Geologic Map of the Cuchillo 7.5-Minute Quadrangle, Sierra County, New Mexico

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Scale 1:24,000

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View looking northwest across badlands developed in the Palomas Formation towards the southern Mud Springs Mountains. Here, the Mud Springs Mountains are composed mainly of Ordovician dolomites and limestones. These strata have been tilted 30-40° to the northeast. Sandstones, conglomerates, and siltstones of the are semi-horizontal, indicating minimal deformation since their deposition 5-1 Ma.

EXECUTIVE SUMMARY

Located northwest of downtown Truth or Consequences, the Cuchillo quadrangle occupies a key location for understanding the geologic history of the Truth or Consequences area. We refine previous mapping, which produced a robust geologic map of the bedrock geology of the Mud Springs Mountains (Maxwell and Oakman, 1990), and focus most of our effort on mapping the internal stratigraphy and structure of the Santa Fe Group—building from the detailed, admirable work of Foster (2009) and Mack et al. (2012). The Cuchillo quadrangle includes the entire Mud Springs Mountains, a northeast-tilted fault block underlain by Ordovician-Pennsylvanian strata composed mainly of limestones, dolomites, and shales—with reddish, fluvial mudstones and sandstone present on the northeastern flank of these mountains. Surrounding this bedrock high are sandstones, with minor siltstones and conglomerates, of the Plio-Pleistocene Palomas Formation, whose age is well constrained at 5 to 1 Ma using magnetostratigraphic and previous biostratigraphic and $^{40}Ar/^{39}Ar$ geochronologic studies. The Palomas Formation comprises the upper basin fill unit of the Santa Fe Group that filled two adjoining basins, the Engle Basin to the northeast and the Palomas Formation to the southwest, during subsidence of the Rio Grande rift. The aggradational surface of the Santa Fe Group is well-preserved on this quadrangle and is called the Cuchillo surface (McCraw and Love, 2012). Near the town of Cuchillo, located in the northwest corner of the quadrangle in the valley of Cuchillo Negro Creek, are exposures of finer-grained, highly tilted, pre-5 Ma strata of the Santa Fe Group.

Two periods of deformation are documented in the Cuchillo quadrangle. Thrust faults and associated compressional folding mapped in the Mud Springs Mountains, particularly evident in the central part of these mountains, appear to be an extension of the North Ridge folds mapped in the northern Caballo Mountains (Kelley and Silver, 1952; Seager and Mack, 2003). Thus we interpret that they are related to the Laramide orogeny (70-40 Ma). A component of the steep northeast tilts in the mountain block likely formed during this time of contraction.

The second period of deformation produced extensional strain features associated with Rio Grande rifting that include normal faulting and further northeastward tilting of the mountain block. Strata in both the Mud Springs Mountains and older (pre-Palomas Formation) Neogene basin fill dip 20-40° NEE, with bedrock strata dips decreasing to 15-20°NE eastward away from the thrust faults exposed in the Mud Springs Mountains. However, Pliocene strata of the Palomas Formation dips <5°, mostly being <2°.

Some normal faults are present in the Mud Springs Mountains. However, the vast majority of normal faults on the Cuchillo quadrangle are located in the Palomas Basin to the west and south of these mountains. Two important fault systems are present: the Mud Springs fault and the Cuchillo Negro fault zone. A system of north-striking, right-stepping en-echelon faults located 4 km west of the Mud Springs Mountains is called the Cuchillo Negro fault zone (per Machette and Jochems, 2016). These faults have created scarps on the Cuchillo surface that are typically 1-3 m tall, but their total vertical displacement remains poorly constrained. Near and north of Cuchillo, the most prominent fault of the Cuchillo Negro fault zone has been called the Willow Draw fault (McCraw and Williams, 2012).

Separating the en-echelon Palomas Basin from the Engle Basin, the northern Mud Springs fault is a major NNE-striking, west-down structure documented by fault scarps, seismic reflection, and well data near the northern quadrangle boundary (Lozinsky, 1987; Adams and Keller, 1996; Cikoski and Koning, 2012). There, this fault has produced ~2 km of west-down throw, and the footwall structural block appears to continue uninterrupted southwards to the Mud Springs Mountains. However, our mapping has found no offset of the Palomas Formation by the inferred southward projection of this fault in Cuchillo Negro Creek nor southwards along the western toe of the Mud Springs Mountains, where there almost certainly needs to be a buried fault to needed to produce these uplifted, tilted mountains. At the southern end of the Mud Springs Mountains, our mapping has delineated a southern strand of what can be called the Mud Springs fault. However, the most recent deformation along this strand does not continue northward along the western flank of the Mud Springs Mountains, but rather strikes due-west, linking with the Cuchillo Negro fault system.

Sedimentologic investigation of Paleozoic strata indicates predominately shallow-water, marine environments in the Ordovician conducive to deposition of dolomites, limestones, and shales. Water depths experienced more extreme fluctuations in the Middle to Late Pennsylvanian, allowing deposition of nearshore marine carbonates, deep-water shales, and coastal plain silicilastics. In the Early Permian, predominately marine environments had transitioned to terrestrial environments, culminating in deposition of reddish floodplain deposits and fluvial channel fills of the Abo Formation between 285 and 295 Ma.

Two units of pre-Palomas Formation, Santa Fe Group strata, correlated to the Rincon Valley Formation, are exposed along the lower flanks of Cuchillo Negro Creek 2.5 km east-southeast of Cuchillo. The older unit is tan-colored and consists of interbedded pebble-cobble conglomerate (30-40%), massive silt-sand (30-40%), and massive pebbly sand (30-40%). Preliminary clast imbrication data suggests southerly paleoflow, consistent with a diverse clast composition (including Paleozoic carbonates, greenish (Mesozoic?) sandstone and siltstone, and lesser felsic volcanics + Abo Formation) that can be explained by erosion of the eastern Sierra Cuchillo, southern San Mateo Mountains, and the northern Mud Springs structural block (presumably not completely buried in the Miocene). The younger unit is reddish and finer-grained than the older unit. It consists of fine-grained, massive sand with minor coarse sand lenses that are internally massive to vaguely trough cross-stratified. Its sparse pebbles are relatively similar in composition to the older unit. The finer texture and local trough cross-stratification suggests a distal piedmont or basin floor depositional environment for the younger unit, whereas the abundance of conglomerates and hyperconcentrated flow beds (tabular, poorly sorted, silt-sand with trace to 3% scattered pebbles) suggests a south-sloping piedmont depositional environment for the older unit.

Three depositional environments can be recognized in the Palomas Formation: piedmont, marginal basin floor, and axial-fluvial. Most of the unit consists of a piedmont lithofacies assemblage characterized by interbedded: (1) light brown to light reddish brown to tan, silt, very fine- to fine-grained sand, and clayey-silty fine sand in medium to thick, tabular beds; and (2) gravelly intervals 0.5-4 m thick (locally as much as 6 m) exhibiting very thin to medium, tabular to lenticular beds with 1-15% cross-stratification. The majority of this sediment was deposited by relatively large, eastward-flowing fluvial systems sourced in the central Black Range that carried volcanic gravel, but a narrow band of piedmont-alluvial fan sediment wraps around the Mud Springs Mountains and was deposited by small, ephemeral streams draining this small mountain block. A tripartite, up-section division can be recognized in the volcaniclastic (Black Range) piedmont lithofacies assemblage, in which the lower and upper stratigraphic levels contain more gravels than the finer-grained, middle stratigraphic level. The toe of the Mud Springs-sourced alluvial fans expanded outward in the lower and upper stratigraphic levels, but shifted back towards the mountains in the middle stratigraphic level.

The middle stratigraphic level of the piedmont deposits grades laterally eastward into a fine-grained strata associated with a marginal basin floor environment, representing the second depositional environment. These fine-grained strata consist of siltstone, very fine- to fine-grained sandstone, and mixed clay-siltstone-very fine-grained sandstone. This depositional environment is present, but much narrower and not mappable, in the easternmost parts of the lower and upper stratigraphic intervals of the volcaniclastic piedmont lithofacies assemblage.

The third depositional environment of the Palomas Formation is represented by an axial-fluvial lithofacies assemblage, which overlies redder strata of the Rincon Valley Formation. The axial-fluvial assemblage consists of clean, light gray to white sand and subordinate gravelly sand deposited by a south-flowing, ancestral Rio Grande. Gravels reflect derivation from highlands surrounding the Engle Basin, with some gravel beds containing extra-basinal cherts and quartzites derived from central and northern New Mexico. We divide the axial-fluvial lithofacies assemblage into two up-section units, with the lower 20-25 m containing more gravel (10-60%) than overlying strata.

Three allostratigraphic units are found in the lower unit of the axial-fluvial facies, two of which fill two separate, 17-20 m-deep paleovalleys. Particularly coarse gravel (abundant cobble sizes), with much extra-basinal clasts (mainly quartzite), is present in the younger of the two paleovalleys. Magneto-stratigraphic work, combined with $^{40}Ar/^{39}Ar$ dating of cryptomelane and discovery of a fossil tooth of *Neohipparian eurystyle* (Koning et al., 2016, 2018), indicate that the Rio Grande propagated southwards into this area immediately prior to 5 Ma, fluvially linking previously closed (endoheroic) basins that existed during Miocene time.

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After the culmination of rift basin aggradation 0.8-0.9 Ma, manifested by the aerially extensive Cuchillo surface (McCraw and Love, 2012), incision occurred in the Cuchillo quadrangle. Episodic halts or short-term aggradational events that occurred during this time of progressive incision created numerous geomorphic levels of terraces and piedmont surfaces inset below the Cuchillo Surface. Three terrace levels are mapped within Canada Honda and Mud Springs Canyon, located southwest of the southern Mud Springs Mountains. There is a nicely preserved terrace record along Cuchillo Negro Creek. There, one can divide terraces into a lower and higher set. The lower set contains four terraces that can be correlated along the reach of the creek in our map area. These generally have thin (<3 m thick) gravelly deposits. The upper set is notably thicker (6-15 m thick) and best preserved in the lower part of Cuchillo Creek.

INTRODUCTION

This report accompanies the Geologic Map of the Cuchillo7.5-Minute Quadrangle, Sierra County, New Mexico (NMBGMR OF-GM 271). Its purpose is to discuss the geologic setting and Neogene geologic history of this area, and to identify and explain significant stratigraphic and structural relationships discovered during the course of mapping. This report presents several background aspects of the quadrangle, including geographic-tectonic setting, climate, and previous work. Then it describes the Neogene geologic map units and their depositional settings by age, oldest to youngest. Because of the focus of the mapping on Neogene stratigraphy, for descriptions and stratigraphy of Paleozoic units and related depositional environments we refer the reader to Appendix 1 and the following references: Lucas et al. (2012a, 2012b, 2012c, 2016); Mack (2004); Seager and Mack (2003). The structural geology of the area is discussed followed by mineralization features of the quadrangle. Detailed unit descriptions are provided as appendices. **Note that figures and associated captions are provided at the end of the document.**

Motivation

Superb exposures of Paleozoic strata in the Mud Springs Mountains, and of the Palomas Formation in surrounding badlands, allow a wonderful opportunity to reconstruct the geologic history for this area of New Mexico, particularly for the Ordovician, Pennsylvanian-Permian, and late Neogene Periods. A previous mapping effort produced a robust geologic map of the Paleozoic bedrock underlying the Mud Springs Mountains

(Maxwell and Oakman, 1990). We slightly refine this earlier bedrock mapping but this report provides much more detail on Pennsylvanian strata and related correlations. Most of our work, however, focuses on refining the stratigraphy and structure of the Santa Fe Group, building from previous detailed mapping and sedimentologic work by Ron Foster (2009) and Mack et al. (2012) of Santa Fe Group strata surrounding the Mud Springs Mountains.

Climate

The Cuchillo quadrangle (and most of the Palomas basin) has an arid climate. The summer months (June through August) experience average temperature highs of 93-96° F and average lows of 63-67° F. In the winter months (December through February), average temperature highs are 55-63° F and average lows are 27-31° F. Average yearly precipitation is 25.5 cm (10 in), of which 8.4 cm (3.3 in) accumulates as snowfall. Over half of the mean annual precipitation (13.7 cm) falls during the North American monsoon in the months of July through September. All climate data listed above are from the Truth or Consequences station (ID# 299128) in the NWS Cooperative network and averaged over the years of 1951-2008 (Western Regional Climate Center, 2015).

Geographic and tectonic setting

The Cuchillo quadrangle covers 64 mi^2 of desert landscape between the city of Truth or Consequences (pop of ~5,950 in 2017; U.S. Census Bureau, 2018) and the small community of Cuchillo in south-central New Mexico. The map area completely encompasses the Mud Springs Mountains and includes surrounding badlands and mesa tops underlain by nonlithofied, basin fill sediments of the Santa Fe Group (Fig. 3). The Cuchillo quadrangle lies in the Rio Grande rift—a >1000 km-long topographic depression, extending from Leadville Colorado, to northern Mexico, formed by localized extensional strain over the past ~30 Ma. The quadrangle spans a fault-boundary separating two right-stepping, en-echelon basins of the rift (Figs. 1-2). To the west of the Mud Springs fault lies the Palomas Basin, which continues southwards to near the towns of Garfield and Hatch. To the east of the Mud Springs fault, the Engle Basin extends ~40 km north from the northern environs of Truth or Consequences and is best known for having Elephant Butte Lake. Mountains surrounding the northern Palomas Basin includes the San Mateo Mountains (to the north) and Sierra Cuchillo to the northeast (Fig. 1). On the east flank of the Engle Basin towers the rugged, western face of the Fra Cristobal Mountains,, which are similar topographically and geologically to the Fra Cristobal Mountains located 3 km southeast of Truth or Consequences.

Within the quadrangle, the crest of the north-northwest trending Mud Springs Mountains generally lies at 5100-5500 ft, rising 200-800 ft above surrounding, flatter terrain. The highest peak is called Mud Mountain, having an elevation of 5479 ft, which stands somewhat detached (to the southwest) of the main crest line of the Mud Springs Mountains. These mountains are underlain by a sequence of Ordovocian, Devonian, Pennsylvanian, and Early Permian strata that have been tilted 20-40° to the ENE since the Paleozoic. Proterozoic crystalline rocks are exposed at the western toe of the Mud Springs Mountains, unconformably underlying Paleozoic strata.

Surrounding the Mud Springs Mountains is lower topography developed on non-indurated sand, gravel, silt, and clay (most to least) of the Santa Fe Group, a formal name designating sediment deposited in the Rio Grande rift after cessation of most late Eocene-early Oligocene volcanism (Spiegel and Baldwin, 1963). About 1/3 of the Santa Fe Group is capped by the low-sloping (1-2° east), planar to slightly concave-up Cuchillo geomorphic surface (McCraw and Love, 2012). This interesting geomorphic was formed when Santa Fe Group deposition ceased about 0.8-0.9 Ma (age from Mack et al., 1993, 1998, 2002). The Cuchillo Surface ends near the east quadrangle boundary in the northern part of the quadrangle, and does not extend >1 km east of the Mud Springs Mountains to the south.

Incised into the Cuchillo Surface are four major canyons and their associated tributaries. Southwest of the southern Mud Springs Mountains lie the southeast-flowing, ephemeral drainages of Cañada Hondo (to the south) and Mud Springs Canyon (to the north). An ephemeral, relatively small drainage called Yaple Canyon drains southeast in the northeastern quadrangle. These three drainages head in the western Palomas Basin east of of the Sierra Cuchillo. In contrast, Cuchillo Negro Creek is sourced in the forested Black Mountains, whose crest near the creek's headwaters stands 8,500-9,000 ft above sea level. Cuchillo Negro Creek flows southeast in the northern part of the quadrangle, cutting a narrow canyon in Paleozoic bedrock at the north tip of the Mud Springs Mountains. Although still considered ephemeral, Cuchillo Negro Creek upstream of this gorge may have flowing water over a few months time.

PREVIOUS WORK

Early geologic mapping and reconnaissance work in the Palomas basin was done by Gordon and Graton (1907), Gordon (1910), and Harley (1934). Kelley and Silver (1952) produced a benchmark geologic map and report of the Caballo Mountains. The Truth or Consequences-Williamsburg area has also been the focus of several studies on groundwater conditions and/or geothermal resources, including those of Murray (1959), Cox and Reeder (1962), and more recently Person et al. (2013). Early work of Paleozoic strata include Clemons (1991), Hayes and Cone (1975), Kelley and Silver (1952), and Thompson (1942); recent publications regarding the Paleozoic section are Lucas et al. (2012a, 2012b, 2012c, 2016), Mack (2004), Seager and Mack (2003).

The Cuchillo quadrangle was mapped previously by Maxwell and Oakman (1990). Although their bedrock mapping of the Mud Springs Mountains is accurate and admirable, the Santa Fe Group was left undifferentiated. Lozinsky (1986) differentiated the Santa Fe Group into a piedmont facies and axial facies, as further discussed in Lozinsky and Hawley (1986a,b). However, it was Ron Foster (Foster, 2009; Mack et al., 2012) who first produced a detailed subdivision of the Santa Fe Group around the Mud Springs Mountains, producing an admirable 1:12,000 scale geologic map that differentiated Santa Fe Group strata based on provenance and depositional environment.

Numerous studies by Greg Mack and Bill Seager (both of New Mexico State University) and their colleagues shed much light on the Palomas basin and its Plio-Pleistocene basin-fill, the Palomas Formation. These studies range from geochronologic (Seager et al., 1984; Mack et al., 1993, 1998, 2009) and sedimentologic and stratigraphic (e.g., Mack et al., 2002, 2008) to investigations of controls on sedimentation (Mack and

Seager, 1990; Mack et al., 1994a, 1994b, 2006; Mack and Leeder, 1999) and soils and paleoclimate (Mack and James, 1992; Mack et al., 1994a, 2000).

Much work has been done on the quadrangle in regards to age control of late Neogene sedimentary strata of the Santa Fe Group, particularly the Palomas Formation. The relatively fine-grained Mud Springs pumice bed was discovered by Ron Foster west of Interstate 25 near Truth and Consequences; it was later correlated geochemically to a pumice bed near Hatch that yielded an age of 3.12±0.03 Ma (Mack et al., 2009). A study pertaining to the early history of the Rio Grande was conducted near downtown Truth or Consequences, utilizing age control provided by $^{40}Ar/^{39}Ar$ dating of cryptomelane (a manganesium mineral) and discovery of a horse tooth fossil (Koning et al., 2016).

Two locales near Interstate 25 have yielded abundant vertebrate fossils. The Cuchillo Negro Creek Local fauna include about 25 sites spread out west of Interstate 25 along a 1 km distance south of the Truth or Consequences border control station. Fossils were collected in 1983 and 1984 by UNM field crews and between 1998 and 2007 by the NM Museum of Natural History. Fossil interpretations are published in Lucas and Oakes (1986), Morgan et al. (2011), and Morgan and Lucas (2003, 2012).

Another important site for age control yielded fossils of the Truth or Consequences Local Fauna, which were collected from the western margin of Interstate 25 at a distance 2 km south of the North Date Street Intersection. The site was discovered by Author Harris of the University of Texas at El Paso (UTEP) and then worked by Charles Repenning and a field crew from the U.S. Geological Survey in the early 1980s (Morgan and Lucas, 2012). Field crews from the NM Museum of Natural History have been excavating and screenwashing this site since 1997. Fossils of the Truth of Consequences Local Fauna are stored at the NM Museum of Natural History, the U.S. Geological Survey in Denver, and at UTEP (Morgan and Lucas, 2012). Fossil and related age interpretations are published in Repenning and May (1986), Morgan and Lucas (2003, 2012), and Morgan et al. (2011).

Manganeses oxide deposits in the Truth or Consequeunces area were located by Albert Ellis during World War I and mined extensively between 1953 and 1954 (Farnham, 1961). The deposits are described in Wells (1918), Russell (1947), Farnham (1961), and Lueth (2012).

MAPPING METHODS

The procedures used to produce this geologic map can be divided into five phases. In contrast to a decade ago, these methods heavily employ digital methods and the input of map data directly into ARC geodatabases by the field mappers. The mapper initially identifies units and contacts with aerial photography coupled with field checks. Stereogrammetry software recently acquired by the N.M. Bureau of Geology (i.e., Stereo Analyst for ARCGIS 10.4, an ERDAS extension, version 11.0.6) results in relatively accurate placement of geologic contacts directly into the ARC geodatabase. Then, specific areas were identified for detailed field mapping based on degree of exposure, uncertainty in aerial photograph interpretations, or problematic geologic relations. A second stage consists of several weeks of detailed field mapping. The third stage involves updating the geologic line work from field observations and entering point data into the ARC geodatabase. Simplifying the map for the purposes of 1:24,000 scale presentation comprises the fourth stage. The fifth stage involves map production and layout. Shortened descriptions are presented in the map layout, with detailed versions of the descriptions given in Appendix 1.

Surface characteristics aid in mapping Holocene and middle-late Pleistocene units. Older deposits generally have older surfaces, so surface processes dependent on age -- such as desert pavement development, clast varnishing, calcium carbonate accumulation, and eradication of original bar-and-swale topography -- can be used to differentiate terrace, alluvial fan, and valley floor deposits. Locally, erosion may create a young surface on top of an older deposit, so care must be exercise in using surface characteristics to map Quaternary deposits.

NEOGENE STRATIGRAPHY

Cenozoic Igneous Rocks

One basaltic lava flow plus four dikes and one sill are found in the Cuchillo quadrangle, the mapping of which remain unchanged from Oakman and Maxwell (1990). Two dikes and one sill were sampled by these previous workers, and based on their major-oxide analyses (table 2, Oakman and Maxwell, 1990) we renamed them according to the nomenclature presented in LeBas et al. (1986). Descriptions of these features follow Oakman and Maxwell (1990).

The basaltic lava unit contains olivine phenocrysts and is preserved as a small polygon at the southern tip of the Mud Springs Mountains, about 1.5 km southeast of Mud Mountain. It contains numerous xenoliths of limestone, shale, jasperoid, and Proterozoic granite. An $^{40}Ar/^{39}Ar$ age of 5.55± 0.21 Ma (McLemore et al., 2012) from this flow makes it one of the oldest late Neogene basalt flows in the region.

Four dikes are mapped that are basaltic, porphyritic rhyolite, and porphyritic trachyte, the latter referred to as quartz latite by Maxwell and Oakman (1990). The two basalt dikes are 0.2-1.2 m wide, highly altered, and have a nesophitic texture, with feldspar laths generally ~0.02 by 0.2 mm. One dike intrudes the Abo Formation near the southwestern margin of Cuchillo Creek (UTM coordinates 287,080 m E; 3,674,305 m N; NAD83). It is truncated by unit QTps of the overlying Palomas Formation, but its vertical orientation within 30° dipping Abo strata implies a late Neogene age—allowing the possibility it correlates with the 5.55±0.21 Ma basalt lava flow described above. The other basalt dike is much longer, more altered, and intrudes the Gray Mesa and Bar B Formations on the east flank of the northern Mud Springs Mountains.

There are two non-basaltic dikes. A 1.2-5.5 m-wide, porphyritic trachyte dike intrudes Gray Mesa Formation at the north end of the long basaltic dike. This dike is light to medium gray and contains white, rounded quartz phenocrysts 1-2.5 mm in diameter and white to pink feldspar phenocrysts 7-15 mm in diameter that are partly altered to clay and calcite. Its groundmass is composed of equant grains of orthoclase, quartz, and plagioclase as well as random biotite and opaques. A porphyritic rhyolite intrudes the Bliss Sandstone on the western foot of the central Mud Springs Mountains. It is light pinkish to reddish gray, relatively crystal-rich, and commonly altered. Its phenocryst assemblage includes 7-10% euhedral biotite and 7-10% whitish, subhedral feldspar. It has a very fine-grained groundmass of feldspar and quartz. K-Ar analyses of biotite returned an age of 40.8±1.5 Ma (R.F. Marvin, written commun. to C.H. Maxwell, 1987; Maxwell and Oakman, 1990).

The sill is trachyandesite in composition (previously called latite by Maxwell and Oakman, 1990) and intrudes the lower part of the Red House Formation in the southern Mud Springs Mountains, where it is up to 27 m thick. It is mostly very fine-grained, with local medium-grained lenses, and has a nesophitic texture (larger feldspar phenocyrsts and interstitial, smaller pyroxene) where phenocrysts are comprised of feldspar laths up to 1.0 mm (partly altered to clay). Other phenocrysts include hornblende (commonly metasomatized to actinolite) and scattered orthoclase and rounded quartz grains (0.2-0.6 mm). Analyses of hornblende gave an $^{40}Ar/^{39}Ar$ age of 43.4±0.2 Ma (L.W. Snee, written commun. to C.H. Maxwell, 1989; Maxwell and Oakman, 1990).

SANTA FE GROUP (LATE NEOGENE)

The term "Santa Fe Group" is applied to clastic sediment, locally interbedded with volcanic rocks, deposited in the Rio Grande rift after cessation of most late Eocene-early Oligocene volcanism (Spiegel and Baldwin, 1963), the latter represented by such units as the Espinaso Formation or Mogollon Group ignimbrites or lavas. The Santa Fe Group can be readily subdivided into two packages on this quadrangle. On top lies 1-230 m of generally weakly cemented, non-deformed sediment correlative to the Palomas Formation of Lozinsky and Hawley (1986a,b). Beneath lies redder, more consolidated-cemented sediment that pre-dates the Palomas Formation. Time-wise, these strata correlate to the Rincon Valley and Hayner Ranch Formations proposed by Seager et al. (1971). Along the western edge of the Palomas Basin to the southeast, pre-Palomas Formation strata fine upwards but generally are difficult to differentiate on a formation-level. Thus, an informal consensus was reached between Andy Jochems and Dan Koning with notable previous workers—William Seager, Greg Mack, and John Hawley—to designate all pre-Palomas Formation strata of the Santa Fe Group north of the Hatch area as "Rincon Valley Formation". In other words, the Hayner Ranch Formation is not formally mapped in the northern Palomas Basin or the Engle Basin. Detailed sedimentologic descriptions for all units are found in Appendix A.

Rincon Valley Formation

The Rincon Valley Formation is typically reddish and finer-grained than the Palomas Formation. It can be subdivided into two stratigraphic levels that we informally coin the "upper Rincon Valley Formation" and the "lower Rincon Valley Formation." The lower Rincon Valley Formation may possibly be time-equivalent to the Hayner Ranch Formation of Seager et al. (1971).

Lower Rincon Valley Formation

Description

The lower Rincon Valley Formation is mapped only 2.5-3.0 km southeast of the community of Cuchillo, where it outcrops at the base of the valley-margin slopes on either side of Cuchillo Negro Creek. There, the lower Rincon Valley Formation (Trpl) is mapped for moderately to well-indurated, tannish, steeply dipping strata comprised of interbedded pebble-cobble conglomerate, silt-sand, and pebbly sand (Fig. 4). The conglomerate is normally graded, moderately imbricated, and occurs as 50-120 cm-thick, broadly lenticular beds. Its clast assemblage is mostly clast-supported, subrounded, poorly sorted, and composed of Paleozoic carbonates (20-25%), undivided tuffs (mostly Kneeling Nun tuff;

~20%), greenish (Mesozoic?) sandstone and siltstone (10-15%), felsic volcanics (10-15%), Abo Formation (10-15%), and less than 10% each of intermediate volcanics, tan sandstone, feldspar porphyry, chert, and petrified wood. Preliminary clast imbrication data suggests southerly paleoflow. The sand fraction is mostly medium- to very coarse-grained and composed of 50-60% lithics (volcanic>carbonate), 25-35% quartz, and 15-25% feldspar with no clay. Of subequal percentage to conglomerate is tan silt to fine-lower sand (5-10% fine-upper-medium-upper sand) in thin to thick (up to 60 cm), tabular, internally massive beds. There is 3% floating fine to very coarse pebbles composed of at least 80% felsic volcanic lithologies. The subordinate lithologic type in the lower Rincon Valley Formation is sand with 5-20%, subangular to rounded, very fine to coarse pebbles (locally cobbles in upper 15 cm of some beds) that exhibit similar compositional ranges as the conglomerates.

