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First-Day Road Log: Bernalillo to San Ysidro, with Stops at Tierra Amarilla Anticline and Twin Mounds Travertine Springs

Karl E. Karlstrom, Koning Daniel J., Laura J. Crossey, Cameron C. Reed, Spencer G. Lucas, and Matthew T. Heizler

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FIRST-DAY ROAD LOG:

BERNALILLO TO SAN YSIDRO, WITH STOPS AT TIERRA AMARILLA ANTICLINE AND TWIN MOUNDS TRAVERTINE SPRINGS

KARL E. KARLSTROM[1], DANIEL J. KONING[2], LAURA J. CROSSEY[1], CAMERON C. REED[1],
SPENCER G. LUCAS[3], AND MATTHEW T. HEIZLER[2]

[1] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131; kek1@unm.edu
[2]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801
[3]New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM, 87104

Assembly Point: Southwestern parking lot, Santa Ana Star Casino
Departure Time: 7:30 AM
Distance: 60 miles (roundtrip)
Stops: 2 (half-day hikes with sub-stops)

Views, landmarks, and outcrops are given using the clock system. For example, 12:00 (12 o'clock) is straight ahead, 9:00 is to the left, and 3:00 is to the right. Waypoints are given in decimal degrees [latitude, longitude] and are listed in the waypoint table on page 102 of this guidebook (also available digitally).

SUMMARY

Day 1 of the field conference travels U.S. Route 550 northwestward from Bernalillo to the Cabezon Road turnoff (on left), 2 miles before San Ysidro. The drive is through the western part of the Rio Grande rift and Santa Fe Group rift fill. The larger area of the nexus is neotectonically active and hosts the Jemez volcanic field and Valles Caldera. From the turnoff, we drive south to the White Ridge Bike Trails parking area through Jurassic and Cretaceous strata. These rocks are similar to those of the San Juan Basin of the Colorado Plateau, but here they have been affected by both Laramide contraction and Miocene to Recent (Rio Grande rift) extensional faulting.

7:30 AM: Leave Santa Ana Star hotel.

8:30–11:30 AM: Stop 1 involves sub-stops as we hike from the White Ridge Bike Trails parking lot. There are numerous stations along the general route. Our goals are to: (1) examine Triassic to Cretaceous stratigraphy and see dinosaur bones in the Jurassic Morrison Formation, (2) examine Laramide-age contractional structures of the Tierra Amarilla anticline and discuss the new model positing it is cored by the southward extension of the Laramide Nacimiento fault system that has been reactivated during rifting, (3) note gypsum veins that record right lateral strike-slip on this fault system, (4) observe the disconformity at the base of the Cretaceous Dakota Sandstone, and (5) examine the San Ysidro erosional surface that bevels the Mesozoic stratigraphy with angular unconformity. The hike takes about 3 hours, and we will convene back at the vehicles before noon.

12:00–1:00 PM: We drive to the north side of the Tierra Amarilla anticline for lunch at the Twin Mounds travertine springs.

1:00–4:00 PM: Stop 2 is a hike from the Twin Mounds southward along a line of artesian carbonic springs and travertine deposits that overlie a strand of the Nacimiento fault system in the core of the anticline. The water level in these springs increases in elevation by about 100 m as we go south. The main goals at this stop are to: (1) discuss the gas and water chemistry of these "continental smokers" (Crossey et al., 2016), 2) examine U–series dated travertines that show travertine deposition to have been episodically active for the past 300,000 years, 3) see another location of the San Ysidro surface and link it to both the travertine accumulation in the core of the anticline and to the Rio Salado terraces across U.S. Route 550 to the north, 4) examine the reactivated reverse fault/ monocline system that forms the eastern segment of the Nacimiento fault zone in the Tierra Amarilla anticline.

4:00–5:00 PM: Drive back to Bernalillo.

6:00 PM: New Mexico Geological Society banquet at Santa Ana Star Hotel.

[Waypoint]
Mileage Description *Distance between stops*

Waypoint 1 [35.325601°, -106.564426°]

0.0 Assemble in the parking lot on the southwestern side of Santa Ana Star Casino. We are on Tamaya (also known as Santa Ana Pueblo) land near the western limits of the town of Bernalillo. Tamaya has a population of ~800 and is composed of three villages called Rebahene, Ranchitos, and Chicale. The original pueblo lies at the foot of Santa Ana Mesa on the north bank of the Jemez River, about 7.5 mi to the northwest. The tribal government includes a governor and lieutenant governor (appointed annually), and the tribal council includes heads of households.

The Tamaya are a Keresan-speaking Puebloan people who have been here since at least the early 1500s (American Indian Alaska Native Tourism Association, n.d.). They pledged their allegiance to the King of Spain in 1598, and Saint Ann was assigned as their patron saint. After the Pueblo revolt in the early

1680s, the returning Spanish forced the Tamaya to flee to the Jemez Mountains and adjoining mesas to the north. In 1693, the Tamaya returned to their pueblo, where they practiced farming to supplement food gained by hunting and gathering. Although impacted severely by smallpox and other epidemics in 1789–1791, and again in the late 19th century, the Tamaya have remained resilient, continuing their traditional practices and displaying a spirit of entrepreneurship. The latter includes raising and selling blue corn products and Native American apparel and food, distributing native Southwestern plants, maintaining various financial investments, and promulgating Indian gaming. Unless noted, all information about the Tamaya is from the Santa Ana Pueblo (2024) website. We are grateful to the Tamaya for letting us use their casino's hotel and parking lot as a base for our field trip.

The main (downtown) part of Bernalillo lies east of the Rio Grande. This area was likely the site of a Tiwa Pueblo and is where Coronado wintered in 1540 due to its proximity to water and wood (Julyan, 1998). If not for the assistance of the Tiwa here and elsewhere (willing or unwilling), Coronado and his men likely would have starved to death (New Mexico Historic Sites, 2024). Spanish colonialists settled here in the 1600s; among them were the Bernal, Griego, and Gonzales families (Julyan, 1998).

A half-mile east of here flows the Rio Grande, the "big river" of New Mexico and the axial river of the Rio Grande rift. Relative to Bernalillo, it has an upstream drainage area of ~14,000 mi^2 (U.S. Geological Survey [USGS], 2024). Here, it flows across the southern part of the Santo Domingo sub-basin of the Rio Grande rift, which recent workers generally consider a sub-basin of the larger Albuquerque basin (e.g., Williams and Cole, 2007; Connell, 2008a, 2008b; Grauch and Connell, 2013; Connell et al., 2013).

The Coronado Historic Site and the ruins of Kuaua Pueblo, the site of our barbeque on Day 2, also lie 0.5 mi (0.5 km) east of the meeting hotel at the Santa Ana Star Casino, situated on a 40-ft-tall (~12 m) terrace tread immediately west of the Rio Grande. Kuaua was the northernmost of 12 Tiwa villages in the area, and its name means "evergreen" in the Tiwa language. The terrace location offered protection from Rio Grande flooding, but it was sufficiently close to the river for drinking water to be procured. The river's floodplain also would have offered plentiful fish and birds for food. Kuaua was first settled around 1325 CE, and its population was ~1200 people when Coronado arrived. Conflict with the early Spaniards led Kuaua's inhabitants to abandon the site by the early 1600s. Kuauan descendants survive in Taos, Picuris, Sandia, and Isleta Pueblos (New Mexico Historic Sites, 2024).

Proceed south from the parking lot and turn right (west) on U.S. Route 550. **ZERO ODOMETER at this intersection.** *0.5*

0.5 Intersection with State Road 528; to the right is Tamaya Boulevard, leading north to the Tamaya Resort. *0.2*

0.7 Slight rise in topography. On the right side of the road are exposures of surficial sand containing minor pebbles, referred to as "unit Qs" in this road log. Weak buried soils, exhibiting ped development and minor precipitation of calcium carbonate (stage I carbonate morphology) form subtle ledges in the road cuts. *0.3*

FIGURE 1.1. Looking north up the Rio Grande. Skyline composed of Santa Ana Mesa (center) and the Jemez Mountains (left). A hot-air balloon floats above and slightly east of the river.

1.0 Safelite intersection; Home Depot on the left (south). The Qs surficial unit drapes the landscape to the right (north) and is seen in the right roadcuts. *0.3*

1.3 Intersection of U.S. Route 550 and State Road 347 (Paseo de Volcan). On the southeast corner of this intersection by the big white water tank is the Bernalillo Well 4. This well is 970 ft deep and is mostly screened in the Ceja Formation and possibly the Picuda Peak Member of the upper Santa Fe Group. It has a water depth of ~120–130 ft and a calculated hydraulic conductivity of 2.6 ft/day (Koning et al., 2024). *0.2*

1.5 Rolling topography is underlain by a surficial unit here. Cross the approximate location of the Santa Ana section of the San Felipe fault zone (Connell, 2008a). This east-down normal fault is part of a broader fault system defining the boundary between the Santo Domingo sub-basin (east) and the Ziana horst block (west). To the north, several faults composing the San Felipe fault zone offset the basalt-capped Santa Ana Mesa and underlying Santa Fe Group strata (Kelley, 1977; Connell, 2008a). There, these faults define a graben centered on the westernmost of two north-trending eruptive centers in the San Felipe volcanic field. The graben is bounded on the west by the Santa Ana fault and the Luce fault, the latter producing an east-down scarp up to 300 ft (~90 m) tall. Given the 2.4–2.6 Ma age of the basalts capping the mesa (Bachman and Mehnert, 1978; Smith and Kuhle, 1998), one can infer the San Felipe fault zone has been considerably active during the Quaternary (Personius et al., 2016). *0.9*

2.4 Cross the Tamaya fault, which has no obvious surficial expression near the highway. Along with the Santa Ana section of the San Felipe fault zone (mile 1.5), this east-down normal fault separates the Santo Domingo basin (east) from the Ziana horst block (west). It is inferred to have ~500 ft (~150 m) of stratigraphic separation of the upper-middle Santa Fe Group (Koning et al., 2024). The fault continues northward to the west side of the basalt-capped Santa Ana Mesa (Connell, 2008a). *0.1*

2.5 Road crests a small hill; in roadcuts to the right are light reddish brown Santa Fe Group strata overlain by an older version of unit Qs (probably middle Pleistocene, given its high geomorphic position). The Santa Fe Group consists of medium-bedded, very fine– to fine-grained sandstone (locally cemented) with 20–25% reddish-brown clayey beds. It is assigned to the Santa Ana Mesa Member of the Ceja Formation by Connell (2008a). The overlying, middle(?) Pleistocene "Qs sand" is ~10 ft (3 m) thick and has minor weakly developed calcic paleosols. The sand is capped by ~3 ft (1 m) of sandy pebbles and cobbles, probably derived mainly from erosion of the Picuda Peak Member of the Arroyo Ojito Formation (stratigraphic nomenclature from Connell, 2008b). *0.5*

3.0 Surficial unit Qs are exposed on the left (south) roadcut here and again 0.4 miles farther west. They are approximately 6–10 ft (2–3 m) thick. *0.7*

3.7 In left roadcut is an exposure of light brown, fine- to medium-grained, well-sorted, slightly arkosic sand with ~5% reddish-brown, clayey beds and 1% pebble lenses. This is also assigned to the Santa Mesa Member (Ceja Formation) by Connell (2008b), although it looks lithologically similar to the Loma Barbon Member of the Arroyo Ojito Formation. *0.3*

4.0 Hard-to-see intersection to left of old highway. *0.6*

4.6 On the right is an amphitheater-like exposure of the Arroyo Ojito Formation (Figs. 1.2 and 1.3). The light reddish-brown to light brown sediment, primarily sandstone with lesser mudstones and pebble conglomerates, is part of the ~8.0–6.6 Ma Loma Barbon Member of the Arroyo Ojito Formation (Connell, 2008a, b). In the distance lie yellowish to tannish sand and minor mudstones of the ~10–7 Ma Navajo Draw Member of the Arroyo Ojito Formation, which lies below the Loma Barbon and interfingers with it (Koning and Personius, 2002; Connell, 2008b). These two Santa Fe Group units are associated with two respective south-southeast flowing drainages that deposited 1400 to >3000 ft (435 to >900 m) of sandy sediment in the northwestern Albuquerque basin (Connell et al., 1999; Connell, 2008b; Koning et al., 2024). Possible modern-day equivalents to these late Miocene drainages are the Rio Puerco (for the Navajo Draw Member) and the Jemez River (for the Loma Barbon Member). *0.4*

5.0 Intersection with the northern extension of Unser Boulevard. *0.3*

5.3 View on right of Santa Ana Mesa, which is capped by 2.4–2.6 Ma basalt flows (Bachman and Mehnert, 1978; Smith and Kuhle, 1998). These basalts are underlain by reddish sediment of the Santa Ana Mesa Member of the Ceja Formation (Connell, 2008a). The Santa Ana Mesa Member was deposited by southeast-flowing drainages sourced in the southern Jemez Mountains and eastern Nacimiento Mountains (Connell, 2008b; Connell et al., 2013). *0.4*

5.7 View on skyline of lower area between the Nacimiento Mountains (left) and the Jemez Mountains (right). This low area is drained by the Jemez River. *0.2*

5.9 At 2:00 is a good view of a ~100-ft-tall (~90 m) fault scarp developed on the 2.4–2.6 Ma basalts of the San Felipe Mesa volcanic field. Beneath lies reddish sandstone-dominated sediment of the Santa Ana Mesa Member of the Ceja Formation. *0.7*

FIGURE 1.2. View to north of the topographic amphitheater formed by erosion of the Loma Barbon Member of the Arroyo Ojito Formation (Tob). At left, a white arrow denotes a small fault. Beyond lies the yellowish to tan Navajo Draw Member of the Arroyo Ojito Formation (Ton). Both were deposited by respective south-southeast-flowing paleodrainages between ~10 and 6.5 Ma, with the Loma Barbon interfingering with and overlying the Navajo Draw Member. The features on the skyline (left to right) are White Mesa, Nacimiento Mountains, upper Jemez River valley, Jemez Mountains, and the basalt-capped Santa Ana Mesa. The Luce fault (part of the San Felipe fault zone) has created a 250–300-ft-tall (75–90 m) fault scarp in the 2.4–2.6 Ma (Bachman and Mehnert, 1978; Smith and Kuhle, 1998) basalt flows capping Santa Ana Mesa.

