

Route map for the Quebradas Back Country Byway. Distance is 24 miles from end to end. Motorized travel is limited to designated routes within Wilderness Study Areas.

The Quebradas (Spanish for “breaks,” a rugged or cliffy area) is a region of splendid scenery and easily accessible geologic exposures. Rocks from some of the most eventful times in our geologic past are exposed along the Quebradas Back Country Byway, in particular sedimentary rocks of Pennsylvanian, Permian, Late Cenozoic, and Quaternary age. Triassic and Upper Cretaceous strata are also present. This short guide will provide you with some explanation of the geologic features visible at ten numbered stops.

GETTING THERE

The Quebradas Back Country Byway is east of the Rio Grande between Socorro and San Antonio, New Mexico. The 24-mile-long dirt road can be accessed from the north via I-25 or from the south via Highway 380. It is most often accessed from the north end, via Exit 152 (the Escondida exit) off I-25, just a couple of miles north of Socorro. After exiting the freeway, turn right (east) and follow the Back Country Byway signs east, then north toward Escondida Lake. In just over a mile, turn right again at the Escondida Lake sign and head east, past Escondida Lake, crossing the Rio Grande. At the village of Pueblito (a T-intersection), turn right (south) and proceed about a mile to the junction of the Bosquecito Road with the Back Country Byway (A-152). This is mile 0.0. Follow the road to the left at this junction.

From the south: The turnout from 380 is 11 miles east of the village of San Antonio (380 is accessible from Exit 139 off I-25). Turn north onto A-129 and drive 3 miles to the junction with A-152. Turn left here; Stop 10 is just west of this junction.

Note: All mileages given below are from the north end of the Back Country Byway, at the “Quebradas Back Country Byway” sign (Mile 0.0) on A-152. All coordinates for latitude and longitude are WGS 84 datum. All UTM readings are NAD 83.

SAFETY

The 24-mile-long road is dirt; a high-clearance or 4-wheel-drive vehicle is recommended. The roads in this area receive infrequent maintenance. Loose gravel, washboarding, gully-ing, tight turns with limited visibility, potholes, and rough arroyo crossings all pose potential hazards. Call the BLM Socorro Field Office (575-835-0412) to check on road conditions. This is a two-way road; drive slowly and carefully and watch for oncoming traffic. Flash floods can occur during times of rain. Watch for snakes, scorpions, or other hazardous animals. This is a desert area: Take plenty of water with you, wear a long-sleeve shirt, long pants, and stout shoes. Use sunscreen, and take maps, a GPS unit, or other navigation aids to keep from getting lost (cell phone service is limited or non-existent). Tell someone where you are going and when you will be back. There are no restrooms or drinking water available along the route. Be aware that the byway crosses private land, and there are private inholdings within the BLM lands in the Quebradas. Do not cross fence lines on private land without permission and stay clear of grazing livestock. All archaeological sites are protected and should be left undisturbed.



AGE myBP	GEOLOGIC AGE UNIT		STRATIGRAPHIC UNIT	THICKNESS IN REGION (feet)
0	Quaternary		unconsolidated sediment	0–100
1.8	Tertiary		Santa Fe Group	0–2000
			Baca Formation and volcanics	
65	Cretaceous	Upper	Mesaverde Group	0–800
			Mancos Shale	0–1000
			Dakota Sandstone	0–200
100		Lower		
145	Jurassic		absent	0
200	Triassic		Chinle Group	0–1000
			Moenkopi Formation	
252		Lopingian	absent	0
~270	Permian	Guadalupian	Artesia Group	0–325
		Cisuralian	San Andres Formation	0–975
			Glorieta Sandstone	0–400
			Yeso Formation or Group	1000–4300
			Abo Formation	230–1700
299	Pennsylvanian	Late	Bursum Formation	0–390
			Madera Group	Atrasado Formation
		Middle	Gray Mesa Fm.	300–500
		Early	Sandia Formation	0–600
323	Mississippian		absent	0
354	Devonian			
417	Silurian			
443	Ordovician			
490	Cambrian			
543	Precambrian		granitic basement (~1.6 by BP)	

Generalized stratigraphy of the Quebradas region. Adapted from *A Geologic Time Scale 2004*, published by Cambridge University Press.

STOP 1 THE GEOLOGIC FRAMEWORK

Mile: 2.7
Coordinates: N 34°06.592'
W 106°49.495'
UTM: Zone 13
331860E 3775840N

Looking west from the top of the small hill just north of the parking area you can see the Magdalena Mountains (the massive ridge forming the far skyline) and a series of lower mountains just east and northeast of the Magdalena Mountains (from south to north: the Chupadera Mountains, Socorro Peak/M Mountain, Strawberry Peak, Polvadera Peak in the Lemitar Mountains, and the Sierra Ladrones). There are Paleozoic sedimentary rocks in most of those ranges, but volcanic rocks make up most of the outcrops.

These ranges mark the northeastern edge of the Mogollon–Datil volcanic field, which extends westward into Arizona. The Mogollon–Datil volcanic field contains 20 identified volcanic caldera complexes (“supervolcanoes”) with an eruption history spanning 12 million years, from 36 to 24 million years before the present time (m.y. b.p.). During that interval this was one of the most volcanically active regions in the world. Many individual eruptions produced more than 24 cubic miles of rock, ash, and pumice into the atmosphere. The largest eruptions yielded 240 cubic miles of such material (compare that with the roughly 0.24 cubic miles erupted during the Mount St. Helens event of 1980 and the 6 cubic miles released in the 1883 Krakatoa eruption). The enormous ash clouds from these eruptions circled the earth, affected global climates, and may have altered ocean chemistry.

At the foot of these volcanic exposures is the town of Socorro. Just west of the southern part of town you can see a white scar on the hillside marking the Dicaperl Minerals Corp. mine and plant, which, since the mid-1940s, has produced perlite, a glassy, water-rich silicate rock which expands greatly when heated. The resulting lightweight product is used in the manufacture of insulating materials, ceiling tiles, soil amendments, and many other products. The operation reflects the long mining history of the Socorro–Magdalena region. From the 1870s to the early 1900s this area was a major producer of zinc, lead, copper, and small amounts of silver, gold, and manganese. Scattered mining continued into the 1940s. Although those mines are now closed, this legacy is reflected in the presence of the New Mexico Institute of Mining and Technology (New Mexico Tech) in Socorro.