Interpretation

We interpret the depositional environment of this unit as a medial piedmont facies. Conglomerates are abundant and represent channel fills or gully-mouth fan lobes. Scattered ("floating") pebbles in the tabular, silt to fine-lower sand beds are consistent with hyperconcentrated flows (Mack et al., 2002; Seager and Mack, 2003). The piedmont sloped to the south, based on preliminary clast imbrication data. The clast compositions of this unit are notably different from the >90% volcanic-bearing gravel composition of the Palomas Formation. The southerly paleoflow data combined with high proportions of gravel composed of limestone-dolomites (Paleozoic), red fine sandstones-siltstones (Abo Formation), and greenish siltstones-sandstones (probably Mesozoic) is difficult to reconcile from an exclusive Sierra Cuchillo-southern San Mateo Mountains source area because in these regions upper Paleozoic carbonates are directly overlain by Eocene-Oligocene volcanic rocks (Fig. 3; Heyl et al., 1983; Koning et al., 2014). We infer that the inferred Abo and Mesozoic(?) clasts, together with an unknown percentage of limestones-dolomites, had to be derived from erosion of an exposed footwall of the Mud Springs fault. The age of the lower Rincon Valley Formation is not known, but given the degree of cementation and high tilts (26-33°), an early to middle Miocene age is reasonable.

Upper Rincon Valley Formation

Description

In contrast to the lower Rincon Valley Formation, the upper Rincon Valley is redder and finer-grained (Fig. 4). We differentiate three exposed units on this quadrangle. Southeast of the community of Cuchillo, the Upper Rincon Valley Formation is preserved in a fault-bounded block down-dropped relative to the lower Rincon Valley (Fig. 4). It consists of fine, massive sand interbedded with 30-35% coarse sand lenses. The fine sand occurs as 70-100 cm-thick, tabular, internally massive beds. These beds contain trace to 2% scattered, subrounded to rounded, medium to very coarse pebbles that tend to be concentrated near the tops of beds. The pebbles are composed of Paleozoic carbonates (30-35%), felsic volcanics (15-20%), undivided tuffs (10-15%), ~10% Abo Formation, and 3-6% each of sandstone, Kneeling Nun tuff, Vicks Peak tuff, chert, basalt, and unknown lithologies. The coarse sand lenses are 5-20 cm-thick and internally massive to vaguely trough cross-stratified. These lenses are generally calcite-cemented and composed of light brown, medium- to very coarse-grained, subrounded, poorly sorted sand composed of 60-65% quartz, 20-25% feldspar, and 15-20% lithics (volcanic) with no clay.

Upper Rincon Valley Formation was also mapped near the towns of Truth or Consequences (Trbut) and along Interstate I-25 northwest of Williamsburg (Trbuw). In both places, strata are reddish, tabular and medium- to thick-bedded, and composed of very fine- to medium-grained sand, clayey-silty fine sand, siltstone, and claystone (Koning et al., 2016, fig. 6). However, northwest of Williamsburg, strata are less consolidated than near Truth or Consequences. Also, fine-grained beds have more sedimentary structures (horizontal-laminated or ripple-laminated), and at least one sand bed is present that is relatively quartzo-feldspathic, consistent with an earliest Rio Grande axial-fluvial deposit. It should be noted that strata northwest of Williamsburg are 5-6 m higher compared to those near Truth or Consequeunces, and thus are very likely younger given there is no mapped faults in between. Near Truth or Consequences, the slightly older unit Trbut is more consolidated, beds are internally massive, and axial-fluvial deposits are not present. The sand has relatively low amounts of quartz (typically, % feldspar + % lithic grains > % quartz grains). Clay-silt beds are internally massive and commonly exhibit nodular calcic paleosols. Pebbly beds are slightly more abundant, being 5-50 cm-thick and composed of mainly of very fine- to very coarse-grained sand, commonly mixed with clay-silt, where pebble percentages are variable. Pebbles are both clast- and matrix-supported. These beds locally fine upward and locally display very thin-thin internal bedding. Pebbles are angular to subangular, poorly to moderately sorted, and composed mainly of Paleozoic carbonates (37-56%), green fine- to medium-grained sandstones correlated to Late Cretaceous Crevasse Canyon strata (7-36%), red siltstones and very fine-grained sandstones correlated to the Abo Formation (5-19%). Paleoflow directions from clast imbrication are southerly (150-215°).

Interpretation

We interpret different depositional settings for the upper Rincon Valley Formation exposed in the northwestern quadrangle versus that exposed in the southeastern part of the quadrangle. In the northwestern quadrangle, we interpret a distal piedmont to marginal basin floor depositional environment. Strata consist mostly of fine-grained sand, commonly in tabular, internally massive beds with trace to 2% scattered pebbles. These characteristics are typical of hyperconcentrated flows (Mack et al., 2002; Seager and Mack, 2003). Local coarse sands may be trough cross-stratified. The clast composition observed in the more pebbly, upper parts of the hyperconcentrated flow beds are broadly similar to that of the lower Rincon Valley Formation. This observation and the high quartz percentage in the sand implies that Paleozoic-Mesozoic(?) sedimentary strata were still partly(?) exposed on the footwall of the Mud Springs fault during deposition of the upper Rincon Valley Formation. This unit appears to be down-dropped alongside the lower Rincon Valley Formation due to normal faulting, so it must be younger than the lower Rincon Valley Formation. We infer that a late middle Miocene to early late Miocene age is most reasonable because this unit is highly tilted (30-40°) within the flock block where it is exposed.

In the southeastern quadrangle, southerly paleoflow directions and clast compositions indicates deposition on a basin floor by drainages sourced in the highlands surrounding the Engle Basin (Koning et al., 2016). An axial river appears to have been established during deposition of the slightly younger Trbuw. Rincon Valley strata are sub-horizontal in the southeastern quadrangle and appear to exhibit a continuous section basin floor lithofacies assemblage from endoheroic conditions to the first arrival of an axial river. Thus, we think an age of 6.0-5.0 Ma for these deposits is reasonable.

Palomas Formation

Overall coarser strata of the upper Santa Fe Group has been formally designated as the Palomas Formation, which in the map area can be readily subdivided into piedmont facies and axial-fluvial lithofacies assemblages (Lozinsky, 1986; Lozinsky and Hawley, 1986a,b). Foster (2009) and Mack et al. (2012) further subdivided the piedmont facies based on gravel composition and provenance. Their Sedimentary, Granitic, and Metamorphic-Clast Facies Assemblage is derived from the Mud Springs Mountains; their Volcanic-Clast Conglomerate Facies Assemblage is sourced from the Black Range. In addition, there is a Fine-grained Facies Assemblage deposited on a basin floor or alluvial flat environment. We follow this conceptual stratigraphic division, but add four layers (vertical-based subdivisions) informally called the lower-transitional, lower, middle, and upper Palomas Formation. We also rename their facies assemblage to be more indicative of depositional environment. The lower Palomas Formation is relatively coarse-grained, the middle layer is finer-grained and characterized by shrinking of alluvial fan size, and the upper Palomas Formation is coarser-grained and witnessed progradation of alluvial fan-piedmont slope deposits. In the following, we integrate our observations with Foster (2009) and Mack et al. (2012) to describe the aforementioned lithofacies assemblages: volcaniclastic piedmont deposits derived from Black Range; sedimentary-clast deposits derived from the Mud Springs Mountains; axial-fluvial; and fine-grained basin margin. For each lithofacies assemblage, we discuss how sediment characteristics change in an up-section manner. We then describe overall stratigraphic relations and their trends and followed by age control.

Volcaniclastic piedmont lithofacies assemblage

Key features and stratigraphy

The majority of the Cuchillo quadrangle is underlain by a piedmont lithofacies assemblage derived from uplands to the west, mostly from the Black Range but also including the southern Sierra Cuchillo and northernmost Salado Mountains. The associated deposits are readily recognized by clast composition, which is >90% volcanic rocks. They are called the Volcanic-clast conglomerate facies assemblage by Foster (2009) and Mack et al. (2012). This assemblage interfingers eastward with either the axial-fluvial lithofacies assemblage or the fine-grained, marginal basin floor lithofacies assemblage. Near the Mud Springs Mountains, this assemblage interfingers with the lower-middle sedimentary-clast piedmont lithofacies assemblage shed from these mountains.

The volcaniclastic piedmont lithofacies assemblage can be subdivided into a lower-transitional zone and lower, middle, and upper layers. The lower transitional zone (Tpvlt) is well consolidated, exhibits a faint light-orange color, coarsens upwards (i.e., gravel proportions increase up-section) and ~30 m thick near the southern quadrangle boundary. Along the southwest margin of Cuchillo Creek 2.5-3.0 km southeast of the community of Cuchillo, it is 3.5-4.0 m thick and lies immediately above an angular unconformity developed at the top of the Rincon Valley Formation.

The lower layer of the volcaniclastic piedmont lithofacies assemblage is 15-30 m thick, being thinnest (15-20 m) on the footwall of the southern Mud Springs fault. Its lower contact with the lower-transitional zone is a scoured disconformity in the southeastern quadrangle, but gradational over 0.5-0.7 m near Cuchillo. In the southern quadrangle, the lower layer interfingers westward with the lower 15-20 m of the middle unit of the axial-facies lithofacies assemblage (Figs. 5-6). The middle layer of the volcaniclastic piedmont lithofacies assemblage is ~60 m thick and interfingers eastward with the fine-grained, marginal basin lithofacies assemblage—which in turn interfingers eastward with the remainder of the middle axial-fluvial unit (i.e., strata above the basal 15-20 m of unit Tpam). The middle layer fines upward and contains less gravel intervals compared to the lower and upper layers (at a given location). The middle layer may also exhibit slightly tanner colors, although the color change is not always apparent. The upper layer of the volcanic lithofacies assemblage, which is 20-40 m thick, presumably interfingered eastward with axial-fluvial strata that has since been eroded away. It also interfingers with the upper layer of the sediment-clast piedmont lithofacies assemblage. Within the upper layer, a coarse-grained subunit (Qpvuc) is differentiated where stacked gravel bodies constitute >50% of strata (over ~10-20 vertical m). Otherwise, the upper layer is called Qpvu where the proportion of gravelly intervals is 15-50% over 10-20 vertical meters. Unit Qpvuc is probably the most aerially extensive unit on the quadrangle, covering most of the land west of the Mud Springs Mountains. The upper layer becomes less gravelly northwards, so unit Qpvuc is not mapped north of Cuchillo Negro Creek.

Superb exposure of the middle layer along Cuchillo Negro Creek permitted differentiation of the middle layer into several subunits based on the proportion of gravelly intervals. The more gravelly nature of the lower part of the middle layer is represented by the transitional subunits Tpvmtf and Tpvmt, which collectively thin westward from ~30 m to 18 m. Subunit Tpvmtf has 5-15% gravelly intervals and interfingers westward with unit Tpvmt, which has 15-50% gravelly intervals. Above this transitional lower zone, the main body of the middle layer can be subdivided into a finer-grained, eastern part (QTpvmf, having 5-20% gravelly intervals) that interfingers eastward with the fine-grained, marginal basin lithofacies assemblage (Tpfm, describe below). Unit QTpvmf interfingers westward with a subunit containing 15-40% gravelly intervals (QTpvm), which in turn interfingers westward with a subunit containing 35-60% gravelly intervals (QTpvmc). It should be noted that the upper 10-15 m of the middle layer is conformably transitional with the upper layer of the volcaniclastic piedmont lithofacies assemblage; this transitional zone is explicitly differentiated where it lies above the fine-grained, marginal basin lithofacies assemblage.

Description

The volcaniclastic piedmont lithofacies assemblage consists of light brown to light reddish brown fine-grained sediment interbedded with gravelly intervals composed of >90% volcanic clasts. Photographs of deposits seen in the lower-transitional, middle, and upper layers are shown in Figures 7-12. Fine-grained sediment consists of silt, very fine- to fine-grained sand (lesser medium-lower sand), and clayey-silty very fine- to fine-grained sand. These fine beds are typically in medium to thick, tabular, internally massive beds and commonly have 1-25%, scattered, mU-vcU sand grains and trace-15% pebbles—consistent with hyperconcentrated flows. The fine beds also locally exhibit very thin to thin lenses of pebbly sand and sandy pebbles. Paleosols are locally present and typically developed below the upper contacts of some fine beds. These paleosols are characterized by cambic (Bw) or illuviated clay (Bt) horizons overlying calcic (Bk) horizons. Illuviated clay (Bt) horizons are typically reddish to orangish. Calcic horizons are characterized by lighter (whiter) hues and exhibit stage I to II carbonate morphologies (Gile et al., 1966).

The proportion of gravelly intervals progressively increase westwards so that near the western quadrangle boundary they are typically subequal with, or volumetrically more, than the fine-grained sediment. Gravelly intervals are mostly 0.5-6.0 m thick and exhibit very thin to medium, tabular to lenticular bedding with 1-15% cross-stratification (foresets up to 1 m tall). Gravels are subrounded (mostly) to rounded, moderately to poorly sorted, and weakly to strongly imbricated. Gravel is comprised mostly of pebbles with subordinate cobbles. Gravels are composed of 35-50% fine-grained intermediate volcanic rocks (about half of which are relatively fine-grained and platy basaltic andesite), 5-30% porphyritic intermediate volcanic rocks, 25-50% (mostly 25-40%) felsic volcanic rocks that are generally crystal-poor (excludes Kneeling Nun Tuff), 1-15% crystal-rich tuffs that mostly correlate to the Kneeling Nun Tuff, <3% monzonitic intrusive rocks, <5% Paleozoic limestones+Abo Formation clasts. There is a north-to-south trend in gravel composition characterized by: (1) a progressive increase in crystal-rich tuffs correlated to the Kneeling Nun Tuff (from 1-3% to 10-15%), (2) an increase of granite and gneiss from 0 to 3-5%, and a slight increase in the proportion of felsic clasts. Sand in the gravel matrix is fine-upper to very coarse-upper, subrounded to subangular, moderately to poorly sorted, and composed predominately of volcanic grains with subordinate feldspar and lesser quartz. Variable amounts of clay are present in the matrix, with higher proportions imparting an orangish color. There are minor poorly to very poorly sorted, matrix-supported, poorly imbricated, gravelly beds consistent with debris flows. However, most of the gravelly sediment shows variably degrees of clast imbrication, is clast- to matrix-supported, and sandy intervals are internally stratified (laminated); thus, we infer most of the gravels were deposited by stream-flow processes.

Depositional environments

Like previous workers, we interpret a piedmont depositional environment for sediment associated with volcanic-bearing gravel. Paleocurrent data (mostly clast imbrication) show a strong ESE flow direction, with indications of southward and northward deflections around the Mud Springs Mountains in all stratigraphic levels. Furthermore, the volcanic rock types match well those seen in the Black Range, southern Sierra Cuchillo, and northern Salado Hills (Fig. 3). The southward trend in Kneeling Nun Tuff mirrors proportions of this tuff in exposed bedrock, where it increases from <3% north of UTM Northing 3,687,000 in the Sierra Cuchillo to 10-20% in the northern Salado Hills.

Detailed interpretations of sedimentologic processes and paleogeomorphology can be made with the volcaniclastic piedmont depositional environment. First, gravels can occur either in concave-up, buttressed channel forms or as broad, tabular bodies. Preservation of cross-stratification is mostly restricted to the former, which is not surprising since the channel forms would promote greater water depths. Although more work is needed to quantify, our field observations suggest that tabular gravel bodies are more common towards the distal (east) end of the piedmont. Where overlain by fine-grained sediment, the tops of the gravels tend to be sharp or abrupt (over 1-3 cm) (Fig. 7). We interpret these observations to indicate that the gravels were deposited on intra-piedmont gully-mouth fan lobes or within paleochannels. Features consistent with paleochannels include limited lateral extents, concave-up basal contacts, cross-stratification, and heavily scoured bases (Fig. 7). Laterally extensive gravels with sparse cross-stratification may be associated with gully-mouth fan lobes. The sharp tops of the gravels are consistent with avulsion-dominated stream processes. As gravels aggraded, particularly on gully-mouth lobes, they eventually produced slight paleotopographic that promoted abrupt stream deflection (avulsion) and deposition on lower terrain surrounding these lobes.

In contrast to floodplain deposits seen adjoining the ancestral Rio Grande facies, the fine-grained deposits in the volcaniclastic piedmont lithofacies assemblage seldom are well-sorted clay, silt, or fine sand. Rather, they generally are poorly sorted clayey-silty fine sand with scattered grains of medium to very coarse sand and trace to 15% scattered pebbles (Fig. 7). Furthermore, these fine beds are typically in medium to thick, tabular, internally massive beds. Rather than being on a floodplain adjoining a topographically lower channel, we advocate that much of the fine-grained beds of the volcaniclastic lithofacies assemblage resulted from broad, unconfined, hyperconcentrated flooding at the mouths of discontinuous, intra-piedmont arroyos. Like gravel deposition, hyperconcentrated flood deposits at the mouths of arroyos would produce topographic highs with time and eventual fluvial inactivity due to avulsion—during which time soil formation would occur on the abandoned geomorphic surface.

Sediment-clast piedmont lithofacies assemblage

Key features and stratigraphy

Surrounding the Mud Springs Mountains are tan deposits consisting of interbedded fine sediment and conglomerate. The conglomerates are composed primarily of Paleozoic limestones and dolostones, with <10% cherts and silicified limestones. Locally, however, a conglomeratic deposit on the southwest side of the Mud Springs Mountains (Qpxu) is composed predominately of granite clasts with minor gneiss.

Mapping and observations by Foster (2009) and this work indicate that the upper 10-60 m of the sediment-clast piedmont lithofacies assemblage (unit Qpsu) prograded outward over finer-grained strata of the volcaniclastic piedmont lithofacies assemblage. In addition to its thick presence on the west-southwestern side of these mountains, the volcaniclastic piedmont lithofacies assemblage occurs as a 10-20 m-thick tongue along the northeastern flank. Away from this tongue, we demarcate the base of this upper, prograding unit by a dashed line of relatively constant elevation.

Below the progradational upper unit (Qpsu), the sediment-clast piedmont lithofacies assemblage fines-upward, as evident by up-section increases in the proportion of fine-grained beds versus gravelly intervals. However, this change is too gradual, and exposure not sufficient, to map a contact within this gradation. Thus, the sediment-clast lithofacies assemblage below the progradational, upper unit is lumped into QTps except for particularly fine-grained intervals at the southern end of the Mud Springs Mountains (QTsf). Unit QTps interfingers with the volcaniclastic piedmont lithofacies assemblage west and northeast of the Mud Springs Mountains. However, east of the southern part of the Mud Springs Mountains unit QTps interfingers with the fine-grained, marginal basin floor lithofacies assemblage.

Description

The progradational, upper 10-60 m of the sedimentary-clast piedmont deposits consists of interbedded conglomreaet and fine sediment that coarsen-upwards in conjunction with a basinward progradation of the associated alluvial fan/piedmont toe (Fig. 13). The conglomerate is in 0.5-3.0 m-thick intervals that are laterally extensive and tabular or else wedge-shaped; bedding within these intervals are very thin to medium (mostly thin to medium) and tabular to lenticular. Gravels are clast- to matrix-supported, locally imbricated, angular to subangular, and comprised of pebbles with subordinate cobbles and ≤10% boulders. The gravels are typically well-cemented by calcite. Fine strata occur in medium to thick, tabular to lenticular, internally massive beds. This fine sediment consists of tan stilstone to very fine- to fine-grained sandstone, in which there is minor coarser, scattered sand grains and up to 20% scattered pebbles. Burrows are locally abundant in the fine sediment and there are minor, thin to medium lenses of pebbles derived from Paleozoic rocks. Also, fine-grained strata exhibit common paleosols with stage III to IV calcic horizons locally overlain by reddish Bt or Bw horizons.

The undivided middle-lower part of the sediment-clast piedmont lithofacies assemblage is composed of conglomerate grading up-section to interbedded conglomerate and fine sediment, in conjunction with retrogradation of alluvial fan toe during the Pliocene. Conglomeratic intervals are in vague, medium to thick, tabular to lenticular beds. Gravel are clast- to matrix-supported, non- to moderately imbricated, and comprised of pebbles and cobbles, with the proportion of cobbles decreasing up-section in conjunction with a decrease in cobble size. Fine grained sediment is pale brown to very pale brown silt and very fine- to fine-grained sand in medium to thick, tabular beds that are internally massive. Within the fine sand and silt is 1-20%, scattered medium- to very coarse-grained sand grains and 1-5% thin pebbly beds. The lower, conglomeratic part of this unit is well-cemented, forming a prominent, whitish ledge over steeply dipping, reddish Abo Formation strata. Cementation of conglomerates becomes more variable up-section.

Depositional environment

The sediment-clast piedmont lithofacies assemblage represents deposition on a piedmont (probably alluvial fans) flanking the Mud Springs Mountains. The map position of this unit is restricted to the flanks of the Mud Springs Mountains. Moreover, the gravel types match what is present in these mountains, and paleoflow obtained clast imbrication are directed outward away from these mountains. These data collectively that this deposit represents piedmont or alluvial fan deposition on the flanks of the Mud Springs Mountains.

A key exposure ~300 m southwest of Cantrell Tank, documented by Foster (2009) and Mack et al. (2012, fig. 8), shows a lateral juxtaposition of sediment-clast piedmont deposits alongside volcaniclastic piedmont deposits. Some interfingering is present and no faults are observed, indicating a depositional contact. Interestingly, in the sediment-clast piedmont deposits are numerous well-developed paleosols, with Bt horizons overlying stage II to III calcic horizons. However, none of these soils extend into the volcaniclastic piedmont deposits. This is also observed in many other places along the eastern flank of the Mud Springs Mountains, where paleosols are more abundant in the sediment-clast piedmont deposits than volcaniclastic piedmont deposits. We interpret this to indicate more fluvial activity in the volcaniclastic piedmont deposits compared to the sediment-clast piedmont deposits. The higher and greater catchments associated with Black Range drainages resulted in more surface-discharge events that reached the distal volcaniclastic piedmont, resulting in more active, less stable geomorphic surfaces than the piedmont surrounding the Mud Springs Mountains. The latter appear to have witnessed fewer high-intensity precipitation events, and the geomorphic surface of the surrounding sediment-clast piedmont was more stable and less active than the volcaniclastic piedmont surface.

Axial-fluvial lithofacies assemblage

Key features and stratigraphy

Axial-fluvial deposits are readily recognized by quartz-rich, relatively clean (i.e., lacking interstitial silt-clay), white to light gray to very pale brown sand interbedded with subordinate gravelly sands or sandy gravels. Generally, the proportion of quartz grains is greater than feldspar + lithic grains. Gravels are mostly dominated by volcanic gravel, inferred to be derived from clastic input from tributaries sources in the Black Range, Sierra Cuchillo, and San Mateo Mountains (Fig. 3). However, their are certain stratigraphic intervals or units where granitic clasts (presumably from the Fra Cristobal Range) or extra-basinal gravel are present in notable quantities. This unit was referred to as the Crossbedded Sandstone facies assemblage by Foster (2009) and Mack et al. (2012).

The axial-fluvial lithofacies assemblage can be subdivided into a lower and middle unit. The middle unit occupies much more exposed area than the lower unit, the latter being restricted to the bluffs immediately north of Truth or Consequences and Williamsburg. The lower ~20 m of the middle axial-fluvial unit interfingers with the lower unit of the volcaniclastic lithofacies assemblage (Fig. 6). The lower axial-fluvial unit contains more gravels than the middle axial-fluvial unit (10-50% vs 1-20%). The lower axial-fluvial unit is comprised of three allostratigraphic subunits. The oldest (Tpal1) consists of sand and pebbly sand interbedded with 30-40% reddish-orangish sandy gravels. This deposit was incised by a paleovalley 17-20 m deep paleovalley that was later backfilled by the middle allostratigraphic unit (Tpal2). After deposition of Tpal2, the Rio Grande carved another paleovalley 17-19 m deep that was backfilled by the younger allostratigraphic unit (Tpal3), whose uppermost strata topped the paleovalley's eastern margin and onlapped Tpal2 strata (Fig. 14). Deposition of the succeeding middle axial-fluvial unit is conformable with the top of unit Tpal3. Below, we describe the lower axial-fluvial unit separately from the middle axial-fluvial unit.

Description

<u>Lower axial-fluvial unit</u>

Lower axial-fluvial deposits consist of very pale brown to white sand interbedded with 10-50% gravelly intervals. Sand is mostly horizontal-planar laminated to low-angle cross-stratified, but locally it may be massive. In terms of texture, the sand is fine- to very coarse-grained (mostly medium- to coarse-grained), subangular to rounded, and quartzo-feldspathic with subordinate lithic grains. The lithic grains are typically dominated by felsic volcanic compositions, but in some beds sedimentary compositions dominate.

Three allostratigraphic subunits are recognized near Truth or Consequences that also differ lithologically. The oldest allostratigraphic subunit (Tpal1) is an upward-coarsening unit consisting of sand and pebbly sand interbedded with 30-40% reddish sandy gravels. These gravels are in 0.2-1.0 m-thick intervals exhibiting vague, very thin, tabular to lenticular beds as well as local, <10 cm-tall cross-stratification.. Gravels are subangular to subrounded and composed of felsic volcanic clasts with 1-18% intermediate volcanic rocks, 0-13% Paleozoic carbonates, 5-30% green fine- to medium-grained sandstone inferred to correlate to the Crevasse Canyon Formation, 0-3% Proterozoic granite, 0-10% Abo Formation, trace-0.5% McRae Formation sandstone (similar to San Jose Member), trace feldspar-bearing porphyry (phenocrysts up to 4 mm long), and 0-1% Proterozoic gneiss. Gravel is exclusively pebble-size in lower 4.5 m of unit, but above contains 1-30% cobbles with 70-99% pebbles (Fig. 15). The reddish color in the sand matrix of the gravel is due to 1-25% clay as clast coatings or chips. Sand (mostly fine- to medium-grained) and pebbly sand intervals are white, massive, or horizontal-laminated to cross-laminated; however, sand in the lower 4 m of the unit is orangish. Where mapped, the subunit's basal contact is marked by a sharp transition to underlying Rincon Valley Formation.

