Rio Grande rift to the Colorado Plateau. First-day road log from Espanola to Abiquiu, Youngsville, Coyote, Gallina and Ghost Ranch

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RIO GRANDE RIFT TO THE COLORADO PLATEAU
FIRST-DAY ROAD LOG FROM ESPAÑOLA TO ABIQUIU, YOUNGSVILLE, COYOTE, GALLINA AND GHOST RANCH

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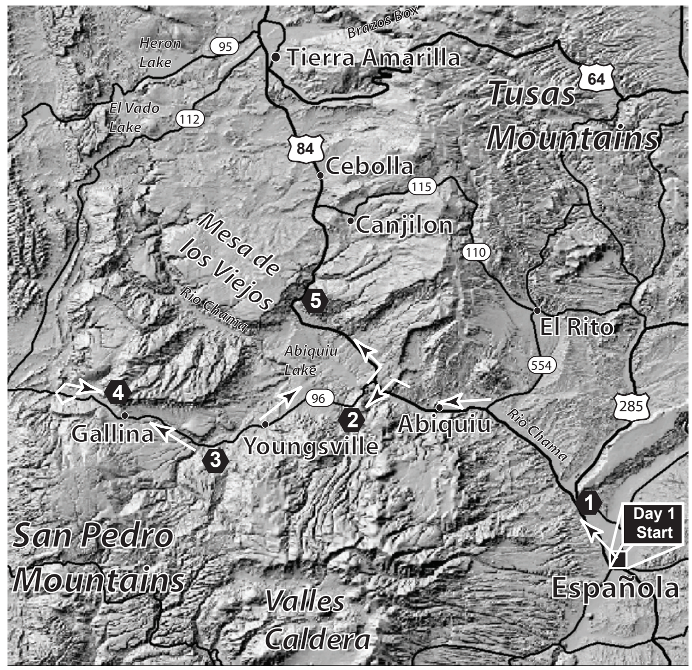
Assembly Point: Parking lot of Northern New Mexico Community College, Española

Departure Time: 7:30 AM

Distance: 109.0 miles

Seven stops (two optional)



SUMMARY

The first day of the conference will focus on Rio Grande rift tectonics and Neogene sediments, and introduce us to Laramide tectonics and the older (Pemian-Triassic) sedimentary cover of the Chama Basin. The tour begins at Española in the Rio Grande rift and takes us across the western boundary of the rift onto the southeastern Colorado Plateau (Chama Basin). The first stop, located in the rift, examines Neogene stratigraphy, tectonics and Quaternary terrace deposits near the confluence of the Rio Chama and the Rio Grande. The second stop, at Abiquiu Dam, is on the Colorado Plateau, and we examine characteristic, nearly flat-lying Upper Triassic strata (depositional systems and magnetostratigraphy). Stop 3 also is in essentially flat-lying strata of the Colorado Plateau, but these are older, Lower Permian rocks at the classic bonebeds of Arroyo del Agua. The fourth stop takes us right to the edge of the structural San Juan Basin, where we examine Upper Cretaceous strata and discuss their economic geology, as well as Laramide tectonics. The route then retraces to Abiquiu Dam and continues to Ghost Ranch, where the last stop is at the world-famous Upper Triassic dinosaur quarry.

0.0 BEGIN ROAD LOG: Northwestern parking lot of Northern New Mexico Community College in Española.

The city of Española lies near the center of the Española Basin. According to the 2003 Española Visitors Guide, the city proper has approximately 10,000 people but about 35,000 reside in the surrounding area (within about a 15 mile radius of Española). Española was founded in the 1880s as a stop on the Denver and Rio Grande Railroad. The city and its environs have been dubbed the "lowrider capital of the United States." Driving down Riverside Drive (NM Highway 84) on a Friday or Saturday night can be culturally interesting but slow. At the stop sign, **turn right and proceed north** on US 84 (which is N. Paseo de Oñate). *0.3*

0.3 Stoplight at intersection with NM Highway 584. Continue straight. The underlying terrace deposit corresponds to Qtcg4 of Koning and Manley (2003). The strath (base) of this deposit is 15-38 ft above the modern Rio Grande, and the top is 37-52 ft above the modern Rio Grande. Age estimates for this general terrace height, using carbon-14 dating and amino-acid racemization ratios, give a range of 12-45 ka (Table 1.1; Dethier and McCoy, 1993; Dethier and Reneau, 1995). *0.3*

Road log continued on page 3 if skipping Optional Stop 1

0.3 OPTIONAL STOP 1 - Arroyo del Gaucho (re-zero at intersection of US 84 & NM Highway 584):

Proceed west on NM Highway 584 (Industrial Park Road) as it climbs onto the top of the Qtcg3 terrace of Koning and Manley (2003). Figure 1.1 and Table 1.1 illustrate the Quaternary terrace stratigraphy of the area.

TABLE 1.1. Summary of Quaternary terrace deposits near the confluence of the Rio Chama and Rio Grande

Terrace map unit[1]	Associated geomorphic surface[2]	Approximate height of strath (m) above Rio Chama or Rio Grande[3]	Measured height of top of quartzite-rich, axial gravel (m)[4]	Estimated age of axial river sediment, in ka[5]
Qtcg4		5-12	N/d	12-45
Qtcg3 [Qtc6]	Q4	27-38	38	70-90
Qtcg2c	Q3	35-47	47	130-150
Qtcg2b	Q3	50-64	55-64	130-150
Qtcg2a [Qtc4]	Q3	68-84	70-84	250-280
Qtcg1[6] [Qtc3]	Q2	90-126	89-120	350-650

Notes:
1. Map label from Koning and Manley (2003); Qtcg4 is youngest and Qtcg1 is the oldest. Label in brackets is the correlative unit in the Medanales quadrangle to the northwest.
2. From Dethier et al. (1988).
3. Height is estimated from the San Juan Pueblo 7.5-minute topographic map and Figures 4 and 5. Estimated measurement error of ± 3-5 m.
4. Heights are from Dethier and Reneau (1995, fig. 3); N/d = Not differentiated as a separate terrace deposit in Dethier and Reneau (1995, fig. 3).
5. Values are from age estimations and related data presented in Dethier and Reneau (1995, table 1) and Dethier and McCoy (1993). The author is of the opinion that parts of Qtcg1 may be older than 650 ka.
6. The two lower straths of this unit were locally differentiated for constructing Figure 5.

0.2 Turn right (north) on Calle de la Merced. *0.2*

0.4 Calle de la Merced merges with Forest Service Road 144 and turns left. Proceed west on the unpaved Forest Service road. *0.2*

0.6 Pass a water supply well for the city of Española. *0.2*

0.8 Road turns slightly left. Ahead is a view of the Jemez Mountains. We are driving on a thin (~10 ft thick) strath terrace, composed of volcaniclastic alluvium derived from the Jemez Mountains, whose tread (upper surface) is graded to the top of the Qtcg3 terrace. The volcaniclastic alluvium overlies floodplain deposits and quartzite-rich, axial fluvial gravel interpreted to belong to Qtcg2. The latter rests on a strath (basal erosion surface) whose elevation corresponds best with that of

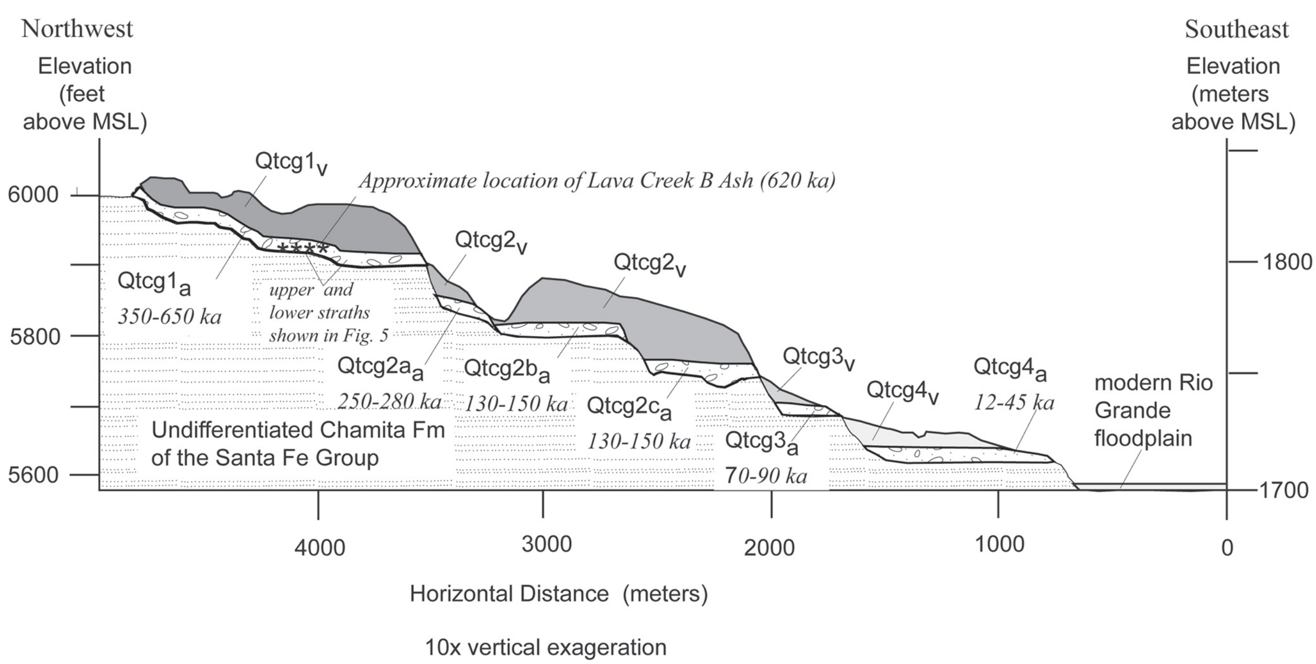


FIGURE 1.1. NW-SE cross-section through the southwest corner of the San Juan Pueblo quadrangle. This section illustrates the Quaternary terrace stratigraphy near Stop 1. The "a" and "v" subscripts on the unit labels denote axial fluvial gravel and locally derived volcaniclastic alluvium, respectively. The UTM coordinates of the northwest and southeast end-points are respectively: 3986190 N, 398630 E; 3984000 N, 402980 E; (zone 13, NAD 27). Interpreted ages are from Table 1.1. Figure is from Koning and Manley (2003).

Qtcg2 of Koning and Manley (2003). This strath terrace is inset into the upper part of the Qtcg2 terrace deposit, which comprises the low hill on the immediate left. Locally, the top of this strath terrace has a soil with a calcic horizon possessing a stage III carbonate morphology (Gile et al., 1966). *0.2*

1.2 Descend into Arroyo del Gaucho. *0.3*

1.5 We are driving on a surface graded to the top of the Qtcg2 terrace deposit of Koning and Manley (2003). The Qtcg1 terrace deposit forms much of the low hill to the immediate right. *0.3*

1.8 Roadcut on the right exposes quartzite-rich, axial fluvial gravel, associated with terrace Qtcg1, unconformably overlying the Ojo Caliente Sandstone Member of the Tesuque Formation. *0.2*

2.0 We are driving on an erosional surface on top of Qtcg1. *0.4*

2.4 The road drops about 20 to 40 ft onto a broad topographic saddle. The orange-pink cliffs 1-2 miles to the south are on Santa Clara Reservation land and not currently accessible. The sediment of these cliffs likely belongs to the Vallito Member of the Chamita Formation underlying grayish gravel of the Puyé Formation. On or before the topographic saddle, park on the right side of the road.

This optional stop examines the Gaucho stratigraphic section (Koning and Aby, this volume). This stratigraphic section starts at the Tesuque Fm-Chamita Fm contact, and extends up to a fine lapilli correlated with the Chamita lower tuffaceous zone (7.9-8.4 Ma). The section encompasses four of the five members newly proposed for the Chamita Formation: Vallito, Cejita, Cuarteles, and Hernandez members (Koning and Aby, this volume).

END OF OPTIONAL STOP 1

Return to vehicles and drive back to the intersection of US 84 and NM Highway 584. Continue main road log.

0.6 Cross Arroyo del Gaucho. On the northern side of the mouth of this arroyo, to the right, is an outcrop of strongly cemented channel sandstone. This fluvial sediment is in planar, very thin to thin beds and belongs to the Pojoaque Member of the Tesuque Formation (Galusha and Blick, 1971). Following the nomenclature of Cavazza (1986), Koning and Manley (2003) differentiate this sediment as a middle Miocene unit of lithosome B of the Tesuque Formation, which was deposited by a river sourced east of the Picuris-Pecos fault in the Peñasco embayment. About 0.3 miles to the west, limited exposures reveal stratigraphically younger Ojo Caliente Sandstone of the Tesuque Formation. Beds strike N-NE and dip 5-8° W-NW (Koning and Manley, 2003). *0.2*

0.8 Ascend onto the sandy gravel terrace deposit north of Arroyo del Gaucho. This is unit Qtcg3 of Koning and Manley (2003) and is discussed at Stop 1. *0.1*

0.9 Enter into the San Juan Pueblo Indian Reservation. Permission is required to leave the highway right-of-way. *0.5*

1.4 Cross Arroyo de la Plaza Larga. Good exposure of Qtcg3 is observed 300 ft to the northeast. San Juan Indian Reservation is in the foreground. *0.3*

1.7 STOP 1 - Dominguez-Escalante Trail

At or just before Historical Marker for Dominguez-Escalante Trail, park on the right shoulder of the highway. Congregate in the wide area to the right of the lead vehicles. In 1776, Fray Silvestre Velez de Escalante attempted to establish a trade route between Santa Fe and Monterey, the Spanish capital of California. His expedition followed the Rio Chama but never reached its goal after 8 months of travel.

This stop will discuss the stratigraphy of the upper Santa Fe Group, tectonic deformation at the south end of Black Mesa, and Quaternary terrace deposits at the confluence of the Rio Chama and Rio Grande (see the accompanying minipaper for discussion of the latter).

In arroyos to the southwest (i.e., Arroyo del Corral de Piedra and Arroyo del Gaucho) are numerous exposures of the Ojo Caliente Sandstone Member of the Tesuque Formation. The sand in this member is generally fine-upper to coarse-lower in grain size and cross-stratified. Foresets dip primarily to the northeast (Dethier and Manley, 1985; Koning, 2004; Koning et al., 2004a). About 0.6 to 1.2 miles southwest of this stop, there are minor mud beds interbedded in the eolian sand. Fine-grained fluvial interbeds are more common eastward, as can be observed ~0.6 miles to the southeast of here under terrace deposit Qtcg3.

The Ojo Caliente Sandstone represents an erg that covered the northwestern and north-central parts of the Española basin (Kelley, 1978), in addition to extending into the San Luis basin (Drakos et al., 2004). The base of the Ojo Caliente Sandstone at the Conical Hill fossil quarry, 4.8 miles southeast of Abiquiu, has a number of taxa that are characteristic of the latest Barstovian assemblages in the Great Plains (14-12.5 Ma: Tedford and Barghoorn, 1993; Tedford et al., 2004). The Ojo Caliente Sandstone south of the Rio Chama is locally overlain by sandy fluvial sediment interbedded with minor eolian sediment, both of which are included in the Vallito Member of the Chamita Formation (Koning and Aby, this volume). About 122 ft above the base of the Vallito Member, 0.6-1.2 miles south of the town of Chili (mile 6.3 of the road log), is a Lobato Basalt flow dated by K-Ar methods at 9.6-9.9 $\pm$ 0.2 Ma (Dethier and Manley, 1985; Dethier et al., 1986). Thus, Ojo Caliente Sandstone deposition south of the Rio Chama had ceased by ~ 10 Ma. Locally, under Black Mesa and in the Chamita badlands, stratigraphic relationships suggest that transient(?) patches of the Ojo Caliente Sandstone locally persisted a little later (perhaps 1-2 Myr) than south of the Rio Chama (Koning et al., 2004b).

Under the Quaternary terrace gravel at this stop is a small exposure of silty very fine to medium sandstone of the Vallito Member of the Chamita Formation. The sand is in thin to thick beds, and interbedded with 10-25% thin to thick, tabular beds of siltstone and claystone. The lack of prominent cross-stratification, the subrounded to subangular texture of the sand, the slightly elevated levels of silt in the sand, and the presence of silt and clay beds suggest a fluvial depositional environment rather than typical eolian deposits of the Ojo Caliente Sandstone. The eolian sediment of the latter is commonly cross-stratified, has subrounded sand grains, and has very little silt. The deposits in this exposure lie within a 152-213 ft-thick stratigraphic interval marking an upward gradation from predominately eolian sedimentation of the Ojo Caliente Sandstone to fluvial sedimentation of the lower Cejita Member (Fig. 1.2). The uppermost interpreted eolian sand is observed 122-152 ft stratigraphically above this site, immediately above the lowest of the coarse white ashes observed in the area. Considering the age of the coarse white ash zone, discussed below, the Santa Fe Group at this site is probably near the boundary of the Barstovian and

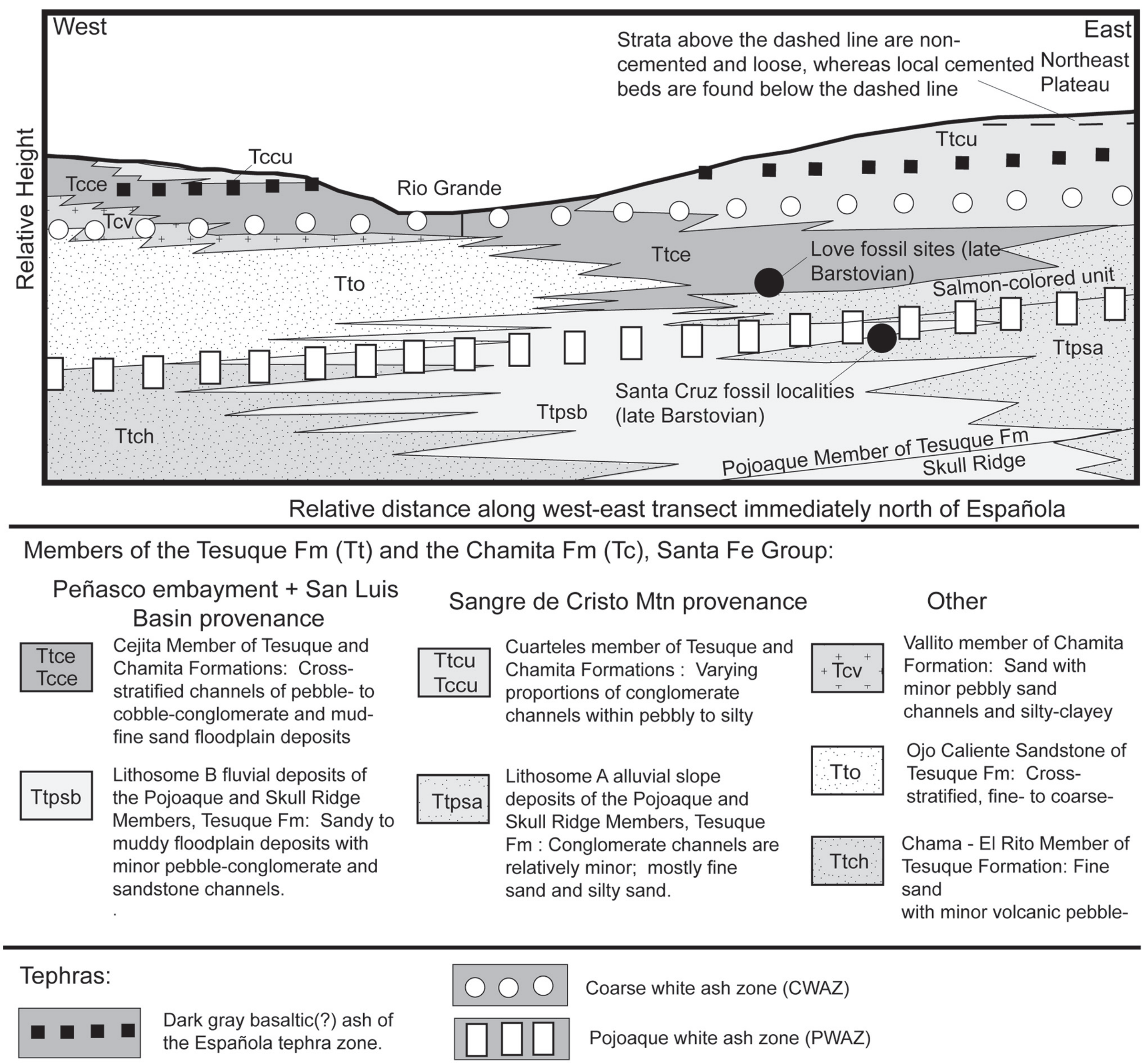


FIGURE 1.2. Schematic diagram illustrating stratigraphic relationships in the upper Santa Fe Group near Española (i.e., middle-upper Tesuque Formation and the lower Chamita Formation). Note that the Cuarteles and Cejita members are included in both the Tesuque Formation (east of the Rio Grande) and the Chamita Formation (west of the Rio Grande), as is allowed by the stratigraphic code (see Koning and Aby, this volume; North American Commission on Stratigraphic Nomenclature, 1983). The Pojoaque and Skull Ridge members are subdivided according to the lithosome nomenclature of Cavazza (1986). Figure slightly modified from Koning and Manley (2003, fig. 4).

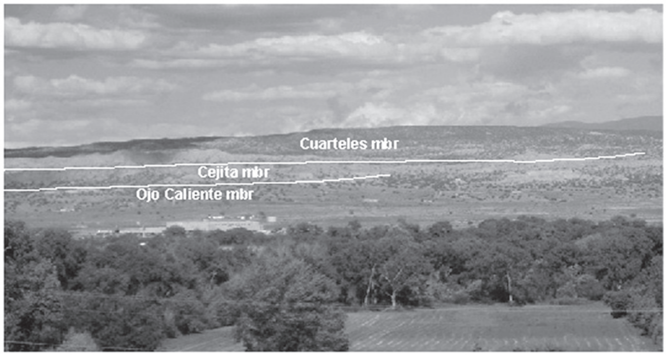


FIGURE 1.3. Photo looking east of Stop 1 illustrating Tesuque Formation members northeast of Española. Here, alluvial slope sediment (Cuartales Member of Koning and Aby, this volume) has prograded over the Cejita Member. The Cejita Member overlies Ojo Caliente Sandstone near the base of the bluffs.

the Clarendonian land-mammal "ages" (~ 12.5 Ma: Tedford et al., 2004). Strata exposed in roadcuts on the left side of highway to the north also lack gravel and coarse sand, and may represent fluvial reworking of concomitant eolian sand or older Ojo Caliente Sandstone. Beds in the Santa Fe Group strike NE and dip ~6 degrees NW (Koning and Manley, 2003).

