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## INTRODUCTION TO THE GEOLOGY AND HYDROGEOLOGY OF NORTHWESTERN NEW MEXICO

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*Yá'át'ééh*...welcome, conferees, to the midst of the most beautiful geology on planet Earth.

The intent of this essay is to provide an introductory, nontechnical historical background for a case study of the water resources of northwestern New Mexico: historical in the geological sense, measured in millions of years. This will be a timeline and a simple picture of the great natural systems of Earth and Sky, which the autochthonous Navajo or *Diné* (din-NEH) refer to as *Nohosdzáán* (no-host-ZAAN) and *Yádi-hi* (YAAH-dilth-hilth; Arthur et al. 1982; Semken and Morgan 1997). All the issues discussed at this water conference are ultimately related to these systems.

### Part of the Colorado Plateau

There are several ways to define what constitutes northwestern New Mexico. Geologically, it is the part of the state that lies on the Colorado Plateau, which

extends across the Four Corners into northeastern Arizona, southeastern Utah, and western Colorado. On the New Mexico side, it is bounded by the southern Rocky Mountains, the Río Grande valley, and the low deserts of the Basin and Range, which lie below a mountainous transition country. The Plateau in New Mexico is characterized by high elevations with generally low relief, a semiarid to arid climate, and a landscape of mesas and canyons cut into a stack of layered sedimentary rocks wherever streams and rivers have run. Compared to the portions of the Plateau in the other states, the New Mexico section might be thought of as somewhat flatter, a little less dramatic perhaps, but with regard to water and energy resources, quite a bit richer.

### Elements of the Colorado Plateau of New Mexico

Because of its geologic wealth, the Plateau of New Mexico has been studied in considerable detail (see

the guidebooks by Fassett and James 1977; Finch et al. 1989; and Lucas et al. 1992), by field mapping, drilling, and methods of imaging such as seismic surveys. It is a region where up to 14,500 feet of mud, sand, organic matter, and gravel have been laid down by water and wind on top of older, deeper, crystalline igneous and metamorphic rocks referred to as basement.

Figure 1 is a cross-section through northwestern New Mexico, extending approximately west to east. In the middle, those layers of sediment, now turned to rock, dip into a large, asymmetrical bowl-like structure, the San Juan Basin. Around the west, north, and east of the Basin, its edge is defined by *monoclines* such as the Hogback just west and northwest of Farmington. The term monocline means “one-sided fold,” and these are simply ridges formed where rock layers are bent over some disruption beneath them, such as a fault in the basement rocks.

Outside the San Juan Basin, the rock layers of the Plateau slope up against surrounding mountains or highlands, as can be seen in the cross-section. In a few places, the most famous being *Tsé bit'a'i* (TSEH-bit-ahi; “Rock with Wings”), also called Ship Rock, molten rock (*magma*) has pierced the basement

and overlying layers to form volcanoes or other igneous features. These are all now extinct, and only their exhumed, eroded remnants are left.

### Significance of the Colorado Plateau of New Mexico

Many people indeed think that the Plateau has been endowed with the most beautiful geology on Earth, and considerable geological significance is contained in that beauty. The Plateau is a segment of the crust of North America that has gone virtually undisturbed for hundreds of millions of years. This is in direct and visible contrast to all of the regions immediately around it, which have either been lifted up into mountains or stretched, thinned, and fractured by *Nohosdzáán*—crustal—forces. Thus, the Plateau has retained most of the sedimentary layers that have been lost from elsewhere in the West, and these constitute a tremendous record of different environments that previously occupied this area.

The differential erosion of hard and soft rock layers into cliffs and slopes, by the flowing water and wind of *Yádi-hi*, has resulted in the classic Plateau landscape of mesas, buttes, pinnacles, and canyons.

