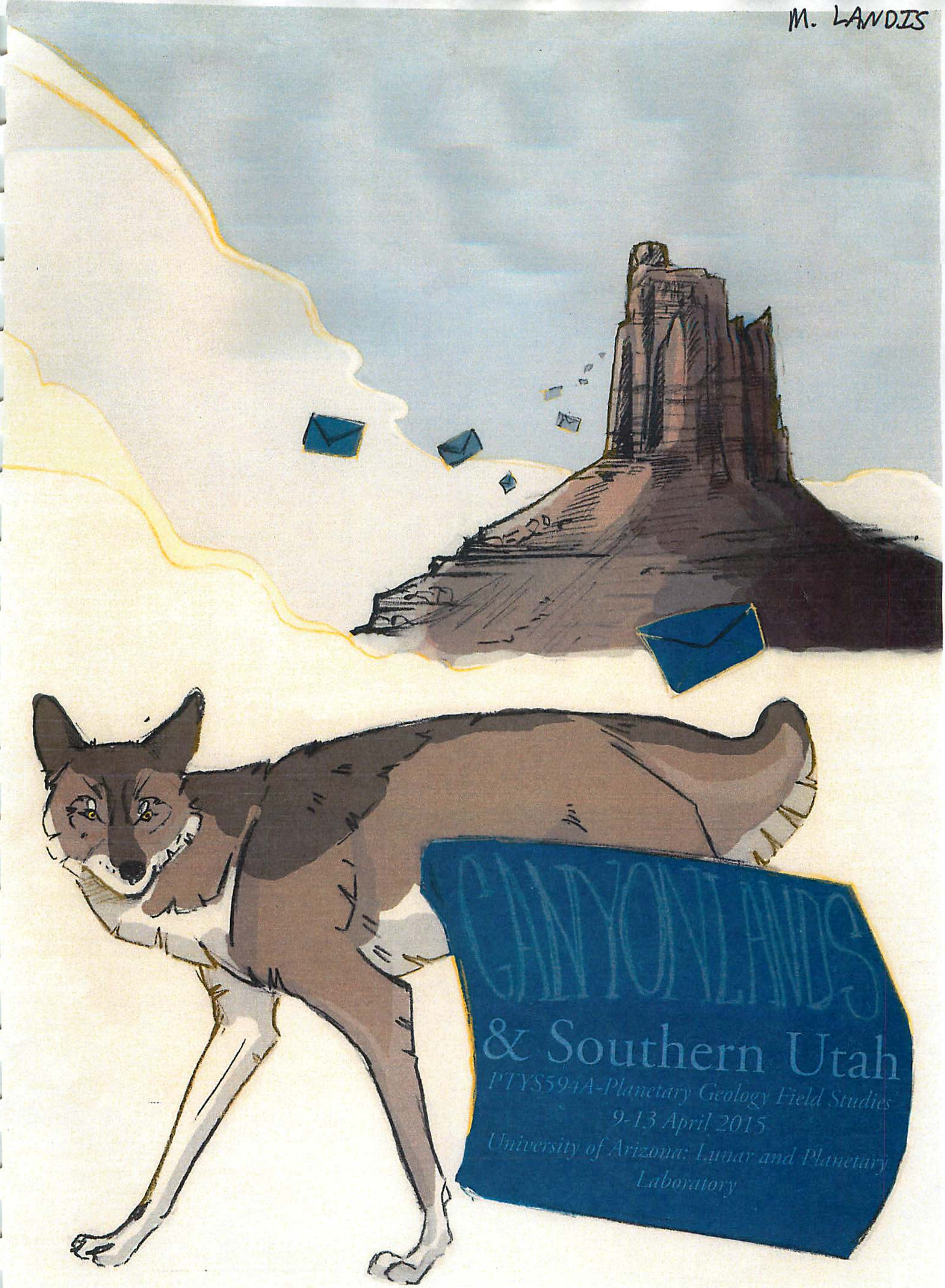
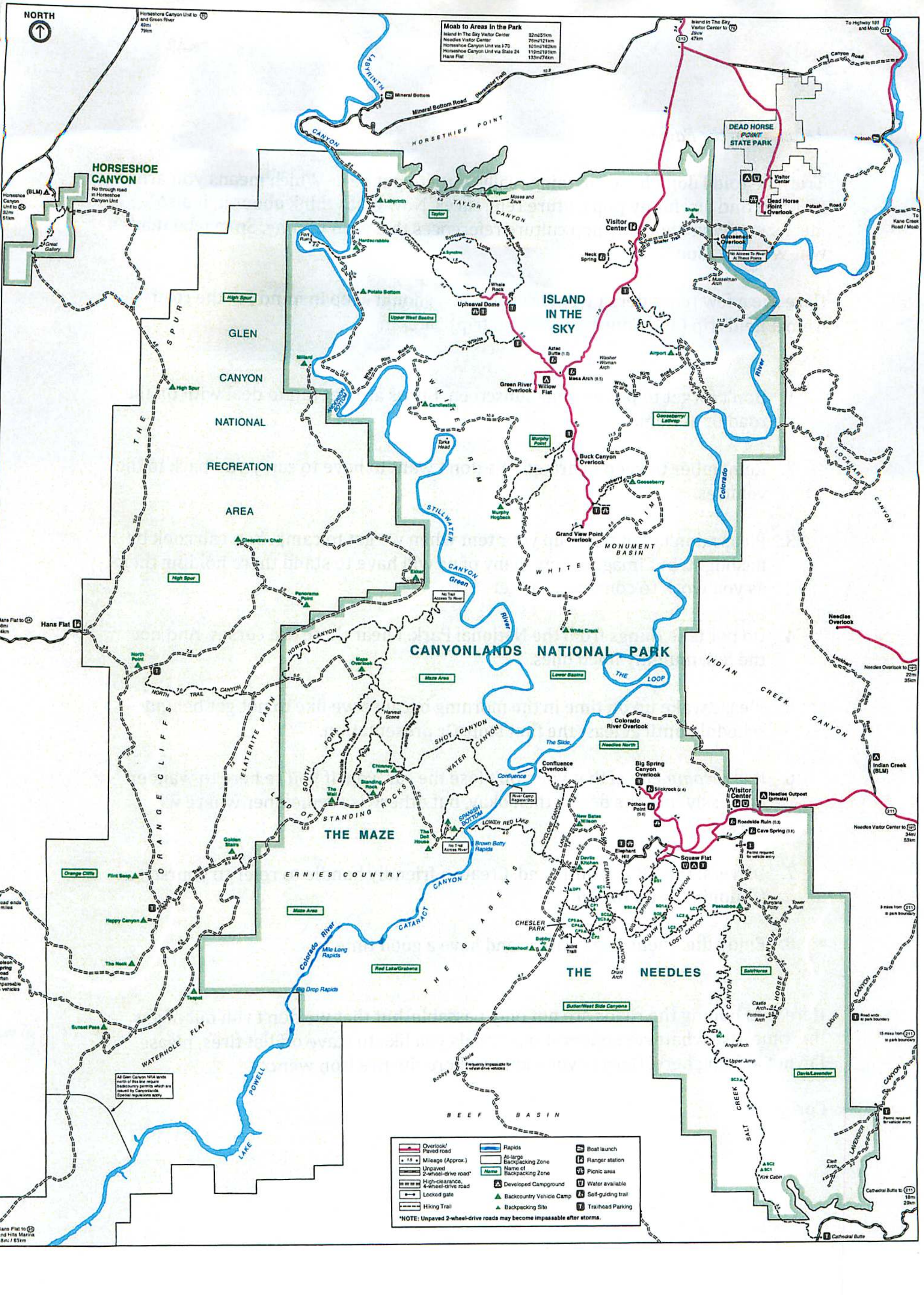
M. LANDIS


CANYONLANDS
& Southern Utah
PTYS594A-Planetary Geology Field Studies
9-13 April 2015
University of Arizona: Lunar and Planetary Laboratory



NORTH
Moab to Areas In the Park
Island In The Sky Visitor Center 32mi/51km
Needles Visitor Center 76mi/121km
Horseshoe Canyon Unit via I-70 101mi/162km
Horseshoe Canyon Unit via State 24 119mi/191km
Hans Flat 133mi/74km
HORSESHOE CANYON
No through road in Horseshoe Canyon Unit
GLEN CANYON NATIONAL RECREATION AREA
ISLAND IN THE SKY
DEAD HORSE POINT STATE PARK
CANYONLANDS NATIONAL PARK
THE MAZE
THE NEEDLES
Mineral Bottom
Mineral Bottom Road
HORSETHIEF POINT
LABYRINTH CANYON
TAYLOR CANYON
Upheaval Dome
Green River Overlook
Willow Flat
Mesa Arch
Aztec Butte
Buck Canyon Overlook
Grand View Point Overlook
Visitor Center
Neck Spring
Shafer Trail
Gooseneck Overlook
Musselman Arch
Potash Road
Dead Horse Point Overlook
WHITE RIM
MONUMENT BASIN
STILLWATER CANYON
Green River
Colorado River
THE LOOP
Confluence
Confluence Overlook
Big Spring Canyon Overlook
Colorado River Overlook
Hans Flat
North Point
Panorama Point
Cleopatra's Chair
THE SPUR
ORANGE CLIFFS
ELATERITE BASIN
LAND OF STANDING ROCKS
HORSE CANYON
SHOT CANYON
WATER CANYON
ERNIES COUNTRY
Spanish Bottom
Brown Betty Rapids
CATARACT CANYON
Mile Long Rapids
Big Drop Rapids
THE GRABENS
WATERHOLE FLAT
POWELL LAKE
BEEF BASIN
CHESLER PARK
Elephant Hill
Squaw Flat
Needles Outpost (private)
Roadside Ruin
Cave Spring
Pothole Point
Slickrock
INDIAN CREEK CANYON
LOCKHART CANYON
SALT CREEK
HORSE CANYON
DAVIS CANYON
LAVENDER CANYON
Needles Overlook
Indian Creek (BLM)
Cathedral Butte
Angel Arch
Kirk Cabin
Overlook/Paved road
Mileage (Approx.)
Unpaved 2-wheel-drive road*
High-clearance, 4-wheel-drive road
Locked gate
Hiking Trail
Rapids
At-large Backpacking Zone
Name of Backpacking Zone
Developed Campground
Backcountry Vehicle Camp
Backpacking Site
Boat launch
Ranger station
Picnic area
Water available
Self-guiding trail
Trailhead Parking
*NOTE: Unpaved 2-wheel-drive roads may become impassable after storms.

Letter from the Editor

Truth be told I don't have anything really witty to put here. Which means you aren't going to find any funny pop culture references. Now that I think about it, it also means you won't find any pop culture references that aren't funny. So maybe that's a win-win situation?

Here are a few reminders I would suggest you should keep in mind for the road from a field trip (and Canyonlands field trip) veteran.

1. Don't forget to put on your sunscreen. Burns are not fun to deal with on the road or at home.

2. Remember to keep hydrated. We don't want to have to carry you back to the vehicles.

3. Please don't wait to set up your tent when we get to camp. You can cook by flashlight, but imagine how many of us will have to stand there holding them as you work to construct shelter.

4. Do not take things from the National Park. I hear there are curses. And not the fun, mummy filled ones.

5. Please wake up on time in the morning because we like to not get behind schedule until at least the first stop. Or presentation.

6. It is *recommended* that you don't lose the caravan. If you're here to wander endlessly into the desert then okay, but otherwise remember where we parked.

7. Drivers: the CB is your friend. Create a friendly handle to refer to yourself as. Or don't. It's up to you.

8. Enjoy the science and nature and have a good time.

Here is to hoping the roads are not only passable, but that we don't run out of gas this time. Use whatever superstitious rituals you like to stave off flat tires, please. I'm not kidding here. Does anyone know where the tire iron went?

Corey

Contents

Cover Illustration courtesy of Eva A. Landis
Visit her page at evalandis.tumblr.com

Canyonlands Spring 2015 Itinerary

Sunset is about 6.50pm Arizona time, sunrise is about 6.05am. All times below are Arizona time (MST).

April 9th

8:00 AM Depart LPL.

12:30 PM Arrive Flagstaff. Lunch at Walnut Canyon where **Shane 'I think I'm funnier than I really *am*' *Byrne*** may ad lib about cross-bedding.

1:30: Depart lunch site.

4:15: Arrive Kayenta. Gas stop. Depart ~4:45.

5:00: Arrive at Agathla Peak. **Jean 'trust me, my HOV certificate is brand new' Masterson** will talk about diatremes.

5:15: Depart Agathla Peak.

5:30: Arrive Monument Valley. **Corey 'this handout is 4.5 years old' Atwood-Stone** will tell us about the stratigraphy of the Colorado Plateau.

5:45: Depart Monument Valley.

6:00: Arrive in Mexican Hat

6:15: Camp on BLM land near Mexican Hat/Goosenecks

April 10th

8:00 AM: Break camp

8:15 Arrive at Goosenecks overlook. **Daniel 'my alternate career is action movie star' Lo** will explain these incised meanders, we'll leave at about 8.30am.

9:00: Arrive at Comb Ridge overlook. **Hannah 'so hot right now' Tanquary** will discuss monoclines.

9:15: Depart. Pass through Bluff at ~9:30.

12:30 PM: Arrive at Upheaval Dome. Lunch.

1:30 Talks and hiking at Upheaval Dome. **Margaret 'craters are my life and that's OK' Landis** will present the impact theory, and **Jon 'The Bapst' Bapst** will discuss the older salt diapir model and maybe salt tectonics in general. This might also be a good place for **Sondy 'I dream in S-band' Springmann** to explain the formation of concretions, in the hopes that we might find a few somewhere.

5:00: Depart Upheaval Dome.

5:30: Camp just outside Canyonlands NP.
(Option: After Upheaval Dome, drive south to Grand View Point, ~15 min from the crater. This place is a good overlook for most of the park)

April 11th

8:00 AM: Break camp. Gas stop in Moab where everyone is encouraged to take a shower. Leave Moab at 11am.

Noon: Newspaper Rock. **Kenny 'why isn't my department as cool as LPL?' Furdella** will tell us about the native peoples of the area, who made these petroglyphs. Lunch here.

1-6pm. Drive down to the graben through Beef Basin and Bobby's Hole.
Either that evening or the next morning **Ali 'life has no meaning if the badgers lose' Bramson** will talk about the Canyonlands graben system and what makes it tick and **Sky '*I promise* this won't go longer than 15 minutes' Beard** *will tell* us about the local flora and fauna.

April 12th

Drive to the joint trail where we'll walk the trail and hear **Tad 'my sweater has more facebook friends than you' Komacek** tell us about jointing in rocks, and **Hamish 'Is everyone in this country crazy?' Hay** can tell us all about fault interactions.

In the second half of the day we'll tackle Bobby's hole in the opposite direction and camp in Beef Basin, but not before **Donna 'I just wish one other person here was an astrobiologist' Viola** will tell us all about cryptobiotic soil.

April 13th

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

Diatremes

Jean Masterson
PTYS 594 Spring 2015

Figure 1: Devils Tower volcanic neck, Wyoming, USA. (Souce: National Park Service [1]).

Overview:

- A diatreme is a specific type of *igneous intrusion*, or magma that has solidified below the Earth's surface.
- Diatremes are shaped like funnels or carrots, with steep walls that taper 80-85 degrees from the horizontal.
- The general depth of a diatreme is 1-2 km.
- Diatremes are composed of *breccia*, or fragments of volcanic rock mixed with fragments of host rock.
- Brecciated texture distinguishes the diatreme zone from the root.
- *Xenoliths*, or rocks that have been carried up from depth, are often present.
- *Kimberlitic diatremes* are often composed of plagioclase, olivine, clinopyroxene, hornblende, biotite, and diamond.

Formation:

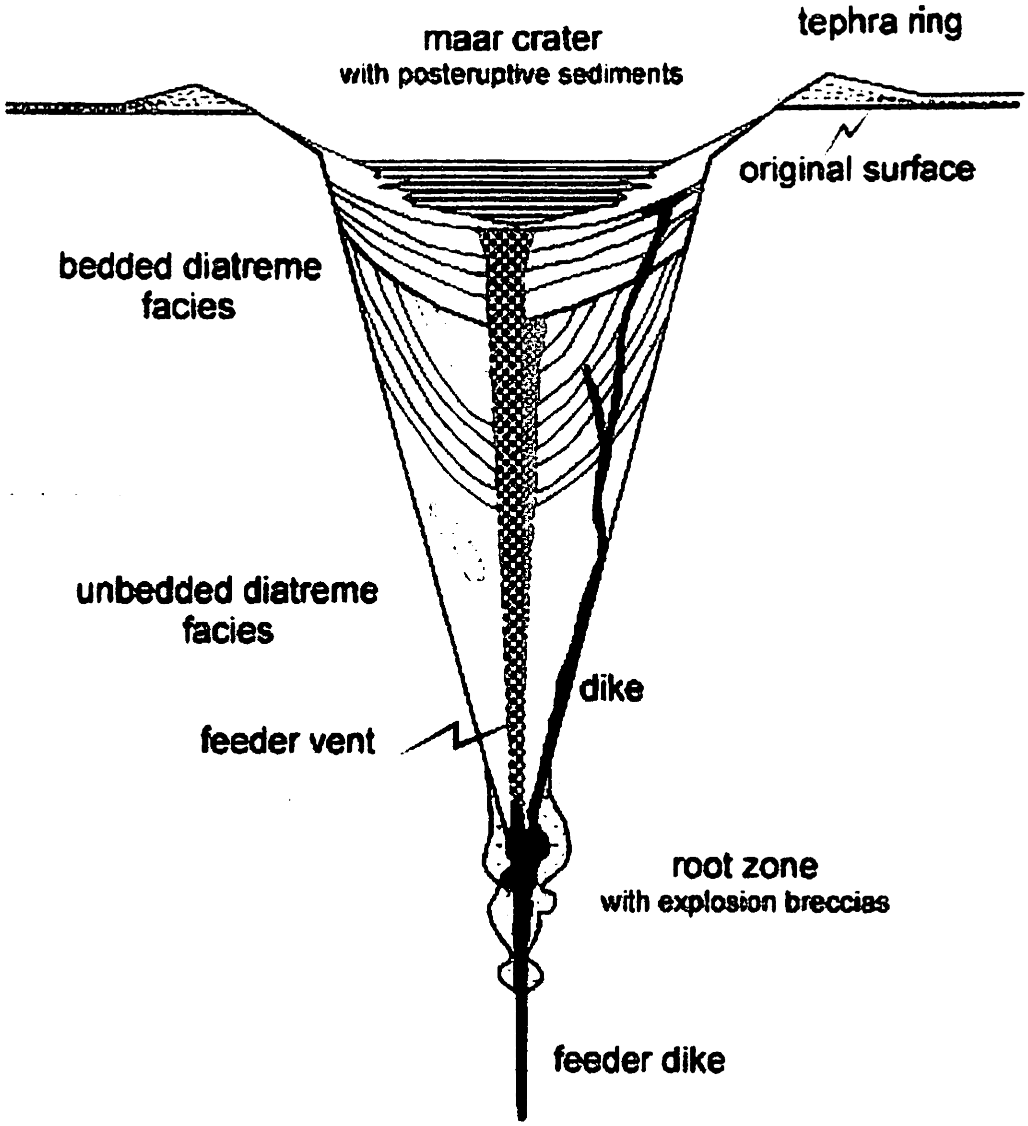


Figure 2: Schematic of a maar-diatreme volcano [2].

Features of Note:

- Feeder dike
- Root zone
- Overlying cone-shaped diatreme
- Unconformity in the bedded sequence (collapse phase)
- Feeder vents
- Maar crater
- Proximal tephra ring and distal tephra veneer

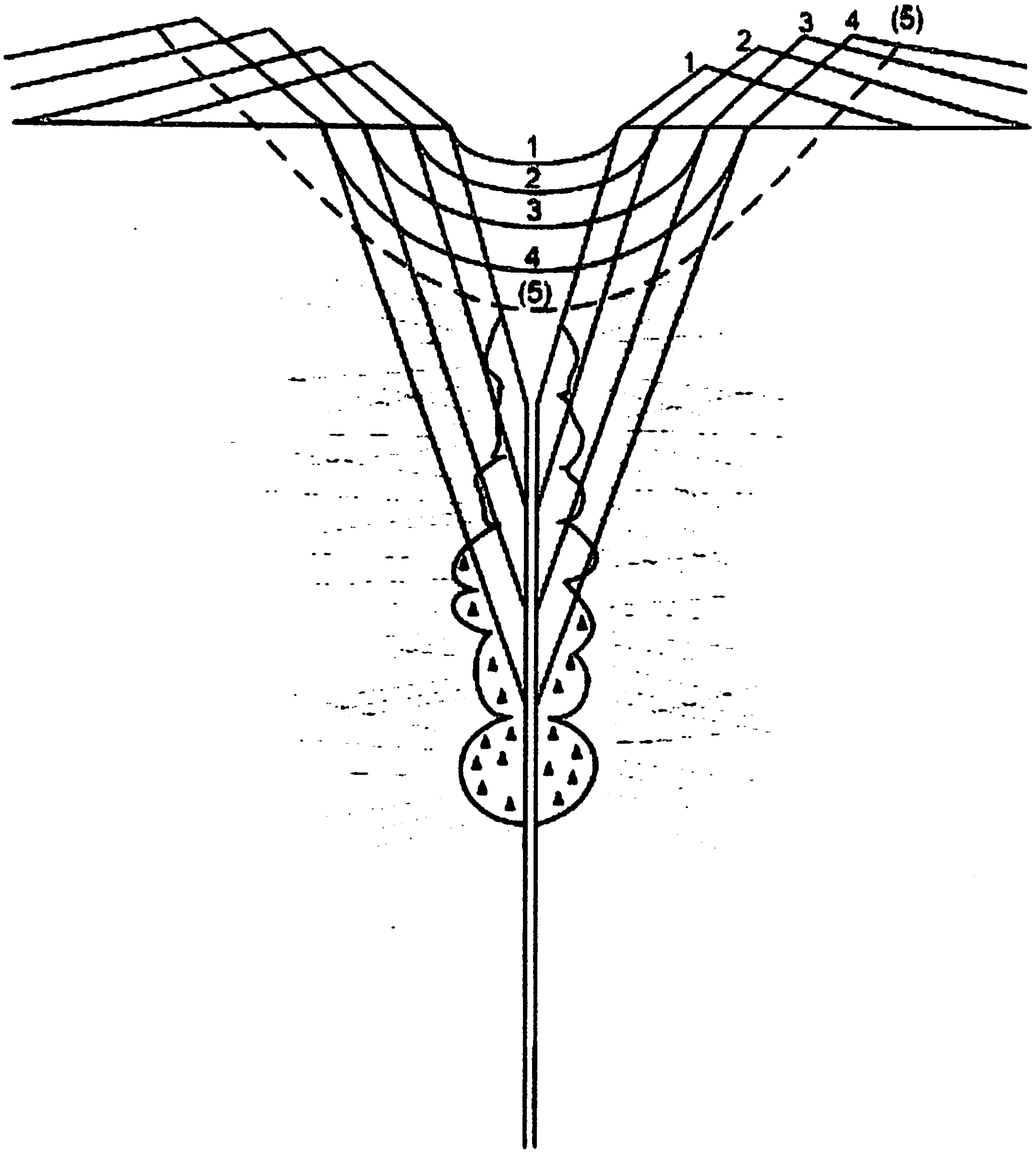


Figure 3: Schematic growth of a maar-diatreme volcano [2].

- Shock waves from the phreatomagmatic explosions fragment the country rocks (explosion chamber).
- The irregularly shaped root zone is formed by a number of explosion chambers.
- Growth occurs via downward penetration of the root zone (collapse phase).
- Progression to a larger and deeper diatreme and maar crater.

Specific Examples – Earth:

1) Agathla Peak

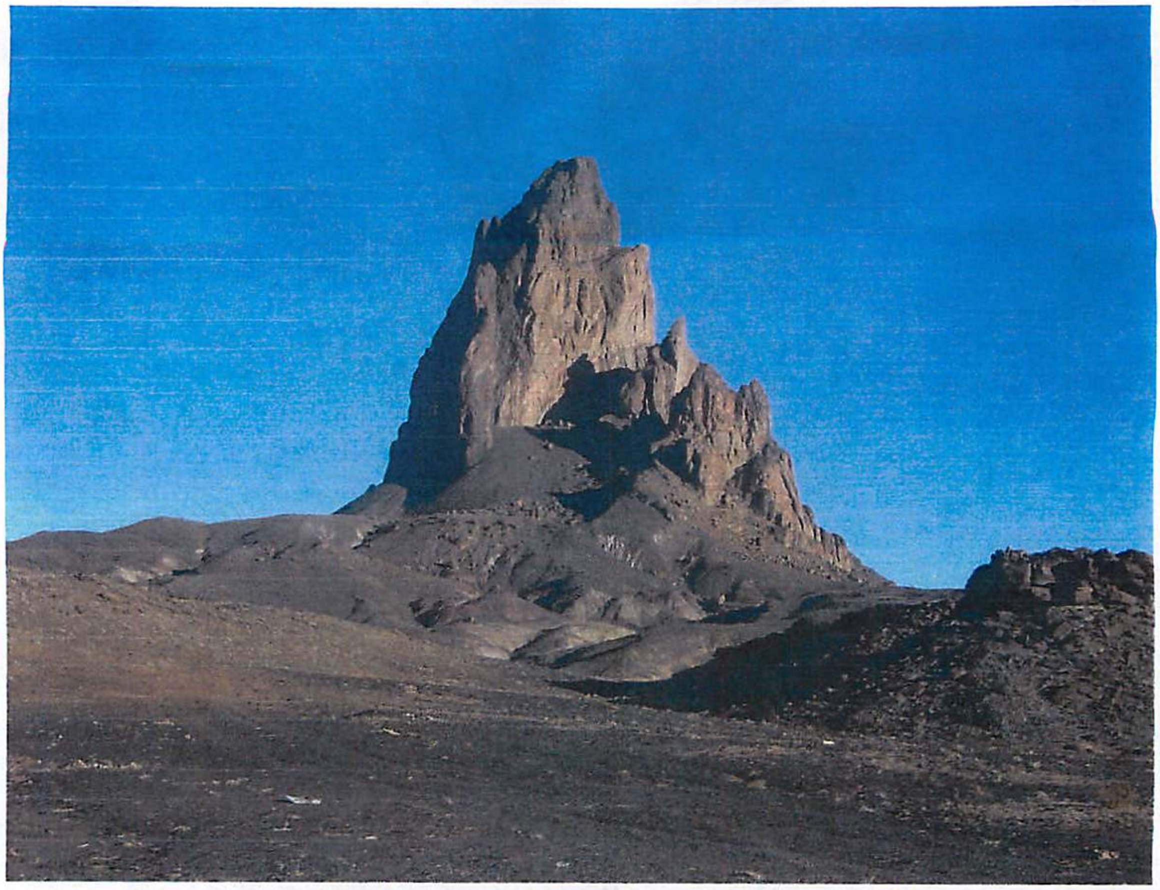


Figure 4: Agathla Peak, Monument Valley, AZ, USA (Source: Wikipedia Media Commons).

- Eroded volcanic plug (diatreme) composed of volcanic breccia.
- Spanish name is El Capitan.
- Part of the Navajo Volcanic Field in the southern Colorado Plateau.
- Approximate age: 25 million years.

Navajo Volcanic Field

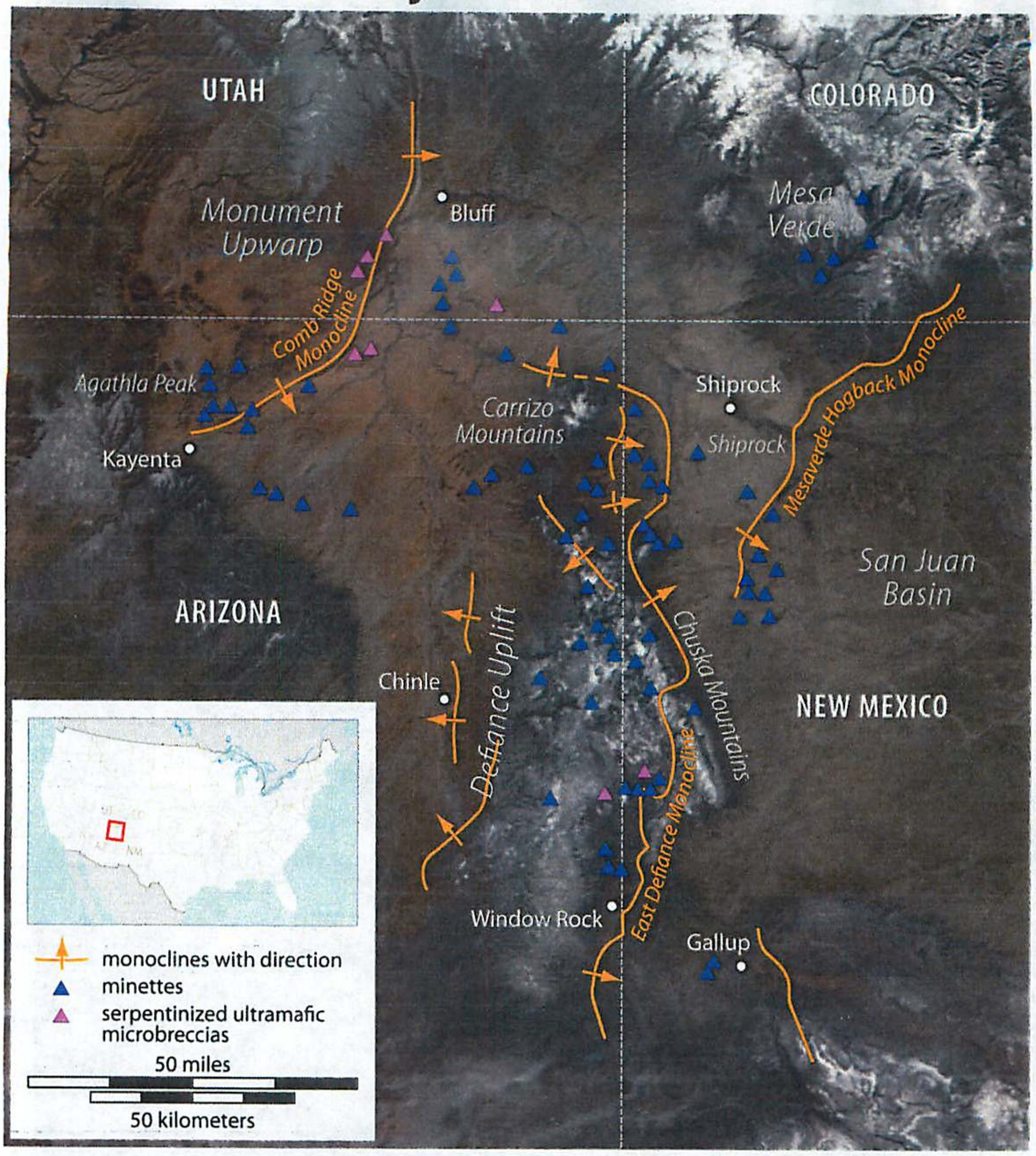


Figure 5: Navajo Volcanic Field (Source: Wikipedia Media Commons).

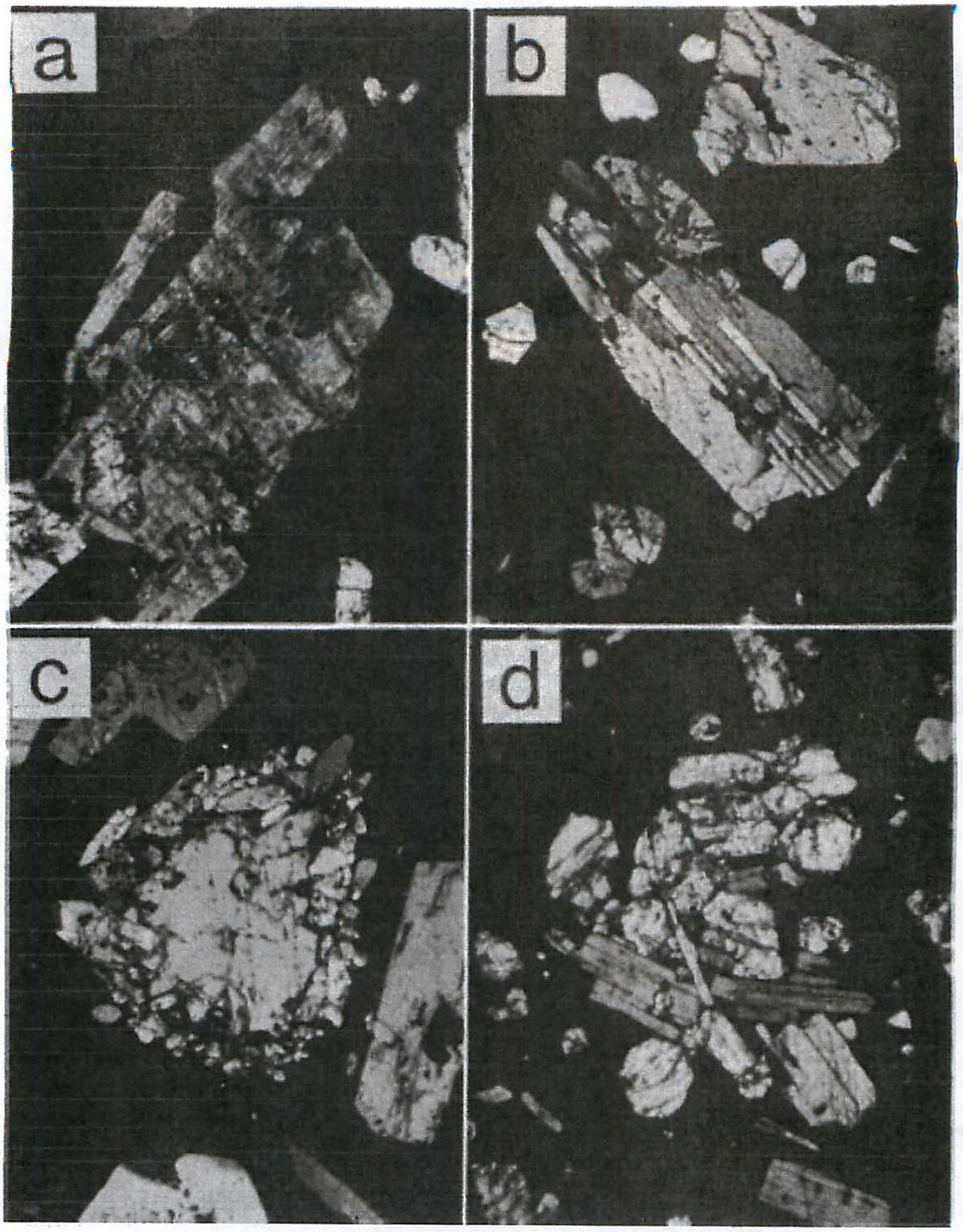


Figure 7: Chilled facies of Agathla Peak minette [3]. (a) phlogopite macrocryst, (b) twinned diopside macrocryst slightly zoned in Cr, Ti, and Na, (c) analcime crystal, (d) cluster of phlogopite plates and diopside euhedra [3].

