Second-day Road Log: From Circle A Ranch to La Jara, Regina, Llaves, and Deadman Peak; Returning Through Canoncito De Las Lleguas, Canada Simon, and The Upper San Jose Valley

Kevin M. Hobbs, Shari A. Kelley, Thomas Valenzuela, and Brian Hampton

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SECOND-DAY ROAD LOG:

FROM CIRCLE A RANCH TO LA JARA, REGINA, LLAVES, AND DEADMAN PEAK; RETURNING THROUGH CAÑONCITO DE LAS LLEGUAS, CAÑADA SIMON, AND THE UPPER SAN JOSE VALLEY

KEVIN M. HOBBS[1], SHARI A. KELLEY[1], THOMAS VALENZUELA[2], BRIAN HAMPTON[2]

[1]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801; kevin.hobbs@nmt.edu
[2]New Mexico State University, 1780 E University Ave, Las Cruces, NM 88003

Assembly Point: Circle A Ranch entry road just west of main ranch house
Departure Time: 7:30 AM
Distance: 95.7 miles
Stops: 4 (plus 2 optional)

Views, landmarks, and outcrops are given using the clock system, where 12:00 is straight ahead, 3:00 is to the right, and 9:00 is to the left. Driving distances are given in imperial units.

SUMMARY

Day 2 of the field conference travels north from Cuba along the eastern margin of the San Juan Basin. From Cuba to Regina, the Sierra Nacimiento, the basin-bounding uplift to the east, stands with over a kilometer of relief over the adjacent basin. Its uplift occurred along the Nacimiento fault. North of Regina, the uplift occurred partly along faults, but also along the broad Archuleta/Gallina anticlinorium. This complex of domes, faults, and anticlines exposes kilometers-long cuestas of classic Western Interior Seaway stratigraphy, including one that is the focus of our Stop 1. Some of the basin-bounding faults at the northern end of our journey today have normal offset—the opposite of what is expected in Laramidia. Stop 2, near Deadman Peak and overlooking the structurally spectacular Rio Gallina Canyon, puts these into context with recent mapping and structural interpretation. A short drive down Deadman Peak brings us to Stop 3, where we investigate the Greenhorn Limestone, one of the few carbonates from the Western Interior Seaway in New Mexico. There, we discuss why the Cretaceous in much of western North America lacks the rock types (carbonates) for which the Cretaceous is named. From there, we travel upsection into the basin through Cañoncito de las Lleguas (Little Canyon of the Mares) through unsurpassed sandstone outcrops of the San Jose Formation. At Stop 4 in Cañada Simon, we get the latest on tectonics, sedimentology, and geochronology as interpreted through a modern investigation of the San Jose Formation. Returning to the south, an optional stop (Stop 5) overlooking the Llaves Valley allows us to consider the neotectonic development of the region. Throughout the day, we consider the timing, sequence, and impacts of geologic events that culminated in the modern San Juan Basin. We also challenge previously held assumptions about how the San Juan Basin has been, is, and should be defined.

7:30 AM: Depart Circle A Ranch in caravan.

8:30–10:30 AM: Stop 1 involves a short walk to and (optional) steep climb up a cuesta comprising the Mesaverde Group: the Point Lookout Sandstone overlain by the Menefee Formation and the Cliff House Sandstone. Sedimentary structures and fossils in exposures of sandstones, mudstones, and coals allow us to interpret the depositional history of these units. Our goal here is to struggle with, debate, and interpret the environmental changes recorded in the Mesaverde Group.

11:00 AM–1:30 PM: Stop 2 takes us on a mostly level walk of approximately 1 km (0.6 mi). Upon arriving at one of the most striking off-the-path vistas in New Mexico, we will discuss recent geologic mapping in the area and the new discoveries, interpretations, and ages that arise from it. Topics to ruminate on include the differences—real or imagined—between the San Juan Basin and the Chama basin, the multiple generations of strain along nearby structures, and the role that tectonic history plays in modern landscape development. We will have lunch among the ponderosa pines before departing for Stop 3.

1:45–3:00 PM: Stop 3 also involves a short (~400 m [~1,300 ft]) walk. This one is up a gentle slope to outcrops of interbedded Graneros Shale and Greenhorn Limestone, both of which are members of the thick Mancos Shale. At this stop, we discuss the periodicity of sedimentary events in the Cretaceous that can be observed at our feet and also traced laterally across the Western Interior Seaway. Close inspection of the limestones here causes us to wonder why there are not more carbonates in New Mexico's Cretaceous System; this question is best considered within the context of an understanding of regional tectonic development.

3:30–5:00 PM: Stop 4 brings us to the highest rocks in the stratigraphic column for the entire conference: the upper members of the San Jose Formation. These rocks are almost undeniably Eocene in age. We will closely inspect the structure, composition, and stratigraphic relationships of these units, comparing what is observed here to what we saw on Day 1. Then, new geochronologic, petrographic, and sedimentologic data are presented and related to our observations. The goal here is to place the San Jose Formation into a geographic and temporal context of basin evolution.

5:00–6:00 PM: Return to Circle A Ranch via Forest Road 313, State Road 96, and U.S. Route 550.

6:30 PM: New Mexico Geological Society barbeque at Circle A Ranch (held outdoors, dress appropriately).

[Waypoint]
Miles since last entry
Mileage Description

0.0
0.0 Assemble caravan just northwest of the main ranch house at Circle A Ranch. The first 4.2 miles of today's road logs are the same as Day 1. Continue down Los Pinos Road to U.S. Route 550.

4.2
4.2 REZERO ODOMETER at intersection of Los Pinos Road and U.S. Route 550.

0.0 Turn right (north) onto U.S. Route 550.

3.0
3.0 Turn right (north) on State Road 96. For the next 40 miles, we retrace the routes of the 1st (1950), 28th (1977), and 43rd (1992) New Mexico Geological Society (NMGS) Fall Field Conferences, giving NMGS's presence along State Road 96 a recurrence interval of 25.0 years. Statistically speaking, we'll return here again on September 19, 2050.

0.4
3.4 Roadcuts on both sides of road of San Jose Formation arenites with cross-beds and soft-sediment deformation structures (SSDSs).

0.1
3.5 Bridge over Arroyo San Jose, here incised 10 m (33 ft) into sandy and silty Holocene alluvium. Arroyo San Jose has an impressive area upstream of here (~170 km^2 [~66 mi^2]), much larger than the area of the Rio Puerco watershed upstream of its junction with Arroyo San Jose. The drainage of Arroyo San Jose is the type locality for the San Jose Formation.

0.3
3.8 Gravel-capped terraces from 10:00 to 3:00. All of them slope down from the high Sierra Nacimiento to the east.

0.8
4.6 Enter the community of La Jara. With a 21st-century population of around 150, La Jara is a traditional northern New Mexico agricultural community. It is stretched along approximately 7 km (4.4 mi) of La Jara Creek, which drains the Sierra Nacimiento to the east. La Jara Creek's water supports around 900 ha (2,220 ac) of irrigated fields, pastures, and orchards; in the late spring, there are few New Mexican locales more bucolic than this. Note that the valley of La Jara Creek here is largely unincised, giving a glimpse of what the Rio Puerco valley at Cuba might have looked like prior to late 19th century incision.

La Jara takes its name for the Spanish word (jara) for several willows, most commonly the Coyote willow (K'ei'łibáhí, *Salix exigua*). This plant's abundance in the Southwest is evidenced by the 86 "Jara" place names in New Mexico, according to the USGS Geographic Names Information System (GNIS; Julyan, 1996).

Of particular note to geologists: From 1947 through 1967, tiny La Jara was the summer home of George Gaylord Simpson (1902–1984), perhaps the most prominent paleontologist of the 20th century. Near the end of his long life, Simpson wrote "The years that I spent in the San Juan Basin with good companions, with heavy, productive physical labor, with mind-stretching problems, with exciting discoveries, with marvelous nature all around me, were among the happiest of the many happy years of my life" (Simpson, 1981).

0.1
4.7 Leaving La Jara. The skyline from 9:00 to 12:00 is (or nearly is) the Continental Divide, here made up of the San Jose Formation.

0.4
5.1 Shallow anthropogenic ponds at left. The house on the small hill just behind them is perched atop a San Jose Formation knob that likely owes its existence to once having been preserved beneath the same 55-m-high (180-ft)-high terrace (the La Jara terrace of Bryan and McCann, 1936) that will be visible on the right for much of the next 3 miles. These ponds are a good site for spotting uncommon ducks and shorebirds who find themselves lacking water during their migration across the San Juan Basin.

0.3
5.4 At 3:00, an unvegetated slope exposes colorful mudstones and siltstones of the Regina Member of the San Jose Formation. Note the color difference between these rocks and the drabber Nacimiento Formation mudrocks seen yesterday.

0.9
6.3 Note the large and numerous south-facing windows on many of the older site-built houses in this valley. Winters here are cold but sunny, and these were built with this in mind!

0.4
6.7 Starting here and for the next 4 miles, the highway passes through many dissected remnants of gravel-capped terrace pediments. Most of these are the 55-m (180-ft)-high La Jara terrace, with some younger 25-m (82-ft)-high Rito Leche terraces.

1.2
7.9 Large pullout on the right. **Stay straight on State Road 96**.

0.6
8.5 Disused gravel pit at left. This pit exploited the pebble- through boulder-sized terrace deposits of a 40-m (131-ft)-high terrace, which is roughly halfway between the heights of Bryan and McCann's (1936) La Jara terrace (55 to 61 m [180 to 200 ft] high) and Rito Leche terrace (23 to 26 m [75 to 85 ft] high). Based on modern topography and the base of the excavated portions of this gravel pit, the gravel deposit here was as much as 11 m (36 ft) thick.

1.1
9.6 Dead ahead are mudstone badlands of the San Jose Formation. Such badlands are common along a 35-km (22-mi) stretch of the Continental Divide between Route U.S. 550 in the south to Llaves in the north.

0.9
10.5 Road to Regina Cemetery at right. The cemetery is atop the cobble- and boulder-capped Rito Leche terrace, which must make gravedigging an excruciating task.

0.5
11.0 Well-kept "ranch" at left, where they raise the finest prices in Sandoval County.

0.1
11.1 San Jose Trail, at right, provides access to higher elevations east of here in the Sierra Nacimiento.

0.6
11.7 Downtown Regina. Founded in 1911 and named after the capital of Saskatchewan (Pearce, 1965). Regina was home to the locally famous Coon Holler Bar, where a young Glen Campbell played in the early 1950s; at the time, he lived and attended the tenth grade in nearby Lindrith. The green-roofed wood house on the west side of the highway 200 m (650 ft) north of the Regina Mercantile occupies the former bar.

0.1
11.8 Leaving greater Regina.

0.5
12.3 Sandoval County Fire Station #46 on left. Volunteers needed.

At 10:00, approximately 1 km (0.6 mi) to the northwest, are the interbedded mudstones and sandstones of Simpson's (1948) type section of the San Jose Formation. Prior to Simpson, San Juan Basin workers called these rocks the "Wasatch" due to their biostratigraphic similarity to fossiliferous sedimentary rocks in the Uinta basin east of the Wasatch Mountains, Utah.

0.7
13.0 Drained artificial lakes, often listed on maps as "Hatch Lake" at right (Fig. 2.01). Iron gates marking "Rancho Cielitos Lindos;" the Aguas de San Pedro need a refill… (Fig. 2.02).

On the Sierra Nacimiento mountain front 3 km (1.9 mi) east of here, note the reappearance of clearly visible tilted strata to the north (Fig. 2.03). Between here and Cuba, much of the bedrock geology of the Sierra Nacimiento mountain front is obscured beneath Pleistocene gravel deposits. North of here, though, that gravel cover is either discontinuous or not present, allowing excellent exposure of complexly deformed Pennsylvanian through Cretaceous strata near the northern terminus of the Nacimiento fault.

0.5
13.5 Crest of hill; leaving Rio Puerco drainage and entering Rio Chama watershed. For the next several

Figure 2.01. Pier in abandoned artificial pond along State Road 96 north of Regina. Check depth before diving.

Figure 2.02. Iron gates at waterless Hatch Lake marking the entrance to Rancho Cielitos Lindos. San Pedro Apóstol, depicted here with his rooster, keys to heavenly gates, and rebar halo, famously sank during perambulation on the Sea of Galilee. You would want to drain the lake, too, if it happened to you.

miles, there are views to the north up the strike valley that marks the eastern margin of the San Juan Basin here.

0.6

14.1 At 3:00, a burned ridge (the Bear Paw fire in 2006) provides unobstructed views of the steeply dipping Mesozoic section at the north end of the Sierra Nacimiento. As the Nacimiento fault bends to the east to merge with (?) the Gallina and Tierra Montañosa faults to the north, accommodation of stress occurs along complex bedding-parallel thrusts, grabens radiating from fault bends, and other structures. The University of New Mexico introductory field geology course mapped here at the ~1:6,000 scale in 2019.

0.4

14.5 Rio Arriba County line.

0.2

14.7 "Texas Ranch" at left. How do you know if someone's from Texas? Don't worry, they'll tell you.

0.3

15.0 **Stay straight.** State Road 595 to the left leads to Lindrith. Lindrith is the only community within the "Lindrith enclave," a ~440 km^2 (~170 mi^2) polygon of small parcels of private land surrounded by the Jicarilla Apache Nation and Santa Fe National Forest.

Dead ahead, note the flat-lying nature of the San Jose Formation, whereas cuestas of older rocks at 1:00 to 2:00 dip steeply into the basin from the Archuleta anticlinorium to the east (Fig. 2.04).

1.0

16.0 **Waypoint 2.01 [36.23716°, −106.92753°]**

Turn left (north) onto State Road 112 in the middle of a sweeping right-hand bend in State Road 96. Note: This is a dangerous intersection; check that the way is clear before proceeding! From here, State Road 96 continues east toward Gallina, Coyote, Youngsville, and Abiquiu.

The thick bed capping the mesa at 9:00 is the persistent sandstone of the Llaves Member of the San Jose Formation.

1.0

17.0 At 1:00, a pyramidal hill of San Jose Formation exposes the east limb of the Schmitz anticline; note east-dipping beds at its base (Fig. 2.05). The cuesta at 3:00 is held up by west-dipping sandstones of the Menefee Formation; this ridge will persist northward, with occasional breaks, for

Figure 2.03. Annotated panoramic photograph of the northern Sierra Nacimiento mountain front east of Regina. View is due east. Just south of Mahan Canyon, extensive outcrops of the Phanerozoic section are exposed, and they persist to the north for many kilometers. To the south between Regina and Cuba, most of the bedrock geology of the mountain front is obscured beneath surficial deposits. The northernmost extensive mountain front terrace deposit in the Sierra Nacimiento, outlined here in blue, forms the drainage divide between Arroyo San Pedro to the south and the headwaters of Almagre Arroyo (a tributary to the Rio Chama) to the north.

Figure 2.04. Annotated photograph looking due north from the junction of New Mexico State Roads 96 and 595.

Figure 2.05. Photographs looking north along State Road 112 of the Schmitz anticline. Dashed lines approximate bedding orientations. Top photo taken summer 2024 along the paved State Road 112. Bottom photo from the 1977 NMGS Fall Field Conference Guidebook, where it appears at mile 115.7 of the Day 2 road log.

the next 20 km (12 mi). The members of the Menefee Formation are not well mapped in this portion of the basin.

0.2
17.2 Well-built and well-preserved log house on left.

0.3
17.5 Bridge over Almagre Arroyo. Almagre is Spanish for red ochre, but this arroyo's bed seems dominated by the whitish clays and sands eroded from San Jose Formation badlands along the Continental Divide to the west (Fig. 2.06). Schmitz anticline dead ahead. Note the deep red Triassic sedimentary rocks in the high country at 2:30.