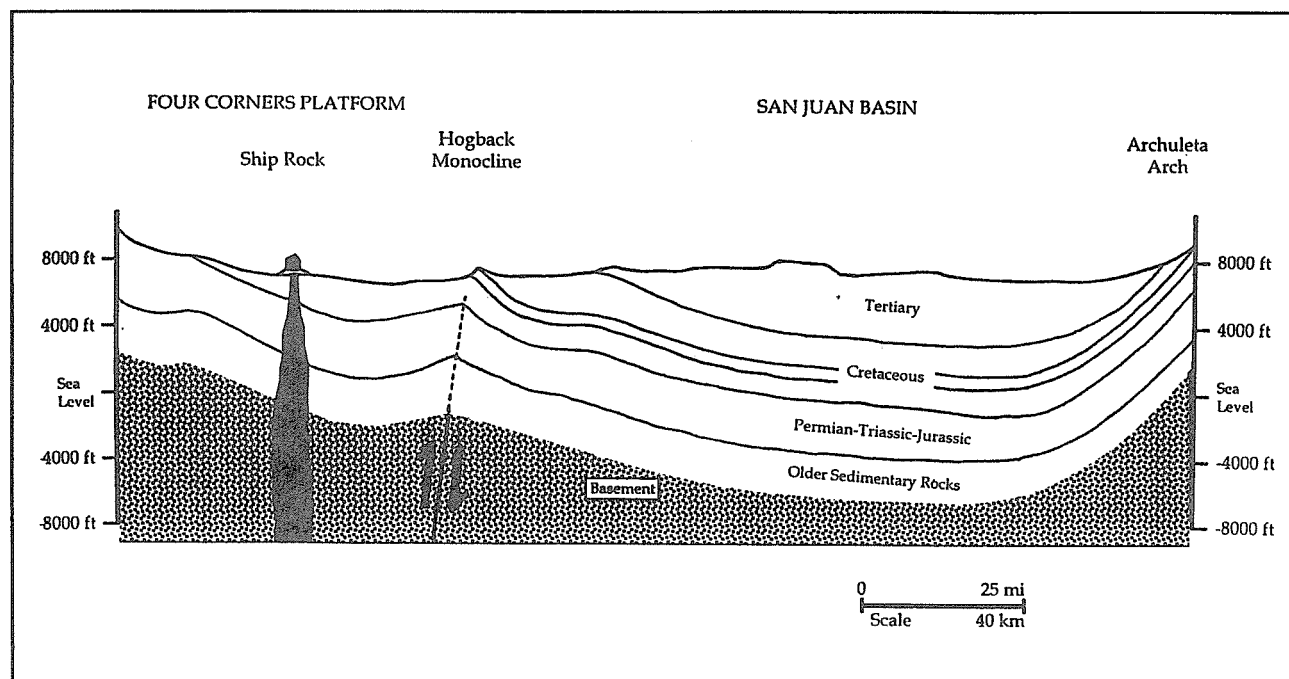


Figure 1. A geologic cross-section through northwestern New Mexico, after El Paso Exploration Company.

*Fossil fuels* such as coal, petroleum, and natural gas are derived from the remains of organisms that become incorporated into sedimentary stacks and deeply buried. Thus, they are always associated with sedimentary rocks, and those of the Colorado Plateau have been well-endowed with all three types of fossil fuel.

Finally, many of the sedimentary layers in the Plateau are porous and permeable, which means they can transmit and store groundwater. These *aquifers* are charged by precipitation and runoff in the highlands around the San Juan Basin, and carry water down into more arid regions where they provide a valuable resource if they are not buried too deeply.

### 280 Million Years of Geologic History and Accrual

Different kinds of sediments are laid down in different kinds of environments on Earth: sands in desert dunes, mud in shallow seas, gravel in streams, and so on. If these are preserved as rock, they become a lasting record of the former environment. Thus, the rock units that are exposed in places such as the Colorado Plateau, and the layered sequences in which we find them, are not random. They are a record that the geologically-minded can read almost as easily as a book.

