Tectonic Evolution of the San Juan River Region

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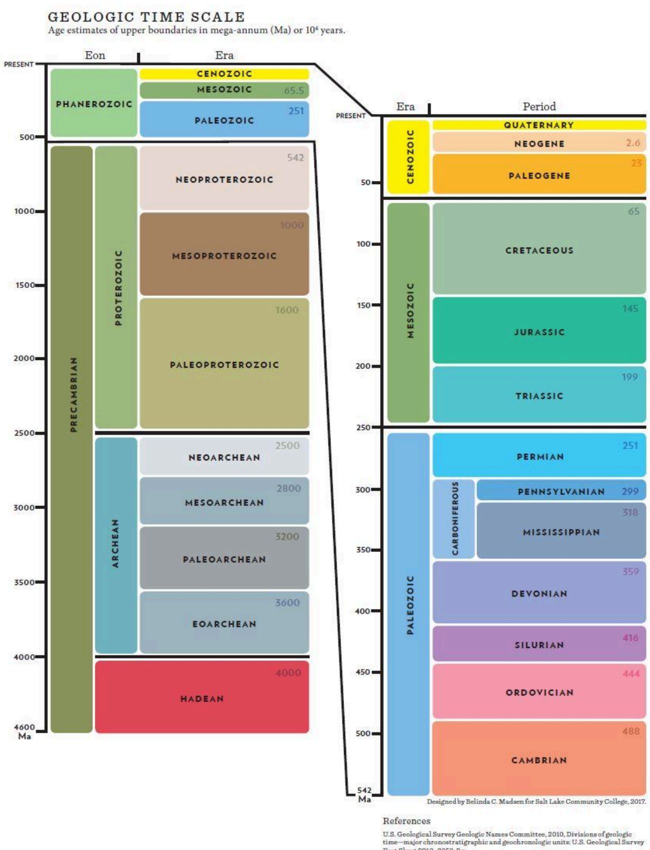


Figure 1. The geologic time scale with various names that represent Earth's time periods. This article refers to this time scale frequently with the use of period names.

Introduction

The idea that the continents are in constant motion and that they used to be attached to each other was first proposed by Alfred Wegener, a German geoscientist. It is important to note that the theory of plate tectonics is still a working theory which is constantly being debated.. According to this theory, the earth's lithosphere is made up of various land masses called tectonic plates. Which have been moving constantly through the earth's history as referenced in figure 2. The continents are seen as gigantic puzzle pieces of crust that are transported by the lithosphere. This is the rocky solid outer part of the earth; it consists of the crust and the upper mantle. The earth's crust is divided into seven major plates (which are described in figure 2) and many other smaller plates; the motion in which these plates move determines the type of plate boundary. Most seismic activity occurs along plate boundaries due to the release of energy accumulated at these settings though time. To reconstruct the ancient continents and their correlating plates, paleoclimate indicators, far flung fossils, mountain ranges, and rocks are used as evidence to support the theory of plate tectonics and continental drift that is defined as the horizontal movement of the continents.

Plate boundaries can be separated into three main types. The three main types are; convergent, divergent, and transform boundaries. A convergent plate boundary happens when two plates collide with each other. This could lead to a continental collision or a subduction zone. A subduction zone is the downward movement of the edge of a tectonic plate beneath a different plate. Convergent plate boundaries are responsible for the formation of volcanoes and mountain ranges like the Himalayas that formed through continent-continent collision and the Andes that formed through oceanic-continental collision. On the contrary, divergent boundaries occur when two tectonic plates diverge apart from each other. When divergent plate boundaries occur at an oceanic setting it leads to the creation of a mid-ocean ridge. When it occurs at a continental setting it creates a rift zone. Locations with divergent plate boundaries are responsible for the formation of new oceanic crust. The Mid-Atlantic Ridge is a great example of oceanic divergence. The Rio Grande Rift in New Mexico and The East African rift in Kenya are great examples of divergent boundaries in continental settings. On the other hand a transform boundary happens where two plates grind past each other in a horizontal motion. The San

Andreas is a great example of transformation. It is important to understand that each plate boundary can possess various types of boundaries.

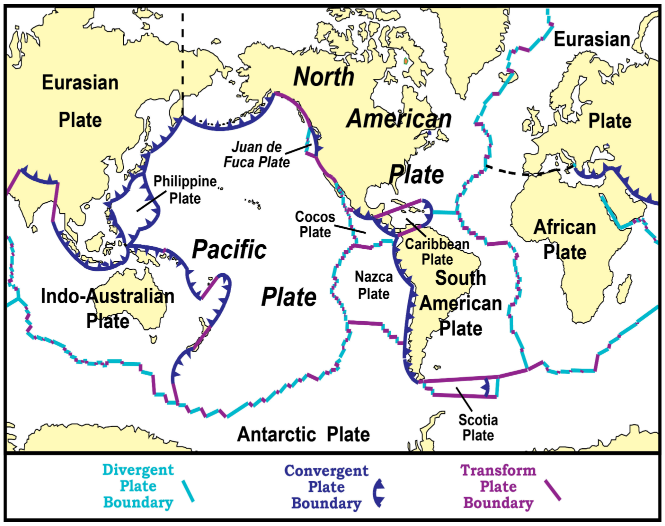


Figure 2 depicts the seven major plates of the earth and the smaller plates. It shows the areas where the different tectonic plates meet. Including the size, shape, and location of each one of the plates. The photo shows each one of the existent plate boundaries and their respective kinds. The seven major plates are The Eurasian plate, The North American plate, The African plate, The Indo-Australian plate, The Antarctic plate, The South American, and The Pacific plate. It is fundamental to note that the image demonstrates how each plate can possess several kinds of boundaries. Image obtained from Lillie et al., 2015.

Scientists believe that the major driving force for plate motion is convection, which takes place in the mantle of the earth. Convection is the idea that more dense and cold materials sink while warm and less dense materials rise. Plumes and rising material from the mantle are the warm and less dense materials. Subducting tectonic plates are the cold and more dense materials. Tectonic plates are able to move due to the higher density of the oceanic lithosphere and the weakness of the asthenosphere. Which is the top layer of the earth's mantle, located beneath the Lithosphere. Viscous drag, ridge push, and slab pull are the three main forces that impact the rate at which tectonic plates move.

Plate tectonics can be considered the unifying theory of geology as each one of the existent geologic theories can be explained and linked to it. It provides an acceptable mechanism for continental motion and helped the scientific community to establish a better understanding of all the major features of the earth's surface and of the features located at the ocean basins, including how they were formed. Plate tectonics are responsible for the properties of the different rock layers at the San Juan River, how they were deposited, and for their current location. Plate Tectonics revolutionized earth sciences and made us change the way that we view the earth and its unique features.

Regional Setting

The Colorado Plateau is an interesting place on the earth. It is located in the four corners region of North America (where the Grand Canyon is). The Colorado Plateau is beautiful, mainly because of its unique geological history. A plateau is defined in the Oxford Dictionary as "an area of relatively level high ground". The Colorado Plateau has an average elevation of about 7000 feet. It is located in a semi-arid region of the southwestern US. This combination has led to relatively fast erosion rates to develop a fascinating landscape with over 30 national parks and monuments.

One of the things that makes the Colorado Plateau so interesting is the canyons (like the Grand Canyon). These canyons were created by a combination of water, rock, and uplift. Rivers (like the Colorado river) tend to carve channels into the landscape. Usually they get wider as they cut down, but sometimes it's much easier for the river to only cut down. This tends to happen when the river is cutting into bedrock. Another thing that helps create canyons is uplift. Uplift is what it's called when an area gets higher than surrounding areas (it is being lifted up in relation to the surrounding land). When uplift happens, rivers tend to cut down more than they already were. The Colorado Plateau has rivers cutting into bedrock in an area that has been uplifted. This has resulted in lots of canyons, some of which are extremely impressive. While most of the plateau is relatively undeformed (few faults and folds) there are several locations with large-scale folds that have created steep ridges in the landscape such as the Waterpocket Fold and Comb Ridge.

Some other things that people seem to be impressed by are interesting rock formations. These include hoodoos, rock arches, and fins, which all exist because of erosion and weathering. The rocks in the Colorado plateau region are mostly sedimentary rocks, meaning they were deposited in horizontal layers. The weaker layers get weathered faster than the stronger ones, which makes interesting rock formations. There are also several locations where ancient magmatism has created resistant bodies of intrusive igneous rock. Over time the softer sedimentary material has eroded away revealing these intrusions which now stand taller than the surrounding regions as isolated mountain ranges such as the La Sal Mountains and Henry Mountains. This combination of geologic variety has led to a diverse and beautiful landscape that many people from all over the world come to visit.

Tectonics of the Precambrian (4,500 Ma to 541 Ma)

The ancient North American continent (often referred to as Laurentia) initially formed during the early to middle Proterozoic, or between 2.0 and 1.8 billion years ago (Ga). During this time, ancient volcanic arcs—chains of volcanoes that form near subduction zones—were accreted onto larger fragments of crust to form a continent. The margin of this continent was located along the present day Colorado-Wyoming border (Gonzales and Karlstrom, 2011). New continental crust was generated along the subduction zones along the edge of Laurentia and the crustal foundation of the Four Corners/San Juan region was formed by 1.7 Ga. Soon after, this rock was covered by marine and river deposits then metamorphosed. Between 1.4 and 1.0 Ga, episodes of magma generation over this region occurred as well, creating igneous rock. Laurentia eventually became the center of one of Earth's first supercontinents, Rodinia, which formed about 1.0 Ga and broke up by about 0.7 Ga (700 million years ago, or Ma), due to a mantle superplume spreading the pieces of the continent apart (Bogdanova et al., 2008). Some of this ancient Precambrian rock is now uplifted and exposed in the San Juan Mountains, especially in a subrange called the Needle Mountains, where the granitic rocks as well as rock types like schist and gneiss are exposed (Whitman and Larsen, 1935).

Because the modern day San Juan river has its headwaters in the San Juan Mountains, these ancient Precambrian rocks can also be seen along the banks of the river. Weathering and erosion deposit these rocks in the river initially, and from there they travel down the river, getting smaller and rounder as they do so. If they are too large and heavy to be carried away by the water, they will be eroded and broken down until they can be. In some instances, very large rocks can travel down the river during periods of particularly high water volume and velocity, such as during flood events. Any of the smooth, rounded rocks you see on the sands of the San Juan River could have potentially traveled hundreds of miles downstream to reach that location. Some examples of these rocks can be seen in figure 3.

Figure 3. Precambrian stones deposited along the San Juan river. In the center of this image, there is also a large spider.

