Third-Day Road Log: From Circle A Ranch to The Fisher Trail, Nacimiento Mine Site, and The San Gregorio Trailhead

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THIRD-DAY ROAD LOG:

FROM CIRCLE A RANCH TO THE FISHER TRAIL, NACIMIENTO MINE SITE, AND THE SAN GREGORIO TRAILHEAD

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Assembly Point: Circle A Ranch entry road just west of main ranch house
Departure Time: 8:00 AM
Distance: 17 miles
Stops: 3

Views, landmarks, and outcrops are given using the clock system. For example, 12:00 is straight ahead, 9:00 is to the left, and 3:00 is to the right.

SUMMARY

Day 3 of the field conference focuses on areas on the Sierra Nacimiento mountain front near Cuba. Neotectonic uplift and erosion recorded in well-developed fluvial terraces are the focus of Stop 1, which affords an early-morning view of the mountain front and hands-on looks at the evidence for past stream power. We cross to the east side of U.S. Route 550 for Stop 2, visiting the site of the former Nacimiento Mine—once the economic lifeblood of Cuba, now a case study in postmining environmental issues—to discuss Triassic sedimentation, copper mineralization, and groundwater remediation at a newly-accessible set of trails and facilities. For Stop 3, we head high into the Sierra Nacimiento to see Paleoproterozoic granites that represent the basement upon which New Mexico's Phanerozoic geologic history has been constructed. There, we discuss the interplay between hydrology and development, what the oldest rocks on the field trip can tell us, and then (hopefully) tie the conference together with a consideration of feedbacks between rock production, weathering, sedimentation, uplift, and subsidence.

8:00 AM: Depart Circle A Ranch in caravan.

8:20–9:45 AM: Stop 1 involves a short walk up the Fisher Trail toward the top of Mesa de Cuba. From a vantage point atop a late Pleistocene fluvial terrace, we will discuss the geomorphic development of the upper Rio Puerco, the incredible contributions of Kirk Bryan to Four Corners surficial geology specifically and to geomorphology in general, and the climate cycles responsible for fluvial changes in area streams and rivers.

10:00–11:00 AM: Stop 2 brings us to the site of the Nacimiento Mine, a minor producer of copper (mainly) and silver (secondarily) in the 19th and 20th centuries. Open-pit mining left a scar now filled with a lake whose waters are acidic. Together, the open-pit mining and questionable groundwater-based metals extraction techniques in the 1980s left a contamination scenario of mythical proportions. We discuss the causes of mineralization, mining history, and the efforts after the mines closed to bring the site back to geochemical equilibrium.

11:30 AM–?: We end the conference at Stop 3 at 2,800 m (9,200 ft) elevation high in the Sierra Nacimiento. The granites exposed here provide a glimpse into the earliest records of crustal construction in New Mexico, as well as a clue to how rocks like these contribute to the long-term geologic record of New Mexico well after their crystallization and uplift. We discuss (and visit, for those who don't mind a walk of a few hundred meters) the anthropogenic alterations of watersheds that have impacted New Mexico's agricultural lands for centuries. Assuming pleasant weather and good humors, we conclude the conference with a lunch under the aspens and spruces on the bank of Clear Creek, perhaps while basking on a 1.7-billion-year-old slab of the continent.

[Waypoint]
Miles since last entry
Mileage Description

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 left (south) onto U.S. Route 550**.

0.1
0.1 Presciliano's Restaurant and the Frontier Motel.

0.2
0.3 Bridge over the Rio Puerco.

0.2
0.5 **Stay straight on U.S. Route 550.** At left, State Road 126 heads east toward Los Alamos. On this corner stood the Young's Hotel, Cuba's bus stop, supplies center, and social hub for much of the middle and late 20th century

(Fig. 3.01). Built by John Young in 1915, the building stayed in the Young family—a well-known one in Cuba—until its demise in a 2022 conflagration.

0.4
0.9 Just past the gas station, U.S. Route 550 passes over the Rito Leche.

0.6
1.5 **Turn right (west) on State Road 197 toward Crownpoint.**

0.1
1.6 **Turn right (north) on the first road (Cubita Road).** Just north of the turn, Cubita Road passes over the channelized Rito Leche.

0.2
1.8 Humate processing facility at left.

0.2
2.0 Bridge over the Rio Puerco. The confluence of the Rio Puerco and Arroyo San Jose is 150 m (500 ft) upstream (northeast) from here.

0.6
2.6 **Waypoint 3.01 [36.0261°, −106.9735°]**

STOP 1. Turn left into gravel parking lot for the Fisher Trail.

Exit vehicles and proceed on foot up the Fisher Trail about 200 m (650 ft) to a small clearing among the junipers with a good view of the Rio Puerco Valley and Sierra Nacimiento mountain front to the east.

Access to this parking lot and the Fisher Trail have been made possible by the Step Into Cuba program. This community-led program was established in the mid-2010s to promote physical activity—and its associated health benefits—through construction and maintenance of sidewalks, paths, trails, and recreation opportunities in and around Cuba, New Mexico. Over the past ten years, Step Into Cuba has developed beautiful hiking and walking trails like the Fisher Trail. Today's Stops 1 and 2 both make use of infrastructure initiated by Step Into Cuba. For the geologist, the Fisher Trail, the Rito San Jose Trail, and the trails near the Cuba schools all provide easy access to Cuba's world-class geology, and from well-built trails that begin right in town! New Mexico Geological Society member Dr. Richard Kozoll—who also happens to be celebrating his 51st year in 2025 as a physician in Cuba—is a champion of these trails and the Step Into Cuba program. Thanks for the trails, Dick! Here's to many more miles of happy hiking. Please slow down so the rest of us can keep up.

Figure 3.01. Photograph from a 1950s picture postcard for Young's Hotel in Cuba. Postcard is captioned, "Young's Hotel, Cuba, N. Mex., Home of the Sunken Fireplace. Gateway to Navajo and Apache Reservations. Hunting-fishing in season. Antique and foreign gun collection. Headquarters for photography and photo supplies. Also Headquarters for Young's Sawmill and complete welding service." Many older Cubanos remember meetings around the fireplace here. The hotel also served as a bus stop for Trailways and Greyhound service between Albuquerque and Durango. The building and all its contents were destroyed by fire in May 2022.

The Fisher Trail ascends the east slopes of Mesa de Cuba, which is capped with the Cuba Mesa Member, the basal member of the San Jose Formation. The parking lot and lower portions of the trail are on the upper Nacimiento Formation. Both the Nacimiento and San Jose Formations here consist of sandstones, siltstones, and mudstones deposited in fluvial systems during the early stages of the Laramide orogeny in the early Paleogene Period. There are isolated lenses of conglomerate in both formations, but they are rare and their largest clasts are only pebbles (maximum clast diameter 6.4 cm [2.5 in]). Like many of the Cretaceous and Paleogene sandstone-dominated landscapes of the San Juan Basin, Mesa de Cuba produces impressive sandy soils and sand-bed arroyos. The arenites of the San Jose and Nacimiento Formations disaggregate quickly upon weathering; eroded clasts of sandstone are largely absent except at the bases of steep cliffs.

As you ascend Fisher Trail, notice the pebbles, cobbles, and boulders alongside the path and capping the small rise that the trail climbs. These subrounded to rounded clasts are a who's who from a freshman geology lab on crystalline rocks: granite, diorite, granodiorite, quartz monzonite, amphibolite, alaskite, and schists abound. The history of these clasts involves a complex interplay of climate, tectonics, geomorphology, and hydrology that has made the upper Rio Puerco the subject of study by geomorphologists for nearly a century.

Early Rio Puerco Geomorphology Investigations

In 1936, the influential western geologist Kirk Bryan published "Successive Pediments and Terraces of the Upper Rio Puerco in New Mexico" in *The Journal of Geology* with co-author Franklin McCann (Bryan and McCann, 1936). Bryan, who was born in Albuquerque 24 years before statehood and was awarded one of the first-ever bachelor's degrees in geology from the University of New Mexico in 1909 (Sharp, 1993), had likely visited the area since his childhood. In the 1936 paper, Bryan and McCann noted that the Rio Puerco Valley near Cuba "has been marked by the development of a series of successively lowered, stabilized, local base levels whose existence is recorded by multiple pediments and terraces." At Stop 1, we climb upon one of these geomorphic surfaces and get a world-class view to the east of several others (Fig. 3.02). Bryan and McCann's (1936) mapping and descriptions are impressive for their accuracy, detail, and coverage. That they made them prior to aerial imagery, large-scale topographic maps, or GPS, makes them all the more remarkable. Even after nearly a century, their interpretations of the causes of and relationships between these pediments and terraces, and the surfaces' relationships to uplift, erosion, and climate, remain sound.

Bryan and McCann proposed four broadly defined stages of landscape development that are preserved in the topographic features of the upper Rio Puerco (Fig. 3.03). They named the highest and oldest ones "residual areas" that have remained above planation surfaces throughout the development of the Rio Puerco. These residual areas include the high country of the Sierra Nacimiento, Mesa de Cuba, Mesa La Ventana, and a few isolated sandstone cuestas of the Dakota and Menefee Formations near San Miguel. All the residual areas are above the planes projected by the next youngest surface, the La Jara surface.

The La Jara surface is the oldest widely distributed preserved geomorphic surface in the valley. It exists 55 to 65 m (180 to 210 ft) higher than modern stream grades, although this height is difficult to ascertain in some higher headwater drainages where stream captures after the deposition of La Jara surface sediments complicate gradient and incision histories. The La Jara surface is named after the drainage of La Jara Creek, just north of Circle A Ranch and the Rito de los Pinos drainage, where it is widely distributed. The La Jara surface primarily is a pediment on the east side of the Rio Puerco and its tributaries. This pediment is graded to the paleo-Rio Puerco, and there also are La Jara surface fluvial terraces along that stream. Bryan and McCann (1936) concluded that the streams draining the Sierra Nacimiento at the time of La Jara surface development "had a relatively strong flow and carried a characteristically granitic gravel." On the west side of the Rio Puerco and its tributaries, the La Jara surface is less well-preserved. Any west-side geomorphic surfaces developed at La Jara time would have consisted of sandy and muddy sediments due to the Paleogene sedimentary bedrock in those portions of the drainage. These materials are less likely to preserve geomorphic surfaces for as long as the granitic gravels derived from the Sierra Nacimiento. Bryan and McCann (1936) suggested that the broad upper valleys of the Arroyo Chihuile *[sic]* (now the Arroyo Chijuilla) drainage likely correspond to the La Jara surface but that further work was needed to test that hypothesis. After 89 years, it remains untested.

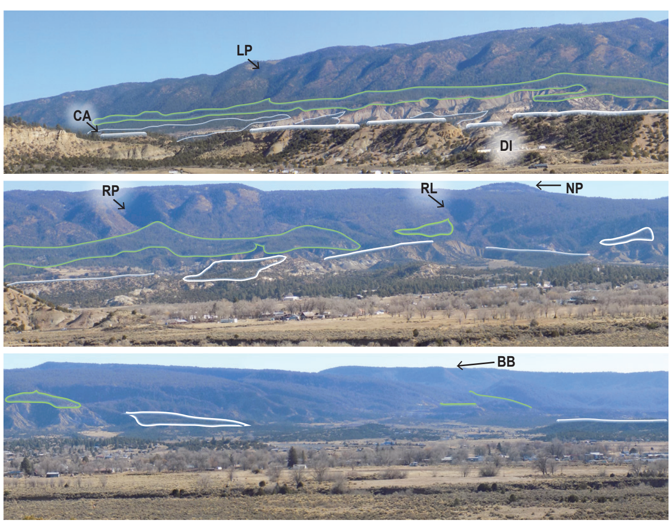

Figure 3.02. Annotated panoramic photograph of the Sierra Nacimiento mountain front viewed from the Fisher Trail parking lot at Stop 1. Panorama is split into 3 sections; left (north) end is on the top, and the right (south) end is on the bottom. Green lines and outlines indicate the La Jara pediment/terrace of Bryan and McCann (1936). White lines indicate the Rito Leche surface. CA = Circle A Ranch. LP = Rito de los Pinos canyon. DI = drive-in theater location. RP = Rio Puerco canyon. RL = Rito Leche canyon. NP = Nacimiento Peak. BB = Blue Bird Mesa. The alluvium of Arroyo San Jose is in the foreground.

