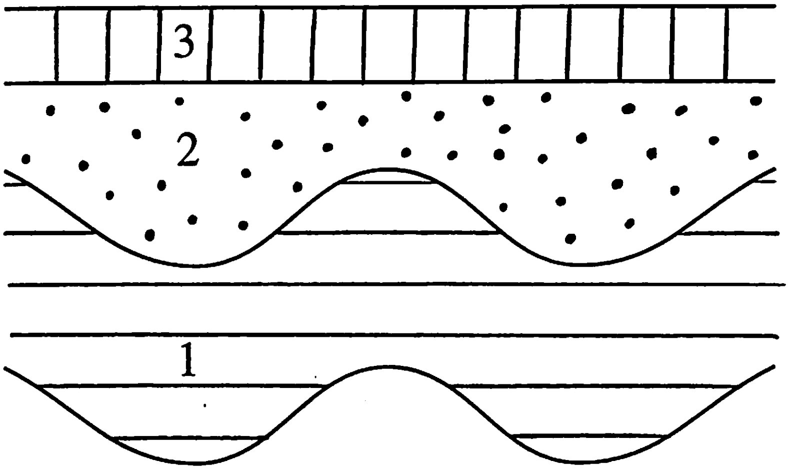


- The truncated surface of the upper Chinle was restored to horizontal
- The strata dip radially outward from the center of the dome
- Can't be due to tilting because of radial symmetry

*** Suggests doming in the late stages of deposition of the Chinle Formation**

Synsedimentary Features Observed at Upheaval Dome

Growth Folds



The folds in layer 1 formed before the deposition of layer 2

Wingate Sandstone Growth Folds

- Folds are formed by circumferential shortening of the basal Wingate Sandstone
- Wavelength = 150-190m
- Thickness of Wingate Sandstone = 100m
- Wavelength/thickness ratio is abnormally small for sandstone folds

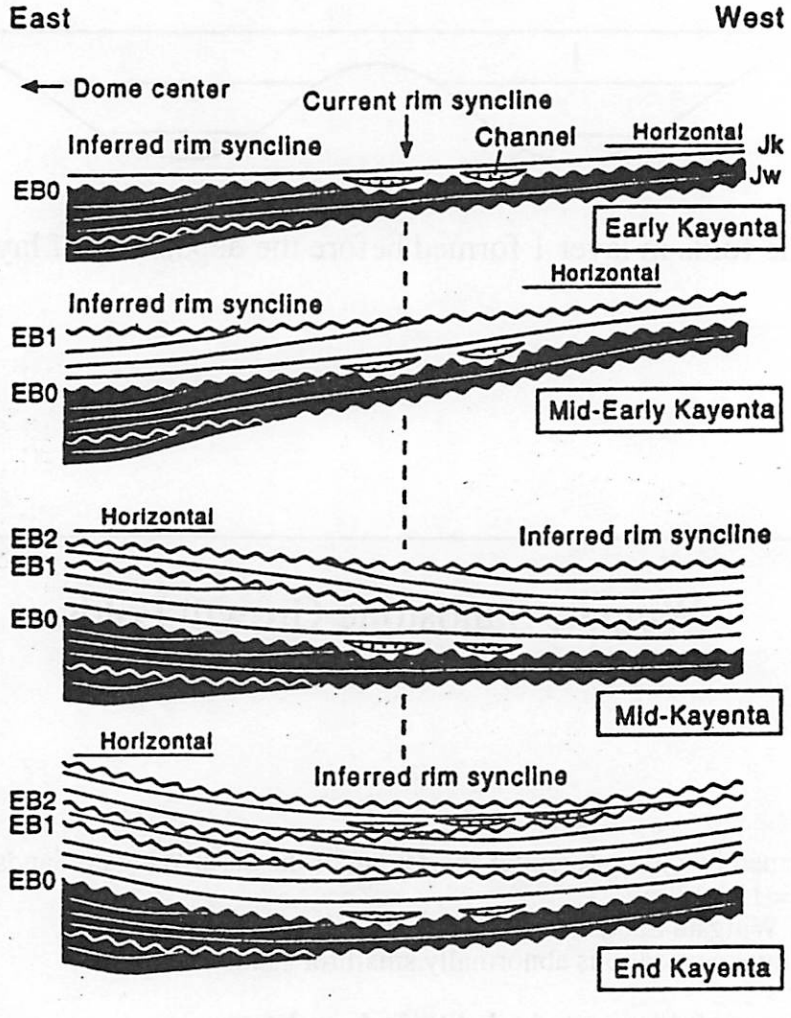
=> probably wasn't folded as a single lithified sandstone

- The top contact of the Wingate Sandstone is folded, but not as tightly as the bottom contact and not in harmony with the bottom contact
- Strata thin over antiforms and thicken over adjacent synforms

*** Folding occurred during the deposition of the Wingate Sandstone**

Synsedimentary Features Observed at Upheaval Dome

Increased Channeling in the Kayenta Formation



- As Upheaval Dome's synclinal rim develops, there is enhanced channeling in the Kayenta Formation due to the increasing gradient

*** Upheaval Dome was being shaped by active tectonic processes (presumably salt tectonics) during the deposition of the Kayenta Fromation**

References:

Jackson M.P.A, Schultz-Ela D.D., Hudec M.R., Watson I.A., and Porter M.L. (1998) Structure and evolution of Upheaval Dome: A pinched-off salt diapir. *Geological Society of America Bulletin*, **110, No. 12**, 1547-1573.

Jackson M.P.A, Schultz-Ela D.D., Hudec M.R., Watson I.A., and Porter M.L. (1998) Structure and evolution of Upheaval Dome: A pinched-off salt diapir. *Geological Society of America Data Repository*, **9891**, 1-40.

Kriens B.J., Shoemaker E.M., and Herkenhoff K.E. (1997) Discovery of impactites at Upheaval Dome, Canyonlands National Park, SE Utah. *Geological Society of America Meeting*, A-215.

Kriens B.J., Shoemaker E.M., and Herkenhoff K.E. (1997) Structure and kinematics of a complex impact crater, Upheaval Dome, southeast Utah. *in Brigham Young University Geology Studies, GSA Field Guide from the 1997 Annual Meeting*, **42**, 19-31.

Koeberl C., Plescia J.B., Hayward C.L., and Reimold W.E. (1999) Impactites at the Upheaval Dome structure, Utah*? Proceedings of the Lunar and Planetary Science Conference*, **30**.

Louie J.N., Chavez-Perez S., and Plank G. (1995) Impact deformation at Upheaval Dome, Canyonlands Nationla Park, Utah, revealed by seismic profiles. *American Geophysical Union Fall Meeting, supplement to Eos*, F337.

Louie J.N. (1998) *http://www.seismo.unr.edu/ftp/pub/louie/dome/*

Melosh H.J. (1989) Impact Cratering: A Geologic Process. Oxford University Press. 245 pgs.

Pilkington M. and Grieve R.A.F. (1992) The geophysical signature of terrestrial impact craters. *Reviews of Geophysics*, **30, 2**, 161-181.

Schultz-Ela D.D., Jackson M.P.A., Hudec M.R., Fletcher R.C., Porter M.L., and Watson I.A. (1994) Structures formed by radial contraction at Upheaval Dome, Utah. *Geological Society of America Meeting*, A-72.

Shoemaker E.M. and Herkenhoff K.E. (1983) Impact origin of Upheaval Dome, Utah. *American Geophysical Union Fall Meeting, supplement to Eos*, **64, No. 45**, 747.

Shoemaker E.M. and Herkenhoff K.E. (1984) Upheaval Dome impact structure. *Proceedings of the Lunar and Planetary Science Conference*, **15**, 778-779.

Unger M. (1995) *http://zephyr.rice.edu/department/students/munger/Comps/Comps.htm*

Cosmogenic Rifting in the Canyonlands National Park

conducted by James N Head

Introduction. The Robert's Rift is exposed subradially between 22 and 32 km north-northeast of Upheaval Dome (Figure 1). The fissure contains proppants up to 30 cm diameter that were carried vertically at least 1000 m upwards from Paleozoic sources into the Mesozoic section. There was considerable circulation of reducing fluids in the Rift after its formation causing a distinctive alteration rim in the country rock (Figure 2).

Formation. The rift was probably formed by hydraulic fracturing (Hite 1975, Huntoon and Shoemaker 1999). Hite favored a mechanism whereby upwelling salt from the locally ubiquitous Paradox Formation increased the fluid pore pressure. The same mechanism is invoked to account for the upward migration of clasts. In contrast, Huntoon and Shoemaker have proposed that the rift is due to the impact that created Upheaval Dome. This of course relies on the correct identification of Upheaval Dome as a deeply (2-3 kilometer) eroded impact structure.

Hydaulic Fracture. Hydraulic fracture refers to the opening of fractures in rock in response to an increase in pore pressure (Figure 3). The diagram is a plot of normal stress σ (abscissa) vs. shear stress τ (ordinate). Compression is positive (to the right), tension is negative. The shear stress depends on the difference in magnitude of the principal stresses σ_1 and σ_3. Failure occurs when the circle intersects the failure curve. Be aware that in the tensile regime nature is better approximated by a parabola, which gives the proper relationship between tensile and shear strengths of common geologic materials. In general, the latter is twice that of the former. The Mohr circles depicted illustrate that as the pore pressure in the rock is increased, the principle stresses (σ_1 and σ_3) are decreased by equal amounts. The result is a leftwards migration of the circle until it (possibly) intersects the brittle failure curve. This is a common technique in the petroleum industry for increasing the flow of hydrocarbons through the strata. Fluid pressure is increased by pumping until the rock fails, increasing the number of fractures through which hydrocarbons can flow into the well. In natural settings, pore pressure can increase under increased sediment load or tectonic forces if the fluids are confined by impermeable beds such as shales. It is manifest that the pore fluids in this region remain highly overpressurized to the present day, despite downcutting of the Colorado River into the underlying salt beds and extensive local drilling. As an example, a blowout in 1925 spewed burning oil 100 m into the air, consuming the drill rig and a supply barge on the Colorado River.

Mechanisms. The drawbacks to Hite (1975) include 1) the unique occurrence of the Robert's Rift. If upwelling from the Paradox Formation was important, there should be rifts all over the place. 2) no salt occurs in the fissure. 3) The energetics of moving 30 cm block 1000 m up the rift. Huntoon and Shoemaker claim that invoking the Upheaval Dome impact resolves these problems. The impact stress wave would have had an amplitude of about 10 bars at the proximal end of the rift. If the stress field was near enough to the failure envelope, the impact could have opened the rift. The impact hypothesis does have the redeeming virtue of both enlarging and shifting leftwards the stress circle on the Mohr diagram. This is because the impact-induced stress wave increases the stress in the rock as well as in the pore fluids. However, it is not clear that this explanation is clearly superior to "natural" hydraulic fracturing since one would think that the stress state in several areas should be near the failure envelope, not just one. In its favor, the impact hypothesis better explains the orientation of the Rift--the hoop stresses from the expanding stress wave could well have been extensional. This is in contrast to the prevailing direction of faulting in the region which is generally along a NW-SE trend parallel to the prominent anticlines (Figure 1).

