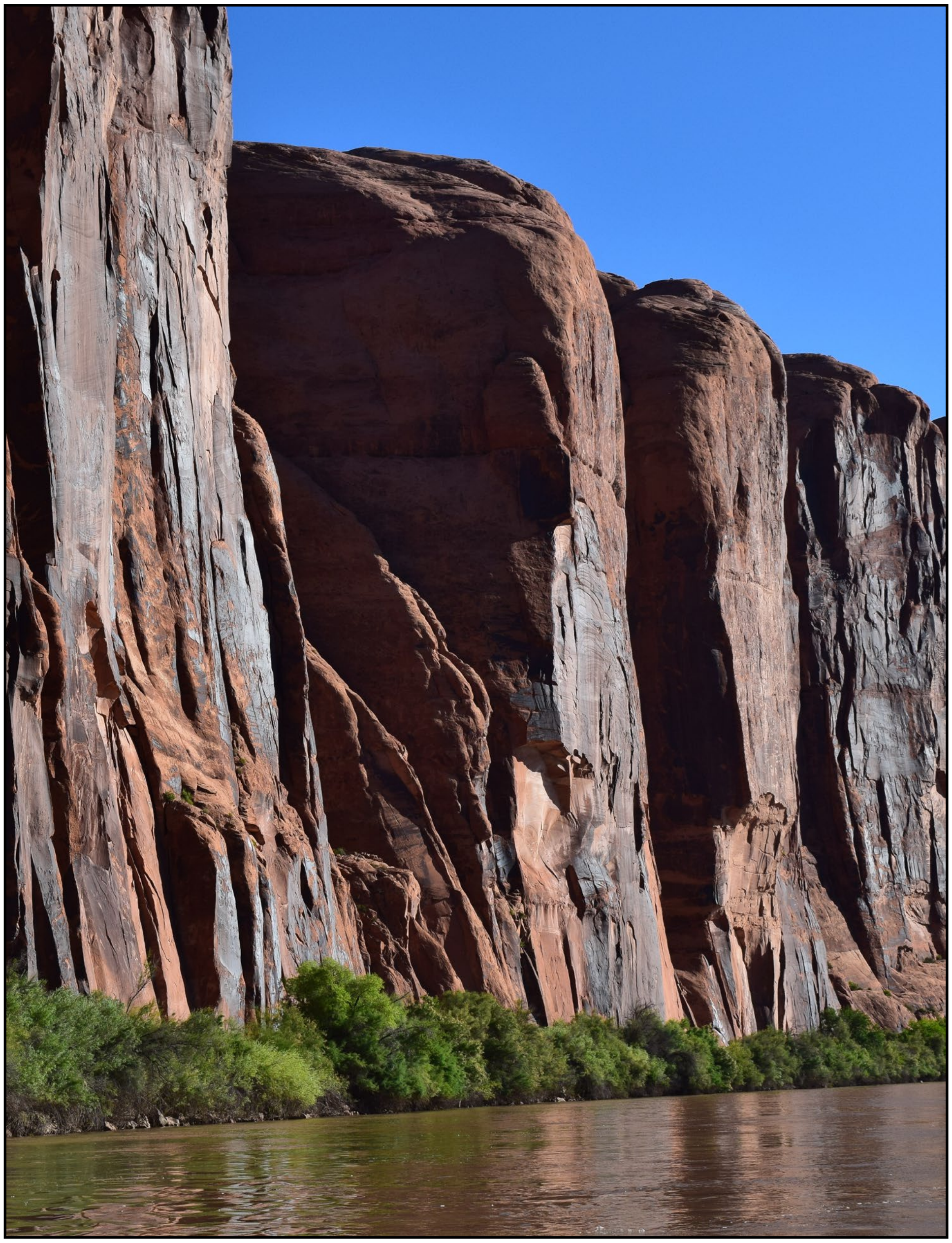
Guidebook for the Union College Geosciences Western Interior Field Trip

24 August to 2 September, 2022



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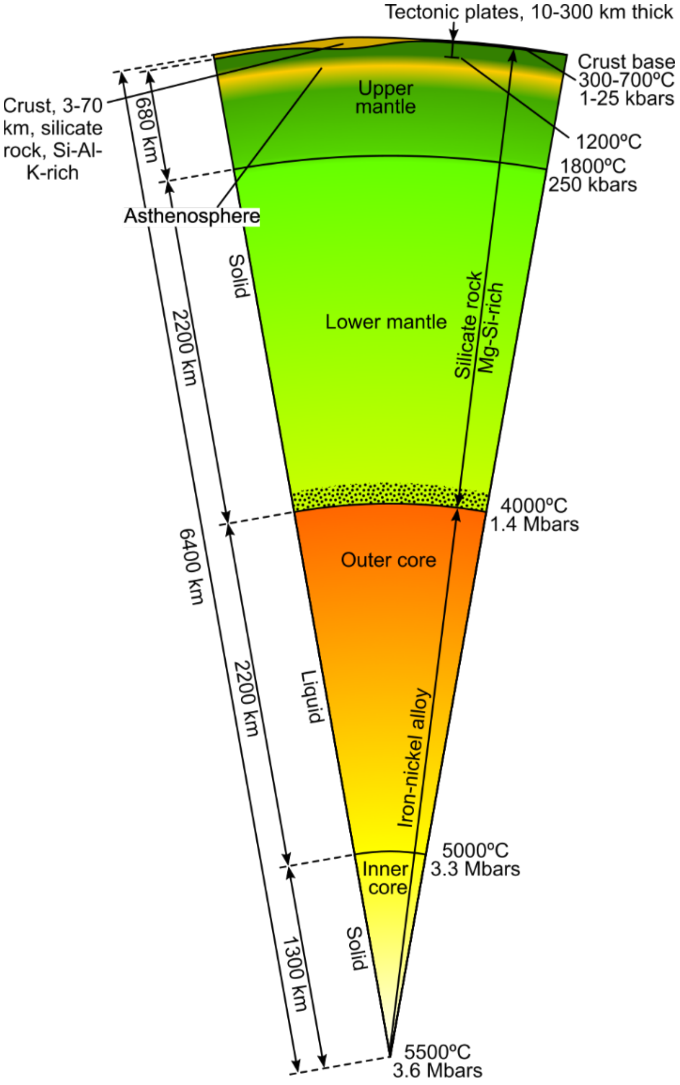
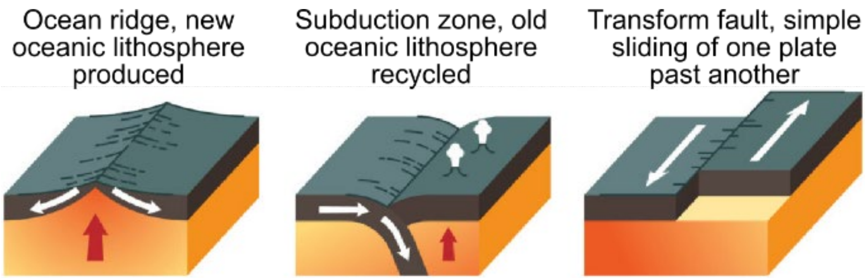
Introduction to How the Earth Works

Earth is a 4.5 billion year old planet, with silicate (silicon-oxygen-rich) outer parts, the mantle and crust, and a metal-rich (iron and nickel) inner part, the core. The mantle and crust are almost entirely solid rock, with small amounts of silicate liquid (melted rock, magma) here and there. The metal core has two parts, a solid inner core, and a liquid outer core. Convection in the electrically conducting outer core produces Earth's magnetic field. The layered structure is caused by material densities: dense things sank to the bottom, and low-density things floated to the top. Movies where people drill to the core, and the liquid metal erupts to the surface, are ridiculous (but fun) because the dense metal wants to stay down there.

The mantle convects too, in complicated ways, including convection that influences plate tectonics. The tectonic plates include the crust, which is typically 3-10 km thick under the oceans and 20-50 km thick on continents, and the upper part of the mantle, down to where the temperature reaches about 1200°C. Plates range in thickness from about 10 km beneath mid-ocean ridges, to 300 km beneath old, stable continental interiors. At low temperatures, nearer to the surface, rocks are strong and resist deforming, making up the tectonic



Schematic cross section of Earth's interior layering.

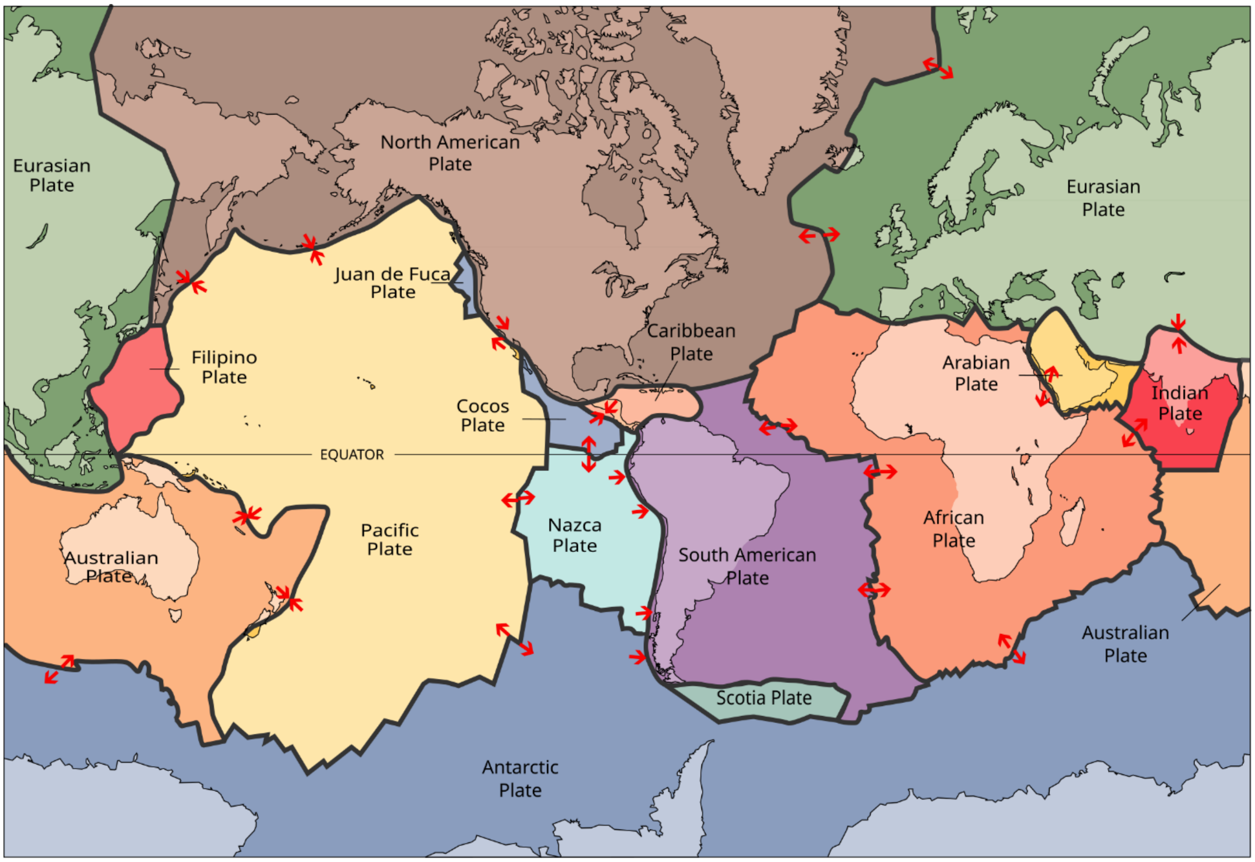


Schematic cartoons of the three kinds of plate boundaries.
https://www.science-sparks.com/orange-peel-plate-tectonics/

plates. Beneath that, the hotter mantle rock is relatively weak and ductile, and so it deforms easily over long periods of time, allowing it to convect.

Earth's surface is broken into several large, internally rigid regions known as tectonic plates. *Plate tectonics* is the description of the large-scale architecture and mechanics of those plates. There are three kinds of boundaries between adjacent plates: ocean ridges where plates separate and new oceanic lithosphere is formed; subduction zones where plates converge and old, cold, dense oceanic lithosphere sinks back down into the mantle; and transform faults, where plates simply slide past one another. The figure above illustrates the ideas.

Plate tectonics is driven mostly by elevation and density differences. Mid-ocean ridges are at high elevation, generally standing 2 to 3 km higher than the ocean floor hundreds of kilometers to either side. Ocean ridges stand high because of the hot, buoyant mantle rock rising up underneath them. As the oceanic lithosphere ages, it cools and thickens, and becomes denser. High ridge elevation allows the plates on either side to slide downhill over ductile asthenospheric mantle below (like a sled sliding down a snowy hill), moving plates slowly away from the ridge. Just like a boat tends to sink when it becomes denser than water, old, cold, dense oceanic lithosphere tends to sink into the underlying hotter mantle when it becomes dense enough, making subduction zones. So, oceanic lithosphere slides down off ocean ridges, pushing along the same plate farther away, and the sinking, dense lithosphere at subduction zones drags along the younger lithosphere behind



Schematic map of large tectonic plates on Earth. Arrows show mid-ocean ridges (←→), subduction zones (→←), and some transform faults. https://en.wikipedia.org/wiki/List_of_tectonic_plates it. Those passive, gravity- and density-driven processes drive plate tectonics, and also some mantle convection.

Melting of mantle rock at mid-ocean ridges and subduction zones produces magmas: melted rock. The magma rises because it (as a liquid) has lower density than surrounding solid rocks, forming volcanoes at the surface, and plutonic rocks where the magma solidified below ground. At mid-ocean ridges, the igneous rocks are mostly basalt and equivalents, dark rock made mostly of the minerals pyroxene, plagioclase, olivine, and magnetite. In the volcanic arcs of subduction zones, basalts are also erupted, but other processes (melting the crust, partial crystallization of magmas) produce more light-colored, low-density, silica-rich rocks including andesite and diorite, and rhyolite and granite.

Multiple melting episodes beneath volcanic arcs allows low-density andesite and rhyolite magmas to rise, making an upper layer of low-density rock that eventually becomes continental crust. Continental crust is dominated by these low-density, silica-rich rocks, which remain buoyant even when cold. That helps continental *lithosphere*, or continental crust plus its previously melted underlying mantle (to a depth where it reaches about 1200°C) to remain buoyant. Oceanic crust is produced and recycled back into the mantle on a time scale of about 100 million years, but continental crust remains on the surface almost forever.

This field trip tells some of the story of continental crust in the western United States. The next section will look at how that region evolved over about the last 600 million years, to produce the rocks that we see today.

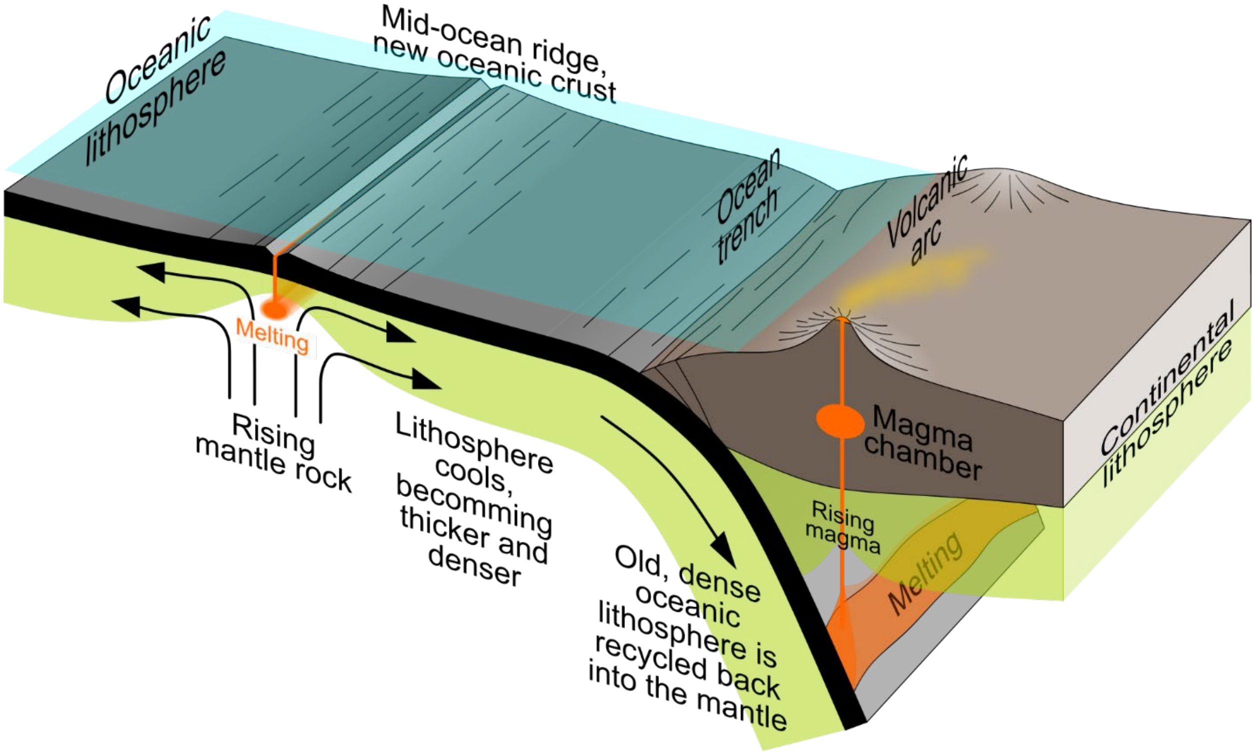
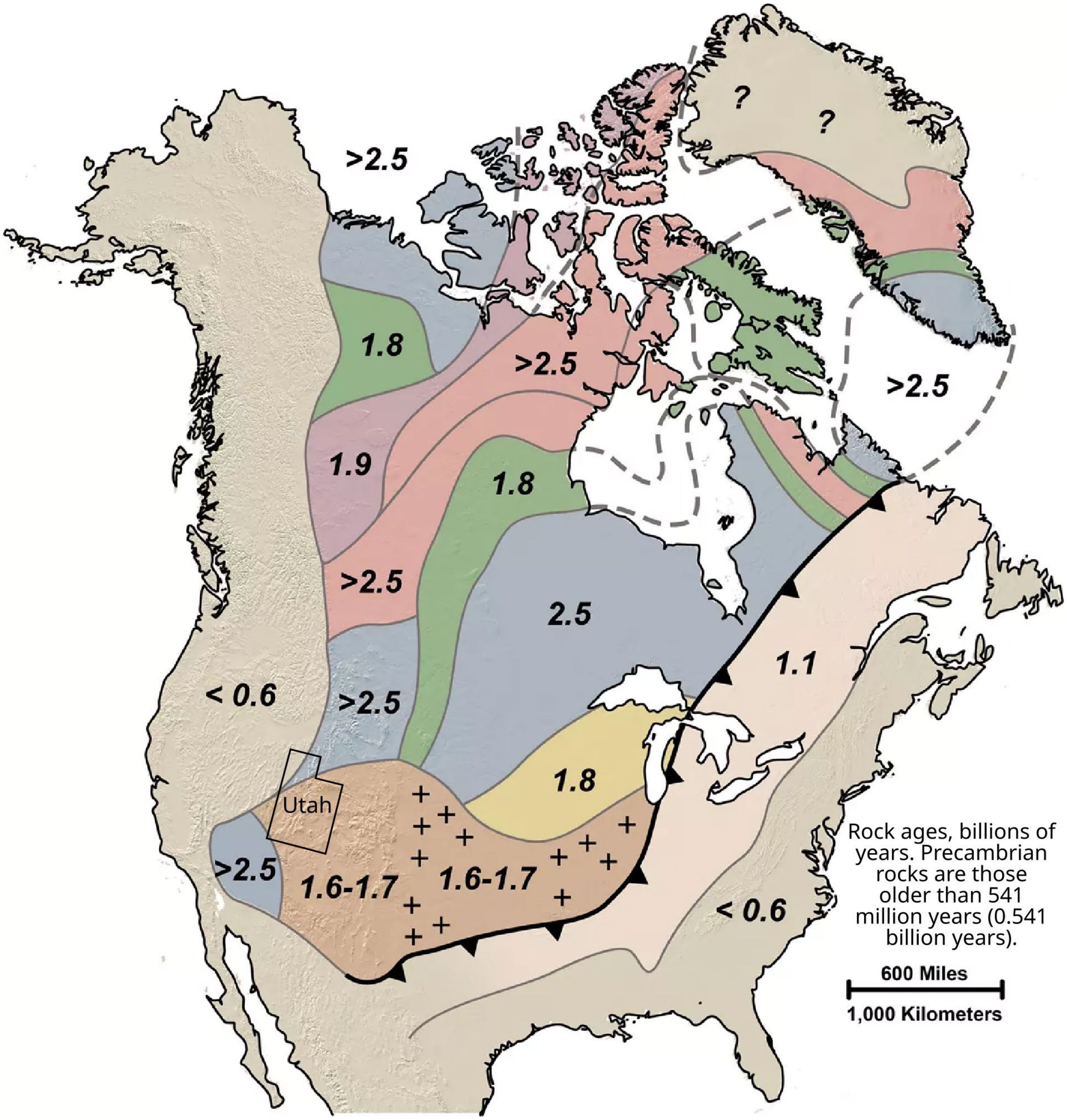


Plate tectonic schematic, showing formation of new oceanic lithosphere (mantle + crust) at mid-ocean ridges, and its recycling back into the mantle at subduction zones. It is principally gravity that drives this motion: sliding downhill off the ridges, and sinking of the dense, cold, thick, old oceanic lithosphere.

Geologic History of the Colorado Plateau

From small islands of continental crust billions of years ago, continents gradually grew in area as more low-density andesitic and rhyolitic crustal material formed in volcanic arcs. Collisions between arcs and small continental fragments welded them together into ever larger land masses. The long history of the Precambrian left the North America of 600 million years ago as an amalgam of welded-together arcs and continental fragments of different ages. Erosion has removed sedimentary rocks in many areas, leaving exposed ancient igneous, metamorphic, and even some sedimentary rocks of the middle and upper crust.

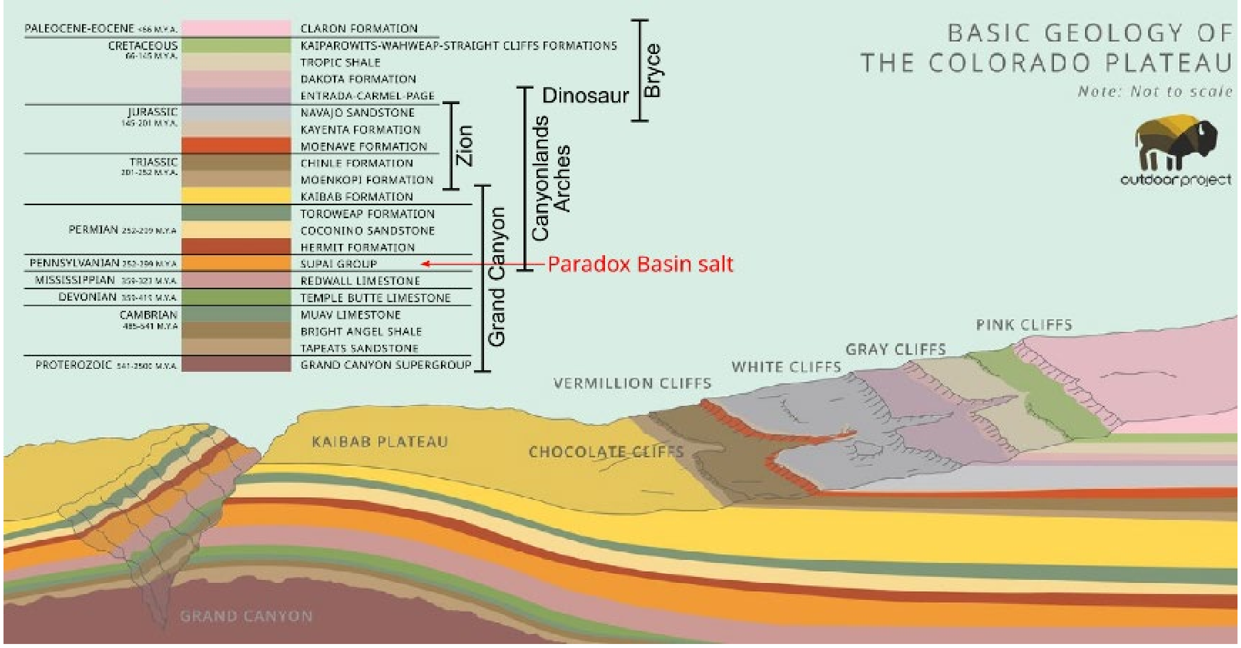


Rock ages, billions of years. Precambrian rocks are those older than 541 million years (0.541 billion years).

Approximate ages that different parts of North American continental crust was formed.
https://www.nps.gov/subjects/geology/plate-tectonics-accreted-terranes.htm

Starting in the Cambrian Period, onto this erosion surface were deposited a series of sedimentary layers that have been given a variety of formation names. Each formation was not deposited in one batch at one time, but rather was deposited over a moderate span of geologic time, commonly in different places at somewhat different times. During some time periods deposited sediments were exposed at the surface, and so were eroded away, and others were not deposited at all. This causes the precise rock layering to be somewhat different in one place as compared to another. Another thing that makes studying sedimentary rocks difficult is that different workers in different areas give similar units different names. It can get very confusing. Nevertheless, in the figures below is an overall summary of the sedimentary layering in the Colorado Plateau.

You might be wondering what the Colorado Plateau is. It is a physiographic province of North America. That is, it is an area with a series of landscapes that make the Colorado Plateau distinct from areas around it. In the figure below, you can see the outline of the Colorado Plateau. It is bounded by high mountain ridges of the Rockies to the north and east, by the Rio Grande Rift to the southeast, a sizable volcanic field to the south, and by Basin and Range provinces to the southwest and west. The deposited sediments, erosion, faulting, and uplift all controlled what can be seen at the surface. What we see is therefore related to the geologic development of this region.



Schematic stratigraphic and landscape diagram of the Colorado Plateau, principally in southern Utah and northern Arizona. https://www.outdoorproject.com/articles/history-stone-basic-geology-colorado-plateau

Physiographic provinces of the western United States. Adapted from: https://gotbooks.miracosta.edu/geology/regions/index.html

Important Concepts in the Geosciences

Although igneous, metamorphic, and sedimentary rocks can all be found in the Colorado Plateau—and we will find examples of each!—the region is especially a showcase for sedimentary geology. Sedimentary rock layers can be deciphered like a text written in an ancient language. Geoscientists who do a lot of stratigraphy (literally, "*description of rock layers*") are skilled in this "ancient language" and can parse out quite a lot of information from the cliffs that will surround us. Many stratigraphers especially enjoy dry canyonlands like those of the Colorado Plateau because a large portion of the rock record is on full display. In forested areas like Schenectady NY, geology classes frequently visit roadcuts in lieu of canyons.

Before we get much further, let's run through a few key geologic concepts that are helpful in understanding the geology we will see. You can flip back to these next pages as needed throughout the rest of our trip.

The Stratigraphic Principles ("Layer-Cake Geology" Rules of Thumb)

The Stratigraphic Principles are a set of basic, intuitive assumptions geoscientists make when interpreting sedimentary rock layers, or *strata*. They form the keystone to our task of reading rocks like a book. No need to remember the principle names…until you take a geology class. Just keep the ideas in mind as we travel around!

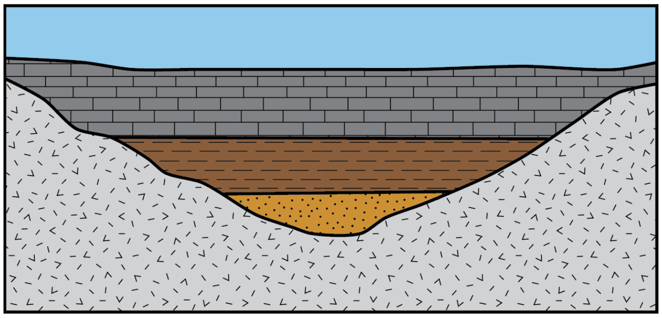
1. Principle of Superposition:

In an undisturbed package of rock layers, the rocks at the top are younger than the rocks at the bottom ***because:*** The older rocks had to be present before the younger rocks could be deposited on top of them.

2. Principle of Original Horizontality:

Due to gravity, sediment is initially deposited in a horizontal layer parallel to the Earth's surface and ***this means:*** Any tilting or folding of rock layers happened *after* they were deposited; they had to be present in order to be deformed.

Superposition: *The oldest rocks are at the bottom and the youngest at the top.*



Original Horizontality: *Rock layers are deposited horizontally and approximately parallel to one another. In this schematic, they were deposited into a basin gouged into granite.*

3. Principle of Cross-Cutting Relationships:

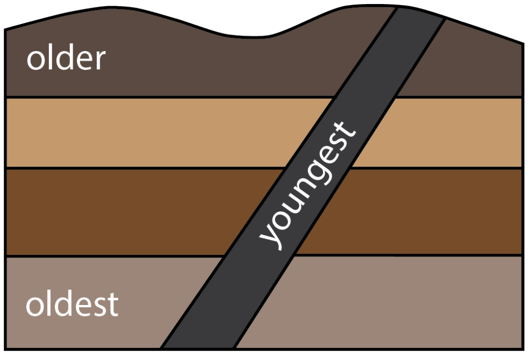
Any feature (like a fault or dike) that crosscuts one or more rock layers is *younger* than the rock layers it cuts ***because:*** The rock layers needed to be present in order to be crosscut; this could not happen the other way around.

But a fresh layer may eventually be deposited on top of the crosscutting feature; this layer, which is *not* crosscut, is necessarily younger than the feature.

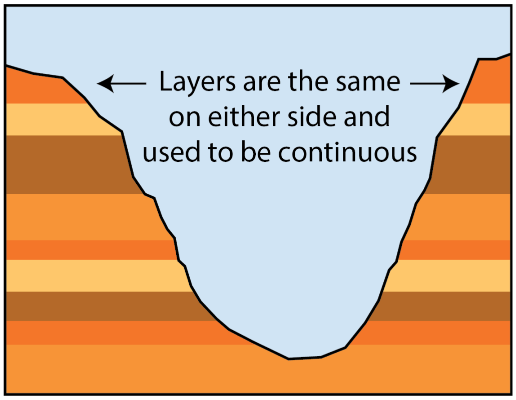
4. Principle of Lateral Continuity:

Rock layers are continuous until they encounter objects that block their deposition (like mountains) or until they are acted upon by erosive agents *after* deposition (like rivers).

This means: Even though they no longer physically connect, the rock layers exposed on one wall of a canyon are the same as the rock layers exposed on the opposite wall of the canyon, and were continuous until erosive agents sliced through them.



Cross-Cutting Relationships: *Cross-cutting features are younger than the rocks they cut through. In this schematic, a dike (igneous intrusion) cut through all of the layered sedimentary strata.*



Lateral Continuity: *Rock layers on either side of a canyon were originally continuous and thus correspond.*

Folds and Faults

Although sediments are deposited into approximately flat, horizontal layers, the motion of tectonic plates can generate forces that shift them out of their original orientation. There are three types of tectonic motion, corresponding to three types of forces:

Tensional (extensional) forces – Generated by plates moving away from each other, thinning and pulling apart (divergent motion).

Compressional forces – Generated by plates moving towards each other and colliding (convergent motion).

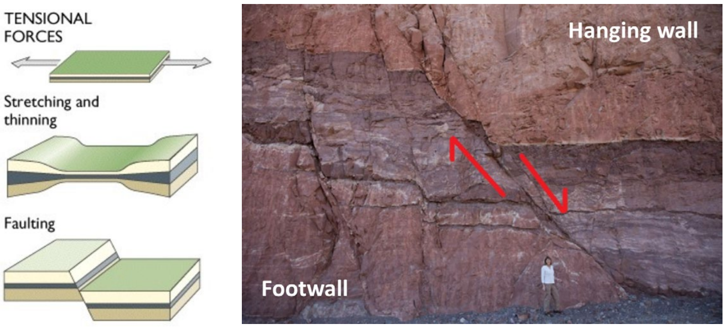
Shear forces – Generated by plates moving laterally to each other, scraping past one another without convergence or divergence.

Rocks can respond to (or more scientifically, "accommodate") tectonic forces in several different ways. The type of response depends on the brittleness of the rock affected—and thus, how deep down it is in the crust. As a general rule of thumb, **cooler rock**, closer to the Earth's surface, is ***brittle***; it breaks into coherent bits under stress, similar to a piece of glass. **Hotter rock**, closer to the heat of the mantle (or *in* the mantle), is ***ductile***; it is a solid that can bend and flow under stress, kind of like what happens if you heat up a piece of stiff plastic below its melting point.

Under stress brittle rocks break into faults, while ductile rocks can be folded and sheared without breaking.

Responses to tensional forces

When plates pull apart, brittle rocks break into **normal faults**. These faults are driven by gravity, which means that the greatest force acting upon the faulted rock is perpendicular to the Earth's surface.



Left: Tensional forces block diagrams. Right: Normal fault. Arrows indicate sense of motion (how each block moved).

A fault is comprised of two blocks: The "hanging wall" and the "footwall." The hanging wall rests on top of the footwall, and slides up or down in relation to the footwall. In a normal fault, the hanging wall drops down (to a lower elevation) relative to the footwall, breaking through preexisting rock layers.

If a brittle rock breaks *without* a sense of motion, rather than "faults" the fractures are called "joints." The crucial distinction between faults and joints is that there is motion along a fault, while there is *no motion* along a joint. If ever motion starts to occur along a joint or other fracture, it is then considered a fault. Joints occur in sets: groups of fractures that are parallel to each other.

Under tensional forces, ductile, stretchable rocks do just that: They stretch out—and thin out—without breaking, like pulling a gob of silly putty from either end.

Responses to compressional forces

When plates collide, brittle rocks break into **reverse faults** (or thrust faults). The greatest force acting upon the rock is provided by the colliding plates, and is parallel to the Earth's surface. In a reverse fault, the hanging wall slides upwards relative to the footwall. Just like in a normal fault, preexisting rock layers are broken.

Left: Compressional forces block diagram. Right: Folded rock, an anticline-syncline pair.

In contrast, ductile rocks are able to bend in response to compressional forces. They crumple up like a piece of cloth, creating upwards (convex) and downwards (concave) folds called "anticlines" and "synclines" respectively. These folds are found together in anticline-syncline pairs.

Notably, compressional forces take a specific amount of crust and pile it up it into a smaller area. This results in an increase in crustal thickness—and in most cases, elevation. Compression may proceed to the extent that new mountain ranges are formed, a process called "orogenesis." Right now, for example, the tectonic plate hosting the Indian subcontinent is converging with Asia, and the Himalayan Mountains are growing where the two plates collide.

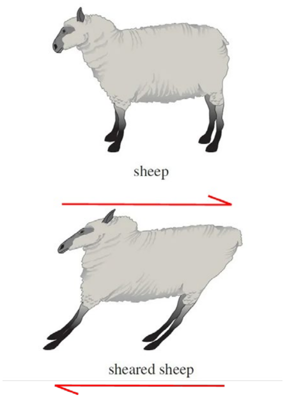
Responses to shear forces

When plates grate past each other, brittle rocks break into **strike-slip faults**, also called **transform faults**. While normal and reverse faults usually occur at a 30-60° angle to the surface, the planes of strike-slip faults are usually vertical—perpendicular to the Earth's surface.

Left: Shear forces block diagrams. Right: Sheared rock photo by Jordi Carreras; arrows indicate sense of motion.

Since there is no convergence or divergence along a strike-slip fault, there is no crustal thinning or thickening. However, the boundary between the two fault blocks (usually two different tectonic plates, in this case) is seldom a straight line, and as a result a strike-slip fault can become locked until it ruptures in a powerful earthquake. A prominent example of a strike-slip fault is the San Andreas Fault in California.

When subjected to shearing forces, ductile rocks are able to…shear (see sheep image for example). Each side of the affected area pulls in the opposite direction, stretching and distorting the affected area, but the rocks are capable of bending and no breakage occurs.



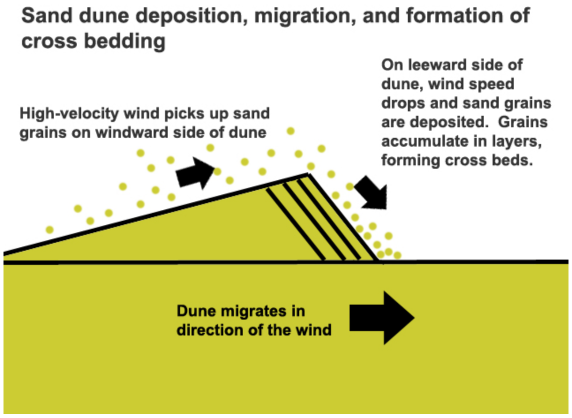
Bedding Styles

By “bedding,” geoscientists are talking about the layering that occurs as sediment is deposited (into beds). It is a prominent feature in sedimentary outcrops and tells us useful information about depositional environment, duration of deposition, and sediment supply. There are two main types of bedding, *planar bedding* and *crossbedding*.

In a rock unit displaying *planar bedding*, as the name suggests, beds were originally laid down parallel to the main bedding plane (which can be thought of as the Earth’s surface at the time deposition began). These beds can be thick (>1 m) or thin (<1 cm), an indicator of sediment supply or duration of deposition. For example, thicker beds = more sediment was available and/or there was a longer timespan of uninterrupted deposition.

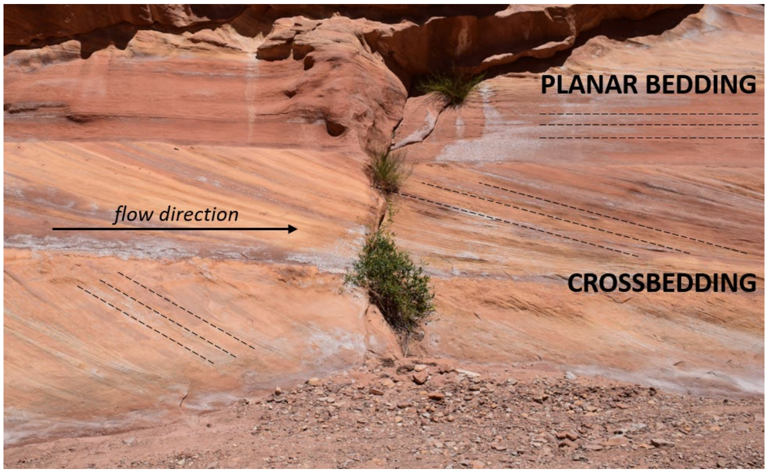
Planar bedding (beds are horizontal).

In a rock unit displaying *crossbedding*, beds were originally laid down at an angle to the main bedding plane. This is a common feature that forms by deposition of migrating bedforms (including ripples and dunes) as a result of flowing water or wind. To create crossbeds, water or wind carries sediment to the top of a ripple or dune, where it topples downhill. Eventually enough sediment falls that a bed develops at an angle to the Earth’s surface and the process continues, resulting in many crossbeds.



Development of crossbedding.

Crossbeds are important features to geoscientists because they record the *paleocurrent direction*, the direction water or wind was flowing at the time of deposition. The beds point downwards in the ancient flow direction, which has been determined in the photo to the right. Layers containing crossbedded rock from subaerial (e.g., desert or beach) environments are generally thicker than those containing crossbeds created at an ancient river bottom.



Sandstone outcrop in Capitol Reef NP including one layer (younger) with planar bedding and two (older) crossbedded layers. Thin dashed lines show orientation of bedding. Flow direction, determined from the crossbedded layers, is marked by an arrow. Horizontal surface at the base of each layer is the bedding plane.

Geologic Time

Geologic time is inconceivably vast. The Earth is 4.543 billion years old (4,543,000,000 years), and the Universe is 13.8 billion years old (13,800,000,000 years). In geologic time, 1,000,000 years is just a blip—and humans only recently started to exist. It can be difficult to grasp the immensity of time preserved in the rock and fossil record, but that timespan was what was required to create the modern-day landscapes of the Colorado Plateau—and to evolve the flora and fauna that call it home today.

Here are some abbreviations geoscientists commonly use:

Ka: thousands of years ago (K for "kilo")

Ma: millions of years ago (M for "mega")

Ga: billions of years ago (G for "giga")

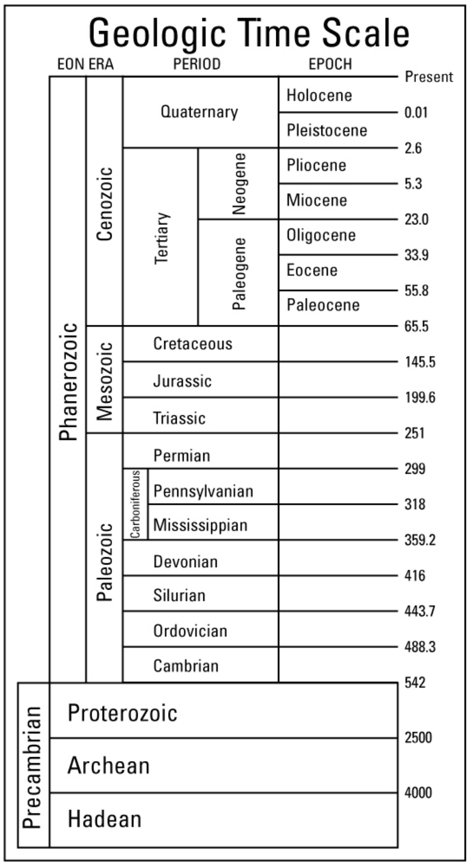
There are four major subdivisions of geologic time you will hear about. From longest to shortest, these are **eons**, **eras**, **periods**, and **epochs.** Multiple epochs make up a period, multiple periods make up an era, and multiple eras make up an eon.

Most (but not all!) of the rocks we will see are from three primary eras, all part of the **Phanerozoic Eon**:

<u>**Paleozoic Era** (541-252 Ma) – Multicellular life takes off</u>
First land animals, first animals with backbones (beginning with fish), first amphibians and then reptiles, first land plants (early on) and first conifers (late); this was when trilobites and *Dimetrodon* lived. We usually discuss this era in terms of periods. All geologic time before the start of this era is often referenced as "Precambrian" time.

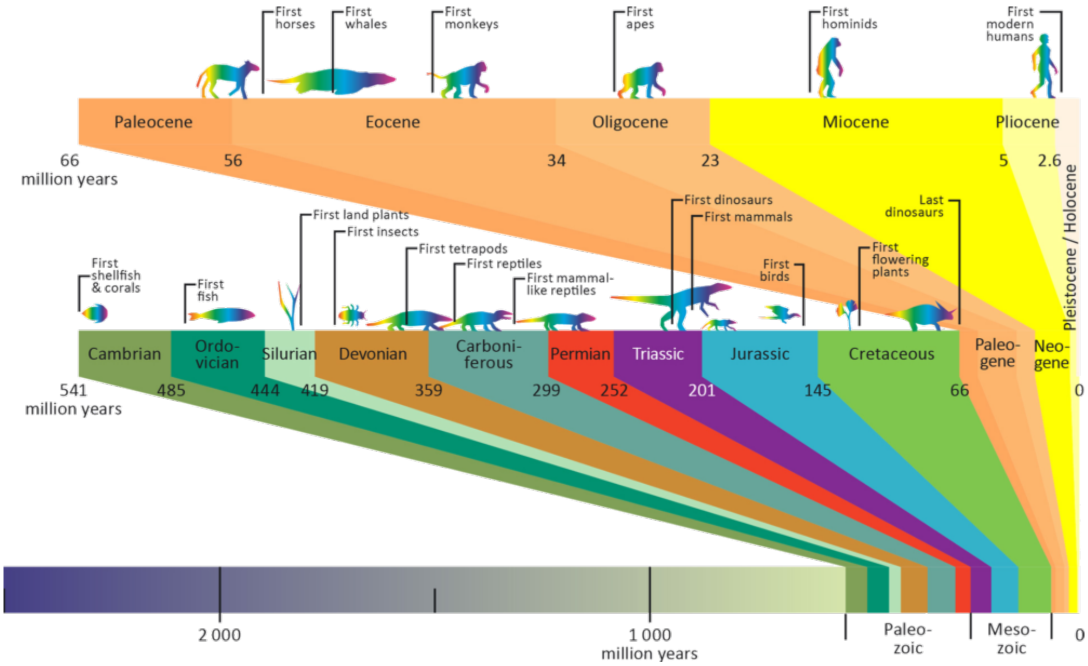
<u>**Mesozoic Era** (252-66 Ma) – "The Age of Reptiles"</u>
Dinosaurs were the dominant large life form, the first mammals and birds (e.g. *Archaeopteryx*) evolved, first flowering plants (late); this was the era that ended with the infamous meteorite impact that killed the non-avian dinosaurs. We usually discuss this era in terms of periods.

<u>**Cenozoic Era** (66-0 Ma) – "The Age of Mammals"</u>
Mammals are the dominant large life form and the species we know today evolved, ice age megafauna (like woolly mammoths) evolved and went extinct, birds continue to diversify, *Homo sapiens* takes off; this is the era we live in today. We often talk about the Cenozoic Era in terms of epochs instead of periods.

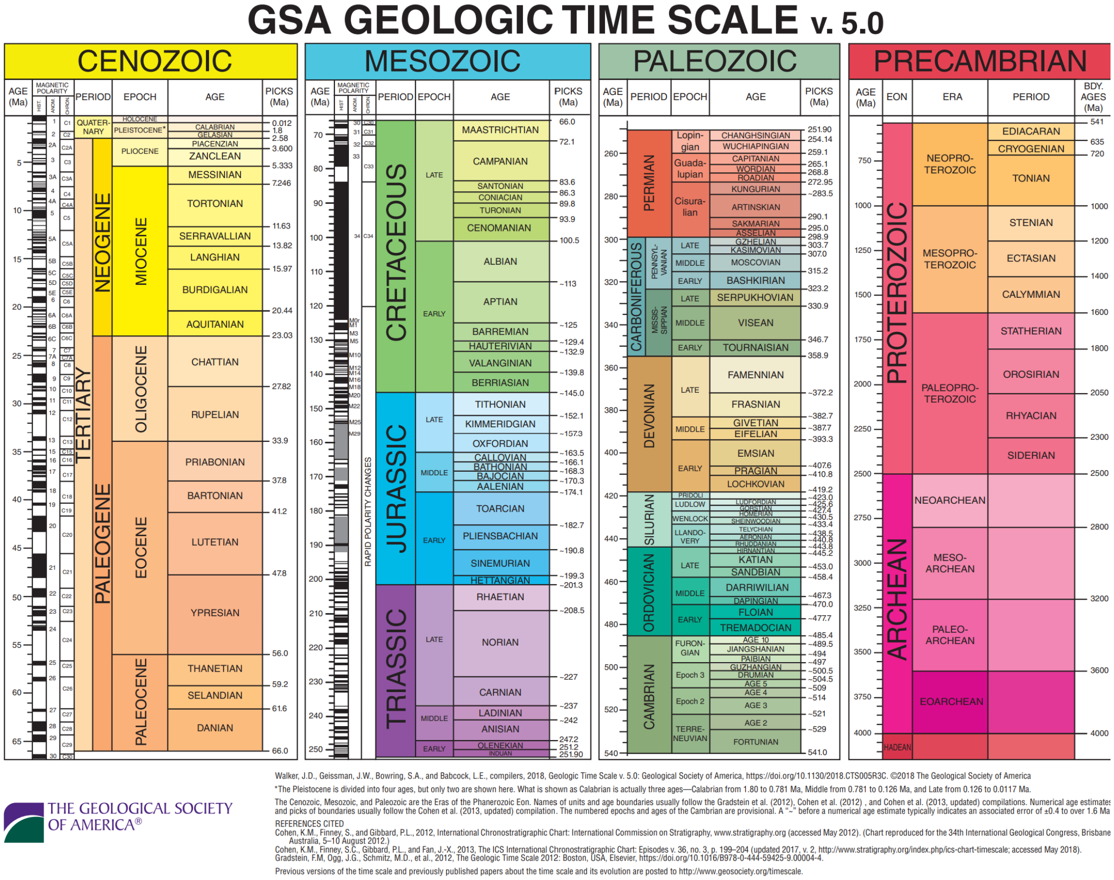


Simplified geologic timescale. The right-hand axis is in units of millions of years. ***Note:*** *The term "Precambrian" simply refers to all geologic time before the Cambrian Period, which marked the beginning of the Phanerozoic Eon.*

Below are two more ways to portray geologic time that I thought might be interesting:



Geologic time, and major steps in the evolution of life. The top of this diagram zooms into the epochs of the Cenozoic Era. Note how recently the first modern humans evolved.



GSA GEOLOGIC TIME SCALE v. 5.0

CENOZOIC

PERIOD		EPOCH	AGE	PICKS (Ma)
QUATERNARY		HOLOCENE		0.012
		PLEISTOCENE*	CALABRIAN	1.8
			GELASIAN	2.58
TERTIARY	NEOGENE	PLIOCENE	PIACENZIAN	3.600
			ZANCLEAN	5.333
		MIOCENE	MESSINIAN	7.246
			TORTONIAN	11.63
			SERRAVALLIAN	13.82
			LANGHIAN	15.97
			BURDIGALIAN	20.44
			AQUITANIAN	23.03
	PALEOGENE	OLIGOCENE	CHATTIAN	27.82
			RUPELIAN	33.9
		EOCENE	PRIABONIAN	37.8
			BARTONIAN	41.2
			LUTETIAN	47.8
			YPRESIAN	56.0
		PALEOCENE	THANETIAN	59.2
			SELANDIAN	61.6
			DANIAN	66.0

MESOZOIC

PERIOD	EPOCH	AGE	PICKS (Ma)
			66.0
CRETACEOUS	LATE	MAASTRICHTIAN	72.1
		CAMPANIAN	83.6
		SANTONIAN	86.3
		CONIACIAN	89.8
		TURONIAN	93.9
		CENOMANIAN	100.5
	EARLY	ALBIAN	~113
		APTIAN	~125
		BARREMIAN	~129.4
		HAUTERIVIAN	~132.9
		VALANGINIAN	~139.8
		BERRIASIAN	~145.0
JURASSIC	LATE	TITHONIAN	~152.1
		KIMMERIDGIAN	~157.3
		OXFORDIAN	~163.5
	MIDDLE	CALLOVIAN	~166.1
		BATHONIAN	~168.3
		BAJOCIAN	~170.3
		AALENIAN	~174.1
	EARLY	TOARCIAN	~182.7
		PLIENSBACHIAN	~190.8
		SINEMURIAN	~199.3
		HETTANGIAN	~201.3
TRIASSIC	LATE	RHAETIAN	~208.5
		NORIAN	~227
		CARNIAN	~237
	MIDDLE	LADINIAN	~242
		ANISIAN	247.2
	EARLY	OLENEKIAN	251.2
		INDUAN	251.90

PALEOZOIC

PERIOD		EPOCH	AGE	PICKS (Ma)
				251.90
PERMIAN		Lopingian	CHANGHSINGIAN	254.14
			WUCHIAPINGIAN	259.1
		Guadalupian	CAPITANIAN	265.1
			WORDIAN	268.8
			ROADIAN	272.95
		Cisuralian	KUNGURIAN	~283.5
			ARTINSKIAN	290.1
			SAKMARIAN	295.0
			ASSELIAN	298.9
CARBONIFEROUS	PENNSYLVANIAN	LATE	GZHELIAN	303.7
			KASIMOVIAN	307.0
		MIDDLE	MOSCOVIAN	315.2
		EARLY	BASHKIRIAN	323.2
	MISSISSIPPIAN	LATE	SERPUKHOVIAN	330.9
		MIDDLE	VISEAN	346.7
		EARLY	TOURNAISIAN	358.9
DEVONIAN		LATE	FAMENNIAN	~372.2
			FRASNIAN	~382.7
		MIDDLE	GIVETIAN	~387.7
			EIFELIAN	~393.3
		EARLY	EMSIAN	~407.6
			PRAGIAN	~410.8
			LOCHKOVIAN	~419.2
SILURIAN		PRIDOLI		~423.0
		LUDLOW	LUDFORDIAN	~425.6
			GORSTIAN	~427.4
		WENLOCK	HOMERIAN	~430.5
			SHEINWOODIAN	~433.4
		LLANDOVERY	TELYCHIAN	~438.5
			AERONIAN	~440.8
			RHUDDANIAN	~443.8
ORDOVICIAN		LATE	HIRNANTIAN	~445.2
			KATIAN	~453.0
			SANDBIAN	~458.4
		MIDDLE	DARRIWILIAN	~467.3
			DAPINGIAN	~470.0
		EARLY	FLOIAN	~477.7
			TREMADOCIAN	~485.4
CAMBRIAN		FURONGIAN	AGE 10	~489.5
			JIANGSHANIAN	~494
			PAIBIAN	~497
		Epoch 3	GUZHANGIAN	~500.5
			DRUMIAN	~504.5
			AGE 5	~509
		Epoch 2	AGE 4	~514
			AGE 3	~521
		TERRENEUVIAN	AGE 2	~529
			FORTUNIAN	541.0

PRECAMBRIAN

EON	ERA	PERIOD	BDY. AGES (Ma)
			541
PROTEROZOIC	NEOPROTEROZOIC	EDIACARAN	635
		CRYOGENIAN	720
		TONIAN	1000
	MESOPROTEROZOIC	STENIAN	1200
		ECTASIAN	1400
		CALYMMIAN	1600
	PALEOPROTEROZOIC	STATHERIAN	1800
		OROSIRIAN	2050
		RHYACIAN	2300
		SIDERIAN	2500
ARCHEAN	NEOARCHEAN		2800
	MESOARCHEAN		3200
	PALEOARCHEAN		3600
	EOARCHEAN		4000
HADEAN			

THE GEOLOGICAL SOCIETY OF AMERICA®

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2018, Geologic Time Scale v. 5.0: Geological Society of America, https://doi.org/10.1130/2018.CTS005R3C. ©2018 The Geological Society of America

*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages—Calabrian from 1.80 to 0.781 Ma, Middle from 0.781 to 0.126 Ma, and Late from 0.126 to 0.0117 Ma.