The remainder of this essay will recount briefly the record of approximately the last 280 million years of Plateau geologic history, as a story simplified into four major chapters. Most of the layered rocks of northwestern New Mexico, the interesting volcanoes, monoclines, and basins and—most importantly for this conference—all of the important aquifers formed within this interval of time. This also was when the energy resources of the San Juan Basin accrued. Table 1 is an encapsulated recounting of this history, which also includes more detail about specific rock formations and places where they are exposed.

The chapters are grouped by geologic *periods*, which are the fundamental units of the time scale that geologists use to record events. If we were to think of the last 500 million years of Earth history as a single year, the periods would correspond to the months, except that they are not all quite the same length. From earliest to most recent, these periods are the *Permian*, *Triassic*, *Jurassic*, *Cretaceous*, *Tertiary*, and *Quaternary*. Boundaries between periods were originally

drawn from changes in sequences of rocks observed in the field: a period was defined as the time interval over which a stack of similar rock layers was laid down. After the advent of quantitative laboratory methods of dating rocks that are based on natural radioactive decay, Earth scientists have affixed actual numbers of years to each period.

### Chapter One: Drylands of the Permian, Triassic, and Jurassic

The Permian, Triassic, and Jurassic periods, extending from about 280 to 144 million years ago, are marked by the rocks they left as an interval of aridity on the Colorado Plateau that was far more intense than what we are experiencing here in the present.

There is considerable evidence that the continents are not fixed, but mobile. Over hundreds of millions of years, they drift atop the Earth at rates of a few centimeters per year, driven along by the circulation of hotter rock in deeper regions, and by gravity. This great system of gradual movement and change is called *plate tectonics*. (See, for example, Kious and Tilling 1995; or any good introductory geology text, for a more detailed description of this fundamental model of contemporary Earth science).

Drifting continents periodically collide with one another and weld together to form *supercontinents*, which are seamed by mountain ranges pushed up by the collisions. The last time this happened was in the Permian Period, and we have named that great former landmass *Pangaea* (pan-GEE-uh), which means “all Earth.” The interiors of continents tend to have more extreme climates than coastal regions, because of their distance from the moderating effects of the oceans. The Northern Plains are bitterly cold in winter, and the Southwest deserts are sizzling in summer. Imagine the climatic extremes that might have occurred on a continent six thousand miles across!

At this time the Colorado Plateau was situated in the western interior of *Pangaea* (Dubiel 1994), flanked on the north and east by high mountains. For much of this interval, particularly in the Permian and Jurassic periods, it had a harsh desert climate (Peterson and Turner-Peterson 1989), with great seas of sand dunes in places. Slightly wetter times in the Triassic Period may have yielded conditions closer to today’s high-desert climate, with intermittent streams and lakes (Parrish 1993; Dubiel 1994; many papers

Table 1. Capsule geologic history of northwestern New Mexico since the Permian Period, in part after Eldridge (1992).