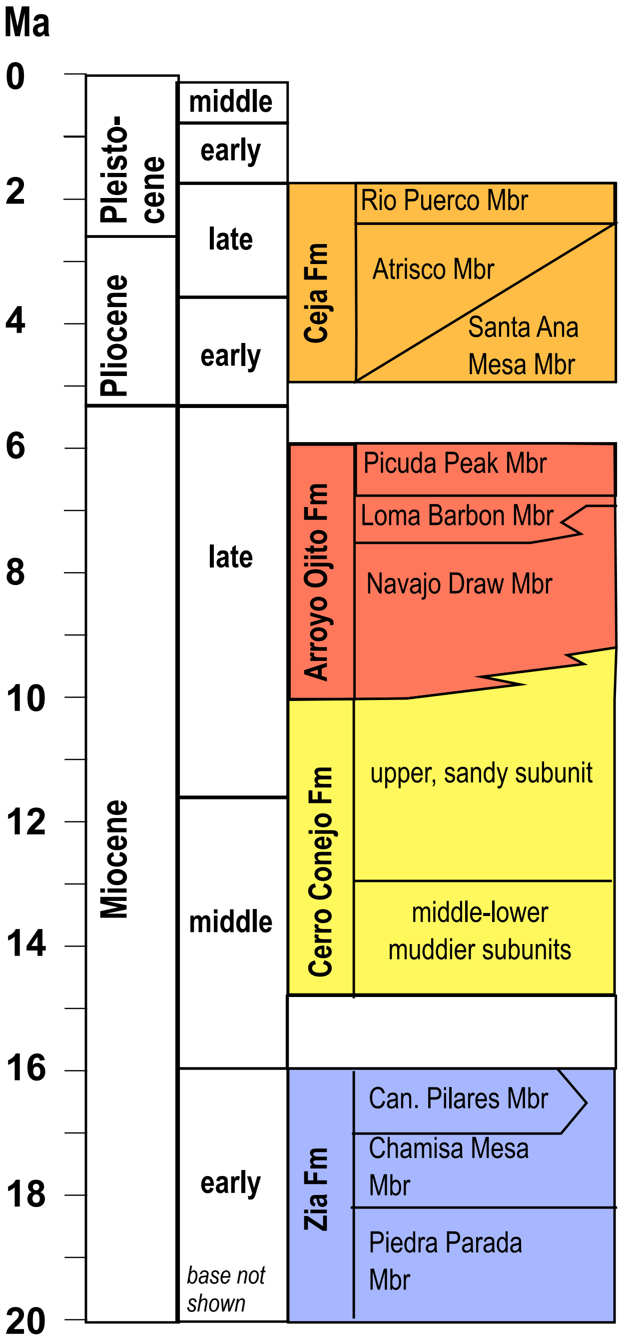


FIGURE 1.3. Santa Fe Group stratigraphic column, slightly modified from Connell (2008b) using Koning et al. (2024). Can. Pilares = Canyada Pilares Member. See Connell et al. (1999) and Connell (2008b, 2013) for respective paleodrainages and other interpretations pertaining to these units. Connell (2008b) discusses the evolution of past stratigraphic nomenclature for the Santa Fe Group in the northeastern Albuquerque basin.

6.6 Road descends into a canyon offering poor exposures of the Cerro Conejo Formation, which conformably underlies the Navajo Draw Member of the Arroyo Ojito Formation (Fig. 1.3). *0.3*

6.9 Cross the wash in an unnamed canyon that offers good exposures of the upper Cerro Conejo Formation (Fig. 1.3). The informal "upper subunit" of the Cerro Conejo Formation consists of 300–500 ft (100–150 m) of very pale brown to pink, fine- to coarse-grained sand. Limited data suggest it has relatively high hydraulic conductivity values where saturated, although water quality (namely TDS and As) can locally exceed EPA limits (Koning et al., 2024). The white ash bed that is a few meters above the bottom of the canyon on the right, southeastern cutbank of the wash (Fig. 1.4) correlates to an 11.2 Ma Trapper Creek ash using tephrochronology (sample MRGB-19-BNW; Koning and Personius, 2002). The same ash can be seen on the north side of the canyon (Fig. 1.5). *0.2*

7.1 The 11.2 Ma Trapper Creek ash can be seen at the base of the right (east) road cut. Above lies fine- to medium-grained sand of the upper subunit of the Cerro Conejo Formation. The right side of the ash is cut out by a northwest-dipping fault. On the north side of the fault, note the locally swirly cementation forms in the upper Cerro Conejo Formation (Fig. 1.6). Calcite cementation along faults like this and in the sandstone may be similar to processes in sandy Santa Fe Group strata to the west, in the older Zia Formation, as described in Beckner and Mozley (1998). *0.4*

7.5 White ash within the upper Cerro Conejo Formation present on the left side of the road is possibly correlative to the 11.2 Ma Trapper Creek ash in mile 6.9. *0.3*

7.8 Highway bends left (northwest). *0.2*

8.0 To the right, historic marker and gated Indian Service Road 74. This road leads northeast to the old pueblo of Tamaya. *0.2*

8.2 Poorly exposed, rolling hills are underlain by the sandy upper unit of the Cerro Conejo Formation. A white ash bed is seen on the left side of the highway, possibly correlative to 10.8–11.2 Ma Trapper Creek ashes listed in Koning and Personius (2002). We are now near the middle of the Ziana horst block, which is interpreted to have an anticlinal shape here (Fig. 1.7). One of the themes of today's field trip is the extent of pre-rift Laramide contractional structures and their reactivation during Rio Grande rifting. Tied to this is the concept that some Colorado Plateau "anticlines" and "synclines" reflect underlying Laramide reverse-fault-cored monoclines (see Fig. 1.10). At a larger scale, early papers by Eardly (1962) and Cather (1983) discussed a north-south-trending Laramide uplift along the east side of the Colorado Plateau that may have somewhat resembled the Colorado Front Range before it collapsed (was inverted) by Rio Grande rifting. This model may be worth new discussions of whether the Ziana horst/anticline might potentially be part of one of these inverted Laramide structures (see Black et al., 2023; Karlstrom et al., 2024) that originally linked the Nacimiento-Lucero-Sierra Grande uplifts. *1.0*

9.2 Hills to the left are underlain by the sandy Cerro Conejo Formation. *0.4*

FIGURE 1.4. View down the canyon from the highway at mile 6.9. Note the ~0.5-m-thick white ash bed within sandstone on the shaded bank. This correlates to the ash bed along the highway (Fig. 1.5) and has been chemically correlated to an 11.2 Ma Trapper Creek ash (Koning and Personius, 2002).

FIGURE 1.5. Roadcut of sandy upper unit of the Cerro Conejo Formation. The white bed at lower right just above the guardrail is a relatively non-altered, fine white ash that has been geochemically correlated to an 11.2 Ma Trapper Creek ash (Koning and Personius, 2002). This same ash is seen on the far side of the drainage in Figure 1.4. White arrows denote a fault (probably northwest-side down) that cuts off the ash.

FIGURE 1.6. Wild cementation forms in the sandy upper unit of the Cerro Conejo Formation. Beckner and Mozley (1998) studied cementation of the Santa Fe Group in older strata of the Zia Formation and found that nodules and rhizocretions with micritic fabrics and alveolar structures are related to vadose zone precipitation. Ovoid or elongate concretions characterized by blocky spar cements, like those in this photo, were inferred to be phreatic. In many places, early vadose cements provided nucleation sites for later phreatic cementation. The wild, swirly cementation forms seen in this photo might possibly be explained by mixing of CO_2-saturated water ascending along faults with lower-CO_2 meteoric groundwater in the aquifer. At regional scale, mixing of higher-saturated (with respect to calcite) groundwater on the western margin of the Albuquerque basin may be taking place with lower-saturated groundwater near its axis (Mozley et al., 1995). Cementation processes in the Zia Sandstone adjacent to rift-bounding faults have been used as an analog for CO_2 sequestration in deep porous reservoirs in the North Sea (Haszeldine et al., 2005).

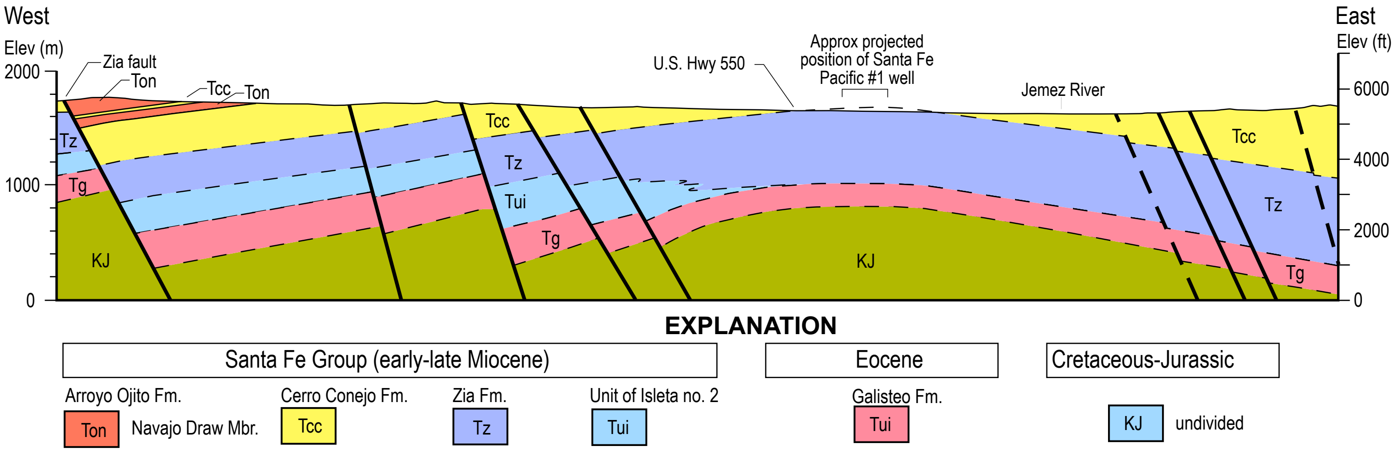


FIGURE 1.7. Cross section of the Ziana horst block has anticlinal geometry near the highway. Cross section simplified from that shown in Koning and Personius (2002).

9.6 Cross sandy wash. *0.1*

9.7 To the right is an exposure of distal, alluvial fan, sandy gravel and subordinate sand (Fig. 1.8). Clast imbrication indicates a north-northwest paleoflow direction, so this deposit is associated with a tributary terrace with tread sloping north toward the Jemez River. At its north end, the tread is ~90–100 ft (~30 m) above the modern Jemez River level; based on this height, it possibly correlates to the Jemez River terrace unit Qt4 in Pazzaglia et al. (1997), which is inferred to be ~150 ka. Qt4 is part of a terrace suite upstream between San Ysidro and Jemez Springs (Formento-Trigilio and Pazzaglia, 1996, 1998; Rogers and Smartt, 1996; Reed et al., 2024). *0.6*

10.3 Cross a sandy wash. Looking upstream, Arroyo Ojito Formation is exposed beneath the Ceja, which is the term ascribed to the sharp top edge of the escarpment. Closer to the highway are poorly exposed sandstones of the older Cerro Conejo Formation. *0.6*

FIGURE 1.8. Alluvial fan deposits from a north-draining tributary of the Jemez River. Relatively poorly developed soil and its relative tread height of ~90–100 ft (~30 m) above the Jemez River suggest a correlation to the Qt4 terrace of Pazzaglia et al. (1997), which was inferred to be ~150 ka. A nicely exposed gravel deposit brings a ready smile to any Quaternary geologist!

