Geologic Map of the Benavidez Ranch 7.5-minute Quadrangle, Bernalillo and Sandoval Counties, New Mexico

By

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New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 234

Scale 1:24,000

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BENAVIDEZ RANCH QUADRANGLE

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View of part of the northeastern study area. The Menefee Formation lies in the foreground. Just beyond lies the north-striking Moquino fault, which has juxtaposed younger Santa Fe Group against the Menefee Formation. The middle hillis underlain by the Zia Formation, where grayish Piedra Parada sandstone is overlain by the ledge-forming, redder Chamisa Mesa Member. The cliff in the back right correlates to the lower Cerro Conejo Formation.

EXECUTIVE SUMMARY

The Benavidez Ranch quadrangle is located in the picturesque Rio Puerco Valley 30 km northwest of downtown Albuquerque, 15 km north of where the Rio Puerco is crossed by Interstate 25. The area encompasses the western boundary of the Albuquerque Basin, the largest in the Rio Grande rift. Northeast-striking, southeast-dipping (5-20° SE) Cretaceous rocks outcrop in the western quadrangle. These strata include, in ascending order: the Pescado Tongue of the Mancos Shale, Gallup Sandstone, Dilco Member of the Crevasse Canyon Formation, Mullato Tongue of the Mancos Shale, Dalton Sandstone Member of the Crevasse Canyon Formation, Gibson Coal-bearing Member of the Crevasse Canyon Formation, Hosta Tongue of the Point Lookout Sandstone, Satan Tongue of the Mancos Shale, the upper Point Lookout Sandstone, and the Menefee Formation. Facies associated with these rocks indicate fluctuating sea levels in the Late Cretaceous. The Mancos Shale tongues record times of high sea level and offshore marine sedimentation (locally nearshore, as interpreted for the western part of the Satan Tongue). Barrier island complexes associated with sea level regressions are reflected in the Gallup Sandstone and the lower part of the upper Point Lookout Sandstone. The Point Lookout Formation is largely a deltaic facies formed during both a transgression (Hosta Tongue) and regression (upper part), with nearshore to offshore, marine sediment of the Satan Tongue separating the two Point Lookout tongues. The Dilco Member is largely a lagoon facies on this quadrangle. Fluvial and swamp sedimentation on a coastal plainsor the proximal part of deltas (i.e., deltaic plain) are found in the Gibson Coal-bearing Member of the Crevasse Canyon Formation and the Menefee Formation. Both of these terrestrial deposits look

relatively similar, but the former contains more coal beds and lacks the greenish-gray mudstones found in the Menefee Formation. Trough cross-stratification measurements in the Menefee Formation indicate a general northeast paleoflow direction of rivers, approximately perpendicular to the shoreline of the Western Interior Seaway.

A prominent northeast-striking fault system, including the Sedillo fault to the south and the Moquino fault to the north, separates the Cretaceous rocks from Miocene-age Santa Fe Group strata to the east. Strata dip steeply (10-25°E) on the immediate footwall of the Moquino fault, which can be described as a faulted, east-down monocline. The Santa Fe Group dips eastward at lower angles and has less faults than on the immediate footwall of the Moquino fault. also dips eastward, but at lesser magnitudes than Cretaceous rocks (3 to 10° NE-SE). This basin-fill sediment exhibits practically all of the Santa Fe Group units previously recognized in the Albuquerque Basin, listed in ascending order: the Zia Formation (including the Piedra Parada, Chamisa Mesa, and Cañada Pilares Members), the Cerro Conejo Formation, the Arroyo Ojito Formation (Navajo Draw and Loma Barbon Members), and the Ceja Formation (Atrisco and Rio Puerco Members). On this quadrangle, the light gray Piedra Parada contains a mix of fluvial and eolian facies, and locally is even conglomeratic. Its coarse sand texture, compared to overlying units, suggest relatively high stream power during its deposition 21-18 Ma, although the climate at the time was relatively arid based on the presence of extensive dunes and available fauna (Gawne, 1973 and 1981). The Chamisa Mesa Member (18-17 Ma) is remarkably different from the Piedra Parada Member in its distinct, tabular beds and redder colors. Furthermore, the Chamisa Mesa Member displays spring mound deposits and relatively abundant rhizoliths. These

features suggest a relatively stable, well-vegetated landscape. The Cañada Pilares Member on the quadrangle is clearly associated with a river and dominated by floodplain facies consisting of interbedded claystones and very fine- to medium-grained sandstones. Evidence of lacustrine or eolian conditions, found to the north (Tedford and Barghoorn, 1999), were not observed here. Fossil and magnetostratigraphic data indicate a 17.5-16 Ma age for the Cañada Pilares Member and a disconformity at the top of the unit (Tedford and Barghoorn, 1999).

The Cerro Conejo Formation is the thickest Santa Fe Group unit and covers the most area. Its age spans 14.5 to 11-10 Ma, based on a single K/Ar age of an interbedded ash, paleontologic data, and magnetostratigraphy (Tedford and Barghoorn, 1999). We differentiate four subunits (**Tcc1** to **Tcc4**, with **Tcc1** being the oldest). **Tcc1** is reddish and composed of ledge-forming, tabular sandstones interbedded with minor claystones, siltstone, and very fine- to fine-grained sandstones. **Tcc2** consists of a pastel-colored unit with a prominent greenish clay bed interpreted to be lacustrine. **Tcc3** is tannish, sandy, and mostly indistinctly bedded, with relatively abundant volcanic granules found in its upper 6 m and a ledge-forming, well-bedded interval in its lower ~6 m. Both **Tcc2** and **Tcc3** are interpreted to be associated with southeast-flowing streams on a basin-floor. The lower part of **Tcc4** is similar to **Tcc1**; both are interpreted to have been deposited in the transition between a distal piedmont to a basin floor. The upper part of **Tcc4** contains chert-dominated pebble beds**,** increasing in abundance and thickness up-section, as well as distinctly cross-stratified fluvial deposits .

The Arroyo Ojito Formation is notably coarser than the Cerro Conejo Formation and ranges in age from 10 to 6 Ma (Connell et al., 1999; Connell, 2008a). Gravel composition and paleoflow data to the north indicate that this formation was deposited by a southeast-flowing river or stream system that drained the eastern Colorado Plateau and the Naciamento Mountains (Connell et al. (1999). The lower Navajo Draw Member occupies much of the southeastern quadrangle and is mostly pale brown. Its clast composition is dominated by tan sandstone (intraformational or older Santa Fe Group sandstone) and chert. The Loma Barbon Member barely extends into the quadrangle, but exposures east of the quadrangle boundary indicate it is dominated by tan sand, minor pebble-conglomerate beds, and 1-5% mudstone beds. Two clast types associated with the Sierra Naciamento Mountains to the north, Pedernal chert and red granite, both increase in abundance up-section in the Arroyo Ojito Member -- indicating progressive unroofing of the Sierra Naciamentos in the Late Miocene.

The uppermost Santa Fe Group unit, the Ceja Formation, disconformably overlies the Arroyo Ojito Formation east of the east-central part of the quadrangle, as evidenced by a paleosol. However, it is uncertain how far south this paleosol extends. The Atrisco Member of the Ceja Formation is notably finer-grained than the underlying Arroyo Ojito Member. The Atrisco is practically horizontal-bedded and dominated by well-bedded, floodplain deposits of very fine- to medium-grained sand and minor clayey mudstone. The Rio Puerco Member of the Ceja Formation is much coarser than the Atrisco Member and disconformably overlies it (Connell et al., 2013).

Five terrace deposits were mapped along the Rio Puerco, mostly preserved on its east side. The upper two are strath terraces. The lower three are relatively thick fill terraces, two of which thin northwards into strath terraces. Age control is lacking for the terraces, aside that they are Pleistocene.

GEOGRAPHIC AND TECTONIC SETTING

The Benavidez Ranch quadrangle stretches across a part of the central Rio Puerco Valley, located about 30 km northwest of downtown Albuquerque and 15 km north of where the valley is traversed by Interstate 25 (Fig. 1). The Rio Puerco in this location contains a 2-2.5 wide, gently southerly sloping (0.2°) valley floor flanked by steeper (0.6°) piedmont slopes and relatively wide tributary drainages. The Rio Puerco has recently incised 5-15 m and small gullies with steep headwalls are propagating away from it. These gullies are generally within 0.5 km of the river, but gullies associated with larger drainages locally extend as much as 4 km away from the river.

West of the Rio Puerco, the landscape contains broad, but relatively low, uplands underlain by sandstone-rich, Cretaceus strata. These are interspersed by east-draining valleys as much as 0.7 km wide. The valley floors are underlain by sandy, relatively young Holocene alluvium. Badland topography is common in the western quadrangle, especially where mudstone-rich strata are at the surface (e.g., the Gibson coal-bearing Member of the Crevasse Canyon Formation or the Menefee Formation).

Except in the north-central quadrangle, weakly to non-cemented, weakly to moderately consolidated Santa Fe Group underlies the terrain east of the Rio Puerco, so the landscape is generally marked by broad, east- to southeast-sloping valleys (0.3-2.0 km). Intervening ridges are relatively low and low-angle. Slightly higher surfaces, underlain by Pleistocene alluvium, are common in the southeastern quadrangle. Near the northern quadrangle border, however, there are numerous steep slopes and cliffs, up to 100 m tall, that nicely display the various units of the Santa Fe Group.

Albuquerque, which lies only 30 km southeast of the quadrangle and at a similar elevation, receives an average of 24 cm (9.4 in) of precipitation a year. Annual high and low temperatures are 68.8°F and 45.4°F (U.S, Climate data, 2014, using normals for 1981-2010). Vegetation on the quadrangle is characterized by a semiarid grassland, with junipers found on the steeper slopes on either side of the Rio Puerco.

PREVIOUS WORK

Most of the previous work on the quadrangle focused on the Santa Fe Group, with previous mapping of the Cretaceous rocks conducted by U.S.G.S. personal (D.A. Sawyer, A.B. Olsen, and J.P. Trexler, whose unpublished mapping was enfolded into Williams and Cole, 2007). This area was also covered by the regional geologic investigation of coal resources by Hunt (1936). The most useful previous work done on the Benavidez Ranch quadrangle was investigations spearheaded by Richard Tedford, who investigated the stratigraphy and fossils of the lower to middle Santa Fe Group along the eastern slopes of the Rio Puerco Valley (Tedford, 1981; Tedford, 1982; Tedford and Barghoorn, 1997 and 1999; Tedford et

al., 1987). Earlier workers who visited the quadrangle area, focusing on the Santa Fe Group or its fossils, included: Bryan and McCann (1937, 1938), Wright (1946), Galusha (1966), Gawne (1973 and 1981), and Kelley (1977). In the surrounding area, relatively recent geologic mapping and stratigraphic work relevant to the Santa Fe Group include: Cather et al. (1997), Koning et al. (1998), Connell et al. (1999), Koning and Personius (2002), Shroba et al. (2003), Connell (2008a and 2008b), Thompson et al. (2009), Cikoski and Koning (2013), and Connell et al. (2013). Investigation of the northeast-trending faults offsetting bedrock strata near the Rio Puerco were conducted by and Slack and Campbell (1976) and Campbell (1967, 1982).

Detailed stratigraphic and paleontologic studies were conducted in a fossiliferous area in Cretaceous strata 4.4 km west of the central western boundary of the quadrangle (UNM V-601, UNM-602, NMMNH locality 297). The fossil-bearing strata included the Gibson Coal-bearing Member of the Crevasse Canyon Formation and the Hosta Tongue of the Point Lookout Sandstone. Results of these investigations are presented in Lucas et al. (1988) and Bourdon et al. (2011).

STRATIGRAPHY

Upper Cretaceous Strata

Upper Cretaceous strata are largely comprised of intertonguing marine shale, nearshore and lagoonal sandstones and minor mudstones, and coastal plain terrestrial sediment, the latter capping the sequence. We will briefly describe these strata in ascending order. Detailed descriptions are found in Appendix 1. Ages of the units come from Molenaar et al.

(2002). Note that all contacts between Upper Cretaceous strata listed below are conformable.

Penasco Tongue of the Mancos Shale (Kmp)

The lowest unit on the quadrangle is the Mancos Shale, which locally contains interbedded sandstone perhaps correlating to the Juana Lopez Member. Above this sandstone, the shale is 170-180 m thick, characteristically gray to pale brown, fissile, and in laminated to very thin, tabular to slightly wavy beds. It grades upward into the overlying Gallup Sandstone. The shale was deposited in an offshore, relatively deep depositional environment between 89.5 and 88.7 Ma.

Gallup Sandstone (Kg)

The Gallup Sandstone on the quadrangle is relatively easy to identify because of the quartzose composition of its sand and fine- to medium-grained textures (Fig. 2). Additionally, it has a biparte division in terms of bedding. The lower 23-27 m consists of medium to very thick, tabular beds (up to 4-5 m thick). These beds contain internal horizontal-planar laminations, local low-angle cross-laminations, or weak to strong bioturbation. The upper 10-12 m is extensively cross-laminated, with tangential foresets up to 50 cm tall), with lesser horizontal-laminated sandstone. The Gallup Sandstone lacks interbedded marine strata on the quadrangle and is interpreted as a barrier island sediment laid down ca. 88.7 Ma during a marine regression (Molenaar et al., 2002). The lower part was deposited largely in the zone of shoaling waves or slightly offshore. The upper part represents deposition in the surf zone and possibly the swash zone.

Dilco Member of the Crevasse Canyon Formation (Kcdi)

The Dilco Member consists of relatively thin (3-4 m thick, thinning to the east), interbedded sandstone, siltstone, and mudstone. The sandstone is quartzose and similar to that of the Gallup Sandstone. However, the sandstone is commonly mottled and bioturbated, or else massive to horizontal laminated. Beds are tabular and of variable thickness. The mudstone is distinctive in that it is brown to very dark gray but locally yellow-stained. It is also locally organic-rich and locally exhibits flaser lamina of fine sand. Also present are minor orange to yellow splotches about ~1 cm^2 in size. These features are consistent with a lagoonal facies, with minor possible coastal swamp sediment. This unit was deposited about 88.7-88.0 Ma in the same regressive event associated with the underlying Gallup Sandstone.

Mullato Tongue of the Mancos Shale (Kmm)

The Mullato Tongue of the Mancos Shale is very different from the Penasco Tongue, particularly in its yellow color and sandy texture (Fig. 2). This offshore, marine sediment generally consists of very fine- to fine-grained sand and silty fine sand, with subordinate pale brown to light yellowish brown to grayish brown, fissile shale. The sediment exhibits laminations to very thin beds that are horizontal-planar to wavy (up to 2 cm amplitude) to hummocky. Organic matter, such as coal, are relatively abundant. The sandy texture and presence of organic matter is suggestive of offshore deposition near a delta front. Local prodelta or delta front sand bars are interpreted in the lower part of the tongue, particularly unit **Kmmsl**. Here, there are also tidal or pro-delta-related channels, where the

basal beds completely drap the channel bottoms and sides. The age range of the Mullato Tongue is 88.0-87.0 Ma (Molenaar et al., 2002) and it is ~95 m thick.