Looking due east across the Rio Grande, 3.6-4.2 miles distant, are 183-305-ft tall bluffs composed of the upper Santa Fe Group (Fig. 1.3). The lower, gray part of these bluffs is composed primarily of sand and gravel channel deposits, whose clasts are dominated by Paleozoic limestone, sandstone, and siltstone together with Proterozoic quartzite (Koning and Manley, 2003). Paleocurrent indicators show that the river depositing this sediment flowed primarily to the south-southwest at this location (Koning and Manley, 2003). These strata are included in the Cejita Member of the Tesuque Formation by Koning and Manley (2003). They are interpreted to be 12-13 Ma because they lie above the Pojoaque White Ash Zone but have yielded fossils of Barstovian age (Koning et al., this volume). This unit is generally coarser than older (middle Miocene) deposits of similar provenance and interfingers westward with the Ojo Caliente Sandstone (Koning and Manley, 2003; Koning et al., this volume).

Above the gray, coarse strata in the aforementioned bluffs lies pinkish, arkosic sediment of the Cuartales Member of the Tesuque Formation (Koning et al., this volume), deposited by west-flowing streams on the distal part of an alluvial slope flanking the western Sangre de Cristo Mountains (Manley, 1976a, 1977, 1979; Koning and Manley, 2003). The gravel assemblage in this sediment is dominated by granite. In the Cuartales Member exposed in these bluffs are numerous interbeds of coarse white ash probably derived from the Jemez Mountains (the coarse white ash zone, or CWAZ, of Koning et al., 2004b). These tephra beds consist of consolidated, coarse ash with abundant plagioclase. In addition, there are minor grains of pink to gray volcanic lithic fragments, biotite, and quartz. The lack of sanidine and common alteration makes it difficult to date these ashes, but $^{40}Ar/^{39}Ar$ dating of biotite in ash correlated to the CWAZ yielded ages of 11.3 ± 1.2 and 11.7 ± 1.1 Ma (Gary Smith, pers. comm., 2003), and 10.9 ± 0.2 Ma (William McIntosh, unpublished data). The CWAZ is interbedded in the Cejita Member within 0.6 miles west of this stop (up-section), but this is not observed east of the Rio Grande (Koning and Manley, 2003). Thus, during the time the bulk of the CWAZ was deposited at ~10.5-12.5 Ma, the Cuartales Member had prograded westward over the lower Cejita Member, and the eastern margin of the river depositing the Cejita Member was between this stop and the bluffs east of the Rio Grande.

To the north are the Chamita badlands, where uppermost Santa Fe Group strata are preserved east of the south tip of Black Mesa and north of the Rio Chama and Rio Grande confluence (Galusha and Blick, 1971). Abundant Hemphillian (5-9 Ma) fossils have been collected in this area, particularly from the San Juan and Rak camel quarries. Here lies the stratotype of the Chamita Formation (Galusha and Blick, 1971), which recently has been further subdivided into the Vallito, Cejita, and Cuarteles members (lowest to highest; Koning and Manley, 2003; Koning et al., 2004c, and Koning and Aby, this volume, fig. 3). The strata here are deformed into a west-plunging syncline, and have been significantly offset by the Santa Clara fault to the west (Koning and Manley, 2003; Koning, this volume). This

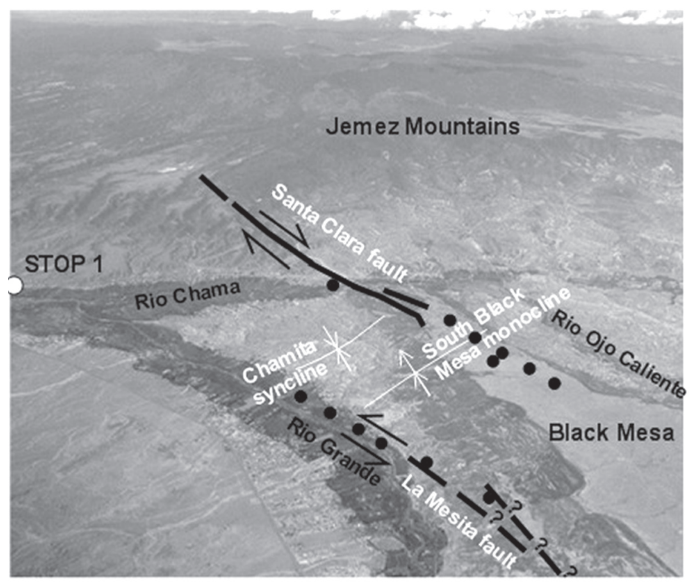


FIGURE 1.4. Aerial view looking southwest towards the confluence of the Rio Chama and Rio Grande (left) in addition to southern Black Mesa and the lower Rio Ojo Caliente (right). The Jemez Mountains and Valles caldera are in the background. Note the prevalent mass wasting on the southeastern slope of Black Mesa. Black Mesa is capped by the Servilleta Basalt (Pliocene), which has been folded downwards 150-180 ft by the South Black Mesa monocline. The west-trending monocline and Chamita syncline lie between the respective ends of the Santa Clara and La Mesita faults, and may be related to the transfer of slip between these two structures (Koning et al., 2004c). Balls are on down-thrown sides of faults, which are dashed where approximate and dotted where concealed. Photo taken by Kirt Kempter.

QUATERNARY TERRACE DEPOSITS ALONG THE LOWER RIO CHAMA AND THE RIO CHAMA-RIO GRANDE CONFLUENCE: STRATIGRAPHIC RELATIONS AND POSSIBLE DISPLACEMENT BY THE SANTA CLARA FAULT

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The road cuts at Stop 1 exhibit terrace sediment of Qtcg3 of Koning and Manley (2003), which underlies the Q4 geomorphic surface of Dethier et al. (1988). Here, there is 3.0-3.3 m of quartzite-rich, axial fluvial gravel alluvium overlain by 3.0-3.5 m of light yellowish brown to light brown floodplain silt. The upper 3-3.5 m of the exposure is composed of sandy gravel whose volcanic composition indicates derivation from the Jemez Mountains. The strath of Qtcg3 is 27-38 m above the present Rio Grande, and the top of the quartzite-rich axial gravel is 33-42 m. Amino-acid racemization data of gastropods suggest an approximate age of 70-90 ka for the axial gravel and floodplain deposits (Dethier and McCoy, 1993; Dethier and Reneau, 1995); the overlying volcaniclastic sediment is probably slightly younger, perhaps 50-70 ka. In places, the volcaniclastic sediment that overlies the quartzite-rich, axial sediment is very thick (30-40 m; see miles 5.5 and 9.3). Recent cosmogenic dating suggests that terrace deposits of 50-70 ka age, coinciding with late Oxygen Isotope Stage 4 and early Oxygen Isotope Stage 3, are extensive in the southwest United States (Gosse et al., 2004).

The stratigraphic pattern of volcaniclastic, locally-derived piedmont alluvium over thinner axial fluvial sediment is characteristic of other Quaternary terrace deposits in this area (Dethier et al., 1988). The significant deposition of this locally derived sediment may possibly be due to increased local erosion rates at the beginning of an interglacial event (Koning and Manley, 2003) – an inference derived from a hillslope process-response geomorphic model presented in Bull (1991) and discussed in Rogers and Smartt (1996) for terraces along the Jemez River.

There are six other mapped terrace deposits in the near-vicinity (Fig. 1.5, Table 1.1). Qtcg4, discussed at mile 0.4, is likely latest Pleistocene in age (12-45 ka; Dethier and McCoy, 1993; Dethier and Reneau, 1995). The next three higher (older) terrace deposits above the Qtcg3 terrace deposit observed at this stop have been mapped as Qtcg2a-Qtcg2c (Koning and Manley, 2003). These three terraces are difficult to differentiate because generally a single geomorphic surface (surface Q3 of Dethier et al., 1988) is preserved on top of the locally derived volcaniclastic alluvium. This volcaniclastic sediment may, in fact, be the same age across Qtcg2a-Qtcg2c. However, the quartzite-rich, axial gravel and respective underlying straths are of sufficiently different elevations as to allow approximate identification of three terrace strath levels, each having a unique age. The strath heights of terrace deposits Qtcg2c, Qtcg2b, and Qtcg2a are 35-47 m, 50-64 m, and 68-84 m above the modern Rio Grande (Table 1.1). The estimated ages of their axial channel and floodplain deposits, using gastropod amino-acid racemization data, are 130-150 ka for Qtcg2c and Qtcg2b, and 250-280 ka for Qtcg2a (Table 1.1; Dethier and McCoy, 1993; Dethier and Reneau, 1995). The highest terrace deposit, Qtcg1, has quartzite-rich axial gravel at its base, whose strath differs in local elevation by 36 m, and lies 90-126 m above the modern Rio Grande. Obvious inset relations within this highest unit could not be confidently identified in the field, but it is very likely that there are small, subtle inset relations, so a large age range for this unit is not unexpected (350-650 ka: Table 1.1; Dethier and McCoy, 1993; Dethier and Reneau, 1995) The lowest two strath levels of Qtcg1 were locally differentiated for constructing the strath elevation profiles of Figure 1.6.

Between Española and Abiquiu Dam, the road log follows the approximate location of two leveling surveys conducted in 1934 and 1939 (Reilinger and York, 1979). The results of these two surveys are interesting because they indicate relative ground subsidence between 1934 and 1939 for approximately 22 km (14 mi) northwest of Española, with the maximum subsidence on the immediate hanging wall of the Santa Clara fault zone (mile 5.7). This subsidence has been attributed to crustal deformation (Reilinger and York, 1979). The author compared these leveling data with an elevation profile of the straths for the various Quaternary terraces mentioned above (Fig. 1.6). The elevation profiles of the Quaternary straths do not support long-term subsidence (over the age range of the terraces, which is tens of thousands of years). Rather, their respective terrace strath slopes steepen downstream in the 4.2 miles southeast of the Santa Clara fault, and decrease in slope slightly upstream of this fault. These strath trends mimic that of the modern valley floor, which also seems to steepen southeast of the Santa Clara fault. Consistent with experimental fluvial geomorphic studies (e.g., Fiedkin, 1945; Schumm and Khan, 1971; Schumm and Khan, 1972), the Rio Chama channel is more sinuous where the valley slope is steeper. This slope change relative to the Santa Clara fault may be due to increased sediment load to the Rio Chama from the Rio Ojo Caliente and Arroyo de la Presa (Fig. 1.6), the effect of which may increase the slope and possibly change the pattern from straight to meandering (Schumm and Khan, 1972).

The straths of some of the terraces in Figure 1.6 may be vertically offset across the fault, particularly two straths associated with terrace deposit Qtcg1 (which are displaced 10-13 m). The straths associated with terraces Qtcg4 and Qtcg3 may also be vertically offset, but their low offset values of 3-5 m are within the error of measurement. Given a 13 m vertical offset for the higher strath of Qtcg1, the correlation of which is constrained by the local presence of Lava Creek B ash (~620 ka) in overlying deposits (Naeser et al., 1973; Dethier et al., 1990), gives a middle-late Quaternary vertical slip rate of 0.02 mm/yr for this part of the Santa Clara fault. This rate is about half as much as that calculated using Pliocene and upper Miocene marker beds (Koning et al., 2004c). In summary, terrace strath profile data do not conclusively demonstrate tectonic deformation fro terrace deposits younger than Qtcg1 (~620 ka), nor do these profiles mimic ground subsidence trends from leveling data of Reilinger and York (1979).

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general area has been called the Black Mesa segment boundary (Fig. 1.4). Here there is an interpreted lateral transfer of slip between the Santa Clara fault (east-down with a possible component of right-lateral slip: Aldrich, 1986) and faults associated with the Embudo fault system to the northeast, which are generally west-down and have a strong component of left-lateral slip (Koning et al., 2004c).

This stop allows views of Servilleta Basalt that was tectonically deformed during the Plio-Pleistocene. The Servilleta Basalt here is 18-55 ft thick and caps Black Mesa, the south tip of which is to the northwest of this stop. The Santa Clara fault (Harrington and Aldrich, 1984) is a northeast-trending, east-down fault (with a possible component of right-lateral slip; Aldrich, 1986) that joins with the Pajarito fault to the south. It passes within 0.6 miles east of the south tip of Black Mesa (Fig. 1.3). Motion along this fault has tilted the basalt in the southern 2.1 miles of the mesa 3-5 degrees E-SE (Koning and Manley, 2003). To the north of this E-SE dipping domain, tectonic activity in the Plio-Pleistocene has folded the basalt into a W-NW trending monocline (the South Black Mesa monocline; Koning et al., 2004c) that seems to coincide with the north limb of the Chamita syncline (Fig. 1.4). This monocline has produced 152-183 ft of topographic relief on the upper Servilleta Basalt surface. *0.5*

END STOP 1

Return to vehicles and carefully return to US Highway 84.

2.2 Road bends to left, offering a good view of the south end of Black Mesa. About 0.6 miles to the northeast is the confluence of the Rio Grande and Rio Chama. *0.3*

2.5 The terrace deposits to the left belong to Qtcg2b of Koning and Manley (2003). Under these terrace deposits are medium to thick, tabular beds of distal alluvial slope deposits of the Cuarteles Member of the Chamita Formation (Koning and Manley, 2003; Koning et al., this volume). These strata contain minor granite pebble beds, and look very similar to sediment deposited in the distal alluvial slope environments of the Skull Ridge and Pojoaque members of the Tesuque Formation. This unit overlies approximately 183 ft of Cejita Member strata, which in turn overlies the Vallito Member discussed in Stop 1 (Fig. 1.2). *0.3*

2.8 Mile marker 193. Enter community of San Jose. *0.4*

3.2 Large, unnamed tributary to the Rio Chama enters from the southwest. Beds between this arroyo and the Santa Clara fault strike N-S and dip relatively steeply to the west at 10-13 degrees (Koning and Manley, 2003). *0.1*

3.3 Entering Hernandez. This farming community was named after an old New Mexican family name known in records from the 16th century. This town was made famous by Ansel Adams' 1941 photograph, "Moonrise over Hernandez." *0.6*

3.9 White beds of the Chamita upper tuffaceous zone are visible in the Chamita badlands north of the Rio Chama valley. These beds are probably 6.8-6.9 Ma (^{40}Ar-^{39}Ar dating of McIntosh and Quade, 1995, Izett and Obradovich, 2001), and are correlated to the Peralta Tuff using geochemistry (Nelia Dunbar, written comm., 2004, summarized in table 2 of Koning and Aby, 2003). *0.7*

4.6 Junction with Rio Arriba County Rd. 0001. *0.4*

5.0 Note the east-dipping Servilleta Basalt on top of Black Mesa at 2:00. The broad Santa Clara fault zone probably passes near the middle of the eastern slope of Black Mesa.

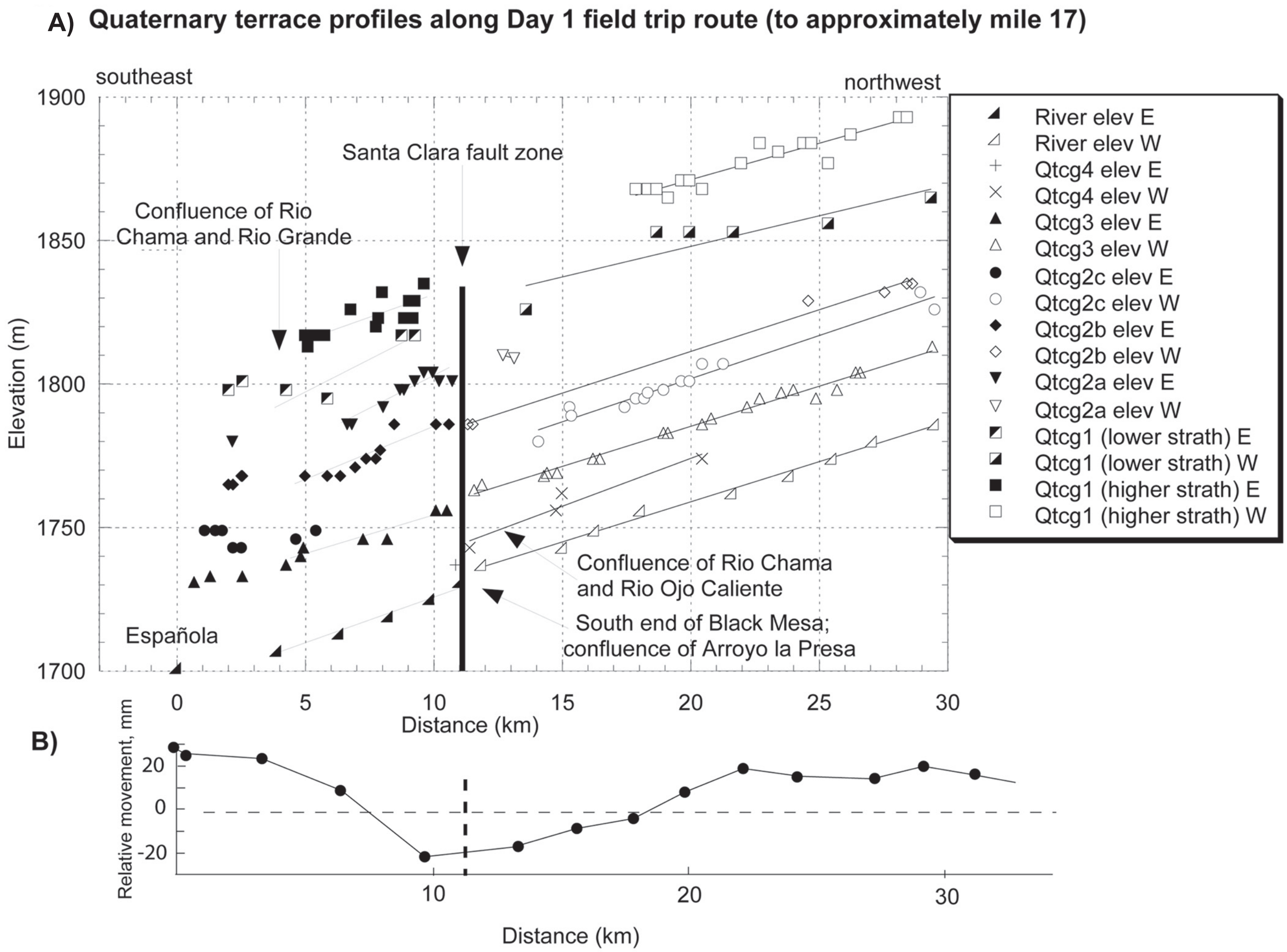

FIGURE 1.6. A, Plot showing elevation of Quaternary terrace straths as a function of distance (from Española to approximately mile 17 of the First Day Road Log). Data for each terrace are separated according to whether they are east (E) or west (W) of the Santa Clara fault zone. Elevations taken from 1:24,000-scale geologic mapping of Koning et al. (2004a), Koning et al. (this volume), and Koning and Manley (2003), and have a probable vertical error of ± 3-5 m. Linear regression lines were calculated for each data set upstream of the approximate confluence of the Rio Chama and Rio Grande; these are shown on the plot. B, Results from leveling survey conducted in September, 1934, and March, 1939 (from Reilinger and York, 1979). Note that the relative subsidence suggested by the leveling data do not match elevation trends of the Quaternary terrace straths.

The fault here is largely inferred from stratigraphic relationships; basaltic talus and difficulty accessing private property have hampered efforts to find the exact location of fault strands. Koning et al. (2004c) interpret that the Santa Clara fault vertically offsets the Black Mesa basalt by 381-411 ft, which translates to a vertical displacement rate of 107-146 ft/Myr. Near the base of the slope at 2:00, near the white water tank, beds dip 50-60 degrees to the north and belong to the south limb of the Chamita syncline (Koning and Manley, 2003). *0.2*

5.2 Sandy fluvial sediment of the Cejita Member of the Chamita Formation underlies the Qtcg2a terrace deposits to the left. Within an approximately 36 ft-thick interval, this sediment has interbeds of coarse gray ash (near the base) and a bed of white coarse ash to fine lapilli, mixed with minor coarse gray dacitic(?) fragments (at the top). These tephra beds are interpreted to correlate to the Chamita lower tuffaceous zone (Koning and Manley, 2003; Koning and Aby, this volume), which is probably 7.9-8.4 Ma (McIntosh and Quade, 1995). *0.2*

5.4 NM Highway 74 to right; entering El Duende. View ahead of Abiquiu embayment. *0.1*

5.5 The 91-122 ft-tall hill to the south is mostly composed of sandy Quaternary sediment. This alluvium was probably deposited by streams associated with Arroyo de la Presa, and consists largely of reworked Ojo Caliente Sandstone mixed with basaltic boulders and cobbles. Exposed at the base of the hill is quartzite-rich, axial fluvial sediment deposited by the Rio Chama. The base of this terrace deposit is approximately 76-91 ft above the present Rio Chama, and likely correlates to the Qtcg3 terrace deposit observed at Stop 1. *0.2*

5.7 Cross the approximate location of the east-down Santa Clara fault, which may also have a component of right-lateral slip (Aldrich, 1986). This fault forms the southeastern boundary of the Abiquiu embayment; the latter is a structurally shallow platform between the deeper part of the rift east of the Santa Clara fault and the Colorado Plateau (Baldridge et al.,

PLIOCENE GEOLOGIC FEATURES AT THE TOP OF SOUTHERN BLACK MESA, ESPAÑOLA BASIN, AND A PECULIAR ALIGNMENT OF TOPOGRAPHIC KNOBS IN SERVILLETA BASALT

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Black Mesa forms a prominent landform in the north-central Española basin. Capped by the Servilleta Basalt, this mesa rises approximately 300 m above the valleys of the Rio Grande and Rio Ojo Caliente, which flank it to the east and west. Black Mesa extends 20 km southwest from Embudo Station to a point 6.7 km northwest of the confluence of the Rio Chama and Rio Grande. Two to three strands of the Santa Clara fault zone pass through the center and along the southeast margin of the south tip of the mesa (see figure 3 of Koning and Aby, this volume; Koning and Manley, 2003). Together, these fault strands have vertically offset (down-to-the-southeast) upper Miocene strata and the Servilleta Basalt by 400-500 m and 125-135 m, respectively (Koning et al., 2004a), and have a possible component of right-lateral slip (Aldrich, 1986). The W-NW trending South Black Mesa monocline lies approximately 3.5 km northeast of the south tip, and has produced a topographic relief of 50-60 m on the upper surface of the Servilleta Basalt.

This Servilleta Basalt flowed southward from eruptive centers in the San Luis Basin at about 2.8-3.7 Ma (Manley, 1976a, b; Lipman and Mehnert, 1979; Gunn, 1980; Dungan et al., 1986; Appelt, 1998). Most of this lava is olivine tholeiite (Lipman and Mehnert, 1979; Dungan et al., 1984). At its southern tip, southwest of the South Black Mesa monocline, the basalt is approximately 6-13 m thick on either side of the mesa. On and northeast of the South Black Mesa monocline, the basalt is 6-12 m thick on the northwestern margin of Black Mesa (the footwall of the Santa Clara fault) but 12-20 m thick on the southeastern margin (the hanging wall of the Santa Clara fault). The basalt overlies Pliocene-age stream gravel and associated floodplain deposits, which are 2-6 m thick on the footwall of the Santa Clara fault but as much as 17 m thick on the hanging wall. Pliocene tectonic subsidence along the Santa Clara fault probably accounts for the southeastward-increase in thickness of the stream gravel. At the time the Servilleta Basalt flowed into this part of the basin, there was evidently a southeastward component of slope in the basin floor to account for the thickening of the basalt in that direction. This slope may possibly have been manifested by a series of stream terraces whose treads (top surfaces) stepped down to the southeast. If these terraces existed, however, their associated risers (i.e., the slope between adjacent terrace treads) must have been relatively small because today they are not obvious beneath the basalt.