10.9 View to the right of sandy strata on the north side of the Jemez River, correlative to the Zia and Cerro Conejo formations. *0.2*

11.1 To the left are poorly exposed sandstones of the upper Cerro Conejo Formation. Three miles to the right across the Jemez River is a topographic fin composed of strongly cemented sandstone along the Santa Ana fault. *0.2*

11.3 Boundary between Santa Ana Pueblo (to the east) and Zia Pueblo (to the west). *0.6*

11.9 Road crosses a big, sandy wash. *0.4*

12.3 North of here (2:00) lies Borrego Mesa, where tannish sand of the Chamisa Mesa Member of the Zia Formation lies beneath an eastward-tilted, 10-Ma basalt (Fig. 1.9). The Chamisa Mesa fossil quarry is located in the tannish sands on the south side of the mesa and has yielded mammalian fauna correlated to the Hemingfordian North American Land Mammal "age" (16–18 Ma; Tedford and Barghoorn, 1999). *0.7*

13.0 Cross a wash. At 10:00 is approximately the upper-middle part of the Cerro Conejo Formation, which is slightly redder compared to the sandy upper unit of the Cerro Conejo Formation. *0.6*

13.6 Small terrace remnant on right. *0.3*

13.9 Road bends left. *1.0*

14.9 White-capped White Mesa is straight ahead; its cap is the Middle Jurassic Todilto Formation. *0.6*

15.5 At 2:00–3:00 is Zia Pueblo on north side of the

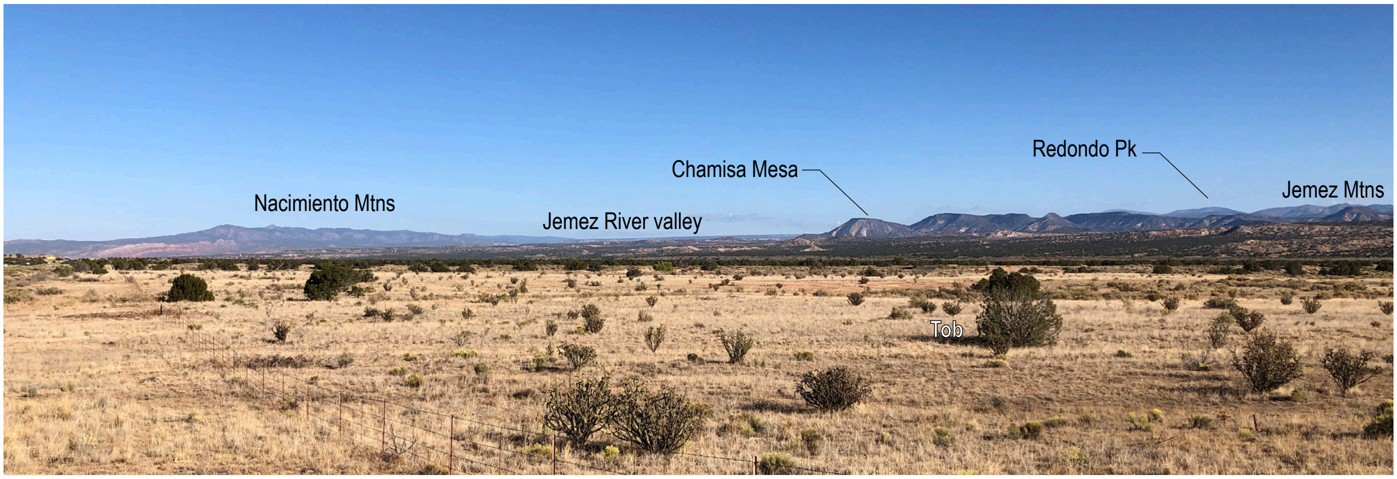


FIGURE 1.9. View to northwest of Nacimiento Mountains, Jemez River valley, Chamisa Mesa, and the southwestern Jemez Mountains. Redondo Peak is a 1.0–1.2-Ma resurgent dome within the Jemez caldera. Chamisa Mesa is capped by 9–10-Ma basalts (Osborn et al., 2002; Chamberlin and McIntosh, 2007).

Jemez River. The main village is situated on an 80-ft-high (24 m) terrace tread of the Jemez River estimated to be about 150 ka (Qt4 of Pazzaglia et al., 1997). *0.2*

15.7 Cross sandy wash. *0.1*

15.8 The entrance road to Zia Pueblo is on the right, along with houses of southern Zia Pueblo. *1.4*

17.2 To the right of White Mesa is a view of the southern Nacimiento Mountains. Note the folding of Triassic and Permian strata (Fig. 1.10). The resistant, uppermost stratigraphic unit is the Agua Zarca Sandstone (Upper Triassic), which is underlain by brownish Moenkopi and tannish Glorieta Sandstone. On the right (east) anticline, immediately west of the San Ysidro fault, west-dipping Glorieta Sandstone is underlain by the reddish Yeso Group. To the north, Pajarito Peak is the prominent peak on the southern end of the higher crest of the Nacimiento Mountains. It is separated from the Permian-Triassic strata by a northeast-striking, southwest-down fault and is composed of Precambrian basement (Woodward et al., 1977). *0.5*

17.7 Good view straight ahead of White Mesa and the southern Nacimiento Mountains (Fig. 1.10). To the left are sandy hills of the Zia Formation. *0.5*

18.2 Sandy hills to the left are composed of the upper Zia Formation. The sand is mainly coarse-grained, subarkosic to quartzose, and whitish-gray to pinkish-gray to tan. *0.4*

18.6 Road bends slightly left; straight ahead is White Mesa, where strata dip 10–15° south. On the east side of the mesa is the east-down San Ysidro fault, which separates Jurassic-Triassic rocks (west side) from yellowish shales of the interbedded Upper Cretaceous Dakota–Mancos succession of

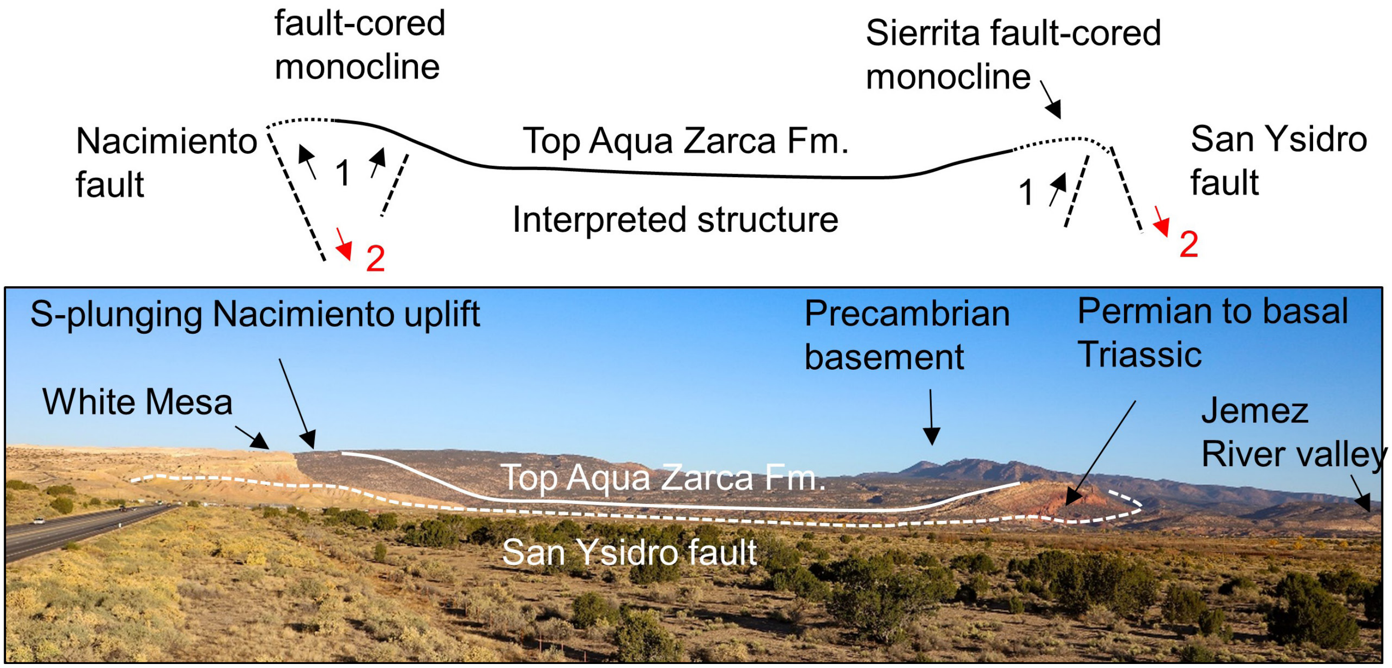


FIGURE 1.10. View to the north of White Mesa and the southern Nacimiento Mountains. The gentle anticlines and synclines are interpreted here as parts of fault-cored monoclines. The southern Nacimiento uplift is interpreted as a Laramide horst block between the Nacimiento and San Ysidro Laramide reverse-fault segments (black arrows in the interpreted structure), some of which were reactivated as normal faults during Rio Grande rifting (red arrows).

FIGURE 1.11. The Permian-to-Jurassic section can be pieced together by combining two views of Fig. 1.10. At right, the Permian Abo, Yeso, and Glorieta formations are overlain by a thin Middle Triassic Moenkopi Formation (not annotated) and the Upper Triassic Aqua Zarca and Petrified Forest formations of the Chinle Group. At left, across the Rio Salado valley, the Petrified Forest Formation is overlain by the Middle Jurassic Entrada Sandstone and Todilto Formation, the latter consisting of a lower limestone member and an upper gypsum member. The Jurassic cliff is retreating south off the Nacimiento uplift as it is undermined by erosion of the weak Petrified Forest Formation mudrocks.

strata (east side). On the San Ysidro geologic map (Woodward and Ruetschilling, 1976), the yellowish shales are called the Dakota Sandstone and presumably represent either the Clay Mesa or Whitewater Arroyo tongues of the Mancos Shale. The San Ysidro fault is a major east-down fault that connects northward into the Sierrita segment (Fig. 1.13). In the USGS Quaternary faults and folds database, the fault system is collectively called the Jemez-San Ysidro fault and is assigned to three sections (south to north): Calabacillas, San Ysidro, and Jemez. The collective length of the Jemez-San Ysidro system is 57 mi (92 km; Jochem et al., 2016), but this may need to be revisited based on new mapping, new subsurface data, and the reactivation complexities that are a focus of discussion in this field conference (see Reed et al., 2024). Figure 1.13 also shows a Sierrita segment. Karlstrom et al. (2024) discuss a suggested nomenclature for this area of the nexus that recognizes naming as originally done by the mappers (Woodward and Ruetschilling, 1976; Kelley, 1977) and the importance of understanding fault systems in terms of linked segments that have different reactivation histories and seismic rupture potential. The USGS nomenclature for regional fault zones is merged with this nomenclature. The western extent of the Rio Grande rift might be considered to be marked by the San Ysidro and Jemez segments that bound the westernmost outcrops of the Zia Sandstone of the Santa Group rift-fill. However, a reinterpretation of two cross sections in Figure 1.13 suggests that east-down normal-fault reactivation of earlier Laramide monoclonal segments took place across a wide zone of Neogene extension in the nexus region. *0.5*

19.1 U.S. Route 550 bends abruptly right. *0.1*

Waypoint 2 [35.523362°, -106.779755°]

0.0 Intersection of U.S. Route 550 and Cabezon Road. **RE–ZERO ODOMETER.** Turn left off U.S. Route 550 onto Cabezon Road; take the middle fork. Drive southwest to the White Ridge Bike Trails parking area and the Ojito Wilderness, which are the subjects of the First-Day Road Log stops. *0.3*

0.3 Don't take the right road to the White Mesa mine or to the left to the gypsum processing area, and **watch for trucks**. *0.1*

0.4 Cretaceous rocks faulted against Jurassic rocks across the San Ysidro fault. A re-interpretation (Fig. 1.12) is that the San Ysidro fault zone included Laramide, west-dipping, reverse-fault conjugates and a Precambrian-cored horst that were inverted during rifting. The San Ysidro segment extends northward to where the fault zone bends left, forming a right-lateral contractional bend called the Sierrita segment that exposes Precambrian basement (Woodward and Ruetschilling, 1976). Note the beveled erosional surface of Quaternary deposits overlying folded Mesozoic strata that we call the San Ysidro surface—one of the subjects for discussion during this field trip. *0.3*

0.7 Road bends left. *0.2*

0.9 View of Morrison Hill; Jackpile Sandstone on top. *0.1*

1.0 Hills to the left are the Lower Santa Fe Group (Zia Formation) in the hanging wall (east side) of the San Ysidro fault. This is the farthest east fault of the Rio Grande rift that offsets Santa Fe Group rocks. *0.9*

1.9 Ahead (11:00), the lowest part of the hills are Eocene Galisteo Formation, overlain by Zia Sandstone, then Cerro Conejo Formation. The Galisteo Formation is an Eocene synorogenic deposit of the late Laramide orogeny. In this area, referred to by Lucas (1982) as the Windmill Hill area, the Galisteo Formation unconformably overlies the Cretaceous Mancos Shale and Menefee Formation of the Mesaverde Group. Approximately 65 ft (20 m) of sandstone, siltstone, and mudstone overlie this conglomerate, and two localities in these strata have produced fossils of large titanotheres remains. Overlying yellow, arkosic, coarse-grained to conglomeratic sandstone contains petrified log, turtle, large titanothere, and artiodactyl remains. Fossil mammals indicate a Duchesnean (middle Eocene age) for the Galisteo Formation in the Windmill Hill area. The Zia Formation unconformably overlies the Galisteo Formation in this area. *0.1*

2.0 Road bends right. Dip slopes of Dakota Sandstone visible on the right. *0.3*

2.3 Mancos Shale forms smooth yellow hills. *0.3*

2.6 The cliff is a Late Cretaceous shoal/bar sandstone complex, the Paguate Tongue of the Dakota Sandstone. *1.1*

3.7 Road bends left. The east limb of the Tierra Amarilla anticline and the adjacent syncline expose (in ascending stratigraphic order) white Jackpile, gray Dakota, and black Mancos strata. *0.2*

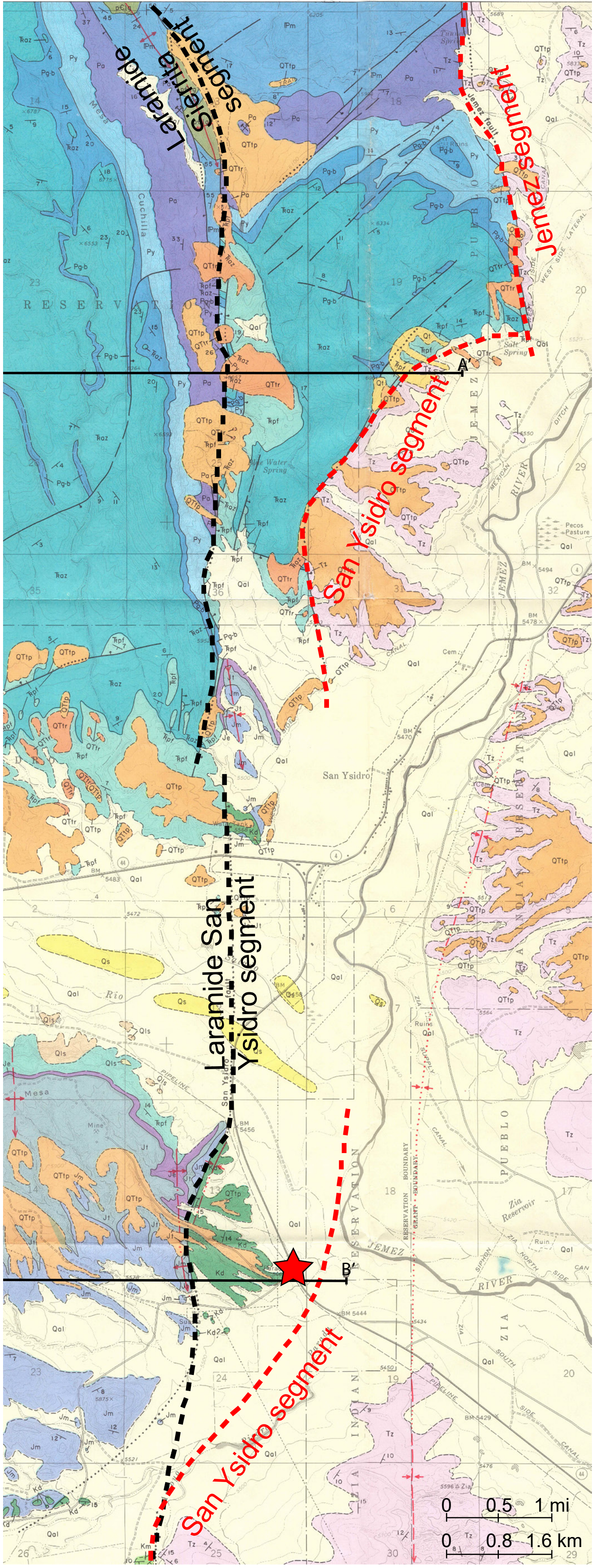
3.9 Cross cattle guard. *0.3*

4.2 Angular unconformity beneath the San Ysidro surface (seen at Stop 1) is visible at right. *0.2*

Waypoint 3 [35.498439°, -106.841308°]

STOP 1. North end of Tierra Amarilla anticline.