0.8
18.3 At right, the southernmost wells of the Puerto Chiquito Mancos oil field are visible at the green produced water tanks. This field was drilled primarily in the late 1960s and 1970s and exploited fracture porosity in the Niobrara interval of the Mancos Shale, which here is about 2,200 m (7,200 ft) below ground surface. Most of the gas produced in this field is gathered and injected back into the reservoir.

Figure 2.06. The white bed of Almagre Arroyo at mile 17.5. View is to the east toward the Mesaverde Group cuesta and the Archuleta arch.

1.8
20.1 Crest of hill. From 8:00 to 11:00, an incredible view of the upper portions of the San Juan Basin Paleogene section, here comprising the Regina and Llaves Members of the San Jose Formation. The low knobs from 2:00 to 3:00 are also San Jose Formation. On the eastern skyline from 1:00 to 3:00, uplifted Paleozoic and Mesozoic sedimentary rocks form the Gallina-Archuleta dome complex—contrast this to the Nacimiento uplift farther south.

0.9
21.0 Road bends to the left/north. Excellent views to the north and northeast of the Triassic through Paleogene section.

0.6
21.6 Note the reddish and thin-bedded nature of the San Jose Formation here. Keep these characteristics in mind as we inspect other outcrops of the same formation at Stop 4 in Cañoncito de las Lleguas.

0.3
21.9 Another fine example of a Llaves valley log house (Fig. 2.07). Note the row of south-facing windows on this one.

0.7
22.6 Note the gentle dip to the west of the San Jose Formation at 11:00 to 12:00.

0.5
23.1 Bridge over Arroyo Blanco.

1.9
25.0 From 2:00 to 3:00 in the middle distance, the Menefee Formation cuesta persists, though it becomes more dissected as it continues northward. Passengers with sharp eyes can start to see coaly layers interbedded with the sandstones holding up the cuesta.

1.5
26.5 Crest of hill. Numerous ramshackle wood buildings on left.

Figure 2.07. A log house along State Road 112 at mile 21.9.

0.7
27.2 At 3:00, a gap in the Menefee Formation cuesta, through which flows Lleguas Arroyo. At 9:00, the mouth of the Cañoncito de las Lleguas. A field outpost of Benson-Montin-Greer Drilling, a Farmington-based drilling contractor, sits at the mouth of the canyon. Behind the drilling office, the bare low ridge at the foot of the cliffs is upper Nacimiento Formation. Just left of dead ahead, a west-sloping dip slope is well forested (as of the fall of 2024) and marks the top of the Ojo Alamo Formation. That cuesta, near Mud Springs, is home to several slot canyons in the Ojo Alamo Sandstone.

This area is near the epicenter of an 11th- to 13th-century culture called the Gallina culture, whose members lived, farmed, hunted, built homes, and made art in this valley. This fascinating culture, and the ceramics they manufactured, is the topic of a paper by Connie Constan in this volume.

0.1
27.3 Bridge over Lleguas Arroyo. Just past the bridge, Forest Road 313 heads west through the canyon toward the Continental Divide. Continue north on State Road 112.

0.5
27.8 Cattle guard. At 10:00 to 11:00, a low sandstone ridge 200 m (650 ft) west of the highway is held up by arenites in the Ojo Alamo Formation.

0.7
28.5 To the east, note that the Menefee Formation cuesta has large V-shaped notches that don't have streams running through them. How did they form? The same cuesta is rather flat-topped farther south.

0.8
29.3 Crest of hill. **Stay straight.** Forest Road 5 heads west from here, then turns north to follow a strike valley in the Nacimiento Formation to the border of the Jicarilla Apache Nation.

0.3
29.6 Cemetery at right.

0.7
30.3 Roads bends left. At 11:00, a kilometers-long trend to the north of good outcrops of unusually thick feldspathic arenites of the Ojo Alamo Formation begins.

0.5
30.8 **Waypoint 2.02 [36.42874°, −106.83299°]**
Turn right on Forest Road 7 after crossing cattle guard and entering the Santa Fe National Forest.

0.6
31.4 Road penetrates gap in the Menefee Formation cuesta that we've paralleled since turning onto State

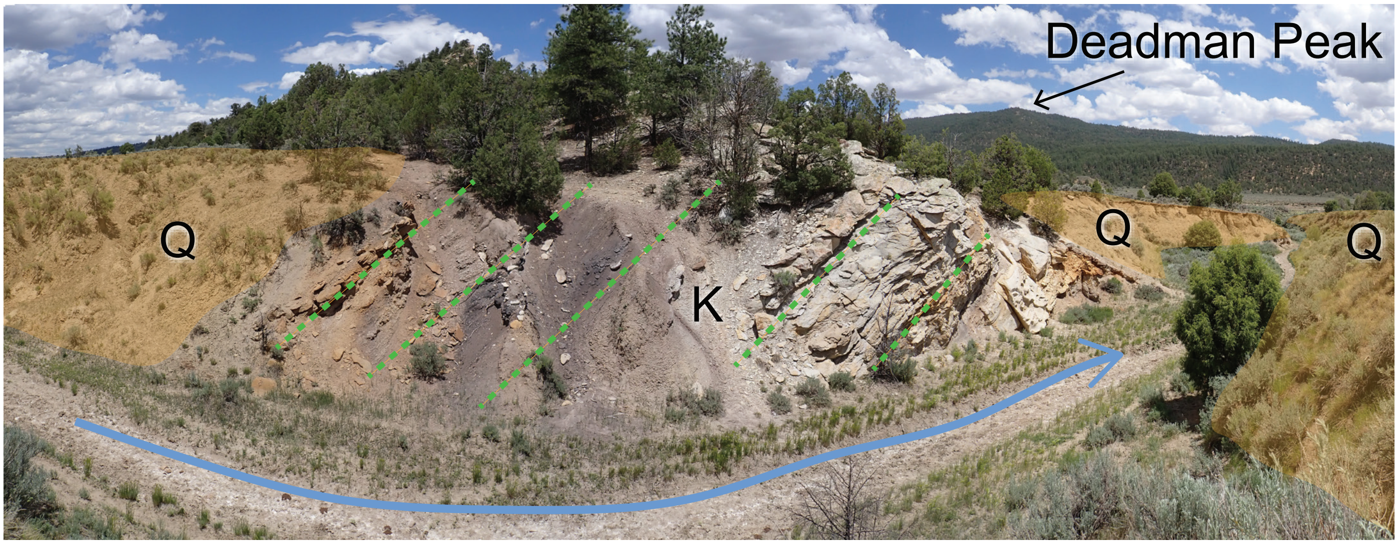


Figure 2.08. Annotated panoramic photograph looking north of the eroded north bank of Chupadero Arroyo where it cuts through the Mesaverde Group cuesta at Stop 1. Q = Quaternary surficial sediments; K = Cretaceous sedimentary rocks. Deadman Peak, the focus of Stop 2, is on the skyline. Arroyo flows left to right.

Road 112, 15 miles back. Note the thickness of fine-grained alluvium abutting the bedrock of the cuesta (Fig. 2.08). How can such a feeble stream excavate bedrock?

0.2
31.6 LEFT TURN onto rough two track toward cattle pond.

Waypoint 2.03 [36.42943°, −106.81889°]

STOP 1. Park here and proceed north on foot approximately 250 m (820 ft) for a discussion of differential basin subsidence, the regression-transgression sequence in the Mesaverde Group, and Cretaceous sedimentology.

The Mesaverde Group

At Stop 1, a cuesta of west-dipping sedimentary rocks provides good exposures of the Mesaverde Group (Fig. 2.09). These rocks were first named the "Mesaverde Formation" by Holmes (1877) during the Hayden Survey after exposures on the northern margin of the San Juan Basin at Mesa Verde, Colorado. Holmes's Mesaverde Formation contained a lower sandstone escarpment, a middle coal zone, and an upper sandstone escarpment; this general pattern can be observed here at Stop 1. In a USGS Coal Resources report, these lithologic zones were promoted to formation rank by the aptly named Collier (1919): the lower sandstone is now the Point Lookout Sandstone, the middle coal zone is the Menefee Formation, and the upper sandstone is the Cliff House Sandstone.

The Mesaverde Group consists of a regression-transgression sequence that records a major withdrawal from, and then return of, the Western Interior Seaway in northern New Mexico. At the time of Mesaverde Group deposition in New Mexico (roughly 85 to 77 Ma; late Santonian to mid Campanian; Lucas et al., 2005a), the shoreline trended roughly northwest-southeast, with open sea to the northeast and a coastal plain and

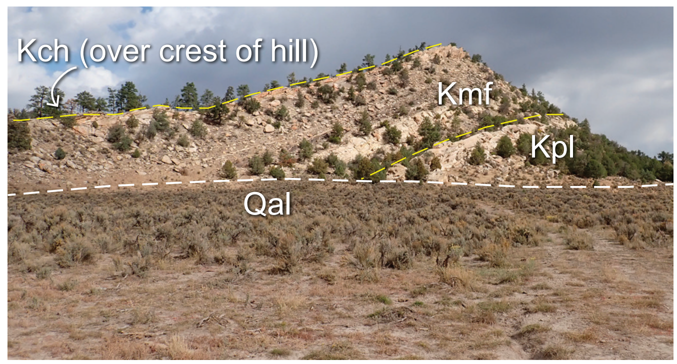


Figure 2.09. View to the north of west-dipping cuesta of Mesaverde Group at Alkali Spring (Stop 1). Kpl = Point Lookout Sandstone; Kmf = Menefee Formation; Kch = Cliff House Sandstone; Qal = Quaternary alluvium.

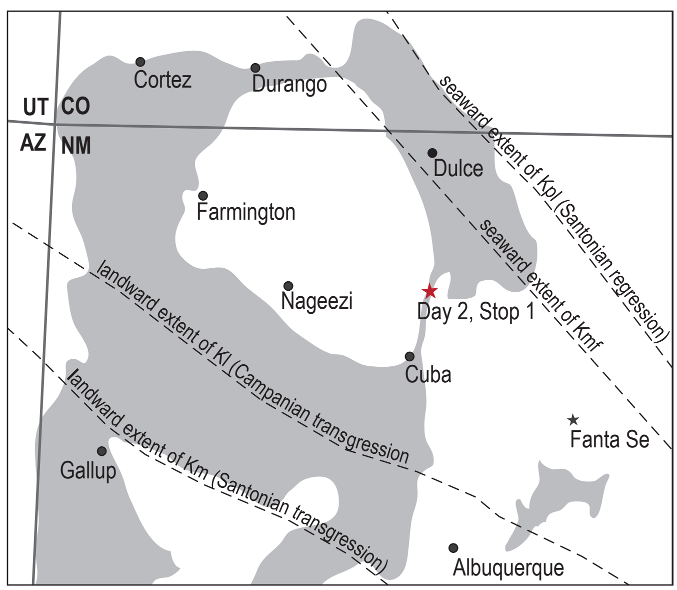


Figure 2.10. Schematic map showing outcrop areas of Cretaceous rocks in northwest New Mexico (gray-shaded areas) and shoreline positions for maximum transgressions and regression bracketing the Mesaverde Group. Adapted from Hoffman (1991).

then continental highlands to the southwest (Hoffman, 1991; Fig. 2.10). Transgressions (the spread of marine environments and their associated deposits onto formerly nonmarine areas) advanced to the southwest in New Mexico. Regressions (the retreat of marine environments and their associated deposits back toward the sea) were to the northeast. Immediately prior to Mesaverde Group deposition, the Western Interior Seaway reached its maximum transgression (i.e., highest sea level), in the San Juan Basin, recorded by the Mancos Shale. Global sea level at that time (roughly 87 Ma; late Coniacian to early Santonian) was as much as 650 m (2,130 ft) higher than at the beginning of the Cretaceous (Hancock and Kauffman, 1979). As the sea that deposited the Mancos Shale regressed, shoreface sands were deposited atop the Mancos muds. These shoreface sands now make up the Point Lookout Sandstone. Since the Point Lookout Sandstone is the result of a northeast-moving shoreline regression, it therefore is generally older in the southwest (say, in Gallup) than in the northeast part of San Juan Basin (say, at Stop 1).

As sea level dropped, the shoreline withdrew to the northeast. Shoreface environments at any one place were gradually replaced by estuarine and then fluvial environments. These estuarine and fluvial deposits from the Campanian San Juan Basin make up the Menefee Formation. The maximum seaward (i.e., northeastward) extent of the Menefee Formation was limited by the location of the Campanian shoreline during the maximum regression at the lowest sea level (see Fig. 2.10). Therefore, Menefee Formation deposition happened for the longest duration of time in the southwestern San Juan Basin (say, near Gallup) and for the shortest duration in the northeastern San Juan Basin (near Dulce). The thickness of the Menefee Formation in San Juan Basin (thickest in the southwest, thinnest in the northeast) roughly correlates to these depositional durations. The Menefee Formation contains estuarine and swampy deposits formed in marginal environments on the landward side of barrier island complexes (Mannhard, 1976; Hoffman, 1991) as well as fluvial-dominated channel sandstone packages (Fig. 2.11). Coals are common in the Menefee Formation, and were exploited in mining districts at La Ventana, Monero, Tierra Amarilla, Gallup, Durango, and elsewhere.

The transition from regression to transgression resulted from another global sea-level rise. This transgression occurred rapidly, with sea level rising at rates as high as 170 m/My (Hancock and Kauffman, 1979). As a result, the shoreface deposits of the southwestward-transgressing Campanian coastline rapidly marched across the San Juan Basin, leaving some areas where none are recorded at all (Fassett, 1974). These transgressive shoreface deposits make up the Cliff House Sandstone, which, in contrast to the Point Lookout Sandstone, youngs to the southwest. The Cliff House Sandstone is as thin as 9 m (30 ft) near its northeasternmost limit (Dane, 1948) and as thick as 250 m (820 ft) in the southern basin (Donselaar, 1989). At Stop 1, its thickness is around 30 m (98 ft).

For full understanding of the relationships among San Juan Basin Mesaverde Group rocks, one must remember that at any one point in time, there was simultaneous deposition of marine shales, shoreface sands, and fluvial coals/muds/sands at various places in the basin (Fig. 2.12). When the Point Lookout Sandstone was being deposited on a beach at Stop 1, Menefee Formation was being deposited in a swamp at Chaco Canyon, and Mancos Shale being deposited offshore in Raton. When Cretaceous sea level fell, all environments of deposition shifted to the northeast; when they rose, environments shifted to the southwest. These geographic shifts required not only changes in sea level, but perhaps more importantly, they required time. It is erroneous to think of San Juan Basin Cretaceous units (or, more widely, Late Cretaceous units anywhere on Earth) from the mindset of simple layer-cake stratigraphic stacking. The base of the Mesaverde Group (here, the Point Lookout Sandstone) is not necessarily older than the middle of the Mesaverde Group elsewhere in the basin (because, again, they were necessarily deposited at the same time!). These rocks, then, are classic examples of time-transgressive or diachronous deposits: each unit varies in age at different areas and cuts across time markers. The complexity of diachroneity in the Western Interior Seaway has been the focus of entire careers' worth of study, with research continuing well into its second century as of this field conference.

