NEW MEXICO FIELD TRIP

North Central New Mexico

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Introduction

This field trip takes place in northwestern New Mexico where there are excellent exposures of Paleozoic through Cenozoic rocks. Indeed, this area is unparalleled as a natural laboratory for studying geological history and processes because it includes a wide variety of rock formations spanning approximately 300 million years of Earth history, from late Paleozoic through early Cenozoic time (Fig. 1). The trip is organized such that the outcrops are viewed in chronostratigraphic order, thus enabling us to investigate the geological evolution of the southeastern Colorado Plateau region within a relatively short traveling distance filled with fantastic geological panoramas that have captured the attention of many landscape artists.

The stratigraphic units we will study include:

1) late Paleozoic mixed carbonate terrigenous sedimentary rocks of the Pennsylvanian Sandia, Madera and Permian Abo formations, including tectonic deltas and alluvial deposits that record uplift and denudation of the Ancestral Rocky Mountains,
2) fluvial, deltaic, lacustrine and eolian deposits of the Triassic Chinle Group and Jurassic Entrada Formation, Todilto Formation and Morrison Formation that contain a record of paleoclimate change and lake-level variations during the breakup of the supercontinents of Pangea and Laurasia.
3) transgressive and regressive marine deposits of the Late Cretaceous Mesa Verde Group, and associated marine Mancos and Lewis formations,
4) latest Cretaceous and Paleogene alluvial fan deposits and braided sheet sands that record emergence of the region during the Laramide Orogeny,
5) Neogene alluvial deposits of the Sante Fe Group that filled the Rio Grande rift basin and record the final stage of basin development and climate change in the region.

The paleogeographic setting and climate varied widely during the time of deposition of these strata in response to North America’s separation from Pangea and Laurasia and northward drift into higher latitudes (Fig. 2). Deposition occurred within four different basins that include the Chama and San Juan intermontane basins, the Western Interior Foreland Basin, and the Rio Grande rift basin. These strata also reflect tectonic influences on sedimentation during the Late Paleozoic Uncompahgre Uplift and later during the latest Cretaceous through the early Cenozoic Laramide Orogeny. During the Oligocene, a new extensional phase of tectonic evolution began in the region, with the development of the Rio Grande rift basin. At this time, volcanism was widespread across the western interior and contributed to the sediment fill of this rift basin.

The first day of the trip is intended for anyone interested in the geological history of the region, episodes of mountain building, and landscape evolution; including non-geologists attracted to the region by its spectacular rock formations. Most of our time will be spent driving through excellent stratigraphic exposures and at a number of brief stops to view outcrops and discuss the stratigraphy, tectonics and basin evolution.

Era	Period	Epoc	Group	Formation	
Cenozoic	Neogene	Pleistocene Pliocene Miocene Oligocene	Sante Fe Group		
		Eocene		San Jose Formation	(54-38 Ma)
	Paleogene	Paleocene		Nacimiento Formation Ojo Alamo Formation	(64-60 Ma) (65-64 Ma)
Mesozoic	Cretaceous			Kirtland Formation/Fruitland Formation	(75-70 Ma)
				Pictured Cliffs Tongue Lewis Shale	(78-76Ma)
			Mesa Verde Group	Cliff House Formation (La Ventana Tongue) Menefee Formation Point Lookout Formation	(80-78 Ma)
				Mancos Formation Dakota Formation	(94-80 Ma) (97-95)
	Jurassic			Morrison Formation Todilto Formation Entrada Formation	(150-144)
	Triassic			Petrified Forest Formation Paleo Formation Salitral Formation Agua Zarca Formation	230-205 Ma
Paleozoic	Permian			Yeso Formation Abo Formation	(245 Ma)
	Pennsylvanian			Madera Formation Sandia Formation	(291 Ma)
Precambrian Igneous and Metamorphic Rocks					

Figure 1. Stratigraphic column for field area

We will end the first day of the trip at Ghost Ranch, New Mexico. For those who plan to continue with Day 2 of the trip, there are group accommodations at Ghost Ranch, but reserve them early. There is also a nice campground at Abiquiu Lake. For those desiring "cushier" accommodations and excellent food, we recommend Abiquiu Inn.

The second and third day of the trip are intended for students of geology who are interested in tectonic influences on sedimentation, basin evolution, paleoclimatology and sequence stratigraphy of marine and continental strata. We will re-trace our route from day one and spend time at select outcrops that will allow us to view and discuss some of the basic principles of sedimentology and stratigraphy, basin evolution and sequence stratigraphy. Most of the outcrops we will visit are on public lands and are easily accessible with a two-wheel drive vehicle. We caution that you not try to cross onto fenced land that is not designated as public land without permission.

For the seriously minded geological groups we recommend a full three days for the trip to allow time to examine outcrops in greater detail. There are motels in Cuba, and for groups we recommend the Circle A Ranch, which is located in a beautiful Ponderosa forest at the base of the mountain just east of Cuba. It is a hostel, so you will need to cook your own meals in a shared kitchen.

Day 1. (Mile 0)

After departing the Albuquerque Sunport we will travel north on Interstate 25. To the east you are looking at the fault scarp of the Sandia Fault, which forms the western boundary of the Sandia Mountains (*Photo 1*). This is also the eastern boundary of the Rio Grande rift's Southern Basin (Fig. 3). The light colored, layered rocks at the top of the mountain are Pennsylvanian limestones of the Madera Formation, which rest on basal conglomerates of the Pennsylvanian Sandia Formation. The Sandia Formation rests unconformably on granites and metamorphic rocks of Precambrian age. This unconformity records the time of emergence of the uplift, part of the Ancestral Rocky Mountains, which were formed by the Uncompahgre Uplift during the late Paleozoic.

As we drive north on Interstate 25 note the road cuts on the east side of the highway that expose alluvial fan deposits shed from the Sandia Mountains (*Photo 1*). These include debris flows and conglomerates that are typical of proximal fan settings.

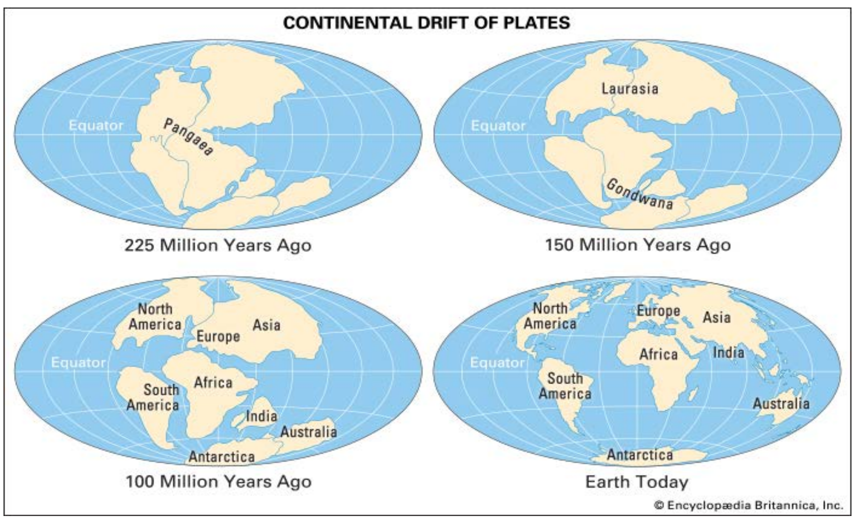
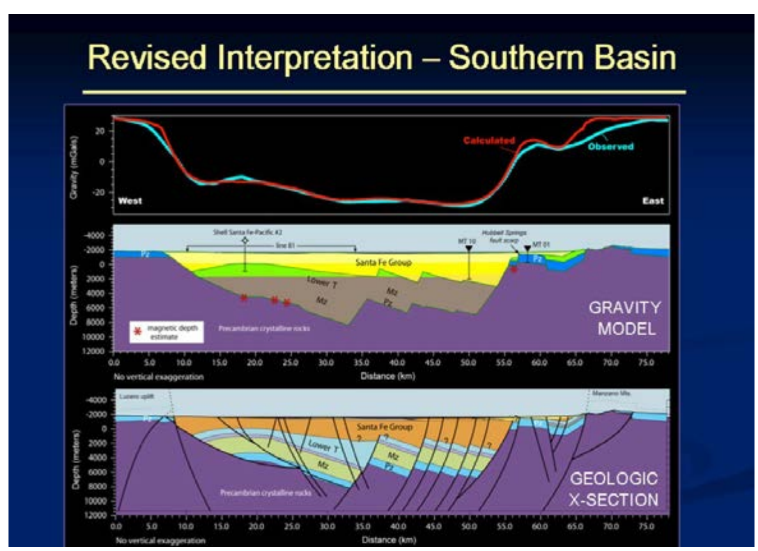


Figure 2. Continental configurations 225 Ma to Present.

Figure 3. Schematic cross-section across the Rio Grande rift basin's Southern Basin near Albuquerque and adjacent uplifts (from USGS).



0 miles Start @ Bernalillo NM @ intersection of US 550 and Camino del Pueblo Rd

At Bernalillo, exit onto Highway 550 and drive west toward the town of San Ysidro. During the drive to San Ysidro we will observe mostly alluvial, volcaniclastic deposits shed from nearby highlands, including the Nacimiento Mountains and Jemez Volcanic district.

Stop 1 Mile 5.6 Pull out and view Sante Fe Group on right side of US 550 (Photo 2)

Our first stop will allow an opportunity to observe volcaniclastic red beds of the Santa Fe Group, which are mainly alluvial deposits that fill the Rio Grande rift basin. Volcanic rocks associated with rifting cap these deposits forming the flat-topped mesas to the east.

Our drive northwest on Highway 550 takes us across the Rio Grande rift basin. The rift is the first sedimentary basin we encounter, one of several basins that comprise the more extensive Rio Grande Trough (Fig. 3). It is a classic example of a continental rift basin. The basin is segmented into a series of alternating half grabens and contains up to 8 kilometers of sediment fill that ranges in age from Pennsylvanian to Holocene age.

Stop 2 21.4 miles Pull off onto parking area, left side of 550 to view the Todilto, Entrada, and Chinle outcrops and rift-shoulder fault (Photo 3)

About one half mile east of the town of San Ysidro we will cross the western margin of the rift. Looking back to the south you can see one of the faults that occur along the western margin of the rift basin (Fig. 3). At this location Jurassic and late Cretaceous strata lie in fault contact with one another (*Photo 3*). There is another fault near the highway that separates late Cretaceous strata from late Cenozoic alluvial deposits of the Santa Fe Group. The mesa to the west is White Mesa, where gypsum is currently being mined from the Jurassic Todilto Formation.

Looking to the north, across Highway 550, we observe the eastern side of a large southward plunging syncline where outcrops of the Triassic Agua Zarca (buff-colored sandstone) rest of red beds of the Permian Abo Formation that dip to the west (*Photo 4*). Later we will drive around the east side of the syncline where we will observe these same formations dipping toward the east. This is one of several northwest-southeast oriented anticlines and synclines that occur along the western margin of the Nacimiento Uplift. We will discuss these structures later in the day.

23.6 miles Intersection of US 550 and NM Route 4 in San Ysidro

At the town of San Ysidro, turn right onto Highway 4 and continue to the north through the Jemez Pueblo where we will begin our study of the Paleozoic history of the region. To the west you see red beds of the Permian Abo Formation overlain by tan sandstone of the Aqua Zarca Formation (Fig. 1). Most of the road cuts we will pass are exposures of the Cenozoic Bandelier Formation.

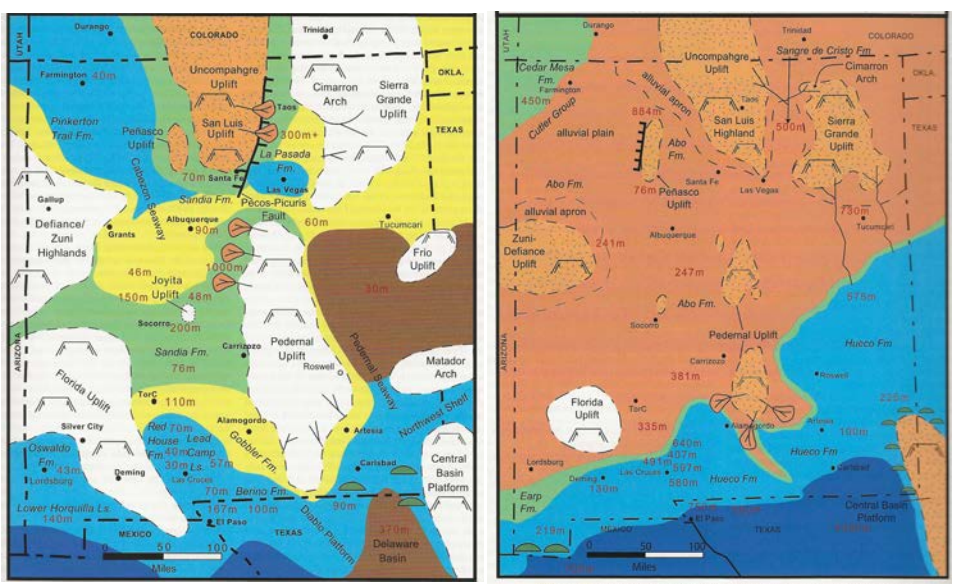
Stop 3 29.9 miles GPS N 35 37.6840 W 106 43.4805 Pull out on west side of highway

At this stop we can view the Bandelier Formation in the stream valley to the west (*Photo 5*). Across the highway is an outcrop of the Bandelier (*Photo 6*). The Bandelier Formation is a distinctive light tan-colored ashfall tuff with many potholes, columnar joints and shallow caves. When exposed to erosion it takes on this characteristic weathering pattern. It records a major eruption of the 13.7 km wide Valles Caldera that occurred 1.14 million years ago and ejected more than 300 km^3 of ash across and extensive area of North America.