2) Moses Rock Dike

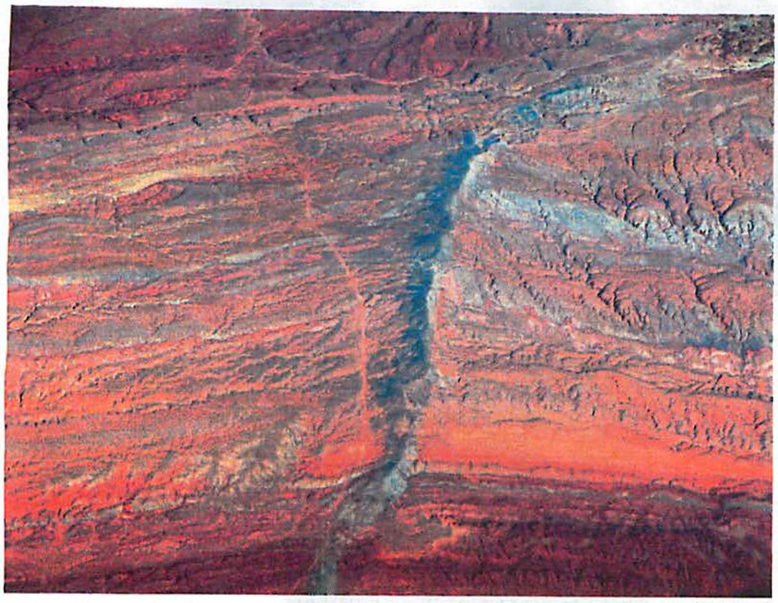


Figure 8: Image of Moses Rock Dike, Cane Valley, Utah, USA. (Souce: Wikipedia Media Commons).

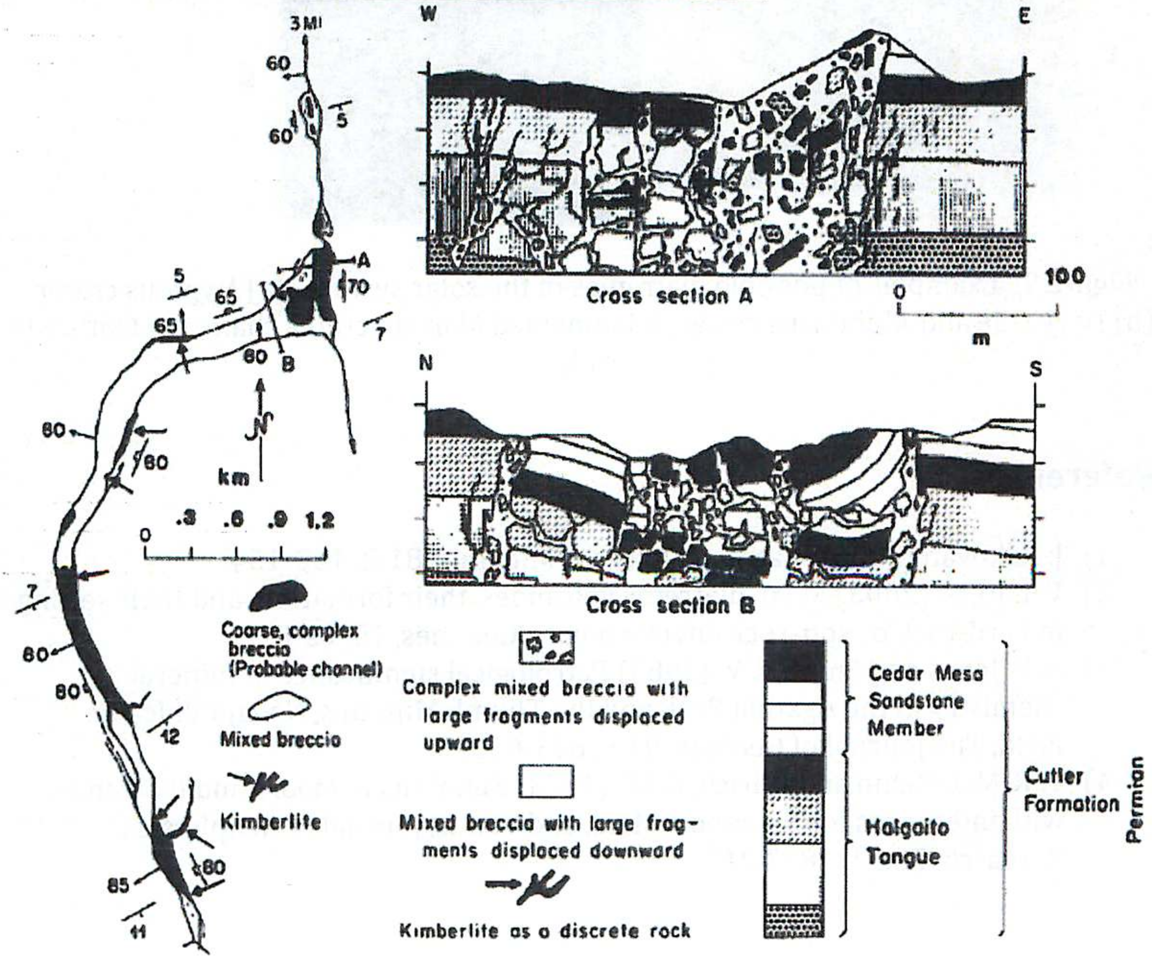
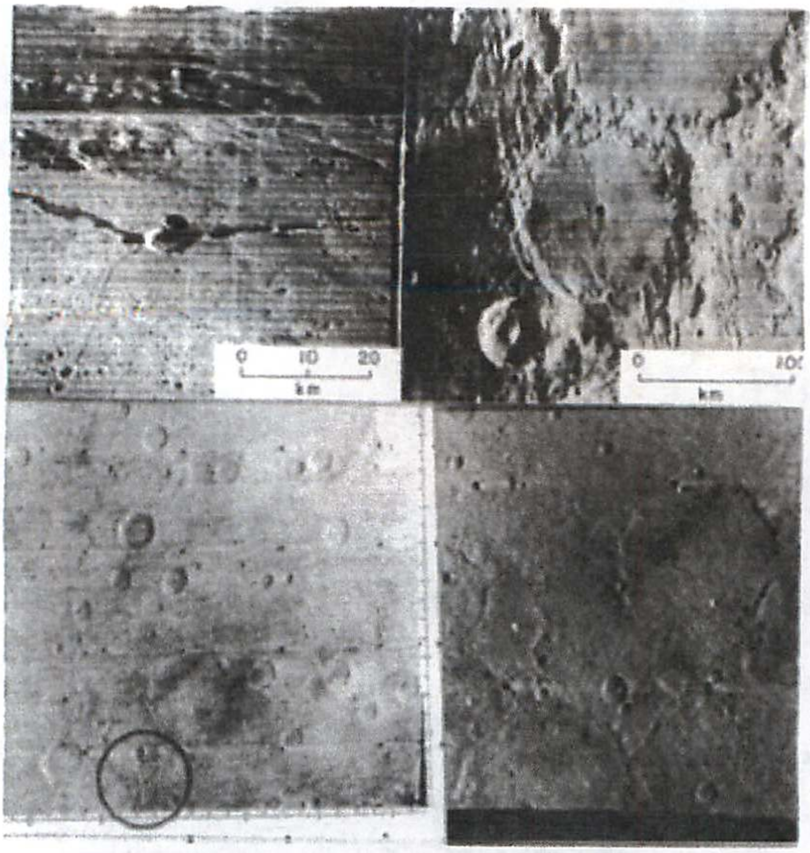


Figure 9: Geological map and cross-section of Moses Rock Dike [4].

Extension to Planetary Geology:

a



b

c

d

Figure 9: Examples of possible diatremes in the solar system. (a) Hyginus crater, (b) Davy rille and Alphonsus crater, (c) unnamed Martian crater chain, (d) feature in c [4].

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2) V. Lorenz (2003) Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments, Geolines, 15, 72-83.
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Stratigraphy of the Colorado Plateau

Corwin Atwood-Stone

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

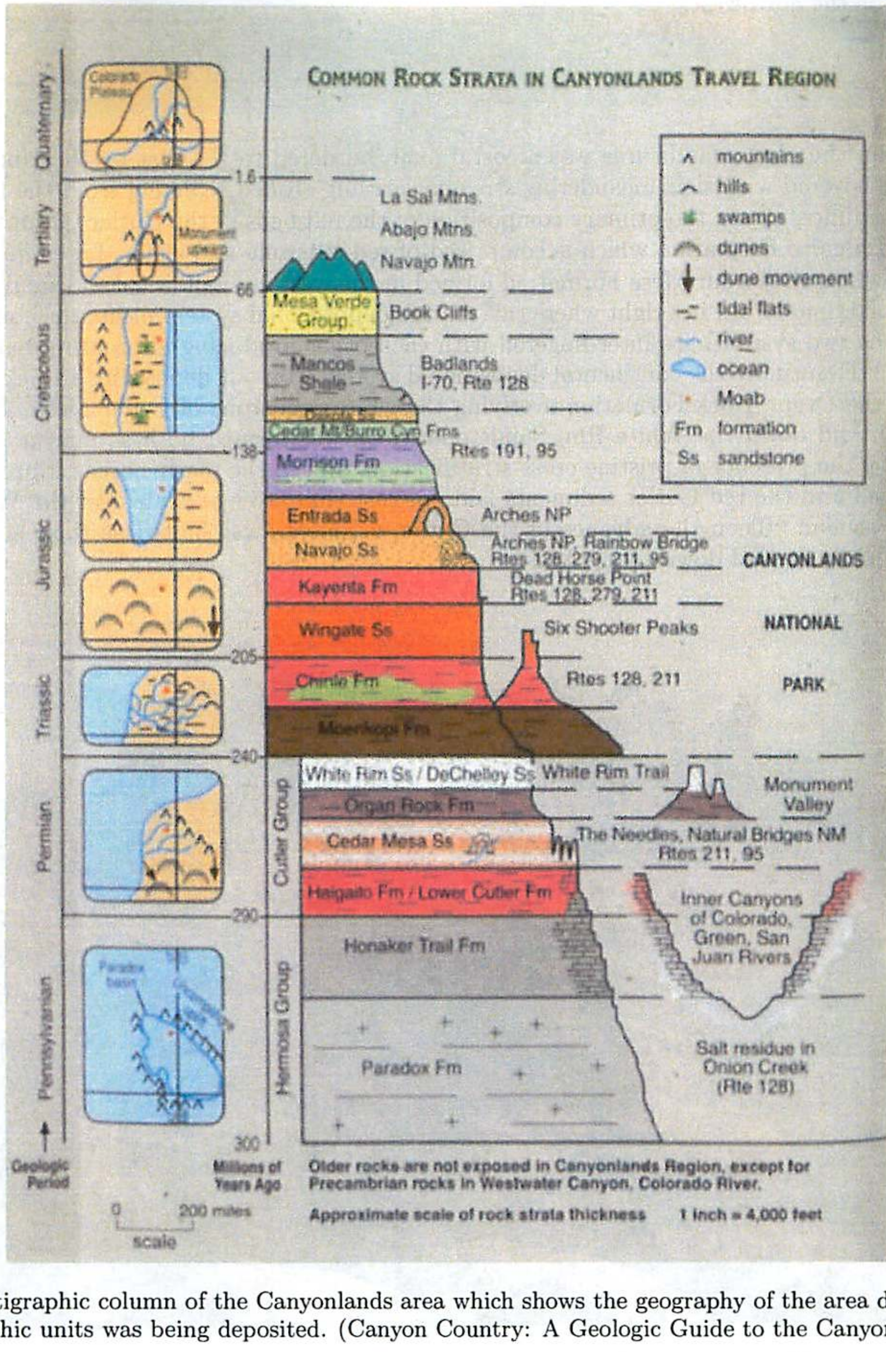

FIG. 1 This is a stratigraphic column of the Canyonlands area which shows the geography of the area during the period when each of the stratigraphic units was being deposited. (Canyon Country: A Geologic Guide to the Canyonlands Travel Region)

I. HERMOSA GROUP

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

II. CUTLER GROUP

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

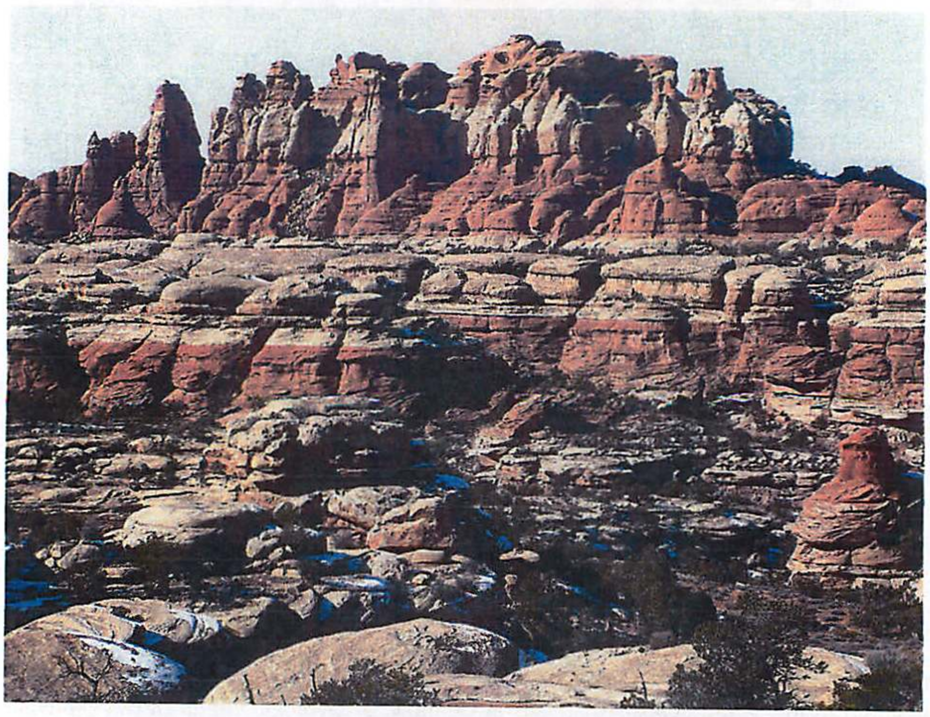

FIG. 2 The Needles in Canyonlands National Park shown here display the red and white banding of the Cedar Mesa Formation. (http://en.wikipedia.org/wiki/File:Canyonlands_Needles.jpg)

III. MOENKOPI & CHINLE FORMATIONS

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

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

IV. GLEN CANYON GROUP

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

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

V. SAN RAFAEL GROUP & THE MORRISON FORMATION

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

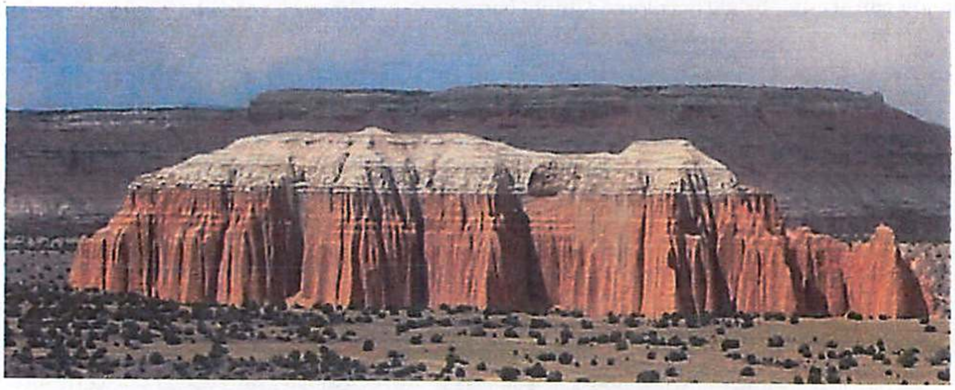

FIG. 5 This cliff exposure shows the reddish Entrada Formation capped by the white sandstone of the Curtis Formation. (http://en.wikipedia.org/wiki/File:Entrada_Sandstone_capped_by_Curtis_Formation_in_Cathedral_Valley.jpg)

VI. CRETACEOUS STRATA

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

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

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

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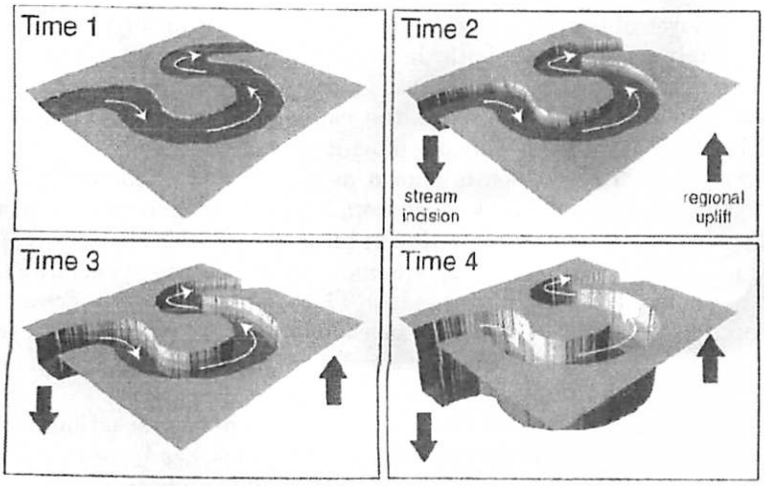
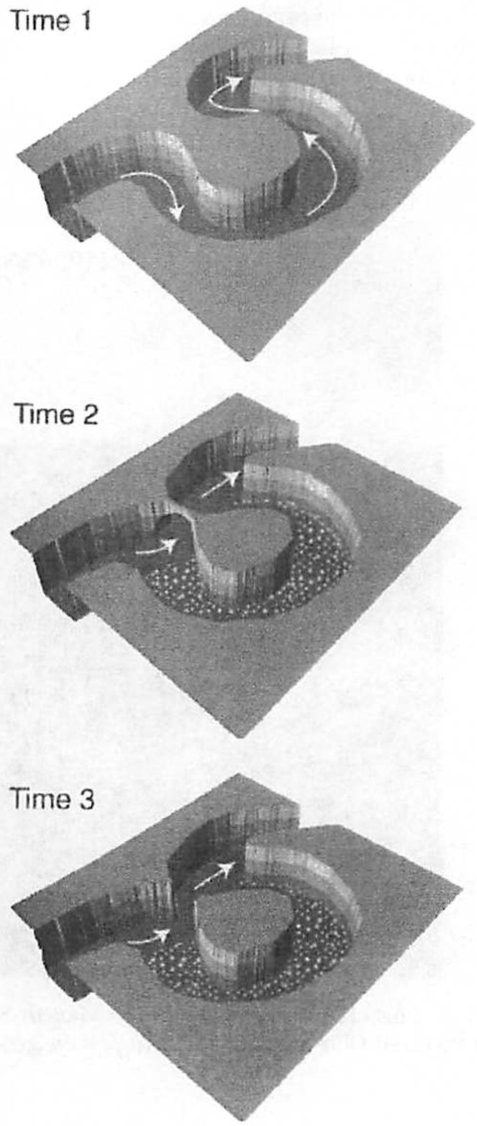
[3] Wikipedia, *Geology of the Canyonlands Area* (http://en.wikipedia.org/wiki/Geology_of_the_Canyonlands_area).



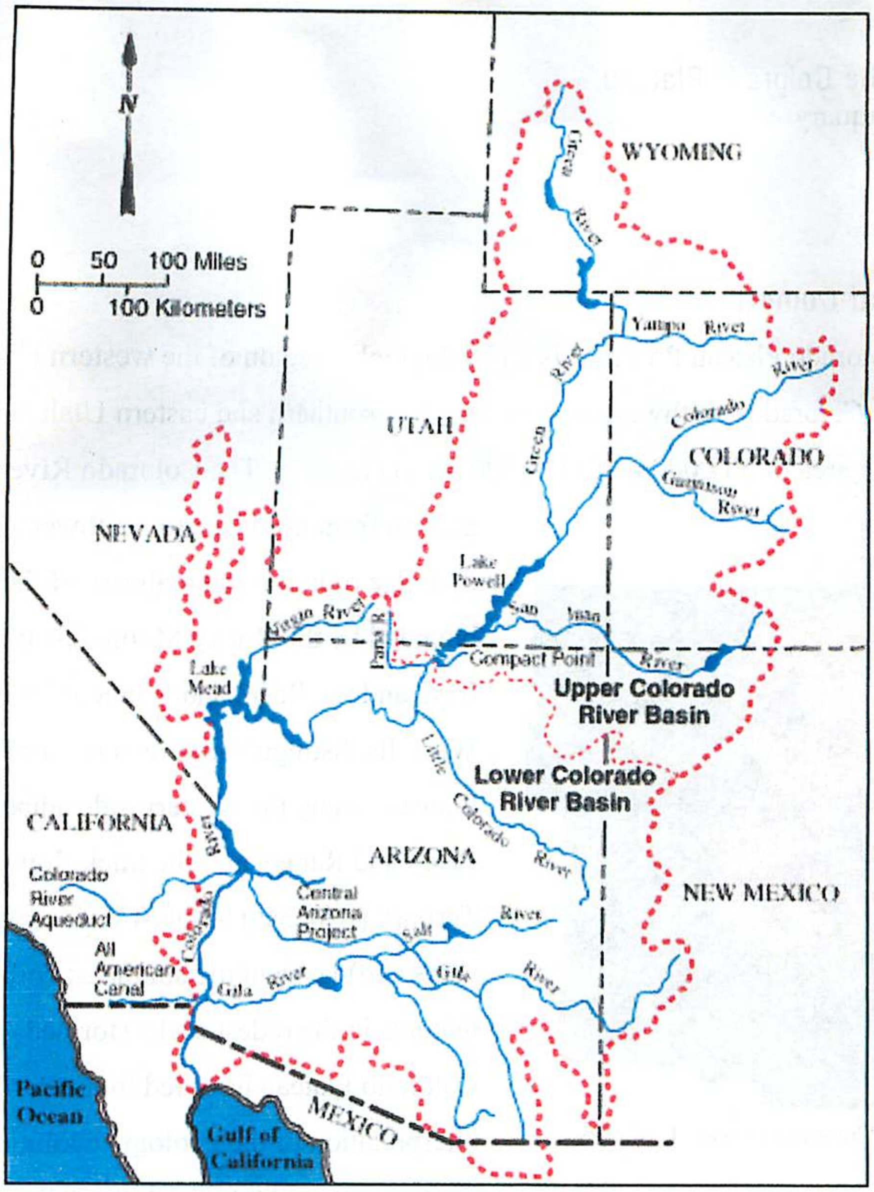
Formation of incised meanders (Image from Orndorff et al).

Incised meanders are geologic features associated with entrenched river systems that form from a rapidly lowering of the base level. The base level of a river is the altitude of the lowest point of the river (typically at its mouth). A (relative) lowering of the base level can occur due to tectonic uplift over the course of the river, a lowering of the oceans due to climate change (if the river drains into the ocean), or the opening of a new channel that allows the river to be drained towards a topographically lower exit. This rapid change in base level results in a sudden increase in gradient over the course of the river, drastically increasing erosion rates. The high erosion rates lead to the rapid downcutting that forms the narrow canyons or gorges in entrenched river systems. If the erosion rate exceeds the meander formation rate, then incised meanders are formed. There is little or no floodplain, and the walls of the canyon hug the river closely. This formation process means that plateau regions around the world are preferred sites for incised meanders, since plateaus form from vertical uplift with little internal deformation or tilting (Blache, 1940). This indeed was what happened at Goosenecks State Park. The Colorado Plateau was uplifted with relatively little deformation more than 2 km from sea level since the Late Cretaceous (~70 Mya). Furthermore, the rise of the Rocky Mountains to the NE and the resulting tilting of the Colorado Plateau resulted in the flow reversal of the ancient "California river" to become the lower section of the Colorado river at about 30 Mya. As a result, the Glen Canyon, initially an inland sea which the San Juan, upper Colorado and ancient California rivers drained into, started draining into the Pacific Ocean. The San Juan river became a tributary of the Colorado river, and its base level was lowered drastically. In a positive feedback cycle, the rapid erosion of sediment also reduces the crustal mass, resulting in further regional uplift from isostasy.

Although downward erosion is much greater than lateral erosion, the latter still occurs. Just as typical rivers can form oxbow lakes when erosion of the banks results in the cutting off of a meander to form an oxbow lake, lateral erosion by entrenched rivers can produce oxbow canyons. Since the erosion occurs from the bottom up, land bridges can form temporarily. Eventually the upper layers making up the land bridge collapse. As the river continues its vertical erosion down the main channel, the oxbow canyon becomes isolated topographically and dries up.



Formation of a land bridge (Image from Orndorff et al).



The Colorado River (Image from http://www.usbr.gov/lc/region/g4000/contracts/watersource.html)

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Prepared by Daniel Lo

Tectonics of the Colorado Plateau

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Geography and Context

The Colorado Plateau Province is a physiographic region of the western United States. It covers western Colorado, northwestern New Mexico, southern and eastern Utah, and northern Arizona with an area of 337,000 km^2 (130,000 mi^2) (Figure 1). The Colorado River traverses the plateau from northeast to southwest, providing the drainage route for the majority of the area. It is bounded by the Rocky Mountains in the North and East, and the Basin and Range Province to the West. Its distinguishing features include the High Plateaus along the western side adjacent to the Basin and Range, and the thick flows of mid-Tertiary (≈ 30 Ma) to late-Cenozoic-aged (≈ 3000 years ago) lavas in the southeast corner. Structural features in the oldest rocks (formed ~2 Ga) of the Colorado Plateau have led to much of the current interpretation of the geologic evolution of the western United States. Additionally, abundant mineral resources are available and easily found by the same means. Due to the arid conditions of much of the region, its geologic history is unusually unobscured, allowing for its exploitation as both a scientific marvel and an economic opportunity (Kiver, 1999).

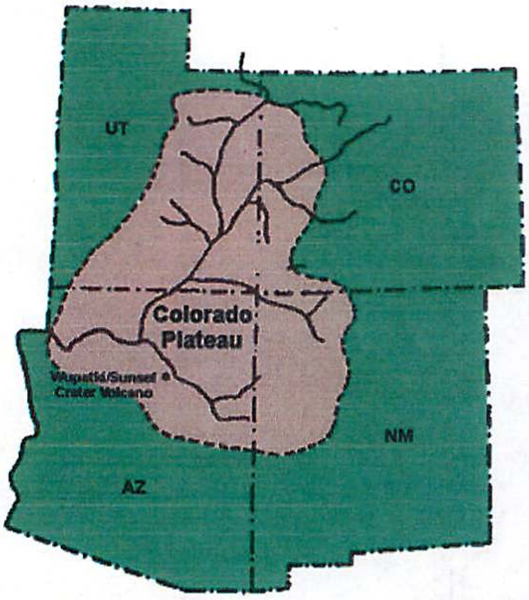

Fig 1. Map of the Colorado Plateau. U.S. NPS image.

Geology and Tectonics

One of the most remarkable features of the Colorado Plateau is its long-term stability as a single unit. Within the last 600 million years, relatively little faulting or folding has affected this crustal region, despite the severe deformation experienced by surrounding provinces. For example, the Rocky Mountains to the North and East were upthrust during a violent mountain building event, and extreme tensional forces created the Basin and Range Province to the West and South.

The relatively static nature of the Colorado Plateau crustal block combined with prolonged arid conditions make it possible to discern a coherent stratigraphic record back to nearly 2 billion years ago. A complex sequence of ocean encroachment, recession, and marine sediment deposition dominate the record until approximately 250 million years ago, when an influx of terrestrial deposits signal the upheavals associated with the formation of the supercontinent Pangea. A series of orogenies (mountain-building events) occurred, deforming western North America and causing dramatic uplift of the region. Volcanism was common during this time. The last great orogeny, the Laramide orogeny, began 70 to 80 Ma. This event closed the seaway and uplifted a large belt of crust from Montana to Mexico. The Colorado Plateau remained intact as the largest uplifted block in this belt. Thrust faults along the eastern portion of the plateau are thought to have formed as the result of a slight clockwise rotation of the rigid region. Compressional forces from the orogeny were unable to deform the Colorado Plateau Province. This could be due to its relative thickness. Some weaknesses did exist in Precambrian rocks through the bulk of the region. These helped relieve compressional tension through gentle flexures such as monoclines (Kiver, 1999).

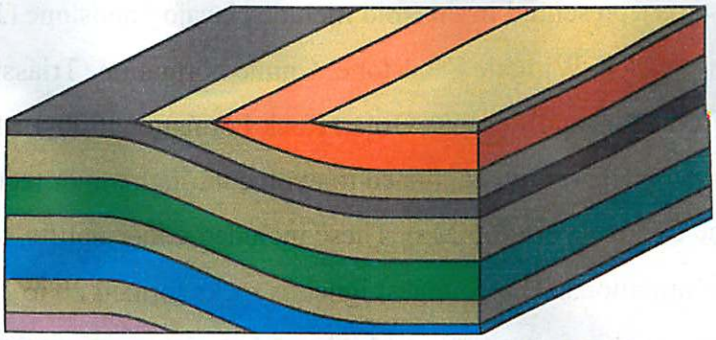

Fig. 2. Block diagram of a monocline. Image credit: Richard Harwood.

Monoclines of flexural origin appear as a bend or fold in otherwise horizontal stratigraphic layers (Figure 2). The Comb Ridge monocline extends North-South for nearly 130 km (80 mi) through southeast Utah and northeast Arizona (Figure 3). The

Fig. 3. Comb Ridge Monocline from the air. Image credit: Doc Searls

strata represented in this fold include Navajo Sandstone (Jurassic, 200-145 Ma), Kayenta Formation, Wingate Sandstone, Chinle Formation (Triassic, 250-200 Ma)), Triassic Moenkopi Formation, and Permian Organ Rock Formation (300-1 Ma) (Geosights, 2012).

The region continued to evolve through minor tectonic events through the beginning of the Cenozoic era (65 Ma). These included minor uplifts, some basaltic lava eruptions, and slight deformations. The youngest igneous rocks formed 20 to 30 Ma and are still visible as impressive topographic features. Some high-pressure igneous intrusions formed laccoliths, lens-shaped plutons which deform the overlying strata into a dome shape (Figure 4). Other intrusions formed diatremes, volcanic plugs of material formed by the gaseous explosion of magma making contact with a shallow body of ground water. Agaltha Peak is one such feature (Figure 5). Another eroded volcanic feature is the San Francisco Peaks near Flagstaff, AZ. These mountains include Humprey's Peak, the tallest peak in Arizona, and are the eroded remnants of a stratovolcano which formed around 6 Ma. The most recent volcanic feature on the Colorado Plateau is the Zuni-Bandera volcanic field which includes the El Malpais flow. This flow occurred only ≈ 3000 years ago.

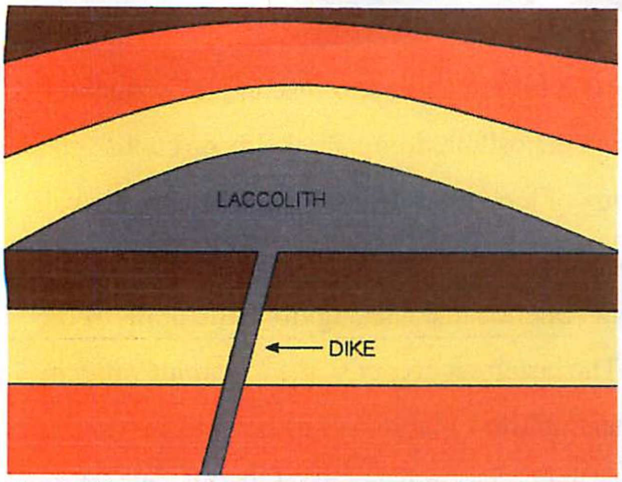

Fig. 4. Diagram of a Laccolith. Image credit: Erimus.

Another moderate uplifting event occurred during the mid-Cenozoic (≈ 30 Ma). This event caused the Colorado Plateau region to tilt due to uneven uplift. This tectonic activity lead to a dramatic increase in stream gradient, and thus an increase in the rate of downcutting. Monoclines formed due to uplift bending. During this time, the crustal stretching caused the Basin and Range to fracture, forming major faults which further separate it from the Colorado Plateau region. The Colorado Plateau eventually rose a kilometer higher than the Basin and Range.


Fig. 5. Agaltha Peak. USGS.

The steep gradient of the Colorado River, combined with the opening of the Gulf of California allowed the downcutting of Grand Canyon over a period of less than 6 million years (Kiver, 1999).

Planetary Connection

Monoclines have potentially been observed on Mars in High Resolution Stereo Camera (HSRC) images of Alba Patera. Alba Patera is a plateau formed by shield volcanism in the Noachian and Hesparian epochs. Linear North-South trending fault systems are observed in a concentric pattern in the northwest region of Alba Patera. Within these faults, monoclines have been documented, and are interpreted as evidence of crustal linkage with fault systems that originate at depth. Understanding this proposed subsurface linkage is important for understanding the evolution of fault systems on the Earth and Mars (McMillan, 2013).

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Upheaval Dome: Case of the Hidden Impact?*

Margaret Landis

What geophysical evidence uniquely determines an impact structure versus some other circular hole in the ground?

- Overturned flap around the rim
- Extensive fracturing around a breccia lens below the impact
- Mineral evidence: shocked mineral phases
- In some cases, gravity anomalies can confirm/refute the existence of an impact structure

Previous interpretations

Upheaval Dome has been postulated to be a salt dome (Harrison, 1927). There is a salt rich formation below most of Canyonlands National Park, called the Paradox formation. However, the salt horizon is well below the present surface and no evidence of salt or rocks associated with the Paradox formation have been found around the faults at the center of the formation (Kriens et al., 1999). While an alternative salt dome hypothesis contends that the faulting is due to karstic collapse of the salt dome (Jackson et al., 1998), a totally alternate interpretation of the data is that the geophysical evidence points towards an impact structure rather than a salt dome (Shoemaker and Herkenhoff, 1984). This would offer an explanation for the fracturing and the uplift at the center of the structure. In order confirm/refute this hypothesis, additional geophysical evidence needs to be examined.

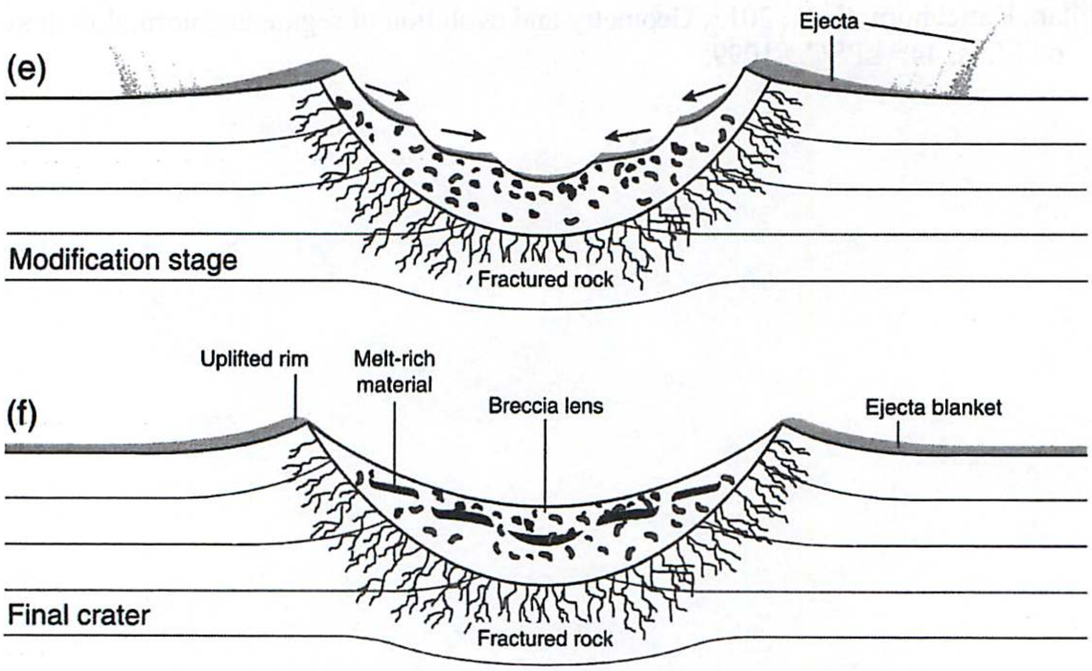


Figure 1: From French (1998), showing the final two stages of crater formation after the excavation stage. Material is modified deep below the structure that is apparent from the surface, including the generation of a breccia lens and extensive fracturing below the visible surface of the impact structure.