GEOLOGIC PERIOD	TIME [Mya*]	GEOLOGIC EVENTS	ROCK UNITS FORMED	REPRESENTATIVE EXPOSURES
Quaternary		<ul style="list-style-type: none"> <li>• Surficial erosion, deposition;</li> <li>• Runoff from melting glaciers in San Juan Mountains cuts terraces and deposits gravels</li> </ul>	Soils; alluvial deposits; terrace gravels	Animas, La Plata, San Juan river valleys
	[1.6]			
Tertiary		<ul style="list-style-type: none"> <li>• Isolated volcanic eruptions</li> <li>• Sediments shed south and west off San Juan Mountains and deposited as sandstones and conglomerates</li> <li>• Extensive volcanic activity</li> <li>• Colorado Plateau uplift</li> </ul>	Navajo volcanoes Chuska Ss* San Jose Fm* Nacimiento Fm Ojo Alamo Ss San Juan volcanics	Ship Rock Chuska Mountains Upper Animas valley La Plata valley San Juan Mountains
	[66]			
Cretaceous		<ul style="list-style-type: none"> <li>• Magma intrudes upper crust, forming domed mountains (continues into Tertiary Period)</li> <li>• Laramide orogeny begins</li> <li>• Western Interior Sea retreats</li> <li>• Western Interior Sea retreats and advances again; deposits sandstones and mudstones; peat (coal) forms in swamps along shore; dinosaurs abound</li> <li>• Western Interior Sea advances</li> </ul>	Igneous domes Monoclines and basins Kirtland Shale Fruitland Fm Pictured Cliffs Ss Lewis Shale Cliff House Ss Menefee Fm Point Lookout Ss (Upper) Mancos Shale Tocolo/Gallup Ss (Lower) Mancos Shale Dakota Ss Burro Canyon Ss	Carrizo, La Plata Mountains Hogback Bisti Badlands Pictured Cliffs Mesa Verde Western San Juan Basin W of Shiprock
	[144]			
Jurassic		<ul style="list-style-type: none"> <li>• Semiarid to arid plains; saline lakes; intermittent streams; dinosaurs in area</li> <li>• Shallow sea encroaches on the northwest</li> <li>• Extreme aridity; dune fields</li> </ul>	Morrison Fm Bluff/Cow Springs Ss Summerville Fm Entrada Ss Carmel Fm Navajo Ss Wingate Ss	Laguna area Four Corners San Ysidro area Red Rock State Park
	[208]			
Triassic		<ul style="list-style-type: none"> <li>• Warm monsoonal or semi-arid climate; Chinle River system; dinosaurs appear</li> </ul>	Chinle Group Moenkopi Fm	Ghost Ranch
	[245]			
Permian		<ul style="list-style-type: none"> <li>• Arid climate; deserts</li> <li>• Sediments eroded off old Uncompahgre range to north; deposited as sands and muds</li> </ul>	Glorieta Ss Cutler Group	Near Abiquiu
	[286]			

\*Abbreviations: Mya = millions of years ago; Fm = formation; Ss = sandstone

in Lucas and Morales 1993). Recently, geologists (Riggs et al. 1996) have found evidence that in the late Triassic, a Mississippi-like river flowed from mountains in the future west Texas to the seacoast, now landlocked in Nevada. This Chinle River, named for the rock formation in which its traces were found, would have flowed right across northwestern New Mexico.

By the end of this chapter of northwestern New Mexico geologic history, Pangaea had begun to break up as supercontinents eventually do, driven by the buildup of heat under their extra-large crustal lids. The fragments of Pangaea, one of which became North America, started to drift toward their present positions.

Rocks deposited in the Pangaeon and post-Pangaeon drylands include red-brown mudstones and sandstones. The uranium ores that have been mined on the Plateau are found in these rocks. Some beds contain abundant petrified wood, and some the Late Triassic fossils of the first dinosaurs to inhabit North America.

In New Mexico, the Permian to Jurassic rocks are visible mostly along the edges of the Plateau, such as in the vicinity of San Ysidro and Ghost Ranch, and the cliffs along Interstate Highway 40 between Gallup and Grants. In the interior, these rocks are buried under younger layers.

Dune fields and stream channels from this time have become sandstones and conglomerates (rocks cemented from gravel). The thickest of these are good aquifers, although some are too deep for easy access. The Jurassic Entrada Sandstone, Bluff/Cow Springs sandstones, and Morrison Formation yield groundwater in certain areas of northwestern New Mexico (Stone et al. 1983).

## Chapter Two: The Cretaceous Coast

The Cretaceous Period extended from 144 to 66 million years ago, but in New Mexico any Cretaceous rocks older than about 100 million years have been removed by erosion. The layers that remain show that during the latter part of the Cretaceous, sea levels rose, possibly from some combination of higher sea floors, elevated temperatures, and a subsiding continent (Kauffman 1977; Eaton and Nations 1991). The interior of North America was then low enough to become inundated by a shallow Western Interior Sea.

The more mountainous eastern and western margins of the continent remained above water (Figure 2).