The overall regression-transgression cycle represented in the Mesaverde Group in the eastern San Juan Basin is a

Figure 2.11. 3D panoramic photograph of the Mesaverde Group cuesta at Stop 1. Formation contacts shown in yellow. White dashed lines enclose the locations of two fluvial channel sandstones within the otherwise mud- and coal-dominated Menefee Formation. View is to the northwest; Stop 1 parking area is just off the lower left corner of the image. Image courtesy of Bruce Hart.

simplified framework around which we can build our understanding of the geologic history of the outcrops at Stop 1 and of the Late Cretaceous in the San Juan Basin as a whole. Overlain on these broadscale sea level change-induced depositional records (called third-order stratigraphic cycles) are shorter-duration and smaller-magnitude records of sea-level fluctuation (fourth-order cycles, with durations of tens to hundreds of thousands of years). Thus, there is not always a perfect one-way transition from marine to terrestrial environments during a third-order regression, nor is there always a perfect transition of terrestrial to marine environments during a third-order transgression. The rocks cropping out at Stop 1 demand consideration of these complications, and these considerations are best made with observation of the outcrops. The manuscript by Bruce Hart in this volume explains stratigraphic cycles' expression in the Mesaverde Group in greater detail and with powerful illustrations.

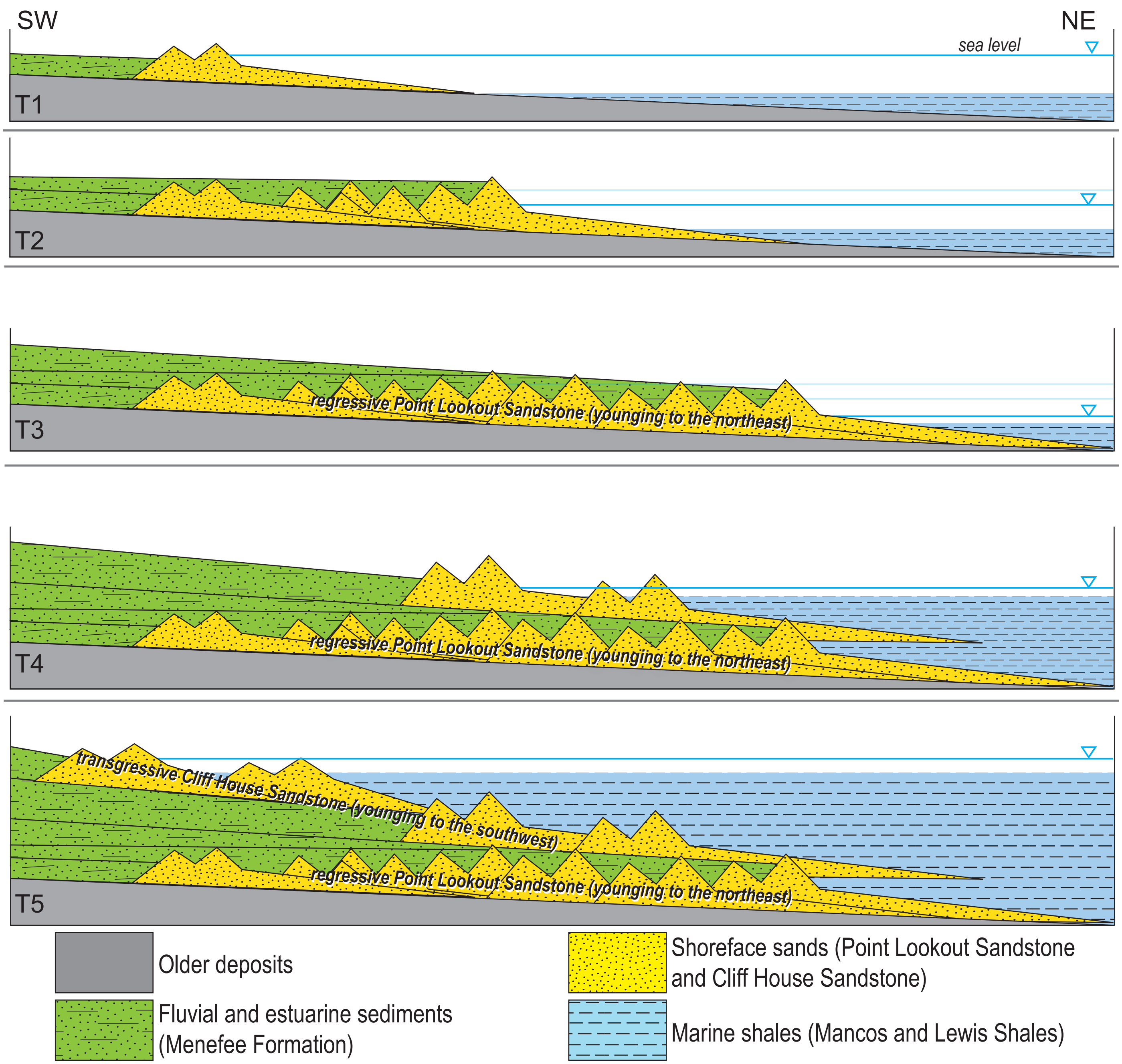


Figure 2.12. Schematic cross-sectional diagram simplifying the regression-transgression cycle that deposited the Mesaverde Group. In all time slices (beginning with T1, top; and ending with T5, bottom), deposition of offshore shales (the Mancos and/or Lewis Shales) occurs at the northeast (seaward) end, while deposition of terrestrial fluvial deposits (the Menefee Formation) occurs at the southwest (landward) end. The interface between those two environments shifts seaward as sea level fall (regression, resulting in the Point Lookout Sandstone) then shifts landward as sea level rise (transgression, resulting in the Cliff House Sandstone). At all times, though, there is simultaneous deposition of fully terrestrial, fully marine, and transitional shoreface sediments. No scale is implied. Note that continental deposits (the Menefee Formation) thicken landward and that marine deposits thicken seaward.

At Stop 1, the broad valley to the east exists because it is floored by the easily erodible Mancos Shale. The broad valley to the west, through which we've driven the past few miles, is floored by the easily erodible Lewis Shale. The cuesta here owes its relief to the relative strength and erosion resistance of the sandstones of the Mesaverde Group. The strata here dip moderately to the west—into the basin—but are otherwise structurally simple (no appreciable faults, overturned bedding, or other deformational tricks). The Point Lookout Sandstone, near the eastern base of the cuesta, is conformably overlain by the Menefee Formation. The Menefee Formation is conformably overlain by the Cliff House Sandstone, found on the cuesta's west slopes.

The environmental changes that allowed the switch from marine to shoreface to terrestrial deposition—and back again—were gradual and involved a complex interplay among sediment supply, eustacy, subsidence, and climate. From a distance, it is easy to estimate the location of contacts between the three formations here (Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone). Upon closer inspection, however, the distinction becomes more difficult. Discussing the observable features of these rocks, making interpretations about the environments of deposition that they represent, and placing them in context of our broader knowledge of the Cretaceous history of San Juan Basin are the primary focus of Stop 1.

Composition of Sandstones at Stop 1

There are interesting textural and compositional variations in Mesaverde Group deposits, especially among the Cliff House Sandstone and other sandstones in the section at Stop 1. X-ray diffraction (XRD) analyses show that sandstones from the Point Lookout Sandstone and Menefee Formation contain a fair mix of quartz and feldspars, fitting the general model for fluvial sandstones and shoreface sands in a regressional setting. The transgressive Cliff House Sandstone, however, produced a diffractogram showing abundant quartz with minor amounts of carbonate cement—no feldpars detected! Thin section microscopy and point counts are in accord with XRD results. Thin sections allow for more detailed compositional and textural description (Fig. 2.13). A sandstone sample from the Point Lookout collected at Stop 1 exhibits a nearly even mix of quartz and non-quartz components and is moderately sorted with a range of grain roundness. A sample from the lowest channel sandstone in the Menefee Formation at Stop 1 (see Fig. 2.11) is slightly more quartzose, but still well within the range of an arkosic arenite. But the Cliff House Sandstone sample collected from atop the cuesta at Stop 1 qualifies as a quartz arenite—there are vanishingly few grains other than quartz present in that specimen. The Cliff House Sandstone also contains a much lower ratio of polycrystalline to monocrystalline quartz.

Sedimentology of the Mesaverde Group

Figure 2.14 provides a summary diagram to aid in observing and interpreting the rocks of the Mesaverde Group at Stop 1. Accepting that the Point Lookout Sandstone and Cliff House Sandstone are shoreface environment deposits, and that the Menefee Formation is a terrestrial deposit, then what can one say about the transition between environments as first a regression and then a transgression caused the Cretaceous shoreline to migrate across the Stop 1 location? What would the hallmarks of a rapid shoreline migration be, and how would those be differentiated from those of a slow migration? Is there evidence for a truly "one-way" migration (i.e., is there a marker horizon in the rock column where one can say, "Below here is marine, and above here is terrestrial")? Questions like these are at the heart of field-based interpretive sedimentology. They are not always easy to answer, but are usually fulfilling to discuss. Fortunately, there are some distinguishing characteristics in the rocks that can aid interpretation.

Hummocky Bedding

A common but subtle bedform in shoreface sandy environments is hummocky bedding (and its requisite counterpart, swaly bedding). Hummocks are low-relief dome-shaped structures caused by oscillatory currents imparting shear stress on the seabed, typically just below the fair-weather wave base. In outcrop, look for meter-scale convex-up laminations (Fig. 2.15). Parting lineations are sometimes found on hummocky lamination bedding planes. Flume experiments show that hummocky bedding requires high oscillatory velocity but low unidirectional velocity (Arnott and Southard, 1990; Fig. 2.16).

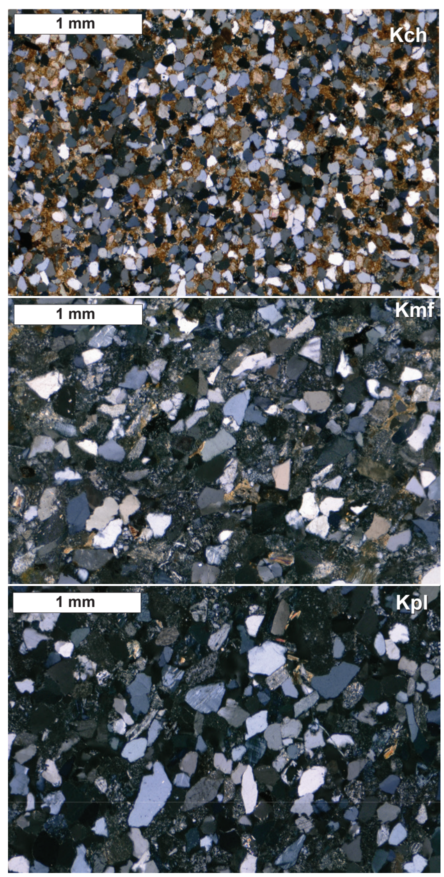
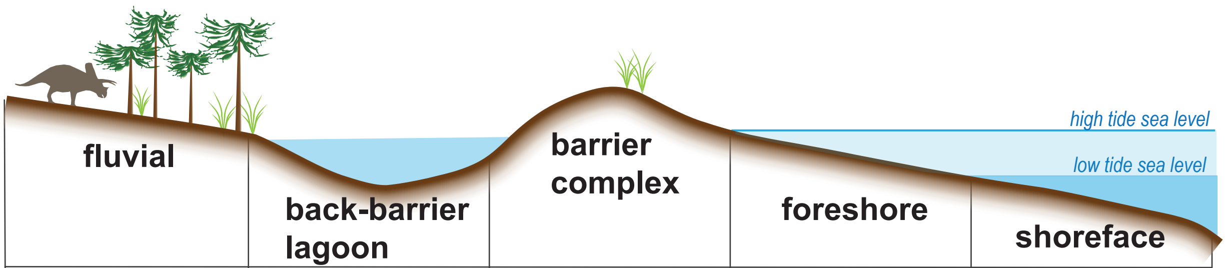


Figure 2.13. Thin section photomicrographs of sandstones at Stop 1. All photomicrographs are at the same scale and in cross-polarized light. Photomicrographs courtesy of Bruce Hart.



	fluvial	back-barrier lagoon	barrier complex	foreshore	shoreface
lithologic composition	Silt, sand, mud, and pebbles; coal beds; often organic-rich; sand often feldspathic and moderately-sorted	Mud, silt, minor sand lenses; often organic-rich; rare coal; rare flood-tide sand deltas	Well-sorted sand (f - c); sometimes quartzose; moderately- to well-sorted	Sand (f - c) with rare and localized heavy-mineral concentrations (a.k.a. *beach placer*); moderately- to well-sorted	Sand (f - c) with trace mud; sand content and grain size increases towards shore; rare pebble lenses
sedimentary structures	Trough cross-beds dipping towards sea; current ripples; cut-and-fill structures; horizontal plane beds	Bioturbation common; horizontal laminae; rare ripples; cross-beds dipping towards land in flood-tide deltas	Wind ripples, trough cross-beds, dunes, laminar sandsheets from washover events	Low-angle seaward-sloping planar laminae; cross-bedding perpendicular to shoreface	Swaly laminae; plane beds; oscillatory ripple marks; tool marks; scours; channels
fossils	Wood; rare burrows; leaf impressions	Bioturbation common; burrows; woody plant material; *Gastrochaenolites; Ophiomorpha*; rare shelly fossils	Mostly absent; sparse burrows or distorted bedding	Mostly absent; very rare vertical burrows or shelly fossils	Absent to sparse; horizontal or vertical burrows might be present; *Ophiomorpha*; rare shelly fossils or imprints; fossil abundance increases with distance from shore

Figure 2.14. Schematic diagrams of likely environments of deposition for the rocks seen at Stop 1.

Its relative paucity in the rock record likely stems from its being erased and replaced by dune or plane beds after storm events when unidirectional currents become the predominant force on the shoreface.

Ripples

Ripple marks, everyone's favorite sedimentary structure from Geology 101, can be useful in interpreting marine versus terrestrial environments of deposition. However, there is considerable overlap in the ranges of environments in which ripples can form and be preserved. In general, ripples form under low to moderate current velocity in sandy systems. There exists a continuum of ripple morphology (Fig. 2.17) that changes with current velocity and sediment supply. Ripples can form on the stoss face of larger dunes (sometimes called megaripples, just to be confusing). For the interpretation of ripples in the Mesaverde Group at Stop 1, one of the key observations can be determining whether the ripples formed under oscillatory or unidirectional currents. Oscillatory ripples are most common in marine and lacustrine environments and have roughly symmetrical slopes on both sides of the ripple crest. Current ripples, on the other hand, can form in fluvial, alluvial, eolian, or tidal environments and have a steeper lee face on the downstream side of the ripple crest and shallower stoss face on the upstream side. In environments with rapid aggradation and high sediment supply, current ripples often climb up the face of the preceding ripple. At Stop 1, evidence of ripples abounds; however, it is not always well-expressed (Fig. 2.18).

Figure 2.15. Bruce Hart indicating a hummocky bedding plane in the Point Lookout Sandstone at Stop 1.

Fossil Wood

While the remains of woody plants in the Mesaverde Group will never be as impressive as those in the Triassic Petrified Forest Formation of the Chinle Group, they can still be useful tools for interpreting paleoenvironments. For instance, at Stop 1, accumulations of woody debris left impressions on bedding planes (Fig. 2.19A). Fossil finds like these are most common from fluvial or estuarine deposits, although they cannot be ruled out in back-barrier lagoons (Fig. 2.19C). Trees in growth position (Fig. 2.20) are definite indicators of terrestrial environments. To the best of the authors' knowledge, none are known from the outcrops at Stop 1 (yet), but are reported from elsewhere in the Menefee Formation in the San Juan Basin.