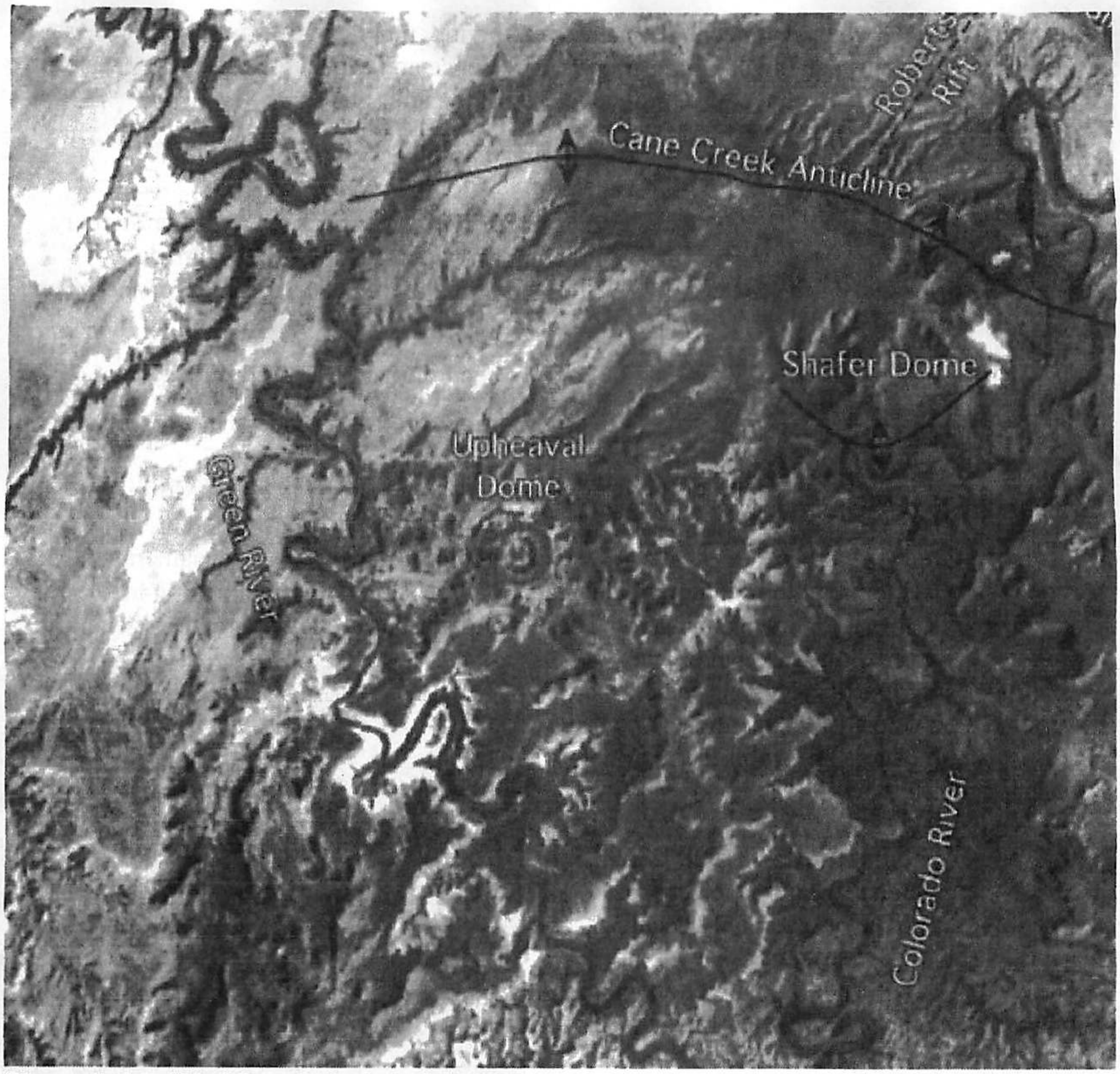


Figure 2: Modified from Kriens et al. (2009), this figure shows Upheaval Dome in a LandSat image with additional annotations. Canyonlands National Park is a complex geological setting, including fluvial erosion and tectonic activity to the southeast of the Upheaval Dome. According to the calculations of Shoemaker and Herkenhoff (1984), they expect an impact of this size in the area of Utah given the then estimated current terrestrial impact rate.

Impact formation and preservation

Highly compressed, fractured material forms the breccia lens and the central uplift of a crater, that originally below the surrounding surface (Figure 1). Are we seeing a breccia lens and central uplift that is all that remains of this crater?

Figure 2 shows context for where Upheaval Dome is located within Canyonlands National Park. There has been extensive faulting to the south east of the suspected impact structure.

On Earth, craters are subjected to intense weathering, making it difficult to see if a crater exists from even orbital data, making mineralogical evidence and exposures of shock cones more important lines of evidence that can be ground truthed at the site (Figure 3).

Figure 3: A LandSat image of the Sudbury impact structure in Ontario, Canada. Modification has obscured the rim and other classic geomorphic structures of an impact visible from orbit. Shatter cones and other impact related structures are obvious once examined on the ground. Image credit: NASA

Planetary connection: Modification of craters can cause a lot of different morphologies, including pedestal craters (Figure 4) and the mound at the center of Gale Crater that are sometimes challenging to determine unique formation mechanisms for. These modifications are less extreme in general on Mars due to lower erosion rates, but exotic morphologies still do exist. There is some debate too about karstic/volcanic versus impact formations about craters on Arabia Terra, Mars (Michalski and Bleacher, 2013).

Figure 4: HiRISE image ESP_037528_2350 shows a pedestal crater, where the ejecta has become armored so that erosion only occurs past the edges of the impact structure. The whole impact structure appears as a positive topographic feature rather than a negative one. Image credit: NASA/JPL/University of Arizona

So, how do determine what Upheaval Dome is?

A geological cross-section from Kriens et al. (1999) is shown in Figure 5 for reference.

The overturned flap, if present, is probably highly eroded. The evidence for this is difficult because the Wingate Sandstone strata do not have well preserved layering even far away from the impact while deeper layers, like the Chinle formation, do (Kriens et al., 1999). Therefore faults can be easily identified but overturned stratigraphy is less detectable.

Faulting and clastic dikes are present in the region (Okubo and Schultz, 2007; Kriens et al, 1999). Determining how much stress would need to fracture the rocks relies on sampling of the Wingate Sandstone layer present in the region, and the capped strength envelope for Wingate Sandstone and accompanying calculations indicate that for the level of fracturing observed in the sandstone to occur, 0.7-4.6GPa of mean stress had to have been applied to the rock (Okubo and Schultz, 2007). These stresses are relatively high for salt doming but a little low for an impact. Further study of the symmetry of fractures within the Upheaval Dome area suggests that the

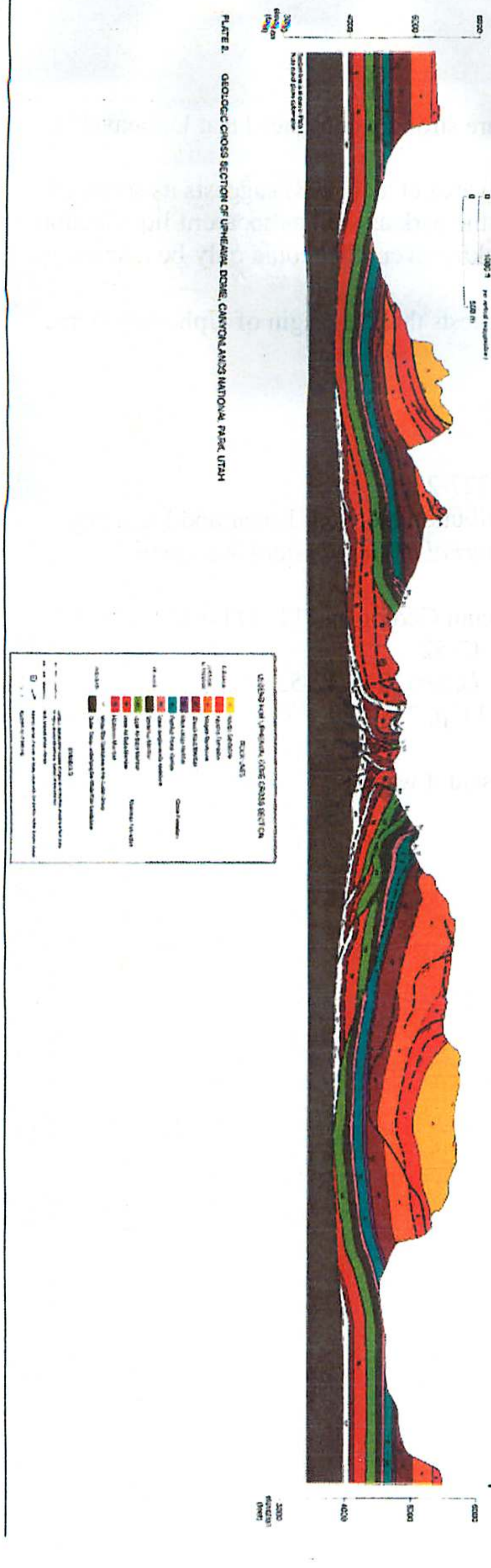
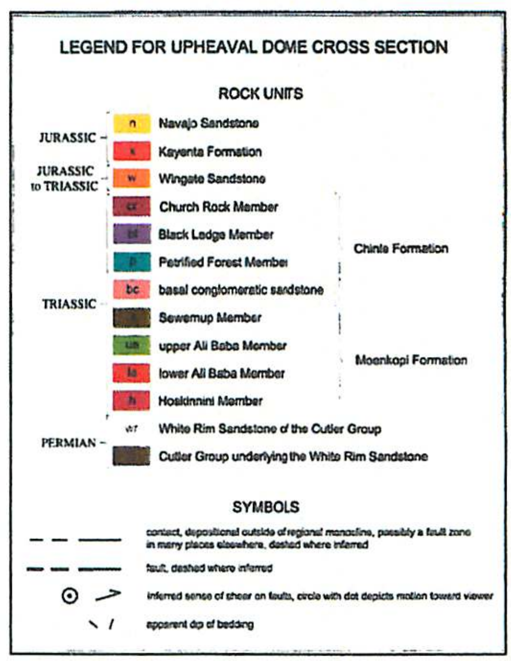


Figure 5: Cross section of Upheaval Dome from Kriens et al. (1999).

overall impact structure is asymmetric, most likely to be due to an oblique impact that would also explain the low mean stresses perpendicular to the surface (Scherler et al., 2006).

Finally, the smoking gun of impact structures are shatter cones and shocked quartz, which takes a high energy event that so far can only be impact in origin. Shatter cones have been rare in the area (Kriens et al., 1999; Buchner and Kenkmann, 2008). However, fracturing in quartz grains in the rocks are consistent with a few GPas of pressure being applied to the site. Buchner and Kenkmann (2008) used TEM analysis and found evidence of shocked quartz with a preferential $\{10\bar{1}3\}$ orientation and a suggested shock pressure of ~10GPa. The authors also discuss the possibility of an oblique impact generating stronger shear waves causing the discrepancy between the few GPa estimates of pressures from faulting versus the pressures necessary to form shocked quartz. Buchner and Kenkmann (2008) subtitle their paper "Impact origin



confirmed", so with the mineralogical evidence, they are strongly convinced that Upheaval Dome is an impact structure.

Impacts also affect the surrounding terrains. Alvarez et al. (1998) suggests as series of folded Carmel and Slickrock Entrada in other areas of the park as well as apparent liquefaction features and deformations are further evidence of a shaking event that could only be a large impact.

All of this evidence taken together strongly suggests that the origin of Upheaval Dome was impact rather than salt dome in origin.

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*Yes, probably and not just because Gene Shoemaker said it was.

Salt Diapir Theory of Upheaval Dome

By: Jon "The Bapst" Bapst

What is a diapir?

A diapir is a type of intrusion in which a more mobile and ductily-deformable material is forced into brittle overlying rocks. This process can occur in a variety of materials, including salt, ice, mud, and magma.

Salt diapirs

We focus on salt diapirs since that's relevant to this site. Salt diapirs can form when massive salt deposits are buried. In this case, the waxing and waning of the Western Interior Seaway led to large evaporite deposits, concentrated during the Mesozoic. Salt has a higher density than typical sedimentary rock at the surface but behaves differently when buried and compressed; salt does not densify as easily as rock. When buried, these massive salt deposits will begin to plastically deform under stress and, due to positive buoyancy, can intrude overlying rock (diapirism).

Upheaval Dome on salt theory

The dome is one of the most enigmatic and controversial geologic structures in North America. Hypotheses for its origin include cryptovolcanic explosion, meteoritic impact, fluid escape, and subsurface salt diapirism.

The most recent, and arguably the strongest case for salt diapirism, is found in Jackson, *et al.* (1998). This work supports the pinched-off salt diapir scenario (Fig 1). The sequence of events is summarized here:

- A relatively shallow, steady-state (passive) diapir exists originally
- As the overburden thickens the diapir "mushrooms" over the existing surface and forms salt glaciers
    - Salt can also intrude between sedimentary units which is used to explain features at Upheaval Dome, dubbed "dog tongues"
- Erosion of the surface and diapiric pinch-off[1] occur
- Intruding salt (albeit without an intact stem) rises upward causing central uplift

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[1] *"However, the mechanism for diapiric pinch-off is unknown. Pinch-off is the core of our hypothesis for Upheaval Dome, yet we are unsure how it occurs." -Jackson et al., 1998*

Fig 1: Schematic reconstruction of the salt-tectonic evolution of Upheaval Dome

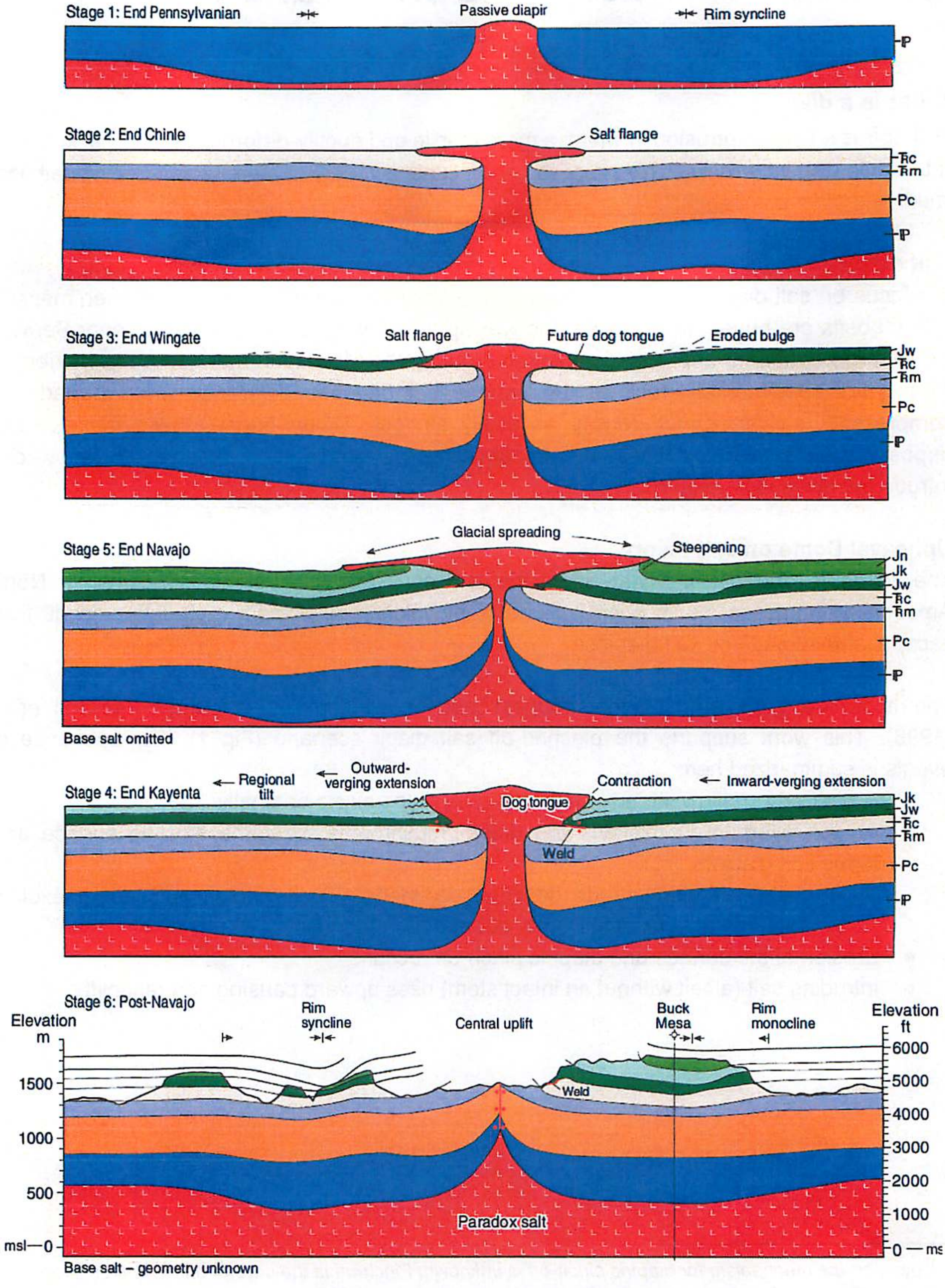


TABLE 1. EVIDENCE FOR PINCH-OFF AND IMPACT HYPOTHESES

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

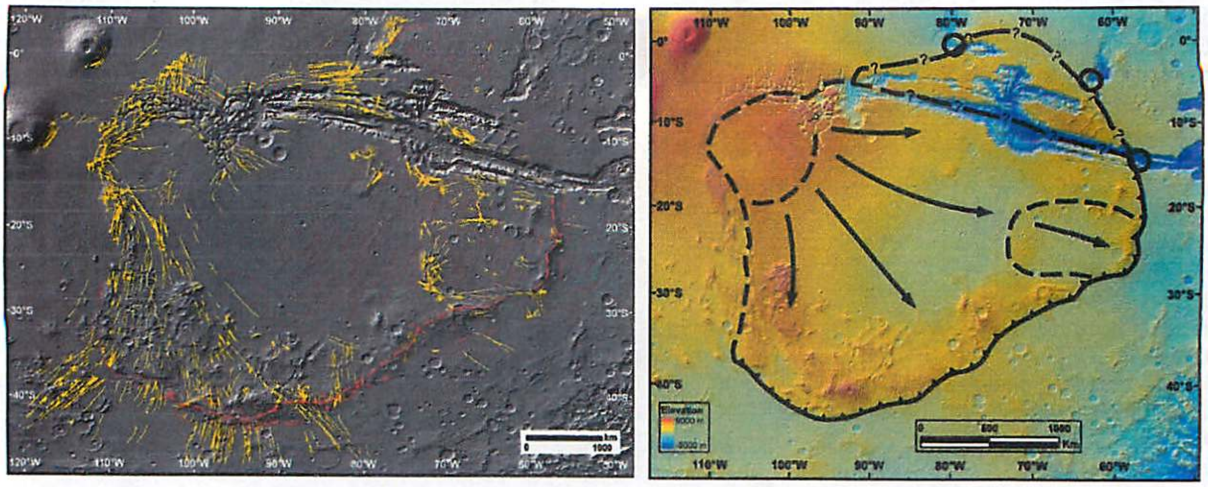
Evidence

Table 1 summarizes evidence for the salt diapir versus the impact scenarios. Evidence that is incompatible with the impact hypothesis are founded mainly from structural geology arguments. This table shows that both hypotheses share incompatible pieces of evidence with each other.

Planetary Connection

Beyond Earth, diapirism has been suggested to occur/have occured on other planetary bodies including Mars, Europa, Enceladus, and Miranda. We will focus on Mars as it is has been suggested to host massive salt deposits, which are necessary on Earth for salt diapirism.

Montgomery *et al.* (2009) postulate that large deposits of salt on Mars (notably Tharsis/Valles Marineris region) allow for large scale deformation. Essentially, geothermal heating and topographic loading of extensive buried deposits of salts and/ or mixtures of salts, ice, and basaltic debris would allow for weak detachments and large-scale gravity spreading. Such activity could be driven by intrusion of salt via diapirism. Although controversial, multiple lines of evidence support abundant evaporites on Mars. Under the proper conditions, large salt deposits could flow at present day.



From Montgomery *et al.*, 2009

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Moqui Marbles/Iron Concretions in Navajo Sandstone

Navajo Sandstone: a Reducing and Oxidizing History

Figure 1: Navajo Sandstone in Zion Canyon showing white and red colors. Credit: author.

Navajo Sandstone has experienced a variety of alteration and weathering processes over the 190 million years since it formed. The sandstone appears red in some areas, and white in others (Fig. 1).

The red colors are due to hematite, as well as other iron minerals and ores; this iron initially coated the precursor sand to the Navajo Sandstone formation. Before the sand turned into sandstone, the sand was saturated with a mixture of reducing water and hydrocarbons, dissolving the iron coatings and bleaching the sandstone white. At some point the reducing fluids mixed with oxidizing groundwater, which caused the iron to precipitate and form concretions that we see today, ranging in size from "marbles" to much larger (Fig. 3).

Moqui Marbles

These iron concretions are known as "Moqui marbles", after the Hopi word for a departed tribe in the region. They contain sandstone surrounded by an iron mineral shell, often hematite, are found throughout southern Utah in Navajo Sandstone formations, and range in size from 1 mm to 20 cm, or larger accumulations, having grown layer by layer. Marbles range in age from 2-25 million years old (Reiners et al. 2014). Moqui marbles provide a record of water movements in rocks from million years ago.

Figure 2: A large iron concretion ~0.6 m in size in Zion Canyon. Credit: author.

Figure 3: Moqui marbles accumulated in a low spot in Utah. Credit: Marjorie Chan, University of Utah.

Analogue to Blueberries on Mars?

The Opportunity rover on Mars photographed spherical concretions, often called "blueberries", which were instantly recognized to be similar to Moqui marbles (Chan et al. 2004). The coatings of these concretions show hematite (Squyres and Knoll 2005). The presence of blueberries on Mars does not require flowing water for their formation; however, the nearby rocks in Meridiani Planum show evidence of cross-stratification, sulfate minerals, indicating eolian and aqueous transport of material (Squyres 2004) and hematite generally forms in the presence of water. Did these Martian blueberries form in an ancient hydrothermal environment? Recent results (Misra et al. 2014) suggest that these "concretions" are the result of meteorite impact on Mars and not hydrothermal in origin.

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LPL Field-trip
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Native People of Utah and Petroglyph

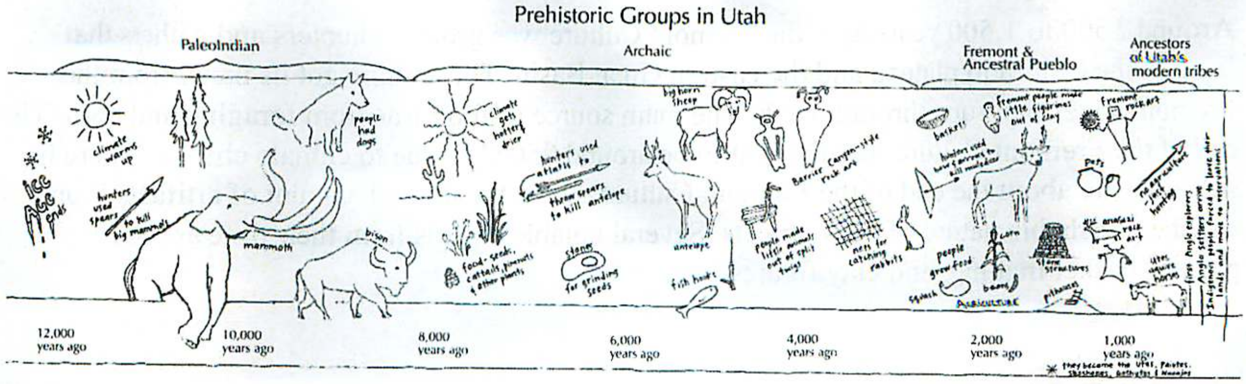
Petroglyphs and Newspaper Rock

Petroglyphs are images made by removing the surface layer of a rock by abrading, incising, and pecking to form images. Petroglyph should be not confused with pictography which is a painted or drawn image onto a rock. Australia has a petroglyph site that has been dated back over 27,000 years with other sites globally dating back even further. The exact reason for petroglyphs have been thought to range from maps, astronomical markers, forms of communication, landforms, stories, and many other meanings.

A famous petroglyph site found in southeastern Utah is Newspaper Rock. It is located in Indian Creek State Park. This site is known to be one of the largest collections of petroglyphs in the southwest! The oldest section of the petroglyph dates back to approximately 2000 years and is from the Anasazi Culture. The most recent art is from the Ute people. The Ute people still inhibit the Four Corners area as of today. The older artwork is darker and the newer artwork is lighter because of the less varnish it has accumulated. There are over 650 designs in the Newspaper Rock which contain humans, animals, and symbols. An image of Newspaper Rock can be seen below.

Newspaper Rock

Native People of Utah



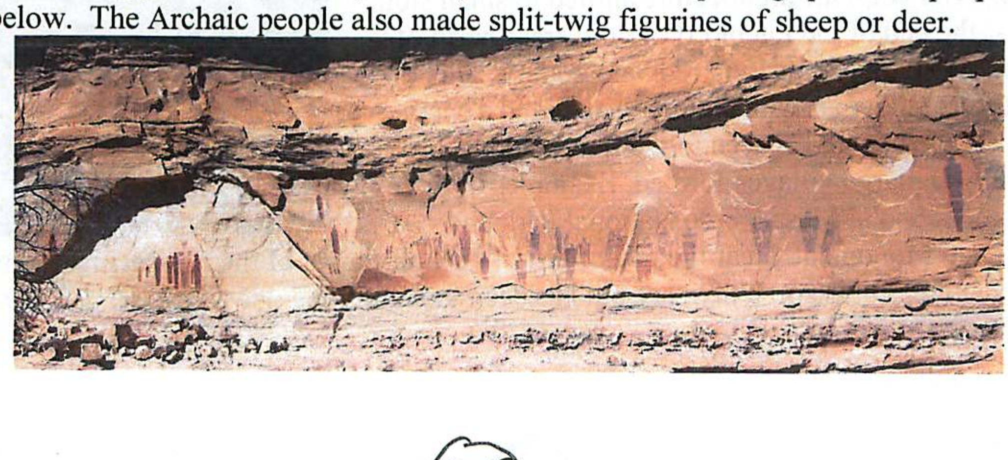
Overview of Prehistoric Groups in Utah

PaleoIndain Culture

The first group of people to inhabit Utah were the PaleoIndians, with paleo meaning early. This ancient culture lasted from 12,000 years ago to 6,500 B.C. The climate was considerably cooler and wetter than the current climate of today. Their main source of shelter was made from wood or from the use of caves. The PaleoIndians tended to live near marshes and shorelines. The earliest remains of the PaleoIndians were found in Wendover, Utah and date back over 11,000 years ago. The remains were found in a cave called Danger Cave, which is famous for its many archeological findings. The main source of food was from hunting and gathering. Near the end of the PaleoIndain culture, the climate begins to warm and the water sources receded.

Archaic Culture

Around 6500 B.C,. the climate became much warmer and drier, much like it is today. It is unclear if a new culture either moved in or just changed. This new culture is called the Archaic Culture. Some of the more notable features of the Archaic culture were their pithouses and hunters began using the bow and arrow. Some signs of their existence can be seen in Canyonlands National park with their distinctive rock art called Barrier Canyon Style pictographs. This type of art form is primarily found in Utah depicting spirit-like people and can be seen below. The Archaic people also made split-twig figurines of sheep or deer.



Fremont Culture

Around 2,500 to 1,500 years ago, the Fremont Culture was group of hunters and gathers that lived in the Colorado plateau and the eastern Great Basin. This culture got its name from the Fremont River that runs through Utah. The main source of food was from foraging and corn. The end of the Fremont Culture was thought to be around 950 C.E. due to climate change. There is still a debate about the end of the Fremont Culture due to the limited amount of artifacts found and the perishable nature of their objects. Several notable objects from their time are gray pottery, basket making, and clay figures.

Anasazi Culture

The word Anasazi means ancient ones and is thought to be ancestors of the Pueblo Indians which inhibited the Four Corners area. An overview of the time periods of the Anaszi people can be seen below:

Basketmaker I: pre-1000 B.C.
Basketmaker II: c. 1000 B.C. to A.D. 450
Basketmaker III: c. A.D. 450 to 750

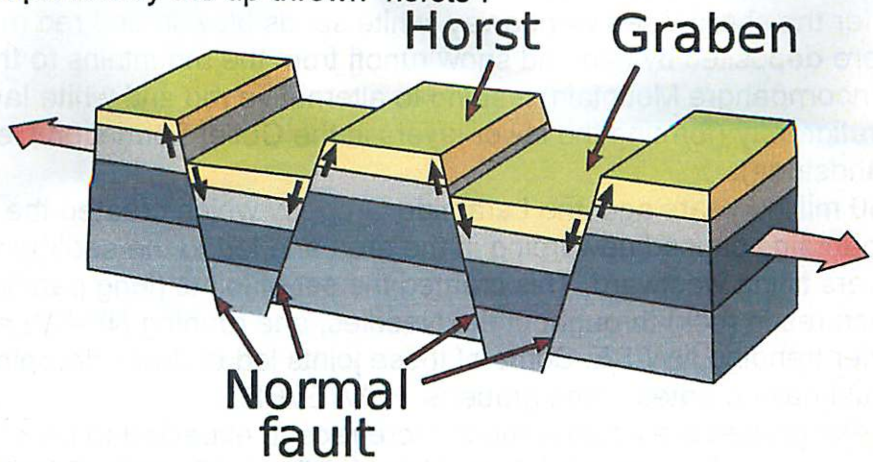
Pueblo I: c. A.D. 750 to 900
Pueblo II: c. A.D. 900 to 1150
Pueblo III: c. A.D. 1150 to 1300

The Anasazi culture can be broken up into two categories the eastern Anasazi, which made up south eastern Utah, and the southwestern Colorado/ Northwestern New Mexico. The culture was known for their proficiency at making baskets and sandals. Food was either hunted and gathered or farmed, but excess food was stored in pits. Another notable addition to the diet of the Anasazi culture was the bean. By 500 AD, The Anasazi culture settled in farming villages with settlements scattering over canyons and mesas. By 700 A.D., village organization formed. The most notable finding from this time was a structure found near BYU that had over a 40 foot diameter. From 900 to 1150 A.D. the architecture shifted to small stone houses. Near the end of the Pueblo II period, areas north of the San Juan river stopped making redware pottery. The reason for this is unknown. The pottery changed to a Mesa Verde Black-on-White and is seen to the right. During 1100 A.D to 1200 A.D., large villages formed. Examples of these villages can be found at Mesa Verde National Park and Navajo National Monument. Near the end of the 13th century most of the Anasazi had moved south. The main reason is still a mystery but has been thought to be due to the harsh climate and shorted growing season.

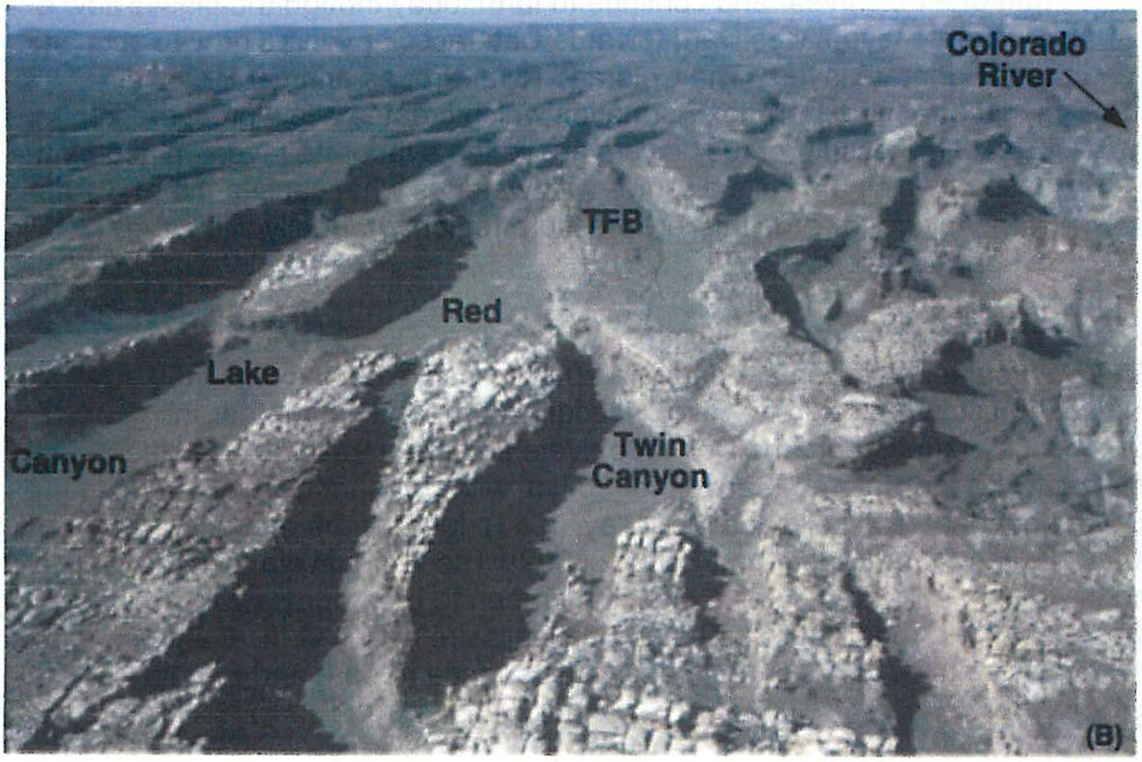
Tectonics of Canyonlands Graben
Ali Bramson

What is a graben?

A block of rock that is down-dropped by parallel extensional faulting. Graben are often accompanied by the up-thrown "horsts".



Fun Fact: Graben is the German word for ditch or grave.



View of the Canyonlands graben from the North looking along Twin Canyon (Trudgill 2002). The segmented nature of the fault structure that parallels the graben can be easily seen by the shadows of the west-facing fault scarps. Flat graben floors have been infilled with Quaternary deposits. Bedrock horsts are cut by joints.