Along the eastern margin of Black Mesa, immediately southwest of the South Black Mesa monocline, is a peculiar NE-SW alignment of several small hills over a distance of 1.6 km (Fig. 1.7). Their location is depicted on figure 3 of Koning and Aby (this volume). These topographic knobs are 4-13 m tall and each range from 60-120 m in width. Servilleta Basalt is found at the top of each of these hills, although it is commonly fractured into talus blocks.

It was initially speculated that these topographic knobs represented possible eruptive vents for the basalt, partly because they lie along the northeastward projection of one of the strands of the Santa Clara fault zone (Koning et al., 2004a). However, detailed examination of these knobs does not support that hypothesis. Specifically, we did not observe any spatter, agglutinate, lapilli, or breccia that is commonly observed in near-vent facies.

The saddles between the basaltic knobs are commonly underlain by 2-4(?) m of silt and very fine sand (Fig. 1.7); this eolian sediment is mixed with, or covered by, minor amounts of gravel. The gravel is generally basalt, but in the southern and middle parts of the knob-alignment there are minor (1-15%) pebbles composed mostly of quartzite with lesser felsic-intermediate volcanic rocks or porphyritic hypabyssal intrusive rocks. The composition of the gravel is consistent with deposition by the Rio Grande.

Although the sides of these basaltic knobs are poorly exposed, close examination did reveal that there is an ~1 m-thick, discontinuous interval of quartzite-rich gravel lag on the side of at least one basaltic knob (on the south end of the knob-alignment). We could not demonstrate that this fluvial gravel is interbedded within basalt flows. Rather, it is likely that this gravel represents the remnants of a Plio-Pleistocene fluvial deposit that once overlay, and also inset into, the top of the basalt. This fluvial deposit has since been largely stripped by erosion.

Our favored interpretation for the origin of these basaltic knobs is that they are due to erosion of the Servilleta Basalt by the Rio Grande shortly after the basalt was emplaced. The sparse, quartzite-rich pebbles scattered amongst more abundant basaltic gravel, found in most saddles of these knobs, forms the primary basis for this interpretation (Fig. 1.7). To the southwest of the South Black Mesa monocline, erosion of the top of the basalt by the Rio Grande may have contributed to the relief observed on the modern surface of southern Black Mesa. However, much of this relief may also be due to tectonic activity along the Santa Clara fault. For example, this tectonic activity tilted the Servilleta Basalt 3-5 degrees E-SE on the southernmost tip of Black Mesa, in addition to forming the South Black Mesa monocline (Koning, this volume).

Although still somewhat conjectural, we believe that tectonic activity along the South Black Mesa monocline may have influenced the course of the Rio Grande in the Pliocene. North of the South Black Mesa monocline, Rio Grande gravel is conspicuously absent from the top of the basalt, strongly suggesting that the river kept east of the basalt after the latter was emplaced. However, tectonic subsidence along the south flank of the South Black Mesa monocline may have allowed the Rio Grande to flow over the basalt on part of its down-thrown side, as manifested by the river gravel near the topographic knobs of interest. Tectonic activity of this structure during this time period is consistent with the relatively high rates of Pliocene tectonic activity inferred for the local area (Koning et al., 2004b).

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1994). The fault has been called the Embudo fault by past workers (e.g., Aldrich, 1986, Aldrich and Dethier, 1990, Golombek and Dethier, 1991). However, Koning et al. (2004c) use the original name of Santa Clara fault for the sake of precedence and because the kinematic behavior of this fault differs significantly from that of faults associated with the Embudo fault system to the northeast, such as the Velarde and La Mesita faults. Approximately 0.6 miles to the north, the base of a late- or latest-Pleistocene terrace deposit, perhaps correlative to Qtcg4 near Stop 1, may be offset 12 inches by the Chili fault (Fig. 1.8). The northwest-striking Chili fault has a southwest-down sense of throw and is interpreted to splay from the Santa Clara fault in the vicinity of the Rio Chama (Koning et al., 2004c). *0.4*

6.1 Cross Arroyo de la Presa. *0.2*

FIGURE 1.7. Photo looking southeast at the aligned basaltic knobs on southern Black Mesa and an intervening saddle. The knob on the left is 9-10 ft tall, and is located near the middle of the knob-alignment. The saddle is underlain by eolian silt and very fine sand mixed with, and overlain by, gravel composed of basalt with minor (1-15%) quartzite-rich gravel. At least part of the gravel is interpreted to have been deposited by the Rio Grande shortly after emplacement of the Servilleta Basalt.

6.3 The hills ~0.6 miles to the southwest are generally capped by a 18-27 ft-thick Lobato Basalt flow that dips 6-9 degrees to the northeast. The attitude of strata here may be largely controlled by northeastward tilting of the hanging wall of the Chili fault. The ~122 ft-thick, slightly reddish sediment under the basalt flow is mostly a very fine to coarse sand and muddy sand, with subordinate clay and mud beds. These deposits are composed of interbedded Vallito and Cejita members of the Chamita Formation, and have approximately 5% coarse channels whose pebble assemblage includes Paleozoic sandstone and limestone, quartzite, and volcanic clasts (Koning et al., this volume). These deposits are very similar to strata that overlie the Ojo Caliente Sandstone on the western slope of southern Black Mesa, which is interpreted to be derived from the southern Taos Range and east of the Peñasco embayment (Koning et al., 2004b). *0.6*

6.9 Highway 285 turns right to Ojo Caliente. **Continue straight on US 84.** *0.5*

7.4 Road cuts are good exposure of the Lobato Basalt flow discussed at mile 6.3. Here, an age of 9.6 ± 0.2 Ma was obtained using K-Ar dating methods (Baldridge et al., 1980). *0.4*

7.8 Town of Chili. The town was originally a station on a railroad line locally dubbed the "chili line." Confluence of the Rio Ojo Caliente and Rio Chama is approximately 0.6 miles to the northeast. *0.7*

8.5 Cross bridge over Rio del Oso; this river joins the Rio Chama to the right and extends into the northern flank of the Jemez Mountains. *0.2*

8.7 Prominent exposures to the right and left of the road belong to the uppermost Chama-El Rito Member

FIGURE 1.8. Photo showing the base of a late- or latest-Pleistocene terrace deposit at the south end of Black Mesa, the strath of which may be offset 1 ft by the west-down Chili fault. This exposure is located on the north road-cut of Highway 74.

and the lower Ojo Caliente Sandstone Member of the Tesuque Formation. These two members underlie most of the Abiquiu embayment (Kelley, 1978). The Chama-El Rito Member is primarily a fluvial unit deposited between 12-18 Ma (May, 1980, 1984; Ekas et al., 1984; Dethier et al., 1986; Dethier and Aldrich, 1991; Tedford and Barghoorn, 1993), whose gravel fraction is dominated by volcanic rocks (May, 1980; Dethier and Martin, 1984; Ekas et al., 1984; Koning et al., 2004a). A possible source for these volcanic rocks is a postulated vent buried beneath the southwestern Taos Plateau (Ekas et al., 1984; Ingersoll et al., 1990; Ingersoll and Cavazza, 1991), but direct derivation from the Latir volcanic field is also possible (Ekas et al., 1984). The boundary between the Chama-El Rito and Ojo Caliente Sandstone members is gradational and marked by much interfingering of eolian and fluvial sediment (May, 1980, 1984; Koning et al., 2004a). The strata here may be well-cemented, especially near faults. *0.6*

9.3 The terrace on the immediate left correlates to Qtc6 of the Medanales 7.5-minute quadrangle (Koning et al., 2004a), and probably to Qtcg3 of the San Juan Pueblo 7.5-minute quadrangle near Stop 1 (Table 1.1). Here, it is 91 ft-thick and contains many basalt boulders. *0.1*

9.4 Cross Arroyo del Palacio. *0.6*

10.0 Cross Arroyo de las Lemitas. Approximately 0.4 miles up this arroyo, a fault zone has elevated groundwater levels on its well-cemented, western (hanging wall) side. Sediment north of this arroyo is in the stratigraphic interval where the Chama-El Rito and Ojo Caliente Sandstone members interfinger, but eolian sediment of the Ojo Caliente Sandstone becomes more common up-section (Koning et al., 2004a). The strata here are cut by numerous north-striking, west-down normal faults. Beds strike N-NE and dip 7-12 degrees E-SE (Koning et al., 2004a). Enter community of Rio Chama. *0.8*

10.8 Mile marker 201. Upstream between here and Abiquiu, the Rio Chama valley has a high-level, sandy Holocene deposit called Qayh by Koning et al. (2004a). Scattered eolian dunes, generally 1.5-3 ft high, may be found on the surface of Qayh. *0.2*

11.0 Good exposure 300 ft to the southwest shows fluvial sediment of the uppermost Chama-El Rito Member. Stratigraphically, this fluvial sediment probably lies in the interfingering contact zone with the Ojo Caliente Sandstone. The sediment contains a 5 ft-thick fine white ash that is possibly correlative to the Pojoaque white ash zone in the central Española Basin (in the Pojoaque Member of the Tesuque Formation); dating and correlation analyses are pending. Two terrace deposits are seen to the southwest (9:00). The lower one is Qtc6 (interpreted to be 40-70 ka), and the middle one is Qtc4 (interpreted to be 250-400 ka); terrace nomenclature is from Koning et al. (2004a) and age estimates are from gastropod amino acid data in Dethier and McCoy (1993) and Dethier and Reneau (1995). At 8:00 is the Qtc3 terrace deposit, which correlates to Qtcg1 near stop 1 (Table 1.1). The top of Qtc3 corresponds to the Q2 surface of Gonzales (1993). It forms broad mesas south of the Rio Chama and locally contains the Lava Creek B ash (Dethier et al., 1990; Dethier and Reneau, 1995), which has an age of 620 ka (Naeser et al., 1973; Sarna-Wojcicki et al., 1987). *0.2*

11.2 Rio Arriba County Rd. 140 to right. View ahead of Cutler Group Pennsylvanian-Permian red beds and light colored Oligo-Miocene Abiquiu Formation. *0.5*

11.7 Cross Arroyo del Toro. One km up Arroyo del Toro, a west-down fault juxtaposes Ojo Caliente Sandstone against uppermost Chama-El Rito fluvial sediment. This and other west-down faults between here and Arroyo del Lemitas (mile 10.0) are interpreted to form the local eastern boundary of the Medanales graben of Gonzales and Dethier (1991). Looking to the east (behind), one can discern the South Black Mesa monocline discussed in Stop 1, in addition to a smaller monocline 1.2 miles north of it. 1.4-1.5 miles to the northeast (2-3:00) is a small butte composed of cemented Ojo Caliente Sandstone. *0.5*

12.2 Cross the west-down fault that passes through Arroyo del Toro (see mile 11.7). Qtc3 of Koning et al. (2004a) forms the high surface on the skyline to the west (9:00). Badlands to the north of the Rio Chama offer good exposures of strata belonging to the upper Chama-El Rito Member and the lower Ojo Caliente Sandstone. Just before the highway bends to the west, at 2:00 on the skyline is a fault that juxtaposes tan-colored Ojo Caliente Sandstone on the east with orangish Chama-El Rito Member on the west. The middle-upper part of the Ojo Caliente Sandstone commonly is a slope-former and creates relatively gentle topography. In contrast, the Chama-El Rito Member (and locally the lower Ojo Caliente Sandstone) is slightly more consolidated and commonly forms steeper slopes. *0.6*

12.8 Cross Arroyo del Pinavetes. This arroyo has incised through Ojo Caliente Sandstone that is overlain by ~100 ft of sand and gravel of Qtc3 (Koning et al., 2004a). Locally, there are a few outcrops of the Lava Creek B Ash in the terrace deposit. The Ojo Caliente Sandstone here and to the west lacks fluvial interbeds and is mostly fine-upper to coarse-lower grain size, which is relatively common in the middle and upper part of the member elsewhere. Just beyond is road to Medanales (State Road 233, County Road 146). The dark red beds ahead in the distance are strata of the Pennsylvanian-Permian Cutler Group. *1.3*

14.1 Cross unnamed tributary to the Rio Chama. Mapping of isolated basaltic, coarse gravel terrace remnants indicates that Cañon la Madera once exited here in the middle to late Pleistocene. Sometime in the late Pleistocene, Cañon la Madera was pirated by another stream and diverted to its present location (see mile 14.5). *0.4*

14.5 Cross La Madera Arroyo (downstream equivalent of Cañon la Madera). 9:00-9:30 to the left, beneath the Ponderosa Pine, is a small topographic fin of Ojo Caliente Sandstone that corresponds to a sand deformation-band fault (east-down). This fin is not cemented, but probably has been made slightly more resistant to erosion by cataclasis and associated grain-size reduction. Hummocky slopes on the north side of the hill to the left, and the east side of the hill at 10:00, west of Cañon la Madera, is due to a mantle of locally derived eolian sand deposited over the Ojo Caliente Sandstone (Koning et al., 2004a). The lack of noteworthy surficial soils strongly suggests a Holocene age for these eolian deposits. *0.4*

14.9 Cone-shaped hills about 0.6 miles to the left (south west) are capped by gravelly remnants of Qtc3 (Koning et al., 2004a). *0.7*

15.6 Cross the El Rito fault, a prominent east-down normal fault that was called “fault 7” by May (1980). Here, the exposed immediate footwall and hanging wall of the fault is composed of the upper Chama-El Rito Member and Ojo Caliente Sandstone Member of the Tesuque Formation, respectively. Koning et al. (2004c) interpret that this fault forms the west boundary of the Medanales graben of Gonzales and Dethier (1991). Between here and the Cañones fault zone to the west, major faults are down-to-the-east and collectively comprise the broad, faulted margin of the Rio Grande rift (Baldridge et al., 1994). Lobato Mesa can be observed at 9-10:00. This mesa is capped by 305-457 ft of Lobato Basalt (late Miocene). *0.4*

16.0 Cross Cañada del Horno. Santa Fe Group strata are well exposed in this arroyo and not faulted. A walk up the arroyo nicely exhibits the upward stratigraphic transition from the gradational/interfingering contact of the Chama-El Rito and Ojo Caliente Sandstone Members up to the middle part of the Ojo Caliente Sandstone Member (Koning et al., 2004a). In the latter, preserved eolian foresets are as much as 20 ft tall. *0.7*

16.7 Road-cut on the left is in the Ojo Caliente Sandstone Member of the Tesuque Formation. *0.6*

17.3 Low gravelly terrace deposits adjacent to the road correlate to the Qtc7 terrace deposit of Koning et al. (2004a). The age of this deposit is interpreted to be latest Pleistocene based on radiocarbon data for Quaternary terrace deposits of similar height (Dethier and Reneau, 1995). *0.2*

17.5 Cross an unnamed, east-down fault. The tan-colored Ojo Caliente Sandstone Member is on the hanging wall and orangish Chama-El Rito Member strata is on the footwall. *0.2*

17.7 Road bends to the left. Good exposures of the middle-upper Chama-El Rito Member are present on the left road bank. Orangish exposures on the north side of the Rio Chama belong to the middle part of the Chama-El Rito Member. *0.2*

17.9 Intersection of Highway 554 to El Rito. At 2:00 are tannish white beds of the upper member of the Abiquiu Formation. *1.1*

19.0 Road bends to the left. The Rio Chama is to the right. Cerro Pedernal stands prominently in the distance (Fig. 1.9). The mesa takes its name from the chert (“pedernal” is Spanish for flint) found below the summit. At an elevation of 9862 ft, it has long been an important landmark for travellers in the Chama Basin. Cerro Pedernal is capped by Lobato Basalt flows, dated at 7.8±0.7 Ma by the K-Ar method (Manley and

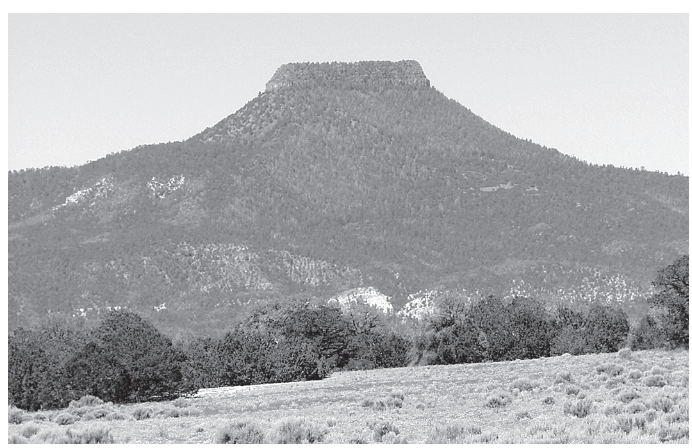

FIGURE 1.9. Photo of Cerro Pedernal, looking west from the Abiquiu embayment and towards the Colorado Plateau. The top of this peak is composed of Lobato Basalt, which is underlain by the Tesuque Formation (Chama-El Rito Member) and the Abiquiu Formation.

Mehnert, 1981), that overlie a relatively thin interval of fluvial sediment probably correlative to the Chama-El Rito Member of the Tesuque Formation (Kelley, 1978). The Chama-El Rito Member, in turn, overlies the upper member of the Abiquiu Formation (upper Oligocene to lower Miocene; Vazzana, 1980; Moore, 2000). Cerro Pedernal is located on the Colorado Plateau geomorphic province. The Colorado Plateau extends eastward to the Cañones fault zone (optional stop 2), the westernmost major fault that constitutes the western margin of the Abiquiu embayment and Rio Grande rift (Kelley, 1978; Manley, 1982; Gonzales and Dethier, 1991). There was tectonic activity along this margin between 3 and 10 Ma because the Lobato Basalt (10-8 Ma; Bachman and Mehnert, 1978; Manley, 1982; Manley and Mehnert, 1981) is displaced across the Cañones fault, and the El Alto Basalt (~3 Ma; Manley, 1982; Baldridge et al, 1980) is not (Moore, 2000; Maldonado, 2004). Several distinct terraces are found north of the Rio Chama. *0.4*

19.4 Los Trujillos Country Store on left. The Chama-El Rito Member is exposed in the canyon to the south. Sierra Negra stands north of the Rio Chama, and is capped by basalt dated at 4.8±0.1 Ma (Baldridge et al., 1980). The basalt overlies gravels that may represent a tributary to an ancestral Rio Chama (Gonzales and Dethier, 1991). On the south flank of Sierra Negra, the NNE-striking, down-to-the-east Madera Cañon fault of Gonzales and Dethier (1991) juxtaposes the upper member of the Abiquiu Formation on the west with pinker Chama-El Rito Member on the east. Looking to the south and southwest are views of Lobato Mesa and Mesa de Abiquiu, respectively. Lobato flows here are dated at 7.8±0.5 Ma by the K-Ar method (Manley and Mehnert, 1981), and overlie gravels (Bailey et al., 1969; Gonzales and Dethier, 1991) that may represent the course of an ancestral Rio Chama. The flows and gravels are about 1767 ft above the modern Rio Chama (Maldonado, 2004) and overlie the Ojo Caliente Sandstone Member. The Mesa de Abiquiu is capped by the El Alto Basalt flows dated at 3.2±0.1 Ma by the K-Ar method (Manley and Mehnert, 1981). The El Alto Basalt is inset into the Lobato Basalt flows and overlies gravels approximately 1200 ft above the modern Rio Chama (Maldonado, 2004). These gravels overlie the Chama-El Rito or Ojo Caliente Sandstone members and may represent a tributary to an ancestral Rio Chama. *1.8*

21.2 Abiquiu Inn on the right and Mesa de Abiquiu on left. *0.4*

21.6 Village of Abiquiu is located on the hill to the left (southwest). Exposures on the northeastern slope of this hill reveal the Ojo Caliente Sandstone Member of the Tesuque Formation. A down-to-the-west fault is present between here and the basalt-capped Mesa de Abiquiu to the east. *0.2*

21.8 Abiquiu post office located to the left. The town was first settled by the Spanish in 1747 and built on the ruins of a pueblo. The name is a Spanish corruption of the Tewa name that referred to San Juan Pueblo. Abiquiu is best remembered as the home of the famous artist Georgia O'Keefe (1887-1986). Many of her works depict the surrounding landscape. *0.1*

21.9 County Road 189 to left leads up to the top of Lobato Mesa. *0.1*

22.0 Bridge over the Rio Chama. Cerrito Blanco, the prominent ridge on the north side of the Rio Chama (Fig. 1.10), is a strongly cemented block composed of the transitional zone of the Ojo Caliente Sandstone and Chama-El Rito Members of the Tesuque Formation (Maldonado, unpublished mapping). The block is composed predominantly of Ojo Caliente Sandstone with some interbedded gravel beds of the Chama-El Rito Member. The down-to-the-east Cerrito Blanco fault juxtaposes this block (east side) against the upper member of the Abiquiu Formation (west side). The minimum age of fault is constrained by a dike dated at 9.8 ± 0.4 Ma (K-Ar method: Bachman and Mehnert, 1978) that appears to be offset by this fault to the north. In some areas, the dike also appears to intrude the fault. In the exposure to the south, numerous, albeit minor, synthetic east-down faults can be observed in the upper member of the Abiquiu Formation. *0.2*

22.2 Cerrito Blanco to right (Fig. 1.10) *0.9*

23.1 Abiquiu Elementary School on right, road to El Cobre Canyon and type section of Abiquiu Formation to right. Good exposures of the upper member of the Abiquiu Formation are found on the north side of the Rio Chama floodplain. *0.7*

23.8 Prominent west- to vertical-dipping basalt dikes are found on the north road-cut, intruding the down-to-the-east Cerrito de la Ventana fault that offsets the upper member of the Abiquiu Formation. Immediately to the west of the dikes is the Garcia fault that appears to merge with the Cerrito de la Ventana fault. The Cerrito de la Ventana fault juxtaposes the lower member of the Abiquiu Formation of Vazzana (1980) and Moore (2000) against the upper member of the Abiquiu Formation. The

FIGURE 1.10. Cerrito Blanco at mile 22.2.

lower member of the Abiquiu Formation was called the Ritito Conglomerate by Barker (1958) and Kelley (1978). *1.0*

24.8 Mile marker 215. Mesa to left is Cañones Mesa exposing El Alto(?) basalt flows and intermediate lavas of the Tschicoma Formation over the Abiquiu Formation. *0.7*

25.5 Historic marker: "Red Rocks." This marker tells us that we are beginning to see typical landforms of the Colorado Plateau, which are high mesas mostly developed in Upper Triassic (Chinle Group) and Middle Jurassic (principally Entrada Sandstone) sedimentary rocks. *0.2*

25.7 OPTIONAL STOP 2 - Boundary of the Colorado Plateau. Stop on right.

We are right at the boundary between the Rio Grande rift and Colorado Plateau here. The Cañones fault marks this boundary, and it trends northeastward along the floor of the narrow valley at the bottom of the grade. Directly in front of us, westward-dipping Morrison Formation sandstones are overlain along a prominent angular unconformity by red conglomeratic sandstone of the southeastward-dipping Eocene El Rito Formation (Figs. 1.11-1.12). This deformation of the Morrison Formation thus was a Laramide event, and the Cañones fault was subsequently reactivated as a rift-bounding structure. This outcrop was also stop 5 of the first-day road log of the 1995 NMGS Fall Field Conference (Smith et al., 1995). *0.2*

END OF OPTIONAL STOP 2

Continue on US 84 to north.