The middle allostratigraphic subunit (Tpal2), filling a 17-20 m-deep paleovalley, consists of sand interbedded with 30-50% gravelly strata (Fig. 16). Gravel is mostly composed of felsic volcanic clasts with minor Paleozoic-Mesozoic sedimentary clasts and 1-3% intermediate volcanic rocks. In the lower-middle part of the unit, these gravels are 0.1-2 m-thick, typically massive with local low-angle cross-laminations, and composed of very fine to very coarse pebbles with minor (10-20%) cobbles in some beds. In the upper 3 m of the unit, cross-stratification is more pronounced in gravelly sediment and trace extra-basinal clasts appear (Pedernal Chert and quartzite) (Fig. 14C). The non-gravel fraction consists mainly of fine- to medium-grained sand that is mostly horizontal-planar laminated or massive, with local cross-lamination up to 20 cm tall. Unit Tpal2 contains a basal, 3-5 m-thick, coarse conglomerate (abundant coarse cobbles and fine boulders) composed of Paleozoic sedimentary rocks (mainly carbonates), subordinate greenish sandstone (probably from the Crevasse Canyon Formation), and ≤20% volcanic rocks + Proterozic rocks (see Koning et al., 2016, fig 2). The basal gravel are interpreted to reflect coarse input from alluvial fans north of the Caballo Mountains, on the eastern flank of the Mud Springs Mountains and, to a lesser extent, from the Fra Cristobal and San Mateo Mountains.

The younger allostratigrphic subunit (Tpal3) fills a 17-19 m deep paleovalley inset into the lower transitional zone of the volcaniclastic piedmont lithofacies assemblage (Tpvl), on the west, and the paleovalley backfill of Tpal2 on the east (Koning et al., 2018). Its strata are in very thin to thick, tabular to broadly lenticular beds that are locally cross-stratified. Gravel occupies an estimated 25-60% of this unit and cobbles are relatively abundant (Fig. 14).

The contrast in gravel proportions between Tpal3 with the overlying, sandier Tpam unit commonly forms a topographic bench at the Tpam/Tpal3 contact. The gravel assemblage has about equal amounts of felsic vs intermediate volcanic rocks, in addition to notable 10-40% of exotic clasts—mainly quartzite and trace Pedernal chert. Sand in gravel matrix is white to very pale brown, mostly medium- to coarse-grained and subrounded, and well sorted.

Middle axial-fluvial unit

The middle axial-fluvial unit consists of white to light gray, fine- to coarse-grained (mostly medium-grained) sand with 1-20% pebbly sand and sandy pebble conglomerates that are in <1 m thick. beds. Strata are cross-stratified (with common trough cross beds 0.1-1.5 m thick) or horizontal-planar laminated to very thinly bedded (Fig. 16). In the lower 20 m of the unit, cross-stratification is very sparse; rather, very thin to medium, tabular to lenticular beds dominate in that interval (Fig. 16). Pebbles throughout the unit are composed mainly of fine-grained, light-colored volcanic rocks inferred to be felsic. Subordinate pebble compositions include: darker, locally porphyritic intermediate volcanic rocks (0-20%), greenish sandstone (0-1%), limestone (0-5%), granite (10-30%), chert (0-25%), quartzite (0-15%). The proportion of extra-basinal clasts may increase up-section as well, but more work is needed to confirm such a trend. It is not uncommon to observe sparse (<5%) intra-formational clay-balls up to boulder-size. This unit exhibits sparse (<7%) intervals of fine-grained, thickly bedded (0.5-1.5 m-thick) sediment composed of clay, silt, very fine-grained sand, and clayey-silty very fine-grained sand. These fine strata are typically pink to reddish brown to brown, internally massive, and overprinted by nodular-calcic or vertic paleosols.

Depositional environment

We agree with previous workers (e.g., Lozinsky, 1986; Lozinsky and Hawley, 1986a,1986b; Foster, 2009; Mack et al., 2012) that these quartzo-feldsparthic, clean (lacking silt or clay) sands and pebbly sands were deposited by an ancestral Rio Grande. The trough cross-stratication in the middle-upper parts of the middle unit indicate that three-dimensional dunes were dominant bedforms (Perez-Arlucea et al., 2000). In the upper part of the middle unit, southerly paleoflow was measured using trough cross-stratification. Moreover, the presence of extra-basinal clasts, such as quartzite and chert, and quartz-rich sand are best explained by southerly transport from central New Mexico along an axial river. Sediment from local mountains is relatively quartz-poor, but quartz-rich sand is characteristic of the Santa Fe Group in the Albuquerque Basin and tributaries draining the Colorado Plateau (Brandes, 2002).

Fine-grained, marginal basin floor lithofacies assemblage

Key features and stratigraphy

Adjoining most of the middle axial-fluvial unit on the west is a large expanse of fine-grained, brown to light brown strata that have been erosionally sculpted to create beautiful badlands between Interstate 25 and the Mud Springs Mountains. The resulting exposures unequivocally demonstrate that this unit interfingers eastward with the middle axial-fluvial unit and westward with distal piedmont lithofacies assemblages derived from both volcanic terrain and the Paleozoic-cored Mud Springs Mountains. This unit is defined where the estimated proportion of gravel beds is less than 5%, whereas it is greater than 5-10% in the aforementioned distal piedmont deposits. This unit conformably underlies a 10-24 m-thick transitional zone at the base of the volcaniclastic piedmont lithofacies assemblage (locally mapped out as unit QTpvmt), in which the proportion of gravels increases above 10%.

Description

Strata of the fine-grained, marginal basin floor lithofacies assemblage consists of siltstone, very fine- to fine-grained sandstone, and mixed clay-silt-very fine-grained sandstone; claystone is subordinate compared to these other lithologies. Siltstone and fine sandstone are in light brown to brown, tabular beds 0.2-1.5 m thick; these beds are internally massive or exhibit faint horizontal lamina. Clayey beds are reddish brown, tabular, and commonly contain vertic and nodular-calcic paleosols. There are 1-5% thin to thick, tabular beds of pebble-conglomerate exhibiting local small-scale cross bedding (<30 cm thick, with the foresets commonly being low-angle). The conglomerates are mostly composed of volcanic rocks, although near the Mud Springs Mountains there are minor beds composed of Paleozoic sedimentary clasts. There are local (<2%) beds of microcrystalline calcite mixed with <5% sand grains (Mack et al., 2012). These ledge-forming features have sharp tops and bases, but some beds have nodular tops and some have root traces in their upper 15 cm. There are very minor (<2%) tongues of axial-fluvial sediment extending into this unit from unit Tpam.

Depositional environment

The fine-grained texture of this unit, and its unequivocal stratigraphic position between axial-fluvial and distal piedmont strata, indicate it was deposited on the margin of a wide basin floor (called "alluvial flat" by Mack et al., 2012). The very minor tongues of axial-fluvial sediment in the eastern part of the unit indicate occasional incursions there by the ancestral Rio Grande, but apparently there was sufficient eastward slope to prevent the river from sweeping across the central and western parts of this unit. This depositional environment received unconfined flow from alluvial fan arroyos to the west; the eastern part of this environment also likely received overbank deposition via Rio Grande flooding. This depositional environment had shallow groundwater that precipitated the white, microcrystalline calcite beds (Mack et al., 2000, 2012). The presence of roots at the tops of some beds indicate precipitation near the land surface. Interestingly, the calcite beds tend to thicken and become more numerous owards the Mud Springs Mountains, indicating that these mountains may have been a source for laterally flowing groundwater (Mack et al., 2012). More details regarding depositional environments of the various features of the fine-grained unit are given in Foster (2009) and Mack et al. (2012).

Age control

There is substantially more age control for the Palomas Formation than the underlying Rincon Valley Formation. These data come from rich fossil collections in the quadrangle combined with geochemical correlation of a pumice bed and reversal magnetostratigraphic work. Reversal magnetostratigraphic work includes previous efforts (Repenning and May, 1986; Mack et al., 1993, 1998, 2002) and new investigations accomplished in conjunction with geologic mapping of this quadrangle. Because of the technical nature of magnetostratigraphic studies, we plan to present and discuss the associated data in a peer-reviewed technical journal in the near-future. But we do summarize the results in our stratigraphic sections (Fig. 15). Below, we present and discuss a synthesis of available age control data for the transitional lower unit of the volcaniclastic piedmont lithofacies assemblage, lower unit of the volcaniclastic piedmont lithofacies assemblage, middle stratigraphic layer of the Palomas Formation, and upper stratigraphic layer of the Palomas Formation.

Transitional lower stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage

Dark gray, olivine-phyric, and vesicular basalt clasts, characteristic of Pliocene basalts in the western Palomas Basin (Jochems, 2015; Jochems and Koning, 2016; Koning et al., 2015), provide a means to constrain the age of the transitional unit of the volcaniclastic piedmont facies. A basalt clast collected immediately above a laterally extensive calcium carbonate bed (4 m below the top of the unit) has a preferred age of 5.06±0.02 Ma (Fig. 8; sample 16C-516, Koning et al., 2018). Thus, the strata overlying the marker calcium carbonate bed must postdate this age. Magnetostratigraphic work in the axial-fluvial facies indicates that the older of the two paleovalley fills are 5.0-4.9 Ma (see below)—providing a minimum age. Thus, the transitional lower unit of the volcaniclastic piedmont facies is interpreted to be 5.10-4.95 Ma.

Lower stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage

As noted in the stratigraphic relations section above, this 18-24 m-thick interval interfingers with the lowest strata of the middle unit of the axial-fluvial lithofacies assemblage. A basalt clast dated from the middle of the lower unit of the volcaniclastic piedmont lithofacies assemblage (Tvpl) returned an $^{40}Ar/^{39}Ar$ age of 4.49±0.03 Ma, which means the middle of the unit must postdate this age (Figs 5-6; Koning et al., 2018). Because it lies below the Truth or Consequences Local Fauna site (i.e, the Repenning Quarry), unit Tpvl must predate 3.3-3.6 Ma. These data, combined with our discussion of the age of the middle stratigraphic layer below, suggest that a. 3.8-4.5 Ma age range is reasonable for unit Tpvl.

Lower unit of the axial-fluvial lithofacies assemblage

Three allostratigraphic units are mapped in the lower unit of the axial-fluvial lithofacies assemblage. The first is unit Tpal1, which is correlated to unit Tpvlt based on overlapping elevations, similar stratigraphic positions, and the fact that both appear to immediately predate the first paleovalley that was backfilled by unit Tpal2. Tpvlt is inferred to be 5.10-4.95 Ma and so a similar age range applies for Tpal1. However, we can use magnetostratigraphic data for the Juniper Street stratigraphic sections to further narrow this age range (Fig. 15). Of the five samples in Tpal1 measured for reversal magnetostratigraphy, all except the lowest are reversed and correlated with C3n.3r within the Gilbert Chron. However, the lowest paleomagnetic sample in unit Tpal1, from unit MJ-3 in the Middle Juniper Street stratigraphic section located 2 m above the base of the unit, is normal and correlated to C3n.4n (Thvera). Given that the 4.997 Ma boundary between

3n.3r and 3n.4n (Ogg, 2012) appears to be only 2-3 meters above the base of unit Tpal1, we restrict the age of Tpal1 to be 5.05-4.95 Ma.

The two other allostratigraphic units of the lower axial-fluvial lithofacies assemblage backfill two paleovalleys incised into unit Tpal1; thus, they must be younger than Tpal1. Incision of the first paleovalley (filled by Tpal2) had to occur after 5.0 Ma (the median of the age of unit Tpal) but before the precipitation of the 4.87 Ma cryptomelane at the top of unit Tpal2. Reversal magnetostratigraphy on Tpal2 strata in the Revised South Poplar section (Figure 6) indicates a reversed polarity for all of this unit, which we correlate to Chron 3n.3r. According to Ogg (2012), the age range of 3n.3r spans 4.896 to 4.997 Ma, which can also apply to unit Tpal2. However, given that unit Tpal1 is also mostly in Chron 3n.3r, we prefer an age range for Tpal2 of 4.95-4.90 Ma.

The age and stratigraphic position of the 4.87 Ma cryptomelane presented in Koning et al. (2016) is critical for interpreting the age of the youngest paleovalley backfilled by Tpal3. The following interpretations is from Koning et al. (2018). The cryptomelane was locally precipitated in the upper strata of unit Tpal2 in a saturated, subsurface environment. The associated manganese precipitation clearly does not extend across a highly scoured contact into overlying younger deposits (Koning et al., 2016). The upper part of the paleovalley buttress contact was thus eroded after precipitation of the 4.87 Ma cryptomelane. Since incision of the younger, nested paleovalley (filled by unit Tpal3) would have dropped the local water table, we interpret that the 4.87 Ma cryptomelane deposit provides a maximum age for the base of the nested paleovalley (filled by unit Tpal3). The 4.5 Ma minimum age constraint is provided by the presence of the dated basalt clast in the middle part of the lower volcaniclastic piedmont lithofacies assemblage (Tpvl) and the eastward projection of this interval to 10-12 m above the base of unit Tpal2; also, the Truth or Consequeunces Local Fauna (~3.6-3.3 Ma) lies >15 m above the Tpam/Tapl3 contact.

Middle stratigraphic layer of the volcanic piedmont lithofacies assemblage

In the middle stratigraphic layer of the Palomas Formation, a key pumice bed and two local fauna sites are found in the Cuchillo quadrangle: Cuchillo Negro Creek and the Truth or Consequences Local Faunas. As noted, above, the lower unit of the volcanic piedmont lithofacies assemblage interfingers with the lower ~20 m of the middle unit of the axial-fluvial lithofacies assemblage. However, all of the middle unit of the volcanic piedmont lithofacies assemblage interfingers eastward with the middle unit of the axial-fluvial lithofacies assemblage above the aforementioned lower ~20 m.

The Mud Springs pumice is 10 cm thick and traceable for several hundred meters in Sections 20 and 29 (T13S, R4W), where it is interbedded in red mudstone and very fine sandstone. This bed consists of sand-size grains of pumice and is internally structureless. Major oxide chemical analyses using and ion microprobe indicate that this pumice bed is compositionally similar, particularly with respect to Fe, Ca, and Mn, to the 3.12±0.03 Ma Hatch Siphon pumice bed (Mack et al., 2009).

The Cuchillo Negro Creek local fauna site consists of 15 subsites north of Cuchillo Negro Creek and west of Interstate 25 where 12 vertebrate species were identified (Lucas and

Oakes, 1986; Morgan and Lucas, 2003; 2012; Morgan et al., 2011). These fauna are approximately at the same stratigraphic level as the 3.1 Ma Mud Springs pumice. Furthermore, the co-occurrence *of S. primitivus, B. hilli, and E. Scotti*, and the absence of post-3 Ma immigrant mammals from South America, tightly constrain the age of the Cuchillo Negro Local Fauna to between 3.3-3.1 Ma (Morgan and Lucas, 2012).

The Truth or Consequeunces Local Fauna is found immediately alongside Interstate 25 at a location 2.1 km south of the North Date Street exit. Stratigraphically, it is located about 30 m below the 3.1 Ma Mud Springs Pumice (using local stratigraphic correlations near the middle of Section 29, T13S, R4W) and ~30 m above the base of the middle stratigraphic layer (using elevation of the Tpam/Tpal contact south of the site). Collected fauna include 5-6 reptiles (turtles, lizards, and coachwhip snake), 17 mammals (rabbits, rodents, horses, deer, gomphothere, ground sloth, dogs, peccary, and antlocaprid.), several species of small fish, and 2 birds. According to Morgan and Lucas (2012), the mammals from the Truth or Consequeunces Local Fauna are most similar to late early Blancan faunas (~3.0-3.6 Ma) found in Benson (Arizona), Rexroad (Kansas), and Hagerman (Idaho). The Truth or Consequences Local Fauna are in sediment exhibiting normal polarity, which was initially interpreted to be the Nunivak Subchron of the Gilberg Chron (C3n.2n), which is ~4.5 Ma. However, Morgan and Lucas (2012) argue that having this normal polarity be in the lowermost Gauss Chron (C2An.3n; 3.33-3.58 Ma) is more compatible with the late early Blancan fauna and the site's stratigraphic position 30 m below the 3.1 Ma Mud Springs pumice (author's measurement using local stratigraphic correlations near the center of Section 29, T13S, R4W). Thus, this site is interpreted to be 3.3-3.6 Ma (Morgan and Lucas, 2012). Using the stratigraphic accumulation rate established for the 30 m of section between the Mud Springs Pumice and the Truth or Consequeunces Local Fauna (0.2-0.5 Ma/30 m), then the base of the middle layer of the axial-fluvial facies (located 30 m below this fauna site) is 3.6-4.1 Ma. A basalt clast dated at 4.49±0.03 Ma projects from the middle of the lower unit of the volcaniclastic lithofacies assemblage to 10-12 m above the base of the middle-layer of the axial-fluvial unit (Tpam) (Figs. 5-6), providing a maximum age for lowermost strata of the middle-layer of the axial-fluvial unit.

As discussed in Jochems and Koning (2015), the top of the middle interval (their unit QTpwm) is 3.0-2.6 Ma based on the co-occurrence of species *Paramylodon* and *Nannippus* that migrated to North America from South America shortly after 3.0 Ma. On the Williamsburg quadrangle to the south (Jochems and Koning, 2015), a transitional zone was mapped between the upper and middle stratigraphic layers (QTpwt) that was constrained by fossils to be 2.5-2.0 Ma. Locally on this quadrangle, a transitional layer was also mapped that is 10-24 m thick, and it interfingers westward with unit Tpfm of the middle stratigraphic layer. In summary, the age of the middle stratigraphic layer is Palomas Formation is constrained at ~4.5 to 2.6 Ma below the QTpvmt transitional zone, and ~ 4.5 Ma to 2.0 Ma where the upper transitional zone is not mapped.

Upper stratigraphic layer

There is no unique age control for the upper stratigraphic layer on this quadrangle. Based on above discussion of the middle stratigraphic layer, the maximum age of the upper layer ranges from 2.6 (where the QTpmvt transitional zone was mapped) to ca. 2.0 Ma (where this transitional zone was not mapped). The minimum age of the upper stratigraphic layer would coincide with the age of the Cuchillo surface, which is interpreted to be 0.8-0.9 Ma (Mack et al., 1993, 1998, 2002, 2009).

POST-SANTA FE GROUP DEPOSITS AND GEOMORPHIC SURFACES

High-level geomorphic surfaces

The Santa Fe Group aggraded until 0.8-0.9 Ma based on reversal magnetostratigraphy conducted between Truth or Consequences and Las Cruces, where the Jaramillo subchron (0.989-1.07 Ma per Ogg, 2012) was likely encountered in at least two stratigraphic sections (Mack et al., 1993, 1998, 2002, 2009). Post 0.8-0.9 Ma incision, likely due to intensification of glacial-interglacial paleoclimatic cycles (Connell et al., 2005), allowed preservation of the broad, gently sloping (1-2° east), planar to slightly concave-up Cuchillo geomorphic surface. Gravelly substrate under this surface in the Palomas and Engle Basins inhibits erosion via valley widening. Consequently, the Cuchillo surface extends over broad areas in and near the study area. This noteworthy geomorphic feature rises ~90 m above the modern floodplain of the Rio Grande and underlain by mature soils with thick argillic horizons overlying petrocalcic horizons (stage III to IV) (McCraw and Love, 2012).

Post 0.8-0.9 Ma incision did not proceed in a smooth, continuous manner. Rather, there were time periods when brief aggradation occurred or local base levels were steady and streams were able to widen the valleys. Subsequent stream incision then preserved remnants of these wider valley floors as terraces (where narrow and flanking a valley) or abandoned piedmont surfaces (flat inter-drainage topographic highs).

Geomorphic surfaces underlain by high-level piedmont deposits

Abandoned piedmont surfaces at moderate to high geomorphic levels, underlain by relatively thin piedmont deposits, are common throughout the Cuchillo quadrangle. South-sloping, abandoned piedmont surfaces/deposits are mapped on the lower northern slope of Yaple Canyon. These surfaces are 2-10 m above the floors of adjacent, larger drainages. Near the Truth or Consequences Border Control Station, higher abandoned piedmont surfaces rise 8-15 m above adjacent canyon floors. A conspicuous, thin piedmont deposit is mapped along Cuchillo Negro Creek northwest of the northern tip of the Mud Springs Mountains (unit Qpc). This surface clearly grades into terrace level 5 of the lower suite of Cuchillo Negro terraces. It is 1-3 m thick and composed of volcanic sandy gravel reworked from the upper Palomas Formation.

East and southeast of the Mud Springs Mountains are extensive, high-level geomorphic surfaces overlying relatively thin, gravelly piedmont deposits derived from the Mud Springs Mountains (where the gravel is composed predominately of Paleozoic carbonate clasts). By far the most extensive of these levels is the middle level (Qpm; Fig 17). This surface rises 6-27 m above adjacent arroyo floors, the large range due to differential incision of local arroyos (with those draining to northeastward towards Cuchillo Negro incising more deeply than those draining southeast towards Truth or Consequences). It appears to grade to terrace level 4 (Qtc4), although correlation to Qtc5 is possible locally, of the lower suite of Cuchillo Creek terraces. The tread (upper surface) of a lower piedmont deposit lies 3-5 meters below the extensive middle geomorphic surface, and higher levels rise 2-7 m above the middle level.

Gravelly piedmont deposits beneath the lower and higher geomorphic surfaces are only 1-3 m thick; thus, the scoured, relatively basal contact of these deposits could be envisioned as a pediment (while the top of the deposits is what we previously referred to as a "geomorphic surface"). However, the alluvium locally is as much as 6 m thick beneath the extensive, middle geomorphic surface—too thick for the basal contact to be considered a pediment. Available exposures of the middle-level piedmont deposit exhibit sandy gravel and pebbly sand in thin to medium, tabular to lenticular beds. There is local cross-stratification in the pebbly sand (very thin to thin, planar to tangential foresets up to 0.8 m tall). The gravel consists of subrounded to subangular pebbles with 10-20% cobbles and trace-5% boulders. Gravel is generally clast-supported and imbricated, consistent with stream-flow or hyperconcentrated flow deposition, but there are minor interpreted debris flows that are matrix-supported, contain more cobbles, and have a sandy matrix with 1-5% silt-clay. Sand is generally medium- to very coarse-grained and composed of detritus from Paleozoic sedimentary rocks

Terraces

Three terrace levels are correlated in Cañada Honda and Mud Springs Canyon. Associated tread heights above adjoining valley floors are approximately: 4-7 m, 8-11 m , and 12-15 m (lowest to highest levels, respectively). Two levels of terrace gravels are mapped near Cantrell Tank, with the higher being ~25 m above adjacent valley floors and the lower being ~22 m. The Mud Springs fault has produced a 3 m tall scarp on the lower of Cantrell

Tank terraces, so the age of this terrace would be a useful complement to previous studies (Foley et al., 1988) in constraining the middle-late Quaternary paleoseismic history and long-term displacement rates of this active fault. We preliminary correlate the two terrace levels by Cantrell tank to the middle and lower of the aforementioned geomorphic surfaces, underlain by high-level piedmont deposits, east of the Mud Springs Mountains.

Terraces preserved along Cuchillo Negro Creek are divided into a lower suite and higher suite (Fig. 17). The lower suite includes 6 terrace levels whose tread heights range from 4-7 m (lowest, Qtc1) to 34-37 m (highest, Qtc6). Terraces Qtc1 through Qtc4 are more laterally extensive than Qtc5 and Qtc6. The higher of these terrace levels (Qtc3 through Qtc6) typically exhibit strongly varnished surface clasts with local areas of well-developed desert pavement. The lower two terrace levels (Qtc1 and Qtc2) have notably weaker clast varnishing on their associated geomorphic surfaces; however, a stage III+ calcic horizon was discovered within the Qtc2 deposit, suggesting this terrace level is older than 60 ka and possibly as old as latest middle Pleistocene (UTM coordinates: 282,840 m E; 3679165 m N; NAD 83, zone 13; age inference based on comparison to the Desert Project (Gile et al., 1981). Gravelly alluvium beneath these treads are typically only 1-2 m thick. However, the second lowest terrace (Qtc2) is >5 m thick near Cuchillo and the fourth terrace level (Qtc4) is 2-7 m thick about 3 km west of the eastern quadrangle boundary. The 4th terrace level is particularly extensive and rises 27-32 m above the valley floor. The 4th and 5th terrace levels are important because the aforementioned middle abandoned piedmont surface (Qpm and Qpc) appears to grade to them, as apparent in SW1/4 Section 17 (T13S, R4W) and N1/2 Section 35 (T12S, R5W) (Fig. 17A).

Exposures of the lower suite of terrace deposits exhibit sandy gravel and subordinate pebbly sand in very thin to thick, tabular to lenticular beds with local cross-stratification (Fig. 17E). The subrounded, volcanic gravel consists of clast-supported pebbles with 10-50% fine to coarse cobbles and 0-7% boulders. The gravel assemblage is composed of 20-25% porphyritic intermediate volcanic rocks, 30% fine-grained intermediate volcanic rocks (including basaltic andesite), 30-50% felsic volcanic intermediate volcanic rocks, trace chert+jasper, trace-1% monzonitic intrusive rocks, trace-8% Paleozoic sedimentary clasts, and 1-3% Kneeling Nun Tuff (visual percentage estimations and data in Koning et al., 2016). The sand fraction is medium- to very coarse-grained and reddish brown, the color being due to 2-15% clay occurring as clast coatings or sand-size chips.

The higher terrace suite along Cuchillo Negro Creek is notably thicker than the lower suite, being 6-15 m thick as opposed to 1-6 m thick (Fig. 18). Their treads exhibit well-developed desert pavement development, strongly varnished clasts, as well as strong soil development manifested by stage III+ to IV calcic horizons. Three terrace levels were differentiated in this higher suite based on strath heights. The highest level (Qtch3) lacks fine-grained interbeds and has a tread that rises 57-63 m above the modern valley floor. The middle level (Qtch2) has a tread rising ~55 m above the modern valley floor. This level is important because a fine white ash was collected midway up the deposit; this ash is undergoing ion microprobe analyses in order to determine geochemical matches with dated ashes. The lower level (Qtch1) occurs on both sides of Cuchillo Negro Creek and is particularly thick (up to 15 m). Near Interstate 25, various erosional surfaces have developed on this the lower (Qtch1) terrace fill.

Deposits of the higher terrace suite are relatively well-exposed. The sediment is composed of sandy gravel in very thin to medium (minor thick), tabular to lenticular beds (Fig. 18). Gravel are clast-supported, subrounded-rounded, and comprised of very fine to very coarse pebbles with 10-40% cobbles and 0-1% boulders. Gravel composition (visual estimation) is 20-35% porphyritic intermediate volcanic, 50% fine-grained intermediate (including basaltic andesite), 15-35% felsic volcanic rocks, trace-1% Kneeling Nun Tuff, 0-1% Paleozoic sedimentary rocks, and trace monzonite intrusions. The sand is mostly medium- to very coarse-grained and reddish brown due to 1-15% clay in the sand matrix occurring as chips or clast coatings. Fine-grained beds of clay-silt, very fine- to fine-grained sand, or silty-clayey very fine- to fine-grained sand are present in units Qtch1 and Qtch2. The terrace deposits thin (wedge-out) laterally away from Cuchillo Negro Creek. Based on observed buttresses, these terrace deposits appear to represent separate depositional episodes separated by incision events.

Valley floor alluvium

Low geomorphic levels are comprised of valley floor alluvial units (Fig 19). Modern alluvium (Qam) is mapped for grayish brown to light brownish gray, sandy gravel underlying fluvially active channels. Gravel includes pebbles with subordinate cobbles and boulders that are mostly subrounded, poorly sorted, and composed of lithologic types reflective of source area (typically volcanic). It is readily noted by fresh-appearing bars, swales, and gullies created by water action in the past ~60 years. Vegetation is sparse and no topsoils present.