Dalton Sandstone (Kcda)

We designated the light-colored sandstone beneath the Gibson Coal-bearing Member as the Dalton Sandstone, consistent with Hunt (1936) and Lucas et al. (1988). It is 30-37 m thick and consists largely of fine- to medium-grained sandstone, whose color ranges from white to pale brown to light gray. There are 1-10% interbeds of gray to brown mudstone beds. The sandstone beds are largely tabular and display horizontal-planar laminations to cross-stratification (trough or tangential foresets). In the northwestern quadrangle, the upper 5 m of the unit contains fossiliferous beds with clams and molluscan shells. The depositional environment is interpreted as a nearshore facies on a delta front, with minor distributory mouth bars. The age is 87.0-86.6 Ma.

Gibson Coal-bearing Member of the Crevasse Canyon Formation (Kcg)

The Gibson Coal-bearing Member is a distinctive deposit composed of dark-colored, fine-grained deposits interbedded with 15-25% sandstone channel-fills (Fig. 3). It is 120-130 m thick. The fine-grained deposits generally consist of laminated mudstone and siltstone that exhibit very dark gray to dark grayish brown to brown colors. 1% of the strata are laminated to thin-bedded, light gray siltstone and very fine-grained sandstone. There are 1-5%, tabular coal or organic-rich mudstone beds, with the coal being up to 50 cm thick. Red klinker is locally present, as are layers with abundant concretionary iron oxides. The presence of <20 cm thick interbeds of fine- to medium-grained sandstone, locally low-angle

cross-stratified, are interpreted as crevasse splays. These features indicate the fine-grained deposits were interpreted in a floodplain or swampy environments.

The sandstone channel-fills are up to 5 m thick and lenticular over distances of 100s of meters, but may also occur as thick, tabular beds. They commonly display cross-stratification or are horizontal-planar laminated. The sand is fine- to medium-grained and light gray, white, or very pale brown.

Near the western quadrangle border, the upper 10-14 m of this unit is transitional with the overlying Hosta Tongue of the Point Lookout Sandstone. This interval consists of interbedded very fine- to fine-grained sandstone and siltstone-mudstone. The sandstone locally contains 10-15% oyster shells and flaser bedding is locally seen. Coal beds are locally observed in the well-laminated siltstone-mudstone beds. These features are consistent with a lagoonal or coastal swamp depositional environment.

The Gibson Coal-bearing Member is interpreted to have been deposited on a delta plain or coastal plain, during the time that the sea level regressed to its farthest point before transgressing again in the early-middle Santonian. This transgression appears to be reflected in the apparent sea level rise observed in the oyster-bearing, upper 10-14 m of this unit -- although one might argue that the apparent sea level rise could be due to lowering of sedimentation rates combined with coastal land subsidence. Molenaar et al. (2002) suggest an age of 86.6-85.7 Ma for this unit

Hosta Tongue of the Point Lookout Sandstone (Kph)

The Hosta Tongue is generally well-cemented and a ledge-former that is 22-30 m thick (Fig. 4). It is composed of white to pale brown to yellow, fine- to medium-grained sandstone. The sandstone is prominently cross-stratified (tangential to trough- cross-laminated), with thick foresets (up to 100-300 cm), but may also be horizontal-planar lamianted. There are sparse (0.5-1.0%), relatively thin, gray shale-mudstone beds or lamina. This mudstone is blocky rather than fissile and clayey laminae may drape wavy cross-laminations, perhaps reflecting tidal modulated fluctuations in stream power. Other noteworthy, but very minor, features include intraformational pebbles composed of very fine- to medium-grained sandstone or siltststone, as well as trace paleoburrows (related to clams?) that are 1-10 mm in width.

The Hosta Tongue is capped by a laterally extensive, 3-150 cm-thick, fossiliferous transgressional lag deposit (Fig. 5). This distinctive bed is light gray, weathering to light yellowish brown, and composed of moderately sorted, fine-to medium-grained sandstone with up to 1% very thin to thin beds of intra-formational conglomerate. The fossils are concentrated near the top of the lag deposit and include an impressive collection of teeth, disarticulated shells, and intact clams (or clam molds). The sandstone is commonly tangentially cross-stratified, and locally its lower contains gray, fissile shale draping cross-laminations (probably reflecting tidal-influenced changes in stream power).

This transgressional lag deposit likely correlates relatively close to the fossiliferous sandstone at NMMNH locality 297. There, Bourdon et al. (2011) report a diverse

assemblage of selachian teeth, including several new species, that are dominated by *Scapanorchynchus*. Other fossils include teleost fish, plesiosaurs, mosasaurs, turtles, crocodiles, and dinosaurs.

We interpret that the Hosta Tongue was deposited on a delta front, in association with a major delta channel that produced prominent dune forms. Sea level rise eventually formed the transgressional lag deposit that was then overtopped by marine deposition of the Satan Tongue of the Mancos Shale. Fossil data indicate an early to middle Santonian age (86.3-85.5 Ma; Bourdon et al., 2011), consistent with an age of ~85.7-85.5 Ma inferred by Molenaar et al. (2002).

Satan Tongue of the Mancos Shale (Kms)

One of the more interesting discoveries we made was the discovery of a marine tongue in the Point Lookout Formation that displays a lateral facies trend to shallower depths. Based on the regional stratigraphy, we assign this marine sediment to the Satan Tongue of the Mancos Shale. This Satan Tongue may correlate with the 5 m-thick zone with calcareous concretions overlying NMMNH locality 297 (Bourdon et al., 2011).

The Satan tongue is composed of interbedded very fine- to fine-grained sandstone, siltstone, and shale (Fig. 6). Overall, the ratio of sandstone to shale is about 60-70% : 30-40%. A basal zone of fissile to extremely fissile, gray shale lies at its base, but fissile shale also is found up-section in the north-central part of the quadrangle. Shale and silstone are commonly grayish brown to light olive brown. Tabular beds of sandstone exhibit internal

low-angle cross-laminations, hummocky laminations, or horizontal-planar-laminations (Fig. 6). Other interesting, localized features include mottling and bioturbation, symmetrical rippmarks whose crests trend ~290-300°, and light yellowish brown to yellow, sandy limestone beds.

The Satan Tongue is 12-15 m thick in the north-central quadrangle, but thins to the west (to ~6 m). The upper contact is gradational but the lower contact is sharp and planar. Near the western quadrangle boundary, the lower 2 m contains fissile, gray to dark gray shale that is interbedded with minor laminated to thin, tabular, white sandstone beds. The sandstone beds may reflect tidally or flood-controlled deltaic sand surges. The middle and upper part consists of clays that becomes less fissile up-section. These upper clays are relatively massive to wavy-laminated. Also found in the middle to upper part of the tongue are 1-2% laminae of yellow and orange Fe)(?), common wood and leaf imprints, and local coal beds in (1-3%, in the upper part) (Fig. 6).

The aforementioned sedimentologic features are consistent with nearshore, offshore, and lagoonal facies. To the west, the more massive mudstone in the upper part of the unit, in addition to coal beds and wood + leaf imprints, indicate lagoonal to swamp facies and westward shallowing trend. The age of the Satan Tongue is about 85.5-84 Ma (Molenaar et al., 2002).

Upper part of Point Lookout Sandstone (Kpu)

Near the western quadrangle border, the upper tongue of the Point Lookout Sandstone looks similar to the Hosta Tongue. There, it is mostly a white, well-cemented, ledge-forming, fine- to medium-grained sandstone that is cross-stratified to horizontal-planar laminated. We interpret this strata as fluvio-deltaic.

However, in the north-central part of the quadrangle, we observe a sequence of facies indicative of marine regression (Fig. 7). There, the lower 5-10 m of the unit consists of very thick, tabular beds of very fine- to fine-grained sandstone that coarsens slightly upsection. These beds are internally horizontal-planar laminated to tangentially cross-laminated. Bedding becomes more distinct up-section, with local very thin to thin, tabular beds in addition to cross-stratification. The top of this sandstone interval locally contains abundant burrows and clam molds 2-4 cm wide; also locally present at the top is a thick, pale brown limestone bed. The base of the interval is gradational over about 1-2 m. This gradational zone is characterized by very thin to thin, tabular, very fine- to fine-grained sandstone beds interbedded with minor light gray siltstone. The sandstone is horizontal-laminated to low-angle cross-laminated, with hummocky laminations becoming more common down-section. Overall, this 5-10 m interval is more yellow, fine-grained, and less distinctly cross-stratified than elsewhere in the Point Lookout Sandstone. We interpret this interval as nearshore facies of a barrier island, with uppermost strata (exhibiting burrows, clam molds, and a limestone bed) probably representing the shoreward side of the barrier island, adjacent to a lagoon.

Above the nearshore facies lies 2-6 m of interpreted lagoonal facies (Fig. 7). This sediment consists of commonly mottled (with yellow to orange splotches 1-5 cm wide), very fine- to medium-grained sandstone and minor shale or clay-rich mudstone. Sandy strata are massive and bioturbated, or in very thin to thin, tabular beds. Shale commonly occurs as light gray lamina. The mudstone is slightly blocky and locally has flasers of light gray, fine-grained sand. Other noteworthy features, observed locally, include symmetric ripplemarks, trace burrows, and organic detritus up to 2 mm long. The lagoonal sediment grades upward over a few 10s of centimeters into the main, cross-stratified, sandstone body of the upper Point Lookout Sandstone.

The main body of the upper Point Lookout Sandstone consists of fine- to medium-grained sandstone. The lower 3-10 m of the main unit is commonly massive to vaguely laminated, but up-section it is tangentially to trough cross-stratified or horizontal-planar bedded (Fig. 7). The geometry of the trough cross-stratification indicates southeast paleo-flow directions. Large, distinctive paleoburrows are locally observed in the sandstone; these are 2-25 mm wide and up to 46 cm long. This sandstone looks similar to the Hosta Tongue and is interpreted largely as a delta front facies. However, up-section it becomes more fluvial in appearance. In the upper part of the unit, channel-fills are more obvious and occur as medium to thick, tabular to lenticular bodies. The channel-fills may be stacked to form amalgamated packages as thick as 12 m. Interbedded with the channel-fills are trace to 1% mudstone beds; the mudstone is blocky, grayish, and occurs as thin to medium, tabular beds. The upper 10 m of the unit is commonly massive or bioturbated.

The entire unit is ~65 m thick and likely postdates the middle Santonian, based on age control of underlying strata (Bourdon et al., 2011). Molenaar (2002) assign a 84-83 Ma age for the unit.

Menefee Formation (Kme)

By far the thickest Cretaceous unit (at ~550 m) is the Menefee Formation. This unit consists of fine-grained floodplain deposits interbedded with 15-30% sandstone channel-fills (Fig. 8). The fine-grained deposits include mudstone, siltstone, and very fine- to fine-grained sandstone. The mudstone is mostly light gray to dark grayish brown, but locally are greenish gray (Fig. 8). These greenish colors have not been observed in the Gibson coal-bearing Member of the Crevasse Canyon Formation. Interbedded in the mudstone are minor, thinly bedded, very fine- to fine-grained sandstones that likely represent crevasse splay deposition; these are lenticular to broadly lenticular (1:10 height : width ratio) and commonly white. Also interbedded in the floodplain deposits are coal beds, commonly 10-50 cm thick (Fig. 8); these decrease in abundance up-section (1-5% in lower ~60 m, trace-0.5% higher in the section). Other interesting, localized features in the floodplain deposits include petrified wood (Fig. 8), layers with abundant iron oxide concretions, and white ashes up to 15 cm thick.

Sandstone channel-fills are commonly white to tan to light gray, but weather to yellowish brown colors (Fig. 8). The sand is very fine- to medium-grained and variably cemented by calcium carbonate and possibly clay. The channel-fills vary in size from relatively narrow ribbon forms (0.2-1.5 m thick and up to 5 m wide) to broadly lenticular, amalgamated

bodies up to 6 m thick and ~60 m wide. Cross-stratification is common, and measurement of trough-cross-stratification generally indicates a northeastward paleoflow diretion. Locally, there is trace amoutns of fine to medium pebbles composed of iron oxide-cemented, intraformational sandstone.

Similar to the Gibson Coal-bearing Member, The Menefee Formation represents fluvial deposition on a coastal plain and possibly a delta plain. However, Menefee fluvial deposition occurred over a longer time span than the Gibson Coal-bearing Member, accounting for its greater thickness. Consistent with Molenaar (2002), we infer a 83-81 Ma age for preserved deposits. Note that the top contact of the formation is not preserved.

Cenozoic basin-fill (Santa Fe Group)

Zia Formation

The Zia Formation comprises the base of the Santa Fe Group. The paleontology and sedimentologic features of this unit were studied by Gawne (1981) and Tedford and Barghoorn (1999). These workers have subdivided the formation into the following members, listed from oldest to youngest: Piedra Parada, Chamisa Mesa, and Cañada Pilares. Note that the unit is generally non-cemented and weakly to moderately consolidated, even though we use the terms "sandstone, mudstone, and claystone" in the descriptions. The contacts between the three members are conformable.

Piedra Parada Member (Tzpp)

The basal unit of the Santa Fe Group, the Piedra Parada Member, is perhaps the most distinctive because of its white to light gray to tan color (Fig. 9). It consists of sandstone in horizontal-planar, very thin beds or laminations. There is subordinate cross-lamination, where foresets are tangential and up to 40 cm thick. The sand is mostly medium- to coarse-grained and contains more volcanic (felsic-intermediate) lithic grains (15-30% of total) than overlying Santa Fe Group units. In the southwestern part of the quadrangle, there are local chert and lesser rhyolite pebbles (Fig. 9). The base of the Piedra Parada Member unconformably overlies the Menefee Formation. Ventifacted pebbles and cobbles of volcanic rocks commonly overlying the basal contact, which exhibits meter-scale paleo-topographic relief. The Piedra Parada is only 14-30 m thick on the footwall of the Sedillo fault, in the southwestern part of the quadrangle, but thickens to ~100 m on the hangingwall of the Moquino fault in the northeast part of the quadrangle.

Based on the local presence of gravel and the less ubiquitous cross-stratification (compared to the north of here), we interpret a notable component of fluvial facies in the Piedra Parada Member in the quadrangle area, in addition to eolian dunes. Paleonotologic work constrains its age to 21-18 Ma (Gawne, 1981; Tedford and Barghoorn, 1999). Gawne (1981) interprets relatively dry conditions during Piedra Parada time, followed by a progressive change to more humid conditions later in Zia time. However, the relatively coarser texture of the sand fraction in the Piedra Parada Member suggests higher competency streams than up-section in the Zia Formation. This coarseness, in addition to greenish mudstones indicative of pond deposits, indicate that the climatic conditions was not overly arid during Piedra Parada time.

Chamisa Mesa Member (Tzcm)

Compared to the underlying Piedra Parada Member, the Chamisa Mesa Member is slightly redder and finer-grained. It also exhibits more distinctive bedding: generally medium to thick, tabular beds that are internally laminated (horizontal-planar to cross-laminated) or massive (Fig. 10). Strata consist of very fine- to medium-grained sandstone and silty very fine- to fine-grained sandstone. There are sparse (up to 10%) reddish, medium to thick and tabular beds of mixed clay, silt, and very fine- to medium-grained sandstone. There is minor (<15%) very thin to thin beds of very fine- to very coarse-grained (vfL-vcU sand, where the coarser sand looks like the volcanic-rich, coarse sand found in the Piedra Parada Member.

