Brief Geologic History of the Central Cordillera Region (Western USA), with a final focus on Monument Uplift in Southeast Utah

Elizabeth Grant, GEL 230, 3 June 2022

Overview

The Cordilleran orogen is a geologically complicated mountain belt that extends from Alaska to Mexico along the western flank of North America (Burchfiel et al. 1992). Within the contiguous United States, the Cordillera system is a region that extends as far west as California and as far east as South Dakota and Colorado (Figure 1) (DeCelles 2004).

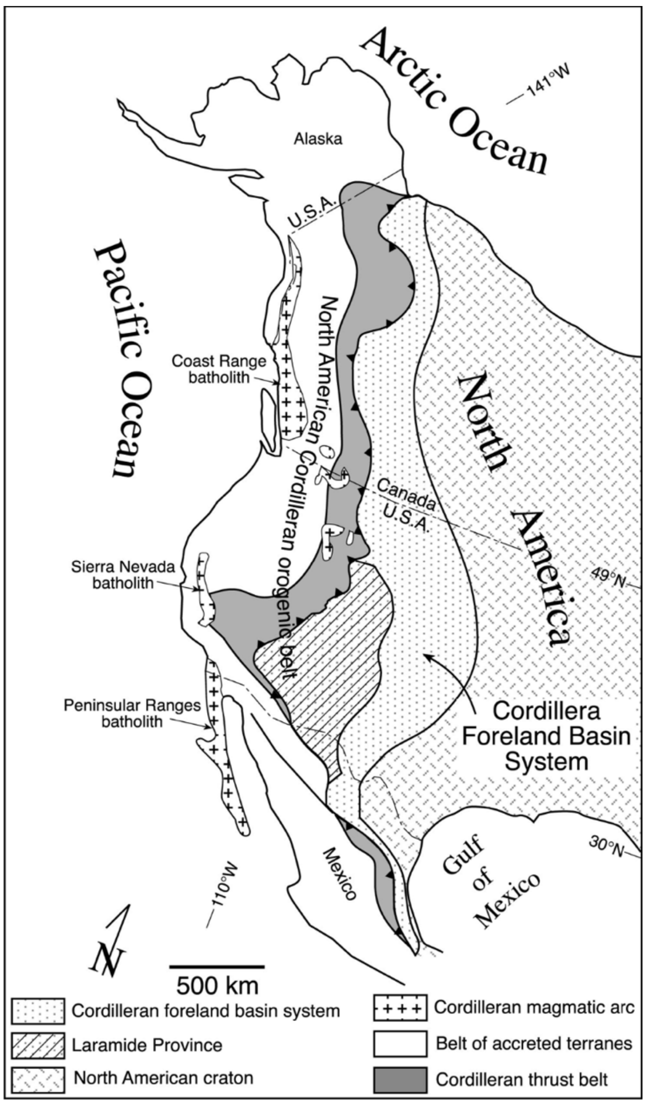

***Figure 1**: From DeCelles (2004), a map of the modern Western U.S. showing the regions of the Cordillera. The Cordillera system extends from Alaska to Mexico, and from the Pacific Coast to as far east as Colorado and South Dakota.*

The Cordilleran region is characterized by mountain belts but also includes a host of other geological and geographical features such as basins, plateaus, and lowlands (Burchfiel et al. 1992). Broadly, the Cordillera is defined by: 1) the development of a miogeocline (passive margin sediments), 2) accumulation of accreted terranes as island arcs and the development of an Andean-type arc, 3) eastward propagation of magmatism and deformation in the retro-arc region, and 4) Cenozoic extension (Burchfiel 1992). The creation of the Cordilleran belt is ultimately the result of the relative motions of lithospheric plates (plate tectonics) and, more specifically, subduction margins creating compressive stress states which give rise to local and regional deformation. The intense compression forces resulting from the collision of two continents, or between a continental margin and young oceanic lithosphere, accommodates compression by accretionary wedge thrust faulting and retro-arc thrust faulting (Figure 2) (Kearey 2009).