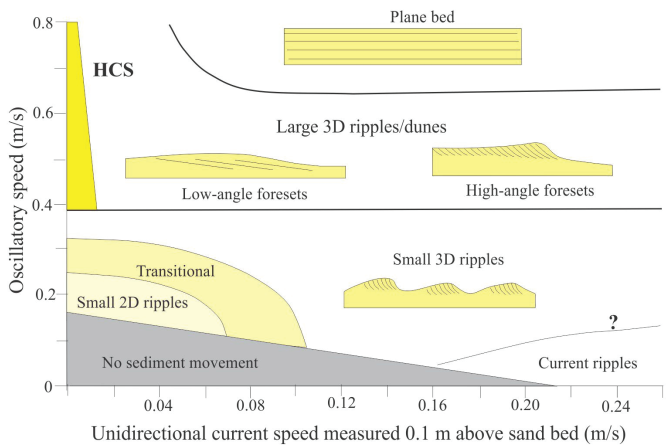


Figure 2.16. Bedform stability under combined oscillatory and unidirectional flow determined from the flume experiments of Arnott and Southard (1990). HCS = hummocky cross stratification. Modified from Duke et al. (1991).

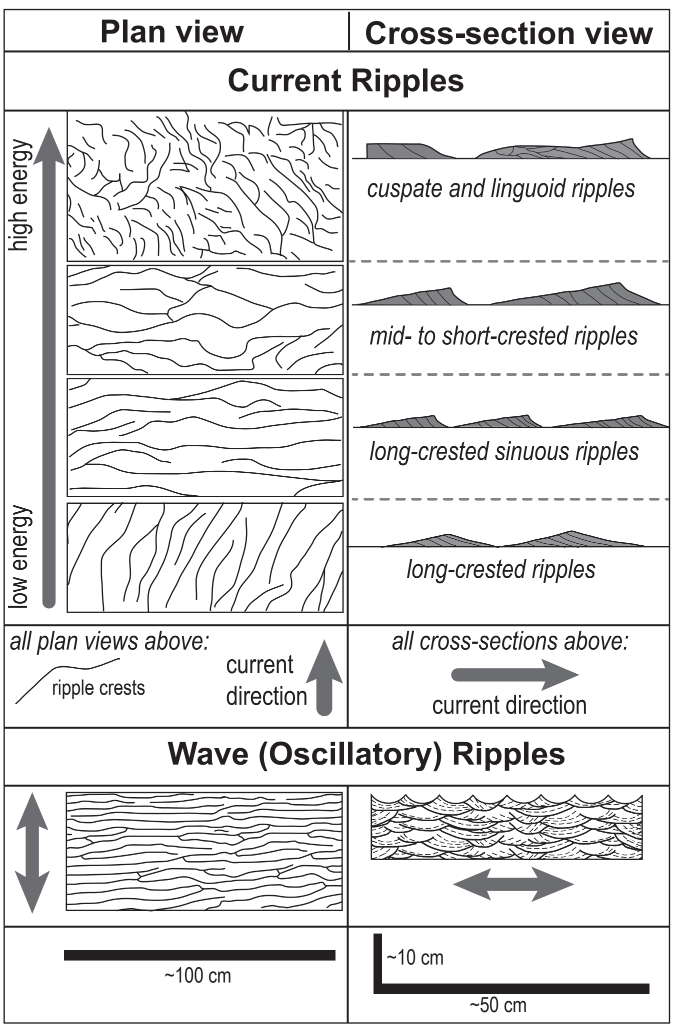


Figure 2.17. Five types of ripples found in subaqueous environments. Modified from Rankey and Reeder (2010).

Ophiomorpha

Charismatic dinosaur bones, shark teeth, and petrified wood excite both the amateur and professional fossil hunter. Each of these is a type of body fossil: the fossil remains of some portion of an individual organism. Also common in the rock record, however, are trace fossils or ichnofossils that are records of biological activity by organisms, but not the preserved remains of the organism itself. Ichnofossils include footprints, trackways, burrows, impressions, coprolites, root cavities, and borings; each can inform the ichnologist about the environment in which it made.

A common Cretaceous ichnofossil is *Ophiomorpha*, a crustacean burrow that is an indicator of nearshore marine deposits. These fossils consist of roughly cylindrical horizontal to vertical burrows lined with round pellets that are typically about a tenth of the diameter of the burrow itself. These pellet-lined burrows are reminiscent of an ear of corn, though typically much smaller in diameter (1.5 to 4 cm [0.6 to 1.6 in]-wide burrows are the most commonly found size in Late Cretaceous rocks in New Mexico; Fig. 2.21).

Coal

In terrestrial and transitional environments of deposition, the remains of woody plants can accumulate and be preserved as coal. The Menefee Formation hosts several coal seams, and small seams are seen at Stop 1 (Fig. 2.22). Most Menefee Formation coal is subbituminous (approximately 10,000 BTU/lb), though bituminous seams are present in the Monero field in the northeast San Juan Basin (Hoffman, 1991). When preserved in seams, coal is a high-confidence indicator of nonmarine environments of deposition. A word of warning: individual clasts of woody material or peat can be transported into marine environments and converted to coal.

*A brief geoetymological aside: The Cretaceous Period takes its name from the Latin *creta*, meaning “chalk.” Chalk is a globally widespread carbonate deposit from this time interval. The White Cliffs of Dover (memorialized in countless English works of art and literature), the Pays de Caux in Normandy (a favorite subject of Claude Monet, Guy de Maupassant, and Victor Hugo), the Stebbenkammer on Rügen in the Baltic Sea, the Danish Møns Klint (also in the Baltic Sea), the Austin Chalk (Texas), the Selma Chalk (Alabama), the Akkergeshen Plateau (Kazakhstan), the Gingin Chalk (Western Australia), and the strata of Kakhtesh Ramon (Negev Desert) all consist of Late Cretaceous chalk. Given the presence of Cretaceous chalk on all seven continents, perhaps it is not surprising that the Cretaceous is one of only two geologic time periods named after a rock type (the Carboniferous, a term used by our European friends who refuse to recognize the United States-centric Mississippian and Pennsylvanian nomenclature, is the other—carbon being coal). An aside to this aside: the Campanian Age, a subdivision of the Cretaceous from 83.6 to 72.2 Ma, takes its name from the province of Champagne, France, itself named from the Latin *campanius*, meaning “level plain” and referring to the low-relief chalk plateau that is well-suited both to growing the fruit of Bacchus and excavating wine cellars. The Coniacian Age (89.8 to 85.7 Ma) takes its name from the commune of Cognac, another French locale with spirited associations and reliant upon the terroir of Cretaceous chalks. Without high global sea level 80 million years ago and the thick accumulations of coccoliths that resulted, then these French regions might be known only for their baguettes, berets, and bicycle races—a terrible thing to imagine!

After stop, return to vehicles and continue east on Forest Road 7.

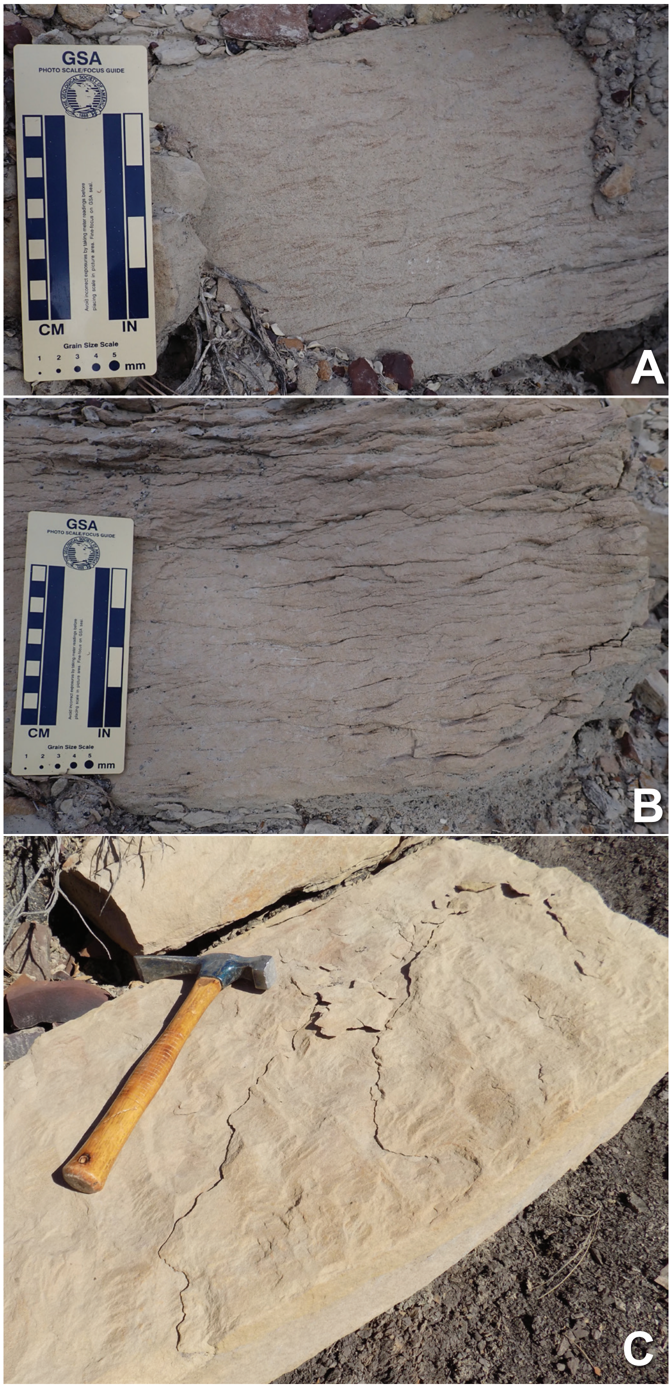


Figure 2.18. Examples of ripples exposed in Mesaverde Group sandstones at Stop 1. A: Cross-sectional view of complex short-wavelength ripples in the Menefee Formation. B: Poorly expressed cross-sectional view of ripples in the Menefee Formation. C: Bedding plane view of current ripples in a block of the Point Lookout Sandstone. Hammer is 31 cm (12 in) long.

0.1

31.7 Berm and culvert over Chupadero Arroyo. This culvert was washed away and replaced in summer 2021. Road enters strike valley carved into the Mancos Shale.

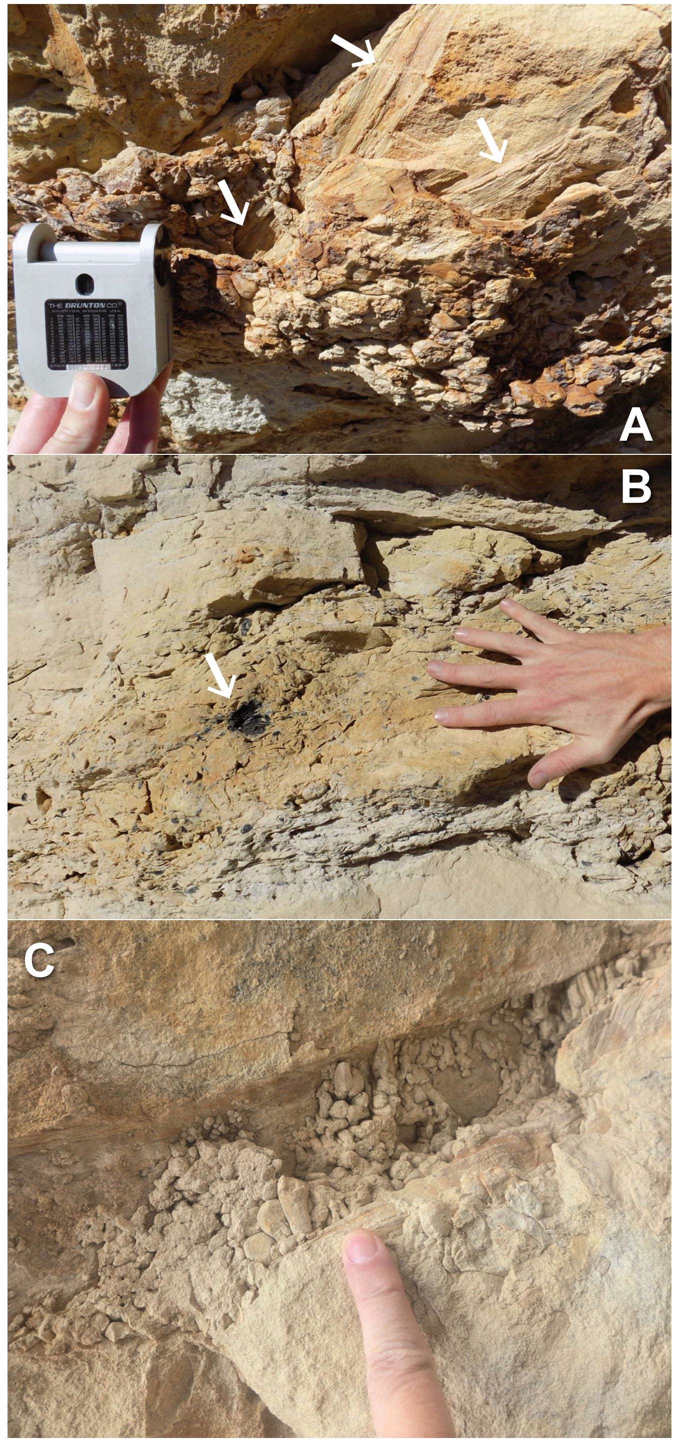


Figure 2.19. Various expressions of fossil wood at Stop 1. A: Wood impressions (molds) (white arrows) in the Menefee Formation. Note cylindrical burrows below wood horizon. B: Carbonized coaly wood clasts in sandstone of the Menefee Formation. Largest piece (white arrow) is approximately 5 cm (2 in) diameter. C: Wood hash with numerous *Gastrochaenolites* burrows in the same woody horizon. *Gastrochaenolites* is the trace of bivalve shipworms that bore into and consume wood in marine environments. *Photo 2.19C courtesy of Bruce S. Hart*

0.2
31.9 Road veers left/north along strike valley.

0.3
32.2 **Turn right/east onto Forest Road 6 (Golondrino Mesa Road).**

Figure 2.20. Petrified tree stump in growth position in the Menefee Formation at Chaco Culture National Historical Park. *National Park Service photograph by Thomas Lyttle*

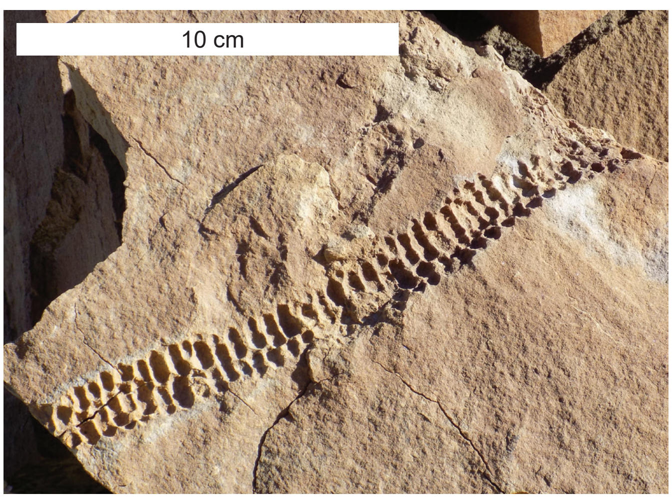


Figure 2.21. *Ophiomorpha* in the San Juan Basin. Top: Mold of *Ophiomorpha* in loose block of Cliff House Sandstone from near La Ventana, New Mexico. Bottom: Cast of iron-stained *Ophiomorpha* in the Pictured Cliffs Formation near La Plata, New Mexico. Pencil is 16.5 cm (6.5 in) long. *Bottom photo courtesy of Andrew Hoxey*

0.4
32.6 Cross cattle guard.