Socorro is one of the few places in the interior of the United States that sits atop an active magma body. The pancake-shaped magma extends 35 miles north-south from Bernardo to San Antonio at a depth of about 10 miles. The progressive inflation of the magma body has made Socorro the most seismically active area in the state.

Socorro also lies along the Rio Grande, a river system that is seen from this stop as a narrow, green strip extending north-south through this desert landscape. The river stretches the length of New Mexico from Colorado to El Paso (Texas) and the Gulf of Mexico. It flows within one of the major features of New Mexico geology: the Rio Grande rift. Heating and stretching of the crust in this region led to the formation of this tear in the earth’s crust. The rift is bounded by uplifted mountains on its flanks, including the ones you see from this



The lens-shaped, lighter-colored limestone at the base of this cliff is a phylloid algal mound in Madera Group limestones south of Stop 1. Note the lateral transition of the mound into darker, thinner limestones to the right.

location and the Sandia and Manzano Mountains near Albuquerque. The rift is a complex of down-faulted blocks of crystalline and pre-Tertiary sedimentary rocks overlain by sedimentary basin fills. Some of the basins have dropped more than two miles relative to the surrounding mountains. Rifting began 30 million years ago, and major sediment filling of the rift took place during the past 20 million years. The Rio Grande has flowed through this area for about 5 million years, but only during the past million years has the Rio Grande become a through-going river that flows all the way to the Gulf of Mexico. Since turning onto the byway, you have been mainly in reddish sandy and conglomeratic Santa Fe Group sediments of Pliocene–Pleistocene age, which were transported by small side streams and alluvial fan channels from high areas on the east flank of the rift.

Major boundary faults, large uplifts, and deep basins characterize the Rio Grande rift. The main boundary fault along this part of the rift is on the west side of the valley, along the face of Socorro Peak. The main fault on the east side of the valley is just a few hundred feet east of where you're standing. These boundary faults control the position and width of the valley. Unlike most valleys, this one was not cut by the river, but was formed by tectonic processes and is merely occupied by the

Rio Grande (which has done some minor downcutting). The rift has been the site of substantial sediment deposition during its history, but the amount of sediment varies along the length of the rift because of differential subsidence from place to place. The deep basins contain many thousands of feet of fill, some of it in the form of porous sands and gravels that constitute the drinking water aquifers for most of the state's population.

Rocks of Pennsylvanian–Permian age can be seen to the south, southeast, and east. Pennsylvanian strata are predominantly gray outcrops consisting of alternating beds of well-exposed limestones and softer, less well-exposed shales of the Upper Pennsylvanian Madera Group (310–300 m.y. b.p.). The reddish rocks visible to the east and northeast are sandstones and shales of the Permian Abo Formation, which will be seen in more

detail at Stop 2. Reddish outcrops to the north and west (as well as the deposits on which you are standing) are poorly consolidated Upper Tertiary and Quaternary sands and conglomerates of the Santa Fe Group. They represent materials eroded mainly from the Pennsylvanian and Permian rocks in this area but include some interlayered volcanic rocks.

To the east and south you can see that some of the Pennsylvanian and Permian outcrops are tilted to a near-vertical orientation; in other places they are nearly horizontal. This is a reflection of the repeated episodes of folding and faulting that have affected this area. Some of the faults are related to the formation of the rift; others are associated with earlier episodes, especially the Ancestral Rockies event in Late Pennsylvanian to Early Permian time. Prominent bands of gray limestone outcrops are visible to the east-southeast. These reflect cycles of sedimentation, discussed at the next stop.

If you walk southeast from the base of the hill and follow the vertical beds to the ridge crest to the south, you can find well-bedded marine limestones that were deposited in a shallow sea that once covered the region. Locally, you can find mounds formed by phylloid (platy or leaf-like) algae, reef-like buildups that are typical of this time period. Crinoids, brachiopods, bryozoans, fusulinid foraminifers, and other marine fossils are common in these rocks.

As you drive the 1.3 miles to Stop 2, you will pass through red beds of Lower Permian Abo Formation and some basal Yeso Formation strata.

STOP 2 ABO REDBEDS

Mile: 4.0

Coordinates: N 34°06.940'
W 106°48.545'

UTM: Zone 13, 333152E
3776460N

Walk toward the southwest a few dozen yards to the viewing area located at a solitary fence post on a small ridge. You are standing on the Lower Permian Abo Formation. As you look down the small arroyo, more exposures of red Abo sandstones, siltstones, and shales are visible. At the far end of the arroyo, one can see the gray limestones of the Upper Pennsylvanian Madera Group.

During the Pennsylvanian–Permian interval North America drifted northward from a near-equatorial position in mid-Pennsylvanian time to a position roughly 15 degrees north of the equator by Late Permian time. The drift of the continent through major climate zones, coupled with the rain-shadow effects of rising mountain belts, led to substantial changes in the types of sediments formed during that time. In particular, Pennsylvanian rocks formed under relatively humid conditions and Permian rocks formed under conditions of ever-increasing aridity.

A third influence on these rocks came from global climate change and large-scale sea-level fluctuations. Late



Pennsylvanian–Early Permian time was one of the earth’s major “icehouse” climate intervals, with widespread continental glaciations in the then-adjacent southern parts of South America and Africa as well as all of Antarctica. As during the more recent Pleistocene glaciations, Pennsylvanian–Permian glaciers waxed and waned repeatedly, locking up more or less water on land and consequently causing worldwide sea levels to fall and rise. During the last modern deglaciation, starting about 12,000 years ago, global sea levels rose approximately 400 feet. Recent studies have shown a comparable scale of sea-level changes (about 260 feet) in Upper Pennsylvanian strata of New Mexico, and more than twenty such sea level changes have been recorded in rocks of that time interval. The intensity of Southern Hemisphere glaciations decreased through Permian time and probably ended at some point in the Late Permian.