25.9 Begin ascent onto Colorado Plateau, ascending from Permian to Triassic strata (Fig. 1.13). Cross Cañones fault hereabouts. *0.4*

26.3 Upper Triassic Chinle Group base on Cutler Group to right. The Chinle Group here is composed of (ascending order): Zuni Mountains Formation, Shinarump Formation (formerly Agua Zarca Formation), thin Salitral Formation

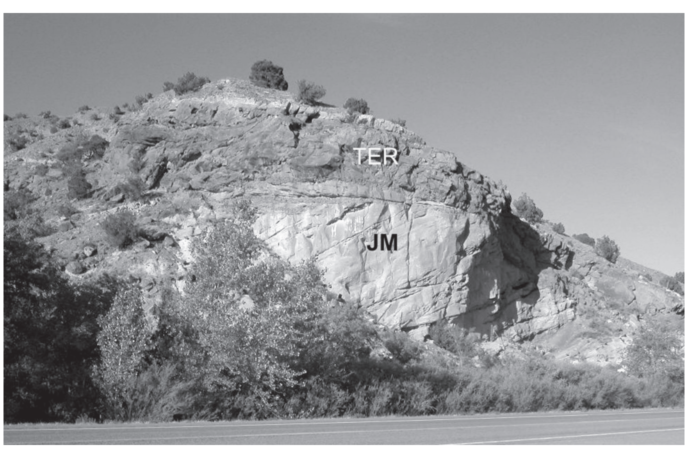

FIGURE 1.11. Angular unconformity between Jurassic Morrison Formation (JM) and Eocene El Rito Formation (TER) at Optional Stop 2.

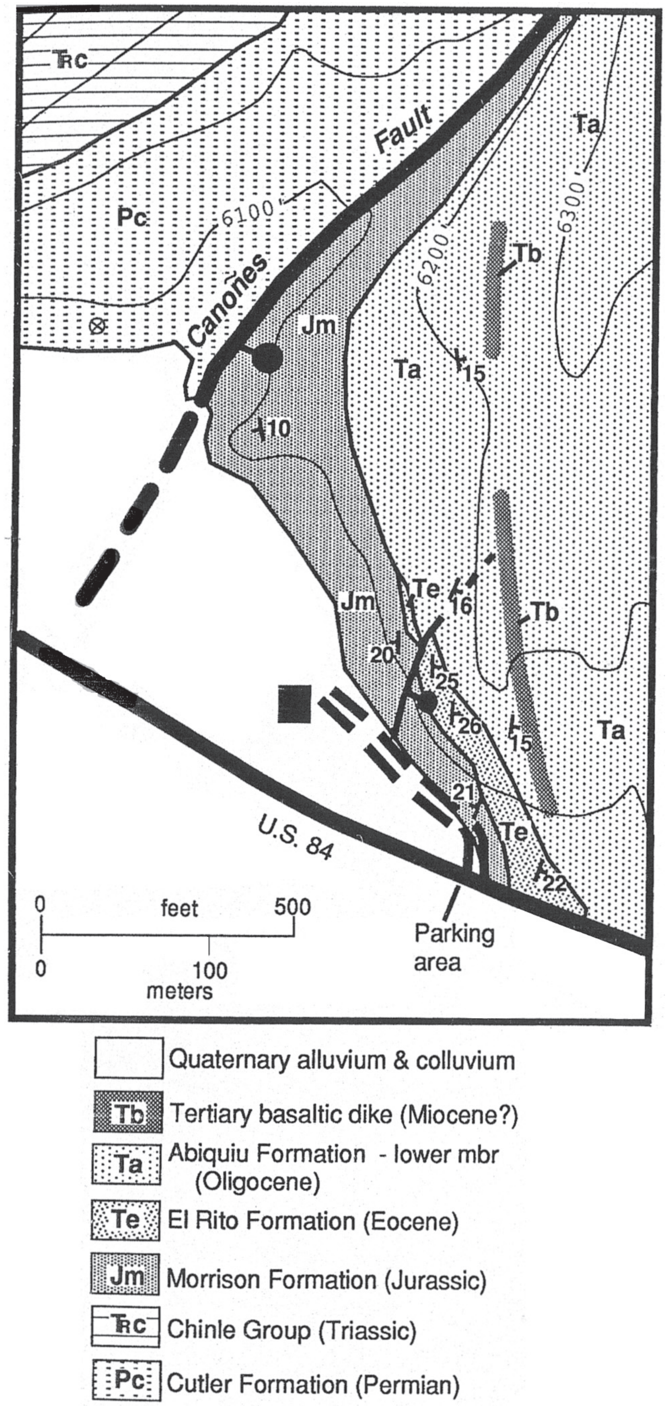

FIGURE 1.12. Geologic map of optional stop 2 (from Smith et al., 1995).

(~ 0.6 m) with thick Poleo Formation section above. The Chinle-Cutler unconformity here is the compound Tr-0, 1, 2 and 3 unconformities of Pipiringos and O'Sullivan (1978). Basal Chinle Group strata are more than 50 million years younger than the underlying Lower Permian strata. *0.2*

26.5 Poleo Formation base is to right of road (Tr-4 unconformity of Lucas, 1993), and we will now drive upsection through the Poleo. The Poleo Formation represents a large river system during the middle of Chinle deposition. Here, and at the upcoming stop, the Poleo Formation is seen at its thickest (about 120 ft). Poleo Formation sediments represent the deposits of a Chinle trunk river system with paleoflow to the northwest. *0.3*

26.8 Rest area to right, to left note section of Chinle up to Entrada on Cañones Mesa. Road is on Poleo Formation here. *0.4*

27.2 Roadcuts in Poleo Formation. *0.2*

27.4 Junction Forest Rd. 23 to right. *0.9*

28.3 Junction US 96 to Abiquiu Dam. **Turn left** and proceed west on US 96. Note panoramic view of Abiquiu Reservoir and cliffs up to Ghost Ranch to north. *0.7*

29.0 Turn-off right to boat ramp. Continue on highway. *0.3*

29.3 Red beds on right are Chinle Group, Painted Desert Member of Petrified Forest Formation. *0.3*

29.6 Riana Campground turn-off to right. Cerro Pedernal at 12:00 (Fig.1.14). Continue on highway. *0.3*

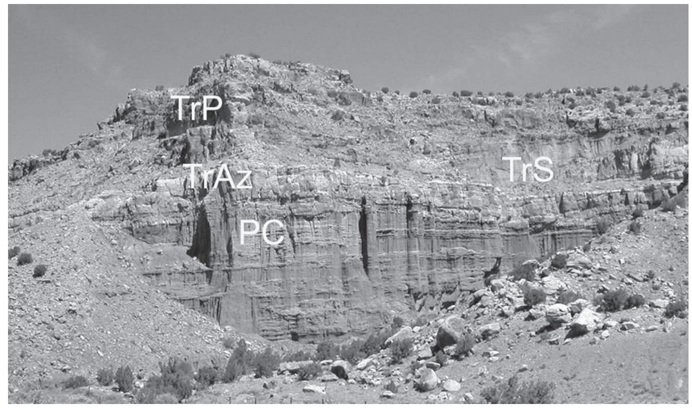

FIGURE 1.13. Permian-Triassic section at mile 25.9. Stratigraphic units are: PC = Cutler Group, TrAz = Shinarump (= Agua Zarca) Formation, TrS = Salitral Formation and TrP = Poleo Formation.

29.9 Turn left on paved road before dam at Abiquiu Lake sign. The dam was built by the U.S. Army Corps of Engineers, authorized under the 1948 Flood Control Act with the purposes of flood and sediment control and water supply. It was completed in 1963, and has a water supply storage of 200,000 af (acre feet), and a total storage capacity of 1.2 million af. Abiquiu Dam is the main flood control structure on the

DAMS AND LAKES OF THE CHAMA BASIN AREA

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Three large dams that impound reservoirs have been built in the Chama Basin area: El Vado, Abiquiu, and Heron, all in the drainage basin of the Rio Chama. El Vado is the oldest and smallest, Abiquiu is the largest, and Heron is the newest.

El Vado (the ford), 12 miles southwest of Tierra Amarilla, was a convenient place to ford the Rio Chama where the resistant ledge of the Paguate Sandstone Member of the Cretaceous Dakota Sandstone crossed the river on the west flank of South El Vado Dome. A lumber town with a railroad developed there in the late 19th and early 20th centuries. A U.S. Bureau of Reclamation dam was completed during 1935 and refurbished during 1954-55. This earth fill dam is 154 ft high and 1362 ft long, impounding El Vado Lake, which holds 195,440 acre-ft of water at an elevation of 6902 ft. The dam is set into the Paguate Sandstone on the east and the Graneros Shale Member of the Mancos Shale on the west, just below the Greenhorn Limestone Member of the Mancos, which is visible in the road cut at the west side of the dam (also see the supplemental roadlog). The spillway cut just below the dam exposes a silty zone equivalent to the Twowells Sandstone Member of the Dakota in the San Juan Basin to the west. The natural gorge just below the dam exposes the Paguate Sandstone, Clay Mesa Shale Member of the Mancos, and the Cubero Sandstone Member of the Dakota, which consists of two sandstone beds with a thin shale break. Except for the small area of Paguate Sandstone shoreline just northeast of the dam, almost all of the shoreline of El Vado Lake is in the Mancos Shale. El Vado Ranch, a short distance downstream, is the put-in site for boat trips down the river through the 25-mile long Rio Chama U.S. Wild and Scenic River area designated in 1988. Permits are available from the U.S. Bureau of Land Management for river trips.

Abiquiu dam, on the Rio Chama downstream from El Vado, 7 miles west-northwest of the town of Abiquiu, was completed during 1963 by the U.S. Army Corps of Engineers. This earth fill dam is 315 ft high and 1540 ft long, impounding Abiquiu Lake, which holds as much as 1,192,800 acre-feet of water at an elevation of 6350 ft. The dam is set into the Poleo Formation (mostly sandstone) of the Chinle Group. A thin section of Lower Permian strata is exposed in the gorge below the dam. Most of the shoreline is in the Petrified Forest Formation (mostly Painted Desert Member mudstone) of the Chinle, but an area northwest of the dam consists of outcrops of the Morrison Formation. The upper end of the lake is downstream from the Rio Chama U.S. Wild and Scenic River area. Most river trips take out of the Rio Chama at Big Eddy, just upstream from the high-water level of Abiquiu Lake.

Heron dam, upstream from El Vado, 9 miles west of Tierra Amarilla on the north flank of North El Vado Dome, is on Willow Creek just north of its confluence with the Rio Chama. This earth fill dam, which is 269 ft high and 1220 ft long, was completed during 1971 by the U.S. Bureau of Reclamation. Heron

Lake holds 399,980 acre-ft of water at an elevation of 7192 ft. Although Heron Lake is east of the continental divide, almost all the water stored in the lake is derived from the upper part of the San Juan River drainage basin in Colorado west of the continental divide by way of a trans-mountain diversion (San Juan-Chama diversion) through the Azotea tunnel west of Chama (see minipaper by Cockerill in day 3 roadlog). The dam ends are set in the resistant Paguate Sandstone Member of the Dakota Sandstone, which forms most of the southwestern shore of the lake near the dam, but the Willow Creek gorge at and below the dam is cut down through the rest of the Dakota Sandstone, Burro Canyon Formation, and into the uppermost part of the Brushy Basin Member of the Morrison Formation at the confluence with the Rio Chama (see stop 3 of third-day roadlog). Most of the rest of the lakeshore is on the Graneros Shale Member of the Mancos Shale with some exposures of Paguate Sandstone along the northeastern lakeshore.

Water from these three lakes flows down the Rio Chama into the Rio Grande 4 miles north of Española. Uses of the water include irrigation, recreation, and municipal supply.

Rio Chama. It is used during most spring runoff periods to store water that would otherwise cause flooding along the Rio Chama and the Rio Grande. In 1981, Congress authorized the use of Abiquiu Reservoir for storing San Juan Chama water. Of the remaining 1 million af of total storage capacity in Abiquiu, only about half this amount is used to store and control flood waters. The rest is designated for "structure protection" and has not been used. *0.7*

30.6 STOP 2 - Chinle Group Magnetostratigraphy

Stop at parking lot below Abiquiu Dam. Here, we examine Chinle Group magnetostratigraphy (see accompanying minipaper). The Poleo Formation exposed here is a relatively thick fluvial succession in the middle of the Chinle Group *0.7*

END OF STOP 2

Retrace route to US 84.

FIGURE 1.14. Newberry's (1876) image of Cerro Pedernal, which he called "Abiquiu Peak."

PRELIMINARY MAGNETOSTRATIGRAPHIC DATA FROM THE UPPER TRIASSIC POLEO FORMATION (CHINLE GROUP) AT ABIQUIU DAM, NORTH-CENTRAL NEW MEXICO

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The Upper Triassic Chinle Group was deposited by a fluvial system and consists predominantly of red mudstones with some orange siltstones and buff sandstones. The distinctive medial unit of the Chinle Group in the Chama Basin is the Poleo Formation, which was named by Von Huene (1911). This unit is equivalent to the Trujillo Formation of West Texas and eastern New Mexico, the Sonsela Member of the Petrified Forest Formation in west-central New Mexico and northeastern Arizona and the Moss Back Formation of southern Utah and southwestern Colorado (Lucas, 1993; Lucas and Anderson, 1997; Lucas et al., 1999, 2001, 2003). In contrast to its equivalents, the Poleo Formation is locally much thicker, has a grayish-yellow coloration, a micaceous litharenite petrography and mixed conglomerate-clast lithotypes (Lucas et al., 2003).

The Poleo Formation is 53 m thick at Abiquiu Dam (36.2°N, 106.2°W) and is composed almost exclusively of medium-grained to conglomeratic sandstone (Fig. 1.15). Poleo sandstones are typically micaceous litharenites and are usually grayish yellow. The upper part of the formation consists of more thinly-bedded buff to light-brown fine sandstones, and grades into the Mesa Montosa Member of the Petrified Forest Formation. Clasts in conglomeratic units are either extrabasinal (chert and quartzite) or intrabasinal (mud rip-up clasts, calcrete nodules). Both the sandstones and conglomerates contain hematite cement in varying abundance. We have analyzed the paleomagnetism of these rocks to construct a reversal chronology for the Poleo Formation at Abiquiu Dam.

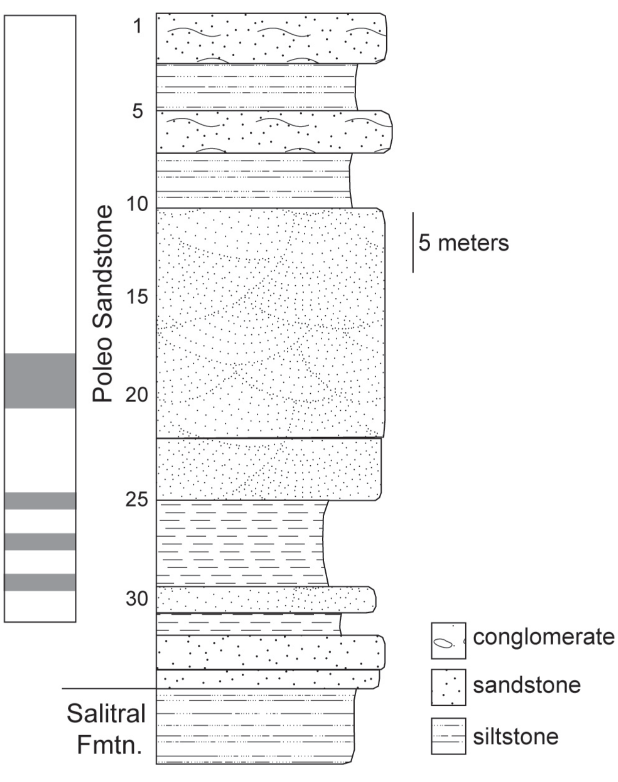

FIGURE 1.15. Stratigraphic column of the Poleo Formation at Abiquiu Dam with reversal chronology.

We sampled sub-horizontal Poleo strata at Abiquiu Dam approximately every 2 m, for a total of 32 sampling sites. In the upper two-thirds of the Poleo Formation, this sampling interval was dictated by bed thickness (one site = discrete bed), whereas part of the lower third of the section had large-scale bedding. At each site, 6-8 samples were drilled and oriented in the field. Most samples were long enough to be prepared into multiple specimens, with at least one specimen/sample subjected to thermal demagnetization techniques. Other duplicate specimens were subjected to chemical demagnetization or rock magnetic experiments. At the time of manuscript preparation, all specimens undergoing thermal demagnetization have been thermally treated to 645°C, and specimens being chemically demagnetized have been immersed in 10M HCl for a cumulative total of 370 hours.

Samples from most sites yield relatively well-defined (Fig. 1.16a), well-grouped (Fig. 1.16b) magnetizations that are of reverse polarity (south-seeking and very shallow inclination). Site mean directions from 21 of 30 sites analyzed yield a grand mean direction of D = 182.7°, I = -0.3°, α_{95} = 5.3 and k = 36.5 (Fig. 1.16b). Several sites yield a totally incoherent magnetization signal; in some cases, this behavior is readily explained through the presence of abundant to occasional light green-gray (reduced) mud rip-up clasts. Samples subjected to chemical demagnetization show a less than 20 percent decrease in intensity of magnetization, after immersion to 370 hours total, with no appreciable change in their direction, indicating that fine-grained pigment hematite, as an authigenic, grain-coating phase, is a relatively unimportant remanence carrier in these rocks.

The preliminary grand mean direction (N = 21 site means) for the Poleo strata provides a paleopole of 53.9° N, 69.2° E (dp = 5.3°, dm = 2.7°), which is fully consistent with a Late Triassic age of magnetization acquisition (Van der Voo, 1993; Molina-Garza et al., 1996, 1998). Notably, compared with other data of somewhat similar age from the Colorado Plateau, the Poleo pole is similar to those of the Blue Mesa and Painted Desert members of the Petrified Forest Formation (north-central Arizona) (56.5°N, 68.2°E and 58.4°N, 68.5°E, respectively) (Steiner and Lucas, 2000). The exclusively reversed polarity signature of Poleo strata may imply deposition and remanence acquisition over a relatively short time period. The Late Triassic polarity record from the Newark Basin (e.g., Olsen et al., 1996) suggests the presence of several reverse polarity chrons of ca. 1.5 to 2.0 Myr duration during the Norian.

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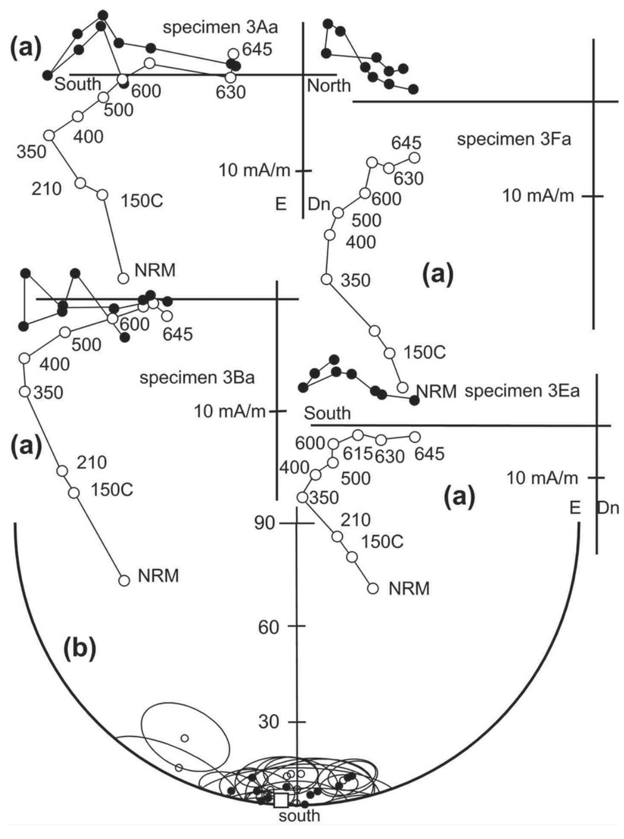

FIGURE 1.16. a, Examples of response to progressive thermal demagnetization by specimens from four (4) samples from Poleo rocks sampled at site #3, upper part of Poleo Formation. Orthogonal demagnetization diagrams show the progressive thermal unblocking of the natural remanent magnetization (NRM), plotted simultaneously onto a horizontal (NS vs. EW, solid symbols) and a vertical (NS-UpDown, open symbols) plane. Each specimen shows the (partial) progressive removal of a south-directed and shallow (positive or negative) inclination magnetization, characteristic of the site and the formation. b, Equal area projection of site mean directions (circles) (N=21) and associated, projected cones of 95 percent confidence (α_{95} radius) about the site mean direction. Large square is the grand mean direction for accepted results from 21 sites. Open (closed) symbols refer to upper (lower) hemisphere projections.

31.3 **Turn left** at stop sign to cross dam on US 84. Note Mesa Montosa on skyline to right. *0.1*

31.4 Cross dam. *0.2*

31.6 Road cut is top of Poleo Formation and Mesa Montosa Member (lower ss interval) of Petrified Forest Formation. *0.2*

31.8 Pull-out on right provides a panoramic view to north. Road is on lower part of Petrified Forest Formation. *1.1*

32.9 Good view of Cerro Pedernal. *0.6*

33.5 Cross bridge over Polvadera Creek. Poleo Formation forms canyon walls. *0.2*

33.7 Rio Arriba County Rd. 194 to left to Cañones. *0.6*

34.3 Poleo Formation road cuts. *0.7*

35.0 Crest hill. View ahead of Mesa Prieta and Mesa Alta. Ahead are Chinle (red at base), overlain by strata of the Jurassic Entrada (yellow), Todilto (gray), Summerville and Morrison (pastel slopes) formations. Mesa Alta and other high mesas to north for the next 20 miles are capped by the Cubero, Oak Canyon, and Encinal Canyon members of the Dakota Formation above the lighter-colored sandstone cliffs of the Lower Cretaceous Burro Canyon Formation above the Morrison. *0.6*

35.6 Roadcuts are in uppermost Poleo Formation. Terraces to the north are developed in the Mesa Montosa Member of the Petrified Forest Formation. *1.6*

37.2 Rio Arriba County Rd. 199 to right. A small uranium deposit in limestone of the Luciano Mesa Member of the Todilto Formation occurred roughly south of this point

THE YOUNGSVILLE MAMMOTH

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In 1992, roadwork along NM Highway 96, west of Youngsville in Rio Arriba County, uncovered remains of a mammoth in Pleistocene fill along the Rito Encino (NMMNH [New Mexico Museum of Natural History] locality 2639). A field crew from the New Mexico Museum of Natural History, led by Peter Reser, collected the mammoth fossils on 3-5 June 1992, and they include part of a tusk and molar fragments, now catalogued as NMMNH P-7177.