The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries usually follow the Gradstein et al. (2012), Cohen et al. (2012) , and Cohen et al. (2013, updated) compilations. Numerical age estimate and picks of boundaries usually follow the Cohen et al. (2013, updated) compilation. The numbered epochs and ages of the Cambrian are provisional. A "~" before a numerical age estimate typically indicates an associated error of ±0.4 to over 1.6 Ma

REFERENCES CITED
Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, www.stratigraphy.org (accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane Australia, 5–10 August 2012.)
Cohen, K.M., Finney, S.C., Gibbard, P.L., and Fan, J.-X., 2013, The ICS International Chronostratigraphic Chart: Episodes v. 36, no. 3, p. 199–204 (updated 2017, v. 2, http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed May 2018).
Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, https://doi.org/10.1016/B978-0-444-59425-9.00004-4.

Previous versions of the time scale and previously published papers about the time scale and its evolution are posted to http://www.geosociety.org/timescale.

Yikes, look away! This is the official geologic timescale according to the Geological Society of America.

Geologic Sequence that Made the Colorado Plateau

This section will be a time sequence that explains development of the Colorado Plateau over about the last 750 million years. This will be done using a series of paleogeographic maps, which are basically cartoons that show where mountains, oceans, lowlands, and rivers are thought to have been, based on the best modern understanding inferred from the geologic record. For example, fossil-rich limestone implies warm, shallow seas. Black shale implies deeper, oxygen-starved ocean basins. Land areas are partly indicated by places where older rocks have been eroded away, despite rocks of that age existing elsewhere. Red rocks containing gravel, sand, and shale layers indicate river deposits on land, where atmospheric oxygen, at the time of deposition, oxidized iron in the sediments to make them red. These paleo-physiographic maps are all from *https://deeptime-maps.com/north-america/*. Note that these maps keep the current U.S. State boundaries static, even though continental drift was actually moving North America and other continents in different directions around the globe.

750 million years ago (Ma), late Proterozoic Eon

750 Ma

At this time, North America did not extend as far west as it does today. Much of the continent was above the ocean surface and was actively eroding, exposing ancient igneous and metamorphic rocks over much of the land surface. That is much like the Canadian Shield today. Some Precambrian sediments were not completely eroded away, such as the Grand Canyon Supergroup of Proterozoic sedimentary rocks, which were preserved from erosion in fault block basins. Farther to the west was the continental shelf of that time, with deep oceans, islands, and other landmasses farther offshore. Green arrows show plate movements relative to the larger part of North America. Here, parts of the continent are rifting away, to drift elsewhere over Earth’s surface

540 Ma, early Cambrian Period

540 Ma

The western landmass is gradually subsiding. Erosion from the highlands to the east deposited the Tapeats Sandstone along the ancient shorelines, one of the first sedimentary layers deposited on the eroded Precambrian rocks in the Colorado Plateau area. As the land slowly subsided, the ocean shoreline moved east, submerging more of the land and allowing more of the Tapeats Sandstone to be deposited. Areas of Texas, Oklahoma, and Arkansas were part of a rift system, which produced new ocean floor and carried away fragments of the southern coast into a new ocean basin.

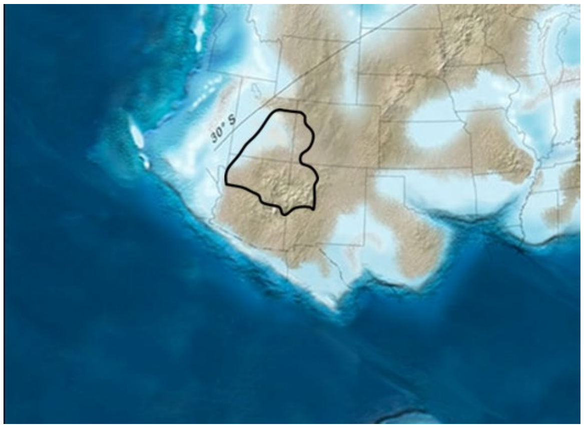
500 Ma, late Cambrian Period


500 Ma

Subsidence of the land through the middle and late Cambrian continued to allow encroachment of the sea. Sediments that were being deposited changed from sands (Tapeats Sandstone) to silt and shale (Bright Angel Shale), as the land sources of the sediment became farther and farther away. Eventually, in the warm, shallow seas, with little or nothing derived from land, limestones were deposited (Muav Limestone).

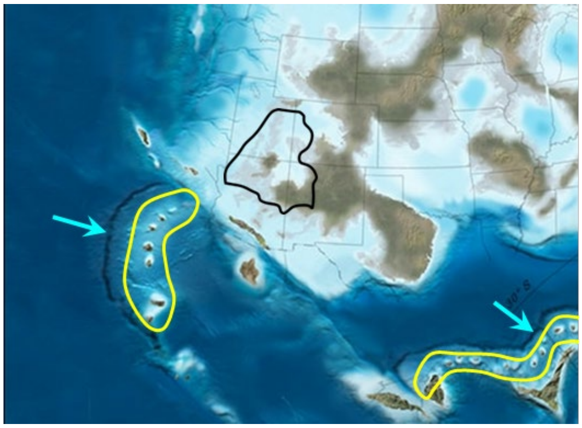
This sequence of beach sand, offshore silt and shale, and far offshore limestone is a package referred to as the “Cambrian global transgressive sequence.” Similar sequences are found in many places throughout the world (including in New York), representing a major episode of submergence of large, deeply eroded continental areas.

420 Ma, late Silurian Period


420 Ma

During long years of the Ordovician and Silurian, different parts of the Colorado Plateau were exposed above sea level, allowing some older sedimentary layers be eroded away and leaving them missing in many areas. These places where the rock layers have been eroded away, or were never deposited because the area was above sea level, are known as unconformities. In some cases, out in the field you can see valleys eroded into the former land surface, now filled in with sediment deposited on top of the erosion surface. Some unconformities even preserve buried soils.

375 Ma, late Devonian Period


375 Ma

The Temple Butte Limestone was deposited in warm, shallow seas around broad, low-lying islands. The Temple Butte is actually a mixture of varying quantities of limestone, sandstone, and shale in different areas. In more western areas, it forms a continuous layer. Farther to the east it was obviously deposited on an unconformity, because in many places the Temple Butte only fills paleo-valleys, with the paleo-ridges on either side being older layers such as the Muav Limestone, and with both overlain by the Mississippian Redwall Limestone and equivalents. Blue arrows on the map show ocean trenches, where oceanic lithosphere is bending down to subduct into the mantle. Melting over the subducted slab produces a chain of volcanos (a volcanic arc), indicated by yellow outlines. The package of trench, subducted oceanic plate, melting, and volcano chain is called a subduction zone.

345 Ma, early Mississippian Sub-Period

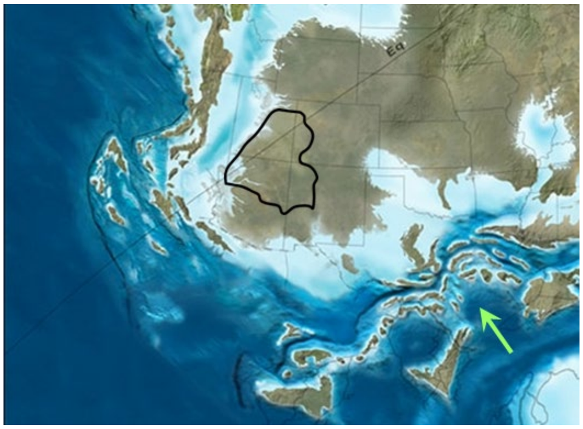
Continued subsidence of southwestern North America produced extensive warm, shallow seas. At the bottom of these well-oxygenated waters was deposited a series of limestones, notably the Redwall Limestone in the Colorado Plateau area. This thick unit is quite erosion-resistant in the arid climate, and is a major cliff-former. The fresh limestone is usually shades of gray. However, oxidation of iron weathering from the limestone itself, and from water washing down from above, stains surfaces red. The green arrow shows movement of another continental plate toward North America, with a long trench and chain of subduction zone volcanoes.

345 Ma

325 Ma, late Mississippian Sub-Period

During this time the region experienced uplift and erosion, producing a widespread unconformity. Erosion of the top surface of the Redwall Limestone, and groundwater dissolving rock around underground fractures, produced cave systems throughout the unit and sinkholes at the top. Today, many of these caves carry subterranean streams, which form springs where they exit to the surface on valley walls. Roaring and Thunder Springs, in the Grand Canyon, are two of these.

325 Ma



308 Ma, Pennsylvanian Sub-Period

During this episode, collision between southern North America and a volcanic arc complex caused mountains to form to the south and east, but only moderate deformation in the Colorado Plateau region. The Supai Group was deposited in and along the margins of warm, shallow seas. It typically consists of a lower layer of shallow marine limestone, covered with layers of river-deposited shale and sandstone. Thick sandstone layers can be cliff-formers. The

308 Ma

upper part of the Supai Group, the Esplanade Sandstone, is a particularly prominent cliff-former in some places. Other parts of the Colorado Plateau region were shallow to moderately deep marine basins. The Paradox Basin (red P) had restricted access to normal ocean water, and so became very salty from evaporation in this arid climate. Eventually, thick layers of salt, gypsum, and other marine sediments formed in it.

280 Ma, early Permian Period

Uplift of the Colorado Plateau region again allowed erosion to strip away some of the upper layers, producing a widespread late Pennsylvanian to early Permian unconformity. Material eroded from mountains to the southeast and west were deposited in basins in western Texas, as well as southern Arizona and New Mexico. Subduction zones with their associated volcanic arcs persisted off the coast, west of Utah. The river-deposited Hermit Shale (includes siltstone and fine-grained sandstone) was deposited at this time, on low slopes near sea level.

280 Ma

260 Ma, middle Permian Period

Continued uplift of the Colorado Plateau region, in an arid subtropical climate, provided sand sources that were blown by winds into an extensive sand dune field, making the Coconino Sandstone. This prominent, white dune sand is a common cliff-former in many parts of the Plateau. At the same time, in shallow waters nearby, the Toroweap Shale (includes sandstone and gypsum) was being deposited, with the Kaibab Limestone being deposited farther offshore. Slow sinking of the land and flooding by the sea caused deposition of these three units at the same time in different places to cover much of the Colorado Plateau region, with deposition of these units extending into the early Triassic.

260 Ma

245 Ma, early Triassic Period

The Moenkopi Formation was deposited at this time, from eroded material sourced in the south and west. Deposition of sandstone, siltstone, and shale by rivers occurred along low coastal plains, deltas, and tidal flats near the shores of a shallow, tropical sea. Slow uplift of the Colorado Plateau area in the middle Triassic permitted erosion of some of the sediments,

245 Ma

creating the middle Triassic unconformity in many areas.

220 Ma, late Triassic Period

220 Ma

Uplift of the region ended deposition of coastal and marine sediments, and instead allowed deposition of continental river sandstones and dune sands of the Chinle Formation. These deposits formed in broad valleys, with erosion continuing to either side where the Chinle was never deposited. Subduction along a volcanic arc continued offshore, and subduction along the west coast, in what will become Washington and Oregon, began.

195 Ma, early Jurassic Period

195 Ma

The Colorado Plateau region was an inland desert basin. Continental river and wind-blown sands were deposited at this time to form the Glen Canyon Group. This group consists of four formations in most areas: The mostly river-deposited, red Wingate, Moenave, and Kayenta Formations, and the mostly white dune sand Navajo Formation. The Navajo in particular forms prominent cliffs with spectacular cross-beds. Another subduction zone and its volcanic chain starts to sail in from the west.

170 Ma, middle Jurassic Period

170 Ma

The San Rafael Group was deposited at this time. This group includes the Carmel Formation and Entrada Sandstone. The Carmel Formation was deposited in a hot, arid, shoreline and shallow marine environment, much like that of the Persian Gulf today. The Carmel is a complex unit that includes near-shore sandstone, mudstone, limestone, and gypsum. Gypsum was precipitated directly from sea water evaporation, in shallow water and mud flats, as also was some of the limestone. The overlying Entrada Sandstone is also complex, including dune sand, beach deposits, and near-shore silty sand.

150 Ma, late Jurassic Period

Exposed mostly in eastern Utah, the Morrison Formation is composed of beds of sandstone, siltstone, shale, and limestone. It was deposited mostly by rivers in a continental interior

150 Ma

basin. This unit is famous for its dinosaur and other fossils, including both bones and footprints. It was in this formation that most of the famous Bone Wars of 1877 to 1892 took place, between the two ruthless paleontologists Othniel Marsh and Edward Cope. They used underhanded means, in the Morrison Formation and elsewhere, to outdo one-another in collecting (or stealing) the best and most unusual dinosaur specimens. In terms of plate tectonics at this time, volcanic arcs start colliding with western North America, adding more to the western part of the continent. In contrast, to the southeast, rifting has opened a new Jurassic ocean basin, allowing that part of the continent to float away to some other part of the globe.

130 Ma, early Cretaceous Period

130 Ma

Collision of volcanic arcs to the west raised mountain ranges and added to the width of North America. New parts include the Klamath Mountain region of Oregon and northern California, and most of what is now the Sierra Nevada and Baja California regions. Rivers, primarily from the east, deposited the Dakota Formation sandstone, siltstone, and shale on top of older units, including on erosion surfaces. The Dakota Formation contains abundant dinosaur and other fossils in some places.

105 Ma, early to middle Cretaceous Period

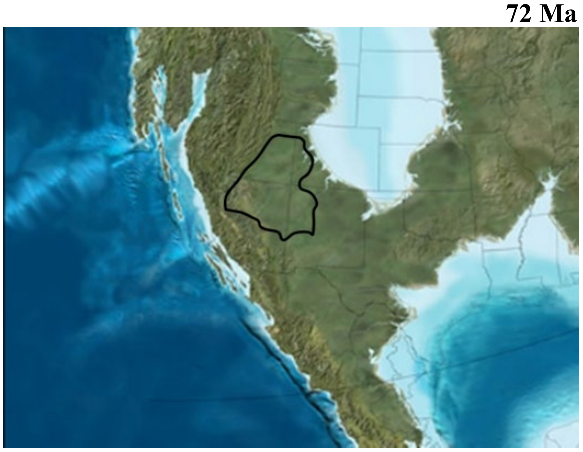
105 Ma

Subsidence at this time produced the North American Cretaceous Inland Seaway, a broad, warm, shallow sea. Into this seaway was deposited the marine Mancos Shale, principally exposed in the northeastern Colorado Plateau. This unit is composed mostly of gray shale, eroded from mountains to the west. It is similar in age to some of the Dakota Formation, having been deposited on land and near shore, on the west side of the seaway.

You may also hear the Cretaceous Inland Seaway referred to as the “Mancos Sea” or the “Western Interior Seaway.”

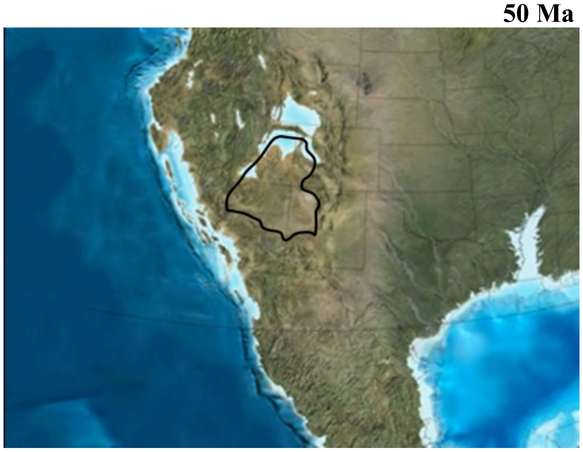
72 Ma, late Cretaceous Period

Uplift of the Colorado Plateau region allowed erosion to remove considerable rock, producing the widespread late Cretaceous unconformity. A mountain building episode known as the Sevier Orogeny took place as a result of subduction and collision on the west coast. This led to crustal thickening west of the Colorado Plateau, and into western Montana to the north. Deformation included Appalachian Mountain-style folding and thrust faulting of sedimentary rocks on the east side of the mountain belt. Deposition was still taking place in the partly closed seaway, northeast of the Colorado Plateau.



50 Ma, Eocene Epoch

The early Paleogene (Paleocene and Eocene) saw some remarkable geologic events. Changes to the way oceanic crust was being subducted beneath North America, and/or what was subducted, resulted in east- to northeast-movement, and possibly uplift, of the Colorado Plateau block. This caused compression of crust to the east and north, producing the “Laramide” fault block structures of the Colorado Front Range, the Uinta Mountains of Utah, the central Rocky Mountains of Wyoming and Montana, and others.



In these areas, fault uplift produced mountains and allowed sedimentary layers to be eroded off of them, exposing the Precambrian igneous and metamorphic rocks beneath. At the same time, intervening fault block valleys received the eroded sediments. Many of those intermountain valleys held lakes, and so lake sediments were common, too, forming rock units such as the Green River Formation. Valley deposits include the muds and sands of the Claron and Wasatch Formations, which were deposited by meandering rivers and in shallow lakes.

10 Ma, Miocene Epoch

While active subduction of Pacific Ocean lithosphere continued on the west coast from the Eocene, the western interior of North America experienced another remarkable geologic episode. For reasons still not clear, the western part of the U.S. and northwestern Mexico underwent 2 to 3 kilometers of uplift, approximately east-west extension, and minor but widespread volcanic activity. Extending the crust makes it thinner. In the deep crust and mantle part of the lithosphere, thinning took place by ductile flow of the hot rocks. At shallower depths, the cold and brittle rock thinned by normal faulting, producing fault block mountain ranges with intervening valleys. The Basin and Range Province (including the Great Basin) resulted from this extension.

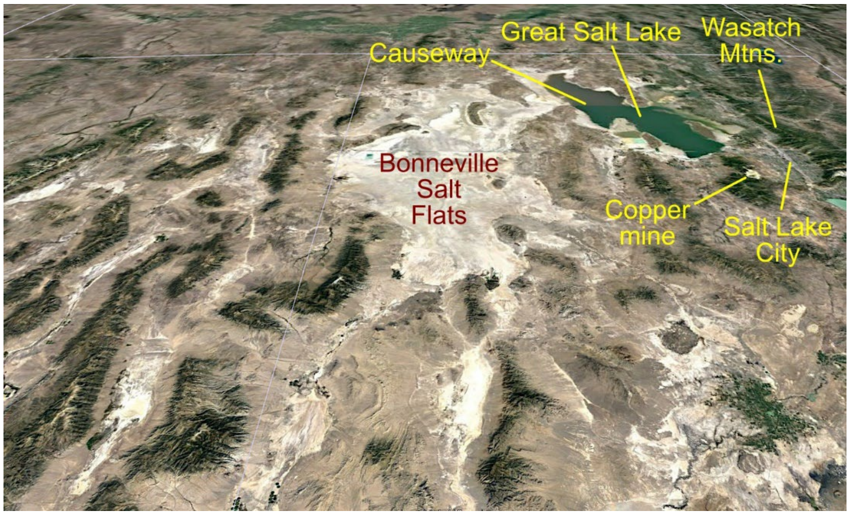
Why did this uplift and extension happen? Evidence has been interpreted to suggest several possibilities, including subduction of an eastern Pacific mid-ocean ridge, detachment and sinking of a piece of oceanic lithosphere that was subducted some time earlier, detachment and sinking of part of the lithospheric mantle under that region, and shear strain associated with San Andreas Fault movement. It is during this regional uplift that the Colorado Plateau became the high plateau that we see today, and started to acquire its stunning array of erosional landforms. Basin and Range extensional faults bound the western and southern sides of the Colorado Plateau. The eastern and northern sides are bounded by the Paleogene Laramide fault blocks, and the southeastern side is bounded by the Rio Grande Rift, a poorly understood Eocene to Recent extensional feature.

Conclusion

Again, the purpose of showing this sequence was to illustrate how dynamic continental crust can be over long periods of time, even for the relatively stable Colorado Plateau region. Sediments of one kind aren't deposited over a whole area at the same time. Uplift and subsidence causes depositional locations to sweep across regions, causing individual formations to be older on one side and younger on the other. Different formations can be deposited at the same time in different places, even while erosion is happening somewhere else. That means that each part of the Colorado Plateau has a somewhat different sequence or characteristics of layers, and so a somewhat different geologic history.

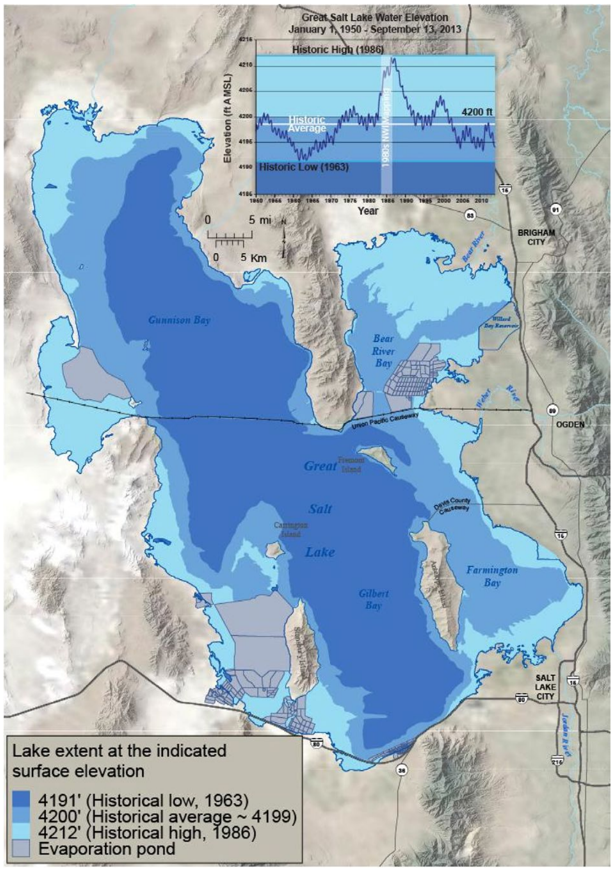
You can think of the Colorado Plateau as having been like a sheet of flexible foam rubber, floating on water. You add a bit of weight here (sediment deposition), that part sinks a little. You remove a little from there (erosion), that part floats a little higher. You remove weight from the bottom (detachment and sinking of part of the deep lithosphere), that part floats higher. You heat up the bottom (rising magmas, upwelling hot, deep mantle), that part floats a little higher. You make the lower part denser (lithosphere cooling for tens of millions of years), that part sinks a little. All of these shifting changes, on the top and bottom, result in different sedimentary layers, sedimentary basins and erosional unconformities at different times and places. That's our dynamic crust.

The Great Salt Lake



View toward the north, showing the Basin and Range province south and west of the Wasatch Mountains. Google Earth image.

The Great Salt Lake occupies a closed (no river outlet), intermountain basin in the Basin and Range Province of the western U.S. The basin formed during east-west extension in the late Miocene and Pliocene, and extensional faulting continues today. Brittle faulting of the upper crust during extension formed a broad series of approximately N-S mountain ridges with intervening valleys, visible in the image above.

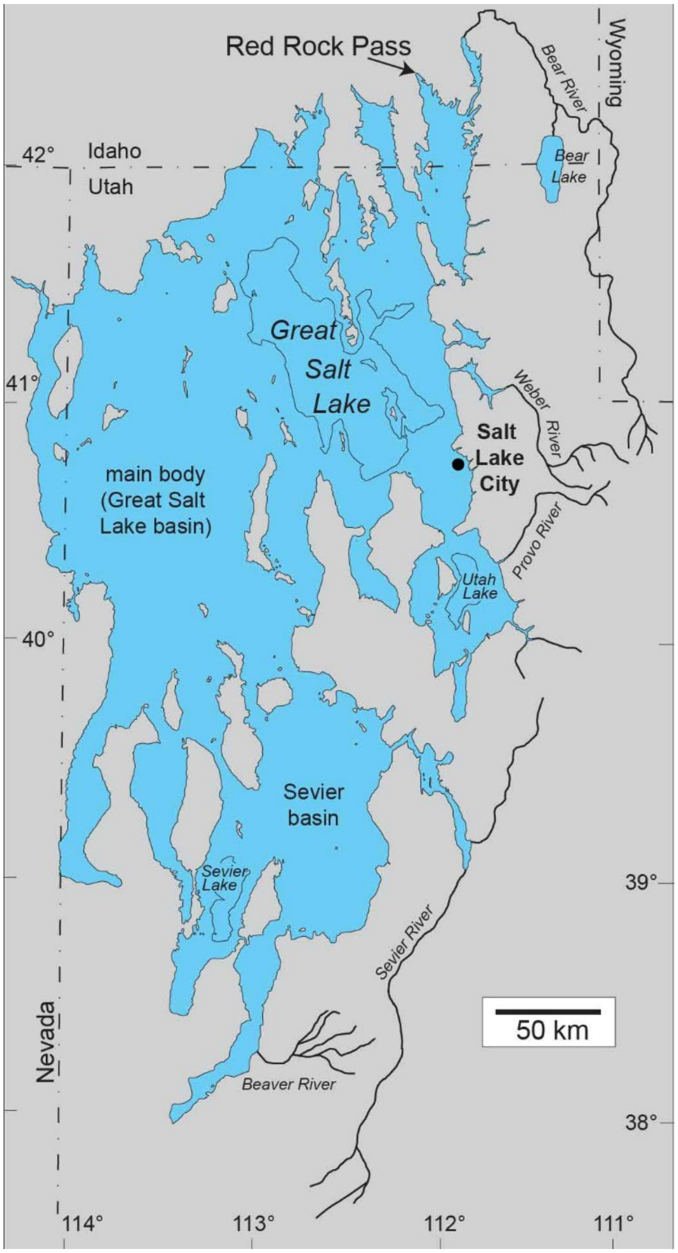


Great Salt Lake size changes (Emerson, 2014).

The Great Salt Lake fluctuates in size with varying evaporative loss and river and groundwater inflow, and has varied in level by a maximum of 21 feet (6.4 m) over historic times. This amounts to a total volume change of about 26 cubic kilometers. The basin slopes are shallow, so the maximum water depth in the lake today is only about 35 feet (11 meters). The lake has several evaporation ponds around its periphery, where progressive evaporation precipitates sodium chloride and potassium sulfate crystals, and also produces magnesium chloride brine, all of which are sold as commercial products. At its highest historical water elevation there are five islands, which are the eroded remnants of fault block mountains. At its current low water level, there are no islands, only mountains and peninsulas rising out of the salt water and salt flats.

During the last ice age, lower temperatures and possibly higher precipitation resulted in much more water in this and other intermountain basins in western North America. Glacial Lake Bonneville is the name given to the lake that filled the Great Salt Lake basin region, to a maximum elevation of about 1552 m, 30,000 years ago, or about 275 m higher than the 1277 m elevation at present. At different lake levels, erosion left erosional scars and beach deposits, and other features, indicating past levels.

At its highest level, Lake Bonneville began to drain northward at Red Rock Pass, Idaho, into the Snake River. This pass was made of easily eroded alluvial fan deposits which were quickly scoured away, resulting in an enormous flood. This drainage event, about 18,000 years ago, released an estimated 5000 km^3 of water during perhaps one year, flooding much of southern Idaho. This reduced lake elevation to about 1440 meters, where it stayed for about the next 2000 years or so.



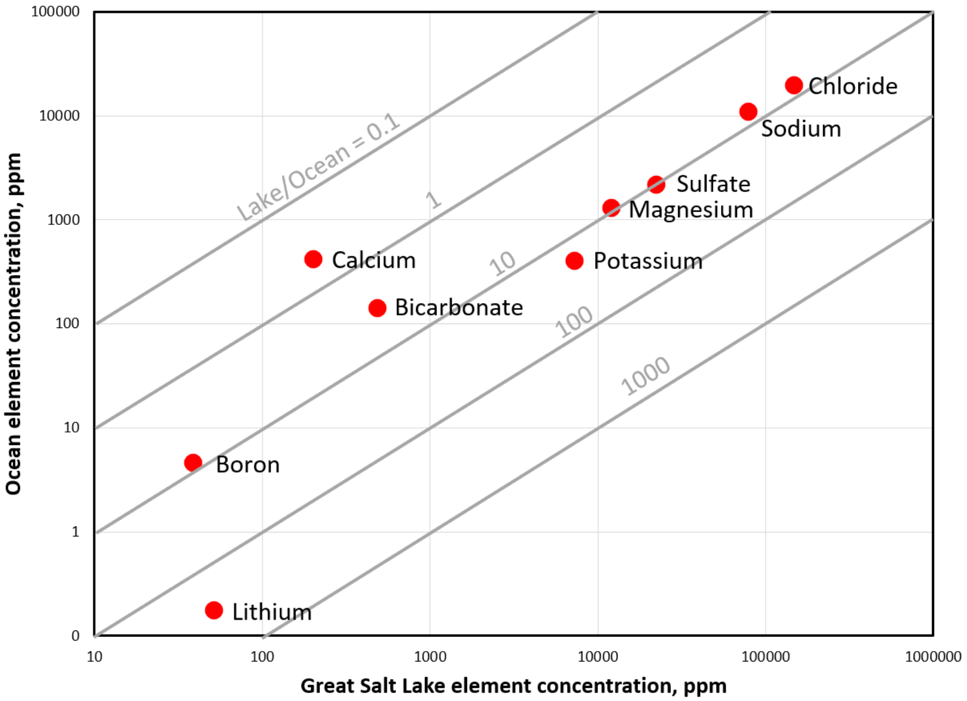
Lake Bonneville, at its maximum Pleistocene extent.
https://en.wikipedia.org/wiki/Lake_Bonneville

With the onset of aridity and higher temperatures in the Holocene, the lake level gradually lowered, and the lake size shrank to its current state, precipitating beds of salt, and itself turning from relatively fresh water to brine. Considering its much smaller area, and the shallow depth of the current lake, the Great Salt Lake is a pale shadow of its former self.

As the lake level fell, successive erosional beach features were left behind, forming nearly horizontal surfaces. Careful measurement of the surfaces show that they are not quite horizontal, but are tilted and somewhat warped. Locally, some of the tilting might be caused by recent tectonic activity, such as uplift of the Wasatch Mountains along the Wasatch Fault east of Salt Lake City. There are also active faults under the lake, visible in seismic reflection profiles, that offset Holocene marker horizons. It is also clear that there has been regional scale uplift, accompanying the drying of Lake Bonneville. This effect is caused by the slow rebound of the local lithosphere, following removal of the weight of most of Lake Bonneville. The rate of this process, coupled with the calculated mass of evaporated water, allows geophysicists to calculate the viscosity of the underlying mantle. This is an important piece of information in trying to understand the mechanics of plate tectonic processes, which are partly controlled by mantle viscosity.

The sources of salt for this lake were basically three: sea salt spray from the Pacific Ocean, salt blown in as dust from surrounding arid basins, and chemical weathering of rocks in the highlands surrounding the lake. In closed basins, salt accumulates but water can come and go. When water inflow is low and evaporation is high, salt lakes and salt flats inevitably result.

One might think that the lake water would be similar in chemical composition to sea water. This is partly true. Sea water gets salts at various concentrations from inflowing rivers, soluble dust blowing in from land, coastal inflowing groundwater, and glacial meltwater. Then, different processes remove or concentrate salts in the ocean: calcium and bicarbonate are removed by limestone precipitation; in coral reefs; and by precipitation by foraminifera, mollusks, and the like. Potassium and boron are removed mostly by adsorption onto clay surfaces. Magnesium is removed by mid-ocean ridge hydrothermal systems, and they put back some calcium into the oceans at the same time. Silica is removed by diatoms, radiolarians, and glass sponges. Over geologic time, ocean salt composition varies somewhat, but at any one time it's a balance between inputs and outputs.



Comparison of modern Great Salt Lake water composition, with ocean water (data from Hahl and Handy, 1969).

Salt lakes work in much the same way, but the processes can be somewhat different, and in different proportions. For example, direct precipitation of soluble salts (e.g., halite, NaCl; mirabilite, $Na_2SO_4 \cdot 10H_2O$) is common in the Great Salt Lake, but is not seen anywhere in the modern oceans (though at times it has been, in restricted-circulation basins in arid climates). It turns out that some salts have about the same proportion in the Great Salt Lake as in the modern oceans (Cl, Na, SO_4, Mg, K, B), and some do not (Ca, HCO_3, Li).

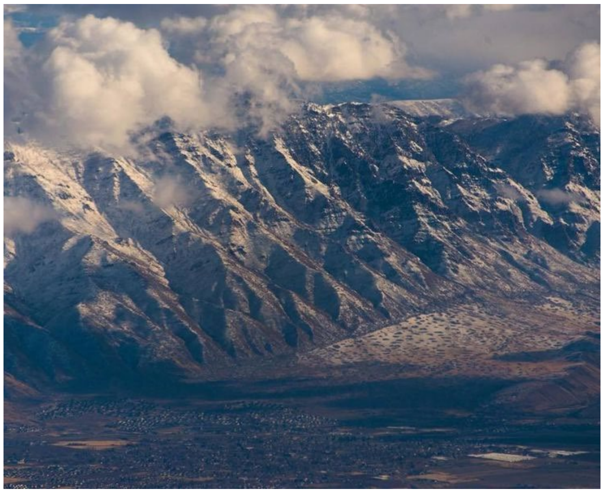
One interesting man-made feature in the lake is a railroad causeway, which divides the lake into north and south basins. This causeway restricts water exchange between the northern and southern sides of the lake. The southern side gets most of the fresh water inflow, so evaporation makes the northern side both saltier and about 1 meter lower in elevation than the southern side. The different salinities of the two sides result in different algae populations. The fresher, southern side is usually green, whereas the northern side is typically brown or reddish-brown. This can be seen in air and satellite images, as well as ground-level images taken at the causeway.

Modern shorelines along the Great Salt Lake vary considerably. These include salt flats, salty mud flats, oolite sands, brackish estuaries where fresh water rivers enter the lake, rocky shores, and even shallow water areas with stromatolites: mineral mounds produced by precipitation of calcite within photosynthetic bacterial mats.

The shorelines of Lake Bonneville were first noted and studied by one of the great minds in American Geology: Grove Karl Gilbert. Gilbert worked on the early surveys of the American West, and was for many years John Wesley Powell's "second in command" at the USGS. He was one of the first geologists to apply quantitative principles to geologic problems as a matter of course, and to recognize the necessity of doing so in almost any meaningful geologic research.

Shoreline biogenic carbonate mounds, produced by photosynthesis in cyanobacterial mats. https://www.audubon.org/news/water-shortages-are-shrinking-great-salt-lake-and-killing-its-corals

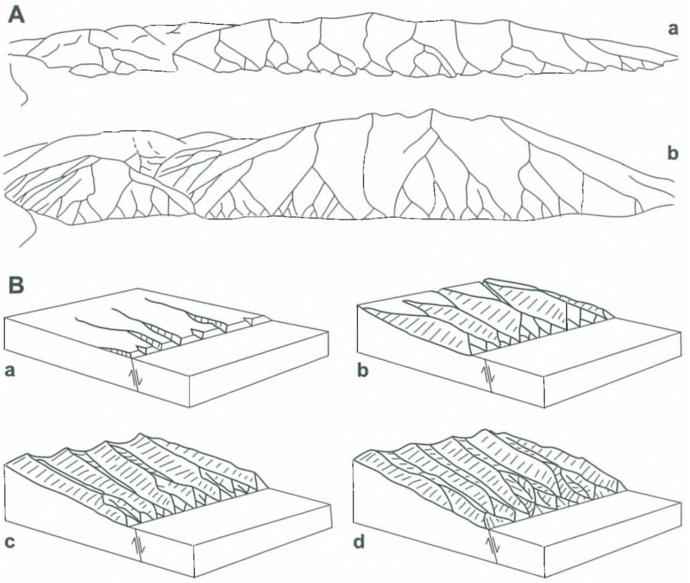
The Wasatch Fault


The Wasatch Front. Each ridge (spur) coming down from the Wasatch Mountains ends abruptly in a triangle-shaped facet. Lynn Recker on Pinterest.

As we make our way south from Salt Lake City, we'll be driving alongside the Wasatch Fault—and we will also cross the fault as we head to our first campsite. The Wasatch Fault is a major active normal fault, about 250 miles in length, that runs parallel to the western front of the Wasatch Mountains. It is split into a series of segments (each around 60-90 km in length) and has been instrumental in the formation of both the Wasatch Mountains and the valley that hosts Salt Lake City, Provo, and other towns. The fault marks the eastern bound of the geologic province called the "Basin and Range," a zone of crustal extension that has resulted in widespread north-south normal faulting—creating basins (down-dropped blocks) and ranges (upthrown blocks) in sequence across the region. We'll be spending most of our time in the stabler Colorado Plateau geologic province.

Statistically, the central part of the Wasatch Fault is overdue for a large earthquake. United States Geological Survey (USGS) research has found that the central five Wasatch Fault segments produce large (magnitude 7.0+) earthquakes approximately every 900-1300 years. The most recent earthquake near the towns of Weber, Provo, and Nephi was between 200-700 years ago, and the most recent earthquake on the segment near Salt Lake City was between 1200-1600 years ago. The segment near Brigham City hasn't seen an earthquake in the past 2200-2280 years.

Aside from the mountains themselves—which are pretty obvious!—evidence of the Wasatch Fault can be seen in *faceted spurs* along the Wasatch Front. "Spurs" are an erosional feature, ridges that extend down from mountain ranges with drainages on either side. Undisturbed spurs taper to a point where they meet the ground, but when spurs are cut by a normal fault like the Wasatch Fault, they end abruptly in a triangle-shaped face—a facet. Seismologists study faceted spurs and fault scarps to better understand fault behavior in the past (for example, to obtain the estimates of fault activity above).



A) Sketches of faceted spurs, as we will see in the Wasatch Range; B) a schematic showing the development of faceted spurs. The triangular faces prematurely truncate the spur, which would have ended in a point if not for the fault. From Zuchiewicz and McCalpin, 2000.

Igneous and Metamorphic Rocks of the Southern Wasatch Mountains

Overview of Major Rock Classifications

To understand the geology we will see *en route* to and at our first campsite, we need to take a moment to define the three overarching categories of rocks:

Igneous rocks crystallize from a melt (liquid rock, called magma or lava). Magmas can be sourced directly from the mantle or from the crust, with the latter a result of secondary melting due to a deeper, mantle-derived magma source. When magmas are erupted onto the surface, they are termed lavas—but not all magmas are erupted. Some solidify underground.

Sedimentary rocks form from sediment grains, sourced from older rocks that have broken down due to weathering and erosion. Sediments accumulate in basins and eventually are compacted and cemented into a new rock. The broken-down older rocks that supply the sediment can belong to any of the three categories, including sedimentary. A second type of sedimentary rock forms when minerals like salts are precipitated from water.

Metamorphic rocks are the result of preexisting rocks of any type being exposed to extreme temperatures and/or pressures *without* melting—sometimes reaching just below the melting point. At these conditions, the rocks undergo a metamorphosis, a change in form. They do not melt (if they did, we'd be talking about igneous rock), but their constituent minerals recrystallize into minerals more stable at the new conditions. The process is *loosely* comparable to cooking food in an oven. The assemblage of minerals present in the rock is modified, but the overall, bulk composition does not change from recrystallization alone—though importantly, water-assisted chemical interactions between neighboring rock types are very, *very* common.

Rocks commonly reach metamorphic conditions due to a combination of deep burial and tectonic stresses (e.g., mountain building events, subduction zones) or proximity to hot magma bodies.

Igneous Rocks and Contact Metamorphism

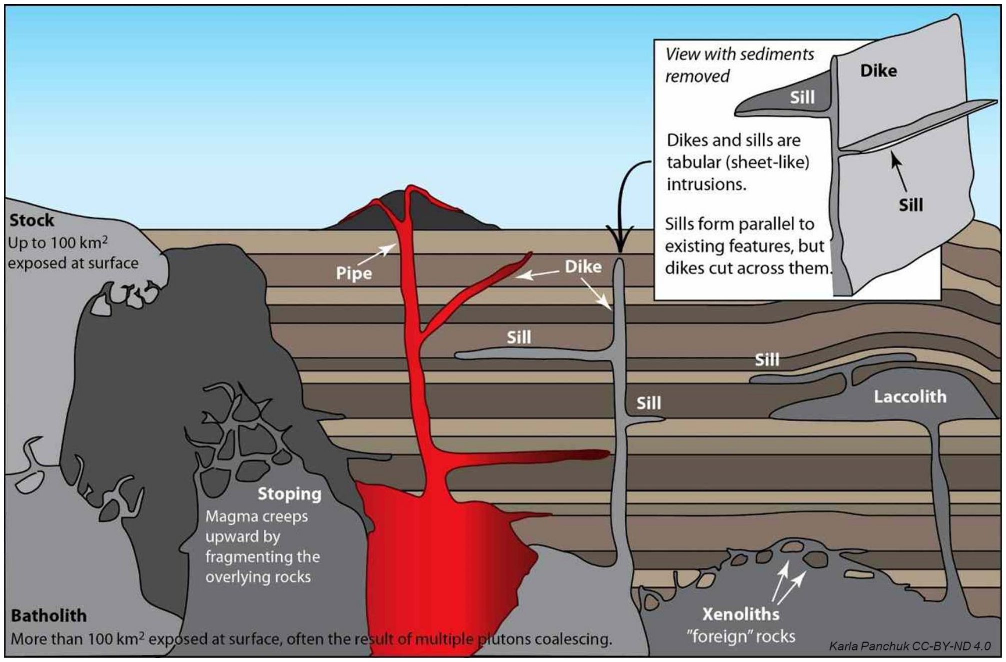
Although for the majority of our trip we'll be observing spectacular examples of sedimentary rocks, our first campsite in Alta, UT gives us a brief chance to consider igneous and metamorphic rocks.

Igneous rocks can be divided into two subcategories based upon whether they crystallized on the Earth's surface or underground. Geoscientists make this distinction because lava on the surface cools and crystallizes significantly more quickly than magma that remains underground—and cooling rate affects the crystal size in the resulting rocks. Thus, crystal size is a major consideration alongside mineral composition when identifying an unknown igneous rock.

Extrusive igneous rocks are erupted onto the surface as lava. They cool rapidly (a matter of moments to weeks), and this rapid cooling means that crystals have little time to grow. The crystals composing extrusive rocks are tiny, frequently too small to see with the unaided eye. In some cases, the rock might not contain significant crystals at all. For example obsidian, volcanic glass, forms when lava is instantly *quenched* (solidified) after being erupted. Obsidian is amorphous, largely composed of a disorganized array of silicon-oxygen tetrahedra (silica) and with a smaller component of minuscule, embryonic crystals like iron oxides. Other examples of extrusive igneous rocks you might have heard of include basalt, andesite, and rhyolite.

At Alta, we will focus on the second subcategory: Intrusive igneous rocks.

Intrusive igneous rocks, also called plutonic rocks, are not erupted onto the surface. They cool deep within the crust, insulated by surrounding “country rock” (bedrock) so that heat dissipates only slowly (Figure 1). It can take thousands of years for an igneous intrusion to solidify completely. The protracted cooling period allows ample time for crystals to grow within the intrusion, and the result is a rock composed of large mineral grains than can be easily observed without a microscope. Under isolated circumstances, some “grains” may even grow to be meters in size! Crystallization proceeds from the chamber walls progressively towards the center of an intrusion. Solidified igneous intrusions may eventually be exposed at the surface by tectonic processes (uplift) and erosion.



Karla Panchuk CC-BY-ND 4.0

Figure 1: Types of igneous intrusions. Also shown are the mechanism of stoping and xenoliths of country rock/other igneous rock. On the diagram, brown rock is sedimentary, gray/black rock is igneous, and red rock is molten (also igneous).

Igneous intrusions are hot—the rock within is *molten*, after all. Magmatic temperatures range from ~800 – 1200 °C (~1472 – 2192 °F). When igneous intrusions are emplaced into the crust, the solid rock surrounding them is subjected to the intense heat they release. The heat instigates a type of metamorphism in the surrounding rock called **contact metamorphism**—namely, metamorphism caused by close contact with a heat source.

The rind of contact metamorphism surrounding an igneous intrusion is the *contact aureole*. Its extent ranges from meter-scale up to kilometer-scale and depends on several factors regarding how well heat can transfer out of the intrusion—including the size of the intrusion, the heat capacity of the surrounding rock, and the initial temperatures of the intrusion and surrounding rock.

Common rock types created by contact metamorphism are marble (contact metamorphosed limestone) and quartzite (contact metamorphosed sandstone), though there are many other possibilities.

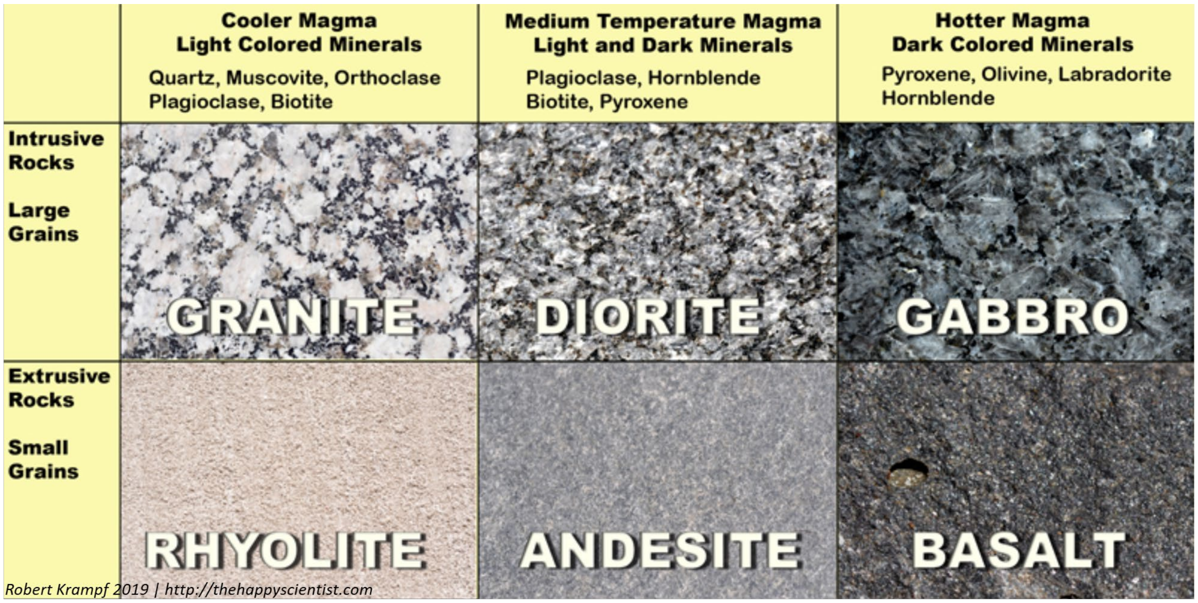


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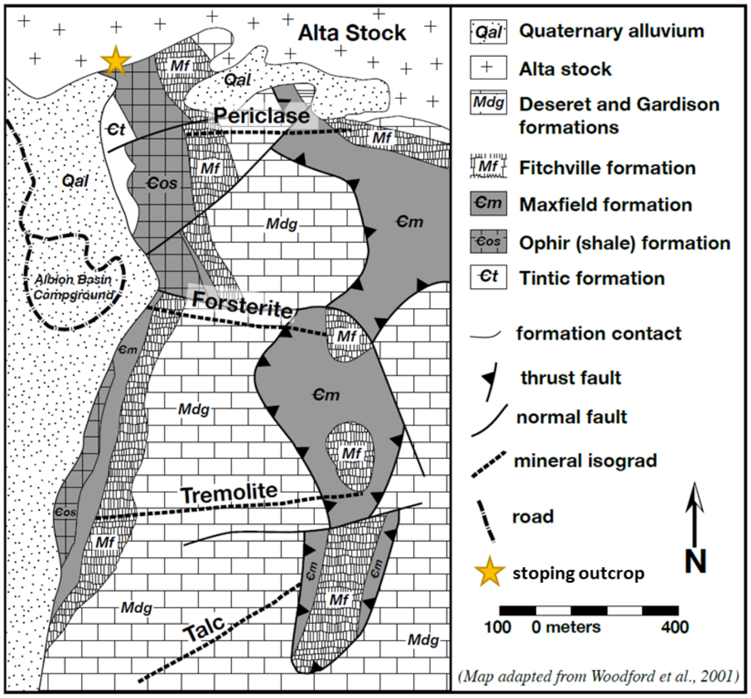
Figure 2: Intrusive vs. extrusive igneous rock textures for three common compositions. Note the grain sizes.

The Alta Granodiorite

The mountains around Alta are primarily composed of an intrusive igneous rock called granodiorite. Granodiorite is similar in composition to granite, with a slightly higher content of metals like magnesium and iron and slightly less silica (SiO_2, quartz). From a distance granodiorite often appears to be gray in color, but up-close inspection reveals a mixture of light-colored minerals like quartz and feldspar and dark-colored minerals like biotite and amphibole.

The granodiorite here is part of a *stock*—an irregular, large-scale igneous intrusion (also called a pluton) with <100 km^2 of area exposed on the surface. A



(Map adapted from Woodford et al., 2001)

Figure 3: A close-up of our campground (Albion Basin Campground) and its relation to the Alta Stock and contact aureole. We will visit the starred outcrop to view an example of stoping.

batholith is an intrusion of larger extent with >100 km^2 of surface exposure, like the Sierra Nevada Mountains. Some stocks might be the uppermost offshoots of buried batholiths. Stocks and batholiths are commonly composed of granite, granodiorite, or monzonite. These are just two of many types of igneous intrusions (see Figure 1 for these and other examples).

The Alta Stock was intruded into the crust about 33 million years ago, and is one of several stocks in the region. Luckily, our campsite is within the bounds of the contact aureole created by this igneous intrusion (Figure 3).

Features We Will See

Glacial landforms

As we drive in, we will be within a U-shaped valley. U-shaped valleys are characteristic of glacial erosion, and not too long ago (~10 – 30 Ka) the valleys here were filled with hundreds of feet of glacial ice flowing into Lake Bonneville, the vast precursor to the Great Salt Lake. Glaciers grind up the rock beneath them, leaving behind a random assortment of sediment (with grain sizes ranging from clay to boulders) called glacial till. The dirt filling our first campsite in the Albion Basin is glacial till, some of which is derived from the much-older Alta Stock.