Bioturbated features are relatively common and include massive beds, rhizoliths, and paleo-burrows (Fig. 10). Rhizoliths may occupy as much as 5% of the exposure and be 0.5-2.0 cm wide. Burrows are as much as 4 cm wide. 10-20% of the beds are well-cemented by calcium carbonate. The cement in some of these beds is well-laminated – suggesting possible deposition in a pond or shallow lake. The cement may also be porous to vuggy and display paleo-burrows and rhizoliths; these features are consistent with spring mound deposits.

This unit is 30-35 m in the northeastern quadrangle. In contrast to the Piedra Parada Member, it thickens to the southwest, where it is 40-80 m thick on the footwall of the Sedillo fault. The finer-grained deposition of the Chamisa Mesa Member, compared to the

Piedra Parada Member, and the abundant bioturbation features suggest a more vegetated, stable landscape than earlier in the Miocene. Given the spring mound deposits and relatively fine textures, we infer the Chamisa Mesa Member on this quadrangle was likely deposited in the transition zone between a relatively flat basin floor and gently sloping piedmont. Tedford and Barghoorn (1999) interpret an age range of 18-17 Ma for the Chamisa Mesa Member.

Cañada Pilares Member (Tzcp)

The poorly exposed, slope-forming Cañada Pilares Member is comprised of interbedded mudstone and fine-grained sandstone that are in very thin to medium beds (Fig. 11). The sandstone is very fine- to medium-grained and ranges in color from pink to light brown to light reddish brown. Within a bed, the sandstone is horizontal-planar laminated or cross-laminated (up to 20 cm-thick foresets). The mudstone is clay-rich and light reddish brown to light brown. This unit is clearly a fluvial deposit dominated by floodplain facies, and likely to have been deposited on a basin floor environment. It has an interpreted age of 17.5-16.0 Ma (Tedford and Barghoorn, 1999).

Cerro Conejo Formation

We follow Connell (2008) in considering the Cerro Conejo as a formation-rank term, rather than as a member of the Zia Formation (*sensu* Connell et al., 1999). Overlying a disconformity, this unit is generally a medium to thickly bedded, tan to pink to reddish, sandstone, with minor intervals that are relatively massive or dominated by cross-stratification. Locally, there is a slight angular discordance of bedding across the

disconformity. Within the Cerro Conejo Formation, we recognize four subunits in the quadrangle, which we informally call subunit 1 through subunit 4 (oldest to youngest). The contacts between the subunits are conformable.

In the west, the Cerro Conejo Formation adjoining the Sedillo fault (**Tccw1**) is a distinctly orange-colored, fine- to medium-grained sandstone, with minor gravelly sandstone and clayey sandstone beds. The gravelly sandstone beds are laterally extensive and thick. The gravel consists of pebbles composed of felsic-intermediate volcanic clasts up to 7 cm long. We infer that the western Cerro Conejo Fromation correlates to Subunit 4 in the northeast.

Subunit 1 (Tcc1)

The lowest subunit of the Cerro Conejo Formation is a ledge-forming, well-bedded, and reddish sandstone that is 45-50 m thick (Fig. 12). Strata are mostly in medium to thick, tabular beds. These exhibit internal horizontal planar laminations, cross-laminations (foresets are tangential and up to 20 cm thick), or are massive. Sand is mostly very fine- to medium-grained, but locally coarse-grained, and pink to light brown to reddish yellow. We observed 10-20% lamina containing fine- to very coarse-grained sandstone, where the coarser grains are similar to those seen in the Piedra Parada Member of the Zia Formation (Fig. 12). There are minor (~10%) light reddish brown to reddish yellow beds of clay, silt, and very fine- to fine-grained sandstone. The degree of cementation increases up-section in the unit, from 1-2% to 20-35%. The lower contact is sharp and locally exhibits a slight angular discordance near the northern quadrangle boundary (Fig. 11). It has been interpreted as a disconformity, where strata of 16-15 Ma age are missing (Tedford and

Barghoorn, 1999). Based on similarities to distal piedmont deposits in the Española Basin (e.g., Kuhle and Smith, 2001; Koning et al., 2007, and unit Ttcuf in Koning and Read, 2010), we interpret that this unit was deposited on a distal piedmont environment or in the transition between the distal piedmont and basin floor. Based on comparison to fig. 3 of Tedford and Barghoorn (1999), this subunit probably is 14.5-14.2 Ma.

Subunit 2 (Tcc2)

Subunit 2 is relatively fine-grained and pastel-colored unit (with colors ranging from light greenish to grayish green to pink). It is composed of very fine- to medium-grained sandstone, commonly in channel-fills that fine-upwards, together with 5-10% interbeds of clay, clay-silt, or clayey sandstone (Fig. 13). The sand occurs in a variety of bedding styles. Most common is horizontal-planar laminations or very thinly beds. Cross-laminations are locally present (with foresets up to 20 cm thick). The sand may also occur as cemented, discrete, fining-upward channel-fills, as thick as 2 m, that locally contain intra-formational conglomerate (with cemented sandstone pebbles). The color of the sand ranges from pink, pale brown, light gray, or white. Clay beds, which are up to 1 m thick, may exhibit reduced or oxidized colors. There are two laterally extensive, greenish clay beds that are likely lacustrine or playa facies (Fig. 13). The upper one has large stramatolites and driftwood fragmetns, and the lower one contains many remnants of the muskrat-like beaver *Eucastor* (Tedford and Barghoorn, 1999). The clay beds may also contain altered ash interbeds as well as pebble-size calcium carbonate nodules. Clayey sand beds are very thin to thin, tabular, and reddish brown to reddish yellow. This unit thickens eastward, from 2 to 30 m. The presence of lacustrine/playa facies, in addition to fining upward channel-fills, indicate

a fluvial environment on a basin floor. Based on comparison to fig. 3 of Tedford and Barghoorn (1999), this subunit probably is 14.2-13.9 Ma.

Subunit 3 (Tcc3)

Fine- to medium-grained sandstone in poorly defined, tabular, thin to very thick beds characterize subunit 3, which is 30-45 m thick. Within these beds, cross-stratification is sparse and the sand is mostly horizontal-planar laminated to very thinly bedded. There are trace amounts of very thin to thin beds with very coarse sand and fine pebbles composed mainly of rhyolite- dacite (with 10% chert and ~10% quartz). These coarse, thin beds are most abundant in the upper 6 m of the unit. Although tan in the upper half of the unit, the sand becomes slightly redder down-section and its lower ~6 m is a ledge-former with well-defined, thin to thick, tabular beds (Fig. 13). Interbeds of reddish mudstone to sandstone become more abundant to the south. Cementation features are common in this unit, occupying 1-15% of the outcrop area and occurring as nodules, flattened concretions, or thin to thick, tabular to lenticular layers. The depositional environment is likely still a basin floor. Based on comparison to fig. 3 of Tedford and Barghoorn (1999), this subunit probably is 13.9-13.5 Ma.

Subunit 4 (Tcc4)

Subunit 4 is the thickest subunit of the Cerro Conejo Formation (~120 m, but relatively poorly constrained). It consists of sandstone with subordinate (~10-20%) mudstone and clayey sandstone and very minor pebble conglomerate beds (Fig. 14). Common sand colors include reddish yellow, pink, or light brown; clayey beds are reddish brown to light brown.

Sand is mostly fine- to coarse-grained and occurs in thin to thick, tabular beds; these beds are internally horizontal-planar laminated to massive to low-angle cross-laminated. The lower part of the unit is a ledge-former in the northeast corner of the quadrangle, forming cliffs as tall as 60 m (200 ft) (Fig. 14). Weakly developed paleosols are locally developed in this unit, particular the middle part, and exhibit ped development and clay illuviation; locally a weak calcic horizon is found in the lower part of the paleosol (Fig. 14). A spring mound deposit was mapped in the middle part of the unit. Chert-dominated pebbles are present in the upper half of the unit, mixed with sand in beds that thicken up-section (from very thin-thin to thick). The upper half of the unit also locally contains intervals, up to several meters thick, displaying distinctive cross-stratification. We interpret that this unit spans the transition between distal piedmont and basin floor. Although its lower contact is relatively sharp and planar, its uppermost part intertongues with the overlying Navajo Draw Member of the Arroyo Ojito Formation. This intertonguing zone appears to be ~30 m thick and is mapped separately (unit **Tcc-Ton**). The base of subunit 4 is about 13.5 Ma, based on comparison to fig. 3 of Tedford and Barghoorn (1999). The interfingering top of the subunit is likely 11-10 Ma (Connell, 2008a), consistent with fig. 3 of Tedford and Barghoorn (1999).

Arroyo Ojito Formation

The Arroyo Ojito Formation of Connell et al. (1999) is present in the east-central and southeastern quadrangle. It is generally manifested as the Navajo Draw Member, but the Loma Barbon Member is found on the immediate hanging wall of the east-down Sand Hill fault. Both members were deposited by a large, southeast-flowing river (or coalescing large

streams) that drained the southeastern Colorado Plateau, San Juan Basin, Sierra Nacimiento, and southern Jemez Mountains (Connell, 2008a). The Loma Barbon differs from the Navajo Draw Member by its tanner color and higher proportions of granite, Pedernal chert, and Mesozoic sandstone. Granite and Pedernal chert were derived from erosion of the Sierra Nacimiento, and their up-section increase reflects unroofing of that mountain range (Connell et al., 1999). Fossils have not been found in the Arroyo OJito Formation near the map area. Based on Connell et al. (1999) and Connell (2008a), we assign and age range of 10-6 Ma.

Navajo Draw Member

The Navajo Draw Member consists of pale brown sand with minor mudstone and conglomeratic interbeds. It is at least 50 m thick and its original top is yet to be observed. Conglomeratic beds are 30-100 cm thick; clasts are composed of tan sandstone (intraformational or older Santa Fe Group sandstone) and chert; other clast types include: 0-50% intraformational calcium carbonate nodules, 1-7% quartzite, 5-7% quartz, 1-5% light gray dacite or andesite, and 1% petrified wood; Pedernal chert increases upsection, from 0% to 15%; granite also increases up-section, from 0-3%. Sand is mostly fine- to medium-grained and in medium to thick, tabular beds that are internally laminated. Mudstone is light brown, clay-rich, and in interbeds that are laminated to thin and tabular.

Loma Barbon Member

The Loma Barbon Member is not well-exposed on the quadrangle, but decently exposed immediately east of the northern part of the eastern boundary, where it is at least 60 m

thick. There, it is a tan sandstone interbedded with minor pebble-conglomerate beds and 1-5% mudstone beds (Fig. 15). Estimated gravel composition in the conglomerates is: Estimated clast composition: 30-50% tan and fine-grained Mesozoic sandstone, 15-30% dark gray to black to brown chert, 10-40% Pedernal chert, 10% red granite, 1-5% quartzite, 1% gray intermediate volcanic rocks, trace lithic-rich sandstone, and 0.5% mudstone rip-up clasts. Sand is mostly fine- to coarse-grained and cross-laminated (up to 50 cm-thick foresets) or horizontal-planar laminated.

Ceja Formation

The Ceja Formation recently received much attention from Sean Connell (formerly of the New Mexico Bureau of Geology and Mineral Resources). East of the east-central part of the quadrangle, a prominent paleosol is present immediately beneath the Ceja Formation (i.e., developed on top of the Loma Barbon Member of the Arrroyo Ojito Formation). To the south, displacement along the Sand Hill fault has down-dropped the paleosol into the subsurface. The paleosol was not observed on the quadrangle to the south (Cikoski and Koning, 2013) and the Ceja-Arroyo Ojito contact may possibly be conformable there.

Connell (2008) divided the Ceja Formation into two members along the Ceja del Rio Puerco, both of which are present on the quadrangle: the lower Atrisco Member and the overlying Rio Puerco Member. Interesting stratigraphic relations of the Ceja Formation are presented in Connell et al. (2013). The lower contact of the Ceja Fromation overlies a paleosol immediately east of the central part of the eastern quadrangle boundary. Both members were laid down by the same system of southeast-flowing river(s) and associated

fluvial fans as the lower Arroyo Ojito Formation. However, the Ceja Formation exhibits a greater variety of rock types than the Arroyo Ojito Formation and represents deeper unroofing of the western flanks of the Albuquerque Basin (Connell et al., 2013).

Atrisco Member

The 49-50 m-thick Atrisco Member consists of well-bedded, generally non-cemented, sand and minor clayey mudstone (Fig. 15). Sand beds are typically thin to medium and tabular. Mudstones are horizontal-planar laminated or in very thin to thin, tabular beds. Sand is very fine- to medium-grained and pink to reddish yellow to light brown. Mudstone is light reddish brown to reddish brown to yellowish red. The reddish hue, well-bedded nature, and fine-grained nature of this unit serve to differentiate it from the Loma Barbon Member of the Arroyo Ojito Formation. This member is 3.2-2.6 Ma (Connell, 2008a; Connell et al., 2013).

Rio Puerco Member

The Rio Puerco Member is much coarser than the Atrisco Member, being comprised largely of tannish, amalgamated channel-fills of sand and pebbly to cobbly sand. Gravel are composed of chert (including Pedernal chert) with 20-30% quartzite, ~10% gray, intermediate to mafic volcanic clasts, ~10% sandstone clasts, and 3-10% granite. The member contains scattered cobbles and boulders up to 1 m in maximum diameter. Its sand is mostly medium- to very coarse-grained. To the south, Cikoski and Koning (2013) interpret a gradational to interfingering contact with the underlying Atrisco Member. East of the northern Benavidez Ranch quadrangle, however, Connell et al. (2013) interpret that

this contact is a disconformity (based on magnetostratigraphic work of their CDRP-CL stratigraphic section). The Rio Puerco Member disconformably gradationally overlies the underlying Atrisco Member and is 2.6 to ~1.5 Ma (Connell et al., 2013).

Cenozoic volcanic rocks (Benavidez maar)

The only volcanic rocks on the Benavidez Ranch quadrangle relate to the Benavidez maar (Fig. 16). This was studied by Kelley and Kudo (1978), who called it a diatreme. However, we interpret this interesting feature as a maar because of: 1) a composition that includes both basaltic ash-lapilli and Santa Fe Group detritus; 2) the ubiquitous thin, relatively planar to contorted bedding that appear to dip inwards (especially in the upper part of the deposit, which is generally composed of Santa Fe Group detritus); and 3) and because of the presence of bombs (Fig. 16). Thus, this feature seems to have been subaerially exposed.

Because of property access issues, we were only able to field chech the north end of the maar. There, the pebble-bearing subunit 4 of the Santa Fe Group dips steeply southward towards the center of the maar, practically parallel to the lowest tuff-lapilli beds that overlie it. Moreover, the type of sediment in the maar itself correlates better to the Cerro Conejo and Zia Formations than the Arroyo Ojito and Ceja Formations. Thus, we interpret that the maar formed during the middle to latter part of subunit 4 deposition that was characterized by local pebble beds. According to the lithostratigraphic-magnetostratigraphic data of Tedford and Barghoorn (1999, fig. 3), Cerro Conejo strata with pebbly beds are 11.5-10.5 Ma. We thus assign a similar age to the Benavidez maar. Note that this age is comparable with the nearest know basalt flow, the basalt of Chamisa

Mesa (Pazzaglia et al., 1998), which was dated by K=Ar at 10.4 ± 0.5 Ma (Leudke and Smith, 1978).