4.4 Park near the White Ridge Bike Trails parking area. The First-Day Road Log has two half-day hiking stops, each with several sub-stops (Fig. 1.13). In the morning, we walk on the faulted south-plunging hinge region of the anticline and see strata on its east limb. The many trails seen in this area belong to the White Ridge Mountain Bike Trail System, a network of spectacular mountain bike trails in a designated



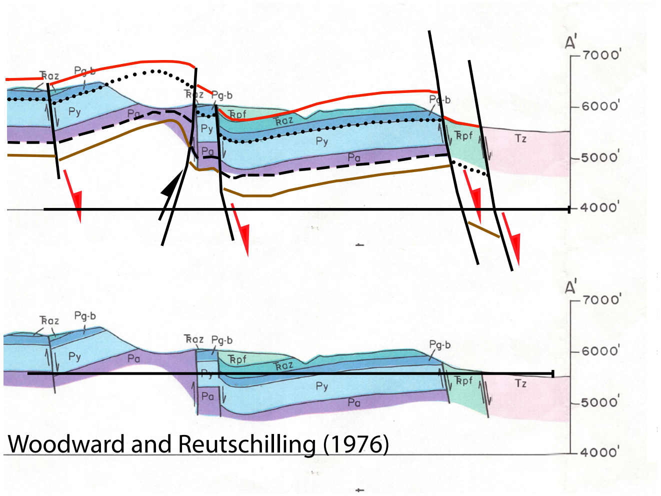
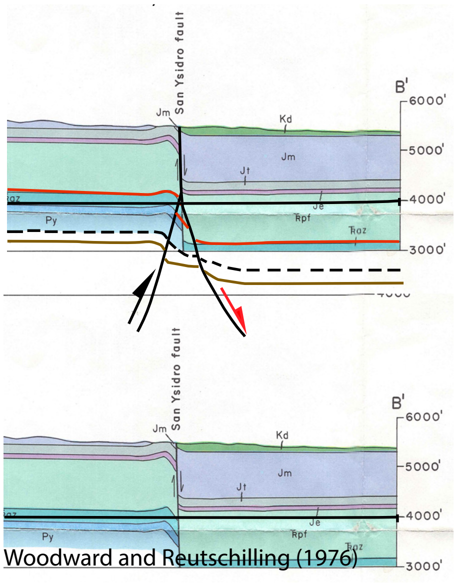


FIGURE 1.12. A star marks the junction of U.S. Route 550 and Cabezon Road; this is a place to discuss the regionally important San Ysidro fault within the Jemez–San Ysidro fault system (Kelson et al., 2015). Both U.S. Route 550 and the Cabezon Road cross the San Ysidro fault, easily seen by the color contrast between the yellowish Cretaceous rocks on the east and variably colored Jurassic strata on the west. The fault "V"s across the hills and drainages, indicating it dips east at about 60°, typical of rift-related normal faults. In their B–B' cross section, Woodward and Ruetschilling (1976) show about 900 ft (275 m) of east-down displacement (stratigraphic throw). But the paired anticline and syncline across this fault are not typical of rift faults and suggest pre-rift contraction across a west–up, reverse-fault-cored monocline, similar to and along strike of the contractional features in Fig. 1.10. Farther north along the Jemez–San Ysidro fault zone, and including the Permian cliff outcrop of Figure 1.11B, the fault–parallel anticline and syncline both become more pronounced in cross section A–A'.



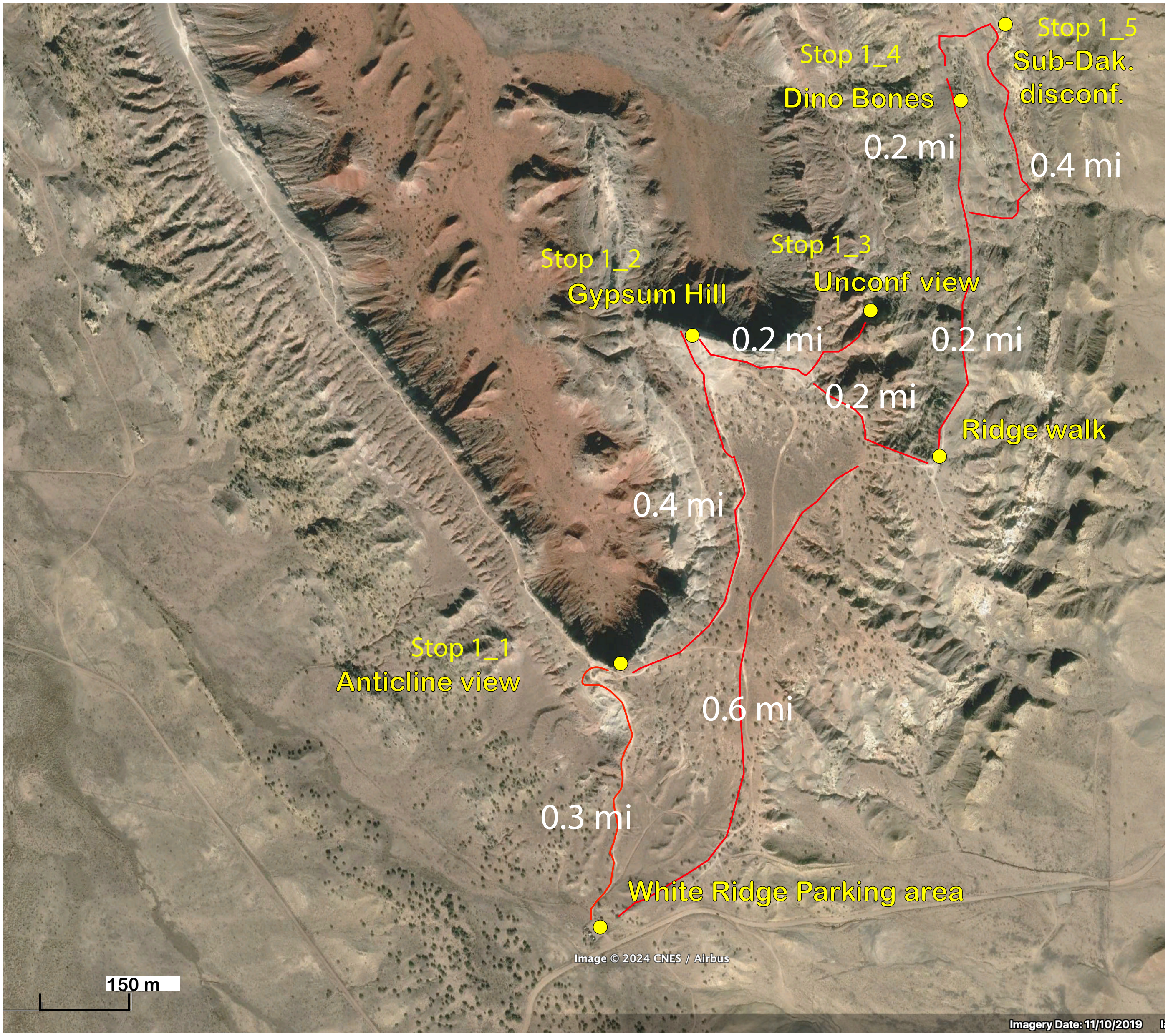


FIGURE 1.13. Stop 1 hiking sub-stops are at the south end of the Tierra Amarilla anticline. You can turn back at any point and linger for the views; the whole hike is a 3-mile loop that takes about 3 hours. *Image from Google Earth*

BLM wilderness area. From the White Ridge Bike Trails parking area, we hike north along various bike paths. There are six main stops; volunteers are stationed at each to provide directions and information.

The goals of the morning hiking stops are: (1) examine Mesozoic stratigraphy of the nexus area; (2) see the complex structure of the Tierra Amarilla anticline, which is interpreted here to contain the southern extension of the Nacimiento fault zone; and (3) examine the Quaternary San Ysidro erosional surface (~ 260–300 ka), which produced a classic angular unconformity above beveled Mesozoic strata. We then drive along the west limb through the same Mesozoic strata to the north end of the anticline for the afternoon hiking stops. There we examine travertine and travertine-depositing spring mounds. These deposits have formed from artesian carbonic waters that have been ascending the Nacimiento fault zone for at least the past 300,000 years. The combined stops link several themes of this year's conference; we discuss the structural history of Laramide reverse faulting, Laramide right-lateral strike-slip, Miocene-to-ongoing east-down Rio Grande rift normal faulting, and how the neotectonic setting influences groundwater flow, fault-fluid conduits, and degassing that are interpreted as active distal effects of the Jemez volcanic system.

Waypoint 4 [35.502400°, -106.840892°]

STOP 1.1. Anticline view.

The Tierra Amarilla anticline is a composite anticline. In aerial photos (Fig. 1.14), its southern end looks like a red mit-

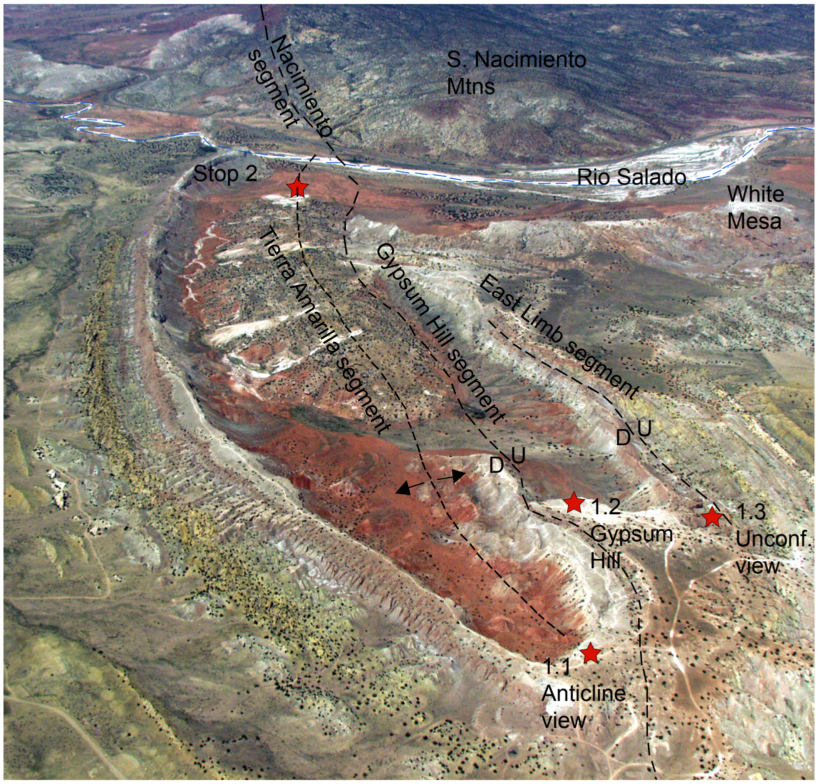


FIGURE 1.14. Aerial view of the Tierra Amarilla anticline. In the background are the south-plunging nose of the Nacimiento Mountains and the Rio Salado. Note the general alignment of the fold axial plane trace with the southern exposed section of the Nacimiento fault. Another strand of the Nacimiento fault system called the Gypsum Hill fault occupies the eastern part of the anticline. Both segments had Laramide east-up reverse slip, followed by east-down Rio Grande rift reactivation. The morning stops of this field trip are at the south; afternoon stops are at the north ends of the anticline. *Photo by Larry Crumpler*

ten (palm down, thumb to the east, fingers scrunched). The red mud rocks in the core are the Triassic Petrified Forest Formation of the Chinle Group. This stop shows the western closure and nice cliff exposures of the Jurassic Entrada Sandstone and Todilto Formation (limestone and gypsum units). To the north, a large travertine accumulation is our stop for the afternoon in the center of the anticline; the white areas coincide with salty springs. In walking to Stop 1.2 (Gypsum Hill), watch for gypsum veins in the Summerville Formation along the east-dipping fault in the core of the anticline (Fig. 1.15).