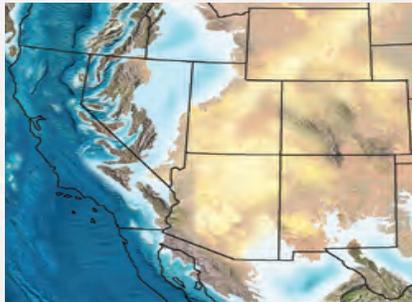
What evidence of this do we see in the rocks of the Quebradas? The cyclic ledges of marine Pennsylvanian limestones alternating with more poorly exposed shales (visible in the distance at Stop 1 and here) reflect the glacially driven rises and falls of sea level of that period. During high sea-level intervals, marine limestones were deposited in the shallow seas that occupied shelf areas; low sea levels led to retreat of the seas, with increased erosion of nearby uplifts and basal deposition of sandstones and shales.

At this stop we see mainly strata of the Lower Permian Abo Formation (299–284 m.y. b.p.). The red, feldspar-rich shales, siltstones, and lenticular sandstones are approximately 650 feet thick in this area. They were derived from Ancestral Rockies uplifts (especially the Pedernal massif, small remnants of which can still be seen in the Pedernal Hills, south of Clines

Corners, NM). Examination of the Abo redbeds shows that they are mainly of terrestrial (nonmarine) origin. The red color of these rocks results from the presence of small amounts (less than one percent) of iron in the form of hematite. Hematite (Fe_2O_3) is the same mineral that gives the planet Mars its red color, and it forms by precipitation or alteration in oxidizing environments. The small, circular white spots (known as reduction spots) that are common in these strata show what the rock looks



Paleogeographic reconstruction of the western U.S. in mid-Pennsylvanian time. The Quebradas then was located in the basin off the western flank of the Ancestral Rocky Mountains.



Paleogeographic reconstruction of the western U.S. in early Permian time. The Ancestral Rockies uplifts in New Mexico had been largely eroded by this time and the intervening basins were filled with detritus from that erosion.

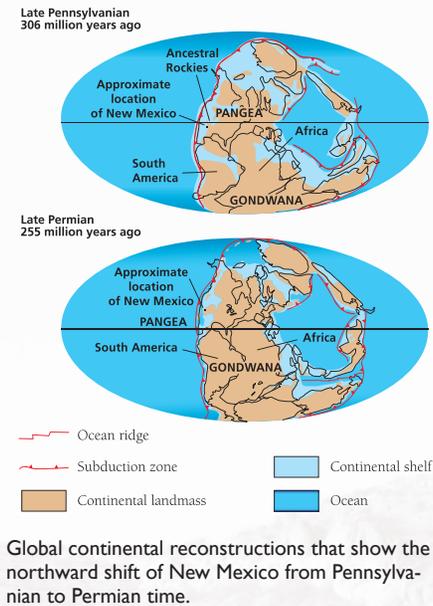
like where it is not as strongly oxidized (probably because of the presence of organic matter).

Looking across the valley at the small cliff (which is on private land), you can

see near the base of the outcrop a thick, lens-shaped sand body surrounded by darker red shales. The sand body is the filling of a Permian river channel; the shale represents overbank or floodplain deposits. Near the top of the outcrop, you can see angled layers (cross-stratification) within individual sand beds; this is evidence of shifting sand bars, again in a river system. The bedding surfaces of many of

the sandstones have ripple marks and mud cracks; more rarely one can find raindrop impressions. The fossils in these deposits include abundant plant remains (leaf and stem impressions and scarcer petrified wood, mainly from conifers and pteridosperms) and, in other areas, the fossilized tracks of four-footed vertebrate land animals and bones of lungfish. These all indicate that in this area Abo deposition took place in a river and floodplain system with at least enough moisture in some seasons to supply ephemeral streams and grow plants. Such a semi-arid terrestrial setting is different from that of the marine Madera limestones of the Late Pennsylvanian, and is different as well from the more arid environments seen in younger, post-Abo Permian strata.

The rock unit that directly overlies the Abo is the Yeso Formation (*yeso* means “gypsum” in Spanish). The lower part of the Yeso has thin gypsum beds and thinner white layers that were once rich in halite (sodium chloride or table



Global continental reconstructions that show the northward shift of New Mexico from Pennsylvanian to Permian time.

salt). Some of those light-colored layers can be seen in the distance up the arroyo to the north of this stop. The upper part of the Yeso Formation also includes massive gypsum and anhydrite beds. These progressive changes in the rock section reflect ever greater aridity as glaciers disappeared, global climates warmed, and New Mexico drifted northward away

from the equatorial rainforest belt and into the world’s desert latitudes.



Channel sandstones west-southwest of Stop 2. Two major channels are bracketed with black bars.

As you drive the 4.1 miles to the next stop, you will pass both Lower Permian (generally reddish) and Upper Pennsylvanian (generally gray) rock outcrops with some mid-Permian deposits visible in the far distance on the high ridge line to the east.

STOP 3 BURSUM SANDSTONES & MADERA LIME- STONES

Mile: 8.1

Coordinates: N 34°04.576'

W 106°46.877'

UTM: Zone 13

335640E 3772040N

This stop shows the deposits that directly underlie the Abo Formation in this region. The parking area is located atop the Bursum Formation, of latest Pennsylvania age (299–284 m.y. b.p.) in this area. Walk to the low outcrops on the east side of the road for a better look at the Bursum. The unit consists of deep violet-to-greenish shales, arkosic sandstones, and conglomerates. Multiple thin layers of calcareous nodules representing discrete soil zones are found at nearby localities (including outcrops between Stops 2 and 3). Much of the sediment in this area is probably of nonmarine origin, although marine limestone and shale layers are present in the Bursum at some localities in the Quebradas and at many localities farther south. The Bursum Formation, approximately 600 feet thick in this area, represents a transition between the underlying, predominantly marine Madera Group and the overlying, fully terrestrial Abo Formation.

East of the road one can see Bursum outcrops that include sandstone and conglomerate beds with internal crossbedding and lenticular, channel-shaped geometries. These coarse-grained deposits contain angular quartz and abundant pink feldspar grains. They look much like granites, and the absence of rounding of the grains, coupled with the abundance of physically weak and

chemically unstable feldspars, indicate that Bursum sediments were derived quite locally from the erosion of uplifted blocks of the granite-cored Ancestral Rockies. The erosional unconformity found in most areas between the Bursum and Abo Formations, the rapid lateral changes in Bursum lithologies, and the derivation of Bursum strata from granitic uplifts indicates that Bursum sedimentation coincided with an active phase of Ancestral Rockies mountain building.