Evaluation. At present it is impossible to date the relative ages of Upheaval Dome and the Robert's Rift. Stratigraphically it is possible for them to be coeval, but it is not possible to demonstrate a temporal linkage. All hypotheses must contend with the uniqueness problem. In its favor, the impact hypothesis at least explains the odd orientation of the Rift relative to regional trends and provides an energetic mechanism for the transport of materials upsection. Also, the the presence of sand-filled clastic dikes within the crater indicates that the proper stress fields can arise from an impact. In its disfavor, the one must explain the great distance of the Rift from the putative impact site. The strength of the implied impact-related stress wave is of little help since it is not possible to reconstruct the ambient stress field prior to impact. Barring the recognition of additional rifts subradial to Upheaval Dome, the cosmogenic theory remains a reasonably outrageous hypothesis.

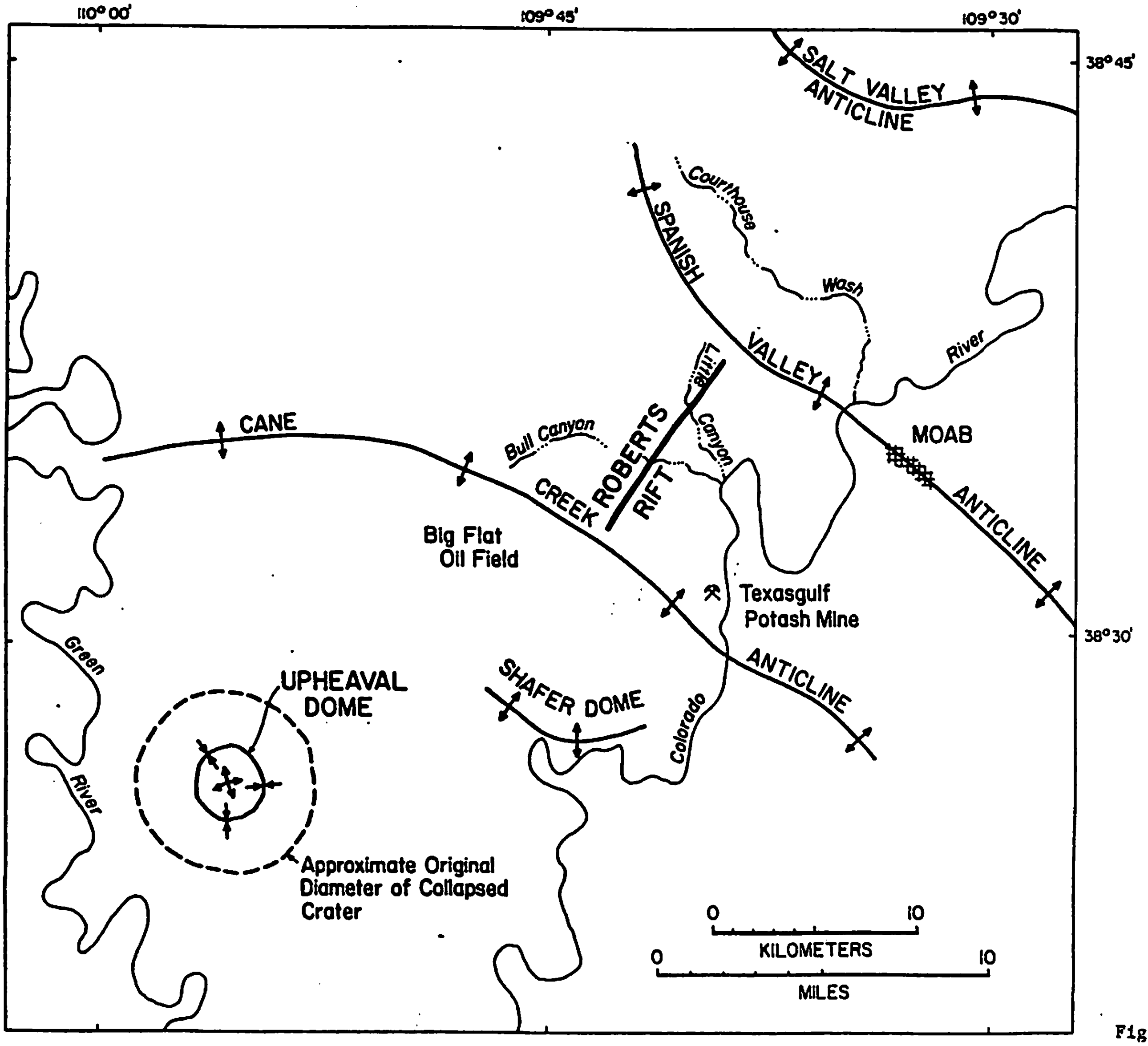


Figure 1.