Tectonics of the Paleozoic (541 Ma to 252 Ma)

Overview

During most of the Paleozoic, the western edge of Laurentia—ancient North America—was a passive margin (Figure 4). In a passive margin, continental crust transitions to oceanic crust without any active tectonism. Marine regions adjacent to passive margins accumulate a lot of sediment. For example, units from the Cambrian Period (541-485 Ma) can reach nearly 10,000 feet thick (Blakey and Ranney, 2008). From the Cambrian Period through the Mississippian (359-323 Ma)—a time of over two hundred million years—this region was tectonically inactive, and sediment continued to accumulate on this passive margin. The first major tectonic activity in that time occurred in the Mississippian, when an island arc collided with North America, creating highlands in Nevada in an event called the Antler Orogeny (mountain building event). A long period of sea rise is recorded in the sedimentary record until the Pennsylvanian age, when the tectonics began to change (Blakey and Ranney, 2008; Hedhli et al., 2022).

The oldest geologic units we observed on our river trip were deposited in the Pennsylvanian Period (323-299 Ma). During this time, the ancient supercontinent Gondwana—composed of Africa, South America, Australia, and Antarctica—collided with the North American plate as Pangea began to form. This put a lot of compression on the two continents, leading to mountain building events known as the Ouachita and Appalachian Orogenies. Related to these orogenies, uplift of an ancient mountain range known as the Ancestral Rocky Mountains in Colorado and surrounding regions occurred as the crust thickened and was deformed, beginning about 315 million years ago in the Middle Pennsylvanian (Kluth and Coney, 1981; Barbeau, 2003; Dickinson and Lawton, 2003; Leart et al., 2003).

Thickened crust of the Ancestral Rocky Mountains placed a load on the continental crust, which pulled down on the surrounding regions, forming basins adjacent to the mountains, known as flexural basins. A portion of these mountains known as the Uncompahgre uplift rose in southeast Utah and southwest Colorado. (Barbeau, 2003; Blakey and Ranney, 2008). Our river trip took us through the southern portion of the Paradox Basin, a flexural basin formed by the Uncompahgre uplift. Erosion of the uplifted region led to deposition of sedimentary units in this basin. Several sedimentary units were deposited in this basin from the Mid-Pennsylvanian through the Permian Period, which ended 252 million years ago.

Also during this time, the passive margin on western Laurentia began transitioning to an active margin (Hedhli et al., 2022), which is a continental-oceanic margin in which subduction occurs

(Figure 5). In this case, an oceanic plate known as the Farallon plate began to subduct under the North American plate due to the plates converging. This setting placed compressional forces on the North American plate, which caused uplift and mountain building. (Blakey and Ranney, 2008).

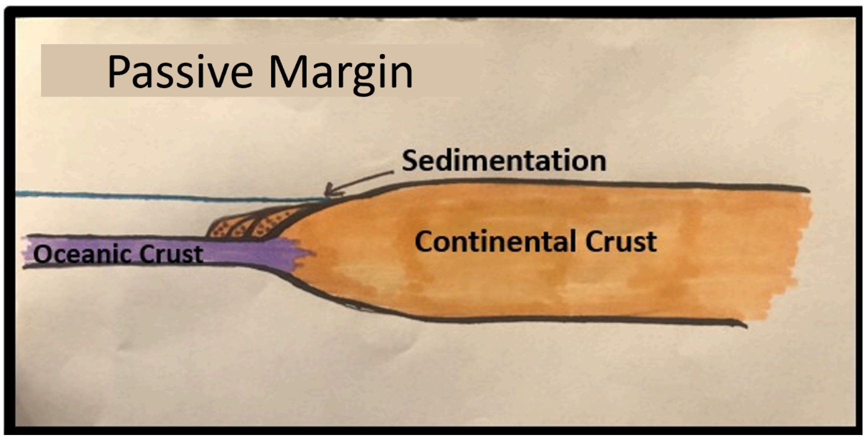


Figure 4. Passive margin. Cambrian through Mississippian. Oceanic crust transitions to continental crust with no active tectonism. High levels of sediment accumulation occur in the marine environment.

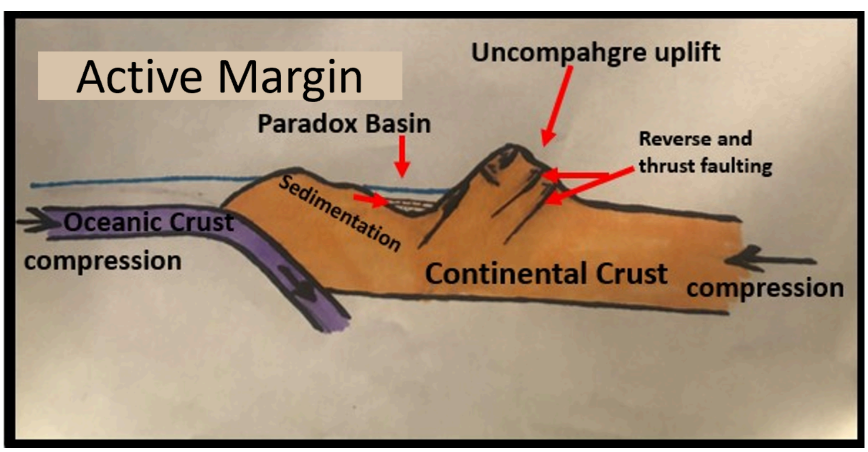


Figure 5. Active margin, beginning in the Pennsylvanian. Oceanic crust subducted under continental crust in a tectonically compressional setting, which led to reverse and thrust faulting, thickened crust, and mountain building. The Paradox Basin formed as a thickened, uplifted crust placed a downward force on the surrounding regions. Sedimentary units derived from the uplift are preserved in this basin.

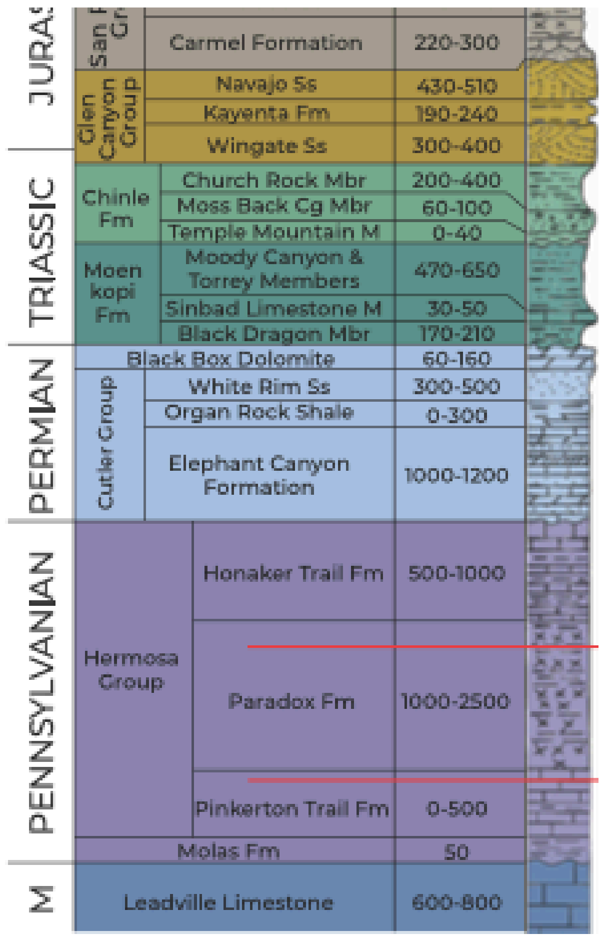


Figure 6. Stratigraphy Column showing discussed layers. Numbers on the right show thickness of the layer. Oldest on bottom to newest on top.

Paleozoic Stratigraphy

Paradox Formation

The Paradox Formation (Figure 6) was formed in the Pennsylvanian Period about 320 to 307 Ma. It is made up of a mix of halite or salt, gypsum, sylvite, sandstone, shale and limestone from the Pennsylvanian Period around 300 million years ago. It was deposited in the Paradox Basin, what is now Southeast Utah and Southwest Colorado. The Uncompahgre Highlands are a result of reverse faults lifting Precambrian basement rock up over Proterozoic strata. Smaller uplifts, the Monument Uplift and Zuni-Defiance Uplift, to the North and South respectively, helped to contain the basin (Peterson, 1963). The Green River Formation from the Eocene in was formed in a similar process where the Uintas uplifted during the Laramide Orogeny and created intermountain basins.

The Paradox Basin then underwent a cycle of a sea rising and falling (Figure 7). Water would fill the basin and remain as sea levels fell. This process happened repeatedly allowing for the formation of minerals left behind when water evaporates (evaporites) like sylvite, gypsum and mostly halite. In the most average cycle, the sea level would rise, depositing gypsum or anhydrite and dolomite. At periods with high sea levels, it would produce dark organic rich shale in calm waters; and as sea level fell would revert back to dolomite and anhydrite capped by salt and sylvite (Fillmore, 2011).