Stoping

When magma intrudes into the country rock, it doesn’t have perfectly neat edges. Upward-moving magma follows preexisting fractures and breaks up country rock from the walls of the developing magma chamber, engulfing chunks of it (Figure 1, left side). This process is called “stoping,” and the isolated chunks of country rock are called “stoped blocks.” Stoped blocks are a type of xenolith (“foreign rock” that did not originate from the melt). At Alta, we will see contact-metamorphosed Ophir Shale suspended in the granodiorite of the Alta Stock.

Contact metamorphism

The contact metamorphism near our campsite is most pronounced in the silicious dolostones (sandy, carbonate-bearing rocks) of the Fitchville, Deseret, and Gardison Formations. Rocks are more or less contact metamorphosed depending on proximity to the stock (further away = less heat = less metamorphism). Fluid exchange between the magma and the dolostone has resulted in chemical change in the rock, often bleaching the country rock and concentrating ore minerals around the margins of the intrusion (ores for copper, gold, silver, iron, and more). In fact, Alta started out as a mining town. While we’re here, we’ll probably spot large piles of rock debris that are the tailings from old mines. In some of the mine dumps, rockhounders can find chunks of chrysocolla—a bluish-green copper ore—and rocks bearing metallic golden pyrite, an iron sulfide.

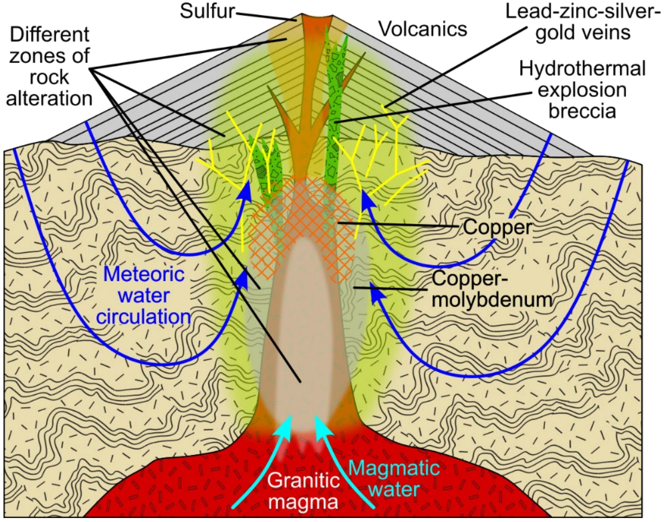
Bingham Canyon (Kennecott) Copper Mine

Kennecott copper mine: 1.210 km (0.75 miles) deep, 4 km (2.5 miles) across, covering 7.7 km^2 (3 miles^2). https://www.mining-technology.com/projects/bingham/

The Bingham Canyon mine is the largest and deepest open pit mine in the world, according to Wikipedia. Over 160 years, this mine has produced more than 17,000,000 metric tons of copper, 380,000 tons of molybdenum, 5300 tons of silver, 642 tons of gold, some lead and zinc, and considerable sulfuric acid.

In terms of its geology, the mine is in and around a body of granitic rock that intruded Paleozoic sedimentary rocks as magma in the late Eocene (post-Laramide, pre-Basin and Range). The magma was emplaced at a depth of a few to several kilometers, and above the magma body there was probably once a volcano.

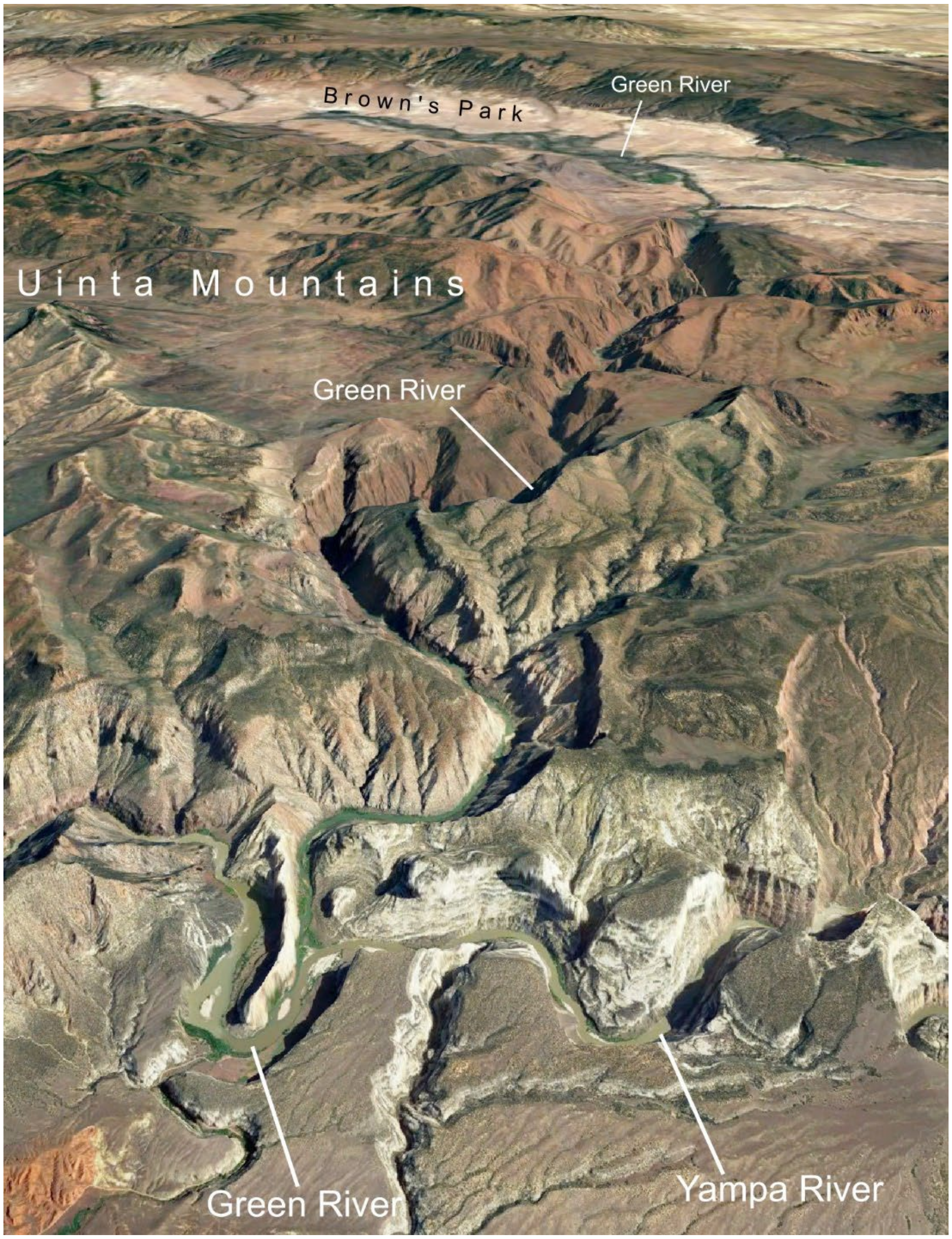
Water escaping from the hydrous magma carried dissolved minerals upward through fractures, where sulfide ore minerals were precipitated. In addition, fractures brought groundwater down close to the magma, where it heated up and began circulating through the fractures. The hot water scavenged metals from the rocks through which it flowed, and then precipitated sulfide and other minerals higher up in cooler areas as veins and fracture fillings. These so-called porphyry copper deposits are common throughout the world, and especially along the west coast of the Americas. Open pit mining is used where ore is relatively close to the surface, ore tonnage is high, and mining and processing costs are low. This mine is a classic example of a major type of multi-metal ore deposit, and shows part of what has to be done to maintain our modern technological society.



Schematic cross section of a forming porphyry copper deposit.

The Uinta Mountains

The Uinta Mountains are an anomalous mountain range of the Laramide Rockies (latest Cretaceous to Eocene in age). Unlike the other Laramide ranges in New Mexico, Colorado, Wyoming, and Montana, which trend N-S to NW-SE, the Uintas are nearly E-W. The mountains have a core of Precambrian sedimentary rocks, mostly red river-deposited sandstones, one of the most extensive exposures of such rocks in the western U.S. Paleozoic and Mesozoic rocks deposited above them are tilted up on the north and south sides of the Uinta uplift. Most of the high elevations along the central axis of the range are underlain by thick, purple Precambrian quartz sandstones.



View due north, across the eastern Uinta Mountains, where the Green River cuts across them to form the Canyon of the Lodore. The strange name was given by Powell, after the Robert Southley poem (1820) which described the Cataract of Lodore in Cumbria, northwestern England. Google Earth image.

The range was uplifted at the same time as the Rocky Mountains during the Laramide Orogeny (~70 – 50 Ma), and might owe its anomalous east-west trend to having been located at the margin of the compressional stresses that resulted from a tectonic plate collision.

To conceptualize how this could result in an inconsistent orientation, imagine using one finger to slide part of a flat, wet napkin a little bit across a tabletop—so, your finger is the compressive stress created by tectonic plate collision, and the napkin the continental crust. As you compress the napkin, it will fold to accommodate. While folds directly in front of your finger will be perpendicular to the direction you are pushing, either end will bow towards your finger—becoming closer to parallel than perpendicular to the direction of compression. In this model, these marginal folds are analogous to the Uinta Mountains.

There are several alternative explanations—including tectonic plate rotation at the time of collision—but there does not seem to be a consensus as to why the mountains trend east-west when all other related mountain ranges trend north-south.

After their uplift in Laramide time, the Uintas were eroded to a subdued topography, as were most of the surrounding mountains. This is shown by the presence of nearly flat-lying, Oligocene and Miocene gravels lying on rather low relief surfaces on what are now the flanks of high mountains. On the southern and eastern sides of the Uintas, the Miocene Brown's Park Formation, consisting of sandstones and conglomerates largely derived from an earlier stage of the Uinta uplift, is now at elevations thousands of feet above the level of the surrounding lowlands and the Green River. Utah State Highway 44, running along the northeastern end of the Uintas, is on a gravel surface within the Brown's Park. The Uintas and these younger sand and gravel surfaces, and indeed the entire Colorado Plateau and much of the surrounding continent, have been more recently uplifted by 2 to 3 kilometers, and eroded to produce the present topography.

The Green River almost certainly followed a course similar to its present one in Oligocene time, when the region started to be uplifted to its modern state. As the mountains rose, the river's erosional power was sufficient to maintain its course by cutting through resistant rocks of the rising mountains. In this way, the course of the present stream cuts a deep canyon through the range, which seems strongly at odds with the mountain range structure and present topography. The Green River is thus an antecedent stream. That is, it was in its present location, flowing over similar rocks and structures, before the most recent mountain uplift.

An alternative explanation is that the mountain structure was already present, but was buried beneath a thick cover of overlying sediments. The stream course was established on the gentle surface of this sediment cover, and the stream then cut downward through the cover. When it encountered the Uinta rocks and structures, it simply continued to cut down through them. In the case of the Uinta Mountains this idea seems unlikely. There is no evidence of such very thick, topography-covering Miocene or younger sediments anywhere in this area. Some of the most incisive ideas concerning the development of stream drainage morphology, and the physiographic history of river systems, have been developed by investigators studying the Green and Colorado Rivers, starting with the work of John Wesley Powell.

Dinosaur National Monument

At Dinosaur National Monument, there is a near-complete *stratigraphic section* (sequence of sedimentary rock layers) spanning from the mid-Neoproterozoic Era (up to ~800 Ma) to the mid-to-late-Cenozoic Era (greater than ~5 Ma), as well as modern surficial deposits (e.g., dirt). This means that there are rocks in outcrop here from all periods between ~800 Ma and ~5 Ma on the geologic time scale, with the only exceptions being the Ordovician (possibly), Silurian, and Devonian Periods, which are absent. Most locations on Earth are missing far more than a few periods' worth of sediment from their stratigraphic sections.

The national monument is on the eastern end of the Uinta Mountains, which are special in their own right. They are one of only a few east-west trending mountain ranges in the US, and include the highest peaks in Utah—stretching up to 13,528 feet above sea level at Kings Peak. Although there is no consensus on why the range trends east-west, due to the regional-scale compression that grew the Uintas most of the rock layers we will see at Dinosaur are no longer horizontal (Figure 1).

Figure 1: Folded strata at Dinosaur National Monument

Surficial Processes and Fossilization

As are the inner layers of the planet, the Earth's surface is ever-changing. Perpetual modification by weathering, erosion, and deposition sculpts the landscape, an eternal interplay between the biotic and abiotic components of an ecosystem. The dynamic nature of the surface strictly limits which organisms' remains will be preserved as fossils. As a preface to our discussion of the dinosaur bones visible in the national monument's Dinosaur Quarry, we will first outline the important surficial processes of weathering and erosion, and then detail a common mechanism for fossilization.

Weathering and erosion

Just like all of the ancient rocks we will see on this trip, the section of tilted sedimentary rocks at Dinosaur National Monument was revealed at the surface through the processes of weathering and erosion. *Weathering* is the physical, chemical, or biological breakdown of rock, and *erosion* is the process that transports broken bits away from their original location, pending eventual *deposition* in a sedimentary basin. Common weathering agents include—but are most certainly not limited to—water and wind (physical weathering), acidic rain (chemical weathering), and tree roots or burrowing creatures (biological weathering) (Figures 2, 3, 4).

Water and wind are the major shapers of the Colorado Plateau; throughout the trip, you will see plentiful evidence of their handiwork. Both fluids serve to transport weathered sediment elsewhere, and the sediment they carry helps them break down additional rock along the way. Through the millennia, flowing rivers and even usually-dry washes—host to water only during precipitation events—become incised into rock, cutting downwards to create ravines and canyons. Similarly, wind can entrain abrasive particles, effectively sandblasting any outcrop in its path.

Figure 2: Two examples of physical weathering. Left: Millennia of exposure to wind and water have gradually sculpted world-famous Delicate Arch (DepositPhotos). Right: Freezing and thawing of water has widened the fractures in this rock; when water freezes inside the fractures it expands, pushing outwards. The river in Figure 1 is another example of active physical weathering.

Some rock types are weaker than others and therefore break down more quickly. This is called *differential erosion*. Softer and/or weaker rocks (such as clayey material like shale, or soluble minerals like salt) are said to be *less resistant* to weathering and erosion while stronger rocks (like sandstone, or igneous rocks like granite) are *more resistant*. The difference in resistance arises due to factors like composition of the grains and the cement that binds them together, grain shape and size, porosity (space between grains for water to infiltrate), the presence of planes of weakness like fractures or foliation, and more.

Photo by: Ernst Kiessling / Flickr

Figure 3: An example of chemical weathering. The Stone Forest in China is made of soluble limestone ($CaCO_3$). Its otherworldly landscape developed when limestone was slowly dissolved away by rainwater.

Multiple rock types are commonly juxtaposed against each other in sedimentary outcrops, making differential erosion evident. On the Colorado Plateau, we will see shales that have crumbled into sometimes-colorful slopes and sandstones that form sturdy, desert-varnished bluffs and ledges. Commonly, a less-resistant layer between two resistant layers may be eroded into a shadowy recess. Such recesses are visible between the beds in Figure 4.

Figure 4: An example of biological weathering. In a process somewhat similar to freeze-thaw weathering, the roots of this tree have slowly widened fractures in the rock, resulting in the displacement of the block on the right.

As weathering and erosion remove rock from outcrops, the rocks might become undercut so that they can no longer support their own weight and are dragged down by gravity (such as in a landslide). Or, during a mountain-building event, rocks might be thrust upwards faster than they can be broken down, leading to steep slopes that may ultimately topple down in rockfalls. Humans can exacerbate such mass-wasting events by cutting out the toe of a slope, for example, to create a road. We'll see an instance of that at Douglas Pass, after we leave Dinosaur. A slope's propensity to collapse should be a major consideration for engineers when altering the natural landscape.

Fossilization

The selfsame processes that expose fossil bone beds at the surface—in conjunction with the food chain's host of decomposers and scavengers—actively work against fossil development. Preservation of biological materials is very unfavorable, especially in terrestrial environments that are rocky and/or forested. Larger bones are more likely to escape mechanical breakdown and the digestive tracts of scavengers than smaller bones—let alone the bodies of creatures *without* bones—so the terrestrial fossil record is skewed towards large vertebrate animals (rather than frogs or insects). However, the fossil record as a whole is greatly skewed towards aquatic organisms. Only a fraction of all species that have ever existed managed to make it into fossil form, with the rest lost to the annals of time.

The most common way that dinosaur bones are preserved is via *permineralization* or petrification, by which biological hard parts are impregnated with minerals and "turned to stone." This is the same mechanism that creates petrified wood. Fossils can form in other ways—such as molds, casts, and carbonization—but we will not delve into them here.

For fossilization to occur, a deceased organism's remains must be rapidly buried to protect them from scavengers and erosive surficial processes. This requirement is part of the reason for the prevalence of marine fossils. Burial in fine-grained sediment like mud is conducive to fossil formation, as finer sediment is less likely to cause mechanical breakdown of the buried bones before they can be permineralized. The soft parts of the animal rapidly decay; to preserve its bones, silica-rich groundwater must percolate through them and precipitate minerals like quartz (silica, SiO_2) into internal cavities (Figure 5). If the groundwater is not rich in dissolved silica, permineralization may not occur.

Quartz is harder than bone, and this is important because the entire rock layer containing the remains will be subjected to an increase in pressure and temperature as it is buried beneath more and more sediment, and as it is compacted and lithified (turned to stone) through a process called *diagenesis*. The quartz is more likely to withstand the heat and pressure without being

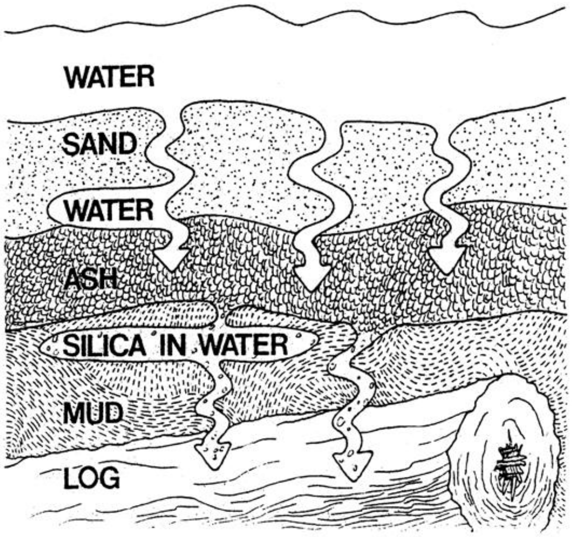


Figure 5: An example of how permineralization could preserve a buried log. If there is no silica (SiO_2) dissolved in the water, quartz cannot precipitate. The layer of volcanic ash is a source of dissolved silica.

destroyed, but breakage is not out of the question. Even when permineralized, most dinosaur skulls—hollow, delicate bones—are flattened like aluminum cans beneath the pressure of burial.

In most instances of fossilization, all biological parts are lost—but sometimes, under special circumstances, bits of original bone, feather, and even soft tissue can persist for millions upon millions of years to be sampled by scientists today. Armed with improving technology, paleontologists over the past several decades have been discovering ever-more biological material—proteins, pigments, DNA, even cells—in specimens once thought to be purely stone. This has allowed for exciting advancements in the quest to parse out the evolution of life.

The Dinosaurs

The density and quality of fossils at Dinosaur National Monument is downright remarkable, and the Dinosaur Quarry has been a veritable treasure trove for paleontologists since 1909. Here, paleontologists have unearthed new species like *Abydosaurus*, a number of intact skulls—even from juvenile animals—lizard bones, and amazingly, a *Camptosaurus* embryo.

The bones are all within the Morrison Formation of the Jurassic Period, a rock layer renowned for its fossil content. The fossiliferous Morrison Formation is composed of mainly-terrestrial floodplain and channel deposits, sandy to silty in nature. A lush, tropical to subtropical climate probably prevailed at the time of deposition, with the landscape blanketed by extensive swamps and forests teeming with life. The bone bed on display at the Dinosaur Quarry illustrates the abundance of dinosaurs that called this place home. It formed when dinosaur carcasses—either individually or as the result of large-scale flooding events—were washed into a sand bar in a Jurassic river and covered with later sands.

Preserved in a matrix of fine-grained sand are dinosaur genera (genus, plural) including:

Sauropods:

Apatosaurus ("false lizard" for its amazingly large size)

Camarasaurus ("chambered lizard" for its chambered vertebrae, host to an air sac system)

Barosaurus ("heavy lizard" again for its size)

Diplodocus ("double beam" for the morphology of the vertebrae in its whip-like tail)

Abydosaurus ("Abydos lizard" for the city overlooking the Nile River where the head and neck of Osiris were buried; holotype head and neck were discovered in 2010 overlooking the Green River)

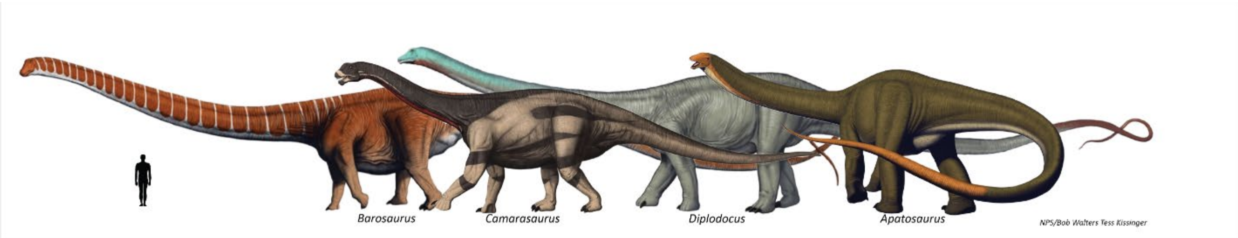


Figure 6: Sauropods of Dinosaur National Monument compared to 1.8 m tall person. Abydosaurus *not shown. Artwork: https://www.nps.gov/dino/learn/nature/dinosaurs-of-dinosaur.htm NPS/Bob Walters Tess Kissinger.*

Other herbivores:

Camptosaurus ("flexible lizard" for the flexibility evident in its sacral (pelvic-area) vertebrae)

Stegosaurus ("roof lizard" for the sails on its back)

Dryosaurus ("oak lizard" for its forested habitat)

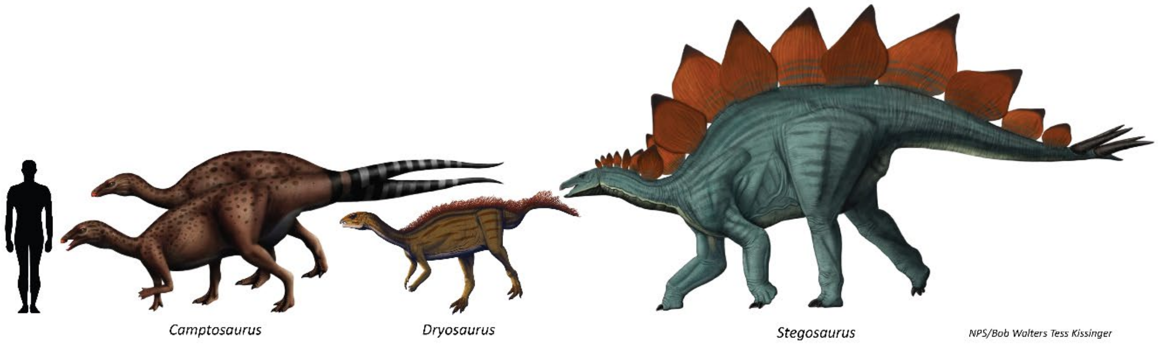


Figure 7: Other herbivores of Dinosaur National Monument compared to 1.8 m tall person. Artwork: https://www.nps.gov/dino/learn/nature/dinosaurs-of-dinosaur.htm-NPS/Bob Walters Tess Kissinger.

Theropods:

Allosaurus ("different lizard" because its vertebrae were different from any other dinosaur when it was discovered in 1877; UT state fossil)

Ceratosaurus ("horn lizard" for the horns on its head)

Torvosaurus ("savage lizard" for obvious reasons…)

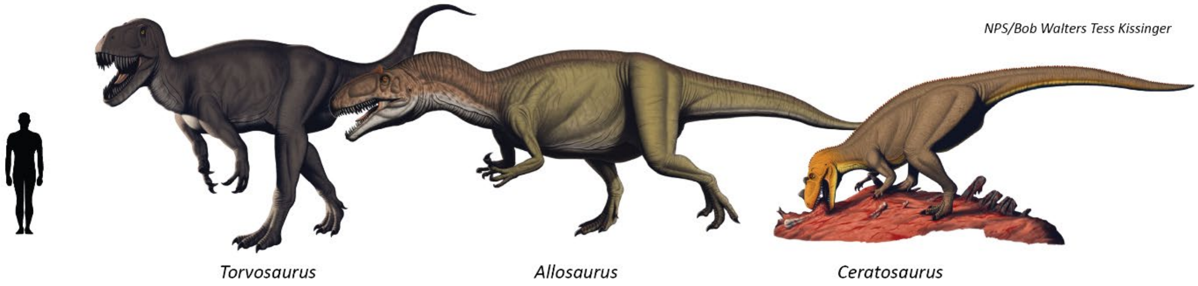


Figure 8: Theropods (bipedal carnivores) of Dinosaur National Monument compared to 1.8 m tall person. Artwork: https://www.nps.gov/dino/learn/nature/dinosaurs-of-dinosaur.htm-NPS/Bob Walters Tess Kissinger.

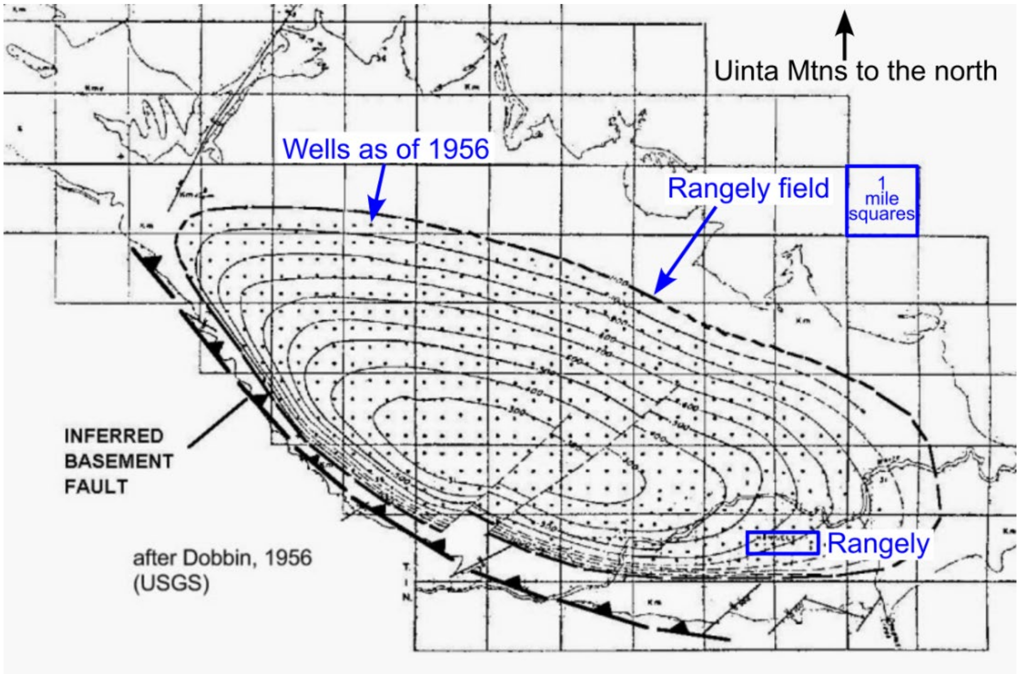
Rangely, Colorado Oil and Gas Field Development

Typical part of the Rangely oil and gas field. Circular bare patches are places where wells have been drilled. Google Earth image.

Paleocene sedimentary rocks are at the surface in much of northeastern Utah and western Colorado. Below them are Pennsylvanian and Permian sedimentary rocks of the Weber Formation, that has produced considerable oil and natural gas. The area around Rangely shows most of the features of “oil country:” pumps, drilling rigs and pads, storage tanks, and pipelines.

In this oil field, sedimentary rocks including the Weber Formation have been folded and faulted into a dome-shaped structure. This structure likely formed in the Paleocene and Eocene, and there is no topographic trace of it on the surface. During burial and possibly deformation, low-grade heating of surrounding carbonaceous rocks, probably shale, caused organic material in them to transform into two parts: carbon-rich, high molecular weight tar-like solids, and lower molecular weight, hydrogen-rich hydrocarbons including natural gas and liquid oil. The low density of these materials, probably also carried along by flowing water released from clay minerals during heating, caused the oil and gas to migrate into pore spaces in the Weber Formation’s dome-shaped “trap.” The Weber is capped with impermeable shales, so the oil and gas couldn’t rise any higher.

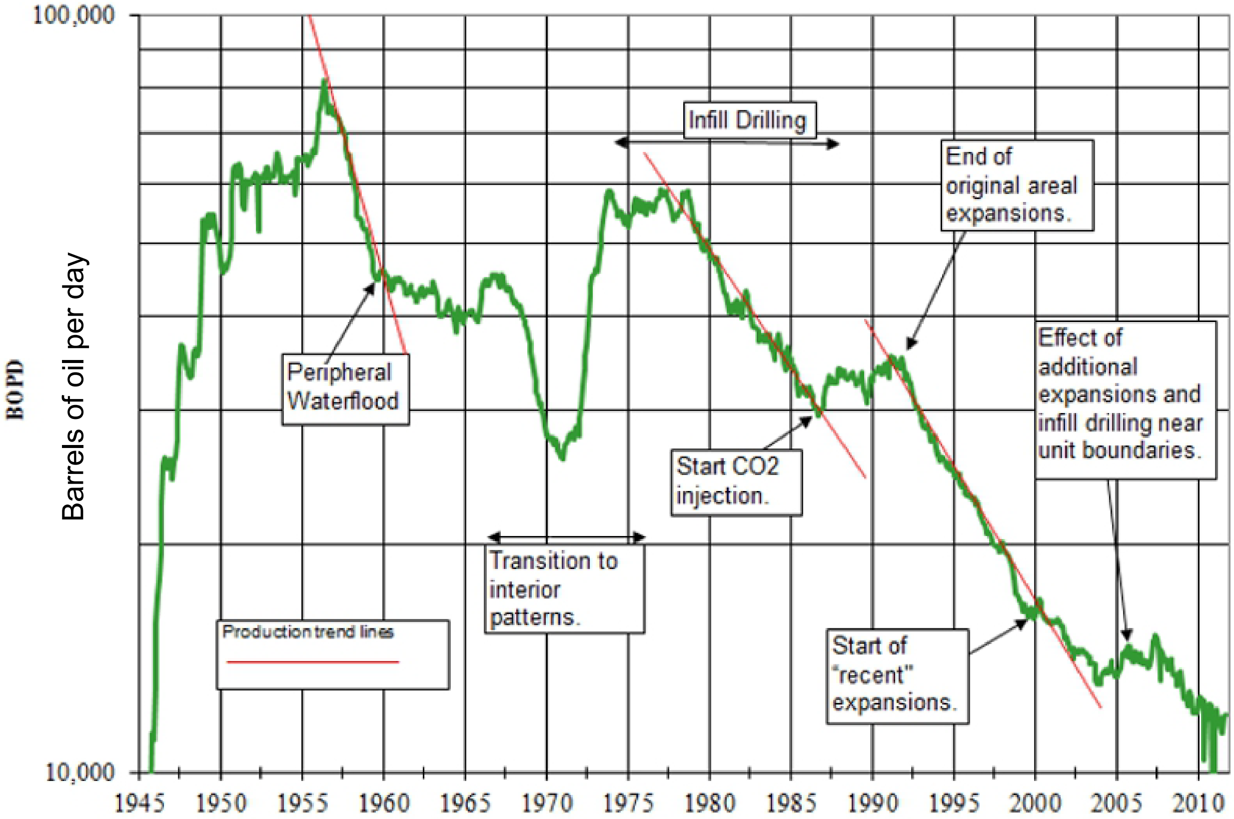
Oil and gas production started here just after World War 2, and reached peak production in 1957. On the graph below, you can see early production rising as more wells were drilled. After the peak, production started to drop as pressure in the oil-bearing layer decreased from oil and water withdrawal. In 1959, water flooding began. That is the process of purposely injecting water into some wells, to flush remaining oil in pore spaces to producing wells. Water injection began around the field edge, but in late 1960s and early 1970s the flooding wells were moved into the field interior, to put the water injection sites closer to producing wells. CO_2 injection started in 1986, to do the same thing as water flooding. CO_2 and water are injected down some wells, where the CO_2 dissolves into the oil, decreasing oil viscosity and also swelling it. This leads to further recovery.



Outline and elevation contours on the Rangely oil and gas field structural dome. Average depth to the producing Weber Formation is about 6000 feet (1830 m), and the dome height from edge to peak is about 830 feet (250 m). http://historyoftheearthcalendar.blogspot.com/2014/07/july-8-rangely-oil-gas-field.html.

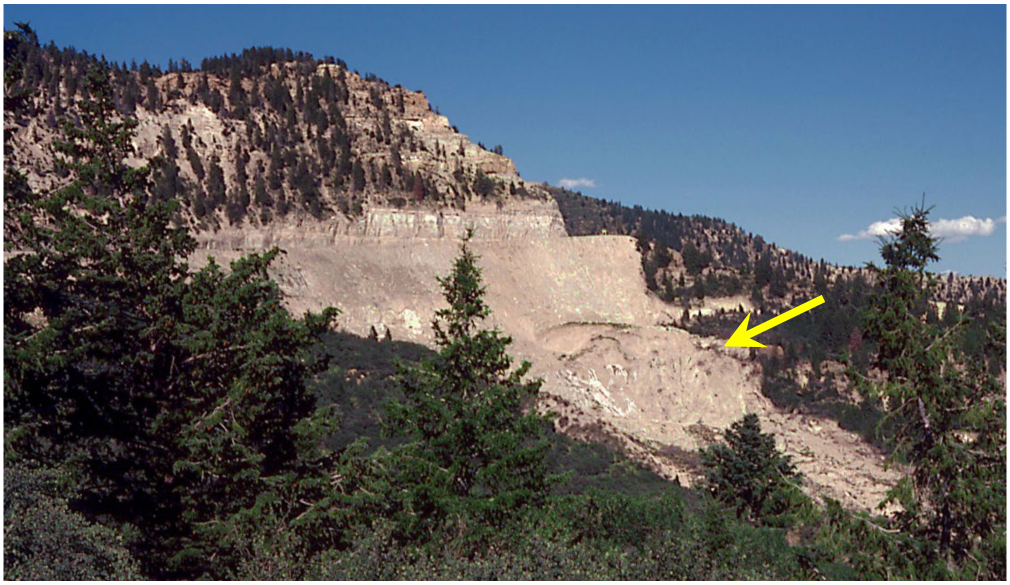
"Infill drilling" refers to drilling wells in between previously drilled wells. Closer well spacing aids recovery of oil stuck between wells. "Expansions" refer to drilling in areas not previously drilled, thus expanding the oil field area. Each time something was done, in the hopes of maintaining or increasing production, the new process worked for a while, but then the limits of that process were reached, and production began a steady decline (steady on the log-linear axis graph). New technology can rejuvenate old oil fields, but not forever. Newer technologies are usually more expensive than old, and so require a higher oil prices. In principle, every drop of oil could be extracted from the Rangely Field, at a sufficiently high oil price, but at the currently high price of oil, that energy source is being progressively replaced by electricity from renewables. Eventually, it seems likely that oil production will only be used for high-price commodities, like chemical feedstocks.

According to several news reports, and the SEC, Chevron sold the Rangely Field to Scout Energy Partners in 2021. My understanding is that Scout Energy Partners specializes in maintaining slow, managed production from old fields, mostly using in-place infrastructure and procedures. Presumably, when the field is no longer profitable, the movable infrastructure will be sold off and the field abandoned.



Rangely, Colorado, oil field production, 1946 to 2017. https://www.geoexpro.com/articles/2016/01/teamwork-at-rangely.

Douglas Pass Landslides, Colorado Rt. 139



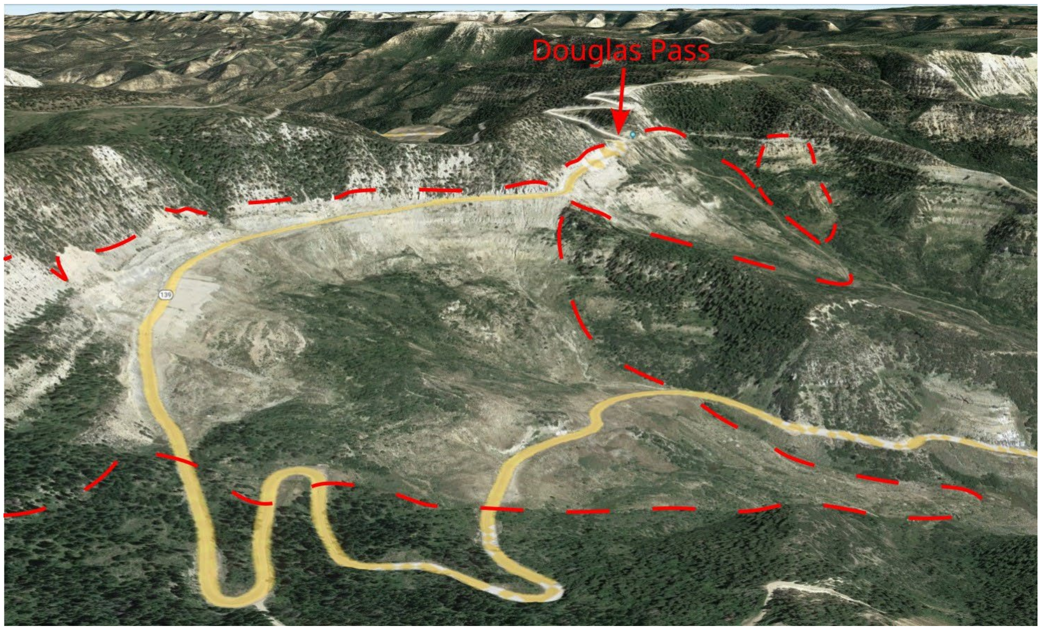
Looking up toward Douglas Pass, from Colorado Rt. 139.

On our trip south from Rangely, Colorado, after climbing up to Douglas Pass, we will crest the pass and proceed down the steep south-facing slopes of the Green River Formation. The weak shale, plus the steep slopes, plus seasonal and sporadically heavy rains, causes episodic, slow-moving landslides that plague this stretch of road. The 1978 image above shows a landslide block that slid down from the slope, right below the road below the pass.

Movement of these landslides is usually slow, though not particularly steady. Every few years the road has to be repaired in one place or another. The photo at the bottom of the page is from a 2010 Colorado DOT study that looked at the effectiveness of pilings driven into the downhill side of the road. They found that small pilings driven to an unspecified depth had failed (didn't hold up the road), but larger ones, driven to a depth of 10 feet (3 meters) in 2004, were still working. This is part of a smaller landslide.

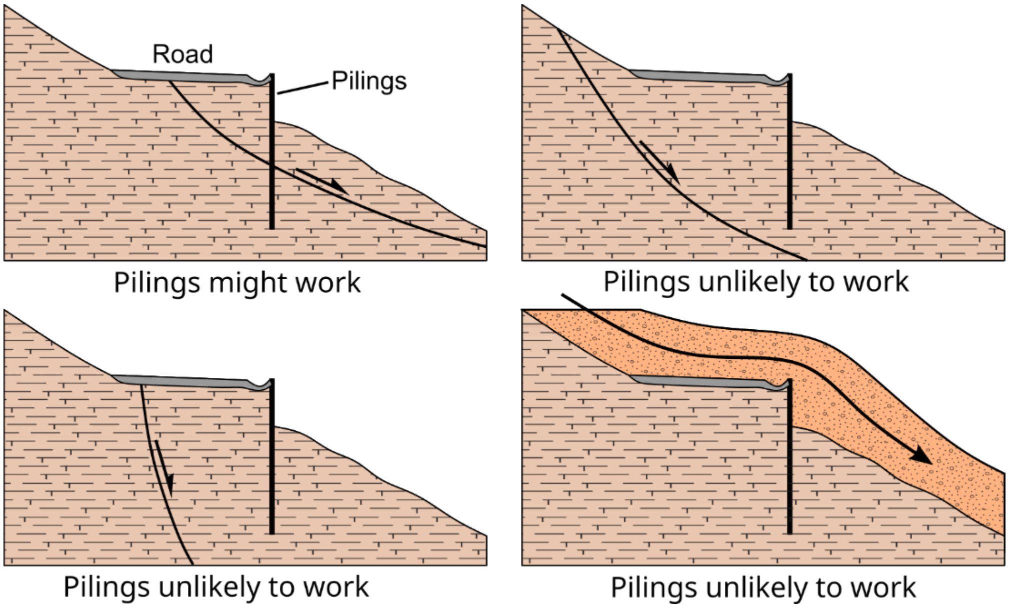
Failure and (at least temporary) success of driven piles to hold up Colorado Rt. 139, south of Douglas Pass (Kiousis et al., 2010).

The larger slide, apparent on the next page, is more problematic. It undergoes sporadic, slow movement that is sufficient to wreck the road, but slow enough to prevent dangerous accidents (usually). We will probably see extensional cracks on the road surface which, here and elsewhere, indicate slow downhill creep of the moving rock masses. However, in this and other cases, the deep sliding surface at the landslide base is unlikely to be amenable to stabilization using shallow pilings. The next image shows outlines of landslides in the Douglas Pass, south side area.



The area south of Douglas Pass. Colorado Rt. 139 is in yellow, landslide outlines are in red. View is to the northeast. Google Earth Image.

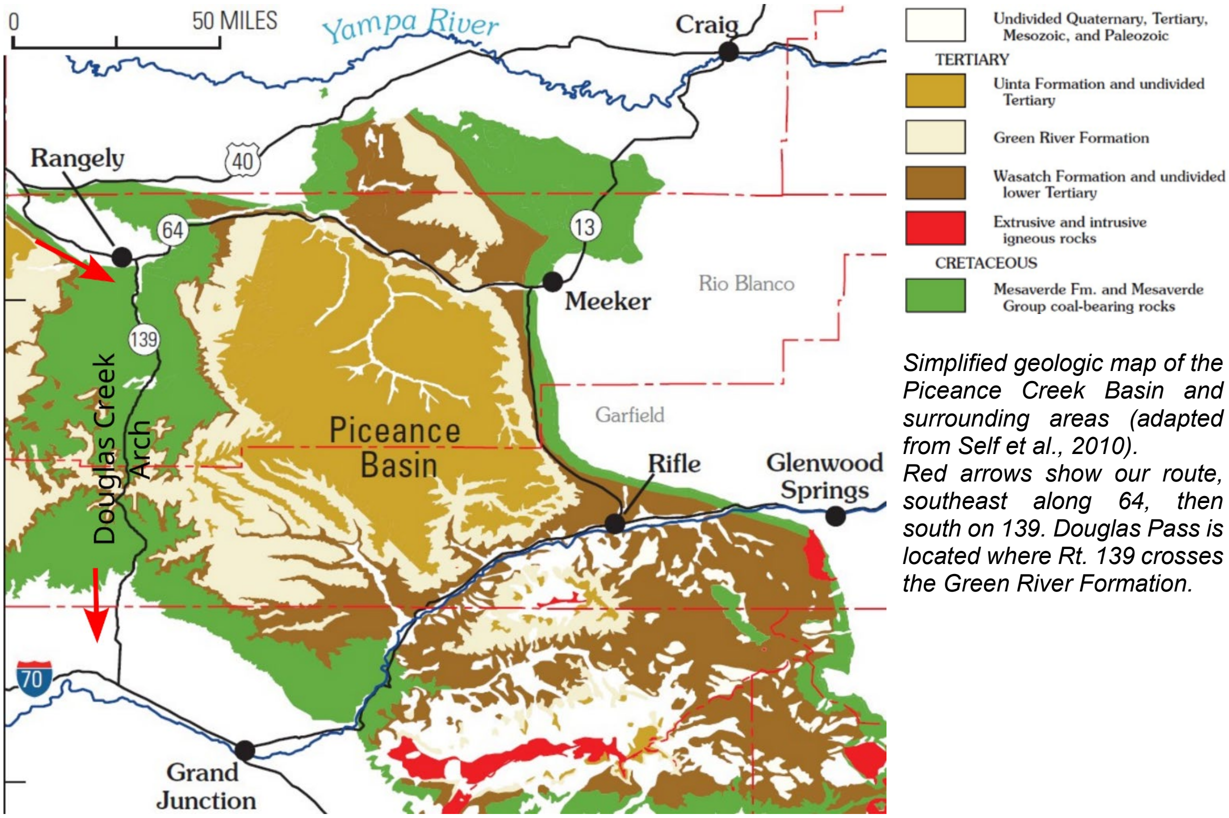
The set of cartoons below illustrates some problems engineers have trying to stabilize landslides, with this example focus being driven pilings below the road (there are also other techniques). In some cases, stabilization can be done successfully, though nothing works forever, of course. In other cases, however, landslide stabilization is more difficult.



Hypothetical success or failure of driven pilings below a road to protect the road from landslides.

Green River Formation, Piceance Creek Basin

The Green River Formation is a sequence of lake and lake-margin river sediments, deposited in a set of Eocene intermountain lakes, north and south of the Uinta Mountain Uplift. The (sometimes) several lakes filled a number of intermountain basins formed by the highlands of the late Cretaceous Seiver Mountains to the west and northwest, and block faulted Paleocene and Eocene Laramide uplifts to the east and northeast. The lakes also partly surrounded the eastern Uinta Laramide uplift. The lakes formed in an arid environment, receiving fresh water from the surrounding mountains. The Green River Formation is exposed in two large, connected basins: Piceance Creek to the east, and Uinta to the west. The image here shows a geologic map of the Piceance Creek Basin and surrounding areas, with the Green River Formation mostly exposed at the edges of a high plateau. We will travel down Rt. 139, along the Douglas Creek Arch that separates the Uinta from the Piceance Creek Basin. We will have many long views of the Green River formation, especially to the east.



Simplified geologic map of the Piceance Creek Basin and surrounding areas (adapted from Self et al., 2010). Red arrows show our route, southeast along 64, then south on 139. Douglas Pass is located where Rt. 139 crosses the Green River Formation.

Most of the Green River Formation consists of shales, limestone or dolostone, and marl, which is a mixture mostly of clay and calcite or dolomite. The lake system started off with relatively fresh water, but over time evaporation caused it to become more saline and density-stratified. The density stratification was caused as salts were concentrated by evaporation in coastal shallows. The brine flowed downhill to make the dense, deep water, with fresh water from river input forming a low-density cap. As salinity and density stratification increased, more and more organic material was preserved in sediment in the deeper, anoxic parts of the lake. Many parts of the Green River Formation are rich enough in organics to be called “oil shale.” This rock is similar to the other shale or marl, but it is light- to dark-brown, smells like oil, can have an organic content of up to 50%, and an extractable (by heating to liquify or vaporize the oil fraction) of up to 15%. The richest oil shale is in the Mahogany Layer, near the formation top (named after the fact that its dark, rich-brown layering looks something like mahogany).

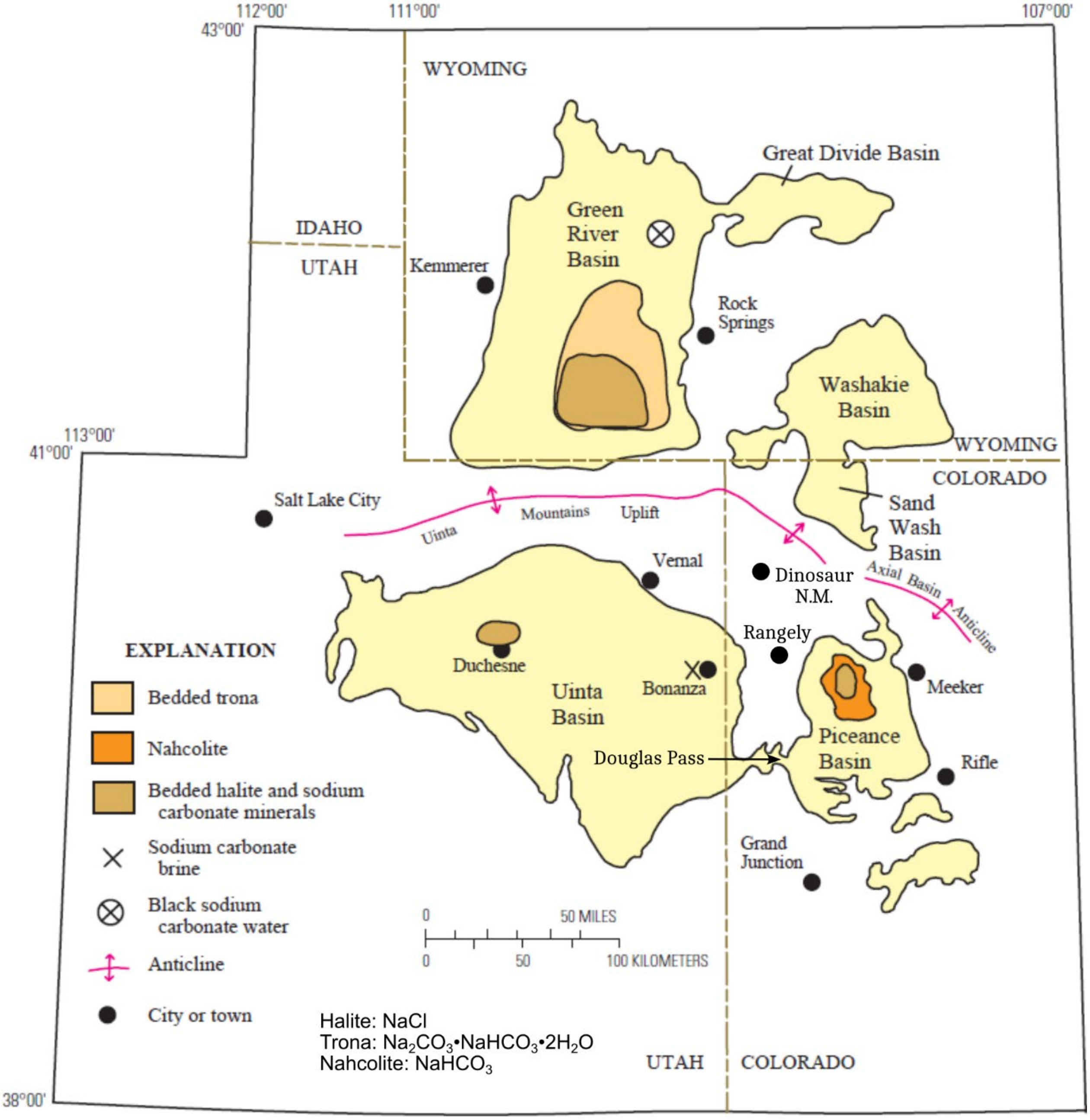
The Mahogany Layer, the cliff-former in the image below, averages about 40 meters thick, and is estimated to have a resource potential of about 200 billion barrels of oil. The formation as a whole has a resource potential of over 1 trillion barrels of oil, making it one of the largest oil resources in the world.

Cliff-forming mahogany layer, near the top of the Green River formation, west side of the Piceance Creek Basin. View is approximately northeast.

Extracting this oil, however, is difficult. It was attempted by several companies in the 1970s, and at other times, but mining or *in situ* extraction methods proved too expensive or impractical. With current high oil prices, there is considerable petroleum industry chatter about starting large-scale extraction. However, the CO_2 released by such enthusiastic petroleum extraction and use would be environmentally disastrous. Anyway, currently-known conventional hydrocarbon resources are probably sufficient to see civilization through to the time, maybe 3 to 5 decades in the future, when burning fossil fuels is no longer a significant source of energy (chemical feedstocks for plastics and other things is another story).