Historical alluvial is mapped for sandy gravel and subordinate pebbly sand that underlie low geomorphic surfaces whose treads are 0.3-1.0 m above adjoining active channels (Fig. 19). Sediment is mostly in very thin to thin, tabular to lenticular beds. Gravel is mostly clast-supported, imbricated, and consists mainly of pebbles with minor cobbles and 0-10% boulders. Its associated geomorphic surface is not varnished, does not have desert pavement, and features bar-and-swale topography (5-50 cm in height, mostly 5-30 cm). Weak A horizons may be present in the upper 5-10 cm of the deposit; underlying calcic horizons, if present, are very weak. Based on age control elsewhere in the Palomas Basin, we assign an age of 600-60 years to this unit (Jochems and Koning, 2015).

Younger alluvium underlies treads (upper surfaces) that are typically 1-3 m above adjoining active channels (Fig. 19). It differs from historic alluvium in both its geomorphic surface and deposit. The geomorphic surface lacks bar-and-swale topography, locally has a weak desert pavement, and is very weakly varnished (compared to the Historical geomorphic surface). Where not eroded, the surface is underlain by weak soils sporting calcic horizons (stage I) locally overlain by ~10 cm-thick, dark gray A horizons. Younger alluvium is composed of sandy gravel and pebbly sand that are mostly in very thin to thin, tabular to lenticular beds. In contrast to historical alluvium, sand beds are more internally massive and less laminated.

Older alluvium is mapped for sandy gravel and gravelly sand deposits whose surfaces are typically >2 m above modern grade and higher than nearby Younger Alluvium treads. Where not eroded, its surface exhibits weak clast varnishing or desert pavement development. The tread of this unit is lower than what we generally mapped as terrace deposits, but it may be at similar geomorphic positions as the 1st and 2nd terrace levels (Qtc1 and Qtc2) along Cuchillo Negro Creek.

STRUCTURE AND TECTONIC HISTORY

General

Stratal tilts

The Mud Springs Mountain are a northeast-tilted bedrock high. Paleozoic strata in these mountains strike 300-360° and dip 20-40° NE. The Palomas Formation, on the other hand, dips less than 2° and can be characterized as subhorizontal. A reliable attitude obtained near Interstate 25 indicates that strata strike 310°, parallel to the trend of the lower Mud Springs fault, and dip ≤2° NE. Underlying uppermost Rincon Valley strata exposed in the bluffs immediately north of Williamsburg and Truth or Consequences have a similar attitude or, to the east, appear to be subhorizontal. However, older Rincon Valley strata exposed 2.5-3.0 km southeast of the community of Cuchillo are highly tilted, similar in magnitude to bedrock strata of the Mud Springs Mountains. There, beds of the upper and lower Rincon Valley Formation (Trbuc and Trpl) strike northerly and dip 26-37° E.

Structural highs vs lows

Gravity data of the region are contoured in Fig. 20 and allow a nice perspective on the general structure of the region surrounding the Cuchilo quadrangle. These data indicate a structural high underlies the Mud Springs Mountains and continues southeast under Truth or Consqueunces to the northern Caballo Mountains. This structural high continues northwards from the Mud Springs Mountains and coincides with the proximal footwall of the Mud Springs fault (discussed below). A prominent gravity low is located present south of Williamsburg and coincides with the structurally deepest part of the Palomas Basin (Jochems and Koning, 2015). Another gravity low is present north-northwest of Cuchillo and coincides with the Monticello graben of McLemore (2012). An oil explatory well indicates that basin fill in the Monticello graben is at least 1988 m thick (Gartland 1 Garner well in Lozinsky, 1987). A region of moderate gravity values extends due west of the Mud Springs Mountains, separating the Palomas Basin from the Monticello graben. As depicted on Figure 20, this region has a relatively high density of faults, consistent with what is typically seen in structurally high accommodation zones between major fault zones.

Faults and folds in Mud Springs Mountaains

Faults mapped in the Mud Springs Mountains generally parallel the trend of the mountains and strike of strata (NNW). Thrust, reverse, strike-slip, and normal faults are present, as mapped by Maxwell and Oakman (1990), but net slip on a given fault is typically <60 m. Most thrust faults dip westward and found on the western, steeper flank in the central Mud Springs Mountains, where they are closely associated with anticlines and synclines whose axial planes dip westward. Fold amplitudes are 10-80 m and relatively tight based on cross-sections of Maxwell and Oakman (1990). Locally, anticlines are overturned. These folds are relatively similar to fault-propagation folds mapped in the Caballo Mountain, including the larger-amplitude McLeod Hills fault-propagation fold (compare section B-B; of Maxwell and Oakman, 1990, with fig. 57 of Seager and Mack, 2003). The system of contractional thrust faults and folds may be a continuation of the North Ridge folds mapped in the northern Caballo Mountains that project WNW under Truth or Consequeunce (Kelley and Silver, 1952; Seager and Mack, 2003). The North Ridge folds affect strata as young as the Late Cretaceous Crevasse Canyon Formation and interpreted as Laramide features (Seager and Mack, 2003).

Most other faults in the Mud Springs Mountains consist of relatively steeply dipping faults with a component of vertical offset. More detailed study is needed to interpret whether they are related to contractional or tensile strain, the latter likely associated with Rio Grande rifting. One strike-slip fault, striking NNE, is mapped near the Cuchillo Creek gorge at the northern tip of the Mud Springs Mountains; local orientation of drag folds indicate right-strike slip on this structure (Maxwell and Oakman, 1990), consistent with NE-SW compression.

Appealing to regional structures and related previous interpretations of their genesis, we thus interpret the contractional structures in the Mud Springs Mountains to be strain features of the Laramide. However, based on data strictly within the Mud Springs Mountains we cannot completely rule out deformation caused by the Pennsylvanina Ancestral Rocky Mountain Orogeny—largely because Paleozoic strata postdating this orogeny are not present (i.e., Yeso Formation and San Andres Formation, which onlapped highlands produced by this orogeny; e.g., Kottlowski, 1963). No specific folds or faults have been directly related to the Ancestral Rocky Mountain orogeny in the well-studied Caballo Mountains (Kelley and Silver, 1952; Seager and Mack, 2003).

Santa Fe Group faults

Faults offsetting Santa Fe Group strata, mapped in the Engle and Palomas Basins away from the Mud Springs Mountains, can be grouped into two fault zones: the Cuchillo Negro fault zone to the west and the Mud Springs fault zone to the east. Both fault zones are found south and west of the Mud Springs Mountains. East and northeast of the Mud Springs Mountains, we (and previous workers) have not discovered faults offsetting the Santa Fe Group within the Cuchillo quadrangle.

Cuchillo Negro fault zone

The Cuchillo Negro fault zone comprises a set of north-striking, left-stepping en-echelon faults located 4 km west of the Mud Springs Mountains (per Machette and Jochems, 2016). These faults have created scarps on the Cuchillo surface that are typically 1-3 m tall, but their total vertical displacement remains poorly constrained. Two north-striking strands are present in the southwest quadrangle that are separated by 1.0-1.4 km. The eastern of these strands turns and strikes northwest at a location 1.2 km southeast of Doolittle Tank No. 1 and then merges with the western strand ~550 m north of this tank. The west-striking southern Mud Springs fault intersects this northwest-striking strand and does not continue across it. The scarp height of the northwest-striking north of this intersection appears to be double than south of the intersection. North of Doolittle Tank, maximum scarp heights on the western strand are only about 1 m. At a location 2.3 km southeast of Pendergrass Tank, The western strand likely curves and parallels an unnamed northwest-striking canyon. At a distance of 0.6 km north of Pendergrass Tank, this northwest-striking fault intersects another north-striking fault that is the southern continuation of the Willow Draw fault of McCraw and Williams (2012). Between Pendergrass Tank and Cuchillo Negro Creek, the Willow Spring Draw fault has produced a ~2 m-tall scarp on the Cuchillo surface. The Willow Spring Draw fault passes through the western part of the community of Cuchillo and then follows Willow Spring Draw northwards. In the southwestern Huerfano Hill quadrangle to the north, the Willow Spring Draw fault has produced an impressive 6 m-tall scarp (Cikoski and Koning, 2013) on the Cuchillo Surface. Thus, throw on this structure increases by a factor of three between Pendergrass Tank and where the 6 m height was measured (8.5 km north of Cuchillo). The Willow Spring Draw fault has produced a subtle, ~0.5 m-tall fault scarp on the highest terrace north of the community of Cuchillo, which we correlate to Qtch1..

Mud Springs fault

It has generally been inferred that a normal fault bounds the western front of the Mud Springs Mountains, and these mountains represent a footwall uplift similar to many other mountain ranges alongside the Rio Grande rift (e.g., Sandia, Magdalena, Caballo and Fra Cristobal Mountains; e.g., Lozinsky, 1987, and Machette and Jochems, 2016). Such a fault would align nicely with a NE- to N-striking fault mapped in the north-center of the Cuchillo quad that continues into the adjoining Huerfano Hill quad. This northern extension of the Mud Springs fault has produced a fault scarp ~2 m tall on the Cuchillo surface, and coincides nicely with a gravity gradient defining the eastern side of the northern Palomas basin (Fig. 20). Cross-section interpretations across this structure north of the Cuchillo quadrangle, constrained by deep oil exploratory wells, indicate ~2 km of west-down throw (Lozinsky, 1987; Adams and Keller, 1994).

The high magnitude (km-scale) of vertical displacement along the Mud Springs fault north of the Mud Springs Mountains, which we call the northern section of the Mud Springs fault, makes it a major structural element. This fault separates two en-echelon, right-stepping, deep basis of the Rio Grande rift: the northern Palomas Basin on the west and the southern Engle Basin on the east. The fault footwall, corresponding to a structural high called the Mud Springs uplift between these two basins, appears to continue uninterrupted southward to the Mud Springs Mountains (Lozinsky, 1987). However, our mapping has found no offset of the Palomas Formation by the central section of this fault in Cuchillo Negro Creek nor southwards along the western toe of the Mud Springs Mountains, where there almost certainly needs to be a buried fault to needed to produce this steep mountain range in late Neogene time. Thus, the central Mud Springs fault did not produce notable offset since 4-5 Ma, the age of the lower Palomas Formation exposed along Cuchillo Negro Creek. The northern segment of the Mud Springs fault only moved 2 m since development of the 0.8-0.9 Ma Cuchillo surface, and probably not much in the Pliocene based on lack of offset of exposed Palomas Formation units on the northern flanks of Cuchillo Negro Creek.

At the southern end of the Mud Springs Mountains, our mapping has shown that the Mud Springs fault inferred by Kelley and Silver (1952) indeed does exist, which we refer to as the southern section of the Mud Springs fault. It very likely connects with the Williamsburg fault southeast of the Rio Grande, as suggested by Foley et al. (1988) and Seager and Mack (2003). This fault strikes northeast and has downthrown the upper layer of the volcaniclastic piedmont lithofacies assemblage of the Palomas Formation alongside the lower and middle layers. It is exposed in the extreme southwest corner of Section 31 and continues northwestward to Cantrell Tank, where about 30 m of the upper, prograding sediment-clast lithofacies assemblage is preserved in the immediate fault hanging wall. From Cantrell Tank, the fault strikes westward and aligns nicely with a prominent west-striking, several meter-tall fault scarp mapped in the southwestern quadrangle. This west-east fault appears to hard-link with the Cuchillo Negro fault zone (discussed below). The only suggestion of a central segment of the Mud Springs fault is a subtle fault scarp located near the road to the Equator mine.

MINERALIZATION

The following discussion of mineralization is based on 1:12,000-scale and 1:1,200-scale mapping performed from 2016 to 2018 and is intended to supplement the findings of Maxwell and Oakman (1990). Refer to their work for discussion of sample mineralogy, sample analyses and the history of mines and prospects.

Structural Controls

The larger fault zone of the central section of the Mud Springs fault, mostly buried by Quaternary deposits but inferred to run along the base of the west flank of the Mud Springs Mountains, is interpreted to be the principal conduit for hydrothermal alteration and silver-base metal mineralization in the Cuchillo quadrangle. The main fault is accompanied by numerous splays whose orientations indicate at least one episode of wrench-style faulting. Local domains of west-verging reverse faults suggest positive flower structures along the wrench fault.

Stratigraphic Controls

Principal ore deposits on the west flank of the range occur within the Bat Cave formation, about 1 meter (a few feet) above the Hitt Canyon-McKelligon Formation contact. Two modes of alteration and mineralization are evident within McKelligon Formation and younger carbonate strata: 1) jasperoid replacements emanating from high-angle fractures and 2) ore mineral matrix replacements in clast-supported karst breccias. Two sub-parallel outcrops of jasperoid are located along or astride the wrench fault trend and can be traced discontinuously for 5.6 km (3.5 mi; Figure 21). These two outcrops have 150180 m separation in the NW ¼ of Section 13, T13S, R5W and converge both northward and southward. Most jasperoid exposures consist of high-angle feeder veins and attendant stratiform siliceous replacements; both display distinct Liesegang-style iron oxide banding. Vein jasperoids commonly contain vugs of quartz +/- calcite druse.

Equator (Three Brothers) mine

Mineralized paleokarst is evident at the Equator (Three Brothers) mine above the highwall of the 4-C quarry (Figure 21). Field relations suggest the probable structural and paragenetic sequence is: 1) pre-orogenic development of karst focused within a network of high-angle faults, 2) cavern roof collapse including development of sinkhole breccias, 3) initial uplift of the Mud Springs Range during the Laramide accompanied by local wrench faulting, 4) reactivation of fault trends that initially focused the karst features, 5) influx of silver-base metal-rich hydrothermal fluids, 6) metal deposition along faults but localized in karst breccia, 7) late (Cenozoic?) deposition of travertine and coarse crystalline calcite in steeply west-dipping dilational fractures.

Intrusive Porphyry Connection?

Structural controls, ore mineralogy and the presence of porphyritic intrusive rocks together suggest mineralization on the west flank of the Mud Springs Range may be the distal expression of a porphyry copper system. The Equator mine breccia reported by Maxwell and Oakman (1990) is exposed in the collars of the uppermost shafts and consists of two or more breccia bodies located at the intersections of E-W and N-S near-vertical fracture sets. Ore stockpiles from these workings contain abundant chrysocolla and copper carbonates. Both exposures exhibit the funnel-shaped geometry common to sinkholes. Intrusive felsic porphyry dikes and sills, though scarce, occur at several locations on the flanks of the range. An induced polarization survey and aeromagnetometry could provide better definition of breccia geometry and the presence of disseminated porphyry-style mineralization at depth.

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FIGURE CAPTIONS

NOTE: Figures are in the pages following the figure captions.

Figure 1. Map showing the Study Area relative to geographic features and Rio Grande rift basins (large, bold font) in southern New Mexico. Freeways and highways are shown as purple lines, while drainages are shown in blue. The Cuchillo quadrangle (denoted by a black rectangle) spans the structural high between the Palomas and Engle basins, occupying 64 square miles between the community of Cuchillo (the quadrangle's namesake) and the much-larger town of Truth or Consequences. Cuchillo Negro Creek, whose headwaters are in the Black Range west of Winston, flows southeast on the north end of the Mud Springs Mountains.

Figure 2. Geographic features within and immediately adjacent to the Cuchillo quadrangle, which is denoted by the black rectangle. The quadrangle totally encompasses the Mud Springs Mountains. Cuchillo Negro Creek flows southeast on the north end of the Mud Springs Mountains. It is mostly ephemeral, but may flow for several days upstream of the Mud Springs Mountains after heavy precipitation in the Mud Springs Mountains. Three named, southeast-flowing drainages are dry except briefly after heavy, localized thunderstorms: Yaple Canyon on the northeast and Cañada Honda and Mud Springs Canyons on the southwest.

Figure 3. Geologic map of the region around the Cuchillo quadrangle.

Figure 4. Fault contact between basin floor (Trbuc) and piedmont (Trpl) lithofacies assemblages of the Upper Rincon Valley Formation (Upper Miocene). The basin floor lithofacies consists of reddish (5YR), massive, fine sand interbedded with brownish (7.5YR), calcite-cemented lenses of medium to very coarse sand. Sparse pebbles in the basin floor lithofacies consist primarily of subequal proportions of Paleozoic sedimentary lithologies and felsic volcanics. The piedmont lithofacies consists of interbedded pebble-cobble channel-fill conglomerates, massive silt-sand, and massive pebbly sand, all pale brown in color (10YR). Clast lithologies in the piedmont lithofacies include Paleozoic sedimentary lithologies with subequal to subordinate proportions of felsic volcanics and greenish sandstone and siltstone; the latter are thought to be derived from Cretaceous bedrock. View faces southwest, which is also direction of stratigraphic throw along pictured fault. UTM 13S 282350 mE 3678855 mN NAD83.

Figure 5. Geologic map of the area northwest of Truth or Consequeunces. Location of basalt clast samples are shown by labeled open circles. The 4.87±0.05 Ma cryptomelane sample of Koning et al. (2016) is shown by the open square. Stratigraphic sections are shown by the thick, bold, white lines and labeled as WJS (West Juniper section), UJS (Upper Juniper section), and MJS (Main Juniper section). Map contours and shaded relief constructed using 4.5 m-resolution digital terrain model constructed by Intermap's STAR technology (Interferometric Synthetic Aperture Radar, or InSAR).

Figure 6. Vertically exaggerated (10X) B-B' cross-section across the geologic map of Figure 5, showing stratigraphic relations and the dimensions of the two paleovalleys backfilled by

units Tpal3 and Tpal2. Stratigraphic locations of dated basalt clasts are shown by open white circles. Stratigraphic position of the dated cryptomelane precipitation is depicted by the very dark gray shade on the right side of the figure. Note the bend in the section.

Figure 7. Photographs of sedimentologic features commonly seen in the volcaniclastic piedmont lithofacies assemblage. A) The basal contacts of gravels are always sharp and scoured, but the degree of scouring varies. The contact may be relatively planar or else wavy to irregular. This photograph illustrates a wavy lower contact of a gravelly channel fill overlying fine-grained sediment. The underlying sediment has scattered ("floating") clasts consistent with hyperconcentrated flow deposition (cf. Mack and Leeder, 1999; Mack et al., 2002; Seager and Mack, 2003). B) The basal contact of this gravelly interval is relatively planar on the right, but above the map board fills a relatively narrow paleo-gully. C through E) The upper contact of the gravelly intervals are usually abrupt (sharp or grade vertically over <3 cm), as illustrated in these photographs where fine-grained sediment overlies the clast-supported gravels. Note the clast imbrication in Photo D. In Photo E, above the sharp contact at the base of the ruler lies 40-50 cm of fine-grained, internally massive sediment with scattered coarse sand and pebbles —consistent with hyperconcentrated flows. F) An example of typical exposure of the fine-grained sediment lithofacies, bracketed on the top and base by pebble-dominated gravels, with a ~10 cm thick, discontinuous, clast-supported pebble bed in the middle of the exposure representing a small channel fill. The fine-grained is composed of very fine- to medium-grained sand with minor, scattered coarse to very coarse sand grains and <5% fines. The

reddish brown horizons at the pen and at the top of the fine-grained sediment correspond to Bt (illuviated clay) horizons of paleosols. G) Compared to those in Photo F, a better-developed paleosol is shown here of an illuviated clay (Bt) horizon overlying a >10 cm-thick stage II+ calcic horizon. The Bt horizon has moderate to coarse, subangular blocky peds with widespread (>50% coverage), distinct clay films on ped faces.

Figure 8. Photographs of the 30 m-thick transitional unit at the base of the Palomas Formation (Tpvlt), located on the west side of the geologic map of Figure 4 near Interstate 25. This unit is coarser than the Rincon Valley Formation, but oranger and less gravelly than the lower, coarse-grained unit of the piedmont volcaniclastic lithofacies assemblage of the Palomas Formation (Tpvl). A) View of the transitional unit east-southeast of Interstate 25, showing an up-section increase in the darker conglomeratic beds (latter noted by the white arrows). B) View of strata corresponding to middle of the cliff in Photo A and B, but located 0.5 km to the north. The paucity of conglomerates here indicates a northeastward lateral gradation, in which gravels decrease but the amount of calcium carbonate-cemented sandstones increase (including inferred travertines and shallow groundwater carbonates described in Mack et al., 2000). C) Photograph of the lower volcaniclastic unit of the Palomas Formation (Tpvl) overlying the basal Palomas transitional interval (Tpvlt). White arrow demarcates a laterally extensive (0.5-1.0 km) calcium carbonate bed interpreted to be travertine. Above this travertine lies ~4 m of a conglomerate-bearing interval that coarsens upwards in most places. D and E) Erosion in a spillway of a dam offers good exposure of the upper 4 m of the transitional unit, but here the upward coarsening is not apparent. This 4 m-thick interval is capped by a 30-60 cm-thick paleosol (Btk). Photo D

shows the upper part of this exposure, whereas Photo E shows the middle part. The black arrow points to the same feature in both photographs. The white arrow demarcates the laterally extensive travertine (same as the travertine noted in Photo C), and the white-filled circle indicates the approximate stratigraphic position of a basalt clast dated at 5.06±0.02 Ma (Koning et al., 2018). F) East of Interstate 25, the lower volcaniclastic unit of the Palomas Formation (Tpvl) lies in buttress unconformity against the basal Palomas Formation transitional unit (Tpvlt). Part of this buttress is outlined on this photograph, and the gray arrow points to a 15 cm-long ruler. This buttress occurs just above the upper contact of the middle axial-fluvial unit and about 3 m below the top of the west edge of the paleovalley (upper shelf seen in Fig. 6 ~110-180 m west of the bend in the section).

Figure 9. Photographs of the lower stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage of the Palomas Formation. This lower unit is dominated by volcaniclastic gravels. The white arrow in Photo A points to the scoured unconformity separating the lower unit from the underlying basal Palomas Formation transitional unit. Lead author's 11-year old daughter for scale.

Figure 10. Photographs of the middle stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage of the Palomas Formation. A) View of the middle volcaniclastic unit. Below the white calcium carbonate bed (about 40-50 cm thick; shown by white arrows), gravels occupy about a third of outcrop area (unit Tpvmt); above the white calcium carboinate bed, gravels are <30% (unit QTpvm). B and C) Transitional base of the middle unit (unit Tpvmt), which contains more gravels (30-50%) than higher in the unit (QTpvm);

person and hammer for scale in Photos B and C, respectively. D) View of a typical outcrop of the middle volcaniclastic unit (QTpvm), where the proportion of gravels is 15-25%; dog in foreground for scale. E and F) Interbedded tabular sandy gravels and fine-grained sediment, typical of the middle stratigraphic layer of the volcaniclastic piedmont lithofacies (QTpvm). Note the dark colors of the gravel, reflective of their volcanic composition. In the fine-grained sediment, the proportion of reddish Bt or Bw horizons is very low (<10%) compared to the upper stratigraphic layer of the volcaniclastic piedmont lithofacies. Arrow points to a hat in Photo F that provides a sense of scale.

Figure 11. Photographs of the finer-grained upper stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage of the Palomas Formation (unit Qpvu). A) and B) Typical exposures of unit Qpvu; note the overall light orange color. C and D) Close inspection of upper layer, volcaniclastic piedmont deposits generally reveals that much of the orangish colors are due to development of Bw or Bt horizons in paleosols—particularly noteworthy horizons are denoted by the white arrows. These reddish/orangish horizons are formed by oxidation and ped development of the original parent material (Bw) or clay illuviation (downward transportation of clay by percolating water). E) Gravelly interval overlying pedogenically altered, fine-grained material composed of a clayey mixture of silt through fine-lower sand. Within the Btk horizon(s) developed in the paleosol, peds are strongly developed and subangular blocky, clay films cover a minor amount of ped faces, and there are 20-25% calcium carbonate nodules ~1 cm across. The white spots by the hammer is calcium carbonate precipitated as nodules. F) A characteristic feature of the upper layer,

volcaniclastic piedmont deposits is the presence of 0.5-15% clay in the gravel matrix, as illustrated in this photograph.

Figure 12. Photographs of the coarser-grained upper stratigraphic layer of the volcaniclastic piedmont lithofacies assemblage of the Palomas Formation (unit Qpvuc). A) Photo of unit Qpvu overlain by a similar, gravel-dominated unit (Qpvuc). Qpvu consists of silty-clayey fine sand interbedded with subequal to subordinate pebble-cobble channel-fill gravels; here, gravels constitute only ~15-20% of unit. Qpvuc consists of gravelly, stacked channel-fills interbedded with subordinate mud and sand. Cross-stratification in upper-left of photo is characteristic of deposition in a fluvial setting. Muddy beds and clay in gravel matrices of both units imparts overall reddish to reddish brown colors (5-7.5YR). View faces north-northwest toward Cuchillo Negro Creek and Vicks Peak on horizon. Fence above outcrop is approximately 1 m high. UTM 13S 281080 mE 3678818 mN NAD83. B) Photo of stage IV calcic horizon in upper 0.5-0.6 m of the gravel-dominated Upper Palomas Formation (Qpvuc) underlying the Cuchillo surface. White carbonate coats clasts, plugs interclast voids, and is capped by laminar carbonate (not visible). Strong (stage III-IV) carbonate accumulation is common beneath the ~0.8 Ma aggradational surface of the Palomas Formation in the Cuchillo quadrangle. Rock hammer for scale is 25 cm long (circle). UTM 13S 283189 mE 3669667 mN NAD83.

Figure 13. Photographs of the sediment-clast piedmont lithofacies assemblage. These deposits are derived from the Mud Springs Mountains and deposited on relatively small alluvial fans surrounding these mountains. A through D) Photographs of the main body of

this assemblage; this sediment interfingers westward with the marginal basin floor, fine-grained lithofacies assemblage (Tpfm) and the middle to lower layers of the volcaniclastic piedmont lithofacies assemblage (Tpam and Tpal). A) Interbedded conglomerate and gravelly sandstone along the northeast flank of the Mud Springs Mountains. B) Bedding is typically tabular to lenticular, with cross-stratification being practically absent. C) Most of the gravel in the sediment-clast piedmont lithofacies assemblage was deposited by debris flows, consistent with the lack of sedimentary structures and weak clast imbrication. D) Fine-grained intervals are typically tan, internally massive, and have minor scattered gravels—consistent with deposition by debris flows or hyperconcentrated flows. The splotchy texture likely reflects differential cementation controlled by paleo-burrows. E) The upper layer of the sediment-clast piedmont lithofacies assemblage (Qpsu) prograded over the middle and lower-upper layers of the volcaniclastic piedmont lithofacies assemblage. This progradation is illustrated in this annotated photograph. The sediment-clast piedmont deposits (Qpsu) are tanner and better-cemented than the red-lt purplish, poorly cemented volcaniclastic piedmont lithofacies assemblage (unit Qpvu). Location of Photo F is shown by the black rectangle. F) Photo of the 2 m thick gradation between units Qpsu and Qpvu (black rectangle in Photo E). The conglomerate at the top of the photograph is composed of clast-supported conglomerate in very thin to medium, lenticular beds; note the heavily scoured contact; conglomerate is composed of >95% Paleozoic limestone clasts. Below lies silty very fine to fine-grained sandstone with 1% scattered, medium to very coarse sand grains; it grades in color from very pale brown (10YR 7/3) downward to light brown (7.5YR 6/3), possibly in conjunction with a downward increase in clay content. Below the pink ruler lies a 15 cm-thick bed of volcanic pebbles.