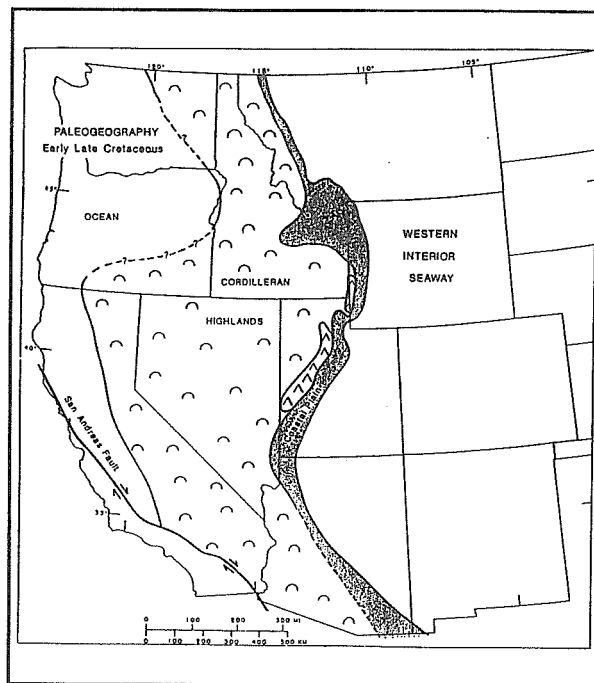


Figure 2. Map of North America during the late Cretaceous Period, showing the extent of the Western Interior Sea (from Peterson and Turner-Peterson 1989).

Northwestern New Mexico occupied what would have been the east coast of western North America. It would have been a low, subtropical coastal region with brackish-water swamps fronted by sandy shorelines. In the shallow water offshore, clays and limy muds were laid down. The beaches left behind beds of clean sands, and the dense vegetation in swamps farther inland piled into thick layers of peat that were subsequently buried in sediments. Heat and pressure encountered in deepening burial converted the peat into seams of Cretaceous *subbituminous* coal that are now mined where they are exposed around the margin of the San Juan Basin. The formation and aging of coal also generates methane (natural gas) that is retained in the seams. In deep mines that gas is a hazard, but in the San Juan Basin, coalbed methane is an important energy resource obtained by drilling.

During this interval, sea level rose, then fell for a time, then rose once more. Parts of northwestern New Mexico were covered by the Interior Sea, exposed, and then covered again. As a result, two distinct groups of sandstone, mudstone, and coal are found

here. A classic example of this so-called *transgressive-regressive* sequence is in the Mesa-verde Group rocks exposed by the Hogback monocline east of Shiprock. The buff-colored Point Lookout Sandstone at its base (on the west flank of the monocline) marks the time when this area was a beach. When sea level dropped for a time and the Interior Sea retreated in the general direction of modern Denver, the area was occupied by a swamp, whose brown muds and sands and coal beds comprise the younger, overlying Menefee Formation. The return of a beach, in advance of the rising sea, resulted in the Cliff House Sandstone that caps the Hogback.

Sands and gravels deposited on beaches and by streams have become valuable Cretaceous-age aquifers such as the Dakota and Gallup sandstones as well as the Mesaverde Group sands discussed above (Stone et al. 1983). These sandstones also produce petroleum in some regions of the San Juan Basin, and the Pictured Cliffs Sandstone is an important natural-gas reservoir (Fassett et al. 1978; 1983).

### Chapter Three: The Laramide Lift, and Old Wounds Reopened

The next interval is one of *Nohosdzáán* rather than *Yádi-hi*: movements of the crust and molten rock rather than erosion and deposition at the surface. This was the *Laramide Orogeny* (or-RAH-gen-ee), a period of mountain building that straddled the latest part of the Cretaceous Period and the subsequent Tertiary Period, from about 80 to about 45 million years ago. Many geologists believe this episode occurred when the western edge of the North American continent rode over a piece of the floor of the Pacific Ocean called the Farallon Plate. As the Farallon Plate was dragged beneath the thicker continental crust, it pushed and fractured the rocks above it, uplifting blocks of basement that formed the Rocky Mountains (Dickinson and Snyder 1978; Bird 1988).