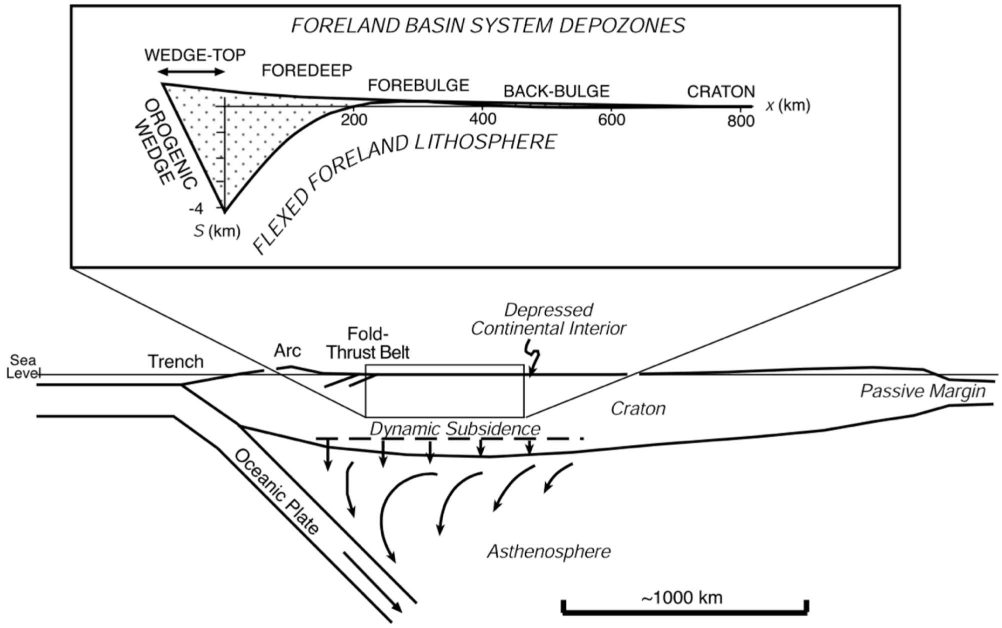

***Figure 2**: From DeCelles (2004), this diagram illustrates a west-east cross-sectional view of the major tectonic regions across the U.S.: the Western U.S. is characterized by eastward subduction of the Pacific Plate beneath the North American Plate, with a magmatic arc above; to the east compressional forces create fold-and-thrust belts in the Rocky Mountain region; the Great Plains and Midwest regions are characterized as a depressed continental interior from flexural loading of sediments; and the East Coast is defined by a passive margin with no tectonic activity. The inset shows a thrust fault foreland basin, which is a system of depositional environments on the footwall side of a thrust fault system that forms due to flexural loading of the crust.*

The development of the Cordillera has been the subject of multi-disciplinary study for many years. Our understanding of how the Cordillera was built through time has come from detailed field mapping, stratigraphic and sedimentological analyses, geochronological studies, and geophysical studies (DeCelles 2004).

The paper will provide a short overview of the development of the Cordillera, with a more focused overview of the history of Southeast Utah and the structures have come to define the Colorado Plateau region.

Proterozoic Eon

During the Proterozoic Eon, what we understand today as North America was a continental land mass known as Laurentia, which included Eastern Canada, the U.S. Midwest, and Great Plains region. Generally, Laurentia is considered to have been composed of stable crystalline rock, mostly granitoids and gneisses, also referred to as the North American craton (Boyce et al. 2016). During the Proterozoic, the western margin of Laurentia developed a depositional system consisting of continental platform, shelf, slope and abyssal plain. Such a region is also called a miogeocline: a down-flexed region along the continental shelf and slope of a passive margin, which accumulates a thick package of sediments (Figure 3) (Dietz and Holden 1966).