Figure 14. Photographs of the lower-layer axial-fluvial lithofacies assemblage (map unit Tpal), which can be subdivided into three allostratigraphic units called Tpal1, Tpal2, and Tpal3 (oldest to youngest). A-C) Photographs of unit Tpal3 onlapping Tpal2, immediately west of the buttress unconformity between the two. Gravel occupies an estimated 25-60% of Tpal3 and cobbles are relatively abundant. D) Close-up of the gravel composition of Tpal3, which contains about equal amounts of felsic vs intermediate volcanic rocks in addition to 10-40% of exotic clasts—mainly quartzite and trace Pedernal chert. In contrast, the gravel of units Tpal1 and Tpal2 is composed of felsic-dominated volcanic clasts and subordinate sedimentary clasts, all of which could be explained by erosion of highlands surrounding the Engle Basin. E) The upper part of the Tpal1 unit, which contains more gravels than the lower part. Exposure is ~3-5 m tall. F) The lower part of the Tpal1 unit, which has less abundant and finer gravels than the upper part. Note the redder color of the Tpal1 unit compared to Tpal2 and Tpal3.

Figure 15. Stratigraphic sections measured in the older and middle allostratigraphic units (Tpal2 and Tpal1) of the lower axial-fluvial facies assemblage. Locations of paleomagnetic samples are shown by solid-black rectangles. Unit Tpal1 differs from Tpal2 by its redder color and cobble-lacking lower 4.5 m. Colored rectangles to the left of the graphic columns summarize sediment colors. Unit labels correspond to those in Appendix 2.

Figure 16. Photographs of the middle-layer axial-fluvial lithofacies assemblage (map unit Tpam). This distinctive deposit interfingers westward with units Tpfm, Tpvmtf, Tpvmf, and

most of Tpvl. A and B) The upper part of Tpam exhibits relatively abundant cross stratification (with common trough cross beds 0.1-1.5 m thick) in fine- to coarse-grained sand and lesser pebbly sand. Foresets in Photo B dip downstream. C) Concave-up basal channel scours, denoted by the white arrows, are relatively common in this photograph of the upper part of Tpam. The lower 1 m of the exposure (right side of photograph) consists of hard, light brown to light reddish brown clay-silt laid down in a floodplain environment. D) Sand (mostly very fine- to fine-grained) and clay-silt in tabular beds characterize this 10-13 m tall exposure of the lower ~20 m of the Tpam unit. E) Thin to medium, tabular beds of sand with 15-20% very thin to medium, lenticular to broadly lenticular pebbly beds are present in this ~12 m tall exposure. Like Photo D, this part of the section is in the lower part of Tpam, which has less cross-stratification than higher in the unit. F) A 10-30 cm-thick lens of pebbles with ~10-15% fine cobbles interbedded in medium-grained sand.

Figure 17. Terrace and high-level deposits mapped alongside Cuchillo Negro Creek. A) View to SSW towards Mud Springs Mountains. Two terrace levels are labaled: Qtc2 and Qtc4. The surface of the middle of the high-level piedmont deposits (Qpm) projects close to the tread of the Qtc4 terrace. At the foot of the Mud Springs Mountains, the Cuchillo surface is preserved on Qpsu. B) A 60 cm-thick, stage III+ K horizon is developed on cobble-rich gravel at the second terrace level (Qtc2) (UTM coordinates: 282,843 m El 3,679,164 m N). Off the photo to the right, this gravel overlain by 3 m of light brown sand (mostly fine-grained) with 15-20% medium, tabular-lenticular interbeds of clast-supported pebbles—interpreted to be distal alluvial fan deposits from side canyons. C) Two subunits of the third-level terrace (Qtc3), view to northwest (up-canyon). The difference in tread heights

between Qtc3a and Qtc3b is only 1.5 m. The white arrows point to the riser between the two terraces. This photograph illustrates the difficulty of determining whether subunits of a terrace (Qtc3a and Qtc3b) are separate cut-and-fill events or simply a younger surface eroded on the same fill (fill-cut terrace). The fill of Qtc3a and Qtc3b appear to be continuous, but a cryptic buttress unconformity may exist. The strath of Qtc3a is ~1-1.5 m lower than the strath of Qtc3b; the difference may reflect younger strath erosion associated with Qtc3a, or it may simply be due to deposition of a single deposit on a northward sloping paleosurface. D) Paleovalley backfilled by unit Qtc3b, view to the northwest. This terrace deposit is only 1-2 m thick to the right of the paleovalley, but 4-6 m thick within the paleovalley. White arrow points to the paleovalley margin. E) Photograph of the deposit of terrace Qtc4. This 1 m-tall exposure shows vague, thin-med, lenticular-broadly lenticular beds of sandy gravel. There is an estimated 1-4% clay in the gravel matrix, which largely consists of fine- to very coarse-grained sand. F) Desert pavement is well-developed on the Qtc4 surface. Note the clast armor and strong clast varnishing.

Figure 18. A) High-level terrace deposits mapped in lower Cuchillo Negro Creek. Looking northwest (up-canyon) from 288,260 m E; 3,674,980 m N (UTM coord; NAD 83, zone 13). The three main terrace levels are seen, labeled Qtc1 (lowest) to Qtc3 (highest). Distinctly different strath elevations plus local exposed buttresses indicate that each of these terraces likely represent separate cut-and-fill events. B) Well-developed desert pavement on top of the highest terrace: Qtc3. However, the pavement doesn't appear appreciably different from pavements locally formed on stable surfaces in terrace deposits Qtc4, Qtc5, Qtch1, and Qtch2 (See Fig. 17F). C) Sandy gravel of the Qtch1 terrace deposit. It is ~25 m thick here,

which is appreciably thicker than sandy gravel intervals observed in the Palomas Formation. D) Sandy gravel interbedded with subordinate brown, clayey-silty sand (mostly fine-grained sand). White arrow denotes a 30 cm-thick bed of fine, white ash that was sampled. E) Sandy gravel of the highest terrace deposit mapped along Cuchillo Negro Creek (Qtch3). This terrace deposit is 4-5 m thick, thinning northwards, and composed of sandy gravel in thin-medium, tabular to lenticular beds.

Figure 19. Photographs illustrating valley floor, Holocene deposits. A) Historical alluvium (Qah) consisting mainly of sandy gravel in very thin to thin, tabular to lenticular beds. The sand is brown and mostly medium- to very coarse-grained. There is no notable topsoil development. The surface (not adequately depicted in the photograph) has >5 cm of bar-and-swale relief. This particular deposit is likely less than 200 years old. B) Younger alluvium (Qay) consisting of sandy pebbles and pebbly sand in very thin to thin, tabular to lenticular beds. There is minor cross-stratification seen in the right of the photograph (white arrow). C) Photograph of the surface of Younger alluvium (Qay) adjacent to the exposure depicted in Photo B. Note how it lacks bar and swale topography and has no notable clast varnishing. Backpack for scale. D) Locally, unit Qay has a desert pavement clast armor with very weak clast varnishing and calcium carbonate rinds around parts of clasts. Pen for scale. Usually, Av ped development is weak and the uppermost 3 cm of the soil is gravelly or sandy rather than silty-clayey (as is the case in well-developed desert pavements).

Figure 20. Complete Bouguer-anomaly gravity map of the area in and around the Cuchillo quadrangle. The Cuchillo quadrangle is outlined in black. Note that lowest Bouguer values are in the eastern Engle basin, Monticello graben, and Palomas Basin south of Williamsburg. Data from Kucks et al. (2001). Reduction density = 2.67 gm/cc; sea level datum. Contour interval = 2 mGal.

Appendix 1. Detailed descriptions of Cuchillo quadrangle map units.

Appendix 2. Stratigraphic sections of early Rio Grande deposits.

Figure 1

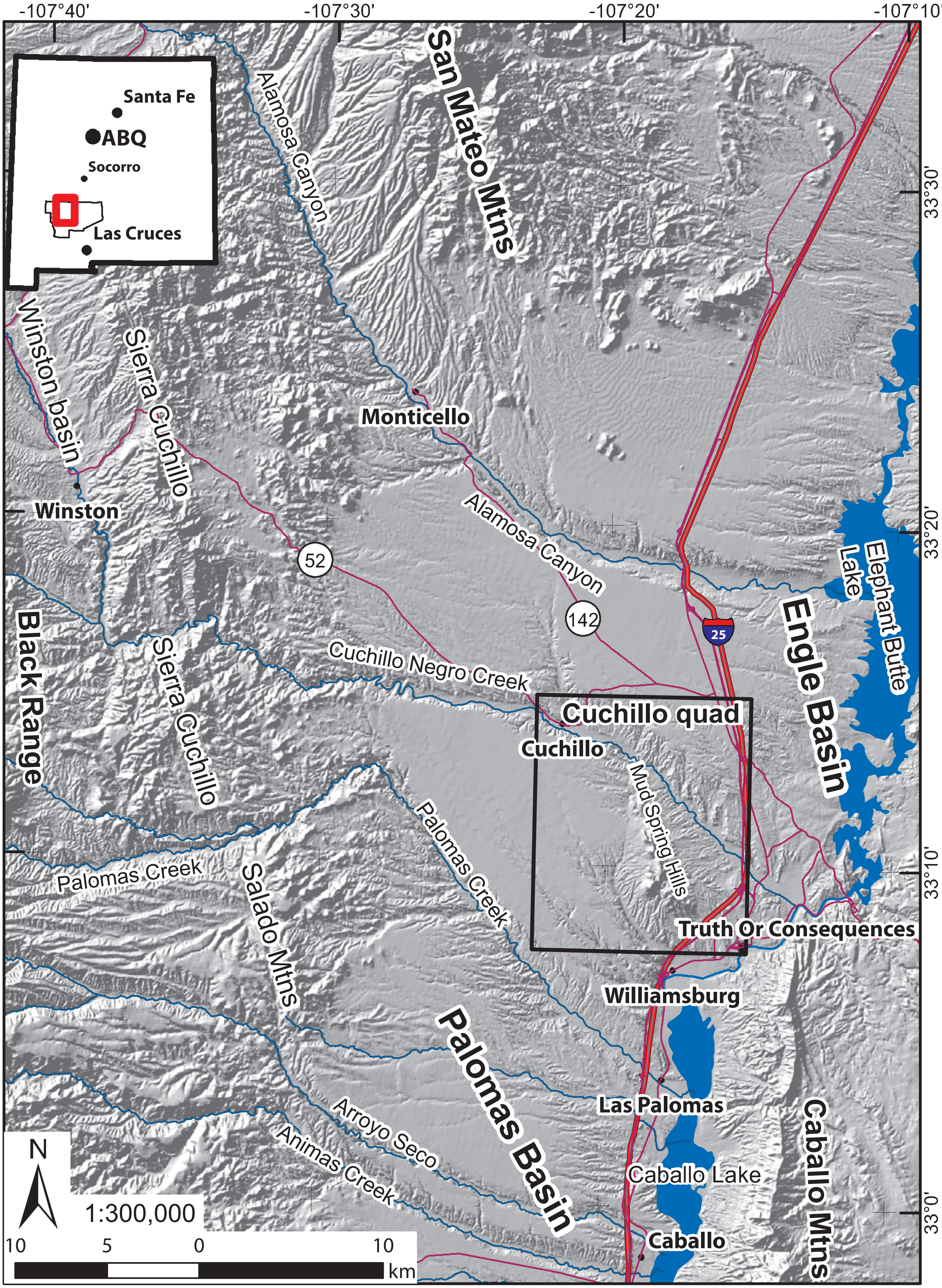
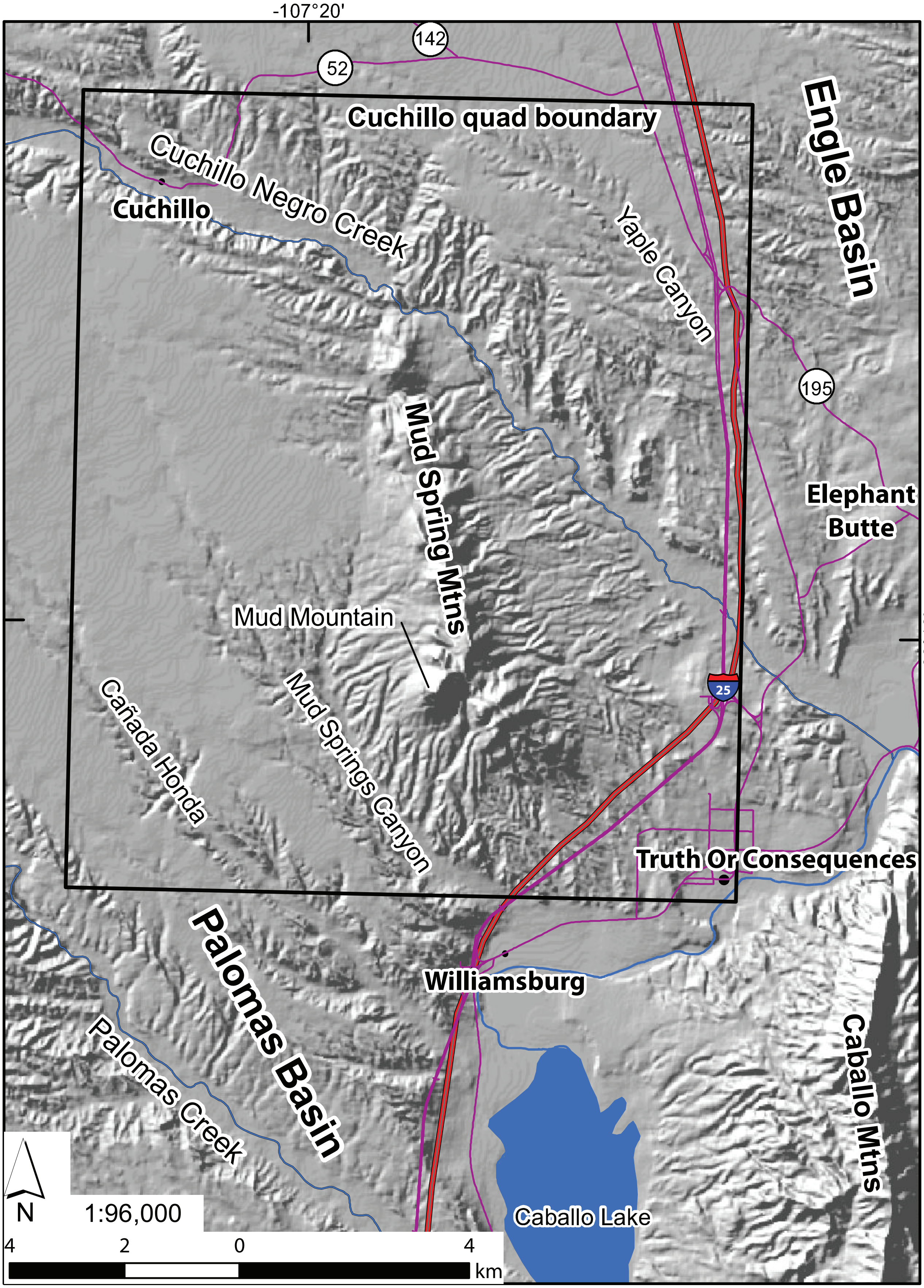
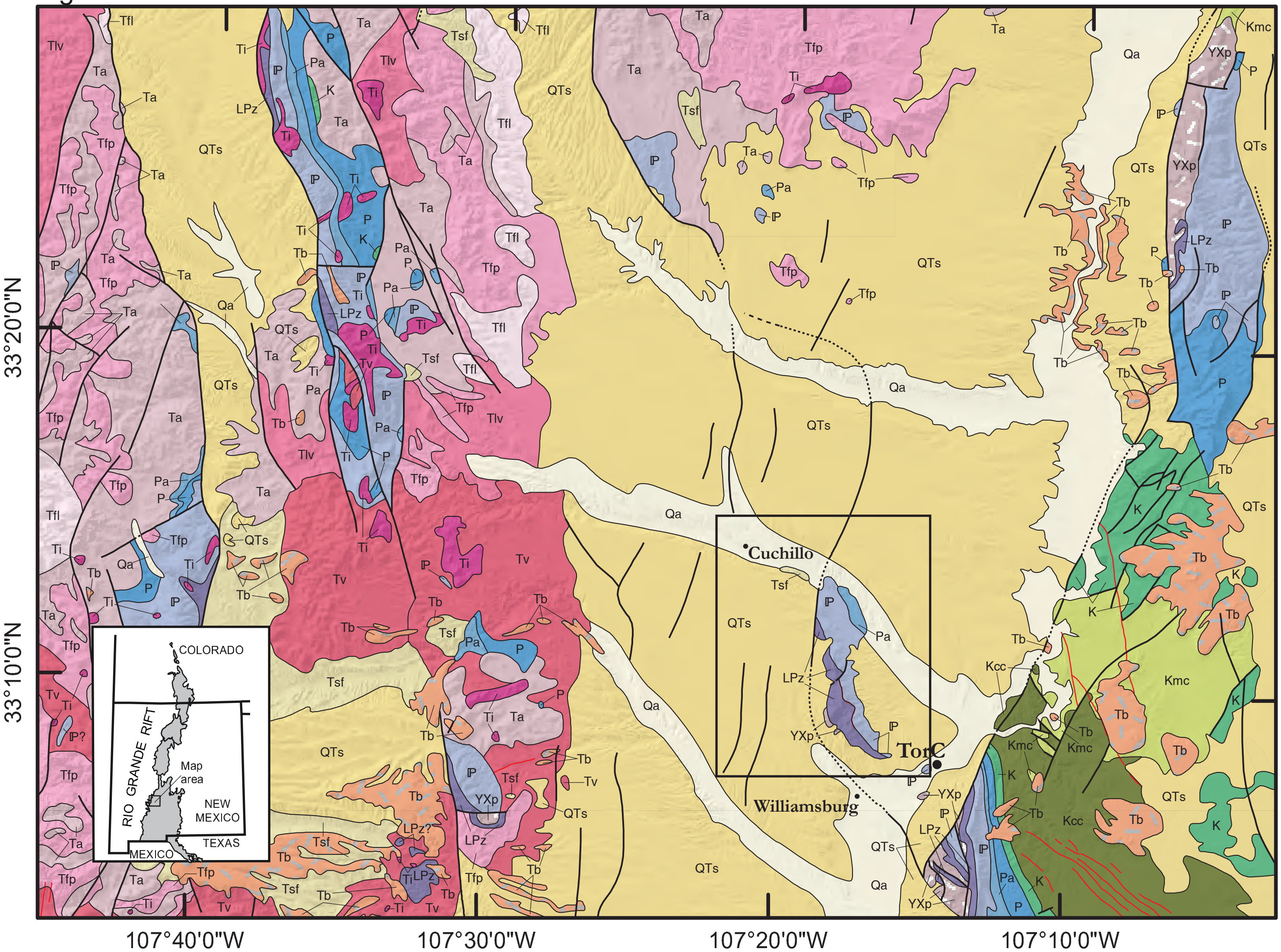

-107°40'
-107°30'
-107°20'
-107°10'
33°30'
33°20'
33°10'
33°0'
Santa Fe
ABQ
Socorro
Las Cruces
San Mateo Mtns
Alamosa Canyon
Monticello
Winston basin
Sierra Cuchillo
Winston
52
Alamosa Canyon
142
25
Elephant Butte Lake
Engle Basin
Black Range
Sierra Cuchillo
Cuchillo Negro Creek
Cuchillo quad
Cuchillo
Mud Spring Hills
Palomas Creek
Salado Mtns
Palomas Creek
Truth Or Consequences
Williamsburg
Palomas Basin
Las Palomas
Caballo Mtns
Arroyo Seco
Animas Creek
Caballo Lake
Caballo
N
1:300,000
10 5 0 10
km

Figure 2



-107°20'
142
52
Cuchillo quad boundary
Engle Basin
Cuchillo Negro Creek
Cuchillo
Yaple Canyon
195
Mud Spring Mtns
Elephant
Butte
Mud Mountain
33°10'
25
Cañada Honda
Mud Springs Canyon
Truth Or Consequences
Palomas Basin
Williamsburg
Palomas Creek
Caballo Mtns
N
1:96,000
4
2
0
4
km
Caballo Lake

Figure 3



EXPLANATION

Middle Pleistocene-Holocene deposits

- Qa — Valley-floor and piedmont alluvium

Miocene-middle Pleistocene basin-floor deposits and basalt

- QTs — Palomas Formation (Upper Santa Fe Group)
- Tsf — Lower Santa Fe Group
- Tb — Pliocene basalt flows (scarce Miocene flows)

Lower-upper middle Tertiary volcanic and intrusive rocks

- Ti — Intrusive rocks of mostly intermediate composition
- Tv — Volcanic rocks, undivided
- Ta — Basaltic andesites and andesites
- Tfp — Felsic pyroclastic rocks (ash-flow tuffs)
- Tfl — Felsic lavas
- Tlv — Intermediate volcaniclastic sediments with minor intermediate lavas

Cretaceous

- K — Cretaceous rocks, undivided; Gallup Sst through McRae Fm
- Kmc — McRae Formation
- Kcc — Crevasse Canyon Formation

Paleozoic

- P — Permian rocks, undivided
- Pa — Abo Formation
- IP — Pennsylvanian rocks, undivided
- LPz — Lower Paleozoic rocks (Cambrian-Mississippian, undivided

Proterozoic

- YXp — Meso- and Paleo-proterozoic plutonic rocks, undivided

Dike

Contact

Fault; solid where exposed, dashed where inferred, dotted where buried

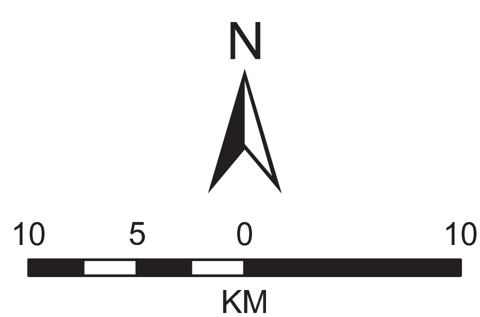
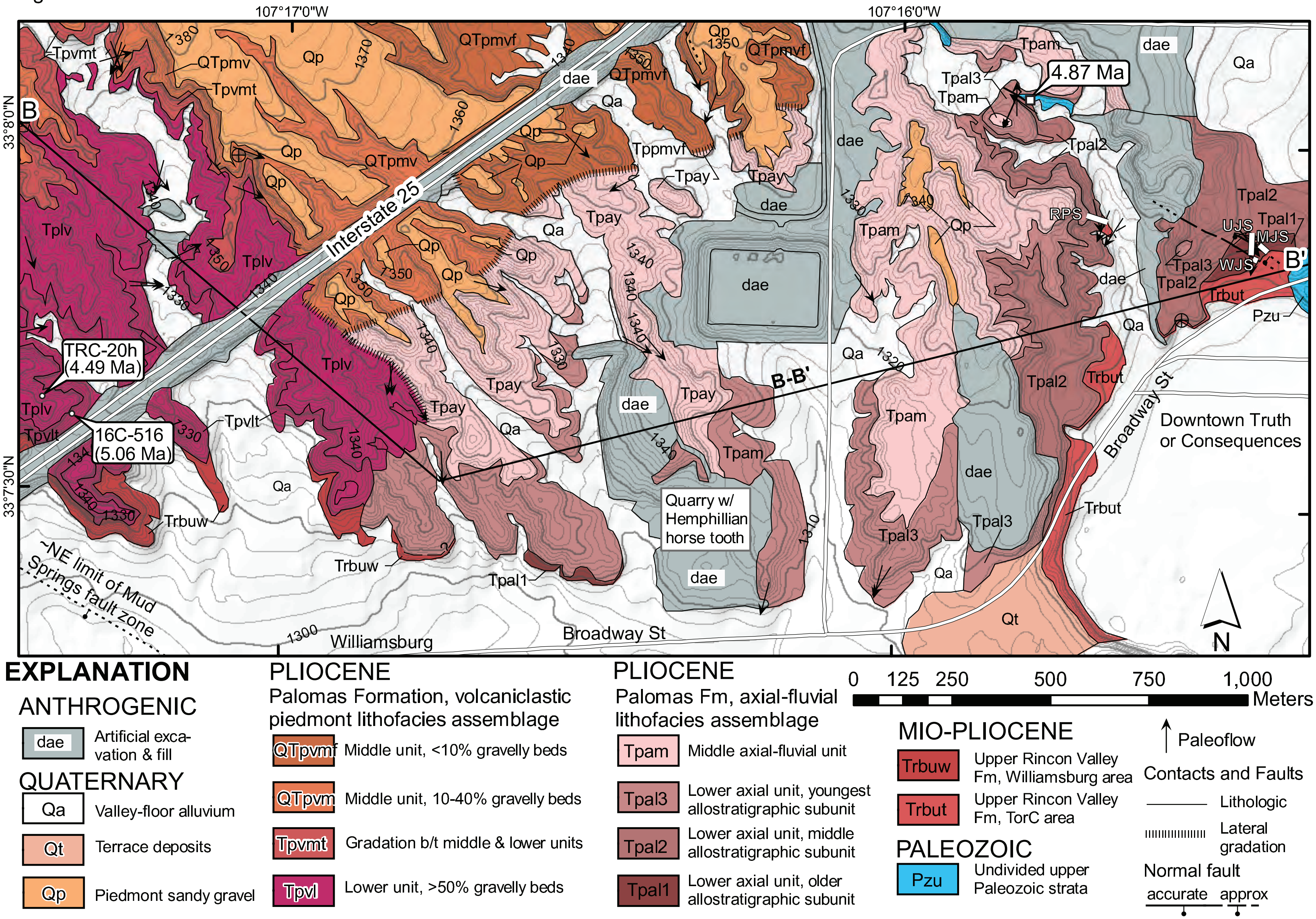


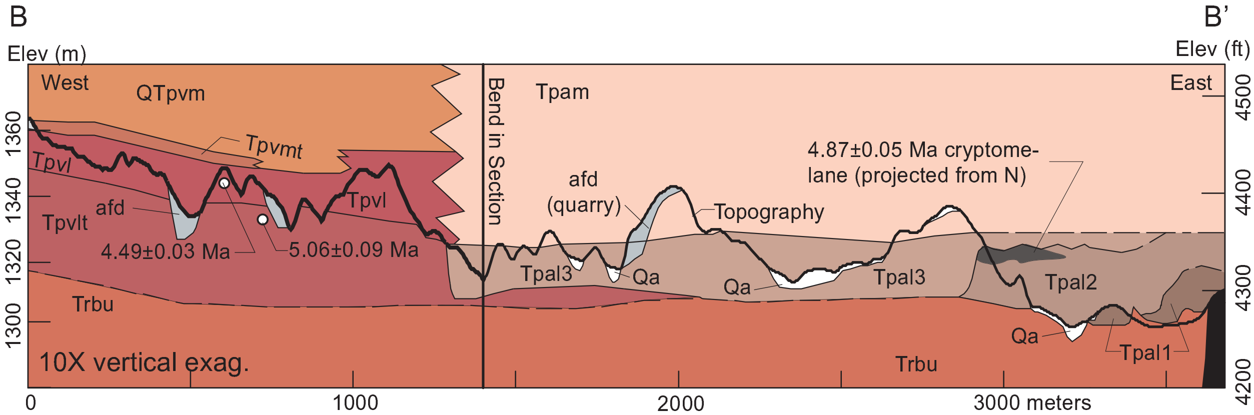
Figure 4

Figure 5



107°17'0"W
107°16'0"W
33°8'0"N
33°7'30"N
Interstate 25
B
B'
B-B'
TRC-20h (4.49 Ma)
16C-516 (5.06 Ma)
4.87 Ma
Quarry w/ Hemphillian horse tooth
Downtown Truth or Consequences
Broadway St
Williamsburg
NE limit of Mud Springs fault zone
RPS
UJS
MJS
WJS
N
EXPLANATION
ANTHROGENIC
dae Artificial excavation & fill
QUATERNARY
Qa Valley-floor alluvium
Qt Terrace deposits
Qp Piedmont sandy gravel
PLIOCENE
Palomas Formation, volcaniclastic piedmont lithofacies assemblage
QTpvmf Middle unit, <10% gravelly beds
QTpvm Middle unit, 10-40% gravelly beds
Tpvmt Gradation b/t middle & lower units
Tpvl Lower unit, >50% gravelly beds
PLIOCENE
Palomas Fm, axial-fluvial lithofacies assemblage
Tpam Middle axial-fluvial unit
Tpal3 Lower axial unit, youngest allostratigraphic subunit
Tpal2 Lower axial unit, middle allostratigraphic subunit
Tpal1 Lower axial unit, older allostratigraphic subunit
0 125 250 500 750 1,000 Meters
MIO-PLIOCENE
Trbuw Upper Rincon Valley Fm, Williamsburg area
Trbut Upper Rincon Valley Fm, TorC area
PALEOZOIC
Pzu Undivided upper Paleozoic strata
Paleoflow
Contacts and Faults
Lithologic
Lateral gradation
Normal fault
accurate approx