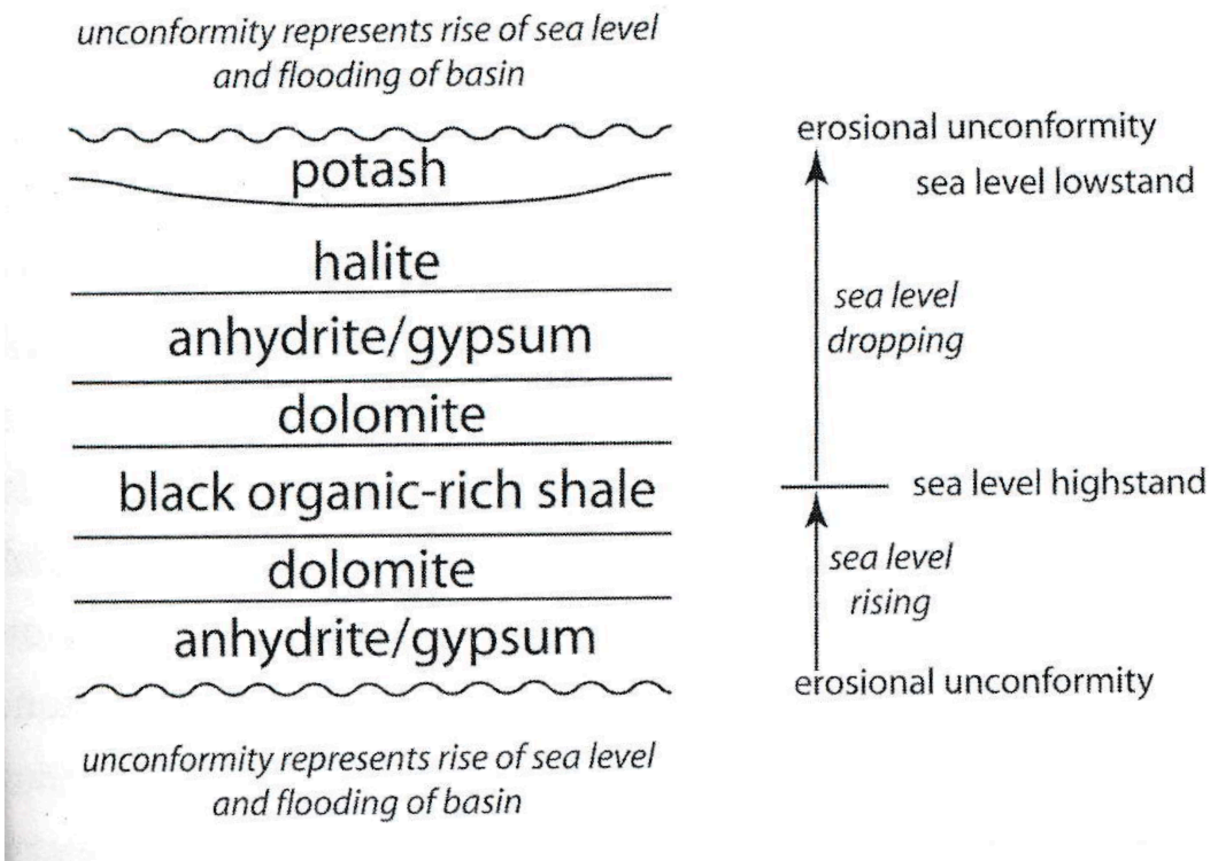


Figure 7. average strat column of a Paradox Formation sea level cycle. One thing to note is that this is the average and any one of these elements might be missing from other cycles, especially the potash/sylvite. Sediment may also be missing as the cycle start is on top of an erosional surface.

Because of the shallow basin and climate, an abundance of algae accumulated. This coupled with limestone deposits lead to carbonate sources and small oil fields pocketing the Four Corners Region as explained in later sections. The Eocene Green River Formation shows similarities to the Paradox Basin to where algae accumulated and eventually turned into the largest deposit of oil shale.

In places the salt was around 2000 feet thick but varied due to ductile deformation once enough sediment was placed on top. The Paradox Valley is a result of this. The basin and formation are both named after Paradox Valley, Colorado where the Dolores River runs perpendicular to the valley. This happened because a salt anticline formed and was dissolved away by the river. As it dissolved, the land collapsed into a valley and the river carved through the valley walls maintaining its original course (Baars, 2000).

Honaker Trail Formation

The Honaker Trail Formation was deposited in the Pennsylvanian Period about 307 to 286 Ma. It conformably overlies the Paradox Formation and similarly records cycles of ancient sea levels. The cyclic pattern of the formation shows sea level rise and shortly after, a decline. However, it lacks evaporites and instead contains a mix of river, eolian (windblown sand dunes), carbonate shale, marine or marginal marine deposits. The primary difference of the Paradox Formation and the Honaker Trail Formation is that this Formation had unimpeded circulation of seawater to the open ocean (Sprinkel, 2010). The formation contains interbedded sandstone and limestone in nearly equal portions and containing a small bit of shale. It is suspected that the eolian dunes would have eroded and scoured the seafloor until the sea rose and made it damp enough to hold it together. Because of this, those portions of the formation have decent amounts of bioturbation, or disturbances to the sediment by living organisms that can be used to track the progression of the shore (Fillmore, 2011). The limestone is also fossiliferous as seen in figure 8 containing brachiopods, crinoids, corals, gastropods and echinoids. The limestone increases towards the base of the unit and the center of the basin. As the formation progresses it upward coarsens and includes more clasts at the top of the unit.

Figure 8 . A piece of limestone collected from the Honaker trail formation containing crinoid fossils near Fossil Camp on the San Juan River. It seems that the fossils in the area have been altered and possibly turned to agate.

The Cutler Group

The Cutler Group is a geologic unit consisting of six smaller formations; the Halgaito Formation, Elephant Canyon Formation, Cedar Mesa Sandstone, Organ Rock Shale, White Rim Sandstone and De Chelly Sandstone. It was deposited around 286 to 273 Ma in the Permian Period. The Uncompahgre Uplift, the northeastern boundary of the basin, induced loading on the crust that resulted in the flexure of nearby crust, forming the Paradox Basin. The Cutler Group members were then deposited in the Paradox Basin, a foreland basin associated with a compressional tectonic setting, sourced from material that eroded off the uplift. It is made up of alternating beds of conglomerate, sandstone, limestone, siltstone and mudstone. In the Western portion of the formation, windblown sand, river and marine sediments are more common. Moving to the Northeast, the formation coarsens and is thicker as it nears the Uncompahgre Uplift. Deposits nearest the uplift are conglomerates and coarse sandstones deposited as alluvial fans and detrital material eroding off of the highlands. The uplift was caused by the compression of the continent and thrust faulting associated. The boundary between the Highlands and the basin is one such thrust fault.

Halgaito Formation

The Halgaito Formation is the oldest portion of the Cutler Group deposited in the Permian Period around 286 to 245 Ma. It is made up of mostly reddish brown or dark brown siltstone and silty sandstone with minor elements of limestone. The layers within the formation are generally thinly bedded from marginal marine mudflats and river sediments and form both slopes and ledges (Condon, 1992). It also contains beds of conglomerates and sediment deposited from the Uncompahgre Highlands.

Cedar Mesa Sandstone

The Cedar Mesa Sandstone deposited around 273 Ma. In between the red beds of the Halgaito Member below and the Organ Rock Member above, is the 250-400 foot thick Cedar Mesa Sandstone. It is the second member of the Cutler Group observed along this stretch of river. White to tan beds of sandstone, 20-40 feet thick at a time, include fine to very fine grained quartz, cemented by mostly calcite. It includes limestone concretions and chert. Based on its high composition of limestone, this unit can be classified as a sandy limestone, or limey sandstone (Gregory, 1938). These strata are thinly interbedded by shales, and thin lenses of limestone. The Cedar Mesa Sandstone is primarily interpreted as an eolian deposit with marine influences in both upwind and downwind directions. Fluvial, Sabkha and Tidal Flat Marine facies are also associated with the structural controls on deposition of this unit (Stanesco, 1989). These low elevation features are a direct result of the formation of the Paradox Basin, and like other Cutler Group members, sediments deposited were sourced from erosion off the Uncompahgre Uplift.

Organ Rock Member

The Organ Rock Member is approximately 290 to 272 Ma, composed primarily of red sandstone, and sandy shale. In its regional extent, the member is observed to be from 250- 421 feet thick. Generally, the lower part in contact with the Cedar Mesa Member is more thinly bedded, with northeastern thickening and upward coarsening of beds. In some areas, this member contains streaks of gypsiferous sandstone. The member has a high lime content, primarily of calcite composition (Gregory, 1938). It is conformably overlain by the Cedar Mountain Formation in the region of this river trip. Mostly associated with fluvial deposits, the shales were deposited in flood plains adjacent to channels within the Paradox Basin (Stanesco, 2000). Some eolian strata have also been identified in this region (Condon, 1997).

De Chelly Sandstone

The De Chelly Sandstone is approximately 280 Ma. It is the youngest unit of the Cutler Group, primarily composed of medium-grained gray sandstone which is partly cross bedded and is also associated with a conglomerate of quartz, clay, limestones and shale fragments. It is 4-90 feet thick. In much of San Juan County this unit unconformably underlies the Moenkopi Formation, and at times, the Hoskininni Member intercedes between the De Chelly and the unconformable boundary with the Moenkopi (Gregory, 1938). As this sits on the Permian-Triassic boundary, a period of high erosion due to the nearby Uncompahgre uplift, which would contribute to the unconformity seen in this region.

Influence on Oil and Gas

Before we get into the tectonics of the paradox basin and how this relates to oil and gas, it might be prudent to first give an overview of how such resources are created. There first must be a source for which the oils and gasses come from. The sources for oils and gasses are organic in nature, typically shale with microorganisms such as plankton found embedded within. The amount of time it takes for the oil to form from microorganisms is typically about 200-300 million years. Compression then pushes down on this organic matter turning it into an oily or gaseous fuel much like one squeezes juice from a fruit. The fuel that forms from the resulting compression is then funneled upward into another layer of rock that is well sorted, porous and permeable in nature (Figure 9) where it is collected in a “reservoir”. Above this porous and permeable layer that is considered a “holding tank” of sorts sits a layer of rock that is not permeable or porous that traps the oils and gas in the reservoir and won’t allow it to continue its upward movement. This is how we get “pockets'' of natural oils and gasses that can then be collected and used.

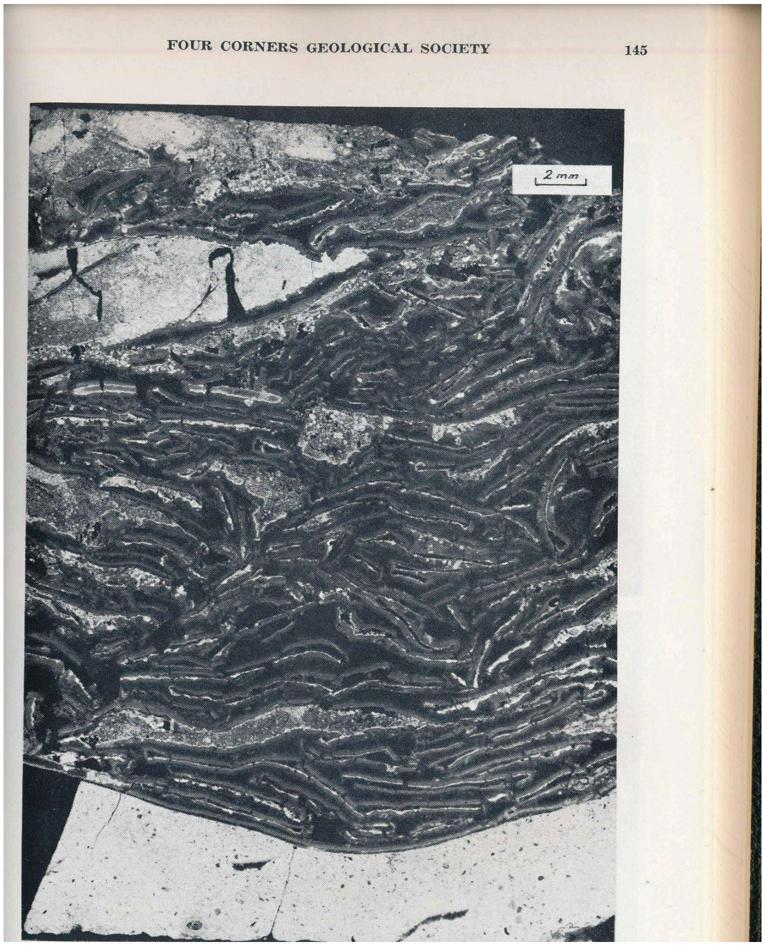


Figure 9. Image shows a section of porous rock that has space to hold pockets of oil. This is where the oil will be accumulated and stay until discovered by oil companies who will then drill down into these pockets and siphon it for use.