Other geologists (Maxson and Tikoff 1996) suggest that the Laramide Orogeny was caused when a smaller continental fragment sideswiped the western edge of North America from south to north, delivering forces that buckled the crust inboard.

But for reasons not entirely understood, as regions surrounding it were broken, uplifted, and denuded, the crust of the Colorado Plateau was not similarly

deformed. Instead, its thick stack of sedimentary rocks was simply folded into the San Juan Basin and the bordering monoclines. These structures appear to have formed above old zones of weakness, such as faults that date back to Pangaea or earlier (Peterson and Turner-Peterson 1989; see Figure 1 for the example of the Hogback). This folding lifted the edges of the buried aquifers up and out to where they could be charged by rainfall, initiating the deep groundwater systems of the San Juan Basin and surrounding platforms.

At the end of the Laramide Orogeny, a major pulse of volcanic activity occurred around the margins of the Colorado Plateau, perhaps fed by magma formed when the Farallon Plate sank into hotter regions and melted. Explosive volcanoes and great extrusions of lava built mountain ranges of *igneous* rock, notably the San Juan Mountains. Volcanic activity also accompanied the opening of the Rio Grande Rift valley to the east, where magmas penetrated the fractured, thinning, subsiding crust (Baldrige and Olsen 1989).

But very little magma pierced the heart of the Plateau itself. Only small and isolated, although very explosive, volcanoes occurred here. Gas-charged magmas mixed in fragments of the crustal layers they penetrated and hardened quite soon after erupting, leaving solid pipes and sheets of igneous rock that was much harder and more resistant to erosion than the sedimentary rocks around it. Thus are revealed today the volcanic necks and dikes (resembling walls) of the Navajo volcanic field along the western border of New Mexico. Most prominent of these is the winged rock *Tsé bit'a'i*, or Ship Rock.

### Chapter Four: The Tertiary and Quaternary—Deposition and Downcutting

This chapter brings us essentially up to the present. The Tertiary Period began 66 million years ago, at the extinction of the dinosaurs and the start of our own Age of Mammals. The Cretaceous sea had retreated for good, and northwestern New Mexico was still in the midst of the Laramide Orogeny.

As lands around the north and east side of the Plateau rose, rocks were exposed to the actions of *Yádi-hi*: rain, snow, wind, and later ice. Mud, sands, and gravels were shed from the young San Juan Mountains and adjacent highlands and carried

down by streams into the San Juan Basin, to form the mudstones, sandstones, and conglomerates of the Tertiary Period. Of these, the Ojo Alamo, San Jose, and Chuska sandstones are important shallow aquifers (Stone et al. 1983).

It is important to note that during the Cretaceous Period, most of northwestern New Mexico was at or near sea level, as marine rocks were being deposited (Nations 1989). Today, it is all more than a mile high. It is obvious that the Colorado Plateau has been uplifted, probably as a consequence of the Laramide Orogeny (Bird 1988; Spencer 1996). This rise has facilitated its denudation and downcutting by streams (Morrison 1985; Graf et al. 1987), which have resulted in the signature canyons, mesas, buttes, and pinnacles of the spectacular present-day Plateau landscape.

As the Tertiary Period passed into the Quaternary Period about 1.6 million years ago, volcanic activity continued around the margins of the Plateau. In the Jemez Mountains, violent eruptions laid down sheets of ash and lava.