The molar fragments have relatively thin enamel (enamel thickness <3.1 mm) and thin plates (plate thickness ~8-10 mm), which supports their assignment to the Columbian mammoth, *Mammuthus columbi* (e.g., Dutrow, 1980; Agenbroad, 1994). *M. columbi* was the common late Pleistocene mammoth in New Mexico and across much of North America (Lucas and Morgan, 2005). *Mammuthus* was the most common ice age proboscidean in New Mexico—a total of 73 sites have been identified in the state (Morgan and Lucas, 2005). Most of these sites are of Rancholabrean age and are in eastern New Mexico. The Youngsville mammoth is one of a handful of mammoth sites in the northwestern part of the state and only the second record of *Mammuthus* in Rio Arriba County (the other is at Abiquiu Dam on the Rio Chama: Simpson, 1963; Morgan and Lucas, 2005). It provides further confirmation of the statewide distribution of these large, grazing elephants during the late Pleistocene (Fig. 1.17).

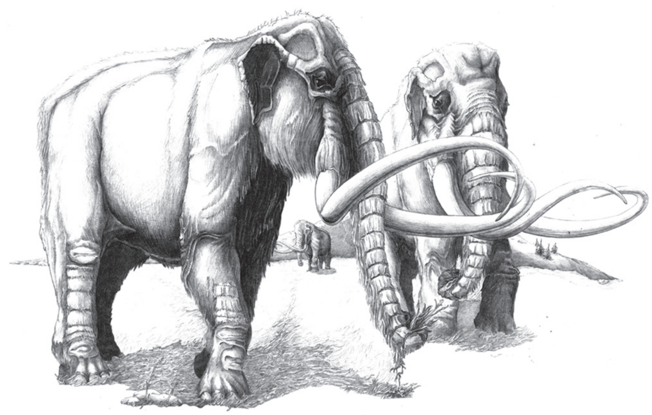

FIGURE 1.17. Downtown Youngsville during the late Pleistocene (drawing by Karl Huber).

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in sec. 28, T23N, R4E. The deposit was unusual in being a considerable distance from the larger Todilto uranium deposits near Grants. Known as the Box Canyon or Wasson deposit, it was localized by intraformational folds similar to those that are prominent in the Grants district. Uranium occurred in an unidentified black material and in a yellow oxidized mineral, most likely tyuyamunite. A small tonnage of low-grade ore was mined from a shallow, open cut in 1957 (Hilpert, 1969). *0.8*

38.0 To left at 10:00 are Jurassic Entrada Sandstone (red-yellow), gray Todilto Formation and pastels of Morrison Formation strata. *2.0*

40.0 Road drops into outcrops of Painted Desert Member of Petrified Forest Formation. Mesa Naranjo ahead at 1:00 with Upper Triassic lower Chinle Group strata (especially visible are the yellow/brown sandstones of the Poleo Formation) over Permian red beds. Road now will drop down section to the El Cobre Canyon Formation of the Cutler Group at the Rio Puerco. *0.9*

40.9 Forest Rd. 100 to left. *0.1*

41.0 Enter Youngsville, a farming and ranching community with a post office since 1914. *0.6*

41.6 Mile marker 37 on left, leaving Youngsville. View ahead of Mesa Montosa to left, Coyote Amphitheater to right. *1.2*

42.8 Youngsville Landfill on left. Rio Arriba County Rd. 211 and excellent exposures of Shinarump Formation on right. Indeed, the section exposed here of the Shinarump, Salitral and Poleo formations of the Chinle Group is one of the best exposed and most accessible lower Chinle Group sections in the Chama Basin (Fig. 1.18). *0.9*

43.7 Mesa Naranjo to right. *1.1*

44.8 Enter Coyote. Coyote is a frequently used place name in New Mexico and refers to the wild dog native to

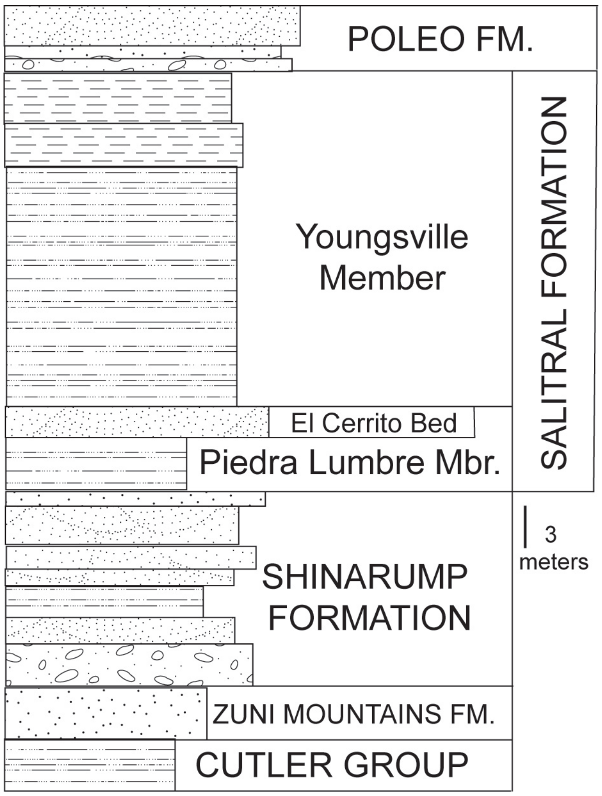

FIGURE 1.18. Measured stratigraphic section of lower Chinle Group at Youngsville landfill (after Lucas et al., 2003a).

North America. Here, the "Coyote Valley" was settled in 1862, and the new human inhabitants named their town after the previous inhabitants that they had displaced. There has been a post office here intermittently since 1885. *0.3*

45.1 Cross Coyote Creek. *0.4*

45.5 Junction Rio Arriba County Rd. 217 (left) and 215 (right). View to right of Coyote Amphitheater. Mesa Montosa to right at 2:00. Dip slope of Nacimiento Mountains ahead, Mesa Ojitos to left at 10:00. *0.7*

46.2 Mesa Montosa to right. *0.3*

46.5 Drop into Cutler red beds that crop out on both sides of the road. Loma Salazar at 10:00. *0.4*

46.9 Slow down and be very careful in order to safely turn left on dirt road before house on left. Stay on main dirt road. *0.3*

47.2 STOP 3: Vanderhoof Fossil Quarry

Stop just past trailer. Walk to quarry to discuss Permian stratigraphy, sedimentology and paleontology.

The Arroyo del Agua area is one of the great collecting areas for Early Permian fossil vertebrates (Fig. 1.19). One of the many localities known here, the Vanderhoof quarry is located at the mouth of a narrow and steep canyon that exposes Lower Permian strata of the El Cobre Canyon Formation of the Cutler Group. The quarry was initially excavated in the 1920s and 1930s by crews led by Charles Camp of the University of California, Berkeley. In the late 1970s and early 1980s, crews led by the Carnegie Museum of Pittsburgh examined the locality briefly. Beginning in the summer of 2002, joint excavations by the Carnegie Museum and the New Mexico Museum of Natural History extracted new fossil material from this and other quarries in this canyon (see accompanying minipaper). The Vanderhoof quarry (and nearby and stratigraphically equivalent Welles quarry) have yielded bivalve impressions, plant material and various vertebrate fossils, mostly of amphibians (Fig. 1.20) and pelycosaurs.

VERTEBRATE BIOSTRATIGRAPHY OF THE UPPER TRIASSIC SALITRAL FORMATION, CHINLE GROUP, NORTH-CENTRAL NEW MEXICO

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In the Chama Basin of north-central New Mexico, the Upper Triassic Salitral Formation, originally referred to as the Salitral Shale Tongue (Wood and Northop, 1946), is part of the lower Chinle Group, and is generally described as a blocky bentonitic mudstone with some interbedded sandstones and siltstones (Lucas and Hunt, 1992; Lucas et al., 2003). The mudstones are mottled and contain carbonate nodules, indicating paleosol development. The Salitral Formation lies conformably above the Shinarump (=Agua Zarca) Formation and disconformably below the Poleo Formation (Lucas and Hunt, 1992; Lucas et al., 2003). Initial collecting of fragmentary vertebrate fossils from the Salitral Formation suggested an Adamanian (late Carnian) age, but until recently, the biostratigraphy of these strata has not been well constrained.

Previously known taxa from the Salitral include the aetosaur "*Longosuchus*," the diminutive metoposaurid amphibian *Apachesaurus*, a theropod dinosaur and indeterminate archosaurian material (Lucas and Hunt, 1992; Hunt and Lucas, 1993). Recent collecting at the Youngsville Landfill has revealed the fragmentary remains of phytosaurs, aetosaurs and metoposaurids. Aetosaur material that had previously been referred to as *Longosuchus* is more likely referable to *Desmatosuchus*, probably *Desmatosuchus haplocerus*. This material consists of scute fragments with a low boss and a radiating pattern of grooves, ridges and elongated pits that is similar to the patterning of *Desmatosuchus* scutes (Long and Murry, 1995). Other scute fragments collected more recently pertain to a new taxon of aetosaur that is currently under study and is also known from Adamanian strata of central New Mexico and West Texas (Lucas et al., 2003).

The *Apachesaurus* material consists of two vertebral centra that are longer than they are wide and are spool shaped. Theropod dinosaurs are represented by a single vertebral centrum (Lucas et al., 2003). Metoposaurid material collected recently consists of fragments of shoulder girdle with the deep pits and grooves (or waffle-iron texture) that are diagnostic of the large metoposaurid *Buettneria*. Unfortunately, none of the phytosaur material collected so far is diagnostic at the genus level.

The Adamanian land vertebrate faunachron (LVF), as defined by Lucas and Hunt (1993) and Lucas (1998), is characterized by the co-occurrence of the following taxa: the temnospondyls *Apachesaurus gregorii* and *Buettneria perfecta*, the aetosaurs *Desmatosuchus haplocerus*, *Stagonolepis wellesi*, and *Paratypothorax andressorum*, and the phytosaur Rutiodon, among others. Thus, with the addition of the material collected more recently, the biostratigraphy of the Salitral Formation has been refined and indicates that the Salitral is definitely Adamanian in age.

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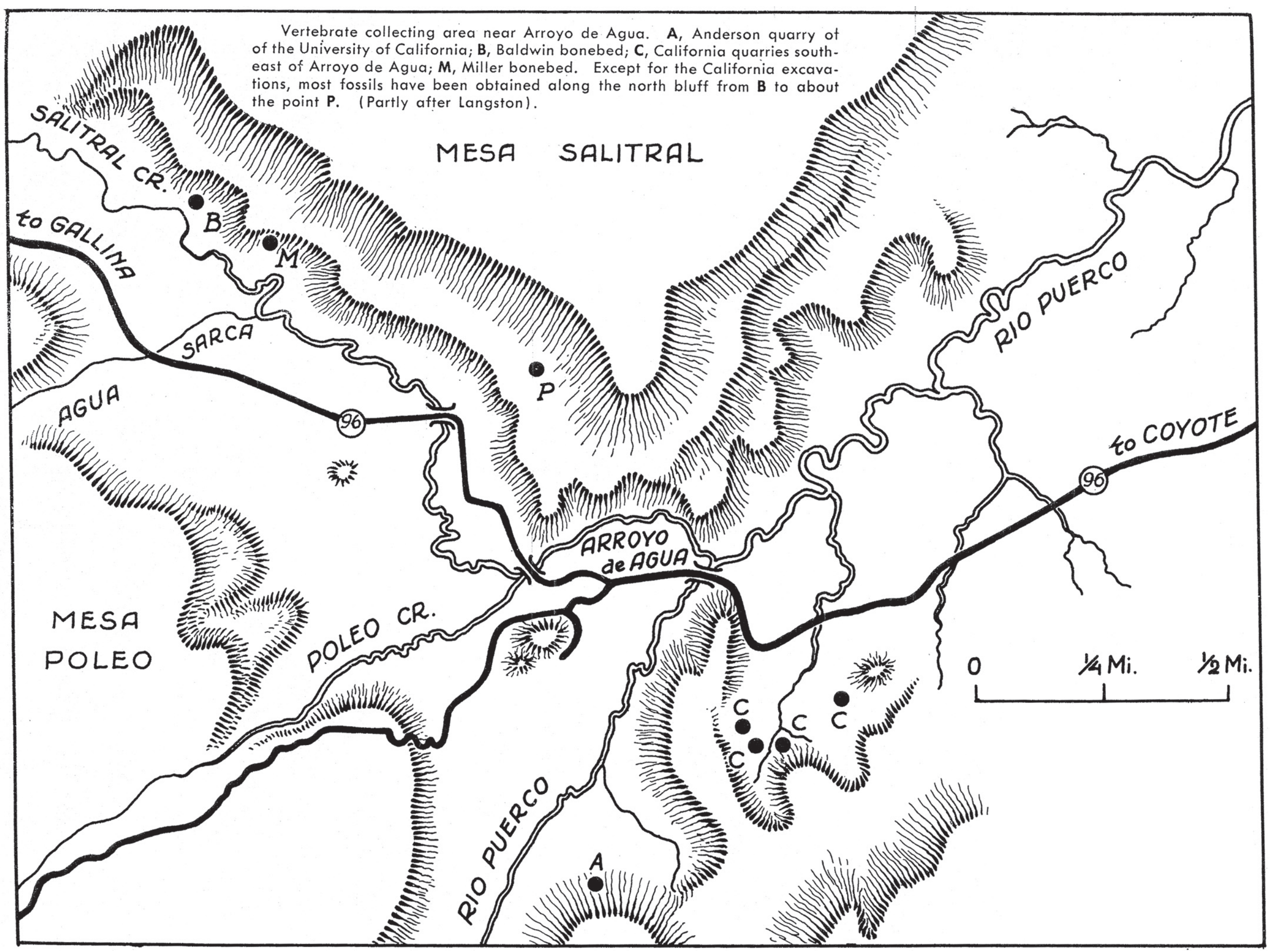

FIGURE 1.19. Vertebrate fossil collecting localities in the Arroyo del Agua area (from Romer, 1961). The Vanderhoof quarry is in the area of "C" southeast of Arroyo del Agua.

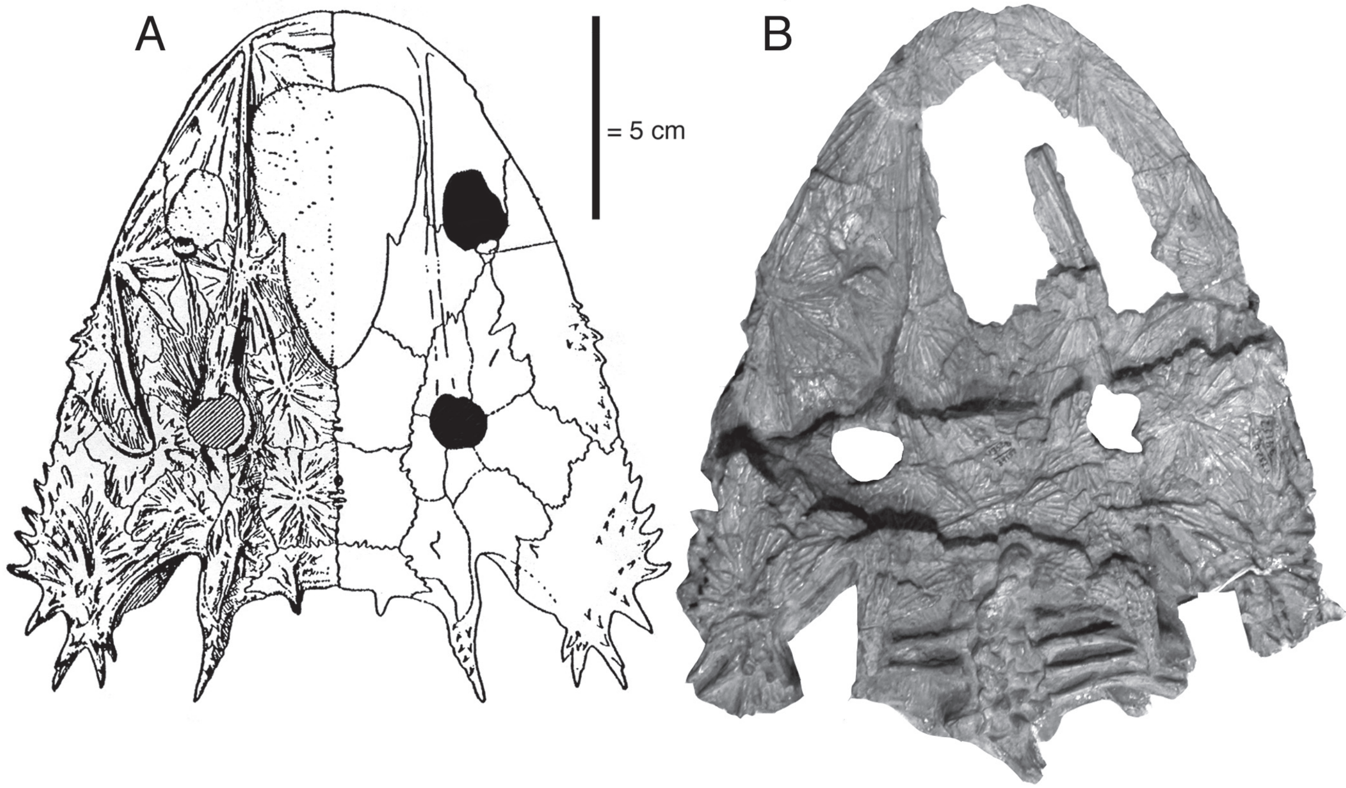

FIGURE 1.20. Skulls of the amphibian *Zatrachys serratus* Cope from the Welles quarry in Arroyo del Agua. A, Reconstruction (modified from Langston, 1953), based largely on UCMP V-34158; B, Photograph of skull and articulated vertebrae of UCMP V-34157.

A taphonomic assessment of this locality indicates that the Vanderhoof quarry is an attritional assemblage that formed in a lacustrine environment. The sediments of the deposit consist of greenish gray to grayish-black, finely laminated mudstone with occasional rare pebbles and vertebrate fossils. We have recovered only a handful of bones from the Vanderhoof quarry, so analysis of long bone orientations and hydraulic sorting was not possible. The bones that have been recovered are not abraded, indicating that there was no long-term transport of the fossil elements.

The bones are all isolated elements, with no partial articulation or association. There is no evidence of weathering or macrobiotic scavenging on the fossil material – in fact, the majority of the bones are very well preserved. Very few of the vertebrate fossils are identifiable to genus, so we make no attempt at calculating either minimum number of individuals or age profiles for the taxa within the quarry.

In terms of the vertebrate material, this assemblage was formed by the slow decay of animals that either drowned in the lake or whose corpses were washed in. As the bodies bloated, they

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TAPHONOMY OF THE LOWER PERMIAN CARDILLO QUARRY, CHAMA BASIN, NORTH-CENTRAL NEW MEXICO

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The Cardillo quarry is a Lower Permian bonebed that is located near Arroyo del Agua, just northwest of the small town of Coyote in north-central New Mexico. This locality was first discovered by a field party led by D. Berman in 1979, and in 1979 and 1980 crews from the Carnegie Museum of Pittsburgh excavated at the Cardillo quarry, removing several jackets. Beginning in the summer of 2002, joint excavations led by the Carnegie Museum and the New Mexico Museum of Natural History removed more than three dozen jackets and a variety of loose skeletal elements.

The Cardillo quarry contains the fossilized remains of amphibians, pelycosaurs and other reptiles. The pelycosaur *Sphenacodon* dominates the bonebed. It is in the Lower Permian El Cobre Canyon Formation of the Cutler Group in a series of pedogenically modified conglomeratic stringers within floodplain mudstone (Fig. 1.21). A taphonomic analysis of both the sedimentologic and biologic data gathered from the quarry reveals that this locality is a classic example of a time-averaged, attritional fossil assemblage.

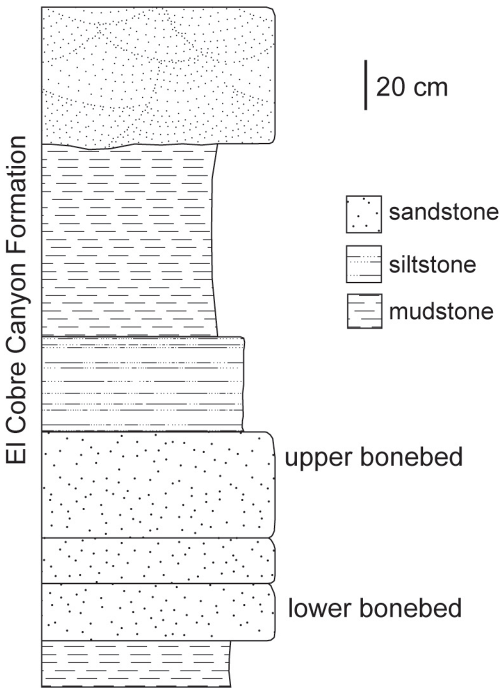

FIGURE 1.21. Measured stratigraphic section at the Cardillo quarry.

The two bone-producing horizons that comprise the Cardillo quarry are extrabasinal conglomeratic lenses within floodplain mudstones. Together with vertebrate fossil material, these conglomerates contain a variety of siliceous (chert and quartzite) pebbles. None of the fossil material shows preferential orientation or hydraulic sorting. All three of Voorhies' (1969) hydrodynamic groups are present, from phalanges to skulls. Both of the principal bone-bearing horizons show moderate densities of fossil material with patchy distribution with two exceptions: the presence of partially articulated skeletal material in the upper bonebed and an articulated pelycosaur in the floodplain sediments just above the upper bonebed. Many of the fossils recovered from the quarry show a variety of abrasion states, suggesting that some material was transported over large distances and/or was reworked. These data suggest that the material was finally deposited by a short-term, relatively high-energy flow that carried a mixture of pebbles, bones and bone fragments, some of which were reworked or carried over long distances.

The lower bonebed has produced only disarticulated, unassociated material, whereas the upper horizon has produced partial skeletons and a single, articulated pelycosaur skeleton. The variety of articulation states suggests that the carcasses that served as the source for the bonebeds were in various stages of decay and disarticulation. As with abrasion states, the bones show a wide variety of weathering stages from unweathered and well preserved bone to cracked and splintered material (where abrasion has not destroyed such evidence) (Behrensmeyer, 1978). There are no signs of scavenging on the material, though again, both abrasion and advanced weathering could have obscured tooth marks and borings. Nearly all the bones are fractured in smooth planes perpendicular to their long axes, and none show the ragged, spiral fracture pattern seen when fresh bone is broken. The fracture patterns indicate that breakage of bones occurred after fossilization, though weathering and abrasion may have obscured spiral fractures in bone fragments. A minimum number of individuals has been loosely estimated by skull and partial skeleton numbers and indicate that the majority of the animals were medium-sized amphibians, pelycosaurs and reptiles. There were not enough complete skulls recovered to attempt an age profile for any of the taxa. The biological data indicate that the skeletal elements deposited were from carcasses in various stages of decay.