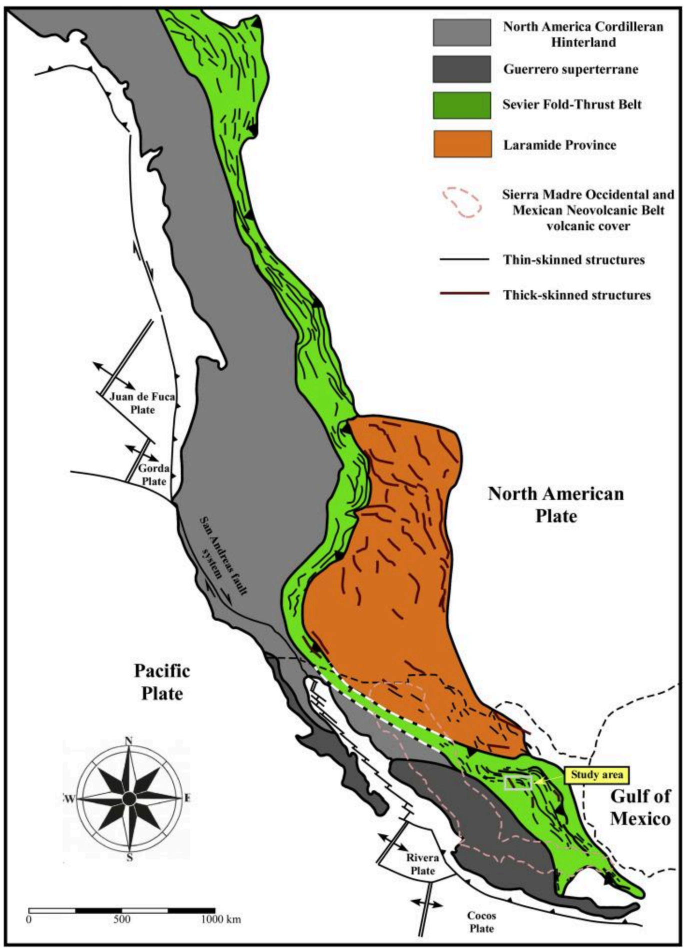
Now that we know how these natural resources came to be, let's tie it into the Paradox Basin. The Pennsylvanian (323-299 Ma) Cane Creek interval is found within the Paradox Formation of the northern Paradox Basin. The Cane Creek interval is an important layer of oil-bearing reservoir rock and was first come across by drillers in the early 1960's but it would not be until the 1990's when significant activity in the Cane Creek interval resumed (Vanden Berg, 2021). As one of the last remaining unconventional oil wells in the United States, the Cane Creek interval was capable of initially producing up to 1,500 barrels of oil per day. Two decades later, in the late 2000's and early to mid 2010's, the Cane Creek interval was still going strong. The Aneth oil field, which includes large portions also located in the Paradox Basin and whose southern end is partially intertwined with the Cane Creek interval, was a top 40 field in terms of proved U.S. oil reserves as recently as 2009, producing around 450 million barrels of oil in its lifetime (NGI, 2022).

Tectonics of the Mesozoic (252-65 Ma)

Overview

The Mesozoic Era was from 252 ma to 65 ma. This era is made up of the Triassic Period, the Jurassic Period, and the Cretaceous Period, and it is noted as being the time of the dinosaurs (Smith, 2011). In this time period, the tectonic plates were having a lot of movement. During the early Mesozoic period the onset of rifting along the future margins of the South Atlantic occurred with intra-continental rifting, generating both strike-slip and extensional basins, within West and Central Africa. This is when pangea started rifting apart creating two new continents, these two continents are called Gondwana and Laurasia. The southern continents created Gondwana while the Northern ones created Laurasia.

This is the time period when the Nevadan Orogeny, Sevier Orogeny, Laramide Orogeny, the formation of the Sundance Seaway, and many other landscape changing events occurred. The Nevadan Orogeny is one of the reasons we have the Sierra Nevada and the Klamath Mountains. It has angular unconformities and also igneous intrusions. Around this time, there was also the formation of the Sundance seaway. "The Sundance Seaway was an extensive epicontinental sea in the Middle to Late Jurassic of western North America, with a terminus in Utah and an inferred connection to the open ocean near the Yukon-Alaska border" (Blakey 2014). This is when the Morrison Formation, famous for Jurassic dinosaur fossils, was deposited in this area. The Sevier Orogeny is a mountain-building event that produced the Sevier Orogenic Belt (Figure 10), a linear zone of deformed rock strata in the western United States extending from southeastern California northeastward through southern Nevada and western Utah to western Wyoming. The Sevier Orogeny shoved stacks of sedimentary rocks from their original positions deep in the crust and further to the west to new positions, upward and to the east. The cause of the Sevier Orogeny was the accretion of numerous terranes from the ancient Pacific Ocean, brought



eastward as the Farallon plate subducted beneath the North American plate.

Figure 10. This figure shows a map including the United States, Canada, and Mexico. The green shows a deformational belt that has extensive folding and thrust faults. This belt was a product of the Sevier Orogeny.

Mesozoic Stratigraphy

Moenkopi

The Moenkopi Formation was deposited in the Early and Middle Triassic, around 240 Ma. The formation is made up of sandstone, mudstone, limestone, and gypsum deposits. The environment would cycle between being a shallow ocean, a broad tidal flat, and a fluvial system (Figure 11) (R. C. Blakey, 1972). This shallow ocean was entirely on continental crust, not oceanic crust like the majority of ocean water. Back then, there was a basin, sometimes called the "Moenkopi basin," where the sea could transgress onto land, and where sediment could be deposited. The environment types would change due to minor changes in sea level, caused by climate and/or the land gradually rising and subsiding, which would have been caused by deformation during the Sonoma orogeny (Levin, 1996). The region was already very flat and low in elevation, so even a slight change in elevation would cause a large change to the depositional environment (Blakey & Ranney, 2008). The basin would have been subsided because of local uplifts, like the Cordilleran arc created during the Sonoma orogeny.

Chinle

The Chinle Formation is a diverse section of rock. It contains layers of coarse sandstones, colorful mudstones, and layers with lots of volcanic material. This formation was deposited in the Late Triassic, around 215 Ma. It has a few prominent members such as the Shinarump and Petrified Forest (although it does not show up along the San Juan River) members, braided and meandering river environments respectively (Figure 11) . The magnitude of the river systems can be compared to some parts of the Amazon River (Blakey & Ranney, 2008). It is also known for having layers with abundant volcanic ash which came from the Cordilleran Volcanic arc to the west, southwest, and south of the Chinle basin (Martz et al., 2017). The surrounding mountains, like the ones created by the Uncompahgre uplift and the volcanic arcs, were the major source for the sediments that make up the formation. Zircon grains have even been found in the Chinle that originated from the southern Appalachian mountains, which was thousands of miles away (Blakey & Ranney, 2008). The Chinle Fm was deposited in a basin, which was created by the Sonoma orogeny. The continued subduction of oceanic crust on the western side of ancient North America, caused the Cordilleran magmatic arc to keep growing. The deformation, caused by the subduction, and the mountain building created a large backarc basin between central Nevada and western Colorado, where the Uncompahgre mountains were (Dickinson, 2006). This is the basin where the Chinle Formation was deposited. It is also the basin where later formations like the Wingate, Kayenta, and Navajo, would be deposited.

Wingate

The Wingate Formation was deposited around 200 Ma, at the end of the Triassic and the beginning of the Jurassic. It is made of a fine to very-fine grained sandstone, which is often reddish-orange. Many rocks from the Wingate Fm show trough cross bedding and very thin horizontal laminations, which indicate, along with the mature textural and compositional sorting, and the color, an arid environment filled with sand dunes (Figure 11) (Tanner & Lucas, 2007).The region would have looked much like the Sahara desert, just not as large. This desert environment formed in a similar latitude as the Navajo Sandstone, around 20° and 30° north (Levin, 1996). The Wingate Formation was being deposited at the same time as the Moenave Formation. They shared the same depositional area, where the fluvial deposits of the Moenave, would migrate and be taken over by the eolian dune deposits of the Wingate, and vice versa (Blakey & Ranney, 2008). The source of sediment that created the sandy dunes in the Wingate Formation predominantly come from the rivers that drained from the ancient “mighty” Appalachian mountains to the east. Once the rivers dried up, the wind was able to blow the sand into the region (Blakey & Ranney, 2008). During this time, there was little to no tectonic activity in the area. The Sonoma orogeny had recently settled down. Because of this, the area was quite stable, and able to accumulate the sediment needed for the vast dunes.