0.2
32.8 Gate, which hopefully is unlocked and open.

1.3
34.1 The roadcut at right illustrates the importance of proper archaeological surveys before road construction. The small, fine-grained alluvium-filled amphitheater at left probably was the garden plot for the folks living here centuries ago.

0.7
34.8 Begin seeing numerous Douglas-firs (Ch'ó deenínii, *Pseudotsuga menziesii*) as we continue to ascend.

Figure 2.22. Menefee Formation coal outcrops at Stop 1. Top: 5-m (16-ft)-thick zone of coals and carbonaceous shales on east side of cuesta. Bottom: 50-cm (20-in)-thick coal seam on west side of cuesta.

0.9

35.7 Turn left at road fork toward Golondrino Mesa/ Chama Canyon. Immediately after the cattle guard, turn right on a two track. If you had continued straight at the fork, you would proceed to Deadman Peak and its occasionally crewed fire tower. Curious about the peak's name? According to a 1911 issue of the *Jemez Forest Ranger*, "Assistant Ranger Sypher reports that on May 11, while riding his lookout points on the south end of Gallina Mountain, he found the headless corpse of a man which from all appearances had lain there for six months. The skull bones were scattered and broken and when placed together showed a bullet hole in the back." The site was called Gallina Mountain in the earliest Fire Plans from 1913, by which time it had a telephone. In 1925, the National Forest allocated $200 for a cabin atop Deadman Peak, as well as $60 for a lookout tower and pasture (earlier lookouts climbed trees or cut them down for clear views from terra firma; the pasture was to keep lookouts' horses fed). In 1965, the U.S. Forest Service decommissioned the cabin and sold it for $1 to Mr. Pablo Casados of Llaves, who took it apart, hauled it down the mountain, and reassembled it at his home in Llaves, where it still stands. There are several amusing stories of Volkswagens in snowstorms, climbing bears, and children falling through the Deadman Peak fire tower's open trapdoor in Barbara Zinn's excellent *Fire History of the Santa Fe National Forest* (Zinn, 2017).

0.1

35.8 There are good views to the distant Tusas Mountains and upper Rio Chama Valley through the trees at left.

0.6

36.4 Waypoint 2.04 [36.42789°, −106.76773°]

STOP 2. Park in small meadow and walk ~500 m (~1,640 ft) south for a discussion of the Archuleta/Gallina anticlinorium, San Juan Basin/Chama basin transition, and recent geologic mapping in the area.

Waypoint 2.05 [36.42300°, −106.76884°]

The main faults cutting the Archuleta/Gallina anticlinorium are the north-northeast striking Gallina and Tierra Montañosa normal faults that are at the north end of the greater Pajarito-Nacimiento reverse fault system that bounds the west side of the Sierra Nacimiento to the south (Woodward et al., 1992). Three structural domes (or doubly plunging anticlines) form the Archuleta/Gallina anticlinorium (Fig. 2.23).

The southernmost doubly plunging anticline is located on French Mesa, which is bound on the west side by the west-down Gallina fault. In one place, Permian Cutler Formation is juxtaposed against the Jurassic Entrada and Todilto Formations. The Nacimiento fault, the reverse fault bounding the west side of the Sierra Nacimiento, is also west down, but the Nacimiento fault dies out south of French Mesa. The Gallina fault dies out at the north end of French Mesa south of the Rio Gallina and offset is transferred to the north along the east-down Tierra Montañosa fault.

The middle anticline is located to the north of the Rio Gallina (Fig. 2.23). Figure 2.24 is the view of the Rio Gallina structure from Stop 2 looking east. Figure 2.25 is a view of the structure looking north from French Mesa.

The Rio Gallina anticline is bisected by the Tierra Montañosa fault, which juxtaposes Permian Cutler Formation on the west against Triassic Chinle Group to the east. The fault is well exposed in places (Fig. 2.26) and springs are common along the Tierra Montañosa fault north of the Rio Gallina. The fault is high angle and both the Cutler Formation and the Poleo Sandstone on the west side of the fault dip steeply to the east adjacent to the normal fault.

Woodward et al. (1992) argued that the Gallina fault has both dip-slip and strike-slip components and that the Tierra Montañosa fault is primarily dip slip. The Tierra Montañosa fault is well exposed in the Rio Gallina anticline at 36.40495°, −106.77416°. In this outcrop, north-striking fault planes dip 55° W to 85° E with dip-slip to slightly oblique-slip (rake 75 S) slickenlines. A second set of north-striking fault planes dip 85° W with dip-slip slickenlines that cut older low-angle slickenlines, indicating a change in slip direction (Fig. 2.27).

The northernmost anticline, located to the east of Gallina Mountain, is elongated north-south with the axis of the fold to the west of the Tierra Montañosa fault. Folded Pennsylvanian sandstones and a fossiliferous limestone bed on the west side of the fault are juxtaposed against Cutler Formation to the east.

Investigations of the Paleocene to Eocene synorogenic Ojo Alamo, Nacimiento, and San Jose Formations by Baltz (1967) and Smith (1988, 1992a, 1992b) have been used to document the timing and progressive development of Laramide uplifts and basins in this area. Baltz (1967) drew structural contours on the base of the Ojo Alamo Sandstone using the distinctive signature of this unit on geophysical logs from petroleum wells. The contours highlight a series of northwest-plunging folds that suggest right-lateral slip on the Nacimiento-Gallina fault system. Smith (1988) examined the structural and stratigraphic relations of the Nacimiento and San Jose Formations west of the Sierra Nacimiento and Gallina uplifts. He found that the basal Cuba Mesa Member of the San Jose Formation was deposited at a time of little tectonic activity and that the stacking of channels in the Regina Member indicate accelerated subsidence in the San Juan Basin. The Proterozoic core of the Sierra Nacimiento was not exposed during the deposition of the San Jose Formation; the Mesozoic and Paleozoic section was eroding from the highlands and providing sediment during the early phases of Laramide uplift. The Gallina-Archuleta arch apparently did not form until after Llaves Member deposition.

0.0

36.4 After returning to cars, turn around and retrace route back toward paved State Road 112.

0.6

37.0 On a clear day, the 650-m-tall (2,100-ft-tall) Brazos Cliffs can be seen to the right here. These cliffs are 50 km (31 mi) to the northeast across the Rio Chama valley.

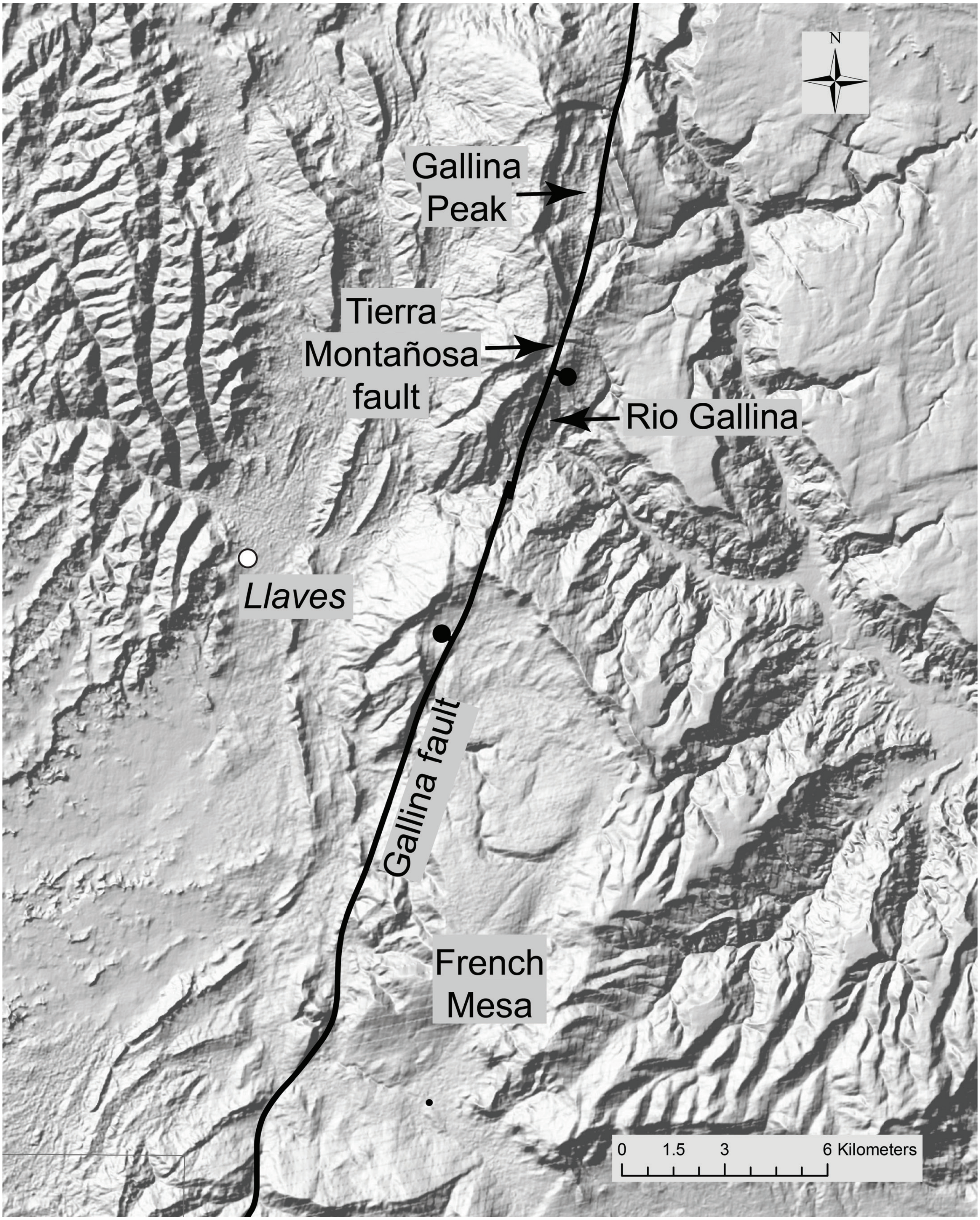


Figure 2.23. Lidar hillshade of the Archuleta-Gallina anticlinorium. The three domal features (French Mesa, Rio Gallina, and Gallina Peak) are highlighted with bold italic text. The ball-and-bar symbols indicates that Gallina fault is down to the west, and the Tierra Montañosa fault is down to the east.

Figure 2.24. View of the eastern side of the structure, which exposes Jurassic Entrada Sandstone in the lower right corner of the photo. The red Recapture Member and the green Brushy Basin Member of the Jurassic Morrison Formation lie above the Entrada Sandstone and the Todilto Formation. The lower part of the bold cliff is Cretaceous Burro Canyon Formation, and the mesa is capped by sandstone and shale members of the Dakota Formation and Manco Shale. The canyon of the Rio Gallina is in the middle ground and the Jemez Mountains are on the skyline.

Figure 2.25. View of the Rio Gallina faulted anticline from the south. The eastern limb (right) is the Mesozoic section shown in Figure 2.24. The western limb (left) exposes Permian Cutler (Abo) Formation, Triassic Chinle Group, Jurassic Entrada Sandstone, and Jurassic Todilto Formation, shown in this photograph.

Figure 2.26. The north-northeast striking Tierra Montañosa fault in the middle of the anticline, looking north. The left side of the maroon area is the fault trace. The Tierra Montañosa fault separates the red Petrified Forest Formation of the Triassic Chinle Group on the right from the orange-red Permian Cutler Formation to the left in the foreground. On the skyline, the fault separates Poleo Formation on the left from Entrada Sandstone on the right.

3.2
40.2 Immediately before a cattle guard, turn left/south on the first two track heading south. Immediately after the turn, there is a good view south showing the thickness of the Menefee Formation here.

0.3
40.5 Waypoint 2.06 [36.43030°, −106.80340°]

STOP 3. Park in a small sagebrush meadow and walk 200 m (650 ft) east (uphill) for discussion of carbonates in the Cretaceous Western Interior Seaway in the San Juan Basin.

The Greenhorn Limestone

During the ~30 My existence of the Cretaceous Western Interior Seaway, there were only two episodes of major pelagic carbonate deposition: the Cenomanian-Turonian Greenhorn interval, preserved in the Greenhorn Limestone, and the Santonian-Campanian Niobrara interval, preserved in the Fort Hays Limestone and Smoky Hill Marl (Hattin, 1987). The Greenhorn Limestone was first named by Gilbert (1896) after outcrops along Greenhorn Creek in south-central Colorado. The unit stretches from Manitoba, Canada, in the northeast to central New Mexico in the southwest, with outcrops present across much of the western Great Plains in Montana, the Dakotas, Nebraska, Kansas, Colorado, and New Mexico. The westernmost known exposures are near Toadlena on the Navajo Nation (Hattin, 1987). In the Great Plains, the Greenhorn Limestone manifests as relatively thick, well-bedded limestones—in fact, the uppermost interval of the Greenhorn Limestone in north-central Kansas has the informal name "Fencepost Limestone" due to its extensive use for that purpose in the area. In the San Juan Basin, its carbonate beds are thinner and flaggier, but carbonate nonetheless.

Across the Western Interior Seaway, a unique feature of rocks in the Greenhorn interval is the presence of carbonate/silicate couplets that can be traced for thousands of kilometers (Gilbert, 1895; Arthur et al., 1986). These couplets have been demonstrated to be time parallel—unlike the Mesaverde Group units discussed at Stop 1, these limestone-shale couplets

Figure 2.27. A rare exposure of slickenlines along the fault trace, looking west. The dip-slip lines are on a surface dipping 85° W and the slickenlines near the finger are subhorizontal.

are synchronous as opposed to diachronous. Time-parallel units like these are formed due to some sedimentary event that occurred at the same time in multiple places. Gilbert (1895) was among the first to propose that these rhythmic couplets in the Greenhorn Limestone were likely formed during alternating climate cycles related to Earth's orbital precession. (He then used the measurement of these beds' thicknesses near Pueblo, Colorado—about 45 cm [18 in]—to estimate the duration of sedimentation for the entire kilometer-plus-thick Cretaceous section in the area. His estimate? Five to 20 million years—within the same range assumed by 21st century workers. Not bad for preradiometric dating Jacobs staff geology!)

Carbonate-siliciclastic couplets in the Greenhorn Limestone, like those observed at Stop 3, are schematically explained in Figure 2.28. During Cretaceous climatic episodes that favored higher precipitation, there were higher rates of sediment delivery via east-flowing rivers to the Western Interior Seaway. River discharges likely also were higher, potentially leading to the development of hypopycnal plumes of sediment-laden fresh water extending hundreds of kilometers offshore atop the normal-salinity marine waters of the Western Interior Seaway. This allowed for clay-sized silicates to be deposited in offshore settings, effectively shutting down the carbonate ecosystem and potentially leading to anoxic or oxygen-depleted benthic conditions (Arthur et al., 1986). When climate shifts led to decreased precipitation, river discharge and sediment load decreased, as well. Siliciclastic sediments were deposited nearshore, while offshore environments experienced normal salinity marine conditions that favored carbonate deposition and high biotic activity. Milankovitch cycles—primarily the ~41 ky obliquity cycle—brought repeating alternations of climate conditions that led to the rhythmites of the Cretaceous Western Interior Seaway (Floegel et al., 2005).

0.0

40.5 Return to vehicles. Turn around and retrace track for 0.3 miles back to Forest Road 6 (Golondrino Mesa Road).

0.4

40.9 Turn left (east) and go downhill onto Forest Road 6.

0.1
41.0 Reentering strike valley. View ahead of ridges of (from near to far) Mesaverde Group, Ojo Alamo Formation, and San Jose Formation. The intervening valleys are Mancos Shale (just before you), Lewis Shale, and Nacimiento Formation (Fig. 2.29).