If you cross back to the parking area and walk west-northwest down the small arroyo, you can see both the Bursum–Madera contact and the limestones of the upper part of the Madera Group. The basal maroon shales of the Bursum strata are in sharp contact with a gray, rubbly, nodular, somewhat brecciated limestone at the top of the Madera Group. This limestone, termed the Atrasado Formation, contains many small, irregularly curved, platy fragments that are the altered remains of phylloid algae, leaf-like or cup-shaped, inch-scale, green algal shrubs. Those leafy plates typically produce a texture that looks like a collection of small, broken corn flakes. These small plants grew in enormous numbers in the warm, shallow, equatorial seas of the Pennsylvanian and early Permian. In some places phylloid algae formed bioherms (essentially small reefs), some of which now act as oil and gas reservoirs in the subsurface.

A number of wispy, irregularly laminated black crusts within these limestones mark paleosols (fossil soil horizons). These paleosols formed directly on marine limestones, indicating abrupt exposure and repeated sea-level changes that reflect either waxing and waning of Southern Hemisphere glaciers or, in this highly active tectonic belt, localized uplift and subsidence of the seafloor (or both).



Phylloid algal limestone from the Madera Group. The small, dark gray fragments are broken pieces of phylloid (leaf-like) green algal shrubs.

Continuing down the arroyo, the low outcrops of Madera Limestone get richer in marine fossils. Small fragments of phylloid algae still dominate the assemblage here, but scarcer crinoid fragments (“sea lilies,” members of the phylum Echinodermata), brachiopods, and small fusulinids (extinct, single-celled marine protozoans that look like tiny cigars) are also present. Long, thin, irregularly spaced, wavy bands of darker rock and thin, elongate cavities are common; these are weathered stylolites, zones along which the rock has dissolved due to the pressure of overlying deposits. A bit farther down-canyon, there are irregularly shaped, white-to-reddish nodules of chert that stand out in relief from the Madera limestone matrix. Chert is a very finely crystalline form of quartz that forms as a replacement of patches of limestone or of individual fossils. You then cross a small fault that has dropped the Bursum–Madera contact back down to creek level. After passing across some Bursum sandstone beds, you will again be in gray Madera limestone. Just before

you reach the fence line, look at the limestone outcrops on the northeast side of the arroyo. Several prominent, nearly black, irregularly laminated rock layers again mark multiple paleosol zones, which are a feature of the uppermost Madera strata in this area.

During the 1.6-mile drive to the next stop you will climb the stratigraphic section from the purple uppermost Pennsylvanian Bursum deposits, through the basal Permian Abo redbeds (seen at Stop 2), and into variegated (red and tan or white) sandstones and shales of the lower Yeso Formation (Meseta Blanca Member) for the final mile of the drive.



Laminated, irregular black crusts in Madera limestone. These have been interpreted as fossil soil zones.

STOP 4 LOWER YESO EVAPORITIC SAND- STONES AND SHALES

Mile: 9.7

Coordinates: N 34°03.325'

W 106°46.483'

UTM: Zone 13

336205E 3769720N

Here in the upper reaches of Arroyo del Tajo is an excellent place to see both the structural geology and sedimentology of the Quebradas. The beds on either side of the road are from the Meseta Blanca Member of the Yeso Formation. This is the lowest of four members (from base to top: the Meseta Blanca, Torres, Cañas Gypsum, and Joyita Members) in the Yeso Formation, which is Early Permian in age. The Meseta Blanca Member (mapped in this area as the lower Yeso Formation) has a maximum thickness of 300 feet in this region. The full Yeso Formation is roughly 1,000 feet thick in the Quebradas, although it gets far thicker in some nearby locations (to the east, in the subsurface near Carrizozo, it exceeds 4,000 feet in thickness).

The Meseta Blanca Member is one of the most distinctive units in the Quebradas. It is marked by cyclic color banding of yellow to reddish-brown quartzose to sub-arkosic sandstones as well as orange-red, gray and white siltstones, shales, and calcareous shales. Compared to the underlying Abo Formation, the Meseta Blanca has a higher percentage of sandstone, has more uniform (less lenticular) bedding, and has more of an orange-red color compared with the deep red of the Abo strata or the maroon color of the Bursum Formation.

The sandstone beds are easily seen on the east side of the road where

folding has rotated them to a vertical orientation, producing what is often called “tombstone topography.” These sandstones are finer grained, have more rounded grains, and contain much less feldspar and more quartz than the older Bursum and Abo sandstones seen at the last two stops. This reflects the fact that most of the Ancestral Rockies uplifts in this region had been deeply eroded or were buried under their own detritus by Yeso time. Thus, younger sediments had to be transported ever longer distances to reach this area, which is reflected in increased abrasional rounding of grains and destruction of



Folded sandstones in the Meseta Blanca Member of the Yeso Formation southeast of Stop 4. The rocks in the foreground are standing on end—a classic example of “tombstone topography.”

unstable minerals such as feldspar. The change in character of the sandstones also reflects increasing aridity with more long-distance wind transport (as indicated by frosting on the quartz grains in the Yeso), coupled with more marine influence and coastal deposition in this area. The Yeso deposits in the Quebradas region generally represent a transition from marine to nonmarine environments in restricted, coastal to near-coastal settings dominated by sand dunes and salt pans.

The structural deformation of these rocks is striking. A major fold affects the rocks here, perhaps with some



Folded siltstones and shales of the Meseta Blanca Member of the Yeso Formation northwest of Stop 4.

associated faulting, and the axis of the fold nearly parallels the road. Looking north or south you can see upended strata with sharp transitions from vertical to horizontal orientations. In some places, the strata are upside down. This deformation obviously postdates deposition of the Permian rocks in this area and, because it involves compressive forces that are not common during rifting events, it is likely that the folding is a product of the Laramide orogeny of early Tertiary age.

If you walk back to the west side of the road and down into Arroyo del Tajo, you can examine some of the finer-grained beds of the Meseta Blanca Member. The stream-level outcrops show distinct bands of orange-red and white siltstones and shales that may reflect Permian climate cycles. The white, calcareous, silty shales once contained extensive halite (sodium chloride) as revealed by the presence of abundant casts of former crystals (now dissolved, leaving behind sediment-filled crystal outlines). You can see these characteristic casts by looking on the bedding surfaces of the very thin, platy, beds that make up the white layers. The crystals appear in raised relief as cubic forms, some with sunken sides (commonly termed hopper crystals).