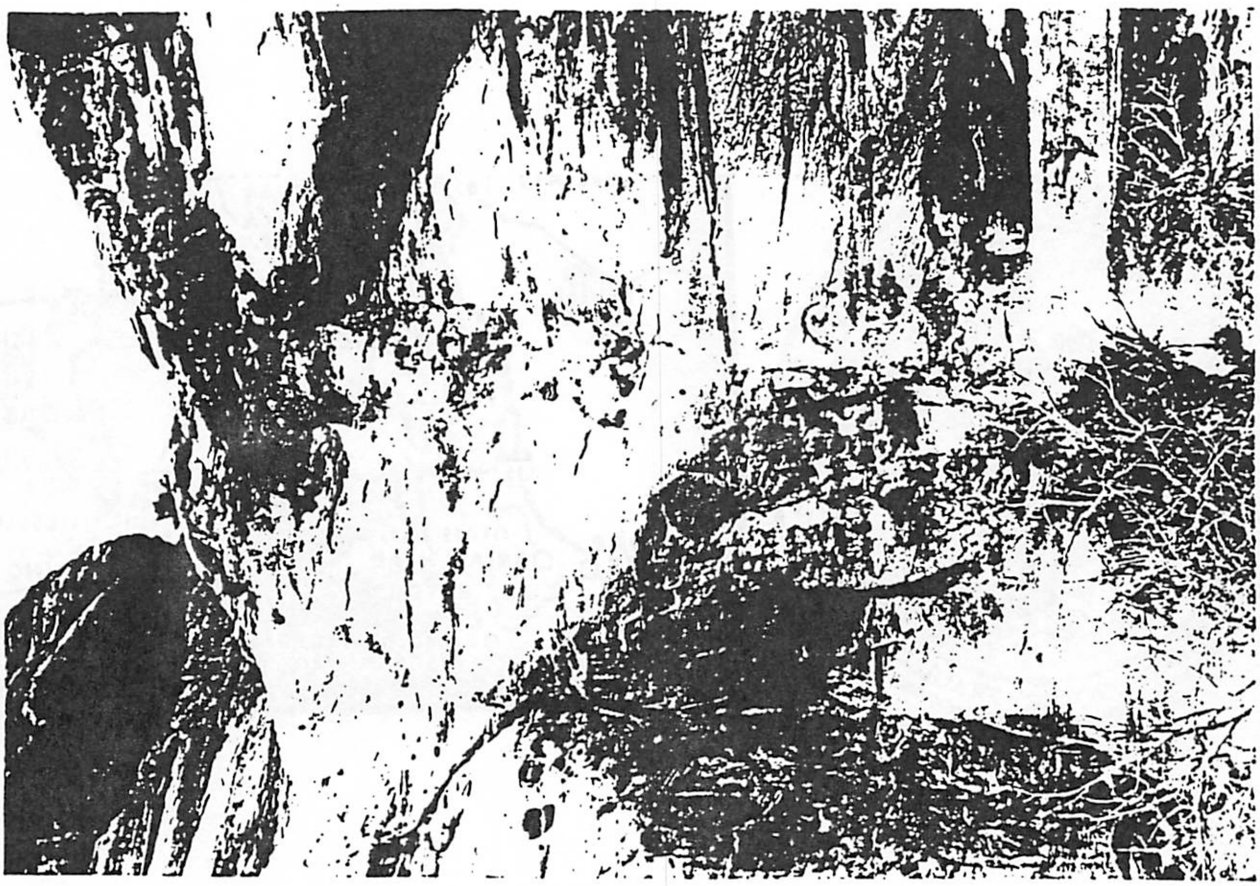


Figure 2

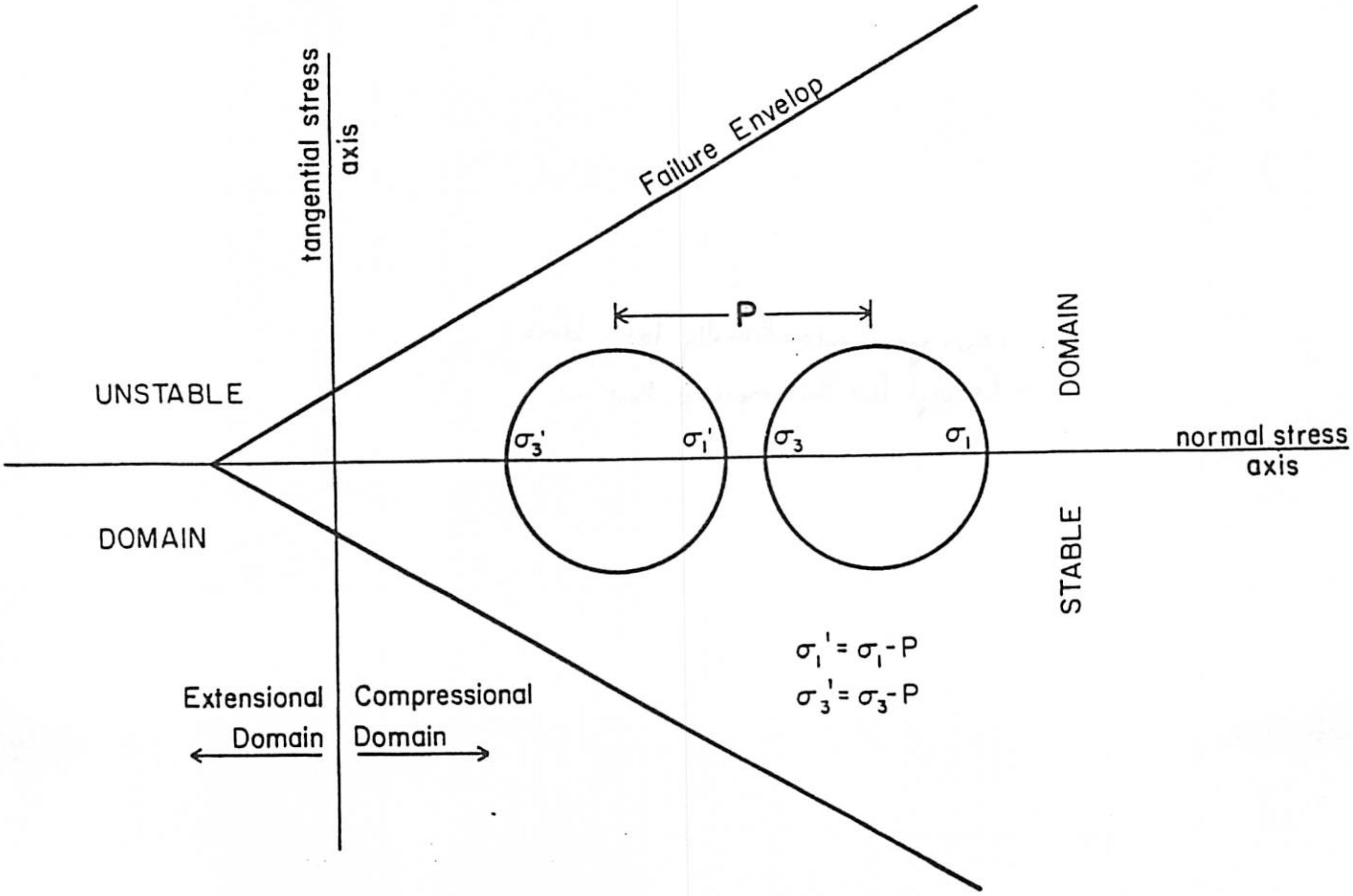
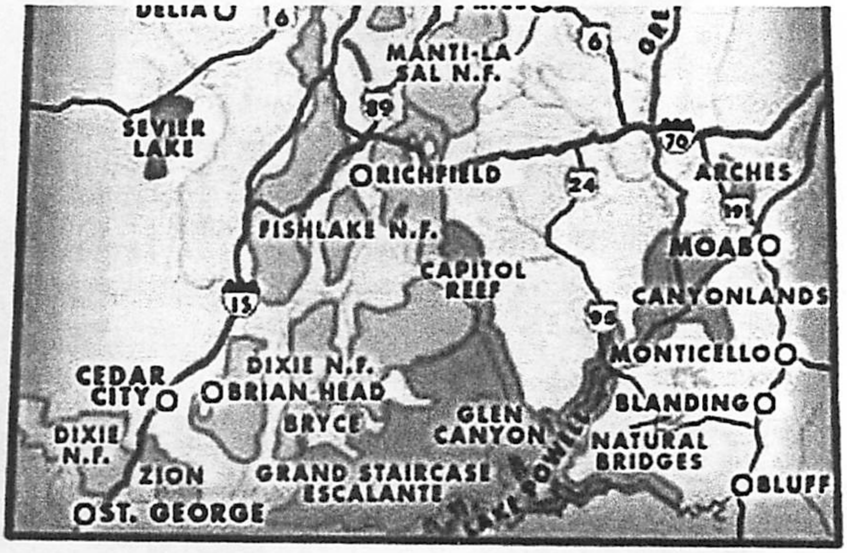


Fig. 3



(this space intentionally left blank)
(except for this message, that is)

Newspaper Rock Petroglyphs

Dave O'Brien

What is a Petroglyph?

petro - rock
glyph - symbol

Petroglyphs are symbols carved or chiseled into rock. Generally, there is a coating of desert varnish or another type of weathering which darkens the rock, and the lighter rock which is exposed by carving or chiseling defines the petroglyph. Over time, the weathering slowly returns and darkens the petroglyphs, eventually erasing them.

Unlike hieroglyphs, petroglyphs have no particular linguistic meaning--they do not comprise a written language. The petroglyphs generally have a broader meaning, as in religious and ceremonial symbols or symbols to commemorate certain events.

What are the Methods for Making Petroglyphs?

Chipping away at the rock with a large 'hammerstone' -- This yields a petroglyph with a rather rough outline and a bumpy texture.

Using a 'hammerstone' to hit a smaller, chisel-like rock -- This yields more well-defined outlines and a somewhat less bumpy texture.

Scraping at the rock with a small chisel-like stone -- This yields a well defined petroglyph with a smooth surface.

Most of the petroglyphs at Newspaper Rock are made by the first two methods. The majority are solidly chiseled or scraped; there are only a few which are simply outlined.

What do Petroglyphs Represent?

Petroglyphs seem to serve many purposes, such as:

Identifying territorial claims
Marking departure from or arrival at a location
Marking a trail
Rudimentary maps
Religious and ceremonial symbolism
Recording legends and stories
Commemorating a hunt or a birth
Recording visions seen while in a trance or 'altered state.' Mmmmm, Peyote.

Who Made the Petroglyphs at Newspaper Rock?

The majority of the petroglyphs are Anasazi style, probably carved between 300 and 1000 AD. In addition, here are some Freemont style petroglyphs, probably carved between 1000 and 1200 AD, and some modern Ute style petroglyphs, probably carved within the past 500 years. Dating the petroglyphs to an accuracy better than this is difficult, if not impossible, as it is based on somewhat subjective analysis of archaeological remnants in and around the area.

What do These Petroglyphs Mean?

I'll lead a 'tour' of some of the symbols, their interpretations, and their tribal affiliations at the site. A few sketches here won't do it justice, and I'm lazy.

What's the 'Planetary Connection'?

Petroglyphs can give a glimpse into the culture and beliefs of ancient civilizations. Thorough exploration of Mars will undoubtedly uncover petroglyphs made by the ancient martian civilizations, and these will be an invaluable tool in our studies of exo-archaeology.

References:

Castleton, Kenneth B. *Petroglyphs and Pictographs of Utah.* Utah Museum of Natural History, Salt Lake city, Utah. 1979.

Josephy, Alan M. Jr., ed. *The American Heritage Book of Indians.* American Heritage Publishing Co., Inc. 1961.

Patterson, Alex. *A Field Guide to Rock Art Symbols of the Greater Southwest.* Johnson Books, Boulder Colorado. 1992.

Schaffsma, Polly 1971. The Rock Art of Utah: A Study from the Donald Scott Collection. *Papers of the Peabody Museum of Archaeology and Ethnology*, vol. 65. Harvard University, Cambridge, Massachusetts.

Paradox Basin

You're damned if you do and damned if you don't.

✿B✿

Paradox Basin is named for Paradox Valley, CO. The town and valley are so named because the Dolores River cuts through the south valley wall, runs transversely across the valley, and exits through the north wall, seemingly a paradox.

The basin structure formed in early Pennsylvanian time and was filled with the **Hermosa Group** rocks. The South American-African plate collided with N. America to make Gondwanaland, and the resulting stress created structures trending NW-SE in the ancestral Rocky Mountain region. Shallow seas covered the area, and as they flooded inland, the soil and regolith was reworked to form the **Molas** formation. Then, in the marine environment, the **Pinkerton Trail** limestones were deposited. The Uncompahgre uplift rose and created a ramp, then downwarping of the ramp in the Desmoinsian created a silled basin. Access to the sea was restricted and the basin waters became hypersaline, depositing the **Paradox** evaporites. As the basin filled up (shoaling), the shallow sills were breached and near-normal marine conditions permitted the deposition of the **Honaker Trail** limestones.

The **Paradox Formation** represents cyclical variations in the Paradox Basin water level due to advance and retreat of Gondwanaland glaciers. Interglacier melting caused the global sea level rise and flood the basin; glacial periods caused a sea level drop, which isolated the basin and all the water could do was evaporate.

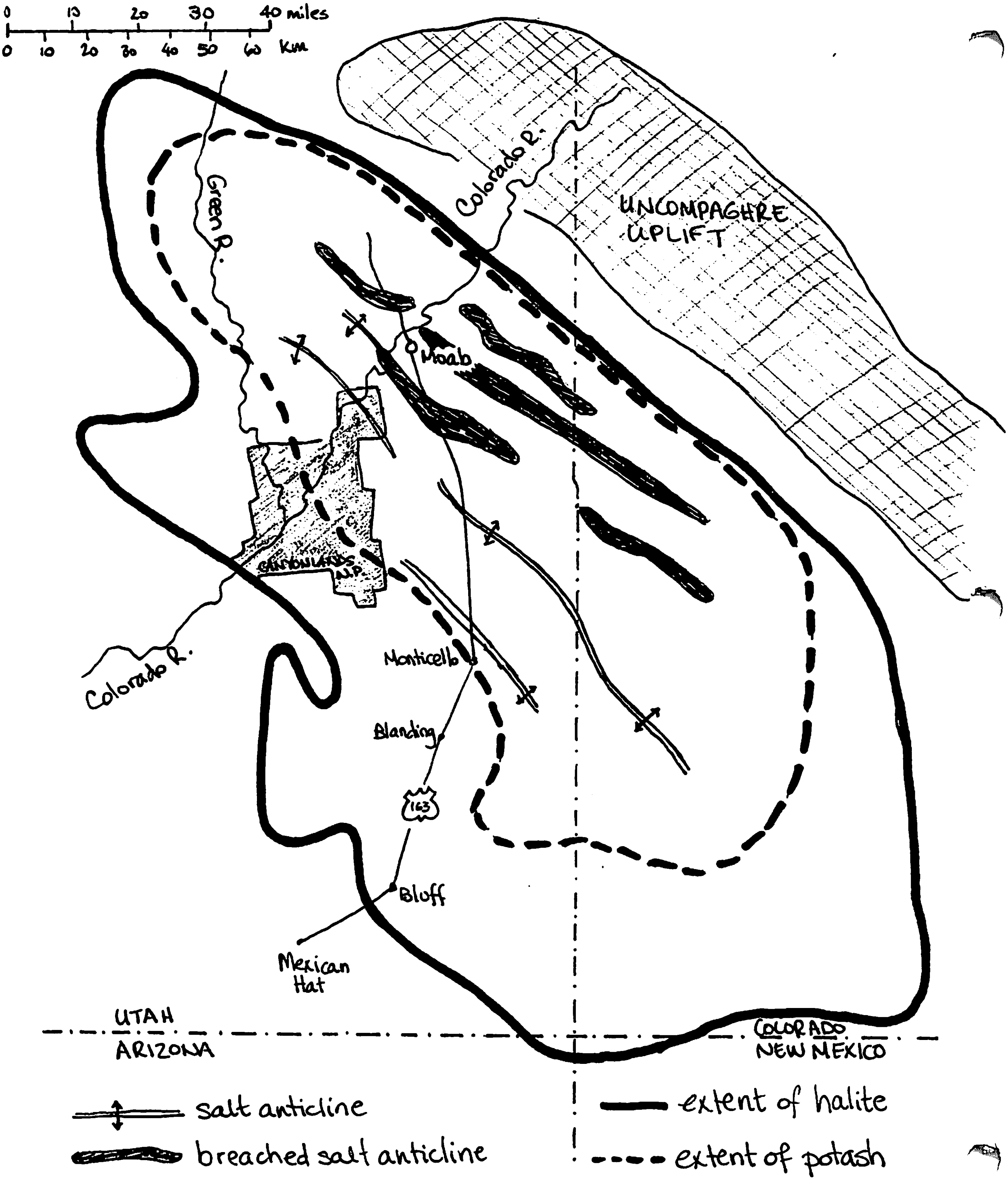
About 33 evaporite depositional cycles have been identified in the deepest areas of the Paradox Basin. The layers are well-correlated across the basin, indicating a deep, quiet environment. Each layer represents one cycle of basin water-level change. The *transgressive* section is deposited as the water level rose, the *regressive* as it got shallower. However, the Paradox Formation cannot be reproduced by simple evaporative processes, which has led workers to believe that there was a significant meteoric water contribution (rainfall or rivers) during evaporation. Basin water-level changes were accompanied by salinity changes that controlled what precipitated. The lack of ripples or mudcracks indicates that the basin sediments never saw subaerial conditions (until now).