Stop 4 31.0 miles GPS N 35 38.5876 W 106 43.4751 At this stop we see exposures of the Abo Formation. across the highway from the welcome center ([Photo 7](#))

Throughout the early Paleozoic, New Mexico was part of a structural high, the Transcontinental Arch, which resulted in a widespread unconformity spanning this time interval. During the late Paleozoic the Uncompahgre Uplift was underway and resulted in the formation of the Ancestral Rocky Mountains. The Ancestral Rockies extended from Colorado into northern New Mexico and consisted of northwest-southeast elongate intracratonic blocks and narrow basins (Fig. 4). They are believed to have been formed either as a result of wrench motion associated with suturing of Laurentia and Gondwana or as a Laramide-style foreland features associated with subduction along the southwest margin of Laurentia (Kues and Giles, 2004). Coarse conglomerates, sometimes containing channels with large clasts of crystalline rocks (Sandia Formation), overlie Precambrian rocks in several of the uplifts in New Mexico and Colorado and record erosion of these blocks when they still stood as topographic highs.

During the late Mississippian and Pennsylvanian, the crystalline blocks of the Ancestral Rockies had been lowered by erosion and shallow, carbonate-producing seas occupied much of New Mexico. Mississippian (Arroyo Penasco Group) and Pennsylvanian (Madera Formation) limestones record this time interval. By Permian time 290 m.y., carbonate deposition was interrupted by the influx of clastic sediments being shed from the eroding blocks of the ancestral Rocky Mountains that still existed to the north in Colorado (Fig. 4). During the early stages of clastic sediment influx, mixed siliciclastic and carbonate deposition resulted in interbedded limestones and red beds that characterize the gradational boundary between the Pennsylvanian Madera Formation and the Permian Abo Formation. The Abo Formation represents a vast fluvial-deltaic complex that prograded in a southwesterly direction across New Mexico, burying the Madera Formation. By middle-upper Wolfcampian time, these clastic deposits had prograded to the southeastern corner of the state (Fig. 4) where these red beds are interbedded with Permian age carbonates that were deposited within the remnants of the seaway (Fig. 5).



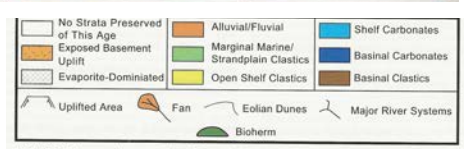


Figure 4. Late Paleozoic paleogeographic maps of New Mexico showing uplifts, sedimentary basins and depositional facie. Map on left is for Atokan time and map on right is for Middle-Upper Wolfcampian Time. (Taken from Kues and Giles, 2004)

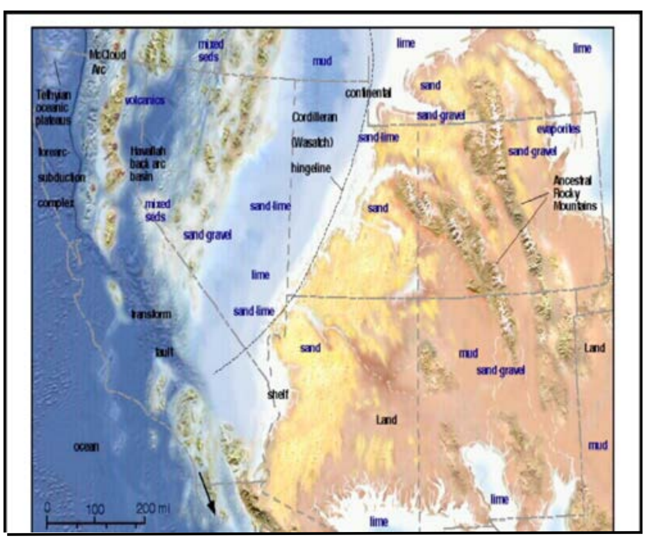
The Madera Limestone is mainly restricted to the eastern side of the Nacimiento Uplift, where it onlaps Precambrian crystalline rocks of variable composition. This stratigraphic relationship indicates that the ancestral Nacimiento Mountains, the Penasco Uplift, consisted of a north-south series of Precambrian blocks that were tilted to the east, not too dissimilar to the present day Nacimiento Mountains (Wood and Northrop 1946; Woodward et al., 1972). This stratigraphic style supports tectonic model calling for Laramide-style deformation during this time. The Penasco Uplift was an effective barrier to sediment transport, restricting clastic sediments to the eastern side of the uplift during the earlier stages of deposition of the Abo Formation. Later, the Penasco was buried beneath the Abo Formation and sediments began spilling through narrow gaps within the Penasco and toward the west (Adams, 1980).

Braided River and Tectonic Delta Deposits of the Abo Formation

Coarse-grained, arkosic deposits of the tectonically influenced Abo Formation are beautifully exposed between the Jemez Pueblo and Jemez Springs. Our first stop will be at the picnic area just north of Jemez Pueblo (*Photo 7)*. The lower part of this outcrop consists of numerous braided channels and large-scale sedimentary structures formed by migrating bars. At this local we observe high-angle forest beds that fill broad troughs (*Photo 8*). These beds are comprised of poorly sorted, coarse arkosic sandstone. Regional paleotransport was toward the south, but locally along the eastern side of the Nacimiento there is an eastward component of paleotransport that indicates at least some relief of the Penasco during early Abo time (Adams, 1980).

By early-mid Permian time, any relief associated with the Penasco Uplift had been removed as crystalline rocks were buried by Paleozoic deposits. The upper part of the Abo Formation contains more fines and reflects decreasing gradients across the region, with paleotransport toward the south. The Yeso Formation overlies the Abo Formation and consists of massive siltstones that are locally bioturbated. Sedimentary structures include current ripples and parallel laminations. Channels are virtually lacking. These combined features indicate that the Yeso Formation represents vast quantities of suspended sediment deposited within a delta front environment.

Figure 5. Early Permian paleogeography of the southwestern US (http://www.thenaturalamerican.com/paleogeography.htm).



Mile 33.0 Turn off of NM Route 4 onto County Route 376 towards Guadalupe Box

Stop 5 Mile 37.7 GPS N 35 43.6467 W 106 45.5038

At Stop 5 we will view a spectacular section of the Permian Abo Formation capped by the Bandelier Tuff (*Photo 9*). Note the irregular basal contact, which reflects the topography of the landscape at the time of the eruption. A large channel filled by tuff occurs on the south side of the exposure. There is a normal fault that offsets the Abo near the center of the exposure.

Stop 6 Mile 38.0 GPS N 35 43.8366 W 106 45.5453 (Photo 10)

At this location we will view a fault that extends through the valley to the north. To the east is the Permian Abo Formation and to the west are highly fractured Precambrian granitic rocks. This is one of several faults that occur along the eastern side of the uplift. Carbonate float at this stop is coming from the up-thrown block to the west.

Stop 7 Mile 38.7 GPS N 35 44.2659 W 106 45.9022 (*Photo 11*)

Drive north through the Gilman tunnels and into Guadalupe Box. Stop at the roadside pullout at end of the pavement and gate that is entrance to the National Forest. At this stop we will observe the highly fractured crystalline basement rocks that are of Proterozoic age (1.8 to 1.0 Ga) and form the core of the Nacimiento Uplift. These rocks record two Precambrian orogenic periods at 1.80 to 1.65 Ga and 1.45 to 1.35 Ga separated by periods of cratonic stability (Karlstrom, 2004). Subsequent deformation occurred during the Uncompahgre and Laramide uplifts. In the Nacimiento Mountains, the complex is mainly granitic and gneissic and varies in composition between separate blocks of the uplift (Woodward et al., 1972). An angular unconformity separates these basement rocks from Pennsylvanian carbonates of the Madera Formation. This is the same unconformity we viewed from a distance at the peak of the Sandia Mountain as we drove north along Interstate Highway 25. During late Pennsylvanian time, widespread uplift resulted in the emergence and denudation of the ancestral Rocky Mountains and exposure of Precambrian basement rocks. Locally, carbonates directly onlap Precambrian crystalline rocks from multiple angles (*Photo 12*), so the landscape at this time was one of islands composed of granite and metamorphic rocks surrounded by warm, shallow seas were fossiliferous limestones were deposited. Fossils are common within the Madera at this location, and include bryozoans, brachiopods, crinoids and corals.

Stop 8. Mile 39.2 GPS N 35 44.5315 W 106 46.2367

We will now drive a short distance north to where a thick section of the Pennsylvania Sandia Formation outcrops (if the gate is locked you can walk to the next outcrop). The Sandia is absent just a short distance away at our last stop where Madera limestone rests on the Precambrian. This localized stratigraphic variability is associated with channels that were cut into the Precambrian bedrock. Take a few minutes to examine these rocks, which were shed from the emerging Ancestral Rocky Mountains (*Photo 13*). The carbonates and clastics are locally interbedded.

Return to San Ysidro (resume mileage along route 550), ***Mile 23.6***

From Guadalupe Box we will return to State Highway 4, then south and back to San Ysidro. At San Ysidro turn right onto Highway 550 to begin our drive toward Cuba, New Mexico, traveling through spectacular outcrops and structures associated with the Nacimiento Uplift. As we begin our drive on Highway 550 we will cross through the large, southward plunging syncline that we observed earlier today from across the highway (Photo 4). On the south side of the highway and across the Rio Puerco is White Mesa, which sits within the syncline. The white unit at the top of the mesa is Todilto Gypsum, which rests conformably on the Entrada Formation. We will take a closer look at these formations at a later stop.

Just past the point where the highway turns to the north, we cross the southern end of the Nacimiento Fault and the southern boundary of the Nacimiento Mountains. Woodward et al., (1972) interpreted the Nacimiento Fault as an upthrust, which is a high-angle reverse fault whose fault plane steepens at depth (Fig. 6). This interpretation is based on the observations that (1) the trace of the fault is more sinuous in areas where the upper part of the fault is exposed and (2) folding associated with the fault is confined to within one to two kilometers of the fault (Anderson, 1970).

Stop 9 ***Mile 27.6 GPS 35 32.8192 W 106 50.7737*** **(*Photo 14*)**

At this stop we will observe the southern end of the Nacimiento Fault where it extends up the valley north of the highway. Here the fault dissects the western limb of the syncline that we have been crossing, juxtaposing the brownish sandstones of the Triassic Agua Zarca Formation against the Jurassic Entrada and Todilto formations. Note the drag within the Agua Zarca along the upthrown side of the fault and the fact that the Entrada and Todilto formations, the down-thrown block, are nearly vertical.

Recall that the Precambrian core of the Nacimiento Mountains was initially exposed during the late Paleozoic Uncompahgre Uplift, as we observed in Guadalupe Box. During latest Cretaceous and Paleocene time, another mountain building episode known as the Laramide Orogeny resulted in the formation of the current day Rocky Mountains. For the most part, the southern Rocky Mountains are characterized by crystalline blocks bounded by high angle faults, indicating that the principle forces involved vertical motion. Here, along the southern edge of the Nacimiento Mountains, we drive through two examples of a series of mainly northward plunging anticlines and synclines that characterize the area (Fig. 7). These folds were initially considered to be evidence for an early phase of deformation that involved compressional forces from the northeast-southwest (Anderson, 1970), but later kinematic analyses showed that similar associations can result from strike-slip motion along high-friction faults (Cather, 2004). Such strike slip motion could be associated with tilting of the southern-most Precambrian block of the Nacimiento, which explains the occurrence of these folds. We will drive through these features as we travel north on Highway 550. These folds were dissected by the Nacimiento Fault, adding to the structural complexity of the uplift. As we drive north on Highway 550, follow the white outcrops of the Todilto Gypsum on either side of the highway. They provide the best markers of the plunging anticlines and synclines through which we are driving (*Photo 15*). You can also see places where the Todilto Formation strikes into and out of the fault, as shown by Figure 7 and Photo 15.

As we drive north we begin to see Precambrian crystalline rocks at the top of the mountain. Thus, displacement along the Nacimiento Fault increases to the north. The red beds of the Permian Abo Formation lie directly on Precambrian granites and metamorphic rocks, again indicating that this block was still exposed during Permian time. Remember that in Guadalupe Box, on the east side of the uplift, we observed Pennsylvanian Sandia Formation and Madera Limestone resting on granites and metamorphic rocks. The limestones onlap Precambrian rocks and pinch out before reaching the highest peaks of the uplift. On the western side of the uplift, Permian Abo rests unconformably on the Precambrian; the Madera Limestone is absent on this side of the mountains. This indicates that the late Paleozoic Penasco Mountains were tilted to the east. In fact, Paleozoic strata, including the Mississippian Arroyo Penasco, Pennsylvania Sandia and Madera Formations and Permian Abo Formation rest on different Precambrian igneous and high-grade metamorphic rocks in different areas of the Nacimiento Mountains. These relationships indicate that the ancestral Penasco Uplift consisted of separate crystalline blocks that together formed a north-south oriented mountain chain that was tilted toward the east, similar to the present Nacimiento Mountains.

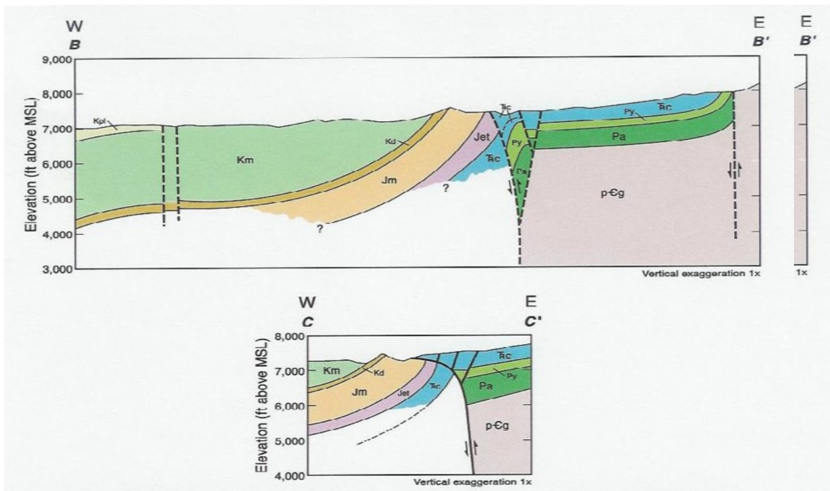
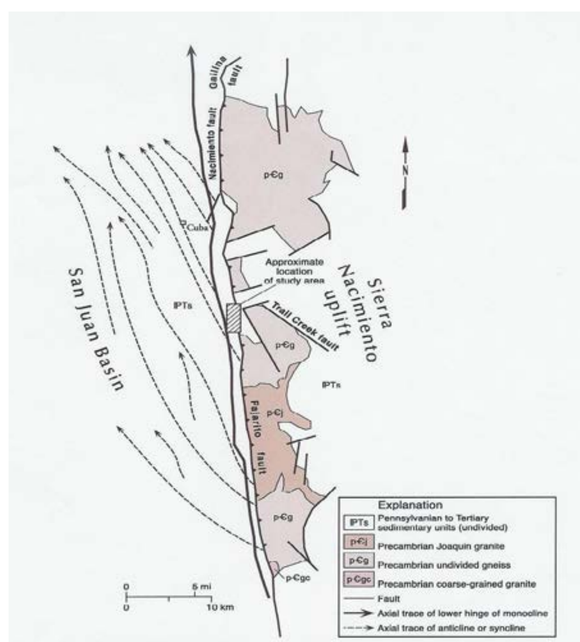


Figure 6. Geological cross-sections through the Nacimiento Fault Zone (from Woodward et al., 1972). Section B-B' illustrates a section where erosion has exposed the deeper, more vertical fault plane, which manifest itself as a relatively straight fault trace in map view. Section C-C' illustrates a section where the shallower portion of the fault is preserved, folding along the downthrown block is more intense and the fault trace is more sinuous in map view.