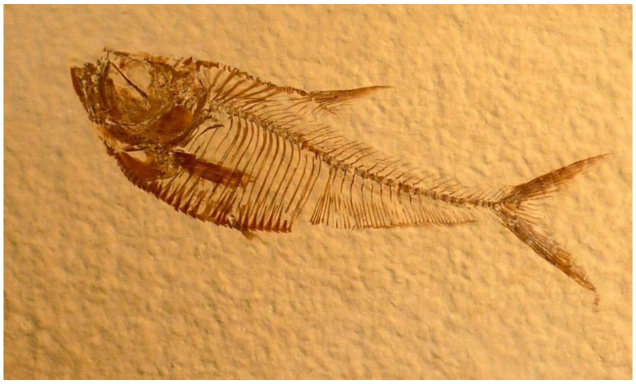
Another resource in the Green River Formation is sodium carbonate minerals, including nahcolite ($NaHCO_3$) and trona ($Na_2CO_3•NaHCO_3•2H_2O$). These were deposited as evaporite minerals, much like halite and mirabilite deposits in the Great Salt Lake, but different because of the different water chemistry. The fact that fish fossils are found in some parts of the Green River formation, and evaporite salts in others, probably indicates climate control of lake water composition and salinity. Fish thrived when lake levels were high and the water relatively fresh (probably in open basins), and salts were deposited when the lakes largely dried out (closed basins). The stratigraphy of the Green River formation varies a lot, indicating swings in climate resulting in great variations in lake sizes.

The Green River Formation has the largest known deposit in the world of sodium carbonate minerals (in the Green River Basin), and one of the largest of sodium bicarbonate (nahcolite, in the Piceance Basin). At present, these are mined industrially by underground mining in Wyoming, and by solution mining in Colorado. Both sodium carbonate salts are used for the production of sodium bicarbonate and sodium carbonate, which are used in, among other things, laundry detergent, manufacturing glass, pH adjustment of water, and chemical processes.



Eocene lake and related deposits in Colorado, Utah, and Wyoming, including the Piceance Creek Basin (Self et al., 2010). Soluble salt deposits are shown in the darker colors.

One spectacular aspect of the Green River formation is the presence of exquisitely-preserved fish fossils. The fossils occur in great numbers on particular horizons, possibly having been killed by a local, catastrophic environmental change, like the sudden wind-driven mixing of oxygen-poor deep lake water upwards to the surface, where the fish lived. Fossil preservation was probably aided by anoxic deeper lake waters (quiet, no scavengers other than bacteria), and fine-grained sedimentary materials.



Fossil fish skeleton in the Green River Formation.
https://en.wikipedia.org/wiki/Green_River_Formation

Another interesting aspect of the Green River formation is not the petroleum reserves or sodium carbonate or fish fossils of the lake centers, but interesting rocks and depositional features of the lake margins. The photos below show a stromatolite (left), a carbonate structure that grew on the shallow lake floor from the growth of cyanobacterial mats, and oolites (right), small carbonate spheres produced by precipitation of calcite in shallow water, where wind-driven currents can roll them around. These samples were from a drill core collected near Douglas Pass, at a drill depth of about 50 meters.

Stromatolites: calcite mounds precipitated by cyanobacterial mats. Gray to brown oil shale surrounds the stromatolite.

Oolites: calcite spheres precipitated in shallow waters that have wind-driven currents to roll them around. Oil shale is above the oolite layer.

Green River, Wyoming was the starting point for John Wesley Powell's Colorado River exploring trips. The first started out in May of 1869, and a second trip started in 1871. Powell gained national recognition through his first expedition, and gathered considerable new information about one of the least-known areas of the U.S. at that time. This was especially true for the second expedition, which involved much overland surveying.

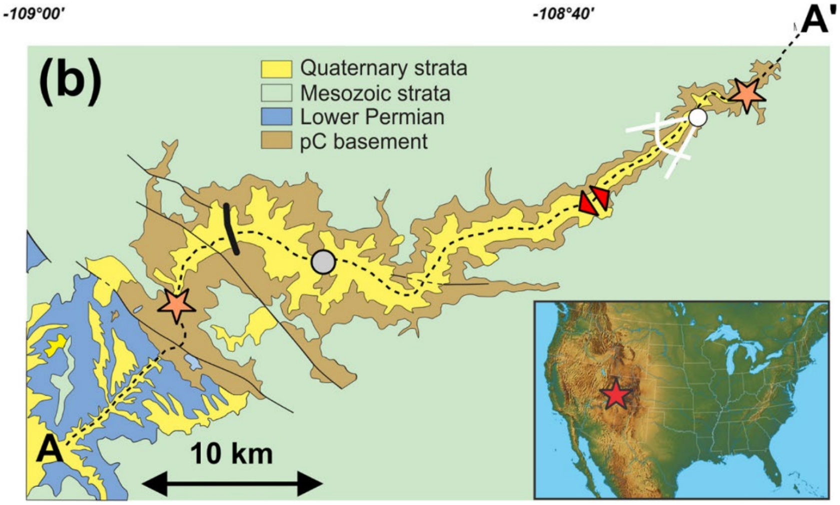
Powell became an important force in structuring the relationship between the Federal Government and scientists. He was instrumental in the formation of a civilian-controlled geological survey for the U.S., the U.S. Geological Survey, and became its second director when the first director, Clarence King, resigned after a year. Powell also founded the Bureau of American Ethnology, which was responsible for preserving much of our best information on Native American tribes of the time. His efforts were certainly key in establishing the Bureau of Reclamation, though this did not actually take place until after his death. He was probably also at least partly responsible for the formation of the National Forest Service.

Unaweep Canyon and Uncompahgre Uplift, Colorado

Looking northeast up Unaweep Canyon, from near the canyon center where its elevation is highest and the stream on the valley floor is almost nonexistent.

Unaweep Canyon crosses the Uncompahgre Plateau between Grand Junction and Gateway, Colorado, along Colorado Rt. 141. The canyon is up to 3.7 miles (5.9 km) wide in its central section, and about 2600 feet (795 m) deep, eroded into Precambrian igneous and metamorphic ("crystalline") rocks. Despite its impressive size, the canyon has only a small stream flowing in it. Indeed, in the middle of the canyon there is no stream at all. To the NE, a small stream gradually develops and flows NE toward the Gunnison River. To the SW, another small stream develops and flows SW toward the Dolores River. How can one explain this large canyon having essentially nothing to erode it? The answer turns out to involve a complex interplay between rate of uplift of the Uncompahgre Plateau and rate of downward erosion by previous rivers.

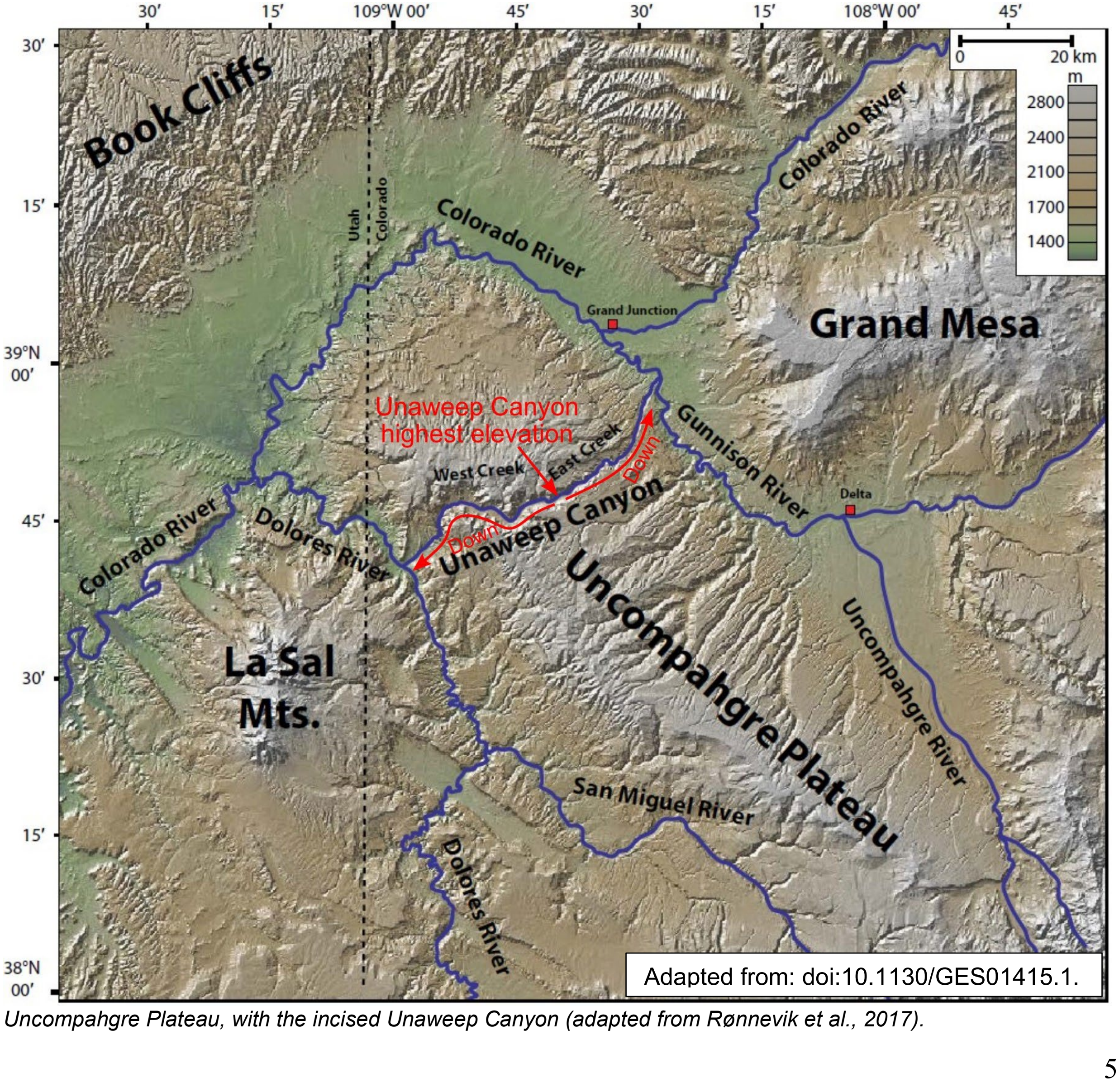
In the late Paleozoic or early Mesozoic, all older sedimentary layers were eroded off from Precambrian rocks in the Uncompahgre Uplift area. This left a clean surface of crystalline rock on which Mesozoic sediments were deposited. Radiometric dating of the thermal history of these rocks indicates only shallow burial during the Mesozoic. The rocks became more deeply buried in the Laramide (latest Cretaceous to Eocene),



Simplified geologic map of the Unaweep Canyon area (Patterson et al., 2021).

presumably from sediments eroded off the Laramide uplifts to the east, such as the Sawatch and Front Ranges. Relatively deep (3 to 5 km) burial at that time is indicated by high temperatures extending into the Oligocene. Rapid uplift of the Colorado Plateau (and surrounding parts of the continent), and erosion of the overlying rocks during the Miocene and Pliocene, is indicated by rapid cooling at that time.

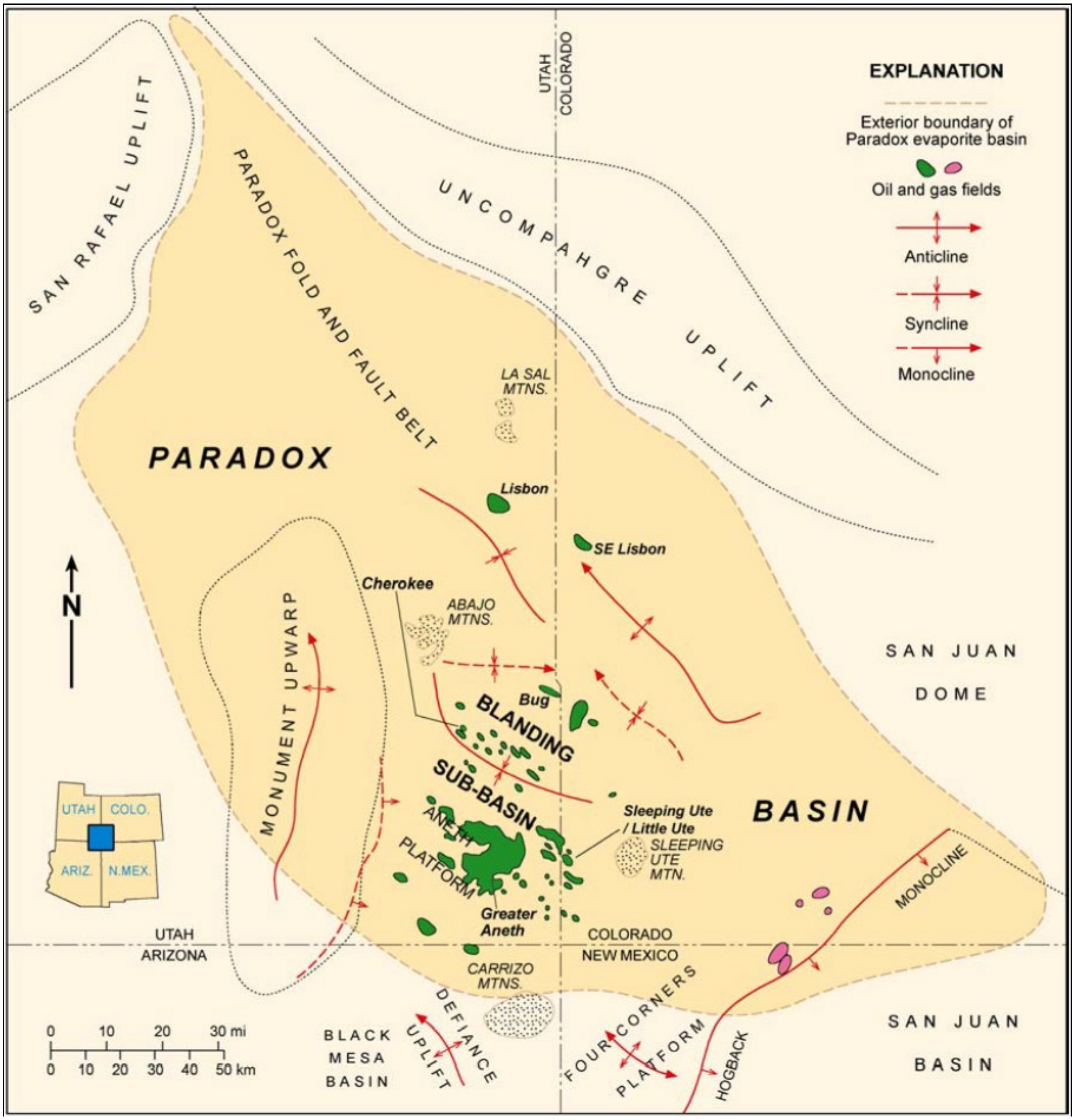
Some rocks are more easily eroded, such as shales and soft sandstones, and others are harder to erode, such as most crystalline rocks, hard sandstones, and limestone in arid climates. During uplift, a large river apparently crossed what is now the Uncompahgre Plateau. The river eroded fairly easily through the Cenozoic (Laramide) and Mesozoic sediments, and eventually into Precambrian crystalline rocks below. The Uncompahgre Uplift is surrounded by sedimentary rocks that include soft varieties. As uplift continued into the Neogene, it became increasingly difficult for the large river to erode through the expanding width of Precambrian crystalline rocks. At the same time, erosion by other rivers and streams proceeded into softer rocks around. Eventually, the rising Precambrian rocks of the Uncompahgre Plateau became, in effect, a dam, forcing the large river to a new, more easily eroded route. Most people think that river was the Colorado.



Uncompahgre Plateau, with the incised Unaweep Canyon (adapted from Rønnevik et al., 2017).

The Paradox Basin, Utah

The Paradox Basin is a down-warped Pennsylvanian structure that is complementary to the up-warped Uncompahgre Uplift to the NE. As it was forming, this region was in an arid climate. At times, warping of the crust severely restricted access of open ocean waters to the basin, even at times leaving the basin an isolated saline lake. Evaporation, plus inflow of salt water through narrow inlets, allowed massive amounts of halite and gypsum to be deposited in parts of the basin, and clastic rocks, limestone, and dolomite to be deposited in others. Irregular subsidence and uplift of different regions led to several cycles of evaporite-dominated deposition, alternating with limestone and clastic rock deposition.

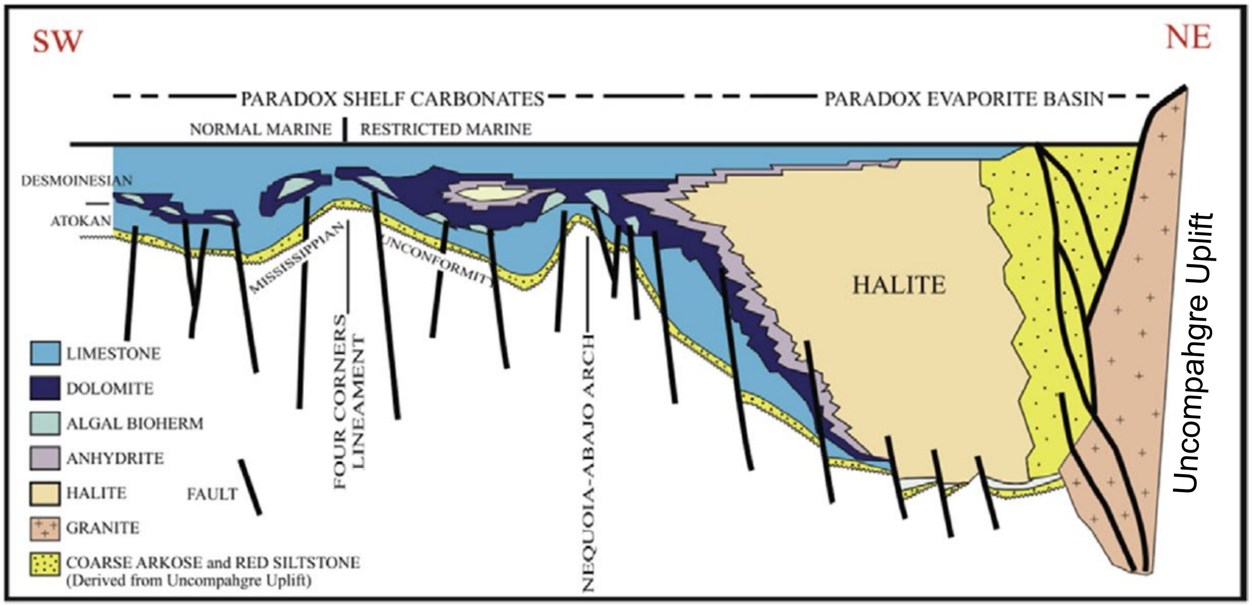


Generalized structure map of the Paradox Basin, showing oil and gas fields, and some landmarks (from McClure et al., 2003).

In the cross section below you can see that the NE part of the Paradox Basin has the thickest salt, compared to the SW side. The section also suggests that the Uncompahgre Uplift was emergent during salt deposition, and was a source of coarse clastic sediments that were deposited adjacent to the uplift, on the NE side of the Paradox Basin. In addition to halite as a commercial commodity, sylvite (KCl) deposits, and bromine- and lithium-rich brines may soon be mined. In the carbonate rocks surrounding the salt, considerable oil and natural gas has been extracted from fault and anticlinal features in the basin, particularly from the south and southwestern parts of the basin.

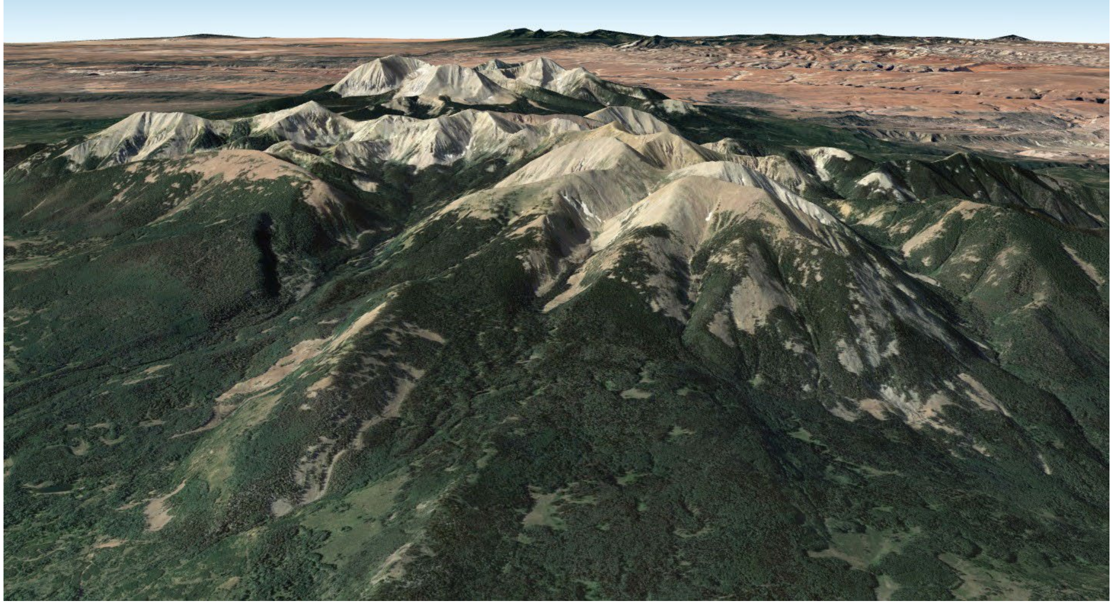
Salt in the Paradox Basin will be an important factor in several other places, as we travel across its northern and western parts. One is Upheaval Dome, where a roughly cylindrical mass of the low-density, ductile salt has risen toward the surface, disrupting flat-lying sediments. Another is Canyonlands, where most of the Permian through Paleogene rock sequence above the salt has been eroded through by the Colorado River. As the river has eroded downward, lateral support was lost for the package of sediments southeast of the river, which are tilted downward in that direction. With loss of support, they have started sliding downhill on the ductile salt, toward the river. Sliding causes extension, which opens joints and forms small normal faults, which cause many of the unusual Canyonlands structures.

One bit of interesting information is that Paradox Basin has been suggested as a permanent repository for high-level radioactive waste. Because salt is ductile, impermeable to small amounts of water, and flows under the weight of overlying rocks, if waste were put in tunnels, they would eventually close and seal themselves off from the rest of the world. One problem with this idea is that the Paradox Basin is riddled with oil and gas drill holes, some of which have doubtless been abandoned and lost, but not sealed. Another problem is that the salt remains a valuable resource, which will always be sought after by technological peoples, particularly if they have lost track of the fact that the radioactive waste is there.



Cross section of the Paradox Basin, emphasizing the Pennsylvanian Paradox Formation (Ritter, 2018). Below the Paradox Formation is the Mississippian Leadville Formation (yellow with dots), and to the right is the Pennsylvanian Honaker Trail Formation, clastic sediments eroded from the Uncompahgre Uplift (also yellow with dots).

The La Sal Mountains

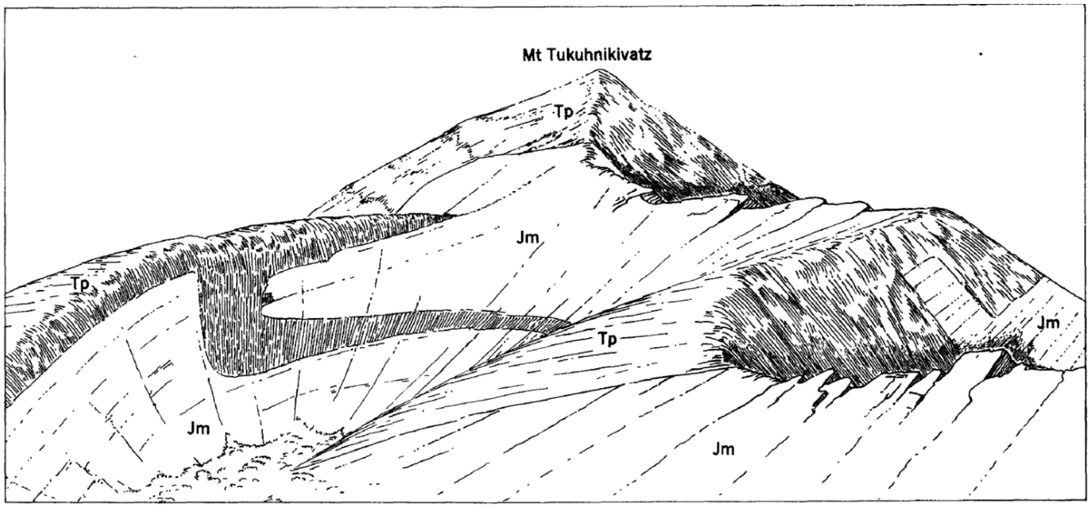


La Sal Mountains (foreground), with the Abajo Mountains on the center horizon, Sleeping Ute Mountains to the upper-left, and the Henry Mountains to the upper-right. Google Earth image.

The Sierra La Sal (Salt Mountains) are one of a group of prominent, though of limited extent, mountain ranges in eastern Utah. These include the Abajo, Sleeping Ute, Carizo, Henry, and Navajo Mountains, which are generally W, S, and SW of the La Sals. These are laccolithic mountains, in which an andesitic (diorite) magma, of high viscosity, intruded and bowed up overlying sedimentary layers, rather than simply breaking through to the surface. This mechanism can be ascertained by examination of the geologic structure of the mountains, such as tilted and fractured sedimentary rocks on the intrusion flanks, as well as geophysical measurements (such as gravity field), which indicate the absence of similar andesitic rocks extending continuously to great depth.

Containing peaks as high as 12,700 feet, these are impressive mountains rising above the surrounding arid, sedimentary lowlands. The intrusive age of the igneous rocks is 29.1 ± 0.3 million years, based on U-Pb ages of zircons, putting magma intrusion in the early Oligocene. This is part of an episode of dispersed volcanism in the region, including early volcanics within and on the flanks of the Rio Grande Rift, and sporadically throughout the eventual Basin and Range Province in the western U.S. and Mexico. Apatite fission track ages of these igneous rocks are about the same as the crystallization ages, suggesting that these rocks cooled below about 100°C soon after intrusion and were never re-heated. That indicates that were never buried very deeply.

Because of their high elevations, the La Sal Mountains were glaciated from time to time during the Pleistocene, with the production of U-shaped glacial valleys, cirques, and glacial moraine deposits. One might think glaciers would be a strange thing in this environment, but the ice ages were a very different time. Just remember the differences between Lake Bonneville and the Great Salt Lake of today.



View west, across the cirque at the head of North Fork of La Sal Creek, in the central La Sal peaks. Tp is diorite, an igneous rock; Jm is upper Jurassic Morrison Formation (Hunt, 1958).

Arches National Park

At Arches National Park, stratigraphy, structural geology, and weathering come together in a *very specific* way to create the largest concentration of stone arches in the world—and some amazing examples of salt tectonics. First, we'll need to build this part of the Colorado Plateau as it currently exists, and then we can discuss the consequences of such a unique convergence of arch-forming criteria.

Stratigraphy and Earth History

Coming back to the Paradox Basin

We'll pick up around 300 Ma in the Late Carboniferous Period, a time also known as the Pennsylvanian (Sub)period—100,000,000 years older than the Jurassic-aged Morrison Formation we focused on at Dinosaur National Monument, and *250,000,000* years older than the Eocene Green River Formation. The ocean at this time was home to some of the first modern-looking fish (as opposed to armor-plated placoderm fish like *Dunkleosteus*), a gradually-declining number of trilobites, and abundant crinoids and brachiopods (Figures 1, 2). The land and shallow water supported tiny proto-reptiles, monstrously large dragonflies, and immense swathes of plants—but these weren't plants as we know them; these were giant horsetails, forests of tree ferns, and club mosses the size of pine trees!

Figure 1: The Carboniferous Period was characterized by a warm, mild climate and abundant plant and animal life. This was when most of the coal (plant-derived carbon) we use today was deposited (hence Carbon*iferous).*

Perhaps not so much around here. This part of Utah was at the equator, a hot and arid environment, and mostly underwater. The area was subsiding—sinking downwards along normal faults—to form an ocean bay that was eventually restricted from ocean circulation, at least for the most part (there might have been a small degree of circulation). The seawater left behind started to evaporate, becoming saltier and saltier as the water level dropped, until finally the salt itself started to precipitate and the majority of the liquid evaporated away. Layers of formerly-dissolved minerals were left behind—compare to deposits at Death Valley, CA or the Great Salt Lake (Figure 3). Minerals that

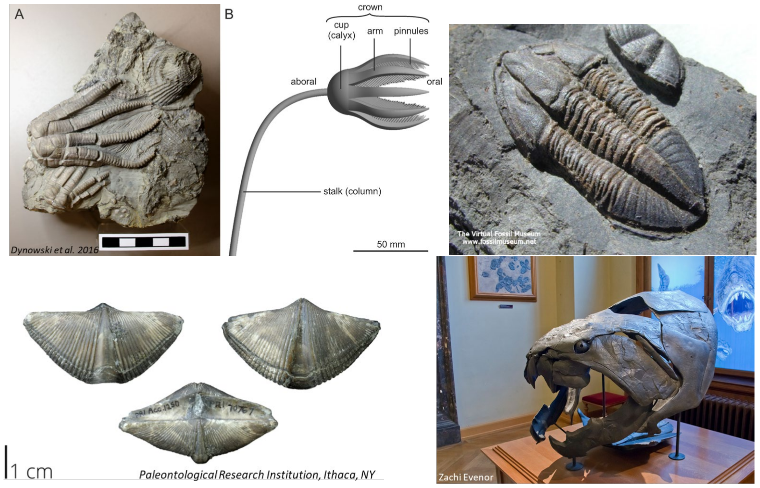


Figure 2: Paleozoic sea creatures: ***Top right****: Crinoid (an echinoderm);* ***top left****: trilobite;* ***bottom left****: brachiopod;* ***bottom right****:* Dunkleosteus, *a top predator from the Devonian.*

are precipitated from evaporating water (like salts and gypsum, $CaSO_4 \cdot 2H_2O$) are called “evaporite minerals.”

The bay, known as the Paradox Basin, was periodically recharged with fresh seawater and this process of evaporation and precipitation proceeded again, and again—a total of 29 times. A vast amount of salt accumulated as a result, an important part of the Paradox Formation.

Salt is buoyant (low-density) and plastic (bendable), making possible some remarkable subsurface rearrangement through the next 75 million years. Squished under the pressure of an increasingly-thick cap of denser, unyielding sediments above, the salt started to squeeze its way upward along planes of weakness such as faults. Coalescing together, the salt bulged towards the surface in massive walls—“salt anticlines”—and left salt-free layers of rock behind. The areas now without salt subsided, while rock above the salt was uplifted, tilted, and eroded. Subsequent rock layers were laid down thicker where the salt had squeezed away and thinner where it had risen upwards (see Figure 6). We’ll come back to the salt later on.

Eventually permanent ocean circulation returned to the Paradox Basin and salt stopped precipitating, but a mountain-building event (orogeny) several miles to the east caused deposition of sediments from the mountain-tops (often as sand) into the sea. When the mountains grew quickly, sandstone sourced from the mountaintops was deposited in the equatorial bay; when the mountains grew slowly, comparatively more limestone was deposited from the seawater. This mode of deposition was the story for a while, as the Uncompahgre Mountains grew and Pangaea continued its assembly, and as large terrestrial reptiles like *Dimetrodon* and the pre-mammal therapsids evolved. Coniferous trees took off at this time, better-adapted than other plants to the dry inner Pangaea.

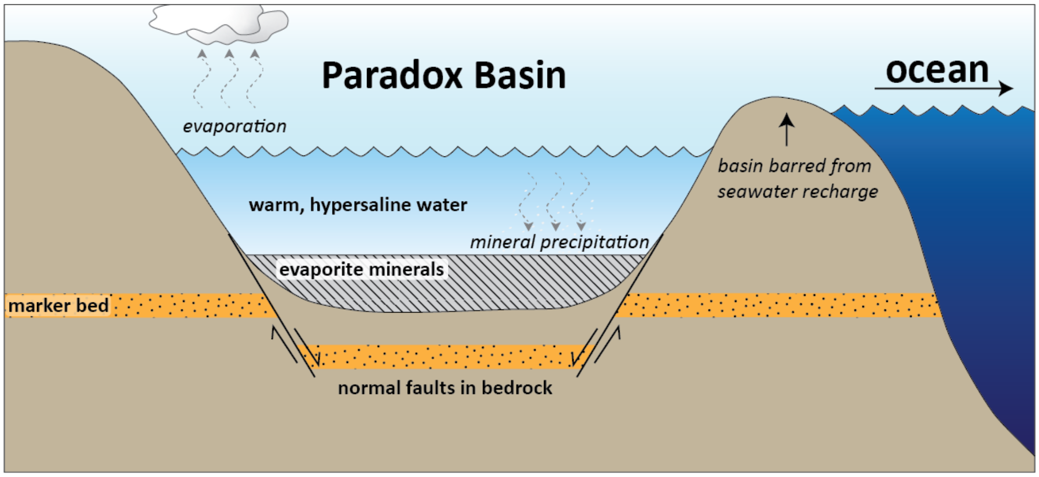


Figure 3: ***Top:*** *Evaporite deposition in a barred basin (hypersaline ≈ “extra salty”). Some parts of the Paradox Basin might not have been fully barred from seawater recharge, but the bay was sufficiently restricted to allow salt precipitation.* ***Bottom:*** *salt deposits from Death Valley, as the basin would have looked after water had evaporated (D. Flaherty).*

By the time the Triassic Period kicked off the "Age of Dinosaurs" and the first true mammals made their debut, the environment here had become terrestrial—primarily a mudflat at the edge of the ocean to the west. We call the rocks from this time "continental redbeds," exemplified by the distinctive chocolate-brown Moenkopi Formation. Water played an important role in the deposition of these clayey rocks—layers of mudstone, siltstone, and shale—which are often ripple-marked. Iron oxide coats the sediment grains, giving the layers their rusty-red color.

The environment migrated yet landward towards the end of the Triassic, with the land covered by a fertile river floodplain. Preserved in the rock record from this time are paleosols—fossil soils—with tubular features thought to be fossil root systems: Casts of ancient plant roots made from shale or siltstone within the colorful, shaley Chinle Formation.

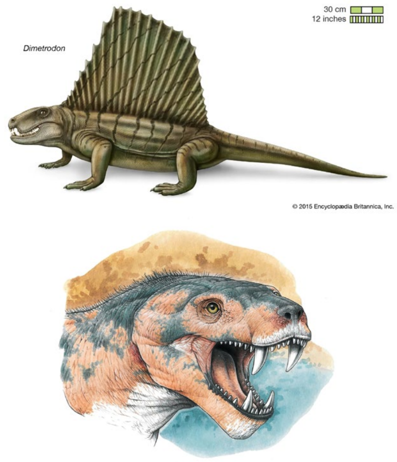


*Figure 4: Permian fauna. **Top**: Dimetrodon (reptile); **bottom**: a cynodont (therapsid, or mammal-like reptile), credit: Abdala et al. 2019 and Gabriel Lio.*

As the Triassic elapsed into the Jurassic, the climate here became dryer. The windblown (eolian) sand of the Wingate Sandstone was a harbinger of the immense deserts to come. After the Wingate had been deposited the area did receive a minor reprieve, where wetter weather brought streams that laid down the fluvial shales, sandstones, and conglomerates of the Kayenta Formation.

In the mid-Jurassic Period, this place looked less like *Jurassic Park*'s tropical "Isla Nublar" and more like *Star Wars*'s "Tatooine"—or the Sahara Desert, if you have no idea what I'm talking about. A vast terrestrial sand dune desert known as an "erg" advanced into the region, depositing massive (thick, uniform, hard) sandstones. Evidence of the erg is seen most prominently in Arches as the crossbedded "petrified dunes" of the Navajo Sandstone. Subsequent to the Navajo Sandstone were the Carmel Formation and the all-important, arch-forming Entrada Sandstone, deposited in a back-beach dune field.

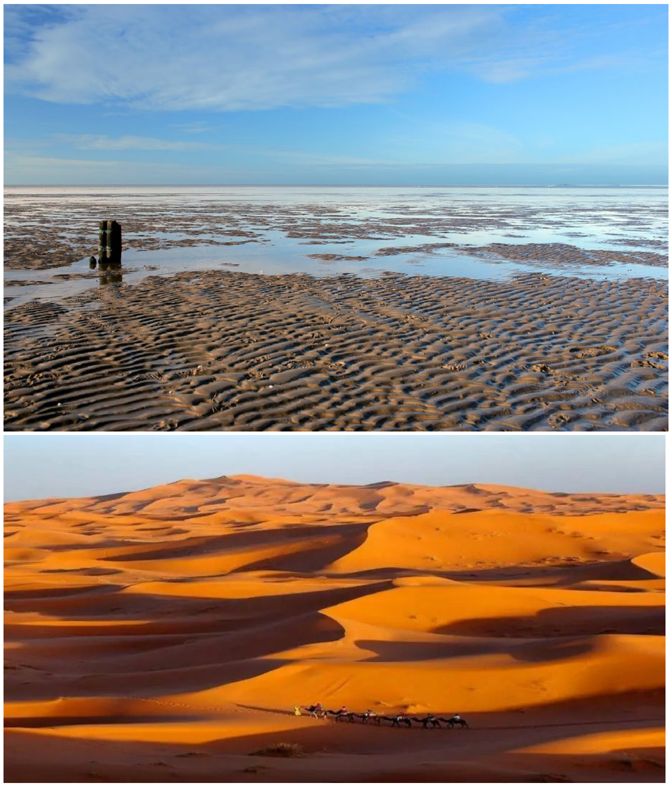


*Figure 5: Example environments. **Top:** Modern-day mudflat with ripple marks (Karina Mannott); **bottom:** modern-day Erg Chebbi in Morocco.*

Sand dunes were dominant until the Late Jurassic Period, when the climate shifted and the sea level rose, and the area became more hospitable perhaps to a few more forms of life. As pterosaurs soared the skies above—and the earliest known birds hatched, destined to outlast them—herds of hadrosaurs and sauropods roamed the fertile floodplains and fled carnivores like Utah's state fossil, *Allosaurus*. We are unlikely to spot dinosaur bones during our time at Arches, but they have been found here as well as Jurassic-aged fragments of petrified wood—part of the Morrison Formation, the same fossiliferous layer we saw at Dinosaur National Monument.

The latest rocks preserved in the area are from the Cretaceous Period, the time of *Triceratops* and *Tyrannosaurus rex* and the first flowering plants. An environment of floodplains and small lakes morphed into seaside lagoons and a broad coastal plain as the Western Interior Seaway advanced into the continent, slowly submerging the Arches area once again. With inundation of the shallow sea, the colorful, slope-forming, and fossiliferous Mancos Shale was laid down, most of it now confined to low-lying areas in Cache Valley and Salt Valley.

Structural Geology and the Formation of Arches

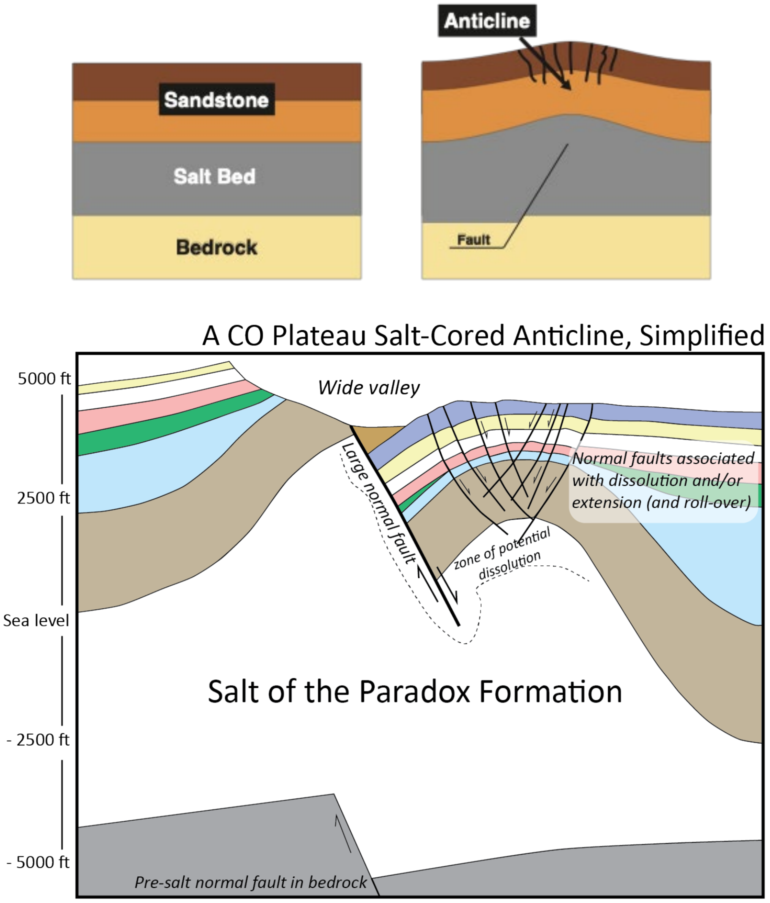


Figure 6: Salt tectonics. ***Top*** *left: salt* in situ*;* ***top*** *right: under pressure of additional sedimentation, salt has coalesced near normal faults and bulged upwards into salt-cored anticlines;* ***Bottom:*** *following dissolution of salt and/or crustal extension, rocks have "rolled over" into the anticline. Additional, smaller normal faults have resulted.*

Now that we have had an overview of the rock layers here and their depositional environments, as well as a refresher on the buried salt of the Paradox Formation, we can discuss the interplay between surface processes (erosion and weathering) and subsurface processes (folding, faulting, salt tectonics) that have made Arches National Park so exceptional.

Salt anticlines

As mentioned earlier, the copious salt of the Paradox Formation squeezed its way out of its original place in the stratigraphy and into preexisting planes of weakness (primarily large normal faults). This movement resulted in the subsidence of now salt-less stratigraphy, and the uplift of layers where salt anticlines rose. There are several salt anticlines beneath Arches National Park, and though we can't see them (any salt extruded onto the surface would quickly dissolve), they are positively gigantic—on the order of **2 miles high, 3-4 miles wide, and 70 miles long**.

Folding, faulting, and jointing

Before stone fins and arches can form, rocks on the surface must have preexisting weaknesses along which erosive processes can operate. The requisite planes of weakness at Arches are provided by joints, parallel fractures which cut rocks in "sets" (i.e., where you find one joint, there are more parallel to it). They are reminiscent of faults, but without any motion ("joints" with a sense of motion are actually faults).

The joints here were formed in the Late Cretaceous Period, when a tectonic plate collision instigated the growth of the Rocky Mountains—the Laramide Orogeny. The collision resulted in folding and faulting across the entire Colorado Plateau, forming large-scale anticlines (upward folds) and synclines (downward folds), superimposed upon a shallow, northward regional dip (the formerly-horizontal layers "sink" into the ground in a northward direction).

When folds form, the rock on the outside of the fold experiences tensile stresses and the rock on the inside of the fold experiences compressional stresses. To visualize, imagine bending a rubber or leather belt: The material on the inside of the bend wrinkles as it is shortened and the material on the outside stretches as it is expanded (or breaks, if it's old and dry). Similarly, if a rock unit being folded is too brittle to *stretch* over the axis of the fold, it breaks into joints instead. This is what geologists believe happened in the Arches region. When the Colorado Plateau was uplifted, the jointed rocks of the arch-forming Entrada Sandstone (among others) were brought upwards and uncovered by erosion.

Mesozoic-Cenozoic salt tectonics

There is one final role for the immense salt walls beneath the Arches region. Large gravity-driven normal faults are associated with each salt wall. The faults formed during the same time period as the Rocky Mountain-related folding event, beginning 80 Ma, even

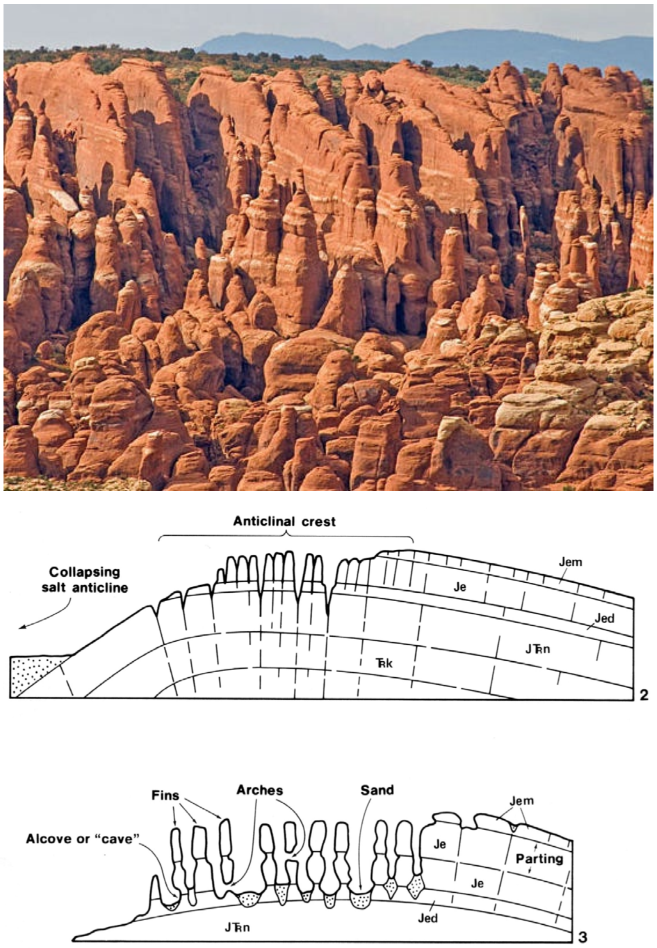


Figure 7: ***Top:*** *Ranks upon ranks of parallel Entrada Sandstone fins in the Fiery Furnace. Each plane of separation between the fins is a joint, widened by rollover and erosion.* ***Bottom:*** *Cross section of rolled-over joints; "anticlinal crest" = Fiery Furnace.*

though they indicate two different types of tectonic motion (compression and extension). Geologists are still somewhat puzzled by the contradiction. We will see one of these large normal faults—the Moab Fault—across from the park entrance.

When the uplift of the Colorado Plateau commenced, the Colorado River started to cut deeper and deeper into the Moab/Arches area. Fresh water from the river migrated along the planes of the normal faults and joints to reach some of the buried salt, dissolving it. As salt dissolved away, the rock on top of it sank downwards along a normal fault, sagging into the now-absent portion of the salt anticline. Newer, smaller normal faults related to the larger, "master" normal fault were formed at the bend to accommodate the change (Figure 6).

Coupled with the normal faulting itself, salt dissolution resulted in the development of broad valleys at the top of the salt anticlines—for example, Moab Valley or Salt Valley. The jointed rocks at the edges of these valleys "rolled over" or slumped into the salt anticlines, fanning out the preexisting joints like the coils on a bent slinky. This opened more space between the joints to allow for faster erosion (Figure 7).

Making the arches, the grand finale

At the mercy of surface weathering, the jointed, uplifted, and rolled-over Slickrock Member of the Entrada Sandstone eroded into fins exemplified by the Fiery Furnace (Figure 7). At a soft bed or parting on a fin or other landform—either within the Entrada itself, or between the Entrada and its neighboring layers—erosion can proceed at a faster rate. A stone "alcove" forms around a zone of accelerated erosion before the sandblasting wind finally pierces through the rock to reveal the other side—creating an incipient arch. From there, the hole in the smooth-weathering Entrada is widened into one of the arches that dot the park.

But erosion doesn't cease once a perfect arch is formed—and eventually, erosive processes undermine the arch itself such that it can no longer support its own weight and collapses. We can see the landforms at all stages in the park—from alcoves, to tiny "newborn" windows, to fully-fledged arches, and arches that have collapsed or are on the verge. Of note is Landscape Arch, the longest arch in the world, which has recently started to lose rock at a rapid rate. Scientists predict that it will naturally collapse within the next few centuries—a timeline that could be greatly precipitated by an earthquake. So take a good look at it when we pass by.

Conclusion in brief

Worldwide, the formation of rock arches is favored by these specific conditions:

- ✓ Massive, hard, and brittle sandstones at the surface,
- ✓ Jointed (often by folding activity),
- ✓ Resting on or containing soft layers or partings,
- ✓ Located in an area affected by salt-cored anticlines, where rollover can occur,
- ✓ And in a dry climate.

Arches National Park meets or exceeds all of the above, leaving it with the highest concentration of stone arches in the world.

Dead Horse Point State Park

Yes, that's what it's officially called. Despite its less-than-happy name, Dead Horse Point State Park is a fitting prelude to the fabulous views found in the Island in the Sky District of Canyonlands.

Within the park, the viewpoint called "Dead Horse Point" is at the edge of a 2,000-foot-high stone peninsula that juts out from a mesa to overlook a gooseneck ("The Gooseneck") in the Colorado River. The inflection at the Gooseneck is so extreme that for about 4 river miles along the bend, the river makes it less than 0.25 miles as the crow flies!

To reach Dead Horse Point, you must drive across a narrow neck of rock that will one day collapse, turning the peninsula into a proper mesa. The state park encompasses more than just the viewpoint, most of it upon a scrubby mesa top. Many common Colorado Plateau desert features—e.g., potholes in rock, miniature arches, and cryptobioitic soil—are on display throughout the area.

The View

Dead Horse Point is famous for its spectacular vista. Here, we stand on the Jurassic Kayenta Formation with the Wingate Sandstone beneath. Peering out at the Gooseneck and southwest into Canyonlands National Park (look for zigzagging Shafer Trail to guide your eye), the Carboniferous-Permian Cutler Formation is at river level and rocks as young as the Jurassic Navajo Sandstone cap the cliffs. Beneath the whitish Navajo are the strata we're standing upon, including the darker, ledgy Kayenta Formation and a thick sheer section of Wingate Sandstone. On the Dead Horse Point peninsula, the Navajo is only present as remnants far from the edge.

Looking southwest, we can also spot the White Rim Sandstone—an important marker bed in the Island in the Sky—pinch out into a reddish arkose (try to trace the white bed until it disappears) (Figure 1). This transition in rock composition indicates a transition in depositional environments from the near-shore dune fields that deposited the White Rim to terrestrial streams and alluvial fans. The lowermost redbeds here—red mudstone weathered into a kind of crumbly, "lumpy" façade with abundant, thin bedding planes—are part of the Cutler Formation. The upper set of redbeds, similarly weathered, are the Triassic Moenkopi Formation.

Paradox Formation salt is in the subsurface here, and subtle evidence of its presence can be seen in the upward-warped beds of the Shafer Anticline to the southwest—cut along its fold axis by the Colorado River SSE of the viewpoint and again at the Gooseneck. The axis of the Shafer Anticline essentially curves around the state park. To the northeast, the Cane Creek Anticline, another salt structure, cuts across a small portion

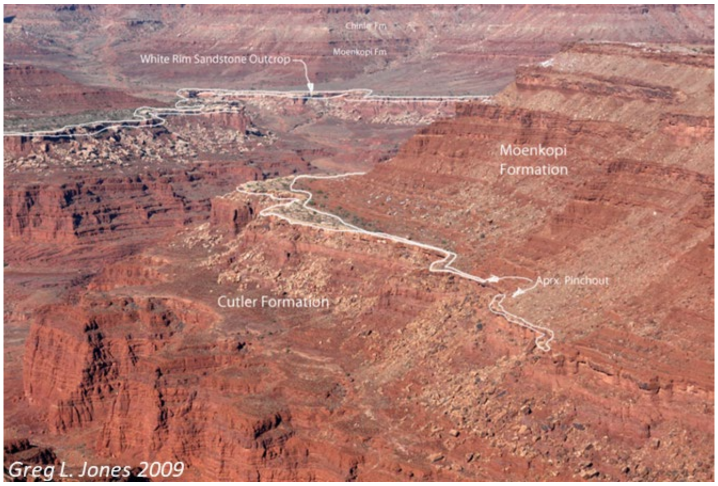


Figure 1: Pinchout of the White Rim seen from Dead Horse Point.

of the park and much of the land visible below. The Cane Creek Anticline has been a center for economic geology for approximately 100 years now, providing a source of both potassium salts and petroleum.