The final contribution to the hydrogeologic resources of northwestern New Mexico came from the ice ages of the Quaternary Period, as global temperatures dropped and mountain glaciers formed in the San Juans. As these thick rivers of ice ground slowly

down valleys, they scraped out more gravel and sand. The San Juan River and its upstream tributaries, periodically swollen with glacial meltwater, carved extensive *terraces*, resembling shelves, in the Cretaceous to Tertiary bedrock along their banks. The terraces were then covered by the gravel carried along by the rivers. Beneath the terraces, the San Juan River valley itself is filled with floodplain deposits of highly porous and permeable sands, gravels, and soils. These deposits, like the terrace gravels, can hold shallow groundwater and are called *alluvial aquifers*. The level of water in the floodplain is generally controlled by the level of water in the river, which can vary considerably even when regulated by the Navajo Dam and Reservoir upstream. Groundwater in these aquifers also is the most susceptible to pollution from agricultural, municipal, and industrial wastes that enter the river system.

#### A Summary of the Hydrogeology of Northwestern New Mexico

Figure 3, a diagram by Stone and others (1983), depicts the major hydrogeologic resources of the present-day Colorado Plateau of northwestern New Mexico. The principal aquifers within the stack of Plateau sedimentary rocks are indicated by hachured and stippled patterns.

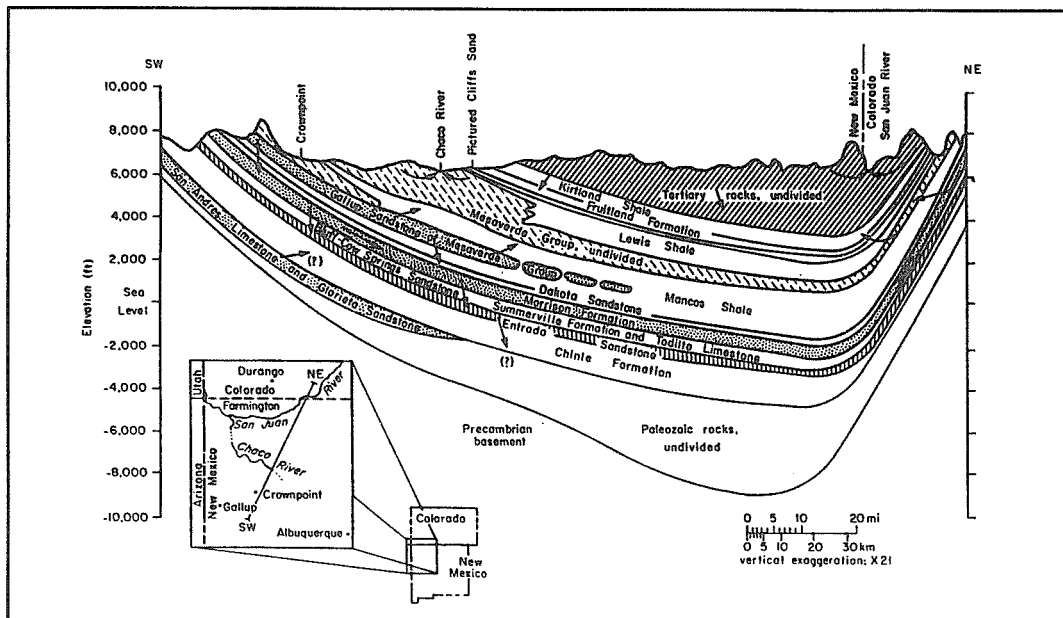


Figure 3. A geologic cross-section of northwestern New Mexico with principal aquifers shown as stippled units. From Stone and others (1983).

The aquifers are generally confined, meaning that the flow of water among them is typically blocked by impermeable beds of mudstones and shales. Where it is possible that groundwater can move in and out of these beds, the likely directions are indicated by arrows. It can be seen that the general movement of groundwater in the San Juan Basin is from the surface exposures of aquifers, the *recharge* zones, toward the deepest part of the basin in the northeast.

### Final Words

Northwestern New Mexico is blessed not only with great geological beauty and an abundance of geologic resources, but also with a uniquely preserved record of their origin that still has much to reveal. With all respect due *Nohosdzáán* and *Yádi-hi* and the indigenous cultures of the region, may those who come to learn more about the geology and hydrogeology of northwestern New Mexico walk in beauty.

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