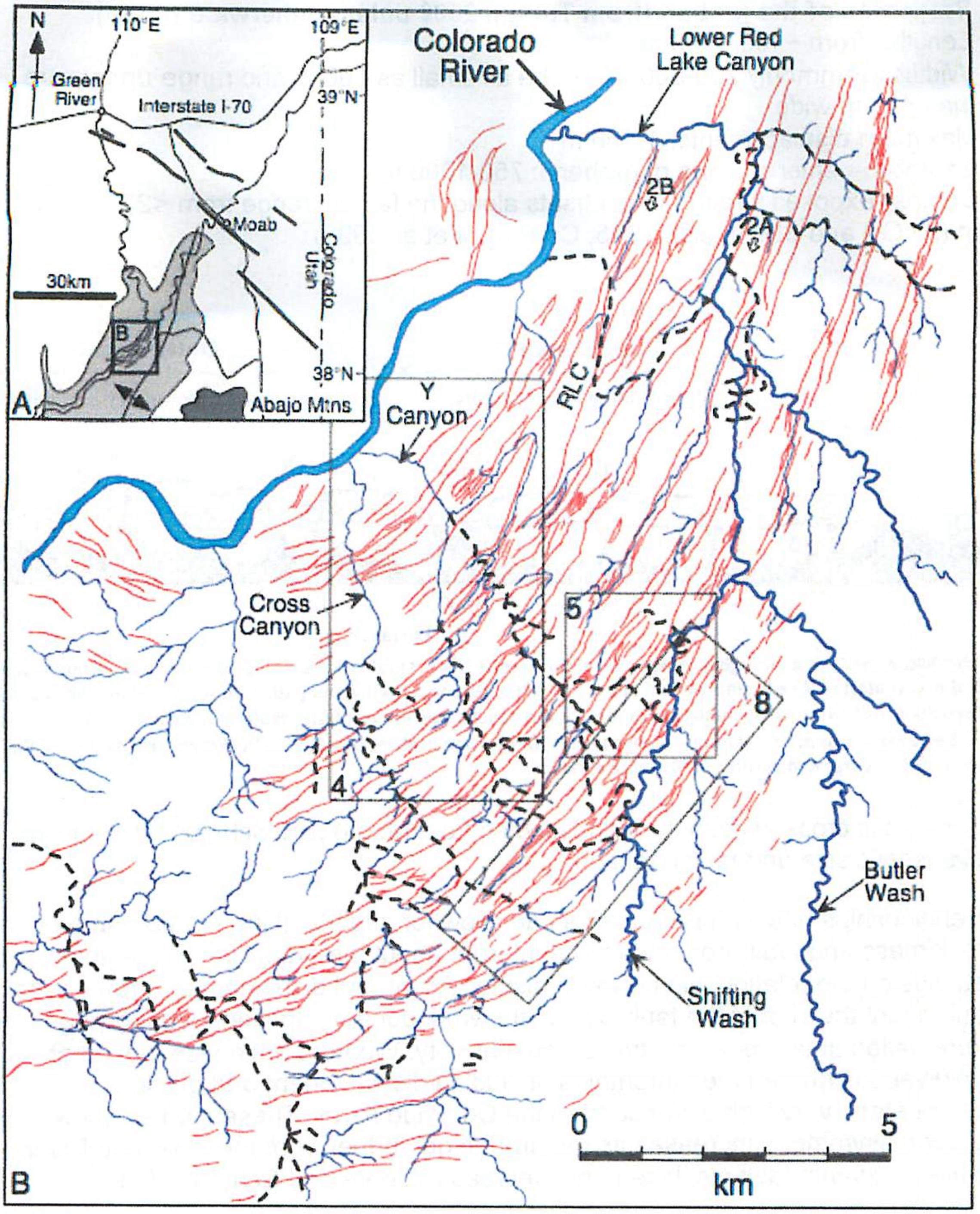
What causes the graben in Canyonlands?

From the National Park Service, 2015:

1. Layers of evaporates in the stratigraphy are deposited ~300 million years ago when the area was a shallow inland sea. These salt deposits are known as the Paradox member of the Hermosa Formation and can be 3000-5000 ft thick in parts of the Needles District.
2. After the shallow sea went away, white sands blew in and red mud and silt were deposited by rain and snow runoff from the mountains to the east (Uncompahgre Mountain) leading to alternative red and white layers in the stratigraphy (forming the lower layers in the Cutler Formation/Cedar Mesa Sandstone).
3. ~60 million years ago, the Laramide Orogeny which created the Rocky Mountains caused upwarping in the area and led to the sedimentary layers tilting westward. This created the set of joints (long parallel fractures in rock) throughout the Needles, one running NE-SW and the other trending NW-SE. Some of these joints led to down-dropping which could have created some grabens. HOWEVER…
4. These graben are actually much more recent, expected to be <100,000 years, according to ages inferred from infilling sediments (Biggar and Adams, 1987; Schultz and Moore, 1996). The grabens have formed at a rate of ~1 inch/year and continue to form today though the plastic flow of evaporate layers westward towards Cataract Canyon as gravity acts on the evaporate layers. The Colorado River erodes and carries away sediment to the Paradox Formation which creates a low pressure zone. The high pressure of rock layers above the evaporate layers, aided by the ease of which the salts dissolve with water, is what causes the movement of the layers towards this low pressure region, gradually tilting the evaporate layers.

Where are the graben?

The Canyonlands graben are part of a 200 km^2 active extensional fault array to the southeast if the Colorado River (Trudgill 2002). They start near the confluence of the Green and Colorado rivers and run parallel (and a little westward) to the Cataract Canyon for 25 km, with Gypsum Canyon marking the South boundary (Nuckolls and McCulley, 1987). Most of the grabens are east of the Colorado River (Moore and Schultz 1999). The regional dip towards the northwest is ~2-4°. Age dates expect the graben to be progressively younger to the southeast (Trudgill 2002). The graben walls are nearly vertical at the surface but decrease to ~75-85° at depth below the surface (Moore and Schultz 1999).



Map from Trudgill 2002. A: Location of Canyonlands graben fault array with towns, highways and fault trends. Light grey regions show where Carboniferous and Permian rocks are exposed by the Monumental uplift, with dark grey indicating the Tertiary Abajo Mountains. B: Present-day geometry of the faults (red). Current stream drainages are in blue and black dashed lines are interpreted to be paleodrainage patterns.

Properties of the graben (from Tudgill 2002 unless otherwise noted):
Lengths: from ~100-6500 m
Widths: Commonly 200-300 m can be as small as 100 m and range up to more than 400 m wide
Maximum *displacements*: 1-150 m
Center-to-center spacing of grabens: 750-1000 m
Depths (exposed stratigraphic offsets along the faults): range from <25 m - >100 m (McGill and Stromquist, 1975; Cartwright et al. 1995)

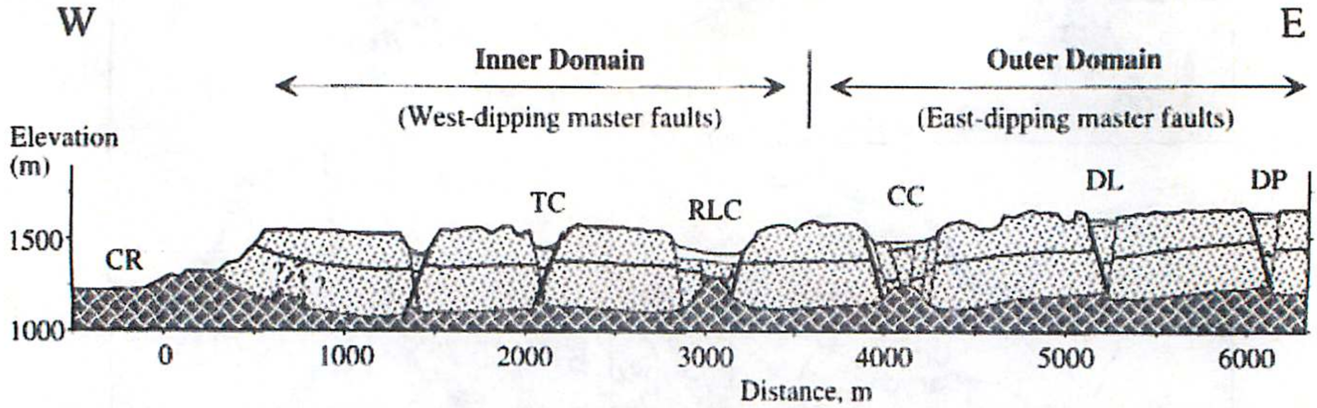
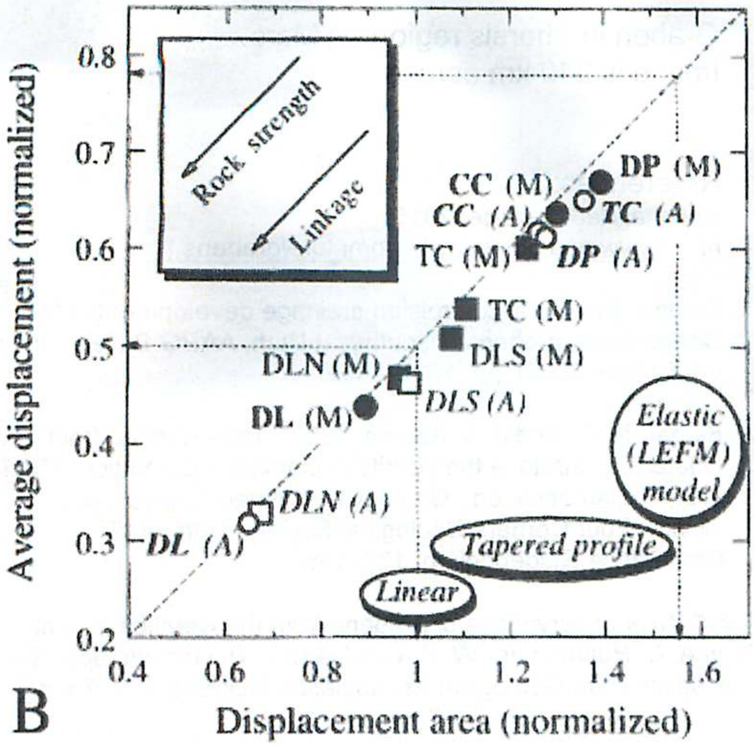


Figure 13. Schematic cross section through northern part of the Needles District graben system (Fig. 3). Reference line midway down in faulted section is approximate contact of Rico Formation and upper part of the Hermosa Formation; patterned region below is the Paradox Member of the Hermosa Formation. Note west-facing master faults in the inner domain, east-facing master faults in the outer domain. TC—southeast Twin Canyon; RLC—Red Lake Canyon; CC—Cyclone Canyon; DL—Devils Lane graben; DP—Devils Pocket graben; White—sedimentary graben fills; CR—Colorado River gorge and position of Meander anticline.

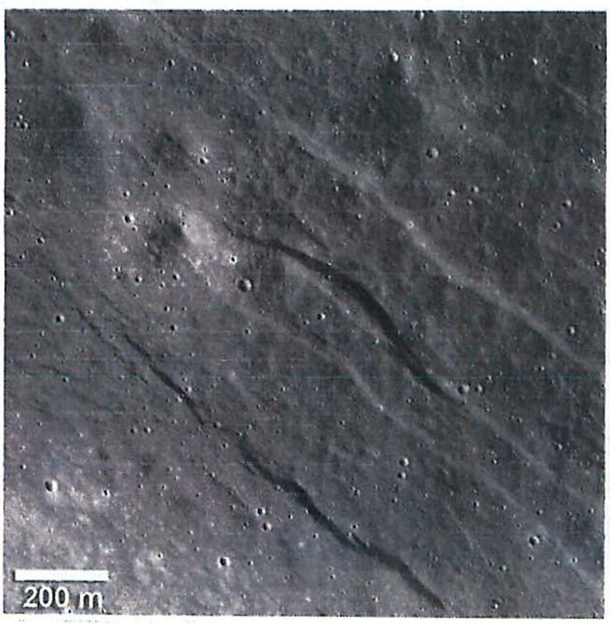
Schematic cross section through Needles from Moore and Schultz 1999 shows systematic size and fault direction.

Relationships between parameters can allow for additional information about rock mass and fault properties to be inferred about the graben. For example, studies on the relationship between displacement and displacement area can tell one about the size of the fault slip vs. the work done by applied loads, giving information about regional strains and elasticity. Workers have also looked at how various graben measurements, including displacement and graben assymetery, vary with distance from the Colorado River. These studies show graben asymmetry increases as the graben get further from the Colorado River, while maximum fault displacements decrease (Moore and Schultz, 1999).



Plot from Moore and Schultz 1999 showing fault-displacement parameters scaling between average displacement and displacement area. The relationship suggests various degrees of implied inelasticity. DL = Devils Lane graben, CC=cyclone canyon, DP=Devils Pocket, TC=Twin Canyon and N=north, south.

Graben in the Solar System:



500 m wide graben on the moon detected by LRO. Stereo images suggest graben is 20 m deep

Graben in Tharsis region on Mars.
Image is 240 km across

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HiRISE image of Martian graben

Flora and Fauna of the Canyonlands!

Sky Beard

The Canyonlands area, like many deserts, can often give a false sense of being lifeless. This rough landscape can hide animals well, but you just have to look carefully and you will see a rich ecosystem of plants and animals. This environment is rather harsh for most mamals, though several still make this their home. The most frequent animals seen include rodents, birds, and lizards, but there is much more here than it may at first seem!

Desert life adaptations come in a variety of forms including large ears for cooling blood, burrowing for protection from the heat, natural ability to survive on little water and a varied diet, and nocturnal (active at night) and crepuscular (active at dawn and dusk) behaviors. One of the best examples of desert adaptation is the kangaroo rats' ability to survive only on dry plant food, never needing to drink water in their life!

- Common Canyonland Nocturnal Animals: Kangaroo rats, packrats, other rodents, skunks, ringtail-cats, bats, owls, jackrabbits, coyotes, bobcats, and mountain lions.
- Common Crepuscular Animals: mule deer, coyotes, porcupines, cottontails, and songbirds.
- Common Diurnal Animals: rock squirrels, antelope squirrels, chipmunks, lizards, snakes, hawks, ravens, eagles, and vultures.

Midget-Fadded Rattlesnake:

The **midget-faded rattlesnake** is a small subspecies of the western rattlesnake and has very toxic venome. It lives in small burrows and rock crevices (watch your step and hand placement!) and are mostly active at night. Only one third of this snake's bites actually inject venom, which is actually more potent than the asian cobra's. All snakes (mostly harmless) in the Canyonlands will escape from human confrontation, so if you encounter one, just stay calm, back away slowly. They grow to a maximum of ~30 inches (75cm) and have a color pattern of pink, pale brown, to redish in color with brown elliptical to rectangular patches along the back.

Bighorn Sheep:

www.wilderness.org

One of the largest animals in the Canyonlands, and though not often seen, **bighorn sheep** are most often found grazing and roaming the talus slopes and side canyons of rivers. These large mamals have the uncanny ability to manuever steep and rocky terrain with great ease. The Canyonland herds are especially important, as they are fueling the species comeback from danger of extinction. In the 1600s, it was estimated that there were roughly 2 million bighorn sheep in the west, by 1975, there were estimated to be 1000, with only 100 living in the Canyonlands. Starting in the 1980's, bighorn sheep were captured in nets fired from helicopters and relocated to historical locations. Today it is estimated that there are around 350 bighorn sheep in the Canyonlands.

Characteristics: Both sexes grow horns that continue to grow through their life (10-20 years), with males ranging from 115-150 pounds, with very large specimens up to 250lbs. They have unique concave hooves that allow them to climb steep and rocky terrian. Predators include mountain lions, coyotes, and bobcats. An adult ram may have horns that weigh more than 30 lbs. Typical diet is mainly grass, followed by cacti (which they can use their horns to break open).

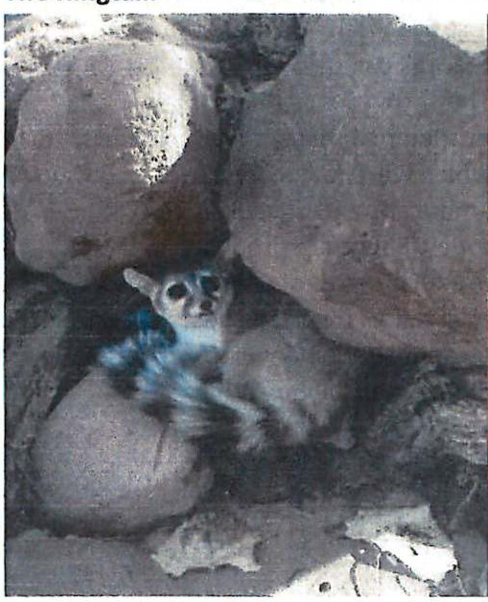
Mountain Lion:

The **mountain lion** is a top level predator and largest wild cat in North America. Males weigh an average of 130-150 pounds and females average 65-90 pounds. They are a tan to grayish color and have dark brown on the end of their tail, ears and on the sides of their nose.

http://www.allposters.com

Mountain lions are rarely seen and are only in parts of the Canyonlands that support mule deer and bighorn sheep populations; preferring to live in mountains and forests. This top predator is a true carnivore, and only feeds on other animals. They prefer mule deer and will feed on bighorn sheep, coyote, fox, rabbit, rodents, birds, porcupines, skunks, and other animals. Hunting is done at night, while traveling is done in the day, though you will most likely never see one even if they pass by you. They locate and stalk prey by sent, and kill large prey by getting within a few meters and leaping onto it and biting at the base of the skull. Large hawks and eagles can kill their young and they are in competition with bobcats and coyotes. Spread of human development has fragmented their habitat and restricts their movements.

The Ringtail:



The **ringtail**, or ringtail-cat, is an interesting animal that inhabits the Canyonlands. It looks very similar to a lemur, is a relative of the racoon, and grows 12-17 inches in length, with a tail that also ranges from 12-17 inches. It weighs between 1.5-3 lbs and usually makes dens inbetween rocks or on cliff ledges. Its ankle bones are able to move *180* degrees, making this animal a very agile climber. It is omnivours and eats insects, fruits, mice, rabbits, snakes, and more.

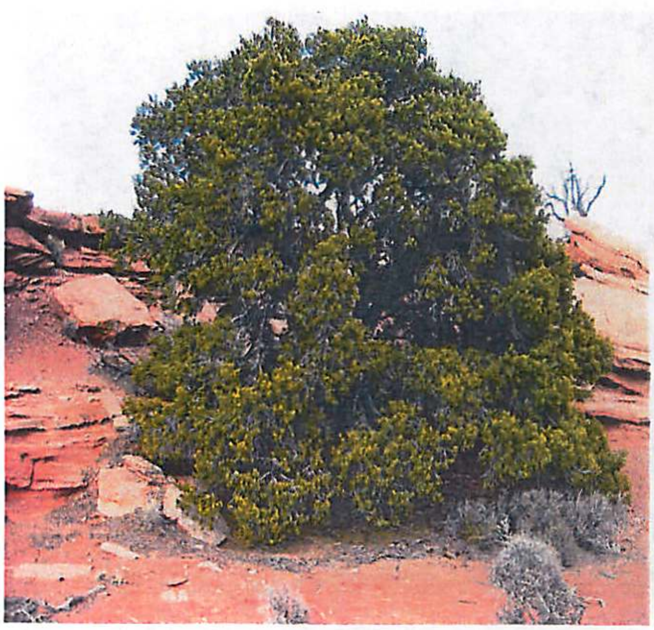
PLANTS

Mormon Tea:

Mormon tea looks like a thick bunch of green jointed stems, growing up to 4 feet tall with no apparent leaves or petals. It has been used for centuries for medicinal uses by boiling the stems and drinking the remaining water. This can be used to help treat menstral cramps, head aches, colds, kidney problems, and STD's (syphilis and gonorrhea) among others. Its a great decongestant and contains a drug similar to ephedrine.

www.kceat.org

Pinyon Pine:

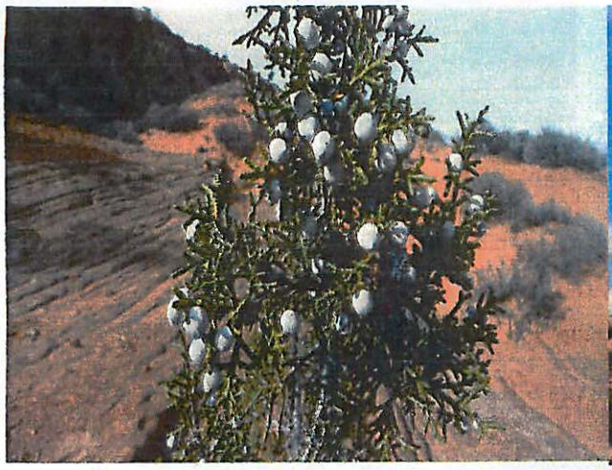


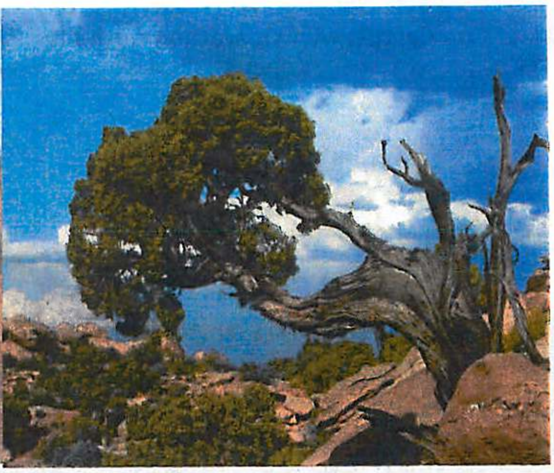
Pinyon pines are a slow growing tree with redish brown bark. Trees just 6 inches in diameter and 10 feet tall can be over 100 years old. They grow cones that contain protien rich seeds, called pinenuts, which were fed on by native americans and are still harvested today. Seeds are produced in irregular cycles of 3-7 years to try to avoid all the seeds being eaten by animals who develop a habit of eating seeds annually

Closer look at Pinyon pine cones and needles.

http://www.nps.gov/cany/learn/nature.htm

Utah Juniper:





Juniper is an important source of food and shelter for deer, wild horses, ground birds, and many other animals. At maturity, the juniper reaches 3-15 feet tall, and can occasionally reach 40 feet in height. It produces berries that are a blue in color and contain two seeds, which are dispersed by birds and other mammals. They commonly have twisted and dead branches, as the juniper can slow or stop the flow of water to the outer branches ensuring the survival of the tree during droughts. To further help conserve moisture, their leaves have scaly structures and their seeds are have a wax-like coating, designed to trap moisture inside.

Biological Soil Crust: Algea, lichens, and bacteria form mats that trap moisture and provide secure foundation for desert plans; please avoid stepping on these areas, they take a very long time to form.

www.fs.fed.us

Claret Cup Cactus: www.marathonmoth.me

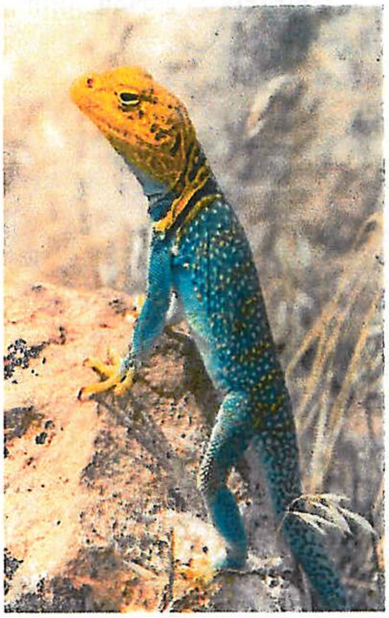
Jackrabbit
http://jimruff.zenfolio.com/p452738032/h7747077#h7747077

Coyote
www.chucksweb.net

Bobcat:
www.animalsofutah.com

Mule Deer:
www.usapictures.com

Tadpole Shrimp, nps.org



Collared Lizard, wildaboututah.org

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JOINTING IN ROCK

THADDEUS D. KOMACEK

1. OVERVIEW

First, what is a joint? Quick definition:

A **joint** is a break of natural origin in the continuity of either a layer or body of rock that lacks any visible or measurable movement parallel to the surface of that fracture.

What do joints look like? Figure 1 shows jointing here in Canyonlands.

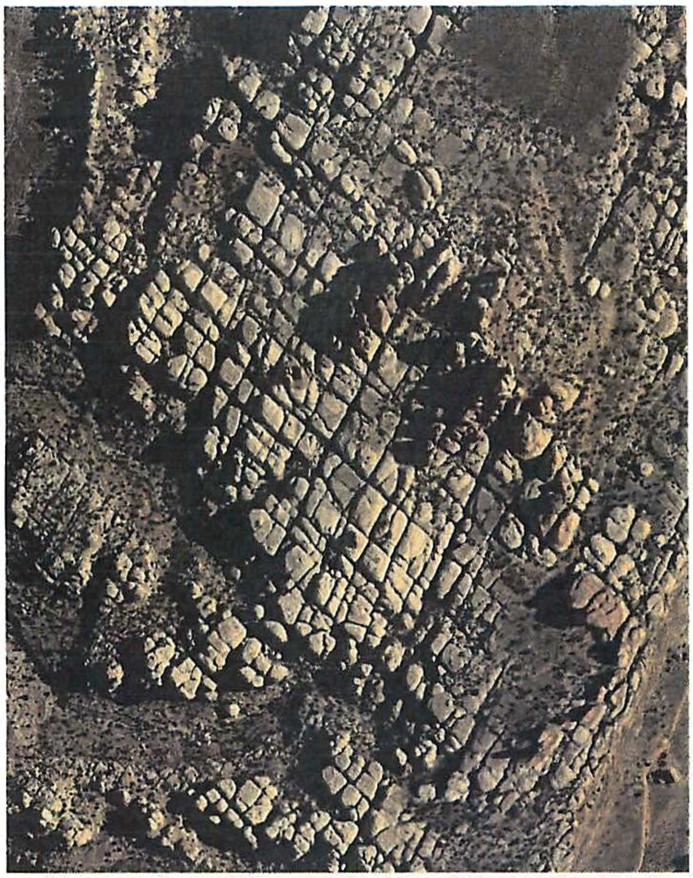

FIG. 1.— Joints in Permian eolian sandstone, Canyonlands National Park. From Fossen (2014).

How do joints form? The common view of columnar jointing is through cooling of igenous rock, but that's probably not the case here. Instead, pressure release is forming these joints, likely due to aqueous processes. This is why sandstone in Canyonlands has jointing, but not siltstone.

Joint spacing increases with layer thickness (see Figure 2). This also supports some form of pressure-release mechanism to form joints in sandstones.

2. CANYONLANDS

What is interesting about the jointing in Canyonlands? They are coincident with graben (Martel 1990; McGill & Stromquist 1979; Moore & Schultz 1999) (see Figure 3).

Figures 4 and 5 show the graben system in Canyonlands, with Figure 3 an image and Figure 4 a schematic.

How do joints affect graben? If faults nucleate on pre-existing joints, faults will increase in length by mechanical interaction and the linkage of slipped joints (Martel 1990). This enhances the graben system seen in Figure 4. Additionally, joints can topple (Figure 6), but this is probably not a large effect on slab rotation in Canyonlands (it's just neat).

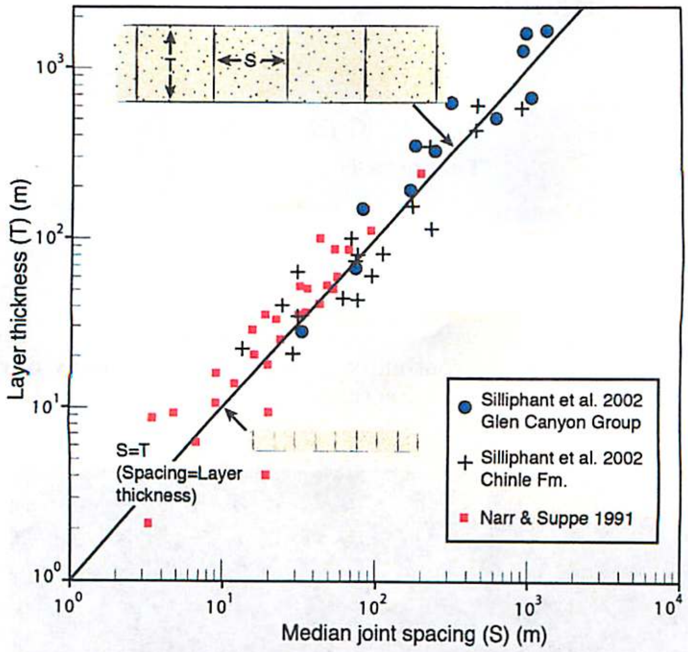

FIG. 2.— Relationship between layer thickness and joint spacing. From Fossen (2014).

FIG. 3.— Cyclone canyon graben, looking south. From McGill & Stromquist (1979).

52

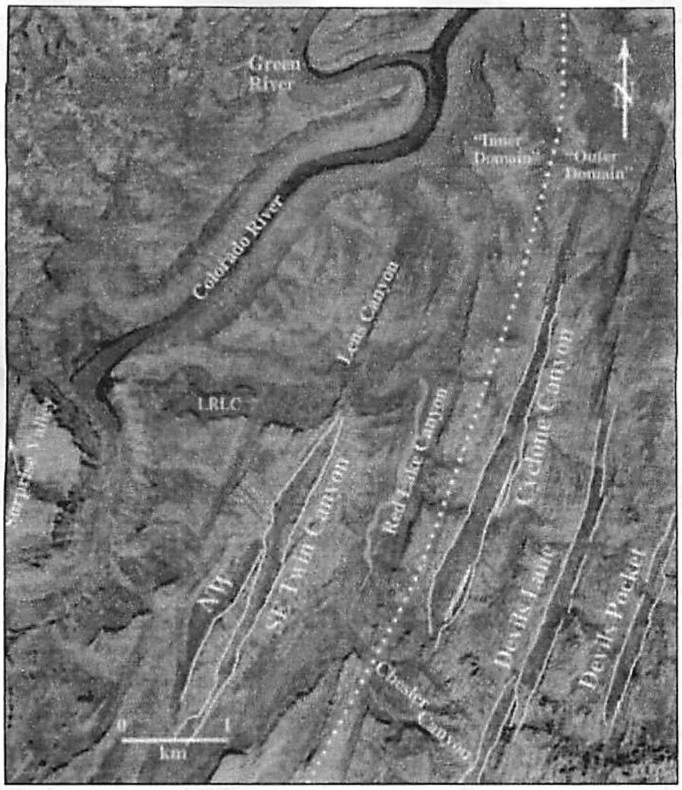

FIG. 4.— Image of Needles District graben system, from Moore & Schultz (1999).

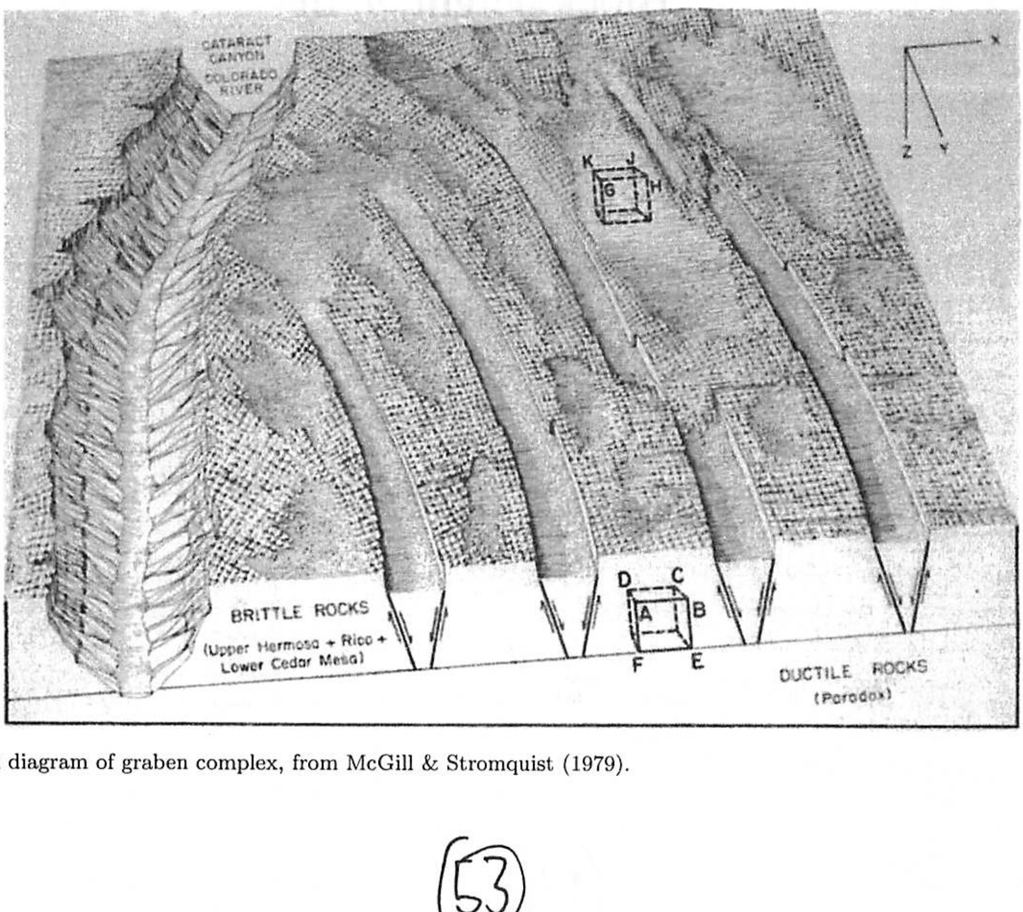

FIG. 5.— Block diagram of graben complex, from McGill & Stromquist (1979).

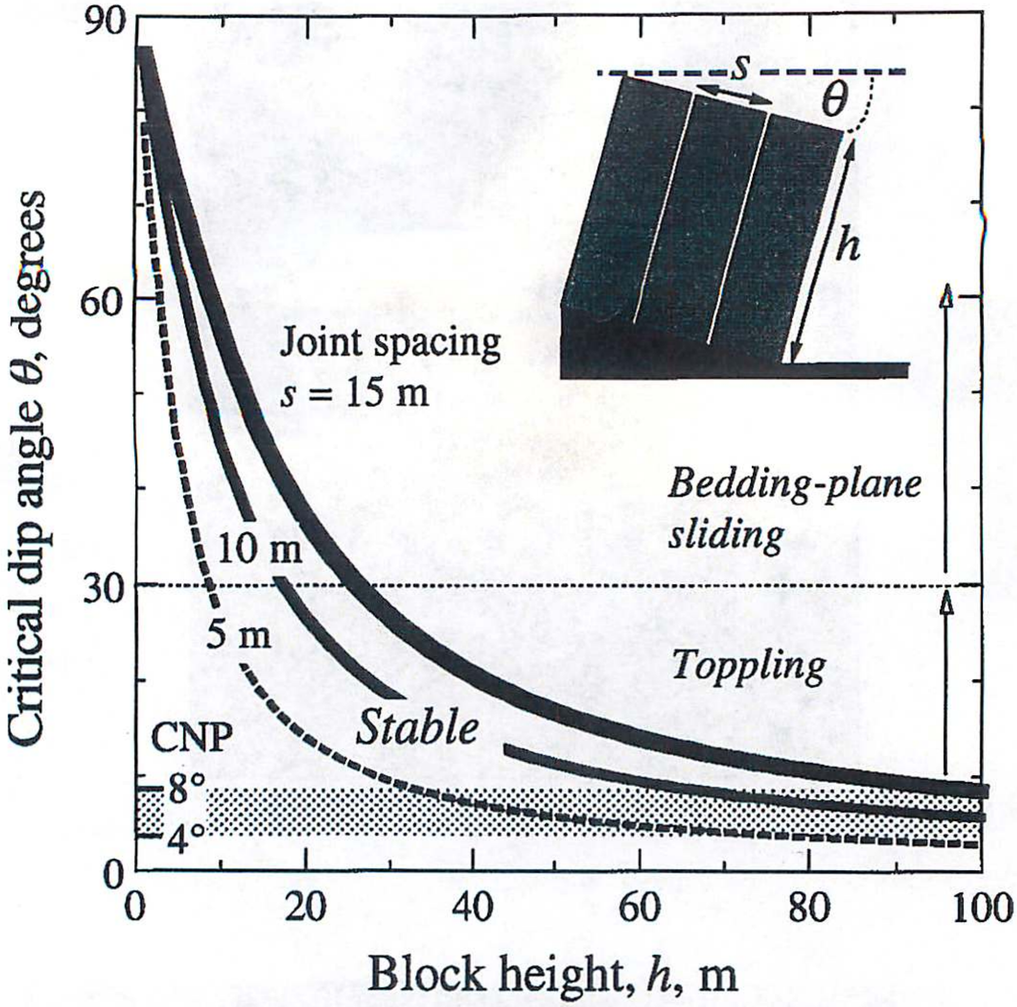

FIG. 6.— Toppling criterion for various joint spacing as a function of dip angle and layer width, from (Moore & Schultz 1999).