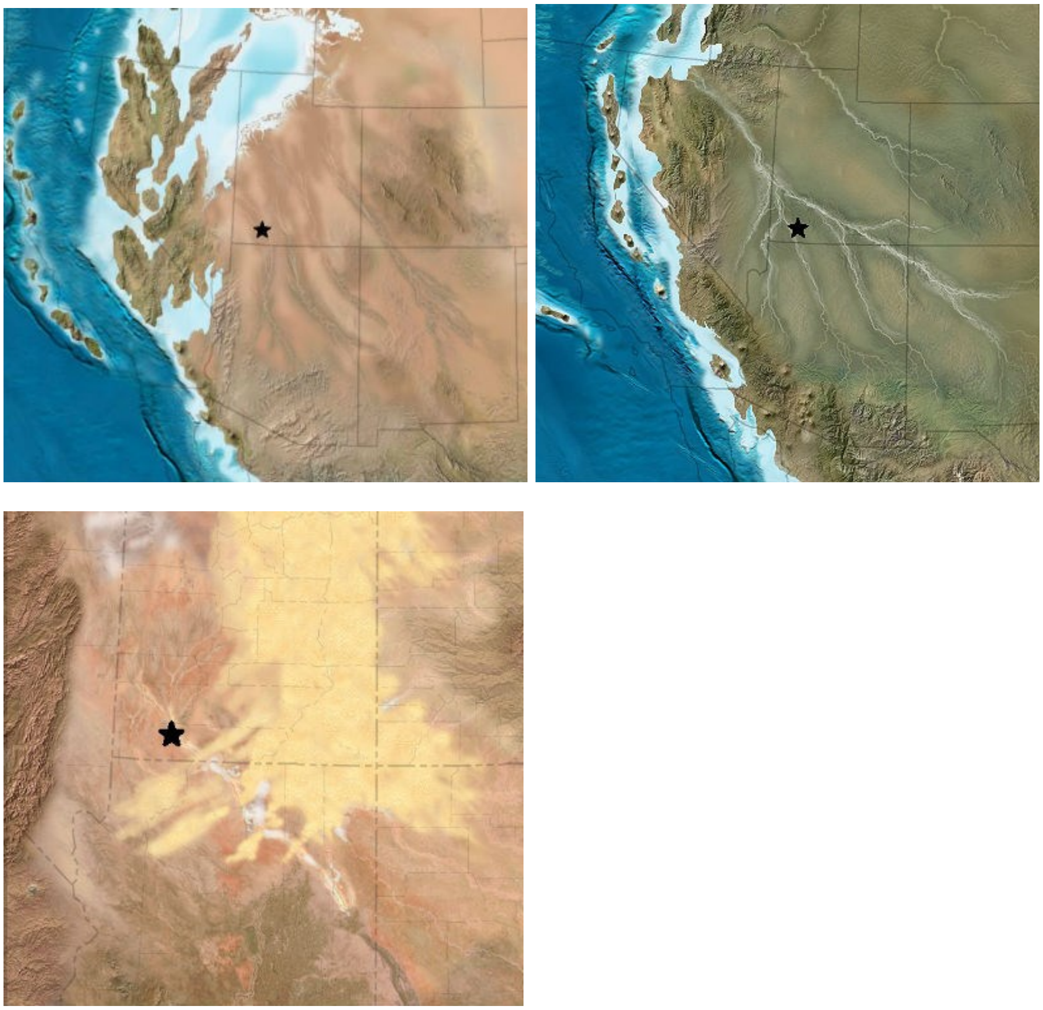


Figure 11. Reconstructed maps based on geologic evidence, showing what the Colorado Plateau and Great Basin regions would have looked like during the time of their respective formations. The black star depicts where Zion National Park is located.(Top Left) Shows the environment of the Moenkopi Fm during the Early Triassic around 240 Ma. The string of islands to the west are the volcanoes of the arc and the accreted terranes added by the subducting plate. (Top Right) The environment of the Chinle Fm in the Late Triassic, around 220 Ma. The river systems have their headwaters in the mountains in the south and east, and they flow northwest. The mountain belt to the west and south is the Cordilleran magmatic arc. (Bottom) The environment during the Wingate (and Moenave) Fm. Around 200 Ma, at the very end of the Triassic and the beginning of the Jurassic. The river system created the Moenave Fm, while the erg, on the eastern portion of Utah, deposited the Wingate Sandstone. All pictures come from the Zion National Park Service,

which got it from the book "Ancient Landscapes of the Colorado Plateau," by R. Blakey and W. Ranney (Blakey & Ranney, 2008).

Kayenta

The Kayenta formation is approximately 190 Ma old, containing varying layers of sandstone and siltstone (Figure 12).The inferred primary depositional environment is braided streams and accompanying floodplains. The sandstone found within the formations is inferred as the actual stream channels whereas the mudstone and siltstone is the surrounding floodplain areas. The time period in which the Kayenta formation deposited was the Early Jurassic, meaning dinosaurs were walking the Earth. The approximated location of what is now the Southwest US, when the Kayenta was depositing in its shallow stream and lake beds with intermittent floodplains, was the far western edge of the Supercontinent Pangea located around the 30-40 degree north latitude lines (Harshbarger et al., 1957). This location on the continent led to an arid environment allowing for braided streams and floodplains flowing off the ancestral Rocky Mountains.

Figure 12. This figure shows the interlayered sandstone and siltstone found within the Kayenta Formation illustrating the different depositional environments.

Navajo

The age of the Navajo Sandstone is approximately 180 Ma. The composition of the Navajo is almost completely quartz sandstone. This formation is extremely widespread, reaching from southern Wyoming to northern Arizona and everywhere in between (Figure 13). Characteristically, the Navajo Sandstone is cross bedded showing the movement of the sand dunes within the Erg, which is a sand dune sea (Weaver, 2015). There are many theories as to why the Navajo Erg formed when and where it did, but one explanation is Hadley Cells. Hadley Cells are low latitude overturning circulations of air that bring hot air from the equator up into the atmosphere and then drop that hot air around the 30° North and South latitude. This Hadley Cell circulation is likely a large reason that the Navajo Erg was able to form and propagate in the way that it did.

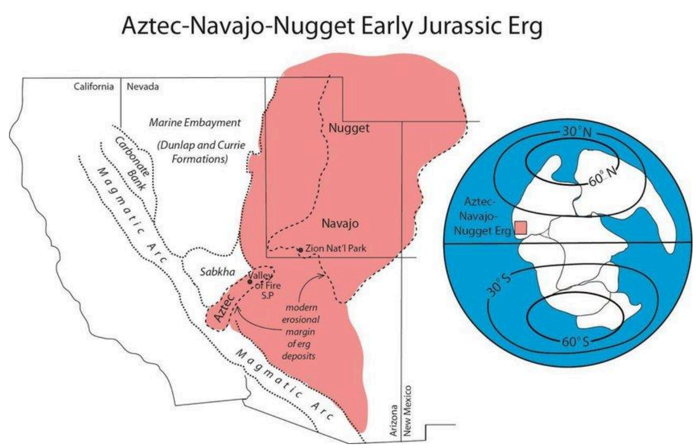


Figure 13 . On the left of this figure, the large pink area shows the approximate location of the Navajo Erg and surrounding environments with some modern state lines shown. On the right of the figure, we have an approximate location of the Erg on a global map scale at the point of deposition, approximately 180 million years ago.

Based on this current information we have about Hadley Cells, we are able to infer that the formation of the Navajo Erg was around the 30°N latitude where the Hadley Cells would drop the hot air from the equator, creating an arid desert environment. Accompanying the Hadley Cell evidence, we know at this time that there was a Supercontinent known as Pangea which incorporated almost all of the known landmass at the time. This Supercontinent allowed for a large desert to form because a large continent equals larger deserts. If you think of Africa today, it is an extremely large continent and the largest desert on the planet is located there.

Carmel

The age of the Carmel Formation is approximately 170 Ma. The composition of the formation is primarily sandstone and mudstone interlayered with limestone and gypsum. Within the layers of the Carmel formation, you will find abundant marine fossils. The depositional environment is what is important to really understand the Carmel formation. Somewhere in 174-163 Ma there was an inland sea known as the Sundance Sea (Figure 14) that came into the continent because of the Nevadan orogeny that caused a foreland basin (Share, 2013) to have an elevation below sea level (Sears, 1985).

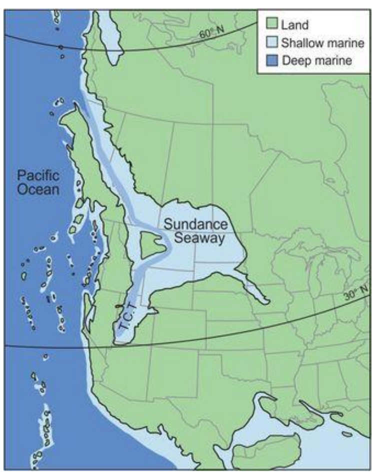


Figure 14. This figure shows a paleogeographic (ancient geography) reconstruction of the Sundance Seaway in and upon which the Carmel formation was able to deposit.

Foreland basins form due to the thickened and heavier material of the orogenic belt causing the surrounding area to sink, in this case, below sea level. This caused the sea to flood into the continent and deposit lots of marine sediment on the inland beaches and underneath the ocean itself. This led to the deposition of many forms of limestone, gypsum, mudstone and sandstone we now see within the Carmel Formation.

Tectonics of Early Cenozoic (66 Ma to ~40 Ma)

Overview

The Cenozoic Era began around 66 million years ago during the middle of the Laramide Orogeny. The Farallon plate has continued to subduct for the past 30 million years underneath the North American continental plate. This subduction created uplift for the development of the modern Rocky Mountains and most of the Colorado Plateau, with some areas being lifted as high as 17,000 feet.(*2008, Ron Blakey and Wayne Ranney)* This movement is also responsible for many of the conjugate fractures seen from California to Colorado. This new elevation led to the Cretaceous Interior Seaway to be phased out, with only a few large lakes remaining. There were also large sweeps of volcanism that moved from west to east over time. This created large igneous intrusions that formed laccolith mountains like the Pine Valley Mountains just north of St. George, or the Navajo mountains just east of Page. Laccoliths are formed when big intrusions of magma push and deform the rock above it, usually resulting in mountainous topography.(*2008, Ron Blakey and Wayne Ranney)*

Entering the early Cenozoic, the Farallon plate was subducting at a very shallow angle. However, as the orogeny progressed, the angle of subduction began to get steeper (Figure 15), leading to another broad sweep of volcanism, this time moving from east to west. This marked the end of the early Cenozoic, as well as the Laramide Orogeny, and the beginning of a new tectonic setting called slab rollback. (*1951, Robert A. Bieberman and Mona Clarich).*