The formation of halite crystals (and their preservation long enough to form casts) requires sustained periods of low humidity and thus indicates times of substantial aridity. The redder shale intervals have fewer halite casts and probably reflect wetter cycles. Such climate cycles apparently paralleled cycles of glacial advance and retreat (and global sea level fall and rise).

The presence of limestone beds (see exposures close to the west side of the road on the north side of the arroyo), some with fragments of fossils, indicates that this section was deposited in a nearshore marine setting with both marine and terrestrial influences. Halite casts and fossil fragments are typical of the kinds of relatively subtle evidence geologists must find in order to decipher past environments. It is very much like the collection of evidence by forensic teams at a crime scene, and part of what makes geology such an interesting field.



Salt casts in the Meseta Blanca Member of the Yeso Formation.

During the very short 0.3-mile drive to the next stop you will stay in Meseta Blanca deposits with views of younger strata to the east and older units to the west.

STOP 5 PENNSYLVANIAN DEPOSITIONAL CYCLES

Mile: 10.0

Coordinates: N 34°03.051'
W 106°46.542' (at the cairn)

UTM: Zone 13

336106E 3769220N

This stop provides a chance to see at a distance depositional cycles within the upper part of the Madera Group. The view to the west shows rocks exposed in and near Arroyo del Tajo. In the foreground are the orange-red, gray, and white beds of the Meseta Blanca Member of the Yeso Formation (discussed in detail at Stop 4). Somewhat farther away are the deeper red siltstones and sandstones of the Abo Formation (discussed at Stop 2). Finally, on the far ridge, the gray limestones of the upper part of the Madera Group (the Atrasado Formation, discussed at Stop 3) are well exposed.

The gray Atrasado Formation limestones of the upper Madera Group, visible to the west of the road at this site, show a very prominent bedding cyclicity. The rocks were folded and thrust faulted during the Laramide orogeny in the early Tertiary and are now standing nearly on end (see cover photo). The vertical beds have been eroded so that the hard, erosion-resistant limestone units are standing out in relief; intervening nodular limestones and shales are less resistant to erosion and form lower, soil- and vegetation-covered intervals. In general, the prominent gray limestone ledges consist of shallow marine limestones (deposited in water depths that were probably 50 feet or less, based on the abundance of phylloid algae, which

required light for growth). The more recessive nodular limestones and black shales were probably deposited in somewhat deeper waters, and there are soil crusts and red shales in the section that reflect episodes of exposure and and/or nonmarine sedimentation.

There are at least two major factors that could have brought about such changes in environmental conditions. Local and regional tectonic movements can raise or lower the seafloor. Alternatively, worldwide sea-level fluctuations of 250 feet or more have been documented as having occurred in the Pennsylvanian due to growth and shrinkage of Southern Hemisphere ice masses (termed glacio-eustasy) discussed at Stop 2.

In the Quebradas it is likely that both tectonic and glacio-eustatic mechanisms produced or influenced Madera cycles. Glacio-eustatic sea-level changes are, by definition, reflected everywhere in the world's oceans, and local and regional pulses of Pennsylvanian–Early Permian mountain building (including both uplift and subsidence of landmasses) are

clearly recognizable throughout New Mexico and adjoining states. However, isolating the relative influence of these two processes on development of marine depositional cycles typically is not possible, given the limited stratigraphic control we have at this time.

The 1.3-mile drive to the next stop will take you initially into the upper Yeso Formation (mainly the Torres Member), which includes some prominent gray limestone beds, commonly marked by an abundance of ocotillo, which thrive on alkaline soils that form on the gypsum-bearing limestones. The high cliffs to the east expose younger strata including the upper two units of the Yeso Formation (the Cañas Gypsum and Joyita Members), the Glorieta Sandstone, and the San Andres Formation. The last stage takes you to a mesa top consisting of a thin veneer of geologically young (less than 5 million year old) Pliocene–Pleistocene mountain-front or piedmont sands and conglomerates sitting on limestones of the Torres Member of the Yeso Formation.

STOP 6 GEOLOGIC PANORAMAS

Mile: 11.3

Coordinates: N 34°02.048'
W 106°46.736'

UTM: Zone 13

335775E 3767370N

This stop provides interesting panoramas in all directions. If you walk toward the south to the mesa edge, you can look down into Arroyo de las Cañas and view the panorama to the south and southwest. Water flow from permanent springs in the canyon keeps the area moist and allows for remarkably lush vegetation and excellent cattle grazing (the valley is a privately owned inholding within BLM lands for that reason). The rocks exposed in the canyon walls consist entirely of Yeso Formation, with gray and yellow limestones and sandstones of the Torres Member in



Top: Panorama looking south to west from Stop 6, showing reddish Permian rocks in the Arroyo de las Cañas (left) and pediments of young piedmont sands and gravels. Bottom: Panorama looking west to northwest from Stop 6, showing pediments of young piedmont sands and gravels (left and center foreground) with some Pennsylvanian and Permian rocks exposed at the right.



upstream areas (to the southeast) and a long exposure of reddish sandstones and shales of the underlying Meseta Blanca Member directly to the south and southwest. The section has undergone extensive folding and faulting which accounts for the variable orientations of beds. The mesa top directly to the south and southeast has modern dunes of loose sand, blown up against the eastern hills by the predominantly westerly winds. The eastern hills here, as at both previous and subsequent stops, consist of the upper Yeso, Glorieta, and San Andres Formations.

The panorama from the northwest to the north provides views of the rocks seen at Stops 2 through 5, with gray Pennsylvanian Madera Group limestones in the background and faulted, red and yellow Abo to Yeso strata in the foreground. Finally, the view toward the east shows high cliffs of younger Permian rocks, including the upper Yeso, Glorieta, and San Andres Formations, which will be discussed further at Stop 7. This remarkable 360° panorama displays almost all the geologic units exposed in this region.

The mesa on which you are standing is formed of a veneer of Pliocene–Pleistocene piedmont sands and gravels that overlie a thick, fine-grained, relatively featureless, gray limestone in the Torres Member of the Yeso Formation. Many eroded pieces of the limestone are visible on the surface of the mesa, and outcrops can be found along the mesa margins.