3. PLANETARY CONNECTIONS

Jointing is evident through fracturing on Solar System bodies. Recall from tectonics that joints propagate to a critical depth, at which displacement leads to normal faulting rather than jointing. This is estimated through the Griffith criterion, see Figure 7 for how this critical depth varies on Solar System objects. Everyone's favorite recent

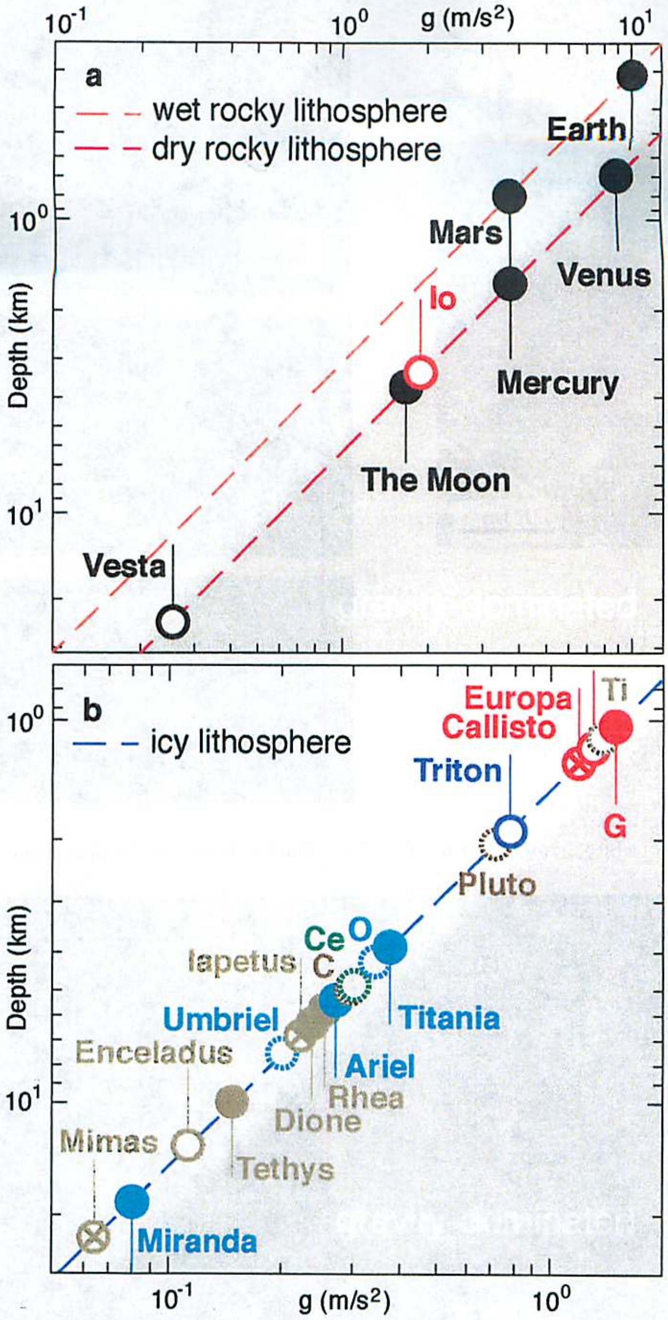

FIG. 7.— Critical depth of jointing as a function of surface gravity for a variety of Solar System bodies, from Klimczak & Byrne (2015).

icy moon tectonics example is Europa, which may have identified subduction zones (Kattenhorn & Prockter 2014). An example of a possible fault boundary is shown in Figure 8. These subduction zones are identified through the lack of rough ice, and hence uplift of non-jointed material. A more simple example of a potential planetary graben is seen in Figure 9, which shows Rhea observed by Cassini. Hence, joints can be seen indirectly on outer solar system bodies by the presence of graben, which grow as a result of jointing.

Jointing has been inferred to have occurred at the Viking 1 lander site (Spohn et al. 2014). The size distribution of rocks there fits well with the distribution expected from fragmentation with an exponential distribution, which one would expect from jointing (Crumpler 1996).

Columnar jointing (the igneous type that you would see at Devil's tower, not Canyonlands) has been inferred in Marte Vallis, Mars by Milazzo et al. (2009). This jointing is seen in the wall of a pristine impact crater, and is seen

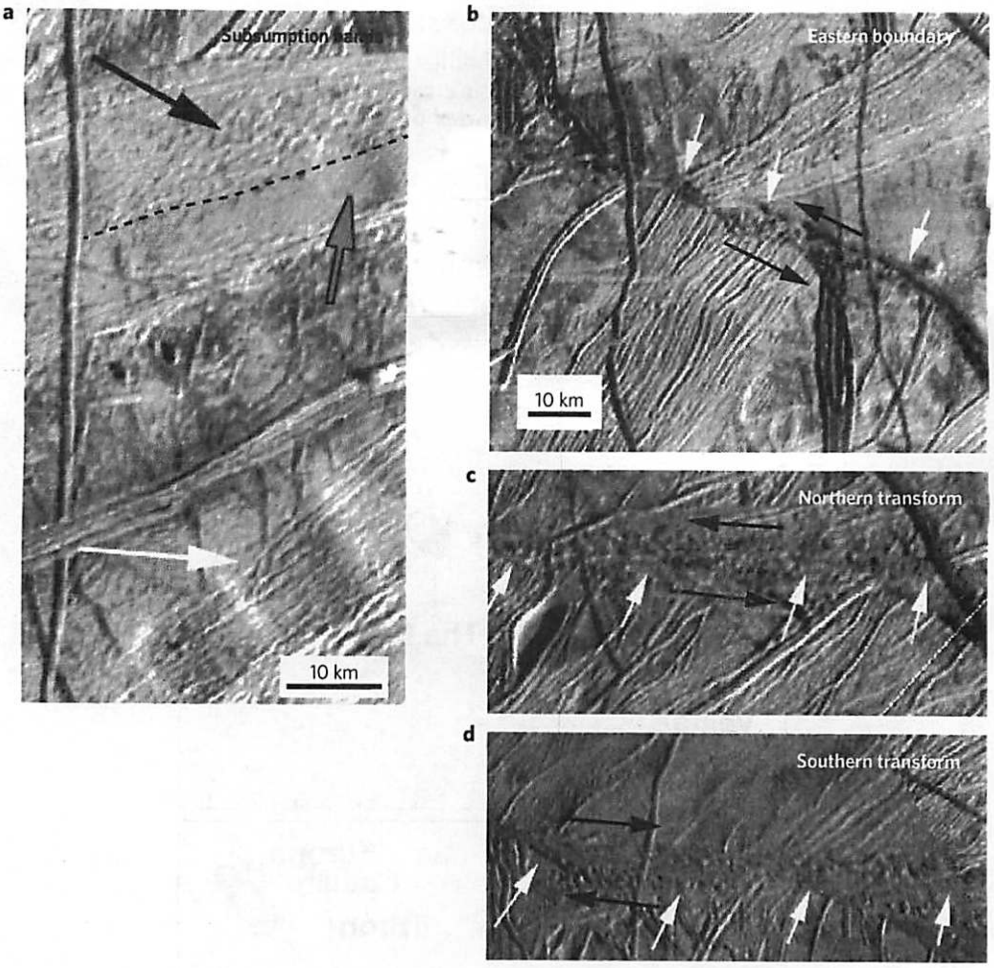

FIG. 8.— Potential fault boundaries (white arrows) and fault motion (black arrows) on Europa, from Kattenhorn & Prockter (2014).

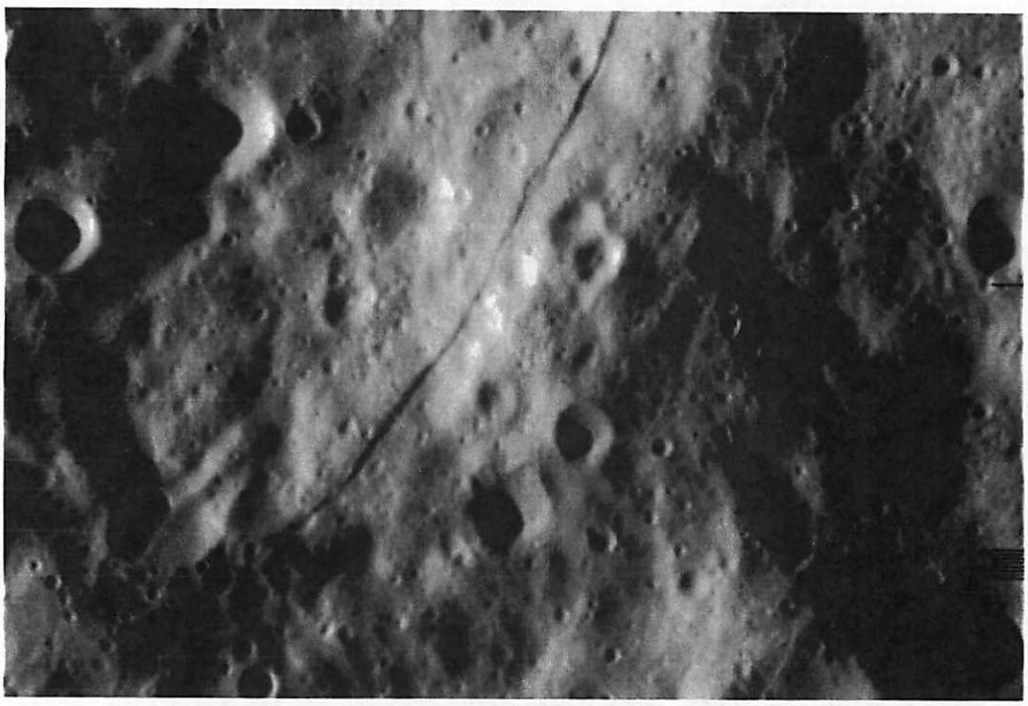

FIG. 9.— Curving narrow feature seen on Rhea by Cassini. This is likely a graben.

in the walls of other fresh craters. Hence, igneous cooling processes dominate the Martian stratigraphy, as one might expect.

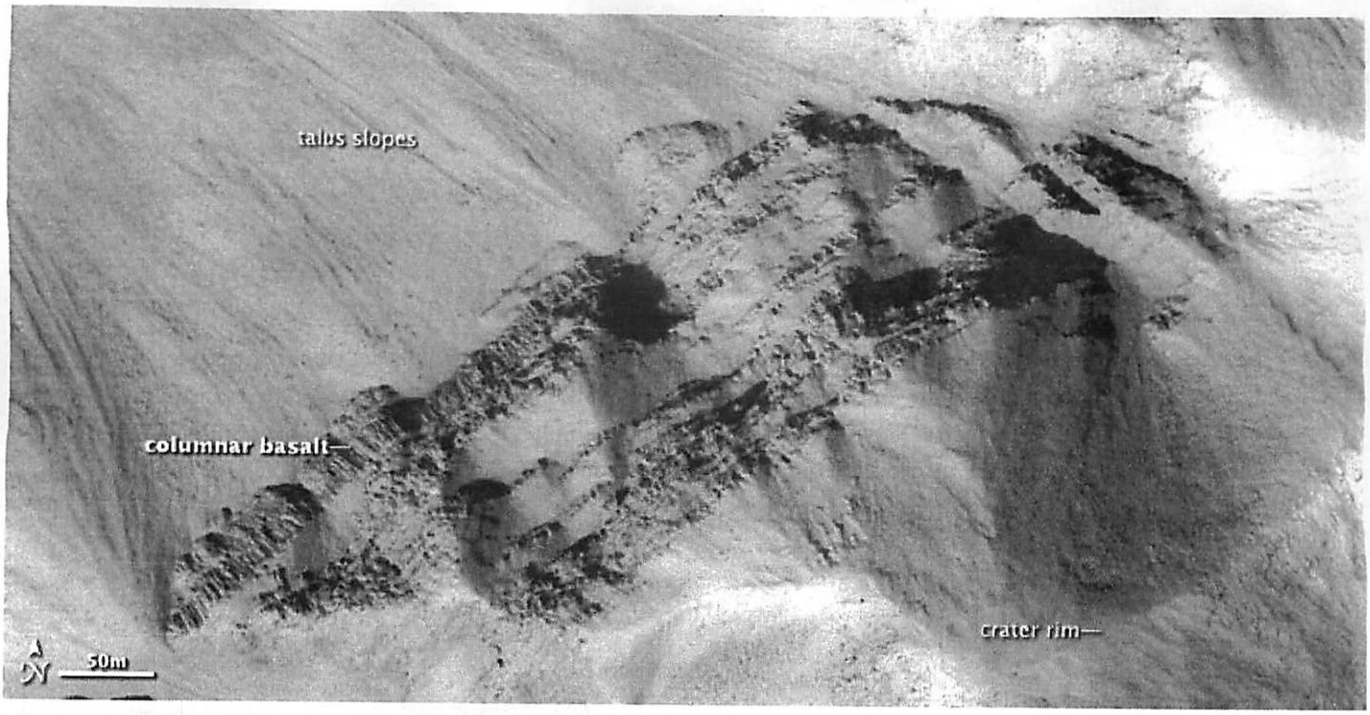

FIG. 10.— Columnar jointing at Marte Vallis, Mars. From HiRISE.

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Fault Interaction

Hamish Hay

1. Normal Faulting of Sedimentary Basins

Sedimentary units under extension tend to undergo normal faulting. These faults are steeply dipping and planar, with displacements on the order of ~ 100 m. Early models of normal fault propagation consistently assumed single plane geometry. However, faults of all types exhibit a less idealised geometry, and due to the complex nature of stress distribution in rock, they interact in a variety of ways.

The two most obvious geological signatures of fault interaction are damage zones and relay ramps.

2. Damage zones

A damage zone is an area of fracture and strain related to a fault (Peacock, 2002), and occurs at all parts of a faults geometry (Figure 1). Typically, "damage" is greatest at the tip of a growing fault, or in the region where two faults interact.

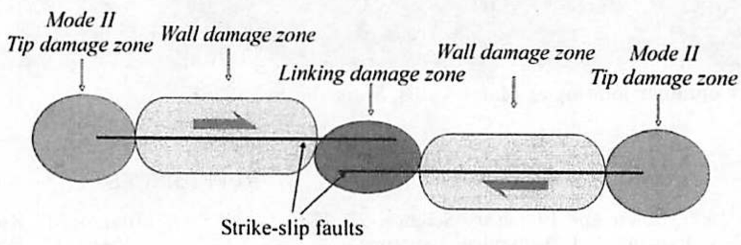
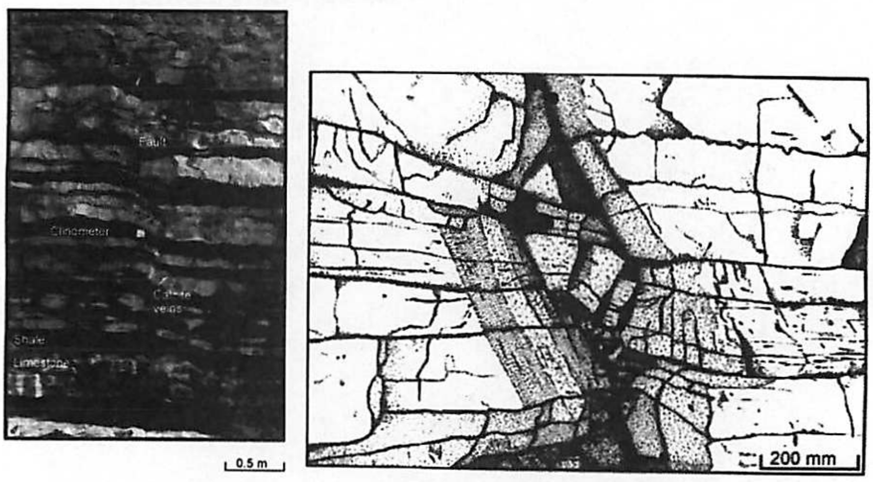


Figure 1: Different damage zone regions in a strike-slip system (Kim et al., 2004)



(a) Vein damage.

(b) Brecciation and block rotation damage.

Figure 2: Two types of fault damage.

Damage can manifest itself in several ways:

- Veining (Fig. 2a)
- Brecciation (Fig. 2b)
- Block rotation
- Extensional fracturing
- Pull-apart basins

Fracturing within a damaged area is a type of faulting in itself, and thus represents a type of fault interaction. The linking damage zone (Figure 1), however, is the greatest expression of fault interaction through damage zones, and develops between two non-coplanar, subparallel faults. It is the natural expression of fault displacement, propagation, and linkage.

3. Relay ramps

This is a tilted area between two overlapping faults that dip in the same direction. It essentially transfers displacement between overstepping segments of the hanging wall and footwall of a normal fault. A small relay ramp is shown in Figure 3. A generalised development of these features is illustrated in Figure 4.

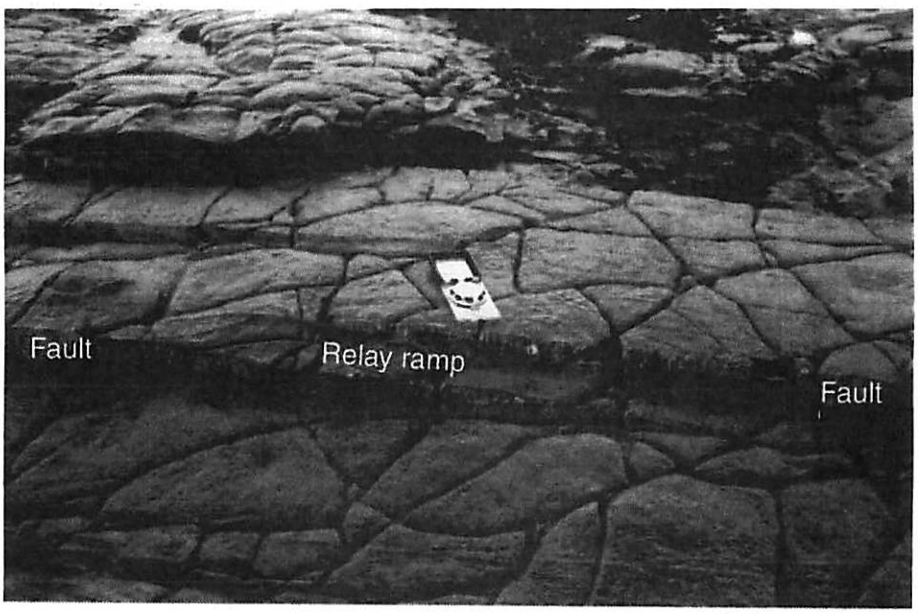


Figure 3: A small relay ramp, that has not yet breached (Peacock, 2002).

Fault interaction via relay ramps is characterised by three types of linkage (Trudgill & Cartwright, 1994):

- Hard linked faults - fault surfaces linked on mapping scales.
- Soft linked faults - linkage occurs via ductile strain of the rock volume.
- Unlinked faults - isolated fault segments with no linkage at all.

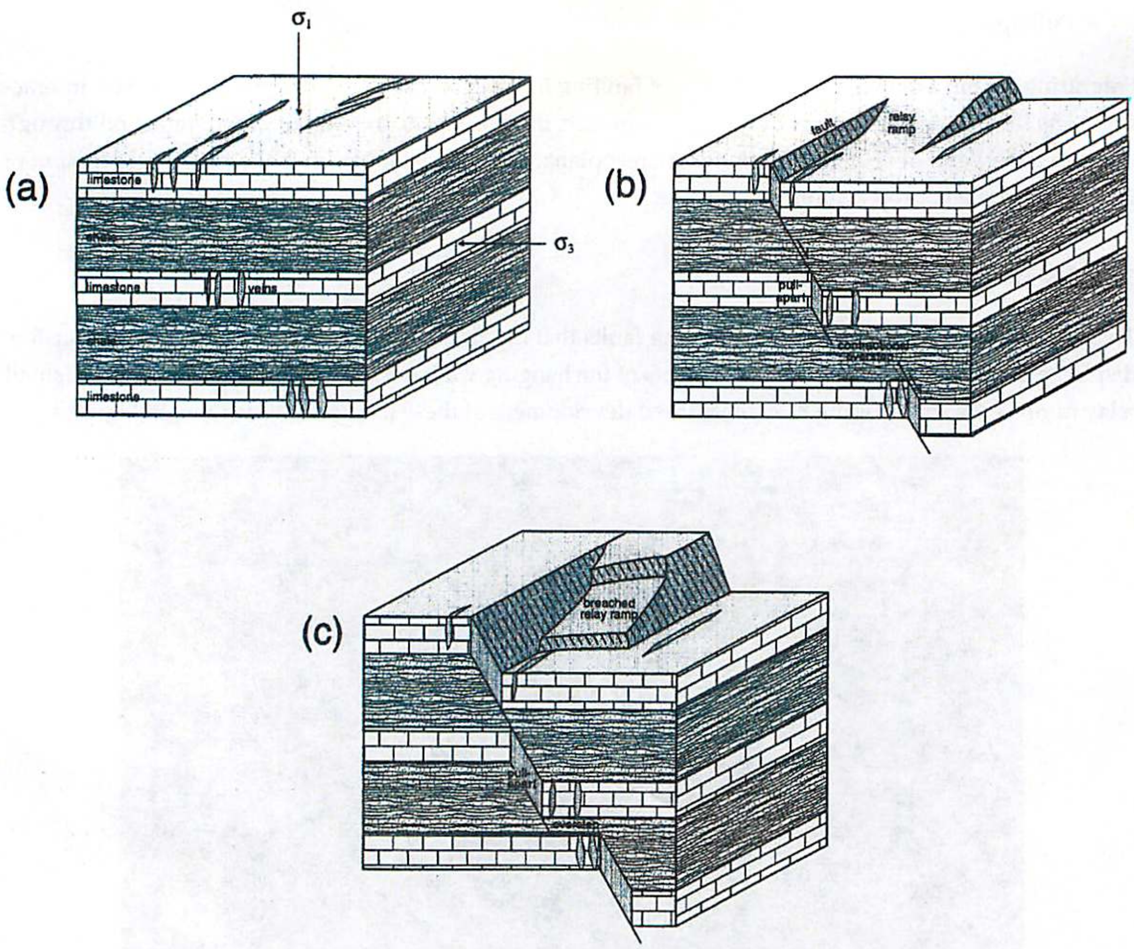
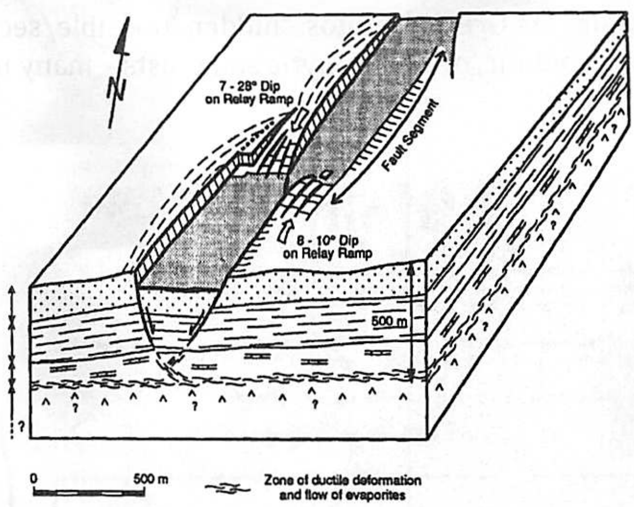


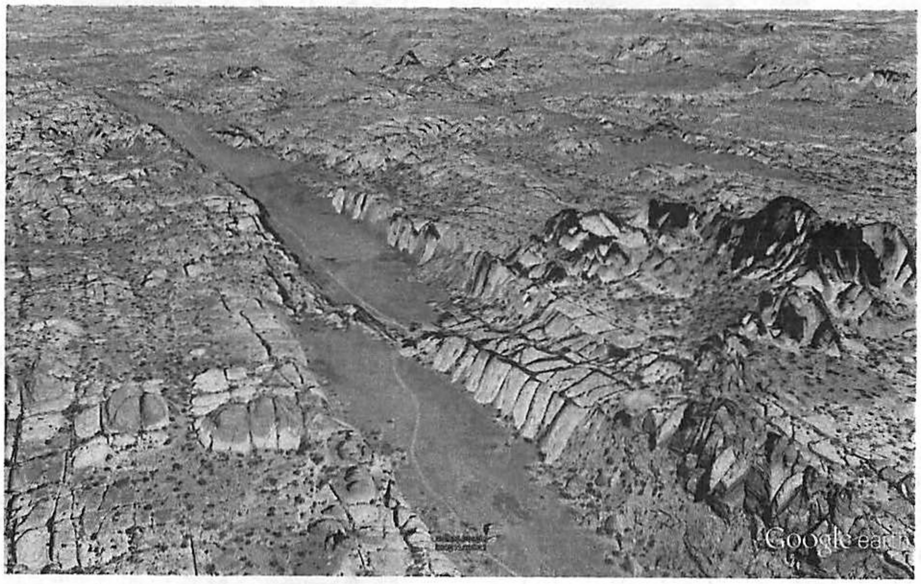
Figure 4: Relay ramp development (Peacock, 2002).

The figure below illustrates a map scale relay ramp within a graben, in Canyonlands National Park.

(a) Map view of relay ramp from Google Earth.



(b) Diagram of the relay ramp. (Trudgill & Cartwright, 1994).



(c) Relay ramp with exaggerated elevation.

Figure 5: Devil's Lane relay ramp, Canyonlands National Park.

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Kim, Y.-S., Peacock, D. C., & Sanderson, D. J. (2004). Fault damage zones. *Journal of structural geology*, *26*, 503–517.

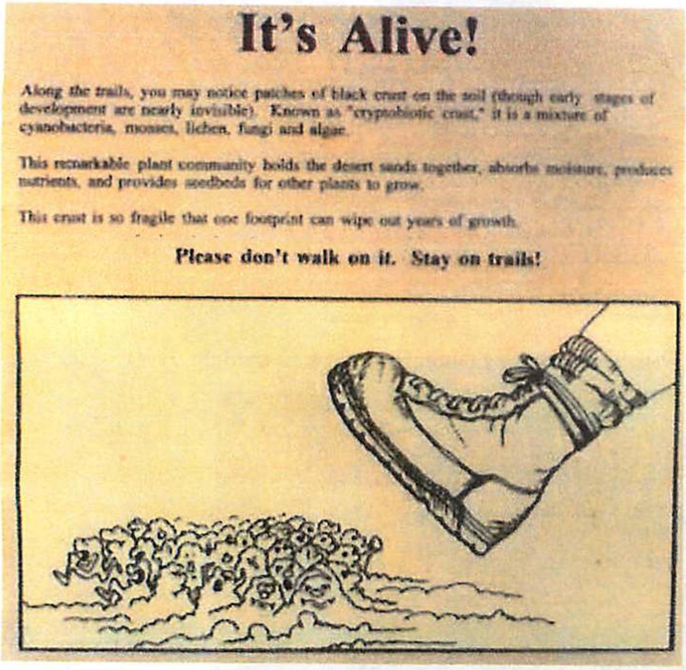
Peacock, D. (2002). Propagation, interaction and linkage in normal fault systems. *Earth-Science Reviews*, *58*, 121–142.

Trudgill, B., & Cartwright, J. (1994). Relay-ramp forms and normal-fault linkages, canyonlands national park, utah. *Geological Society of America Bulletin*, *106*, 1143–1157.

Cryptobiotic Soil Crusts

Donna Viola

From the Greek, kruptos, "hidden/invisible/secret" and bio, "life". AKA cryptogamic, *microbiotic*, or microphytic soil crusts – many names, two key points:



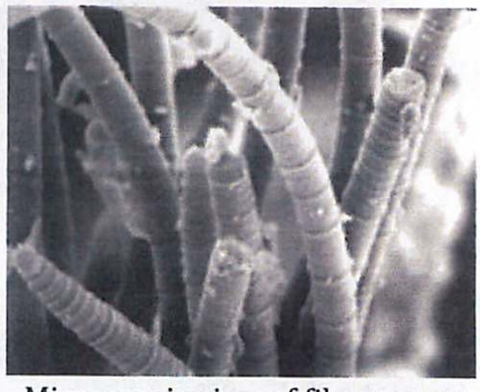
It's alive!!

It's important! (So watch your step)

Composition:

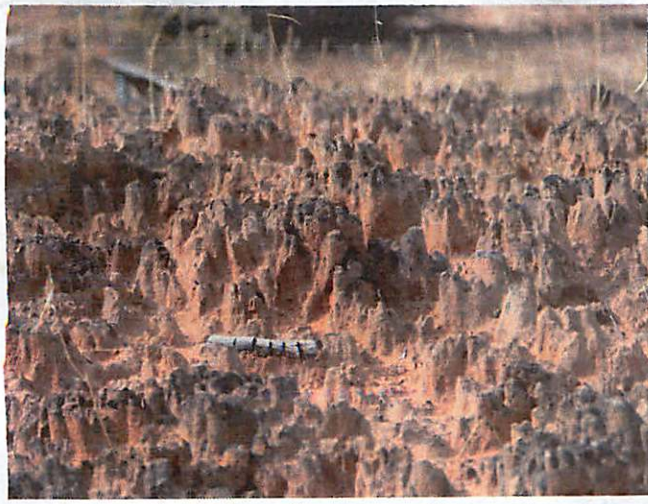
Microbes! Primarily filamentous cyanobacteria, but can also include lichens, mosses, microfungi, and other bacteria.

Microbial by-products! Organic materials, including polysaccharides, that are excreted by microorganisms.



Microscopic view of filamentous cyanobacteria.

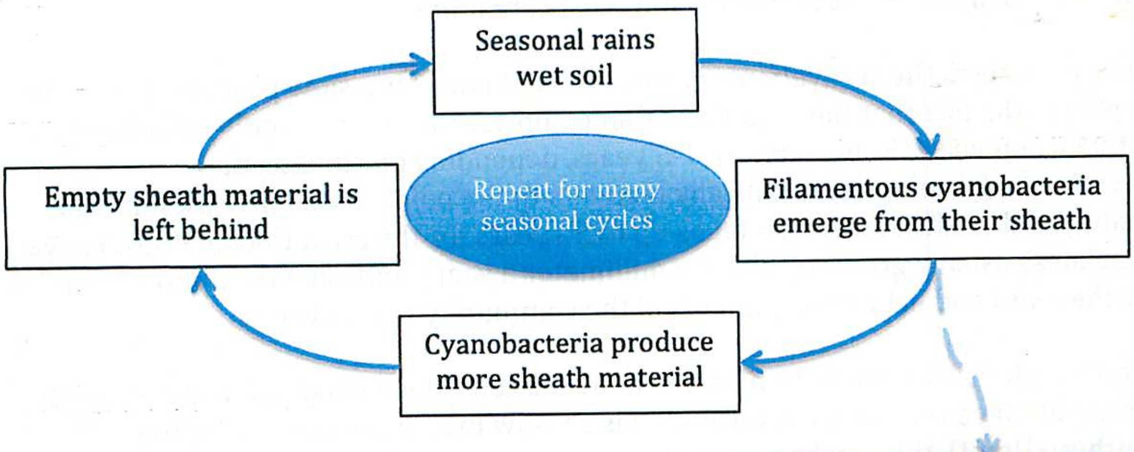
Structure:

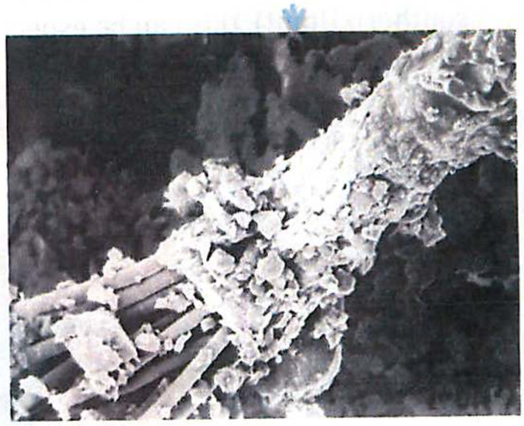


Small scale: Pinnacles, up to 10 centimeters in height, capped with darker-colored material due to the density of cyanobacteria.

Large scale: Knobby texture, dark-colored, can cover extensive land area (most notably in arid regions).

Formation:





Significance:

~Soil stability: Cyanobacteria help to bind soil particles, as do fungi and lichens, using different chemical substances. This helps to increase resistance to soil erosion by wind or water.

~Water infiltration: Cryptobiotic crusts typically increase surface roughness (and surface area), which helps to increase the ability of water runoff to infiltrate into the soil.

~Increased soil *nutrients*: Many cyanobacteria have pathways for nitrogen fixation (converting atmospheric N_2 into more biologically-accessible forms like ammonium). Soil crusts are also important sources of fixed carbon, and their structure allows for the trapping of other nutrients as well.

~Increased plant survival: Increased nutrient content encourages plant growth and health.

Soil particles bound by organic materials in a cryptobiotic crust.

Destruction and Recovery:

Although vey well adapted to surviving in the harsh desert environment, cryptobiotic soil crusts are very sensitive to compressional stresses. This is because they are dry and brittle, and largely composed of empty microbial sheaths; when these sheaths break, it becomes very difficult for the soil community to function. Other potential disturbances include crust burial (cyanobacteria photosynthesize, so they must have a source of light readily available) and fires, which also tend to be common in areas where abundant soil crusts are found.

Once disturbed, the recovery of cryptobiotic soil crusts is a slow process. This is due in part to the fact that the organisms that comprise the crust are only metabolically active when water is available. In 1-5 years, depending on climate, the cyanobacterial component typically recovers to the point of visually resembling a healthy soil crust. However, it takes up to 50 years for the crust thickness to recover (thickness usually grows by about a millimeter a year), and can take up to 250 years for the moss and lichen components of the community to recover!

After a disturbance, soils are typically more susceptible to wind and water erosion for about 20 years. Since soil formation is so slow in arid regions (including southern Utah!), this can be especially problematic – leading to a loss of soil fertility and organic matter.