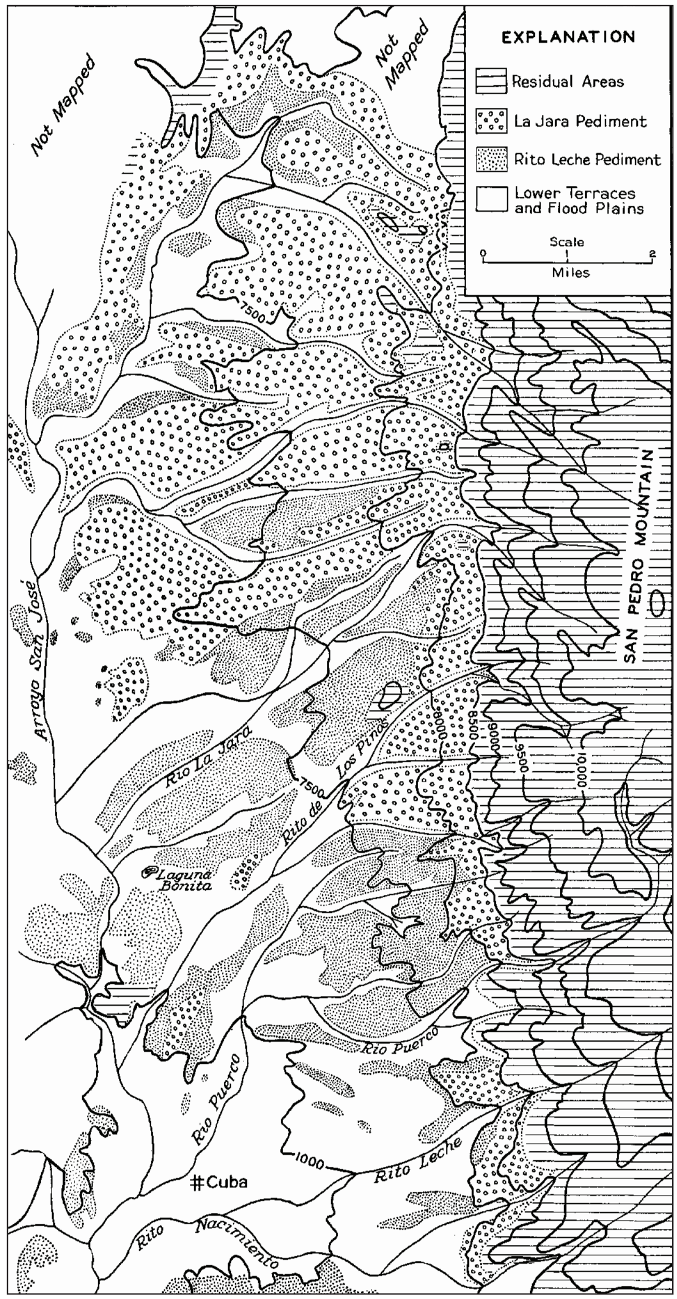

Figure 3.03. Bryan and McCann's (1936) map, which is captioned, "Map showing remnants of the La Jara and Rito Leche pediments near Cuba, New Mexico."

On day 1, we drove through the upper Arroyo Chijuilla drainage between Stops 1 and 2. Above La Ventana, the La Jara surface gravels of the main stem of the Rio Puerco are difficult to distinguish from those of east-side tributaries based on composition or texture. Downstream from La Ventana and as far as at least Cabezon, however, the gravels of the main stem are notably more rounded than those of the tributaries (Bryan and McCann, 1936).

The Rito Leche surface developed after the La Jara surface, into which it is inset. The Rito Leche surface exists approximately 20 to 26 m (65 to 85 ft) higher than modern stream grades. This surface is a broad pediment rising from the paleo-Rio Puerco to the foot of the Sierra Nacimiento. The remnants of the La Jara surface stand above but parallel to this sloping surface. One interesting facet of the Rito Leche surface noted by Bryan and McCann (1936) and clearly evident in topographic maps and remote sensing imagery is that the slope of the remnants of the Rito Leche surface are sometimes considerably different from those of the modern stream (Fig. 3.04). This author agrees with Bryan and McCann's interpretation that post-Rito Leche surface stream captures have significantly altered the courses and drainage areas of streams between Regina and San Miguel. It is likely that the paleo-Rito Leche responsible for the deposition of the Rito Leche surface pediment and terrace gravels had a considerably larger drainage area and associated greater stream power than the modern Rito Leche. The topographic divide between the Rito Leche and the Rio Puerco at the proposed capture point is low (Fig. 3.05). The Rito Leche terraces along the main-stem Rio Puerco are traceable to at least Cabezon, and possibly as far as Guadalupe.

The youngest geomorphic surfaces in the upper Rio Puerco Valley are two sets of fluvial cut terraces, one at 7 to 9 m (25 to 30 ft) above modern stream grade, and another at approximately 3.5 m (12 ft) above modern stream grade. These are limited in areal extent and difficult to match to widely developed pediments on the Sierra Nacimiento mountain front.

Geomorphic Development of the Sierra Nacimiento Mountain Front

The oldest widely preserved geomorphic surface, the La Jara surface of Bryan and McCann (1936), formed at a time when the Sierra Nacimiento mountain front had about 100 m (330 ft) less relief above the valley to the west than it has now. The landscape on and west of the mountain front was largely a low-relief plain with a few cuestas made of resistant Dakota and Menefee Formations. Broad, flat-floored valleys penetrated eastward into the mountain mass. Episodes of deep weathering led to thick regolith developed on crystalline bedrock in the Sierra Nacimiento. The fractured nature of this bedrock (seen at Stop 3 today) facilitated the formation of cobble- and boulder-sized clasts through core-stone weathering. These clasts were transported down the paleo-Rio Puerco during episodes of much greater stream power than exists today. In addition to episodes of greater stream power, there also were episodes of considerable soil development and accumulation of fine-grained sediment on these surfaces, even near the mountain front (see Day 1 road logs); hence, the thick soils and development of agriculture on these surfaces above Cuba.

La Jara surface sediments have not been dated. They are prime targets for future detrital grain dating or luminescence dating and such data would fill a crucial gap in Quaternary geochronology in the eastern Colorado Plateau and southern Rocky Mountain provinces. Based on published long-term incision rates from nearby regions—particularly the middle Rio Grande and the upper San Juan River (Dethier, 2001)—and the height of the La Jara surface above modern grade, the La Jara surface likely developed between 600 and 333 ka, using a minimum incision rate of 10 cm/ky (Izett and Wilcox, 1982; Dethier, 2001) and a maximum rate of 18 cm/ky (Dethier et al., 1990).

After development of the La Jara surface, there was widespread lowering of base level. Streams incised into the previous pediment while main-stem fluvial terraces were abandoned and left well above new stream grades. Streams draining the highlands of the Sierra Nacimiento, which during La Jara time had many shifting outlets into the Rio Puerco Valley, were confined to the San Jose, Rito Leche, San Pablo, San Miguelito, and San Miguel canyons where they carved deep notches through the steeply dipping Mesozoic section (such as the one we drove through just prior to Stop 4 on Day 1; see Fig. 1.74). West of the mountain front, remnants of the La Jara surface persisted as long low-sloping ridges parallel to the Rito Leche surfaces. Based on published incision rates from nearby river basins, the Rito Leche surfaces likely developed between 250 and 139 ka, although this is based on long-term incision rates since the deposition of the Lava Creek B ash at ~640 ka and should be interpreted cautiously and with healthy skepticism. Geochronology of the Rito Leche surface deposits is likely complex and should be a priority for future neotectonicists.

The Rito Leche surface was abandoned in the Late Pleistocene when the Rio Puerco and its tributaries entered a long and still-ongoing episode of downcutting. A few short-duration episodes of backfilling produced the lower and rarer fluvial terraces noted by Bryan and McCann (1936) at ~8 and 3.5 m (~26 and 11 ft) above the modern stream, but they are difficult to link to any widespread pedimentlike surface on the mountain front. They likely correspond to short regional climate cycles or potentially to small stretches of the system readjusting their stream power after upstream stream piracy events.

Climate and Tectonics Implications

The gravel-dominated deposits of the La Jara and Rito Leche surfaces of Bryan and McCann (1936; Fig. 3.07) were a priori deposited by streams with enough power to transport them. Some of these clasts are considerably larger than the ones found in Holocene alluvium of streams in the same locations (Fig. 3.07A). Although the alluvial systems that existed during deposition of sediments atop both the Rito Leche and La Jara surfaces occasionally were relatively low power (see fine-grained sediments in terrace outcrops in Figs. 1.02, 1.03, and 3.07), the landscape seems to have undergone the most geomorphic alteration during episodes of higher stream power. The modern-day Rio Puerco in this area transports little material coarser than pebbles and is predominated by sand and silt.