The **Moab Valley** and fault system is a response to the dissolution of Hermosa Group evaporites in the subsurface. The gypsum and halite have flowed upward into the core of the Spanish Valley anticline, a broad north-northwest trending upfold that defines the Moab Valley. As the fresh waters of the Colorado River cut down to the salt layers, the soluble salts dissolved away, resulting in volume loss at depth. The overlying sandstones and shales have slid downward along the Moab and other faults along the flanks of the valley.

Raup, O.B., and R.J. Hite (1992) Lithology of Evaporite Cycles and Cycle Boundaries in the Upper Part of the Paradox Formation of the Hermosa Group of Pennsylvanian Age in the Paradox Basin, Utah and Colorado. USGS Bulletin 2000-B.

Condon, S.M (1997) Geology of the Pennsylvanian and Permian Cutler Group and Permian Kaibab Limestone in the Paradox Basin, Southeastern Utah and Southwestern Colorado. USGS Bulletin 2000-P.

Many more of the USGS Pubs 2000-n.


0 10 20 30 40 miles
0 10 20 30 40 50 60 Km
Green R.
Colorado R.
UNCOMPAGHRE UPLIFT
Moab
CANYONLANDS N.P.
Colorado R.
Monticello
Blanding
163
Bluff
Mexican Hat
UTAH
ARIZONA
COLORADO
NEW MEXICO
salt anticline
breached salt anticline
extent of halite
extent of potash

Typical Paradox Basin Evaporite Cycle

Halite NaCl/table salt. This only precipitates in supersaturated saline solutions, so you can imagine how briny the Paradox basin waters got! Halite occurs only in the deepest parts of the basin; it gets thinner and peters out at basin margins. There are thin but regular anhydrite layers in the halite, which has been attributed to periodic (probably annual) temperature changes controlling gypsum solubility. The top of the halite layer is always a sharp unconformity, caused by halite dissolution as the basin refilled in the next cycle. Potash (K-Na hydroxides and carbonates) is mined directly and brine extraction is a major source of sylvite (KCl), both for fertilizer.

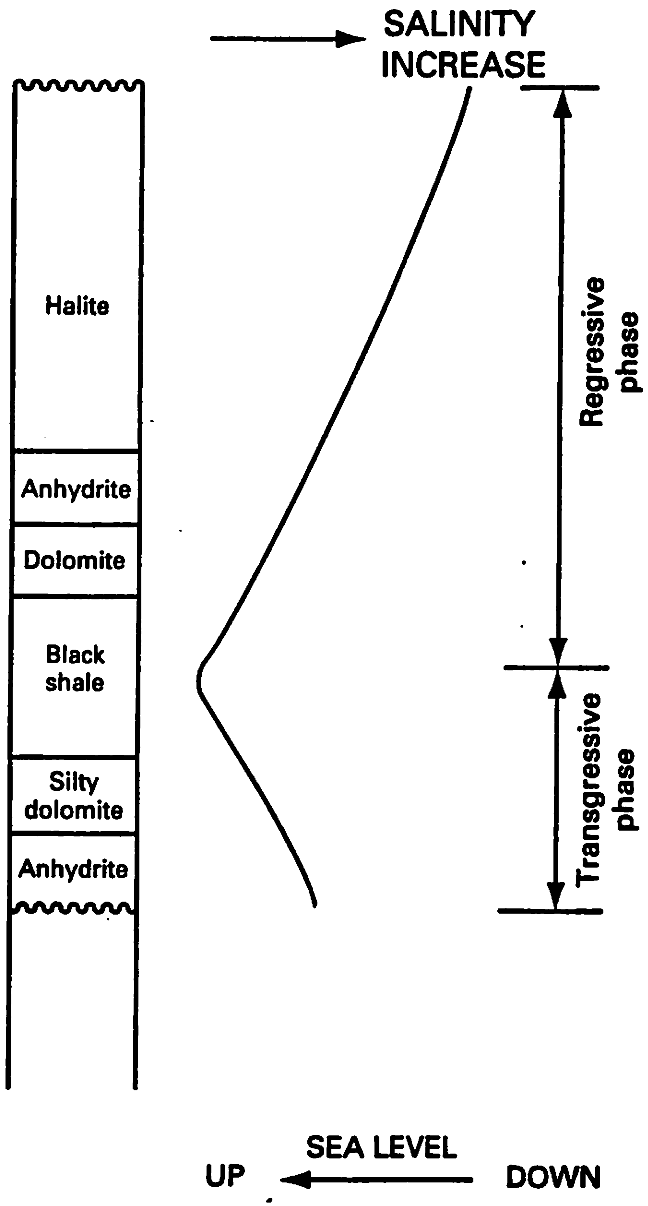
Anhydrite. This time the anhydrite grades up from the dolomite and is often interbedded. Some layers are wavy, possibly representing mineralization of algal mat structures (if so, this must have been in photic zone, where the water depth was less than 80m). Also grades into the halite bed above it.

Dolomite. Sea level is falling, evaporation causes salinity to rise, water becomes saturated with CO_3 ions and dolomite starts coming out again. There is less siliciclastic material included this time because shoreline material is not being swept in.

Black shale. Shale is a common shallow-marine rock. This layer represents the peak of the water level, when the water was freshest. Consists of dolomite, calcite, quartz, clay minerals, mica, and some pyrite. Bottom brines (more dense) maintained an anoxic environment at the bottom, plant and animal debris from marine and continental sources, as well as algae and bacteria accumulated in these shales (why they're black). Actually, the black shales are an economic oil source; much of the knowledge of the basin comes from oil drilling studies.

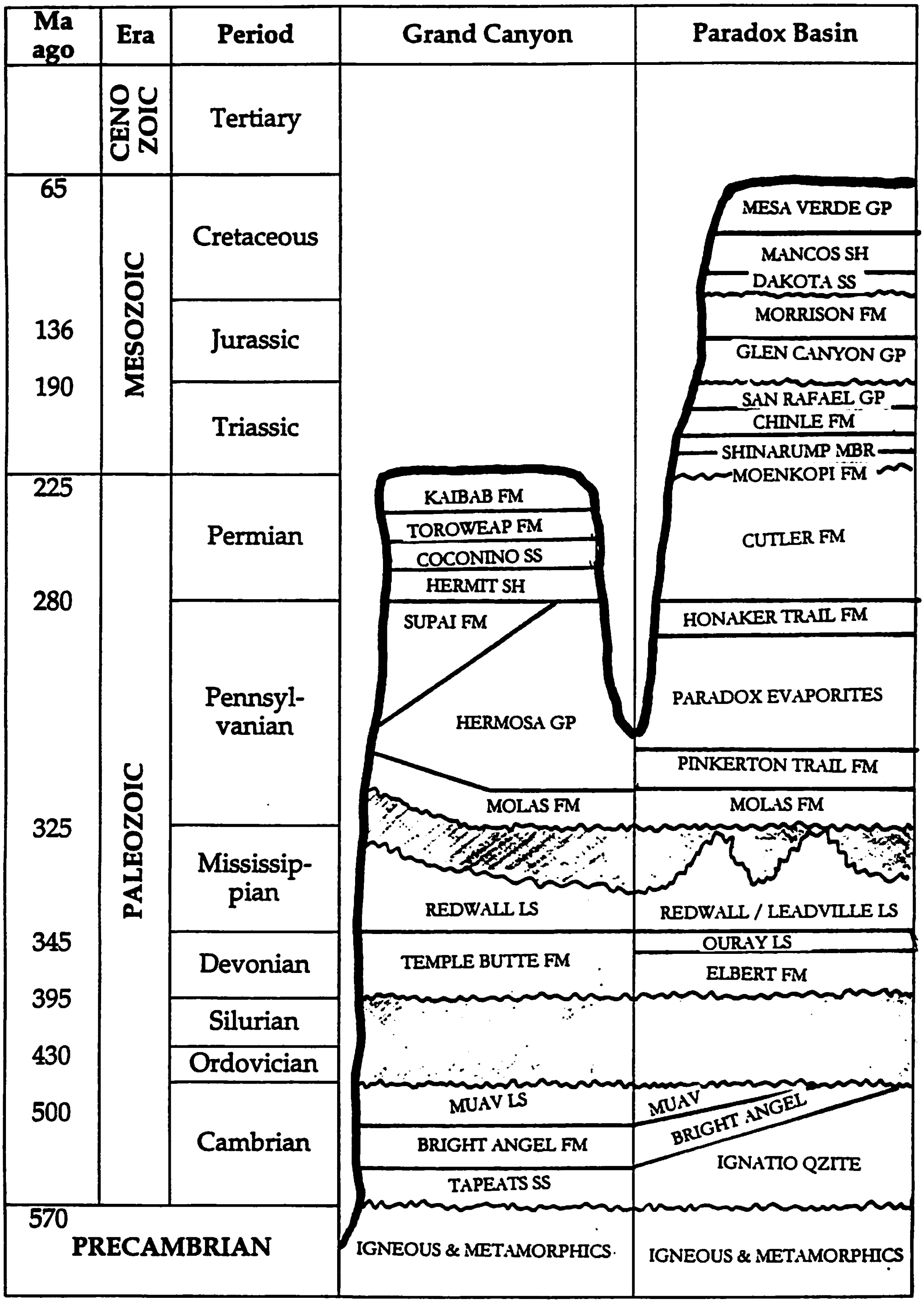
Silty dolomite $CaMg(CO_3)_2$. Dolomite is usually a diagenetic product of limestone in marine settings because of lack of Mg ions in seawater, but here the water was briny enough (lots of dissolved cations) to precipitate dolomite directly. The silt comes from shorelines as the sea fills in.