The maar deposits can be divided into an upper and lower unit (Fig. 16). The lower unit is gray to greenish gray, well-bedded to massive, basaltic + quartz-feldspathic sand interbedded with very fine to very coarse basaltic lapilli. Where it is well-bedded at its base and its upper 6 m, the sediment is laminated to very thin, tabular, and parallel-bedded. Dips in this lower unit decrease up-section.

The upper unit of the maar is lighter-colored (pale brown) and contains comparably little basaltic debris (Fig. 16). Strata are distinctly parallel-bedded and consist of very thin to medium beds and laminations, ranging from cross-stratified to tabular to contorted. Sandstone is mostly very fine- to medium-grained and composed of quartz-feldspathic sand similar to the Cerro Conejo Formation. However, there are local intervals, up to 3 m thick, that consist of greenish gray, coarse, basaltic sediment. Some (~1%) of the beds contain coarse to very coarse sand with very fine to fine pebbles composed of chert and quartz. A noteworthy feature of the upper unit are local bombs composed of very fine- to fine-grained sandstone, up to 80 cm long, that have caused sagging of the underlying sediment. Dips decrease up-section in the upper unit, similar to the trend seen in the lower unit.

Pleistocene terraces

Five terrace levels were correlated along the Rio Puerco and are Pleistocene in age. Detailed age control is lacking. These were mapped as terrace deposits and labeled **Qtrp1** through **Qtrp5**, with **Qtrp1** being the youngest and lowest level. The deposits are generally sand and gravel laid down by the Rio Puerco. However, the lower part of **Qtrp3** consists of locally derived sand and minor clay-silt. Pleistocene terrace gravel contain abundant andesite-basaltic andesite and Mesozoic sandstone. Other lithologic types are less abundant and include chert, red granite, vesicular basalt, and quartzite. Sand is mostly pale brown to light yellowish brown and fine- to very coarse-grained.

The terrace deposits vary in thickness and display interesting buttress relations. The older terrace deposits (**Qtrp5** and **Qtrp4**) are thin (1-2 m). The two middle ones (**Qtrp3** and **Qtrp2**) are thicker (10-18 m) and definitely fill terraces. **Qtrp1** is also generally a fill terrace, with a minimum thickness of 6 m. The fill of unit **Qtrp2** is inset into the fill of unit **Qtrp3**, and the fill of **Qtrp1** is inset into the fill of **Qtrp2**. Both **Qtrp1** and **Qtrp2** transition to northward to strath terraces that are only a few meters thick.

STRUCTURE

Stratal tilts

One can divide the map area into two structural domains separated by the major northeast-striking fault system that traverses the entire length of the quadrangle (the Sedillo-Moquino faults, which are discussed below). The western structural domain is underlain by Cretaceous strata that strike northeast and dip 5-20° SE. The steepest dips occur close to the northeast fault system, as discussed below. In the northwestern corner of the

quadrangle, strata have a south-southeasterly dip of 4-5°. The eastern structural domain is characterized by northwest- to northeast strikes and dips of 3 to 10° NE-SE. Dips decrease up-section and to the east. Near the eastern quadrangle border at about its midpoint, strikes appear to bend to the west-northwest, based on the map pattern of stratigraphic units and the few attitudes taken there; dips are 2-4°S. Beyond 2 km west of the midpoint, however,, strikes appear to resume the typical northeast trend, based on the orientation of unit **Tcc4c**.

Faults

A prominent, large-displacement, east-down fault system extends northeast across the length of the quadrangle. The southern fault of this system is called the Sedillo fault to the south (after Campbell, 1967, and Hawley, 1982). The northern fault is called the Moquino fault (after Gawne, 1981, and Tedford and Barghoorn, 1999). The two faults project towards one another under Holocene alluvium in the Rio Puerco Valley, but it is not known if they are actually hard-linked. The fault zone of the Sedillo fault is not exposed in the map area. The Moquino fault dips 58° to near-vertical (Fig. 17). Inspection of cross-section A-A' indicates that the Moquino fault has 660 m (2160 ft) of east-down throw and 810 m (2660 ft) of dip-slip (using offset Cretaceous strata and assuming the thickness of the Menefee on the hanging wall is the same as on the footwall). Slickenstria lineations measured on the Moquino fault (UTM coord: 323463 m E, 3900545 m N, NAD83) indicate a slight degree of left-lateral slip (106° slickenstria plunge vs. 122° dip direction).

Several northeast-striking fault are found on the footwall of the Moquino fault in the northwestern quadrangle, in a zone that spans as much as 3.3 km west of the fault. These faults coincide with relatively high stratal tilts (10-25°E), and together they mark a wide zone of deformation. These footwall faults are generally down-to-the-east in the west-central part of the quadrangle; these exhibit dips ranging from 48° W to 83° W (mostly 48° to 59°W). The relatively shallow dips probably are a result of westward tilting of the fault plane after fault formation, considering that the strata in the area generally dip 10-20°W. The structural zone here can be considered an antithetically faulted, east-down monocline.

In the north-central part of the quadrangle, northeast of the Rio Puerco, the faults on the Moquino fault footwall include both east- and west-down faults. Again, strata dip steeply east in the faulted zone, reflecting a larger structure characterized by a faulted, east-down monocline (illustrated by cross-section A-A'). Here, measurement of five west-down faults found bimodal dips of 45-59°W (n=2) and 74-76° W (n-3). Interestingly, restoring the dips of the 74-76° W faults (relatively to dipping strata) result in them being near-vertical. Measurements of three east-down faults found dips ranging from 49 to 61°E. Rotating these faults to account for stratal tilt would result in relatively shallow dips, perhaps these fault formed after most of the stratal tilting occurred? Interestingly, there were no faults observed on the footwall of the Sedillo fault to the south.

There are relatively few faults displacing the Santa Fe Group. Within 0.9 km east of the Moquino fault, near the northern quadrangle border, are several west-down faults. The largest of these is a west-down structure 0.9 km east of the Moquino fault. Cross-section A-

A' indicates a throw of 20 m on this structure. The Pilares fault of Gawne (1981), having 130 m of west-down throw (according to cross-section A-A'), strikes slightly east of north at a distance of ~4 km east of the Moquino fault. An anticline is found on its immediate footwall near the northern quadrangle boundary. East of this anticline, at a location 0.4 km south of the northern quadrangle boundary, the fault plane is well exposed and dips 56-68° W. Measurement of slickenstria indicate normal to slightly right-oblique slip. The southern extent of this fault is poorly constrained, but it likely extends south for 6 km.

Near the eastern quadrangle border lies the east-down Sand Hill fault, which extends slightly east of north for 9 km. Exposed fault planes on this fault zone (UTM coord: 329080 m E, 3897225 m N, NAD 83) show dips of 54-72°E, consistent with normal faulting. This east-down fault has displaced strata around the Navajo Draw-Cerro Conejo contact into the subsurface. Considering the thickness of both the Navajo Draw Member (50 m) and the intertonguing Navajo Draw-Cerro Conejo interval (30 m), the throw on the Sand Hill fault is likely >100 m in the central part of the eastern quadrangle boundary.

All faults mentioned above can be considered normal faults, locally exhibiting slight oblique lateral slip. There is one small, oblique-slip fault with an apparent reverse sense of throw (UTM coord: 321090 m E, 3897990 m N; NAD 83). This fault strikes 345° and dips 48°E. Slickenstria trend 016° and plunge 25°NE. Considering that Cretaceous strata are apparently up-thrown on the east side of the fault, and that these strata strike north and dip east (e.g., 007°\18°E), this fault can be considered a dextral strike-slip fault with a component of reverse throw (with a dip separation of 1.5 m). The kinematics along this

particular fault are consistent with a slightly north of northeast vergence direction in the Laramide and right-lateral wrenching along the Rio Puerco fault zone, as interpreted by Campbell and Slack (1976).

Folds

There are relatively few folds on the quadrangle. One prominent anticline found on the immediate hanging wall of the Pilares fault, exposed 0.4-0.6 km south of the northern quadrangle border, likely is due to a bending (convex to the west) of the fault plane at depth.

A south-plunging anticline is found immediately west of the Rio Puerco in the northwest quadrangle. It is manifested by the Gallup Sandstone bending from an east strike to a northeast strike (from west to east). This fold probably reflects interaction of a slight southerly, regional dip with the east-down monocline associated with the northern Moquino fault.

GEOLOGIC HISTORY

The geologic history can be subdivided into five phases: 1) Sedimentation along the Western Interior Seaway during the Late Cretaceus; 2) Laramide wrench faulting; 3) Rio Grande rift-related extension and Santa Fe Group deposition in the late Oligocene through early Pleistocene; and 4) middle-late Pleistocene incision.

The Upper Cretaceous section is remarkably thick at 1.4 km. The strata preserved on the Benavidez Ranch quadrangle were deposited during three cyclical transgressive-regressive cycles of the Western Interior Seaway between 90 and 83 Ma. The lowest exposed deposits of the Mancos Shale occurred when an ocean covered the quadrangle at 89 Ma. By 88.7 Ma, a sea level regression allowed the barrier island sands of the Gallup Sandstone and lagoonal sediment of the Dilco Member to be deposited. This was followed by a brief transgression ca. 88-87 Ma, when the Mullato Tongue of the Mancos Shale extended across the map area. The following regression between 87 and 86 Ma witnessed deposition of the Dalton Sandstone and the Gibson Coal-bearing Member; the former was likely laid down at a delta front and the latter is associated with a coastal or deltaic plain. The last marine transgression on the quadrangle (of which we have evidence) occurred between 86 and 85 Ma, when deltaic sediment of the Hosta Tongue of the Point Lookout Sandstone was deposited over the Gibson Coal-bearing Member, followed my marine deposition of the Satan Tongue of the Mancos Shale. The overlying upper tongue of the Point Lookout Sandstone exhibits an illustrative regressive sequence of the following succeeding facies: barrier island, lagoon, deltaic, and fluvial. The uppermost and thickest Cretaceous unit, the Menefee Formation, was fluvially deposited on the coastal plain (possibly partly on a deltaic plain) between 83 and 81 Ma.

We have scant evidence of a Laramide tectonism on the quadrangle. In general, faulting and folds can be more simply explained by Rio Grande rift extension. However, there is one northwest-trending, oblique slip fault (dextral, with a component of reverse throw) that exhibits slickenside lineations. The lineation orientation and sense of stratigraphic offset

supports the idea of Slack and Campbell (1976) of right-lateral wrench faulting along the Rio Puerco valley during the Laramide.

Tectonism associated with Rio Grande rifting was probably underway before deposition of the Zia Sandstone, accounting for the steeper eastward dips of the adjoining Cretaceous strata and the lack of preservation of pre Zia deposits (e.g., unit of Isleta well # 2). The Sedillo-Moquino faults appear to have been active during deposition of the Piedra Parada Member, based on the thickness discrepancy of this unit across the fault system. That the overlying Chamisa Mesa Member actually thickens across this fault system suggest it was not notably active between 18 and 17 Ma. The inferred presence of piedmont deposits by Cerro Conejo time (represented by subunits 1 and the lower part of subunit 4), in addition to the disconformity between the Cerro Conejo and Zia Formations (Tedford and Barghoorn, 1999), indicate tectonic extension and faulting between 16 and 14.5 Ma. This tectonism probably enhanced topographic relief west of the quadrangle boundary, allowing distinctive piedmont deposits of the Cerro Conejo Formation to develop. By ~12 Ma (upper part of subunit 4 of the Cerro Conejo Formation), fluvial sedimentation associated with a relatively powerful southeast stream/river system deposited the Arroyo Ojito Formation followed by the Ceja Formation. The up-section changes in clast lithologic types in the two formations indicate a progressive unroofing of the Sierra Naciemento Mountains to the north (Connell et al., 1999).

Santa Fe aggradation ceased ca. 1.5 Ma, and was followed by significant incision in the middle to late Pleistocene. Glacial-interglacial shifts in this overall erosive regime

occasionally resulted in thick filling of the valley floor. These thick fills were later largely excavated during times of higher stream power along the Rio Puerco (probably during glacial times). Remnants of these fills, in addition to relatively thin gravels associated with carving of the valley floor, are manifested by the prominent terrace deposits west of the Rio Puerco.

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FIGURE CAPTIONS

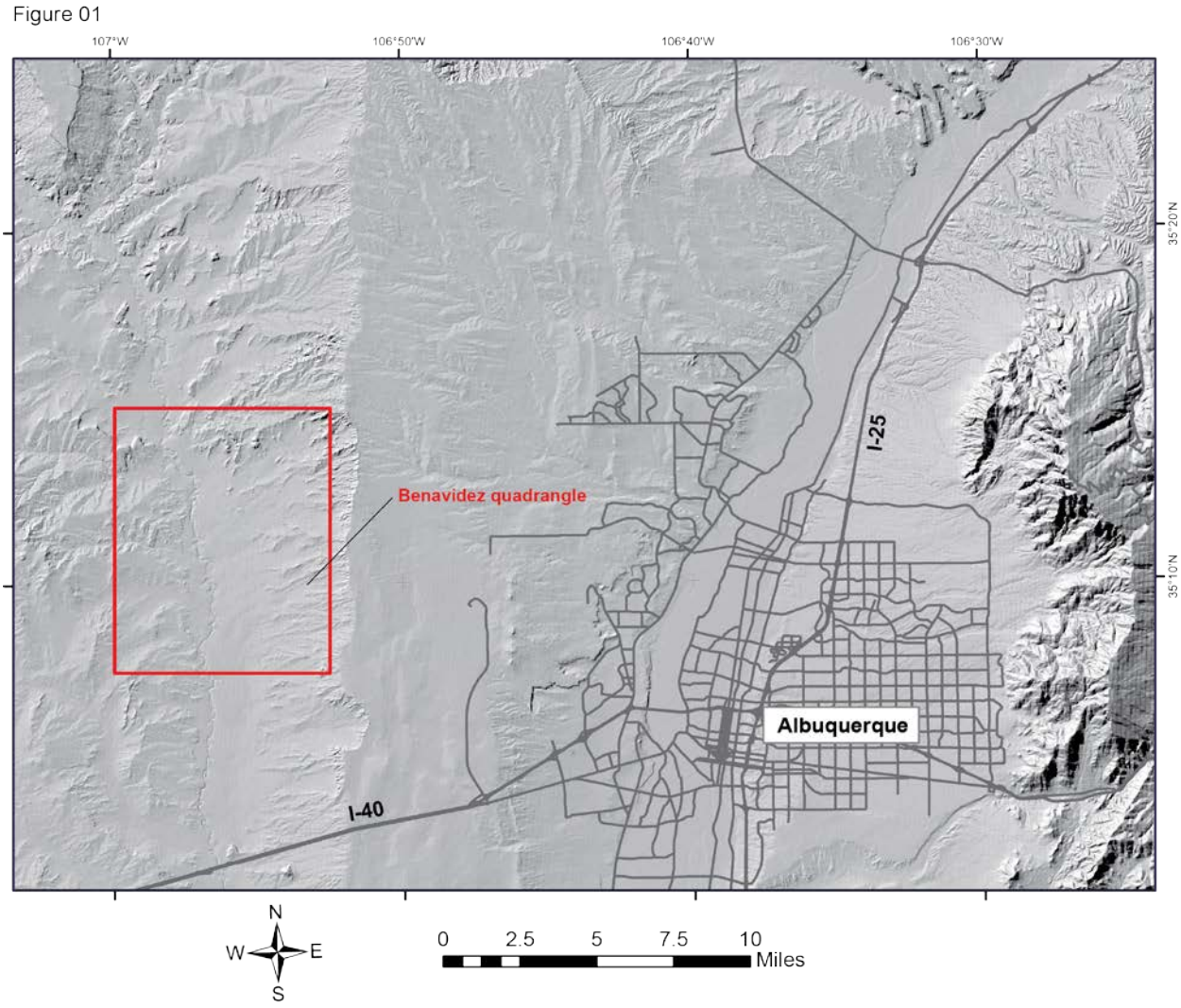

Figure 1. Geographic setting of the Benavidez Ranch quadrangle. The boundaries of the quadrangle are shown in red.