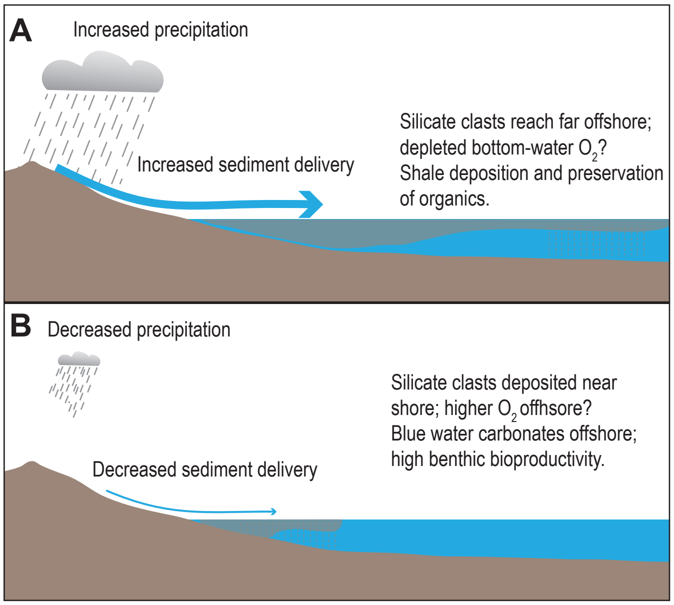


Figure 2.28. Schematic diagrams of shale and limestone depositional scenarios in the Cretaceous San Juan Basin. A: During climatic episodes when there was high precipitation, there was also increased clastic sediment delivery to the Western Interior Seaway. A hypopycnal plume delivered a sediment-laden freshwater lens far into the Western Interior Seaway. Clay-sized clasts dropping from that plume overpowered carbonate deposition in offshore settings. B: During climatic episodes of lower precipitation and runoff, siliciclastic deposition in the Western Interior Seaway was concentrated nearshore. Offshore environments experienced marine conditions favoring carbonate deposition and high benthic bioproductivity. See Arthur et al. (1986) for detailed discussion of these cycles.

1.6
42.6 REZERO ODOMETER at terminus of Forest Road 7 at State Road 112.

0.0 Turn left (south) on State Road 112.

3.3
3.3 Waypoint 2.07 [36.38539°, −106.85819°]
Turn right (west) onto Forest Road 313 before the bridge. This road heads west through an outlier of the Santa Fe National Forest, over the Continental Divide, and into the Lindrith Enclave. The chasm through which it passes, Cañoncito de las Lleguas, is in places over 300 m (1,000 ft) deep and provides excellent exposures of several members of the San Jose Formation.

0.1
3.4 Mouth of Cañoncito de las Lleguas at 12:00. Note the slight south component of dip in beds south of the canyon, becoming a nearly pure west dip north of the canyon. Kelley et al. (2024) mapped this area at the 1:62,500 scale; their mapping shows the mud- and silt-dominated Regina Member pinching out 1.6 km (1 mi) south of the canyon here. Given the overall sandy nature of the rocks seen in this exposure, that interpretation is easy to believe.

0.4
3.8 Benson-Montin-Greer Drilling field office on right.

Figure 2.29. Annotated photograph looking west into strike valleys and ridges on the east margin of the San Juan Basin.

0.1
3.9 Cattle guard. Enter National Forest. **Stay straight.** The road at right leads to the mouth of Nogal Canyon, one of several deep canyons in the San Jose Formation highlands here. Dead ahead, a green produced water tank sits atop an 18-m (59-ft)-high terrace of Lleguas Arroyo. Could this be correlative to the Rito Leche terrace in the Rio Puerco drainage farther south?

0.2
4.1 At 11:00, an example of the importance of slope aspect on vegetation communities in semiarid environments. On the east-facing slopes, there are sparse piñon-juniper woodlands; the north slopes host denser ponderosa pines and Douglas-firs (Fig. 2.30). These vegetation differences reflect differences in soil thickness, moisture, and chemistry, all dictated simply by the overall budget of solar insolation—north-facing slopes receive less energy per unit of soil area than do those on east, west, or south aspects. This leads to lower soil temperature and higher soil moisture. These differences, though subtle, lead to real effects in landscape development on the Colorado Plateau, as shown by Burnett et al. (2008). These aspect-related differences also allow insight on what past geomorphic and/or ecological conditions might have been like in different climates by presenting a microcosm of what soil scientists call a climosequence. A climosequence is a series of soils that vary due to differences in climate conditions, with all other soil-forming factors held constant. By observing the wetter, cooler soils (and associated ecosystems) on north slopes like the forested one seen here, we can estimate what overall soil (and ecosystem) conditions might have been like during the generally colder and wetter glacial episodes that dominated the Quaternary Period (which was 85% glacial and 15% interglacial!). The increased soil depth and soil moisture in such conditions likely lead to deeper and more intense weathering of bedrock and the creation of large volumes of transportable regolith. Ever wonder where all that Quaternary alluvium in southwestern landscapes came from? It came from glacial episodes!

0.5
4.6 On the left, a copse of hybrid cottonwood (*Populus* sp.), likely something between a narrowleaf and Fremont.

0.3
4.9 Corral Canyon enters from the north at 3:00. The canyon entering from the south at 9:00 is Horse Heaven Canyon.

0.4
5.3 At left, a view of the persistent 1.5–2-m (5–7-ft)-tall terrace and the older 7-m (23-ft)-tall terrace of Lleguas Arroyo. The lower terrace supports ricegrass (Ndídlídii, *Oryzopsis hymenoides*), skunkbush (Ch’iłłichiin, *Rhus trilobata*), and young cottonwoods. Inundation still occurs on this lower terrace during high flow events. The older 7-m (23-ft)-high terrace supports piñon, juniper, big sagebrush (Ts’ahtsoh, *Artemisia tridentata*), rabbitbrush (Ch’ildiilyésiits’ǫ́ǫ́z, *Chrysothamnus viscidiflorus*), chamisa (Ch’ildiilyésiits’óóz, *Ericameria nauseosa*), and prickly pear (Hoshniteelí, *Opuntia* spp.). The road here is atop the 7 m (23 ft) terrace.

0.3
5.6 Pumpjack by road on right. This well (Cañada Ojitos #2, API# 30-039-05997) is set in the lower Mancos Shale at 1,836 m (6,022 ft) total depth and was fracked upon initial completion in 1963. As of 2024, it has produced 44,064 bbl oil and 32,892 MCF gas. At 10:00, Cañada Gurule joins Lleguas Arroyo.

Figure 2.30. View to the west-southwest of the 200-m (650-ft)-tall ridge to the south of Cañoncito de las Lleguas. The east-facing slope on the left side of the photo is less vegetated overall and supports predominately piñon and juniper, while the north-facing slope on the right side is more densely vegetated with ponderosa pine and Douglas-fir.

0.4
6.0 Road ascends off terrace to a hill crest with roadcut exposure on the right of reddish muddy sandstones with popcorn surface texture; Kelley et al. (2024) mapped this as Llaves Member of the San Jose Formation.

Beware of ascribing colors off the cuff: this outcrop's color is 7.5 YR 4/2 according to the Munsell system, making its official color brown, not red! Beware also of naming lithology of San Juan Basin sedimentary rocks without close inspection with hand lens or microscope. Many overconfident and under-intelligent geologists have grossly overestimated the amount of mudstones in the Nacimiento and San Jose Formations based on outcrop morphology rather than close inspection. For instance, this outcrop, with its popcorn texture and lack of cliffs, might initially appear to be a shale or claystone. However, it has 60% very fine to medium sand, 35% silt, and 5% clay. Scientists must always be skeptical. But be especially skeptical of the geologist without a loupe, grain-size card, and dirty hands.

6.4
6.4 The road here takes a few wiggles. Depending on where in the wiggles you are, dead ahead are the 300-m (980-ft)-tall cliffs at the mouth of Cañada Ojitos, the longest and largest tributary to Cañoncito de las Lleguas (Fig. 2.31).

0.1
6.5 Dirt road to well pad at right. At 9:00, note the mature ponderosa pines on the 7 m (23 ft) terrace. The largest of these are likely 250–350 years old, based on comparison to similarly sized trees cut in the area.

0.3
6.8 For the next 0.3 miles, a thicket of coyote willows indicates perennial high water tables in this reach. This species, *Salix exigua*, is an evolutionary champion, and has colonized the entire North American continent, from the North Slope of Alaska east to Hudson Bay and the Gulf of St. Lawrence, south to the Gulf of Mexico, and west to the Gulf of California. If you find a small willow along a stream anywhere between these extremes, it's probably *S. exigua*.

Figure 2.31. The north side of Cañoncito de las Lleguas at the confluence with Cañada Ojitos. This canyon wall exposes a 330-m (990-ft)-thick section of the San Jose Formation.

0.2
7.0 **Artificial pond at left. Take left fork immediately after pond.** The right fork enters Cañada Ojitos.

0.5
7.5 Steep road at left crosses Lleguas Arroyo then climbs into Cañada Jesus Moya, which debouches here. **Continue straight on Forest Road 313**.

0.2
7.7 An abandoned (as of 2024) pumpjack, then the road climbs onto a higher terrace we haven't seen yet. This one is 17 m (56 ft) above modern stream grade.

0.3
8.0 On the right, note the sandy reddish deposits extending all the way to the base of the bedrock cliffs (Fig. 2.32). These sand-dominated deposits preserved in high, abandoned landscape positions seem to be unique in this area to Cañoncito de las Lleguas and its tributaries. No organized study has been undertaken upon them, but these authors assume that they represent long episodes of regolith production, limited transport, and sediment storage during past Quaternary climate episodes that were quite different from that we live in today. Hillslopes here today are producing large blocks of sandstone that accumulate in talus piles at the bases of cliffs. In the past, as evinced by deposits like these, climate conditions produced much finer-grained sediment, and the system was unable to transport it much farther than the foot of the slope from where it was derived.

0.2
8.2 At left, a thick exposure of three geomorphic surfaces (Fig. 2.33).

Figure 2.32. Thick silty sand deposits extending to the base of steep bedrock cliffs at right in Cañada de las Lleguas.

Figure 2.33. Photograph of the south side of Cañoncito de las Lleguas showing three geomorphic surfaces, labelled here with numerals. The oldest surface (1) consists of silty sand and stands as much as 22 m (72 ft) higher than the modern arroyo bed. The middle surface (2) contains its own fill—also silty sand—and stands about 7 m (23 ft) above the modern arroyo bed. The youngest surface (3) is the modern erosion surface.

0.3

8.5 Cross cattle guard. The canyon begins to widen, largely because we've come upsection to the base of the Tapicitos Member of the San Jose Formation, which contains fewer thick, resistant sandstones amenable to forming steep canyons. Since entering Cañoncito de las Lleguas 4.5 miles back, we've ascended through some 300 m (980 ft) of the San Jose Formation.

0.2

8.7 **Waypoint 2.08 [36.41239°, −106.93572°]**

Turn left (south) at four-way crossroads to enter Cañada Simon. Continuing straight will get you to the Continental Divide and private lands north of Lindrith.

0.3

9.0 Cross cattle guard. Bucolic Cañada Simon opens before you. At 9:00, note the partially incised small tributary valley, and the thickness of the alluvium exposed therein (Fig. 2.34). Turning to look upstream in Cañada Simon, imagine the volume of sediment stored in this valley alone. Where did it come from? How was it produced? What is its fate?

0.5

9.5 **Waypoint 2.09 [36.40200°, −106.94164°]**

Figure 2.34. Photograph looking east of the east side of Cañada Simon. Note the thickness of fine-grained alluvium in this valley.

STOP 4. Road bends to the left, then a faint two track veers off to the right. Park in a small clearing just past the two track. Walk northwest toward sandstone bluffs for discussion of recent research on the sedimentary history, provenance, tectonic significance, and geochronology of the San Jose Formation.

Sedimentology and Tectonics of the San Jose Formation

The Laramide orogeny of western North America represents widespread thick-skinned deformation caused by the shallow northeastward subduction of the Farallon plate (e.g., Liu et al., 2010). The San Juan Basin of northwestern New Mexico is a subcircular Laramide basin with four basement-cored uplifts along its flanks (Nacimiento to the east, Defiance to the west, Zuni to the south, Monument and the Needle Mountains uplifts to the northwest; e.g., Cather, 2004; Pecha et al., 2018; Pecha et al., 2022). The San Juan Basin preserves strata spanning from the early Paleozoic to the Cenozoic. The basin itself has seen a considerable amount of prior study focused largely on basin stratigraphy, provenance, and resource potential, as it is still one of two hydrocarbon-producing basins of New Mexico.

Previous work, such as provenance and sediment dispersal trends, has been carried out on Jurassic through earliest Paleogene strata in the San Juan Basin (e.g., Cather, 2003; Cather, 2004; Dickinson and Gehrels, 2008; Hobbs, 2016; Donahue, 2016; Pecha et al., 2018; Cather et al., 2019; Fig. 2.35). Sediment dispersal during the Cretaceous and early Paleogene transitioned from far-field transport and deposition to near closed-basin local-sediment provenances (e.g., Pecha et al., 2018; Pecha et al., 2022). Except for limited mapping and regional stratigraphic studies (e.g., Baltz, 1967; Smith and Lucas, 1991), little is known about the age and stratigraphic relationships of early Eocene strata in the San Juan Basin.

The San Jose Formation is one of the youngest stratigraphic successions in the San Juan Basin and represents deposition during the latest stage of Laramide deformation in the southwestern United States (e.g., Cather et al., 2019). The formation is made up of nonmarine sandstone interlaid with multicolored siltstone and claystone (Fig. 2.36). The San Jose Formation is the most extensively preserved and exposed Eocene stratigraphic unit in New Mexico and contains well-preserved vertebrate and plant fossils that provide the only current age constraint on the formation (e.g., Smith and Lucas, 1991; Smith, 1992a), placing it in the early Eocene. The San Jose Formation consist of fluvial channel sandstone bodies and thick succession of well-preserved floodplain siltstone and claystone (Fig. 2.37). Based on previous work, the formation is subdivided into five members of which four are preserved regionally throughout the basin (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992a).