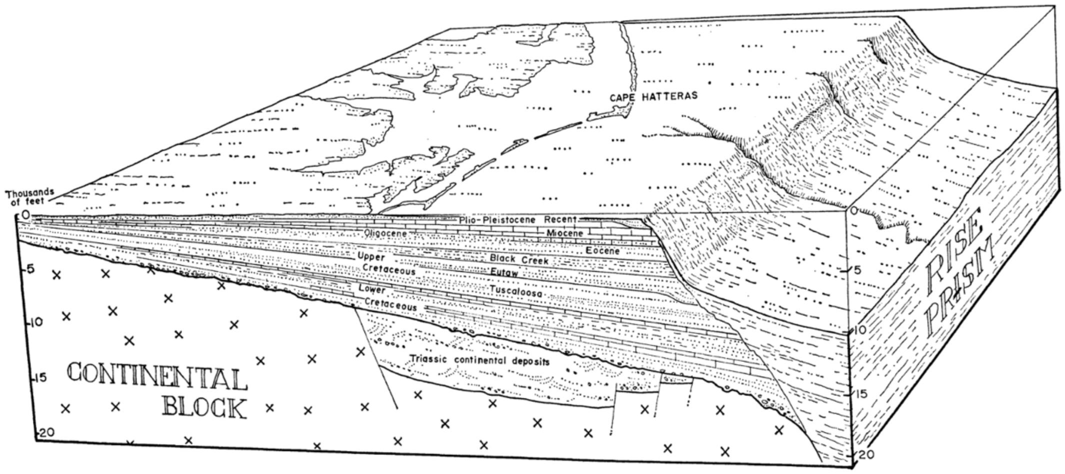

__Figure 3__: From Dietz and Holden (1966), this schematic illustrates the depositional regions that define a miogeocline. A miogeocline develops along a passive margin, mainly on the continental shelf and slope.

As the stable craton was eroded, sediment was transported and deposited within the depositional environments of the miogeocline. Thus, the easternmost Cordillera region is underlain by Proterozoic-aged crystalline rocks and capped with a thick sequence of craton-derived sediments (Stewart and Poole 1974). During the Late Proterozoic through the Devonian Period (Paleozoic), the miogeocline continued to develop and thickened westward to a maximum depth of 6000 meters, entirely composed of sediments shed from the craton (Burchfiel et al. 1992, Poole et al. 1992). Paleotectonic reconstructions of the Western U.S. suggest that Southeast Utah was submerged for most of this time period, and accumulated thick deposits of limestone, mudstone, and siltstone as a result (DeCelles 2004).

Paleozoic Era

Through the early Paleozoic Era, the miogeocline off the western edge of the craton continued to develop (Figure 4, Phase II).