Figure 02

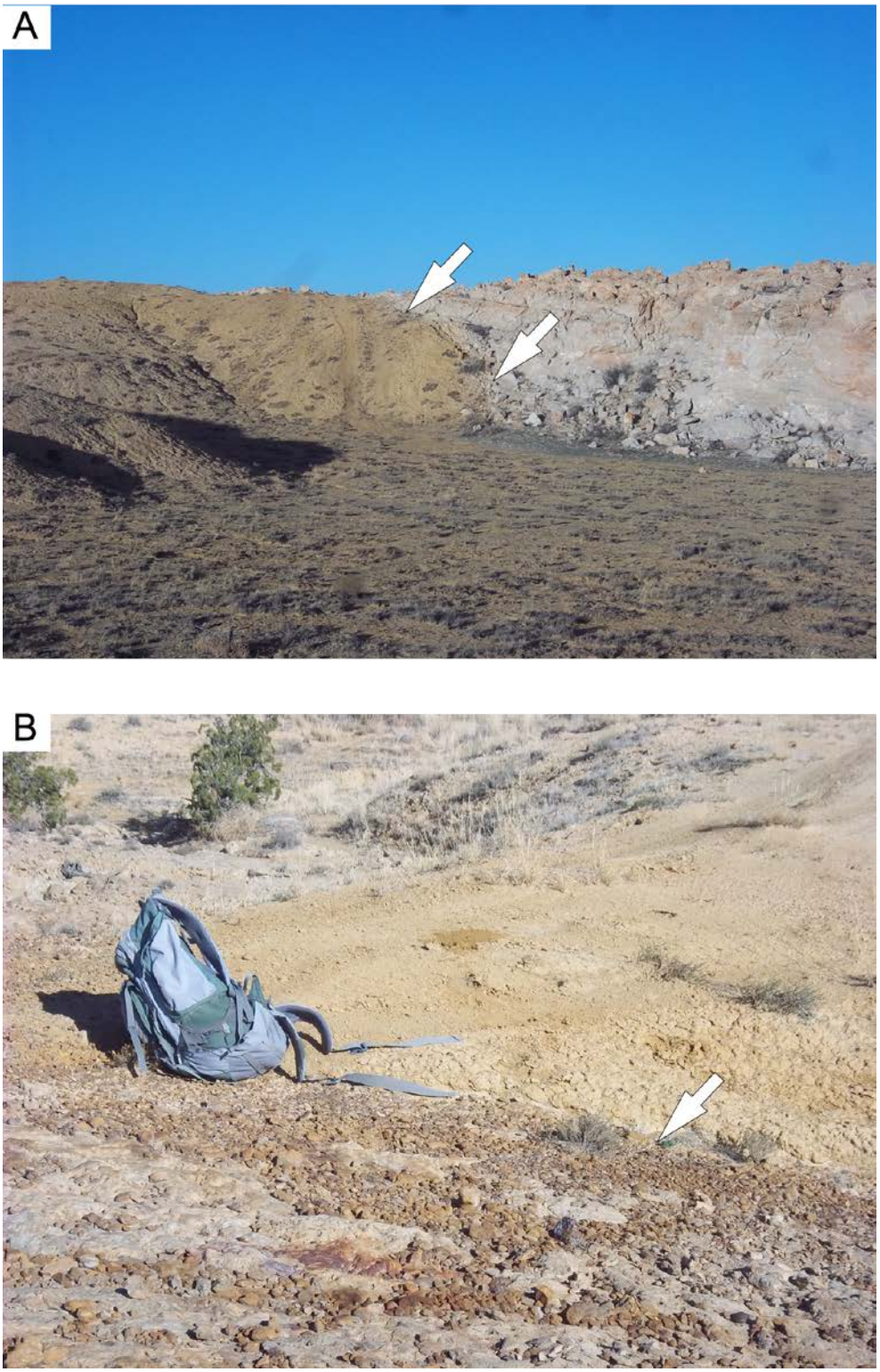

Figure 2. Photographs illustrating the Mullato Tongue of the Mancos Shale and the underlying Gallup Sandstone. A) In this north-facing photo, an east-down fault, marked by

the arrows, separates the Mullato Tongue (left) from the upper Gallup Sandstone (right). B) The arrow shows the depositional contact between the Gallup Sandstone (left) and the Mullato Tongue of the Mancos Formation (right). Photograph taken in the northeastern quadrangle. The top of the Gallup Sandstone is typically strongly bioturbated and burrowed, as can be seen here. In the western quadrangle, the Mullato Tongue and the Gallup Sandstone are separated by the dark-colored Dilco Member of the Crevasse Canyon Formation. However, the Dilco Member thins to the northeast; here, it is about 1 m thick and consists of yellowish lagoonal sediment. Without digging into it, the Dilco looks very similar to the Mullato Tongue of the Mancos Shale.

Figure 03

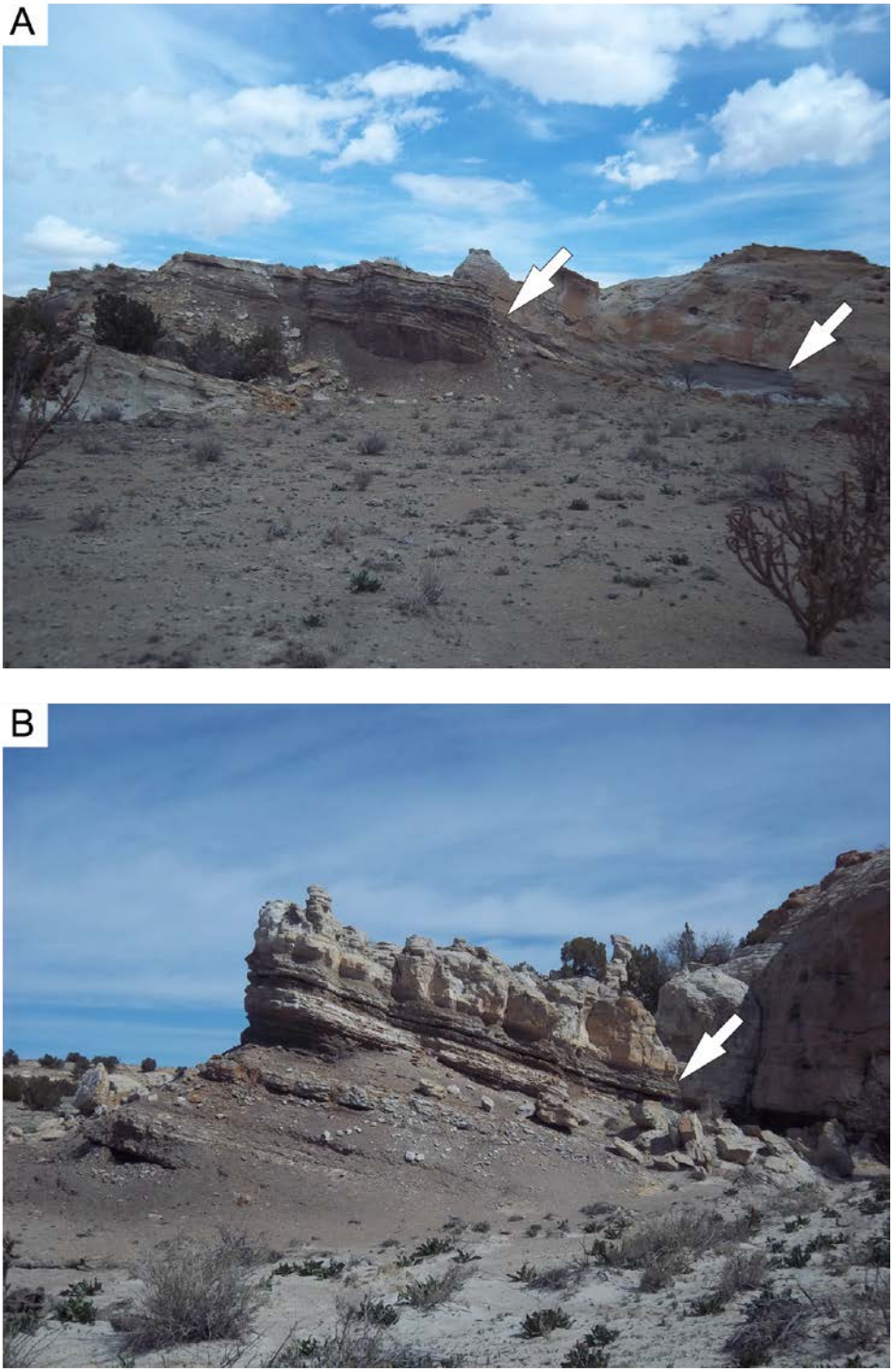

Figure 3. Views of the upper, dark-colored, generally fluvial Gibson Coal-bearing Member of the Crevasse Canyon Formation. It is sharply overlain by interpreted deltaic sediment of the Hosta Tongue of the Point Lookout Formation in both of these photographs (arrows

note the contact). However, near the western quadrangle border, the upper 10-14 m of the Gibson Coal-bearing Member is transitional with the overlying Hosta Tongue of the Point Lookout Sandstone. In this transitional interval, the sandstone locally contains 10-15% oyster shells and flaser bedding is locally seen. These features are consistent with a lagoonal or coastal swamp depositional environment, and suggest a seaward shift in depositional environments at the end of Gibson Member deposition.

Figure 04

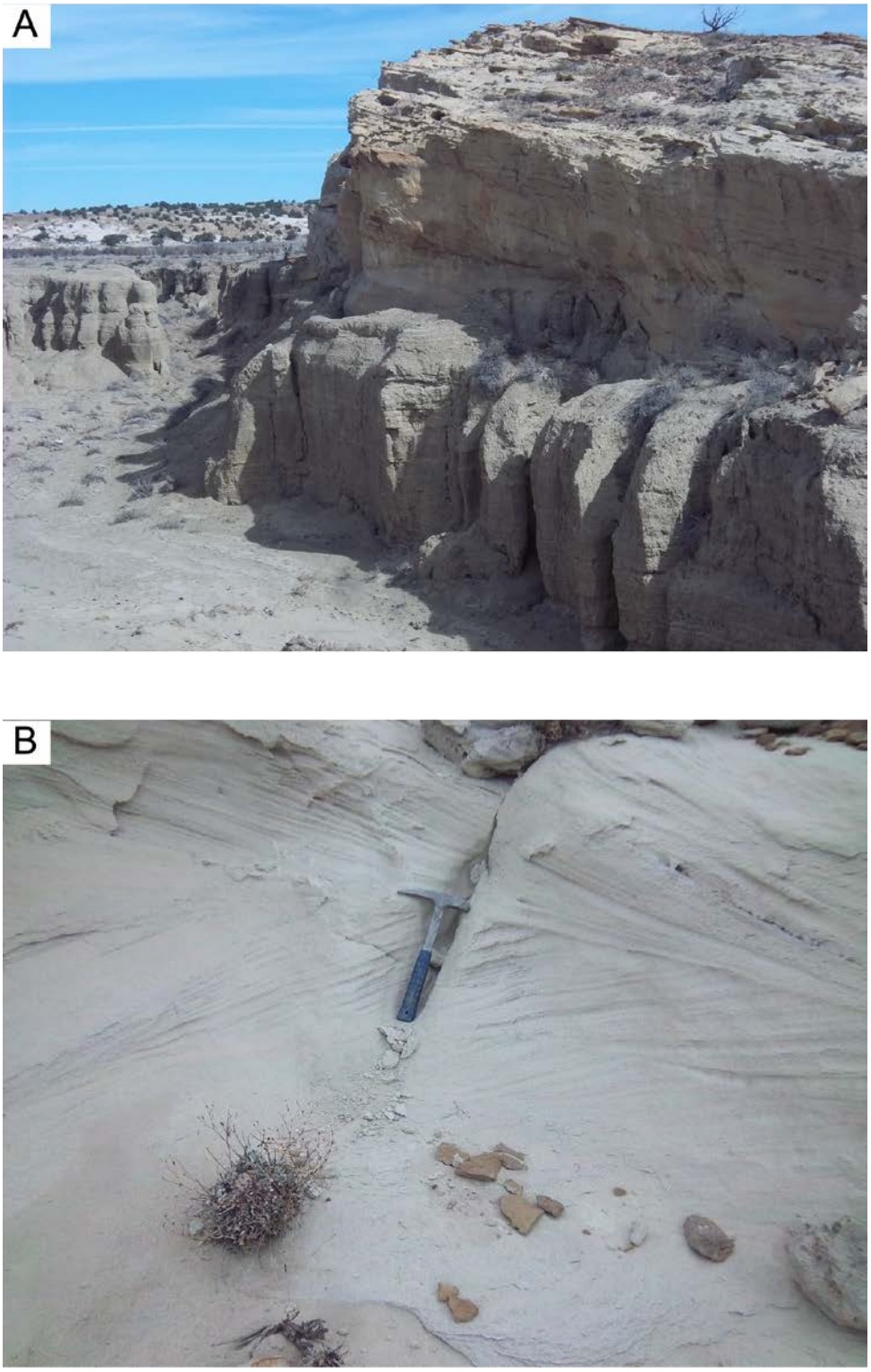

Figure 4. Photographs of the Hosta Tongue of the Point Lookout Formation. A) 6-10 m of middle-upper Holocene sediment (foreground) lies in a buttress relation against the Hosta

Tongue. B) The Hosta Tongue is prominently cross-stratified. We interpret that it was deposited in a relatively major deltaic channel.