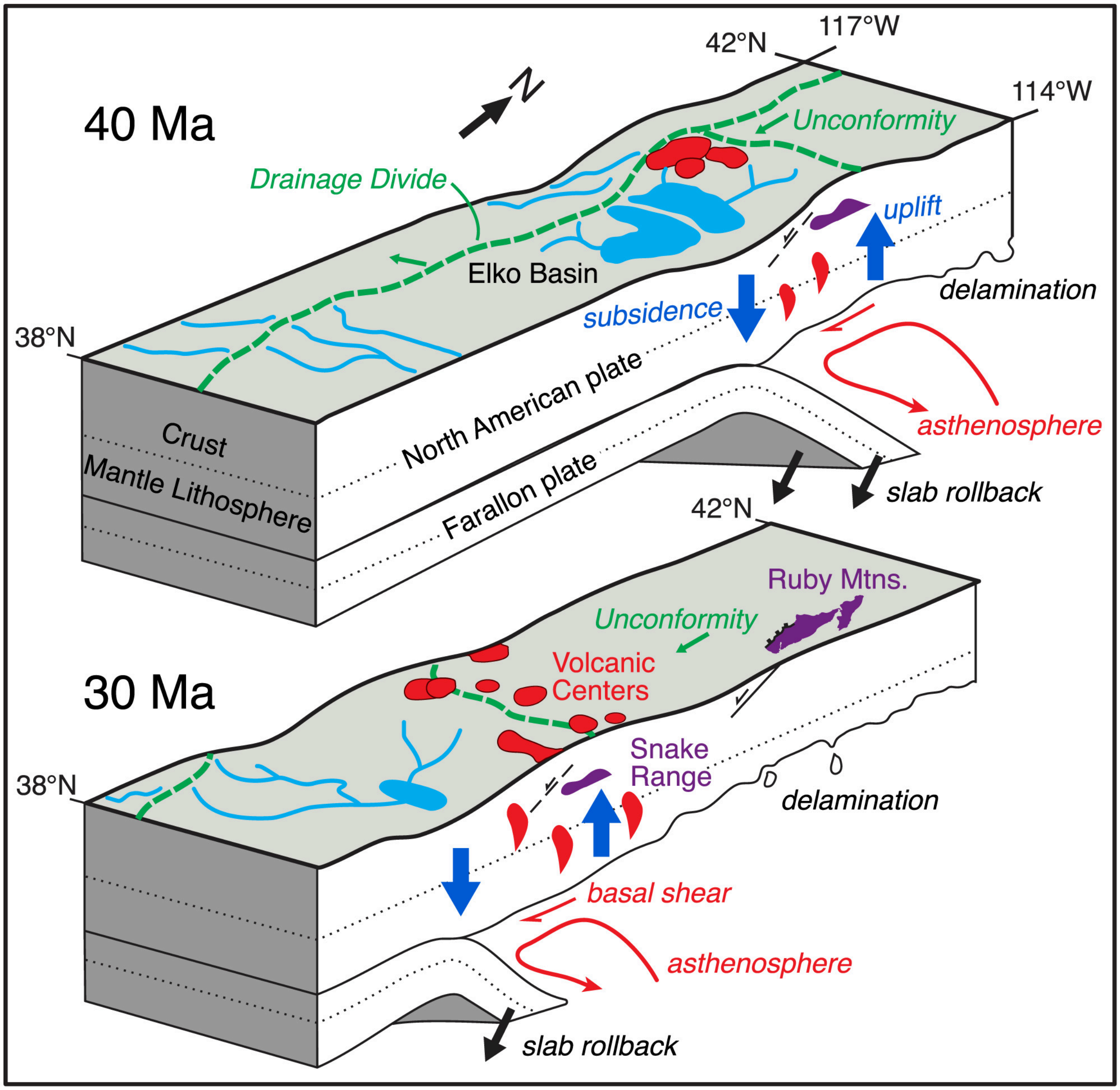


Figure 15. Laramide Orogeny to Slab Rollback

Comb Ridge and Monument Upwarp

An outlook of Comb Ridge can be seen from San Juan Hill, accessible from a trail on the San Juan River. Comb Ridge got its name from its resemblance to a roosters comb (Robinson, 2012). The feature that can be seen at Comb Ridge is a monocline. A monocline is a fold that is roughly shaped like a step, with one side of the fold being flat and the other dipping down. The strata exposed in Comb Ridge include Navajo Sandstone, Kayenta, Wingate, Chinle, Moenkopi and Organ Rock Formations (Robinson, 2012). The Navajo Sandstone is located at the top of the ridge and the Organ Rock Formation is at the base of the ridge. Comb Ridge is the eastern limb of the Monument Upwarp. The Monument Upwarp as a whole is classified as a large anticline. An anticline is a fold in the stratigraphic layers of the earth that roughly takes the shape of an inverted U (Figure 16). The Monument Upwarp covers a vast area. It spans from its eastern point at Comb Ridge to the Great Bend of the San Juan River in the west, and from north to south it extends from Moab, Utah to the Black Mesa Basin in Northern Arizona (Wengerd, 1973). The tectonic event that caused the Monument Upwarp was the Laramide Orogeny. (Holyoak et al, 2019) The Laramide Orogeny is the Late Cretaceous to Paleocene mountain-building event. (English et al, 2008) What distinguishes the Laramide Orogeny from the previous mountain-building events is the change to shallow subduction of the Farallon plate. This change in subduction angle caused a shift in deformation style from thin to thick-skin deformation. Thick-skin deformation is characterized by basement rock being faulted and displaced causing the ductile deformation of the overlying sedimentary strata.(Holyoak et al, 2019) This deformed stratum is what can be observed in the Monument Upwarp and in Comb Ridge.

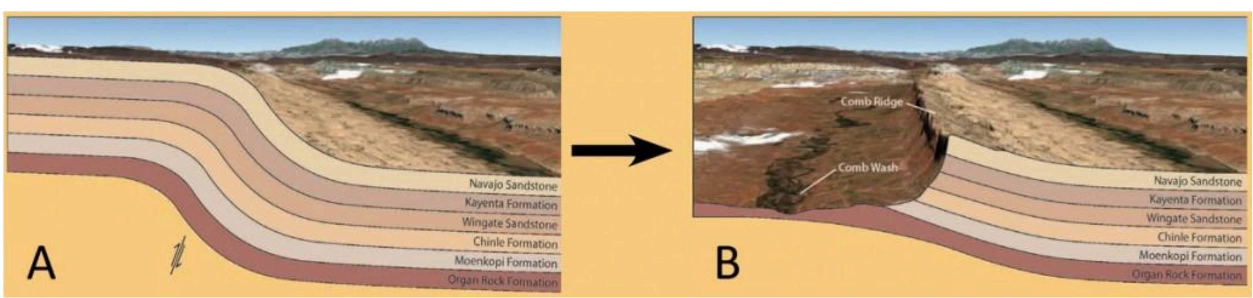


Figure 16. The stratigraphic layers involved with the comb ridge monocline. The layers were folded by thick-skin deformation associated with the Laramide Orogeny and the Monument Upwarp.

Tectonics of Middle Cenozoic (~40 Ma to 20 Ma)

Overview

At this point in time, the North American continent has taken form, the subduction of the Farallon plate has stopped, ending the Laramide Orogeny, and slab rollback is well underway. Slab rollback occurs when a subducted plate detaches from the overlying plate, melting as it sinks into the mantle (Figure 17). The melt produced is differentiable from the North American plate, due to the oceanic origin and lithology of the Farallon plate. As the detached plate melted in the lithosphere, it produced large amounts of gasses and magma, which forced its way to the surface, creating volcanic features all across the Colorado Plateau. During the late Oligocene, volcanics of the San Juan volcanic field consisted mainly of medium-silica composition which then shifted during the early Miocene Epoch to more of a high-silica composition (Lipman et al., 1970). These volcanic events produced large deposits which are associated with the uplift of the San Juan Mountains.

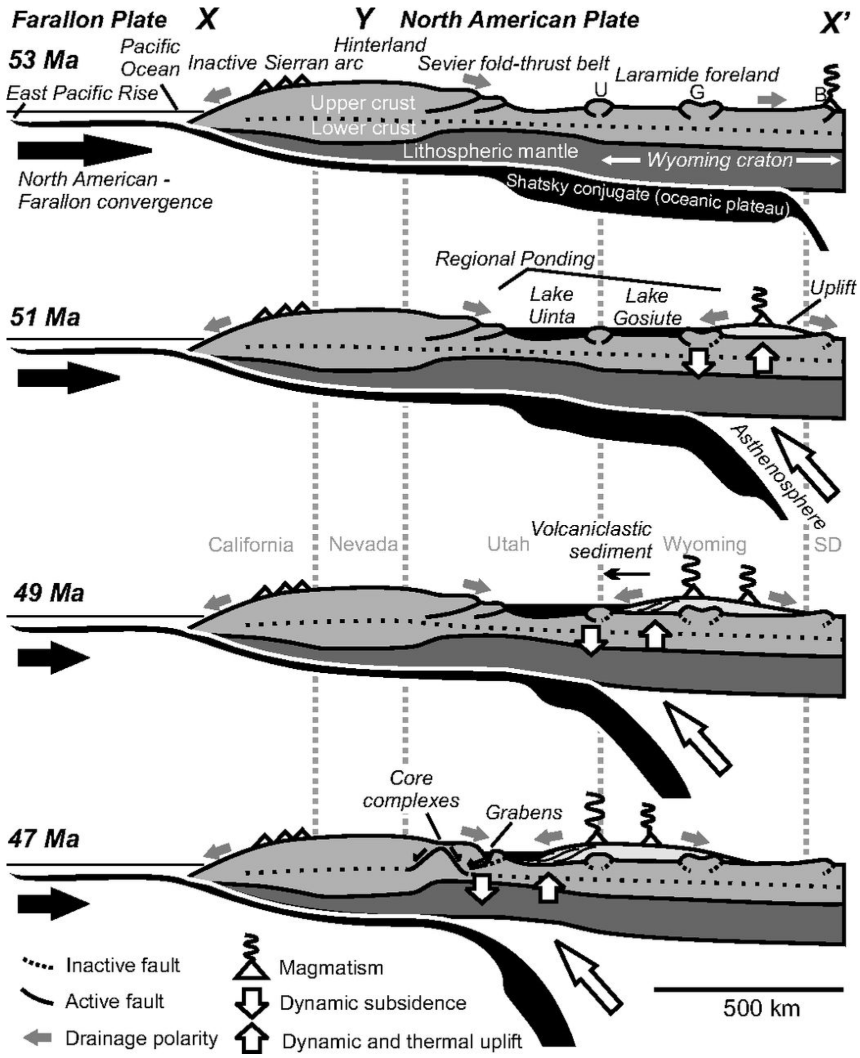


Figure 17. The series of events that took place from 53 Ma to 47 Ma as the detachment of the subducted Farallon plate progressed westword from Colorado and Wyoming, into Utah.

As of Today, the source of the San Juan River starts among the Rocky Mountains in Colorado from the occurring snowmelt and the springs. It then flows through New Mexico and south-eastern Utah where it joins the Colorado River in Glen Canyon. Before the San Juan River, the ancient Crooked Ridge River was a main drainage of the Colorado Plateau from the Oligocene Epoch to about 2 Ma. During this time, Padovani and his associates estimate that the present erosion surface is about 1 km below what the ground surface was about 30 Ma when uplift of the San Juan Mountains caused the Crooked Ridge River to begin flowing. The ancient river left behind exotic gravel deposits of well rounded river stones that range in size from small pebbles to large boulders and can be found today along the San Juan River from the River House Ruins until it enters Comb Ridge.

Volcanic Features

The Mule Ear Diatreme, which is a volcanic pipe formed by gaseous explosions, is visible from the San Juan River to the southeast, approximately ½ mile before the river enters Comb Ridge. It stands out from the surrounding red sedimentary rocks as a mix of yellow, brown and black metamorphic rocks. These colors resulted from volcanic activity that can be directly tied to material that melted from the subducting Farallon plate (Schulze, et. al., 2015). Using samples taken from the Mule's Ear Diatreme, the apparent ages identified are 28 to 30 ma.(Padovani, et. al., 1982).