Stop 1.1 shows stratigraphy and the western hinge region of the anticline. Rotated Toreva landslide blocks dot the floor of the valley. The west limb of the structure dips ~50° west (we drive along it to the afternoon stops). The top is flat, and even the beds of Todilto on the east side of this nose are pretty flat—not much of an anticlinal closure. The mudstone-dominated Petrified Forest Formation was deposited by northwest-flowing rivers in a hot, low-latitude (within 10° of the equator), relatively tropical environment ca. 220 Ma (Stewart et al., 1972; Blakey and Gubitosa, 1983). The underlying Agua Zarca Formation that forms the Nacimiento dip slope in the distance consists of 150–250 ft (450–75 m) of very thickly bedded, medium- to very coarse–grained, quartz arenite sandstone and conglomeratic sandstone. Cross-stratification is common. Dominant clasts in the conglomerates are gray metaquartzite pebbles; other compositions include red jasper, petrified wood, and intraformational clasts. The Agua Zarca in this area is in-

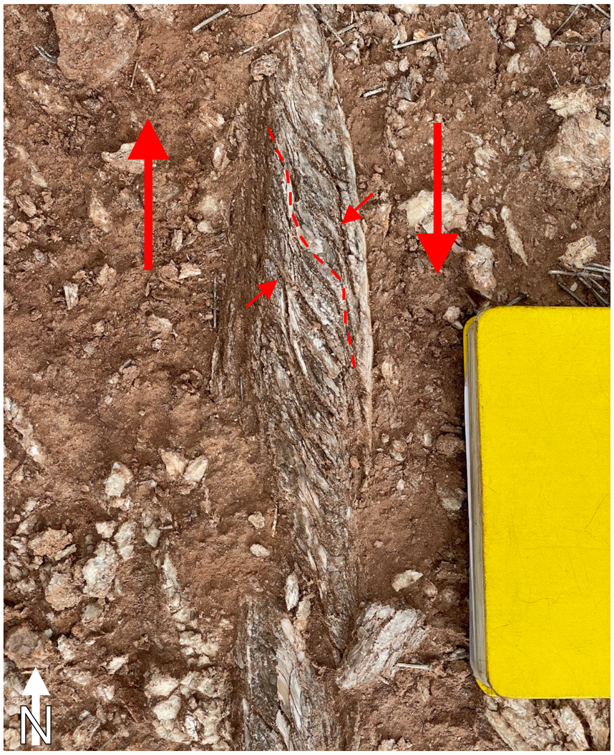


FIGURE 1.15. Gypsum vein shows right-lateral shear of gypsum fibers with strike-slip displacement of about twice the width of vein (shear strain ~2). During simple shear, the shortening direction at any instant (a proxy for stresses) is oriented at 45° from the shear zone (small red arrows).

ferred to have been deposited by a north-flowing fluvial system (Stewart et al., 1972; Kurtz, 1978). The sandstone is well indurated and forms cuestas and topographic benches in this area. Strata dip 10–15° to the southeast (details of structure and stratigraphy are from Woodward and Ruetschilling [1976] and Lucas and Heckert [2003]).

Between Stops 1.1 and 1.2 check out gypsum veins in the Summerville sandstone fault sliver. The Summerville directly overlies the Todilto Formation. Many veins have gypsum fibers oriented perpendicular to the walls of the veins, indicating they formed as progressively opening tensile fractures (Fig. 1.15); however, a progression of dextral shear is visible, sometimes in the center, sometimes at the edges. Fibers are in a sigmoidal geometry of an S-C fabric (C- is the shear plane; S- is perpendicular to the shortening direction shown by the small arrows). The gypsum fibers grew as the vein widened during right lateral shearing (a syntaxial vein).

Waypoint 5 [35.507374°, -106.839801°]

STOP 1.2. Gypsum Hill.

Take in the view looking north from Gypsum Hill, but don't get close to the cliff, as the gypsum is unreliable. Also, be careful of the holes in the gypsum. Late Pleistocene fissure development, inferred to be caused by tectonic extension, would occasionally trap and kill various large mammals, kind of like New Mexico's version of the La Brea Tar Pits. Remains of such fossils were discovered two decades ago in the White Mesa gypsum mine that you can see from here. The fossils were in narrow fissures (<14 in. [<35 cm] wide), which presumably widened upward. The unfortunate animals fell into the wider, upward part of the fissure, which has subsequently been stripped away, and the bones eventually fell into the narrower, lower part. The trove of species collected from these fissures include the stilt–legged horse (*Equus* cf. *E. francisci*), camel (*Camelops hesternus*), extinct bison (*Bison antiquus*), and mule deer (*Odocoileus hemionus*). More details of this interesting site are in Morgan and Rinehart (2007).

We are looking north along the Nacimiento fault system, which forms the boundary between the Nacimiento Rocky Mountain uplift cored by Precambrian rocks and the San Juan Basin of the Colorado Plateau (Fig. 1.16A). Cabezon Peak is in view to the west (the location of the Second-Day Road Log), and Redondo Peak in the Valles Caldera is visible to the east, just above White Mesa. Figure 1.16 B shows a new interpretation of the Tierra Amarilla anticline as the southward continuation of the Nacimiento fault zone, with both strike-slip and dip-slip components on several fault segments.

Waypoint 6 [35.507388°, -106.836528°]

STOP 1.3. San Ysidro surface.

The San Ysidro erosional surface represents a time of local erosional beveling to create the spectacular angular unconformity atop Mesozoic rocks that were previously folded in the Laramide (location 1 in Fig. 1.13). The alluvial deposits just above this surface record the small streams that beveled the unconformity. Locations that constrain the age of the San Ysidro surface to ~ 300–250 ka are shown in Figure 1.16B: (1) dune sands overlying the lower calcic soil horizons have a maximum depositional age of 261 ka (Fig. 1.19); (2) travertines that overlie the San Ysidro surface in the core of the anticline get as old as 269 ka (Cron et al., 2024); (3) a location where travertine overlies the San Ysidro surface is shown in Figure 1.30; (4) the San Ysidro surface appears to grade to a Rio Salado terrace gravel dated as 250 ka (Fig. 1.32).

Waypoint 7 [35.510428°, -106.834776°]

STOP 1.4. Dinosaur fossils.

The ridge walk (starting at 35.505329°, -106.835255°) follows the strike of the east-dipping Brushy Basin Member of the Morrison Formation. Note the lenticular channel sandstones surrounded by mudstone. Casts of dinosaur bones are present along the trail. Indeed, in this general area there are many

FIGURE 1.16A. Looking north from Gypsum Hill, Cabezon Peak is on the left and Redondo Peak in the Jemez Mountains is on the right skyline. What is the significance of the "extra" Todilto gypsum ridge in the middle of the Tierra Amarilla anticline? You might visualize it like the dashed line (a small syncline within the crest of the anticline), but this wrinkle needs further discussion.

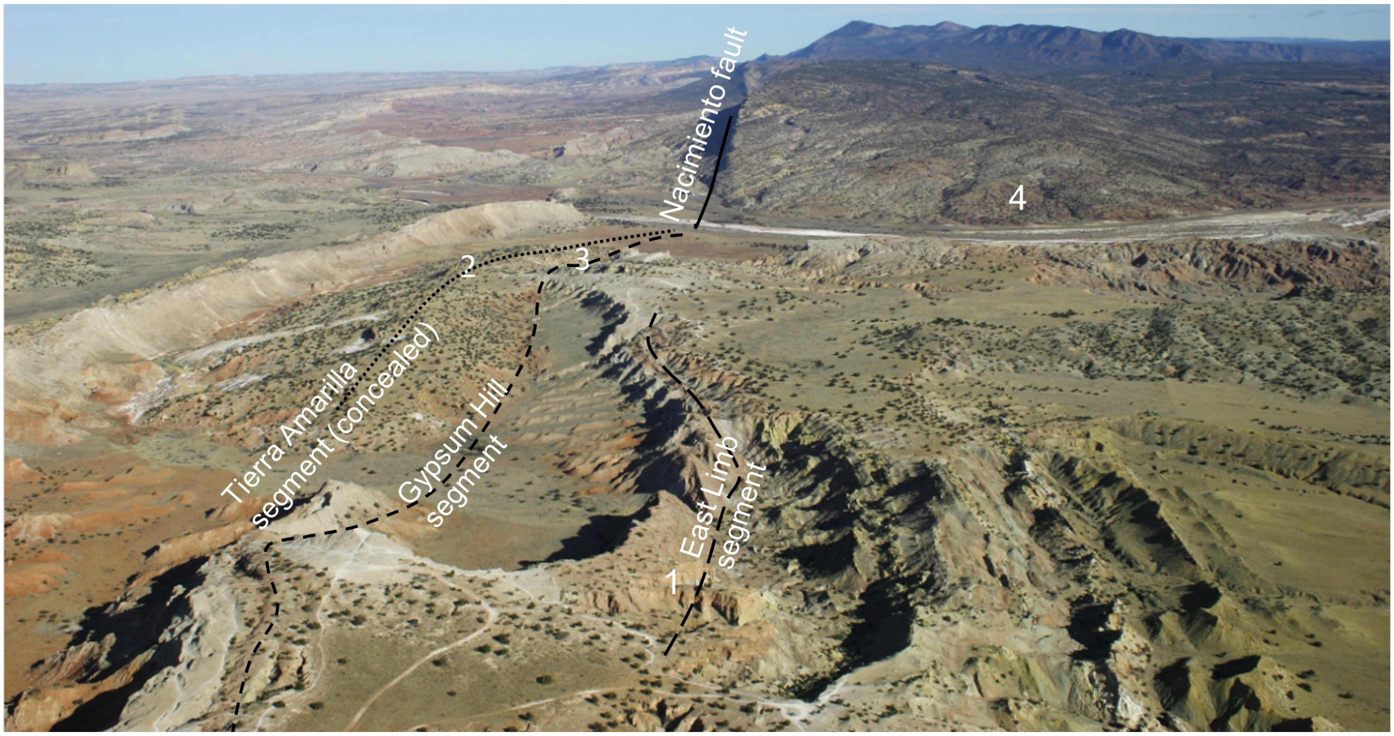


FIGURE 1.16B. View north along the Nacimiento fault zone from above Gypsum Hill, with a new interpretation of the Tierra Amarilla anticline as a series of initially east-up Laramide reverse fault/monoclinal structures that form a southern continuation of the Nacimiento fault zone. These have now been inverted with east-down Rio Grande rift and Quaternary displacement and used as fluid conduits for artesian carbonic springs and related travertine deposits. Locations (1–4) that constrain the age of the San Ysidro surface are shown. (see text). *Photo by Kenneth Ingham and Brandi Cron*

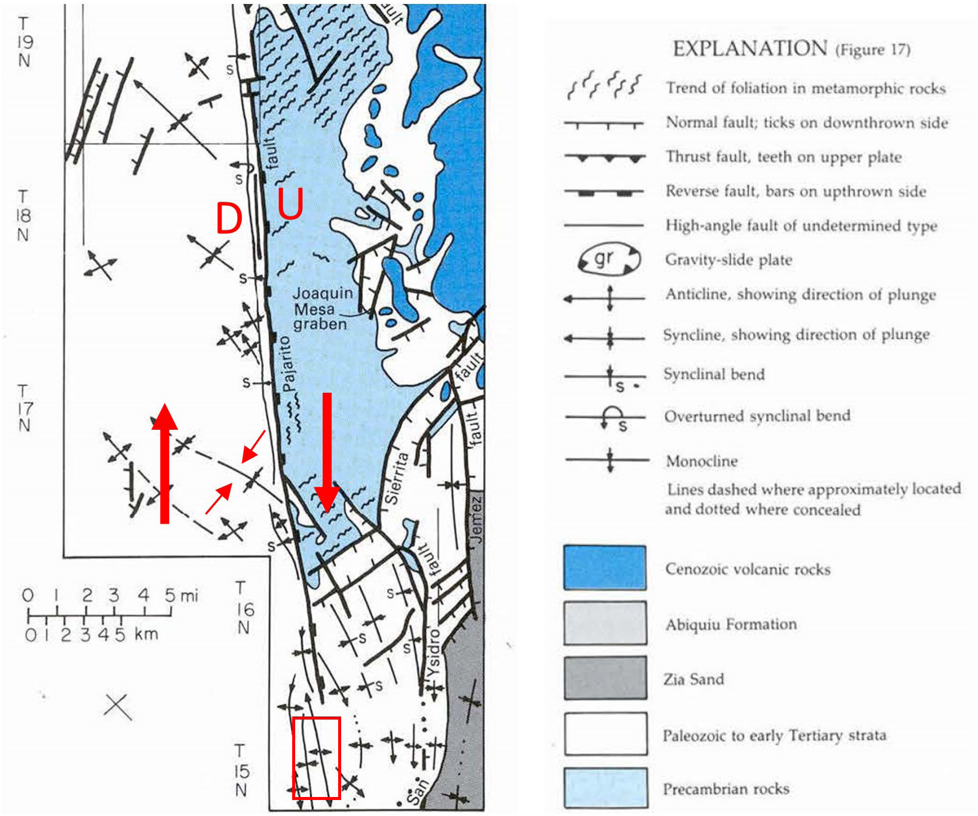


FIGURE 1.17. Woodward's (1987) tectonic map of the southern Nacimiento fault (labeled Pajarito fault in this figure), with Precambrian rocks in upthrown east block (U) indicating reverse faulting, plus ~320°-trending folds of Paleocene and Eocene strata indicating Laramide (Paleocene–Eocene) right-lateral displacement. Red arrows show strike-slip shear component that generates northeast-southwest compression (small arrows) to form folds during Laramide transpression. Box shows area of Figure 1.18.