The basal Cuba Mesa Member, named for its type locality at Mesa De Cuba located just west of the town of Cuba, New Mexico, consists primarily of what was originally described as coarse-to-very-coarse sandstone with minor mudstone lenses (Baltz, 1967). More recent studies describe the Cuba Mesa as consisting primarily of sandstone bodies (3 to 7 m [10 to 23 ft] thick) that are interbedded with extensive floodplain siltstone and claystone that range in thickness from 0.5 to 3 m (1.6 to 10 ft; Smith and Lucas, 1991; Smith, 1992a). New provenance data from the Cuba Mesa sandstone bodies reveal an arkosic to

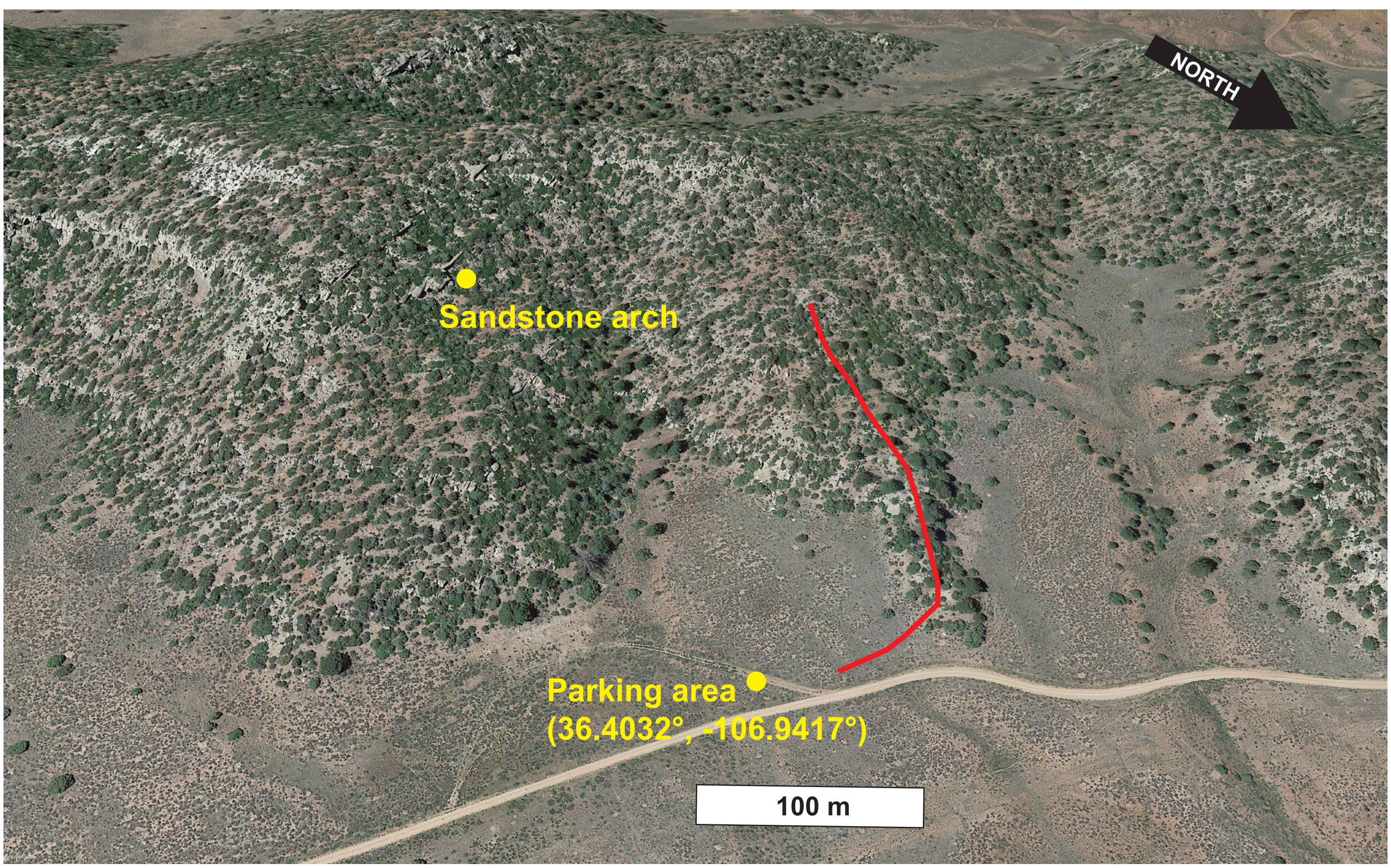


Figure 2.35. Stop 4 walking path for measured section on outcrop (red path). Use caution on the outcrop, as some of the sandstone bodies are cliff formers and rock falls are possible. To the northeast, one can view the sandstone cliffs of the Llaves Member (see Fig. 2.38).

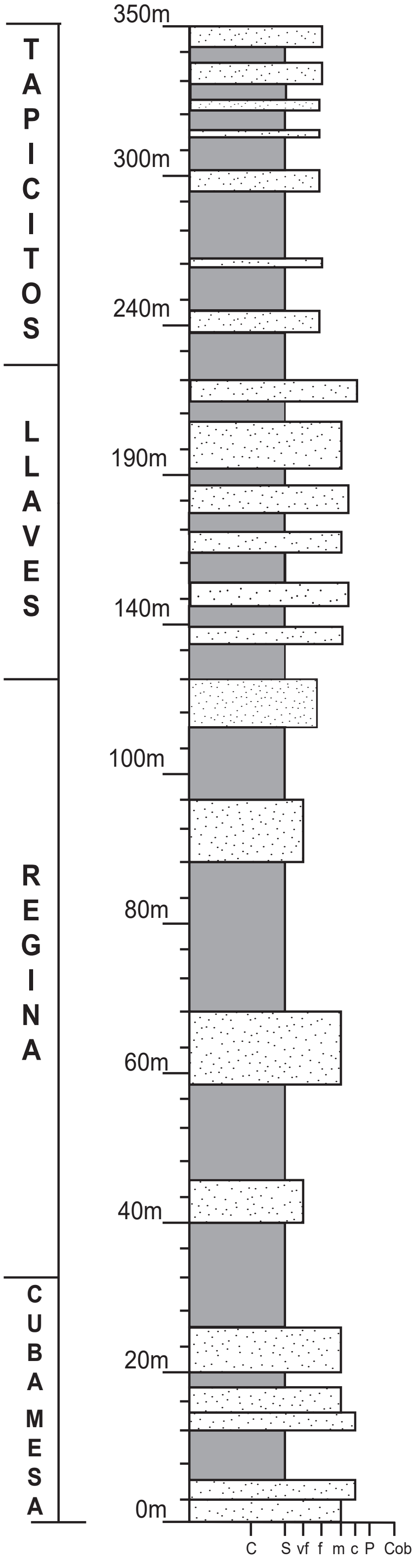


Figure 2.36. Simplified stratigraphic column of the San Jose Formation (excluding the Ditch Canyon Member). The basal Cuba Mesa Member has a sandstone versus mudstone/siltstone ratio of (43% sand to 57% mud). The Regina Member has a sandstone versus mudstone ratio of (55% sand to 45% mud). The Llaves Member has a sandstone versus mudstone/siltstone ratio of (43% sand to 57% mud). The capping Tapicitos Member has a sandstone versus mudstone/siltstone ratio of (35% sand to 65% mud). Note scale changes to reflect relative thicknesses of individual members.

lithic arkose lithology (Valenzuela et al., this volume). Locally, the Cuba Mesa can reach upward of 240 m (790 ft) thick and is defined in part by a basal sandstone body that is observed throughout much of the San Juan Basin. Common sedimentary structures in channel sandstones include ripple cross-stratification, horizontal stratification, and soft-sediment deformation structures (SSDSs; Fig. 2.37). The Cuba Mesa pinches out toward the center of the basin and gives way to the Regina Member that overlies and intertongues with the Cuba Mesa in the central portion of the basin (Baltz, 1967; Smith and Lucas, 1991; Smith, 1992a).

The overlying Regina Member is lithologically similar to the Cuba Mesa but preserves a higher percentage of floodplain deposits (that range in thickness from 2 to 25 m [7 to 82 ft]) and overall thinner sandstone channel complexes (2 to 5 m thick [7 to 16 ft]; Figs. 2.36 and 2.37). Siltstone and claystone in both the Regina and Cuba Mesa are variegated and generally weakly consolidated with a variety of colors, including gray, white, red, brown, pink, and gray with hints of green. The thickness of the Regina in outcrop ranges from ~50 to ~150 m (~160 to ~490 ft; Smith and Lucas, 1991). However, there is not an accessible complete section of the Regina from base to top in the San Juan Basin. It is assumed that the true thickness of the Regina is likely greater in the subsurface. This member reportedly intertongues with the overlying Llaves Member in the northeast but a distinct contact between these members is not well defined.

The Regina Member has yielded a multitude of nonmarine vertebrate fossils that provide some of the only biostratigraphic age constraint for the San Jose Formation. Vertebrate fossils collected from the Regina Member include multiple small mammals (e.g., *Phenacodus primaevus*, *Coryphodon* spp., *Hyracotherium angustidens*, and *Hyopsodus miticulus*), multiple reptile specimen (including Crocodilia and *Echmatemys* spp.), and fossil fragments of fish in the gar family of Lepisosteidae (Smith and Lucas, 1991). Many of these taxa are correlative to specimens found in Wyoming and elsewhere in the western United States. Age correlations for these taxa are placed at ~53 Ma in the Wasatchian (Lysitean).

Conformably overlying and in places interfingering with the Regina is the cliff-forming Llaves Member. The Llaves is as thick as ~150 m (~500 ft; Fig. 2.37). This member consists of laterally extensive sandstone channel bodies (2 to 5 m [7 to 16 ft] thick) interbedded with floodplain siltstone and claystone (2 to 11 m [7 to 36 ft] thick; Fig. 2.36). From afar this unit appears to be made up of a primarily sandstone, but recent studies reveal a ratio of nearly 50% sand to 50% silt and mud (Fig. 2.38). In this cliff-forming member, the fine-grained floodplain deposits can be identified on an outcrop scale by the intervals of thick vegetation growing between sandstone bodies. The sandstone bodies of the Llaves range from medium- to coarse-grained sandstone that exhibit horizontal stratification and faint small-scale planar cross-stratification preserved (Fig. 2.39). Soft-sediment deformation structures are common in channel sandstone bodies and likely destroyed any evidence of primary sedimentary structures (Fig. 2.40).

The uppermost member of the San Jose Formation is the

Tapicitos Member. The contact between the Llaves Member and overlying Tapicitos Member is marked by a siltstone interval and the contact has been recently identified based on color changes and minor changes in grain size upsection into

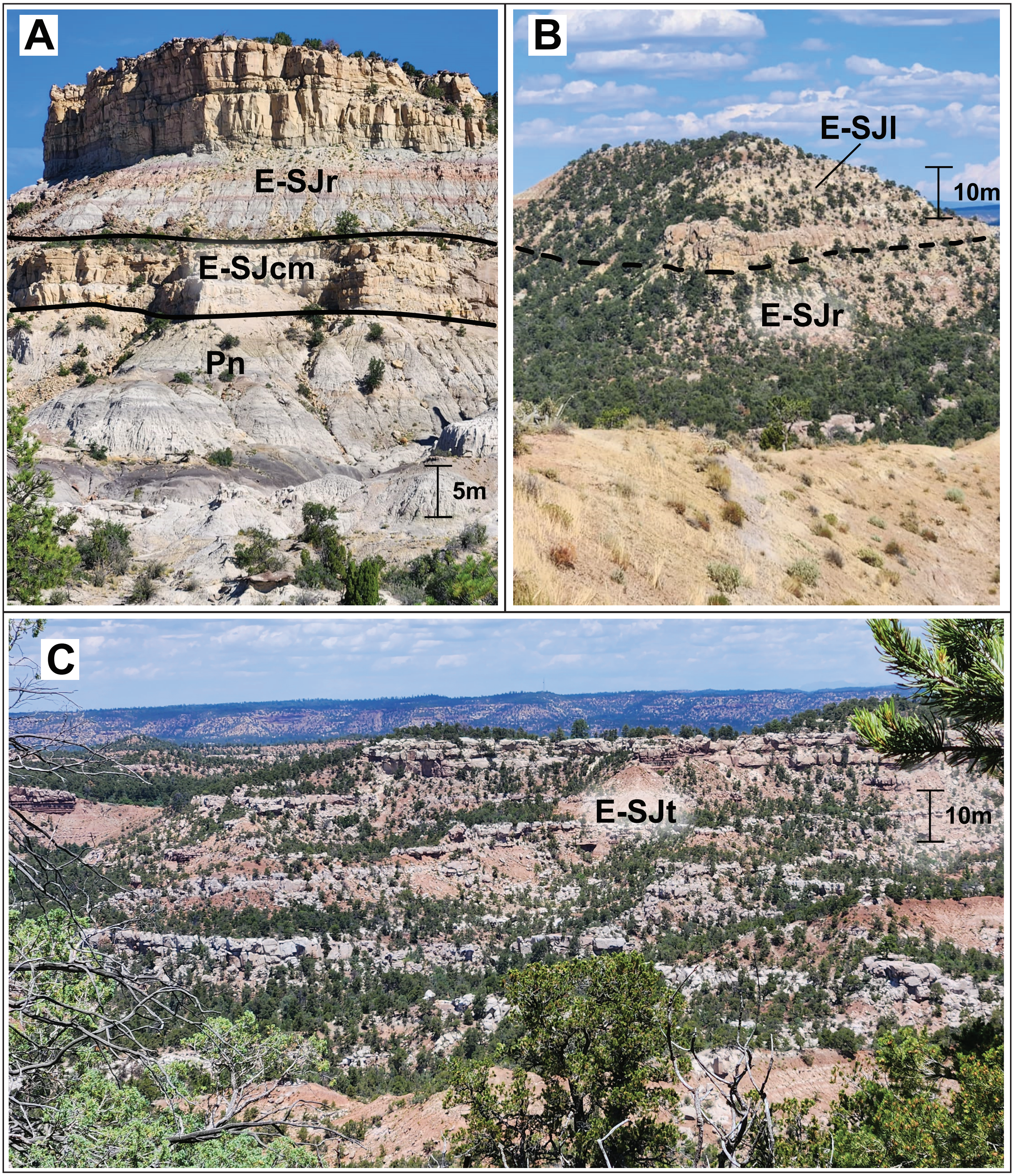


Figure 2.37. Annotated field photographs of each member of the San Jose Formation. A: To the north the Llaves Member of the San Jose Formation overlying the Regina Member. The contact between these two members is not well defined and estimated based on grain size and color changes. B: Looking north, the Nacimiento Formation unconformably(?) underlying the Cuba Mesa Member that in turn underlies the Regina Member. C: Wide view to the north of the Tapicitos Member of the San Jose Formation.

the Tapicitos Member. The Tapicitos Member ranges in thickness from 60 to 100 m (200 to 330 ft) and is composed of ~60% siltstone, ~5% mudstone, and ~35% sandstone (Fig. 2.37). The siltstone intervals are generally pink, red, and white, and they range in thickness from 1 to 15 m (3 to 49 ft; Fig. 2.38). Various mudstone intervals contain abundant root casts. Sandstone intervals range from 0.5 to 4 m (1.6 to 13 ft) in thickness and are generally red and pale white in color. Sandstone bodies are generally coarse grained with minor conglomeratic intervals that are less than 1 m (3.3 ft) in thickness. The sandstone contains rare trough cross-stratification, minor ripple cross-stratification, small-scale planar cross-stratification, and horizontal stratification.

Figure 2.38. Cliff-forming sandstone complexes of the Llaves Member of the San Jose Formation (looking to the northeast from atop the outcrop at Stop 4). Sandstone bodies range from 2 to 7 m (7 to 23 ft) thick.

Observations of this outcrop should focus on answering the following key questions:

1. Using the descriptions of the four main units of the San Jose Formation (using the handout provided), determine what member we are looking at here in Cañada Simon.
2. Focus your attention to the cliff outcrops to the north and east of the vehicles (Fig. 2.38). What information can be gleamed about those outcrops? What percentage of sandstone versus siltstone is present? Are the sandstone bodies lenticular? Tabular? And on what scale?
3. Using the handout provided, create a simple measured section of the western outcrop and make a general estimate of sandstone versus siltstone/mudstone percentages. Also note any sedimentary structures present. Estimate the lithologic composition of these sands.
4. Based on your observations, what type of fluvial system deposited these sediments? What maturity level are these sandstones? How far did this sediment travel along the fluvial system before arriving in this location? What can that tell us about the provenance of the sediment?
5. Is there any evidence at this location to suggest any coeval activity along faults and uplifts in the area? Could motion on the nearby Nacimiento fault have influenced the nature of the fluvial system in this area?