Solution Mining of Paradox Formation Potash

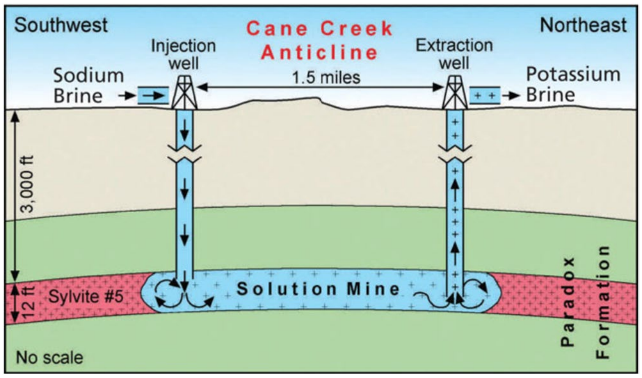


Figure 2: Utah Geological Society schematic of solution mining at the Cane Creek Anticline.

Figure 3: Potash fertilizer for plants.

The big, intensely blue ponds far below Dead Horse Point are hard to miss. These ponds, visible to the southeast, are not on park land and are owned by Intrepid Potash, Inc. They are solar evaporation ponds used in solution mining of Paradox Formation salt from the Cane Creek Anticline (Figure 2). Rather than digging for salt—as was perilously attempted in the past—the mining company pumps hot brine (saline water) down into the salt deposits, where it dissolves the potash (potassium-bearing) evaporite minerals carnallite ($KMgCl_3 \cdot 6H_2O$) and sylvite (KCl). The brine is brought back up to the surface and pumped into the evaporation ponds, where the dissolved salts are precipitated from the evaporating water under the searing desert sun. Potash salt is used primarily in fertilizers (Figure 3). Halite (table salt, NaCl) is brought to the surface as a by-product and sold for use in products like water softeners and animal feed.

Oil and Gas

We should be able to spot oil derricks from the viewpoint, or at least on our drive in. The Cane Creek Anticline and neighboring geologic structures serve to trap oil and gas produced in the organic-rich shales of the Paradox Formation. Near the crests and troughs of anticlines and synclines here, fractures in the Paradox Formation shale have collected oil. At first oil was extracted using a series of vertical wells, but since the 1980s drillers have been using horizontal drilling practices to remove oil from the source rock. Horizontal drilling allows a single well to tap a wide area, minimizing environmental impact (as compared to having multiple derricks).

The Name

I'm sure everyone is wondering about the name. Dead Horse Point got its name from an old local legend, of which there are many versions. Its sheer cliffs made it a natural corral for wild mustangs (or stolen horses, depending on the version of the story) herded by cowboys (or horsethieves) in the 19th century. All they had to do was fence off the narrow neck and the horses were effectively penned in, giving the wranglers plenty of time to select the best to keep and let the others run free. In this version, one band of horses was left too long without water and perished, giving the peninsula its morbid name. I guess a euphemism could be "Dehydrated Horse Point."

Canyonlands National Park

Utah's largest national park is a sprawling testament to time behind our comprehension: The sheer magnitude of *time* required to erode its constituent layers from earlier rocks and deposit the sediment, to deform the strata to their current orientation, and then for the rivers to grind the rocks back into sediment as they incised deep canyons and exposed the stratigraphy under our feet. And these processes have by no means ceased—Canyonlands provides an up-close look at erosion and salt tectonics in action.

Stratigraphy

The stratigraphy at Canyonlands is quite similar to the stratigraphy at Arches and Dead Horse Point, so I (HM) will only highlight the differences.

The oldest rock layers visible in Canyonlands National Park are near the park's southern boundary. Here, 400 feet of Paradox Formation gypsum, dolomite, and black shale dominate Gypsum Canyon. Atop the Paradox Formation are the alternating limestones, sandstones, and shales of the Carboniferous Period's Honaker Trail Formation. Like the Paradox evaporites, the Honaker Trail is buried at Arches. It was deposited when mountains were beginning to grow near the then-undersea basin. When the mountains rose quickly, more sandstone and shale was laid down; when the mountains rose slowly, comparatively more limestone was deposited from the ocean water.

The Carboniferous-Permian Cutler Formation is visible at river level in Dead Horse Point State Park but is buried completely at Arches. At Canyonlands, the Cutler takes center-stage. During Cutler time, the mountains to the northeast (the Uncompahgres) rose rapidly and vast volumes of sediment—much of it derived from the mountains' granitic core—were dumped into the basin. The sediments lithified into arkoses, reddish sandstones characterized by significant proportions of feldspar. Because feldspar weathers rapidly to clay during transport, its presence alongside quartz indicates close proximity to the mountain source. Thus, the Cutler arkoses are alluvial fan sediments, debris deposited into fan-shaped sprawls at the foot of a highland.

However, in Canyonlands the Cutler is so thick and varied that it is elevated from the "Cutler Formation" to the "Cutler Group." The Cutler Group is then split into the following formations (from oldest to youngest): The Elephant Canyon Formation/Halgaito Shale, the Cedar Mesa Sandstone, the Organ Rock Shale, and the White Rim Sandstone. These formations all grade into typical Cutler arkose north and east of the park, where the "Group" relinquishes its starring role and is downgraded to "Formation." Additionally, the marine-to-terrestrial Elephant Canyon grades southward into the shallow-marine Halgaito Shale (both Cutler Group).

The early-Permian Cedar Mesa Sandstone (also Cutler Group) was deposited at or near a fluctuating shoreline, with the depositional environment alternating between shallow-marine to coastal as sea level rose and fell. Through the mid-Permian, the environment transformed into a mudflat and the redbeds of Organ Rock Shale were laid down. Finally, as the Permian drew to a close, the sea level fell and the White Rim was deposited as windblown beach sand—either on the main shoreline or on an offshore sandbar. Following a hiatus in sedimentation (which resulted in an unconformity) into the Triassic, the deposition of the Moenkopi continental redbeds—*not* part of the Cutler Group—commenced. From then on, the story is much the same as that of Arches.

The Districts

The Green and Colorado Rivers split exceptionally large (337,598 acres) Canyonlands National Park into three districts: The Maze, the Needles, and the Island in the Sky. These districts allow visitors unique access to both the sweltering low canyons and the windy high plateaus of southeastern Utah (Figure 3). The rivers are nearly-absolute barriers—there are no bridges spanning the water within the park. The only way to get to one district from another without a boat is to drive *all the way around*.

The Maze

By far the remotest and least-accessible of the districts, the Maze got its name for a reason: its tortuous complex of intricately-carved canyons in the Cedar Mesa Sandstone. Also in the Maze, one can view up-close the presumed "offshore sandbar" where some of the White Rim Sandstone was deposited. On the mound-shaped sandbar, the White Rim Sandstone contains seeps of a tarry petroleum substance called elaterite—the namesake of associated Elaterite Basin in Glen Canyon National Recreation Area. The White Rim Sandstone has acted as a classic structural trap for the upward-oozing tar. Small tar seeps from the White Rim are a common sight in this area, and the redbeds above the sandstone have been bleached white from reduction of red hematite by natural gas, further evidence that hydrocarbons are present.

The Needles

While Cutler rocks were at river-level in Dead Horse Point State Park and completely buried in Arches, in the Needles District they are just about the youngest strata you will see. Here, the Cutler *Group*'s Cedar Mesa Sandstone interfingers with plain-old undifferentiated Cutler *Formation* arkose (confusing, I know). It is a *facies change* (a change in depositional environments) from near-shore to terrestrial, and has resulted in streaky orange and white coloring on the curious Cedar Mesa-capped spires that give the Needles its name. Much like the Firey Furnace's fins of Entrada, these spires are a product of the combined efforts of jointing, salt tectonics-enhanced widening of fractures, and erosion.

In the Needles District, the activity of salt in the subsurface becomes quite apparent. In addition to accelerating the creation of the "needles," the movement of Paradox Formation salt has resulted in striking normal faulting of overlying strata.

Salt has collected beneath the Colorado River to form the Meander Anticline, likely coalescing here due to a decrease in sedimentary overburden with thanks to the river's erosion. The strata in the Needles already dip westward (towards the Colorado) because of the Monument Upwarp—a monocline (fold) partially outside of the park—and with salt flowing west into the Meander Anticline and no longer supporting the tilted strata, a complex of *horsts and grabens* has developed. In the Needles District, this area is called "The Grabens."

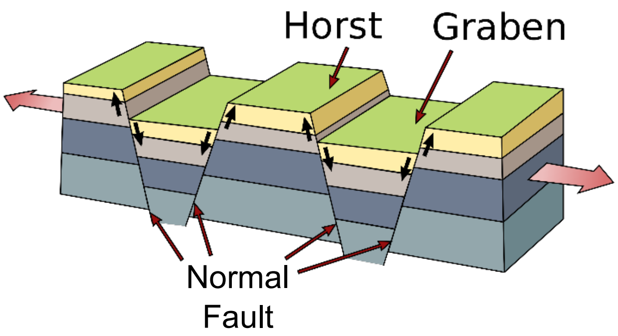


Figure 1: Schematic showing horsts and grabens.

Horsts and grabens go together, indicating normal faulting and gravity-driven extensional motion. Grabens are fault blocks that drop downwards relative to horsts to form basins (Figure 1). In the Grabens at Canyonlands, fault blocks glide along the tilted surface of what salt remains *in situ* and slump down towards the Colorado River (Figure 2). This slumping, further enhanced by salt dissolution near the river, has resulted in a narrowing of the river at Cataract Canyon.

The Grabens are widening at a measurable rate, with new, sometimes-deep fissures opening to this day. If you take a hike in the Needles, watch your step so that you don't fall in!

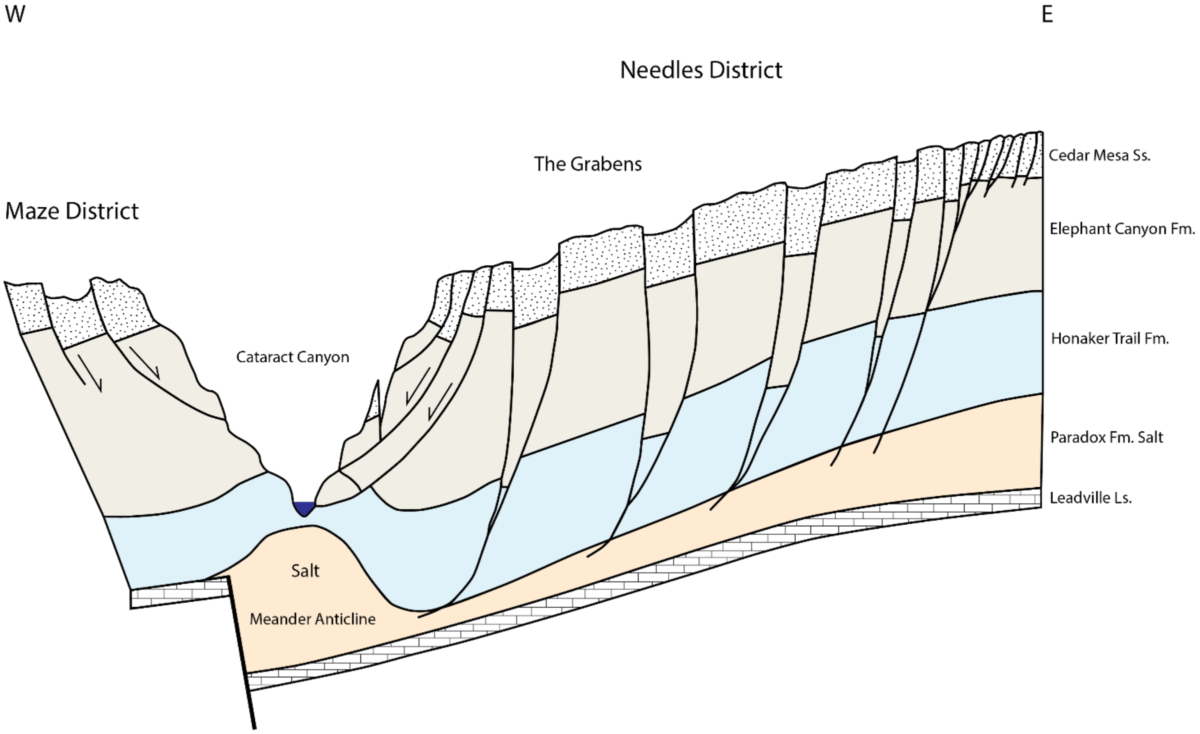


Figure 2: Fault blocks slumping towards the Colorado River in the Grabens, gliding over Paradox salt (orange). Adapted from Baars, 2010.

The Island in the Sky

The Island in the Sky is a zone of high plateaus, mesas, and peninsulas overlooking the rest of the park. In this district, as in Dead Horse Point State Park, we stand on *top* of the Wingate and Kayenta—and often on top of the Navajo as well. The rusty-hued Cutler Group beds at ground-level in the Needles and the Maze are far below our feet in the Island in the Sky, but they are beautifully exposed across the district's broad vistas that look out over a carved-out landscape to the south. It's not Mars, but it kind of looks like it! The White Rim Sandstone, part of the Cutler, is a prominent marker bed and forms the resistant cap of the White Rim Bench far below us.

The Confluence of the Green and Colorado Rivers

Meandering towards each other to craft the canyons that bound the Island in the Sky, the Green and Colorado Rivers converge near the center of the park. The resulting river retains the name "Colorado River"—this is where the Colorado becomes the broad, powerful, turbulent river that gouged out the Grand Canyon.

In the past, the Colorado River upstream of Canyonlands's confluence was known as the *Grand* River; only after it joined the Green did it earn the name Colorado. This changed on July 25, 1921 after a debate between the federal government and the Colorado state legislature (clearly, Colorado won). Colorado Congressman Edward Taylor wanted the river his state was named after to actually *extend* into the state. The name change was not before places like "Grand Junction" (named for the confluence between the Grand (Colorado) and Gunnison Rivers) and "Grand County" in Colorado had been named.

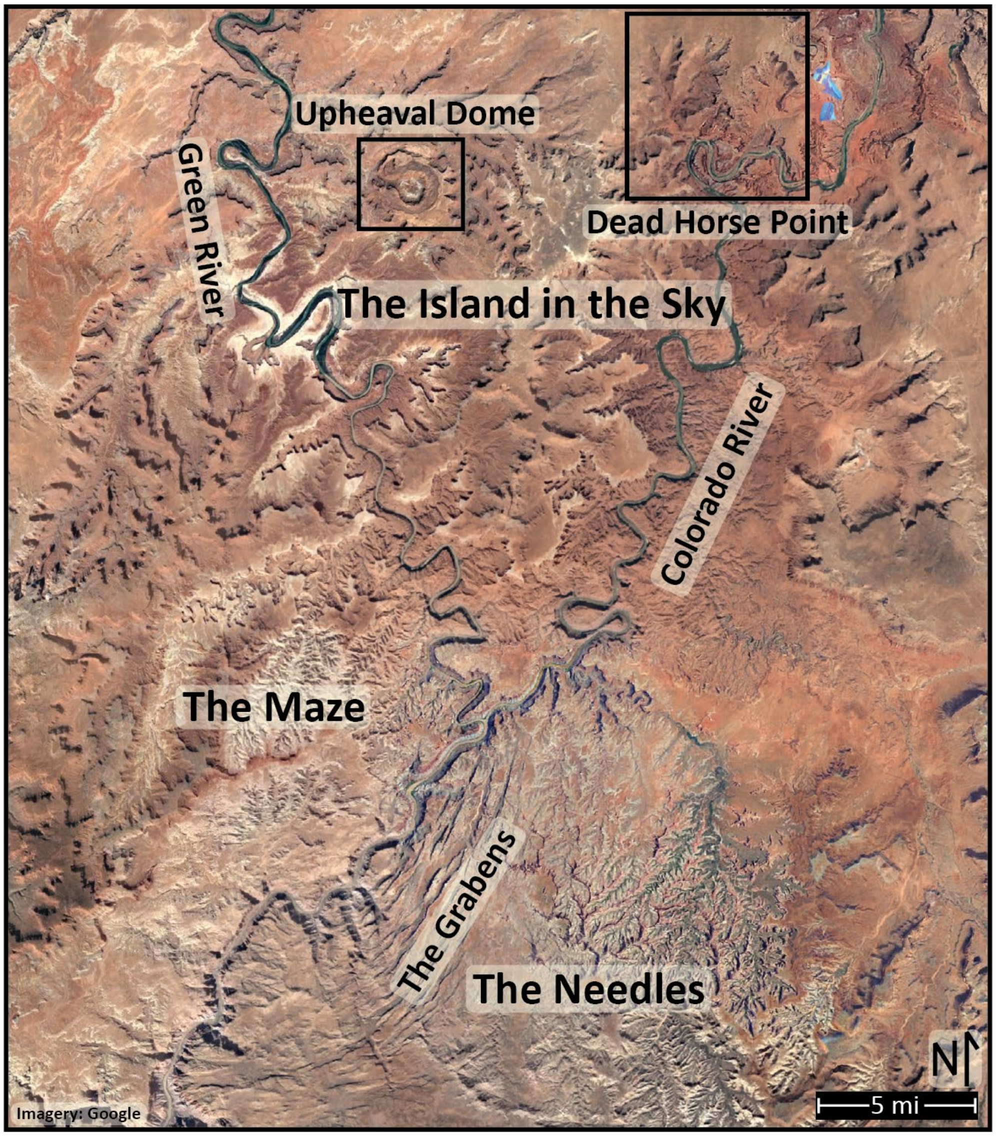


Figure 3: Satellite view of Canyonlands National Park (Google). Note Intrepid Potash, Inc. evaporation pools in top right. Also of note are the Grabens and Upheaval Dome.

Upheaval Dome

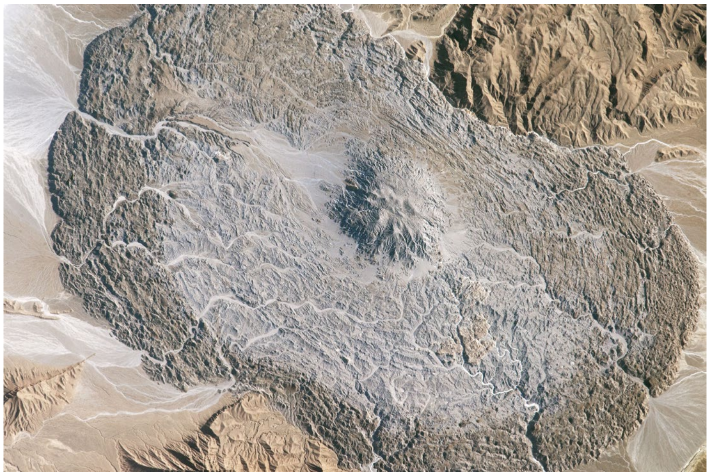
Now for a bit of controversy.

Upheaval Dome is in the Island in the Sky District of Canyonlands National Park (see *Canyonlands National Park*, Figure 3). It is a ring of sharply-upturned beds, with the younger Navajo Sandstone on the outside and the Chinle, Moenkopi, and a glimpse of the White Rim on the inside. The dome focused the travel of natural gas through the Cutler Group; just as in the Maze District, the Moenkopi redbeds overlying the White Rim have been bleached by hydrocarbons.

The origin of Upheaval Dome has been debated for generations of geoscientists. At first, in the 1950s, scientists thought it must represent the surface expression of a salt dome. The interpretation stood to reason, as salt is certainly active in the subsurface throughout the region. However, a later survey in the 1980s found that there was no salt beneath Upheaval Dome and concluded that it must have formed due to a meteorite impact roughly 60 million years ago. In this model, the beds warped upwards beneath the crater as the affected crust reached a new equilibrium. Upheaval Dome, then, would be the innards of an impact crater that has since eroded away. This idea also stood to reason; similar impact structures exist elsewhere on Earth.

And then, in 2000—just after another paper came out with ample evidence for the meteorite hypothesis—a new study was published with equally-ample evidence that Upheaval Dome *is* a salt structure. The researchers presented a detailed argument, supported by fracture patterns and the continued growth of the structure through the Jurassic Period, that long-term salt activity was *required*. To explain the current absence of the salt, they hypothesized that the "salt bubble" had extruded through the strata and pinched off above this part of the stratigraphy when Upheaval Dome as we know it was in the subsurface. Thus, the salt that ended up above the dome has since been eroded away with the rest of the overlying strata. If true, Upheaval Dome would be the most deeply-eroded salt structure on Earth. And there is another option: When a salt dome breaches the surface in areas that are dry enough, salt can extrude onto land as a "salt glacier." Perhaps that is what happened here.

Who is correct? Scientists have "proven" that Upheaval Dome is a deeply-eroded salt structure. And scientists have *also* "proven" that it is the remains of a meteorite impact crater. Recent research findings (2008) are in favor of the meteorite hypothesis, or at least that is what the NPS wrote on the Canyonlands website—but the debate is very much still out. (And it sure seems like a salt structure to me...)



A salt glacier in the Zagros Mountains of Iran (gray = salt). The high point in the middle is the central salt dome. Maybe Upheaval Dome was also covered in salt at some point.

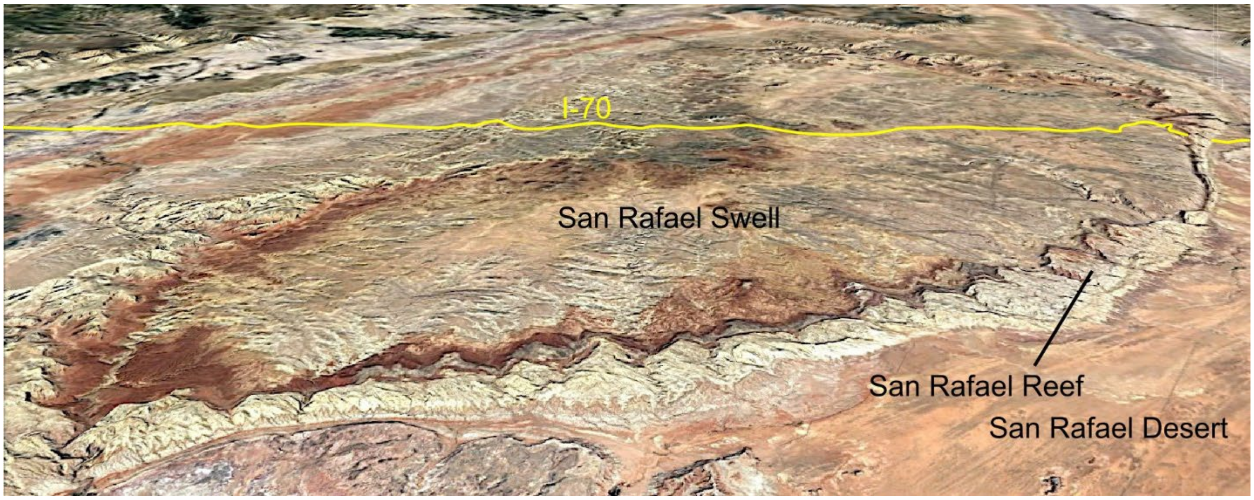
The Book and Roan Cliffs

Classic view of part of the Book Cliffs (called Mt. Garfield, though it is really the edge of a plateau), near Grand Junction, Colorado.

The cliffs north of Interstate 70, near Green River, form a typical escarpment (cliff). The cliffs are retreating as a result of erosion of less resistant units that underly the resistant cliff-forming sandstones at the top. There are two sets of cliffs readily discernable. The nearer ones are called the Book Cliffs, capped by weathering-resistant late Cretaceous Castlegate and Bluecastle Sandstones, which overlie a major, nonresistant sandstone, shale, and coal-bed sequence that includes the Late Cretaceous Blackhawk and Star Point Formations (coastal and marine delta deposits, west) and time-equivalent Mancos Shale (marine shale, east). These deposits are from erosion of sediments from the rising Sevier mountain chain to the west, and deposition on the edge of and in the Cretaceous Interior Seaway. The lowlands below the cliffs are underlain by the Mancos Shale and early Cretaceous Dakota Sandstone.

The more distant Roan Cliffs, to the north, consist of weathering-resistant Paleocene Wasatch Formation sandstones at the top, a river-deposited conglomerate and sandstone unit, underlain by easily-eroded, late Cretaceous Price River Formation conglomerate, sandstone, and mudstone of the Mesa Verde Group. Somewhat beyond these cliffs is the Green River Formation, which forms another set of cliffs farther northeast. The Castlegate and Bluecastle Sandstones form a set of modest cliffs to the south of the Roan Cliffs, which connect to the east and southeast to the Book Cliffs.

The San Rafael Swell

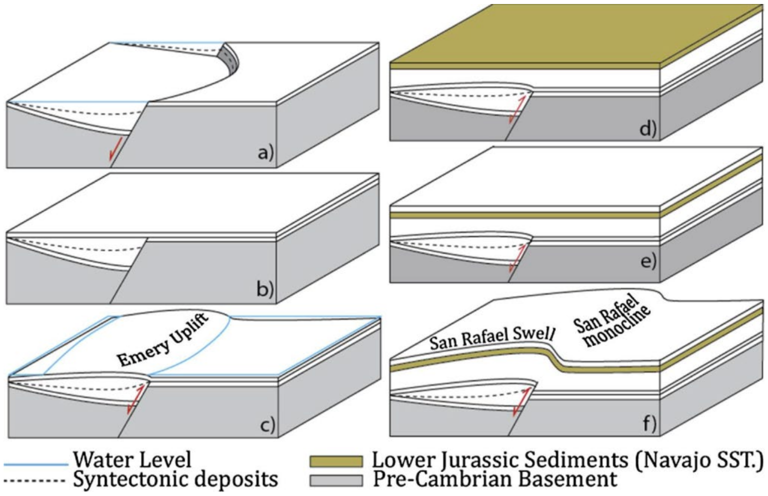


San Rafael Swell, showing 45 miles (72 km) of Interstate 70 crossing it. Google Earth image.

As we move westward from the Book Cliffs and Green River, we will enter the northern tip of the San Rafael Desert. This landscape occupies a lowland on the east flank of the San Rafael Swell, one of the more elevated blocks within the Colorado Plateau. The San Rafael Desert is underlain by Jurassic sandstones, shales, and evaporites, and is covered by a thin veneer of wind-blown sand.

The San Rafael Desert and Swell are separated by the San Rafael Reef, a monoclinal fold structure. In a monocline, the underlying brittle basement rocks are faulted and displaced. However, the overlying weak sedimentary rocks are sufficiently ductile to form a continuous drape across the fault without being broken themselves. This leads to a fold in which the rocks on either side are nearly horizontal, but at different elevations, and they are connected by (in cross section) an S- or Z- shaped fold. These features are typical of the Colorado Plateau.

As we continue along I-70, we will cross the San Rafael Reef, where thick, east to southeast-dipping Jurassic Kayenta and Navajo Sandstones form prominent cuestas and hogbacks. The center of the Swell has exposed older underlying rocks, including the Triassic Moenkopi and Chinle Formations, and the Permian Kaibab Formation and White Rim Sandstone.



Tectonic evolution of the San Rafael Swell (Sørensen, 2017). Step a is late Proterozoic normal faulting, b is early Paleozoic deposition, c is Paleozoic reverse faulting, d is Mesozoic deposition, e is continued Mesozoic deposition, and f is reverse faulting to produce the monocline, during Laramide time (latest Cretaceous to Eocene).

Goblin Valley State Park

Goblins at Goblin Valley. They're bigger than they look! The whitish formation on the very top of the cliffs in the background is the Curtis; the reddish formation dominating the photo is the Entrada. Photo by Matt Morgan.

I'm sure the comparison has been made a million times by this point, but at the risk of beating a dead (dehydrated?) horse: Welcome to Mars. Although, I am halfway serious—the Mars Desert Research Station (MDRS) is located only 13 miles away from Goblin Valley State Park. It's a private facility owned by the Mars Society, which in spite of its kind of…dubious name *does* include credible scientists like Buzz Aldrin himself. At MDRS, researchers simulate field studies in a Martian-*esque* environment in preparation for an eventual manned mission to Mars.

In case being in an area deemed especially similar to Mars is not "offworld" enough, Goblin Valley State Park has also been formally designated as an "International Dark Sky Park"—meaning it has one of the darkest skies around, ideal for stargazing. Good thing we're spending the night here! If the weather cooperates, we should have astonishingly clear views of the Milky Way where it sweeps across the heavens—while, in keeping with the theme, the congregation of alien-shaped hoodoos called "goblins" looks on from below.

Goblin Valley State Park is located on the southern flank of the San Rafael Swell, within the San Rafael Desert. It is certainly desert-like here; vegetation cover ranges from sparse to nonexistent, and badlands and sandy washes prevail. Last time I (H) came into the park, there was an isolated sand dune (a barchan dune; see figure at the end) slowly making its way across the road at the behest of an exceptionally strong, exceptionally sandy wind. County or state workers must periodically clear this road of sand and the debris carried by flash floods, as otherwise it would quickly become impassible.

The Jurassic Entrada Sandstone—the arch-forming unit to the east—takes a different form at Goblin Valley, although it is once again responsible for the park's most unusual erosional feature: The mushroom-shaped "goblins." This part of the Entrada was laid down in a tidal flat, as

The "Three Sisters" at Goblin Valley. The only rock unit pictured is the Entrada Formation. Photo by Matthew Dillon.

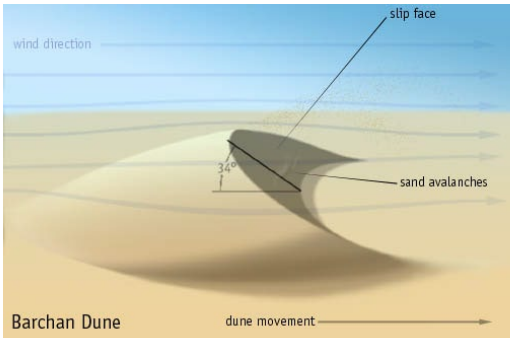
opposed to the dune field that yielded the sandstone-rich Slickrock Member seen at Arches National Park. Owing to its different depositional environment, the formation here contains significant proportions of shale and siltstone stacked between layers of fine-grained sandstone. It is this combination of rock types that allows the unit to erode into such unusual shapes. Further assistance is provided by prevalent jointing of the rocks here—a nearly-ubiquitous aspect of the Colorado Plateau.

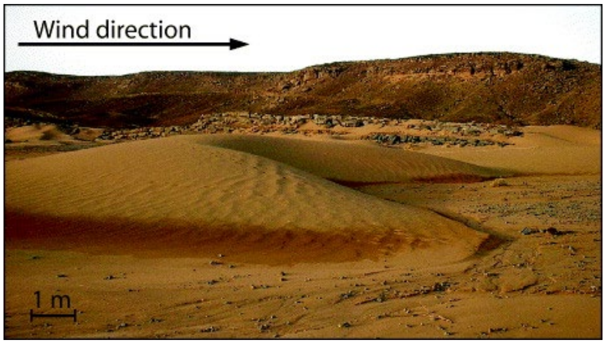
The goblins are the handiwork of weathering and erosion. First, erosive processes excavate a set of goblins (as a jointed, sandstone-rich bed) from the subsurface by removing the sediment on top. The sets of joints are roughly perpendicular to one another, giving the unsculpted goblins a "squarish" shape. These joints provide initial planes of weakness along which weathering can work. The sharp sandstone edges of the goblins break down more quickly than the rest of the rock, resulting in rounded shapes (an example of spheroidal weathering).

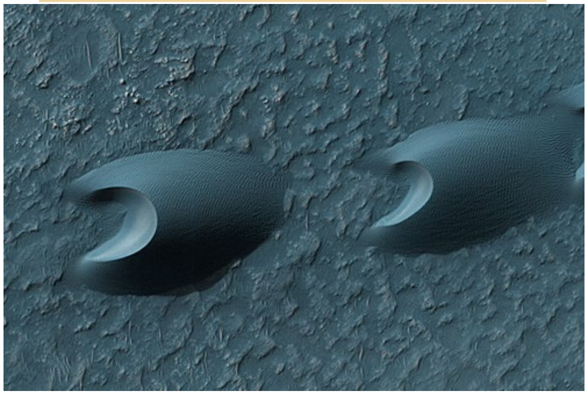
The smooth-weathering sandstone bulbs at the top of the hoodoos are made of more-resistant material than the softer shales and siltstones beneath, and this difference in weathering rate results in the goblins' stacked appearance, elongated shapes, and the narrow pedestals upon which they sit. The goblin-making process is slow to human standards, but the rock formations are ever-changing as weathering and erosion continually undermine older goblins and unearth and shape new ones.

The Entrada Sandstone is accompanied only by the Curtis, Summerville, and Morrison Formations in Goblin Valley State Park. All are Jurassic-aged and all are younger than (thus, on top of) the Entrada. The Curtis Formation forms a greenish-beige-gray cap, meeting the Entrada at a low angle. This is an angular unconformity, which indicates the Entrada was tilted and partially eroded before the Curtis was deposited. The Curtis is marine in origin and contains wave-rippled shale; its minor content of glauconite, a marine clay, imparts a green cast to some beds.

Sea level dropped after the Curtis had been deposited, and the Summerville Formation was laid down in tidal flats much like central Utah's Entrada. The Summerville consists of rippled shale and siltstone with thinner beds of gypsum and sandstone. We will pass an intriguing outcrop of the Summerville Formation, rife with white gypsum beds, if we have time to explore the nearby Ding and Dang slot canyons. The terrestrial Morrison Formation is the youngest unit in Goblin Valley State Park, typified by ripple-marked, varicolored mudstone (some beds are purple or green!), sandstones, and conglomerate.







***Barchan dunes** are a type of sand dune that is common where wind direction is constant—long washes in the San Rafael Desert are a favorable location. Dunes can be other shapes, mainly depending on wind patterns.*

***Top left**: Barchan dune diagram. Slip face is ~34°, the angle of repose for sand on Earth. **Top right**: Barchan dune on Earth. **Bottom left**: Barchan dunes on Mars. Note the wind ripples superimposed on both the terrestrial and Martian dunes.*

Top photo credit: New Journal of Physics. Bottom photo credit: HiRISE/NASA/UA.

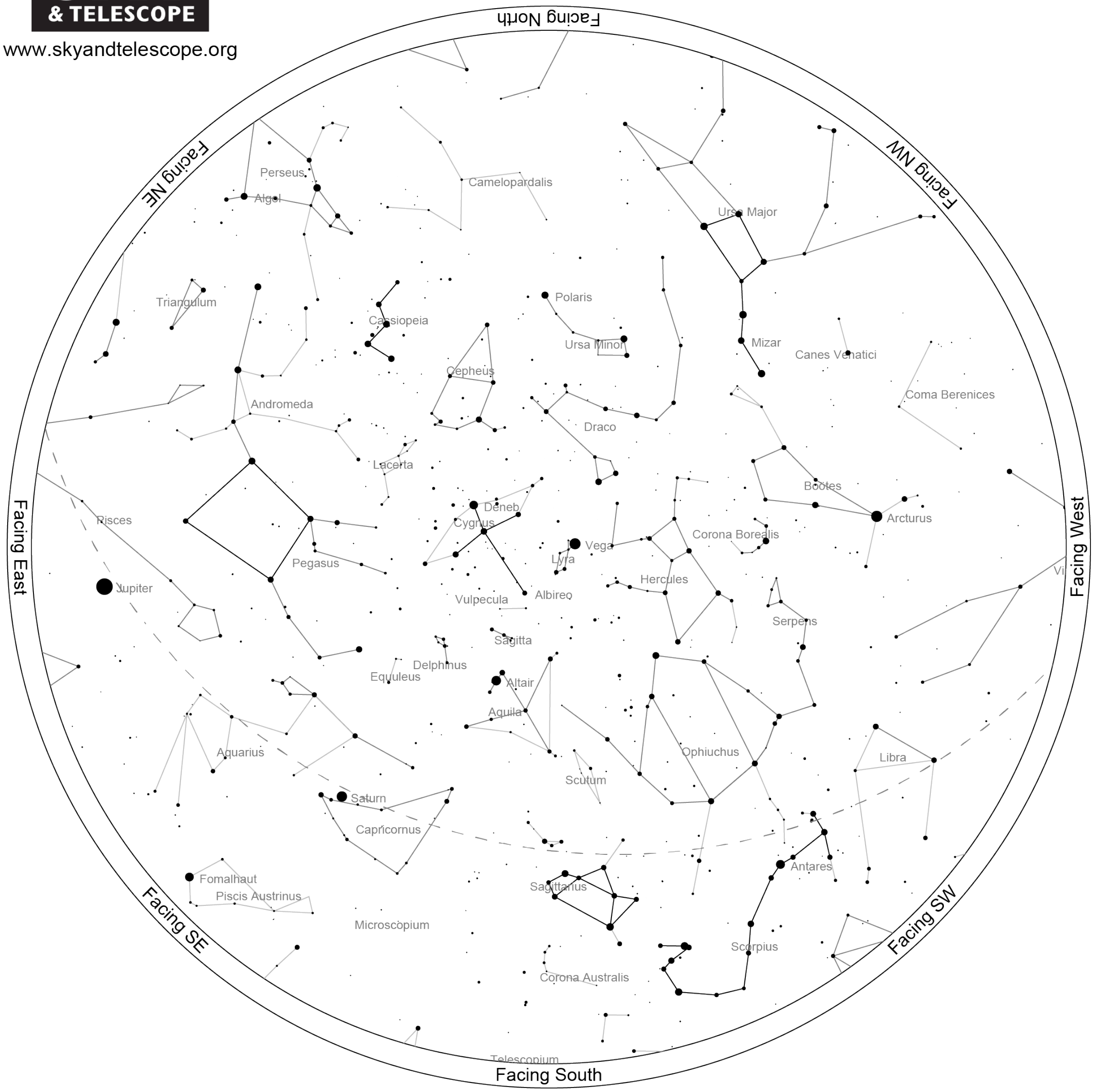
Wild Horse Butte. Here, all four rock units found in Goblin Valley State Park can be seen at once. From oldest to youngest: Entrada, Curtis, Summerville, Morrison. All are Jurassic-aged. Photo: Ken Lund.

This should be a map of the night sky over Goblin Valley on 8/28 at 9 PM (assuming I did the UTC offset correctly, and the free website isn't wrong). The Milky Way goes right through the center, NE to SW.

SKY & TELESCOPE

www.skyandtelescope.org

Sky Chart



Location: Hanksville, UT 84734

Latitude: 38° 17' N, longitude: 110° 40' W

Time: 2022 August 28, 9:00 PM (UTC -07:00)

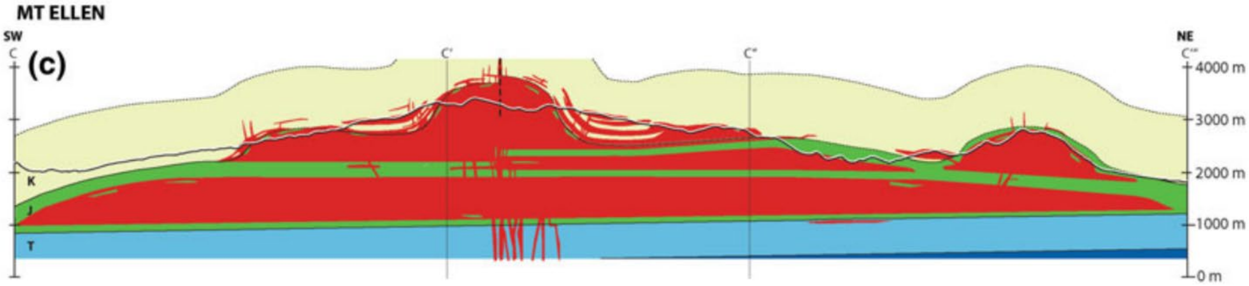
Powered by: Heavens-Above.com

The Henry Mountains: Another Laccolith Range

View to the southeast toward the Henry Mountains, which rise in the distance. https://geology.utah.gov/map-pub/survey-notes/geosights/the-henry-mountains/

As we approach Capitol Reef on State Routes 24 and 12, we will catch glimpses of the Henry Mountains in the distance, which reach heights of up to 11,522 feet (3512 m). The Henry Mountains were the last major mountain group "discovered" in the lower 48 states, and were named by Major John Wesley Powell for the president of the Smithsonian Institution at the time: Joseph Henry. These mountains were the subject of a classic study by G.K. Gilbert, a giant of American geology. This is also one of the classic sites for the study of laccolithic intrusions and their intrusion mechanisms.

The mountains themselves are held up by a set of erosion-resistant, Oligocene-aged, andesitic to rhyolitic laccolithic intrusions that are much like those of the La Sal Mountains. These igneous masses intruded several more or less flat-lying Mesozoic units, including the late Cretaceous Mancos Shale and Morrison Formation, and the Jurassic Entrada Sandstone. Intrusion depth is estimated to have been 2 to 4 kilometers. You can think of laccoliths as being like a balloon under a rug: as the balloon is inflated, the overlying material is warped upward, and sometimes fractured.



Simplified geologic cross section of Mt. Ellen, Henry Mountains. Mt. Ellen is the left-most mountain in the top image (Horsman et al., 2016). There are multiple intrusives, and intrusive levels to this laccolithic body. Intrusive igneous rocks are red, other units are sedimentary: Cretaceous, light-green; Jurassic, dark-green; Triassic, medium-blue; Permian, dark-blue.

The Waterpocket Fold

The Waterpocket Fold is a typical monocline, a structure that is common and important on the Colorado Plateau but rare elsewhere in the US. A monocline is a step-like fold, typified by a short zone of steeply-dipping strata between two limbs with shallow dip. Horizontal strata on one side of a monocline are at a higher elevation than the strata on the other side. In the case of the Waterpocket Fold, the eastern side is dropped relative to the western side.

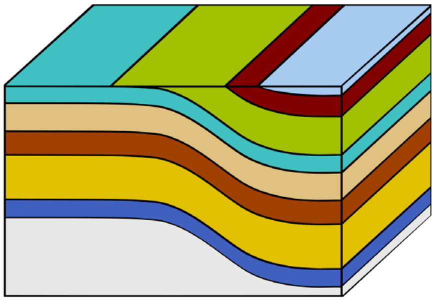


Figure 1: Block diagram of a monocline.

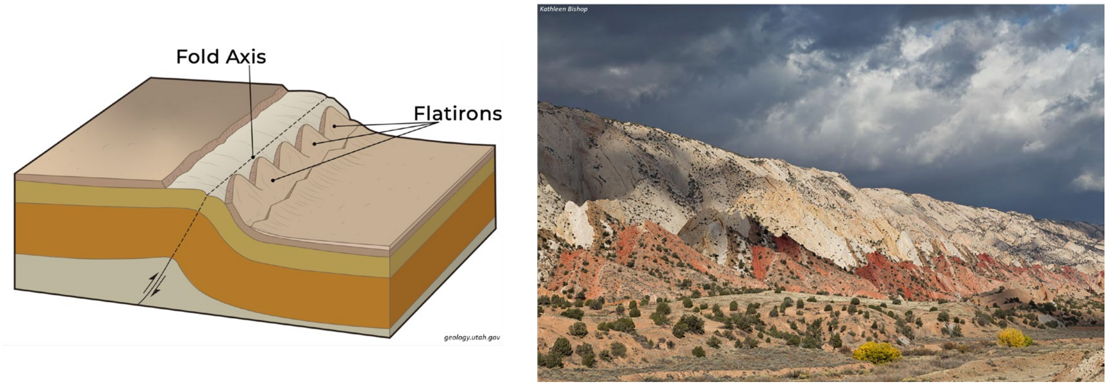


Figure 2: A thrust fault-related monocline featuring flatirons (or hogbacks), and an image of actual flatirons seen from the dropped (eastern) side of the Waterpocket Fold.

The Waterpocket Fold monocline formed during the Laramide Orogeny (50-70 Ma), around the same time as the Rocky Mountains. Like most monoclines, it is the result of deeply-buried thrust faulting (compressional motion) in the igneous and metamorphic basement rocks and folding in the weaker sedimentary layers on top—so, the basement rocks behaved as brittle materials, while the sedimentary cover behaved ductilely. This structural style may be imagined as two books side-by-side with a number of sheets of paper covering them. If one book is displaced up or down (along a fault separating them) the paper sheets will become folded.

In this area, the Waterpocket Fold deforms and exposes rocks as old as the Permian Kaibab Limestone and as young as the late Cretaceous Mancos Shale. The latite and basalt flows on Boulder Mountain and farther west are Oligocene to Pliocene in age, and so post-date the Laramide folding that created the Waterpocket Fold. The structure extends for almost 100 miles across Utah, trending NNW-SSE. Uplift of the Colorado Plateau beginning ~15 Ma accelerated the erosion of the fold, revealing its inner layering at places like Capitol Reef National Park.

Figure 3: Aerial view of the Waterpocket Fold monocline, taken facing roughly south (flatirons are on the eastern side).

Capitol Reef National Park

Capitol Reef National Park is at the upturned and eroded edge of the Waterpocket Fold monocline. The layers here are at a high angle to the horizontal, and the top of the fold has eroded away to expose the stratigraphic section in succession along the ground (see *Waterpocket Fold*, Figure 3). As we traverse the park perpendicular to the monocline, we'll drive over this stratigraphic section essentially one layer at a time (Figure 1).

The rocks visible in Capitol Reef range from Permian to Cretaceous in age, although most are from the Mesozoic Era (Triassic, Jurassic, and Cretaceous Periods). Because the rock layers are steeply titled into an east-dropped monocline, the youngest rocks are exposed at the eastern bound of the park and the oldest rocks in the west. As we pass the badlands around Cainesville and then through Capitol Reef, you'll see familiar formations like the Mancos, Entrada, Navajo, Wingate, Chinle, Moenkopi, and more in sequence.

The park gets its name for the white domes of Navajo Sandstone that resemble the US capitol building (*Capitol*) and the fact that it is a barrier to travel like an ocean reef (*Reef*). Capitol Reef National Park is host to the only paved road that traverses the Waterpocket Fold.

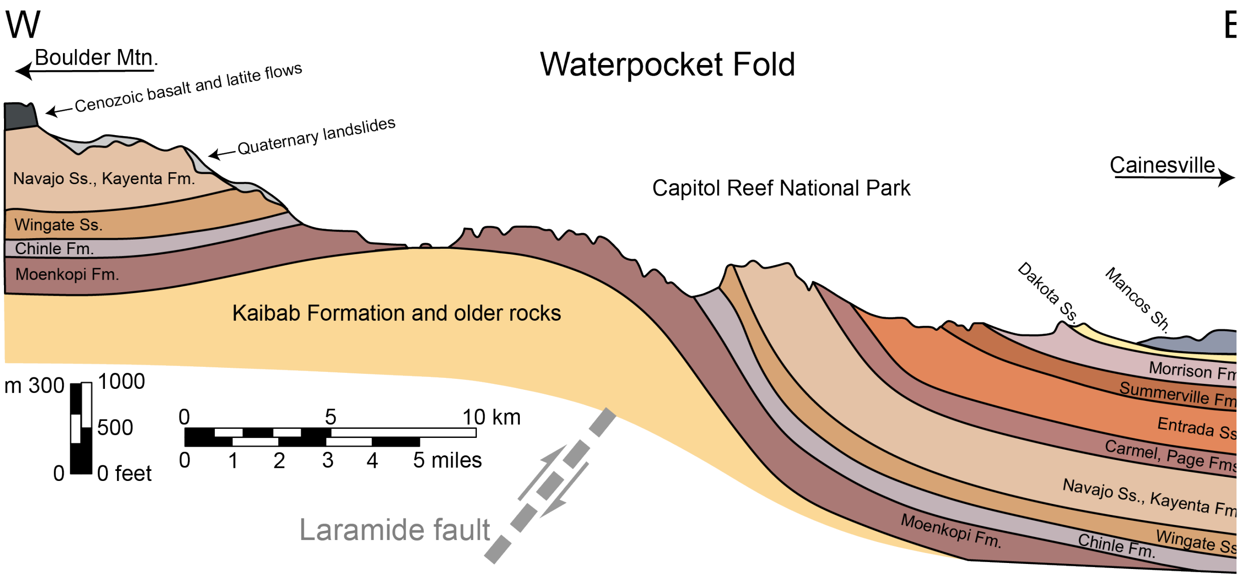


Figure 1: Cross section of Capitol Reef National Park and its position on the Waterpocket Fold. We will pass through the park from east to west. The badlands around Caineseville are formed from the Mancos Shale.

The Aquarius Plateau and Boulder Mountain Volcanics

The Aquarius Plateau, named for its abundance of lakes, is the highest timbered (tree-covered) plateau on North America, and was uplifted at the same time as the larger Colorado Plateau it is a part of. It reaches its maximum elevation of 11,328 feet at Bluebell Knoll (part of Boulder Mountain). The plateau is part of Dixie National Forest and consists of more than 900 square miles of mostly-forested highlands, 50,000 acres of which is hilly terrain over 11,000 feet in elevation. Bryce Canyon National Park has been carved into the edge of the plateau.

Figure 1: Part of the Aquarius Plateau seen on the horizon from Bryce Canyon NP.

During the Oligocene (33.9 – 23 Ma) and Miocene (23 – 5.3 Ma) Epochs, the Aquarius Plateau was a center of basaltic and andesitic volcanism. In fact, the relatively flat top of the highland is a lava flow of black basalt—a resistant igneous rock that protected the sedimentary layers beneath from erosion. As we drive through the region, keep an eye out for chunks of basalt (black rock) in the washes and pastures. You might also have spotted some out-of-place black rocks in Capitol Reef National Park. All of these boulders are derived from the volcanism on the Aquarius Plateau.

Figure 2: Black basalt boulders seen in Capitol Reef National Park, sourced from the Aquarius Plateau.

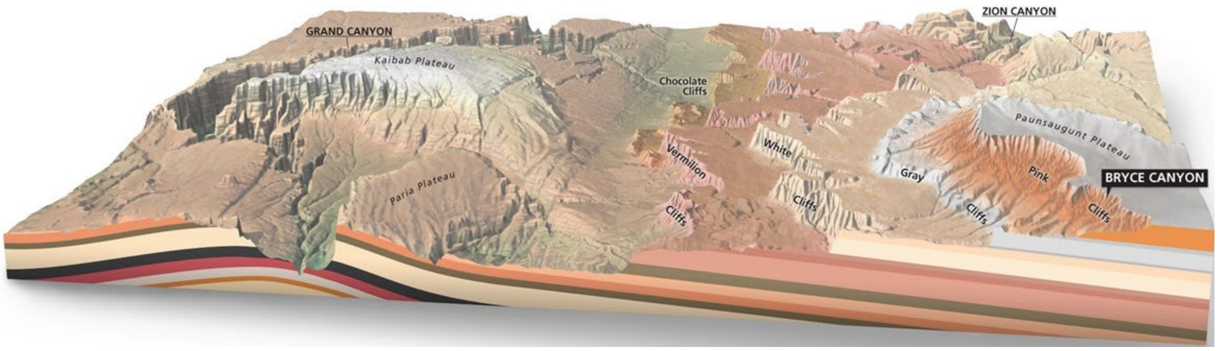
It has long been thought that the basaltic boulders found below the Aquarius Plateau are glacial erratics, volcanic rock carried away from the lava flow by the glaciers that covered Boulder Mountain during Pleistocene Ice Age. However, more recent evidence suggests that many of the basalt chunks might have been moved by mass wasting events like landslides and debris flows tumbling off of the high plateau.

Bryce Canyon National Park

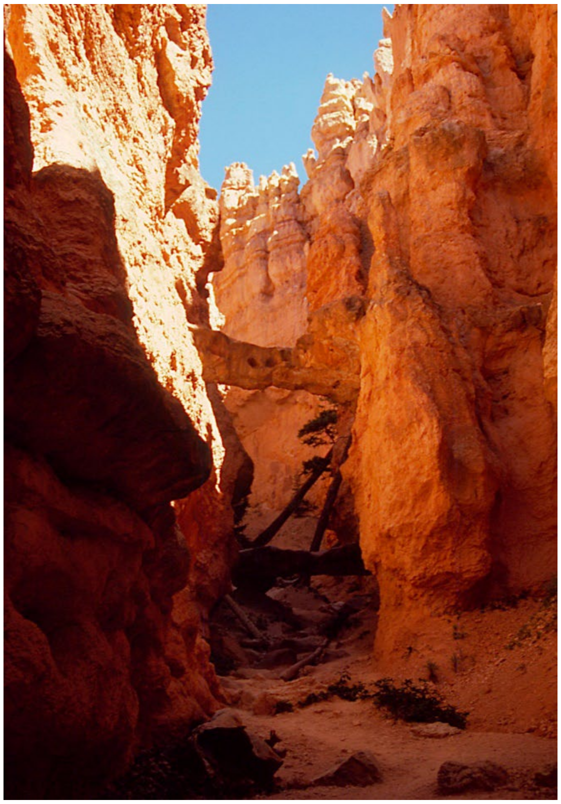
View into Bryce Canyon, with pinnacles and badlands.