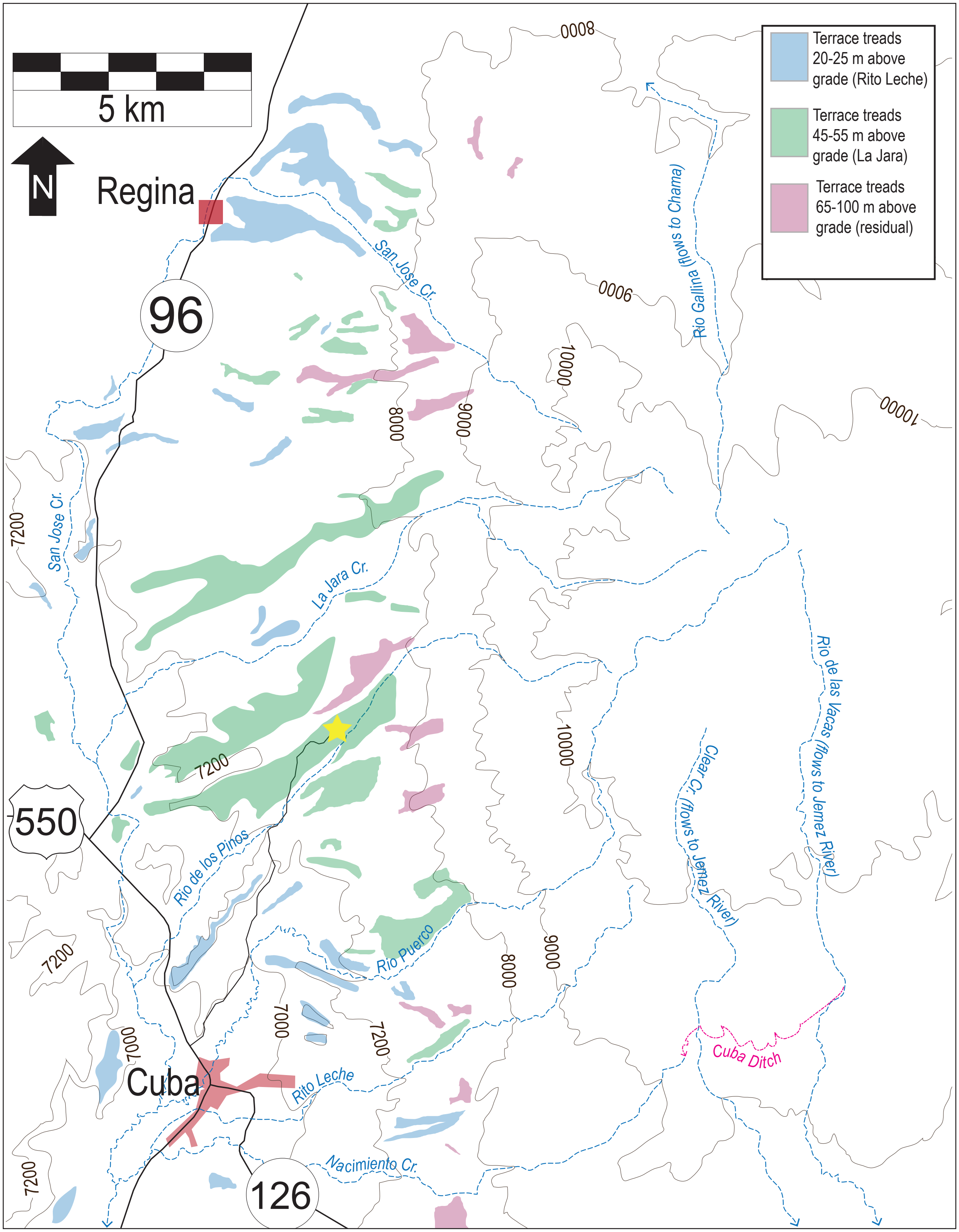

Figure 3.04. Updated map of geomorphic surfaces on the northern Sierra Nacimiento mountain front. At this scale, only large surface remnants can be shown; smaller remnants of all 3 surfaces abound throughout the area. The Cuba Ditch, shown in pink at bottom right, for a time diverted waters of the upper Jemez River from the Rio de las Vacas and Clear Creek into Nacimiento Creek in order to increase irrigation availability for farmers in and near Cuba. The ditch is now unused but still recognizable in the landscape. Yellow star marks the Circle A Ranch.

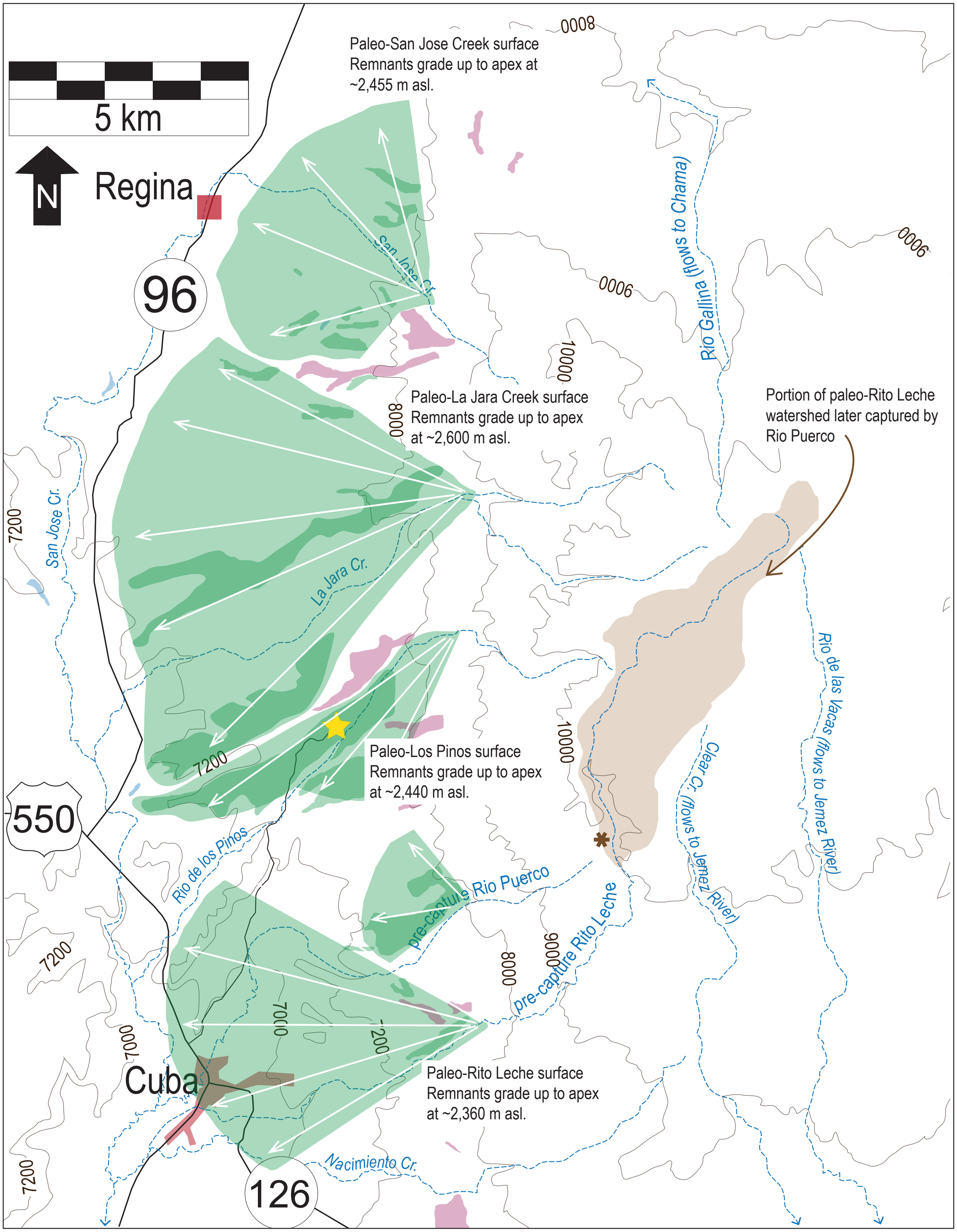

Figure 3.05. Paleogeographic interpretation of the Sierra Nacimiento mountain front at the time of development of the La Jara surface of Bryan and McCann (1936). The pediments associated with these surfaces would have covered essentially the entire mountain front in the Late Pleistocene. Given the size and slope of terraces that grade to the mouth of the canyon of the Rito Leche and the geography of the uppermost Rio Puerco and Rito Leche, it is hypothesized that the Rito Leche watershed once included what is now the upper Rio Puerco watershed (the brown-shaded area) prior to stream capture sometime after deposition of the La Jara surface gravels.

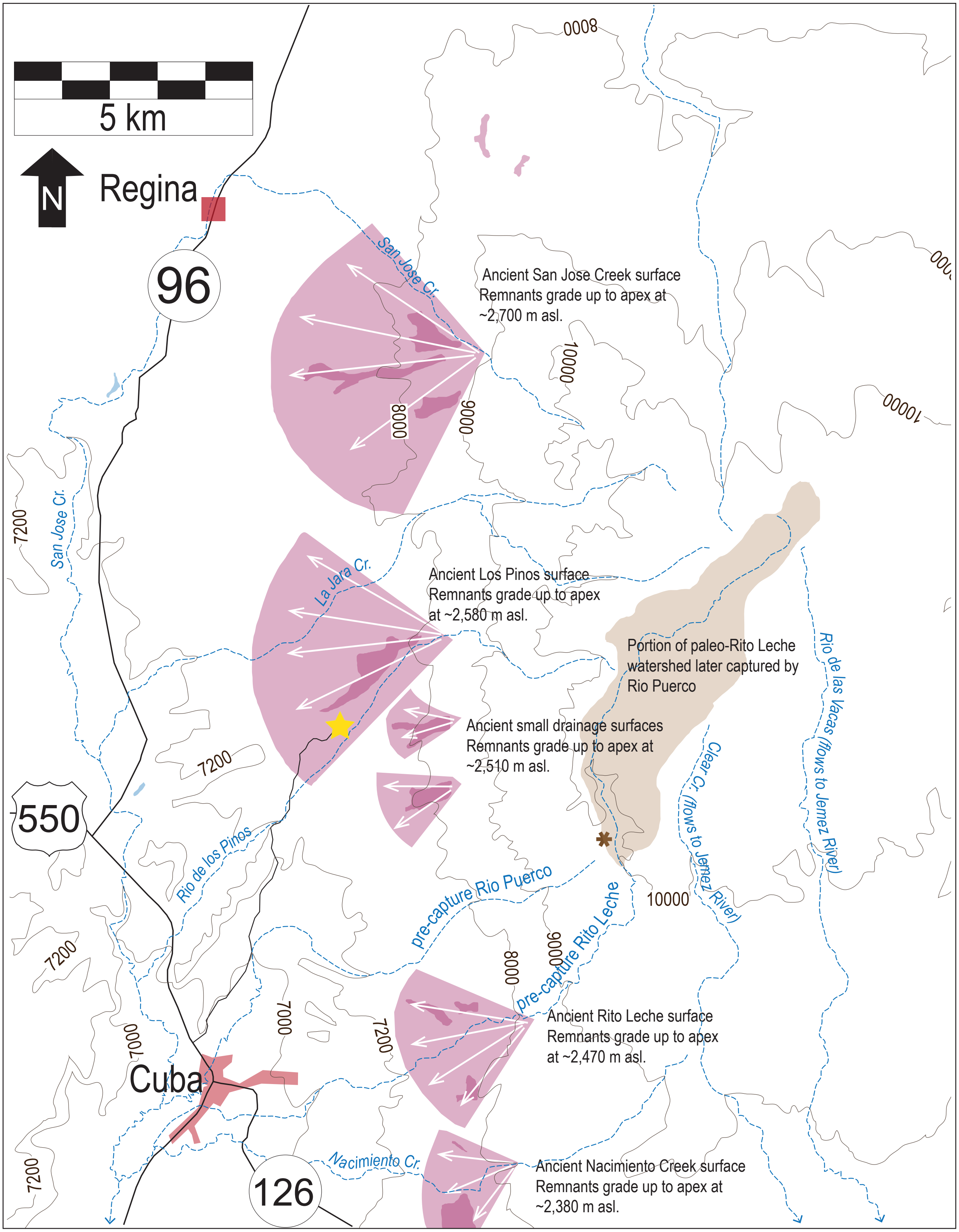

Figure 3.06. Paleogeographic interpretation of the Sierra Nacimiento mountain front prior to development of the La Jara surface of Bryan and McCann (1936). Fewer remnants of geomorphic surfaces stand above the La Jara surface than there are of younger surfaces, so this interpretation is conjectural. It is possible that significant migration of drainage divides, including potentially the Continental Divide, has occurred since deposition on these older surfaces, particularly in the headwaters of San Jose Creek near Regina.

This raises the question, "What changed?" The Pleistocene Rio Puerco must have been an impressive gravel-bed stream, at times transporting and depositing cobbles and boulders. Today, it is relatively feeble, receiving essentially no sediment load from the crystalline-cored highlands to the east and scarcely able to transport its silt and sand-dominated load. A simplified model of the factors contributing to aggradation and degradation in alluvial streams was put forth by Rosgen (1996) after the fundamental concepts introduced by Lane (1955; Fig. 3.08). If the factors that drive stream incision (i.e., degradation) and the factors that drive sediment deposition (i.e., aggradation) are considered in terms of a balance, then one can imagine numerous potentially minor changes that can shift a fluvial system. In the context of the Pleistocene-to-Holocene changes in the upper Rio Puerco (broadly speaking, a change from an aggrading stream system transporting coarse gravel to a degrading stream system transporting sand and fine sediment), a few scenarios should be considered: perhaps the sediment load decreased, the stream slope increased, the discharge increased, or the average sediment particle size decreased.