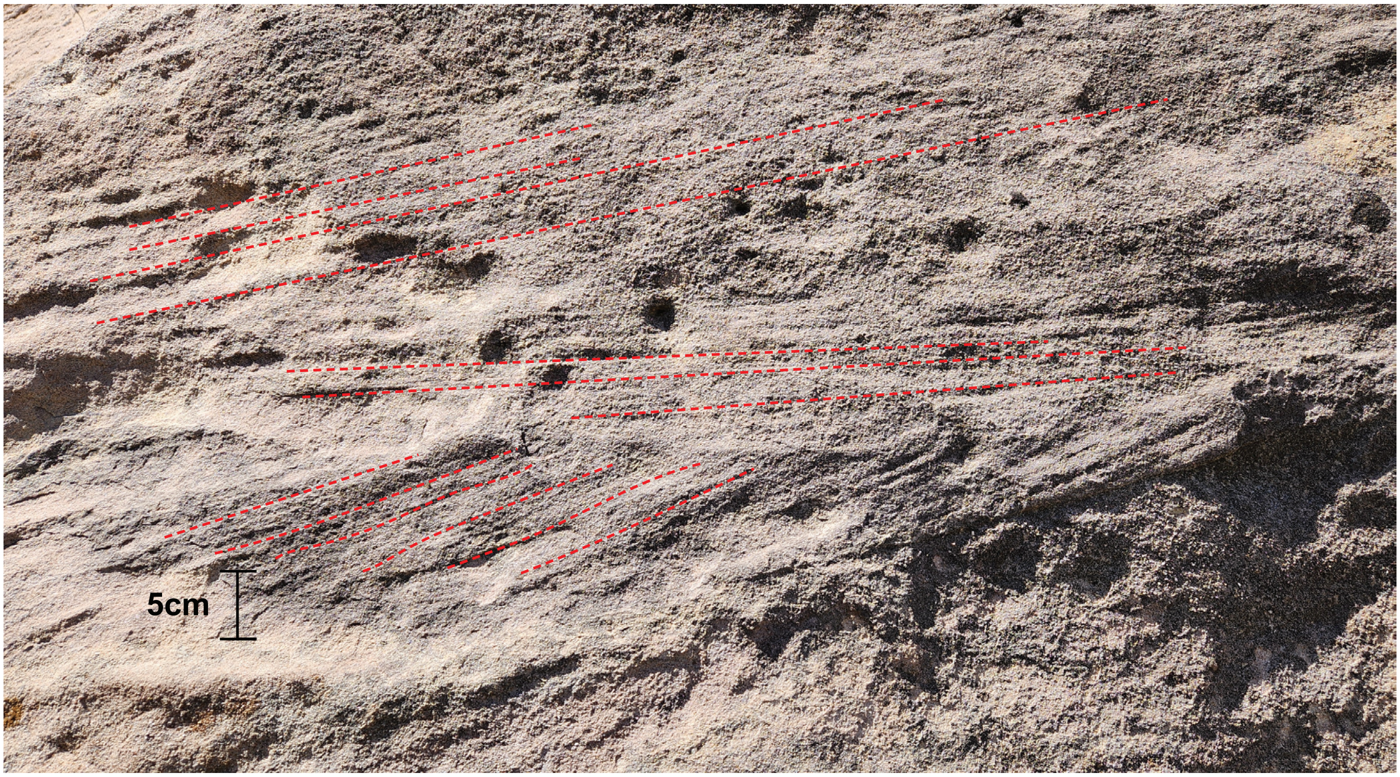


Figure 2.39. Sedimentary structures in the sandstone of the Llaves Member of the San Jose Formation. Lower package of planar cross-stratification with low angle cross-stratification above, all trending to the left (southeast).

The Stop 4 site sits just a few kilometers away from the Nacimiento fault that bounds the eastern side of the San Juan Basin. Such proximity to a fault that may have been active during deposition would lead one to assume that sediment would likely have been derived in at least some capacity from the uplifted hanging wall. What would this sediment look like? Would the deposits be composed of very coarse clastic detritus, fine grained, or combination of both?

What we can observe is that the strata found in this location actually consists of broadly channelized coarse to very-course granular sandstone interbedded with extensive siltstone and claystone. Sedimentary structures in channel sandstone bodies are rare and consist primarily of horizontal stratification and ripple cross-stratification. Soft-sediment deformation structures occur in some sandstone bodies whereas other sandstone bodies are entirely massive. The fluvial depositional system seems to have been that of high energy poorly confined fluvial channels.

After this stop, return to cars and retrace route back down Cañada Simon toward Cañoncito de las Lleguas.

0.4
9.9 Cross Cañoncito de las Lleguas.

0.1
10.0 **Turn Right (east) at four-way intersection; start down the canyon.**

Figure 2.40. Coarse sandstone of the Llaves Member of the San Jose Formation. Massive at the base with soft sediment deformation structure (SSDS) on the top right. This SSDS appears at isolated sandstone horizons throughout the San Jose Formation.

1.0
11.0 **Stay straight.** At right, Cañada Jesus Moya enters from the south.

0.5
11.5 **Stay straight.** Forest Road 312 enters from the north.

1.5
13.0 **Turn right (south) just after left bend in road.** This intersection is partially obscured by a roadside juniper. After turning, cross Cañoncito de las Lleguas again, noting how much less incision there seems to be here compared with at the mouth of Cañada Simon 5 km (3 mi) upstream. After the crossing, begin climbing Cañada Gurule.

0.6
13.6 The ridge at right separates Cañada Gurule from Cañada Simon. This ridge burned in July 2024 (while this volume was being prepared) by the lightning-caused Tanques fire (Figs. 2.41 and 2.42). The ridge had previously

Figure 2.41. The Tanques fire receiving helicopter treatment in July 2024. Ledges of San Jose Formation sandstones are visible through the pines in the foreground. *U.S. Forest Service photograph*

Figure 2.42. The Tanques fire burning at the mouth of Cañada Gurule in July 2024. *U.S. Forest Service photograph*

undergone effective forest management, including prescribed burns and tree thinning. Likely because of this preemptive management, the Tanques fire was a low- to medium-intensity burn and was effectively contained with a small crew of 36 personnel and light aircraft. Approximately 1,100 ha (2,800 ac) burned. The geomorphic effects of this fire are yet to be seen.

0.8
14.4 The sandstone here is mapped as the Llaves Member of the San Jose Formation (Kelley et al., 2024). Those authors show a northward pinch out of the Regina Member just to the south, meaning that as we continue south, we drive into the northernmost tongue in this area of Regina Member. Lateral variations in the San Jose Formation are the rule, not the exception, and the application of stratigraphic nomenclature derived from one measured section becomes difficult the farther one gets from the reference section. Nonetheless, in upper Cañada Gurule, there are marked geomorphic changes (a widening and shallowing of the canyon) and lithologic changes (a decrease in the abundance of thick, well-cemented arenites) that support Kelley et al.'s (2024) map interpretations.

0.8
15.2 Road here ascends onto a higher geomorphic surface not yet seen in Cañada Gurule. The preservation of thicker, older alluvial sediments higher upstream in canyons is a phenomenon seen in nearly all of Cañoncito de las Lleguas's tributaries.

0.2
15.4 **Left at road fork.**

0.2
15.6 Culvert and berm over deeply incised wash. Alluvial fill here is at least 9.2 m (30 ft) thick. Note the fine-grained, sand- and silt-dominated character of the alluvium (Fig. 2.43).

0.5
16.1 As the road is squeezed between the hillslope on the right and the arroyo on the left, note the presence of sandstone bedrock in the streambed below you. Exposures like these give insight into maximum thickness of alluvial fill as well as the potential topography of the bedrock-alluvium contact.

Figure 2.43. Thick fine-grained alluvium of Cañada Gurule at mile 16.7.

0.9
17.0 **Turn left (east) on two track.**

0.2
17.2 Stock pond, named "Lee Tank" on USGS quadrangle maps, at left.

0.3
17.5 Road crests a bumpy rutted rise among ponderosa pines.

0.1
17.6 OPTIONAL STOP 5. Park near crest of hill and walk a short distance south for an overview of the Llaves valley and discussion of neotectonic development of the region.

Return to cars after stop and retrace path back toward Cañoncito de las Lleguas.

0.9
18.5 **Take right fork;** descend Cañada Gurule.

0.9
19.4 OPTIONAL STOP 6.

If time allows, park along right side of road and climb down into streambed for discussion of stream power, landscape lowering, and when geomorphic work can happen on a landscape.

0.5
19.9 At right, note the 7-m (23-ft)-tall cutbank again showcasing the thick and fine-grained nature of alluvium in this valley (Fig. 2.44).

0.1
20.0 Just after road bends to the right, note the intense vertical fractures in the sandbody of the San Jose Formation in the cliffs above you (Fig. 2.45). Is there any offset, or are they just joints?

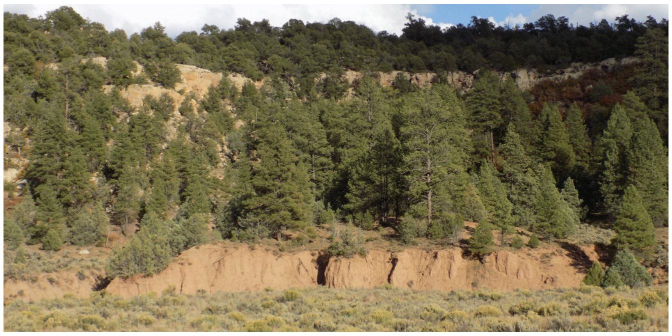


Figure 2.44. Ponderosa pines growing atop an abandoned terrace of fine-grained alluvium in Cañada Gurule.

Figure 2.45. Systematic joints developed in a sandstone of the San Jose Formation at Cañada Gurule.

Figure 2.46. View to the north down Cañada Gurule to the north side of Cañada de las Lleguas. Note the shallow west dip of San Jose Formation sandstones.

1.1
21.1 Straight ahead, down the mouth of Cañada Gurule, is exposed the north wall of Cañoncito de las Lleguas 2 km (1.2 mi) distant. Note the gentle west dip of the San Jose Formation in that exposure (Fig. 2.46).

0.2
21.3 At 10:00, another well-developed vertical joint set in a sandstone; this time closer to the level of the road.

0.8
22.1 **Turn right (east) at the junction with Forest Road 313.** Continue east toward State Road 112.

2.5
24.6 **REZERO ODOMETER at stop sign.**

0.0 **Turn right (south) onto State Road 112.**

9.3
9.3 As you exit a right-hand bend, the "fickle finger of fate," a mudstone spire in the Regina Member of the San Jose Formation, is visible ahead and to the right (Fig. 2.47). This feature can be seen from high points to the south as far away as Mesa de Cuba.

Figure 2.47. Mudstone badlands of the Regina Member of the San Jose Formation.

2.0
11.3 **Turn right (south) onto State Road 96.**

2.5
13.8 Pass the Kingdom Hall of Jehovah's Witnesses; shortly after, crest a hill and reenter the Rio Puerco drainage.

0.4
14.2 In a sweeping right bend, note the increasing topographic height of the Sierra Nacimiento to the south. The forested (as of fall 2024) high country here contains the northernmost crystalline rock exposed in the entire range. Merrick and Woodward (1982) mapped the Proterozoic rocks there as primarily granitic gneiss with minor metasedimentary and metavolcanic rocks, and mafic and aplite dikes. There are also mapped outcrops of terrace gravels containing granite cobbles at an elevation of 2,620 m (8,600 ft)!

Well-developed and extensive mountain-front terraces reappear as we head south (Fig. 2.48). Their reappearance coincides with the latitude of the northernmost crystalline rock in the highlands to the east. This is not a coincidence—terraces are more likely to form when the sediment supply includes high-strength clasts like granite and high-grade metamorphic rocks, and they are more likely to persist through time when the terrace-capping gravels are made of rocks more resistant to chemical and physical weathering.

10.1
24.3 **Turn left (east) on U.S. Route 550 toward Cuba.**

2.7
27.0 Reenter greater Cuba. Mind your velocity and look out for the Kojak with a Kodak.

0.4
27.4 **Turn left (north) onto Los Pinos Road toward Circle A Ranch.**

End of Day 2 Road Log

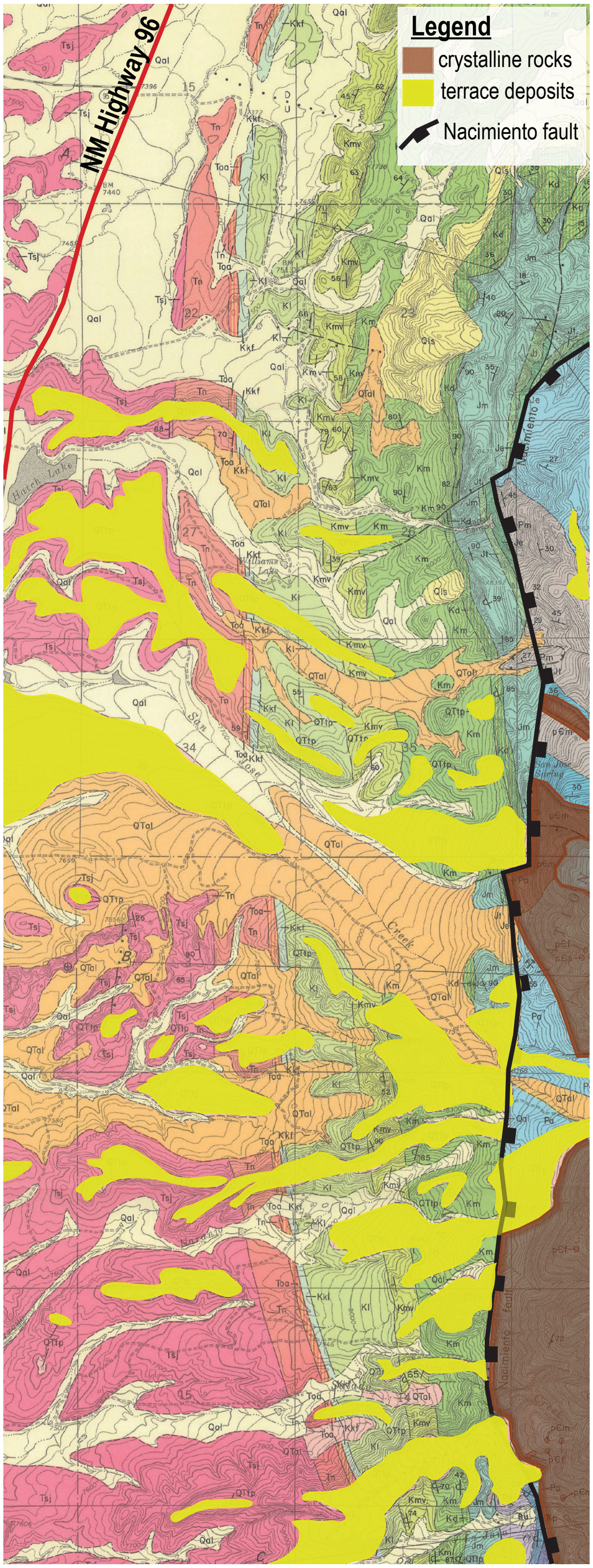


Figure 2.48. Annotated geologic map of the northern Sierra Nacimiento showing the spatial relationships between outcrops of crystalline rocks on the east side of the Nacimiento fault and the presence of extensive gravel-capped terraces in the valley to the west. The crystalline rocks shown on this map are the northernmost ones in the Sierra Nacimiento. Base map from Merrick and Woodward (1982).

Pavement outcrop of the Paleoproterozoic San Miguel Gneiss at the San Gregorio Trailhead above Cuba. The rocks here are the subject of the final stop of Day 3.