Common Rock Forming Minerals

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

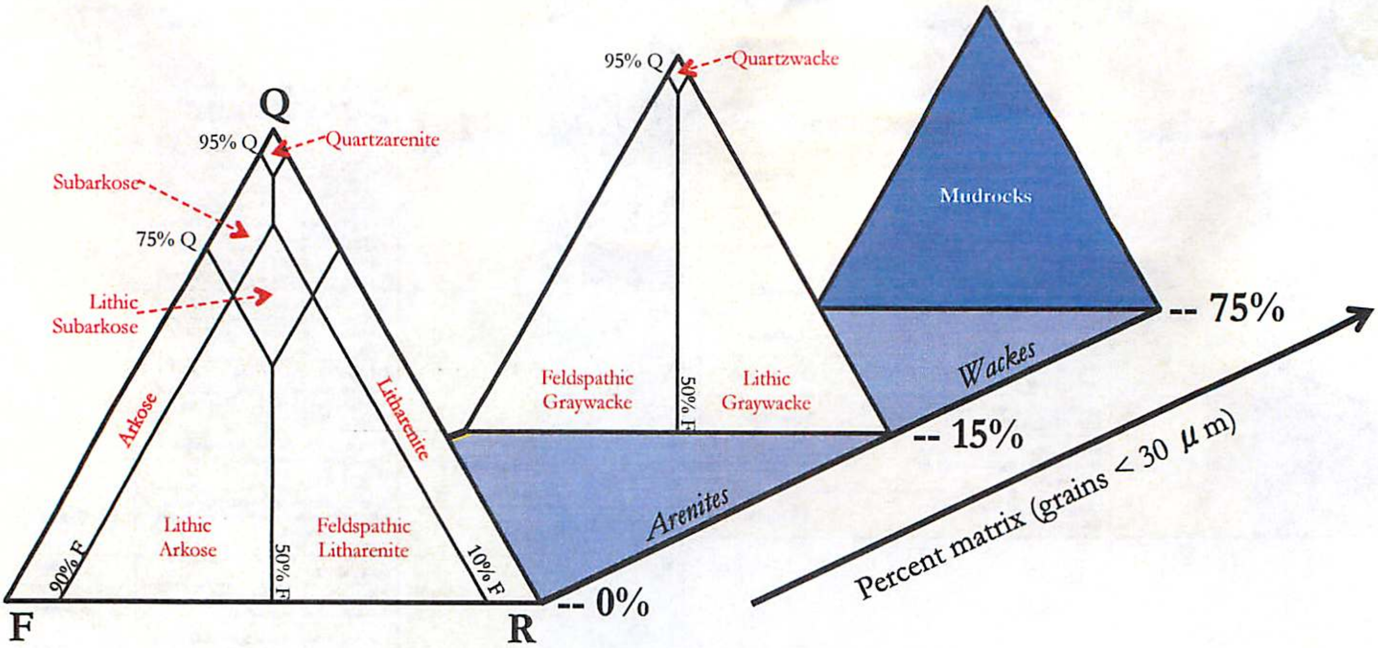
Light-colored minerals			
Hardness	**Cleavage**	**Physical Properties**	**Name**
Hardness >5	Excellent or good	White or gray. Cleavage in 2 planes at nearly right angles. Striations. Hardness-6	**Plagioclase Feldspar**
		Orange, brown, white, gray, green or pink. Cleavage in 2 planes at nearly right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

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

Sedimentary Rocks

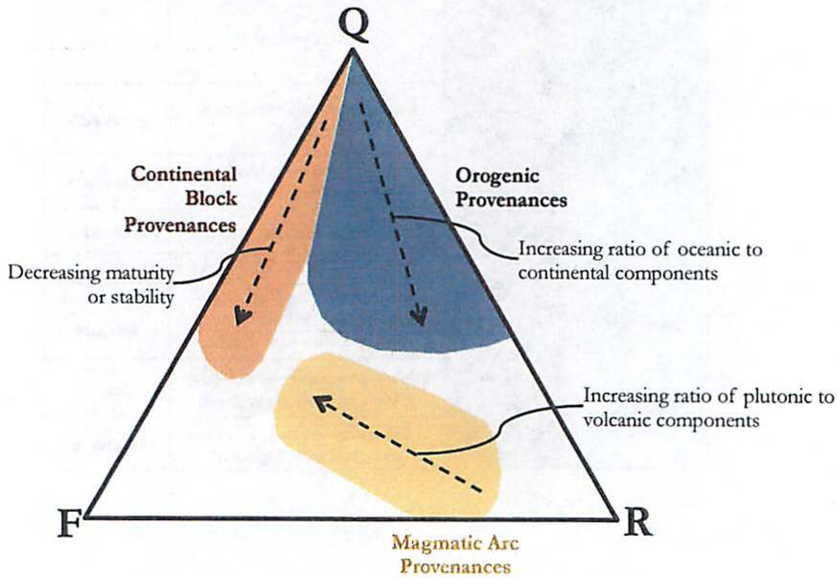
McBride, 1963 & Dott, 1964 Classification Scheme for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert(Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt)



Tectonic Setting for Clastic Sedimentary Rocks

Scheme based on the normalized percentages of the visible grains: quartz and chert (Q), feldspar (F), and lithic rock fragments (R) – as well as the percent composed of matrix (mud & silt). Regions based upon field data.



Sedimentary Rocks

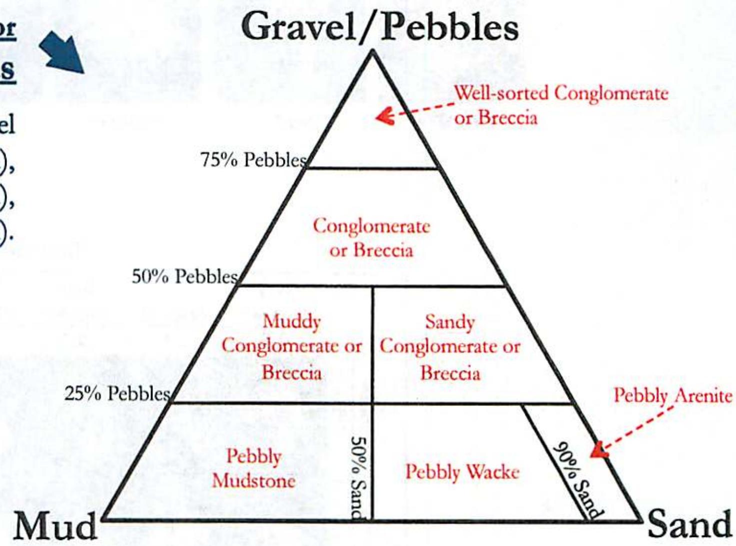
	Mudrocks (containing > 50% mud)			Rocks with <50%mud
	Silt dominant (> 2/3 of rock)	Clay and Silt	Clay dominant (> 2/3 of rock)	Sand-sized or larger grains dominant
Non-laminated	Siltstone	Mudstone	Claystone	Conglomerates, Breccias, Sandstones, etc.
Laminated	Laminated Siltstone	Mudshale	Clayshale	

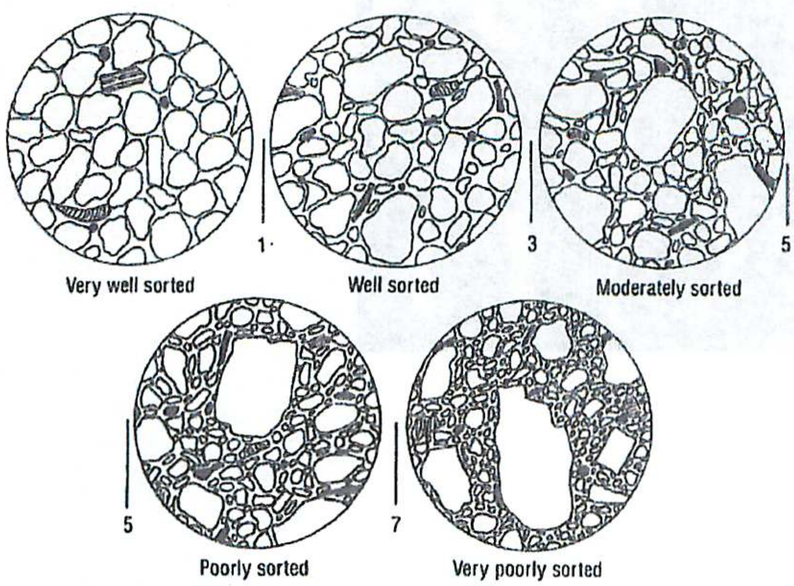
Classification Scheme for Mudrocks

Scheme based on clay/silt content, and whether the rock is laminated *(layered) or* not.

Classification Scheme for Sub-Conglomerates and Sub-Breccias

Scheme based on percent of a rock composed of: gravel or pebbles (size >2 mm), sand (2 mm > size > 1/16 mm), and mud (size < 1/16 mm).





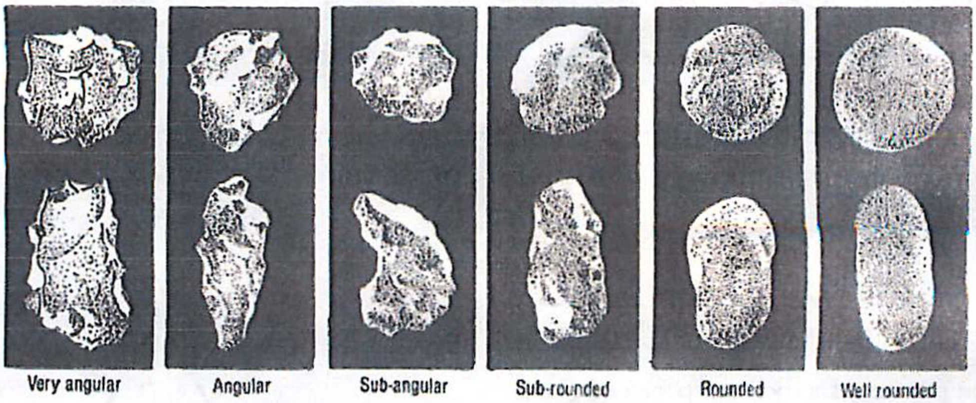
Estimating Sorting

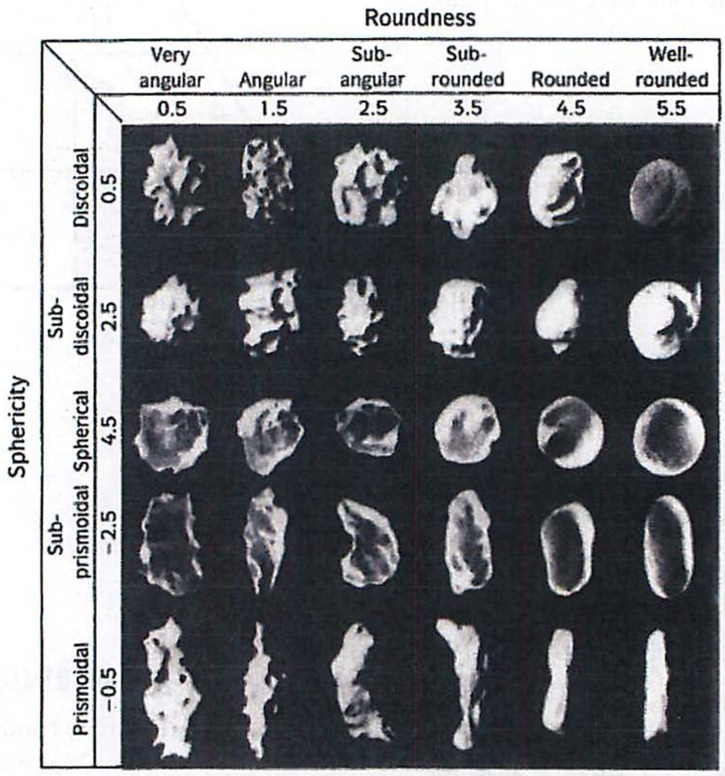
Example hand-lens view of detritus. From Compton, 1985

Sedimentary Rocks

Degrees of Rounding

Example hand-lens view of detritus of varying degrees of roundedness. The top row are equidimensional (spherical) grains, while the lower row are elongated grains. From Compton, 1985 and Davis & Reynolds, 1996, respectively.

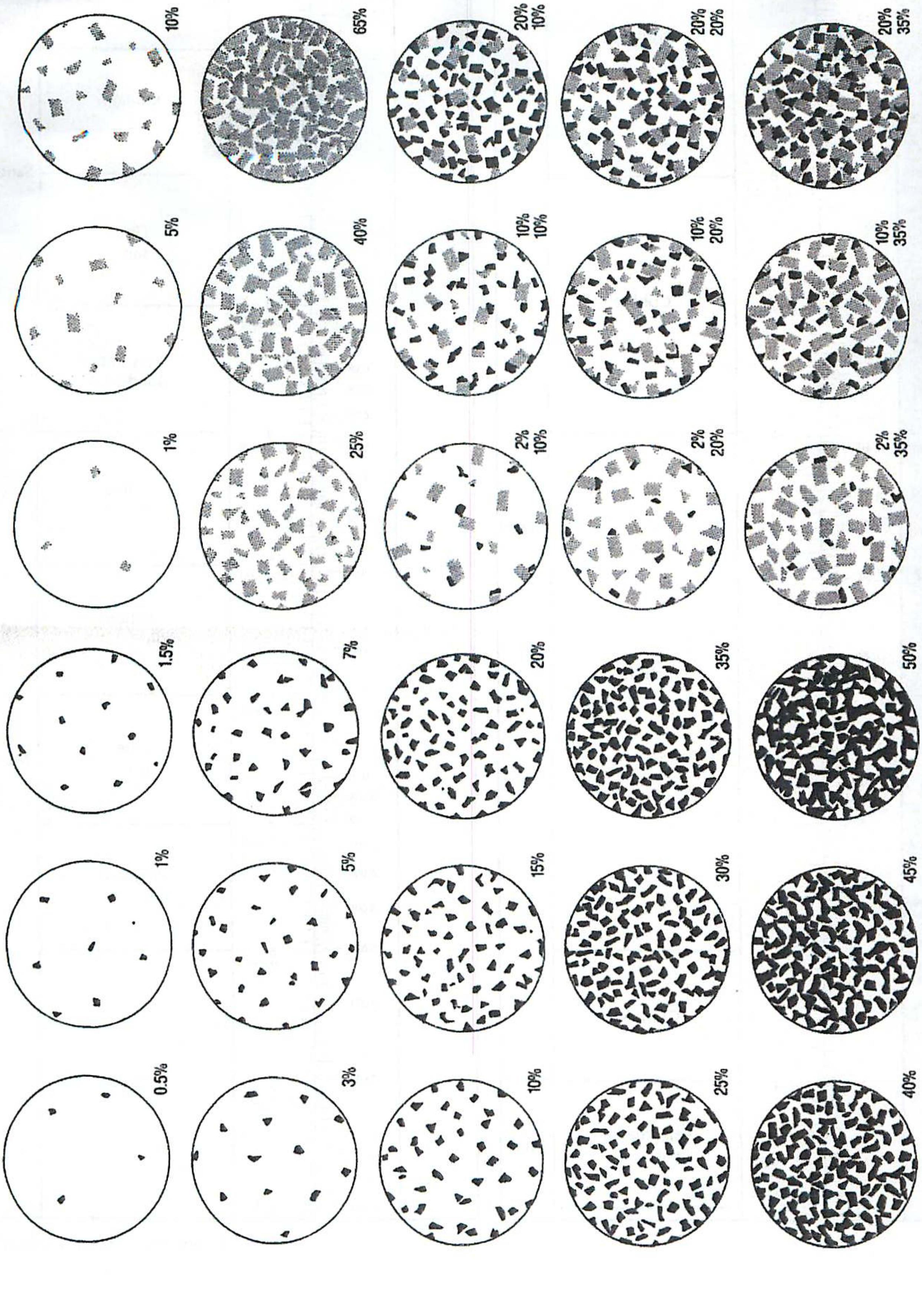




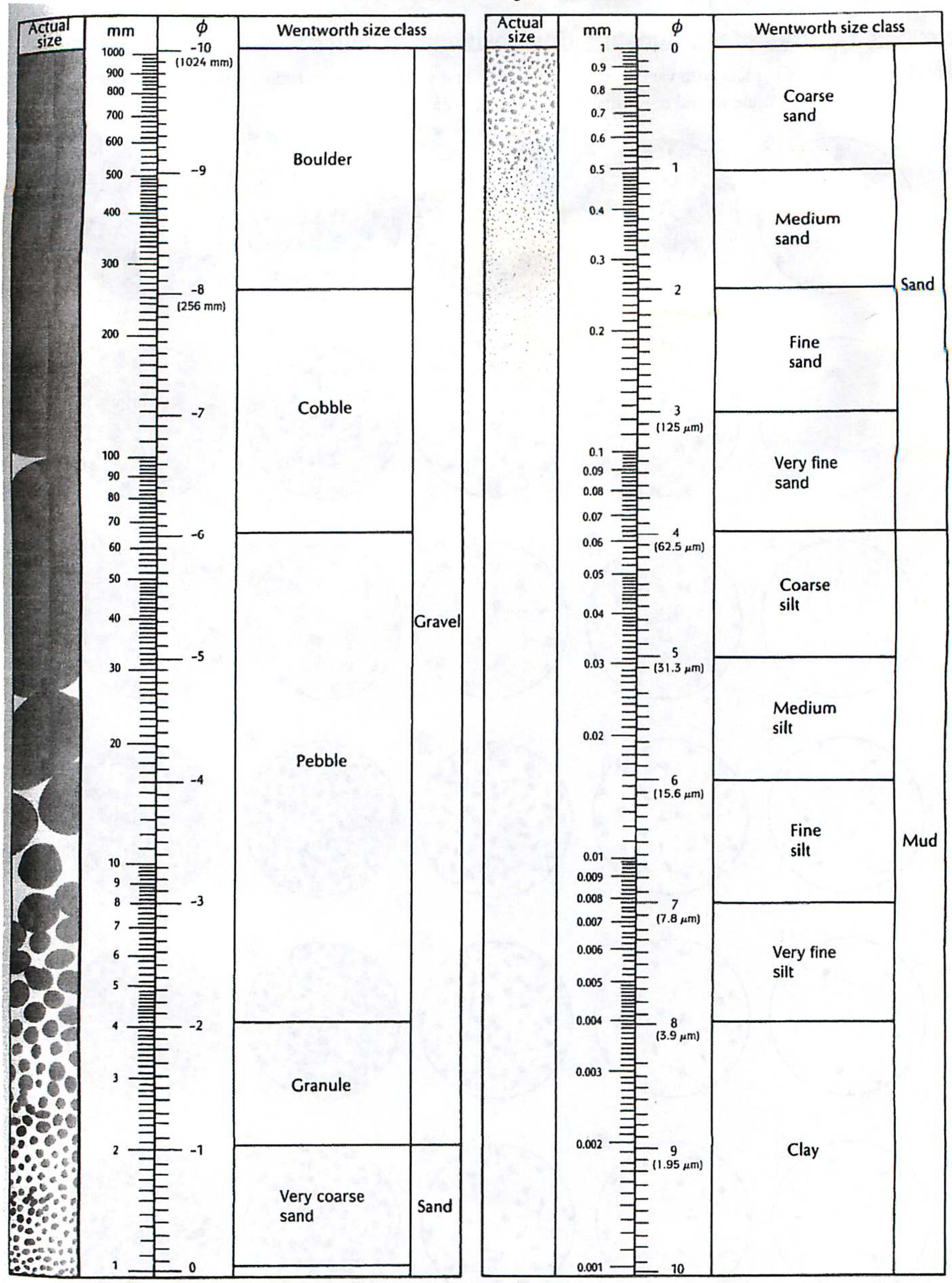
Sedimentary Rocks

Percentage Diagrams for Estimating Composition by Volume

Example hand-lens view of rocks with varying composition. To find weight percents, simply multiply each volume percent by the specific gravity of that mineral, and re-normalize. Compton, 1985



Sedimentary Rocks

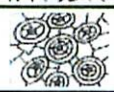
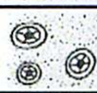
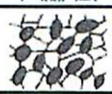
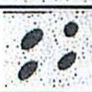
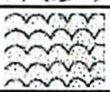


From Prothero and Schwab, 2004

Sedimentary Rocks: Carbonates

Folk Classification Scheme for Carbonate Rocks

Folk's classification scheme is based upon the composition (and type of allochems) within a limestone. Figures from Prothero and Schwab, 2004

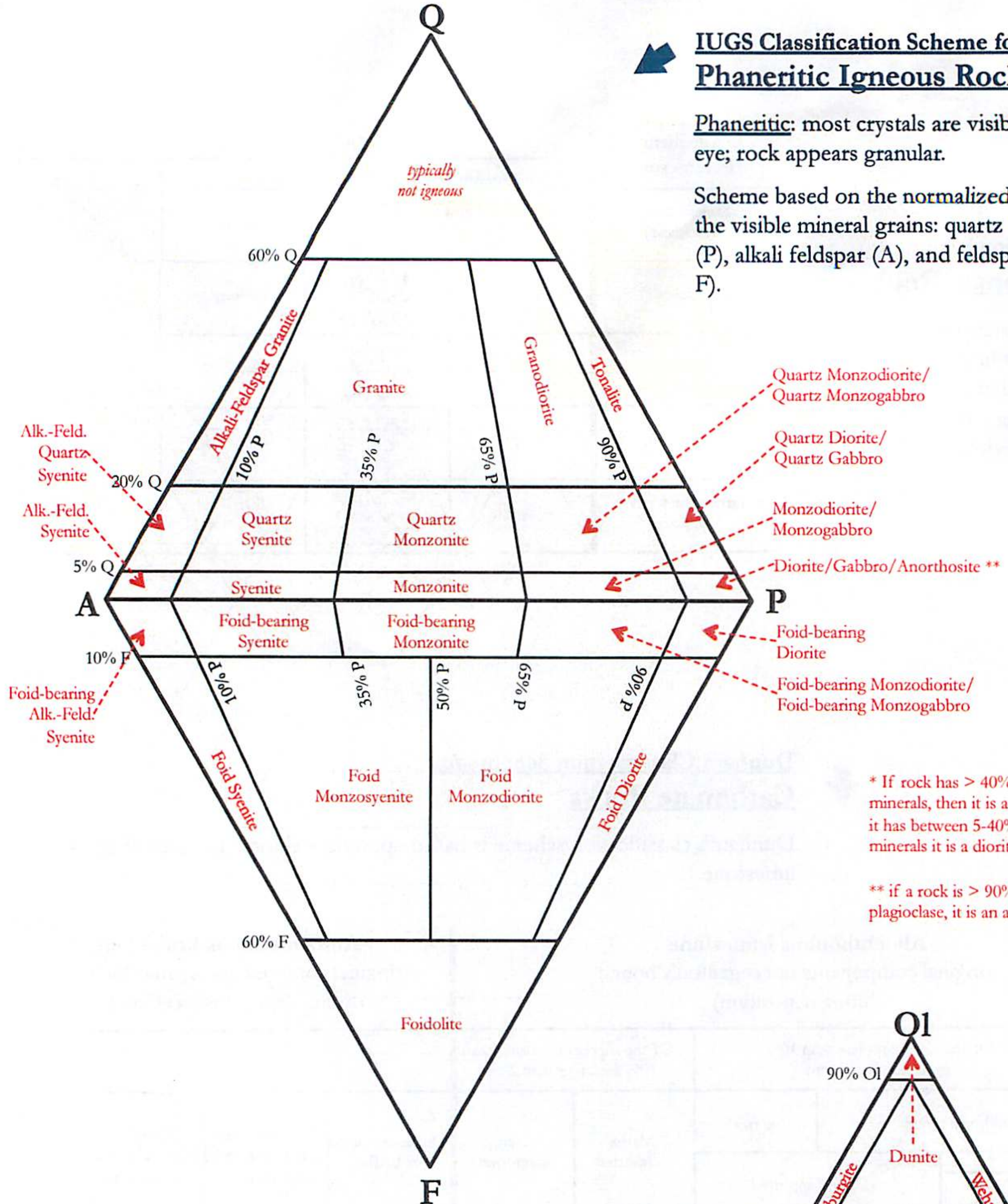
<table>
<tr><th rowspan="2">Principle Allochems in Limestone</th><th colspan="4">Limestone Type</th></tr>
<tr><th colspan="2">Cemented by Sparite</th><th colspan="2">Cemented by Micritic Matrix</th></tr>
<tr><td>Skeletal Grains (Bioclasts)</td><td>Biosparite</td><td></td><td>Biomicrite</td><td></td></tr>
<tr><td>Ooids</td><td>Oosparite</td><td></td><td>Oomicrite</td><td></td></tr>
<tr><td>Peloids</td><td>Pelsparite</td><td></td><td>Pelmicrite</td><td></td></tr>
<tr><td>Intraclasts</td><td>Intrasparite</td><td></td><td>Intramicrite</td><td></td></tr>
<tr><td>Limestone formed in place</td><td>Biolithite</td><td></td><td>Terrestrial Limestone</td><td></td></tr>
</table>

Dunham Classification Scheme for Carbonate Rocks

Dunham's classification scheme is based upon depositional textures within a limestone.

<table>
<tr><th colspan="6">Allochthonous Limestone
(original components not organically bound during deposition)</th><th colspan="3">Autochthonous Limestone
(original components organically bound during deposition; reef rocks)</th></tr>
<tr><td colspan="4">Of the allochems, less than 10% are larger than 2 mm</td><td colspan="2">Of the allochems, greater than 10% are larger than 2 mm</td><td colspan="3"></td></tr>
<tr><td colspan="3">Contains carbonate mud</td><td>No mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">Grain supported</td><td rowspan="3">Organisms acted as baffles</td><td rowspan="3">Organisms are encrusting and binding</td><td rowspan="3">Organisms building a rigid framework</td></tr>
<tr><td colspan="2">Grain supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

Igneous Rocks



IUGS Classification Scheme for
Phaneritic Igneous Rocks

Phaneritic: most crystals are visible to the naked eye; rock appears granular.

Scheme based on the normalized percentages of the visible mineral grains: quartz (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).

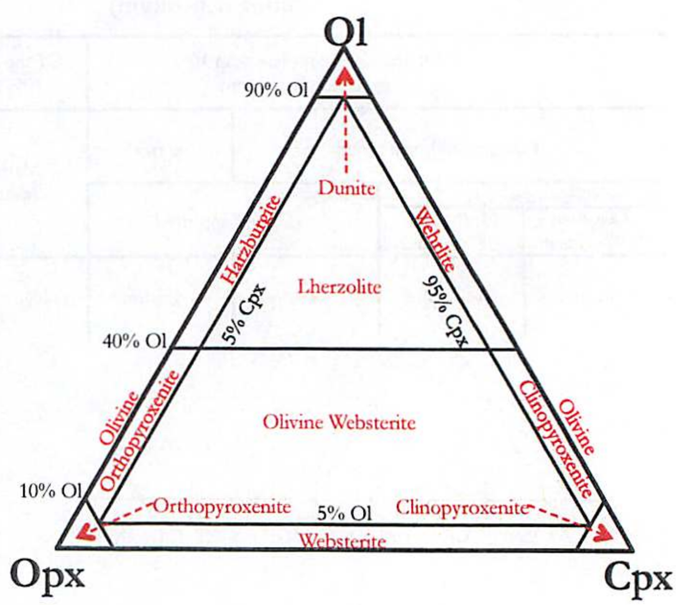
* If rock has > 40% mafic minerals, then it is a gabbo. If it has between 5-40% mafic minerals it is a diorite.

** if a rock is > 90% plagioclase, it is an anorthosite

IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (1)

Ultramafic: more than 90% of the total minerals are mafic.

Scheme based on the normalized percentages of the visible minerals: olivine (Ol), orthopyroxene (Opx), and clinopyroxene (Cpx).

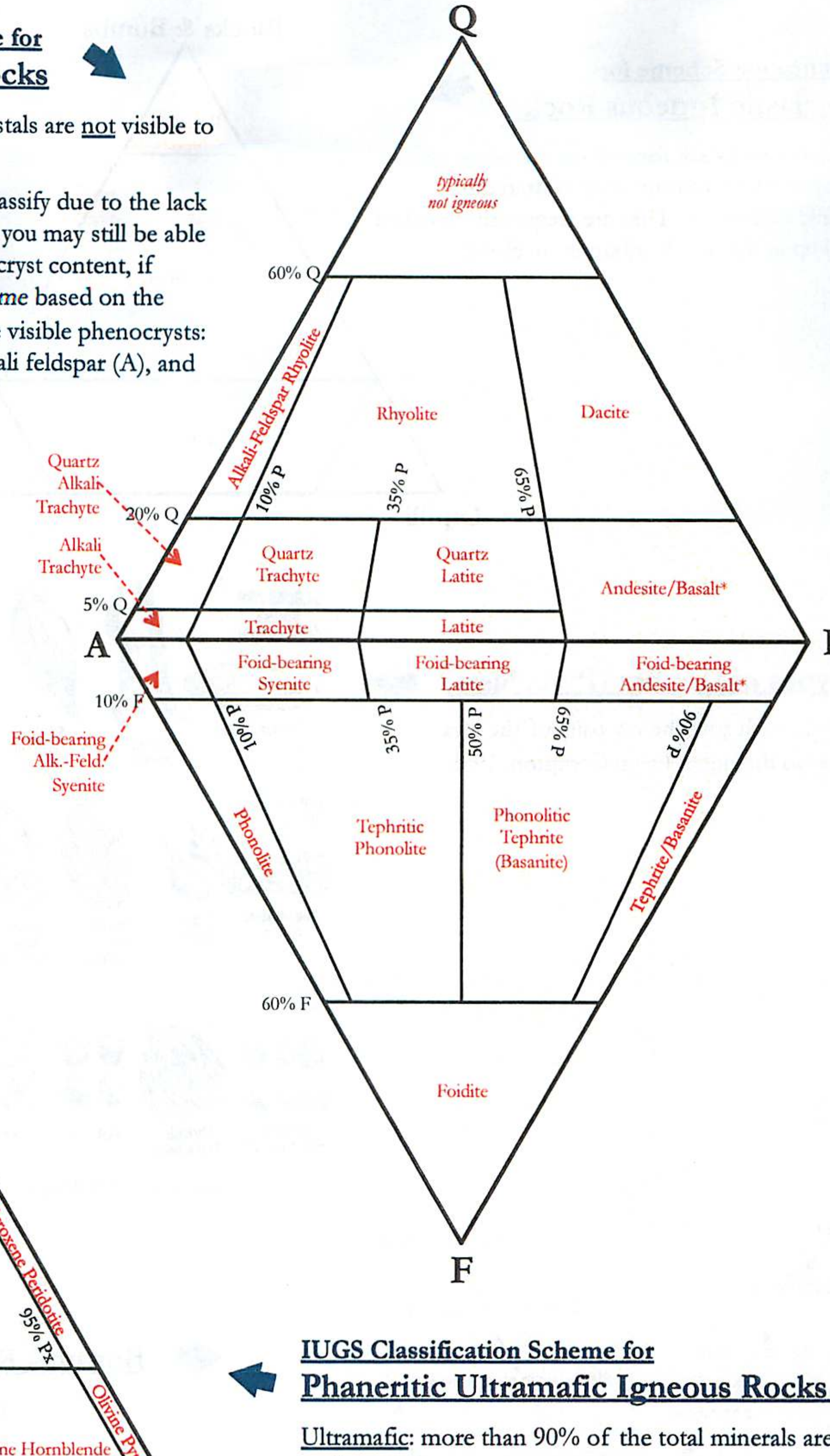


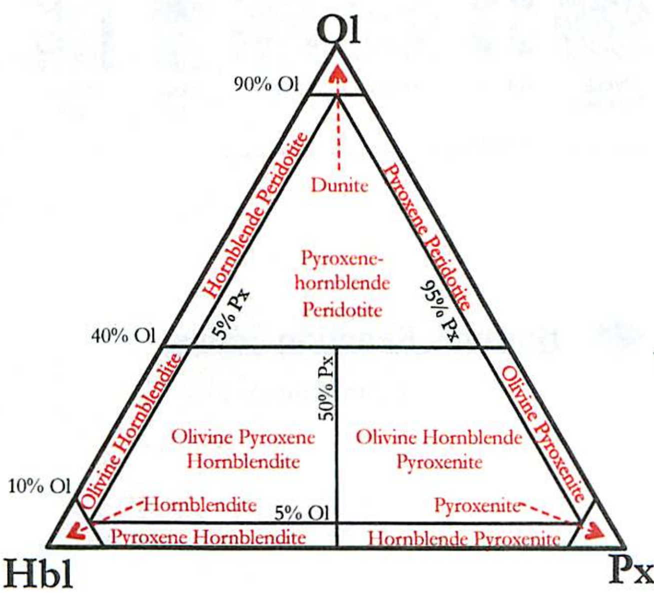
Igneous Rocks

IUGS Classification Scheme for
Aphanitic Igneous Rocks

Aphanitic: the majority of crystals are not visible to the naked eye.

Aphanetic rocks are hard to classify due to the lack of visible minerals. However, you may still be able identify them based on phenocryst content, if phenocrysts are present. *Scheme* based on the normalized percentages of the visible phenocrysts: *quartz* (Q), plagioclase (P), alkali feldspar (A), and feldspathoids (foids, F).





IUGS Classification Scheme for
Phaneritic Ultramafic Igneous Rocks (2)

Ultramafic: more than 90% of the total minerals are mafic.

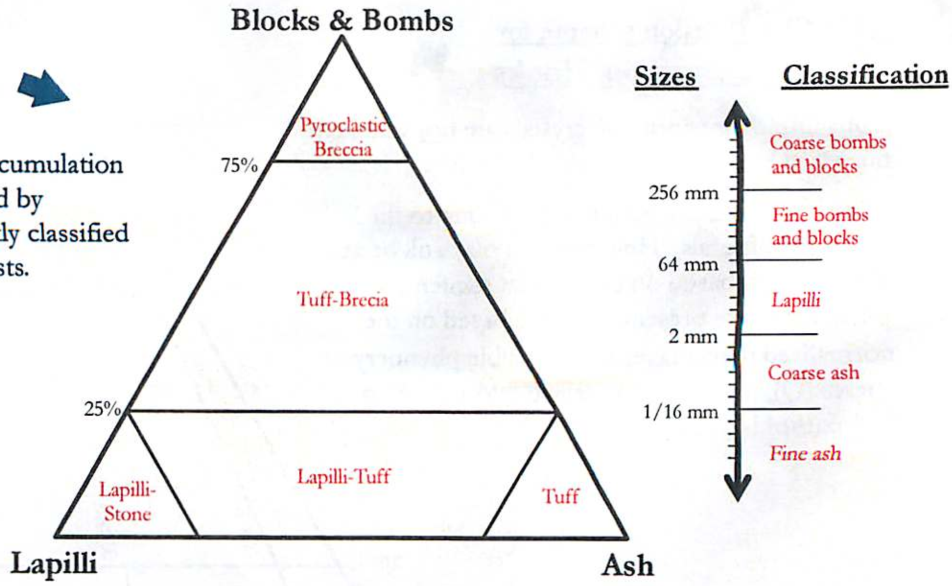
Scheme based on the normalized percentages of the visible minerals: olivine (Ol), hornblende (Hbl), and pyroxene (Px).