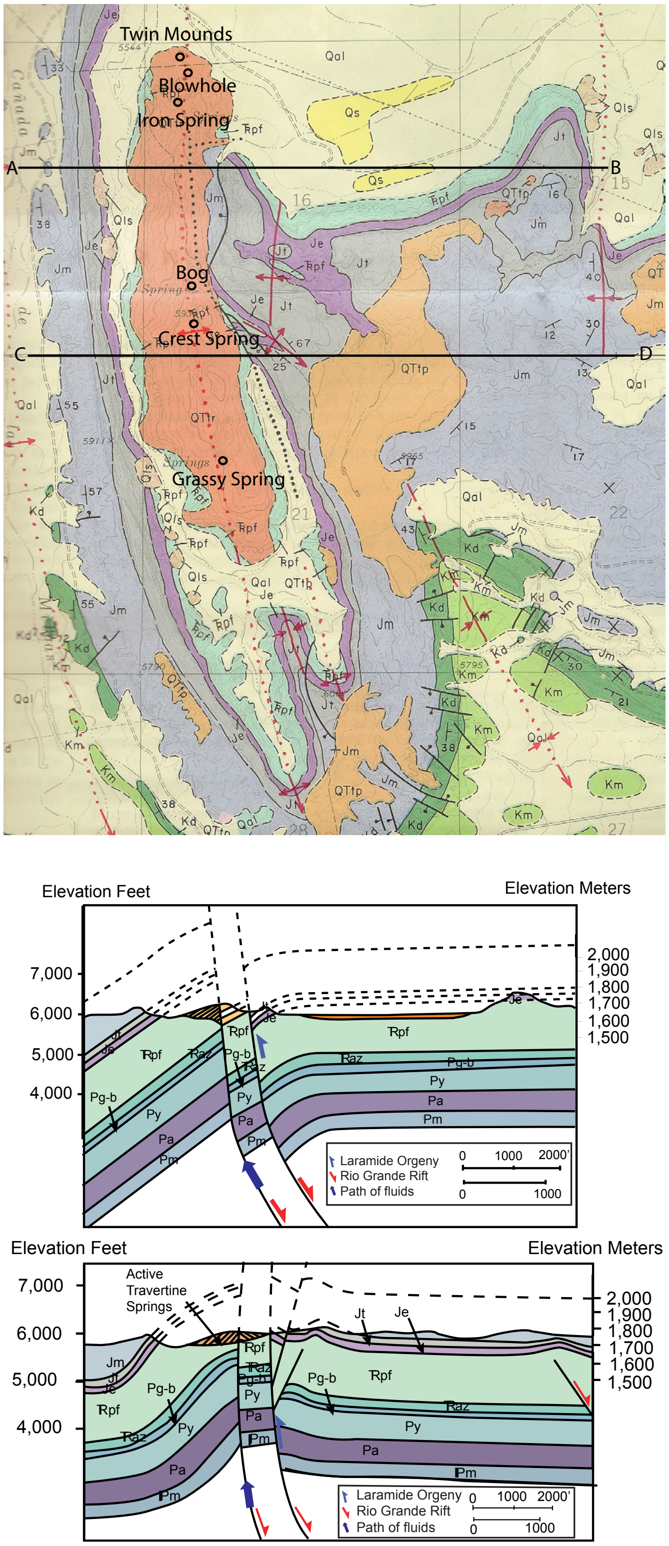


FIGURE 1.18. Map (from Woodward and Ruetschilling, 1976) and cross sections (modified from Cron, 2012; Cron et al., 2024; Karlstrom et al., 2024) showing interpretation of Tierra Amarilla anticline as an inverted Laramide flower structure. Compressional features are shown as anticlines, synclines, and monoclines; most are sharp fault-propagation folds adjacent to faults similar to Colorado Plateau monoclines. The steep limb of monoclines near the propagating fault tip of fault-propagation folds can have complex geometry, and the significant right-lateral strike-slip along these faults (west side moving away in this view) makes two-dimensional cross sections unrestorable.

incomplete and/or fragmentary dinosaur bones in the Brushy Basin Member, a small part of the classic Late Jurassic Morrison dinosaur fauna, better known from fossils found in Colorado, Utah, and Wyoming. The Morrison bones in the nexus are mostly of sauropod dinosaurs, but stegosaurs and allosaurs are also represented. Note at this location how the fossils were transported into and came to rest in the base of a river channel. Not far from here, an incomplete skeleton of a very large sauropod dinosaur was excavated and named *Seismosaurus* by Gillette (1991), but it is now considered to be a specimen of the earlier-named *Diplodocus* (Lucas et al., 2006). A complete reconstruction of the skeleton can be seen on display at the New Mexico Museum of Natural History and Science in Albuquerque. *Diplodocus* was a 110-ft-long (33 m) quadrupedal plant eater with a very long neck and tail (a typical sauropod).

Waypoint 8 [35.511520°, -106.833925°]

STOP 1.5. Sub-Dakota disconformity.

The sharp disconformity contact between the Dakota Formation and underlying white kaolinitic sandstone of the Jackpile Sandstone is the subject of this stop. Cather (2021) and Lucas (2021) discussed alternate correlations for the Jackpile. Most workers have considered it as the uppermost member of the Jurassic Morrison Formation (~150 Ma), but Cather suggested it may be equivalent to the Lower Cretaceous Burro Canyon Formation (~125 Ma). The overlying Dakota Sandstone is ~100 Ma, so the disconformity represents a time interval of between ~50 to ~25 million years, during which the Cretaceous inland seaway developed. Samples have been collected for detrital sanidine analysis which could resolve this uncertainty. **Return to vehicles.** *0.4*

4.5 Leave the White Ridge Bike Trails parking area and head west. *0.3*

Waypoint 9 [35.496185°, -106.844585°]

4.8 Turn right. *0.5*

5.3 Turn right again, driving in a synclinal valley in Cañada del Milpas. The Milpas fault on the west side of the valley omits much of the Morrison section. *0.3*

5.6 Go through the gate. Close and latch the gate behind the last vehicle. Driving north, we parallel the Jackpile-Dakota contact on the west limb of the Tierra Amarilla anticline. *0.7*

6.3 Drive past the windmill; stay left. *1.3*

7.6 Todilto dip slope to the right and overlying hogbacks of the Brushy Basin Member of the Morrison Formation. *0.8*

8.4 Stay right past the "homestead," and drive east along

FIGURE 1.19A. (A) View looking south (with Sandia Mountains in the distance) of the angular unconformity at the base of the San Ysidro erosional surface. The deformation zone to the right of the erosional window is interpreted to be a thrust-sense zone in the Summerville Formation. The yellow sandstone at left dips left (east) as part of the east limb of the Tierra Amarilla anticline and may be Summerville or Salt Wash Member(?). Detrital sanidine samples were taken from south of this outcrop, but stratigraphic positions are shown: TA-1A and TA-1b are from the bottom and top of the thick calcic soil, and the <261-ka TA2 is from eolian sands just above.

the Rio Salado, bending north as you pass the Todilto ridge and staying on the same road. *0.9*

9.3 Make a sharp left at the pipeline, and park near the Twin Mounds.

Waypoint 10 [35.537361°, -106.848415°]

STOP 2. Tierra Amarilla travertines and springs.

Stop 2 is in the core of the Tierra Amarilla anticline at its north end. The core of the anticline should have its oldest strata, and it does. The red mud "rocks" we are parked on are the eroded products of the Petrified Forest Formation of the Triassic Chile Group (Fig. 1.23). The main goals of this stop focus on the younger (neotectonic) history of the nexus. We "chase" the artesian carbonic springs up the hill (100 m elevation gain for the water level in the springs); examine the mounds (chemical volcanos); taste the bubbles (xenowhiffs); see travertine textures of terracettes, hollow cisterns, and prograding mounds; and summarize the U-series-dated travertine record that extends back 269,000 years.

Waypoint 11 [35.536866°, -106.847765°]

STOP 2.1. Twin Mounds.

The Twin Mounds are a classic type of travertine deposit also seen in the Peñasco drainage along the west side of the Nacimiento fault to the north (Formento-Trigilio and Pazzaglia, 1996), along the Lucero uplift on the west side of the Rio Grande rift farther south (Ricketts et al., 2014), and in the Little Colorado River tributary to Grand Canyon. In Australia, similar travertine mound springs dot the "mound springs line" in the Simpson Desert north of Adelaide (Crossey et al., 2013a). What these mound springs have in common geologically is their location along fault conduits that convey deeply sourced, CO_2-rich waters. The CO_2 itself is mostly of magmatic origin and carries trace gases that originated in the mantle, as shown by the helium isotope ($^3He/^4He$) values (McGibbon

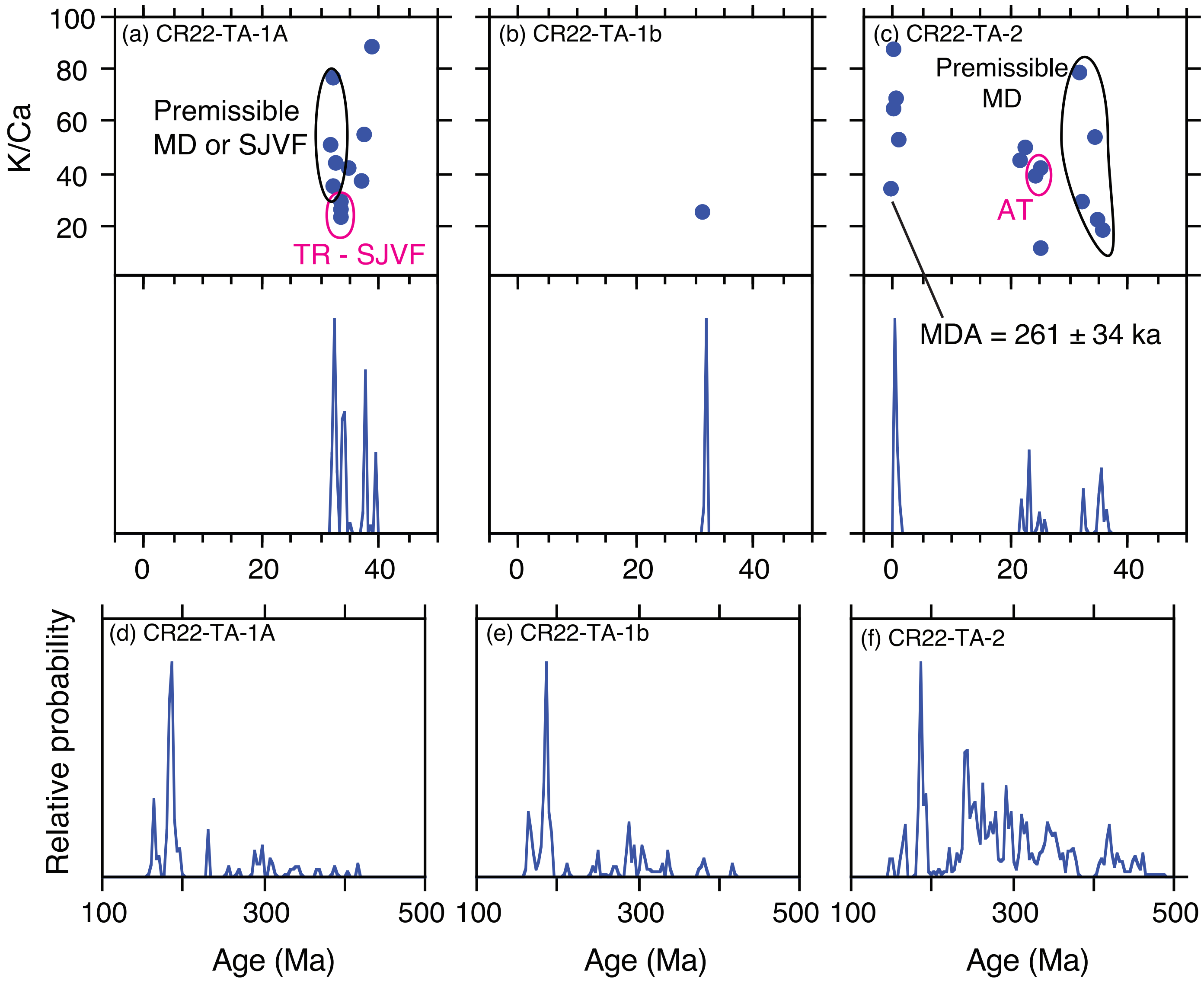


FIGURE 1.19B. The youngest detrital sanidine grain in TA2 constrains the erosion of the San Ysidro surface to have been ≥261±34 ka. Full detrital sanidine spectra show reworking of Paleozoic and Mesozoic strata (lower panel) with volcanic grains from the Mogollon Datil (MD), Latir Amalia Tuff (AT), and San Juan volcanic field (SJVF), specifically Thorn Ranch Tuff (TR) of SJVF.

FIGURE 1.20A. Original (1979) discovery of the partial skeleton of the sauropod dinosaur later named *Seismosaurus*. Note the large vertebrae in a channel sandstone bed of the Brushy Basin Member of the Morrison Formation. *Photo courtesy of New Mexico Museum of Natural History and Science*

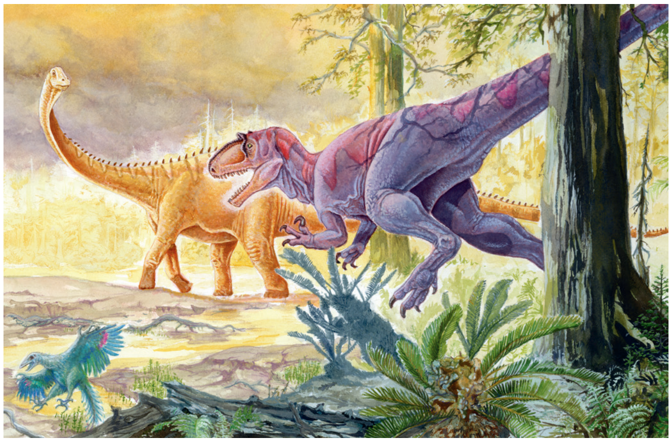


FIGURE 1.20B. Artist's reconstruction of a scene on the Brushy Basin floodplain of Late Jurassic New Mexico. A *Seismosaurus* is attacked by a large allosaurid while a Jurassic bird recoils. *Artwork by Matt Celeskey and Mary Sundstrom, courtesy of New Mexico Museum of Natural History and Science*

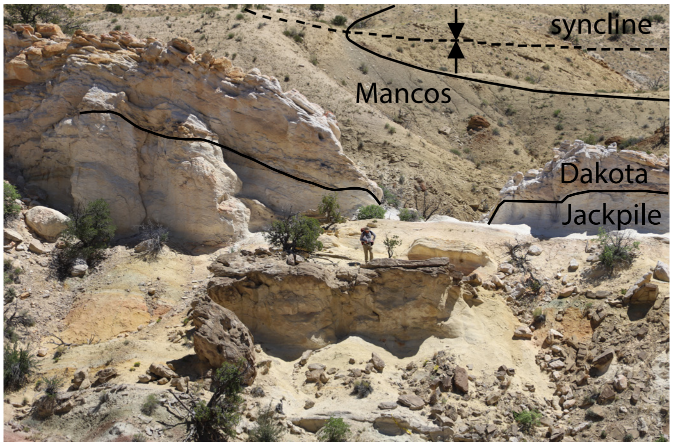


FIGURE 1.21. The sub-Dakota disconformity is well exposed on the east limb of the Tierra Amarilla anticline and also bounds an adjacent south-plunging syncline cored by Mancos Formation. Can you put your finger on the disconformity?