The combination of sedimentologic and biologic data suggest that the Cardillo quarry was formed by a series of crevasse splays, with each splay depositing a mixture of bones, bone fragments, the rare articulated corpse and siliceous pebbles. Thus, these bone-producing horizons are time-averaged fossil assemblages because skeletal material entered the depositional systems from a variety of locations and in various stages of decay. The Cardillo quarry is an excellent example of an attritional bonebed and contrasts well with the catastrophic fossil assemblage represented by the Upper Triassic Snyder quarry (Zeigler, 2002, 2003).

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floated out over deeper water and subsequent sinking and disarticulation scattered the bones across the bottom of the lake. *0.3*

END OF STOP 3

Retrace route to US 96

47.5 At asphalt, **turn left. Be careful!!** *0.1*

47.6 Cross Rio Puerco and enter Arroyo del Agua. Excellent exposures of Permian strata on right. *0.7*

48.3 Mile marker 31 on left. Mesa Montosa on right (Fig. 1.22). Mesa Poleo on left. Begin climb back up section. *0.2*

48.5 At curve in road note Cutler Group strata to left dipping into a fault. *0.3*

FRIEDRICH VON HUENE AND TRIASSIC STRATIGRAPHY IN THE CHAMA BASIN, NEW MEXICO

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Friedrich Freiherr Von Huene (1875-1969) was one of the most important paleontologists of the 20th century. Born and educated in Tübingen, Germany, Von Huene spent his professional career there as well, mostly as a professor at Tübingen Universität (Maisch, 1999). Nevertheless, Von Huene traveled widely and conducted field expeditions to South Africa, Argentina, India and Brazil, among other places. By the early years of the 20th Century, he was widely recognized as one of the foremost authorities on fossil reptiles and the world's expert on early dinosaurs.

In 1911, Von Huene joined two American paleontologists, Samuel Wendell Williston (1851-1918) and Ermine Cowles Case (1871-1953), on an expedition to the Pennsylvanian, Permian and Triassic red beds of the Chama Basin in northern New Mexico. Williston, a professor at the University of Chicago, was then a world famous vertebrate paleontologist who had just published a comprehensive book on the Permian vertebrates of North America (Williston, 1912). Case, a professor at the University of Michigan, was a protégé of Williston, who was rapidly becoming Williston's successor as the authority on North America's Permian vertebrates.

Williston's study of the Yale University collection of Pennsylvanian-Permian vertebrate fossils from New Mexico was the primary impetus for the Chama Basin expedition. These fossils had been collected in the 1870s by David Baldwin, a hired fossil collector who then worked for O. C. Marsh (1831-1899) of Yale University. One of the outstanding specimens Baldwin collected was the complete skeleton of *Limnoscelis*, which Williston considered to be one of the oldest known reptiles. No doubt his desire to find out more about *Limnoscelis* drove Williston's desire to explore Baldwin's collecting areas in northern New Mexico.

The expedition took place during July-August 1911 and has been recounted by Williston and Case (1912) and Shor (1971). Von Huene joined the expedition for three weeks, and I focus here on the scientific results of his participation. These were published by Von Huene (1911) and included the first naming of a Triassic lithostratigraphic unit in the Chama Basin.

The 1911 expedition camped along the Rio Puerco at Arroyo del Agua (Fig. 1.23). Here, they collected vertebrate fossils and documented the stratigraphic section along the southern flank of Mesa Montosa (which they called Mesa Poleo). Williston and Case (1912, p. 8-10) described this section, and Von Huene (1911) not only did this, but he presented a sketch of a columnar section (his plate 32; see Fig. 1.22). Furthermore, Von Huene (1911, p. 732) named the thick sandstone that caps this mesa the "Poleo-top-sandstone." This name was readily adopted by later geologists as "Poleo Sandstone" to denote a sandstone-dominated lithostratigraphic unit in the Chama Basin (Darton, 1922, 1928; Wood and Northrop, 1946; Lucas and Hunt, 1992) and is now referred to as the Poleo Formation of the Upper Triassic Chinle Group (Lucas et al., 2003).

Von Huene's (1911) article on the stratigraphy at Mesa Montosa is remarkably modern in its detail and mode of presentation. It is ample testimony to his stratigraphic acumen. After the 1911 expedition, Von Huene never returned to New Mexico, though he did publish a re-evaluation of the Triassic vertebrate fossils (also collected by David Baldwin) from the Chama Basin then in the collection of the American Museum of Natural History in New York, (Von Huene, 1915). Von Huene's contribution to Triassic stratigraphy in the Chama Basin remains a little discussed but significant result of the 1911 expedition.

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48.8 Note Mesa Montosa to right (Fig. 1.24) *0.8*

49.6 Type sections of Agua Zarca and Salitral Formations of the Chinle Group to right (Lucas and Hunt, 1992) *0.4*

50.0 Approximate base of Upper Triassic Chinle Group in roadcuts *0.1*

50.1 Approximate base of Poleo Formation in roadcuts. *0.4*

50.5 Road to right to Coyote Amphitheater, Mesa Alta and Jurassic section to north. *0.7*

51.2 Coyote Ranger Station to left. *0.2*

51.4 Poleo Formation in roadcuts. *0.6*

52.0 Roadcuts in Painted Desert Member of Petrified Forest Formation. *1.2*

53.2 Poleo Formation roadcuts on left. *0.8*

54.0 Petrified Forest Formation roadcuts on left. Road travels around Poleo/Petrified Forest contact. *0.5*

54.5 Mesa Montosa Member in roadcuts. *0.8*

56.3 Forest Road 76 to left. *0.5*

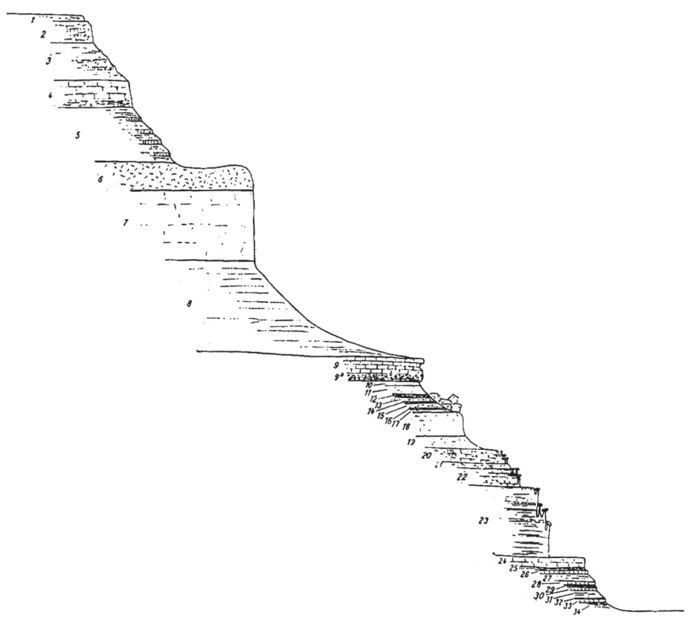

FIGURE 1.22. Stratigraphic section of Mesa Montosa (from Von Huene, 1911). The numbered units are: 1 = Burro Canyon Formation (Cretaceous), 2-4 = Morrison Formation (Jurassic), 5 = Summerville Formation (Jurassic), 6 = Todilto Formation (Jurassic), 7 = Entrada Sandstone (Jurassic), 8 = Petrified Forest Formation, Chinle Group (Triassic), 9-9a = Poleo Formation, Chinle Group (Triassic), 10-17 = Salitral Formation, Chinle Group (Triassic), 18 = Shinarump Formation, Chinle Group (Triassic), 19-34 = Cutler Group (Permian).

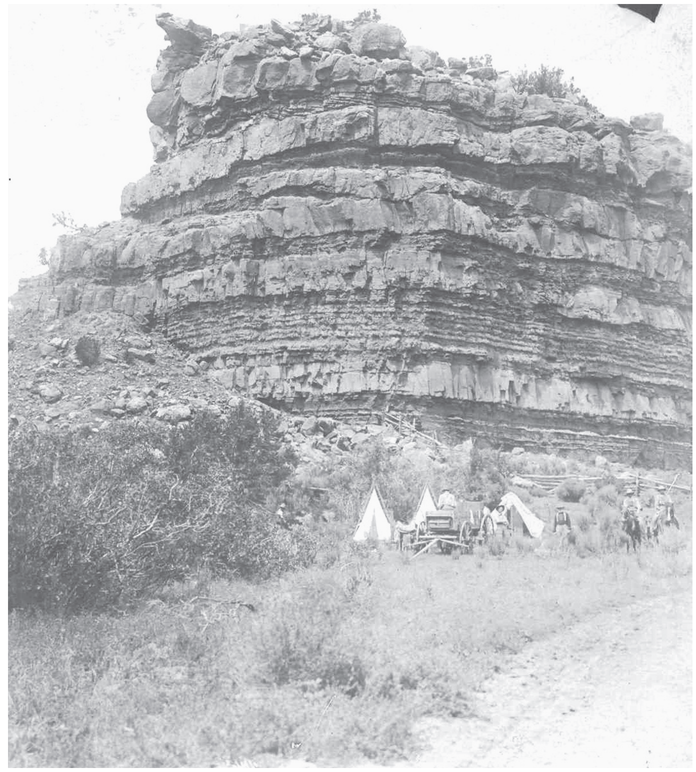

FIGURE 1.23. Photograph of the 1911 Williston-Case-Von Huene expedition campsite at Arroyo del Agua. Photograph by E. C. Case, in NMMNH archives.

56.8 Roadcuts in Petrified Forest Formation. *0.6*

57.4 Mile marker 22 on left. Capulin Mesa on right with Jurassic Todilto Formation over Jurassic Entrada Sandstone. *1.5*

58.9 Rio Arriba County Rd. 421 on left. *0.7*

59.6 Enter Gallina. Settled in 1818 (post office, 1890-), Gallina takes its name from the New Mexican Spanish words for the local wild turkey, "gallina de la tierra." *0.3*

59.9 Gallina post office on left. *0.6*

60.5 Crest hill. Cretaceous section along Gallina hogback at 12:00 in distance. Roadcuts in Painted Desert Member of Petrified Forest Formation on right. *0.7*

61.2 Cerro Blanco to right is a knob of Todilto gypsum. Beyond it is a classic Triassic fossil locality (see accompanying minipaper). *0.4*

61.6 Jurassic Entrada-Todilto cuesta on right. *0.5*

62.1 Cross Rio Gallina *0.5*

62.6 Note Brushy Basin Member of Morrison Formation and Burro Canyon Formation in roadcuts in fault zone. Note west-dipping, tan Dakota Sandstone on dipslope of hogback 1.5 miles north of road. Dipslope held up by Cubero Sandstone Member underlain by Oak Canyon Member, Encinal Canyon Member, and Burro Canyon Formation above Brushy Basin Member of Morrison Formation. *0.2*

62.8 Mancos Shale roadcuts. *0.6*

63.4 Mile marker 16 on left. Road in Cretaceous Mancos strike valley. Cuesta to right is El Vado Member of Mancos Shale. *1.2*

64.6 Roadcuts in El Vado Member of Mancos Shale. *0.4*

65.0 Strike valley in upper shale member of Mancos. *0.4*

E. D. COPE AND THE FIRST DISCOVERY OF TRIASSIC VERTEBRATE FOSSILS IN THE AMERICAN WEST

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Triassic vertebrate fossils were first discovered and scientifically documented in Europe in the 1820s and were largely described by Hermann von Meyer (1801-1869), one of the great German comparative anatomists of the 19th Century. Discoveries of Triassic vertebrate fossils soon followed in the eastern United States, particularly in coal mines in the Carolinas and Virginia in strata now termed Newark Supergroup. However, it was not until 1874 that Triassic vertebrate fossils were discovered in the American West.

In that year, the U.S. Army Corps of Topographical Engineers sent an expedition under the leadership of Lieutenant George M. Wheeler to northern New Mexico. The Wheeler Expedition of the previous year (1873) had uncovered fossils of Miocene mammals near San Ildefonso. Edward Drinker Cope (1840-1897), an independently wealthy and astute paleontologist based in Philadelphia, became aware of the 1873 discoveries and "signed up" for the 1874 Wheeler Survey.

Cope accompanied the Wheeler Survey as one of its geologists. The expedition began on July 22nd, leaving Colorado Springs and proceeding to Taos, Ojo Caliente, San Ildefonso, Santa Fe and then back to Tierra Amarilla on September 4th. Throughout this nearly seven weeks, Cope was in constant conflict with Wheeler over his duties. Wheeler expected Cope to undertake only geological work in conjunction with the mapping that was the primary focus of this expedition of the U.S. Army Corp of Topographical Engineers. Of course, Cope was there for the paleontology, and collect fossils he did.

On August 10, 1874, in El Rito, a local priest had shown Cope a tooth of an Eocene fossil mammal (*Coryphodon*) found west of Gallina. This piqued Cope's interest, so on returning to Tierra Amarilla in September, Cope totally disregarded the Wheeler expedition itinerary and broke off with a small party towards Gallina and the Eocene fossil collecting area beyond. As Simpson (1951) recounted in detail, there Cope discovered an extensive assemblage of Eocene fossil vertebrates (from strata now termed San Jose Formation), one of the most remarkable discoveries of his career. However, Cope also made a second remarkable discovery—bone fragments of a fossil reptile found in the Triassic red beds north of Gallina.

Cope's published sketch (1875, fig. 8) of the Triassic fossil locality allowed Lucas and Hunt (1992, fig. 9) to relocate it, and it is just north of Cerro Blanco (Fig. 1.25). Cope (1875) coined the new name *Typothorax coccinarum* for the bone fragments he found there, closely comparing the new reptile to "the Belodonta [phytosaurs] of the Carolinian and Würtembergian Trias" (Cope, 1875, p. 85). Cope went on to conclude that "the evidence derived from the *Typothorax coccinarum* is favorable to the identification of this horizon with that of the Trias, although it cannot, of course, be regarded as conclusive until more perfect specimens are obtained."

We now know *Typothorax coccinarum* as a valid species of aetosaur, not phytosaur, and the first aetosaur discovered in the New World (Heckert and Lucas, 2000). Furthermore, *T. coccinarum* is an index fossil of a specific interval of Late Triassic time, the Revueltian land-vertebrate faunachron (Lucas, 1998; Lucas et al., 2002). Cope's discovery thus was not only the first record of a Triassic fossil vertebrate in the American West, but also a first step toward developing a global Triassic biostratigraphy based on tetrapod fossils.

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FIGURE 1.24. Mesa Montosa at mile 48.8. Stratigraphic units are: PC = Cutler Group, TrAz-S = Shinarump and Salitral Formations, Chinle Group, TrP = Poleo Formation, Chinle Group.

65.4 Enter Gallina hogback. *0.1*

65.5 STOP 4: Gallina Hogback

Pull off to right.

Here we will discuss the Menefee Formation at the Gallina hogback and San Juan Basin Laramide structure (see the accompanying minipapers). After stop, retrace route through Gallina, Arroyo del Agua, Coyote and Youngsville to US 84. *5.0*

END OF STOP 4

Retrace route to US 84

70.5 Enter Gallina. *14.3*

84.8 Enter Coyote. *4.2*

89.0 Enter Youngsville. *9.8*

98.8 Cross Abiquiu Dam. *2.0*

100.8 Junction US 84. Turn left to go north on US 84 towards Ghost Ranch. *0.4*

101.2 The road now drives down section through roadcuts developed in the the Petrified Forest Formation (Painted Desert and Mesa Montosa members) to the Poleo Formation. *0.3*

101.5 Cross Arroyo de Comales. *1.0*

102.5 Driving on Poleo Formation bedrock surface with Chama gravels and some Petrified Forest Formation hummocks on top. Ouctrops of Mesa Montosa Member of Petrified Forest Formation to right. *1.5*

Roadlog continues on page 34

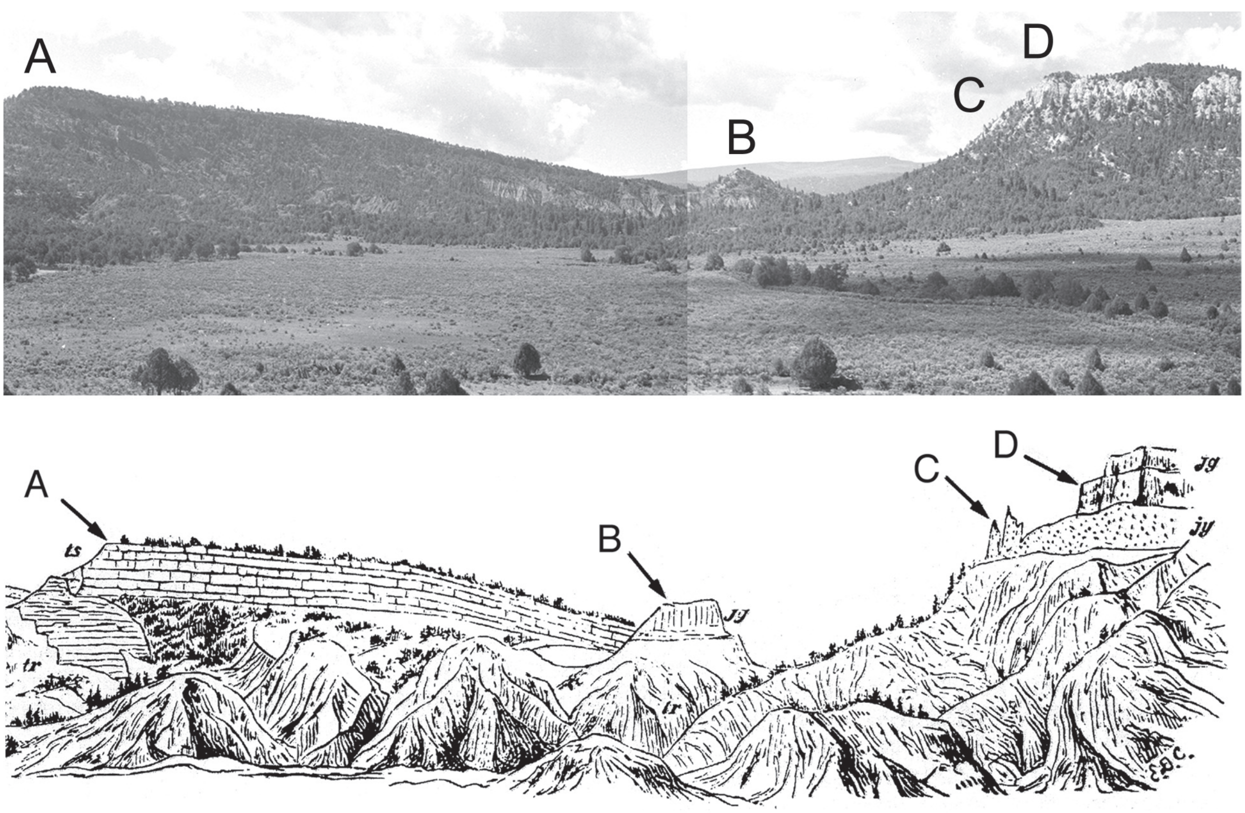

FIGURE 1.25. Photograph (above) of Triassic and Jurassic strata exposed on northern end of Cerro Blanco and Cope's (1875, fig. 8) drawing (below) of the same location. A, B, C and D are corresponding points on the photograph and drawing. In the drawing, below B is a tr indicating the Triassic strata where Cope collected the first Triassic vertebrate fossils discovered in the Southwest.

MENEFEE FORMATION AT THE GALLINA HOGBACK

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Along the eastern monoclinal flank of the San Juan Basin, Mesaverde Group strata dip westward toward the basin center at roughly 45 degrees. An outcrop belt of the Mesaverde Group is well exposed for several miles, and in many places the exposure expands to include portions of the Lewis Shale and/or the Mancos Shale. The outcrop belt, sometimes referred to as the "eastern hogback" begins in Sandoval County near the town of Cuba and extends into the Santa Fe National Forest in Rio Arriba County.

To the northeast of Regina, a roadcut exists where Highway 96 intersects the outcrop belt. Here, the Menefee Formation, the middle formation of the Mesaverde Group, is remarkably well exposed and is easily accessible (Fig. 1.26). This roadcut is significant because it is one of the few locations where a lateral transect of the Menefee Formation can be seen. The overlying Cliff House Sandstone can also be seen at this location, but a short hike is required. Surface cover, and perhaps the presence of a fault, prevents the underlying Point Lookout from being readily exposed here, but the lower contact of the Meefee Formation is well exposed nearby along the hogback.

The Menefee Formation is subdivided into three members from top to bottom: the upper coal member, the Allison Sandstone, and the Cleary Coal Member. The Cleary Coal Member derives its name from an abandoned mine located 2 miles west of La Ventana in section 31, T19N, R1W (Beaumont, 1956). This member is dominated by coal seams and mudstones, but does contain a few lenticular sandstones and thin sandstone interbeds. The middle member of the Menefee, the Allison Sandstone, is composed of a series of lenticular sandstone bodies. The Allison Member sandstone bodies are not a laterally continuous unit, but appear to be at the scale of the roadcut exposure. Although they are concentrated in the mid-region of the formation, similar lenticular sandstone bodies are sparsely distributed throughout the formation. The uppermost member is called the upper coal member, and is similar in lithology and structure to the Cleary Member.

Within the formation, four primary lithologies can be identified: mudstone, coal, sandstone, and siderite. The mudstones are the most abundant rock type present, and occur as several different types based on color, silt content, and coal content. When measuring sections, the mudstones were identified as gray, brown or black, and then if necessary, modified as silty, coaly, or organic. Mudstone beds that occur adjacent (or nearly adjacent) to coal seams are generally dark brown to black, and have a much higher amount of coaly organic material.

The coals of the Menefee Formation have an apparent rank of sub-bituminous A (Hoffman, 1991). They are dark black, and have a high cleat density. At the roadcut, the coal seams range in thickness from less than 0.1 to 0.4 m thick. Across the outcrop, the seams are commonly found associated with two lithologies: mudstone and sandstone. When found adjacent to mudstone, the coals are usually encased by either a brown or brown coaly mudstone. Also, the coals may be found in contact with sandstone beds that may act as reservoirs for methane sourced from the coal seams.

Siderite is present throughout the formation, most commonly as reddish seams or large nodules (30-60 cm diameter). Siderite formation is believed to be an early diagenetic product resulting from the decomposition of organic materials in brackish or marine pore fluid (Mozley and Burns, 1993).