Anhydrite $CaSO_4$ (dehydrated gypsum). Precipitated from briny waters, probably as gypsum and then dehydrated by mild diagenesis. Finely laminated at base, nodular on top (early diagenesis as water became less saline). It is now extracted by surface mining for plaster, plaster of Paris, and the manufacture of wallboard or sheetrock.



From Raup and Hite, 1992

Generalized Stratigraphy
of the Grand Canyon and Paradox Basin



Graben Formation in Canyonlands

Fred Ciesla
Spring 1999

A graben is defined as a block of rock or sediment dropped between two parallel or nearly parallel faults whose length is much greater than its width. The Needles District of Canyonlands National Park is home to many well preserved grabens that range in width from 100 to 600 m and in depth from 25 to 75 m. Individual grabens are anywhere from half a kilometer to a few kilometers long. The grabens are found on the eastern edge of Cataract Canyon, in which the Colorado River flows.

There were many events that led to the formation of the grabens in this area. Firstly, about 300 million years ago, this area of Utah was covered with a shallow inland sea. As the sea disappeared, the area was layered with a deposit of evaporates which is known as the Paradox member of the Hermosa Formation. This layer varies between 1000 and 1500 m in thickness.

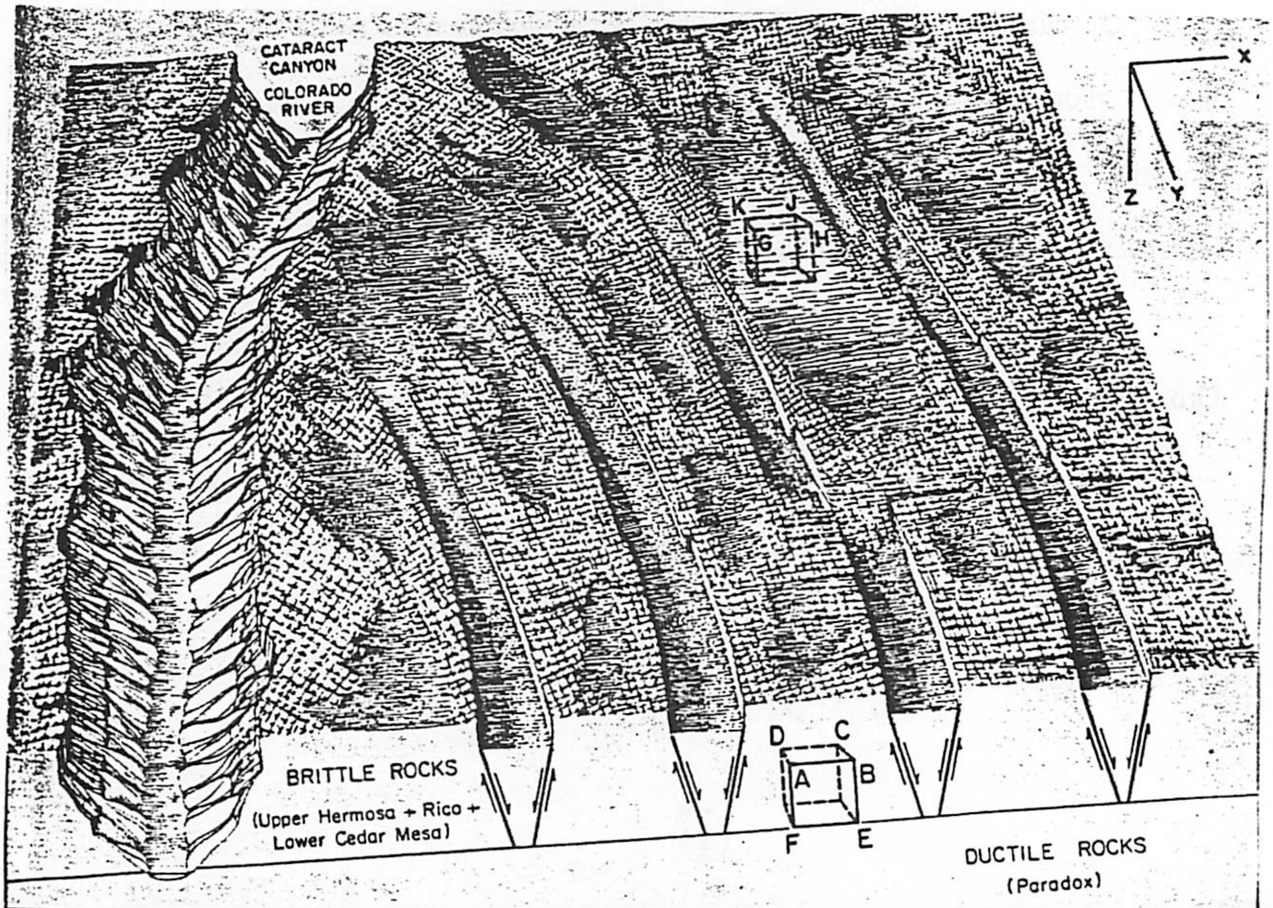
Once the sea completely disappeared, white sand from the west blew in, forming large sand dunes. At the same time, red mud and silt was carried in by rain and runoff from the Unompahgre Mountain to the east. This resulted in red and white beds, which are observed in the Cedar mesa Sandstone found in the Needles District.

Roughly 60 million years ago, the tectonic plate collision known as the Laramide Orogeny formed the Rocky Mountains. An upwarping , known as Monument Uplift, took place in the Needles District, which caused the sedimentary layers to tilt westward at an angle of roughly 4 degrees. This upwarping also created fractures, or joints, in the overlaying brittle rock.

The next major event that led to the development of the grabens in the Needles District was the Colorado Plateau uplift, which in turn, allowed the Colorado River to begin to flow. As the Colorado dug its way down through the sedimentary layers, it carried its eroded material out to the Pacific, removing it from the area. Eventually, the river cut its way down to the Paradox layer.

It was at this point, roughly 55,000 years ago, that the grabens actually began to form. Due to the tilt of the area and the pressure from the rocks above, the evaporates in the Paradox layer began to flow down the slope. This was aided by the removal of the evaporates by the Colorado. The evaporates are still flowing westward towards Cataract Canyon.

As the evaporates flow, they create a shear stress at the sandstone-evaporate boundary. This stress increases down the slope, with a maximum near Cataract Canyon. This stress is the driving force of extension between the horsts of the graben system, and explains why the grabens are widening with time.



Controls on Graben Width/Mechanisms of Formation

Andreas Ekholm

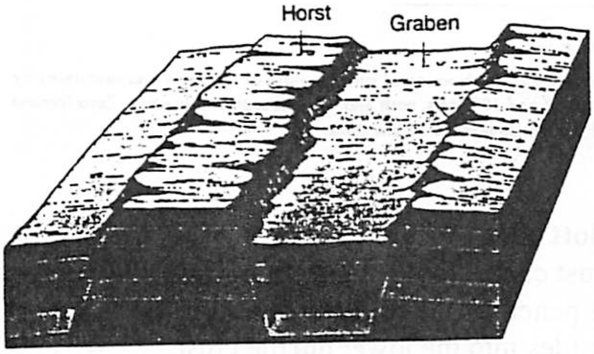


FIGURE 15.20
Diagrammatic sketch of downfaulted block (graben) and upfaulted block (horst).

Graben

- A wedge-shaped downdropped block bound by converging (antithetic) normal faults.
- Found in extensional environments. Fault dips generally 60° from the horizontal.
- Anderson hypothesis: Theoretically, the plane of maximum tangential stress will be oriented at 45° to the vertical compressive stress. Because of internal friction, the faults which actually develop are closer to the vertical:

  $$\theta = 45^\circ + \phi/2$$

  where θ is the fault dip and ϕ the angle of internal friction (typically 30°).
- Half graben: Depending on who you ask, either a
  - single normal fault (most common definition)
  - pair of parallel (synthetic) normal faults (Reiter et al. 1992)
  - graben with the secondary fault suppressed (Bott and Mithen 1983)

Original model of graben formation (Vening Meinesz 1950)

- The faults penetrate the entire crust into the upper mantle (which is treated as a fluid).
- Predicted graben width: 65 km.
- Downbending of the crust on the downthrow side of an initial normal fault produces a supplementary tension ⇒ second normal fault at position of maximum bending. The crustal block between the faults subsides into the mantle isostatically if the second fault is antithetic to the first (i.e. dipping towards the first fault, not away from it).

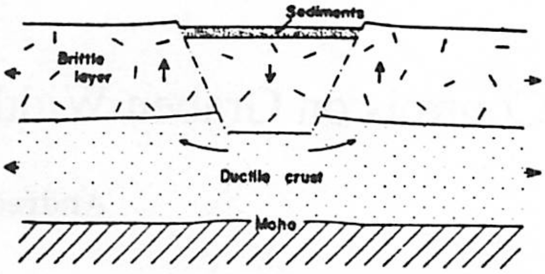


Fig. 1. Graben formation by wedge subsidence, adapted from Bott (1976).

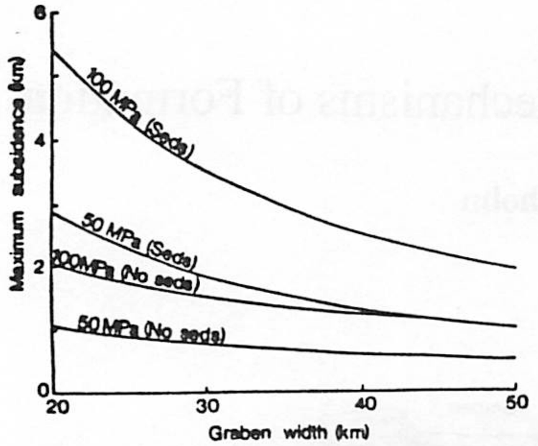


Fig. 2. Maximum possible graben subsidence as a function of surface width of the graben as calculated by Bott (1976) for applied tensile stress of 50 and 100 MPa, with and without sediment loading. Zero friction on the faults has been assumed and the brittle layer is 10 km thick.