Considering the possibility that the sediment load decreased, we look for a potential cause, including decreasing sediment production in the stream's headwaters. Climate-driven changes, such as a general decrease in soil moisture and increase in the elevation of periglacial environments associated with the Pleistocene-to-Holocene transition (Brakenridge, 1978), could cause the reduction in weathering rates responsible for a lowered rate of sediment production. While a change in stream slope is a viable mechanism for altering stream power, it can be rejected as a potential cause for observed changes in the upper Rio Puerco on account of the La Jara and Rito Leche surfaces being parallel to the modern Rio Puerco gradient. A decrease in discharge is another viable mechanism to consider: while average annual precipitation in the Pleistocene glacial episodes was likely the same as or slightly less than modern amounts, decreased temperatures and a lower snowline likely led to increased stream discharge during some intervals (Anderson, 2001; Dethier, 2001). As average temperatures and the average annual snowline rose across and after the Holocene transition, stream discharge in the Rio Puerco—as well as most southwestern streams—likely decreased, along with stream capacity to transport coarse and/or abundant sediment. Finally, we consider the possibility that a decrease in particle size in the stream's sediment load was the causative factor for the change to a degrading Rio Puerco. This factor is difficult to explain without a more complicated interplay among other factors or a deus ex machina of stream capture introducing a geologically unique sediment source to the system. The headwaters of all the Rio Puerco tributaries are geologically uniform, with crystalline rocks upstream of the Phanerozoic section. Because of this, a decrease in sediment size alone (i.e., in the absence of any other changes) seems to be an unlikely cause for degradation of the Rio Puerco in the late Quaternary.

After stop, return to vehicles and drive south on Cubita Road.

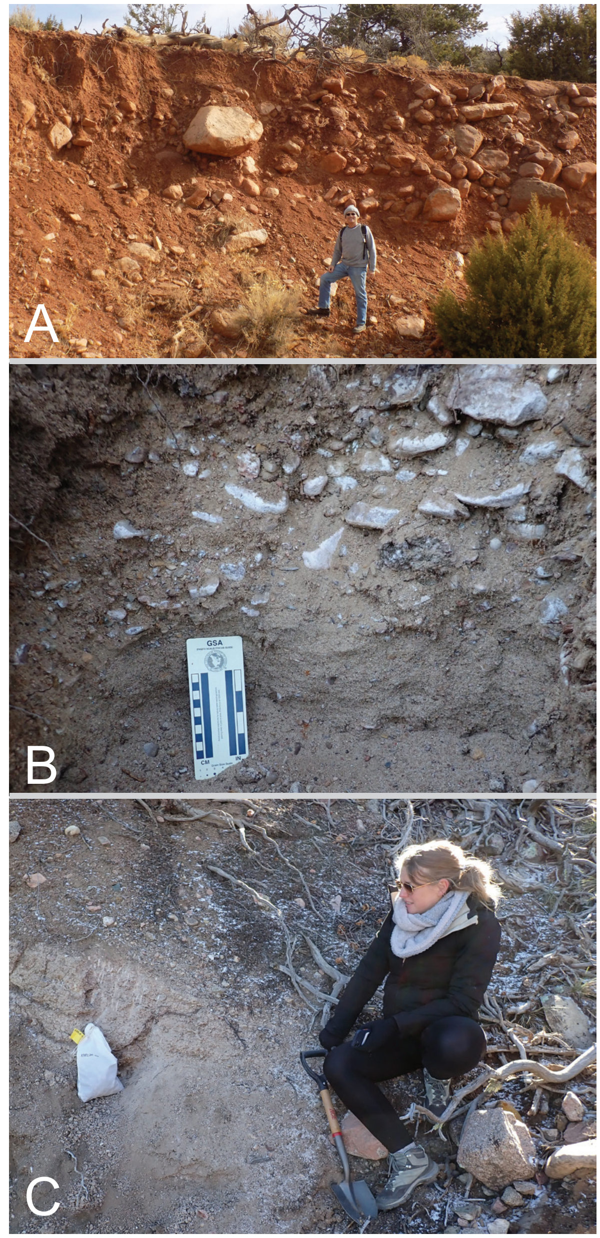

Figure 3.07. Field photographs of gravels deposited on Sierra Nacimiento mountain front geomorphic surfaces. A: Boulder gravel in a Rito Leche surface at the Nacimiento Mine site, probably deposited by the paleo-Rito Leche. Largest clasts are >1.6 m (>5.3 ft) diameter; all clasts are of crystalline rock. Note the appreciable proportion of sand in the deposit. B: Pebble- and cobble-gravel on the La Jara surface at a site 5 km (3.1 mi) upstream from La Ventana. These clasts' stratum is host to a Stage II Bk soil horizon, but pedogenic carbonate development on sandy and gravelly terrace deposits is notoriously capricious. The clasts here are angular to subangular; Bryan and McCann (1936) remarked that there is little difference in rounding between tributaries and the main stem of the Rio Puerco until downstream of La Ventana. This site's position ~400 m (~1,300 ft) away from the present-day Rio Puerco suggests it likely was a main-stem deposit. All clasts are of crystalline rock. Note the well-sorted sand just to the right of the photo scale; some of this sand was collected and is being analyzed for detrital sanidine geochronology as of this writing. C: A Rito Leche surface deposit near the Rio Puerco at the mouth of Rio de los Pinos near La Ventana. The sediments are well indurated into a Stage III+ Bk soil horizon. Note the size of clasts weathering out of this deposit at bottom right. Most clasts in this deposit were pebbles, with trace boulders. This site was also sampled for detrital sanidine geochronology but results are not available as of this writing.

0
2.6 **Drive south on Cubita Road.**

1.0
3.6 **Turn left (east) on State Road 197.**

0.1
3.7 **Intersection with U.S. Route 550. Proceed straight across to the east when the way is clear.**

0.1
3.8 U.S. Forest Service Cuba Ranger District Station on the left. The dense willows just south of the Ranger Station mark the course of Nacimiento Creek, which heads at Nacimiento Peak near today's Stop 3.

0.1
3.9 **Turn left (east) onto Southern All-Around Road.**

0.5
4.4 Sandoval County transfer station on the left.

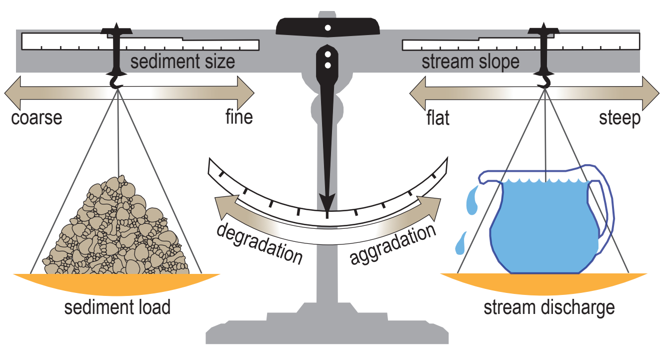

Figure 3.08. Schematic diagram showing the driving and resisting factors affecting stream aggradation and degradation. Modified from Rosgen (1996) after Lane (1955).

0.2
4.6 At left, a good view of the geomorphic surfaces emanating from the mountain front above Cuba (Fig. 3.09).

0.6
5.2 **Road terminates at State Road 126. Turn right (south) on State Road 126.**

0.2
5.4 In a curve to the left, a 45-m-high (150-ft-high) mountain front terrace lies from 10:30 to 12:00, probably comprising ancient deposits of Nacimiento Creek.

0.7
6.1 Crest of hill. Badlands outcrops of the Kirtland Formation on left.

0.7
6.8 **Stay straight on State Road 126.** Intersection with Eureka Mesa Road to the north and Duke City Road to the south.

0.6
7.4 Note the hogback/cuesta ahead. The road curves to the right/south and enters a strike valley developed in the Lewis Shale.

0.7
8.1 **Waypoint 3.02 [35.9813°, −106.9154°]**
Pass through hogback. An overturned section of the Mesaverde Group, here comprising the Point Lookout Sandstone, Menefee Formation, and the La Ventana Tongue of the Cliff House Sandstone, is exposed in an intensely deformed cuesta (Fig. 3.10). These are the same units seen at yesterday's Stop 1. The valley to the east is underlain by the Mancos Shale.

Figure 3.09. Annotated panoramic photograph of the Sierra Nacimiento mountain front looking northeast from the Southern All-Around Road. Photograph is vertically exaggerated 250% to highlight subtle topographic detail. Blue arrows mark the Rito Leche terrace surface. Green arrows mark outcrop exposures of the La Jara terrace surface. Green shaded areas mark approximate locations of remnant fan-pediments of the La Jara surface. The valley of the lower Rito Leche and Nacimiento Creek is in the foreground.

Figure 3.10. State Road 126 roadcut through the Mesaverde Group on the Sierra Nacimiento mountain front. Top: View to the north of the north side roadcut. Overturned beds of the Menefee Formation dip eastward. The valley at left (west) is formed in the Lewis Shale, the lower portions of which are seen in the bottom left of the outcrop next to the road. The Point Lookout Sandstone forms white outcrops in the middle distance at right. Bottom: View to the south of the south side roadcut. Intensely deformed and faulted coaly units of the Menefee Formation exhibit a variety of dip angles; in general, the units are dipping about 80° to the east (left).

0.5
8.6 Dakota Formation at left is dipping about 50° to the east (toward the Nacimiento fault) as part of the same overturned section exposed a half-mile back at the cuesta road-cut. The outcrop here is nearly buried beneath spoils dumped from the nearby Nacimiento Mine.

0.4
9.0 Bridge over Señorito Creek.

0.1
9.1 Sign indicating entrance into the Santa Fe National Forest.

0.3
9.4 **Turn left (north) into Nacimiento Mine site.**

0.3
9.7 **Waypoint 3.03 [35.9903°, −106.8974°]**

STOP 2. Park in trailhead parking lot at the top of the hill just past the fenced-off ponds on the right.

Access to this site is relatively new and involved a collaboration between local trails groups, the Continental Divide Trail Alliance, and the Santa Fe National Forest. The newly rerouted Continental Divide Trail passes through the former mine site here before climbing the mountains to the east into the San Pedro Parks Wilderness.

The Nacimiento Mine

The Nacimiento Mine is the largest, most-heavily exploited, and most recently abandoned of several copper mines on the Sierra Nacimiento mountain front between San Miguel and Cuba. Sporadic mining and smelting by Spanish colonists or Indigenous people may have occurred, but records are anecdotal (Walsh, 2003). Copper mining at the site likely started in 1881 and continued to the early 1900s. Development of short adits and shallow workings continued sporadically, largely dictated by market forces, through the late 1960s.

In 1970, a pit was opened to economically exploit the copper-mineralized zone along the steeply dipping strata. The pit was deepened until 1975 when increasing costs of overburden removal and spoils transportation, groundwater seepage, and a mine wall collapse led to the mine's closure. Low-grade ore piles (Fig. 3.11) were left on site after pit mining operations ceased.