Igneous Rocks

Classification Scheme for

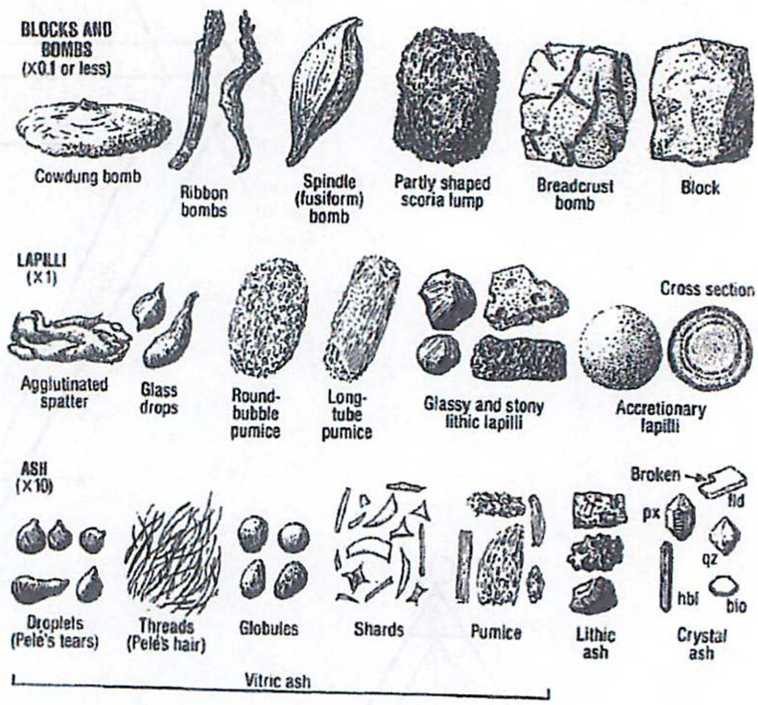
Pyroclastic Igneous Rocks

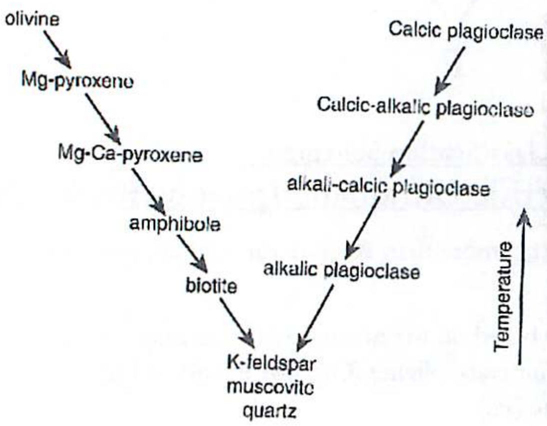
Pyroclastic rocks are formed via the accumulation of fragments of volcanic rock scattered by volcanic explosions. They are frequently classified based upon the size distribution of clasts.



Types of Tephra (Pyroclasts)

In each row, the viscosity of the lava increases to the right. From Compton, 1985.





Bowen's Reaction Series

From Winter, 2010.

Metamorphic Rocks

Classification Scheme for Metamorphic Rocks

Based upon texture and mineralogical composition.

Structure &Texture		Characteristic Properties	Characteristic Mineralogy	Rock Name
Foliate (layered)	Increasing grain size, and degree of metamorphism ↓	Dull luster; very flat fracture surface; grains are too small to readily see; more dense than shale	No visible minerals	Slate
		Silky sheen; Crenulated (wavy) fracture structure; A few grains visible, but most are not	Development of mica and/or hornblende possible	Phyllite
		Sub-parallel orientations of individual mineral grains; wavy-sheet like fracture; often contains porphyroblasts; thinly foliated	Abundant feldspar; Quartz and mica are common; hornblende possible	Schist
		Sub-parallel, alternating bands or layers of light and dark material; coarsely foliated; blocky fracture	Abundant feldspars; Quartz, mica, and hornblende are common	Gneiss
Foliate (layered)		Interlocking crystals; effervesces in dilute HCl; softer than glass	Calcite	Marble
		Nearly equigranular grains; fracture across grains (not around them); sub-vitreous appearance; smooth feel compared to sandstone	Quartz	Quartzite

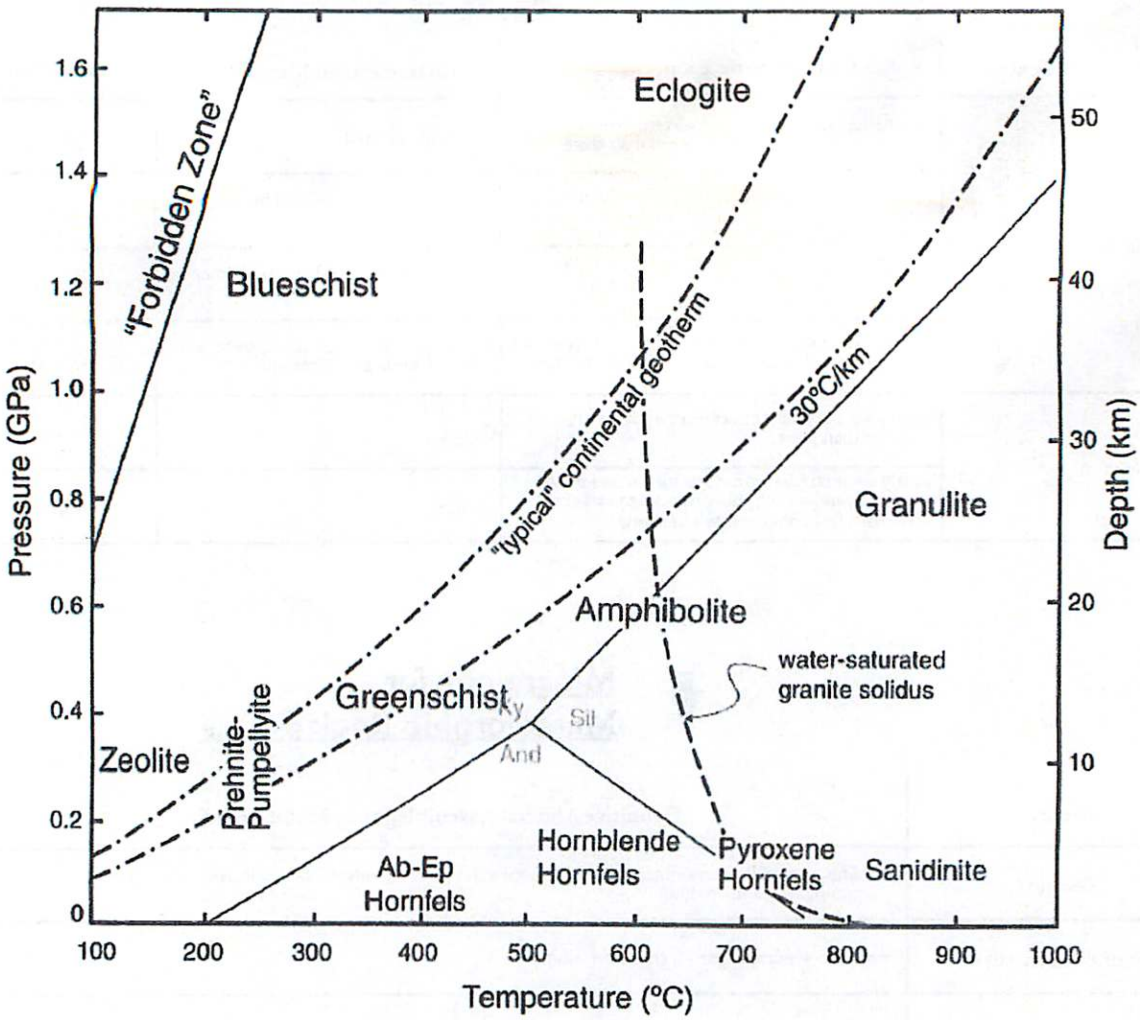
Mineralogy for Metamorphic Rock Facies

Facies	Definitive Mineral Assemblages in Mafic Rocks
Zeolite	zeolites: especially laumontite, wairakite, analcime (in place of other Ca-Al silicates such as prehnite, pumpellyite and epidote)
Prehnite-Pumpellyite	prehnite + pumpellyite (+ chlorite + albite)
Greenschist	chlorite + albite +epidote (or zoisite) + actinolite ± quartz
Amphibolite	hornblende + plagioclase (oligoclase, andesine) ± garnet
Granulite	orthopyroxene + clinopyroxene + plagioclase ± garnet
Blueschist	glaucophane + lawsonite or epidote/zoisite (± albite ± chlorite ± garnet)
Eclogite	pyralspite garnet + omphacitic pyroxene (± kyanite ± quartz), no plagioclase
Contact Facies	mineral assemblages in mafic rocks of the facies of contact metamorphism do not differ substantially from those of the corresponding regional facies at higher pressure

Metamorphic Rocks

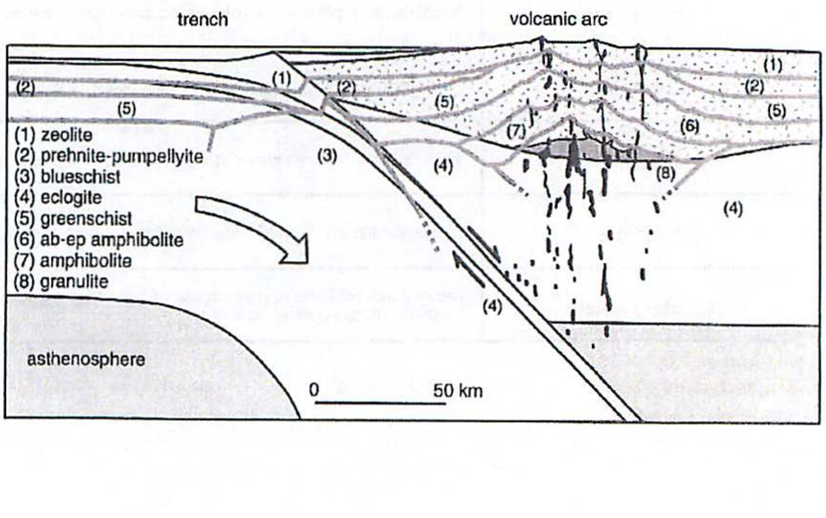
Metamorphic Rock Facies, P vs. T diagram

From Winter, 2010



Schematic of Island Arc, and the origins of Metamorphic Facies

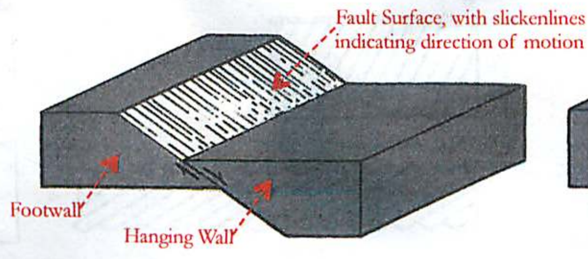
A schematic cross section of an island arc. Light gray lines are isotherms. From Winter, 2010



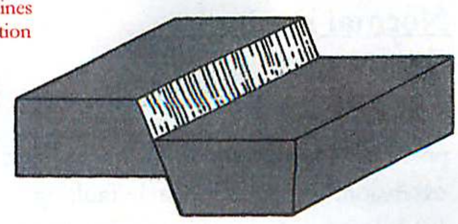
Structural Geology: Normal Faults

Normal Faults

In normal faults, the footwall goes up with respect to the hanging wall. Normal faults are indicative of extension. Figures from Davis & Reynolds, 1996.



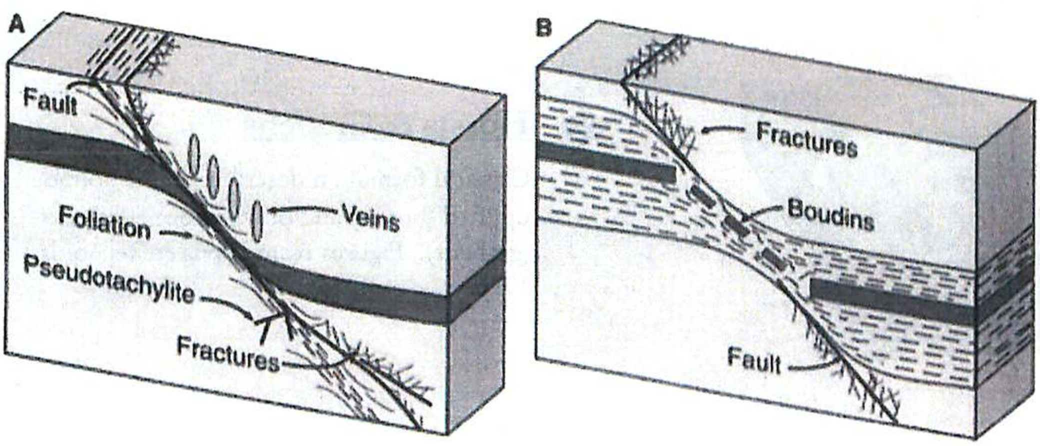
Low-angle Normal Slip Fault



Normal Slip Fault

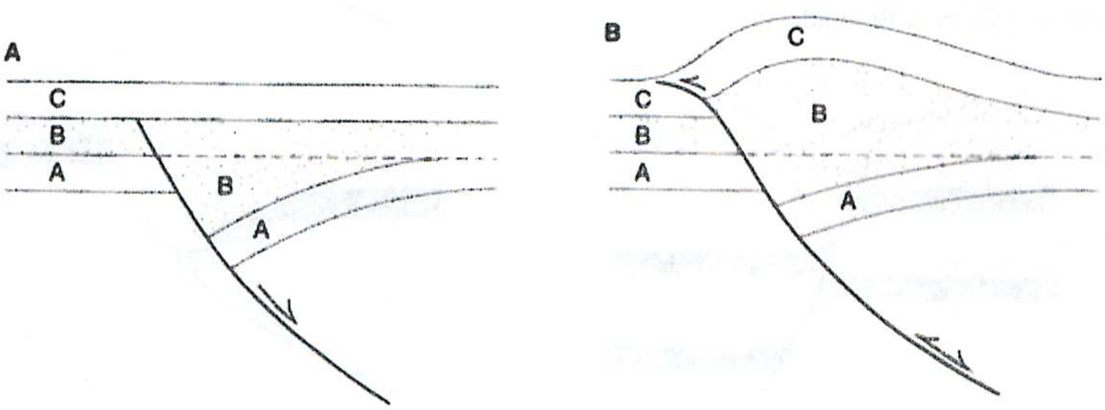
Effects of Brittle or Ductile Shear in Normal Faults

The block diagrams below illustrate the effects of changing the nature of deformation, between brittle deformation (which results in clear fault planes, fractures and fault rocks), ductile deformation (which causes deformation over a larger shear zone). Often, strata of different rheologies will behave differently, as is shown in the figure at right. The dashed layer was weak and deformed ductilely, while the middle grey layer was rigid and formed boudins. Figures from Davis & Reynolds, 1996.



Inversion Tectonics

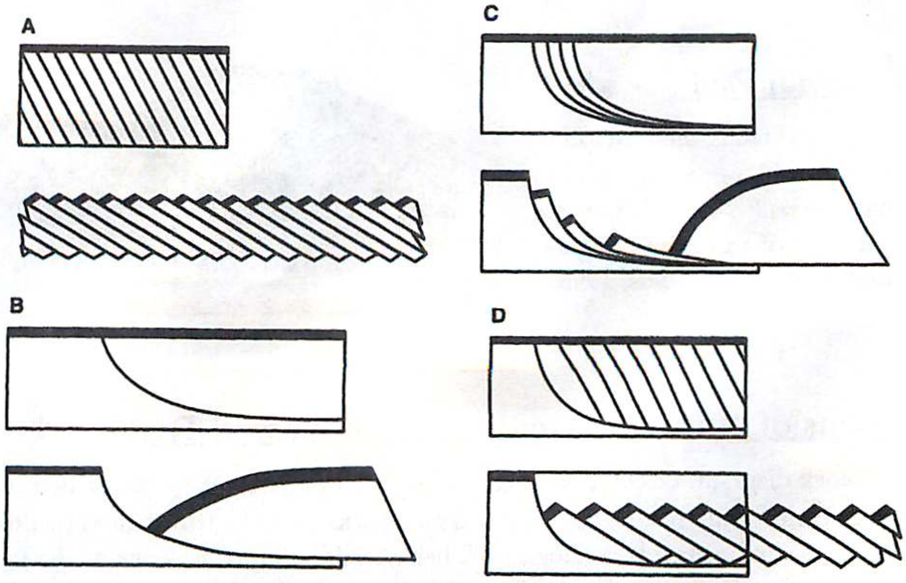
If the regional stresses change, previously inactive faults can reactivate, and change their sense of motion. In the figure at left, layer-A was formed prior to the formation of a normal fault. Layer-B and layer-C were deposited after the formation, and shut down of the fault. In the figure at the right, the fault has reactivated, though as a reverse fault. The resulting stratigraphic sequence is a combination of effects one would expect from both normal and reverse faults. Figures from Davis & Reynolds, 1996.

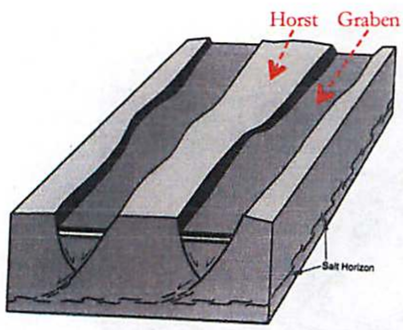


Structural Geology: Normal Faults

Normal Faults Geometries

Various normal *fault* geometries are possible. They all allow for lithospheric extension. (A) Domino style faulting. (B) *Listric normal* faulting with reverse drag. (C) Imbricate listric normal faulting. Note that listric faulting can cause extreme rotation of faulted blocks. (D) Listric normal faulting bounding a family of planar normal faults. Figures from Davis & Reynolds, 1996.



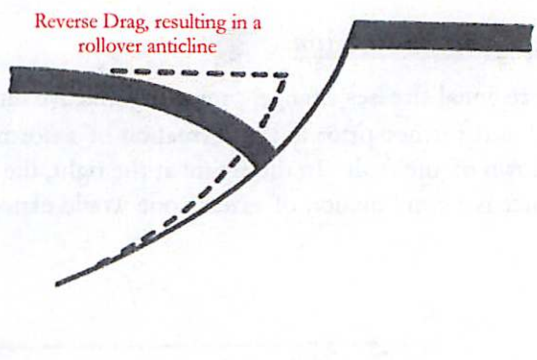


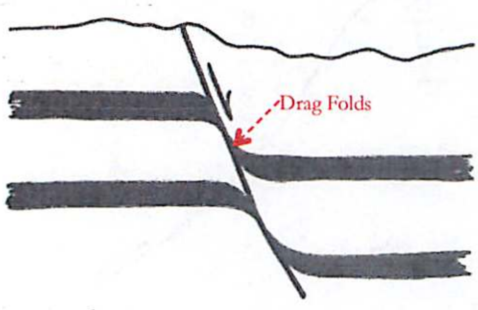
Horsts & Grabens

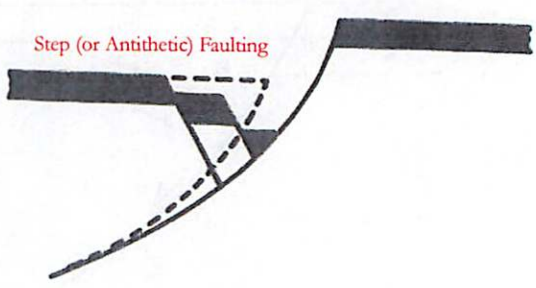
Classical formation describing fault-bounded uplifted (horsts) and down-dropped blocks (grabens). Figures from Davis & Reynolds, 1996.

Drag Folds, Reverse Drag, and Step Faulting

Faulting does not always produce clean displacement along the fault surface. Fault blocks are frequently folded or fractured, and the nature of these deformations are non-trivial. Figures from Davis & Reynolds, 1996.



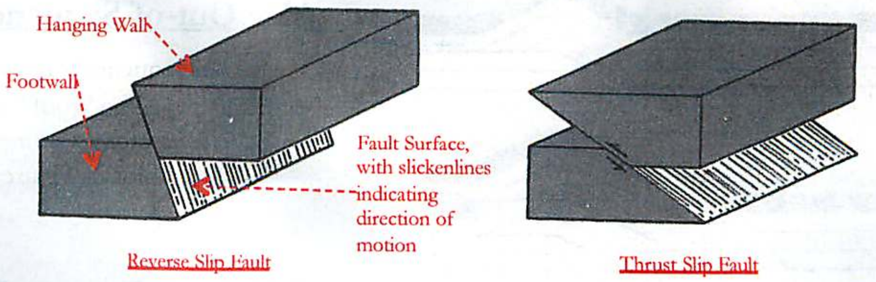




Structural Geology: Reverse & Thrust Faults

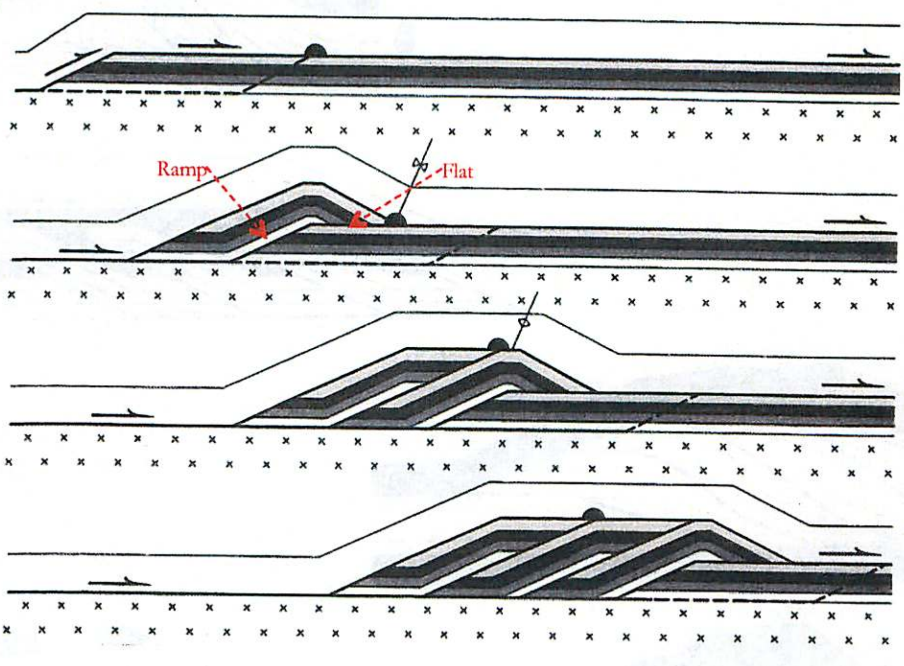
Reverse Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.



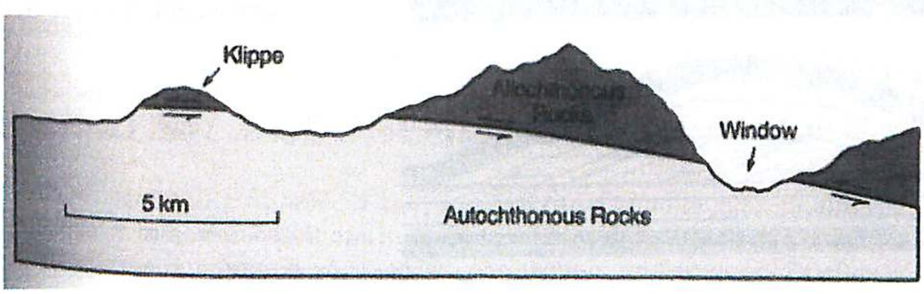
"Ramp-Flat" Geometry of Typical Thrust Fault Systems

In a regional thrust, faulted blocks are "thrust" on top of younger strata. The exact geometry of these thrust systems can vary significantly. Figures from Davis & Reynolds, 1996.

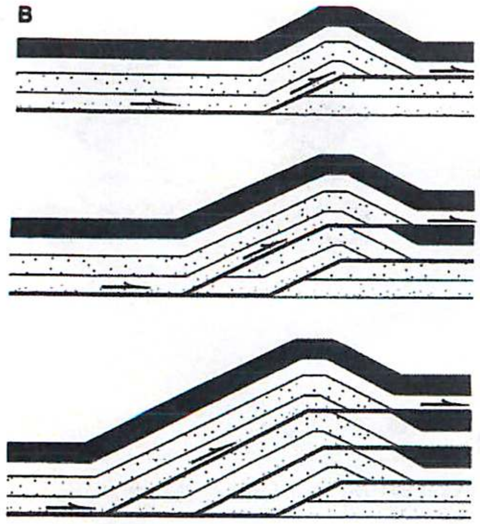


Klippe & Windows

Thrust faults move large blocks of non-indigenous rock (referred to as "allochthonous" rock) over emplaced rock (referred to as "autochthonous" rock). If the overlying allochthonous rock is eroded, it can create windows into the lower underlying autochthonous rock. Erosion can also create islands of isolated allochthonous rock, called klippe. Figures from Davis & Reynolds, 1996.



Structural Geology: Reverse & Thrust Faults

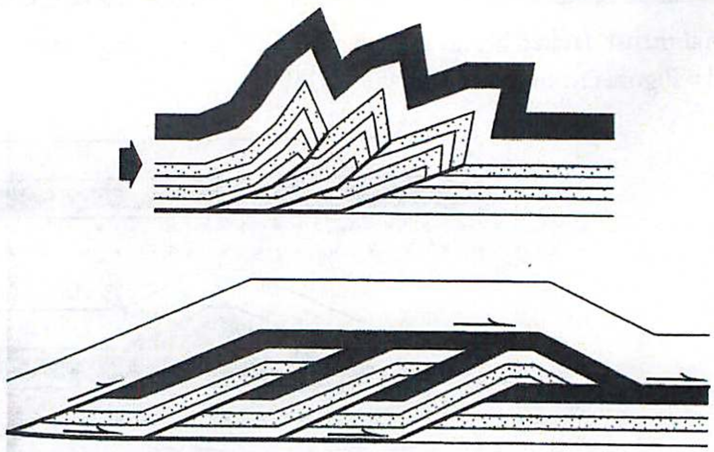


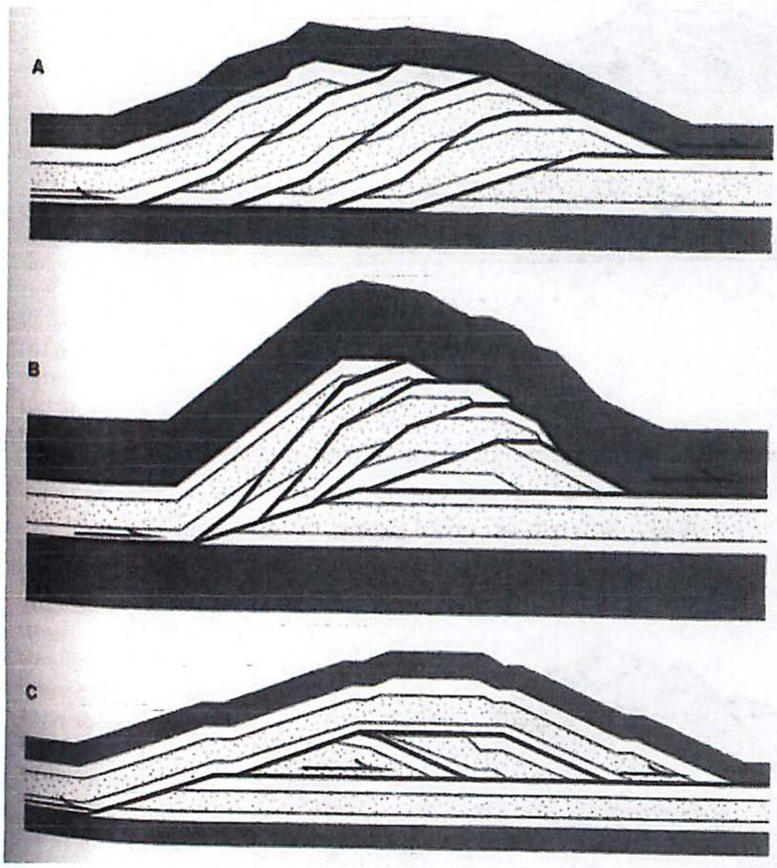
Out-of-Sequence Thrust Fault System

Unlike "in-sequence" thrust fault systems (as shown on the previous page, the "roof" of the thrust block in an out-of-sequence system becomes the "flat" for subsequent fault blocks. Figures from Davis & Reynolds, 1996.

Imbricate Fans vs. Duplexes

Two thrust fault geometries: imbricate fans (top) and duplexes (bottom). Figures from Davis & Reynolds, 1996.





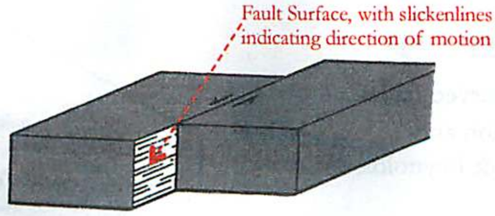
Forms of Duplexes

The exact form of a duplex or imbricate fan depends on the spacing of ramps and the amount of slip. (A) A normal duplex develops when slice length exceeds the fault slip. (B) An antiformal duplex develops when slice length and fault slip are effectively equal. (C) A forward-dipping duplex develops when the fault slip is greater than the slice length. Figures from Davis & Reynolds, 1996.

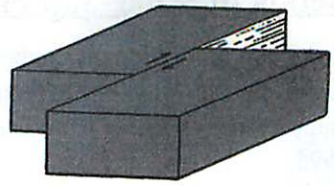
Structural Geology: Strike-Slip or Transform Faults

Strike-Slip Faults

In reverse faults, the footwall goes down with respect to the hanging wall. Normal faults are indicative of compression. Thrust faults are reverse faults with fault dips <45 degrees. Figures from Davis & Reynolds, 1996.



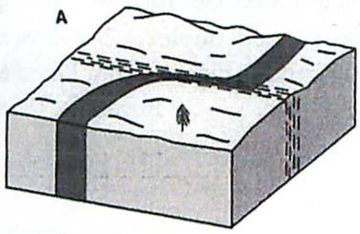
Left Lateral (Sinistral) Strike-Slip Fault



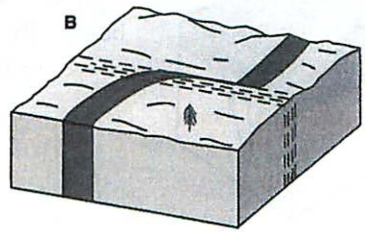
Right Lateral (Dextral) Strike-Slip Fault

Ductile Shear Zones

Shear in a strike-slip fault is not always located in a single plane. Sometimes, shear takes place over an extended region. Figures from Davis & Reynolds, 1996.



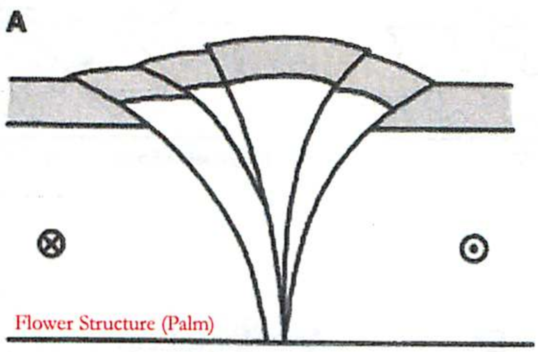
Continuous Shear Zone

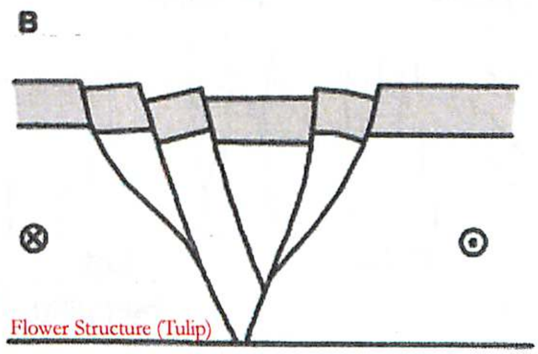


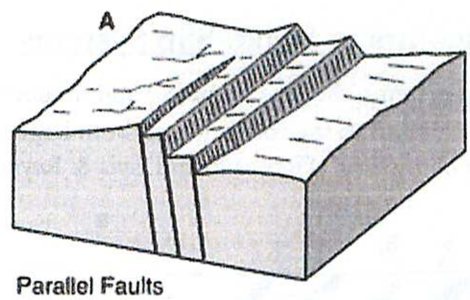
Discontinuous Shear Zone

Brittle Shear Zones

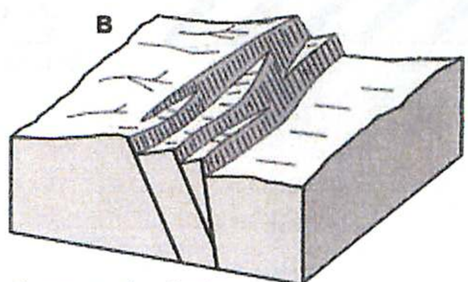
Figures from Davis & Reynolds, 1996.



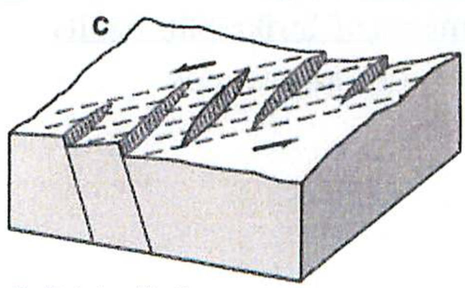




Parallel Faults



Anastomosing Faults

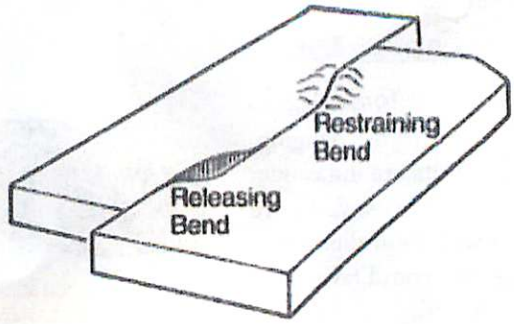


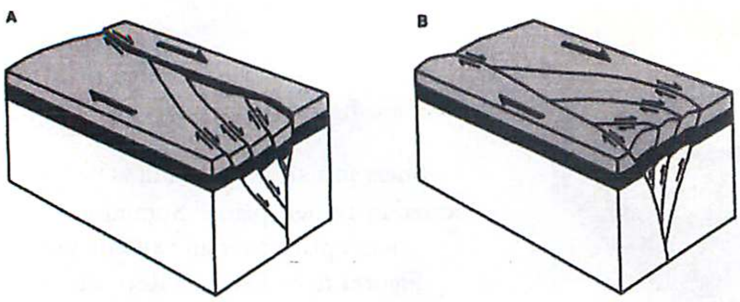
En Echelon Faults

Structural Geology: Strike-Slip or Transform Faults

Bends in Strike-Slip Faults

Strike-slip faults along irregularly curved faults creates localized regions of extension and compression. Figures from Davis & Reynolds, 1996.



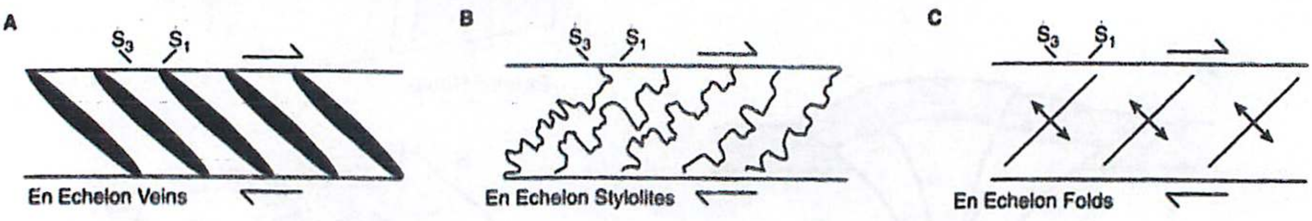


Strike-Slip Duplexes

(A) Extensional duplexes can form at releasing bends. (B) Compressional duplexes can form at restraining bends. Figures from Davis & Reynolds, 1996.