Figure 6



B
B'
Elev (m)
Elev (ft)
West
East
QTpvm
Tpvmt
Tpvl
Tpvlt
afd
4.49±0.03 Ma
5.06±0.09 Ma
Tpvl
Bend in Section
Tpam
afd
(quarry)
Topography
4.87±0.05 Ma cryptome-
lane (projected from N)
Tpal3
Qa
Qa
Tpal3
Tpal2
Qa
Tpal1
Trbu
Trbu
10X vertical exag.
1360
1340
1320
1300
4500
4400
4300
4200
0
1000
2000
3000 meters

Figure 7

Figure 8

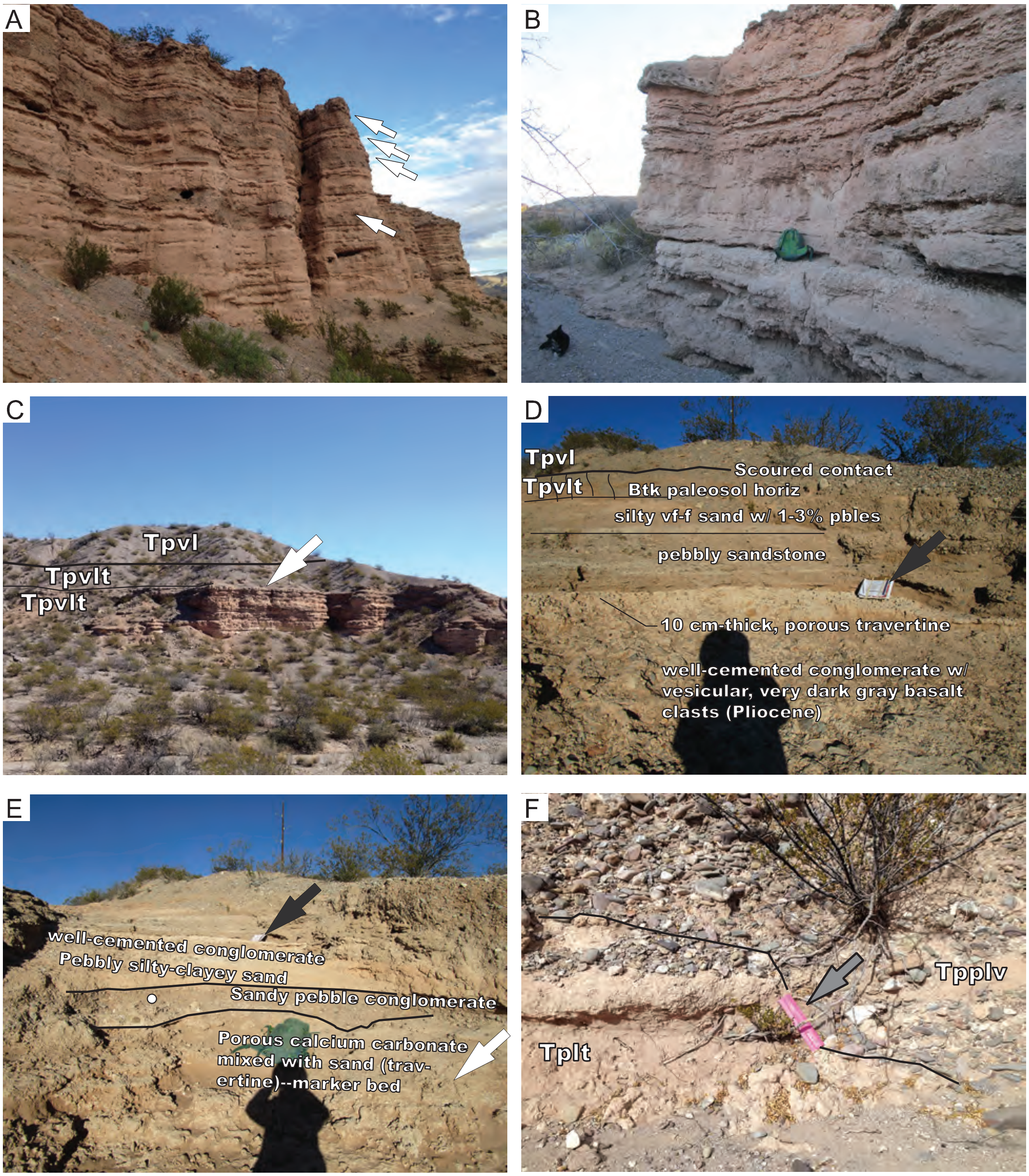

A
B
C
Tpvl
Tpvlt
Tpvlt
D
Tpvl
Tpvlt
Scoured contact
Btk paleosol horiz
silty vf-f sand w/ 1-3% pbles
pebbly sandstone
10 cm-thick, porous travertine
well-cemented conglomerate w/ vesicular, very dark gray basalt clasts (Pliocene)
E
well-cemented conglomerate
Pebbly silty-clayey sand
Sandy pebble conglomerate
Porous calcium carbonate mixed with sand (trav-ertine)--marker bed
F
Tpplv
Tplt

Figure 9

Figure 10

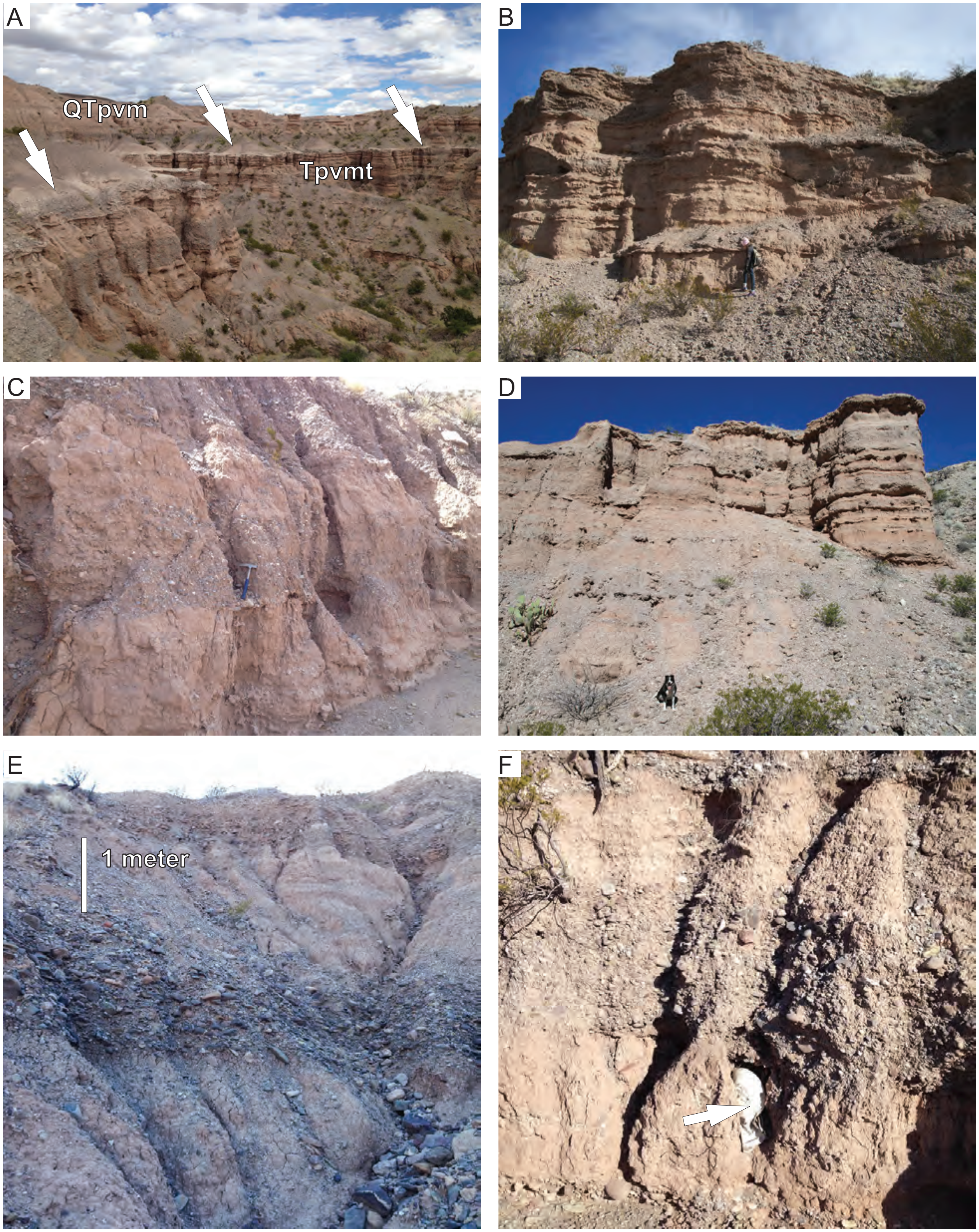


Figure 11

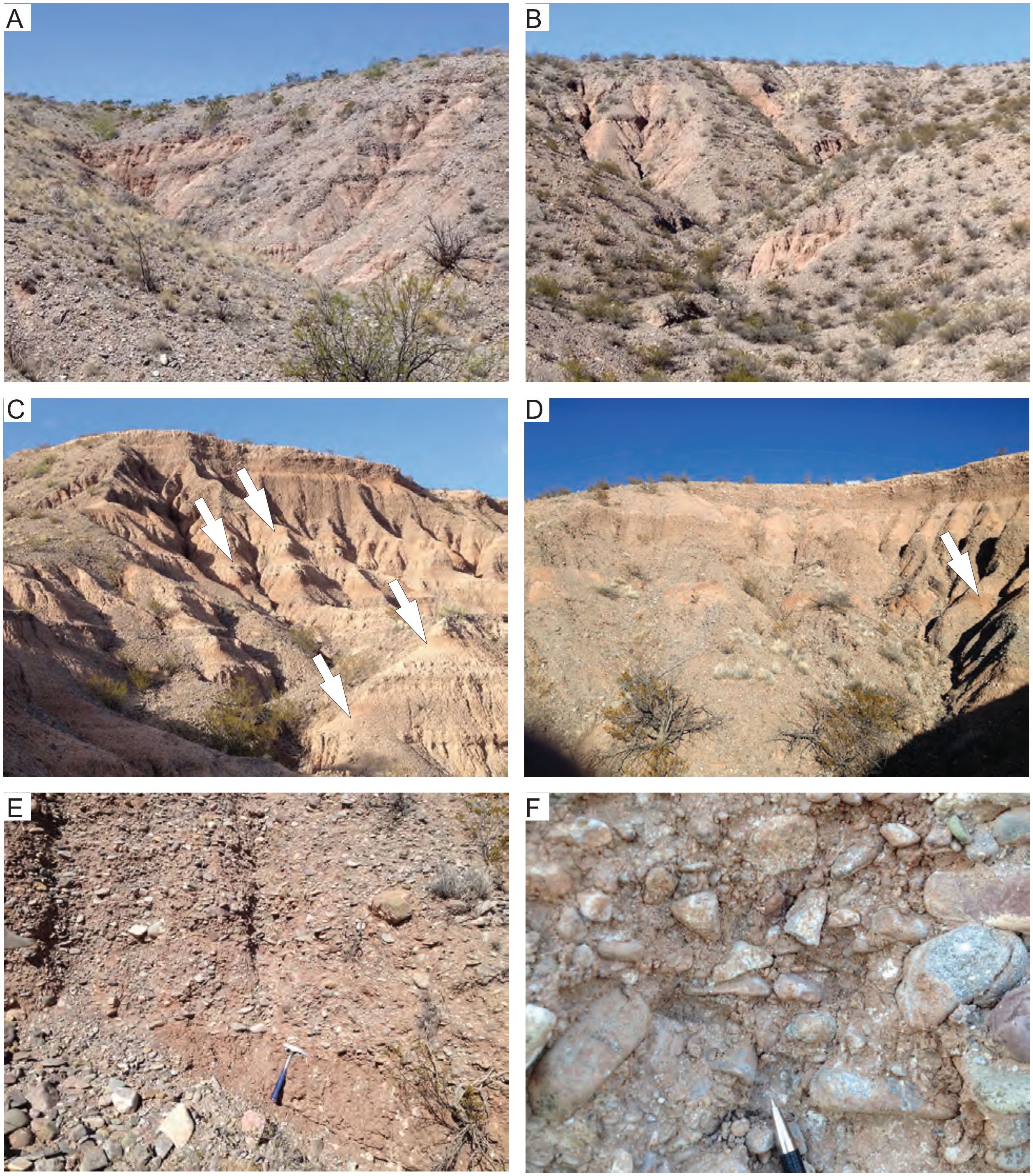


Figure 12

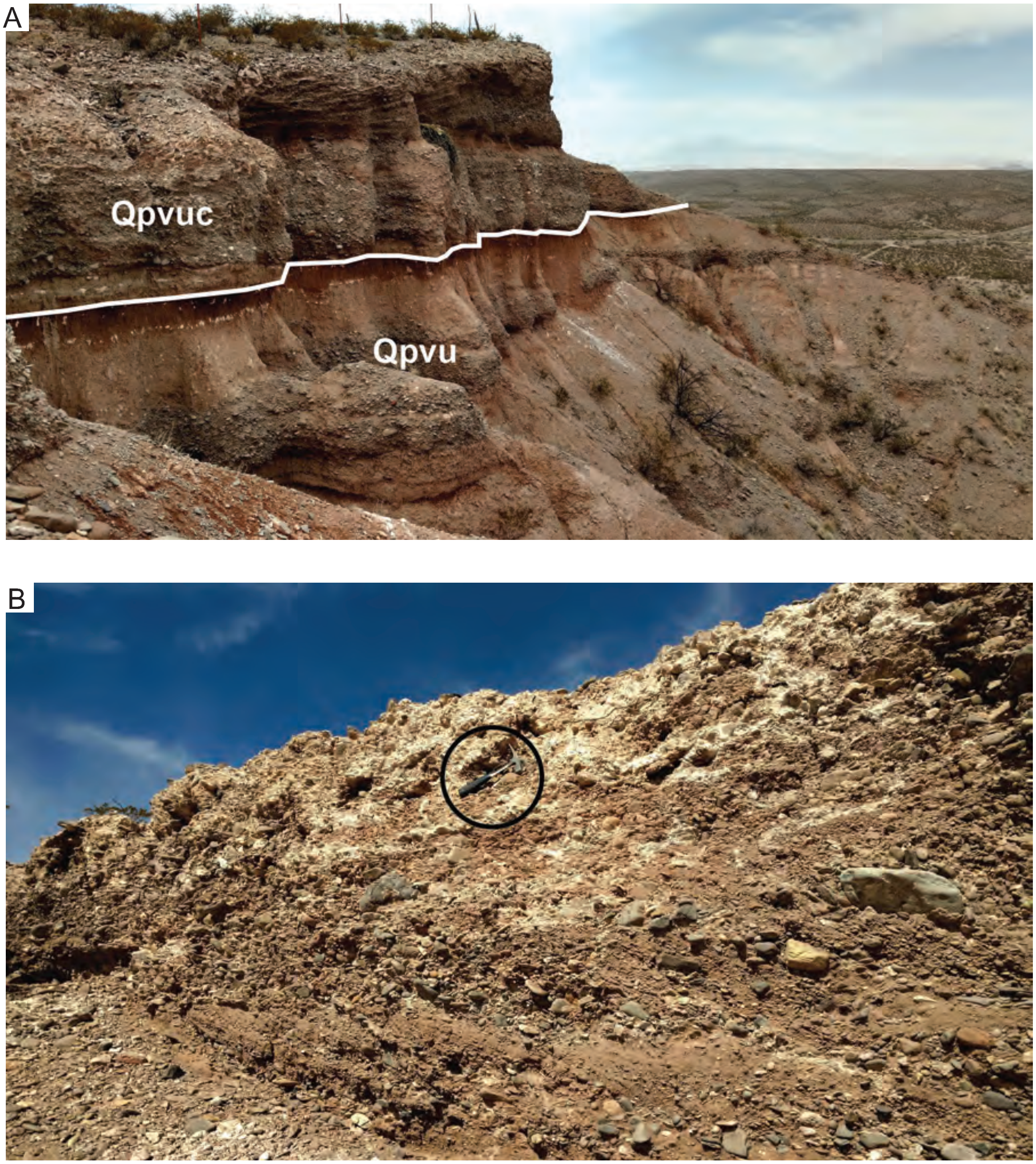


Figure 13

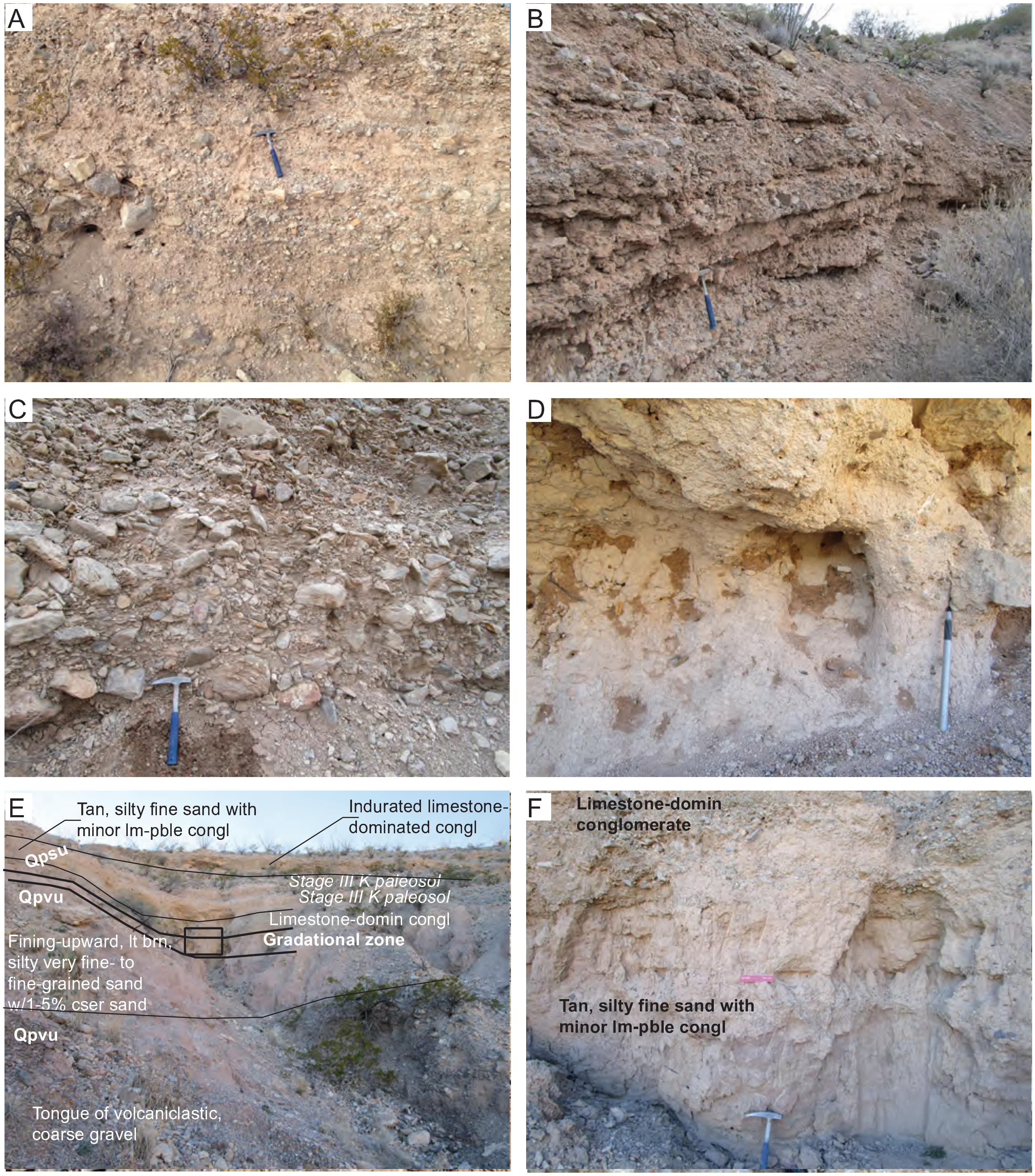

A
B
C
D
E
Tan, silty fine sand with
minor lm-pble congl
Indurated limestone-
dominated congl
Qpsu
Stage III K paleosol
Qpvu
Stage III K paleosol
Limestone-domin congl
Gradational zone
Fining-upward, lt brn,
silty very fine- to
fine-grained sand
w/1-5% cser sand
Qpvu
Tongue of volcaniclastic,
coarse gravel
F
Limestone-domin
conglomerate
Tan, silty fine sand with
minor lm-pble congl