Figure 05

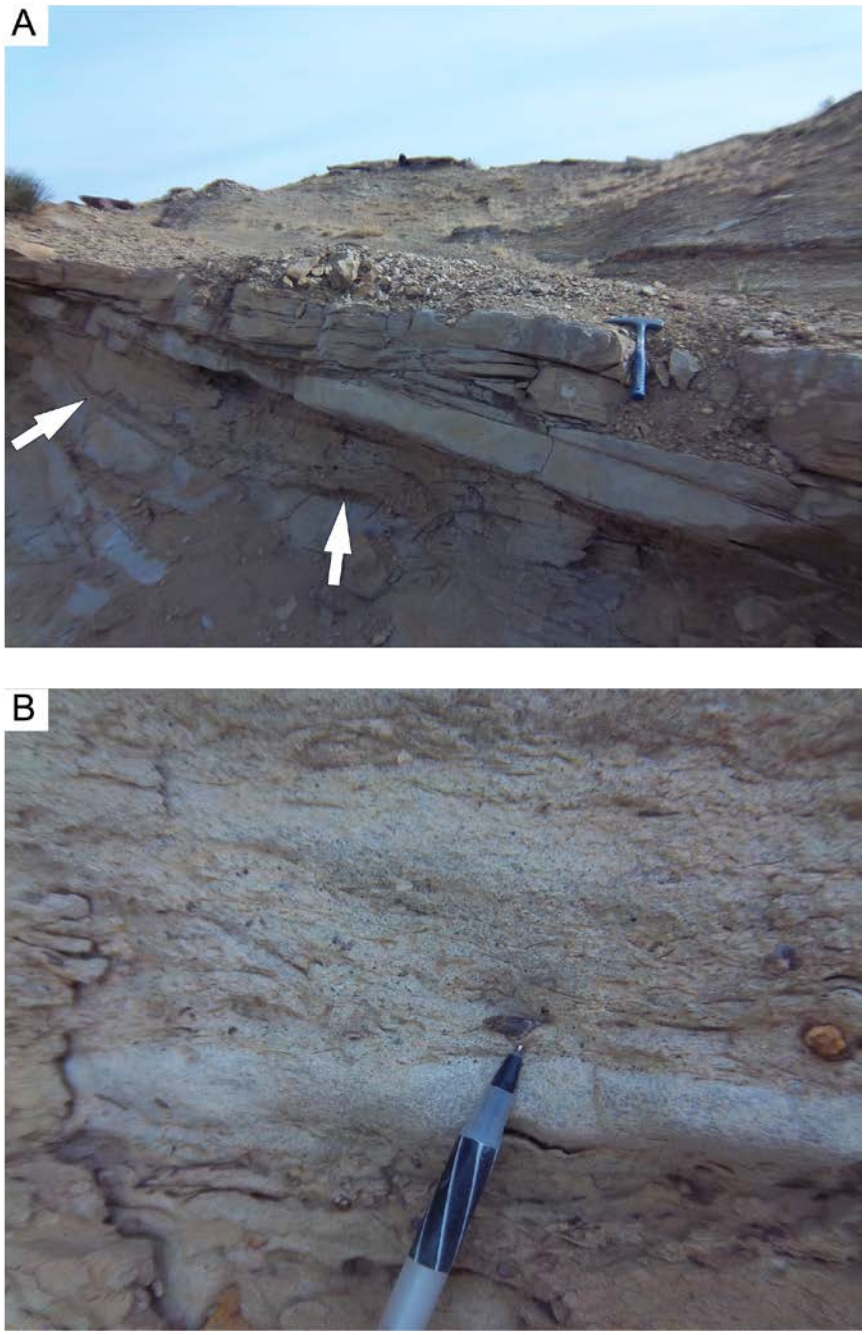

Figure 5. A transgresssional lag deposit is commonly preserved at the top of the Hosta Tongue of the Point Lookout Formation, especially in the northeastern quadrangle. A) This

cross-stratified transgressional deposit extends from the hammer to the white arrow and features tangential foresets. Fissile, marine shale of the Satan Tongue (Mancos Formation) overlies the transgressional deposit. B) The transgressional lag deposit is generally fossiliferous. The pen points to a tooth. A paper by Bourdon et al. (2011) discuss the fossil assemblage in an upper Hosta Tongue bed 4.4 km west of the central western boundary of the quadrangle; we suspect that their fossiliferous bed correlates to the transgressional lag deposit pictured here.

Figure 06

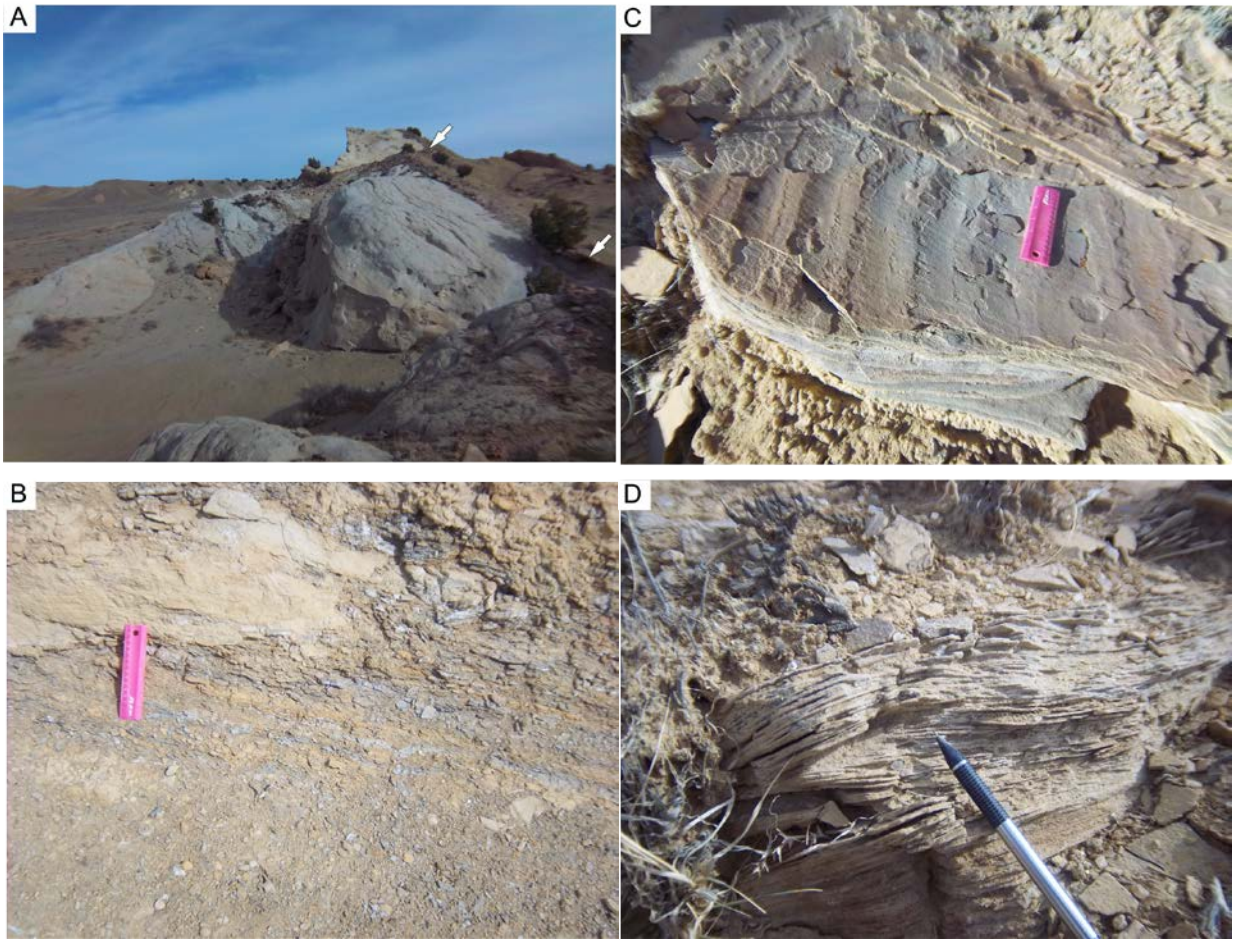

Figure 06

Figure 6. Depictions of the Satan Tongue of the Mancos Shale. A) Contact between the white, ledge-forming Hosta Tongue of the Point Lookout Formation and the grayish brown, slope forming Satan Tongue is demarcated by the arrows. The transgressional lag deposit discussed in Figure 6 forms a brown, medium to thick bed immediately under the basal shale of the Satan Tongue. B) Very thinly bedded fissile shale and fine sandstone. C, D) In the middle part of the Satan Tongue, ripple-marked sandstone hummocky cross-laminations indicate offshore deposition, below the fair weather wave base. and . E) To the west, the middle to upper parts of the Satan Tongue were deposited in shallower. Here, a coal bed is present in the upper Satan Tongue, as pointed out by the smaller white arrows. Note the mottling in the sandstone below (black arrows). The depositional environments

here include a lagoon and coastal swamp. The larger white arrows mark the top of the Satan Tongue.

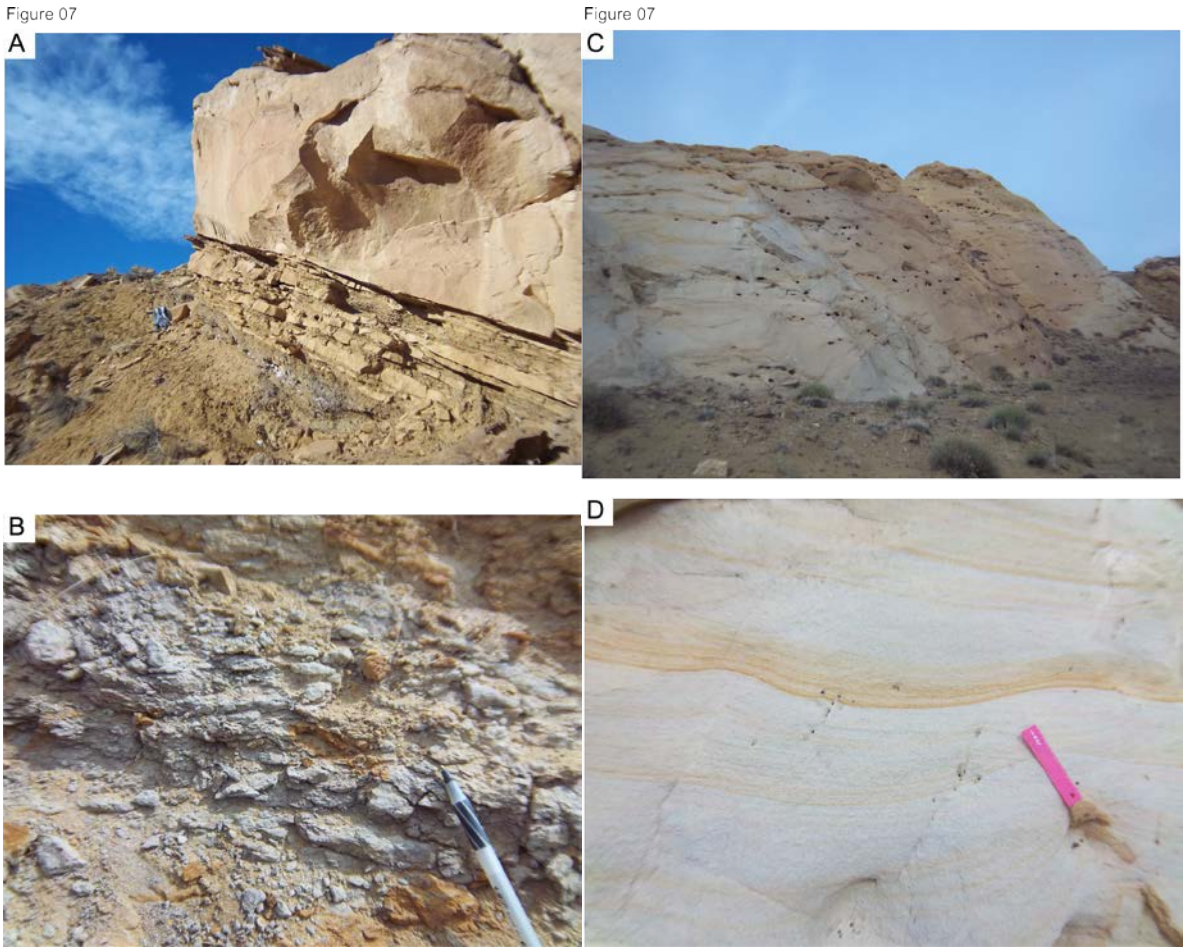

Figure 7. Photographs of the upper part of the Point Lookout Formation. A) Gradual base between nearshore sandstones (basal upper Point Lookout Formation) and underlying Satan Tongue of the Mancos Shale. B) Above the nearshore sandstones (5-10 m thick) lies 2-6 m of mottled lagoonal sediment. C, D) Above the lagoonal sediment lies ~50 m of cross-stratified sandstones, progressing up-section from deltaic to non-deltaic fluvial. Ruler is 15 cm long.

Figure 08

Figure 08

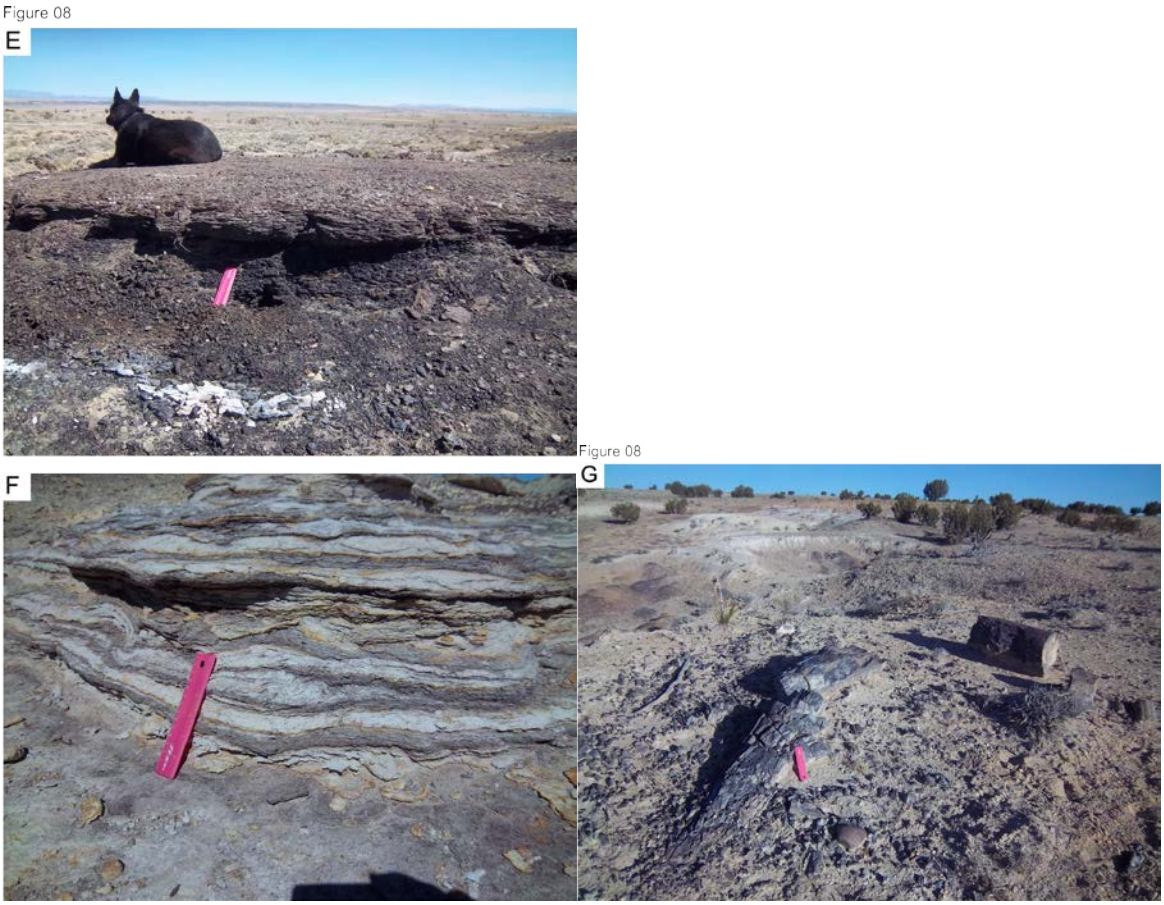

Figure 8. The uppermost Cretaceous formation on the quadrangle is the terrestrial Menefee Formation, which is ~550 m thick. A, B) Typical badland topography developed on the Menefee Formation. On the skyline in A is the Ceja del Rio Puerco, which developed in the Santa Fe Group. In B, note the greenish gray colors on the left, which are not seen in the stratigraphically lower Gibson Coal-bearing Member of the Crevasse Canyon Formation. C,D) Relatively thick sandstone channel-fills. Channel-fills vary in size from relatively narrow ribbon forms to broadly lenticular, amalgamated bodies up to 6 m thick and ~60 m wide. E) Coal bed in floodplain deposits. F) Thinly bedded sandstones, inferred to be crevasse splays, and brown claystone. Ruler is 15 cm long. G) Petrified logs are relatively common in the Menefee Formation. Ruler is 15 cm long.