Figure 7. Geological map of the southern portion of the Nacimiento Uplift (from Woodward et al., 1972) showing northwest-southeast oriented, northward plunging anticlines and synclines that have been dissected by the Nacimiento Fault Zone on the western side of the uplift.



Triassic Strata Mile 32.6

For the first part of our journey north on Highway 550 we will drive through Triassic and Jurassic rocks with excellent exposures of the Triassic Chinle Formation and Jurassic Entrada and Todilto formations on both sides of the highway (*Photo 16*). As we drive to the north we will pass through progressively younger strata that dip toward the northwest, away from the uplift and toward the San Juan Basin.

During the late Paleozoic and early Triassic, North America was part of the supercontinent of Pangea and was situated near the equator (Fig. 2). By Jurassic time, Pangea had begun to break apart and North America, now part of the supercontinent Laurasia, began drifting to the north. As it did, the continent experienced a gradual change from warm subtropical to semi-arid and eventually arid conditions. The Triassic and Jurassic rocks of the Colorado Plateau were deposited in continental settings far removed from the nearest seas. The Agua Zarca is composed of braided river deposits, including conglomerates with boulder size quartzite clasts derived from the Ancestral Rocky Mountains. Thus, the high gradients that existed during the Permian existed into Agua Zarca time. The Salitral Formation was deposited in a vast lake, so the region was relatively flat at that time. There are limited exposures of the Poleo Formation in the southern part of the Nacimiento Mountains.

A major unconformity separates the Chinle Group from the Jurassic Entrada Formation. The Entrada is composed of well sorted sandstones with sedimentary structures that indicate an eolian origin. In fact, extensive dune fields occupied the region during Entrada time. Above the Entrada Formation is the Todilto Formation, which was deposited in a large lake that extended across the Four Corners region. Initially, the lake was filled with freshwater limestone, which is the brown unit at the base of the formation. During Todilto time, the climate became more arid and the lake was filled with evaporates that compose the upper part of the Todilto Gypsum. Between the limestone and the massive gypsum that composes most of the Todilto is a unit composed of alternating thin limestone and gypsum layers (*Photo 17*). Anderson and Kirkland (1960) interpret the entire Todilto sequence as representing a climatic transition from arid conditions of Entrada time to more humid conditions of Morrison time. They argued that the laminations recorded 10-13-year sunspot cycles packaged as 60-,85-,170- and 180-year cycles. Based on this interpretation, they further argued that the limestone member was deposited in about 14,000 years and that the gypsum member in about 6,000 years.

Stop 10 Mile 34.6 Nose of a plunging anticline

As we drive north, follow the white Todilto Gypsum members on both sides of the highway. We are driving through an anticline whose nose plunges beneath the highway at this location. (*Photo 15*)

Morrison Formation Mile 36.4 GPS N 35 39.5334 W 106 53.420 (Photo 18)

At this location we pass through exposures of the Jurassic Morrison Formation on both sides of the highway. The basal member of the Morrison is composed of maroon-colored sands and shales of the Sommerville Member (exposed in the canyon on the west side of the highway), which was deposited in a vast flood plain environment (*Photo 18*). Large fluvial channels (buff-colored sandstones) become more prominent upwards within the Morrison Formation. These channels are interbedded with floodplain deposits, mostly greenish shales, with thin sand beds that are interpreted as overbank deposits. By the end of Morrison time, the channels become more prominent and braided in character, recording an increase in relief. The dramatic change from a large evaporitic lake to a vast fluvial flood plain records climate change to more humid conditions. The sharp contact that separates the Morrison and Todilto formation is therefore interpreted as an unconformity that spans several million years. While the Morrison is none for an abundance of dinosaur fossils, here in New Mexico actual fossil discoveries have been limited, but dinosaur tracks are fairly common. The best place to look for tracks is on the bottom sides of overbank sands. Gastroliths are also common.

Cretaceous and early Cenozoic History

During the middle to late Cretaceous, a vast fold and thrust belt (the Sevier Thrust Belt) extended across mid-western North America from Canada to the Gulf of Mexico (Fig. 8). This was the source of clastic sediments shed to the east and deposited in the late Cretaceous Western Interior Basin, an expansive basin that resulted from flexural and sediment loading. The basin is on average 1500 kilometers wide at the U.S. Canadian border and much narrower in northern New Mexico (Fig. 8), (Nummedal, 2004). The asymmetric foreland basin had a subsidence profile that was the opposite that of a passive continental margin in that subsidence was greatest near the coast and decreased in a seaward direction. It also differs in the absence of a distinct continental shelf break and continental slope. Instead, the offshore profile was that of a seaward deepening ramp. This unique basin configuration led to preservation of thick coastal and marine shales that taper to the east into Texas, Oklahoma and Kansas.

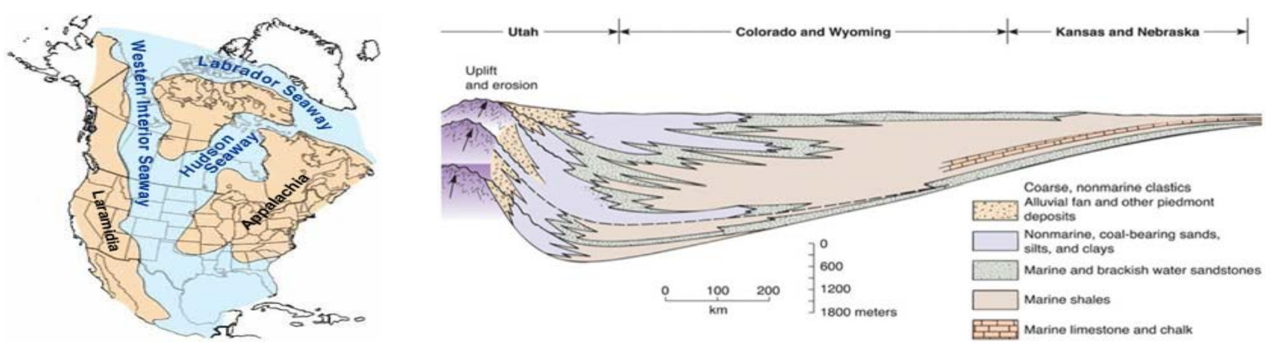


Figure 8. Map view and ross section of the Western Interior Basin

The evidence for large ice sheets during the Cretaceous is strongly debated, but it is generally believed that the magnitude of sea-level rise and fall during that time was relatively small (generally less that 50 meters) compared to glacial eustatic cycles of the late Cenozoic. Still, the gentle offshore profile of the basin resulted in significant (up to a few hundred kilometers) oscillations in the shoreline with a few tens of meters sea-level rise and fall, resulting in regressive - transgressive cycles of deposition and stratigraphic architecture that reflects these changes (Fig. 9). (Nummedal, 2004). The overall succession begins with the Dakota Formation, a transgressive sequence that records the initial inundation of the seaway.

Stop 11 Mile 38.0 Dakota Formation GPS N35 40.1764 W 106 54.6986 (Photo 19)

The transgressive deposits of the Dakota Formation record the initial incursion of the sea into the Western Interior Seaway. The red sandstone outcrops on the east side of the highway are the upper sand of the Morrison Formation. Above them are buff colored sands of the Dakota Formation. Both are fluvial sands and, therefore hard to distinguish, despite the fact that they are separated by an unconformity that spans more than 50 million years. Closer inspection of this contact and the fluvial sands above and below this unconformity reveals differences in composition and paleotransport direction. We will study this contact later in the trip near Ghost Ranch, New Mexico.

Mile 38.7

We are now passing though rolling hills within the late Cretaceous Manco Shale. Initial marine incursion into the Western Interior Seaway culminated with deposition of marine shale of the Mancos Formation. This formation consists of brownish-gray shale with isolated carbonate beds. These carbonate beds typically contain marine fossils, including ammonites.

To the west is a nice view of Cabezon Peak. a large volcanic plug that is a prominent feature in northwestern New Mexico. It rises to 7,785 feet in elevation (*Photo 20*). Cabezon was a prominent landmark in the area that was used by wagon trains traveling west through “indian territory”.

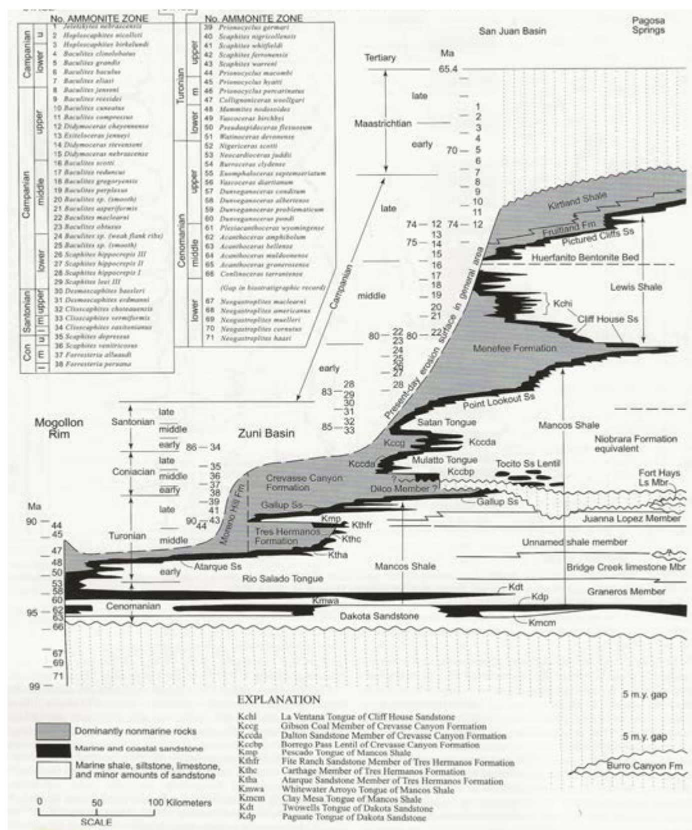


Figure 9. Chronostatigraphy Late Cretaceous stata across eastern Arizona and New Mexico showing the relationship between regressive and transgressive (from Nummedal, 2004).

Above the Mancos is the Mesa Verde Group, which forms magnificent outcrops in the mesas around the town of LaVentana (*Photo 21*). We will stop at the pull-out on the east side of the road to view the spectacular outcrops that make up this group in the mesas on both sides of the highway. The Mesa Verde Group is composed of a basal regressive sandstone, the Point Lookout Formation, a middle coal-bearing unit, the Menefee Formation, and an upper transgressive sandstone, the LaVentana Sandstone. These deposits record a regressive/transgressive cycle.

The overall stratigraphy and thickness of the Mesa Verde Group in the field area is similar to that of Colorado, indicating that the Western Interior Basin was the principle depocenter throughout this time interval. Following deposition of the Cliff House Formation, stratal accumulation rates more than doubled during deposition of the Lewis Shale in the northern portion of the San Juan Basin, heralding the early formation of the San Juan Basin and Laramide deformation in the region (Cather, 2004). The San Juan Basin is an inter-montane basin that covers approximately 12,000 km^2 of the Four Corners region of Northwestern New Mexico, southwestern Colorado, and parts of Arizona and Utah (Fig. 10). The basin is mostly filled with Mesozoic and Tertiary strata, but experienced its most significant subsidence at the onset of Laramide deformation.

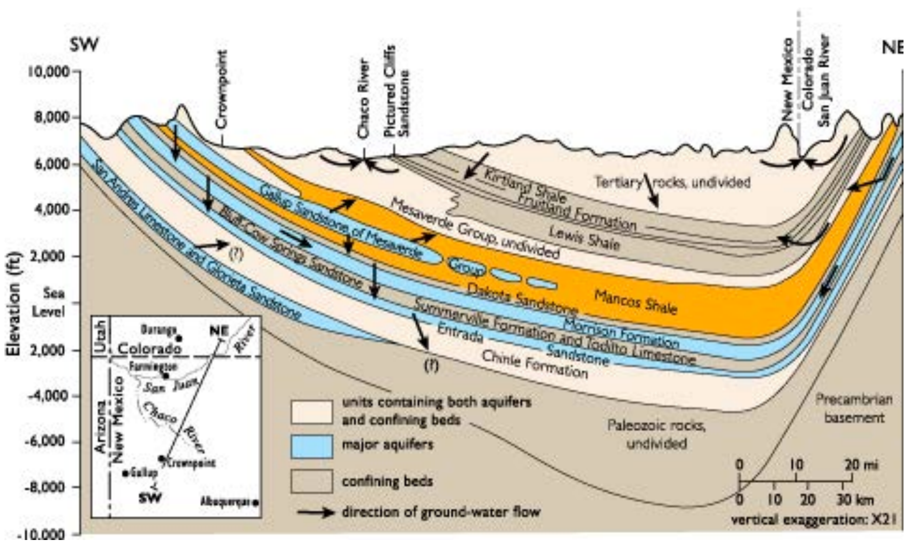


Figure 10. The San Juan Basin

Stop 12 Mile 49.3 GPS N 35 49.5655 W 106 58.1154

At this stop we can observe the contact between the marine Mancos Shale and the Point Lookout Formation. These strata record progradation of shorelines and deltas into the Western Interior Seaway. Note the transitional contact with the Mancos Shale. If you walk up the hill you first pass through Mancos Shale and then through thin beds of very fine-grained sandstone with hummocks, which indicate a lower shoreface to inner shelf setting. Further up the hill is a massive muddy sandstone unit capped by a well-sorted sandstone. These two units are interpreted as wave-dominated delta deposits by Wright (1983), who studied the continuous outcrops between here and Cabezon, some 20 kilometers to the south. During the late Cretaceous, the shoreline was oriented northwest-southeast across New the region (Fig. 11), so the outcrop belt studied by Wright follows the paleoshoreline.