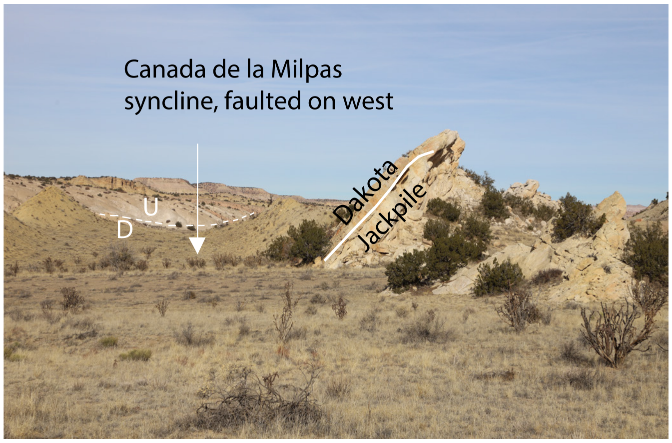


FIGURE 1.22. Driving south along the west limb of the Tierra Amarilla anticline, we see the same section we saw on the east limb: Jurassic Morrison, Jackpile, and Dakota/ Mancos. The syncline is faulted on its west limb, resulting in the Todilto Formation being juxtaposed with Dakota Formation.

et al., 2018; Crossey et al., 2016). The central vents over time deposited travertine around the vent semi-symmetrically due to degassing of CO_2. Rimstone dams and terracettes on the side of the mound and other slopes form as water cascades down the sides and degas. As the ridges form and grow, they enhance turbulence that promotes further degassing in a nice positive feedback loop. The water level in these mounds has been fairly constant (within a meter or so) for the time we have monitored them (McGibbon et al., 2018), but which mound has a higher water level varies. On the way to Stop 2.2, we pass a collapsed, extinct mound (at 35.535744, -106.847648) that may convince you the mounds are hollow inside.

Waypoint 12 [35.535441°, -106.847999°]

STOP 2.2. The Blow Hole.

The Blow Hole and Iron Spring are two instructive springs along the north-south line of artesian springs we walk up. Like the Twin Mounds, the gas bubbles are mostly CO_2 but contain trace gases that include a significant proportion (a few percent) of the primordial isotope ^{3}He; this documents the presence of mantle-derived fluids entrained in the groundwater system—xenowhiffs! The iron is derived from water-rock interactions.

Waypoint 13 [35.534752°, -106.847837°]

STOP 2.3. Travertine drapes.

The geometry of travertine drapes is shown here. Two generations of older drapes that mantled the hillside are frozen in place at this outcrop, separated by a non-tectonic, angular unconformity.

Waypoint 14 [35.529065°, -106.846784°]

STOP 2.4. Bathtub Spring.

Bathtub Spring is an active spring. We have ascended about 80 m in elevation from Twin Mounds, and the water is the same temperature, pH, and conductance; collectively this indicates aquifer connectivity. We are about 90 m above the Rio Salado's alluvial water table, which is the local groundwater base level. An equipotential surface for groundwater must slope from here to there (Fig. 1.32). McGibbon et al. (2018) suggested that groundwater gains its artesian head from the Nacimiento and Jemez Mountains and follows various sedimentary aquifers (Madera, Abo, and Aqua Zarca, among others), then ascends along the north-south confined fault-aquifer system that cores the anticline.

Waypoint 15 [35.526613°, -106.846734°]

STOP 2.5. Fissure ridge.

A fissure ridge is a common travertine feature and is seen at this stop. Like a "spreading center," deeply sourced fluids ascend up the fissure and deposit travertine on the flanks. Famous fissure ridges are found at hot spring spas in many places (Pentecost, 2005), and we see a similar fissure ridge at Soda Dam on the Third-Day Road Log.

Waypoint 16 [35.52579°, -106.846608°]

STOP 2.6. High Mound.

High Mound is as high as we go today, although Grassy Spring is another spring at similar elevation to the south. The U-series ages of the travertine near High Mound are 250–290 ka. The thickness of the entire travertine carapace that sits on the Petrified Forest Member is ~10 m, as seen at the edges of the deposit. Monitoring of this spring for several years showed very little seasonality in terms of temperature and conductance within this confined artesian aquifer system. Look north at the line of springs we have ascended; they are all parallel to and form a southward extension of a concealed strand of the Nacimiento fault system.

Different routes down are possible (see Fig. 1.23): (1) back the way we came up, or (2) back a bit to the east to see the San Ysidro surface that bevels the eastern monocline and where the base of the travertine deposit is built on the San Ysidro surface.

The travertine carapace in the center of the Tierra Amarilla anticline was built on top of the San Ysidro erosional surface as we will see on the way back (Fig. 1.30). The detrital sanidine dating of the soil that overlies this surface at Stop 1.3 (Fig. 1.19) has a youngest sanidine grain age of 261±34 ka, indicating that the erosional surface is overlain by sediments

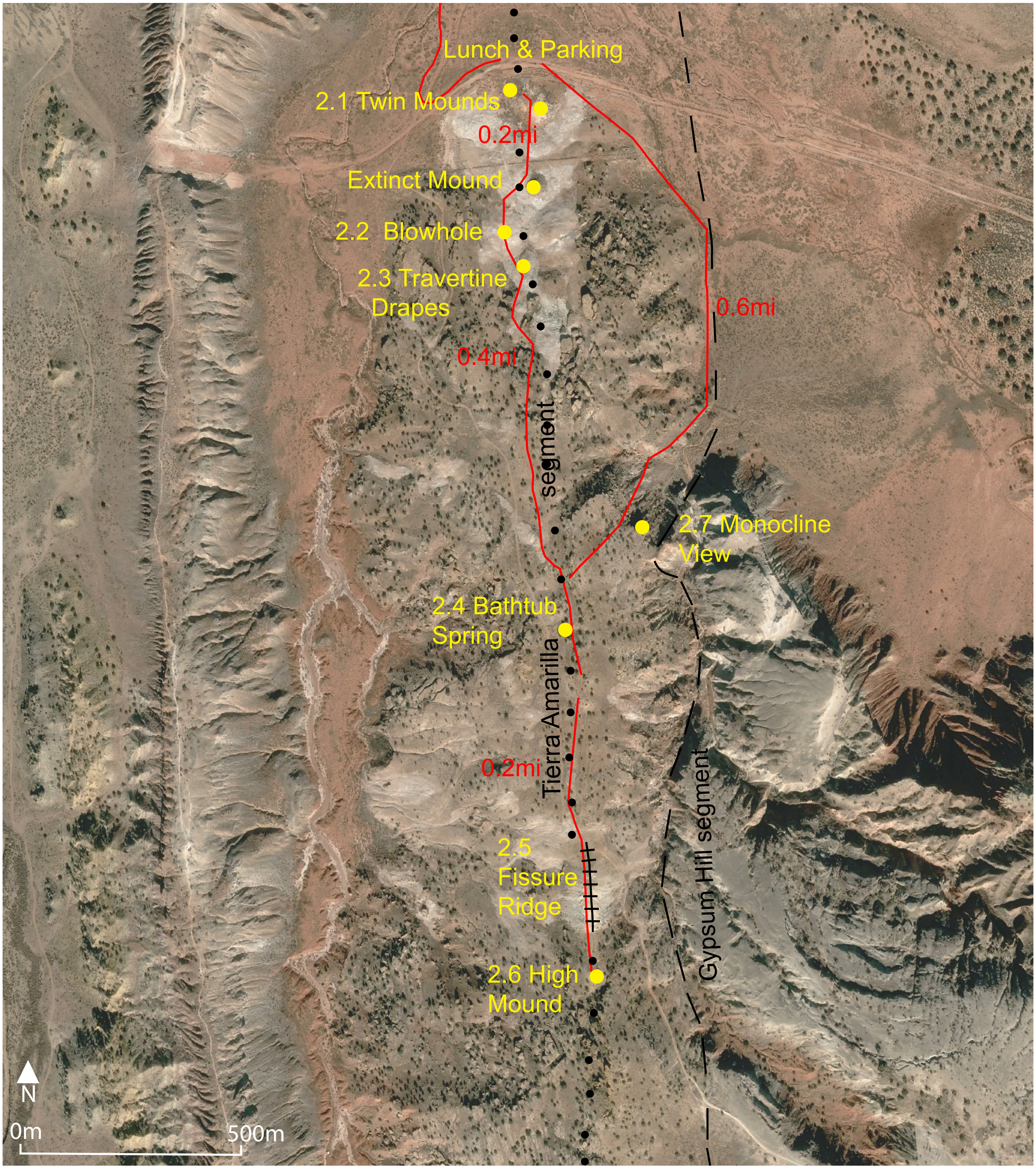


FIGURE 1.23. Hiking routes for Stop 2 involve six uphill stops. You can return in one of two ways: by the same way you came or by way of the easternmost of the two faults. These faults are inverted monoclines that form the core of the Tierra Amarilla anticline. Image from Google Earth.

FIGURE 1.24. View looking north of Twin Mounds (in foreground) and the Aqua Zarca dip slope of the Nacimiento uplift in background with beds dipping 10–15° south (toward us); west-dipping Todilto gypsum ridge at left side of photograph. This and other mounds are effectively water-filled cisterns, so the whole group shouldn't stand on top of any mound all at once. The depth of water in Twin Mounds East is ~23 ft (7 m)!

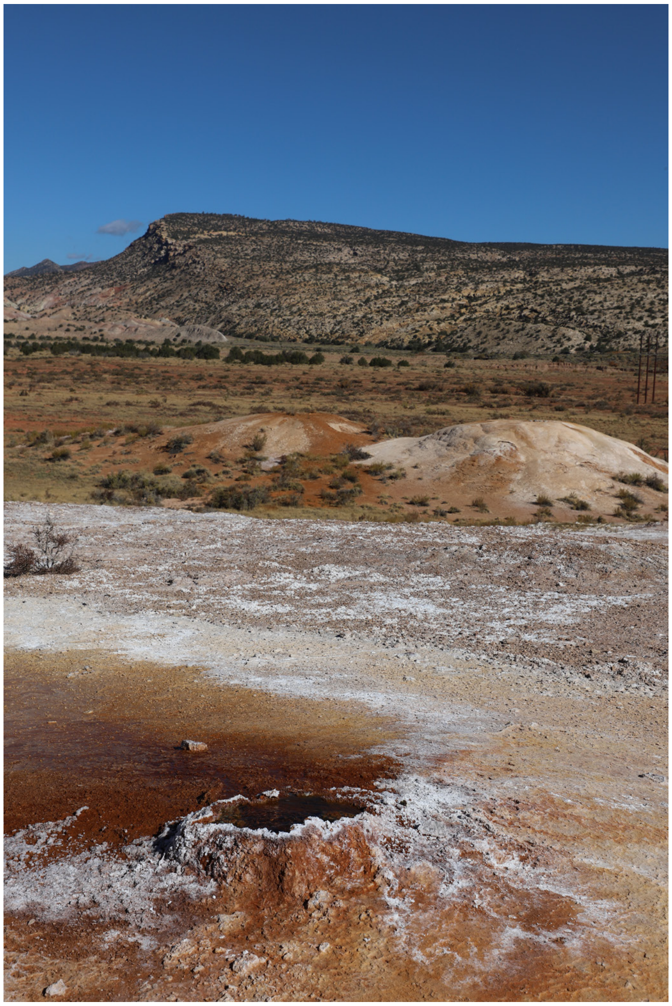


FIGURE 1.25. The Blow Hole, looking north to Twin Mounds. The bubbles are mostly CO_2, the iron content is from water-rock interactions. Taste it and see what you think.

FIGURE 1.26. This travertine drape geometry formed as one mound sequence prograded downhill over an earlier one.

FIGURE 1.27. Bathtub spring has its water level at about 262 ft (80 m) above the Rio Salado groundwater level.

FIGURE 1.28. The fissure leading to High Mound. The white area is actively seeping water and depositing travertine on both sides of the fissure ridge.

that are ≤261 ka. This carapace has fractured, and huge blocks have slid downhill, exposing several places where you can see a cross section of most of the deposit. Sampling was done to test an oldest-at-the-bottom stratigraphy. Although this is generally the case with the 269-ka age nearer the bottom and the 212-ka age nearer the top, it is complicated by infillings of flowstone travertine that crystallized at various levels into older layers (Cron et al., 2024). We see this again at Soda Dam on the Third-Day Road Log. The conclusion from combined U-series and detrital sanidine geochronology is that the erosion that formed the San Ysidro surface may have taken place before ~250–270-ka travertines, soils, and eolian deposits developed on top of it.

Waypoint 17 [35.531182°, -106.845994°]

STOP 2.7. Monocline view.

This stop is an outcrop of the San Ysidro surface overlying near-vertical Entrada sandstone within the fault zone that cores the west-facing monocline that forms part of the larger Tierra Amarilla anticline (Fig. 1.30A). The inferred east-up reverse fault displacement (white arrow) indicated by the monoclinal bend is now inverted by reactivation of the fault as an east-down Rio Grande rift normal fault (yellow arrow).