Figure 14

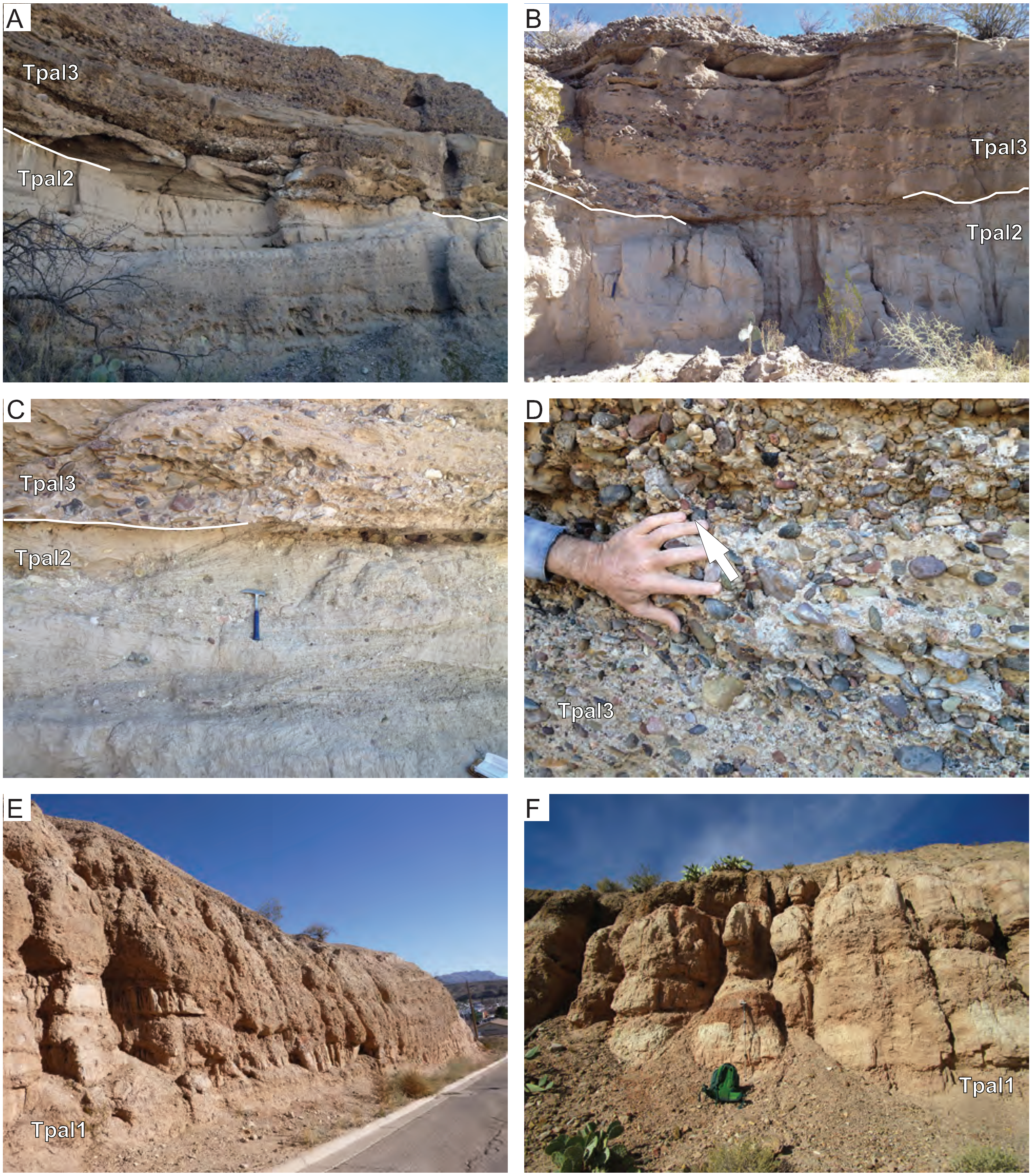

A
Tpal3
Tpal2
B
Tpal3
Tpal2
C
Tpal3
Tpal2
D
Tpal3
E
Tpal1
F
Tpal1

Figure 15

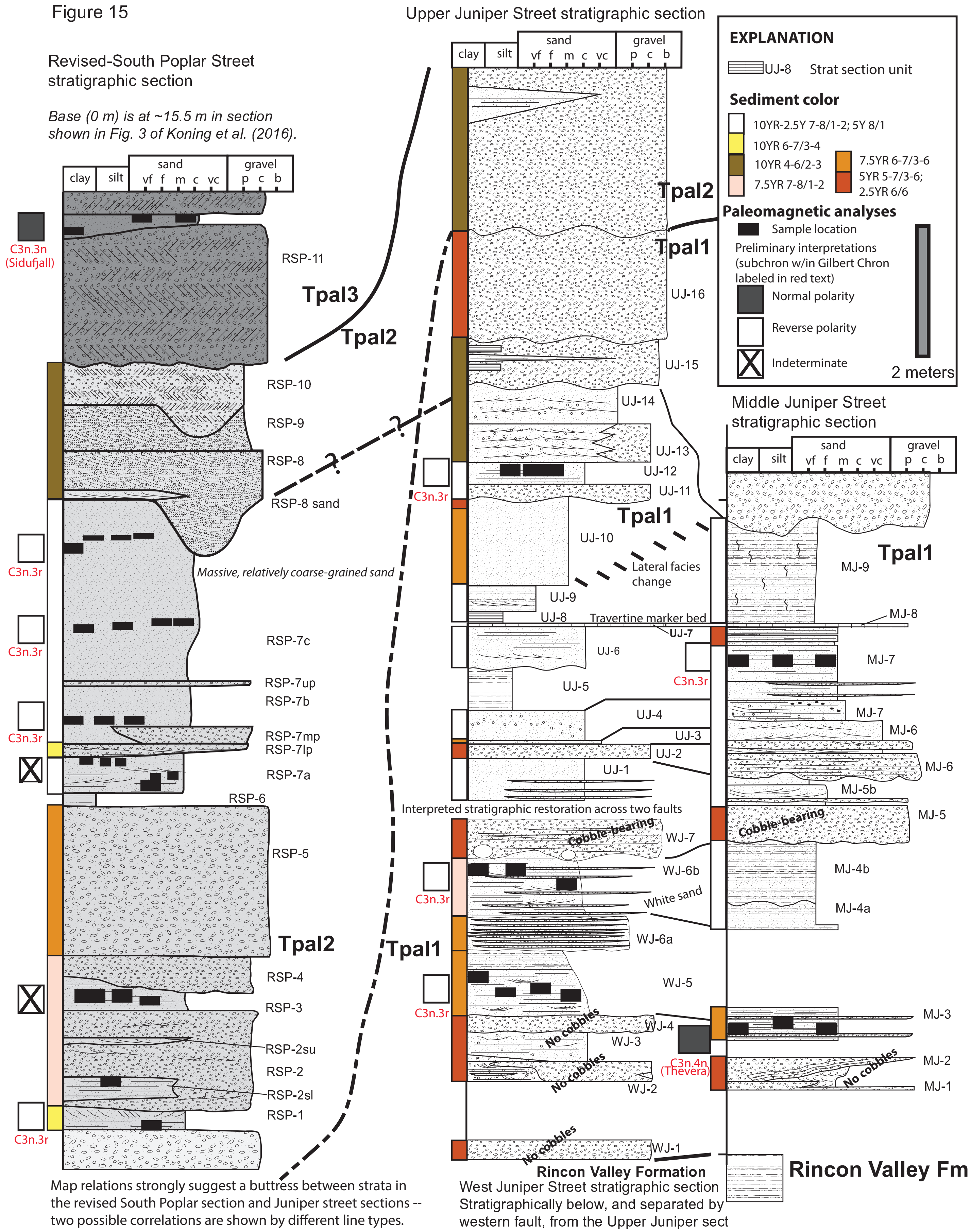

Revised-South Poplar Street stratigraphic section
Base (0 m) is at ~15.5 m in section shown in Fig. 3 of Koning et al. (2016).
clay
silt
sand
vf f m c vc
gravel
p c b
C3n.3n (Sidufjall)
RSP-11
Tpal3
Tpal2
RSP-10
RSP-9
RSP-8
RSP-8 sand
C3n.3r
Massive, relatively coarse-grained sand
RSP-7c
RSP-7up
RSP-7b
RSP-7mp
RSP-7lp
RSP-7a
RSP-6
RSP-5
Tpal2
RSP-4
RSP-3
RSP-2su
RSP-2
RSP-2sl
RSP-1
Upper Juniper Street stratigraphic section
Tpal2
Tpal1
UJ-16
UJ-15
UJ-14
UJ-13
UJ-12
UJ-11
Tpal1
UJ-10
Lateral facies change
UJ-9
UJ-8
Travertine marker bed
UJ-7
UJ-6
UJ-5
UJ-4
UJ-3
UJ-2
UJ-1
Interpreted stratigraphic restoration across two faults
Cobble-bearing
WJ-7
WJ-6b
White sand
WJ-6a
Tpal1
WJ-5
No cobbles
WJ-4
WJ-3
WJ-2
C3n.4n (Thevera)
WJ-1
Rincon Valley Formation
West Juniper Street stratigraphic section Stratigraphically below, and separated by western fault, from the Upper Juniper sect
EXPLANATION
UJ-8 Strat section unit
Sediment color
10YR-2.5Y 7-8/1-2; 5Y 8/1
10YR 6-7/3-4
10YR 4-6/2-3
7.5YR 7-8/1-2
7.5YR 6-7/3-6
5YR 5-7/3-6; 2.5YR 6/6
Paleomagnetic analyses
Sample location
Preliminary interpretations (subchron w/in Gilbert Chron labeled in red text)
Normal polarity
Reverse polarity
Indeterminate
2 meters
Middle Juniper Street stratigraphic section
Tpal1
MJ-9
MJ-8
MJ-7
MJ-7
MJ-6
MJ-6
MJ-5b
MJ-5
Cobble-bearing
MJ-4b
MJ-4a
MJ-3
MJ-2
No cobbles
MJ-1
Rincon Valley Fm
Map relations strongly suggest a buttress between strata in the revised South Poplar section and Juniper street sections -- two possible correlations are shown by different line types.

Figure 16

Figure 17

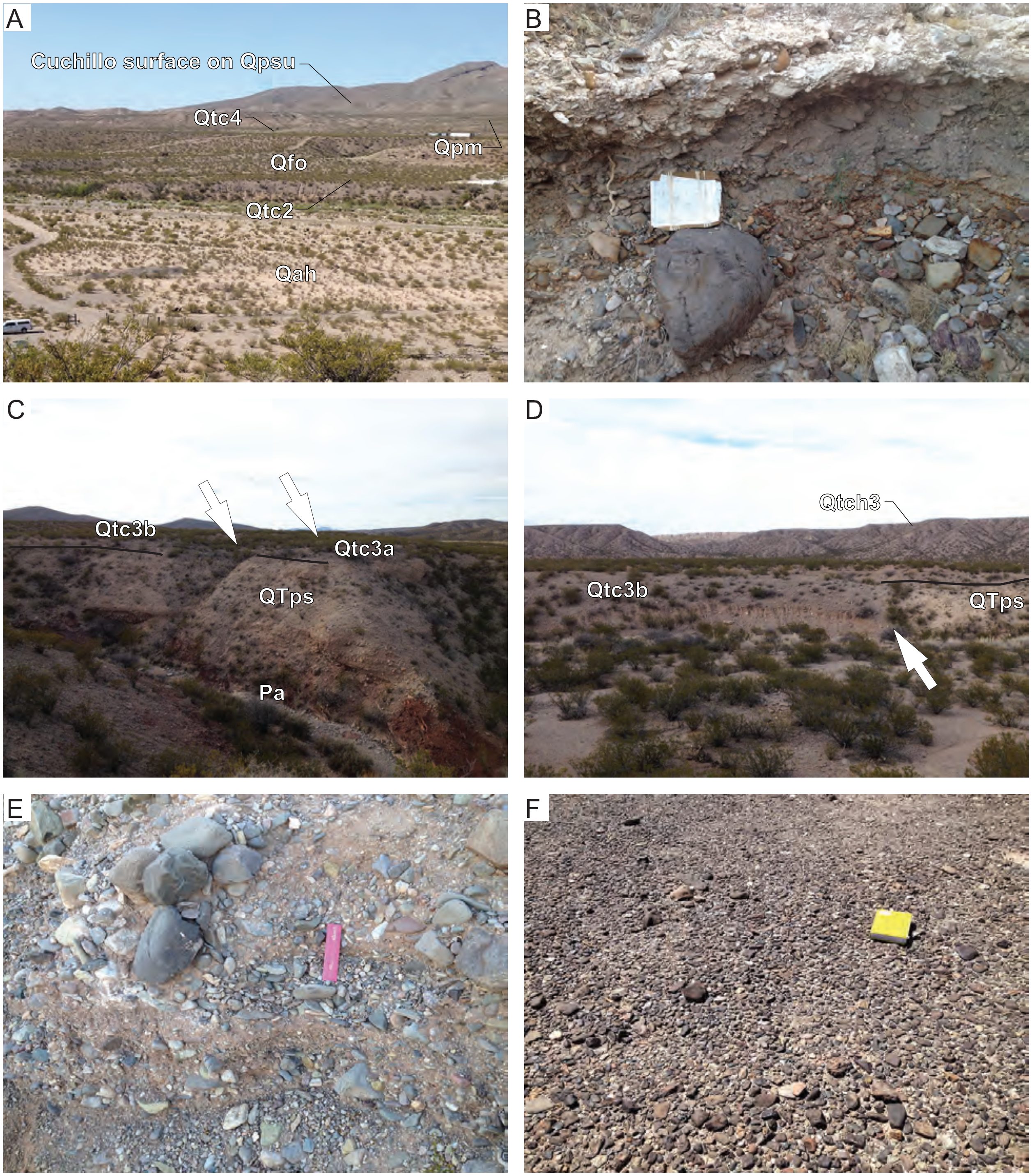

A
Cuchillo surface on Qpsu
Qtc4
Qpm
Qfo
Qtc2
Qah
B
C
Qtc3b
Qtc3a
QTps
Pa
D
Qtch3
Qtc3b
QTps
E
F

Figure 18

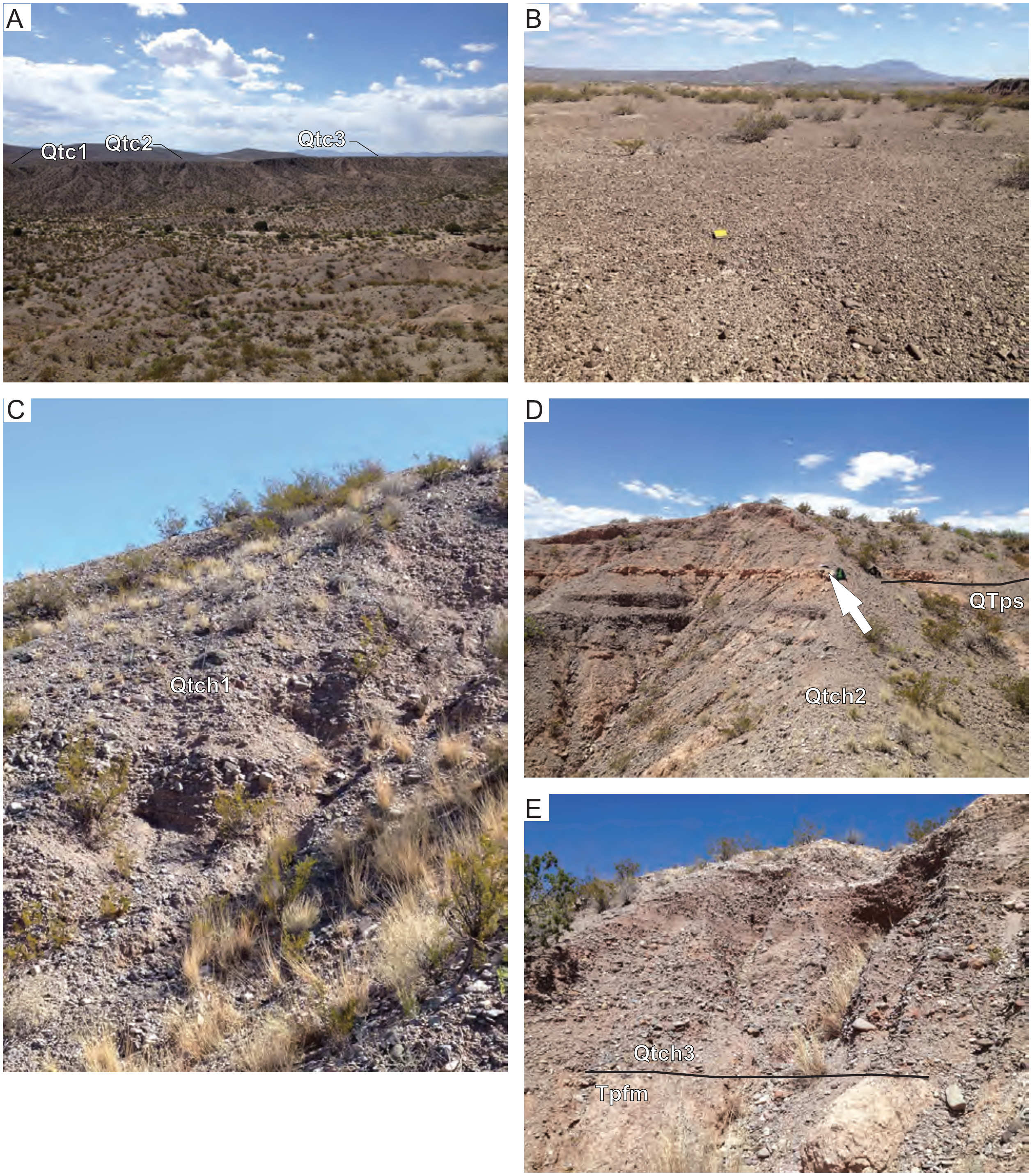


Figure 19

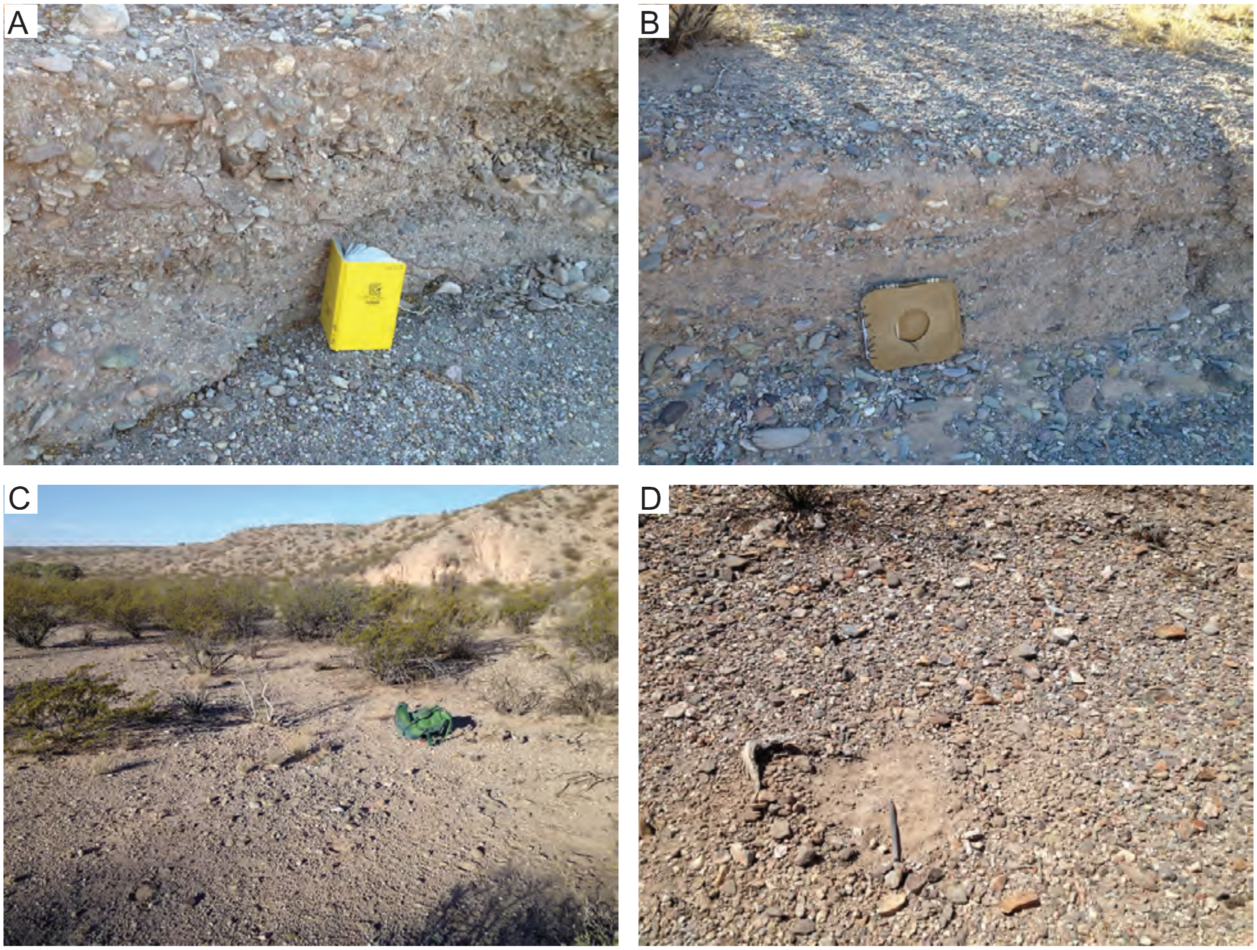
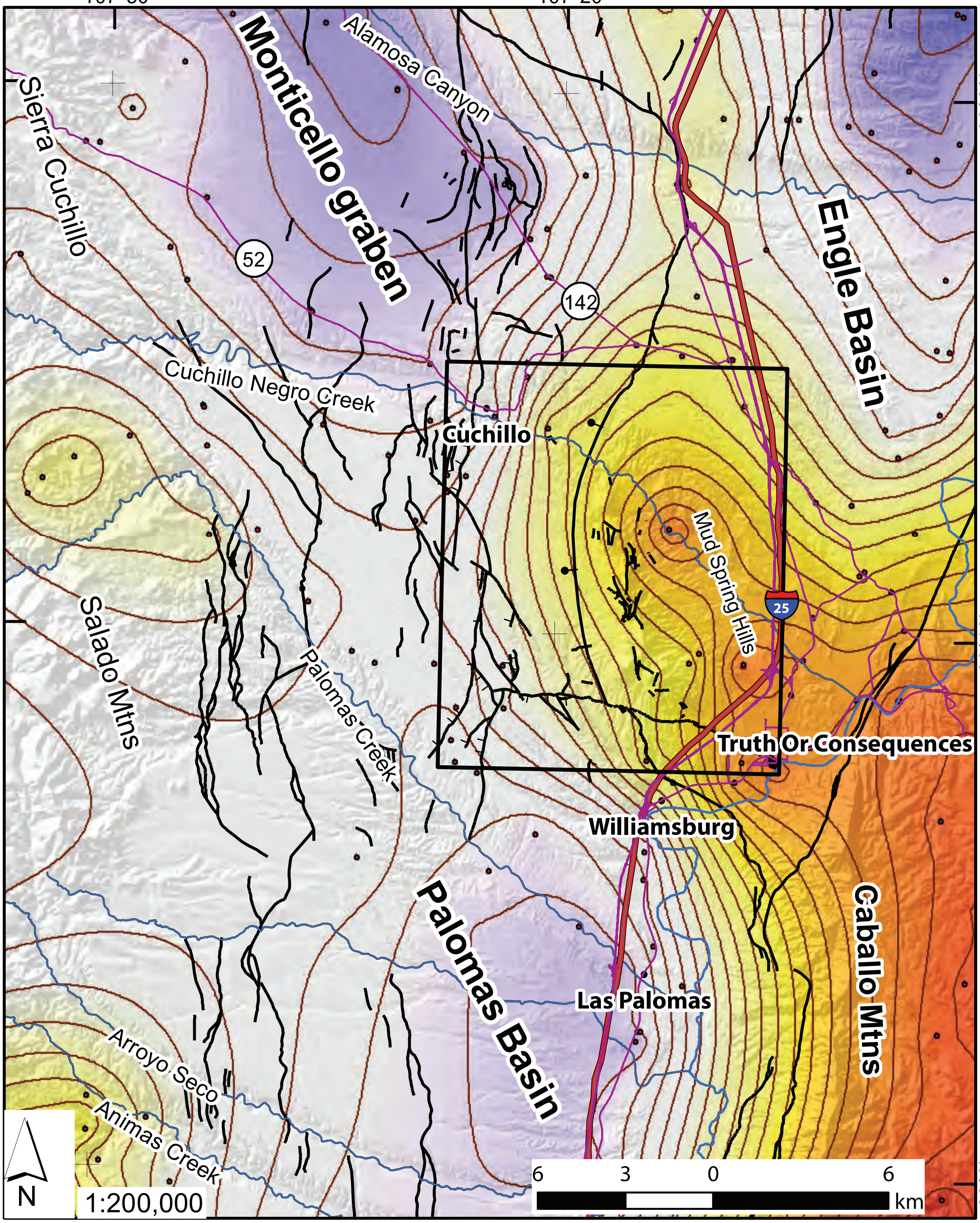


Figure 20



-107°30'
-107°20'
33°20'
33°10'
33°0'
Monticello graben
Alamosa Canyon
Sierra Cuchillo
52
142
Engle Basin
Cuchillo Negro Creek
Cuchillo
Mud Spring Hills
25
Salado Mtns
Palomas Creek
Truth Or Consequences
Williamsburg
Palomas Basin
Caballo Mtns
Las Palomas
Arroyo Seco
Animas Creek
N
1:200,000
6
3
0
6
km

Figure 21a

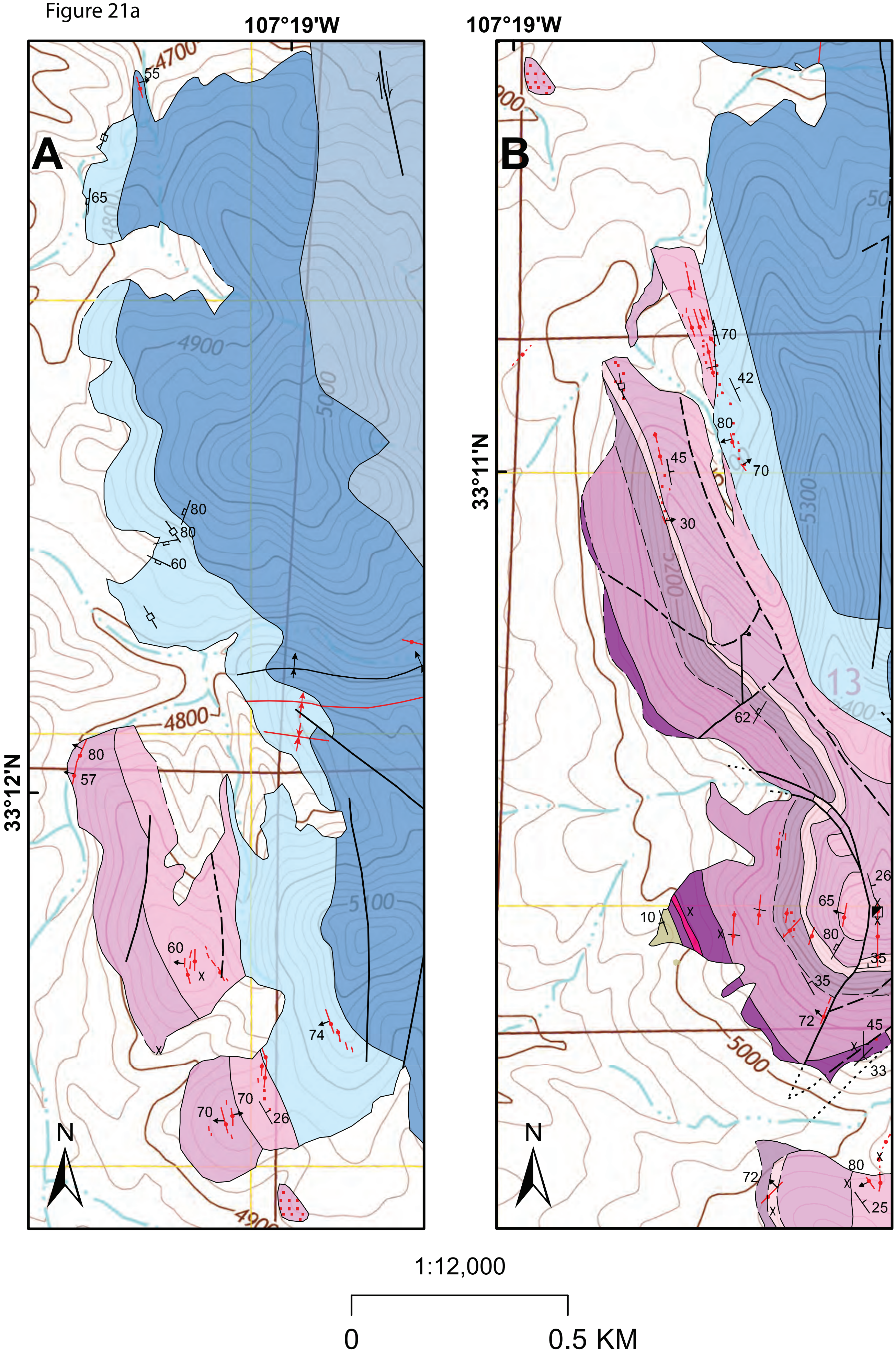
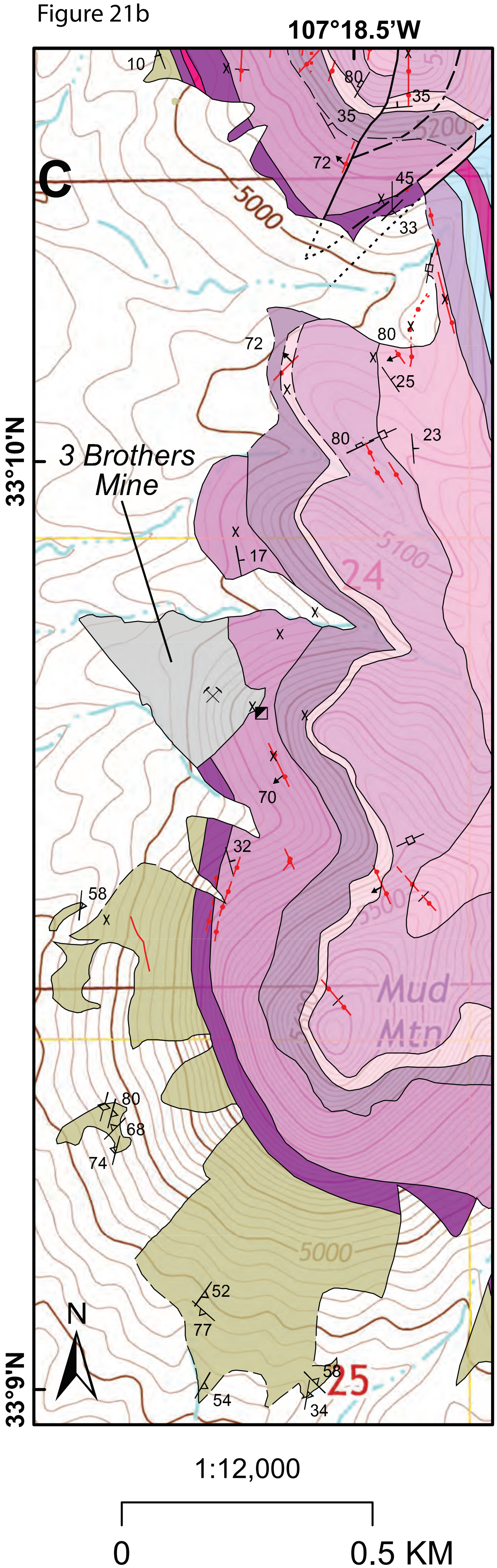

107°19'W
107°19'W
A
B
33°12'N
33°11'N
4700
4800
4900
5000
5300
13
N
N
1:12,000
0
0.5 KM

Figure 21b



KEY

Contact; solid where exposed, dashed where intermittent

Fault; solid where exposed, dashed where intermittent, dotted where concealed; arrows indicate relative strike-slip motion where present

afd
Tl
Tr
ℙbb
ℙn
ℙr
Dp
Omc
Oma
Omsv
Oem
Oeh
€Ob
p€u

see text and geologic map for unit designations and descriptions

Area of jasperoid mineralization

Jasperoid vein; solid where exposed, dotted where concealed

Aplite dike in granite

80 (|) Dip of vein (vertical)

75 ( ) Foliation (vertical)

75 ( ) Joints (vertical)

30 Strike and dip of bedding

x Prospect pit

Vertical shaft

Quarry

APPENDIX 1. DESCRIPTIONS OF MAP UNITS

QUATERNARY (VARIOUS POST-SANTA FE GROUP CLAST DEPOSITS)

Anthrogenic units

af Anthrogenic artificial fill (~60 years ago to present-day) – Thick accumulations of sand with minor gravel and silt from construction activities. Mapped for thick road fill along Interstate 25 as well as levees or dams. 1-10 m thick.

afd Anthrogenic artificial fill and disturbed ground (~60 years ago to present-day) – Intensely disturbed land surface by human activity, to such an extent that identification of pre-development geologic units is very difficult. Local accumulations of sand with minor gravel and silt from nearby excavations or past construction activity. Includes mix of fill and excavated areas along Interstate 25 and some stock ponds. 0-10 m thick.