Farther south, near Cabezon, the Point Lookout Formation is characterized by a more transitional, coarsening upwards sequence composed of lower shoreface interbedded sands and shales, overlain by upper shoreface sand and capped by parallel laminated sands that are interpreted and foreshore deposits. Thus, the sequence is more representative of the classic progradational shoreline and shoreface sequence. We will study these deposits later in the trip.

Figure 11. Late Cretaceous paleogeography of the southwestern US. (from http://www.thenaturalamerican.com/paleogeography.htm).

As the shoreline migrated across the basin a vast coastal plain was established. The strata of this coastal plain succession are collectively named the Menefee Formation. This succession is composed of carbonaceous shales and coals deposited in marshes, fluvial sands, bay muds, bayhead deltas and washover deposits (*Photo 22*).

Washover deposits composed of well-sorted quartzose sandstone are restricted to the upper part of the Menefee and are the first indicator of transgression (*Photo 23*). An irregular surface of erosion separates these washover deposits from the LaVentana Sandstone. Sedimentary structures and trace fossils within the LaVentana Tongue of the Cliff House Sandstone indicate deposition in a the upper shoreface environment. The contact between these formations is a planar surface of erosion that separates these upper shoreface sands from lower shoreface deposits composed of thin storm beds interbedded with marine shales. The surface between these two units represents a transgressive surface of erosion (transgressive ravinement surface) that removed upper portions of the upper shoreface, foreshore and subaerial coastal deposits. Sands eroded from the shoreface and foreshore were deposited as a transgressive sheet sand of the La Ventana. This stratigraphic association is similar to the Holocene MAFLA sheet sand that covers much of the present Mississippi, Alabama and Florida continental shelf.

Mile 52.3

Continuing to the north, we pass through exposures of the Lewis Shale, which is similar to the Mancos Shale and records another episode of marine transgression (Fig. 9). Note that there are several sand bodies within the lower part of the Lewis Shale. These sand bodies record pulses of shoreface progradation that were limited in extent; they do not occur just a few kilometers to the east. The final progradation is recorded by the Pictured Cliffs Tongue (Fig. 9), which can be viewed in outcrop on the east side of the highway (*Photo 24*).

The Pictured Cliffs shoreline reached its seaward limit about a kilometer northeast of this location, where the Lewis Shale contains no significant sand bodies. Given its limited extent, the Pictured Cliffs is considered a tongue of sediment and not a formation. The pinch-out of the Pictured Cliffs and other sand lenses with the lower part of the Lewis Shale at this location may be an early sign of emergence of the Nacimiento (Baltz, 1967; Woodward, 1987).

Stop 13 Mile 57.8 GPS N 35 56.6409 W 106 59.1198 Roadside stop to view Ojo Alamo, Fruitland/Kirtland and Nacimiento formations. (Photo 25)

Above the Lewis Shale are the late Cretaceous Fruitland and Kirtland Formations, which are difficult to distinguish, but the Fruitland is generally characterized by dark gray, organic-rich beds and occasional coal seems while the Kirtland tends to display more buff-colored shales. The Fruitland Formation records the final retreat of the Western Interior Seaway from the region to form a land-locked seaway. This change is recorded in the form of a transition from marine to brackish water fossils, including alligator plates, ostracods and foraminifera, near the contact with the Lewis Shale. Higher in the section there are abundant silicified wood fossils. Like the Lewis Shale, the Fruitland and Kirtland formations exhibit increasing thickness into the northwestern part of the San Juan Basin (Silver, 1951; Cather, 2004).

The Kirtland Formation is overlain by the Paleocene Ojo Alamo Formation (*Photo 25*), which is an extensive sheet of interbedded coarse sandstone and conglomerate. An unconformity spanning nearly 8.0 million years separates the two formations and includes the Cretaceous Tertiary boundary (Fassett, 2009). Note the large dark concretions, which resemble eyes (ojo in Spanish). Channel size and stacking patterns and variable transport directions indicate deposition by braided streams within a vast alluvial plain. The regional paleotransport direction is toward the south. The increase in gradient associated with these braided channel deposits are the first evidence of an actual change in relief associated with the Laramide uplift. The Ojo Alamo contains dinosaur fossils which, if not reworked, could have been survivors of the Cretaceous-Tertiary extinction event (Fassett and Lucas, 2000).

Above the Ojo Alamo Formation is the syntectonic (Laramide) lower Paleocene Nacimiento Formation, which records emergence and denudation of the region that began during Ojo Alamo time. The age of the Nacimiento is 64.5-61 Ma. The lower portion of the Nacimiento is composed mainly of variegated shale representing lacustrine and flood plain deposition in a distal fan setting. The Nacimiento Formation approaches a half kilometer in thickness near Cuba, New Mexico and is known for its spectacular, badlands type outcrop patterns and colors (*Photo 26*). Later will be driving through excellent exposures of the Nacimiento Formation on Highway 96 in route to Abiquiu Dam.

Stop 14 Mile 64.6 Drive through Cuba, New Mexico to Cuba Mesa (Photo 27)

At this stop we can observe an outcrop of the Eocene (55-51 Ma) Cuba Mesa Member of the San Jose Formation resting on the Nacimiento Formation (*Photo 27*). The Cuba Mesa Member is composed of poorly sorted arkosic sands and conglomerates. We will drive a short distance up the highway to have a closer look at the Cuba Mesa Member.

Stop 15 Mile 66.1 GPS N 36 2.278 W 106 58.051 (Photo 28)

We will make a short stop to study braided channels of the Cuba Mesa Member. Note that this outcrop contains stacked channels that are on average less than 10 meters across and less than 2 meters deep. Channels are filled with coarse, angular, lithic sandstones and conglomerates Sedimentary structures indicate variable transport directions from channel to channel. Combined, these observations indicate deposition within braided streams. The San Jose Formation is a fluvial sheet sand composed of braided channels that were deposited within a broad alluvial fan. Sedimentary structures indicate paleotransport toward the west and into the San Juan Basin.

Intersection of Hwy 550 and Hwy 96 (Mile 67.4)

After turning onto Highway 96 we will pass through exposures of the Cuba Mesa Member of the San Jose Formation followed by exposures of the Nacimiento Formation.

Intersection of NM 96 and 112 (Mile 80.3)

Stop 16 Mile 81.4

Approximately 14.0 miles after turning onto Highway 96 we will cross the northern margin of the Nacimiento Uplift, which at this location is manifest as a northward plunging anticline exposing Menefee formation shales overlain by the La Ventana sandstone at this location. This anticline is the northern most structure you can observe that was formed as a result of the uplift of the Nacimiento Mountains.

Mile 88.3 View point of the thick Entrada Formation overlain by the Todilto Formation in the distance on the north side of NM 96

As we continue to drive east we pass spectacular outcrops of Entrada Formation, Todilto Formation and Chinle Group (Photo 29). These formations are all significantly thicker than they are along the southern portion of the Nacimiento, as viewed earlier today. They dip gently to the northwest into the Chama Basin, which was the depocenter for the Mesozoic deposits.

Mile 97.6

Near Coyote, New Mexico we encounter a thick section of Abo Formation overlain by the Aqua Zarca that occurs within the southern margin of the Chama Basin (*Photo 30*). Continue driving north on Highway 96 toward Abiquiu Dam.

Stop 17 Mile 103.3 GPS N 36 11.3679 W 106 35.1632 At the intersection of NM 96 and Rio Arriba County route 211. Approximately 50 meters down route 211 and to the right, there are excellent exposures of the Aqua Zarca Formation composed of conglomeritic sandstones just above the contact with the Abo formation.

Mile 114.9 Corp of Engineers facility GPS N 36 14.4203 W 106 25.6753

We will end the day here where there is an excellent view of the Mesozoic strata that fill the Chama Basin. Clean restrooms

Day 2—*Reset Miles to 0* at *the Corp of Engineers Facility*

The Abiquiu and Ghost Ranch area contains excellent outcrops that were deposited within the Chama Basin, which is situated east of the San Juan Basin and along the eastern margin of the Colorado Plateau. It contains an unusually thick stratigraphic succession of Permian Abo Formation through Dakota Formation that has experienced relatively little tectonic deformation.

Stop 1. Abiquiu Dam Spillway GPS N 36 14.3873 W 106 25.4221 (Photo 31)

At this location we will examine outcrops of the Late Triassic Chinle Group, including the basal Aqua Zarca Formation, Salitral Formation, Poleo Formation and Petrified Forest Formation. These include both high energy braided (Agua Zarca) and low sinuosity (Poleo) river deposits interbedded with lacustrine deposits (Salitral and Petrified Forest formations) that reflect dramatic changes in base level, river discharge and regional topography. We will also examine the response of a single fluvial system (the Poleo Formation) to changes in base level. Our examination of the Chinle Group will begin at the parking area at the base of the spillway (0.2 miles from turn off from Hwy 96) and work our way up the section to the highway.

During Triassic time, coarse clastics were still being shed from the ancestral San Juan Mountains of Colorado into northern New Mexico (Fig. 4). These rocks occur in the basal part of the Triassic Chinle Group in the Agua Zarca Formation. Walk south across the dirt road from the Spillway Station to the outcrops of Agua Zarca near the road. There are a number of large displaced blocks near the base of the hill that provide excellent examples of the conglomerates with cobble size quartzite clasts, so it is not necessary to climb the hill (Photo 32).

The Agua Zarca Formation is mainly restricted to the Nacimiento Mountains and the Abiquiu area. It is interpreted as having been deposited by high-energy braided rivers with sedimentary structures indicative of south to southwest paleotransport. Locally the Agua Zarca contains sedimentary copper deposits (malachite and azurite, Photo 33) that have been mined near Cuba, New Mexico, but none of these mining activities were profitable.

The Aqua Zarca Formation is overlain by the Salitral Shale Formation, which was deposited in a vast lake that extended across the Four Corners region. The Salitral Formation and Petrified Forest Formations provide excellent examples of lacustrine sequences that were deposited under relatively humid climatic conditions. These lakes were large and relatively shallow, as indicated by interbedded mudstones and siltstones with oscillation ripples that are interspersed throughout both units. Wood fossils and vertebrate fossils are found in both members. The best exposures of the Salitral Formation are on the north side of the road behind the Spillway station (*Photo 34*). The change from braided rivers to a lake setting indicates a dramatic reduction in the relief of the area, specifically the relatively steep southward gradients associated with the ancestral Rocky Mountains. This contact undoubtedly represents and unconformity.

Above the Salitral Formation is the Poleo Formation, which is well exposed in the outcrops on the north side of the spillway. Study the base of the Poleo Formation behind the spillway where it is composed of chert pebble conglomerates (*Photo 35*). Now drive about half way up the winding road where, from the south side of the spillway, you can view the Poleo exposures in the opposite side of the spillway to the north (*Photo 36*). Take some time to study these exposures and the channels, looking for changes in their depth to width ratios upward in the section. Note that lateral accretion is minimal, indicating low sinuosity rivers. Now, go to the top of the hill and study the exposures along the spillway road, just below where it intersects with Hwy 96. We recommend parking your car at the Corps of Engineers station and walking back to this outcrop, being extra careful when crossing the road. The road cut on the east side of the spillway road contain sedimentary structures that consist mainly of decimeter scale troughs and forest beds. Note that these forest beds indicate a fairly consistent paleotransport direction (*Photo 37*), consistent with fairly strait channels. Note also that the paleotransport direction is toward the northwest, opposite the paleotransport direction of the Agua Zarca Formation. These observations are consistent with paleogeography reconstructions for this time, which depict large rivers flowing from Texas and southeastern New Mexico to the northwestwest (Fig. 12) and indicate large scale changes in gradient across the region.

Near the top of the hill are beds with ripples and parallel laminations, indicative of an upper point bar setting. This reflects a decrease in gradient and increase in channel sinuosity associated with the change from a fluvial (Poleo Formation) to a lacustrine (Petrified Forest Formation) setting. Now study the gradational contact between the Poleo Formation and the Petrified Forest Formation. Near the base of the Petrified Forest Formation you will observe very fine sand beds with oscillation ripples interbedded with shale (*Photo 38*), marking the initial flooding of the region and onset of lacustrine conditions. Now walk across the highway to the entrance road to the Corps of Engineers facility. Note the large-scale, low-angle cross bedding within the interbedded sandstone and shale beds in the road cut (*Photo 39*) and the parallel laminations within the sandstone beds. These outcrops were interpreted as deltaic deposits by Kurtz and Anderson (1980).

We will now drive to our next stop, which follows the paleotransport direction observed in the channels.

Figure 12. Late Triassic Paleogeography of the southwestern US. (from http://www.thenaturalamerican.com/paleogeography.htm).

Stop 2. Poleo Delta Mile 5.8 GPS N 36 18.3747 W 106 26.8646 (Photo 40)

Return to the cars and drive north on Highway 96 to the intersection with Highway 84. Turn left onto Highway 84 and drive west to Stop 2. Along the way we will drive through several road cuts into the Poleo Formation. At Stop 2 we will need to park on the right side of the highway and walk across the road, so be careful and watch for cars. Walk down the hill and look back toward the outcrops of Poleo to the east. The outcrops in these road cuts include sandstones, siltstones, and shales that represent a variety of deltaic environments that prograded into a vast lake. Kurtz (1978) was able to trace the outcrops in Abiquiu Dam to this location and thus link these deltas to the fluvial channels that are exposed at Abiquiu Dam. Note the change in the dip of the beds, which indicates a delta lobe shift (Photo 40). Now walk up to the outcrop and take a closer look at these well-sorted mouth bar sands.