Bryce Canyon is not really a canyon, but is an irregular eroded cliff on the side of a plateau. The cliff is made of relatively soft mudstone, limestone, and sandstone of the Eocene Claron Formation (equivalent to the Wasatch Formation farther north). The Claron Formation was deposited by a series of meandering rivers, and also in near-shore environments and deeper parts of temporary intermountain lakes. These lakes formed in basins between the Sevier Mountains to the west and the Laramide Rockies to the east. In the arid conditions, the lake waters were frequently saturated with calcite, which precipitated as impure (clay-bearing) limestone in shallow coastal waters. The formation generally consists of a lowermost level of conglomerate and sandstone, two middle members of shale and shaley limestone, and an uppermost sandstone layer, which forms much of the plateau above the cliff.

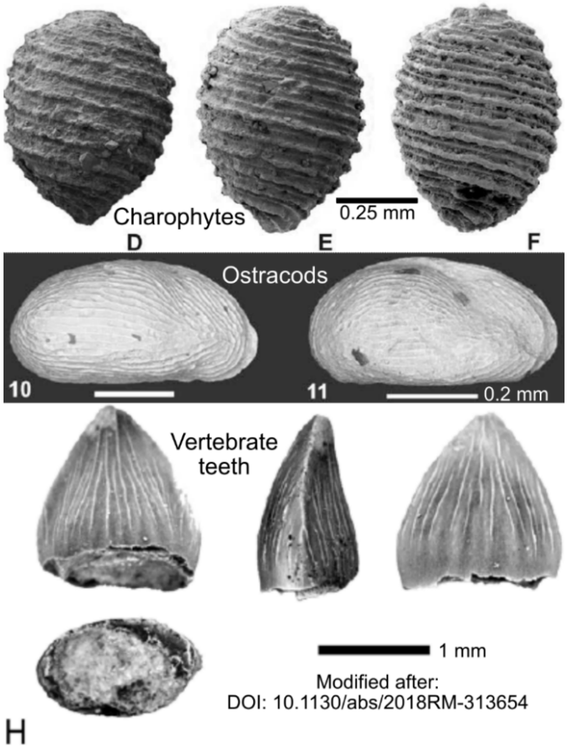
The actual rocks vary from place to place, and vertically within the layered sedimentary stack. There is commonly sandstone, limestone, calcareous mudstone, and mudstone in easily-eroded, thinly interlayered sequences. These and older units are cut by faults, both thrust and



Bryce Canyon location, with respect to the Grand Staircase of southern Utah, between the Paunsaugunt Plateau to the north and the Grand Canyon to the south. http://milesbarger.com/project/grand-staircase



Slot canyon and natural bridge, Bryce Canyon NP.



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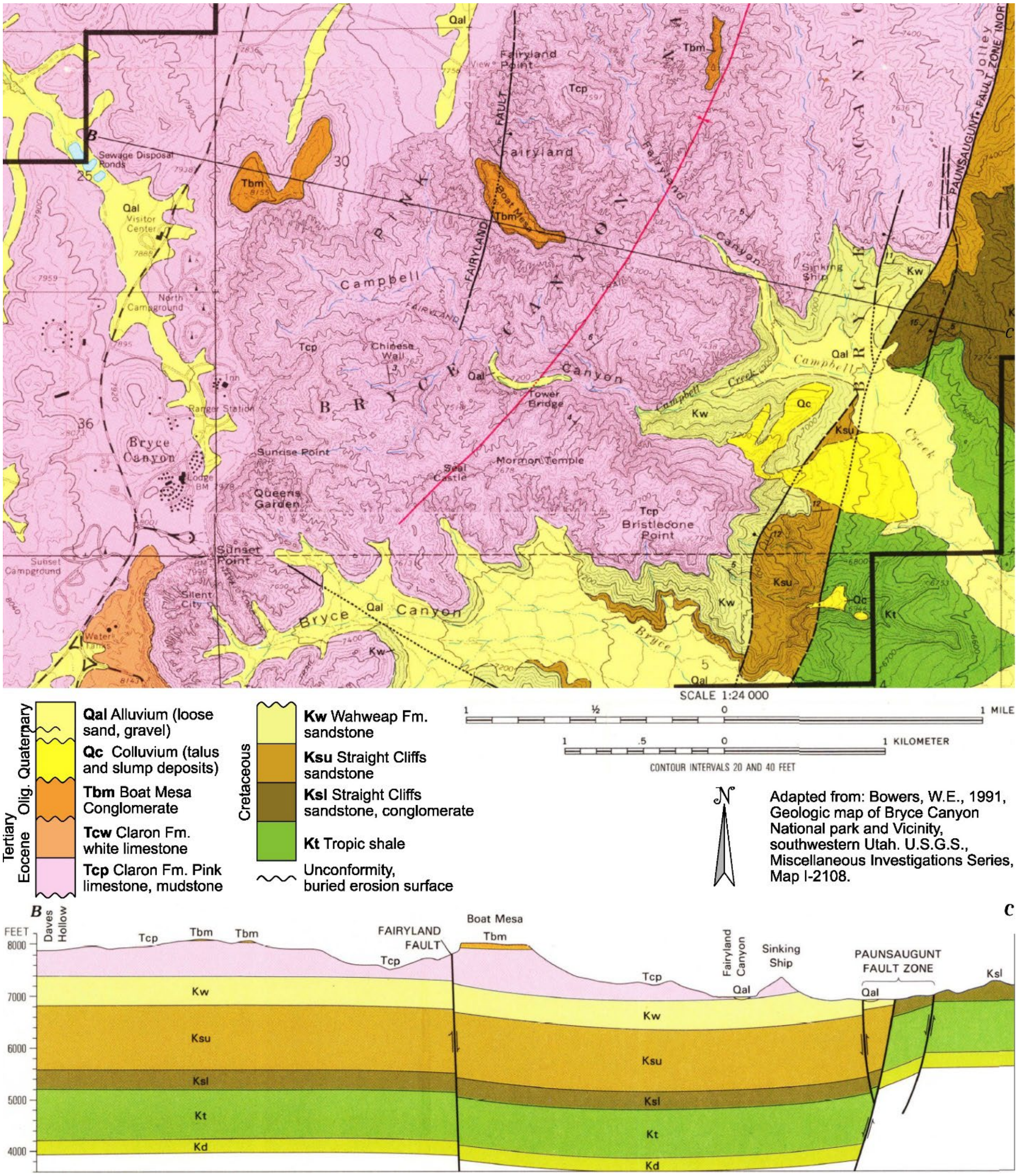
normal, that are interpreted to include both Sevier/Laramide Paleogene faults (mostly thrust), and Basin and Range extensional Neogene faults (normal).

The Claron Formation lies directly under the Green River Formation of the Piceance Creek Basin, and is underlain by late Cretaceous and early Paleogene sediments, mostly river-deposited sandstone, shale, and conglomerate, that were laid down during the Sevier Orogeny (a bit earlier) and Laramide Orogeny (a bit later). The Claron Formation forms the "pink cliffs" of the "Grand Staircase" of cliffs in the southern Colorado Plateau.

The differing rock types, commonly in thin layers, in combination with two dominant sets of vertical fractures (tectonic joints), allow differential erosion to be abundantly expressed. Easy water access down the joints accelerates weathering, and much of the rain comes as heavy downpours and flash floods. These processes conspire to produce vertical columns and slot canyons. Different weathering rates of the various rock types causes the columns to vary in diameter, producing weird shapes known in Bryce Canyon as hoodoos.

The Claron Formation contains abundant fossils in some places, but preservation is mostly restricted to calcareous skeletons (snails, ostracods), algae (filamentous mats, charophytes), burrows of crayfish and other arthropods, and teeth of vertebrates.

Hikes in the Bryce Canyon National Park almost all start at the plateau rim, and then proceed down paths into the irregularly eroded canyons below the plateau. Some parts can be steep, but in general grades are moderate. The slopes face generally southeast, and so catch the sun for much of the day. Any rain will make the soft rocks slippery, especially where they are clay-rich, so hikes are best left for dry weather.



Adapted from: Bowers, W.E., 1991, Geologic map of Bryce Canyon National park and Vicinity, southwestern Utah. U.S.G.S., Miscellaneous Investigations Series, Map I-2108.

Geologic map of part of Bryce Canyon National Park, with cross section (modified after Bowers, 1991).

The Sevier Fault

The Sevier Fault is one of several active, major, NE-trending normal faults (another being the Hurricane Fault) that are responsible for the "stepping down" from the uplifted Colorado Plateau Province in the east into the Basin and Range Province in the west (Figure 1). Thus, the hanging walls (down-dropped) blocks along these faults are on the western side.

The Sevier Fault extends from an area south of the Grand Canyon well into SW Utah, spanning a distance of at least 150 miles (Figure 1). Like most large-scale faults, it is composed of discrete segments that generally rupture independently (rupture: slip catastrophically quickly, causing an earthquake). Geoscientists haven't conclusively pinned down the time when faulting began along the Sevier Fault, but many suggest it was the mid-Miocene (~12-15 Ma).

We will see the Sevier Fault in an excellent roadside outcrop just outside of Bryce Canyon National Park. Here, it juxtaposes a 500 thousand year old basaltic lava flow against the 50 *million* year old Claron Formation (Figures 2-4). The fault did not pose such a geographic barrier 500 thousand years ago, and the then-newly-erupted Red Canyon lava flow spread across either side. Since that time, the fault has offset the Red Canyon flow by 750-1130 feet. The total displacement (displacement since faulting began) along the Sevier Fault Zone in this area is ~3000 feet. This is the maximum measured displacement along the entirety of the fault's length.

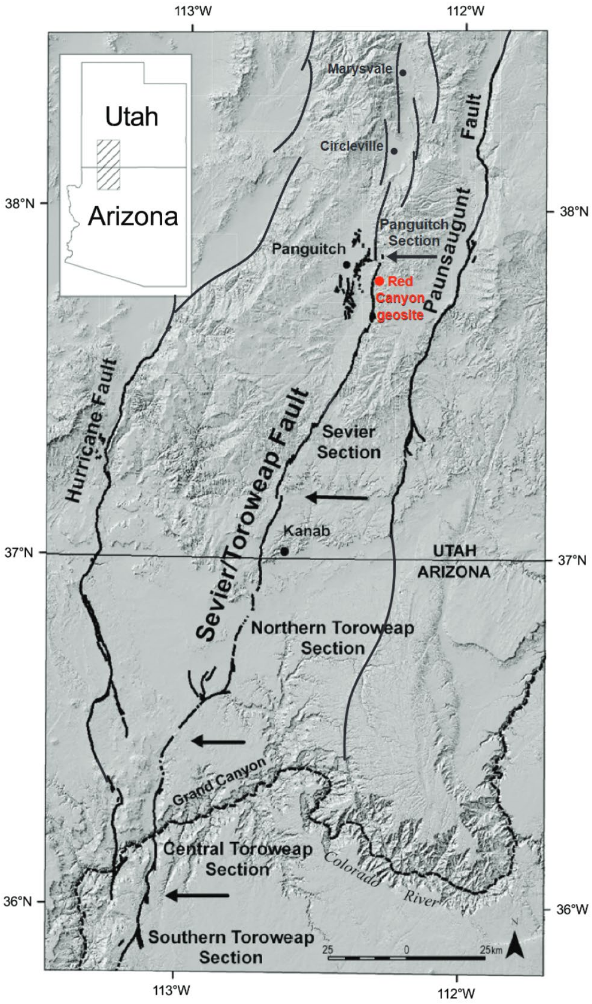


Figure 1: The Hurricane, Sevier/Toroweap, and Paunsaugunt Faults, major normal faults that "step down" from the Colorado Plateau to the Basin and Range. Biek, 2019; Lund et al., 2008.

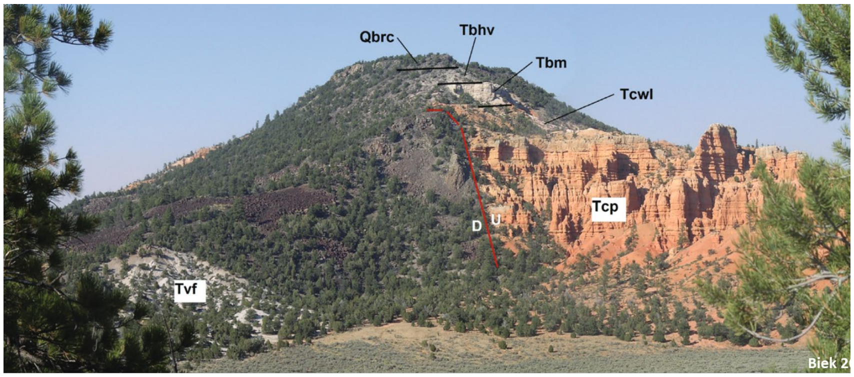


Figure 2: Annotated photo of the Sevier Fault outcrop near Bryce Canyon. Tcp = pink Claron Fm., Tcwl = white Claron Fm., Tvf = basin-fill deposits; Tbhv = Brian Head strata; Tbm = Boat Mesa conglomerate, Qbrc = Red Canyon lava flow; U = upthrown (footwall), D = downdropped (hanging wall).

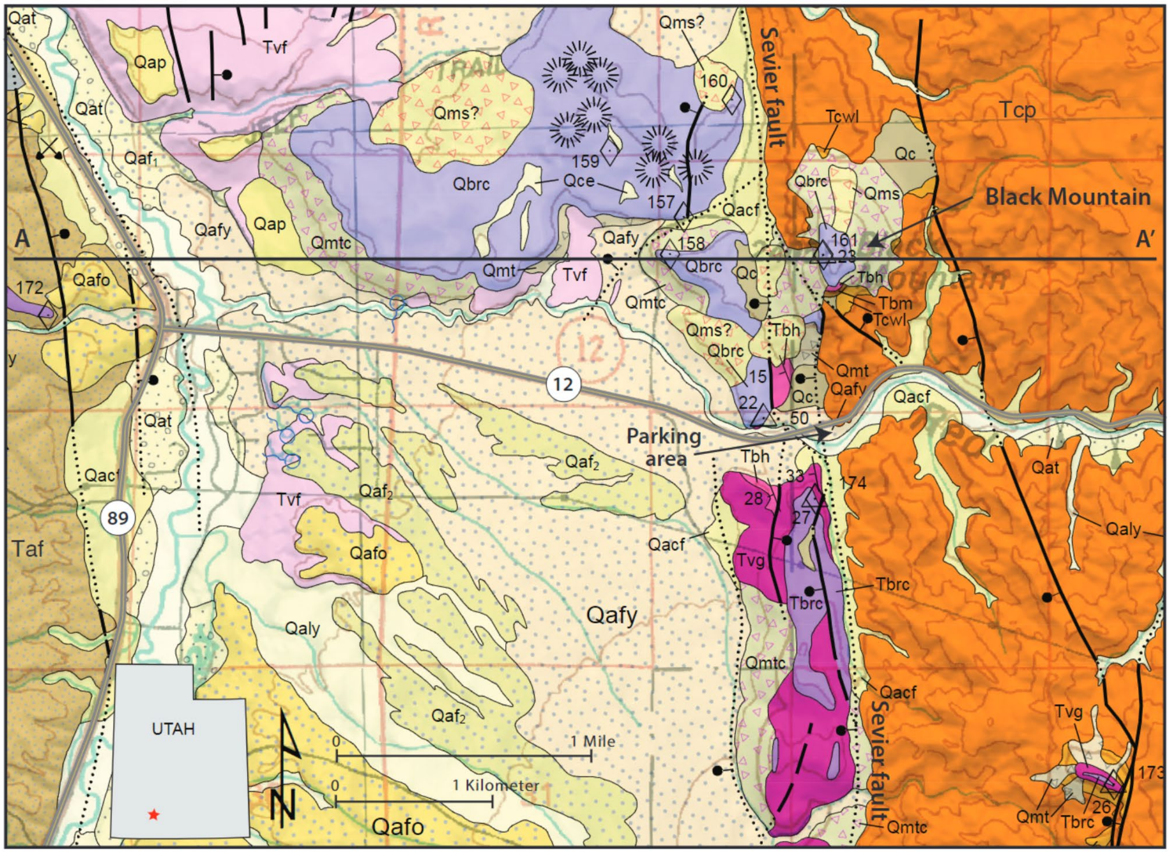


Figure 3: Map of the area (Biek, 2019). We will pull off at "Parking area" on Hwy 12, and the outcrop is to the north. Purple is lava flow, orange is Claron Fm.

***Caption from Biek, 2019:** "Geologic map of the Red Canyon area, showing parking area to view the Sevier fault zone. Note numerous vent areas (stars) on Rock Canyon lava flow. Q = various surficial deposits; Qbrc = Red Canyon lava flow; Tbrc = Rock Canyon lava flow; Taf = old alluvial-fan deposits; Tvg = coarse-grained volcaniclastic deposits; Tvf = fine-grained volcanic deposits; Tbh = Brian Head Formation; Tcp = pink member of the Claron Formation. Modified from Biek and others (2015)."*

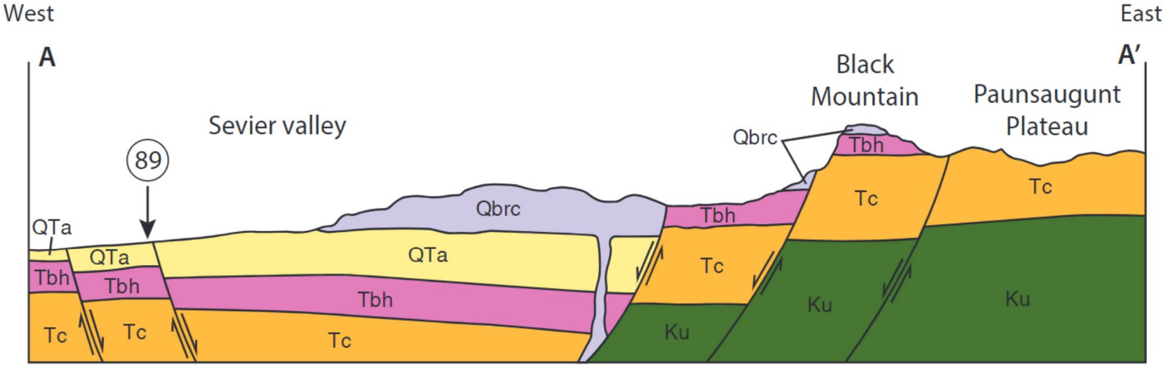


Figure 4: Cross section from A-A' on map above (Biek, 2019). Unit names same as above, except Tcp and Tcwl consolidated into Tc (Claron Fm.).

Zion National Park

Zion National Park is among the lushest of Utah's National Parks and Monuments, and the state's most popular with tourists. We will spend our time here in geologically-young Zion Canyon, carved over 2 million years' time by the North Fork of the Virgin River (compare to the ~15 million years it took to carve Canyonlands). The Virgin River is bordered by cottonwood trees on the canyon floor, but the vegetation is dominated by hardier plants like juniper, sagebrush, and pinyon pine up-slope and away from the water (and ponderosa pine on the ridge tops, which we aren't likely to encounter). Upon first glance, Zion Canyon is notable for its sheer sandstone walls towering above its flat valley floor, with the transition between vertical and horizontal eased by a gentle scree slope at the base of the cliffs shrouded by low, dark green plants.

Stratigraphy

The most prominent rock formation in Zion National Park is the Jurassic Navajo Sandstone, which achieves its maximum thickness of 2200 feet within the park's bounds. The Navajo forms the precipitous upper chunk of the soaring cliffs and fins here, streaked red by iron oxides from the thin layer of Temple Cap tidal flat mudstones above. The thick chunk of erosion-resistant Navajo is underlain by the Jurassic Kayenta Formation, the younger portion of which forms slopes atop a narrow ledge of the older Springdale Sandstone Member (Figures 1, 2).

Beneath the small ledge of Springdale Sandstone is a Jurassic-Triassic formation we haven't heard much about yet, the Moenave Formation: Sandstones and mudstones deposited in the beds of streams and lakes. The slope-forming Moenave overlies the colorful paleosols and fluvial mudstones and conglomerates of the Triassic Chinle Formation. In some of the more deeply-incised parts of the park, the Triassic Moenkopi redbeds and—in one location near the Hurricane Fault—even the limestones of the Permian Kaibab Formation are exposed.


US Dept. of the Interior

Figure 1: Zion Canyon. Walls of Navajo Sandstone are stacked atop a vegetated slope of the Kayenta Formation. The Springdale Sandstone Member forms a ledge near the base of the cliffs. The North Fork of the Virgin River meanders in a flat canyon bottom, ultimately carrying away over 1 million tons of sediment per year.

A Monument to Erosion

Zion Canyon owes its existence to the North Fork of the Virgin River, which appears deceptively placid outside of flood stage (Figure 1). The river is an erosional powerhouse, with a relatively steep gradient of 71 feet per mile through the park. Measured upstream at Springdale and downstream at Virgin, its average annual discharge is around 100 and 200 cubic feet per second (cfs) respectively. However, the range is tremendous: The river's peak discharge can be as low as 20 cfs on calm days, but reaches over 9,000 cfs during flooding events at Springdale—and over 20,000 cfs at Virgin! The drastic increases in flow rate lend the normally-tranquil stream massive erosive power. The North Fork of the Virgin River carries over 1 million tons of sediment away from the park per year, equivalent to more than 3,000 tons of sediment per day if flow rate were constant. As it is, a disproportionate amount of this sediment is moved during floods.

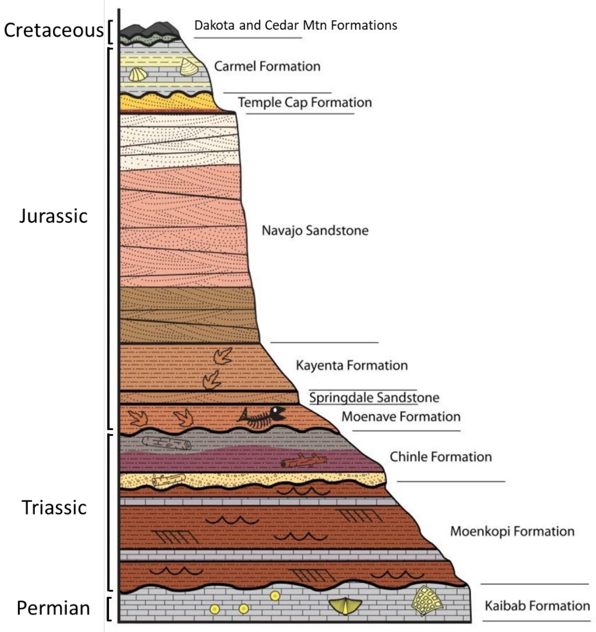


Image by Geoscientist-In-the Park David Tarailo, sponsored by the Geological Society of America, GeoCorps Program, 2012.

Figure 2: Stratigraphic column for Zion National Park (adapted from David Tarallo/GSA, 2012). Cretaceous and Permian strata are rarely expressed.

Following the Virgin River upstream along Zion Canyon, past the Temple of Sinawava, the canyon walls narrow considerably to tightly enclose the water. Here, the resistant Navajo Sandstone is the oldest layer exposed, and the rapidly-incising river is unable to inflect its course as easily as it can when eroding the softer layers below. As the river slices downwards through the Navajo, the sturdy canyon walls remain coherent and sheer to form a slot canyon known as "The Narrows." The canyon walls extend up to 2000 feet above the river. Weather permitting (beware *any* nearby rain, in a slot canyon!) we will hike up the Narrows by wading through the Virgin River itself. All parts of Zion Canyon could have looked like the Narrows at one point in time, when the river downstream was still chewing through the Navajo Sandstone.

Figure 3: Hanging valleys, one on a dry day (left) and another with an ephemeral waterfall during a summer storm (right). Both slice the Navajo Sandstone.

Also cut into the Navajo Sandstone along Zion Canyon's walls, we will spot examples of an erosional feature called a hanging valley (Figure 3). Hanging valleys are ravines or canyons that truncate hundreds or thousands of feet above the main canyon floor in an abrupt drop-off. These valleys in Zion only contain water during snowmelt or when it rains—because in the desert, when it rains, it floods. Torrents of water run off of the slickrock on the mesas, funneled through the stony chutes of hanging valleys before plummeting down to contribute to the Virgin River below.

Due to the transient nature of streamflow in these smaller canyons, they have failed to incise as deeply and as quickly as the main canyon cut by the Virgin River. This is an example of differential erosion, with the main canyon eroding at a considerably quicker pace than the tributary canyons.

Recent (Cenozoic Era) Geologic History

While the rock layers in Zion were deposited during the Mesozoic Era, the canyon itself started to truly take shape during the late Cenozoic Era. Along with the inexorable downward cutting of the Virgin River, the area experienced significant volcanism and mass wasting, both of which are connected to the presence of paleo-lakes.

Basaltic volcanism

Zion is part of the Western Grand Canyon basaltic field, a nexus for Cenozoic Era basaltic volcanism in the form of cinder cones and lava flows. The oldest basalt flows in southwestern Utah are ~23-17 million years old, but most are younger than 7 million. Basalt flows around Zion are less than 1.4 million years old, with the youngest only about ~600 years old. The flows are usually 10-40 feet thick but can reach up to several hundred feet in thickness where they fill canyons.

Paleo-lakes and mass wasting

Rapid downwards erosion undermining steep cliffs have made Zion prone to rockfalls, landslides, and debris flows. In recent geologic history, the park's canyons have host to at least 14 landslide- or basalt flow-dammed lakes. Most of the paleo-lakes only contained water during part of the year, but Sentinel Lake—formed ~5000 years ago as a result of the Sand Bench landslide in Zion Canyon—likely contained water year-round. Each of the lakes eventually filled with sediment, leaving behind a flat bench of lake deposits for the river to carry away.

The sediments that filled Sentinel Lake, covered again by the thin deposits of the meandering river, are part of the reason for Zion Canyon's relatively flat bottom between the Court of the Patriarchs and the Temple of Sinawava. The Virgin River has removed an estimated 200 feet of Lake Sentinel's sediments but has at least 70 feet of lake and landslide deposits to slice through before it reaches its pre-landslide level and begins eroding bedrock again.

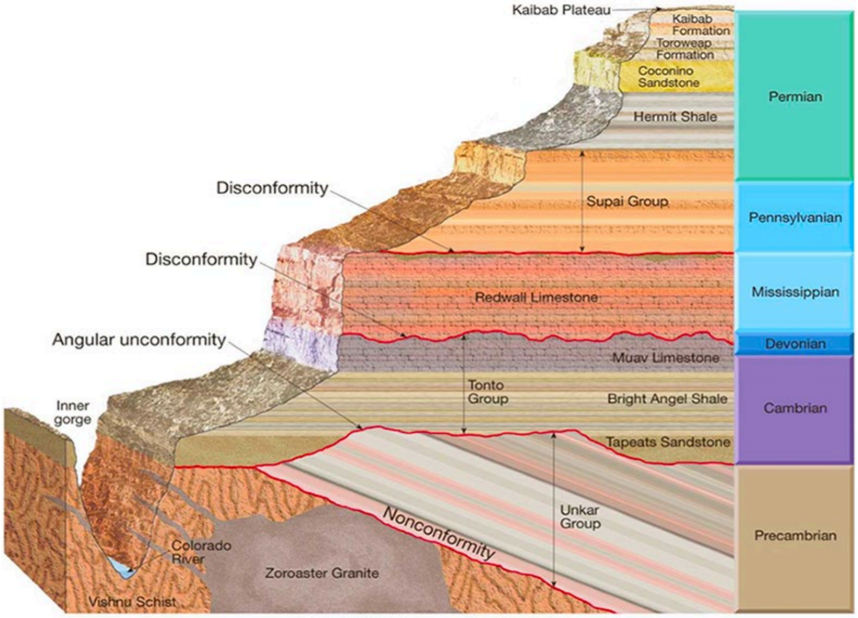
Periodic landslides have occurred in recent human memory as well, some caused by above-average rainfall and another potentially caused by an earthquake. A major landslide in 1995 dammed the river and resulted in a temporary, 20-foot-deep pond that the water eventually overtopped.

Grand Canyon National Park: Overview

Eastern Grand Canyon, looking east. https://knowablemagazine.org/article/physical-world/2019/deeper-understanding-grand-canyon

The Grand Canyon is one of the best-known geologic features in the United States. It is a deep canyon, approximately a vertical mile from rim to river in many parts (1600 meters). The Colorado River has here eroded through most of the Paleozoic section on the Colorado Plateau, from the Permian Kaibab Limestone on the plateau surrounding the canyon, through the Tapeats Sandstone at the Paleozoic sequence base. Tilted, faulted, and eroded middle to late Proterozoic sedimentary and basaltic rocks of the Grand Canyon Supergroup lie below the Paleozoic stack, representing an older episode of sedimentary deposition, volcanism, and tectonic activity.

Below that is a complex set of early Proterozoic igneous and metamorphic rocks, representing even older emplacement of granitic magmas, sedimentary deposition and volcanic activity, metamorphism, and intrusion of additional granitic magmas. Exposure of these mid-crustal igneous and metamorphic rocks at the surface illustrates not only the tectonic and other processes that produced them, but perhaps 20 or 25 kilometers of erosion that has brought them to the surface.



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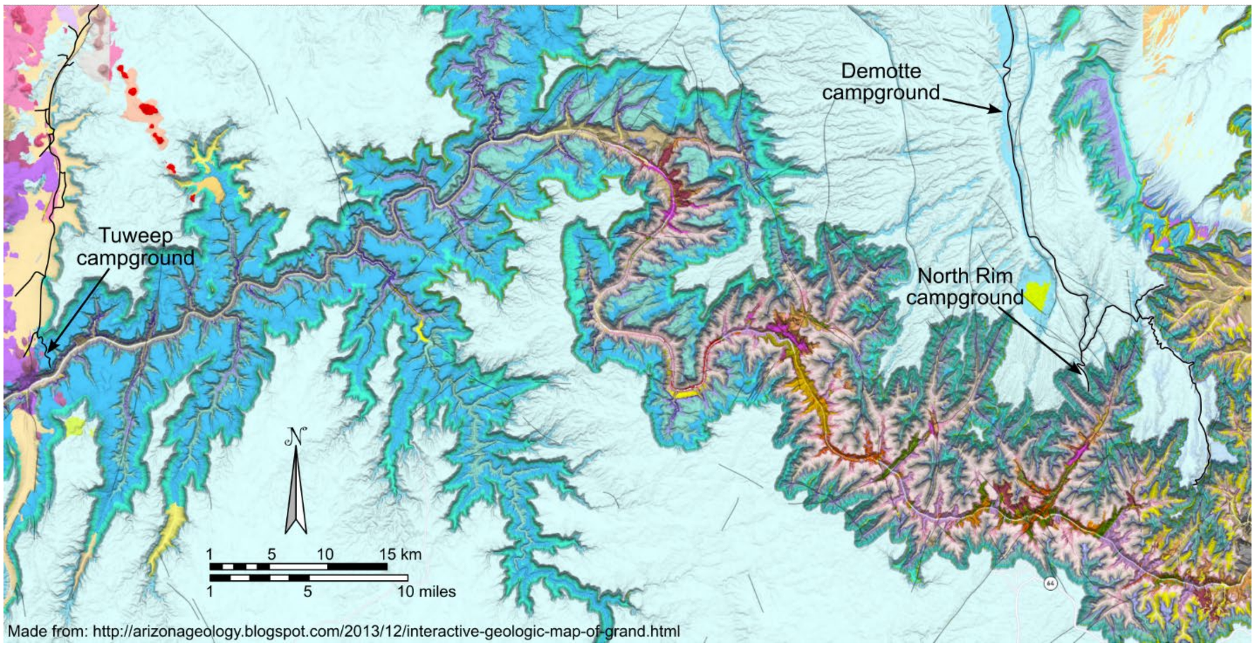
Schematic geologic profile and column of the Grand Canyon.

Tilted, Precambrian sedimentary rocks intersecting the horizontal Tapeats Sandstone, along an unconformity (buried erosional surface).

Visible in the image above is the angular unconformity between the thick, horizontal Cambrian Tapeats Sandstone at the bottom of the Paleozoic stack, underneath which are tilted red sandstones of the Precambrian Grand Canyon supergroup. The two intersect at an angle of about 15°, along which is an erosion surface representing hundreds of millions of years of time, and kilometers of erosion.

Precambrian igneous and metamorphic rocks exposed in the central canyon. The lowest dark-brown sedimentary rocks are the Tapeats Sandstone.

In the picture at the bottom of the previous page, the dark-brown Tapeats Sandstone is just below the skyline, below which on the canyon wall are early Proterozoic igneous and metamorphic rocks. The metamorphic rocks are gray, layered, and dip to the left. They are typically referred to as Vishnu Schist, but I'm not sure just what this particular rock unit is it is mapped as now. The metamorphic rocks are cut by numerous dikes of pink granite, typically referred to as the Zoroaster Granite. These rocks represent at least one episode of mountain building, followed by extensive erosion that brought these (once) mid-crustal rocks to the surface, where the Grand Canyon Supergroup sediments and lavas were deposited onto them. Then the rocks were rifted and tilted, and eroded again, following which deposition of the Paleozoic and younger rocks took place. Though only given two names (Vishnu, Zoroaster) in older literature and simple maps, the metamorphic and igneous rocks actually are complex in their ages, compositions, and origins.



Geologic map of part of the Grand Canyon. Made from: http://arizonageology.blogspot.com/2013/12/interactive-geologic-map-of-grand.html

In this geologic map, thick black lines are dirt roads (north rim only). The geologic features, in rough age sequence from youngest to oldest, are:

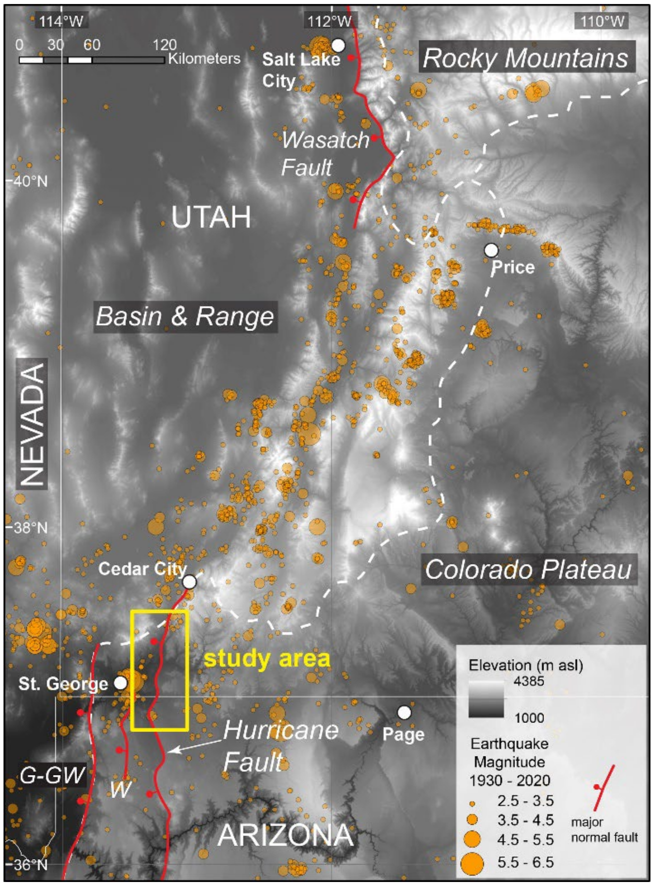
Light-yellow in the canyons are talus, landslide, and stream deposits.
Beige is alluvial fan deposits.
Bright yellow in the canyon are huge travertine deposits, accumulations of limestone deposited by water seeping out of the canyon walls.
Reds, purples, and pinks in the northwest are volcanic rocks, including lava flows and volcanoes.
Thin black lines are faults.
Pinks, greens, and blues represent Paleozoic sediments that were deposited on an ancient erosion surface on top of Precambrian rocks. The extensive light-blue is the plateau-covering Kaibab Formation.
Magenta and dark-browns in the central canyon are the Grand Canyon Supergroup.
Medium brown, yellow-brown, and purple in the central canyon are the metamorphic rocks and granites, beneath the Paleozoic sediments and the Grand Canyon Supergroup.

The Hurricane Fault

As we head toward the Grand Canyon, southward into Arizona, we pass close to the Hurricane Fault. The Hurricane Cliffs, which run along the fault, are partly the result of the normal fault offset. The vertical fault offset distance is variable, but has measured offsets between 600 and 850 m in the "study area," shown in the image, downward to the west. That offset becomes much less as we continue south, until it is only 300–500 m.

The Hurricane Fault is 250 km long, and in this area represents the boundary between the extensional Basin and Range province to the west, and the Colorado Plateau to the east. The Hurricane Fault is equivalent to the Wasatch Fault just east of Salt Lake City. This fault system is seismically active, and produced a 5.8 magnitude earthquake in 1992.

Water circulates in fault fractures and emerges in a few places as warm springs, one of which, Pumpkin Spring, is shown here. Studies of springs and mineral samples collected from the fault zone indicate a range of water compositions, from low oxygen-18 (δ^{18}O), low salinity to high oxygen-18, high salinity. The more or less linear relationship between these compositions, and other information, leads to the conclusion is that there are two water end members that mix within the fault zone: fresh water from rain and snow that percolates into the ground (NaCl ≈ 0, δ^{18}O ≈ -12‰) and deep, saline water in underlying rock formations (NaCl ≈ 11%, δ^{18}O ≈ 5‰).



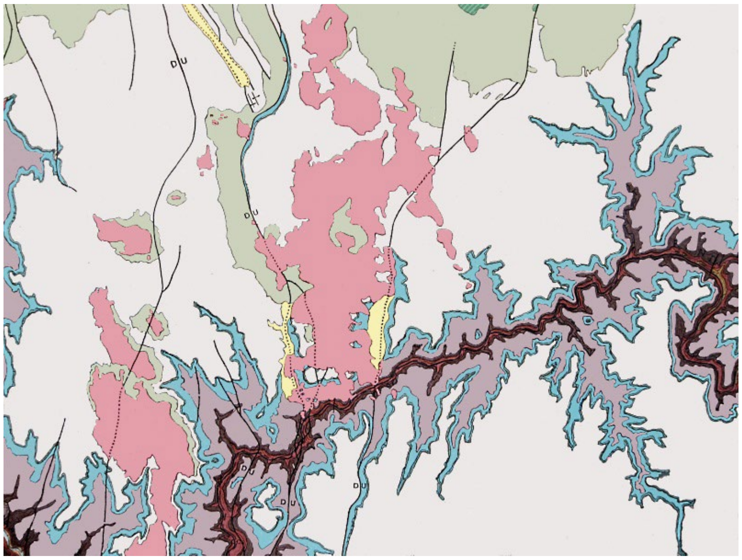
Elevation model map showing the location of the Hurricane and Wasatch faults, with earthquake epicenters and magnitudes superimposed. The Grand Canyon is near the map's southern edge (Koger and Newell, 2020).

Pumpkin Spring, on the edge of the Colorado River, Grand Canyon. Although hikers are bathing in this travertine pool, that's probably a bad idea. The water contains high concentrations of arsenic (0.11%), lead, zinc, and copper.

Grand Canyon National Park: Toroweap Canyon

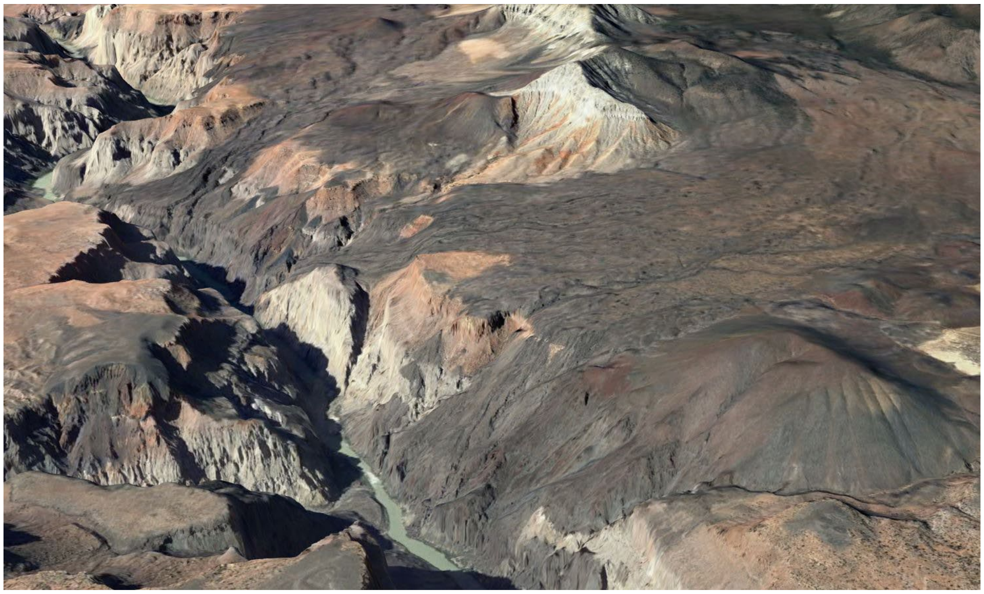
Uinkaret Volcanic Field

The route we are following passes between the Shivwits Plateau to the west and the Uinkaret Plateau to the east. Both of these plateaus are mantled by Quaternary volcanics. The very arid conditions result in extremely slow weathering rates, so flows that are very old are difficult to distinguish from young flows, at least by appearance. The volcanics of the Uinkaret Plateau can be seen to fill older topography, indicating that an eroded canyon terrain similar to the present terrain existed when eruptions occurred. Extreme examples of this are seen as we go south to the Grand Canyon. The Toroweap Valley has, in fact, been partially filled by Quaternary lavas.



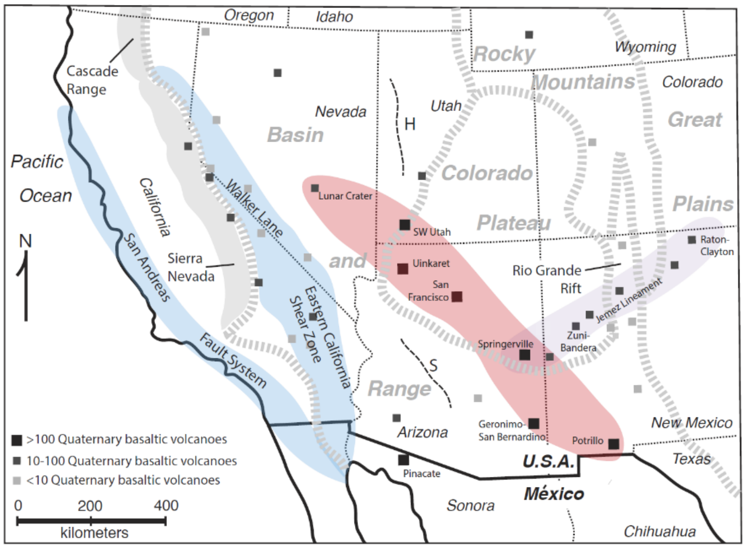
Uinkaret volcanic field, with the volcanics shown in pink. Other units are nearly flat-lying sedimentary rocks, except dark-brown, which represents igneous and metamorphic rocks at the bottom of the Grand Canyon. http://skywalker.cochise.edu/wellerr/Google-geology/AZ-Grand-Canyon-lava/index.htm

The Uinkaret volcanics occur as basaltic flows and cinder cones, just within northern Arizona. The field has at least 213 eruptive vents, most of which are north of the Grand Canyon. Volcanism in this field began about 3.6 million years ago, with the most recent eruption having been about 1300 years ago. Compositions of the lavas range from relatively normal basalts, to highly alkaline varieties (unusually high in potassium, sodium, and other elements). Such a



Lava flows from the Uinkaret volcanic field that flowed over the rim of the canyon, down to the river. These formed high dams at several times in the past. North is to the right, Vulcan's Throne is the cinder cone in the lower-right. Google Earth image.

compositional range is typical of basalts that erupt in continental areas, as compared to, say, mid-ocean ridge basalts, which tend to have low potassium and sodium. Several eruptions in the Uinkaret field brought up fragments of mantle rock, indicating rapid rise of the magmas from mantle depths.



Quaternary volcanic fields in the western U.S. (Valentine et al., 2021). The Uinkaret field is almost exactly in the map center.

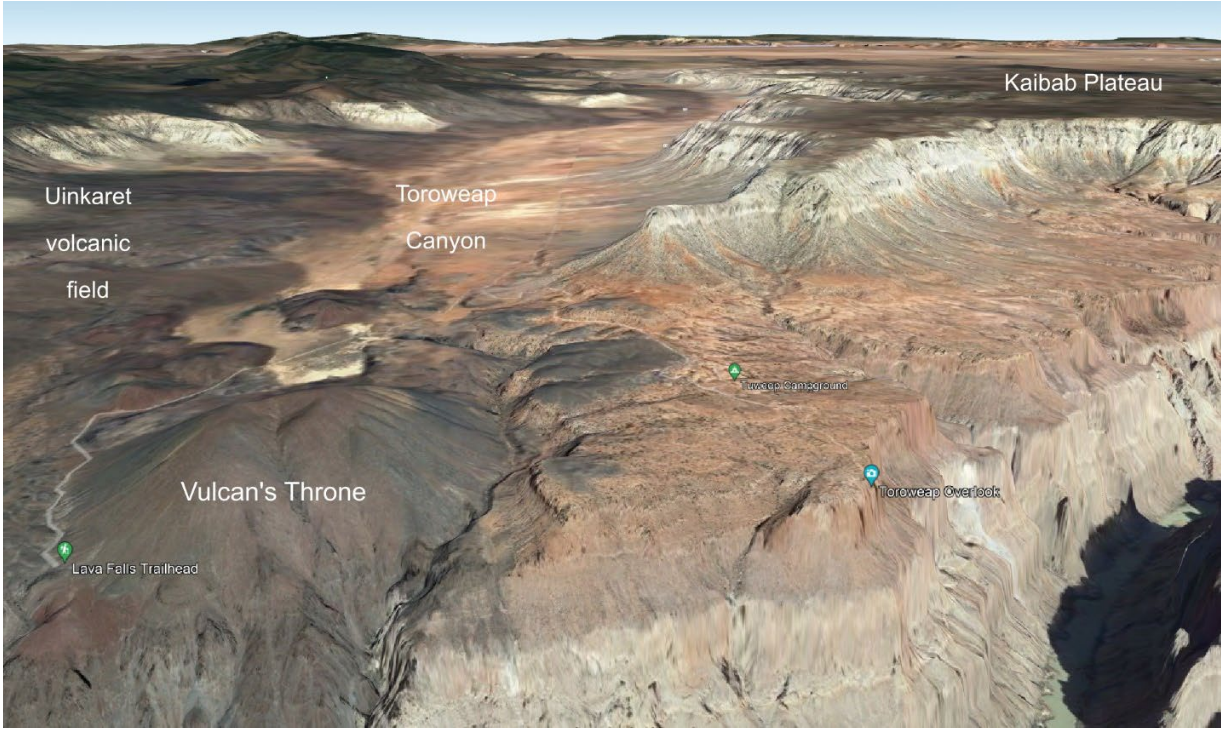
Basaltic lavas have low viscosity, and so flow downhill very easily. As many as 17 times in the past, from about 750,000 to 100,000 years ago, lavas formed dams that blocked the Colorado River. Dams were up to 400 m high (1310 feet), and lava flows below the dams went as far as 122 km (76 miles). That means the Uinkaret volcanic field would be much larger now, if the Grand Canyon hadn't drained away a substantial fraction of the lavas. Remnants of lava flows still plaster the canyon walls below the Uinkaret field, and remnants canyon-bottom lava flows remain on the river banks downstream.

Volcanic fields of Quaternary age extend in a broad zone in and closely surrounding the Basin and Range Province, and also in an odd linear zone extending into NE New Mexico. Much of this volcanism is basaltic, but rhyolitic rocks are also present. The volcanoes in northern Arizona are on the Colorado Plateau, but are very near the border with the Basin and Range.

Toroweap Overlook

At this location we can see the extent of lava filling preexisting canyons. Prospect Canyon, which is across the river from the Toroweap Valley, was once filled by basaltic flows, and is currently being re-excavated by Prospect Creek. These old tributary canyons ran into the Grand Canyon, which was also affected by the volcanism occurring on the adjacent plateau. There are a number of places where lava flows on the plateau flowed over the side and into the Grand Canyon, forming dams and lakes at times. In fact, some eruptions also took place within the Grand Canyon itself. A small volcanic neck, called Vulcan's Anvil, actually remains within the present channel of the river. Vulcan's Throne, a roughly 73,000-year-old cinder cone, perches on the edge of the canyon near the southern end of Toroweap Valley.

Vulcan's Anvil, an eroded basalt intrusion in the Colorado River.



Intersection of Toroweap Canyon and the Grand Canyon. Colorado River is to the bottom right. View is to the north. This is a remote, sometimes inaccessible location on the north side of the Grand Canyon. Google Earth image.

There are numerous different lava units which flowed into the canyon and temporarily dammed the Colorado River. After damming the river, continued flow of lava into the canyon resulted in flows extending down the river channel. The lava dams produced reservoirs that backed up the river for many miles. The highest of these dams was about 400 m high, and produced a temporary lake perhaps 250 km long.

Patches of lake sediments have been found upstream, indicating that some of these lava dams survived for extended periods. The filling rate for such a reservoir can be estimated from present flow of the Colorado, suggesting that years to decades may have been involved simply to fill the lake to overflowing. Once a lava dam overflowed it was probably quickly removed by the erosive power of the river. The lava was highly jointed, as can be seen in preserved patches of lava on the canyon walls, and this would lead to rapid breakup and washing away of the pieces by the river. The removal of the dam would have been aided by the release of water from the large lake behind the dam as erosion proceeded.

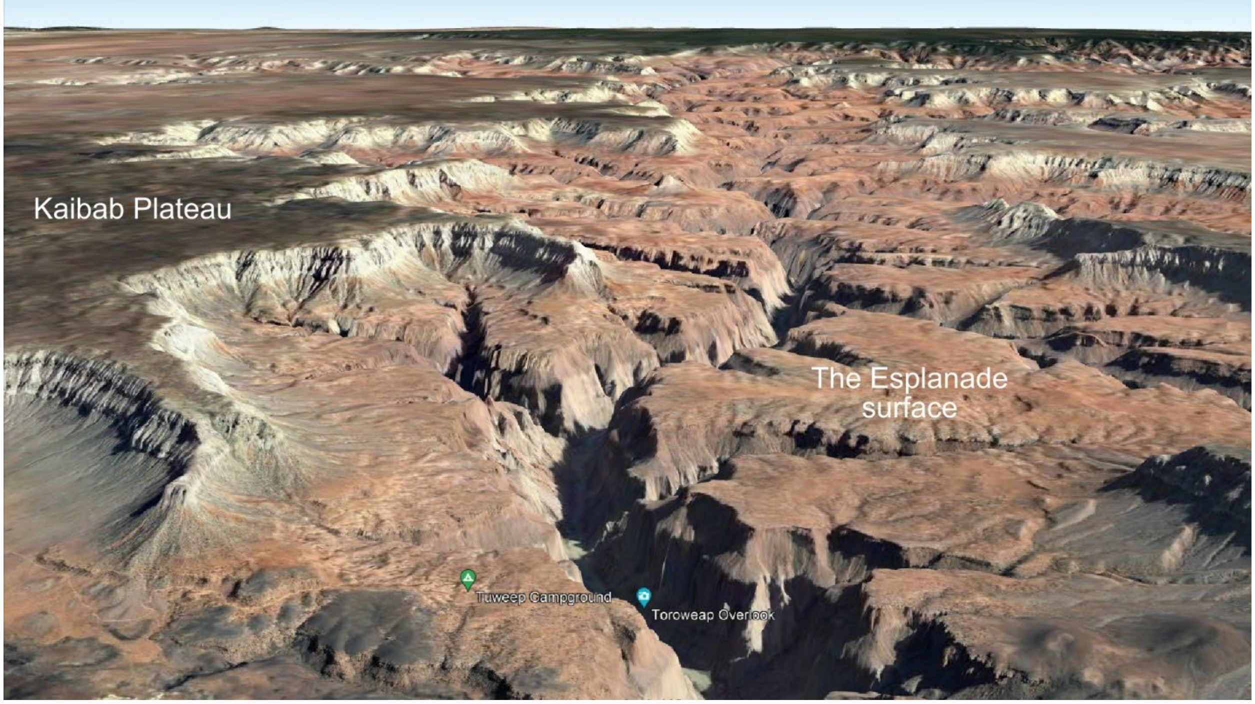
Eroded, canyon-filling Uinkaret lava flows, looking up from the Colorado River.