Ductile crust model (Bott 1976)

- Assumption: The crust can be divided into an upper brittle part and a lower ductile part. The faults only penetrate the brittle crust (modeled as 10 km thick) and the resulting wedge subsides into the lower ductile crust.
- Secondary fault development same as in original model.
- Graben width of 30–60 km and up to 5 km of wedge subsidence predicted.
- Graben development:

  1. *Faulting stage* The tensional stresses dissipate in the ductile layer as it stretches and thins, while stresses in the brittle layer build up until failure occurs. The stress in the brittle layer then drops, and it contracts elastically an amount equal to the extension caused by faulting. There is thus no overall change in length of the crust, just an internal adjustment.
  2. *Stretching stage* The decreased stress in the brittle layer leads to an increased tension in the ductile layer ⇒ the stress in the brittle layer builds up again until faulting is re-initiated.
- The ductile lower crust deforms to accommodate the subsiding brittle block; the material pushed aside causes horst formation or elastic upbending of the flanking brittle crust.
- A high geothermal gradient makes the process more effective.
- Four factors influence the amount of subsidence:
  - Sediment loading increases the amount of subsidence possible by a factor of two to three, depending on the mean sediment density.
  - Greater tension also increases the possible subsidence (~100 MPa needed for 5 km subsidence, with sediment loading).
  - Narrower graben allow for greater subsidence.
  - Friction can severely inhibit graben formation; dry rock coefficients of friction ($\mu \approx 0.8$) are so high that fault slip is effectively prevented. The presence of lubricating water-filled pores seems necessary (bringing μ down towards 0.1; for comparison, for steel sliding against steel, $\mu = 0.15$–0.2).

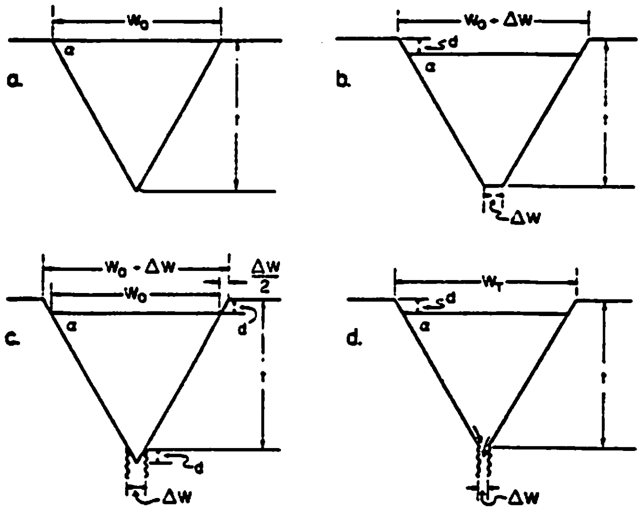


Fig. 1. Various possible mechanical models for the formation of lunar grabens. (*a*) Initial formation of graben faults. All models begin with bounding faults initiating at the base of the megaregolith of thickness t and propagating upward at angle $\alpha = 60°$, producing an incipient graben of width W_0. (*b*) Elastic response model. Material below the magaregolith expands elastically. Extension of ΔW produces a graben of depth d and width $W_0 + \Delta W$. (*c*) Brittle response model without drainage. Material below the megaregolith fractures with an open extension fracture of width ΔW. The relatively coherent megaregolith of the graben wedge drops a distance d, producing a graben of width $W_0 + \Delta W$ and depth d. (*d*) Brittle response model with drainage. Material below the megaregolith fractures with an open extension fracture. A graben of width W_T and depth d is produced by drainage of megaregolith down the extension crack. Note that in this case, $0 < \Delta W \leq 2d/\tan \alpha$.

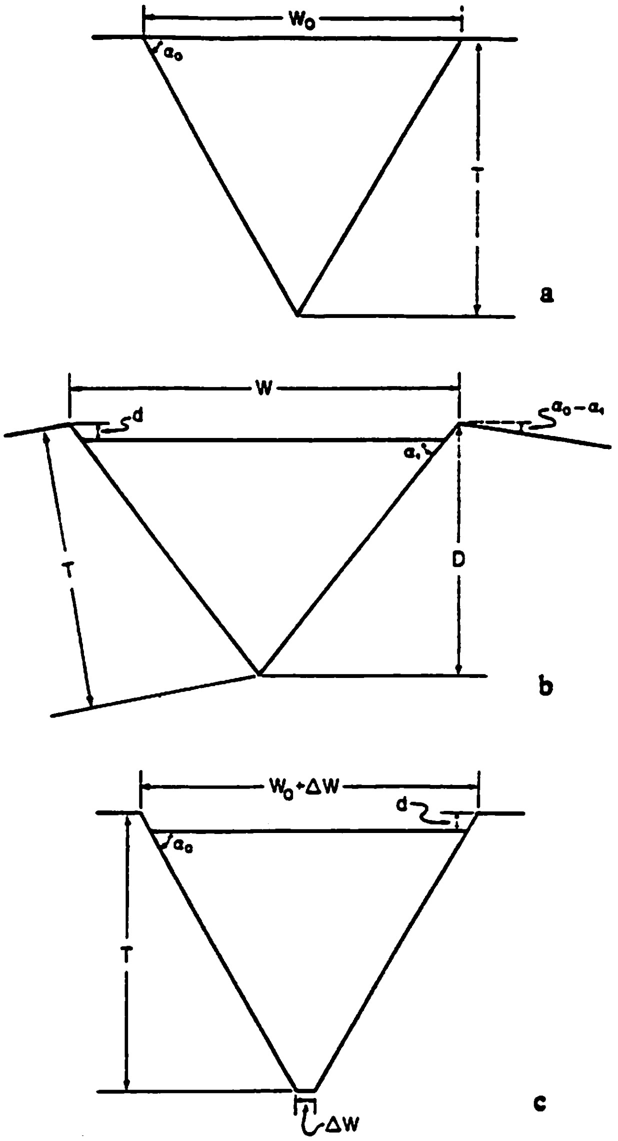


Fig. 5. Mechanical models for the formation of lunar grabens. (*a*) Graben faults begin at depth T and propagate upward at angle α_0 resulting in initial width W_0. (*b*) Bending model, $\alpha_1 < \alpha_0$. $D < T$, bulk dilatancy equals 0. (*c*) Simple extension model, bulk dilantancy equals 0.

Mechanical discontinuity model [e.g. Golombeck (1979)]

- The two faults develop from, and intersect at, a mechanical discontinuity in the crust. Faulting is initiated as a response to bending or extension of the crust.
- Extension: In response to the tension, the material below the discontinuity can expand elastically or fracture. If it fractures, the subsiding wedge may either descend into the open crack as one piece, or, if it is poorly consolidated, drain down the crack, in which case a much deeper graben may form.

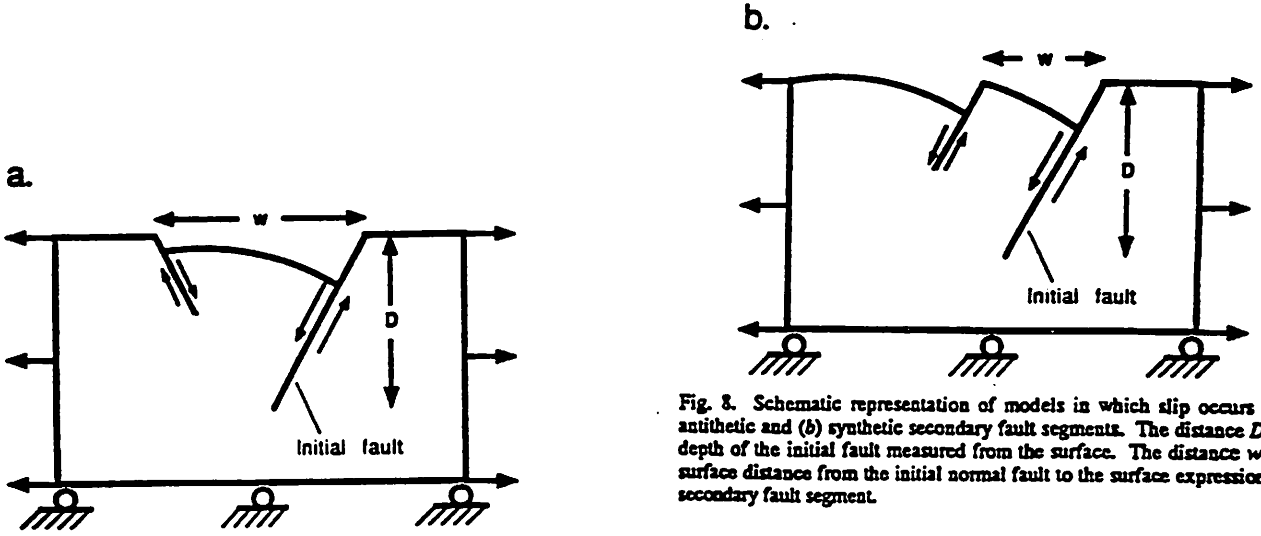


Fig. 8. Schematic representation of models in which slip occurs on (*a*) antithetic and (*b*) synthetic secondary fault segments. The distance *D* is the depth of the initial fault measured from the surface. The distance *w* is the surface distance from the initial normal fault to the surface expression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

Finite element modelling by Melosh and Williams (1989)

- The formation of a normal fault generally relieves the stresses around the fault over a horizontal distance a few to ten times the depth of the fault, except for a point on the surface of the downfaulted block at a horizontal distance slightly less than the depth of the fault (compared with 3–6 times the depth of the fault in Bott's model). Failure occurs at this point already at very small displacements on the first fault (<10 m), so the graben structure is essentially developed in a single failure event.
- An antithetic second fault is energetically more favorable than a synthetic one. This agrees well with grabens being the much more common structure (except in the Basin and Range province, ironically).
- The width of the graben is controlled by the depth of the initial fault; the presence of a mechanical discontinuity does not seem to have any effect. However, it is possible that the mechanical discontinuity controls the initial fault depth.

Canyonlands (McGill and Stromquist 1979)

- Analogous to a valley glacier in extending flow. The plate of brittle rocks is held fixed by shear stresses at the southwest/northeast edges of the graben field, causing the graben to curve (the trajectories of the two horizontal principal stresses are curved).
- The greatest stresses are vertical, and the smallest are parallel to the direction of flow.
- The faults begin at or near the base of the brittle plate and propagate upward. They dip at 75°–85°, but are vertical within 100 m of the surface because of the preexisting joints. The joints also influence the curvature of the graben, giving rise to en-echelon straight segments and sawtoothed walls.
- The depth T at which the initial faults intersected (presumably corresponding to the interface between the brittle plate and the ductile evaporites) can be calculated using the following formula (β is the fractional increase in volume of the downfaulted material due to fracturing, otherwise see figure below for variable definitions):

$$T = \frac{d}{2\frac{\Delta w}{w_0}}\left(1+\frac{\Delta w}{w_0}\pm\sqrt{1+\beta+\left(\frac{\Delta w}{w_0}\right)^2}\right)$$

The initial width of the graben, w_0, is estimated from the width of the ramps at the graben ends. As the present width is known, Δw is easily calculated. The depth d is of course known, while β has to be estimated (it is usually assumed to be zero). All the required quantities can be measured with remote sensing techniques, so the above equation is of use for other planets as well.