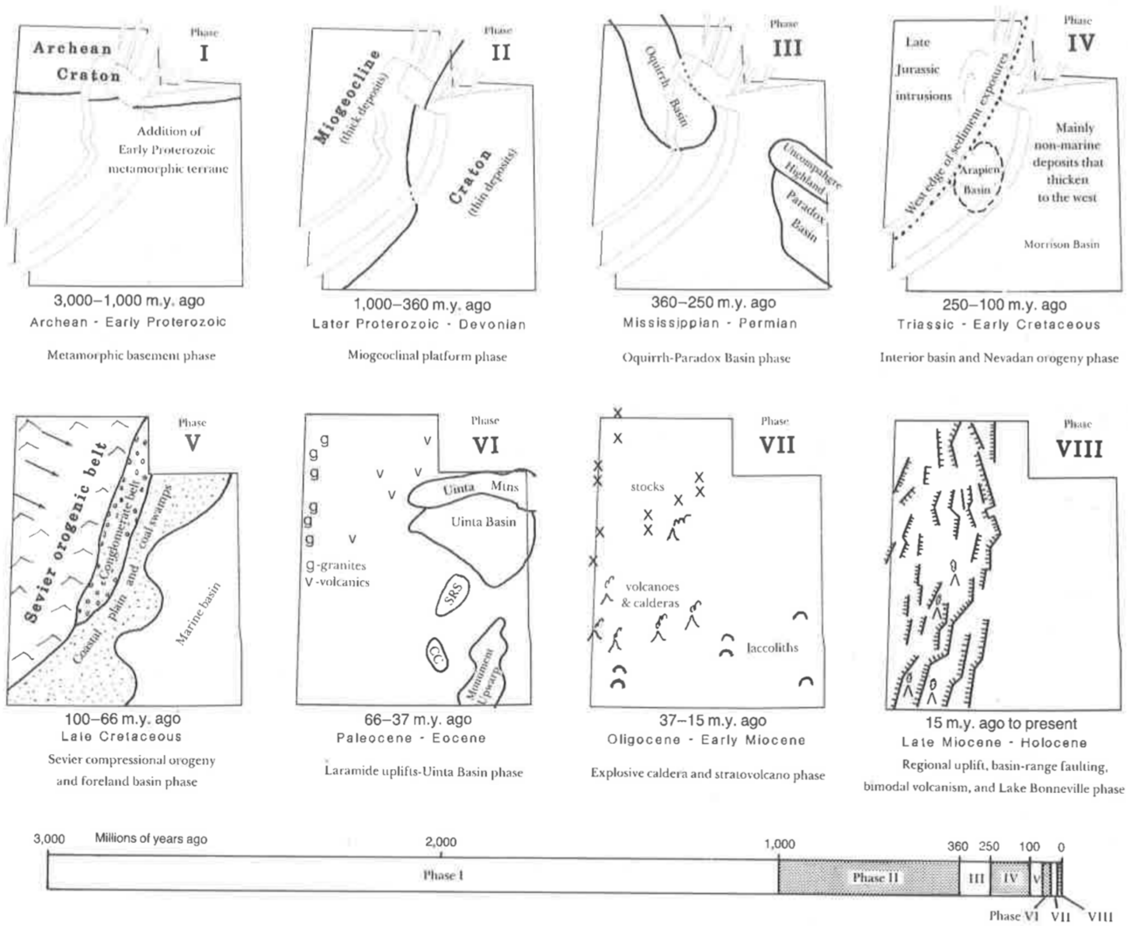

Figure 4: *From Hintze (1988) this figure shows a time progression of the geologic development of Utah. Starting with Phase II Utah was positioned along a miogeocline and transitional continental shelf environment, the black line shows the estimated hinge line of the miogeocline; Phase III: The Antler and Sonoman orogenic events create a compressional stress state, forming basins in Utah; Phase IV: Initiation of Sevier Thrust to the west, depositional of massive sand dunes along the Sundance Sea boundary to the east; Phase V: Sevier Thrust front in Utah, promotes deposition in foreland basin, and in the east a coastal environment is developed along the boundary of Western Interior Seaway; Phase VI: Laramide deformation front forms uplifts in Utah, the Colorado Plateau begins to separate from surrounding terranes; Phase VII: shows the distributed location of magmatism and volcanism in Utah, minimal volcanic activity on the Colorado Plateau; Phase VIII: Location of Basin and Range extensional normal faults (does not affect Colorado Plateau).*

This region was also marked by episodic sea-level change resulting in a variation of supratidal, intertidal, and shallow marine sedimentation (sandstone, siltstone, mudstone, and limestone deposition). From the Western direction, plate convergence thrust Paleozoic sedimentary rocks onto the miogeoclinal rocks in an orogenic event (mountain building) called the Antler Orogeny, which occurred between the Late Devonian and Early Mississippian Periods (Stewart and Poole 1974, Miller et al. 1992, Dickinson 2000, Ketner 2012). The compressive state created by the eastward movement of the Pacific Plate and the westward movement of the North American Plate (craton) caused the shallow marine and continental shelf and slope deposits to deform as fold and thrust belts. The chief thrust sheet associated with the Antler orogeny is the Robert Mountain Thrust, which is composed of siliciclastic sediments and moved rocks as far as 200 miles eastward (Poole et al. 1992). To the east of the Robert Mountain Thrust, in West-Central Utah, silicic sediments were shed off the Antler orogen and deposited in the foreland basin (Figure 2), interfingering with miogeoclinal sediments from the east, and even traveling as far as the craton interior (Dickinson 2009). Flexural loading from sediment accumulation promoted the formation of these foreland basins (Burchfiel et al. 1992).

During the Pennsylvanian Period (Figure 4, Phase III), the uplift of the ancestral Rocky Mountains was most likely initiated by compressional stresses that propagated eastward from the Antler orogenic event. Although there is no clear understanding of how event began, some researchers believe that uplifts were caused by high-angle thrust faulting along pre-existing faults that cored into the crystalline basement (Kluth and Coney 1981, Miller et al. 1992, Burchfiel et al. 1992). This formed adjacent fault-bounded basins which accumulated erosive sediments shedding off the newly uplifted mountains. One such basin, Paradox Basin in East-Central Utah, was filled with evaporites and shales (Paradox Formation), carbonates (Honaker Trail Formation), and siliciclastic sediments (Cutler Group) from marginal marine environments flooding the basins (Barbeau 2003). Paradox Basin was subsequently deformed by later orogenic events, uplift of the Colorado Plateau, and river incision (Nuccio and Condon 1996).