Miles 6.4-8.0 Return to the cars and drive north toward Ghost Ranch. At the bottom of the hill we pass through some excellent exposures of the Petrified Forest Formation (*Photo 41*). Petrified logs do occur in the area, but they are not near as common as in Arizona. The Petrified Forest and Salitral formations have yielded fossils of some of the earliest dinosaurs, which can be seen at the museum in Ghost Ranch. There are also lungfish trace burrows near the contact of the Petrified Forest and Entrada formations that record a sift to more arid conditions and drying up of the lake (Dubiel et al., 1987).
As we drive past Ghost Ranch, we will pass spectacular outcrops of the Morrison, Entrada and Todilto formations.

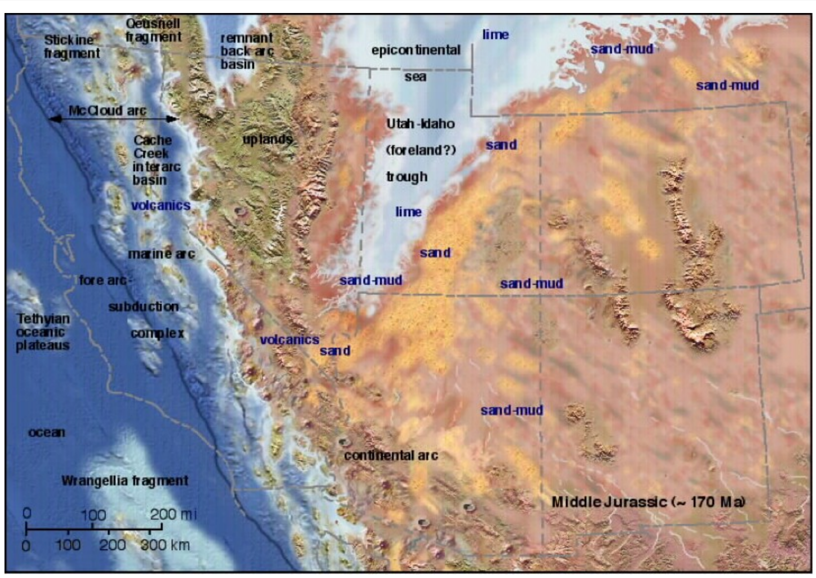
Stop 3 Mile 12.0 Echo Amphitheater GPS N36 21.535 W 106 31.378

At the Echo Amphitheater we can examine exposures of the Petrified Forest Formation, (just up the hill from the restrooms), the Entrada Formation and the Todilto Formation (Photo 42).

During the early Jurassic through the middle Jurassic, a large oceanic plateau (Wrangellia) was being thrust against the western margin of North America (Fig. 13). Thrusting in Nevada created uplands that shed sediment to the east. In the Four Corners region, vast deserts and salt lakes existed. These were the environments in which the Todilto Formation (salt lake) and Entrada Formation, representing desert conditions, were deposited. Typical of eolian deposits, the Entrada Formation is comprised of well-sorted, well- rounded, quartz sands. Individual grains are frosted. Sedimentary structures include ripples with ripple indices >15, which is characteristic of dune deposits. Very large, high angle cross-beds also point to an eolian origin for the Entrada Formation. Paleotransport directions for the Entrada Formation are consistently toward the south, which is at almost right angles to the paleoslope of the Colorado Plateau. The absence of pebbles, fine matrix (excluding secondarily derived iron oxides), and channels is further evidence of an eolian origin for the Entrada Formation.

The Todilto Formation represents an arid lake deposit. The lower part of the Todilto consists of gray, laminated, fetid limestone. This basal unit contains non-marine ostracods, fish and insects. Basal carbonates grade upward into interlayered limestone and gypsum laminae, reflecting wet-dry climate cycles, perhaps even seasonal cycles. Gypsum gradually becomes more prominent upwards in the section, with the upper part of the formation consisting of massive gypsum 60 to 80 meters thick, recording the time when the Todilto Lake dried up to form a large salt flat.

Figure 13. Jurassic paleogeography of the Colorado Plateau region



The Todilto Formation was buried beneath thick flood plain and channel deposits of the Morrison Formation, which was sourced by uplands in Arizona and Nevada. It covers virtually the entire Four Corners region.

Stop 4 Mile 17.7 Start of roadside section of Morrison/Dakota formations along highway 84 GPS N 36 25.0774 W 106 28.8667

At this location we will visit an extensive outcrop in the road cuts along State Highway 84 north of Ghost Ranch. Here we will study the Morrison and Dakota Formations along the west side of the highway, working our way toward the north. The base of the section consists of flood plain deposits including green and reddish colored shale (*Photo 43*) and thin, tabular sandstones that represent crevasse splay deposits. As we drive along the highway toward the north, we will observe a change to more massive sandstones with trough cross bedding within gravel-lined channels. This large channels are part of the Brushy Basin Member of the Morrison Formation.

Continuing toward the north we will encounter channel sands with interbedded carbonaceous shale and coal (*Photo 44*). This is the lower sand member of the Dakota Formation, which is separated from the Morrison Formation by a major unconformity that spans approximately 50 million years. (~***Mile 18.2 (Dakota/Morrison Unconformity)*** The basal sands are characterized by trough cross beds lined with gravel and displaying highly variable westerly paleotransport directions. At this point, cross the highway (be sure to look both ways) where you can view the channels within the lower Dakota Member. Note that the scale of the channels increases upwards in the section, similar to what we observed in the Poleo Formation at the Abiquiu spillway. If you study the large channels on both sides of the highway closely you will observe lateral accretion in some of the upper channels.

Continuing north where the road cuts are set back from the highway you will observe low-angle, planar cross-bedded sands interbedded with carbonaceous shale (~***Mile 18.3 Dakota Bayhead Delta***) (*Photo 45)*. Note that the large-scale cross bedding is similar to the deltaic deposits we observed at the top of the Poleo Sandstone section in the Corps of Engineers entranceway. However, the Dakota delta is rich with organic material, indicative of a coastal setting. There is a gap in the outcrop at this point, but continue walking north where you will encounter a thick section of carbonaceous shale. This is the middle coal-bearing member of the Dakota Formation (*Photo 46*). At this locale the middle member is composed mainly of black shale that contains trace fossils indicative of a bay setting. As you walk north and higher in the section you will begin to observe thin, tabular sands with abundant burrows (*Photo 47*). These are washover sands that in other locations have sedimentary structures that record the landward migration of the washover deposits (*Photo 48*). At the top of the hill is a massive sandstone, which is the upper marine sandstone member of the Dakota Formation. We will study an exposure of the upper Dakota sandstone member later in the trip.

Our interpretation of the Highway 84 Dakota section is that it was deposited within an incised valley, which accounts for the unusually thick lower fluvial and middle carbonaceous units. The sequence records a transition from braided to more sinuous channels upwards in the section, followed by bayhead delta and thick bay deposits within the middle member. A transgressive ravinement surface separates this incised valley fill succession from the capping barrier island marine sand unit at ***(~Mile 18.8)*** Later we will observe the upper member of the

Dakota Formation near Cuba where the lower fluvial and middle coal-bearing members are much thinner.

Return to the vehicles and drive back to Cuba.

Highway 126 Geologic Transect Reset Mileage to 0
Intersection of US 550 and NM 126 in Cuba

Stop 1 Mile 5.7

In the town of Cuba, New Mexico drive east on State Road 126 where we will observe a virtually complete stratigraphic section and two road cuts through the Nacimiento Fault Zone. About a half mile from the intersection of Highway 550 and State Road 126 the road will split. Stay to the right on 126 and continue driving east for approximately 5 miles to the National Forest Boundary. From there, continue driving east past the mine tailings on the north side of the road and park at the entrance to the mine (Mile 5.7). Park at the mine entrance and walk east along the road approximately 200 yards. Remain behind the road guard and watch for cars. Along the north side of the road there are excellent exposures of the Abo Formation and Agua Zarca Formation. Walking back to the west you pass through the Salitral Shale at the mine entrance and the contact of the Poleo Sandstone and Petrified Forest Formation west of the entrance.

The tailings pile on the north side of the highway is from an open pit copper mine that was active during the early 1970's (Photo 49). The sedimentary copper occurs as malachite and azurite within the Agua Zarca Formation (*Photo 34*). The mining terminated when it was discovered that the Agua Zarca sandstone abruptly terminates in the subsurface where it is offset by the Nacimiento fault zone. This is a classic example of poor geology that resulted in a tarnished landscape and polluted waters that flow through the mine tailings, into the adjacent creeks and eventually into the Rio Puerco.

S***top 2 National Forest Boundary GPS N 35 59.088 W 106 54.119***

Return to the vehicle and drive back toward Cuba. Stop briefly at the cattle guard at the National Forest boundary and study the outcrops on the north side of the road where the Petrified Forest Formation is in fault contact with the Morrison Formation. This is one of two faults that form the Nacimiento Fault Zone at this location. Note that the beds to the east of the fault, the upthrown block, are tilted to the west at angles of 25° to 35°. As you drive toward the west of the fault you observe near vertical beds on the downthrown side of the fault.

Stop 3 Mile 7.75 GPS N 35°58.870, W 106°54.919

At the top of the hill pull off the road where there is a road cut through a large hogback within the Mesa Verde Group (Photo 50) This is one of the few locations where the Nacimiento Fault Zone can be observed in outcrop. At this location the fault plane cuts through the strata and splays into a number of bedding plane faults within the coal and carbonaceous units. This is an excellent illustration of brittle-ductile deformation, with the sandstones behaving in a brittle fashion while the carbonaceous shales exhibit ductile deformation.

Return to the vehicles and continue driving west toward Cuba. After passing the last stop you will drive through a thick section of Lewis Shale, followed by exposures of the Fruitland/Kirtland Shale. Note the distinctive change in the color of the shale and weathering profile; it becomes much darker in color and forms rounded hills upward in the section passing into the Kirtland Shale. Note also that the beds dip gently to the west, so we have already passed through the zone of intense deformation associated with the Nacimiento Fault Zone. Continue driving west through road cuts within the Ojo Alamo Formation, then back to Cuba.

Reset Mileage to 0

San Miguel Canyon Road Geologic Transect

Stop 1 Upper Dakota Sandstone

On the south side of Cuba, at the intersection of Highway 550 and County Road 11, turn left just before the USDA forest service office where CR11(Old Highway 44) veers to the left. Drive ~6.4 miles south to San Miguel Canyon Road (County Road 78). As you drive to the south from Cuba, you first pass through outcrops of the Ojo Alamo Formation and then Lewis Shale. Note that the Pictured Cliffs Tongue, which is exposed in road cuts on Highway 550 just west of here, are not present at this location. Continue driving south through the Lewis Formation to San Miguel Canyon Road, turn east and go to the end of the paved road. Continue on the dirt road to the left, which will take you to the National Forest Boundary.

The prominent hogback located at the entrance to the National Forest Boundary is the upper sand member of the Dakota Formation (Photo 51). This is the best location to study the upper sand member of the Dakota. At this location it contains abundant trace fossils and oscillation ripples that occur on bedding surfaces of individual sandstone beds (*Photo 52)*. These beds represent storm deposits and surfaces with ripples and trace fossils record intervals between storms. The upper contact of the Dakota Formation with the Mancos Formation is poorly exposed at this location, but elsewhere along this outcrop belt it is quite sharp and records transgressive ravinement (erosion to the depth of storm wave influence) that has removed much of the lower shoreface deposits. Along the Texas coast the current depth of shoreface ravinement occurs at -8 to -10 meters water depth, which corresponds to the physiographic toe of the shoreface and the location where marine muds onlap lower shoreface deposits (Rodriguez et al., 2001).

Recall from our discussions yesterday that the Dakota Formation records the initial transgression into the Western Interior Seaway. Here too the Dakota consists of three members, a lower conglomerate and sandstone member that is of fluvial origin, a middle carbonaceous shale and coal member that is a coastal plain deposit, and an upper sandstone member that is a transgressive marine deposit. The lower two units are poorly exposed at this location, but they are roughly 25% the thicknesses that we observed along Highway 84. The upper marine sandstone member is of similar thickness at both locations. This is consistent with the interpretation that the lower and middle Dakota members along Highway 84 were deposited within an incised valley. It is also consistent with the sequence stratigraphic interpretation that the unconformity of the lower Dakota fluvial sand and the Morrison Formation is a sequence boundary and the middle coal-bearing unit and upper marine sand are part of the transgressive systems tract.

Stop 2

Before continuing the transect through the late Cretaceous strata to the west, we will make a short diversion to view one of the few locations where the basal Todilto limestone unit is well exposed and accessible in a road cut. Just to the east of the Dakota hogback the road splits. Take the road to the north and drive .8 miles to the point where the road makes a sharp turn to the right. There is a pull out here where you can park. Walk from here to the east through the road cut into the Lower Morrison Sundance Member and Todilto. The contact between the basal limestone unit and gypsum is at the east end of the road cut (*Photo 17*). The contact between the Todilto and Entrada formations is also exposed. Break off a piece of the limestone and smell the distinctive petroliferous odor.

Stop 3 ~ 1 mile east of the intersection of CR 11 (Old Hwy 44) and CR78 (San Miguel Canyon Road) GPS N35 55.599 W 106 55.502

Return to the vehicles and drive back towards CR 11 (Old Highway 44) along San Miguel Canon Road where we will spend some time looking at exposures of the Menefee Formation, which is capped by La Ventana Sandstone in an anticline on the north side of the road (*Photo 53*). The Menefee Formation was deposited in a wide range of coastal plain environments, including tidal creeks, bays, bay-head deltas. fluvial channels and washover environments. As we drive east on San Miguel Road we will pass several isolated channel sand bodies within the carbonaceous shale and mudstones. These channels are generally less than 100 meters wide and 8 meters deep and display lateral accretion sets (*Photo 54*). Sedimentary structures indicate flow toward the south and southwest. Based on their relatively small size and lower width to depth ratios, these are interpreted as distributary channels. Most of the channels are on private land, but there is one exposure along the road near the cattle guard that is accessible.