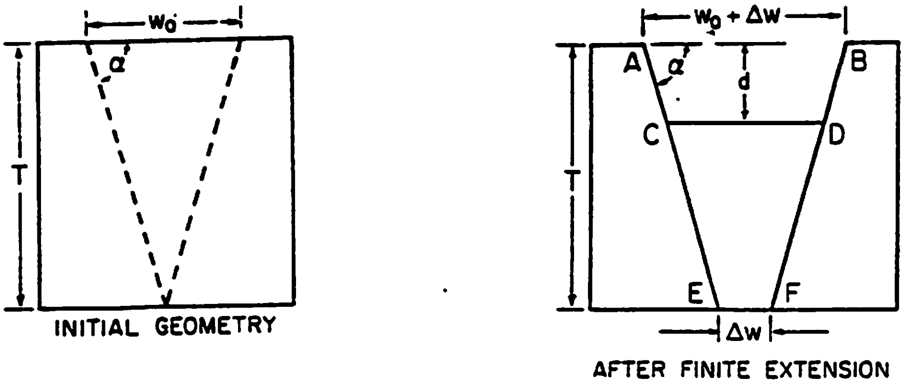


Fig. 9. Definition of parameters used in calculating thickness of faulted layer. (*a*) Cross section of incipient graben (before significant slip on faults). (*b*) Cross section of graben after significant slip on faults.

References

Bott, M. H. P., 1976, Formation of sedimentary basins of graben type by extension of the continental crust, *Tectonophysics,* 36, 77–86.

Bott, M. H. P., and Mithen, D. P., 1983, Mechanism of graben formation—The wedge subsidence hypothesis, *Tectonophysics,* 94, 11–22.

Golombeck, M. P., 1979, Structural analysis of lunar grabens and the shallow crustal structure of the Moon, *J. Geophys. Res.*, 84, 4657–4666.

Golombeck, M. P., and McGill, G. E., 1983, Grabens, basin tectonics, and the maximum total expansion of the Moon, *J. Geophys. Res.*, 88, 3563–3578.

McGill, G. E., and Stromquist, A. W., 1979, The grabens of Canyonlands National Park, Utah: Geometry, mechanics, and kinematics, *J. Geophys. Res.*, 84, 4547–4563.

Melosh, H. J. and Williams, C. A., 1989, Mechanics of graben formation in crustal rocks: A finite element analysis, *J. Geophys. Res.*, 94, 13,961–13,973.

Reiter, M., Barroll, M. W., and Cather, S. M., 1992, Rotational buoyancy tectonics and models of simple half graben formation, *J. Geophys. Res.*, 97, 8917–8926.

Vening Meinesz, F. A., 1950, Les grabens africains, resultat de compression ou de tension dan la crôute terrestre?, *Bull. Inst. R. Colon. Belg.*, 21, 539–552.

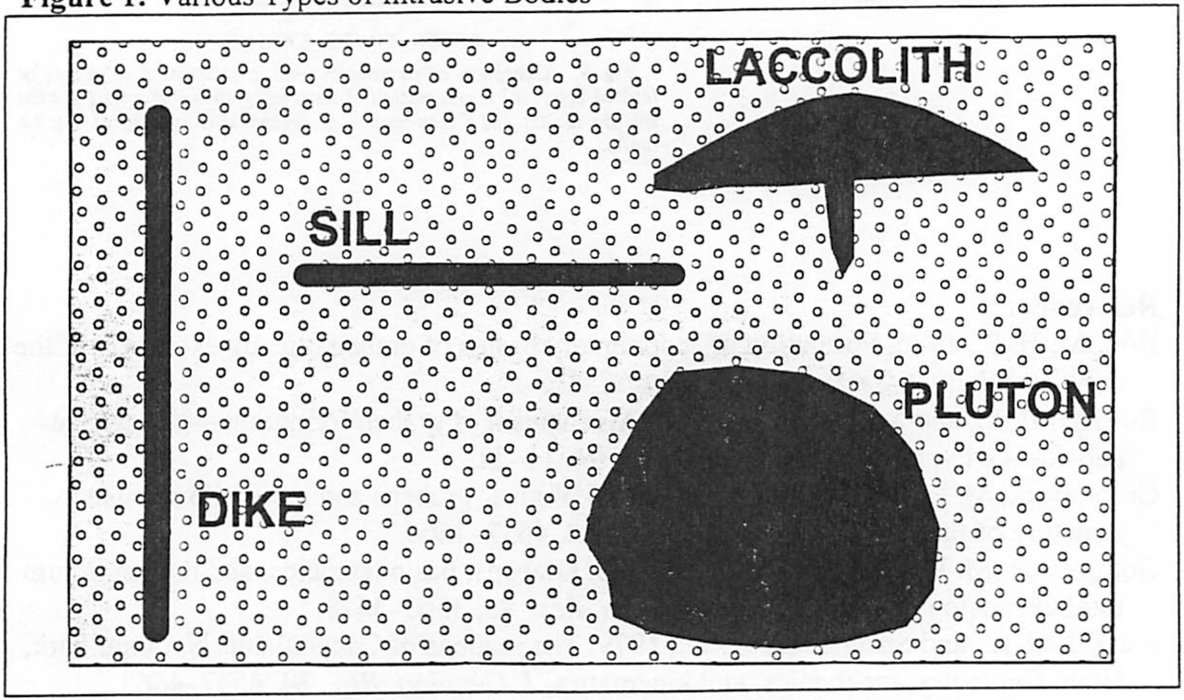
Graben Formation over Dike Intrusions

Aileen Yingst and Laszlo Keszthelyi

Introduction:

The intrusion of *dikes* (subvertical, subplanar intrusive magmatic bodies) can cause visible deformation of the surface, if the intrusion is sufficiently large and shallow. Dikes can be of any composition, but lower viscosity magmas are more likely to form relatively thin tabular bodies. This is because the more fluid magmas can work their way along thinner cracks that are largely controlled by the regional stress field. Higher viscosity magmas tend to form larger and more equant bodies – normally called *plutons*. Figure 1 shows some typical intrusive forms.

Figure 1: Various Types of Intrusive Bodies



The viscosity of a magma is lowered by (a) reduced concentrations of network forming cations (primarily Si and Al), (b) increased temperature, and (c) molecules that disrupt silicate networks (primarily OH). Thus *mafic* (Mg-rich) magmas often produce dikes and *felsic* (Si-rich) magmas usually only form dikes at depths where temperatures are high or when they contain high concentrations of water. *Basaltic* volcanism, i.e., producing mafic lava with only 48-55 wt.% SiO_2, is common on all the terrestrial planetary bodies, so dikes are expected to be common in our solar system.

Ground Deformation Over Shallow Dikes

The intrusion of magma requires shoving the surrounding rocks out of the way. While the intrusion adds material to the region and produces net compression and uplift on a regional scale, immediately above the dike, the ground is extended. This extension is accommodated by cracks that dip steeply toward the dike (Figure 2). In this case there is no volume conservation problem below the graben because the "missing" volume is the volume of the intrusion. In order to push the ground sideways (rather than push a plug of rock straight up) the intrusion must start as a knife-thin crack that is dilated by filling with magma (Figure 3). This type of intrusion is aided by having a pressurized gas phase at the tip of the advancing crack.

Figure 2. Cracks in Flour/Sugar Mixture Intruded by a Cardboard Dike.

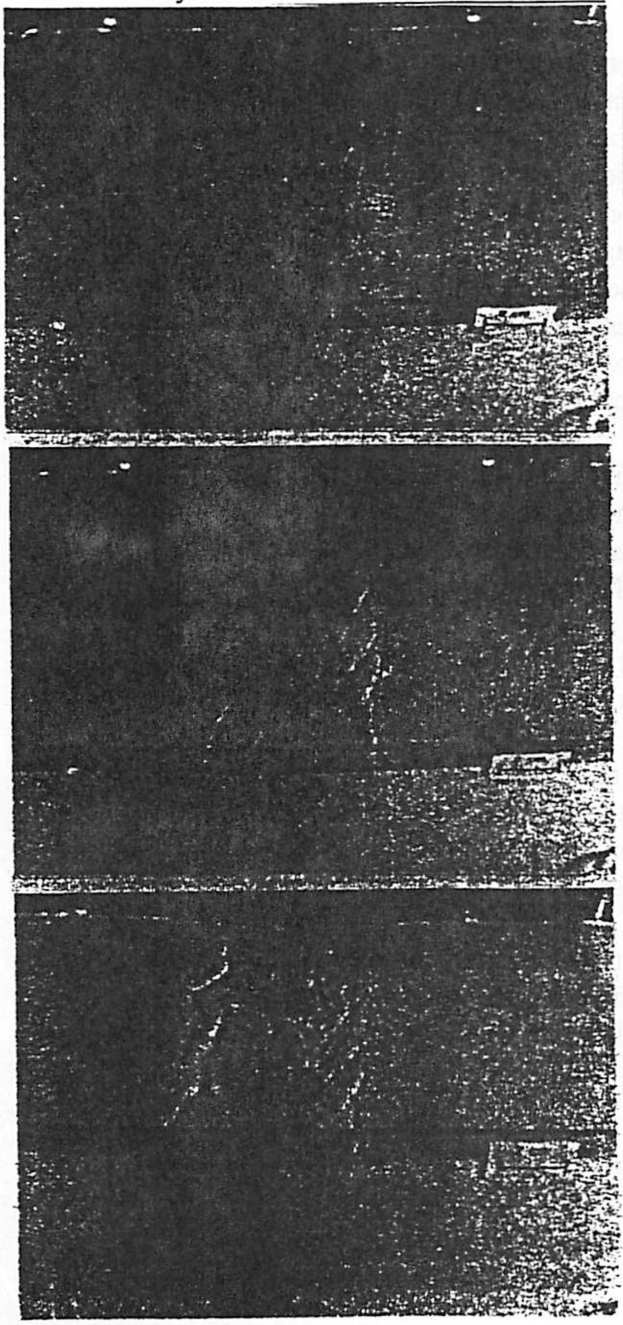
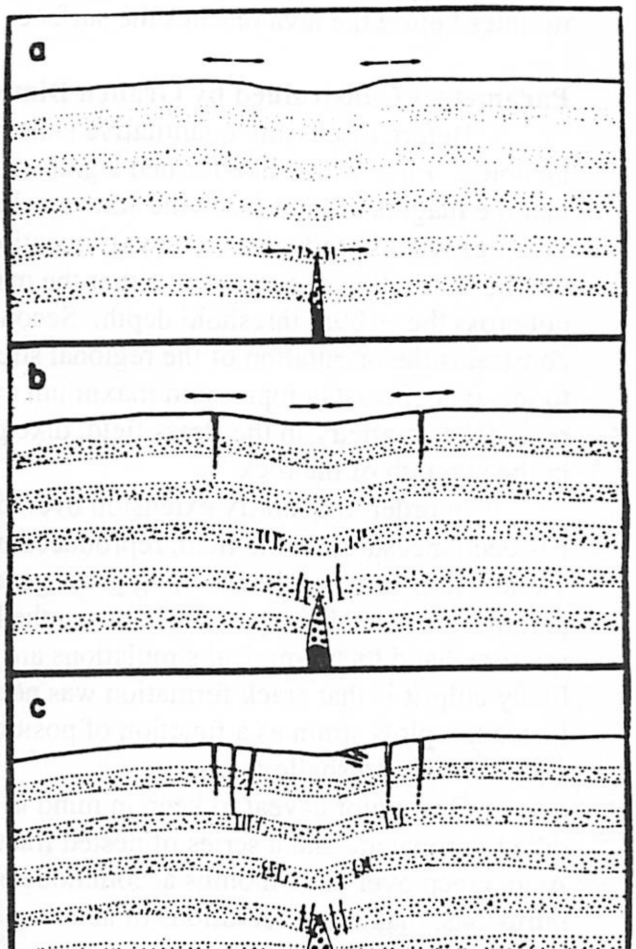