In the early Paleozoic, Utah is broadly divided into two portions: miogeoclinal sediments to the northwest, and transitional sediments between the miogeocline and the craton margin to the southeast (Figure 4, Phases II and III). During the Paleozoic, Southeast Utah was a transitional environment where multiple transgressive and regressive sequences deposited thick packages of carbonates, interspersed with sporadic beds of shale and siltstone, between the continental shelf and the craton margin (Poole et al. 1992). These limestone and siliciclastic sedimentary rocks are deposited uncomfortably on Proterozoic crystalline basement rocks (Poole et al. 1992).

Mesozoic Era

The accretion of island arcs and terranes throughout the Paleozoic and Mesozoic Eras effectively clogged the subduction zone to the west of the miogeocline, creating tremendous compressive forces that propagated into the retro-arc region where laterally continuous thrust faults emplaced older rocks onto youngers rocks. Compression was so pervasive during the building of the Cordillera that shortening is estimated at >350 km in Central Utah (DeCelles 2004). As a result of the pervasive shortening in the region, extensive erosion of the Mesozoic thrust sheets deposited sediments in the foreland basins that reach what is now the Colorado Plateau (Figure 4, Phase IV) (Burcfiel et al. 1992).

Triassic Period

Following the Antler orogeny, the next significant orogenic event is the Sonoma orogeny (Late Permian – Early Triassic), whose chief thrust system was the Golconda allocthon (series of thrust sheets compositionally derived from a non-local source). The Goldconda allocthon was thrust onto Paleozoic shelf sediments of Utah east of the Robert Mountain Thrust (Saleeby et al. 1992). Although neither the Antler nor the Sonoma orogeny occur in Utah, Utah serves as the depositional basin for the bulk of the sediments shedding off of these mountain building events.

In the Triassic Period, Southeast Utah was still along the margin of the craton, sloping toward the miogeocline. Sedimentological analysis suggests that the depositional environments were shallow lacustrine systems within a broad coastal plain (Saleeby et al. 1992). However, by Mid-Triassic, modern Utah was no longer submerged and marine deposition ceased (Carr and Paull 1983). As the Triassic progressed, the Southeast Utah region was dominated by floodplains. The resulting package of sediments from the Triassic is the Moenkopi Formation (limey-siltstone) capped by the Chinle Formation (sandstone and siltstone) (Hintze 1988). Both formations are separated above and below by unconformities (Saleeby et al. 1992).

Jurassic Period

The Sonoman period ended by the Late Jurassic, and a new deformation front, the Sevier fold and thrust belt, had initiated thrusting in Utah, east of the Antler and Sonoma orogenies (Figure 4, Phase V) (Yonkee et al. 2019). Deformation associated with the Sevier thrust (Jurassic-Cretaceous) can be traced from southern California into Canada, and there are estimates suggesting that the Sevier Thrust moved rocks 50-100 km to the east (DeCelles 2004). Sevier deformation is characterized by "thin-skinned" fold and thrust belts in sedimentary layers. "Thin-skinned" deformation occurs as weaker sedimentary layers are deformed above a stronger decollement layer (Figure 5). The Sevier sheet was thrust upon the hinge of the miogeocline, and it shed sediments into the foreland basins and shallow marine system covering Utah.

By the Jurassic Period, eolian (wind-blown) deposition of massive sand dunes dominated what is now Southeast Utah. The Wingate, Kayenta, and Navajo Formations (sandstones) are all found in Southeast Utah, and their presence suggests that the depositional environment must have been a coastal dune field (Hintze 1988). In the Late Jurassic and Cretaceous, flexural loading from Sevier thrust sediment accumulation formed a series of foreland basins in Southeast Utah (Cowan and Bruhn 1992, Burchfiel et al. 1992). This flexural downwarping caused local inundation which promoted the formation of a playa lake system that eventually became the depositional environment for the Morrison Formation. In the Late Jurassic to Early Cretaceous, Southeast Utah is dominated by nonmarine fluvial and lacustrine deposits as the topography is cut by local uplifts and basins from Laramide deformation.

Cretaceous Period

Starting in the Late Cretaceous Period the Laramide deformation period beings, overlapping with the tail end of the Sevier deformation period (Figure 4, Phase VI). Laramide deformation is characterized by "thick-skinned" thrusting style, where large packages of sedimentary rocks are transported along thrusts within the crystalline basement (Figure 5).