Volcanic features like the Mules Ear Diatreme are common throughout the entire region that the San Juan river encompasses. These features are remnants of the melt produced by slab rollback, and are a good example of what that sort of tectonic setting can produce. As seen in figure 18, the main structure of the diatreme includes sections of layered and unlayered deposits, with the pyroclastic (or volcanic) material cross cutting through all of these. An important feature of an active diatreme includes what is referred to as a feeder dike, this is where the new, melted material enters into the system. Along with the dike, another distinct feature of an active diatreme is the crater that forms on the surface; this crater, otherwise known as a Maar, is filled in with surrounding sediment eroded from the surrounding landscape. Overtime, the pyroclastic material will harden, be eroded to the surface, and eventually result in what we see in the Mule's ear Diatreme.

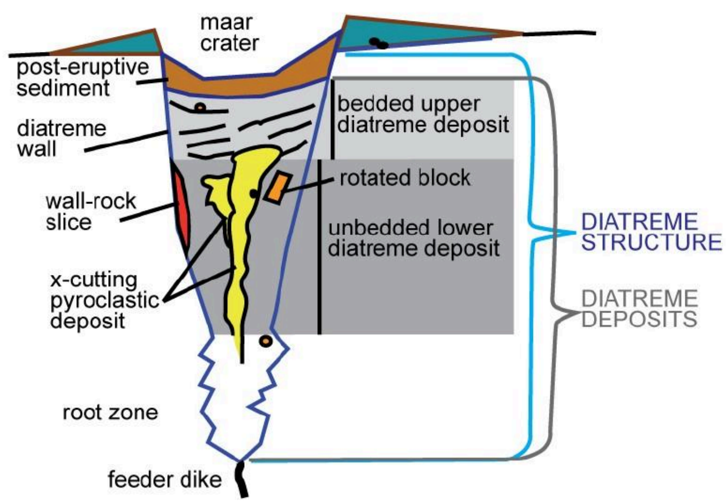


Figure 18. This figure gives an example of what a diatreme/maar system looks like while it is active. Prominent features include the Diatreme itself, the maar, and the feeder dike. Edited from White JDL et al, 2011

Samples taken from the Mule's Ear diatreme, as seen in figure 19, represent the pyroclastic material that makes up the deposit of the diatreme, and are on the surface as a result of uplift and erosion of this depositional body. The most prominent minerals that we can see in the samples include; Quartz: The large and semi cloudy minerals most clearly observed in the lower right specimen, Feldspar: The pervasive white mineral that can be observed throughout the entire sample collection, and Amphibole: The small but equally pervasive black mineral that can be seen throughout all 3 samples.

Figure 19. This figure shows 3 individual samples taken from the Mule's Ear Diatreme.

Tectonics of the Late Cenozoic (~20 Ma to present)

Overview

By the late Cenozoic (23 Ma to the present day) the Farallon Plate had already subducted underneath the North American Plate. This had pushed up the previously discussed Mogollon-Sevier Highlands during the Cretaceous. The San Andreas fault had also already started to form as the mid-ocean ridge between the Pacific and Farallon Plates started to subduct and changed the previously convergent motion between the Farallon and North American plates to relatively transform motion between the North American and Pacific plates.

Slab rollback took place from 50-25 million years ago, so was just ending during the beginning of the late Cenozoic. Slab rollback occurs with the "retreat and steepening of the downgoing tectonic plate during subduction" (Cassel et al, 2018). In this case the Farallon Plate had rolled back.

Collapse of the Mogollon-Sevier Highlands due to the lack of pressure from subduction after the San Andreas had started forming made it so that "compressional forces were replaced by tensional forces" (Eicher, 2003). This, combined with slab rollback which alters the stresses on the overriding plate, drove crustal extension; the main event of the late Cenozoic. In crustal extension, which started around 20 million years ago, continental crust thins as massive blocks of crust drop, tilt, or slump; producing a basin and range region on which volcanic activity was present. Throughout the basin and range region normal faulting separated uplifted mountain ranges (horsts) from downdropped basins (grabens) (Figure 20). This deformation has led to the development of a hydraulic basin known as the Great Basin where all tributaries terminate in this region and none reach the ocean.

Crustal extension probably aided in the uplift of the Colorado Plateau, which is thought to have lifted from the heat of the upwelling plume of hot mantle rock, but is still not fully understood. Tensional forces opened up the Gulf of California which changed the direction of nearby streams towards the sagging and lifting region. Uplift in the upstream part of the rivers and sagging in the downstream part of the rivers caused faster downcut, or erosion. These streams flowing from the Gulf of California formed the Colorado River System, and today the San Juan River flows from the previously talked about San Juan Mountains to meet the Colorado River in Glen Canyon.

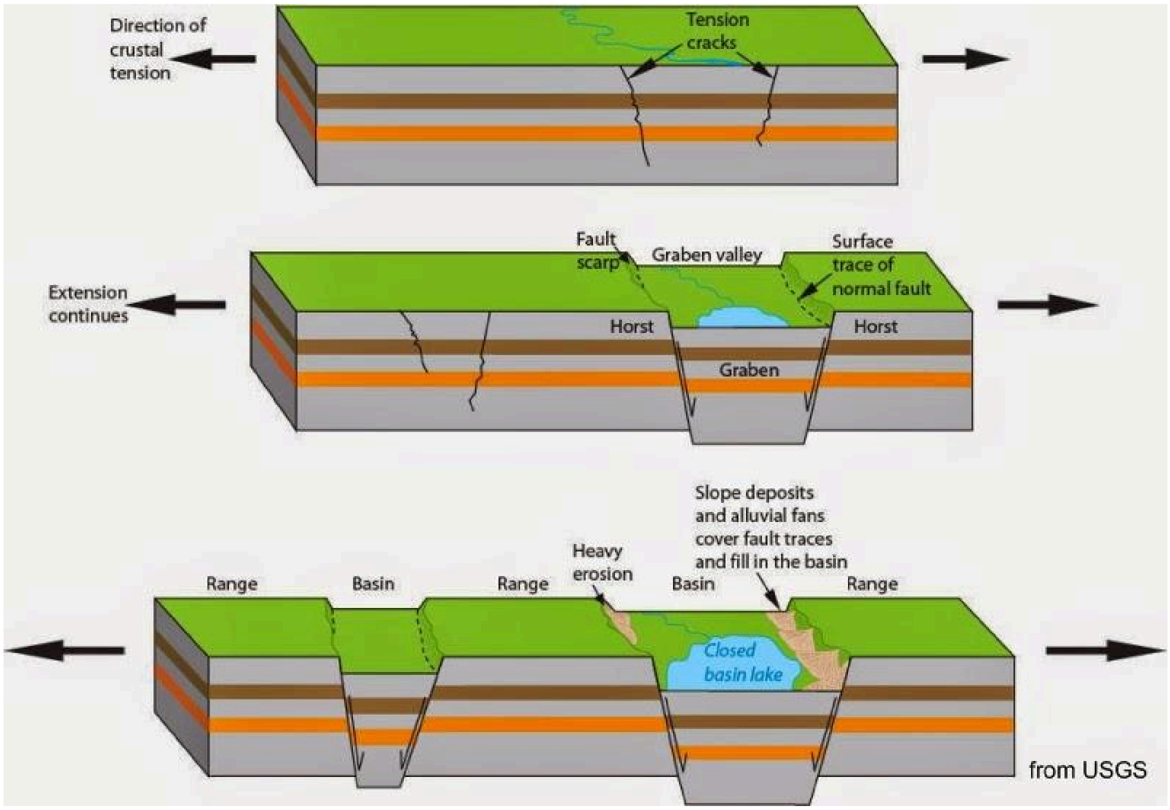


Figure 20. Brittle continental crust breaks when pulled from two sides, usually breaking into steep normal faults that separate the basin (graben) and range (horst) regions.

Canyon Incision

Among the most impressive features of the San Juan River is the San Juan Canyon, which cuts through millions of years worth of Mesozoic and Paleozoic sedimentary rock. The incision of this canyon likely began during the late Pliocene (5.33-2.58 Ma) with the inner gorge being incised about 1.36 Ma during the early Pleistocene (Cooley et al, 1969; Wolkowinsky and Granger, 2004). This incision is part of a period of widespread erosion which has dramatically shaped the southwest over the past six million years in response to tectonic activity, especially the opening of the Gulf of California and the uplift of the Colorado Plateau (Cather et al, 2012).

Starting about 5 Ma, during the early Pliocene, rapid incision of the central Colorado Plateau began (Murray et al, 2016). The factors contributing to this incision are diverse. Extensional tectonic forces along the western margin of North America opened the Gulf of California about 6 Ma, intensifying the North American monsoon, a weather system which involves a period of frequent, heavy precipitation during the summer in the Southwest (Adams and Comrie, 1997), which increased the discharge and, subsequently, rates of erosion of river systems throughout the southwest. Incision of the Colorado Plateau is also attributed to late Miocene (23 Ma - 5.3 Ma) through Holocene (11,700 years ago – present) uplift of the Colorado Plateau due to mantle upwelling (the rising of mantle material due to convection) and isostatic rebound (uplift of the basement rock in response to the removal of heavy material from the surface of the lithosphere) in response to ongoing erosion. The increase in sea level proximity due to the opening of the Gulf of California also initiated the integration of the Upper and Lower Colorado Rivers into the present course of the Colorado River, of which the San Juan River is a tributary, triggering further incision (Cather et al, 2012).

Arguably, the most famous feature resulting from the integration of the Colorado River is the Grand Canyon. The San Juan River may still be responding to the incision of the Grand Canyon, resulting in features such as the incision of the San Juan Canyon (Wolkowinsky and Granger, 2004). Incision controlled by uplift occurred because the gradient from the system's highest point to its base level (the level region at which the course of a river ends, such as sea level or a lake) steepened, throwing it out of equilibrium and causing increased erosion. A river system in equilibrium will have a gentle, arcing profile, which evenly distributes the energy of the system. If the gradient of a river system is altered so that the surface over which it flows is not even with the profile at which it would be in equilibrium, the energy of the flow will be greater in areas where the surface is at a higher elevation than its stable profile, triggering rapid erosion and cutting down into the rock until it becomes even with this profile as seen in figure 21 (Schumm, 1993). After the Grand Canyon was incised, the profile of the river system, including the San Juan River upstream, was significantly affected, which undoubtedly contributed to shaping the San Juan Canyon as it appears today.