Standing in the road and viewing the outcrops from the road, study the contact between the Menefee Formation and the LaVentana Tongue. The white sands in the upper part of the Menefee are stacked washover sands that record the initial transgression of a coastal barrier into the area (*Photo 23*). Note the relief at the base of the LaVentana sandstone. The irregular nature of this surface suggests that it is not a wave-cut surface, which should be more planar. Rather, the depressions at the base of the sand are filled with washover sands and are interpreted as back-barrier tidal creeks and/or storm surge channels that were filled during transgression. A few meters above this surface there is a less distinct, planar surface that is interpreted as a wave cut surface. Above this surface are well sorted sandstone with oscillation ripples and current ripples and abundant trace fossils, indicative of a shoreface environment. This upper, planar surface is the transgressive surface that separates the Menefee and the LaVentana. This is similar to what we observed at the contact between the upper Dakota sand member and the Mancos Shale. These sharp contacts are interpreted as transgressive ravinement surfaces that are formed at the toe of the shoreface were storm waves erode shoreface deposits that are eventually buried by marine mud. We will see later that this transgressive coastal succession is quite different from the progradational coastal successions that occur at the base of the Point Lookout Formation and Pictured Cliffs Tongue, which are characterized by thick shoreface deposits.

Return to CR 11 (Old Highway 44) and drive south. As we drive along CR 11, we will remain at about the same stratigraphic level as the distributary channels we observed along San Miguel Road. About 1.65 miles from the intersection with San Miguel Road, we begin to observe a much more laterally extensive, white sand body in outcrops on the east side of the road. This represents the facies transition between distributary channels and mouth bar deposits of a delta. Field work in this area has shown that there are six individual sand bodies, representing six delta lobes, that stack into an overall succession that is ~20-30 meters thick.

Stop 4 Menefee Delta N 35°53.891, W 106°56.579 Barboa Ranch Entrance

Park on the side of the road and remain on the public access near the driveway entrance where there is an exposure of one of these delta lobes (*Photo 55)*. Remain outside the fence or you will be entering private property.

Note the large scale cross beds and laminated intervals comprised of well-sorted, trough-bedded sandstone with lenses of organic material (*Photo 56*). These are interpreted as mouth bar deposits. Remember this delta occurs within the Menefee Formation, so it is a bayhead delta. The scale of the delta, its distributaries and the main feeder channel are similar to the modern Trinity bayhead delta of east Texas (Anderson et al., 2008).

The Menefee Formation records the turnaround from regression (Point Lookout Sandstone) to transgression (Fig. 9) and therefore contains the sequence boundary, which marks the maximum fall of sea level. For the most part, the Menefee is composed of carbonaceous shale, organic mudstone, coal and lignite beds, which indicates that deposition occurred at or near sea level and within coastal plain and bay environments. Given this, and since deltas form relatively fast in geological time, it seems logical that the delta complex was filling accommodation space within an incised river valley. This implies that the contact between the carbonaceous shales and the delta sands is the sequence boundary associated with the base-level fall and most seaward shoreline location, which occurred about 80 Ma (Fig. 9). The bayhead delta is within the transgressive systems tract.

Stop 5 GPS N 35°53.596 W 106°56.528

We will now continue about 0.3 miles south on CR 11 (Old Highway 44) and park on the side of the road. Walk to the top of the hill east of the road and look back toward the north at the white mouth bar sands of the Menefee delta (Photo 57). At this location we can view an excellent example of a lobe shift (*Photo 58*).

Continue driving south on CR 11 (Old Highway 44) for approximately 2 miles to where the road becomes a gravel road and veers to the west. As you drive to the west follow the contact between the Menefee Formation and the La Ventana Tongue in the exposures on the north side of the road. If you are feeling energetic you can climb to the top to study the excellent exposures the Menefee Formation and LaVentana Tongue. As you drive west on the gravel road study the large displaced sandstone blocks of the La Ventana sandstone on the north side of the road. You may want to pull over and walk over to the largest of these blocks, which contains nice examples of ripples that reflect variable transport directions (Photo 59). These are interpreted as upper shoreface sands and record variable coastal currents.

Old Highway 44 Transect

Continue driving west on the gravel road to Hwy 550 and turn south. Drive approximately .95 miles to Old Highway 44, which is the paved road on your left. Turn onto the paved road and drive to the top of the hill. The road is in very poor condition, so watch for pot holes. Park the cars at the top of the hill, there is a pull out on the west side of the road just past the cattle guard, which is a public access road. Walk down the road toward the south. As you walk down the hill, trace the sand bodies within the mesas on both sides of the road. Start at the bottom of the hill and walk up the road observing the road cuts along the road. Note that the lowest sand body, which is best exposed in the section at the bottom of the hill and to the east of the road, is characterized by trough stratification and displays paleotransport toward the south. Next, walk back to the road and count the number of individual channels as you walk to the top of the road. These channels contain beautiful sedimentary structures that can be used to measure paleotransport directions (*Photo 60*). Note that the foreset beds in the lower channel indicate flow toward the northwest, almost opposite the paleotransport direction observed in the lower sand body and roughly parallel to the shoreline trend shown in Figure 11. As you walk up the hill you come to a second, younger channel with sedimentary structures indicating flow toward the west. The third and youngest channel is at the top of the hill and it displays an excellent example of lateral accretion (*Photo 61*). Note also the increase in organic material within the floodplain deposits as you walk to the top of the hill, indicating a change to more marsh-like conditions. These combined observations indicate that these were highly sinuous channels, which indicates that they existed when sea level (base level) was rising. Regional mapping has shown that these channels are situated stratigraphically above the proposed incised valley and associated bayhead delta that we observed to the north along old Hwy 44. Thus, this section records the beginning of the final major transgression of the late Cretaceous seas into the Western Interior Seaway (Fig. 9).

San Luis Road Transect

At the intersection of Route 197 and 550 drive south from Cuba for approximately 21.8 miles to NM 279 (San Luis Road), which goes to Cabazon. Go about 8 miles, where there is a good observation point looking north, to view seaward stepping shoreface sands downlapping onto Mancos shale along **Bosque Grande Mesa** ***(Stop 1) GPS N 35 41.163 W 107 3.602*** (*Photo 62*). This section is a classic example of a progradational marine shoreline succession (Fig. 14). The section, from bottom to top, is composed of Mancos Shale, lower shoreface, upper shoreface, and foreshore. There are also good examples of tidal creeks cutting through the foreshore, and tidal inlet facies that are capped by carbonaceous shales of the Menefee Formation. The contact between the Point Lookout Sandstone and the underlying Mancos Shale is highly gradational, consisting of a relatively thick sequence of interbedded siltstones, mudstones, sandstones and sandy shale of the lower shoreface.

There are excellent examples of storm bar deposits within the Mancos and these display good examples of hummocky cross bedding and other types of storm-related sedimentary structures (*Photo 63*). The thin sand beds near the contact of the upper Mancos and Point Lookout transition contain hummocks and are composed of very fine sand. Sedimentary structures on the undersides of sand units include flutes, grooves and gutter marks (*Photo 64*) that provide paleotransport directions that are generally toward the east, consistent with the paleoshoreline orientation at this time (Fig. 11). The massive sandstone at the top of the section are upper shoreface and foreshore deposits (Fig 14). Sedimentary structures are difficult to see in these outcrops because of the uniform grain size, but trough orientations in the lower portion of the massive sand are consistent with the shoreline orientation indicated by features at the base of the lower shoreface storm deposits.

At the top of the section you can observe laminated sandstones representing the foreshore environment (*Photo 65*). Carbonaceous shale of the Menefee Formation lies directly above these foreshore deposits and record the final stages of progradation.

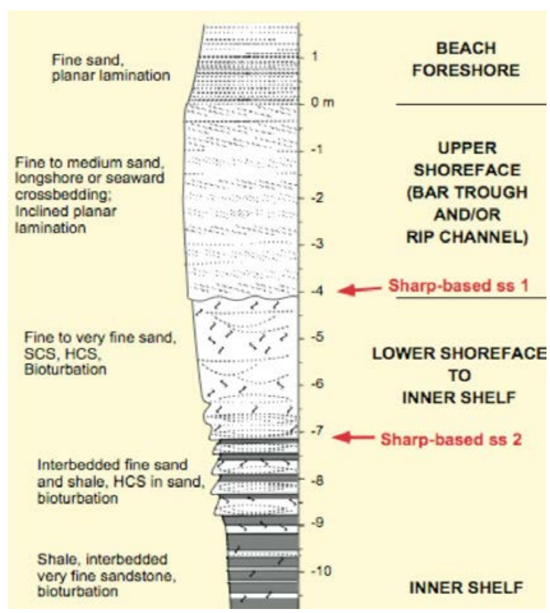


Figure 14. Idealized sequence of progradational shoreline.

(Note, Access to outcrops along the north side of San Luis Road is on private land, and requires permission. You can access outcrops of the Point Lookout and Mancos along Pipeline Road because this area is on BLM land (*Reference USGS 1:24000 Topographic Map, San Luis, NM****)***

To access the Mancos/Point Lookout Section continue another ~.5 miles on San Luis Road and turn right on Pipeline Road. Proceed 1 mile and pull off the road and park. Here you can walk under a barbed wire fence, cross Arroyo Balcon and walk up and observe the outcrops along Bosque Grande Mesa

The sequence observed at this location differs from that of the Pictured Cliffs exposures we observed on our first day on Highway 550. Both are characterized by interbedded sandstones and shales that grade upward into massive sandstone (Photos 24 and 62). However, the upper massive sand of the Pictured Cliffs is capped by marine shales of the Lewis Formation. Thus, a transgressive ravinement surface occurs between the sandstones and marine shale. What is also lacking is a transgressive sand body that would be analogous to the La Ventana Tongue. The absence of a transgressive sandstone is attributed to the fact that the Pictured Cliffs outcrops we observed on Highway 550 are situated near the seaward limits of the progradation; remember that the Pictured Cliffs pinches out to the east and does not cross Old Highway 44. During transgression there were no sand bodies situated offshore that would have sourced a transgressive sheet sand, such as the La Ventana Tongue. This succession is more similar to the sand starved Holocene deposits of the east Texas coast, where the transgressive ravinement surface separates shoreface deposits from overlying marine muds.

This completes the trip. We hope you enjoyed it and learned a lot.

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Appendix A: Useful Maps

U.S. Department of the Interior, Bureau of Land Management, Surface Management Status 1:100000 Scale

a. 2012 Chaco Mesa New Mexico
b. 2010 Albuquerque New Mexico
c. 2010 Los Alamos New Mexico
d. 2011 Abiquiu New Mexico
e. 2012 Chaco Canyon New Mexico

U.S. Department of Agriculture, U.S. Forest Service (America's Great Outdoors) 1:126720 Scale

a. 2004 Sante Fe National Forest New Mexico
b. 2010 Carson National Forest New Mexico

2018 New Mexico Recreation Map, Benchmark Maps 1:829187 Scale

1970 New Mexico Bureau of Mines and Mineral Resources, Geologic Map #25
Geological Map and Cross Sections Cuba Quadrangle 1:24000 Scale, SE Corner Precambrian 1:12000
Lee A. Woodward et al.

1970 New Mexico Bureau of Mines and Mineral Resources, Geologic Map #26
Geological Map and Cross Sections San Pablo Quadrangle 1:24000 Scale
Lee A. Woodward et al.

1973 New Mexico Bureau of Mines and Mineral resources, Geologic Map #28
Geological Map and Cross Sections La Ventana Quadrangle 1:24000 Scale
Lee A. Woodward et al.

1946 U.S. Department of the Interior, U.S. Geological Survey and the Department of Geology, University of New Mexico
Geology of the Nacimiento Mountains, San Pedro Mountain, and Adjacent Plateaus in Parts of Sandoval And Rio Arriba Counties, New Mexico. Oil and Gas Investigations Map OM-57
G.H. Wood and S.A. Northrop

2005 New Mexico Geologic Highway Map, New Mexico Bureau of Geology and Mineral Resources, 1:100000 Scale

U.S. Department of the Interior, U.S. Geological Survey, Topographic Quadrangle Maps 1:24000 Scale

a. 2002 Gilman, New Mexico
b. 2011 San Pablo, New Mexico
c. 2002 La Ventana, New Mexico
d. 1969 San Ysidro, New Mexico
e. 2002 Cuba, New Mexico
f. 2013 Ojito Spring, New Mexico
g. 1969 Holy Ghost Spring, New Mexico
h. 2002 Regina, New Mexico
i. 1961 Cabezon Peak, New Mexico
j. 1961 San Luis, New Mexico