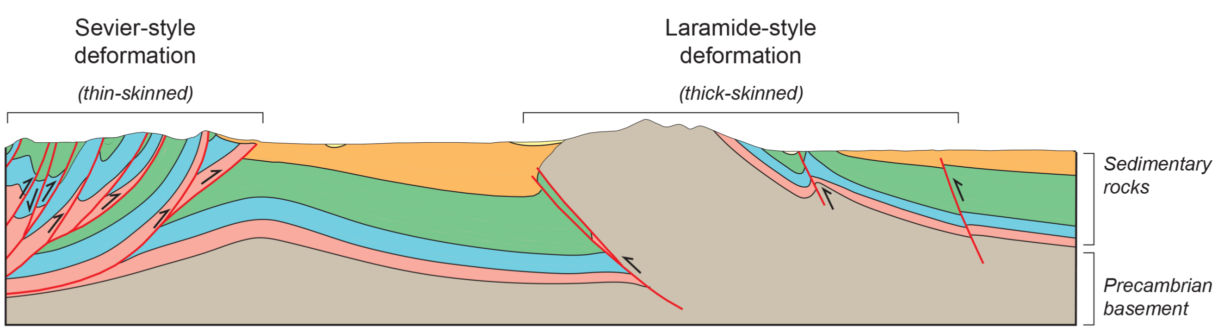

Figure 5: *Thin-skinned (Sevier style) deformation style (left) transports slivers of sedimentary packages along a basal decollement (pink layer). Conversely, thick-skinned (Laramide style) deformation (right) transports packages of rock that include the crystalline basement. (Figure from Wyoming State Geological Survey.)*

The difference between the Sevier and Laramide thrust styles is that Laramide involves crystalline basement (crystalline basement is thrust onto younger rocks), whereas Sevier deformation is “decollement-style” thrusting. Although the origin of Laramide uplift deformation is actively debated, most researchers attribute it to the shallowing of the slab dip angle and the intense compressional forces generated from flat slab subduction (Miller et al. 1992). This process allowed viscous drag forces between the subducting flat slab and the overriding plate to create a stress state wherein faulting and uplift of crystalline basement (Laramide style) was possible (Miller et al. 1992).

Thick-skinned Laramide deformation during the Late Cretaceous saw the rise of thrust fault bounded uplifts (crystalline basement) with associated sedimentary basins (Miller et al. 1992). Intense compressional forces and thrusting from the Laramide broke up the foreland uplifts and basins and gave rise to the modern Rocky Mountains (Miller et al. 1992). Near uplifts, basins were subsequently filled with terrigenous sediments shedding off of the uplifts. Simultaneously, the basins served as depositional environments for marine and fluvial sediments from the many transgressive-regressive marine sequences during the Mesozoic (Nuccio and Condon 1996, Barbeau 2003). The most significant of the marine transgressions were the Western Interior Seaway during the Cretaceous (which itself contained upwards of ten smaller transgressive-regressive episodes) and the Sundance Seaway of the Jurassic period (He et al. 2005, Danise and Holland 2017). During the Cretaceous Western Interior Seaway inundation, marine waters submerged Utah, but during low-stands (regressive sequences), fluvial systems built large fans in basins and around uplifts (DeCelles 2004) while eastward directed fluvial systems build deltaic and swamp systems toward the Western Interior Seaway. Organic matter deposition in these quiet waters eventually leads to the formation of oil and coal deposits (Hintze 1988).

Cenozoic Era

The shallowing of the slab in the Central Cordillera is considered one of the chief causes of Laramide deformation and the eastward migration of magmatism. Within the Colorado Plateau region, underthrusting from the shallow slab promoted the formation of several northwest and northeast trending monoclines, activated along pre-existing basement faults (Bump and Davis 2003). Due to lithological and thermal coherence of the Colorado Plateau block, the few monoclinal upwarps on the Colorado Plateau are relatively rare when compared to the copious number of Laramide structures in the adjacent Basin and Range province (Parsons and McCarthy 1995, Roy et al. 2009). Laramide deformation continued through the Eocene Epoch, actively creating uplifts and monoclines in Utah. One such monocline is Monument Uplift (or Upwarp) located in Southeast Utah. By the end of the Laramide deformation period in the Late Eocene – Early Oligocene, Basin and Range extension became the dominate tectonic stressor in Nevada and Northwest and Central Utah (Hintze 1988). Extension tore apart structures and caused rapid erosion and sedimentation into nearby basins (Hintze 1988, Christiansen et al. 1992). The Colorado Plateau, however, was little affected by the tensional forces, and Laramide monoclines were preserved (Burchfiel et al. 1992, DeCelles 2004).