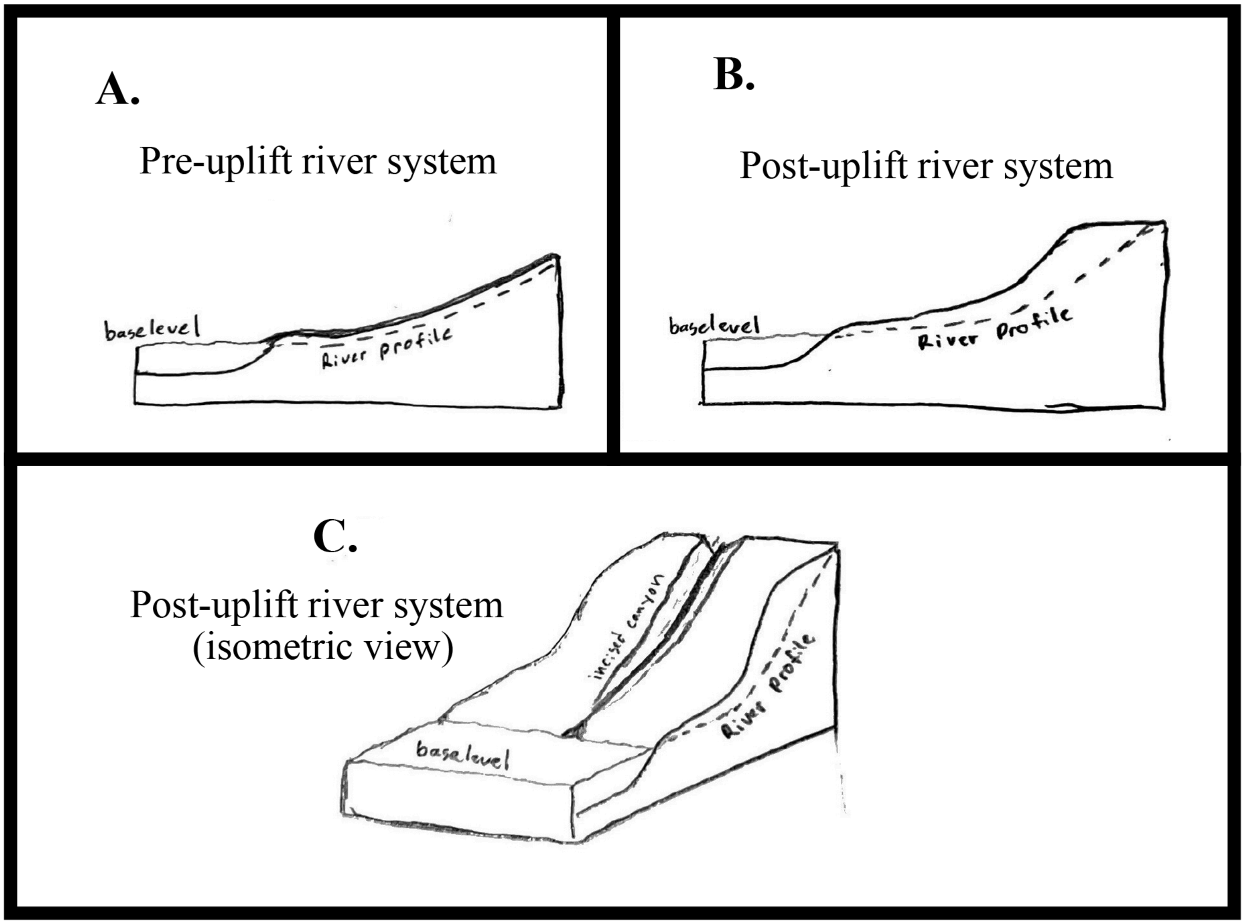


Figure 21. A simplified, visual representation of post-uplift incision.

a. Shows a cross section of a landscape with a river in equilibrium whose profile is even with the surrounding terrain.

b. Shows a cross section of the landscape after uplift. The profile is no longer even with the terrain, and the river is not in equilibrium.

c. Shows an isometric view of the landscape after uplift. The river profile has incised into the surrounding landscape in order to reach equilibrium.

Summary

The San Juan River starts to drain from 25,800 square miles in the San Juan mountains located in Southeast Colorado, just west of the Continental Divide within the San Juan basin. The San Juan basin was created by an intrusion of igneous rock during the beginning of the Cenozoic period. The San Juan river is 360 miles long with only 125 miles within Utah. The river cuts and crosses through several different features and terranes like various types of stratigraphy and various tectonic settings. As the river travels downstream the ages of the rock tend to become older unless the region was affected by a structure from tectonic movement. It is made up of 75% silt and sand that is deposited into Lake Powell at the rate of 25 million tons a year. This region has over 30 different federal designated areas as well as several state designated areas (Parry, 2008).

Starting from Laurentia during the Middle Proterozoic volcanic arcs spewed out material to start to form a continent. Other parts of the continent were formed at subduction zones on the coasts of Laurentia. Later on about 1.7 Ga the area referred to today as the Four Corner/San Juan region was covered by marine and river deposits while the environment was under the process of metamorphism. From 1.4-1.0 Ga there were periods where magma would flow throughout the surface of the region. About 1.0 Ga following all of the accretion Rodina formed and stayed around until it broke up 700 Ma. Today we are able to find evidence of this process from metamorphosed rocks being exposed in a subrange of mountains referred to as the Needle Mountains.

A passive margin was known at the western edge of Laurentia during the Paleozoic where sediment accumulated until the Mississippian Period. When the Antler Orogeny occurred and built mountains in the area. At this point sea level rose until the Pennsylvanian Period until Gondwana collided with the North American plate. Over time as the passive margin transitioned into an active margin it resulted in compressional forces on the North American plate to create uplift and mountain building to start the formation of Pangea. As Pangea formed two orogenies occurred, referred to as the Ouachita and Applalchian. The uplift of Ancestral Rocky Mountains (ARM) resulted from the two orogenies. Because the ARM was in place it resulted in creating uplift and erosion within the area and resulted in units known as the flexural basins where one example is known as the Paradox Basin. This basin had sediment deposited within it from the Mid-Pennsylvanian Epoch to the Permian Period. Within the Paradox Basin formation is the

Uncompahgre Highlands. This sediment is known as evaporites and shale. From the shale held within the Paradox Basin formation at the Cane Creek interval. Drillers have been able to extract oil and gas as early as the 1960s. As of 2009 over 450 million barrels of oil have been extracted from this area. Sitting on top of the Paradox Basin is the Honaker Trail formation, which is younger than the Paradox Basin Formation. It has a mixture of marine/river deposits, sand, and shale. On top of the Honaker Trail formation is the Cutler group, which is younger than the Honaker Trail formation. It consists of smaller formations that were deformed due to the Uncompahgre Uplift. These formations are made up of various materials but mostly consist of limestone and sandstone. The Moenkopi Formation was deposited next and it was deposited during the Sonoma Orogeny. It is made up of sandstone, mudstone, limestone, and gypsum. The Chinle Formation is the next layer, it was deposited in the Late Triassic Period. It is made up of layers of volcanic material, sandstone and mudstone. The Wingate follows on top of the Chinle; it was deposited at the end of the Triassic and the beginning of the Jurassic Period. It is made up of sandstone and some fluvial deposits. The Kayenta is found on top of the Wingate; it was deposited in the Early Epoch of the Jurassic Period. This layer is made up of sandstone surrounded by mudstone and siltstone. The Navajo is on top of the Kayenta and was also deposited in the Early Epoch of the Jurassic Period but is younger than the Kayenta by about 10 Ma. The Navajo is composed of primarily Navajo sandstone. The Carmel Formation was deposited on top of the Navajo Formation. It was deposited about the Middle Epoch of the Jurassic Period. It is composed of primarily sandstone and mudstone, interlayered with limestone and gypsum.

Among the Mesozoic Era there was rifting occurring within the continents. During the time Pangea started breaking apart into Gondwana and Laurasia. Within the era the Nevadan and Sevier Orogenies occurred to form the Sundance Seaway and form igneous intrusion. The Cenezoic Era began 66 Ma during the middle of the Laramide Orogeny. As the Farallon plate has continued to subduct underneath the North American continent for the past 30 Ma. The occurring subduction has promoted the effect of uplift for the Rocky Mountains and the Colorado Plateau. This is shown by conjugate fractures within the area. As the Laramide Orogeny came to a close, the Farallon plate started at a shallow angle and continued getting steeper until it was almost vertical and it folded. This started slab rollback from 50-25 Ma due to isostatic rebound. One of the areas that was affected by slab rollback was the Monument Upwarp which is known as an anticline. On the limb of that anticline there is a monocline known as Comb Ridge.

At the point of the Middle Cenozoic slab rollback is continuing to surge forward and subduction at the Farallon plate collapsed. Volcanic events in this region caused uplift from additional sediment to build the San Juan Mountains. One of the events was the creation of the Mule Ear diatreme that showed up about 30-28 MA. These remnants are evidence from the melt process during the Slab Rollback that originally created a feeder dike and a Maar. During the Oligocene Epoch to about 2 Ma the San Juan Mountains created the ancient Crooked Ridge River which helped to erode the area.

The Late Cenozoic occurred 23 MA, where the oceanic ridges underneath California turned into the San Andreas Strike-Slip Fault. Crustal extension happened 20 Ma when the crust started to slump and constructed the Basin and Range. During the Early Pliocene in the central Colorado Plateau a chain of events were triggered due to the opening of the Gulf of California, to create rapid incision. As the process of incision continued into the Late Pliocene, and into the feature of the San Juan canyon because it was a tributary for the Colorado River. As the areas continue to erode away fragments of rock are carried and deposited downstream.

We were able to raft down the San Juan River and view all of these amazing features in person as seen in figures 22-24. We invite you to take your turn and look for these features as you go down the river. To help you understand the context above please view the map within the following link. Which will direct you to an interactive map that shows some of the important geological features:
https://earth.google.com/earth/d/1dym6uvBpEiR7hKtd_Omsi8e5FiSIKm59?usp=sharing

Figure 22. Our fearless river guide Levi and five of the duckies. As we raft past the east dipping layers of the canyon. This photo was taken by Anna Lorence.

Figure 23. Picture with all of the water craft. All eight of the duckies upfront and four of the rafts in the back. This picture shows how the water has cut into the canyon walls. This photo was taken by Anna Lorence.

Figure 24. A small group of us that made it to the top of a hill made out of Navajo Sandstone. On the left side is Comb Ridge. This picture shows how the stress and faulting of the monocline affect the surrounding area. This photo was taken by Terance Dopp.

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