Toroweap and Prospect Canyons are aligned along a significant, although not particularly obvious, fault. The movement on this nearly vertical fault is about 100 m. Although this is not a large structure, its effect on the topography has probably been accentuated by the lack of vegetation cover on the plateau, as well as the presence of the nearly horizontal sedimentary rocks. In this situation the weakness introduced by the fault has influenced the location of stream drainages into the Colorado. It is also possible that the deeper crustal weakness along the fault helped to localize volcanic activity, by providing an easy path to the surface for the magmas.

In the western part of the Grand Canyon there are two prominent features in the topography of the valley sides that relate to the paleogeography. The most obvious is the broad platform called the Esplanade, below the Kaibab Plateau but above the central canyon. This wide bench is formed by the erosion-resistant Esplanade Sandstone. Above the bench, the non-resistant Hermit Shale, and finer grained parts of the Supai Formation, have eroded off. The Kaibab Plateau, on top of the Kaibab Limestone, surrounds most of the canyon in this area. The erosion-resistant Kaibab Limestone at the plateau edge forms a set of retreating cliffs.

In the eastern Grand Canyon, the Esplanade bench is much narrower. This is because the Supai Formation in that area consists of more massive, and more abundant sandstones, rather than finer grained sediments, and is thus more resistant to weathering and erosion. The presence of a greater fraction of sand indicates that the area of the eastern Grand Canyon was closer to the original sediment source. In this case, the Supai sediments were being shed from the Pennsylvanian and early Permian highlands of western Colorado (e.g. the Ancestral Rockies, Uncompahgre highland). The sediments which were transported the extra 100+ km further west were generally finer grained, and became shale units rather than resistant sandstones.

The second feature of the western Grand Canyon is the impressive height of cliffs developed in the Paleozoic limestones (Muav Formation, Cambrian; Temple Butte Formation, Devonian; Redwall Limestone, Mississippian). These form a massive cliff nearly 1000 m high in the western



View to the east from above the Toroweap Overlook. The broad, red surface is the Esplanade, underlain by Esplanade Sandstone. Google Earth image.

Grand Canyon. In the eastern Grand Canyon only the Redwall is a prominent cliff-former. This difference is related to the position of the edge of the continent throughout lower to mid-Paleozoic time. The continental shelf edge was to the west, and the continental interior to the east. In the eastern Grand Canyon the deposits were nearer to the shoreline, and in the case of the Muav Formation, incorporated shale layers that weaken its resistance to weathering and erosion, making the Muav a less prominent cliff former.

In the western Grand Canyon, further offshore, the shale layers are much diminished, producing a more massive, resistant unit. The Temple Butte Formation is partially absent in the eastern Grand Canyon since this area was above sea level during the late Devonian. In the western Grand Canyon, which was considerably far offshore at the time, the Temple Butte is as much as 200 m thick. Finally, the Redwall Limestone is also thinner in the nearshore, eastern Grand Canyon than it is in the deeper-water western Grand Canyon. The combination of these factors leads to the thicker, more massive cliff-forming limestones near Toroweap.

Vertical cliffs of Redwall Limestone, rising above the Colorado River.

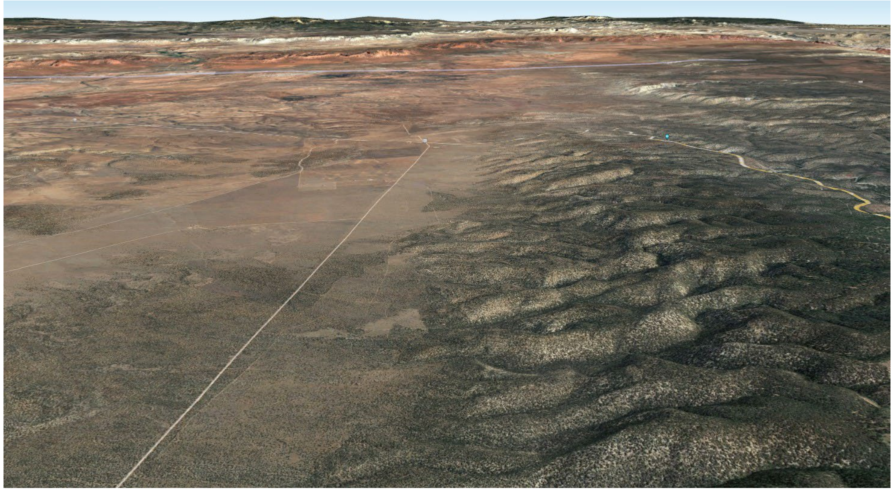
Vulcan's Throne

If we have sufficient time, we will take a hike up Vulcan's Throne, the 73,000 year old cinder cone next to the Tuweep Campground. This will be a somewhat strenuous hike, this time going up, then down. The loose cinders provide difficult footing, lying at an angle of about 30°, close to its angle of repose. The climb is about 590 vertical feet (180 m). The slope is mostly barren, with a few miserable sagebrush, and some cacti. At the top you will be rewarded with a view nearly unchanged from that enjoyed by the "earliest" explorers of the region: Powell's survey parties of the early l870s. The monograph prepared by C.E. Dutton: "Tertiary History of The Colorado Plateau" has a number of views from the Toroweap area, including from the top of Vulcan's Throne.

Powell Survey Monument

The western survey of Major John Wesley Powell began in earnest with his trip by boat through the Grand Canyon in 1869. He led eight men on the expedition, the end of which was in doubt until the last minute, when they emerged from the canyon near the mouth of the Virgin River. Three of the men had decided to leave the expedition a scant four days earlier, and climbed out onto the plateau by way of a side canyon. Unfortunately, they were killed by the Shivwits Indians. Powell used the substantial publicity and fame associated with this expedition to raise funds to continue the exploration of this most desolate part of the continental US. In 1871–1872 another trip through the Grand Canyon was undertaken, and a survey of the land surface from the plateau on the north side of the canyon completed the topographic measurement of the US. The land survey was based near the present site of Kanab, Utah. Powell's men laid out a carefully measured base line to carry out a classical triangulation survey. The north end of the base line was located in Kanab (actually south of the town as it existed at the time), and the southern end was over 10 km away. The base station markers were subsequently destroyed, though a monument for the north end was reconstructed a number of years ago. With the further development of Kanab, even this monument was later moved to its present obscure location at an undistinguished street corner near a schoolyard.

West Kaibab Monocline



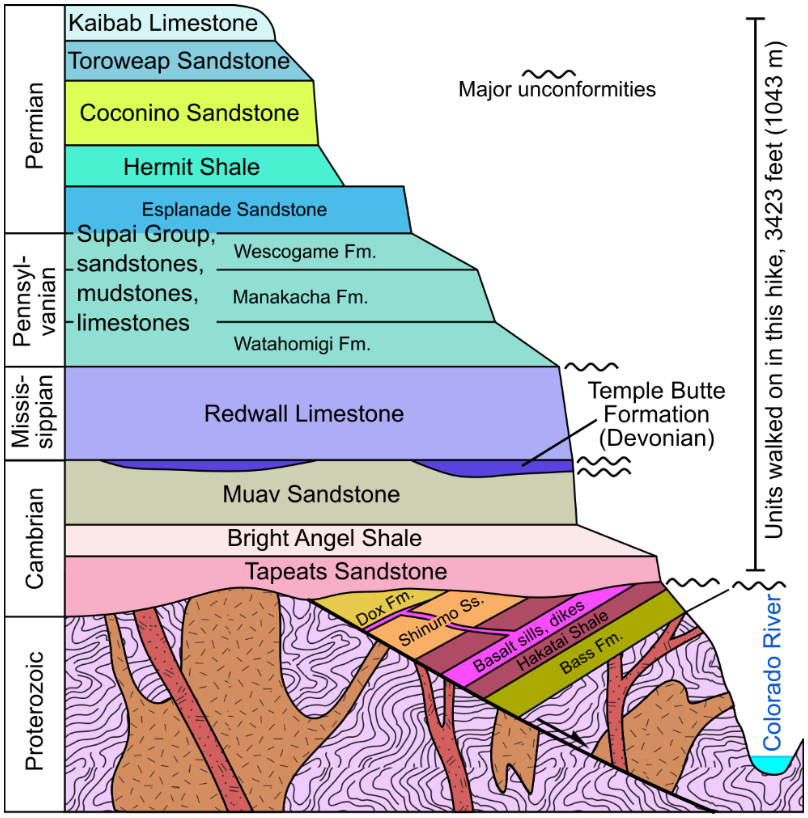
West Kaibab Monocline, with the greenish Kaibab Plateau to the right, and lowlands to the left. View is to the north. Google Earth image.

Most of the surface of the Colorado Plateau, in the vicinity of the Grand Canyon, is defined by the upper surface of the Kaibab Limestone, a late Permian resistant limestone. The immediately overlying Mesozoic layers are highly erodible, and have been stripped off. The Kaibab Limestone surface has been offset by a number of monoclinal folds, producing smaller plateau areas separated by "steps." One of the larger of these is the Kaibab Plateau. The western edge of this plateau is defined by the West Kaibab Monocline. Crossing the broad, treeless plateau southeast of Kanab on Arizona Rt. 89A, the forested slopes of the Kaibab Plateau loom in the distance. The highway climbs the rounded surface of the West Kaibab Monocline, and ascends into the ponderosa pine-covered Kaibab Plateau 300-500 m higher. The elevation increase produces a profound change in the vegetation. This in itself is not a surprising phenomenon, but the effect is strikingly accentuated by the appearances of the two distinct, broad (in area) ecological zones immediately adjacent to one another.

Grand Canyon National Park: Hike to Roaring Springs

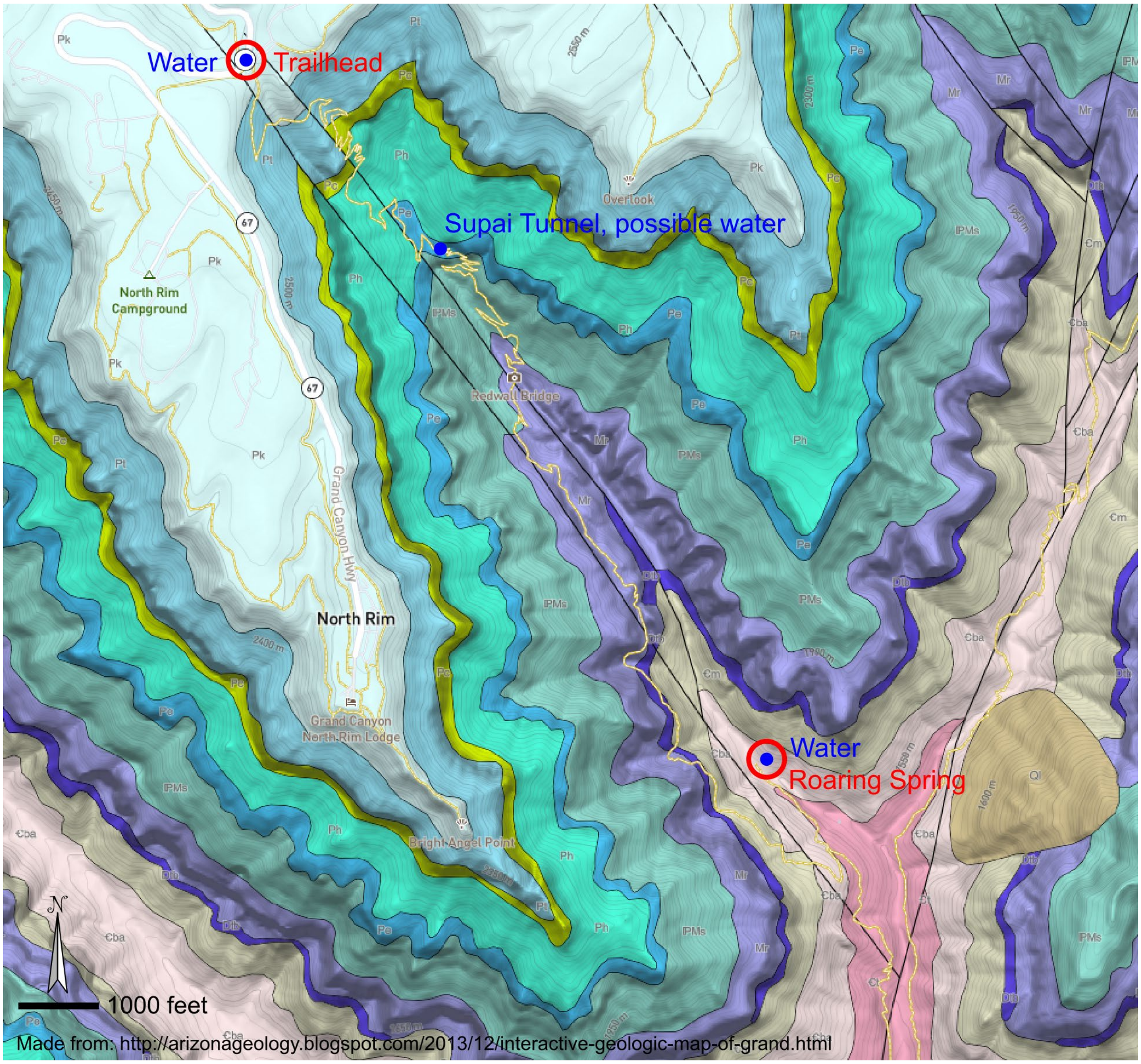
The hike to Roaring Springs will take all day. This hike is only about 9.6 miles (15.5 km) round trip, but it descends 3423 feet (1043 m), and of course ascends afterward. Using the usual rule of ½ hour per mile plus ½ hour per 1000 feet of climbing, that makes this a nominally 6.5 hour hike. Factoring in the fact that the trail goes up and down a bit, plus rests, lunch, playing in the stream, and the heat, you can see why this hike will take all day. Though this is the most difficult hike of the trip, it is only so because of the time it will take. While cooling off at the spring, you might think it a fun idea to walk a bit further to get to the Colorado River, but it's another 2398 feet of descent (731 m), and 9.5 miles (15.3 km) one way. That will at least triple the hiking time. Don't even think about it as something to do today.

Thunder Spring, emerging from a cave in the Redwall Limestone. Roaring Springs will look something like this.



Schematic stratigraphic column of rocks we pass through on the Roaring Springs hike (modified after Connors et al., 2020; color scheme and local stratigraphy follows https://rclark.github.io/grand-canyon-geology/).

On the other hand, we will be descending into the spectacular Grand Canyon, and you will have the experience and training from previous hikes on this trip. You will descend through most of the Paleozoic sedimentary section, from the Permian Kaibab Limestone at the top to the Cambrian Tapeats Sandstone at the lowest elevation we reach, near Roaring Spring. Shales, thin-bedded sandstones, and some other rocks (e.g., Toroweap Sandstone, Bright Angel Shale) weather easily, and form inclined slopes or wash away to expose benches. Weathering resistant rocks, like thick-bedded sandstones and limestones (e.g., Coconino Sandstone, Redwall Limestone), in contrast are cliff-formers and also form the benches themselves. Tectonic stresses at different geologic times have produced a number of vertical fracture sets (joints). As the weak layers underneath weather and wash away, vertical blocks fall off the cliff-forming layers, thus maintaining the cliffs.



Made from: http://arizonageology.blogspot.com/2013/12/interactive-geologic-map-of-grand.html

Geologic map showing the trail to Roaring Spring (https://rclark.github.io/grand-canyon-geology/). Water at the Supai Tunnel depends on pipe maintenance, and should not be relied upon.

The trail itself winds its way through innumerable switchbacks, through a tunnel, over a bridge, and along blasted half-tunnel-like excavations into vertical rock faces. There can be steep drops next to the trail, but as long as you pay attention and don't fool around, things should be fine. Water is available for certain only at the trailhead and at Roaring Spring. Because of maintenance problems in the 70-year-old pipe system, water at Supai Tunnel should not be relied upon.

This map is the same scale and area as the geologic map, above. Water at the Supai Tunnel depends on pipe maintenance, and should not be relied upon. Base image is from Google Earth.

Rock Units We Will Walk On

11) **Kaibab Formation** - Permian - A mostly dolomitic carbonate unit with some sandstone and evaporitic horizons, and gypsum in western areas. These rocks indicate a shallow marine, possibly lagoonal environment. In detail there is evidence for at least three transgression–regression cycles. This unit forms the cliff at the top of the canyon, and is the rock at the plateau surface in most places.

10) **Toroweap Formation** - Permian - Mostly limestone in western sections, between thin lower gypsum-bearing beds, and upper gypsum beds which are thicker than those in the lower member and thicken to east. Grades into massive, then crossbedded sandstones to the east and south, where it is difficult to separate this unit from the underlying Coconino Sandstone. In other words, deposition of dune sands continued into Toroweap time to the south and east. One major transgression–regression cycle.

9) **Coconino Sandstone -** Permian - Aeolian sand, pure quartz sandstone. Large scale cross-bedding. Occasional animal trackways on bedding surfaces. Very prominent, light-colored cliff-former. Thickness decreases dramatically going toward the NE, from about 200 m thick on the South Rim, to perhaps 20 m at Navajo Bridge in Marble Canyon.

8) **Hermit Formation -** Permian - Mostly red shale with some sandy and silty layers. Marginal marine to terrestrial. The red color of lower units is largely caused by leaching of iron from the Hermit and redeposition of oxidized iron compounds on exposed surfaces of underlying units, especially the Supai Group and, most characteristically, the Redwall Limestone.

7) **Supai Group** - Pennsylvanian to Permian **-** A collection of four formations, all sandstones with finer grained parts: A) Esplanade Sandstone, especially prominent in western Grand Canyon. You saw this at Toroweap. B) Wescogame Sandstone. C) Manakacha Sandstone. D) Watahomigi Sandstone These units are distinguished mainly by alternation of massive, thick sandstone beds with intervening slope-forming silty and shaly beds. These are largely terrestrial deposits, from rivers and aeolian dunes. Many of the sandstones were once thought to be river and floodplain deposits, but are now thought to be aeolian. Based on what you have seen elsewhere, what do you think?

6) **Surprise Canyon Formation -** Pennsylvanian - Very heterogeneous lithology including limestone breccias and conglomerates, sandstones, siltstones, mudstones and limestones, found in discontinuous patches as channel fills and collapse (sinkhole) infilling. Not shown in the geologic map or section illustrations, above.

5) **Redwall Limestone** - Mississippian - The most prominent cliff-former in the Grand Canyon, and in Marble Canyon. There are several members to the Redwall. The most prominent are a lower member, having numerous chert bands and nodule layers, and the massive middle to upper layer which forms most of the Redwall Cliff. The Redwall and the Coconino Sandstone are the most difficult barriers to traverse in any attempt to get into or out of the canyon.

4) **Temple Butte Formation -** Devonian **-** In the eastern Grand Canyon and Marble Canyon, this unit is discontinuous and occurs as fills in channels cut into the underlying Muav Limestone

or other Cambrian limestones. Away from the channels, the Redwall is deposited directly on Cambrian limestones. In the central and western part of the Grand Canyon the Temple Butte forms a continuous layer, with channels at the base in many locations.

3) **Muav Limestone** (with undifferentiated Cambrian limestones above) - Cambrian - A shelf carbonate, probably in part lagoonal. Part of the prominent, global transgressive sequence that includes the two underlying formations. As such, the Muav represents the offshore unit, beyond the reach of clastic debris derived from land.

2) **Bright Angel Shale** - Cambrian - a green/brown/gray shale, red in places. The middle member of the global transgressive sequence. It is one of the least resistant rocks in the Grand Canyon, and a prominent erosional bench has developed at its level, on top of the much more resistant underlying Tapeats Sandstone. This bench is called the Tonto Platform, and the group of three Cambrian layers is called the Tonto Group.

1) **Tapeats Sandstone** - Cambrian - The basal unit of the Cambrian global transgressive sequence. This beach sand was deposited as the sea gradually encroached on the deeply eroded continental interior from the west. The Tapeats is in unconformable contact with Precambrian units at all places in the Grand Canyon where its base is exposed. This unconformity is called the Great Unconformity and represents a variable amount of missing geologic time, depending upon the underlying formation. Where it rests on the early Proterozoic Vishnu Schist or Zoroaster Granite, and other early Proterozoic rocks, the missing time is about 800 to 1300 million years. Where the underlying units are late Proterozoic sedimentary rocks of the Grand Canyon Supergroup, the missing interval may be 100-400 million years.

We will not proceed downhill from Roaring Spring, on the North Kaibab Trail. However, if we did go all the way to the river, we would also see sedimentary rocks of the Unkar Group (Proterozoic sedimentary rocks, lower part of the Grand Canyon Supergroup), and early Proterozoic igneous and metamorphic rocks of the central canyon. The latter are highly variable in their lithology and age, and enormously complex in their structures. These are now subdivided into several main units:

Zoroaster Granite, a general name given to all granitic rocks in the Grand Canyon. In fact, this term includes a variety of plutonic bodies that range in composition from diorite to granite, and in age from about 1.74 to 1.4 billion years old.

Vishnu Schist is principally quartz-mica schist, with smaller amounts of feldspathic quartzite and amphibolite. Approximately 1.75 billion years old.

Brahma Schist is mostly amphibolite, with lesser hornblende- or biotite-rich volcaniclastics, and feldspathic quartzite. Approximately 1.75 billion years old.

Rama Schist is mostly quartzofeldspathic schist and gneiss, and metamorphosed rhyolitic volcanics, and amphibolite. Approximately 1.75 billion years old.

Elves Chasm Gneiss includes 1.84 billion year old dioritic and granitic gneisses and amphibolite. This unit is thought to be the oldest in the Grand Canyon, and possibly part of a continental fragment on which the younger metamorphic units were deposited.

If we were to continue our walk down to the river, we would walk over Zoroaster Granite and Rama Schist. These rocks are usually exposed only in the Inner Gorge of the Grand Canyon, also called the Granite Gorge, which is at least partly a misnomer. The minerals contained in the Rama indicate they were formed at pressures of around 5000 atmospheres and temperatures of about 600°C, at an approximate depth of 15 to 20 kilometers below the surface. They were almost certainly metamorphosed in the roots of a long-since eroded mountain range, and have been exposed at the surface by uplift and erosion, not only recently but in previously events preceding the deposition of the overlying sedimentary rocks, both Proterozoic and Paleozoic.

One might wonder why so many Grand Canyon features and rocks are named after deities or prophets of southern Asian religions. Here is one explanation that sounds plausible to me:

> "Many of the canyon's landmarks were named by geologist Clarence Dutton who published one of the earliest (and best) detailed geologic studies of the canyon in 1882. Dutton believed that the canyon was such an important and impressive feature on the planet, that the names of its features should reflect all the world's cultures and thus he chose many names from mythologies and legends from around the world. Other examples of canyon landmarks named in this way are Wotan's Throne, Cheops Pyramid, Budda Temple, Solomon Temple, Jupiter Temple and Tower of Ra (all of these are major buttes, spires or mesas in the canyon)."
> (Alan English: https://www.quora.com/Grand-Canyon-Why-are-the-schists-names-after-Vishnu-Bramha-and-Rama-in-Grand-Canyon-rock-layers).

On the other hand, there are alternative points of view:

> "…we call them Vishnu, Brahma, and Rama because the naming fool I won't name clearly thought it made more sense to honor the improbable deities of Indians from the Indian Subcontinent than the local deities of the Hualapai and Havasupai tribes who lived there. There is not one feature, spire, peak, fin, canyon, or cave in the Grand Canyon that did not have a name long before the first white person set eyes on it."
> (D. Woods: https://www.quora.com/Grand-Canyon-Why-are-the-schists-names-after-Vishnu-Bramha-and-Rama-in-Grand-Canyon-rock-layers)

In any case, it is the landscape features that were first given those names, and the geologic layers were simply named after the nearby landforms where the units were well-exposed. That is standard procedure during geologic mapping.

East Kaibab Monocline

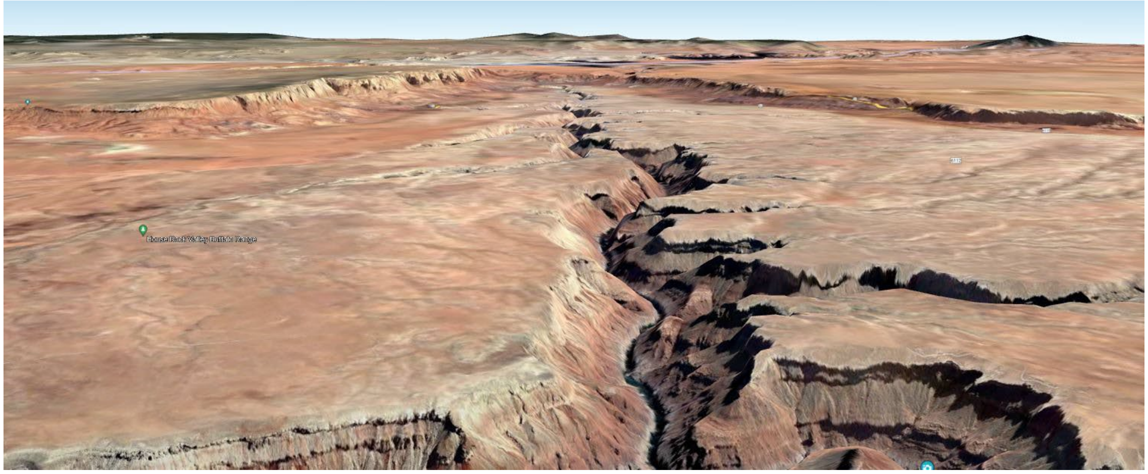
East Kaibab Monocline, Mather Point, as seen from the air. View is to the north. https://www.knau.org/land-lines/2012-05-17/land-lines-the-east-kaibab-monocline.

The East Kaibab Monocline is the eastern, down-warped transition from the Kaibab Plateau to the lowlands beyond. It is dramatically exposed and expressed by the stripped surface of the Kaibab Limestone, from which non-resistant Triassic sediments have been eroded. As with other monoclines, this one is caused by a deep fault cutting brittle Precambrian rocks, but folding the more ductile sedimentary rock layers that overlie them. The lowlands to either side of the Kaibab Plateau are covered by a sparse growth of grass and sagebrush, characteristic of other dry parts of the Colorado Plateau. At the higher elevations of the Kaibab Plateau, vegetation changes to a type favoring a cooler, somewhat wetter climate. Plateau vegetation includes juniper, pinyon pine, and even ponderosa pine. The understory is generally quite sparse, unlike most eastern forests. That is because periodic fires keep the underbrush subdued. The main shrubs at higher elevations are oak brush (Gambel's oak) and holly.

Marble Platform

The Marble Platform is the flat-lying, stripped surface of the Kaibab Limestone, on the downthrown side of the East Kaibab Monocline. The Colorado River has cut a deep gorge (Marble Canyon) into the platform. Note that the Kaibab Limestone is not actually marble, which is metamorphosed limestone. The distant trace of the eastern Grand Canyon is the only evidence for the Colorado River below the Platform. Marble Platform rises gradually from north to south, along a shallow dip slope of approximately one degree, the regional dip of Paleozoic strata for about fifty miles from Lee's Ferry to Saddle Mountain. Softer rocks have been removed by erosion from the structurally tilted, resistant surface at the top of the Kaibab Limestone.

A good part of Marble Platform is BLM (Bureau of Land Management) land, and a large amount of land has been reserved for a bison herd. We will be lucky to see any of them, as this is a large area and the herd is usually away from the roads. Some important tributaries of the Colorado River cut across the Platform and drop precipitously over the resistant Kaibab Limestone, Toroweap Limestone, and Coconino Sandstone into deep canyons. The broader, upper reaches of these canyons (North Canyon, South Canyon, Buck Farm Canyon and Saddle Canyon) are formed in eroded areas of Hermit Shale, and especially Supai Formation. At the bottom of the Supai, streams drop over the Redwall Limestone cliffs into narrow canyons, which merge with the Colorado River (except at North Canyon where the top of the Redwall Limestone is below river level).



Marble Platform, the light-pink surface above the canyon, but below cliffs in the distance. View is to the NE, toward Lake Powell. View is looking northeast. Google Earth image.

Vermillion Cliffs

The Vermillion Cliffs are composed of brilliant red to white rocks of Triassic and Jurassic age. These include Triassic sandstones, siltstones, and shales of the Moenkopi and Chinle Formations, and Jurassic sandstones, siltstones, and shales of the Glen Canyon Group, which includes the Navajo Sandstone (aeolian) at the top. It is the Navajo Sandstone that holds up the cliffs, with more easily eroded Mesozoic rocks below it. The area above the cliffs, north of the Vermillion Cliffs, is the Vermillion Cliffs National Monument. The Monument has no visitor's center or established campgrounds, but it offers spectacular canyons, complexly layered and colored rocks, and other remarkable landscapes. Though a rugged and dry place to hike, it is like another world.

The Vermillion Cliffs, rising out of the Marble Platform. https://www.phototraces.com/b/vermillion-cliffs-national-monument/

Crossing the Colorado at Lee's Ferry

Lee's Ferry, with a rafting party getting ready to depart onto the Colorado River. Triassic Sedimentary rocks in the background.

Lee's Ferry is one of the oldest crossing points on the Colorado River. The Echo Cliffs Monocline crosses the river here, bringing non-resistant Mesozoic shales and sandstones in a broad sweep down to and across the river, producing relatively gentle slopes for river access. John Doyle Lee, a famous (or infamous) Mormon operated a ferry here for a number of years. It remains one of the few places where the Colorado can be easily reached and crossed, for hundreds of kilometers in either direction. Lee's Ferry is now the point of departure for river raft trips that go through the Grand Canyon.

The high cliffs upstream and on either side of the river are in Triassic and Jurassic sedimentary rocks. The lowermost unit is the Triassic Moenkopi Formation, consisting of weak shales. Above the Moenkopi is the Triassic Shinarump Conglomerate, which forms a low cliff along the east side of the river. Above the Shinarump are the Triassic Chinle shales, and finally Jurassic terrestrial shales and sandstones of the Glen Canyon Group, topped by the Navajo Sandstone, which we have seen before. The weak shales of the Moenkopi and Chinle Formations have been eroded out to produce the gentle slopes, and the more resistant rocks of the Glen Canyon Group stand out as the Vermilion Cliffs, forming yet another retreating escarpment.

Why was John Doyle Lee infamous? Well, here you go:

> "In 1857, public complaints about [LDS] church power and polygamy spurred the United States government to send an army to Utah. Panic ensued in the Mormon community.
>
> "In a series of unfortunate events associated with the panic, a group of Mormon militia members and Paiute forces murdered over 100 men, women, and children of the Fancher Wagon Train. The immigrants, suspected of hostility toward the LDS church, were seized as they passed through southern Utah on their way to California in September 1857. John D. Lee was one of the leaders present at the scene of the still-controversial tragedy, known as the Mountain Meadows Massacre.

“Lee remained active within the church leadership after the massacre. However, by the 1860s questions surrounding the massacre were unavoidable as federal authorities pressed the LDS Church to identify a responsible party.

“In October 1870, John D. Lee was excommunicated from the LDS Church for his role in the massacre. … Lee was exiled to the canyonlands of northern Arizona, where he settled with two of his wives [he previously had 19, and 56 children], Rachael and Emma, at the confluence of the Colorado and Paria Rivers.

“…After three years of hiding from authorities, Lee was eventually captured in 1874. He was tried and found guilty of murder. On March 23, 1877, he was taken to the Mountain Meadows Massacre site and was executed by firing squad.”
https://www.nps.gov/articles/featured_stories_lee.htm)

Glen Canyon Dam and Lake Powell

Glen Canyon Dam, with Lake Powell behind.
https://en.wikipedia.org/wiki/Glen_Canyon_Dam

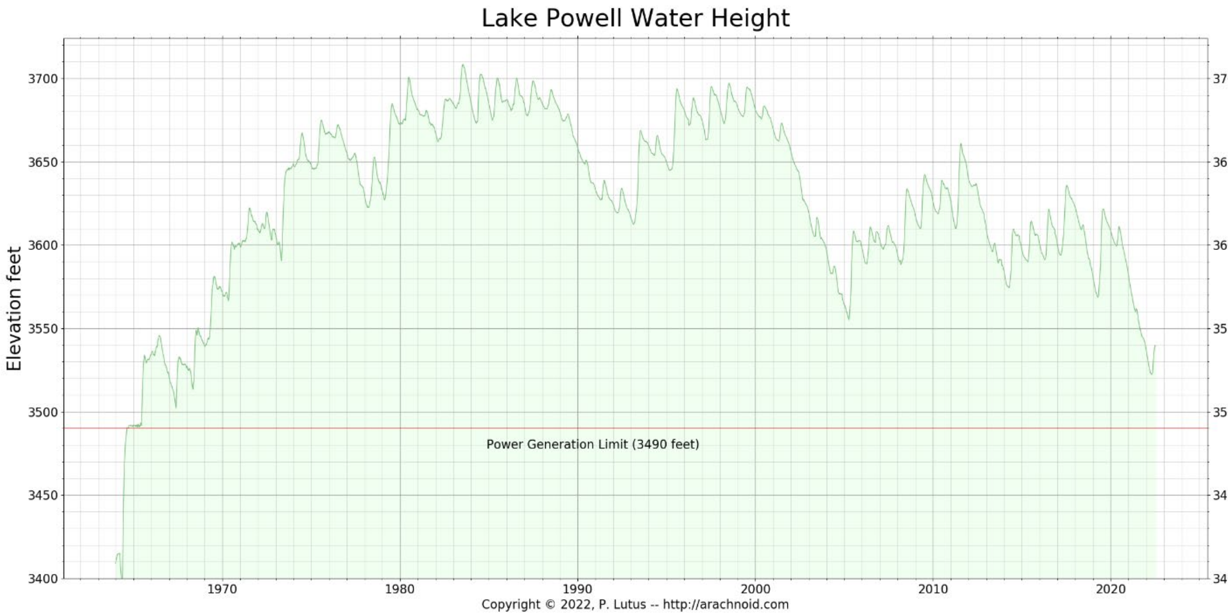
Glen Canyon Dam is a major water control structure on the Colorado River. It was built for water storage, sediment trapping, electric power generation, and recreation. The operation of the dam has changed the environment of the Colorado River, both upstream and downstream. The upstream changes are obvious! The downstream changes are the result of regulation of flows, leading to an absence of major flood events which maintain the equilibrium of channel deposits by clearing debris brought in by side canyon flooding, and by depositing sand in bars. Water is released from near the base of the dam, where the water is about 4°C. Consequently, the Colorado River downstream from the dam is much colder than in the past, when water flowing great distances from upstream allowed water to heat up to near ambient temperatures. The water downstream is also quite clear most of the time, except after rainfall and flooding events in side canyons. The cold, clear water is favorable for trout, but the original fish populations, which were adapted to warm muddy water, have disappeared.

Dam construction began in 1956, and was completed in 1966. The reservoir reached its filling capacity in 1980. The dam itself is 710 feet high, 1560 feet long, and has an installed electrical generating capacity of 1320 MW. The lake behind the dam has a pool-full surface area of 65.3 km^2, and a volume of 31.0 km^3. Unfortunately, allocation of reservoir water for electric power, drinking water, and irrigation was based on stream gauge measurements made during a particularly wet period of time, about 1890 to 1920, biasing dam designers to promise too much water for the several purposes by 28-34%. An additional slight problem, early on, was seepage of about 16.3 km^3 into the surrounding porous rocks, more than twice the initial estimate. Lake Powell, behind the dam, also loses nearly half a cubic kilometer of water annually to evaporation, a bit more than 3% of the total water flowing into the lake.

Lake Powell’s pool-full level is 3700 feet (1128 m), which it achieved in 1980. The minimum lake level to generate electric power is 3490 feet (1064 m). As of mid-July, 2022, the lake level was at 3540 feet (1079 m), up from an historic low of 3523 feet (1074 m) in June, 2022. Why is the lake level falling? Well, we are currently in an historic drought that has lasted for about the last two decades. This drought episode is similar to many the area has had over the past thousands of years, as indicated by various types of climate records including lake levels and tree rings. Climate models suggest that, as a result of global warming induced by human release of greenhouse gasses, the drought is expected to continue and may well get worse. Although it is difficult to predict the future, even with sophisticated computer models and statistical study of past droughts, it seems probable that the Glen Canyon Dam will have to cease electricity generation, at least occasionally, within the next decade. In addition, from pool-full levels, the 31 km^3 volume last reached in 1986, Lake Powell is now down to a volume of only 8.5 km^3, 27% of its capacity (7.3 km^3, 23%, in June, 2022).

There were plans in the early to middle 20th century to build additional dams on the Colorado River: in Marble Canyon, west of Grand Canyon National Park, and NE of Lake Powell near Dinosaur National Monument, among others, but these were abandoned (at least temporarily) in the face of vigorous (and justified, I believe) protests by environmental organizations. The damage done by Glen Canyon Dam was extensive. Though there is obviously room for disagreement about the balance between benefits obtained and loss of scenic value, the natural characteristics of this major river were a powerful motivation for preventing further dams on the river.

It is interesting to speculate what might have happened to the Colorado River water supply had all three additional dams been completed, with the Glen Canyon and Hoover Dams. ~3% loss of Colorado River water to evaporation in Lake Powell might have been increased substantially (3% x 5 = 15%?), leaving even less water for power, irrigation, and other purposes.



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Lake Powell water levels, from 1963 start of filling to today. Note that the red line is the lowest level where electric power generation is possible. https://arachnoid.com/NaturalResources/powell.html

A need for electrical power, which the developers had hoped to obtain from the additional dams, led to the construction of large coal-fired generating plants to be fed by coal from the San Juan Basin to the east. One of these plants was constructed near Page, Arizona, and can be seen from the highway. The coal is transported by electric railroad built solely for that purpose.

Hydroelectric dams are a renewable form of electric power generation, and are excellent tools for load leveling, which is needed for adapting the electric grid to variable demand, and intermittent power production by other renewable energy sources like solar and wind. However, reductions in the ability of dams like Glen Canyon to generate electric power will be an increasing problem as time passes, here and elsewhere, as a result of global warming. Already, Glen Canyon generates less power than it used to. Many hydroelectric power plants in the American west will probably become unreliable power sources in the relatively near future, requiring the development of alternatives. Preferably not burning coal.

2022 water levels near the Glen Canyon Dam. The white 'bathtub ring' shows previous higher water levels, here shown down about 175 feet (53 m). https://theconversation.com/what-is-dead-pool-a-water-expert-explains-182495

Kodachrome Basin State Park

Figure 1: A sedimentary pipe (white spire) at Kodachrome Basin State Park.

The Kodachrome Basin was named in 1949 after the Kodak color film that was popular at the time. The vibrant rusty reds and whites of the Mesozoic rock formations exposed within the park contrast with the green of the vegetation beneath and the blue of the sky above, inspiring the National Geographic Society's name choice. The Kodachrome Basin is notable for the presence of nearly 70 curious stone spires called "sedimentary pipes" within the Jurassic Entrada Formation. The sedimentary pipes range from 6 to 170 feet in height (Figure 1). Their origin continues to be the subject of debate, with explanations ranging from:

1. Ancient liquefaction (Figure 3)
    a. Evidence in the rock layers indicates that the area was seismically active at the time of sedimentary pipe formation. Vibration from earthquakes can cause sediment (particularly coarse-grained, water-saturated sand) to behave like a liquid and rise to the surface in a process called liquefaction. These areas of coarser sediment could have then been cemented into sandstone that was more resistant to weathering than the surrounding rock, and eventually the rest of the layer was eroded completely away to leave behind standalone sedimentary pipes.
2. Ancient springs
    a. The pipes could be remnants of ancient springs, choked with sandy sediments that ultimately lithified into sandstone that was more resistant to weathering than the rest of the rock layer. As in explanation 1, the resistant rock was left behind after the softer surrounding rock eroded away.
3. Water-saturated pockets under pressure of overburden
    a. This idea is similar in concept to the formation of salt walls. Water-saturated pockets of sandy

Figure 2: 1940s Kodachrome film.

sediment beneath the weight of increasing sediment cover could have squeezed their way upwards due to a density contrast, scouring pathways towards the Earth's surface. In the same fashion as explanations 1 and 2, the pipes then lithified into rock more resistant than the surrounding rock, and were eventually left behind by erosive processes.

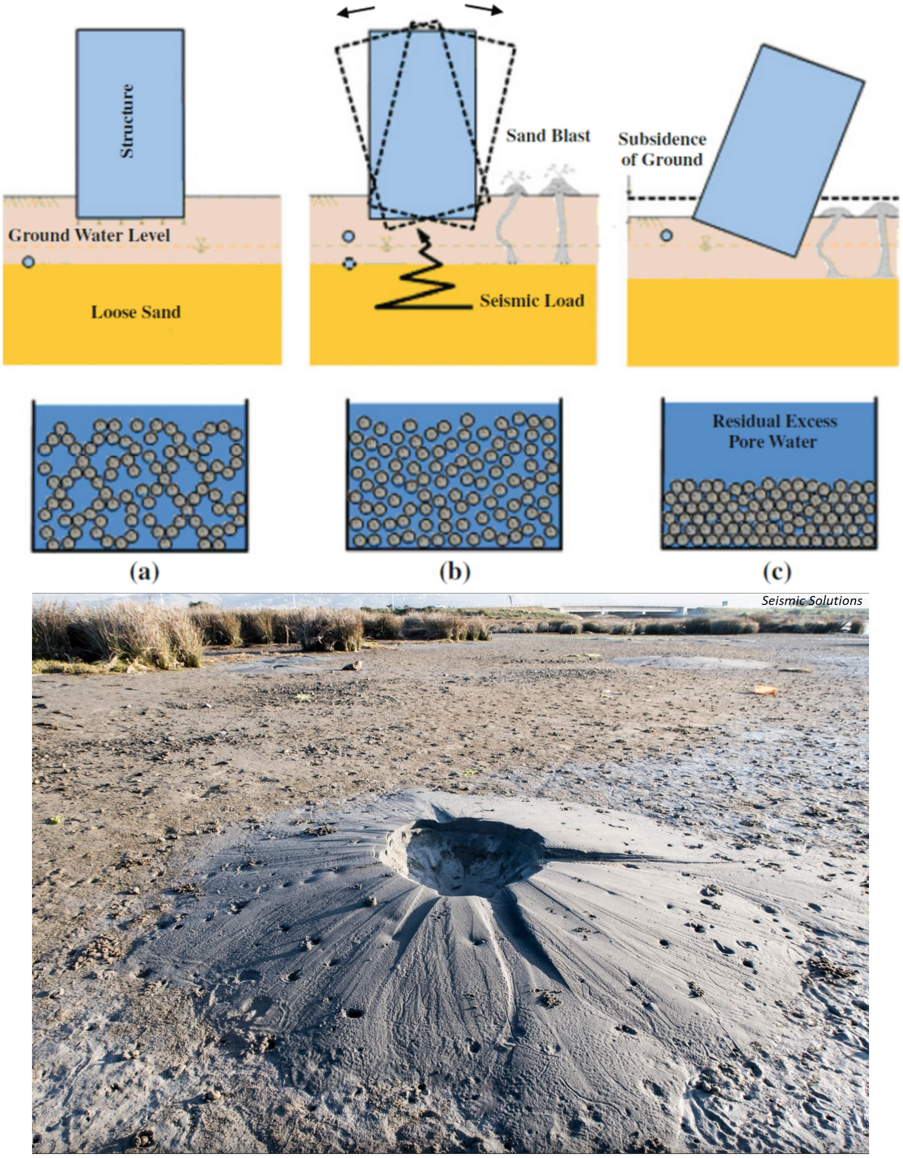

Figure 3:
Top: *Diagram describing liquefaction. a) Pre-earthquake, the loose sand is saturated with groundwater; b) during the earthquake, the sand becomes suspended in groundwater (grains lose contact with each other) and behaves like a liquid (liquefaction), causing a structure on top to lose support from the ground; c) after the earthquake the sand is compacted, resulting in both subsidence of the ground and a decrease in water table (groundwater) depth relative to the surface (from Cai et al., 2021). Note the "pipes" of sand that made its way to the surface as "sand blasts."*

Bottom: *"Sand volcano" or "sand blast" created by liquefaction of sand beneath the surface. Active sand blasts are shown in the top diagram during the earthquake.*

Glossary

acidic:	pH below 7.
adsorption:	The process of (usually dissolved) materials sticking to the outside of things, like Ca^{2+} ions onto clay surfaces.
aeolian (eolian):	Wind-transported, as in sand dunes.
alkaline:	pH above 7, containing soluble alkaline salts such as sodium carbonate.
alluvial:	Pertaining to rivers, such as sediment deposited by rivers.
alluvial fan:	Fan-shaped deposit of sand and gravel, deposited onto desert flats by streams and mudflows at the exit of mountain valleys during flash floods.
amphibolite:	A metamorphic rock composed mostly of hornblende and plagioclase, typically metamorphosed basalt.
andesite:	Volcanic rock, fine-grained, typically gray, with intermediate silica content, typically 54-66% SiO_2, chemically the same as diorite.
anoxic:	Little or no free oxygen (O_2), usually referring to lake or ocean water, or groundwater.
antecedent river:	A river that maintains its course despite uplift of rock structures below it.
anticline:	Folded rock structure, usually forming an arch-like shape. Oldest rocks are in the fold center.
apatite:	Mineral: $Ca_5(PO4)_3(OH)$.
arkose:	A sandstone with a high feldspar content, generally stained rusty-red; presence of feldspar indicates close proximity to sediment source.
arthropod:	Animal with a jointed exoskeleton.
asthenosphere:	A part of the upper mantle that is close to its melting point, and therefore more ductile than mantle above or below. This is typically at depths of 200-300 km beneath continents, and 60-300 km beneath oceans.
badlands:	An erosional landscape in soft shale or mudstone, characterized by steep slopes and gullies.
basalt:	Volcanic rock, fine-grained, typically black, with low silica content, typically 45-54%, chemically the same as gabbro.
batholith:	A large igneous intrusion with an exposed surface area >100 km^2.
bedding:	The layering of sedimentary rocks.
bicarbonate:	HCO_3^- ion, dissolved in water or in a mineral structure.
biogenic:	Produced by living organisms.
biotite:	Mineral, soft, layered silicate, usually black: $K(Mg,Fe)_3Si_3AlO_{10}(OH)_2$.
buoyant:	Something that is less dense than its surroundings, and so tending to rise through its surroundings, like bubbles in water, magma through the crust, or a buoy in the lake.
brackish:	Salty water, with a salt content less than ocean water.
breccia:	A rock made of angular fragments of any kind of rock.

brine:	Salty water, with a salt content more than ocean water.
butte:	A relatively narrow, flat-topped hill or mountain with steep sides.
calcareous:	Containing calcium, but usually referring to the presence of calcite or other carbonate mineral.
calcite:	Mineral, a relatively soft, usually white or gray: $CaCO_3$.
carnallite	Mineral. Potassium salt found in the Paradox Formation; $KMgCl_3 \cdot 6H_2O$.
carbonaceous:	Containing organic carbon, like oil shale.
carbonate:	Any mineral containing the carbonate ionic group, or also this ionic group dissolved in water: CO_3^{2-}.
charophyte:	A broad group of fresh water, single- to multi-celled algae, including stonewort.
chert:	Sedimentary rock, made of microcrystalline quartz. Usually found in thin layers or nodule layers between layers of a different sedimentary rock type.
chrysocolla:	Mineral with a variable formula, possibly non-crystalline at least in part: approximately $(Cu,Al)_2H_2Si_2O_5(OH)_4 \bullet 0.25H_2O$.
cinders:	Bubbly, loose volcanic fragments thrown into the air from a volcanic vent, solidifying before they hit the ground.
cirque:	A half-bowl-shaped head of a glacial valley.
clastic rock:	A sedimentary rock made of solid pieces (clay, silt, sand, pebbles) that were formed by the breakdown of other rocks.
clay:	Mineral group that includes a wide variety of sheet silicates, generally <10 µm across. Most are formed by chemical weathering of feldspars and other minerals.
coal:	A carbon-rich rock made mostly of the remains of land plants, modified from its original form by heat and pressure.
conglomerate:	Sedimentary rock made of rock grains larger than 2 mm, such as pebbles or cobbles.
contact aureole:	Metamorphosed zone in rocks surrounding a hot magmatic intrusion.
continental deposits:	Sediments deposited on land surfaces. These are typically river deposits, which are often red from the oxidation of iron to make fine-grained hematite.
convection:	Movement of fluids or fluid-like materials, commonly driven by density differences.
creep:	The slow typically steady movement of soil or rock masses downhill or along a fault.
crossbeds:	Minor sedimentary layers at an angle to, and making up, major sedimentary layers, such as the downwind, slip face layers of sand dunes, which are typically at about 30° to the sand dune deposit as a whole.
crust:	The outer rock layer of the Earth, made of rocks lower in density than the underlying mantle. Continental crust averages granitic or andesitic in composition, and is typically 20-50 km thick. Oceanic crust is basaltic in composition, and is typically 3-10 km thick. May also refer to thin mineral coatings on rock surfaces.
crystalline rock:	A general term for igneous and metamorphic rocks as a whole, as distinct from sedimentary rocks (though a misnomer, because even sedimentary rocks are composed almost entirely of crystals).

cuesta:	Landscape ridges held up by weathering resistant rocks, with a relatively shallow dip slope on one side, typically <45°, and a steep slope on the other.
cyanobacteria:	Common photosynthetic bacteria, also called blue-green algae. These can be found in waters where eukaryotic algae can't survive.
delta:	River deposits in the area where a river reaches an ocean or lake. Characterized by numerous distributary channels, channel and overbank deposits, and steep layers at the delta front where it meets deep water.
δ^{18}O:	Delta-18-oxygen: $((^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard})-1$. Heavy and light isotopes are somewhat separated by various processes, and so their ratios differ slightly. Measuring isotope ratios like these can be used to estimate different conditions or processes in the past.
desert varnish:	The reddish to black coating streaking rock faces in desert areas. Composed of oxide minerals and clays. Dark desert varnish has an unusually high content of manganese.
diagenesis:	Changes that occur to deposited sediment, excluding metamorphism. This can include precipitation of cements from groundwater, mineral changes like transformation of feldspar to clay, or recrystallization of carbonate minerals.
diatoms:	Single-celled, eukaryotic algae, having a two-part shell made of amorphous, hydrated silica (opal).
dike:	A thin but laterally extensive (sheet-shaped) plutonic rock body that cuts host rock layers. These form as magma fills opening fractures.
diorite:	Plutonic rocks, coarse-grained, typically gray, with intermediate silica content, typically 54-66% SiO_2, chemically the same as andesite.
dip:	The angle of a rock surface from the horizontal, ranging from 0° (horizontal) to 90° (vertical).
dolomite:	Mineral, relatively soft, typically white, gray, or pinkish: $CaMg(CO_3)_2$.
dolostone:	Sedimentary rock made mostly of dolomite.
emplace(d):	To be put somewhere, particularly magma intruding other rocks to form a dike, laccolith, or other plutonic rock body.
epicenter:	The spot on Earth's surface directly above where an earthquake occurred or started.
erg:	A vast, terrestrial sand dune desert like the modern Sahara.
erosion:	The physical transport of materials on Earth's surface from one place to another, to expose deeper levels of rock. Transport may be by running water, wind, waves, moving glaciers, or other processes.
estuary:	Place where a river reaches the ocean or a salt lake, typically with water having variable salt contents between fresh and the ocean or lake.
evaporite:	Sedimentary rock made of soluble salts, such as halite (NaCl), that precipitated from evaporating water.
extension:	The process of making something wider, for example, widening of the Basin and Range province in the Neogene has made western North America wider, and has caused brittle faulting to produce alternating fault block mountain ranges and intervening valleys.
extrusive:	Descriptor for igneous rock extruded (erupted) onto the Earth's surface (as opposed to "intrusive" rock).