Sandstone packages occur frequently throughout the Menefee Formation, and are identified as one of two types. The first type is described as thin interbeds that are generally found within light-colored mudstone sequences. The interbeds tend to be yellowish gray, fine to medium grained, and commonly exhibit laminae or small-scale cross-bedding. The second type is described as lenticular sandstone bodies. Because this roadcut is a lateral expo-

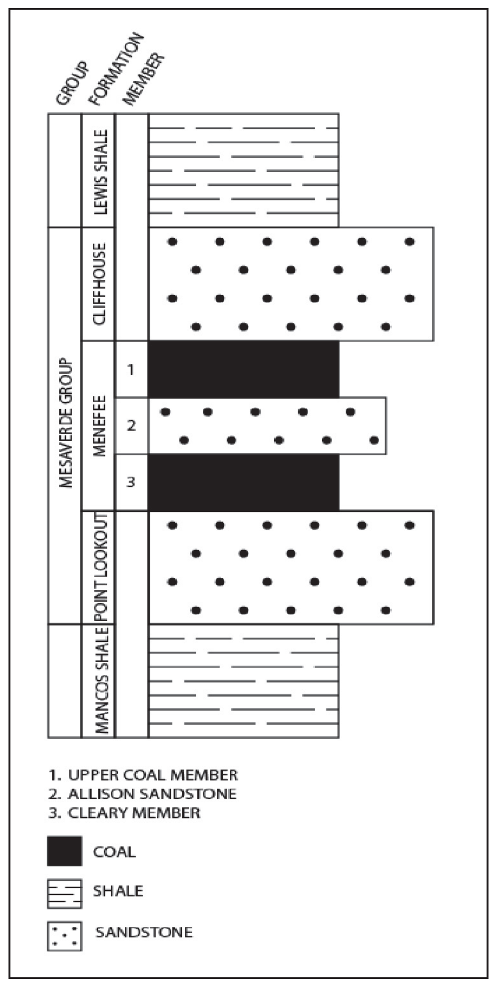

FIGURE 1.26. Generalized Upper Cretaceous section at the hogback west of Gallina (stop 4).

sure, the thick sandstones appear to be continuous, blanket-type deposits, but are actually a series of either isolated or coalesced lenticular units. They vary in thickness between 2 and 15 m, and exhibit medium to coarse grain sizes. Nearly every sandstone lens observed exhibits trough cross-bedding, ripple marks, or rip-up clasts. Both the porosity and the permeability of the sandstone lenses are very low. The primary porosity system has been reduced to negligible, primarily by infiltrated clay material. The sandstones are classified as tight-gas sands in petroleum industry terminology, as the permeability ranges from 1 to .01 md.

The abundant mudstone, coal, and other organic-rich lithologies of the Menefee Formation are believed to have been formed in the back-shore setting behind the shoreline of the Cretaceous Interior Seaway (Hollenshead and Pritchard, 1961). This environment is interpreted to have been dominated by brackish-to-marine marshes, lagoons, tidal flats and estuary channel systems (Peterson et. al., 1968; Amarante et al., 2002). The extensive coal deposits are believed to have accumulated in the marsh-like behind-shore region. The lenticular sandstone bodies are interpreted as estuary-type channel deposits, cutting through the back-shore and draining toward the sea.

The Point Lookout Sandstone underlies the Menefee Formation, and is the lowermost formation in the Mesaverde Group (Fig. 1.26). The Point Lookout Sandstone is a thick sandstone unit dominated by cross bedding and ripple marks, and has minor interbeds of clean mudstone near the upper contact with the Menefee Formation. This formation has been interpreted as a beach facies deposited during a regressive phase of the Cretaceous Interior Seaway (Amarante et al., 2002).

The uppermost formation of the Mesaverde Group is the Cliff House Sandstone, which sits directly above the Menefee Formation (Fig. 1.26). The Cliff House Sandstone is interpreted as the transgressive phase of the eustatic shift in the shoreline of the Cretaceous Interior Seaway that is responsible for the deposition of the Mesaverde Group. The formation exhibits significantly less sedimentary structures than the Point Lookout, which may be due to reworking of the sediment during the advance of the shoreline.

The depositional environment of the Menefee Formation represents behind-shoreline non-marine deposition and at this location represents the point of maximum regression of the Cretaceous Interior Seaway (Peterson et al., 1968; Amarante et al., 2002). It is proposed that the transition of the Interior Seaway from the regressing to transgressing system (the 'turn-around' point) is located within, or at the top of, the Allison Member of the Menefee Formation. The Menefee Formation would have been deposited directly behind the Point Lookout Sandstone as the beach facies was shifting during the regression of the Interior Seaway. After the transition of the Interior Seaway from a regressing to transgressing system, the Menefee Formation was symmetrically deposited on top itself, and then overlain by the transgressive Cliff House Sandstone.

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A MODEL FOR LARAMIDE TECTONIC DEVELOPMENT OF THE NACIMIENTO-GALLINA REGION

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The Gallina area marks the northern limit of the Nacimiento uplift, a north-trending, east-tilted basement block that bounds the southeast part of the San Juan Basin (Woodward, 1987). Structural relief on Proterozoic basement from the high part of the uplift to the adjacent San Juan Basin is at least 10,000 ft (3050 m), although a significant part of this is attributable to a late Paleozoic precursor, the Peñasco uplift (Woodward, 1996). Steeply dipping to overturned beds as young as Eocene occur in the eastern limb of a syncline adjacent to the faulted western margin of the uplift. An en echelon series of northwest-plunging growth folds that may have begun in the Late Cretaceous (Baltz, 1967, p. 85), but mostly developed synchronously with Paleocene-Eocene sedimentation, occurs west of the uplift (Kelley, 1955; Baltz, 1967) and are indicative of dextral components of slip on the range-bounding Nacimiento fault.

The earliest stratigraphic evidence for Laramide uplift of the Sierra Nacimiento is the thinness or absence of the late Campanian (~75 Ma) Pictured Cliffs Sandstone in the steeply dipping to overturned eastern limb of the basin-margin syncline that parallels the Nacimiento fault (Baltz, 1967; Fassett and Hinds, 1971; Woodward, 1987). By early Eocene time, south-flowing paleorivers were focused in a belt west of, and parallel to, the Nacimiento fault (Smith, 1992). The oldest AFT (apatite fission-track) cooling age in the Nacimiento uplift is Campanian (80.8 ± 7.5 Ma); most of the remaining cooling ages are Paleocene and Eocene (Kelley et al., 1992).

The western boundary fault system of the Nacimiento uplift has been interpreted by some workers (Woodward, 1987, 1996; Woodward et al., 1992) to consist of two faults, the Pajarito and Nacimiento faults, that are separated along strike by a gap in which unfaulted Permian strata are exposed. Recent mapping, however, has demonstrated that faulting is continuous through this gap (Pollock et al., 2004). The term Nacimiento fault is used herein to denote the continuous western boundary structure of the Nacimiento uplift. The Nacimiento fault is contiguous with the Sand Hill fault to the south (Santos, 1975; Kelley, 1977; Cather et al., 1997; Cather, 1999).

In surficial exposures, the Nacimiento fault is generally steep to subvertical, although the structurally higher parts of the fault may locally flatten to gentle or subhorizontal dips (Woodward, 1987; Pollock et al., 2004). Alternatively, the low-angle fault may represent the slip surface of a younger landslide (E. H. Baltz, written comm., 2001). The general steepness and linear trace of the Nacimiento fault has led many previous workers (including the writer) to assume that horizontal shortening across the range front was minor. Gravity modeling and construction of balanced cross-sections across the western range front and adjacent parts of the San Juan Basin by Pollock et al. (2004), however, have produced some important new insights: (1) the Nacimiento fault system may sole downward into an east-dipping master thrust, the tip of which is blind and lies beneath the Phanerozoic strata of the San Juan Basin about 8 km west of the Nacimiento fault trace (Fig. 1.27); and (2) a west-tilted basement wedge between these faults is responsible for the observed lack of a steep gravity gradient along the Sierra Nacimiento front. Based on their model, Pollock et al. (2004) calculate an east–west (range–normal) component of shortening of about 7 km (Fig. 1.27).

Based on en echelon folds in the southeastern San Juan Basin that appear to be cross-cut by the tight syncline that parallels the western border of the Nacimiento uplift, some workers have inferred that Laramide strike-slip preceded shortening and development of major structural relief across the Nacimiento fault system (Woodward, 1987; Pollock et al., 2004), despite the fact that the en echelon folds formed relatively late in the Laramide. In a contrasting analysis, Erslev (2001) used Laramide minor fault data to interpret that east–northeast shortening occurred first, followed by more oblique (northeast) shortening. Erslev's (2001) observations are in accord with interpretations of sequential Laramide deformation elsewhere in New Mexico (Chapin and Cather, 1981, 1983; Erslev, 1999, 2001). A third possibility, favored by the writer, is that the en echelon folds formed contemporaneously with the development of major structural relief on the range front during middle and late Laramide deformation. This contemporaneity is supported by: (1) Paleogene development of greater shortening of the San Juan Basin–Archuleta anticlinorium relative to the Nacimiento uplift–Chama Basin area, which requires dextral slip on the Nacimiento and Gallina faults (Baltz, 1967); (2) Paleogene dextral slip on the Nacimiento fault, as shown by en echelon folds that exhibit growth relationships with Paleocene and early Eocene strata (Baltz, 1967); and (3) the dominance of Paleocene–Eocene AFT cooling ages in the Nacimiento uplift (Kelley et al., 1992), which indicate that most of the structural relief was attained in the Paleogene.

The magnitude of the dextral strike-slip along the western margin of the Nacimiento uplift has been a topic of much debate. Baltz (1967) used the apparent offset of en echelon folds to estimate 5 km of dextral displacement along the Nacimiento fault. Woodward et al. (1992) argued that such correlation of fold axes is ambiguous and therefore cannot be used to estimate lateral offset. Woodward et al. (1992) instead preferred the <2 km offset estimate of Slack and Campbell (1976) for the Rio Puerco fault system, a series of en echelon normal faults bounded on the east by the Sand Hill fault, a southward continuation of the Nacimiento fault system (Cather, 1999). The estimate of Slack and Campbell (1976), however, was based on the summation of heave across en echelon faults of the Rio Puerco fault system. Their technique did not evaluate the potential for dextral slip on the Rio Puerco faults or the through-going Sand Hill–Nacimiento fault system. Karlstrom and Daniel (1993) estimated ~25 km dextral offset of aeromagnetic anomalies across the Nacimiento fault system, which they attributed largely to Laramide deformation. Cather (1999) noted that the seaward regressive limit of the Turonian Gallup Sandstone is deflected dextrally 20–33 km across the Sand Hill–Nacimiento fault system, and argued that the deflection was the result of Laramide strike-slip. Pollock et al. (2004) interpreted 3–15 km of dextral separation of Proterozoic lithologies across the Nacimiento fault, which they regarded as the net product of Proterozoic, late Paleozoic, and early Laramide displacements.

To the north, the Nacimiento fault bends to the north–northeast to become the Gallina fault. The Gallina fault is subvertical and alternates from west-down to east-down along its trace (Baltz, 1967; Woodward et al., 1992). It was interpreted by Baltz (1967) to be a dextral strike-slip fault with small but unspecified displacement. Linkage between the Nacimiento and Gallina faults, and the fact that the Gallina fault is not strongly contractional or extensional, implies that the Gallina fault is subparallel to the convergence direction between the San Juan Basin and the Nacimiento Uplift.

The Gallina fault appears to terminate northward in the area south of El Vado reservoir (Fig. 1.28), where it splays into a closely spaced, polygonal set of small-displacement faults (Landis and Dane, 1967). The north–northeastward projection of the Gallina fault in the El Vado–Chama area corresponds to an enigmatic and poorly exposed segment of what Baltz (1967) termed the Salado–Cumbres discontinuity. Passages from the original description of the discontinuity by Baltz (1967, p. 83–84) are quoted below, along with comments by the writer in brackets.

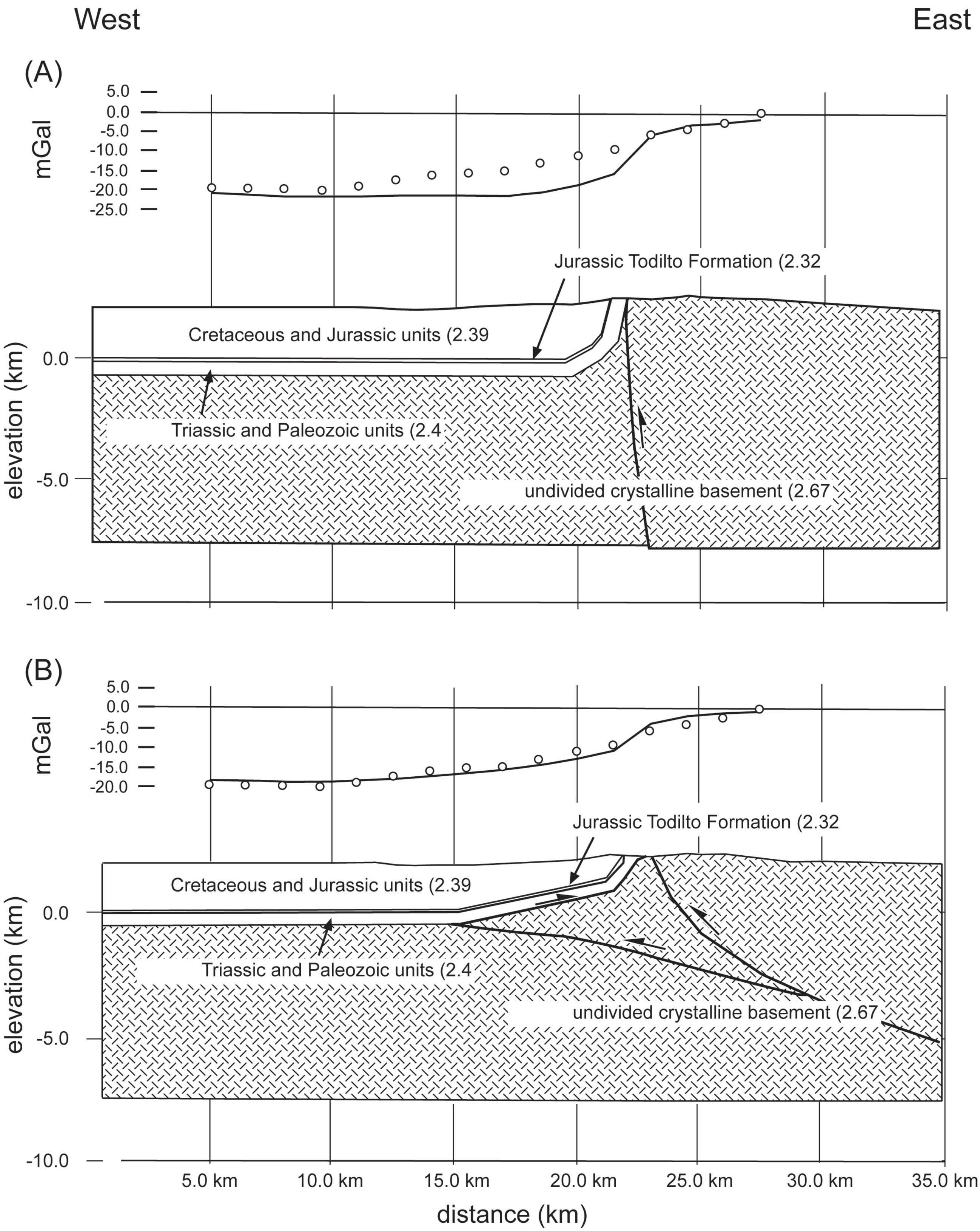

FIGURE 1.27. Gravity and structural models of the eastern San Juan Basin and the Nacimiento uplift (Pollock et al., in press). A, Upthrust interpretation of Woodward (1987). Note poor fit between measured complete Bouguer anomaly values (circles) and calculated complete Bouguer anomaly profile (solid line) and the lack of structural balance in the cross section. East–west shortening is minimal. B, Thrust-wedge interpretation of Pollock et al. (in press). Note good fit between observed (circles) and calculated (solid line) complete Bouguer anomaly values. This model requires approximately 7 km of east–west shortening.

The Nacimiento and Gallina faults and the eastern margin of the Archuleta anticlinorium mark parts of a major regional structural discontinuity. The two faults themselves are sharp and easily recognized as a discontinuity, but north of the surface termination of the Gallina fault there is no equivalent single structural feature that delineates the discontinuity. However, the patterns of deformation are considerably different on either side of a slightly curved line projected north–northeastward from the northern termination of the Gallina fault. The folds and faults of the Archuleta anticlinorium do not terminate abruptly at the north–northeast-trending . . . east boundary of the anticlinorium north of the Gallina fault; nevertheless, many of the structural features do terminate very near this boundary, and the structural grain of the Chama Basin at the southeast is dissimilar to that of the anticlinorium.

The line or band of discontinuity can be projected north–northeast past the northwest-plunging end of the Brazos uplift and the southeast end of the San Juan sag, but it is lost beneath the Tertiary rocks of the San Juan Mountains volcanic field in the vicinity of Cumbres Pass north of the Colorado boundary. The total length of the discontinuity from the vicinity of the place where the Rio Salado crosses the south end of the Nacimiento uplift to the vicinity of Cumbres Pass is almost 110 miles [175 km]. The structural discontinuity is here called the Salado–Cumbres structural discontinuity. . . The San Juan sag and the northern part of the Brazos uplift in Colorado are buried beneath the San Juan Mountains volcanic field, and it is not known how far the discontinuity persists to the northeast from Cumbres Pass. Precambrian rocks lying directly beneath the Tertiary Potosi Volcanic Group [Conejos Formation] are exposed at a few places along the Conejos River in T. 33 N., Rs. 5 and 6E. (Larsen and Cross, 1956, pl. 1), northeast of Cumbres Pass in Colorado. These Precambrian rocks may be in the buried northern part of the Laramide Brazos uplift. Therefore, the discontinuity might persist, beneath the volcanic rocks, at least as far northeast as the westernmost outcrops of Precambrian rockson the Conejos River. [Subsequent drilling has shown that the discontinuity, represented by the Del Norte fault, resumes a northerly strike and delineates the eastern boundary of the San Juan sag at least as far north as the latitude of Saguache, Colorado (Brister and Chapin, 1994).]

The differences in amount of shortening between the northwest-aligned San Juan Basin and the north-aligned Nacimiento and French Mesa–Gallina uplifts were accommodated mainly by right shift on the Nacimiento and Gallinas faults. The folding and crumpling of the Archuleta anticlinorium that caused a small amount of shortening in a northeasterly direction seem to imply some right shift between the anticlinorium and the Chama Basin. If the shift took place along a deep-seated shear zone in the basement rocks, the overlying sedimentary blanket would have been twisted and dragged above the shear zone . . .The subsurface geometry of the Nacimiento fault system, and the extent of its regional interconnectivity with other Laramide faults, has major implications with regard to the allowable magnitude of

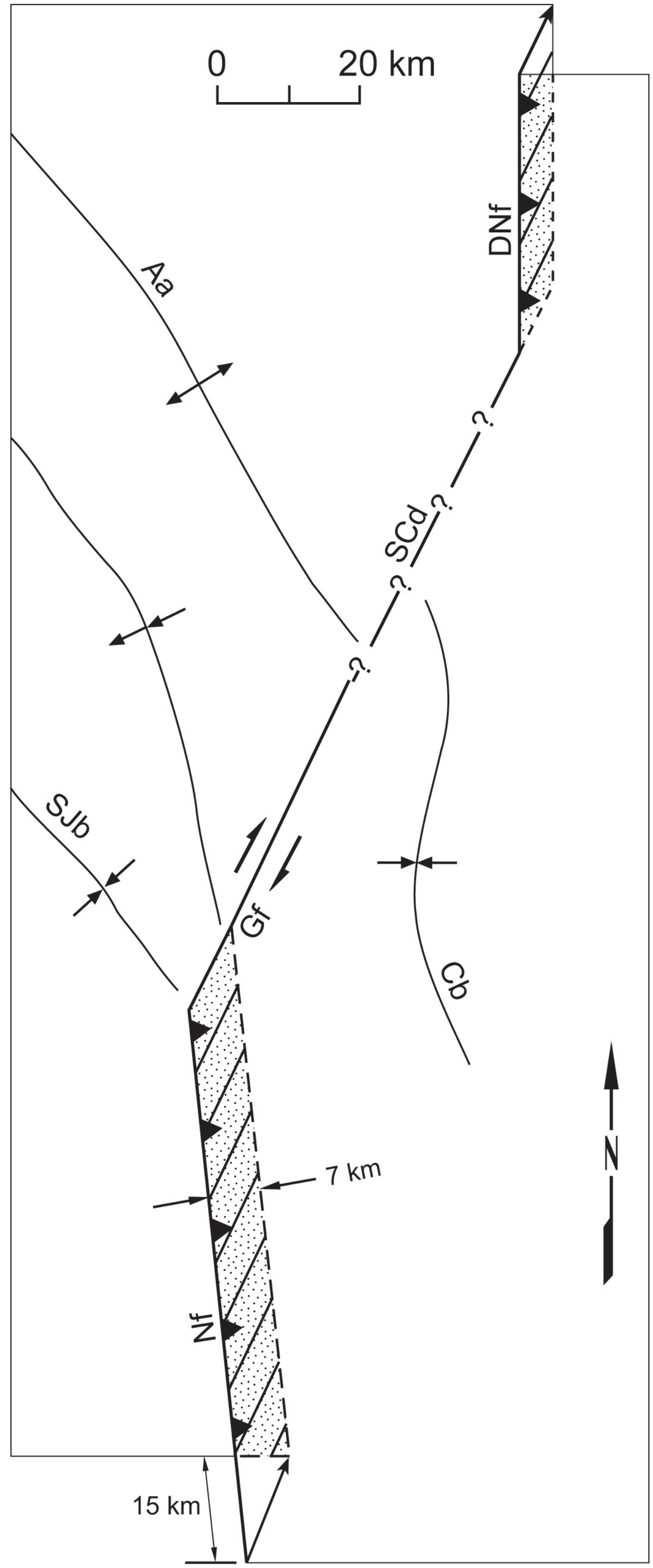

FIGURE 1.28 Simplified tectonic model for Laramide development of Nacimiento Uplift–Archuleta Anticlinorium area (see text). DNf, Del Norte fault; Aa, Archuleta Anticlinorium; SCd, Salado-Cumbres discontinuity; SJb, axis of San Juan Basin; Gf, Gallina fault; Cb, Chama Basin; Nf, Nacimiento fault.

strike slip on the Nacimiento fault system. Many previous workers (the writer included) considered that the apparent steep dip of the Nacimiento fault system is compatible with only minor amounts of fault-normal contraction. Such a geometry would dictate that any major horizontal relative motion between the eastern San Juan Basin and the Nacimiento uplift necessarily would be nearly parallel to the north-striking Nacimiento fault. As pointed out by Baltz (1967, fig. 21), dextral strike-slip on the Nacimiento fault would create extension where the Nacimiento fault bends north–northeast to become the Gallina fault. Although there are numerous normal faults scattered throughout the Nacimiento uplift (Woodward, 1987), the cumulative heave on these faults is not large and therefore cannot balance more than modest amounts of strike-slip dilation at a releasing bend at the north end of the uplift.