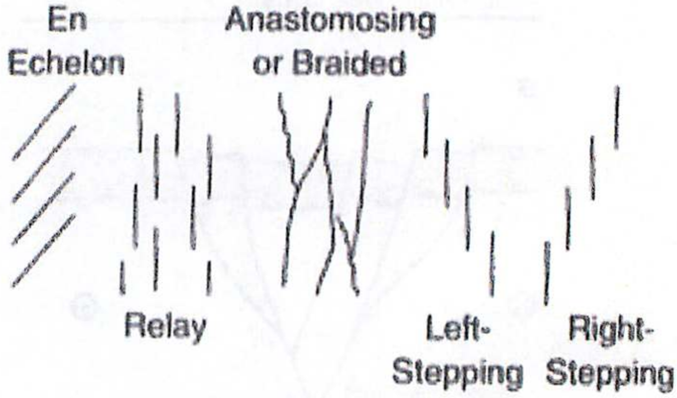
Slip Indicators in Strike-Slip Systems

In strike-slip systems, the maximum (S_1) and minimum compressional stresses (S_3) are at an angle with respect to the sense of shear. This can lead to the formation of both large scale folds and faults, or small scale fractures or veins, which are indicative to the sense of motion. Figures from Davis & Reynolds, 1996.



Even more Geometric Arrangements of Strike-Slip Faults

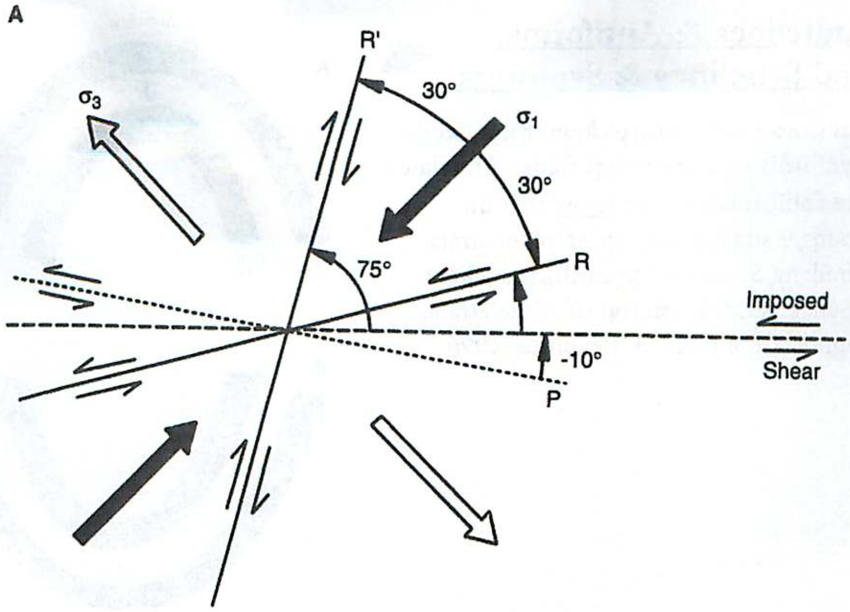
Figures from Davis & Reynolds, 1996.

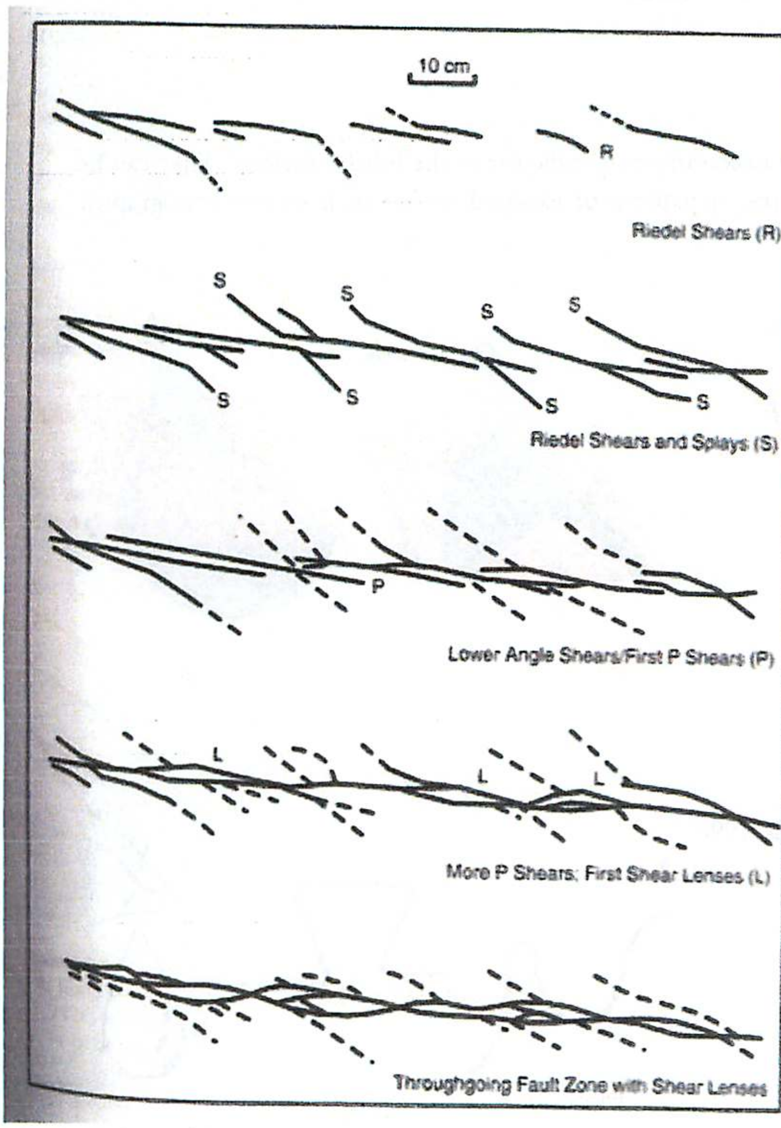


Structural Geology: Strike-Slip or Transform Faults

Riedel Shears

When under compression, rocks tend to form fail with faults forming 30° from the primary compressional stress. In a strike-slip fault, the primary compressional stress (σ_1) is 45° away from the plane of strike-slip shearing. The combination of these two facts results in fractures at interesting angles with respect to the motion of shear. These are called Riedel shears. The figure below shows a left-handed strike-slip zone. Figures from Davis & Reynolds, 1996.



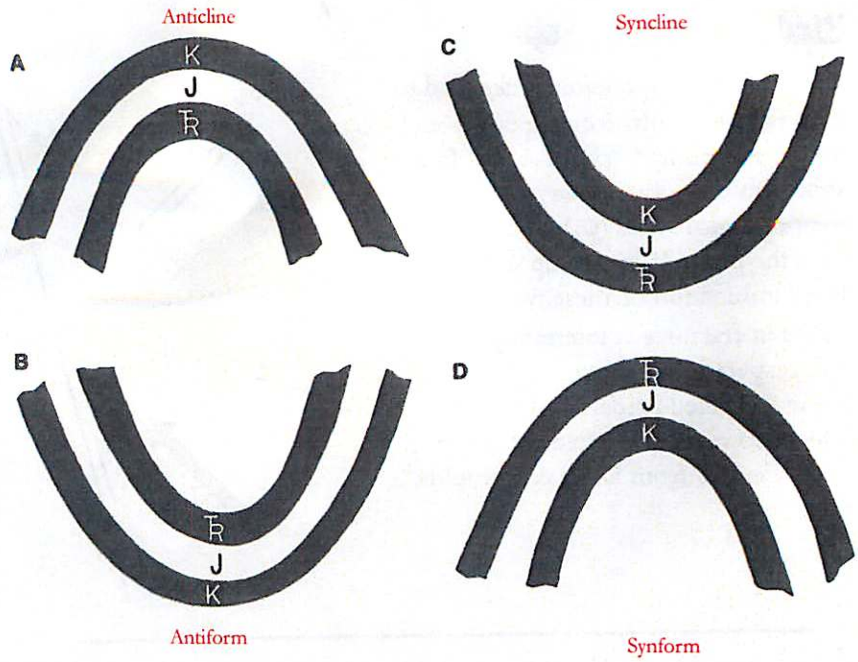


The figure at left illustrate the formation sequence of Riedel shears and other splays and shears in a right-handed strike-slip zone. Figures from Davis & Reynolds, 1996.

Structural Geology: Folds

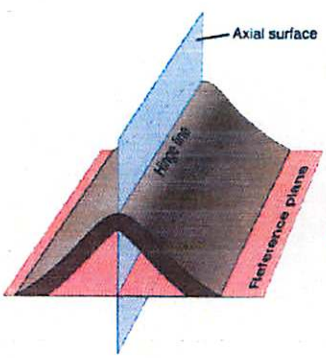
Anticlines & Antiforms, and Synclines & Synforms

Antiforms are concave-down folds, while Synforms are concave-up folds. Anticlines are antiforms were we <u>know</u> that the younger strata lie on top of older strata. Similarly, Synclines are antiforms where younger strata lie on top of older strata. Figures from Davis & Reynolds, 1996.

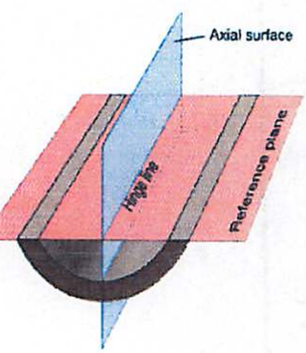


Plunging Folds

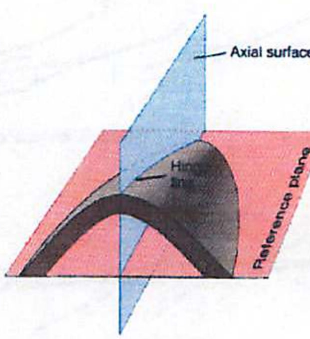
Folds (defined by hinge lines and axial surfaces) are not necessarily perpendicular to the Earth's surface. They can be dipping into or out of the surface. This can create interesting patterns of exposed surface rock, or even topography. Figures from Jones, 2001.



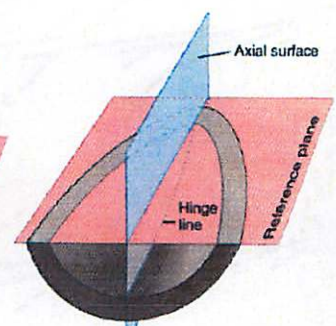
Non-plunging antiform



Non-plunging synform



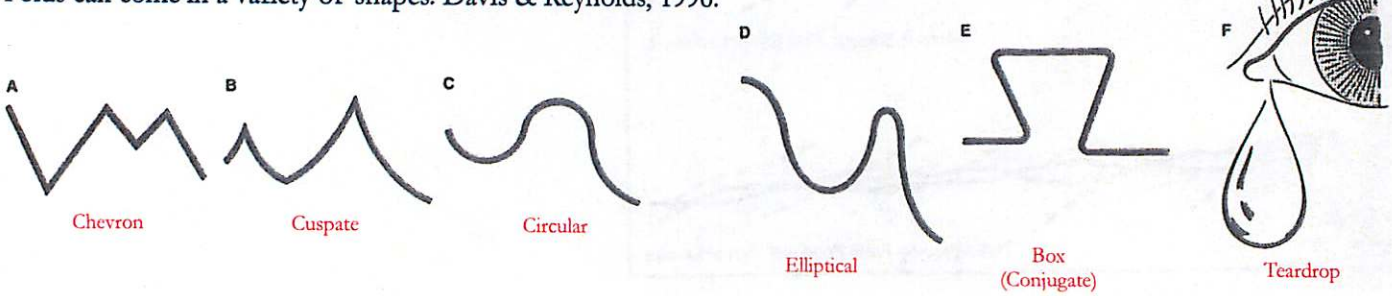
Plunging antiform



Plunging synform

Fold Shapes

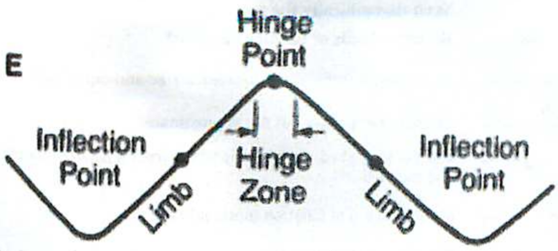
Folds can come in a variety of shapes. Davis & Reynolds, 1996.

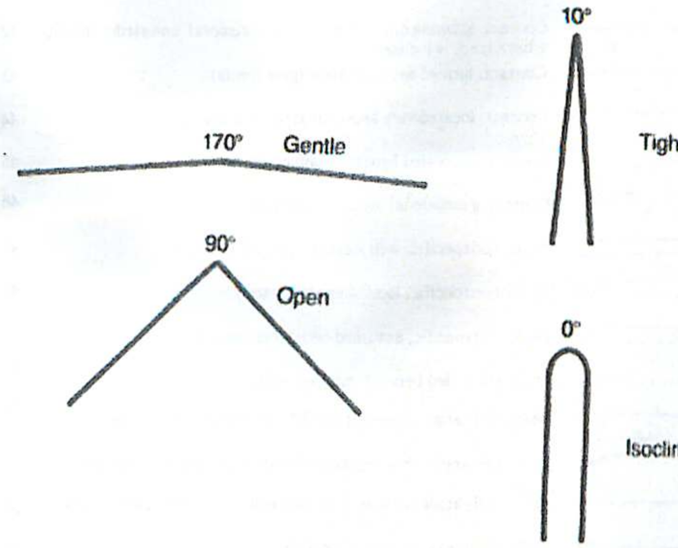


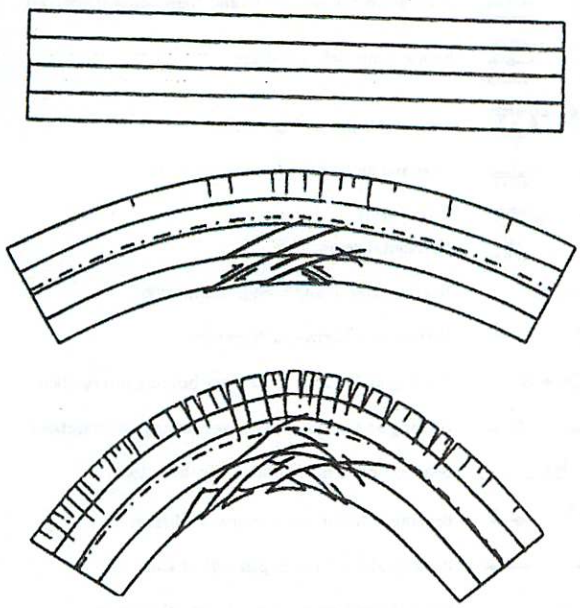
Structural Geology: Folds

Fold Tightness

Fold tightness is based upon the size of the inter-limb angle. Figures from Davis & Reynolds, 1996.





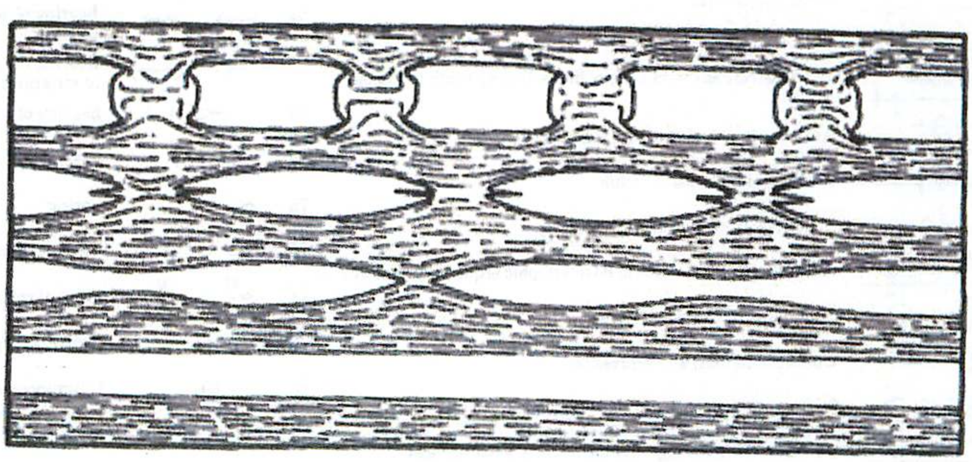


Minor Structures in Folds

When folding layers of strata, layer-parallel stretching occurs in the outer arc of a folded layer, while layer-parallel shortening occurs in the inner arc. Figures from Davis & Reynolds, 1996.

Boudins

Layer-parallel stretching can pinch off layers of strata, depending on the ductility contrast between layers. This can result in pinch-and-swell structures or boudins (where the pinching completely pinches off portions of a given strata). Figures from Davis & Reynolds, 1996.



Geologic Map Symbols

1. Contact, showing dip where trace is horizontal, and strike and dip where trace is inclined
2. Contact, located approximately (give limits)
3. Contact, located very approximately, or conjectural
4. Contact, concealed beneath mapped units
5. Contact, gradational (optional symbols)
6. Fault, nonspecific, well located (optional symbols)
7. Fault, nonspecific, located approximately
8. Fault, nonspecific, assumed (existence uncertain)
9. Fault, concealed beneath mapped units
10. Fault, high-angle, showing dip (left) and approximate dips
11. Fault, low-angle, showing approximate dip and strike and dip
12. Fault, high-angle normal (D or ball and bar on downthrown side)
13. Fault, reverse (R on upthrown side)
14. Fault, high-angle strike-slip (example is left lateral)
15. Fault, thrust (T on overthrust side)
16. Fault, low-angle normal or detachment (D on downthrown side)
17. Fault, low-angle strike-slip (example is right lateral)
18. Fault, low-angle, overturned (teeth in direction of dip)
19. Optional sets of symbols for different age-groups of faults
20. Fault zone or shear zone, width to scale (dip and other accessory symbols may be added)
21. Faults with arrows showing plunge of rolls, grooves or slickensides
22. Fault showing bearing and plunge of net slip
23. Point of inflection (bar) on a high-angle fault
24. Points of inflection on a strike-slip fault passing into a thrust
25. Fault intruded by a dike
26. Faults associated with veins
27. Anticline, showing trace and plunge of hinge or crest line (specify)
28. Syncline (as above), showing dip of axial surface or trough surface
29. Folds (as above), located approximately
30. Folds, conjectural
31. Folds beneath mapped units
32. Asymmetric folds with steeper limbs dipping north (optional symbols)
33. Anticline (top) and syncline, overturned
34. Antiformal (inverted) syncline
35. Synformal (inverted) anticline
36. Antiform (top) and synform (stratigraphic sequence unknown)
37. Separate dome (left) and basin
38. Culmination (left) and depression
40. Vertically plunging anticline and syncline
41. Monocline, south-facing, showing traces of axial surfaces
42. Steeply plunging monocline or flexure, showing trace in horizontal section and plunge of hinges
43. Plunge of hinge lines of small folds, showing shapes in horizontal section
44. Strike and dip of beds or bedding
45. Strike and dip of overturned beds
46. Strike and dip of beds where stratigraphic tops are known from primary features
47. Strike and dip of vertical beds or bedding (dot is on side known to be stratigraphically the top)
48. Horizontal beds or bedding (as above)
49. Approximate (typically estimated) strike and dip of beds
50. Strike of beds exact but dip approximate
51. Trace of single bed, showing dip where trace is horizontal and where it is inclined
52. Strike and dip of foliation (optional symbols)
53. Strike of vertical foliation
54. Horizontal foliation
55. Strike and dip of bedding and parallel foliation
56. Strike and dip of joints (left) and dikes (optional symbols)
57. Vertical joints (left) and dikes
58. Horizontal joints (left) and dikes
59. Strike and dip of veins (optional symbols)
60. Vertical veins
61. Horizontal veins
62. Bearing (trend) and plunge of lineation
63. Vertical and horizontal lineations
64. Bearing and plunge of cleavage-bedding intersection
65. Bearing and plunge of cleavage-cleavage intersections
66. Bearings of pebble, mineral, etc. lineations
67. Bearing of lineations in plane of foliation
68. Horizontal lineation in plane of foliation
69. Vertical lineation in plane of vertical foliation
70. Bearing of current from primary features; from upper left: general; from cross-bedding; from flute casts; from imbrication
71. Bearing of wind direction from dune forms (left) and cross-bedding
72. Bearing of ice flow from striations (left) and orientation of striations
73. Bearing of ice flow from drumlins
74. Bearing of ice flow from crag and tail forms
75. Spring
76. Thermal spring
77. Mineral spring
78. Asphaltic deposit
79. Bituminous deposit
80. Sand, gravel, clay, or placer pit

From Compton, 1985

Geologic Map Symbols

81	Mine, quarry, or open pit
82	Shafts: vertical, inclined, and abandoned
83	Adit, open (left) and inaccessible
84	Trench (left) and prospect
85	Water wells: flowing, nonflowing, and dry
86	Oil well (left) and gas well
87	Well drilled for oil or gas, dry
88	Wells with shows of oil (left) and gas
89	Oil or gas well, abandoned (left) and shut in
90	Drilling well or well location
91	Glory hole, open pit, or quarry, to scale
92	Dump or fill, to scale

Fossil and Structural Symbols for Stratigraphic Columns

- Algae
- Algal mats
- Ammonites
- Belemnites
- Brachiopods
- Bryozoans
- Corals, solitary
- Corals, colonial
- Crinoids
- Echinoderms
- Echinoids
- Fish bones
- Fish scales

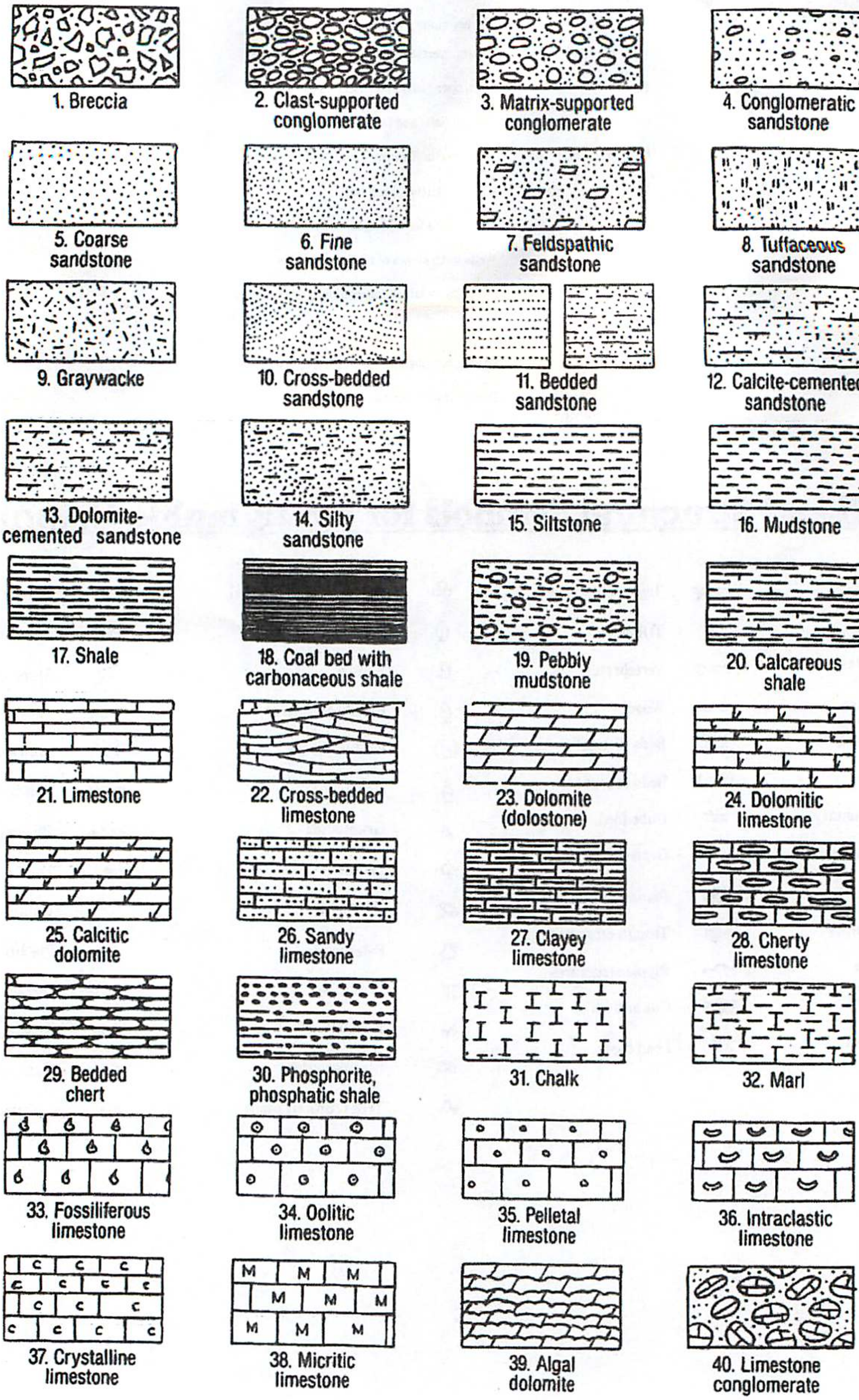
- Tree trunk fallen
- Trilobites
- Vertebrates
- Wood
- Beds distinct
- Beds obscure
- Unbedded
- Graded beds
- Planar cross-bedding
- Trough cross-bedding
- Ripple structures
- Cut and fill
- Load casts

- Foraminifers, general
- Foraminifers, large
- Fossils
- Fossils abundant
- Fossils sparse
- Gastropods
- Graptolites
- Leaves
- Ostracodes
- Pelecypods
- Root molds
- Spicules
- Stromatolites
- Tree trunk in place

- Scour casts
- Convolution
- Slumped beds
- Paleosol
- Mud cracks
- Salt molds
- Burrows
- Pellets
- Oolites
- Pisolites
- Intraclasts
- Stylolite
- Concretion
- Calcitic concretion

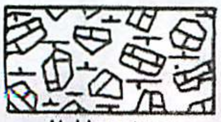
From Compton, 1985

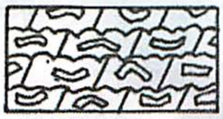
Lithologic Patterns for Stratigraphic Columns & Cross Sections



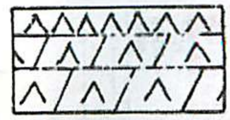
From Compton, 1985

Lithologic Patterns for Stratigraphic Columns & Cross Sections

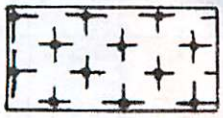

41. Limestone breccia

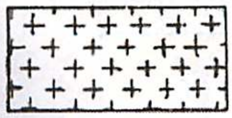

42. Algal dolomite breccia

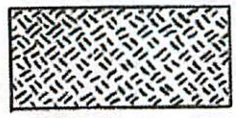

43. Gypsum bed, gypsiferous shale

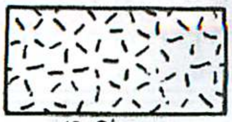

44. Anhydrite, anhydritic dolomite

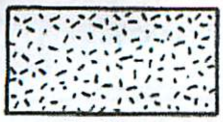

45. Rock salt, salty mudstone

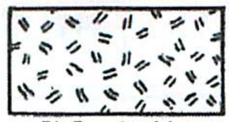

46. Peridotite

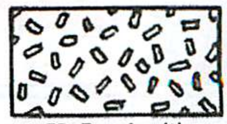

47. Gabbro


48. Mafic plutonic rock

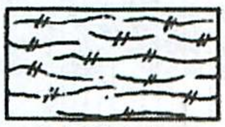

49. Coarse granitic rock

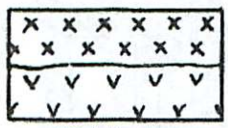

50. Fine granitic rock


51. Porphyritic plutonic rock

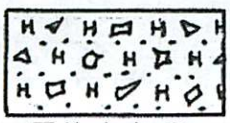

52. Porphyritic plutonic rock

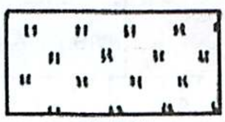

53. Mafic lava

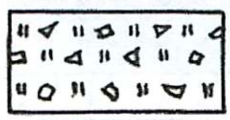

54. Silicic lava

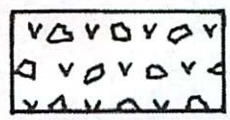

55. Intrusive volcanic rocks

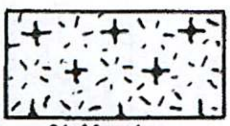

56. Pillow lava


57. Hyaloclastite

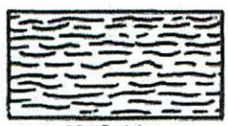

58. Tuff

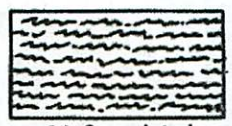

59. Tuff-breccia

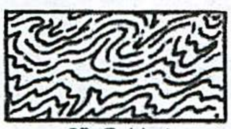

60. Volcanic breccia

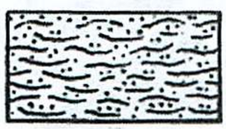

61. Massive serpentinite


62. Foliated serpentinite

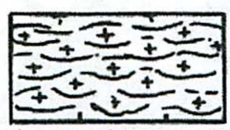

63. Schist

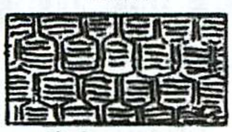

64. Crenulated schist


65. Folded schist

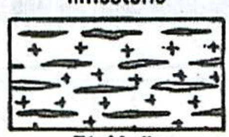

66. Semischistose sandstone

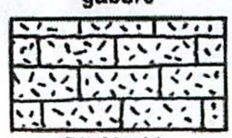

67. Semischistose limestone

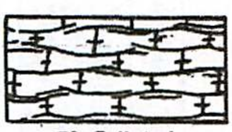

68. Semischistose gabbro

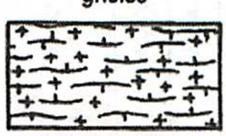

69. Greenstone


70. Silicic gneiss

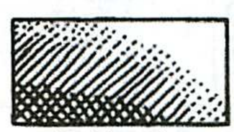

71. Mafic gneiss

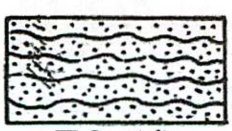

72. Marble

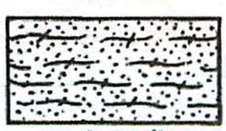

73. Foliated marble

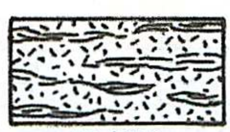

74. Foliated calc-silicate rock

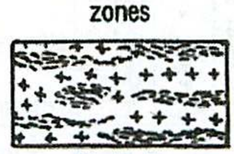

75. Massive skarn


76. Alteration zones


77. Quartzite

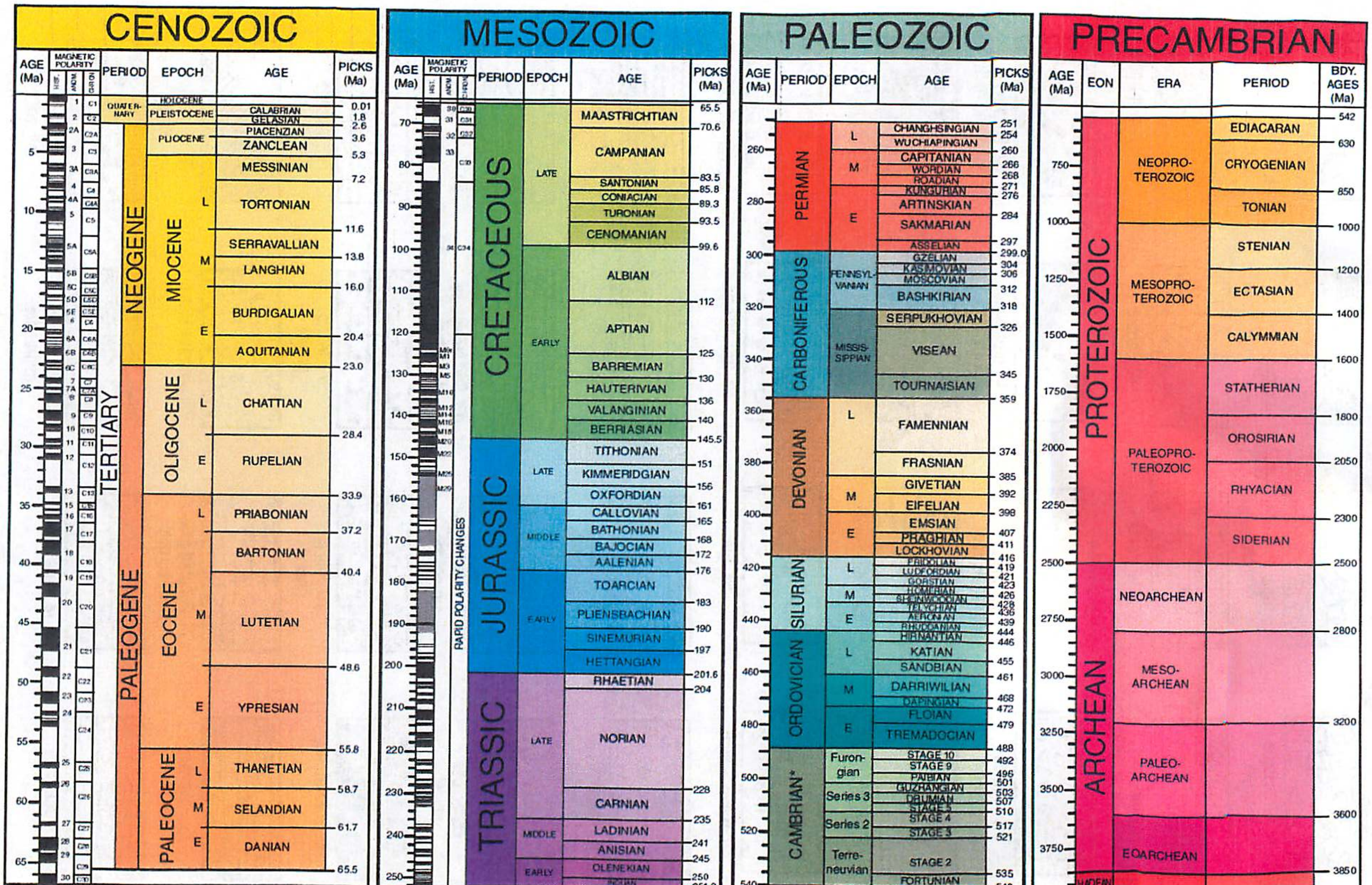

78. Quartzite


79. Silicic migmatite


80. Mafic migmatite

From Compton, 1985

Geologic Timescale



2009 version, from the Geologic Society of A

10 cm ruler

ROCK DENSITIES

Material type	Density range (Mg/m³)	Approximate average density (Mg/m³)
Sedimentary rocks		
Alluvium	1.96–2.00	1.98
Clay	1.63–2.60	2.21
Gravel	1.70–2.40	2.00
Loess	1.40–1.93	1.64
Silt	1.80–2.20	1.93
Soil	1.20–2.40	1.92
Sand	1.70–2.30	2.00
Sandstone	1.61–2.76	2.35
Shale	1.77–3.20	2.40
Limestone	1.93–2.90	2.55
Dolomite	2.28–2.90	2.70
Chalk	1.53–2.60	2.01
Halite	2.10–2.60	2.22
Glacier ice	0.88–0.92	0.90
Igneous rocks		
Rhyolite	2.35–2.70	2.52
Granite	2.50–2.81	2.64
Andesite	2.40–2.80	2.61
Syenite	2.60–2.95	2.77
Basalt	2.70–3.30	2.99
Gabbro	2.70–3.50	3.03
Metamorphic rocks		
Schist	2.39–2.90	2.64
Gneiss	2.59–3.00	2.80
Phylite	2.68–2.80	2.74
Slate	2.70–2.90	2.79
Granulite	2.52–2.73	2.65
Amphibolite	2.90–3.04	2.96
Eclogite	3.20–3.54	3.37

Udden-Wentworth Grain Size Scale

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

MOHS HARDNESS SCALE

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