Photo1

Photo2

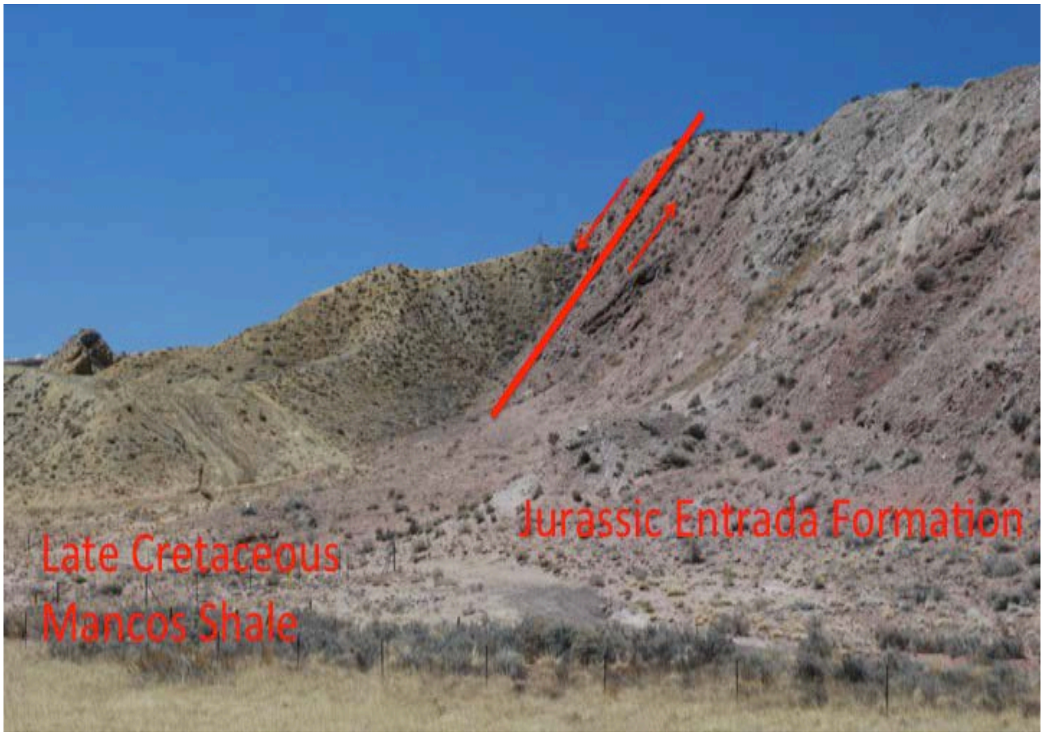

Photo3


Precambrian Cyrstalline Rocks
Agua Zarca Formation
Abo Formation

Photo 4

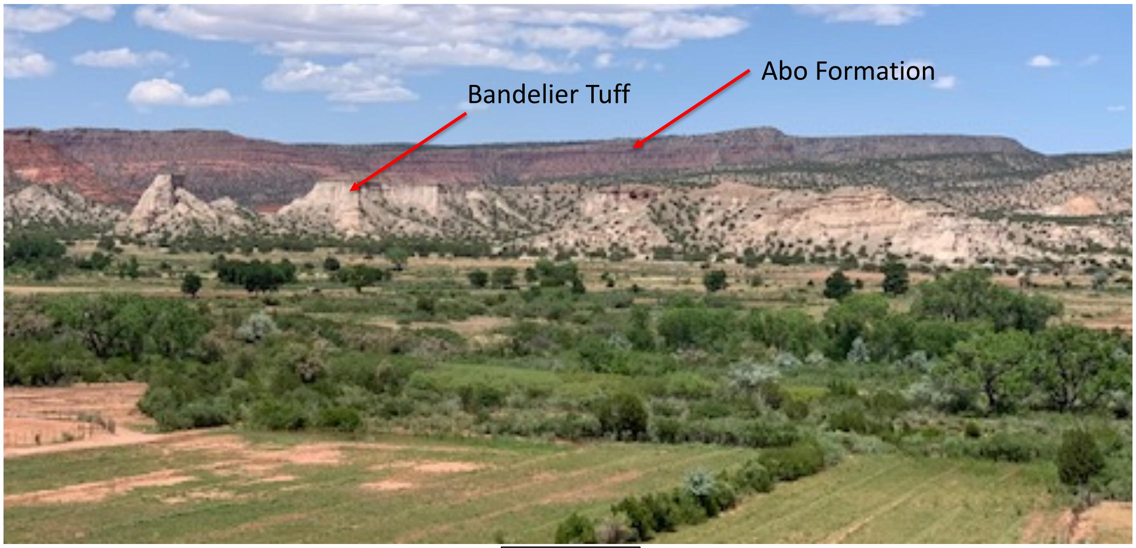

Photo 5

Photo6

Photo7

Photo8

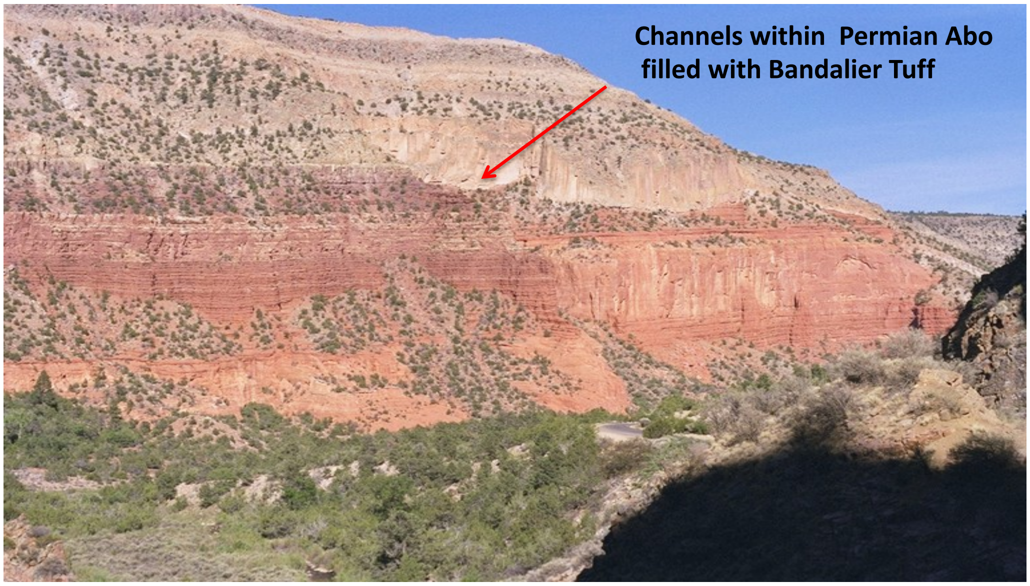

Photo9


Precambrian Granite/
Metamorphic rocks
Permian Abo
Formation

Photo10

Photo11

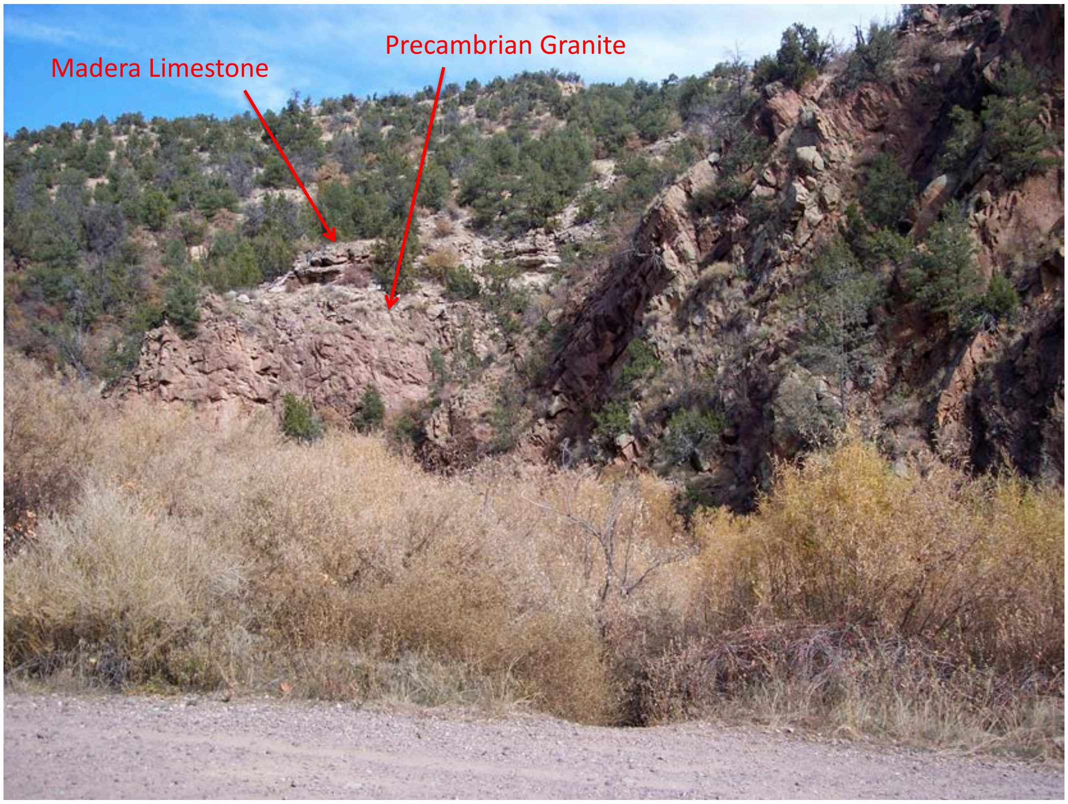

Photo12

Photo13

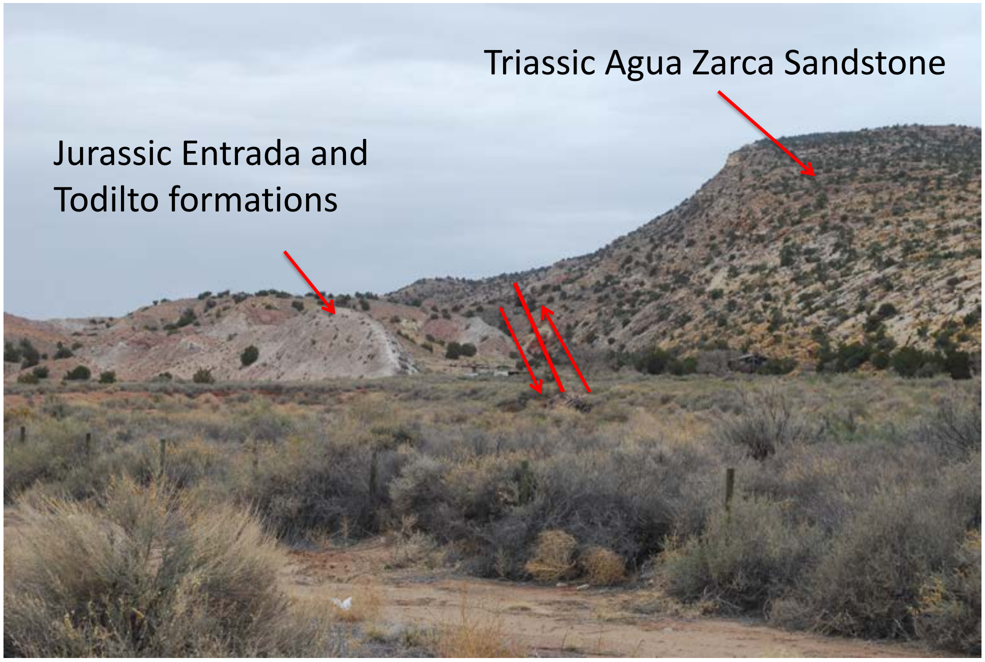
Triassic Agua Zarca Sandstone
Jurassic Entrada and
Todilto formations

Photo14

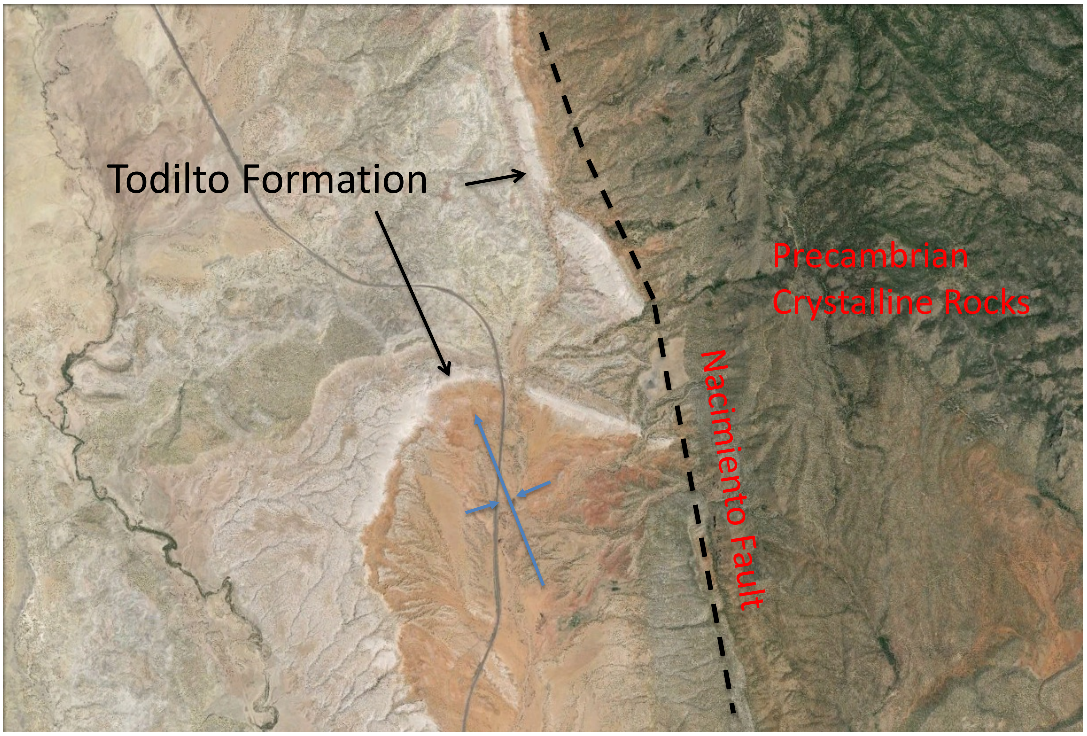
Todilto Formation
Precambrian
Crystalline Rocks
Nacimiento Fault