In the early 1980s, a new mining operation attempted to recover copper from unmined ore by in situ leaching. This process entailed injecting sulfuric acid into the copper-hosting strata, manipulating groundwater flow via extraction wells, extracting the sulfuric acidic groundwater (now laden with dissolved copper), and precipitating copper from solution at the surface. The chemical fundamentals of the process are well established and widely used in heap-leach mining methods; and in situ leaching simply removed the need for ore removal prior to leaching. The major difference is that heap-leaching occurs in engineered environments that, if properly functioning, prevent the loss of contaminated waters into the natural environment. In situ leaching as applied at the Nacimiento Mine lacked similar engineered safety checks. The operation used 27 wells for injection and recovery ranging in depth from 58 to 125 m (190 to 410 ft) below ground surface and set in the copper-bearing portion of the Agua Zarca/Shinarump Sandstone (Fig. 3.12). In situ leaching occurred at the Nacimiento Mine until 1991. There were no groundwater reclamation activities prior to abandonment (Cowart et al., 2004; Sinclair and Thompson, 2015).

Copper at the Nacimiento Mine occurs primarily as azurite, malachite, chrysocolla, cuprite, antlerite, and spangolite, with abundant secondary chalcocite. Native copper was present at the site but is rare. Ore minerals are disseminated in sandstone pores as well as in veins and cement. Carbonaceous material, especially woody material, in the host rock seems to have induced mineralization. Many mineral museums and private collectors hold chalcocite-replaced wood from the Nacimiento Mine (Mustoe, 2018; Fig. 3.13).

The host for the mineralized zone was originally mapped as the Triassic Agua Zarca Member of the Chinle Formation by Woodward et al. (1973) but later referred to as the Agua Zarca Sandstone of the Chinle Group (Cowart et al., 2004; after Lucas and Hunt, 1992). Now it is known as the Shinarump Formation (Lucas et al., 2005b). If this is confusing to you, then fret not! Stratigraphers will surely think up a new name soon enough; maybe that one will please you. No matter the formation's name, the ore zone has medium- to coarse-grained subarkosic arenites with minor conglomeratic lenses that seem to have induced mineralization (as green- and blue-hued rounded pebbles abound) in a 20–30-m (66–98-ft)-thick multistory sand package. The sediments were deposited around 225 Ma in broad, low-relief fluvial systems in an intracratonic setting by west-flowing rivers draining the remnants of Pangean highlands to the east and southeast.

Contamination and Cleanup

The Nacimiento Mine is one of countless mines throughout the United States that was left contaminated when operations ceased. As usual, taxpayers have been responsible for cleanup at the Nacimiento Mine site, and our expenditure is nearing completion as of this field conference. The combination of geology, groundwater, access, and regulations have made for a unique remediation effort that hopefully will never need to be repeated.

The in situ leaching method left about 25 million gallons (95 million liters) of contaminated groundwater (Cowart et al., 2004). Given the site's position above Cuba, there was legitimate concern of contaminated groundwater affecting the community's water supplies. Initial groundwater monitoring at the site after in situ leaching but prior to remediation efforts found groundwaters with pH values as low as 2.2 and dissolved copper concentrations as high as 385 mg/L—nearly 300 times the maximum level allowed by the Environmental Protection Agency (EPA) for drinking water (1.3 mg/L).

A preliminary study by Cowart et al. (2004) showed that

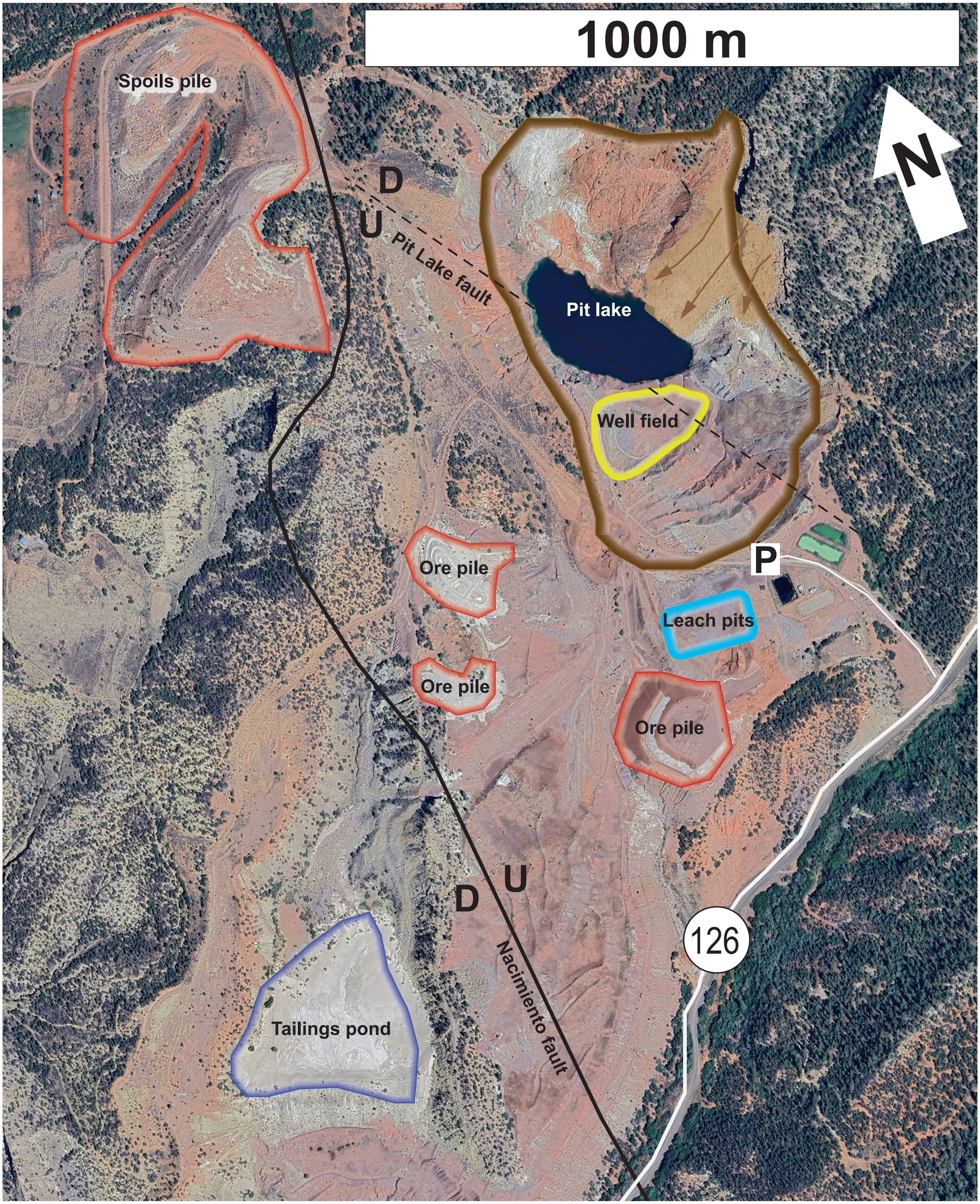

Figure 3.11. Annotated aerial photograph of the Nacimiento Mine site. The parking site for Stop 1 is marked with a "P" near the location of former leach piles and ponds, since removed. Three low-grade ore piles are capped with native soil to encourage vegetation. The ponds just northeast of the parking site are part of the modern groundwater remediation project. The approximate extent of the 1970s open pit is marked in brown. A rockfall into the pit, marked in shaded brown with arrows indicating direction of motion, is still visible on the pit's east side extending into the lake. The locations of the Pit Lake and Nacimiento faults are approximate and based on interpretations of mapping of Woodward et al. (1970) and transferred to modern aerial imagery; actual locations might vary by as much as 100 m.

essentially no natural attenuation of groundwater acidity had occurred in the first 12 years after cessation of in situ leaching and that a minimum of 50 years would be required for natural attenuation under ideal conditions. Given these conclusions, the U.S. Forest Service, who manages the land on which portions of the mine site are located, decided to pursue active remediation. Former leaching ponds were closed, capped, and sealed in 1998. A pump-and-treat groundwater system came online in 2007 and operated until early 2025. During that interval, around 110 million gallons (416 million liters) of contaminated water were treated in a semipassive alcohol-enhanced rock bioreactor system (Tsukamoto and Weems, 2010).

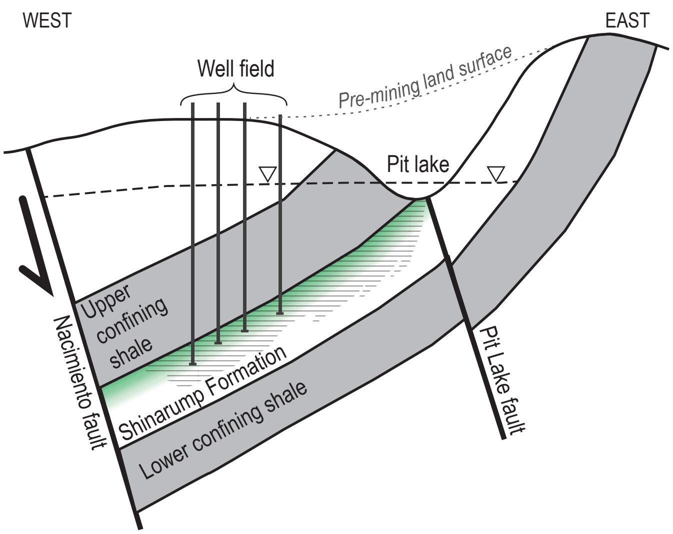

Figure 3.12. Schematic cross section through the Nacimiento Mine site. The open-pit method of mining became uneconomical in the 1970s due to increasing depth of the ore zone in the top of the Agua Zarca Sandstone/Shinarump Formation, indicated in green. The pit had also reached lower than the local water table. After open-pit mining ceased, the pit filled with water to a level equal to the local water table, forming the pit lake. Economically viable grades of ore remain in the subsurface. These were exploited via in situ leaching with injection and recovery wells in the well field illustrated. After in situ leaching ceased in 1991, pH levels in the Agua Zarca Sandstone/Shinarump Formation aquifer were as low as 2.2. Later groundwater remediation efforts used wells in roughly the same location as the well field shown here. Wells were 58 to 125 m (190 to 410 ft) total depth below ground surface. No scale implied. Modified from Cowart et al. (2004).

This system operated by extracting acidic groundwater containing high levels of dissolved metals and sulfates that was then pumped into a settling pond for the removal and storage of solids and sludge. Sodium hydroxide (aka lye) was added to the settling pond to enhance metal-hydroxide precipitation. Water was held temporarily in the settling pond, then piped into a rock-matrix bioreactor seeded with sulfate-reducing bacteria. Ethanol was added into the bioreactor to feed the bacteria an energy and carbon source, thus keeping alive the centuries-old tradition of laborers at mines being placated with the world's most common psychoactive depressant. The simplified bioreactor chemistry is as follows:

<u>Sulfate Reduction</u>

$$C_2H_6O + SO_4^{2-} + H^+ \rightarrow CO_2 + H_2S + H_2O$$

ethanol + sulfate + acidity →
carbon dioxide + hydrogen sulfide + water

<u>Sulfide Precipitation of Minerals</u>

$$H_2S + M^{2+} \rightarrow MS + H^+$$

hydrogen sulfide + metal ions →
metal sulfides + hydrogen ions

The bioreactor used a crushed rock substrate to provide the pore space into which metal sulfides would be precipitated. The ponds adjacent to the parking area for Stop 1 are one of the last stages of active groundwater remediation here. Treated waters were aerated in these ponds and a concrete-step aerator chute (seen on the drive into the mine site) before being discharged to Señorito Creek.