Figure 09

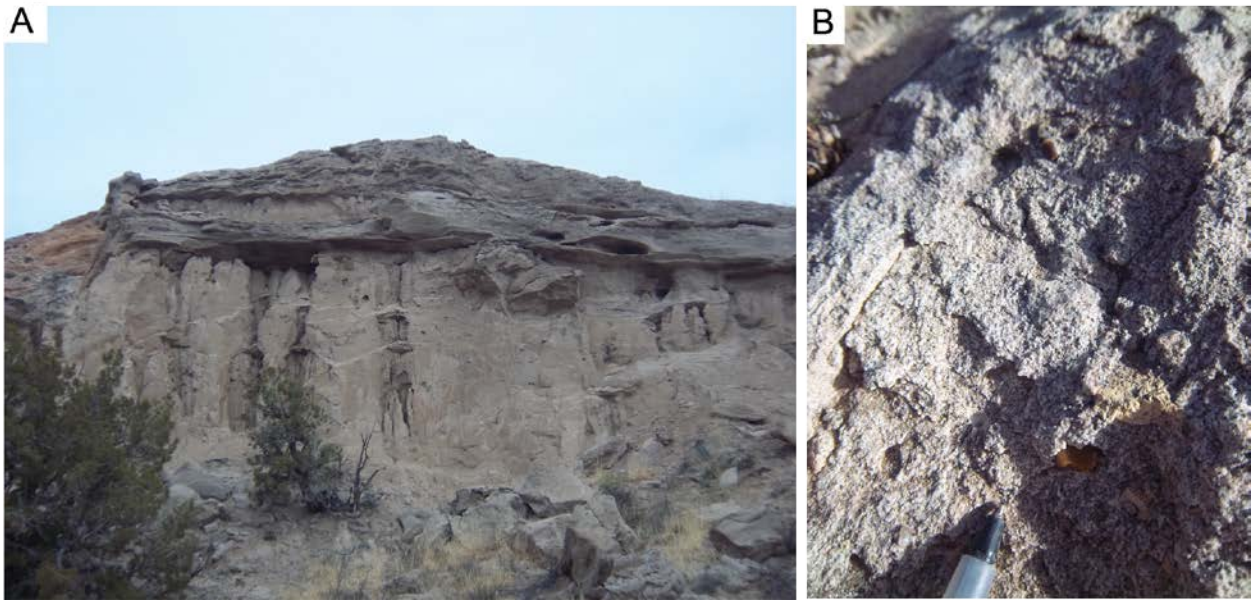

Figure 9. The Piedra Parada Member of the Zia Formation, the lowest Santa Fe Group unit on the quadrangle. A) Typical exposure showing both horizontal-planar bedding (cemented top) overlying cross-stratified sandstone (left). B) In the southwest quadrangle, pebbles of chert and rhyolite are found in the sandstone, indicating fluvial deposition. This photograph shows a brown chert pebble. Head of a ballpoint pen for scale.

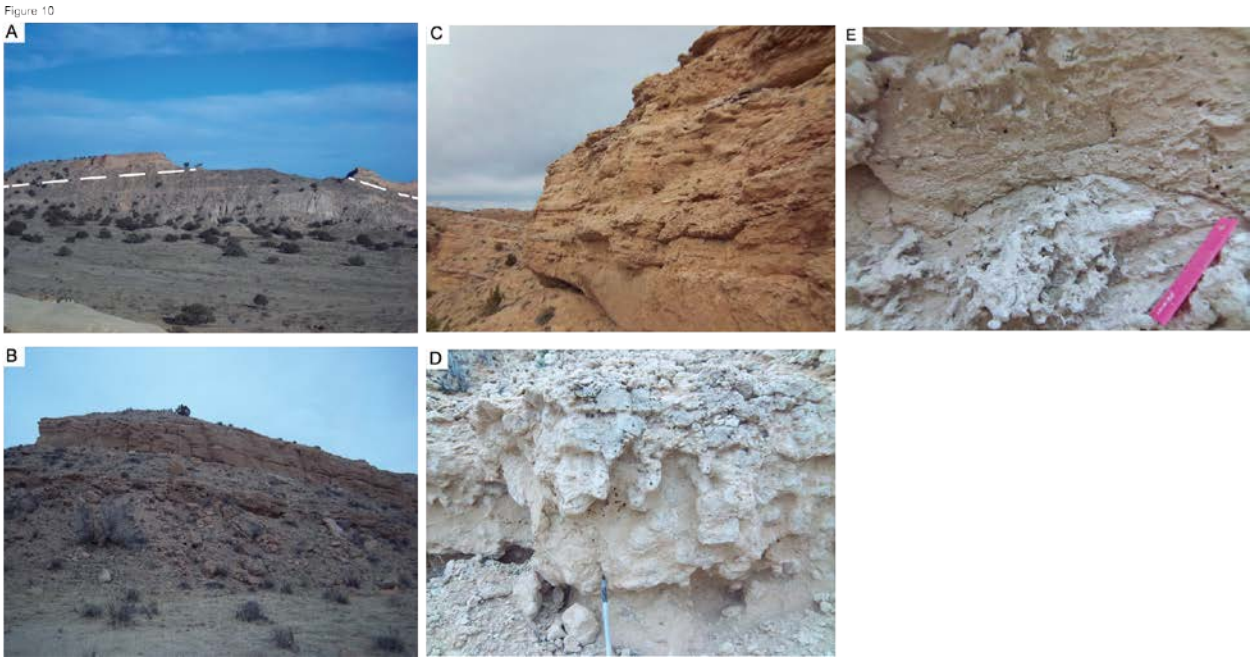

Figure 10. Outcrops of the Chamisa Mesa Member of the Zia Formation. A) The gradual, basal contact of the Chamisa Mesa Member is shown by the dashed white line. B) Cemented, tabular-bedded outcrops near the northern quadrangle border. C) Orangish, thin to thick, tabular sandstone with much evidence of bioturbation. D) Paleoburrows in cemented sandstone; pen for scale. E) Rhizoliths in biturbated sandstone. 15 cm-long ruler for scale.

Figure 11

Figure 11. Basal strata of the Cerro Conejo Formation (Tcc1) overlying floodplain facies of the Canada Pilares Member of the Zia Formation. Arrows demarcate the contact, which locally is a slight angular unconformity in this area. Magneto stratigraphic studies, coupled with paleontologic data and a K/Ar age from a Cerro Conejo ash, also indicate a disconformity at this contact (Tedford and Barghoorn, 1999).

Figure 12

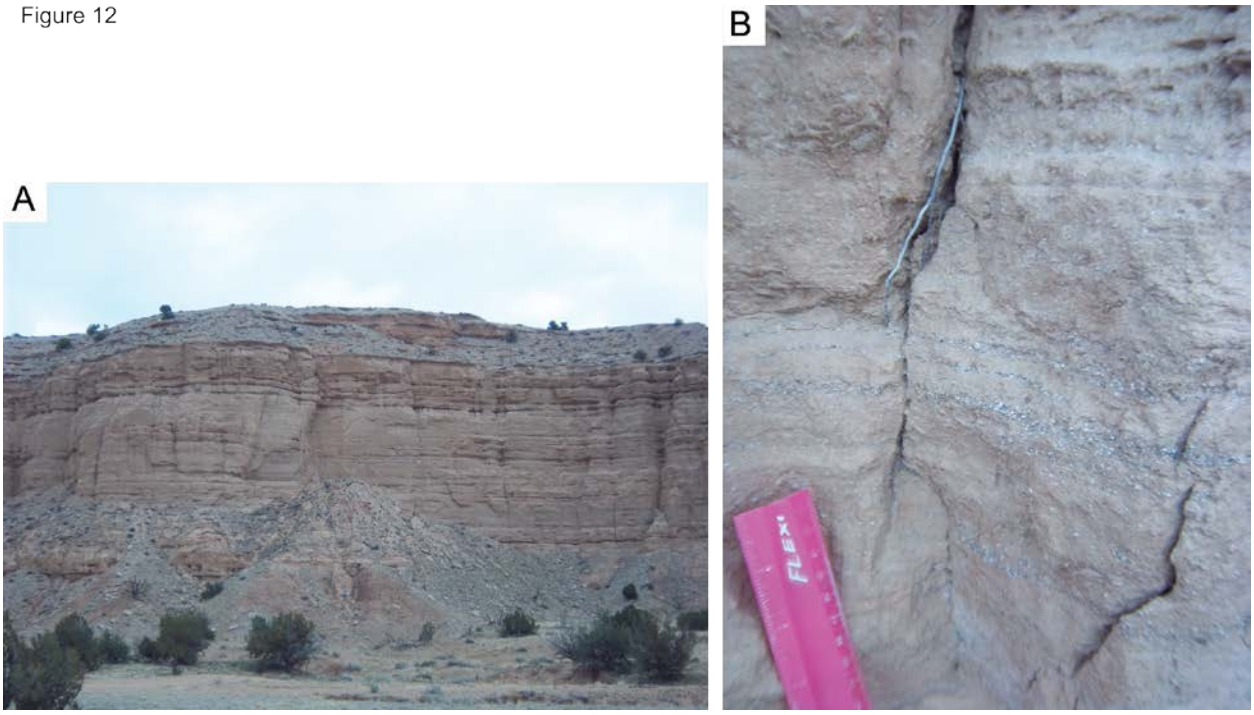

Figure 12. A) Ledge-forming, tabular-bedded sandstone of the lowest subunit of the Cerro Conejo Formation (Tcc1), interpreted as a distal piedmont facies. B) This subunit has local lenses of volcanic-dominated granules whose composition is similar to the volcanic sand in the Piedra Parada Member (Zia Formation).

Figure 13

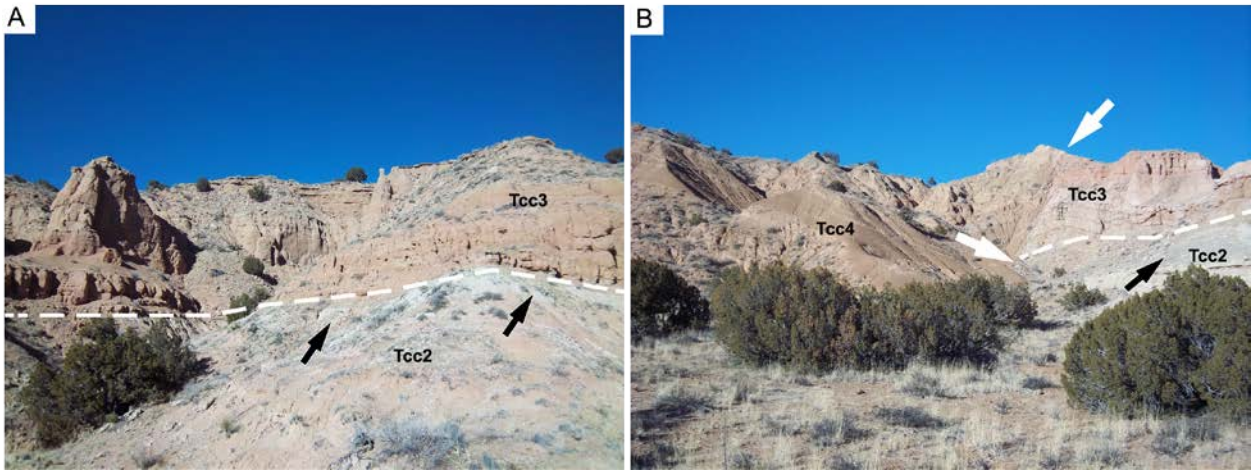

Figure 13. A,B) The pastel-colored subunit of the Cerro Conejo Formation is labeled in these two photographs (Tcc2). Greenish, lacustrine beds are marked by the black arrows.

The white, dashed line shows the upper contact of the unit; note that the basal part of Tcc3 is relatively red and well-bedded, in contrast to the tanner colors and less distinct bedding up-section in the unit. B) The west-down Pilares fault juxtaposes the upper unit of the Cerro Conejo Formation (Tcc4) againts subunits Tcc2 and Tcc3. View is to the north. Note how Tcc4 beds dip steeply into the west-dipping fault plane.