The 0.9-mile drive to the next stop takes you across the mesa-top piedmont deposits and then back into the upper Yeso Formation (the Torres and Cañas Gypsum Members). As before, the high cliffs to the east expose younger strata including the Joyita Member of the Yeso Formation, the Glorieta Sandstone, and the San Andres Formation.

STOP 7 UPPER YESO CARBONATE AND EVAPORITE DEPOSITS

Mile: 12.2

Coordinates: N 34°01.938'

W 106°45.957'

UTM: Zone 13, 336106E
3769220N

In the valley below and toward the north are excellent exposures of limestones and sandstones of the Torres Member of the Yeso Formation. Overlying that unit are massive gypsum deposits of the Cañas Member of the Yeso Formation, which is well exposed in the low, rounded, whitish hills that line the south side of the (upstream) part of the Arroyo de las Cañas. Farther east, in the higher hills, yellowish and reddish sandstones mark the highest unit of the Yeso Formation, the Joyita Sandstone Member. Above that lies a white-to-pale-yellow, roughly 200-foot-thick section of quartzose sandstones of the Glorieta Formation. Finally, the hills are capped with dark limestones, dolostones, evaporites, and sandstones of the San Andres Formation. This section includes some of the most prolific oil-producing strata in the Permian Basin of southeastern New Mexico and west Texas. The San Andres (along with the overlying Grayburg interval) had yielded more than 1.7 billion barrels of oil and 1.9 trillion cubic feet of gas through 2000 in southeastern New Mexico alone—roughly 36 percent of New Mexico's total oil production and 6 percent of its gas production. The Yeso–Glorieta interval has produced an additional 430 million barrels of oil and 3.4 trillion cubic feet of natural gas.

You can look at some of these units

in more detail by walking downhill into the arroyo. Although the Torres Member here consists of sandstones, evaporites, and limestones, limestones dominate these exposures. Most are fine grained and nearly featureless, although some layers are fossiliferous or contain laminations and clasts of carbonate mud. In some zones, the calcite (CaCO_3) of the limestones has been replaced by dolomite [$(\text{Ca},\text{Mg})\text{CO}_3$] or chert (SiO_2). In places, the rocks are contorted or intricately fractured (forming boxwork fabrics), or contain coarse breccia (rubble) layers and lenses. These structures may be caused by normal tectonic events, but more commonly such features are associated with sliding of rigid units on evaporite beds that behaved plastically, or the collapse of hard and brittle limestone and sandstone beds where near-surface dissolution of underlying layers of highly soluble evaporites (anhydrite, gypsum and halite) occurred. The Torres beds not only contain collapse breccias, they also show molds of nodules and crystals of gypsum and anhydrite. The overlying unit, the Cañas Gypsum Member, still contains massive gypsum at this locality, despite significant exposure and alteration.

The limestone outcrops along the streambed north and northeast of the parking area show many of the features mentioned above. The beds have large-scale undulations and contain lens-shaped patches of coarse breccia with angular limestone blocks. The breccia lenses are bounded by bedded limestone and probably are related to cave dissolution in underlying evaporite beds with localized collapse of the brittle limestones that formed the roofs of the caves. Some of the dissolution of evaporite and collapse of associated limestones may have taken place during humid climate cycles in the Permian. Much of it, however, likely happened



Oncolites, some with visible fossils as their cores, in Torres Member limestone (Yeso Formation).

during more recent uplift.

Most of the limestone layers in the Torres Member contain few or no visible fossils. A few layers, however, have fragments of gastropods (snails), bivalves (clams), and rare cephalopods. Most such layers, including ones just downslope from the parking area, contain large numbers of only one or two species of organisms and contain microbially-coated grains, termed oncolites. The oncolites are roughly 0.5–2 inches in diameter, have many irregular concentric coatings of calcium carbonate, and commonly have a fossil fragment at their core. Please refrain from collecting samples so others can see these features as well.

Limestone beds such as these, with large numbers of only a few species of organisms, or beds that contain mainly salinity-tolerant groups such as bivalves, gastropods and microbes, are interpreted as evidence for deposition in a restricted, hypersaline coastal embayment. Further evidence for hypersalinity comes from the abundance of calcite-lined cavities, the solution-collapse breccias, and the boxwork fracture fabrics that all

are related to former evaporites. The marginal marine embayment in this area probably was directly connected to more normal marine environments known to exist in regions to the south and southeast of the Quebradas.

A short and easy walk upstream along the east-west oriented section of Arroyo de las Cañas will bring you to superb exposures of the Cañas Gypsum Member of the Yeso Formation. After crossing a yellow sandstone bed that



Contorted gypsum-limestone laminations (varves) within the Cañas Gypsum Member of the Yeso at Stop 7.

marks the top of the Torres, the next several hundred yards of exposure on the south side of the valley consist of massive gypsum (the hydrated form of calcium sulfate, $\text{CaSO}_4 \cdot 6\text{H}_2\text{O}$). In most climates, gypsum is removed through dissolution by near-surface ground water. In the warm, dry climate of New Mexico, however, gypsum can reach the surface and survive there for some time. This is an exceptional outcrop, and it is one of only a handful of places in the U.S. that such fresh gypsum outcrops can be seen.

The Cañas Gypsum Member in this area can be as much as 190 feet thick, although at this site only 30–40 feet of gypsum is exposed. The gypsum displays a number of distinctive fabrics, especially laminations of alternating dark and light layers, an eighth to a

quarter of an inch thick. The dark layers consist of limestone and organic matter. The light layers contain mainly gypsum. Such repeated cycles are interpreted as representing varves —annual cycles with dry-season evaporation producing gypsum and cooler, wetter seasons yielding organic limestone layers. The laminated deposits are indicative of a large and relatively deep-water saline coastal lake (salina) or restricted marine embayment that extended 110 miles from just north of Mountainair to south of Alamogordo and Truth or Consequences.