An analysis of treated effluent at the Nacimiento Mine site bioreactor by Tsukamoto and Weems (2010) found that the

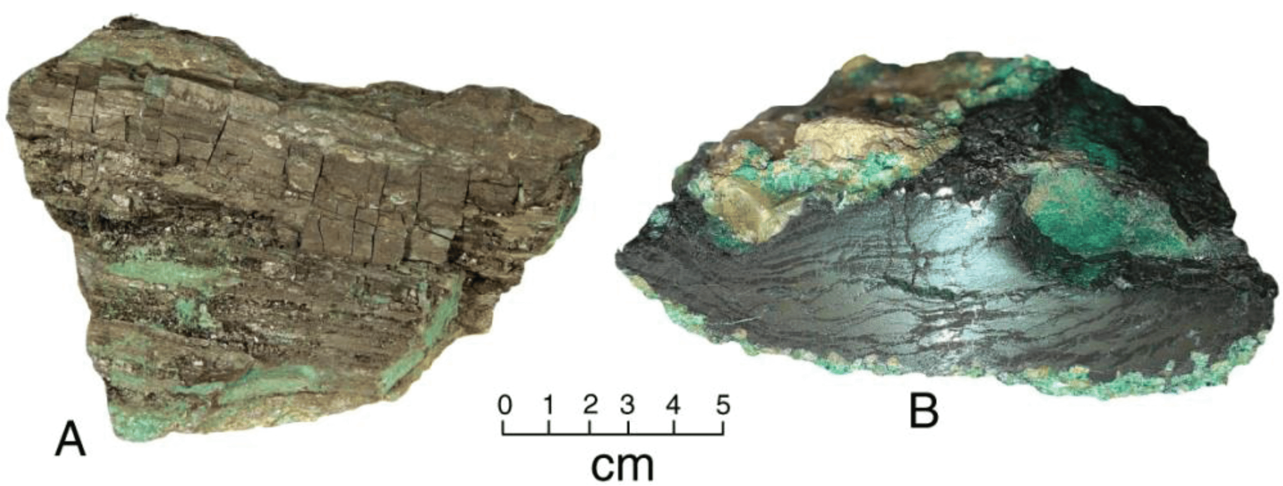

Figure 3.13. Copper-mineralized wood from the Nacimiento Mine, New Mexico. A: Carbonized wood in sandstone matrix stained green from malachite. B: Polished sawn surface. Wood has been replaced by chalcocite and is encased in malachite-bearing sandstone. Image from Mustoe (2018).

process raised pH to 6.9, reduced dissolved sulfate from 884 to 385 mg/L, and reduced dissolved copper from an average of 25 mg/L to 0.004 mg/L. As of this writing, most equipment associated with the bioreactor pump-and-treat system has been removed and the site is being repurposed as the trailhead where we parked for Stop 2.

After the stop, return to cars, then drive back to the intersection of the Nacimiento Mine entrance road and State Road 126.

0.3
10.0 **Turn left (east) on State Road 126.**

0.1
10.1 Beginning here and continuing for the next mile, deep red sandstones of the Permian Abo Formation crop out on the north (left) side of the highway. Note the moderate west dips, essentially opposite the direction we travel here.

0.3
10.4 On the right (south) side of the highway, note the appearance of Douglas-firs (Ch'ó deenínii; *Pseudotsuga menziesii*) on the hillside. Douglas-firs are among the most widespread gymnosperm trees in the Americas, ranging from central Coahuila, Mexico, to central British Columbia, Canada. In New Mexico, they are found at elevations from ~2,100 to ~3,050 m (~6,900 to ~10,000 ft) in highlands and mountains. Neither a true fir (genus *Abies*) nor a true hemlock (genus *Tsuga*), the Douglas-fir genus is sometimes split into two species: one on the Pacific coast from California to British Columbia and another in interior mountains and highlands from Coahuila to central British Columbia. Douglas-firs are one of the few trees on Earth that reach heights greater than 100 m (328 ft), and they might have been the tallest trees ever to have existed before logging removed the largest specimens. A Douglas-fir in Whatcom, Washington, measured 142 m (465 ft) tall when felled in 1896. Our versions are less vertiginous, with the tallest known specimen in New Mexico reported at 51 m (168 ft) height and 148 cm (58 in) diameter. Douglas-fir cones (Fig. 3.14) are easy for the amateur to identify on account of the papery bracts that look like the back half of a mouse hiding among the cone's recesses.

0.7
11.1 Enter right-hand hairpin curve, the first of several in the next mile.

0.9
12.0 Forest Road 533 takes off to the right. This road connects to an impressive network of graded unpaved roads that one can travel to the Gilman Tunnels, Fenton Lake, the upper Rio San Antonio, and lower Rio de las Vacas. This author recommends night bicycle rides on the June full moon along these roads.

0.6
12.6 Straight ahead, a view of the cliff-face Eureka Mine (Fig. 3.15). This mine was operated intermittently between the 1880s and 1950s. Like the Nacimineto Mine, the Eureka Mine targeted copper ore in mineralized sandstone and conglomerate of the Agua Zarca Sandstone/Shinarump Formation. Three side-by-side-by-side adits exploited a green-stained horizon and produced copper and silver.

0.7
13.3 **Stay straight.** Deer Lake Road takes off to the left.

0.6
13.9 **Stay straight.** At left, Old State Road 126—now a dirt two-track road—enters. At right, Forest Road 98 leads to Blue Bird Mesa. At this hillcrest, we cross the drainage divide from the Rio Puerco into the headwaters of the Jemez River. Although similar in elevation and area, the waters of the upper Rio Puerco and the Jemez River are chemically quite distinct. The natural waters of the upper Jemez River are acidic (see Lavery et al., this volume).

0.3
14.2 Enter Rio Arriba County, home of New Mexico's tallest Douglas-fir (see mile 10.4).

0.1
14.3 **Turn left (north) onto Forest Road 70 toward San Gregorio Lake and the San Pedro Parks Wilderness.**

Figure 3.14. Douglas-fir cone with its distinctive mouse-tail bracts. Note also the flattened leaves; spruce leaves are square in cross section.

Figure 3.15. The Eureka Mine above State Road 126.

0.2
14.5 Outcrops of reddish Abo Formation at left. For the next mile or so, this road roughly follows the contact between the Abo Formation on the left and the Proterozoic basement on the right (Woodward et al., 1974).

0.1
14.6 A meadow opens at right.

0.3
14.9 Note the red hues of the soils near here. Soils can become this red via intense humid weathering in warm climates—hence the infamous red clay soils of Alabama and Georgia—or via long-duration weathering and clay accumulation in drier and colder climates. Another cause of soil redness is responsible for what is seen here: red parent material. The soils here are developed in regolith derived from the Abo Formation, which was red long before any pedogenic alteration.

0.2
15.1 The road crosses the contact into crystalline rocks, seen in low outcrops on the right. The rock at this spot is mapped as quartz monzonite with dikes of aplite, lamprophyre, and pegmatite by Woodward et al. (1974).

0.3
15.4 Cross a yellow cattle guard. Road bends to the left (north).

0.7
16.1 Clear Creek valley at right. Outcrops of Paleoproterozoic crystalline rocks abound.

0.3
16.4 At right, a large pavement outcrop of quartz monzonite contains excellent examples of the blue-tinged quartz crystals and rapakivi textures that typify this unit. We will see these features at Stop 3.

0.3
16.7 **Stay straight.** The road at left, Forest Road 267, provides access to the top of Eureka Mesa and upper Nacimiento Creek.

0.3
17.0 **Waypoint 3.04 [36.0272°, −106.8469°]**

STOP 3. Turn right (south) into the parking area for the San Gregorio Trailhead.

The Cuba Ditch

The stream at Stop 3, Clear Creek, has a role in the Euro-American colonization of the upper Rio Puerco in the 19th and 20th centuries. While the soils and climate are conducive to agriculture in the upper Rio Puerco Valley, the intermittency of the Rio Puerco itself demanded that most early agriculture could not rely on predictable irrigation schedules and instead used intermittent irrigation or dry-farming methods. To increase agricultural opportunities in the upper Rio Puerco Valley, in 1882, local farmers dug a 1,000-m (3,300-ft)-long diversion to shunt the waters of Clear Creek (a tributary to the Jemez River) into Nacimiento Creek (a tributary of the Rio Puerco that flows into Cuba; Fig. 3.16). This anthropogenic stream capture, named the Nacimiento Community Ditch, increased discharge in the Rio Puerco and decreased discharge in the Jemez River by moving approximately 9.6 km^2 (3.7 mi^2) of drainage area from the Clear Creek watershed into the Nacimiento Creek watershed. Sometime after 1895, the ditch was extended another 4,300 m (14,100 ft) to capture the flow of the Rio de las Vacas, another Jemez River tributary, artificially adding an additional 30 km^2 (11.6 mi^2) to the Nacimiento Creek watershed via the Cuba Ditch. The Nacimiento Community Ditch is occasionally operable and can be seen conveying water in aerial imagery from May 2012. The Cuba Ditch was stated to have been in disrepair by 1981 (Fischer and Borland, 1983) and there is no apparent evidence of recent use, although it is still clearly visible in the landscape (Fig. 3.16). In 1958, San Gregorio Dam was built on Clear Creek above the diversion site (about 1 km [0.6 mi] north of the parking area for Stop 3), further augmenting irrigation availability for Cuban farmers. The dam and reservoir were included within the boundary of the San Pedro Parks Wilderness Area in 1964, which had a