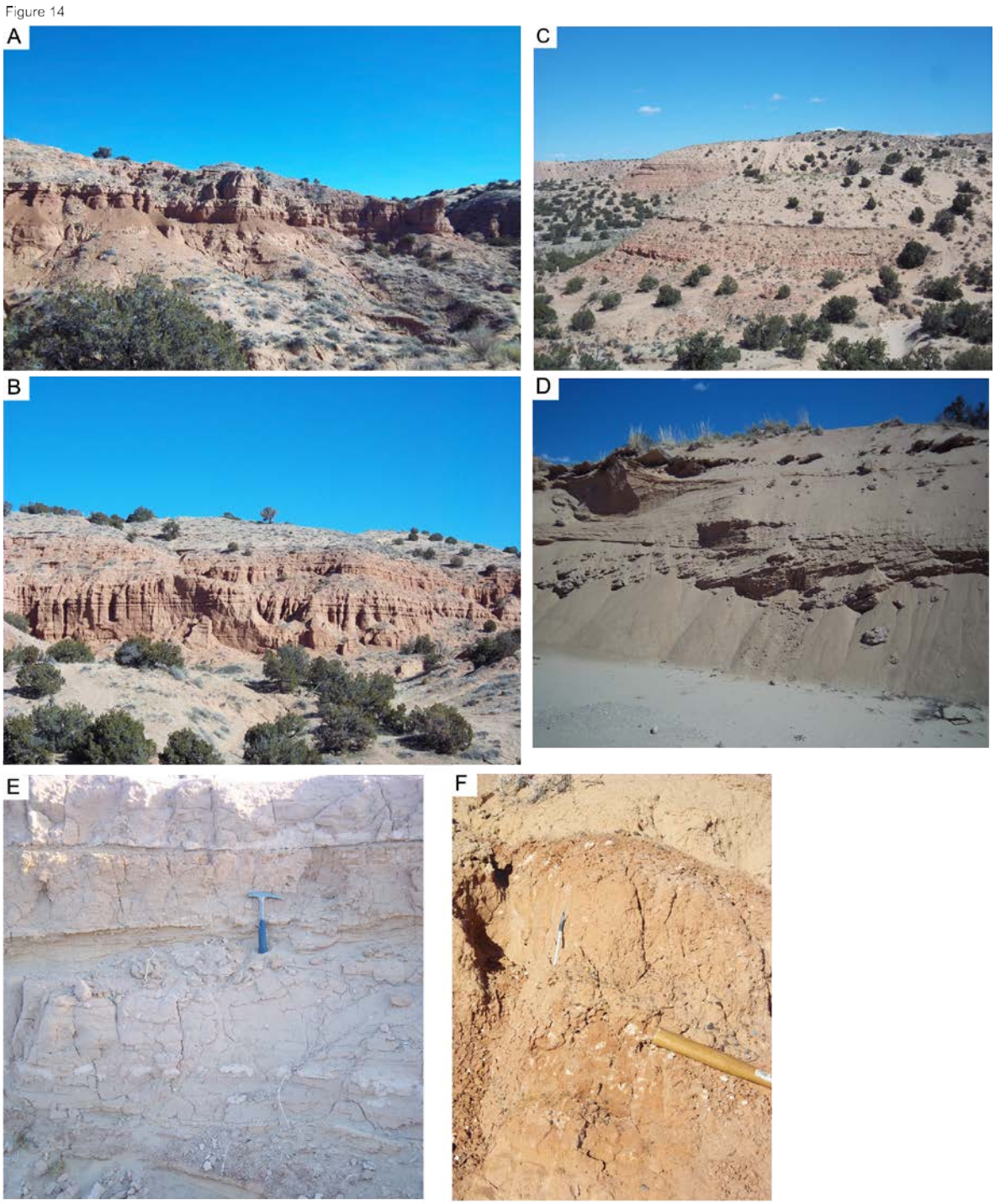

Figure 14. A,B) Ledge-forming, orangish, tabular-bedded lower part of subunit 4 of the Cerro Conejo Formation. C) The ledges formed by the lower part of subunit 4 are overlain by loose, eolian and colluvial sands of unit Qesc. D) In the upper part of subunit 4, there are

local intervals with distinctly cross-stratified, fluvial sands. Outcrop is about 6 m (20 ft) tall. E) Sandstone in upper part of subunit 4. F) Tcc4 on the immediate hanging wall of the Pilares fault (Fig. 13B) contains paleosols and pebbly beds. The paelosols are reddened and exhibit ped development, clay illuviation, and precipitation of calcium carbonate nodules. Two paleosols are present here on either side of the rock hammer handle. Note the chert-dominated pebbles in the sediment.

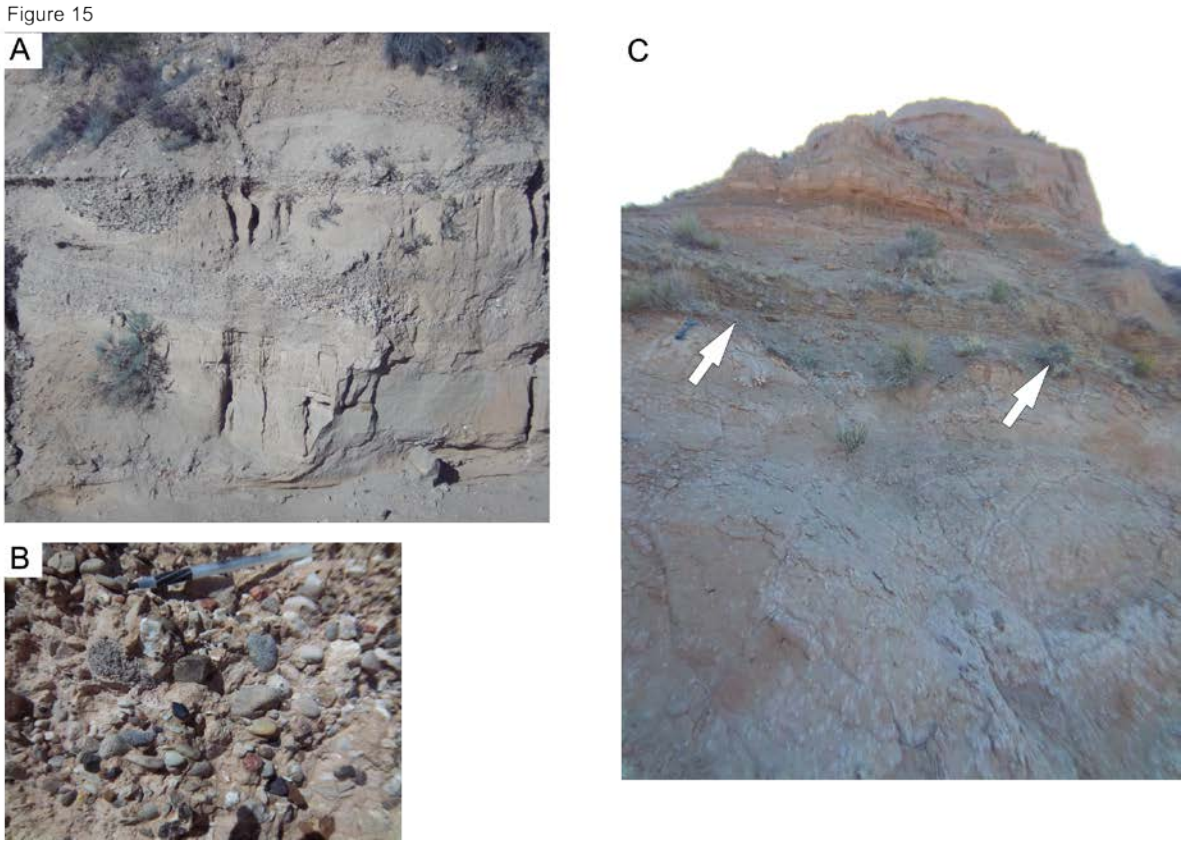

Figure 15. A) Exposure of the Loma Barbon Member (Arroyo Ojito Formation) immediately east of the eastern quadrangle boundary. Here, it is dominated by sandstone, with lesser conglomerates and mudstones. Exposure is ~ 4 m tall. B) Close-up shot of the gravels seen in a channel-fill in photo A. Estimated clast composition: 30-50% tan and fine-grained Mesozoic sandstone, 15-30% dark gray to black to brown chert, 10-40% Pedernal chert,

10% red granite, 1-5% quartzite, 1% gray intermediate volcanic rocks, trace lithic-rich sandstone, and 0.5% mudstone rip-up clasts. C) The upper contact of the Loma Barbon Member is shown by the white arrows. Above lies the well-bedded, redder Atrisco Member of the Ceja Formation. A paleosol extends down from the arrows, as evidenced by calcium carbonate nodules, bioturbaton, and lack of original sedimentary fabric.

Figure 16

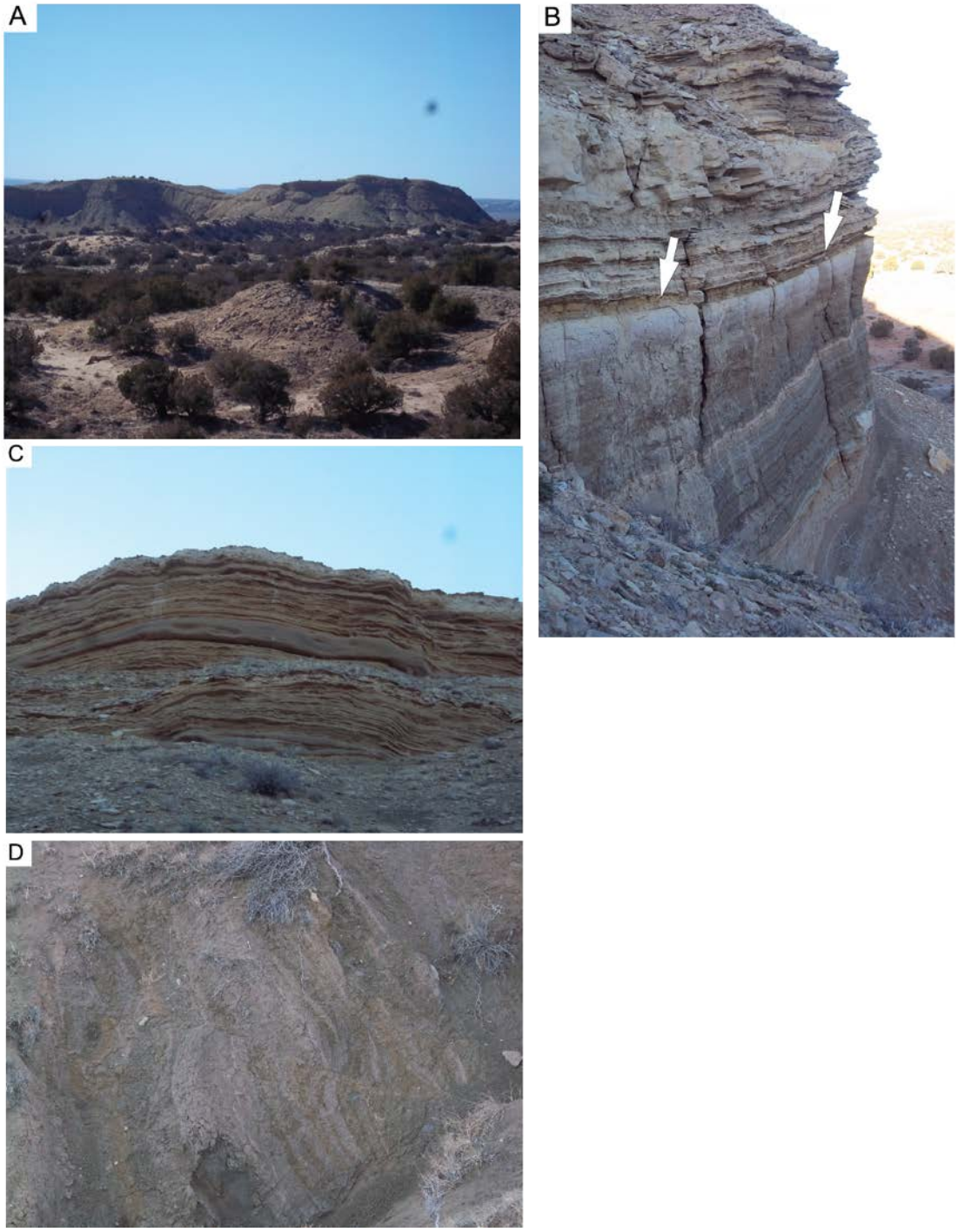

Figure 16

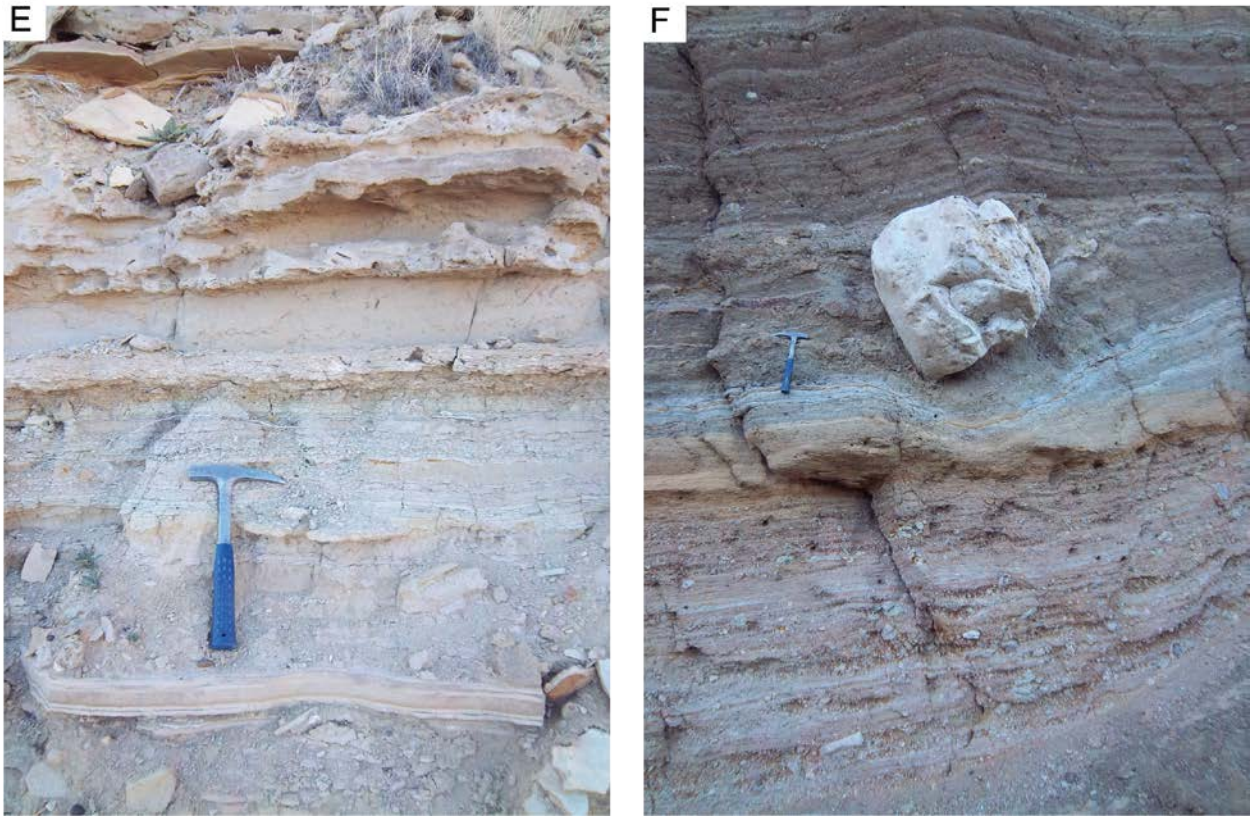

Figure 16. Photographs of the Benavidez maar (called a diatreme by Kelley and Kudo, 1978). A) View of the western side of the maar strata, which are more resistant than the surrounding Santa Fe Group and form a topographic high. B) The maar has two units, the contact of which is demarcated by white arrows in this photograph. The lower unit is dark-colored and contains abundant basaltic ash and lapilli. The upper unit is a quartzo-feldspathic sand derived from the Santa Fe Group. Note the parallel, distinctive bedding, although down-section the lower unit becomes massive. C) Lower part of the well-bedded, upper unit, with a prominent basalt-rich lapilli bed near its center. D) Basal part of the lower unit, where strata dip steeply towards the center of the maar (60-90°). Upper unit, dominated by quartzo-feldspathic sand similar to that seen in the Cerro Conejo Formation. F) Bomb and sagging of maar strata below it.

Figure 17

Figure 17. Photo of the Moquino fault in the northern quadrangle, looking north. The fault is demarcated by white arrows. To the left lies the upper Point Lookout Sandstone. To the right lies the Zia Formation (orangish Chamisa Mesa Member overlying the