Figure 3. Cartoon of Dike Emplacement



The magma is driven upward by buoyancy forces resulting from the lower density of the magma compared to the solid rocks. This buoyancy force is generally weak unless the magma contains some gas phase. Because volatiles exsolve as pressure decreases, the buoyancy increases as the magma rises. On the Earth, once the magma passes through about 100 m depth, massive exsolution of water rapidly propels the magma to the surface, producing lava. Thus in places like Hawaii, cracking of the surface is usually followed by eruption within a few tens of minutes. The rate of extension is usually on the order of 1 cm/minute and the sound of the earth rending in two is accompanied by a flurry of small earthquakes that can be used to precisely predict the location of the eruption minutes before the lava reaches the surface.

Parameters Constrained by Graben Dimensions/Orientation

Before discussing quantitative constraints, several qualitative constraints should be noted. First, if the dike formed a graben but did not form an eruption, this suggests that the magma did not reach the state at which vigorous exsolution of water and other volatiles would produce a "runaway" reaction that would drive the magma to the surface. On the Earth, this suggests that either the magma was very volatile-depleted or that it did not cross the ~100m threshold depth. Second, the orientation of the dike/graben constrains the orientation of the regional stress field. The graben will form perpendicular to the axis of least compression/maximum extension. In the absence of any significant regional asymmetry in the stress field, dike propagation will be controlled by anisotropy in the strength of the rock.

In order to quantify extension over dikes, the deformation pattern around dikes has been measured in the field, reproduced in the laboratory and modeled numerically. Table 1 lists some of the resulting gross generalizations between readily measured parameters. The discrepancies between the laboratory simulations (done in flour/sugar mixtures) and the numerical simulations are not well understood. However, the most likely culprit is that crack formation was not explicitly built into the numerical modeling. Instead, it plots strain as a function of position. Figure 5 shows a model profile of surface extension over a shallow dike.

One major caveat to keep in mind is that, in the real world, it takes time for the dike to propagate and a series of nested fractures can be expected as the magma rises. Also, creep over days-months accommodates much of the strain related to these intrusions, making observations of active systems difficult to relate to ancient examples.

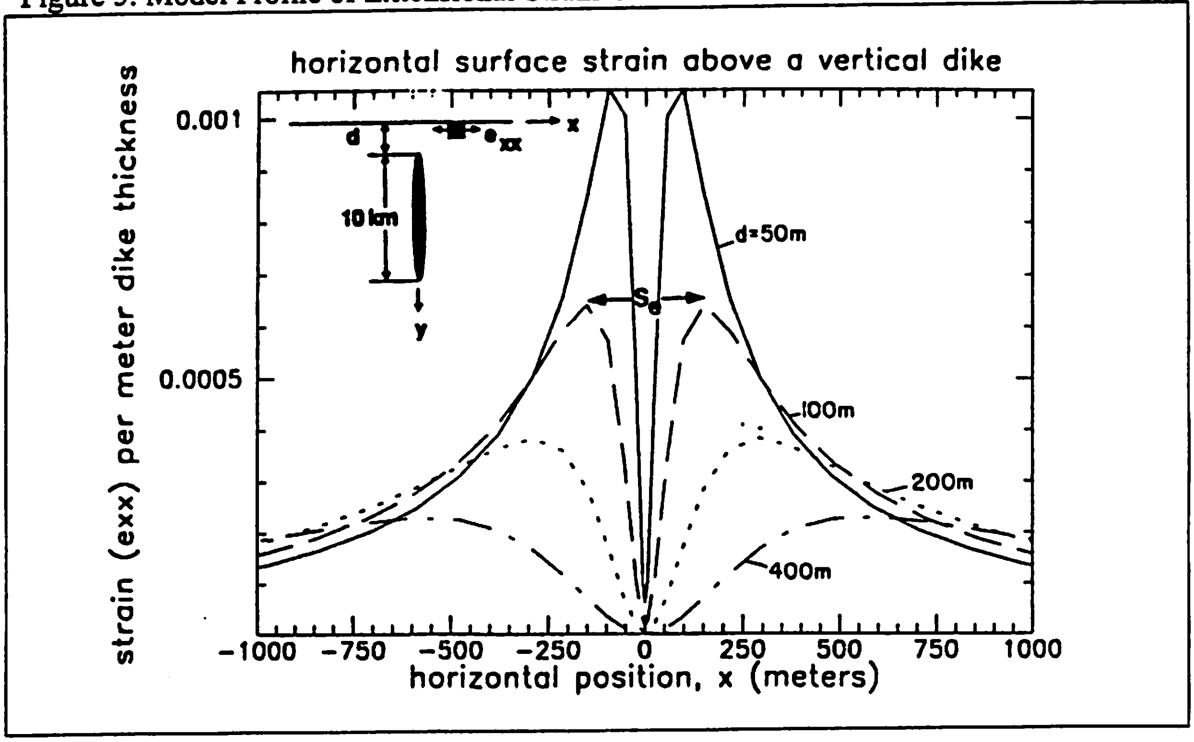
Table 1. Numerical and Laboratory Simulations of Extension over Shallow Dikes (from Mastin and Pollard, 1988) compared to Field Observations from Episode 54, Kilauea Volcano, January 31, 1997 (USGS unpublished data).

	surface extension/width of dike	width of graben/depth to top of dike.
Numerical	0.22-0.41	2.8-3.0*
Lab	0.59-0.73	~1.5-2.5**
Kilauea 1997	~0.5±0.4	0.1-0.3***

* width of "graben" = distance between points of maximum surface extension.

** width of "graben" = distance between outermost fractures.
*** width of graben = width of down dropped block.

Figure 5: Model Profile of Extensional Strain Over a Shallow Dike



Planetary Applications

On the Earth, basaltic dikes are typically 1-5 m wide and only extremely rarely attain widths of tens of meters. Thus terrestrial grabens over dikes tend to have little extension and are relatively insignificant features. However, it has been argued that dikes should be much wider on the Moon and perhaps Mars. The grabens on the Moon have been particularly difficult to explain by any other mechanism since the entire body should be in a compressional regime. Differences in dike related graben morphology are influenced by the greater depth of the brittle regime in which dikes propagate. Because smaller planets cool more quickly, their lithospheres thicken more quickly as a function of time. A thicker brittle layer (lithosphere) requires that much greater driving pressures be employed in order to keep a dike open the long distance from source to near-surface. Consequently, dikes potentially capable of creating grabens on the Moon and Mars must be much larger than those on Earth and would therefore produce wider, deeper grabens. For example, for a dike to reach the surface from typical basaltic magma source depths of 60-100 km, excess pressures of 15-25 MPa would be required, yielding dikes of 150-200 m mean width. The most salient argument against this scenario is that it is difficult to conceive of a mechanism capable of stopping a dike under such high driving pressures from propagating to the surface rather than stalling.

Early Geologic Exploration of the Colorado Plateau

Erich Karkoschka

By the 1860s, there were good maps of all the United States including its territories with the exception of the Colorado Plateau. Until then, only few white men had traversed the Colorado Plateau, considered "the least usable of all regions".

John Wesley Powell was the first scientific explorer of the Colorado Plateau. In 1865, he was professor of geology in Illinois. In 1866, he established the local Natural Historic Museum. In 1867, he managed to divert funds from the museum for a small expedition with students to Colorado. In 1868, he headed a longer expedition. While its primary purpose was collecting specimen for the museum, he explored the existing trails, especially access routes to the Colorado River and Green River. The following winter, he spend with Ute Indians to learn more about the region.

On May 24, 1969, Powell started going down the Green River at the town of Green River, Wyoming with 10 men and four boats. The same month, the railroad bridge across the Green River was finished providing transcontinental rail service. After an eventful journey, he finished the trip with six men on August 30 at the end of the Grand Canyon to which point there had been access by steam boats. Powell made many side trips off the river and recorded geography and geology with his scientific instruments and eyes. Most of the area near the river had not been seen by white men before.

At the same time, Captain Samuel Adams tried to go down the Colorado River starting from Colorado. He had the idea that the Colorado River would be suitable for steam boats all the way to Colorado. He wanted to prove it, not prepared for running rapids. His river expedition fell apart quickly.

In 1870, Powell got a grant of $10,000 to explore the Colorado Plateau and the Colorado River. He hired mostly amateurs for the expedition. He did not want the usual military escort, since he had a good understanding of the Indians although several tribes had guerrilla wars. He set out on the Green River in May, 1971. He explored the area north of Glenn Canyon which had no roads as late as 1929. He found the last unknown river, the Escalante River. He stayed the following winter in the Colorado Plateau with headquarters in Kanab. At the same time, the National Park System was established (Yellowstone).

By 1872, Powell was head of the Geographic and Geologic Survey of the Rocky Mountain Region. He explored with Grove Karl Gilbert, director of the new United States Geologic Survey. Gilbert refined geologic ideas in the 1870s that Powell touched and left. Powell's "left hand" was Captain Dutton whom Powell considered his geologic heir. Dutton explored lava flows of Southern Utah. Volcanism was Dutton's specialty. While many explorers came to the Colorado Plateau because of its challenges, Dutton was attracted by its scenery as a nature lover.