Photo15

Photo16

Photo17

Photo18

Photo19

Photo20

Photo21

Photo22

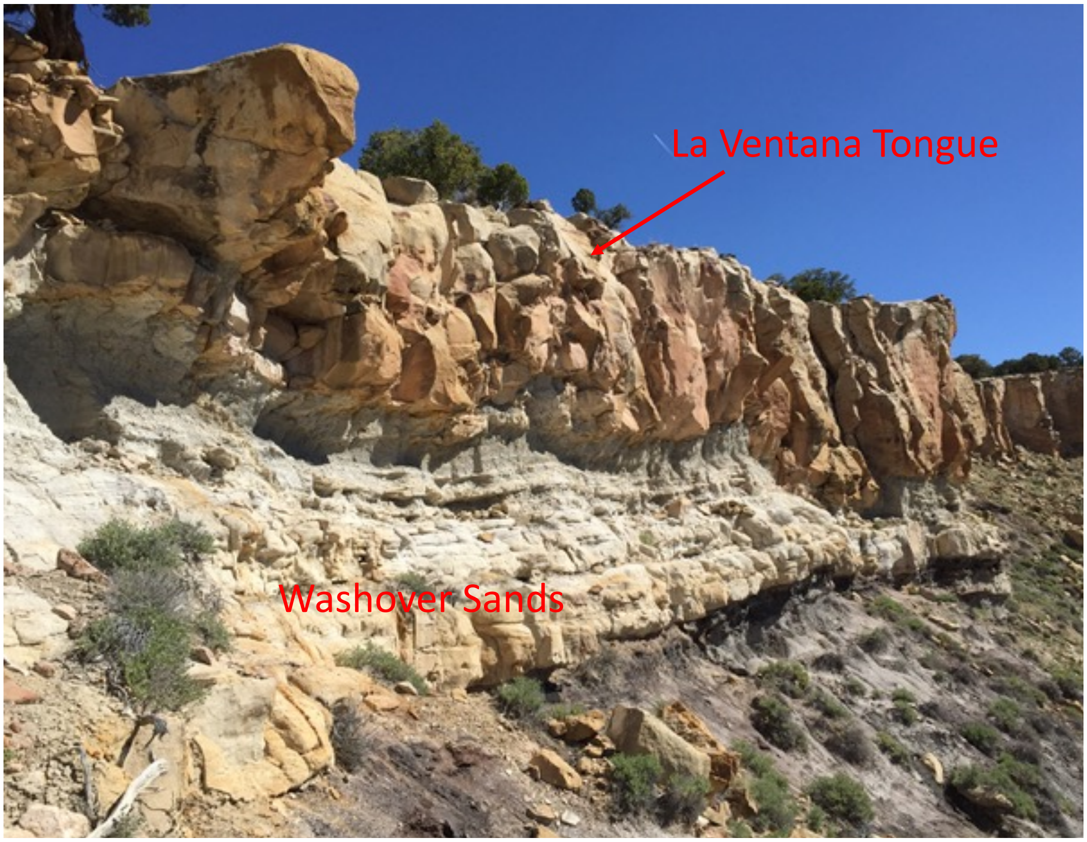

Photo23

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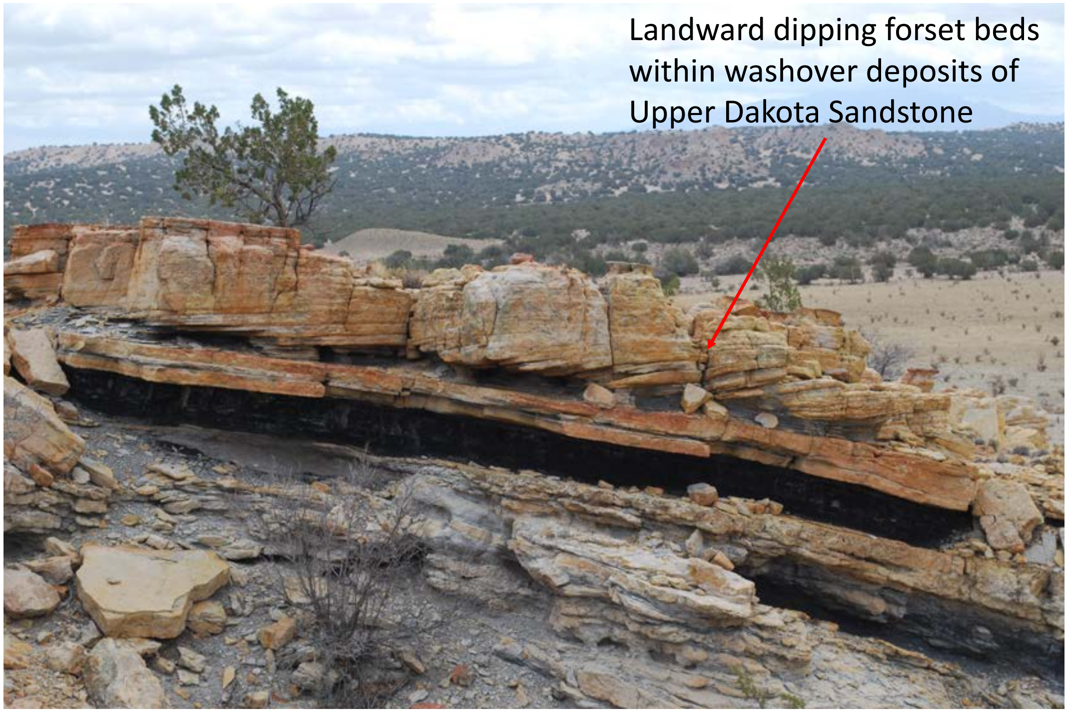
Landward dipping forset beds
within washover deposits of
Upper Dakota Sandstone

Photo48

Photo49

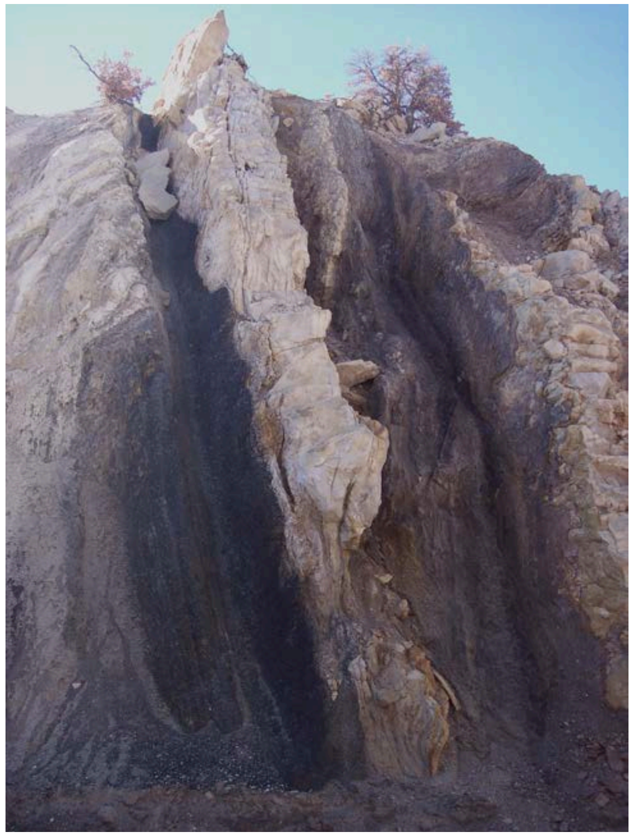

Photo50

Photo51

Dak… ples

Photo52

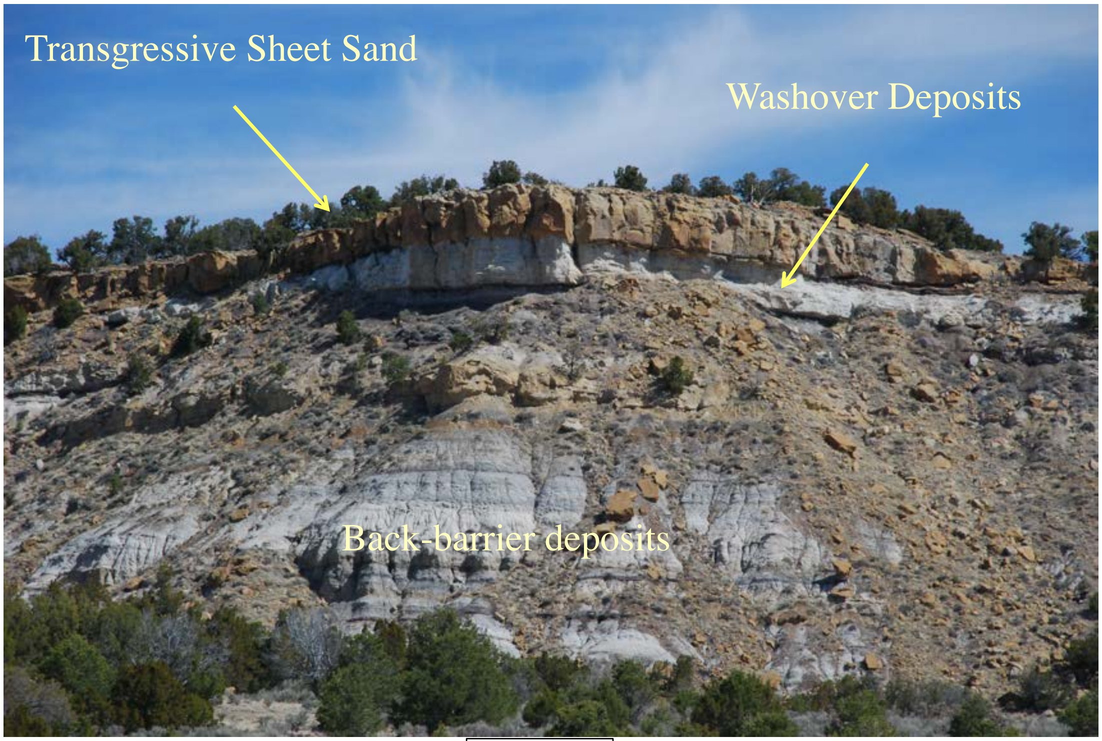
Transgressive Sheet Sand
Washover Deposits
Back-barrier deposits

Photo53

Photo54

Photo55

Photo56

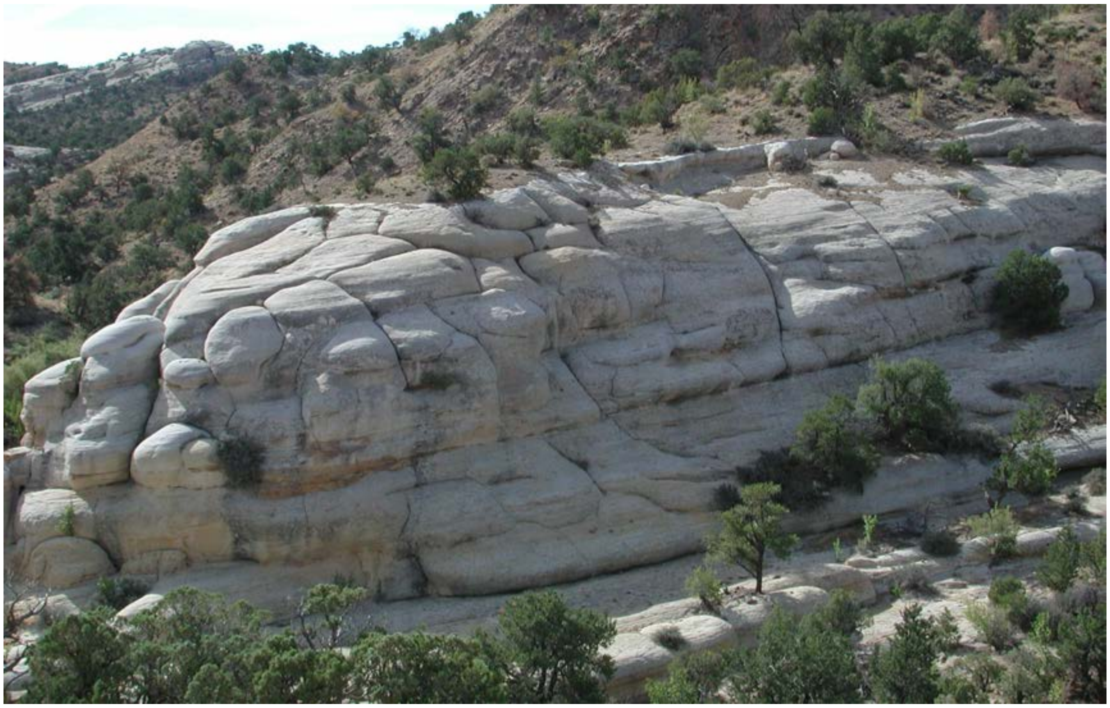

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Photo59

Photo60

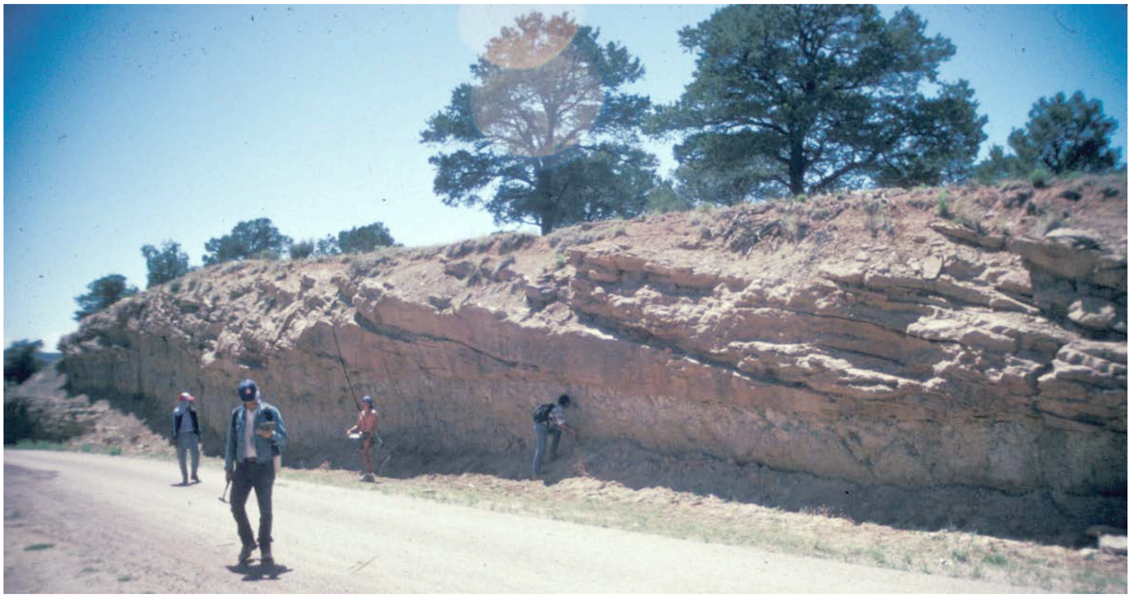

Photo61

Photo62

Photo63

Photo64

Photo65