The results of Pollock et al. (2004) have important implications for regional tectonics. If their estimate of ~7 km for the east–west component of shortening between the eastern San Juan Basin and western Nacimiento uplift is resolved into a vector parallel to the north–northeast striking Gallina fault, ~16.5 km of dextral separation would be predicted for the Gallina fault and ~15 km dextral separation for the Nacimiento fault (Fig. 1.28). The dextral separation estimate for the Nacimiento fault (15 km) is compatible with the range of net offset given by Proterozoic lithologies (3–15 km; Pollock et al., 2004), but is somewhat less than the deflection of the Gallup Sandstone pinchout (20–33 km; Cather, 1999) and the offset of basement aeromagnetic anomalies (~25 km, Karlstrom and Daniel, 1993). The biggest problem with this construction is that the predicted dextral offset along the Gallina fault (~16.5 km) is too large to be balanced by shortening northwest of the fault, if the fault ends near El Vado Reservoir. If, on the other hand, there is strike-slip linkage along the Salado–Cumbres discontinuity with the Del Norte fault in southern Colorado, then the construction may be viable. Despite poor exposure, it seems unlikely that a single, throughgoing shear exists in surficial exposures along the discontinuity in the El Vado–Chama area. It is possible, however, that the Salado–Cumbres discontinuity in this area may have accommodated broadly distributed dextral wrenching. Perhaps the polygonal pattern of faults described by Landis and Dane (1967) near the termination of the Gallina fault results from regional detachment, interstratal shear and vertical axis rotations above a basement strike-slip fault. If so, such rotations should be testable through paleomagnetic analysis. Detachment may have been facilitated by thick (>100 ft or 30 m) gypsum of the Todilto Formation in the subsurface near the termination of the Gallina fault (Ash, 1958; Cather, 1999, fig. 5).

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104.0 Poleo Formation sandstones in roadcuts. *0.5*

104.5 Poleo Formation roadcuts. *0.6*

105.1 "Arroyo Seco" fault on right puts upper part of Upper Triassic Rock Point Formation down on Upper Triassic Poleo Formation (up to 180 m of throw). *0.5*

105.6 Rest area pull-out on left, Painted Desert Member to right. Orphan Mesa on right is composed of slopes of Upper Triassic Painted Desert Member and overlying Rock Point Formation capped by cliff of Middle Jurassic Entrada Sandstone topped by Todilto Formation. Orphan Mesa is almost certainly the type locality of the Triassic dinosaur *Coelophysis* (Sullivan et al., 1996). *1.5*

107.1 Descend to surface developed on Upper Triassic Poleo Formation. **Turn right to Ghost Ranch Conference Center**, pavement ends.

The name Ghost Ranch was derived from local Spanish folklore, where it was also known as "el rancho de los brujos"---ranch of the witches (warlocks)-- apparently derived from tales of ghosts and purported hangings. Originally part of the Piedra Lumbre land grant, the A. B. Renehan estate purchased the land for about $20,000 in 1929. The property title then went to Arthur and Phoebe Pack (who had founded the Arizona Sonora Desert Museum in Tucson), and they gave it to the Presbyterian Church Board of Christian Education in 1955. The ranch is now operated primarily as an educational and conference center.

Note armored terraces of Rio Chama developed on red mudstones of the Painted Desert Member of the Petrified Forest Formation here along road. *0.4*

107.5 The cabin on the right, and much of the surrounding landscape, were featured in the 1980s Hollywood western "Silverado." *0.7*

108.2 Fork in road, **go left**. *0.3*

NEW MEXICO'S TRIASSIC DINOSAUR DISTRICT

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Ghost Ranch, Gallina, Orphan Mesa, Arroyo Seco and Canjilon are all world-famous locales, not to most international citizens, perhaps, but certainly to the global community of scholars studying Triassic dinosaurs. The badlands of the Upper Triassic Chinle Group in the Chama Basin have more than 120 years of dinosaur-collecting history, dating from the Cope-Marsh "bone wars" to the present day.

New Mexico's place in the study of Triassic dinosaurs was assured by the 1880s. E. D. Cope had passed through the area in the early 1870s, collecting (and naming) fragmentary Triassic vertebrates, including the aetosaur *Typothorax coccinarum* Cope (1875). Accordingly, he hired a New Mexico resident and collector, David Baldwin (whom he hired away from arch-rival Marsh) in 1880. Shortly thereafter Baldwin sent Cope fragmentary theropod dinosaur bones from no fewer than three localities—one near Gallina, and two near "Arroyo Seco," including "Rincon near Huerfano camp" which roughly translates as "hollow near Orphan camp" (Baldwin's 1881 letters to Cope). These fossils became the types of Cope's (1887a,b) *Coelurus bauri, C. longicollis, and C. willistoni* (Padian, 1986; Colbert 1989; Sullivan et al., 1996; Sullivan and Lucas, 1999). While much of this material is fragmentary, it is extremely important in the history of paleontology, and has been described, redescribed, debated, and reinterpreted for more than 100 years (e.g., Cope, 1887a, b; Von Huene, 1915; Padian, 1986; Colbert, 1989; Hunt and Lucas, 1991; Sullivan et al., 1996; Sullivan and Lucas, 1999). Indeed, these fossils are so important that Friedrich Von Huene, a German scholar and the preeminent Triassic reptile paleontologist of the first half of the 20th century, traveled to the Chama Basin in 1911 in the company of some prominent American paleontologists in search of Triassic dinosaurs. Although their attempts to discover more *Coelophysis* fossils were unsuccessful, they did relocate the Gallina locality (Williston and Case, 1912), and Von Huene (1915) would redescribe Cope's material, even as the "Great War" raged on the European continent.

It is not until the end of the Second World War that more dinosaur discoveries were made in the Chama Basin. The University of California Museum of Paleontology (UCMP) had secured great success in the Permian and the Triassic of the Chama Basin throughout the 1930s, but their big Triassic excavation, the Canjilon quarry (Day 2, stop 1) was a phytosaur quarry that lacked dinosaurs. Still, in 1947 Edwin Colbert of the American Museum of Natural History (AMNH) in New York City launched an expedition to Ghost Ranch, hoping to collect more *Coelophysis* specimens. On June 22, 1947, after some mild success finding other, more common Triassic vertebrates, Colbert's preparator and field hand, George Whitaker, stumbled upon the treasure trove of *Coelophysis* skeletons now known as the Ghost Ranch Coelophysis quarry (Colbert, 1989; also referred to as the "Whitaker quarry," e.g., Paul, 1993; Sullivan et al., 1996; Sullivan and Lucas, 1999). This spectacular bonebed yields hundreds of complete, articulated skeletons of *Coelophysis bauri*, and is the basis for *Coelophysis*' recognition as New Mexico's state fossil. The AMNH would excavate this quarry in 1947 and 1948, and casts of one of the skeletons they prepared (AMNH 7224) can be found in museums the world over. In the 1980s, David Berman of the Carnegie Museum of Natural History in Pittsburgh, Pennsylvania would launch another excavation at the quarry, distributing large blocks to almost every major natural history museum in North America (see Colbert, 1989).

But the story does not end there. Beginning in the 1980s, modern researchers have enjoyed continued success finding theropod dinosaurs in Triassic strata of the Chama Basin. First, there was the holotype partial skeleton of *Eucoelophysis baldwini* Sullivan and Lucas (1999), found near Orphan Mesa in 1983, and other fragmentary theropods have been found in the same area (Sullivan et al., 1996). Following this was the discovery of several coelophysids at the Upper Triassic Snyder quarry (Heckert et al., 2000, 2003), including a partial skull strikingly similar to that of Coelophysis. The Snyder quarry is at the same stratigraphic level as the Orphan Mesa locality and, we believe, Baldwin's original collecting areas, and is also less than a quarter mile (0.4 km) from Arroyo Seco. Still, more recently, Alex Downs of Ghost Ranch has excavated additional theropods at the "Hayden quarry," which also appears to be at the same stratigraphic level as the Orphan Mesa and Snyder quarry sites. We may never know exactly where Baldwin's original collecting localities were, but we have determined that many were at the same stratigraphic level as the more recent discoveries, that is in the Painted Desert Member of the Petrified Forest Formation (Sullivan et al., 1996).

The singular importance of the Ghost Ranch quarry sample cannot be overstated. Although the fossils are exceedingly difficult to prepare, this is the single largest accumulation known for any dinosaur. The fact that many of the skeletons are fully articulated and are from a geologically old (early) dinosaur ranks as a most important occurrence. Indeed, these are the oldest known articulated dinosaur skeletons from North America and the most complete and most abundant dinosaur specimens known anywhere. Unfortunately, the sample is so rich and so important that, in some ways, it has overwhelmed the scientific community's ability to research it. Paleontologists, perhaps too accustomed to working with isolated bones or fragmentary skeletons from widely dispersed localities, have trouble quantifying the variation present in hundreds of skeletons that are not only spread out across 20+ natural history museums, but also presumably represent different sexes and ages. Indeed, there has even been much debate over the proper name, with the name *Rioarribasaurus colberti* proposed for the Ghost Ranch dinosaur sample, which is now clearly not the same as the fossils collected by Baldwin (Hunt and Lucas, 1991, 1993; Sullivan, 1993, 1995; Huber, 1994; Sullivan et al., 1996). Still, the rulings of the International Code of Zoological Nomenclature prevailed, and the theropod at Ghost Ranch is now the official type (holder of the name) of *Coelophysis bauri.* Still, much research has been published on the *Coelophysis* quarry sample, including a monograph and paper by Colbert (1989, 1990) and many shorter contributions by diverse authors (e.g., Paul, 1993; Smith, 1997; Downs, 2000). Along somewhat more frivolous lines, *Coelophysis* also holds the title of the only dinosaur to reach space; a fossil of the dinosaur travelled aboard the space shuttle Endeavor in January, 1998.

In summary, no place on earth has such a rich assemblage of Triassic theropod fossils as the Chama Basin. From the world's richest dinosaur quarry, the Whitaker quarry, to the records of theropods in the Painted Desert Member at Orphan Mesa, the Snyder quarry, near Arroyo Seco, Gallina, and the Hayden quarry, this is truly the world's greatest accumulation of Triassic theropods. Indeed, in the Chama Basin, Triassic theropod localities, which are usually rare, are instead the norm.

Why is the Chama Basin so rich in Triassic dinosaurs? It may be stochastic—the sheer random nature of what enters the fossil record and then is subsequently discovered may have simply yielded a relative bonanza in the Chama Basin. Certainly the *Coelophysis* quarry itself is one of the most spectacular dinosaur quarries known, and whatever processes may have led to its formation were certainly unusual (Schwartz and Gillette, 1995). The stratigraphically lower Arroyo Seco localities (Orphan Mesa, Snyder quarry, Hayden quarry, and the UCMP's Canjilon quarry) are all at the same stratigraphic level (Lucas and Hunt, 1992; Heckert et al., 2000; Lucas et al., 2003), and at least some preserve evidence of a large-scale paleowildfire (Zeigler, 2002, 2003). Perhaps it is just a fluke that two taphonomically unique events entrained Triassic dinosaurs, which are otherwise rare, into the fossil record on a scale thus far unmatched in the millions of square kilometers of Upper Triassic rocks exposed in the American West. Another, more testable possibility is that, during Late Triassic time, the area now included in the Chama Basin was a particularly favorable environment for small theropod dinosaurs. Dinosaurs were more terrestrial than most Chinle vertebrates, which typically consist of large aquatic amphibians (metoposaurs) and reptiles (phytosaurs). During Late Triassic time the general vicinity of the Chama Basin was on the flanks of the remnants of the Uncompahgre uplift and other Ancestral Rocky Mountain (ARM) highlands, some of which were only buried at the end of the Triassic. Dinosaur preservation in the Chama Basin therefore may reflect a greater population of dinosaurs than other Chinle locales. The answer remains to be seen, but there can be no doubt that this string of localities is not only New Mexico's, but one of the world's most important "Triassic Dinosaur Districts."

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108.5 Ghost Ranch museum and headquarters on left. *0.2*

108.7 **Turn left** on narrow road just beyond buildings to left. *0.3*

109.0 STOP 5 - *Coelophysis* Quarry

Road forks, bear right. Park here to walk to *Coelophysis* quarry on Box Canyon Trail.

The Late Triassic dinosaur *Coelophysis* (Fig. 1.29) is New Mexico's official state fossil. In 1947, Edwin Colbert lead an expedition from the American Museum of Natural History to the Ghost Ranch area in search of Triassic dinosaurs. At Ghost Ranch, George Whitaker, a member of his team, discovered a remarkable bonebed packed with dinosaur skeletons. Colbert thought that Whitaker had relocated Baldwin's original locality and that the dinosaurs in the bonebed were the same dinosaur Cope had named *Coelophysis*. Both of those conclusions were later demonstrated to be incorrect (see accompanying minipaper), but the name Coelophysis has stuck to the dinosaurs from the Ghost Ranch bonebed discovered by Whitaker (which paleontologists now call either the Whitaker, *Coelophysis* or Ghost Ranch quarry).

Most of what we know about *Coelophysis* is based on the dinosaur quarry at Ghost Ranch, a bonebed with hundreds of skeletons of the dinosaur. *Coelophysis* lived during the Late Triassic, about 205 million years ago. It was a small (6-10 ft long as an adult) terrestrial predator that fed on insects and other small animals such as early mammals and small reptiles. *Coelophysis* also was a cannibal as demonstrated by an adult skeleton from Ghost Ranch that contains the skeleton of a *Coelophysis* baby in its abdomen.

Hundreds (perhaps thousands) of *Coelophysis* skeletons are preserved in the bonebed at Ghost Ranch. However, what killed and buried these dinosaurs is difficult to determine with certainty. The most defensible idea is that the bonebed formed in what was a pond on the vast Late Triassic river floodplain. A flood washed the bodies of the dinosaurs into the depression in which the pond had formed. But, whether the flood or something else actually killed the dinosaurs is uncertain.

The dinosaur bonebed at Ghost Ranch also includes other kinds of fossils. These include ostracods, conchostracans, scales and bones of bony fishes, skulls of phytosaurs (crocodile-like archosaurs), a skeleton of a rauisuchian (predatory terrestrial archosaur), a sphensuchian skeleton (early crocodile) and jaw fragments of a sphenodont (small, lizard-like reptile).

END OF DAY ONE ROAD LOG

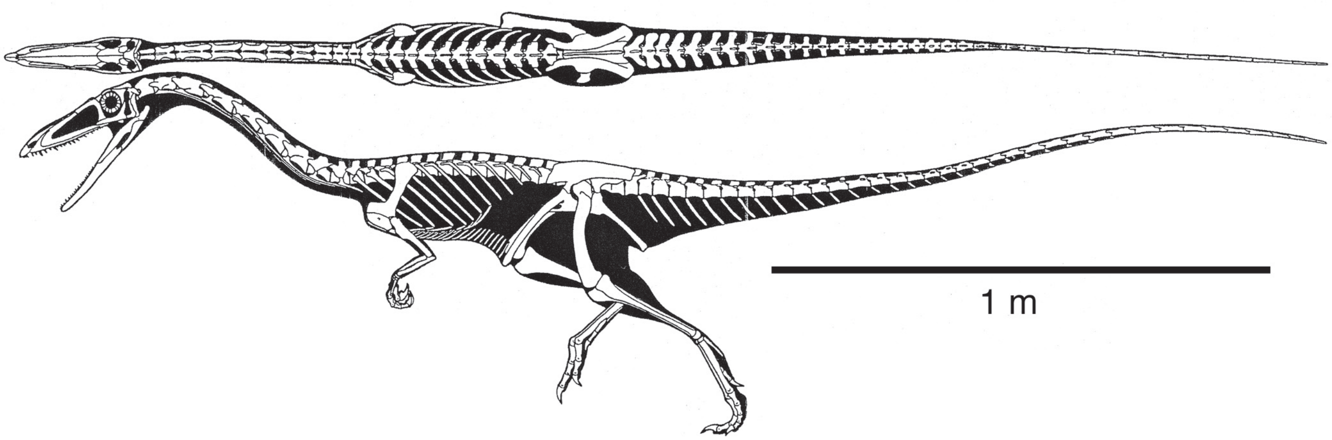

FIGURE 1.29. Skeleton of New Mexico's official state fossil, *Coelophysis bauri* (after Paul, 1993).

THE SAGA OF *COELOPHYSIS*

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Coelophysis is a Late Triassic theropod dinosaur that is now the Official State Fossil of New Mexico by a 1981 act of the New Mexico State Legislature. The history of the name *Coelophysis*, and the fossils attributed to it, however, is far from straightforward.

In 1881, David Baldwin, a hired fossil collector working for E. D. Cope, discovered various dinosaur bones in Upper Triassic strata at two localities: (1) "Gallina Canyon," according to Baldwin, "400 feet below gypsum horizon, 180 feet above grey sandstone;" and (2) "Arroyo Seco," in a layer "about four hundred feet below gypsum stratum" (Colbert, 1989, p. 5). The gypsum stratum Baldwin referred to is obviously the gypsum of the Middle Jurassic Todilto Formation. Sullivan et al. (1996) further explained the geographic locations (as best as can be determined) of Baldwin's sites, and their stratigraphic level, which appears to have been in the Painted Desert Member of the Petrified Forest Formation of the Chinle Group (Lucas et al., 2003). The problem is that the exact location of the dinosaur bones Baldwin collected (whether they were from "Mesa Gallina" or "Arroyo Seco") was lost long ago (e.g., Von Huene, 1915).

In 1887, Cope described the dinosaur fossils Baldwin had collected in 1881. He assigned them to two new species of the previously described genus *Coelurus*: *C. longicollis* and *C. bauri* (Cope, 1887a). In an article published later that year, Cope (1887b) then assigned the species to *Tanystrophaeus* and named a third species, *T. willistoni*. However, Cope (1889) changed his mind again, coining the name *Coelophysis* ("hollow form," in reference to the hollow bones of the fossils Baldwin had collected) for the three species. Hay (1930) designated *Coelophysis bauri* the type species of the genus (Cope had failed to do this), and Von Huene (1911, 1915) first illustrated the fossils of *Coelophysis* Baldwin had collected.

In 1947, an American Museum of Natural History field party, led by Edwin H. Colbert, discovered the dinosaur bonebed at Ghost Ranch, New Mexico. This fossil locality, variously known as the Ghost Ranch, *Coelophysis* or Whitaker quarry (we prefer the latter, named for George Whitaker, who actually discovered the site) yielded thousands of skeletons of a small theropod dinosaur that Colbert (1947) immediately assigned to *Coelophysis* and later (Colbert, 1964) to *C. bauri* (also see Colbert, 1989). Eventually, Colbert (1989) would designate a lectotype specimen of *C. bauri* from Cope's original material, something that had not previously been done (Padian, 1986).

Hunt and Lucas (1991), however, argued that the type of Cope's species *Coelophysis bauri*, four sacral vertebrae and a pubic process of the ilium (AMNH 2708: Fig. 1.30), is not diagnostic, so *C. bauri* is a *nomen dubium*. Furthermore, the Whitaker quarry is not one of Baldwin's localities where he collected the type material of *C. bauri*; those localities are much lower stratigraphically (in the Petrified Forest Formation; the Whitaker quarry is in the Rock Point Formation) and kilometers (Arroyo Seco) or tens of kilometers (Mesa Gallina) distant from the Whitaker quarry (Sullivan et al., 1996). Consequently, Colbert was not justified in applying the name *C. bauri* to the theropod dinosaur fossils from the Whitaker quarry.

Therefore, Hunt and Lucas (1991) proposed a valid name for the Whitaker quarry theropod—*Rioarribasaurus colberti*—with the type specimen a skeleton (AMNH 7224) from the quarry. This, however, was not accepted by Colbert, who together with several supporters, petitioned the International Commission on Zoological Nomenclature to transfer the type specimen of *Coelophysis bauri* from its lectotype (AMNH 2708) to the holotype of *Rioarribasaurus colberti* (AMNH 7224). This step would validate *C. bauri*, invalidate *R. colberti*, and thus legislate 50 years of error by Colbert in identifying the Whitaker quarry theropod as *C. bauri*. Furthermore, it violated the principle of priority and was proposed by Colbert et al. (1992) without the necessary revisory work called for by the International Code of Zoological Nomenclature.

Politics won on this issue, though, and the Commission set aside its principles to approve the petition of Colbert et al. (1992). Thus, the Ghost Ranch dinosaur is now "legally" called *Coelophysis bauri*. The saga of the name *Coelophysis*—from *Coelurus* to *Tanystrophaeus* to *Coelophysis* to *Rioarribasaurus* to *Coelophysis* again—is a confusing one!

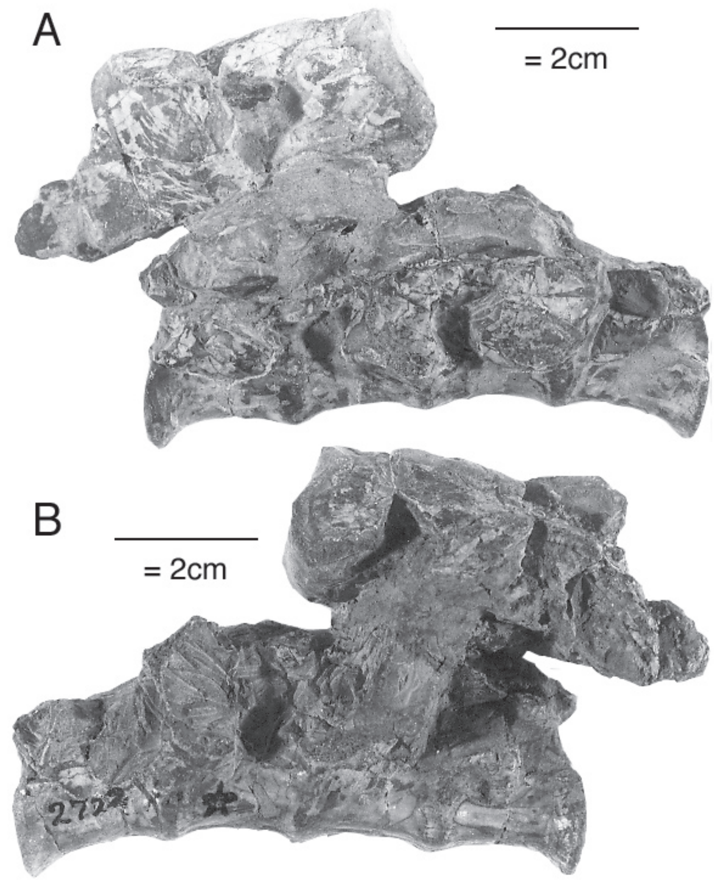

FIGURE 1.30. The lectotype of *Coelophysis bauri*, a sacrum and part of a pelvis.

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