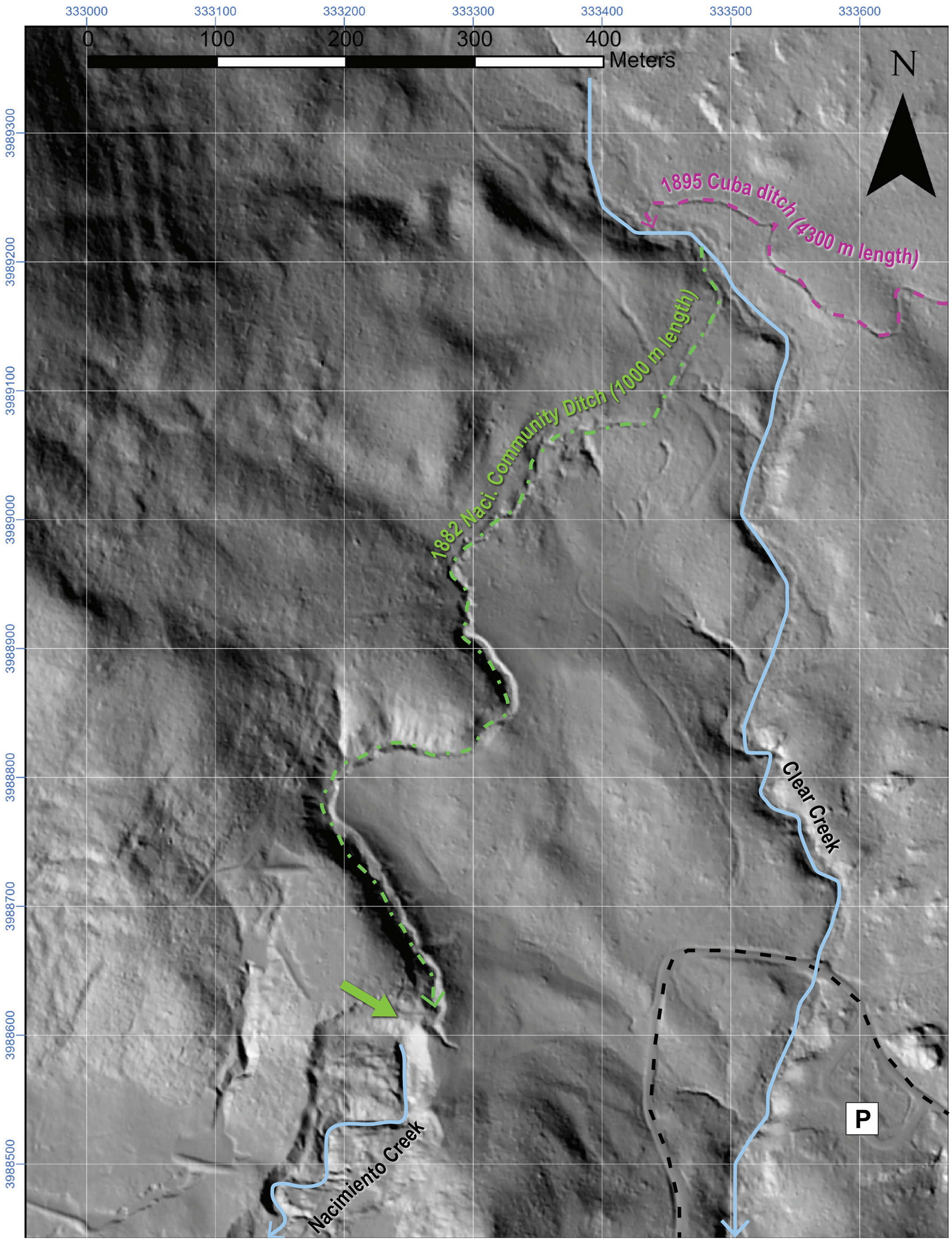

Figure 3.16. Annotated digital hillshade map of the Nacimiento Community Ditch and the lower end of the Cuba Ditch. The 1882 Nacimiento Community Ditch transferred water from the Clear Creek watershed (Jemez River drainage) into Nacimiento Creek (Rio Puerco watershed). The green arrow at the head of Nacimiento Creek marks the topographic divide between the two watersheds; water conveys from the ditch into Nacimiento Creek via a short tunnel with a 10 m (33 ft) vertical drop. The later Cuba Ditch, an impressive 4.3 km-long (2.7 mi-long) hand-dug ditch, conveyed water from the Rio de las Vacas into Clear Creek just above the Nacimiento Community Ditch, after which it was diverted down the Nacimiento Community Ditch for agricultural use around Cuba. Stop 3 parking site is marked with a "P." Forest Road 70 shown in dashed black line.

unique effect on later repairs and maintenance. Due to the Wilderness Act's prohibition of mechanized transport, the dam's 2002 upgrades required that 10 tons of sand, 45 tons of stone, 100 sacks of cement, and 120 wood vigas be delivered to the site via horse and mule (Van Hart, 2013). Using a humane load of 150 pounds per animal per trip, this would have required around 800 round trips from our parking spot to the dam!

Crystalline Basement of the Sierra Nacimiento

Throughout the Sierra Nacimiento, crystalline plutonic, metasedimentary, and metavolcanic rocks provide a glimpse into not only the complicated multistage magmatic and metamorphic history of central New Mexico, but also a clue to the timing, geography, and methods responsible for constructing this portion of the North American continental crust. At last year's field conference, Day 3's Stop 1 brought us to the Gilman Tunnels, where some of the younger plutonic rocks on the range are exposed. This year's Day 3 Stop 3 brings us to the older plutonic rocks in the range, the San Miguel Gneiss (1,700 ± 8 Ma; the name "gneiss" here refers to the fact that it often exhibits a very weak foliation, either due to emplacement flow or later metamorphism) and the monzogranite* of Clear Creek (1,696 ± 4 Ma). These rocks were emplaced as plutons and intruded into preexisting metavolcanic rocks and quartz-mica schists that can be found as xenoliths within the plutonic rocks as well as in outcrops in the northern Sierra Nacimiento (Woodward et al., 1974; Premo et al., 2023). These ~1.7 Ga intrusions were later intruded themselves by voluminous monzogranites at approximately 1,455 to 1,420 Ma (Grambling et al., 2015; Premo et al., 2023).

*If, like the author, you cannot reproduce a QAPF diagram from memory and might be foggy about the definition of a monzogranite, it's a granitic rock with roughly equal parts plagioclase and alkali feldspar. A granite with more plagioclase than alkali feldspar is a granodiorite, and one with more alkali feldspar than plagioclase is a syenogranite. A granite is a coarse-grained igneous rock composed mostly of quartz and feldspar, the two most common silicate minerals in Earth's crust. An igneous rock is formed from the cooling and crystallization of magma or lava and is one of three rock types on Earth, but you should have known that already.

The Paleoproterozoic magmatic rocks seen at Stop 3 are interpreted to have been emplaced on the south side of a regional mountain range that extended from at least northern Arizona in the west to northern Colorado in the east (Hillenbrand et al., 2023) during the waning stages of the Yavapai orogeny. The granitic rocks here are essentially the same age as the Uncompahgre-Vadito-Ortega quartzites that were deposited in a rift (?) basin on the thinning Yavapai crust (Premo et al., 2023; Hillenbrand et al., 2023). The >1.7 Ga rocks of northern New Mexico, west-central Colorado, and northern Arizona belong to the Yavapai province, a suite of similar-aged rocks thought to have formed during accretion of new crustal material to the margin of Laurentia in the late Paleoproterozoic (Shaw and Karlstrom, 1999).

Rapakivi Textures

The granitic rocks at Stop 3—and in many other places in the northern Sierra Nacimiento—exhibit a unique mineralogic phenomenon that can be observed with the naked eye (although thin section microscopy helps to make it stand out). This feature, rapakivi texture, is characterized by megacrysts of feldspars that have orthoclase (an alkali feldspar) cores with rims of oligoclase (a plagioclase feldspar; Fig. 3.17). Usually associated with anorogenic granites (Åhäll et al., 2000; Larin, 2009), the texture here is little studied.

Xenoliths and Enclaves

The granitic bedrock at Stop 3 showcases features that are decidedly not granitic, even to the neophyte such as this author who is a sedimentary geologist. At first glance, the darker-colored and more aphanitic portions of the outcrop seem to be xenoliths (pieces of the country rock that were incorporated into the granitic magma but remained solid during the process; Fig. 3.18). Upon closer inspection, however, many of these features exhibit field-observable characteristics that cast doubt on a xenolithic provenience: diffuse boundaries, megracrysts of the same texture and composition as the encapsulating granites, and rounded or undulatory edges (Fig. 3.19). Are these, in fact, mafic enclaves—that is, irregular bodies of mafic magma that were injected into the otherwise-granitic pluton and crystallized before being fully chemically assimilated? If so, then how did the orthoclase phenocrysts crystallize in a mafic magma? Some of these megacrysts even exhibit rapakivi texture!

The answer to these questions likely requires some aspects of magma mixing, a term which generally describes the processes of chemically and physically dispersing one or more magmas of differing composition into a single host magma (Perugini and Poli, 2012). Magma mixing requires that the two (or more) magmas exist at similar rheological conditions. This can occur

Figure 3.17. Annotated photograph of rapakivi texture in granite at Stop 3. Arrows indicate oligoclase rims around orthoclase cores. Pen lid is 13 mm (0.5 in) diameter.

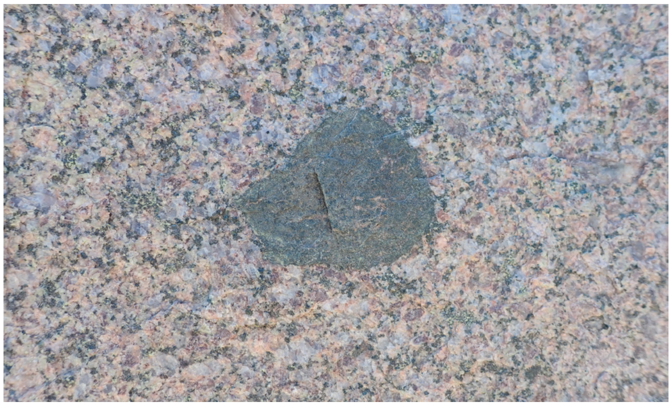

Figure 3.18. Photograph of not-granite (center) within granite (everything else). Is this an enclave, a xenolith, neither, both, or something else? Not-granite portion is 7 cm (2.8 in) across.

at nearly any stage in the evolution of a magma system and does not require the existence of endmembers derived from different sources. Instead, magma mixing can occur whenever chemical gradients exist within a magma body (Perugini and Poli, 2012). Such gradients are necessarily created within an originally homogenous magma body when fractional crystallization occurs along the cooler edges of the chamber: the magma there is enriched in the elements that are excluded from initial crystallization. Similarly, the assimilation of country rocks into the magma chamber will cause chemical gradients except in rare cases of magma and country rock having the exact same composition. Partial melting, magma migration, and magma chamber replenishment also create chemical gradients. In plutonic systems such as the ones responsible for the crystalline rocks at Stop 3, it is possible—and probably likely—that more than one of these processes may act together, amplifying the magma mixing processes and creating heterogeneity in the magma chamber (Bateman, 1995).

Fractures and Weathering

The granites at Stop 3 are fractured by at least two systematic joint sets. These fractures have interesting tectonic implications, and they provide an opportunity to discuss the feedbacks between rocks' physical and chemical properties that ultimately turn crystalline basement into regolith.

Nearly any large outcrop of granitic rocks in the northern Sierra Nacimiento will exhibit joints (Fig. 3.21). Joints form via brittle fracture when tensile stress exceeds the strength of the rock; this stress can be from elevated pore pressure, tectonic forces, thermal contraction, desiccation contraction, or lithostatic pressure release. Joints open as planes that are parallel to maximum principal stress (sigma-1, if you remember your geomechanics) and perpendicular to minimum principal stress (sigma-3). These geometric relationships are well established with experimentation and thus make joints a useful tool for interpreting past stress orientations in Earth's crust. As you wander around Stop 3, see if you can determine a systematic orientation of joints (Fig. 3.20 should give a clue) and what the stress orientations responsible for their formation might have been.

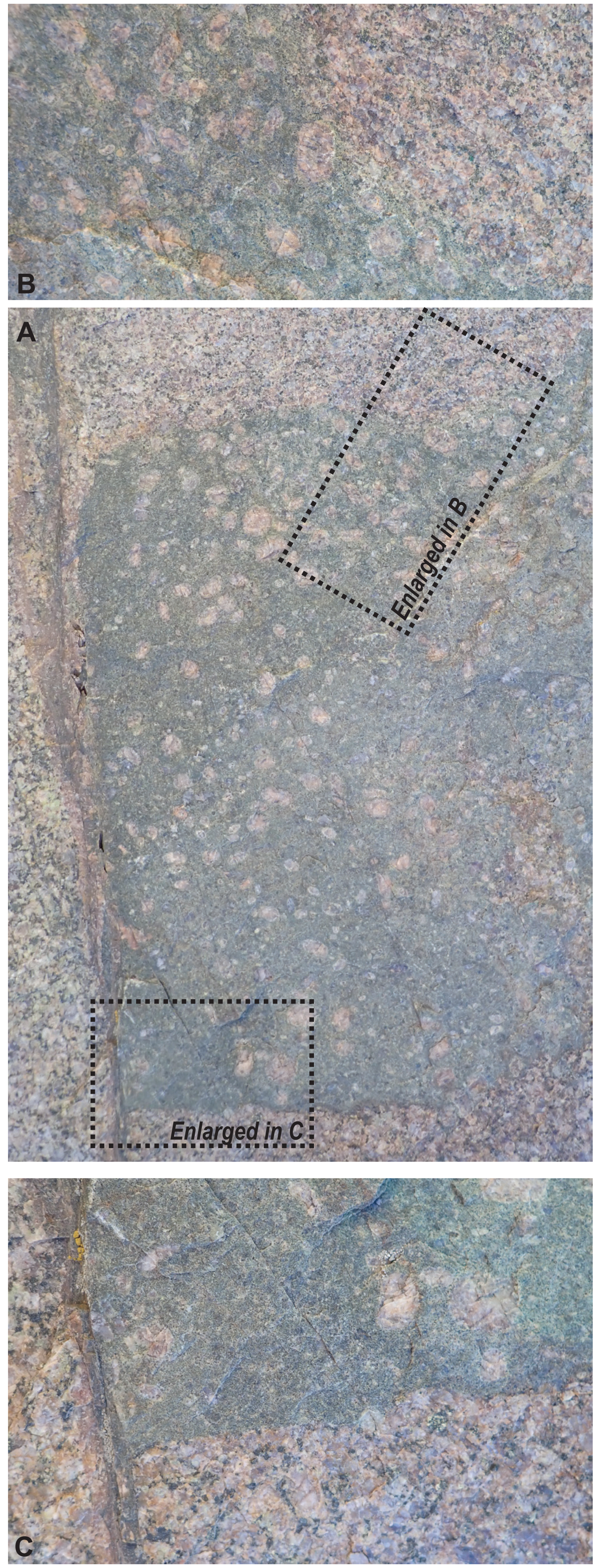

Figure 3.19. Not-granite textures and boundaries at Stop 3. A: dark gray not-granite within granite. Dark area is approximately 90 cm (35 in) across. B: Margin between granite and not-granite enlarged to show detail. The boundary is diffuse, with some megacrysts seeming to cross it. C: Another margin enlarged to show detail. Here, the distinct boundary seems to suggest a xenolith.