Colorado Plateau Province

The Colorado Plateau sits at an elevation of 2 km, in stark contrast to the Basin and Range and Rio Grande rift regions adjacent to it (Parsons and McCarthy 1995). Uniformly distributed Cretaceous-age marine sediments and a dearth of Cenozoic age sediments suggest that it was uplifted shortly after or during the Late Cretaceous Period (Spencer 1996). By the end of the Laramide period (Early Eocene), extension along local structures and preexisting faults began to detach the Colorado Plateau block from surrounding structures, allowing the clockwise rotation and uplift of the block (Burchfiel et al. 1992). Although there is no agreed upon mechanism for uplift, there are several aspects of the uplift model that are largely accepted. Most researchers agree that heat derived from the flat slab subduction of the Pacific Plate promoted thermal expansion and crustal thickening. Subsequent density driven fractionation and delamination of more mafic materials then caused the plate to respond with isostatic rebound (uplift). Finally, upwelling of asthenosphere mantle buffered the thermal state of the plateau, supporting its elevated state (Parsons and McCarthy 1995, van Hunen et al. 2002, Roy et al 2009).

Basin and Range Province

Basin and Range extension is accompanied and partly controlled by slab rollback of the Pacific Plate which promotes the migration of extensional magmatism (both plutonic and volcanic activity) (Figure 4, Phases VII and VIII). The chief pulse of magmatism was focused from the Eocene to the Oligocene, and was dominated by small eruptions of alkali basalts and andesites, and maar eruptions preserved as diatremes, necks, and stocks. Diatreme (volcanic pipes) are common in parts of the Colorado Plateau. Diatremes are deep-rooted gas-rich eruptions that can bring mantle xenoliths to the surface. Mantle-derived CO_2 was likely the chief volcanic propellant in these eruptions, but there is evidence that some eruptions interacted with the water table or with water in fractured rock. The result was a gas-fueled explosive eruption that blasted through the overlying rock, creating a breccia-filled deposit.

Quaternary Period

San Juan River incision began during the Pliocene and Pleistocene Epochs. The average incision rate of the San Juan River is estimated around 110 (+/- 14) m/Myr over the past 1.36 Myr (Wolkowinsky and Granger 2004). Importantly, this is a minimum rate of vertical incision and does not account for lateral river migration or Holocene erosion. For comparison, river incision rates for the Little Colorado River near the Eastern Grand Canyon are 140 m/Myr. It is postulated the San Juan River is still responding to the rapid incision of the Grand Canyon (6 Ma) and remains in a state of disequilibrium (Wolkowinsky and Granger 2004, Karlstrom et al. 2008). This topic is highly contested as more recent work by Pederson et al. (2013) suggests river incision rates of ~300 m/Myr for the San Juan River.

Economic Impact

Utah is an oil and gas producing state. In Southeast Utah the chief source of oil comes from the Paradox Formation (Bradish 1952). If trapped by an impermeable layer, the antiformal shape of the rocks trap and concentrate oil and gas. In effect, this makes these compressional structures targets for oil and gas prospectors (Mynatt et al. 2009). The economic drivers behind oil and gas mining present potential threats to river conservation, as oil and gas mining can be environmentally destructive (Vartan 2019).

Geologic Features in Southeastern Utah (Bluff, Utah, to Clay Hills, Utah)

Monument Uplift (or Upwarp) is a broad, north trending monocline (Laramide compressional structure) located in Southeast Utah between Bluff, Utah and Clay Hills, Utah. Structurally it is bound by a steeply dipping forelimb on the East (Comb Ridge Monocline) and a gently dipping backlimb to the West the Henry Basin (Nuccio and Condon 1996, Bump 2004). There is a thick sedimentary package covering the basement-cored fault. Thus, any study of the paleostresses in the region is conducted by examining small brittle features in the sedimentary cover (Bump and

Davis 2003). Subsidiary to Monument Uplift are Comb Ridge Monocline, Raplee and Lime Ridge Anticlines, and the Mexican Hat Syncline (Bump and Davis 2003). Raplee and Lime Ridge Anticlines are en echelon folds within the greater monoclinal structure of Monument Uplift (Bradish 1952). Within Monument Uplift, the Pennsylvanian-aged, oil-bearing Paradox Formation (evaporites and shales) is the oldest exposed rock unit, and it is visible at Goosenecks State Park (Bradish 1952).