The other structures visible in the Cañas Gypsum mainly reflect alteration produced during 270 million years of burial and subsequent uplift and exposure. Greenish clayey and silty zones are insoluble material left behind by dissolution of more soluble layers. Nodular zones are especially widespread and probably formed during cycles of conversion of gypsum to anhydrite and back to gypsum. Other intervals show small-scale folds within laminated evaporites and more rarely include structures that look like wisps or tongues of flame; both probably result from flow (plastic deformation) within the evaporite masses. That property of plastic flow of evaporites (similar to the behavior of Silly Putty or taffy) can be quite important. For example, evaporite deposits very similar to these are widespread in the Delaware Basin south and east of Carlsbad. Those deposits now host the WIPP site (the Waste Isolation Pilot Plant), the only active underground nuclear waste repository in the U.S. The reason for choosing that unit for waste disposal is because the evaporite deposits, in time, flow in around the wastes and heal any fractures in the rock, forming a largely impermeable seal.

The 3.9-mile drive to the next stop takes you back through both the upper and lower parts of the Yeso Formation and, in a few down-faulted areas, even

goes as low in the section as the Abo Formation. As before, the high cliffs to the west expose younger Permian strata including the upper members of the Yeso Formation, the Glorieta Sandstone, and the San Andres Formation.

STOP 8 STRUCTURAL DEFORMATION

Mile: 16.1

Coordinates: N 33°59.033'

W 106°45.721'

UTM: Zone 13

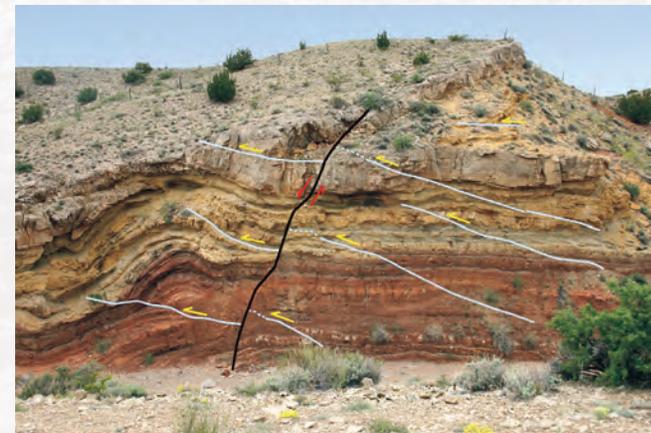
337148E 3761770N

We are now in slightly older rocks: the two lowest members of the Yeso Formation (the Meseta Blanca Member overlain by the Torres Member). The main rock types exposed here are red and yellow sandstones and siltstones and gray limestones and dolomites; evaporite layers probably once were interspersed, but were dissolved during exposure of these strata.

This location provides an excellent opportunity to see some of the complex, multi-generational structural features of this region. Walk south to the edge of the arroyo. In the rock cliff on the far side of the arroyo a single large fold is immediately apparent. A number of associated faults are also visible, and their traces are marked on the pho-

tograph. One set of faults are nearly parallel to the bedding planes; these are thrust faults indicating compressional stresses. The fold is termed a fault-propagation fold because it is the sliding of rocks along the thrust fault that caused associated strata to buckle and fold near the tip of the fault. The former presence of evaporite layers in these rocks (before they were dissolved) may have contributed to the abundance of small thrusts by providing planes of easy sliding.

The thrust faults and related folds in this area are generally interpreted to have formed during the Laramide orogeny (early Tertiary), a time when what is now the Socorro Basin in the Rio Grande rift was a high-standing area. The later inversion of this highland into a basin, through the extensional tectonics that led to rift formation, produced a second set of faults that cut the rocks at a high angle. At least one of these high-angle normal faults can



Fault-propagation fold in the Yeso Formation at Stop 8. Several generations of faults are visible, including low-angle compressional faults (marked in yellow), probably of Laramide age, cut by a high-angle normal fault (marked in red), probably of late Tertiary age.

be seen at this location. The normal faults consistently cut and offset the thrust faults, allowing geologists to

confidently interpret that they must be younger than the thrusts. This is clear evidence of two tectonic events: the rocks were first squeezed in an east-west direction about 60 million years ago during the Laramide orogeny, and then were pulled apart during east-west stretching associated with formation of the Rio Grande rift during the past 30 million years.

If you look toward the west down the arroyo, more such folds and faults are visible. Toward the east you can see, as at Stops 3–7, the higher cliffs consisting of upper Yeso, Glorieta, and San Andres strata. The yellowish quartzose sandstones of the Glorieta are especially well exposed here.

The 4.3-mile drive to the next stop takes you across mesa-top piedmont deposits and then back into underlying Yeso and Abo Formations. As you get to the lower part of the Abo section, massive ledges of gray Pennsylvanian limestone outcrop to the west of the road. As before, the high cliffs to the east expose the Joyita Member of the Yeso Formation, the Glorieta Sandstone, and the San Andres Formation. At approximately 1 mile before Stop 9, the road passes very close to the prominent yellow sandstones of the Glorieta Formation and affords an opportunity (for those willing to do some hiking and climbing) to examine those rocks.



STOP 9 TRIASSIC CHINLE GROUP

Mile: 20.4

Coordinates: N 33°57.340'

W 106°43.720'

UTM: Zone 13

340269E 3758590N

We have left the Upper Paleozoic (Pennsylvanian and Permian) strata and are now in Lower Mesozoic (Triassic; roughly 220 m.y. b.p.) deposits. Although once classified as belonging to the Dockum Group, these rocks are now generally placed in the Chinle Group.

The isolated outcrops at this stop show only a small portion of the roughly 500-foot maximum thickness of the full Triassic section in this region. Purple-to-nearly white (where weathered), crossbedded, micaceous sandstones dominate the small cliffs west of the road. The bedding planes of some of the sandstones show mud cracks, and the coarser, conglomeratic deposits have fragments of shale, limestone, and older red sandstone, presumably all derived from erosion of Permian strata. Such erosion is not surprising, considering that there is a 30–40 million-year time gap between the youngest of the Permian and the oldest of the Triassic strata found in this region. It may imply some uplift during that hiatus, which, through erosion of a variety of Permian units, would have provided a source for these clasts.

East of the road one can examine less obvious but more extensive exposures of

Crossbedded siltstones and sandstones of the Triassic Chinle Group on the west side of the road at Stop 9.

brown-to-maroon shales with interbedded siltstones and sandstones. Small lenses of conglomerate, again containing clasts of Permian rocks, are present locally. The siltstones and sandstones are laminated and crossbedded, with color contrasts between fresh maroon or purple layers and slightly weathered, whiter bands. Widespread layers of fist-sized calcareous nodules indicate zones of Triassic soil formation.