fault:	A relatively thin surface along which there has been measurable movement of rocks on either side. May be a single thin crack, or a wider zone 10’s to 1000’s of meters wide.
facies:	The same geological formation that differs from place to place, because of different original depositional environments.
feldspathic:	Containing feldspar, such as a sandstone. Because feldspar weathers much more quickly than quartz, feldspathic sandstones indicate a deposit relatively close to the sediment source area.
fluid:	A substance with no fixed physical shape that can flow (liquid or gas). Common fluids in surficial geology are wind and water; carbon dioxide is a specific fluid given off during metamorphic reactions.
fluvial:	Pertaining to rivers (i.e., fluvial processes like flooding).
fold:	Bent layers of rock, as compared with planar, parallel layers of rock. Can potentially be found in any sort of rock.
foliation:	The parallel alignment of plate-shaped minerals like micas. Foliated rocks tend to break parallel to the foliation surfaces.
foraminifera:	Marine eukaryotic protozoans having a calcite shell.
formation:	A named package of sedimentary, metamorphic, or volcanic rocks that has been determined to have similar rock types, ages, or environments of origin. Formation names are usually from the location (town, farm, geographic feature) where the formation is best exposed.
gabbro:	Plutonic rock, coarse-grained, typically dark-gray to black, with low silica content, typically 45-54%, chemically the same as basalt.
"goblin":	Vertical rock columns with variable diameter, formed by the differential erosion of different rock layers within the column.
gneiss:	Pronounced “nice.” Metamorphic rock, typically rich in both quartz and feldspar, and also containing micas, hornblende, or other minerals. These may have been metamorphosed andesitic or rhyolitic igneous rocks, or metamorphosed feldspathic sandstones.
graben:	A block of rock that was dropped downward along normal faults, relative to blocks (horsts) on either side.
granite:	Plutonic rock, coarse-grained, typically light-gray or pink, with high silica content, typically 66-78%. Chemically the same as rhyolite.
group:	In the rock layer context, this is a set of named formations, one above the other, that have some combination of a narrow span of ages, similar rock types, or similar depositional environments.
halite:	Mineral, relatively soft, soluble salt, usually colorless: NaCl.
hematite:	Mineral, red when fine-grained, hard: Fe_2O_3.
hogback:	Landscape ridge held up by weathering resistant rocks, with a steep dip slope on one side, typically 45 to 90°, and a steep slope on the other. Also called “flatiron.”
hoodoo:	Vertical rock columns with variable diameter, formed by the differential erosion of different rock layers within the column.
hornblende:	Mineral, typically black, relatively hard, common in igneous and some metamorphic rocks: approximately $Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$.

horst:	A block of rock that was raised upward along normal faults, relative to blocks (grabens) on either side.
hydrocarbon:	Materials made primarily of carbon and hydrogen, including tar, oil, and natural gas.
hydrothermal:	Hot water, usually referring to convectively circulating hot water that chemically altered rock mineralogy, and/or precipitated veins or formed mineral deposits.
hydrous:	Water-bearing. For example, hydrous minerals have OH^- groups or H_2O molecules as part of their crystal structure. Hydrous magmas tend to erupt explosively, driven by the rapid expansion of water vapor, unmixing from the magma near the surface.
igneous:	A rock that formed from solidification of magma (melted silicate rock). These may be volcanic or plutonic.
impermeable:	Cannot be penetrated by fluids, particularly water, oil, or natural gas.
intrusion:	The process or result of magma moving into part of the Earth's crust, displacing other rocks to make room. This process results in a plutonic rock body, or forms a conduit to erupt magma at the surface (volcano).
intrusive:	Descriptor for igneous rock intruded into the Earth's crust (as opposed to erupted "extrusive" rock); approximately synonymous with "plutonic"
joint:	Planar cracks in rocks, usually coming in parallel sets. Most joints we will see are approximately vertical, formed by broad tectonic stresses. Others can be caused by local stresses, including the erosion of overlying rocks, or cooling and contraction of a lava flow.
laccolith:	A blister-shaped igneous intrusion, typically having a flat bottom and a dome-shaped top, where overlying layers have been pushed up.
Laramide:	A latest Cretaceous to Eocene mountain building episode in the central Rocky Mountains, characterized by broad-scale folding and block faulting in northern New Mexico, Colorado, Wyoming, and Montana, east and north of the Colorado Plateau.
latite:	Volcanic rock, usually gray, similar to rhyolite but with higher Na and K concentrations.
lava:	Volcanic rock that flows on the Earth's surface as a river of liquid.
limestone:	Sedimentary rock made mostly of calcite.
lithosphere:	The relatively rigid outer parts of the Earth that make up the tectonic plates. Includes the crust, and underlying mantle to a depth where the temperature reaches about 1200°C.
magma:	Melted (liquid) silicate rock, usually when it is below ground. Above ground it is usually called lava.
magnetite:	Mineral, black to dark-gray, magnetic, common in igneous and metamorphic rocks, and in sands eroded from them: Fe_3O_4.
magnitude:	Earthquake energy released, scaled to approximately resemble the old Richter magnitude scale. Scale is open-ended, so values <0 and >10 are possible. Each unit magnitude difference represents an energy release difference of x 33.6.
marble:	Metamorphic rock composed of metamorphosed limestone or dolostone, often resulting from contact metamorphism surrounding a pluton. The term may also be misused for limestone.
marine:	Formed in the ocean, like marine shale.

marl:	Sedimentary rock, usually a mixture of clay and calcite or dolomite.
mass wasting:	Downhill movement of large masses of rock or loose material by gravity. This is a kind of erosion. Processes can include landslides, rockfalls, slumps, and so on.
member:	In the rock layer context, a subdivision of a formation—usually a layer within the formation that may not be found everywhere the formation as a whole has been identified.
mesa:	A relatively broad, flat-topped hill or mountain with steep sides. Smaller than a plateau.
metamorphic:	An igneous or sedimentary rock that has been modified by heat, pressure, and/or differential stress. These can form locally, as around a single, hot igneous intrusion, or broadly, in the deep parts of a mountain belt, formed during a continent-arc collision, or similar.
mica:	Mineral, a group of sheet silicates that include muscovite and biotite as their most common examples.
mid-ocean ridge:	The ocean floor line along which new ocean lithosphere is produced. The ridge is elevated 2-3 km higher than its surroundings, held up by the buoyancy of rising, hot, deeper mantle rocks. Melting of those rising rocks produces basalt magmas, which rise and erupt to form the oceanic crust.
mineral:	A naturally occurring, solid, crystalline material.
mineraloid:	Non-crystalline but otherwise mineral-like material.
mirabilite:	Mineral, soluble salt, usually colorless: $Na_2SO_4 \cdot 10H_2O$.
monocline:	A one-sided fold, as compared to typical folds where the layers slope down away from the center (anticlines) or down toward the center (synclines), on both sides. These usually separate flat-lying rocks on both sides of the monocline, and are usually inferred to be caused by a fault beneath the draping sedimentary layers over it.
moraine:	Sediment formed and deposited by moving glaciers, underneath, at the sides, or at the downhill end. Usually composed of a mixture of clastic materials ranging from clay- to house-size.
mudstone:	Sedimentary rock, composed of different proportions of clay, silt, and fine sand.
nahcolite:	Mineral, soluble salt, usually colorless: $NaHCO_3$.
nodule:	A lump of something in another kind of rock. For example, a layer of chert lumps in a limestone.
normal fault:	A fault where the hanging wall drops down in relation to the footwall; occurs due to extensional stresses (crustal thinning). Fault plane typically dips at ~60°.
obsidian:	Volcanic rock made of glass, as a result of cooling so fast that crystals are rare or absent. Usually black.
olivine:	Mineral, hard, usually olive-green, common in basalts and the upper mantle: $(Mg.Fe)_2SiO_4$.
oolite:	A round, layered deposit of microcrystalline calcite, usually 0.5-2 mm in diameter. These form in shallow, salty, warm waters that have tidal or wind-driven currents, where the water is supersaturated with respect to calcite. Calcite precipitates on the grain surfaces, and the currents keep them rolling around so they don't stick together.
opal:	Mineraloid, amorphous, hydrated silica: $SiO_2 \bullet nH_2O$, where $n = 0.05–0.2$.

orogeny:	An episode of mountain building, commonly associated with continent-continent or continent-arc collision. Usually accompanied by igneous intrusion and eruption, and formation of metamorphic rocks.
ostracods:	Small, fresh to salt water crustaceans having a chitin or calcite shell.
oxygen-18 (^{18}O):	The heaviest stable oxygen isotope, containing 8 protons and 10 neutrons. Similarly, oxygen-17 has 9 neutrons, and oxygen-16 has 8 neutrons.
parting:	In the geologic context, a horizontal layer along which otherwise-massive rocks break or are eroded, such as thin shale layers between thicker sandstone layers.
pinnacle:	A vertical tower of rock, usually formed from erosion along intersecting joint sets on the pinnacle sides.
plagioclase:	Mineral group, corresponding to a solid solution series between two end members: $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$.
plateau:	A broad, generally flat highland surface, surrounded by lower elevations. May be dissected by stream valleys.
plates (tectonic):	Thick, relatively rigid parts of Earth’s outer layers, that deform mostly at their edges and move more or less independently of one another (plate tectonics).
pluton(ic):	Igneous rock body that solidified underground.
porphyry:	Igneous rock, having a large proportion (~50%) of large crystals set in a matrix of much finer-grained crystals.
pyrite:	Mineral. Metallic, brassy-colored iron disulfide (FeS_2).
pyroxene:	Mineral group, typically black to dark-green, hard, common in basaltic and andesitic rocks, and some metamorphic rocks: For example, $Ca(MgFe)Si_2O_6$.
quartz:	Mineral, hard, usually colorless: SiO_2.
quartzite:	Well-cemented, hard quartz sandstone (sedimentary rock), or metamorphosed quartz sandstone (metamorphic rock).
quartzofeldspathic:	Rock characteristic, the principal minerals include both quartz and feldspar. Usually refers to metamorphic rocks or sandstones.
radiolarian:	Marine eukaryotic protozoan, usually having a silica shell.
radiometric dating:	Determining the age of a material by measuring the ratio of a stable isotope decay product to its radioactive parent isotope. For example, ^{206}Pb/^{238}U, or ^{40}Ar/^{40}K. Gives absolute ages under appropriate circumstances.
rebound:	Spontaneous uplift of the crust following removal of weight from the upper surface, such as melting of a glacier, evaporation of a large lake, or erosion of large amounts of surface rock.
reef:	Sedimentary deposit made mostly from organisms that precipitate calcium carbonate: corals, sponges, or cyanobacterial mats. In Utah, this term also refers to any high rock ridge sticking up from the desert (which poses a barrier to travel in the same way an ocean reef does for ships).
reservoir:	A place where something is held, in this context usually in porous rock underground. These include oil and natural gas reservoir rock, or water aquifers. Also a common word for a man-made lake.

reverse fault:	A fault where the hanging wall moves upwards in relation to the footwall; occurs due to compressional forces (crustal thickening). Fault plane typically dips at ~60°.
rhyolite:	Volcanic rock, usually gray to pink, fine-grained, with high silica content, typically 66-78%. Chemically the same as granite.
rift:	An elongate part of the crust that has been extended, commonly dropping down one or a few central fault blocks to form a rift valley (which may become filled with sediments or lavas). The Rio Grande Rift, mostly in New Mexico, is an example.
saline:	Contains a lot of salt, either water or soils, usually.
sandstone:	Sedimentary rock, clastic, dominated by grains in the size range 0.06 to 2 mm.
schist:	Metamorphic rock, containing a large proportion of mica or other sheet silicates.
scree:	Fallen broken rocks that have accumulated at the base of a very steep slope (usually smaller chunks than talus, though sometimes the terms are used synonymously).
sediment:	Loose material or rock that was transported across Earth's surface by moving water, wind, or moving glaciers. This includes rocks made of minerals precipitated from water solution (limestone, evaporite) as well as clastic rocks (shale, sandstone). Usually excludes volcanic ash deposits and lavas.
Sevier:	Late Jurassic to early Eocene mountain building episode, extensively developed in western North America, from Arizona to the northwest Canadian Rockies. Involved subduction beneath North America, and collision of continental fragments with the volcanic arc. West of the Laramide structures, north and west of the Colorado Plateau.
shale:	Sedimentary rock, clastic, made mostly of clay, grains mostly <0.004 mm.
shield (continental):	Extensive exposures of ancient igneous and metamorphic rock on continents. Usually areas that have not experienced mountain building episodes for many hundreds of millions of years.
shield (volcano):	A low-relief volcano covering a large surface area that erupts basaltic lava flows (like Kilauea in HI).
silica:	SiO_2, referring to it as a chemical component (rhyolite, a silica-rich volcanic rock), or referring to a non-quartz, solid material (amorphous, hydrated silica shells of diatoms).
silicate:	A mineral containing SiO_4^{4-} groups.
silicious:	Rich in silica, often in the form of silicate sediments.
siltstone:	Sedimentary rock, clastic, made mostly of grains in the size range of 0.004 to 0.06 mm.
sinkhole:	Collapsed roof of a cave, making a hole in Earth's surface.
solution mining:	A mining method for soluble salts: Hot water is pumped down an injection well. The hot water dissolves salt, and rises to the surface through a production well. The water is cooled, precipitating the salts, then the water is heated and recycled back into the injection well.
stock:	A large igneous intrusion with an exposed surface area >100 km^2.
stoping:	The process by which wall rock is broken up and removed by an igneous intrusion, with chunks sometimes preserved in the magma chamber as xenoliths.
strain:	The amount a rock mass has been deformed.
strata:	Layers of sedimentary rock (sing. *stratum*).

stratigraphy:	The particular layering of rocks (strata) in an area, usually involving different formations, rock ages, and rock types. Also the study of such rocks.
stream:	Any flowing body of water, ranging in size from tiny rivulets to broad rivers.
stress:	The applied force needed to deform a rock mass.
stromatolite:	A layered carbonate structure, composed mostly of calcite, that was precipitated by cyanobacterial mats in shallow, warm salt water. These can range in size from a thin stack of dimes to the size of a trash can. The calcite is replaced by dolomite in some cases.
subduction:	The downward movement of oceanic lithosphere back into the mantle, beneath a volcanic arc. This process is driven by the higher density of the old, cold oceanic lithosphere, than the underlying hot mantle rock.
supergroup:	A collective term for a set of geological formations to make them easier to talk about. The included formations may be of very different types or have very different ages.
sylvite:	Mineral, soluble salt, usually colorless: KCl.
syncline:	Folded rock structure, usually forming a U-like shape. Youngest rocks are in the fold center.
talus:	Fallen broken rocks at the base of a very steep slope (usually larger chunks than scree, like boulders, but the terms are sometimes used synonymously).
tectonics:	The large-scale processes that make and close ocean basins, produce chains of volcanoes, raise mountain ranges, and so on.
terrestrial:	Usually refers to sediments that are deposited on land, distant from the oceans, such as river or sand dune deposits.
thrust fault:	A low angle (~30° or less) reverse fault typical of continental collisions and orogenesis.
time-equivalent:	Two differently-named formations that were deposited in different areas at the same time. The formations may interfinger or otherwise grade into one another horizontally (static depositional environments) or vertically (moving depositional environments) where they meet.
transform fault:	A fault found at a plate boundary where the two adjacent plates slide horizontally past one another.
transgression–regression:	Refers to a moving ocean shoreline position. As relative sea level rises (water level rises or land subsides), the ocean transgresses over land. As relative sea level falls (water level falls or land rises), the ocean regresses from land. Repeated cycles of this can give a stratigraphy in one place with alternating marine and terrestrial sediments.
travertine:	Deposits of calcite precipitated from calcite-supersaturated water, exiting the ground at a spring.
trench:	The deepest parts of the ocean floor, narrow deep areas where old, cold oceanic lithosphere sinks back down into the mantle, beneath a volcanic arc.
trona:	Mineral, soluble salt, usually white: $Na_2CO_3 \bullet NaHCO_3 \bullet 2H_2O$.
unconformity:	Most simply, a buried erosional surface, representing a place in the stratigraphy where sediments of a particular time range are missing.
unit:	In the rock layer context, this refers to a specific group of formations, a formation, or member of a formation that is currently being discussed (say, in the same paragraph).

	Used as a shorthand so what is being discussed doesn't have to be written out every time. "Rock unit."
veins:	Fractures containing minerals deposited underground by flowing cold to hot water.
viscosity:	The resistance of a material to flow. Water flows easily, and so has low viscosity. Wet concrete flows less easily, and so has higher viscosity.
volcanic:	A rock or landscape feature produced by the eruption of magma on the surface.
volcanic arc:	The chain of volcanoes that forms over a subduction zone. The subducting oceanic lithosphere releases water, which rises and causes melting in the overlying mantle wedge beneath the arc. The magmas then rise upward to form plutons and volcanoes.
volcaniclastics:	Volcanic materials that have been transported and deposited, usually by running water. Such deposits can be sandstones, but are remarkable in that they are made mostly of volcanic rock fragments, rather than quartz and/or feldspar crystals.
weathering:	All processes that break down rocks at and near Earth's surface, so they can be transported to make sediments. Physical weathering processes include falling rocks, and plant roots wedging rocks apart. Chemical weathering involves chemical reactions that transform minerals like feldspar and micas into clay, oxide and hydroxide minerals, and dissolved chemicals.
xenolith:	Chunk of wall rock included in a magma chamber.
zircon:	Mineral, hard, usually as very small crystals: $ZrSiO_4$. Usually contains uranium and thorium, and so is useful for radiometric dating.

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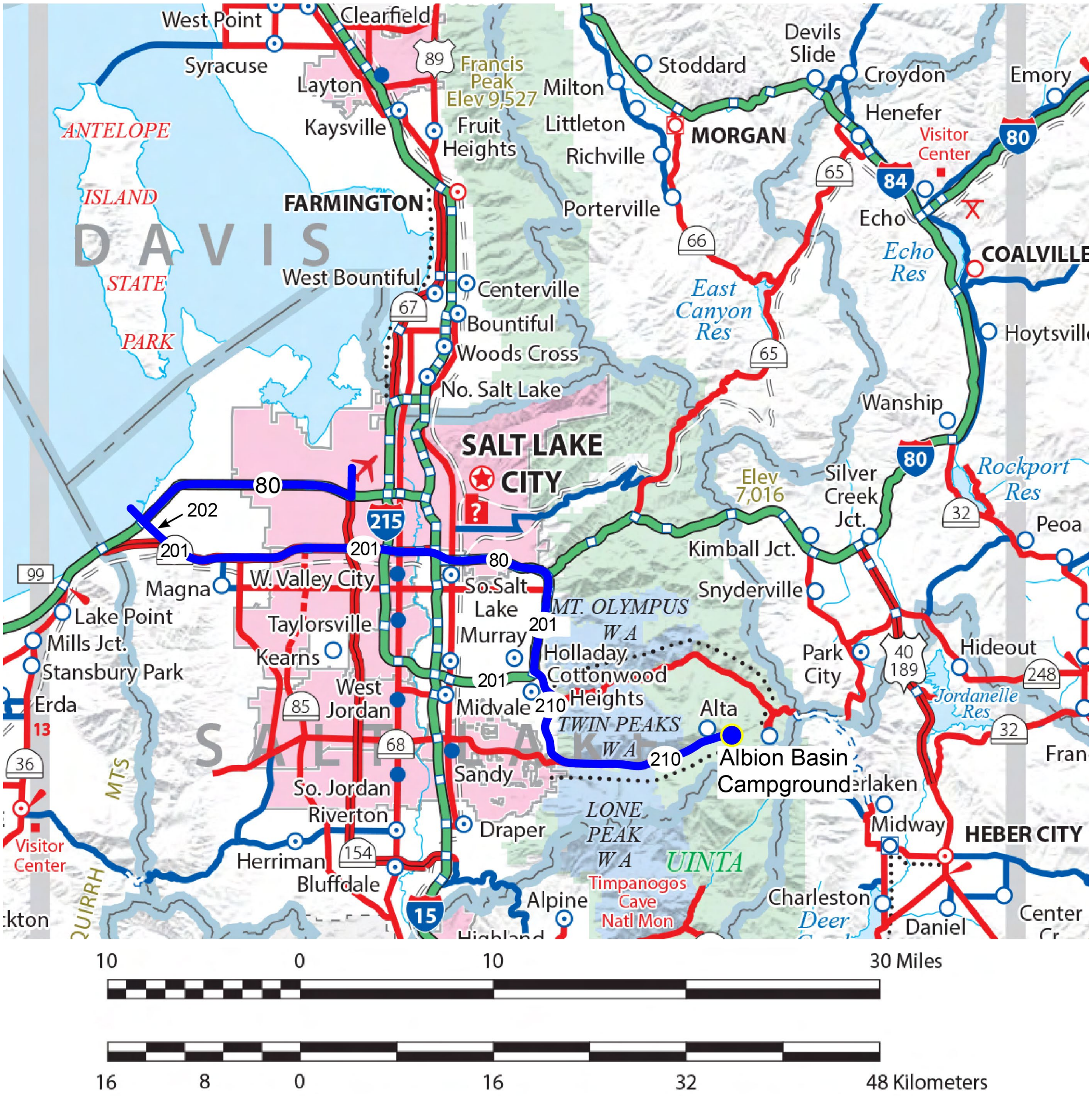
Travel Maps

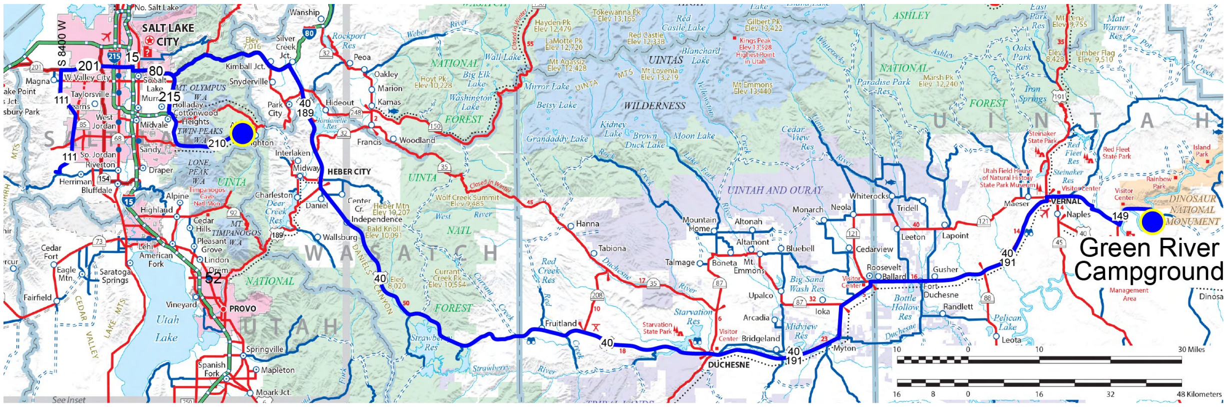
Day 1

Campsite: Albion Basin Campground, Alta, UT



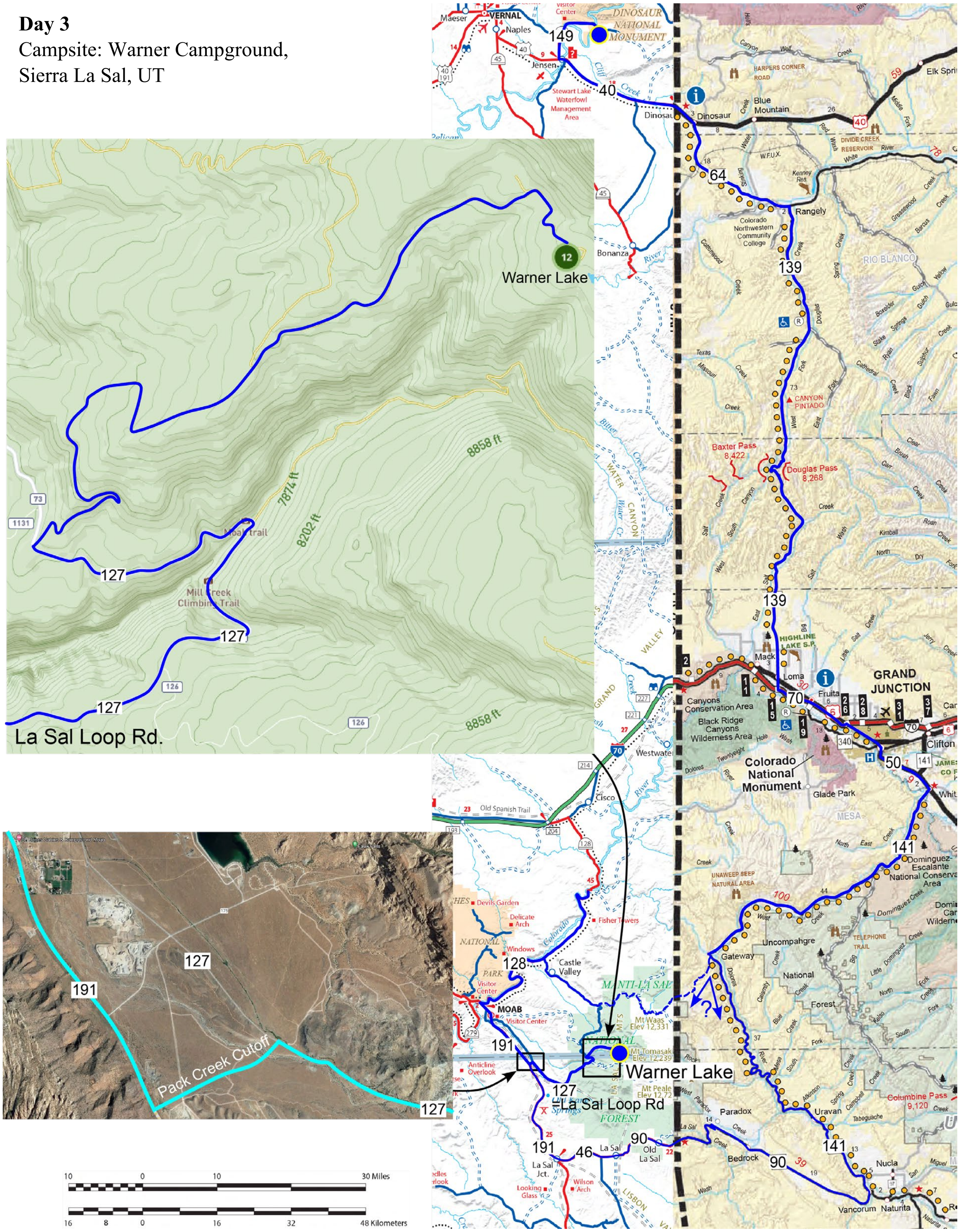
Day 2

Campsite: Green River Campground, Jensen, UT



Day 3

Campsite: Warner Campground,
Sierra La Sal, UT



Day 4
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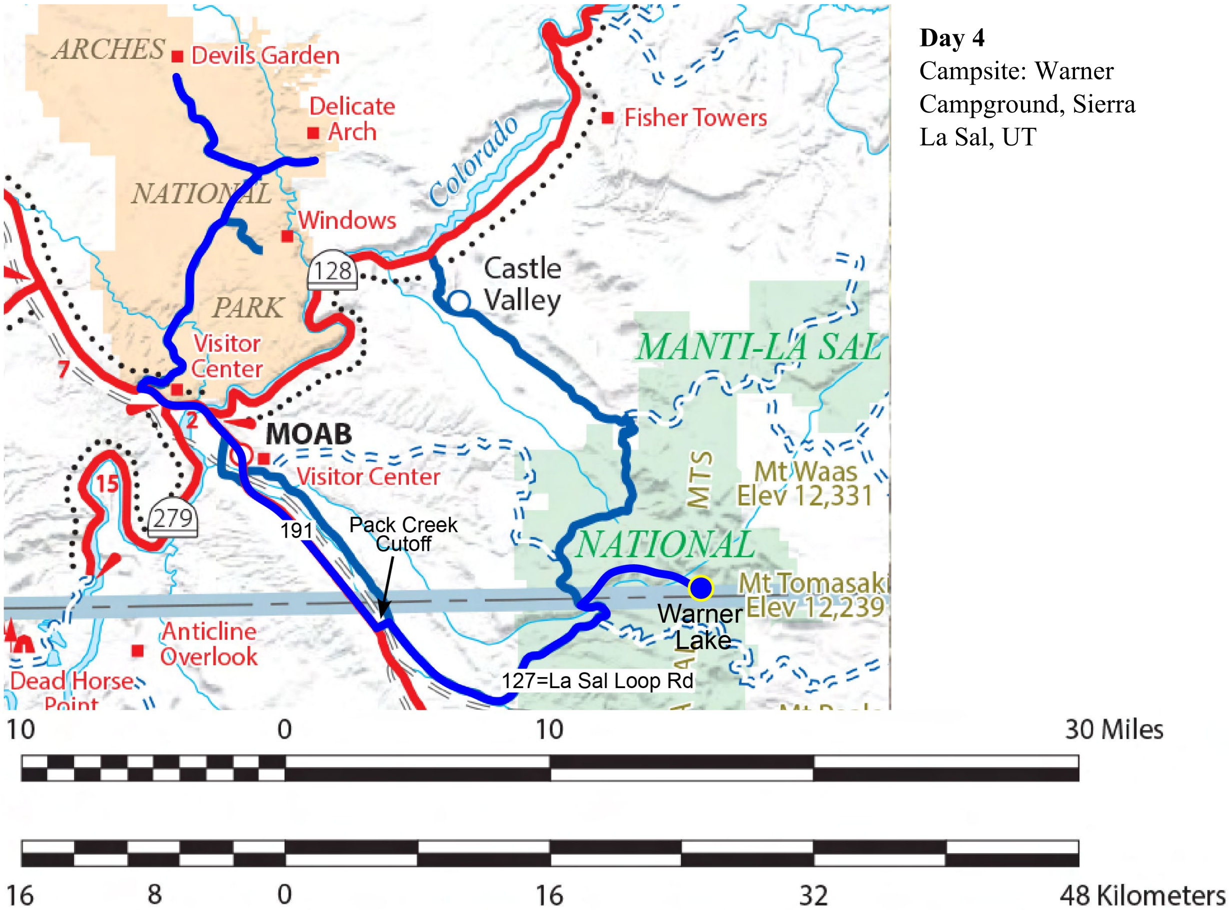

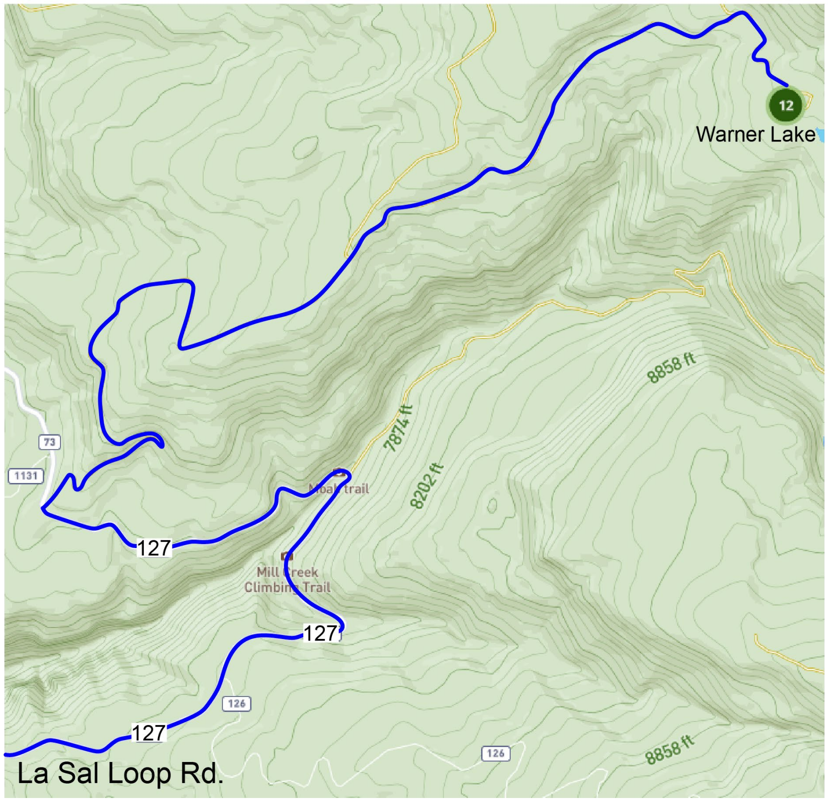

Day 5

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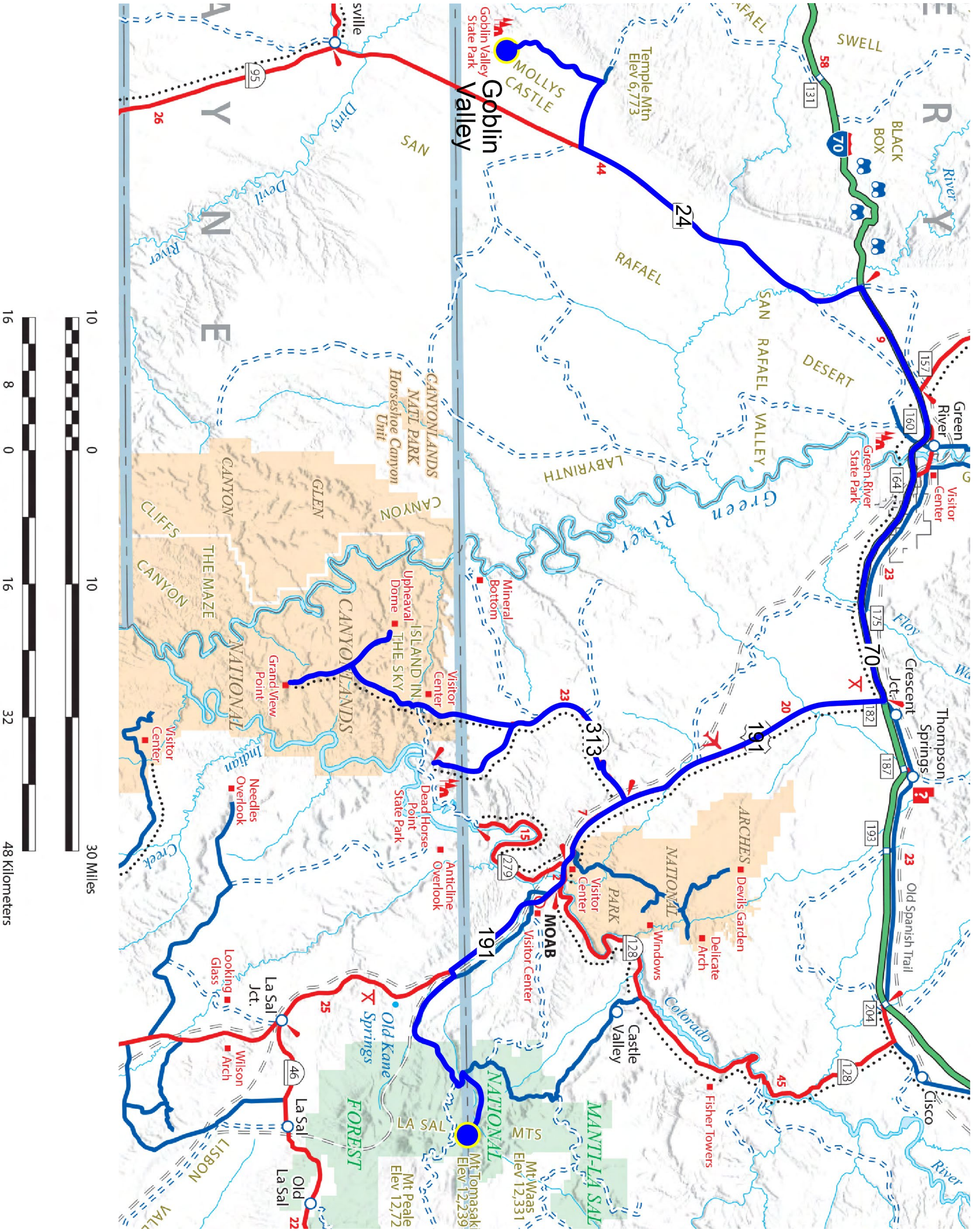
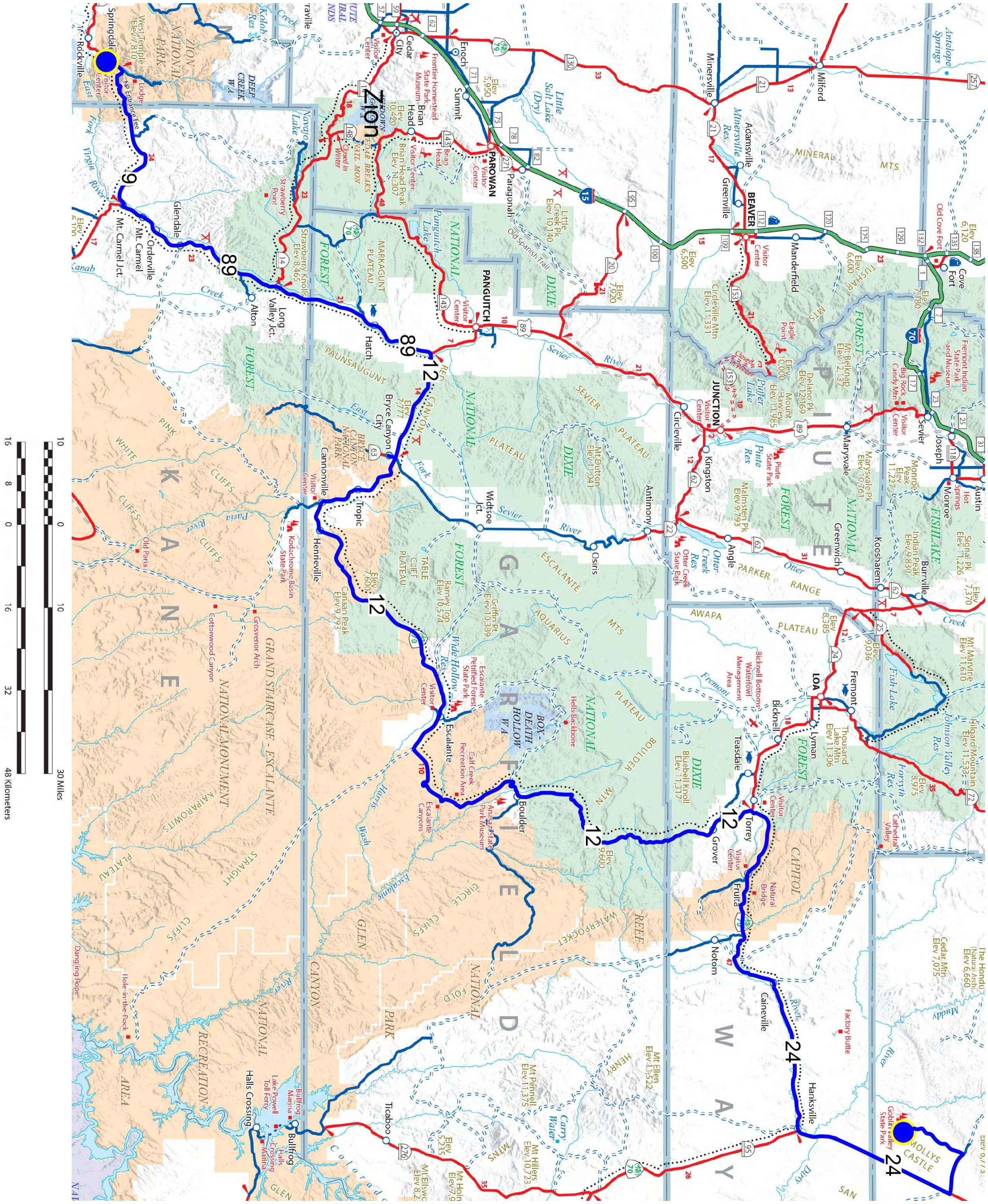
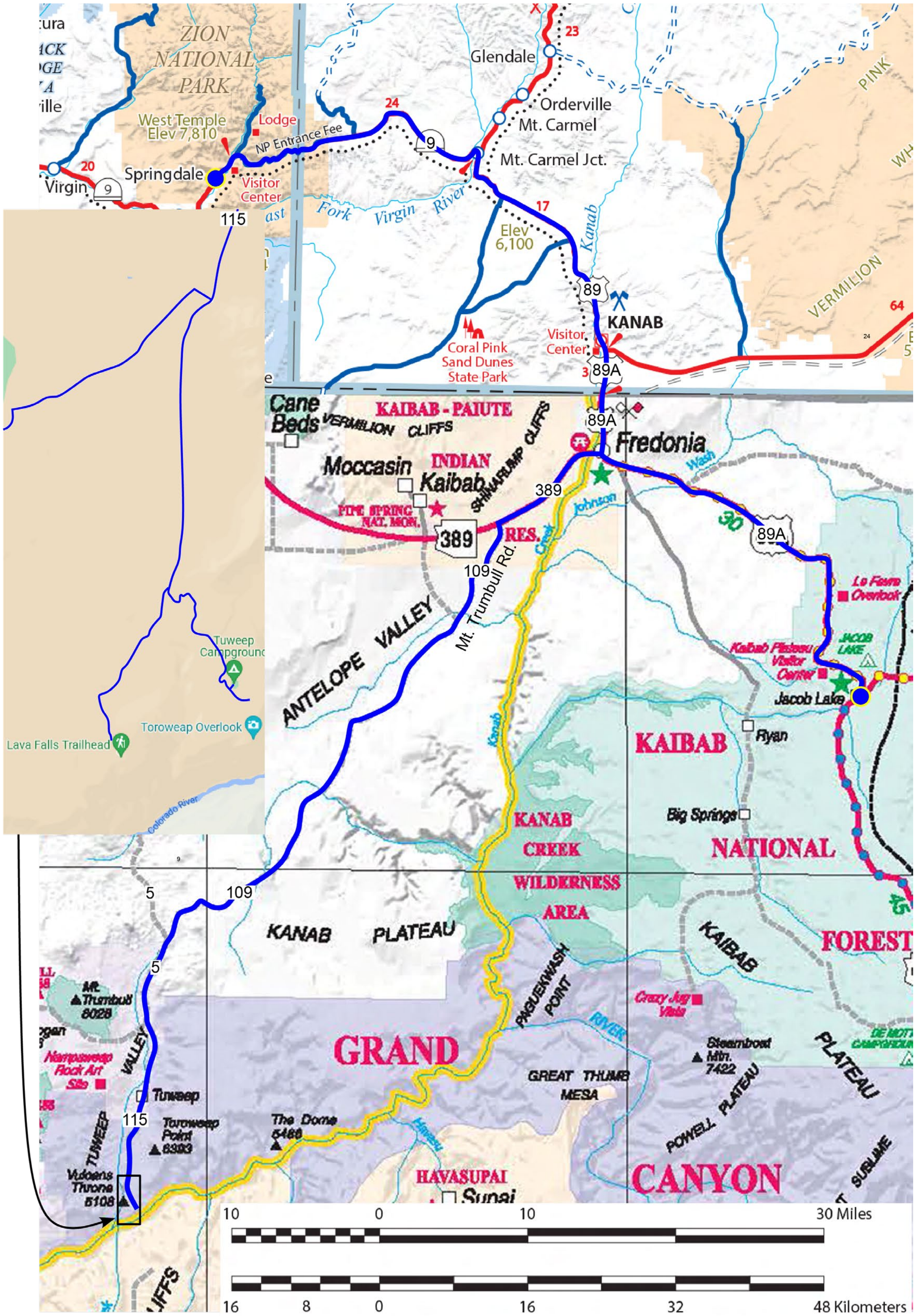


Day 6

Campsite: Watchman Campground, Zion National Park, UT

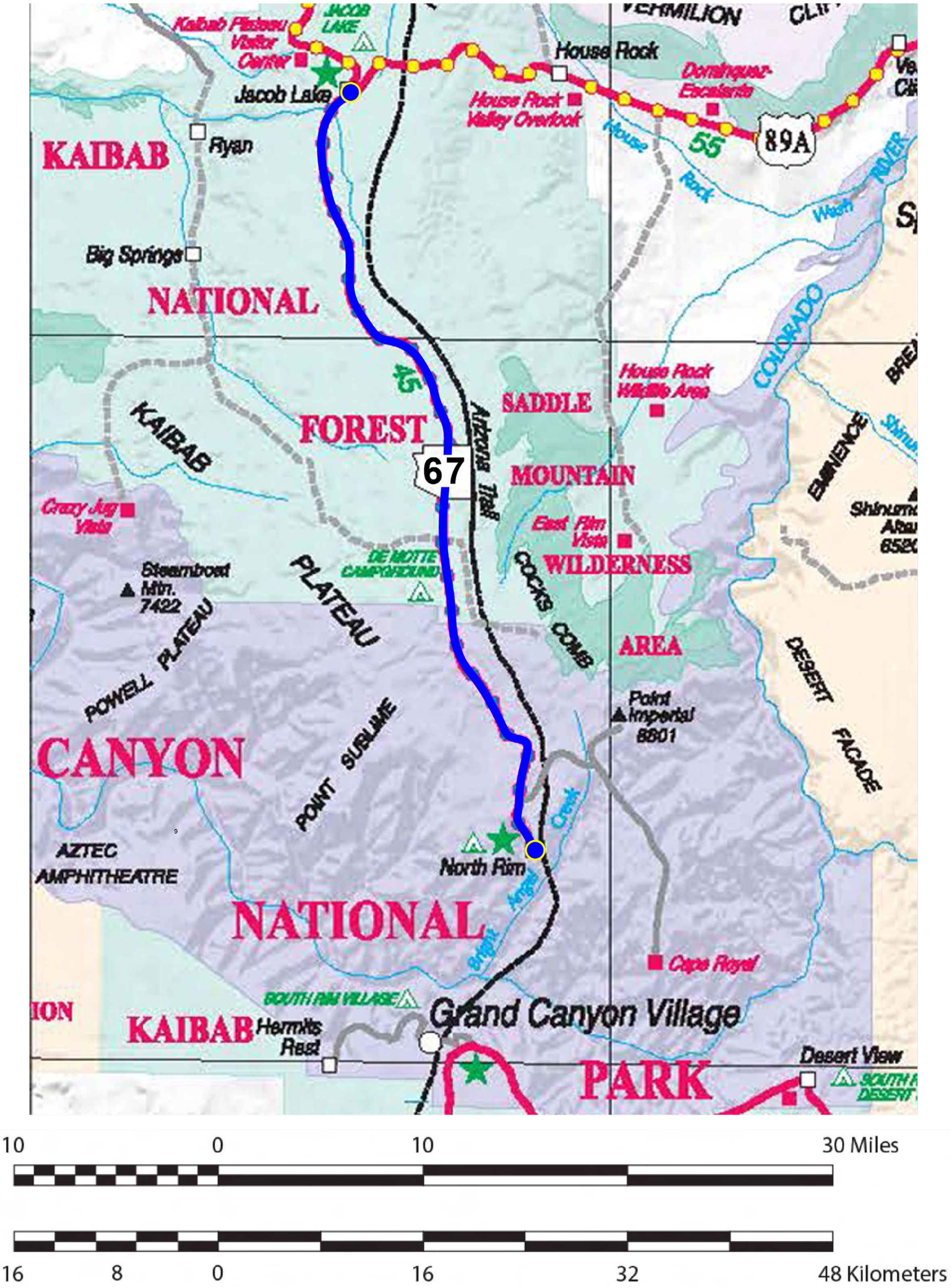


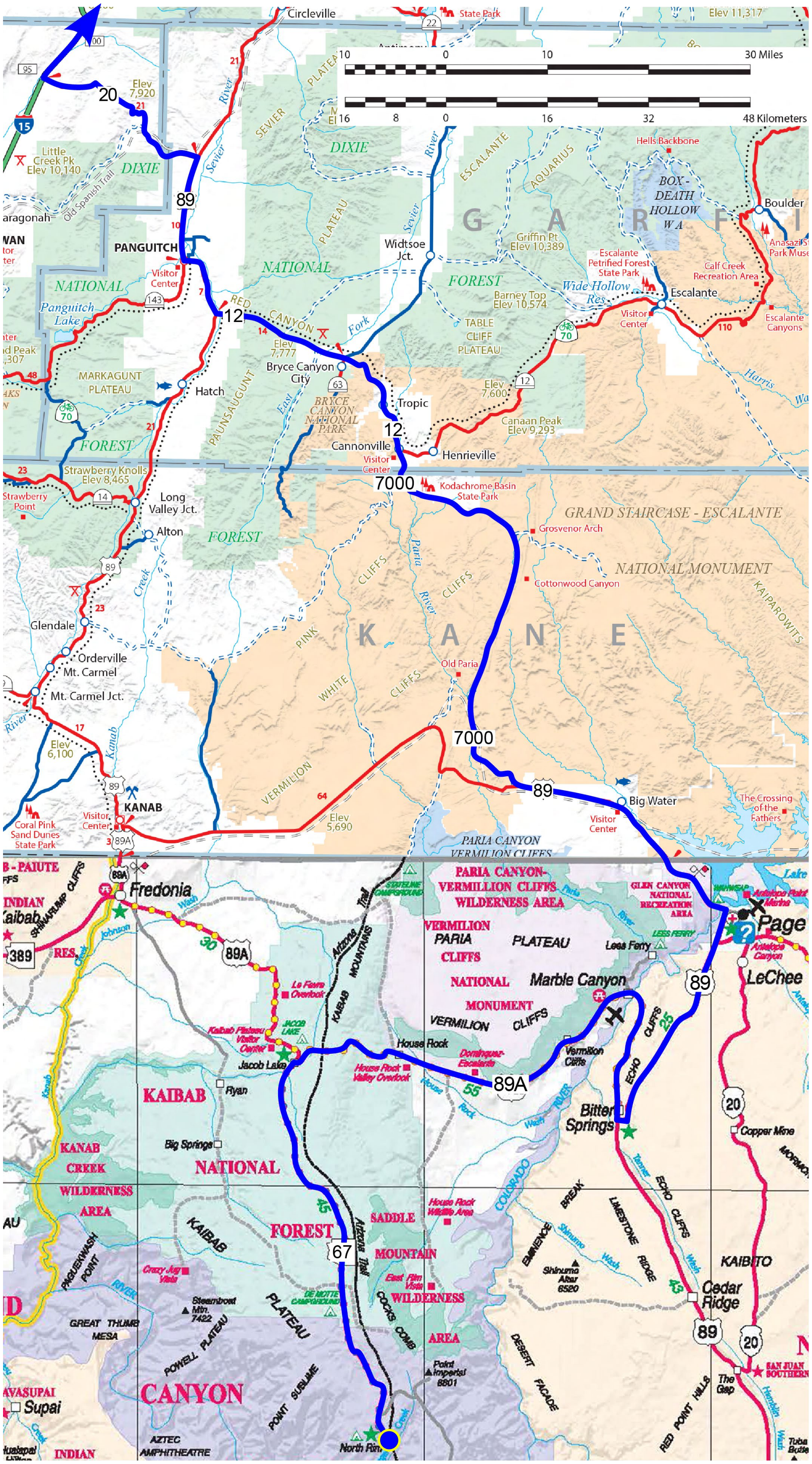
Day 7
Campsite: Jacob Lake Campground, Fredonia, AZ



Day 8

Campsite: North Rim Campground, Grand Canyon National Park, AZ





Day 9
Hotel, Salt Lake City, UT