The Mule Ear Diatreme erupted through Comb Ridge Monocline (Figure 6).

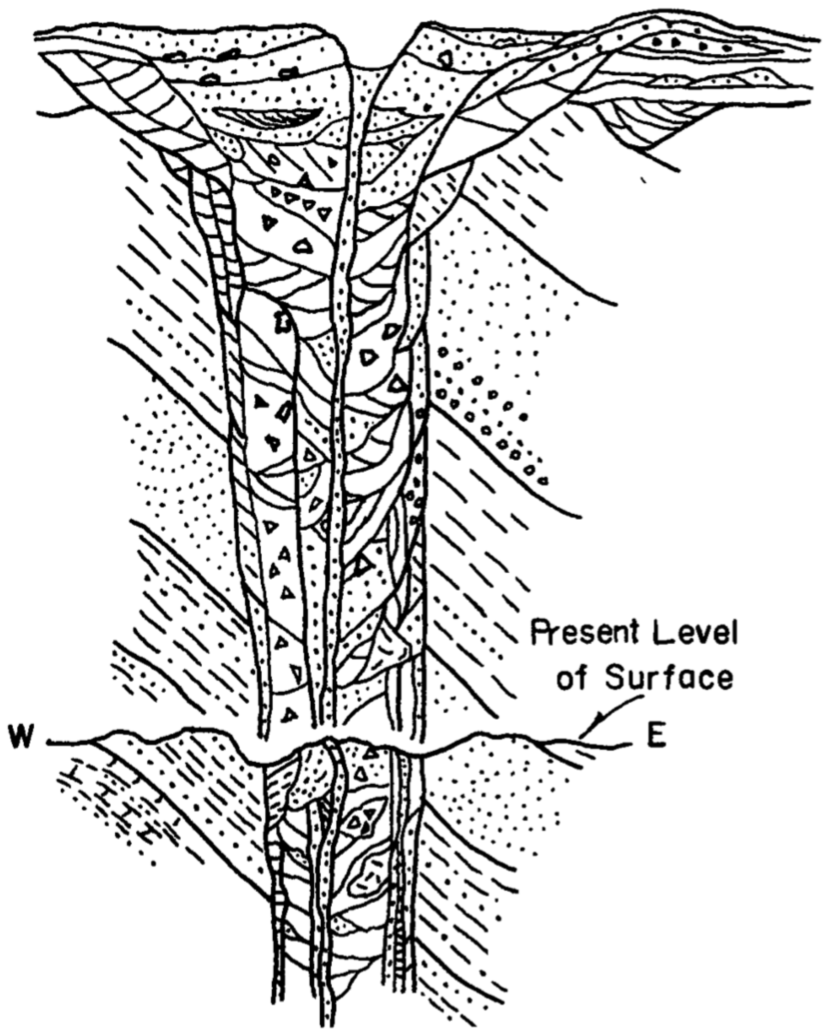

Figure 6: *From Ellingson 1973, this schematic illustrates the basic relationship between the explosive volcanic feature and the surrounding sedimentary rocks. The Oligocene-aged diatreme erupted through Permian and Triassic aged rock, and collapsed in on itself filling with brecciated sedimentary and volcanic material.*

The Oligocene-age diatreme is evidence of a gas-rich explosive eruption, which caused the brecciation of the country rock through which it erupted (Permian and Triassic sediments) (Ellingson 1973). The well indurated volcanic deposit is more resistant than the sedimentary rock into which it intruded. Thus, erosion of the surrounding sedimentary rock has left the Mule Ear diatreme exposed. The eruption carried up Precambrian basement rocks, as well as eclogite with mantle xenoliths.

The above geologic features are a couple of highlights that can be observed along the San Juan River. Despite the aridity of Utah's current climate, the geologic history of this section of the San Juan River reminds visitors that for most of its existence, Utah was a marine environment.

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