FIGURE 1.29. High Mound, looking north along the Nacimiento fault system.

Detail of the San Ysidro surface (Fig. 1.30B) shows gravels from small streams above an irregular angular unconformity overlain by and cemented by travertine. Todilto crops out in this general area as well, but units are attenuated and disrupted, which is common within the steep limbs of monoclines and in transpressional flower structures. We have sampled locally derived gravel (at hammer) for further detrital sanidine analyses. **Assemble back at Twin Mounds by 4 pm.**

SUMMARY OF TOPICS FOR CONTINUED DISCUSSION

The water and gas chemistry, travertine record, and fluid movement along faults all have connections to topics we also discuss on Day 3 of the field conference. McGibbon et al. (2018) suggested that the hydrochemistry of groundwater in the Tierra Amarilla system is influenced by geothermal waters that have migrated down San Diego Canyon along the Jemez fault system. The waters then crossed the southern Nacimiento Mountain block along northeast-trending faults. This mixing from the Valles geothermal system explains the waters' relatively high CO_2 and mantle-derived ^3He. Aspects of this "hydrotectonic" view of groundwater include fault zones as confined and semiconfined fast conduits for the geothermal fluids that mix in the groundwater system. Significant groundwater recharge to the Albuquerque basin comes from the high elevations of the Jemez and Nacimiento Mountains, such that the Nacimiento physiographic and structural nexus is also a hydrological nexus that can provide clues to the complexity of fault systems, partitioned hydrologic sub-basins, and groundwater mixing. Varying water quality in Rio Grande rift aquifers reflects the hydrotectonic influences of high-TDS "lower world" water moving along faults mixing with more potable "upper world" waters in ways similar to surface water mixing along the Rio Salado and Jemez River, as described by Crossey et al. (2013b).

The Tierra Amarilla hydrotectonic setting has persisted for at least 269,000 years in this area, as shown by the travertine record summarized in Cron et al. (2024). Travertine records such as this one are also present at Soda Dam and in many areas of New Mexico and the southwestern United States (Crossey et

FIGURE 1.30A, B. Looking south at the east-up monocline of folded Chinle, Entrada, and Todilto that bounds the relatively unfaulted White Mesa fault block. This fault connects with the Gypsum Hill fault segment. An inferred Tierra Amarilla segment is to the west (right) beneath the travertine-depositing springs we walked up earlier. This is the eastern fault in the core of the Tierra Amarilla anticline that extends to the Gypsum Hill area. The inferred western fault is beneath the travertine-depositing springs we walked up earlier. Entrada/Todilto disappear below the ground surface on the east of the fault (red line), then appear on the west side of the fault as fault slivers just below the San Ysidro surface. Figure 1.30B shows detail of the San Ysidro surface; the hammer is inside the circle.

al., 2011; Priewisch et al., 2013; Ricketts et al., 2014). The paleoclimate record in travertine is complex but ultimately needs to be combined with speleothem and other proxy records.

Landscape evolution and river incision are themes for all three days of this field conference. Looking north from Twin Mounds, Figure 1.31 provides a good view of the southern toe of the Nacimiento uplift and the dip slope of Triassic Aqua Zarca Sandstone dipping south toward us. A prominent point on the skyline has the San Ysidro USGS benchmark atop it, embedded in travertine. The travertine is underlain by Rio Salado river gravel containing Precambrian granite clasts. Other knobs of resistant travertine dot the dip slope, and most have paleo Rio Salado gravel underneath that is cemented by travertine and often underlain in turn by a thin bit of basal Petrified Forest. A modern spring and travertine mound across the highway in the present Rio Salado floodplain called North Spring is a modern analog of travertine springs venting into the river, breaking through a thin bit of the Petrified Forest confining layer, suggesting that the U-series ages on the travertines that cement the gravels provide close-to-direct ages on the terraces.

Along the Rio Salado, U-series dating of travertine-cemented sandy gravels of various levels of terraces provides a good record of the incision of the Rio Salado (Fig. 1.32). The top four terraces are 195 m, 164 m, 130 m, and 114 m above river level. The top two are outside U-series range (>500–600 ka), but the 164-m terrace gives a ^{234}U model age of 534±148 ka, and the 164-m and 130-m terraces give U-series ages of 415±16 and 395±17 ka, respectively (Cron et al., 2024). Regression of the age and height of these terraces (Fig. 1.32) gives an R^2 of 0.966, predicts a depth to bedrock of 14 m, and suggests that the 195-m terrace may correlate with the Qt1a terrace 630 ka Lava Creek B terrace. This regression supports a steady average bedrock incision rate of 334 m/Ma over the past 630 ka for the San Ysidro terraces (Reed et al., 2024).

We report these bedrock incision rates in units of m/Ma, emphasizing that this is a long-term average bedrock-incision, valley-deepening, rate. During this time, the river went through many cycles of terrace aggradation and incision related to glacial-interglacial climate cycles. In this case, the measured duration spans about 16 major climatic cycles during which the river carved progressively deeper into bedrock. Consistent long-term downcutting rates in most rivers of the Colorado Plateau–Rocky Mountain region has led to models for regional mantle-driven surface uplift, discussed in Karlstrom et al. (2011). A long-term average incision rate of ~300 m/Ma is one of the highest rates in New Mexico; this is interpreted by Reed et al. (2024) to reflect the amplification of epeirogenic uplift of the entire Rocky Mountain–Colorado Plateau region (Karlstrom et al., 2022) by magmatic inflation of the Jemez Mountains and fault-block-enhanced differential uplift that is recorded by the differential river incision.

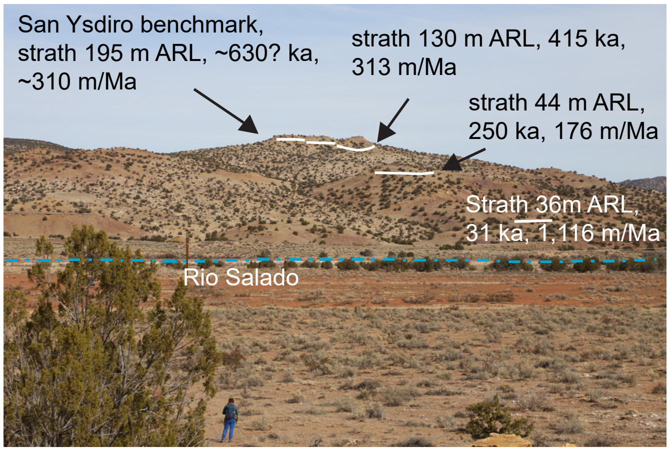


FIGURE 1.31. View north across the Rio Salado of U-series-dated, travertine-cemented Rio Salado gravels. Strath heights above river level, U-series age, and incision rate are listed for each. The highest strath terrace (195 m above river level) is outside of U-series range, >500 ka. This highest terrace may correlate with the Qt1 630-ka Lava Creek B terrace at the Jemez-Guadalupe river confluence, which would give a 310 m/Ma incision rate, similar to the rate of 313 m/Ma for the Qt2 415-ka terrace.

Quaternary and ongoing neotectonics in the Tierra Amarilla

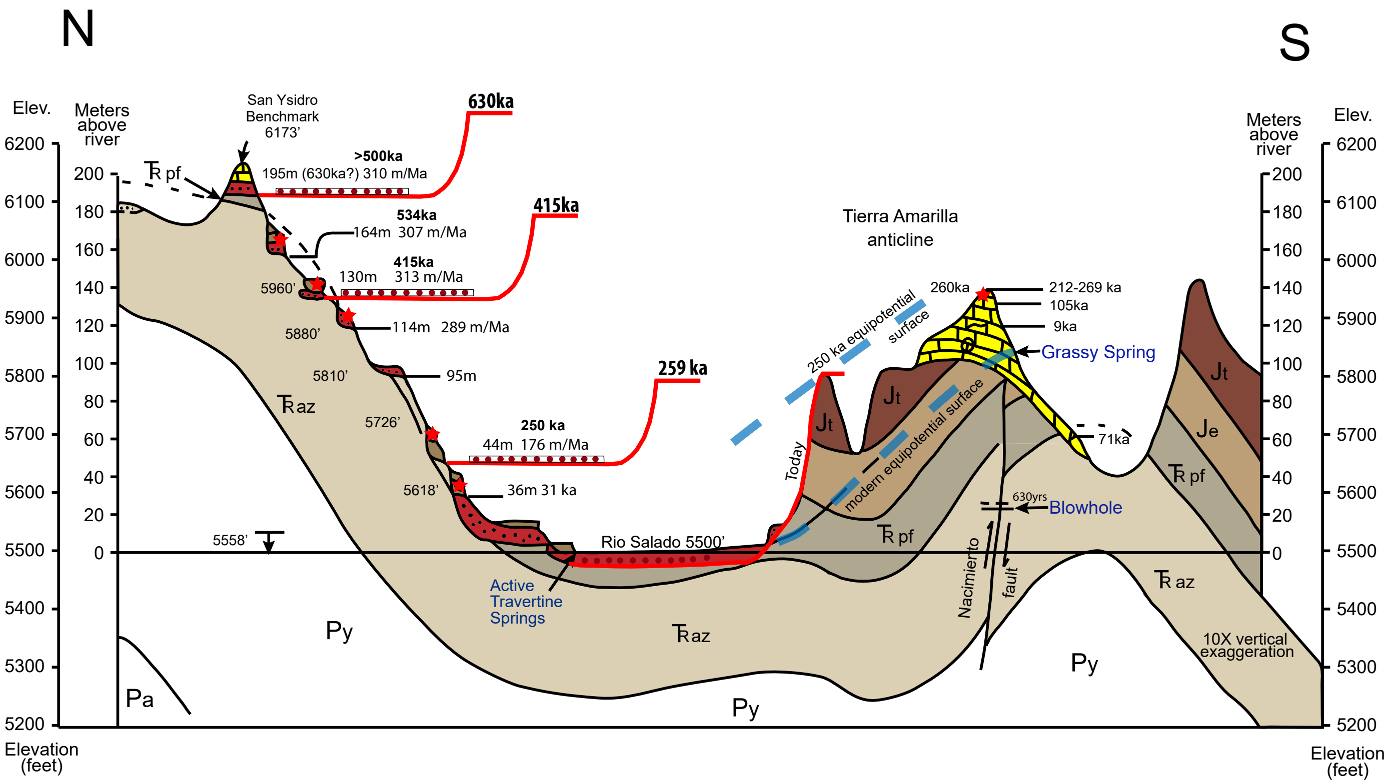


FIGURE 1.32. Schematic north-south cross section from the San Ysidro benchmark north of the Rio Salado to Gypsum Hill showing incision rates and inferred paleoriver elevations as the river "slid down" the south-plunging Nacimiento dip slope. Active travertine deposition in the core of the Tierra Amarilla anticline above the San Ysidro surface has been taking place since 270 ka. The active mounds cementing modern day Rio Salado gravels suggest that U-series dates provide direct ages on strath terraces.

area involve an interplay between uplift, faulting, river incision, travertine deposition, and retreat of the White Mesa Jurassic Entrada-Todilto cliffs. This interaction is schematically shown in Figure 1.32. Cliff retreat takes place by undermining of resistant cliffs (Entrada-Todilto) by more erodible layers (Petrified Forest) and transport of the fallen material by rivers (Rio Salado). This causes cliffs to retreat in a self-similar cliff-slope geometry during regional denudation. In Figure 1.32, paleoriver positions are recorded by the terraces, and an inferred self-similar cliff retreat is depicted as the river "slid down" the Aqua Zarca–Petrified Forest dip slope to unroof the southern Nacimientos over the past >600,000 years. Erosional beveling of the San Ysidro surface took place by 269–261 ka, based on the oldest travertine date and youngest detrital sanidine date from material overlying the surface. This was accomplished by north-flowing, small streams that were probably graded to a level near the 44-m terrace on the Rio Salado system. The deposition of thick travertine in the core of the Tierra Amarilla anticline after ~ 290 ka can be explained by a similar artesian head as today's springs (blue lines in Fig. 1.32), potentially in combination with a wetter time interval in the Southwest during Marine Isotope Stage 8.

Load back into vehicles, and retrace our driving route back to the intersection of Cabezon Road and U.S. Route 550. Turn right to Bernalillo.

END OF FIRST-DAY ROAD LOG

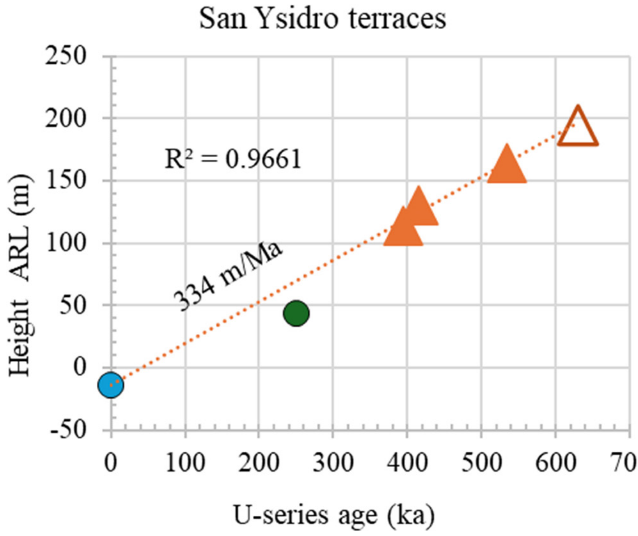


FIGURE 1.33. Regression of the highest three terraces gives a long-term bedrock incision rate of 334 m/Ma and a calculated 14-m depth to bedrock, reinforcing the correlation of the highest terrace with the 630 ka Qt1A Lava Creek B terrace.

Combined references for the First-Day, Second-Day, and Third-Day Road Logs are available on p. 95 and on the NMGS website at: https://nmgs.nmt.edu/publications/guidebooks/downloads/74