The absence of marine fossils in Chinle deposits (and the presence, in other areas, of extensive vertebrate remains), the occurrence of soil-formed nodules and mudcracks, the abundance of lenticular or channel-shaped bodies of sandstone and conglomerate within predominantly finer-grained shales, all provide evidence that these rocks formed along ancient river systems in a continental environment. The shales were deposited on broad floodplains, whereas the crossbedded sandstones and conglomerates reflect small, migrating channels and bars. The deep red-to-maroon color of the Triassic strata indicates deposition (or alteration) in a semi-arid environment in which iron minerals were strongly oxidized (as in the older Bursum, Abo, and Yeso deposits).

From this stop, one also gets an excellent view to the north of the youngest of the Permian deposits in this area. The long, light-colored cliffs expose at their base the upper part of the Yeso Formation; the middle zone of the cliffs consists of the well-bedded, yellow sandstones of the Glorieta Formation; and the upper parts of the cliffs consist of erosion-resistant beds of the San Andres Formation. A fault separates the younger (downthrown) reddish-brown Triassic strata in the valley in the foreground from the older, uplifted Permian rocks in the cliffs in the immediate background. Through gaps in those cliffs, one can see the Magdalena

Mountains and Socorro Peak in the far distance.

As you proceed southward 3.1 miles to the next stop, outcrops become sparse and low but stay in Triassic strata. Eventually all outcrops disappear underneath young, valley-fill sediments of the northern Jornada del Muerto. The views from the road include a panorama of mountains from the Oscura and San Andres ranges and the hills surrounding the Cerro de la Campana in the southeast and south, to the San Mateo, Magdalena and Socorro Mountains to the southwest and west-northwest.

STOP 10 SOUTHERN PANORAMA

Mile: 23.5

Coordinates: N 33°55.812'

W 106°41.280'

UTM: Zone 13

343981E 3755700N

This stop provides a wonderful view of the region to the south: the broad plains of the northern part of the Jornada del Muerto bordered by a series of mountain ranges. This desolate region, now largely part of the White Sands Missile Range, was the site of early Spanish expeditions northward from Mexico into central and northern New Mexico. The mountains in the background include (from southeast to south) the Oscura Mountains (with Mockingbird Gap at the southern end), Capitol Peak, Sheep Mountain and Salinas Peak, the more distant main part of the San Andres Mountains. The Trinity site, location of the world's first atomic bomb test on July 16, 1945, lies on the plains just west of the Oscura Mountains.

These mountains all are tilted blocks, separated by half-graben basins, formed by faulting during rifting of the Basin and Range Province, which extends from the Guadalupe and Sacramento Mountains of southeastern New Mexico westward for nearly 600 miles into southern California. That entire region features landscapes similar to those visible from this stop, with rugged, tilted, north-south oriented mountain ranges, separated by flat-floored basins, with young sediment filling deep depressions. The province thus has a strong topographic grain that makes north-south travel, through elongate valleys, much easier than crossing multiple ranges while journeying in an east-west direction. It is that grain that strongly influenced routes of the conquistadors for more



Generalized cross section looking south in the vicinity of Stop 10. Note the extensive faulting on both sides of the Rio Grande.

than 100 years and continues to affect trade and transport to this day.

The mountain ranges visible to the east and south all contain rocks comparable to those present in the Quebradas—predominantly Pennsylvanian and Permian sedimentary deposits with exposures of underlying Precambrian basement rocks. They differ in that they preserve remnants of Cambrian–Ordovician, Devonian, and Mississippian sedimentary strata. Cambrian-to-Mississippian strata are well exposed and easily accessible in the Franklin Mountains (in and near El Paso, Texas) and on the west side of the Sacramento Mountains in the vicinity of Tularosa

and Alamogordo, New Mexico.

The small sharp, distinctive peaks to the south-southwest include the Cerro de la Campana (which translates as “Hill of the Bell”). They look like a series of small volcanoes but, although they are composed of rocks of volcanic origin, the peaks are not volcanic cones. These hills are erosional remnants of once much larger deposits of mid-Tertiary (30–35 m.y. b.p.) volcanoclastic breccias and lava flows (along with some associated east-west oriented dikes). They were derived from a stratovolcano that was centered to the west of the current outcrops and now is probably mostly buried under the Rio Grande basins.

To the west of Cerro de la Campana are low hills largely composed of Cretaceous rocks, and in the farther distance lies the Rio Grande valley

with its western border ranges, the San Mateo and Magdalena Mountains and Socorro Peak. These mountains expose primarily volcanic rocks of mid-Tertiary age with subordinate Paleozoic sedimentary strata. The volcanic units, which extend westward into Arizona, represent the edge of the Mogollon-Datil volcanic field, which contained 20 or more enormous caldera complexes. During the roughly 12 million years of its main eruption history (36–24 m.y. b.p.), this was the place to be if you were into explosive and destructive volcanic eruptions, some as much as to 1,000 times the magnitude of the 1980 Mount St. Helens eruption.

ABOUT THE AUTHOR

Peter Scholle is the state geologist for New Mexico and the director of the New Mexico Bureau of Geology and Mineral Resources, a research and service division of New Mexico Tech in Socorro. Peter's rich and diverse career has included nine years with the U.S. Geological Survey, many years of working for and with the petroleum industry, seventeen years of university teaching, and eleven years in state government. His specialty is carbonate sedimentology and diagenesis. He has published broadly and continues to find time for teaching, at New Mexico Tech and elsewhere.

Cover: View to the southwest from Stop 5 showing reddish Permian rocks (foreground) and cyclic bedding in Madera Group limestones (background). These strata have undergone Tertiary-age folding and thrust faulting, and the limestones now have a near-vertical orientation.

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Below: Panorama looking from east-southeast to west-southwest at Stop 10. The mountains to the east are the Oscura Range. To the south lie Mockingbird Gap and the San Andres Mountains. The tallest of the distinctive conical peaks at the right is the Cerro de la Campana. The Jornada del Muerto occupies the flat foreground of the entire vista.