Aside from their utility as records of past stresses, joints like those at Stop 3 also play a crucial role in the rock cycle by increasing the surface area of rocks, often by orders of magnitude (remember, the much maligned but widely used fracking in oil and gas wells merely creates fractures in subsurface reservoir rocks for the explicit purpose of increasing surface area across which hydrocarbons can flow!). In natural rock systems, the vast majority of both physical and chemical weathering occurs at or very near a rock's surface (Fig. 3.21). In an unfractured body of homogenous rock, such as granite, surface weathering is limited to the rock's top surface (Ruxton and Berry, 1959). In fractured rock, weathering occurs not only along the top surface, but also along fractures. The more closely spaced the fractures are, the higher the overall weathering rate of the rock. This phenomenon expedites both physical and chemical weathering. Physical weathering is increased due to the propensity for water to occupy fractures, leading to frost wedging during diurnal or seasonal cooling-heating cycles, as well as through the penetration of fractures by roots (another effective wedging agent). Chemical weathering is expedited along and near fractures due to increased exposure to meteoric water and atmosphere, both of which contain chemical agents that increase weathering rates in most settings, especially O_2, CO_2, and H_2CO_3.

The role of fractures in weathering—and therefore, the rock cycle—is also manifest in core-stone weathering, wherein originally orthogonal blocks of homogenous rock are reduced to rounded shapes through deep weathering (see Fletcher and Brantley, 2010). Core-stone weathering is especially evident in stable granitic landscapes (the Sandia Mountain front, near the high-rent neighborhoods in far northeast Albuquerque, displays some of the best granite core-stone weathering in the region). The progressive rounding of weathered rock at fracture boundaries produces characteristic round cobbles and boulders in systematically jointed areas such as Stop 3 (Fig. 3.22) leads not only to core-stones, but also liberates granular material (in granitic terrains, the familiar grus comprising grains of the crystalline components of granite) that expedites soil formation, increases overall water storage capacity, and further expedites weathering. Core-stone development under stable conditions is therefore operating under partial positive feedbacks—the more core-stones develop, the faster core-stones can develop!

Consideration of the weathering of granitic rocks here at Stop 3 allows for a broader discussion of the geologic history of the San Juan Basin as a whole. In précis: weathering in highlands produces regolith that remains in place until transported downgradient via sedimentary processes. This weathering also liberates ions that become dissolved chemical sediment that ultimately is transported elsewhere. Long-term and/or deep weathering in highlands can lead to the development of immense volumes of regolith, whereas intense transport can strip regolith and leave exposed bare bedrock. Most geologic systems on continents exist in equilibrium most of the time (Ahnert, 1994). The founder of modern geomorphology, G.K. Gilbert, proposed the term "dynamic equilibrium" to describe the balance between the driving and resisting forces of climate, weathering, tectonics, and rock properties (Gilbert, 1877).

Seeing the initial processes and products of weathering here at Stop 3 can give us context for many of the features observed throughout this year's conference. Consider the pediment- and terrace-capping gravels observed throughout the upper Rio Puerco drainage, many of them are dominated by clasts of crystalline rocks: did those clasts originate as core-stones at 3,200 m (10,500 ft) ASL? It is simple to invoke hypothetical past episodes of raging rivers or grinding glaciers to create all the granitic gravel on the Rio Puerco's terraces. However, it is equally likely that long episodes of deep weathering are a more effective producer of that sediment. No known evidence for Quaternary glaciers exists in the Sierra Nacimiento,

Figure 3.20. Pervasive systematic joints in crystalline rock trending 004° at Stop 3.

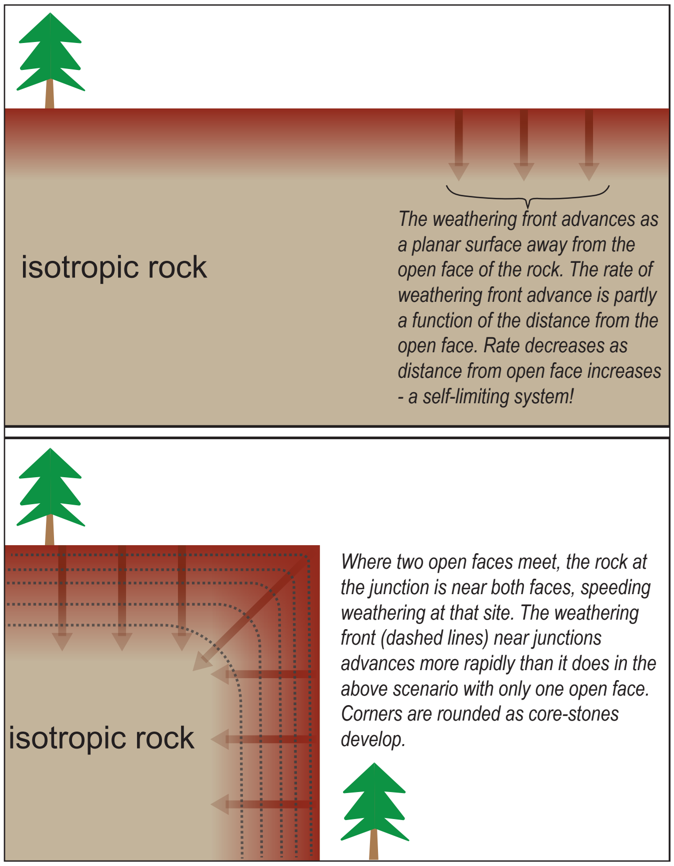

Figure 3.21. Schematic diagram of the relationship between surfaces and weathering. Top: In an isotropic rock with only one open surface, weathering begins at that surface and advances into the rocks' interior at some rate dependent on rock properties, climate, and biological activity. In general, the rate of advance decreases as the weathering front advances farther from the open face. Bottom: In the same rock, where two open faces meet at a junction, the rock near that junction is effectively experiencing weathering from two fronts simultaneously. This causes the weathering front near the junction to advance at a higher rate that it does with only one open face. Over time, the angular corner between two planar fractures becomes rounded.

and it is unlikely that the Rio Puerco, Rio de las Vacas, Rito Leche, or Clear Creek were ever capable of plucking boulders from unweathered rock by sheer stream power. Deep weathering, however, requires no dramatic special pleading for the introduction of coarse clasts into the headwaters of these streams—time is the only requisite factor. The large-magnitude orbitally forced climate oscillations of the Quaternary are likely responsible for the alternating episodes of regolith production and sediment transport recorded in the pediments and terraces of the field conference area (e.g., Hancock and Anderson, 2002).

The Mesozoic and Cenozoic sedimentary rocks visited on Days 1 and 2 can also be reconsidered with thoughts brought up here at Stop 3. These rocks contain an almost-incomprehensible volume of sediment. The late, great, Bill Dickinson (1931–2015) channeled Walter Scott's *The Lay of the Last Minstrel* when he quipped, "Breathes there the geologist with soul so dead/Who never to himself hath said/*I wonder where the hell all that quartz came from*?" when looking over the

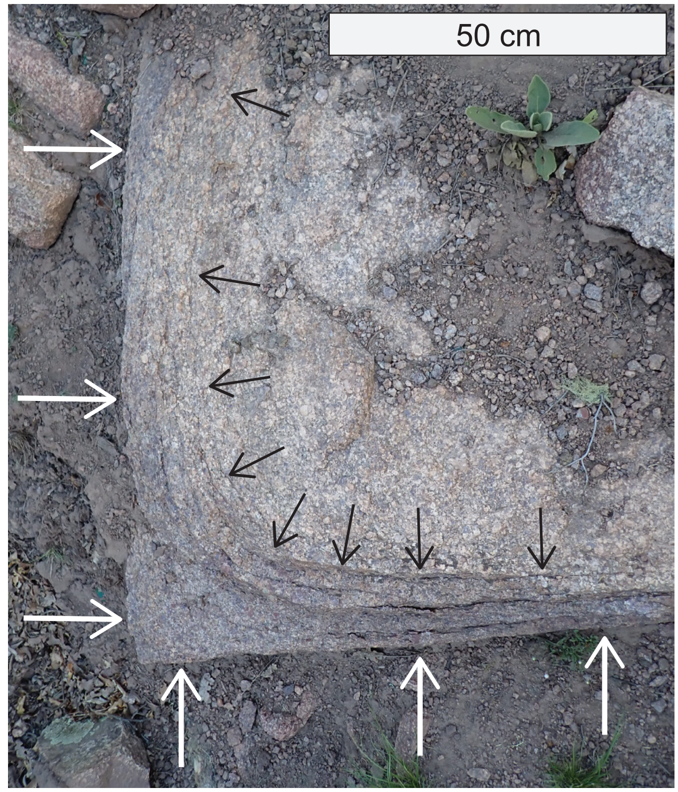

Figure 3.22. Annotated photograph of core-stone development along two orthogonal joint faces in a monzogranite boulder at Stop 3. White arrows mark the planar faces of the boulder. Black arrows are positioned normal to developing weathering joints advancing into the boulder's interior. Note the increasing roundness of the corner as weathering advances inward.

Mesozoic section in the Four Corners country (Lawton, 2015). Dickinson's sense of wonder is well placed, and still in need of more research treatment. As we near the conclusion of the conference, try to imagine the processes necessary for the existence of the San Juan Basin's sedimentary rocks and deposits, all of which circle the overall job of turning basement rock into sediment. The cycles of uplift, weathering, transport, deposition, burial, lithification, and uplift again are all interconnected and nonlinear. While the rock cycle is one of the fundamentals of geology that we expect middle schoolers to know, this author wonders if we overlook or oversimplify it in favor of higher-tech and more expensive science. To understand the sedimentary deposits that have been the focus of this trip and those that provide our energy, water, fossils, minerals, and aggregate, we must strive better to understand their context in the cycles of weathering.

> "The ruins of an older world are visible in the present structure of our planet; and the strata which now compose our continents have been once beneath the sea, and were formed out of the waste of preexisting continents. The same forces are still destroying, by chemical decomposition or mechanical violence, even the hardest rocks and transporting the materials to the sea."
>
> James Hutton (1788)

End of Day 3 Road Log—¡Hasta Luego!