Windblown and sheetwash deposits

Qse Sheetwash and eolian deposits, undivided (middle to upper Holocene) – Sheet-like sand that overlies gently sloping geomorphic surfaces; inferred to have mainly accumulated via sheetwash (or sheet-flooding) and, to a lesser degree, by eolian processes. 1-3? m thick.

Qs/Tpam Sheetwash deposits overlying axial sand lithofacies assemblage of the Palomas Formation (Holocene) – Sheet-like sand that overlies gently sloping geomorphic surfaces developed on the middle axial-fluvial unit (Tpam) of the Palomas Formation (unit Tpam); inferred to have mainly accumulated via sheetwash (or sheet-flooding). Sand predominately derived from reworking of unit Tpam. Unconsolidated and approximately 1-2 m thick.

Valley-floor units

Qam Modern alluvium (~60 years ago to present-day) – Sandy gravel underlying active channels. Gravel includes pebbles with subordinate cobbles and boulders that are subrounded (lesser subangular), poorly sorted, and composed of lithologic types reflective of the drainage's source area (typically volcanic in the quadrangle, except for drainages sourced in the Mud Spring Mountains); gravel typically clast-supported and imbricated. Sand is light brownish gray to pinkish gray to grayish brown (7.5-10YR 6/2; 10YR 5/2), mostly medium- to very coarse-grained, subrounded to subangular, poorly to moderately sorted, and composed of detritus reflective of the drainage's source area. Estimated grain lithologies of one sample are 60-70% lithics (volcanics>carbonate+chert), 20-30% quartz, and 10-20% feldspar with little to no clay present. Bars and steep-walled channels characteristic of arroyo bottom. Margins of this unit may be sandier with sparser gravel. Apache plume (*Fallugia paradoxa*) grows in less active parts of channel. Sparsely to no-vegetated. Likely <3 m thick.

Short—

Grayish brown to light brownish gray, sandy gravel forming bars and underlying active channels. Gravel includes pebbles with subordinate cobbles and boulders that are mostly subrounded, poorly sorted, and composed of lithologic types reflective of source area (mostly volcanic). Bars and steep-walled channels characteristic of arroyo bottom. Sparsely to non-vegetated; no topsoil. <3 m thick.

Qah Historical alluvium (~600 years ago to ~60 years ago) – Sandy gravel and subordinate pebbly sand underlying low geomorphic surfaces whose treads are 0.3-1.0 m above adjoining active channels. Sediment is mostly in very thin to thin, tabular to lenticular beds; minor medium, lenticular beds. Gravel consist mainly of pebbles with minor cobbles and 0-10% boulders; generally clast-supported, rounded to subangular (mostly subrounded), poorly sorted, and composed of volcanic rocks (drainages sourced in the Mud Spring Mountains have abundant Paleozoic sedimentary rocks). Gravel commonly clast-supported and imbricated. Sand is brown (7.5YR 5/3-4/4), fine- to very coarse-grained (mostly medium- to very coarse-grained), subrounded to subangular, poorly sorted, and composed of detritus reflective of the drainage's source area.. Estimated grain lithologies of one sample are 70-80% lithics (volcanic), 20-25% quartz, and 0-10% feldspar with 10-15% clay chips. Geomorphic surface is not varnished, does not have desert pavement, and features bar-and-swale topography (5-50 cm in height, mostly 5-30 cm). Weak A horizons may be present in the upper 5-10 cm of the deposit; no to very weak calcic horizons. Surface of deposit supports abundant mesquite (*Prosopis* sp.) with subordinate creosote (*Larrea tridentata*) and Mormon tea (*Ephedra viridis*). Loose-weakly consolidated and generally <3 m thick.

Short—

Sandy gravel and subordinate pebbly sand underlying low geomorphic surfaces whose treads are 0.3-1.0 m above adjoining active channels. Geomorphic surface is not varnished, does not have desert pavement, and features bar-and-swale topography (5-50 cm in height, mostly 5-30 cm). Weak A soil horizons may be present in the upper 5-10 cm of the deposit; no to very weak calcic horizons. <3 m thick.

Qay Younger alluvium (Holocene) – Sandy gravel and pebbly sand underlying terraces adjoining active channels. Sediment is in very thin to thin, tabular to lenticular beds; 1-10% cross-stratification; 0-20% med-thick, lenticular beds composed of sandy gravel that is cobble-rich. Gravel is subrounded, poorly to moderately sorted w/in a bed, & typically composed of volcanic rocks (except for drainages sourced in the Mud Springs Mountains). Gravel consists of pebbles, minor cobbles, and 1-10% boulders. Gravel is imbricated and clast- to sand-supported. Sand is brown to light brown to pale brown (7.5-

10YR 5-6/3), fine- to very coarse-grained, subrounded to subangular, poorly to moderately sorted, & generally rich in volcanic grains; commonly internally massive or laminated. Its geomorphic surface is very weakly varnished, locally has a weak desert pavement, and lacks bar-and-swale topography. Where not eroded, geomorphic surface is underlain by weak soils sporting calcic horizons (stage I) locally overlain by ~10 cm-thick A horizons having accumulation of organic matter. Surface has variable vegetation density. Tread height is 1-3 m above modern grade. Weakly consolidated and 1-5(?) m thick.

Short—

Sandy gravel and pebbly sand underlying 1-3 m-tall terraces adjoining active channels. Its geomorphic surface is very weakly varnished, locally has a weak desert pavement, and lacks bar-and-swale topography. Where not eroded, geomorphic surface is underlain by weak soils sporting calcic horizons (stage I) locally overlain by ~10 cm-thick A horizons. 1-5(?) m thick.

Qao Older alluvium (Upper Pleistocene to lower Holocene) – Sandy gravel and gravelly sand deposits whose surfaces are typically >2 m above modern grade and higher than nearby Qay treads. Where not eroded, its surface may exhibit weak clast varnishing or desert pavement development. Similar to unit Qt, but may be thicker and occupies more of a valley floor geomorphic position. 1-3 m thick.

Qamh Modern alluvium with subordinate historical alluvium ((~600 years ago to present-day) – See descriptions above for units Qam and Qah.

Qahm Historical alluvium with subordinate modern alluvium (~600 years ago to present-day) – See descriptions above for units Qah and Qam.

Qar Recent alluvium containing comparable proportions of modern and historical alluvium (~600 years ago to present-day) – See descriptions above for units Qam and Qah.

Qamy Modern alluvium with subordinate younger alluvium (primarily middle Holocene to present) – See descriptions above for units Qam and Qay.

Qahy Historical alluvium with subordinate younger alluvium (primarily middle Holocene to present) – See descriptions above for units Qah and Qay.

Qary Recent alluvium with subordinate younger alluvium (primarily middle Holocene to present) – See descriptions above for units Qar and Qay.

Qaym Younger alluvium with subordinate modern alluvium (primarily middle Holocene to present) – See descriptions above for units Qay and Qam.

Qayh Younger alluvium with subordinate historical alluvium (primarily middle Holocene to present) – See descriptions above for units Qay and Qah.

Qayr Younger alluvium with subordinate recent alluvium (primarily middle Holocene to present) – See descriptions above for units Qay, Qam, and Qah.

Valley-margin units

Qfm Modern fan alluvium ((~60 years ago to present-day) -- Similar to unit Qam, but present on alluvial fans.

Qfh Historic fan alluvium (~600 years ago to present-day) – Similar to unit Qah, but present on alluvial fans.

Qfr Recent fan alluvium (~600 years ago to present-day) – Relatively comparable proportions of modern and historic alluvium, similar to units Qam and Qah, deposited on alluvial fans.

Qfry Recent fan alluvium with subordinate younger fan alluvium (primarily middle Holocene to present-day) – Similar to units Qar and Qay, but present on alluvial fans.

Qfhm Historic fan alluvium with subordinate modern fan alluvium (~60 years ago to present) – Similar to units Qah and Qam, but deposited on alluvial fans.

Qfhy Historic fan alluvium with subordinate younger fan alluvium (primarily middle Holocene to present-day) – Similar to units Qah and Qay, but deposited on alluvial fans.

Qfy Younger fan alluvium (primarily middle Holocene to present-day) – Similar to unit Qay, but present on alluvial fans.

Qfyr Younger fan alluvium with subordinate recent fan alluvium (primarily middle Holocene to present-day) – Similar to units Qay and Qar, but present on alluvial fans.

Qfo Older fan alluvium (Upper Pleistocene to lower Holocene) – Reddish brown to brown (5-7.5YR 4/4), sandy pebble-cobble gravel in thick to very thick (60-130 cm), tabular to wedge-shaped beds. Gravel consists of clast- to matrix-supported, very poorly to poorly sorted, angular to subrounded pebbles (75-85%) and cobbles (15-25%) that are weakly to moderately imbricated. Clast lithologies are mostly volcanic gravel reworked from the Palomas Formation. Matrix consists of angular to subrounded, very poorly sorted, silt to cU sand composed of 65-80% lithics (volcanic) and 20-30% feldspar+quartz with 10-20% reddish brown clay chips. Unit interfingers somewhat with mainstem valley margin deposits. Calcic horizons are commonly not preserved (perhaps due to surface erosion during parts of the Holocene), but the top of the deposit may feature a young 10- to 20-cm-thick A horizon overlying a reddish 30-cm-thick Bw horizon. Weakly consolidated and weakly calcareous. 2.0-4.2 m thick.

Short—

Weakly consolidated deposits of reddish brown to brown (5-7.5YR), sandy pebble-cobble gravel. Unit interfingers somewhat with mainstem valley margin deposits. Silt-sand matrix contains 10-20% clay chips. Calcic horizons appear to be erosionally stripped, but the top of the deposit may feature 10-20 cm-thick A soil horizons overlying cambic (Bw) horizons up to 30 cm thick. 2.0-4.2 m thick.

Deposits adjoining fault scarps

Qasc Alluvium, slope-wash, and colluvium (upper Pleistocene to Holocene?) – Brown to yellowish brown (7.5YR 4/3 to 10YR 5/4), sandy to pebbly silt and silty to pebbly sand. Loose and weakly to moderately calcareous. Sand consists of very poorly to poorly sorted, angular to subrounded, very fine to coarse grains that are predominantly volcanic lithics. Fine to medium pebbles are composed of felsic to intermediate volcanics, tuff, and scarce chert and Paleozoic carbonates. Gravel comprises <30% of unit by volume. Fills shallow depressions along fault scarps on Cuchillo surface. Typically <3-5 thick [description modified from Jochems and Koning, 2016].

Short—

Loose deposits of brown to yellowish brown (7.5YR 4/3 to 10YR 5/4), sandy to pebbly silt and silty to pebbly sand. Fills shallow depressions along fault scarps on Cuchillo surface. Typically <3-5 thick [description modified from Jochems and Koning, 2016].

Terrace and high-level piedmont deposits

Qt Terrace deposits, undivided (middle or upper Pleistocene) -- Sandy gravel and gravelly sand deposited under terrace treads in smaller drainages throughout the map area. Composition of sand and gravel reflects the local source area, which is commonly the Palomas Formation. Generally 1-5 m thick and weakly consolidated.

Terrace deposits along Willow Springs Draw

Qtw Reddish brown (5YR 4/3-4), sandy gravel in medium to thick (15-70 cm), tabular to lenticular beds. Weakly consolidated, very weakly calcareous, and well imbricated to planar cross-stratified (foresets up to 25 cm thick) or trough cross-stratified (less common). Gravel consists of clast-supported, very poorly to moderately sorted, subrounded to well rounded pebbles (60-100%), cobbles (0-40%), and boulders (0-10%). Clast lithologies include felsites (60-70%), intermediate volcanics (25-35%), and Paleozoic carbonates (0-5%). Gravel matrix consists of very poorly sorted, subrounded to well rounded, fL-cL sand (up to 20% cU sand to granules) composed of 70-75% lithics (volcanics), 15-20% quartz, and 10-15% feldspar with 15-20% reddish clay films, bridges, and chips. Approximately 5% or less of unit consists of thin, elongate lenses of brown (7.5YR 4-5/3), pebbly sand similar to gravel matrix. 3-6 m thick. Includes two deposits distinguished by tread height above modern grade:

Short—

Weakly consolidated deposits of reddish brown (5YR 4/3-4), sandy pebble, pebble-cobble, and pebble-cobble-boulder gravel. Gravel is imbricated to planar or trough cross-stratified. Minor thin lenses of brown (7.5YR 4-5/3), pebbly sand. 3-6 m thick. Includes two deposits distinguished by tread height above modern grade:

Qtw1 Lower terrace gravel of Willow Springs Draw (middle Pleistocene) – Terrace tread lies 9-10 m above modern grade. It correlates to terrace suite Qtc2.

Qtw2 Middle terrace gravel of Willow Springs Draw (middle Pleistocene) – Stage I-I+ carbonate morphology in upper 60 cm. Moderate varnish on 30-45% of clasts at surface. Projects to the Qpc piedmont deposit. Terrace tread lies 15-17 m above modern grade. It correlates to terrace Qtc3d.

Lower suite of terrace deposits along Cuchillo Negro Creek

Qtc Sandy gravel and subordinate pebbly sand in very thin to thick, tabular to lenticular beds; local cross-stratification. Gravel consists of clast-supported pebbles with 10-50% fine to coarse cobbles and 0-7% boulders. Gravel are mostly subrounded (lesser rounded), poorly sorted, and have a composition of: 20-25% porphyritic intermediate volcanic rocks, 30% fine-grained intermediate volcanic rocks (including basaltic andesite), 30-50% felsic volcanic intermediate volcanic rocks, trace chert+jasper, trace-1% monzonitic intrusive rocks, trace-8% Paleozoic sedimentary clasts, and 1-3% Kneeling Nun Tuff (visual percentage estimations and data in Koning et al., 2016). Important differences are noted in the descriptions below. Sand is reddish brown (5YR), medium- to very coarse-grained (<15% very fine- to fine-grained sand), subrounded, moderately to poorly sorted, and composed of 80-90% lithics (volcanic>>chert) and 10-20% feldspar+quartz. Estimate 2-15% clay (in sand fraction) as coatings or sand-size chips. Weakly cemented by clay and weakly to moderately consolidated. Six terraces, labeled 1 through 6 (lowest to highest, respectively) are recognized below a suite of prominent, high-level fill terraces (Qtch).

Qtc1 Terrace deposit #1 (lowest terrace) along Cuchillo Negro Creek (upper Pleistocene) – Sand and gravel; locally correlating to straths eroded on bare rock outcrop. Tread lies 4-7 m above the Cuchillo Negro Creek valley floor (Qah). 1-2 m thick. [Modified slightly from Maxwell and Oakman (1990)].

Qtc2 Terrace deposit #2 along Cuchillo Negro Creek (middle to upper Pleistocene) –Tread lies 7-10 m above the Cuchillo Negro Creek valley floor and 3-4 m above adjacent Qtc1 treads. Near Cuchillo, >2 m of coarse gravel (pebbles with 35-50% cobbles) has a 60 cm-thick stage III+ K horizon underlying its upper contact, which in turn is overlain by 3 m of light brown (7.5YR 6/4) fine sand (with 1-10% scattered medium- to very coarse-grained sand and 1-5% scattered pebbles) containing 15-20% medium, tabular-lenticular interbeds of clast-supported pebbles. 1.5-2 m thick, but locally >5 m thick near Cuchillo. Surface exhibits weak clast varnishing. Includes two sub-deposits distinguished by tread height, although we cannot rule out that the lower of these is a cut-fill terrace:

Short
Tread lies 7-10 m above the Cuchillo Negro Creek valley floor. Near Cuchillo, >2 m of coarse gravel (pebbles with 35-50% cobbles) has a 60 cm-thick stage III+ K horizon, which in turn is overlain by 3 m of finer sediment. Surface exhibits weak clast varnishing. Includes two sub-deposits distinguished by tread height, although we cannot rule out that the lower of these is a cut-fill terrace:

> **Qtc2a Lower sub-terrace of Terrace deposit #2 along Cuchillo Negro Creek (late-middle late Pleistocene)** – Tread is ~2 m below tread of Qtc2b.
>
> **Qtc2b Upper sub-terrace of Terrace deposit #2 along Cuchillo Negro Creek (late-middle late Pleistocene)** – Tread is ~2 m above tread of Qtc2a.

Qtc3 Terrace deposit #3 along Cuchillo Negro Creek (late-middle Pleistocene) – Sandy gravel terrace deposits underlying a series of closely spaced (vertical sense) treads. These treads generally lie 14-26 m above the Cuchillo Negro Creek valley floor and surface clasts are mostly strongly varnished with local areas of well-developed desert pavement. Includes four sub-terrace deposits distinguished by tread height, although some of these may in be fill-cut terraces. ~2 m thick.

> Q**tc3a Lower sub-terrace of Terrace deposit #3 along Cuchillo Negro Creek (late-middle Pleistocene)** – Tread is 2 m below tread of Qtc3b. Areas of well-developed pavement are less common than on the Qtc3b tread.
>
> Q**tc3b Lower-middle sub-terrace of Terrace deposit #3 along Cuchillo Negro Creek (late-middle Pleistocene)** – Tread is 1-2 m below tread of Qtc3c and 2 m above Qtc3a tread. ~2 m thick.

Q**tc3c Upper-middle sub-terrace of Terrace deposit #3 along Cuchillo Negro Creek (late-middle Pleistocene)** – Tread is 2 m below tread of Qtc3d and 1-2 m above tread of Qtc3b. 1-2 m thick.

Q**tc3d Upper sub-terrace of Terrace deposit #3 along Cuchillo Negro Creek (late-middle Pleistocene)** – Tread is 2 m above tread of Qtc3c. 1-2 m thick.

Qtc4 Terrace deposit #4 along Cuchillo Negro Creek (mid-middle Pleistocene) – Sandy gravel underlying a typically broad tread about 27-32 m above the valley floor. Surface clasts are well-varnished. About 3 km west of the eastern quadrangle boundary, this terrace deposit is 2-7 m thick. Near Cuchillo, the deposit is thinner (1-2 m thick) and two treads can be differentiated that are called Qtc4a and Qtc4b.

Q**tc4a Lower sub-terrace of Terrace deposit #4 along Cuchillo Negro Creek (mid-middle Pleistocene) –** Tread lies about 1 m below the tread of Qtc4b.

Qtc4b Upper sub-terrace of Terrace deposit #4 along Cuchillo Negro Creek (middle Pleistocene) – Tread lies about 1 m above the tread of Qtc4a.

Qtc5 Terrace deposit #5 along Cuchillo Negro Creek (mid-middle Pleistocene) – Sandy gravel lying about 2 m above the tread of Qtc4 (29-35 m above the valley floor). ~1-2 m thick.

Qtc6 Upper terrace deposit along Cuchillo Negro Creek (middle Pleistocene) – Sandy gravel terrace deposits underlying treads located 34-37 m above the valley floor. Subdivided into two subunits:

Qtc6a Lower sub-terrace of Terrace deposit #6 along Cuchillo Negro Creek (middle Pleistocene) -- 10-70% strongly varnished clasts are observed at surface. Tread lies 1-2 m below tread of Qtc6b. 1-2 m thick.

Qtc6b Higher sub-terrace of Terrace deposit #6 along Cuchillo Negro Creek (middle Pleistocene) – Sandy gravel (mostly pebbles and boulders) that is typically ~1 m thick. Terrace tread lies 1-2 m above the tread of Qtc6a.

Higher suite of terrace deposits along lower Cuchillo Negro Creek

Qtch Thick fill terraces preserved alongside along lower Cuchillo Negro Creek and north of Cuchillo. Sediment composed of sandy gravel in very thin to medium (minor thick), tabular to lenticular beds. Gravel are clast-supported, subrounded-rounded, poorly to moderately sorted, moderately imbricated, and comprised of very fine to very coarse pebbles with 10-40% cobbles and 0-1% boulders. Estimated gravel composition of 20-35% porphyritic intermediate volcanic, 50% fine-grained intermediate (including basaltic andesite), 15-35% felsic volcanic rocks, trace-1% Kneeling Nun Tuff, 0-1% Paleozoic sedimentary rocks, and trace monzonite intrusions. Sand is reddish brown (5YR 5/3-4/4), fine- to very coarse-grained (mostly medium- to very coarse-grained), subrounded-subangular, poorly to moderately sorted, and mostly composed of volcanic lithic grains. 1-15% clay in the sand matrix as clay chips and clast coatings. Weakly cemented by clays and moderately consolidated. Each terrace subunit appears to be a separate depositional event. Deposits thin (wedge-out) laterally away from Cuchillo Negro Creek.

Qtch1 Lower of the higher suite of terrace deposits along Cuchillo Negro Creek (early middle Pleistocene) – Preserved tread stands about 50-52 m above modern valley floor. Contains local (0-20%) fine-grained beds of clay-silt, very fine- to fine-grained sand, or silty-clayey very fine- to fine-grained sand; fine sand and silt are light brown to light reddish brown (5-7.5YR 6/3); fine sand may contain minor scattered grains of medium- to very coarse-grained sand + pebbles. Up to 15 m thick.

Qtch2 Middle of the higher suite of terrace deposits along Cuchillo Negro Creek (early middle Pleistocene) – Preserved tread rises about 55 m above modern valley floor. Tread and strath are 3-5 m above those of Qtch1. Lower 3 m is particularly cobble-rich; above, gravel is finer and there are interbeds of brown (7.5YR 5/4) clayey-silty very fine- to fine grained sand (with 10-15% scattered medium to very coarse sand grains and 1-3% scattered very fine to fine pebbles). At one locality, fine white ash was collected about midway up the deposit in the fine-grained deposits; ash is preliminarily inferred to correlate to the 640 ka Lava Creek B ash. Topsoil has a stage III+ calcic horizon. 6-10 m thick.

Short—

Tread is ~55 m above modern valley floor. Tread and strath are 3-5 m above those of Qtch1. Lower 3 m is cobble-rich; above, gravel is finer and there are interbeds of brown (7.5YR 5/4) clayey-silty fine grained sand. At one locality, fine white ash was collected in the fine sand, possibly correlative to the 640 ka Lava Creek B ash. Topsoil has a stage III+ calcic horizon. 6-10 m thick.

Qtch3 Upper of the higher suite of terrace deposits along Cuchillo Negro Creek (early middle Pleistocene) – Terrace deposit typically lacks fine-grained interbeds seen in Qtch2 and Qtch3. Tread lies 57-63 m above the modern valley floor. Topsoil has a stage IV calcic horizon. Deposit is 6-20 m thick.

Terrace deposits along Cañada Honda and Mud Springs Canyon

Qthm Reddish brown (5YR 4/4) to light brown (7.5YR 6/3), sandy pebble and pebble-cobble-boulder gravel in thin to thick, tabular to lenticular beds. Loose to very weakly carbonate-cemented and massive to imbricated. Gravel consists of clast-supported, very poorly to poorly sorted, subangular to rounded, pebbles, cobbles, and <10% boulders. Clast lithologies are dominated by intermediate and felsic volcanics with minor Paleozoic sedimentary lithologies. Matrix consists of poorly to moderately sorted, angular to rounded, very fine- to coarse-grained sand composed of 30-60% feldspar, 30-50% lithic, and 10-30% quartz grains with up to 15% reddish clay films. Rare sand lenses may be planar cross-stratified. Older (higher) deposits may exhibit stage I-II carbonate morphology in places as well as greater surface varnish and possible desert pavement development. 1-4 m thick. Includes three deposits distinguished by tread height above the valley floor [description modified from Jochems and Koning, 2015]:

Short—

Loose to weakly consolidated deposits of reddish brown (5YR 4/4) to light brown (7.5YR 6/3), sandy pebble and pebble-cobble-boulder gravel. Gravel is imbricated; sparse sand lenses may be cross-stratified. 1-4 m thick. Includes three deposits distinguished by tread height above the valley floor [description modified from Jochems and Koning, 2015]:

Qthm1 Lower terrace gravel of Cañada Honda and Mud Springs Canyon (late Pleistocene) – Terrace tread lies 4-7 m above the valley floors of both drainages.

Qthm2 Middle terrace gravel of Cañada Honda and Mud Springs Canyon (late middle to early late Pleistocene) – Terrace tread lies 8-11 m and 11-13 m above the valley floors of Cañada Honda and Mud Springs Canyon, respectively.

Qthm3 Upper terrace gravel of Cañada Honda (middle Pleistocene) – Terrace tread lies 12-15 m above the valley floor of Cañada Honda.

Qtfmh2 Qthm2 terrace deposit and alluvial fan prograding over this terrace deposit, undivided, in Cañada Honda (middle to upper Pleistocene) – Sandy gravel and gravelly sand deposited as a main-stem terrace or as alluvial fan deposits prograding over the main-stem terrace. The two are left undifferentiated because of desired 1:24,000 map scale. Weakly consolidated and up to 6-9 m thick.

Terrace deposits near Cantrell Tank in Mud Springs Canyon

Qtct1 Lower terrace gravel near Cantrell Tank (middle Pleistocene) – Lithologically similar to unit Qtct2, but its tread and strath lies approximately 3 m below those associated with unit Qtct2. 1-2 m thick.

Qtct2 Upper terrace gravel near Cantrell Tank (middle Pleistocene) – Brown to pinkish white (7.5YR 5/4-8/2) pebble-cobble gravel in medium to thick (30-55 cm), mostly tabular (occasionally lenticular) beds. Loose, moderately to very strongly calcareous, and massive to well imbricated. Gravel consists of clast-supported (65-70%), very poorly to poorly sorted, subangular to rounded pebbles (60-95%), cobbles (5-40%), and boulders (no more than 3%). Clast lithologies are a mix of volcanic clasts and Paleozoic carbonates, Precambrian granitic + metamorphic lithologies derived from the backside of the Mud Springs Mountains. Matrix consists of poorly sorted, subangular to rounded, silt to mU sand (up to 15% cL-vcU sand) composed of >75% carbonates with <10-15% quartz+feldspar and no clay. Stage IV carbonate morphology (K horizon) is observed in the upper 0.8-1.0 m of the deposit and indicated by carbonate impregnation and laminations in the upper 20-30 cm of the soil profile. Moderate desert pavement is observed at surface as are 10-20% weakly varnished clasts. Terrace tread lies ~25 m above adjacent valley floors. 1.5-2.0 m thick.

Short—

Loose deposits of brown to pinkish white (7.5YR), calcareous pebble-cobble gravel. Gravel is massive to well imbricated. Silt-sand matrix consists of >75% carbonate and <15% quartz+feldspar grains. K horizon observed in the upper 0.8-1.0 m of the deposit. Surface features moderate desert pavement and 10-20% weakly varnished clasts. Terrace tread lies 21-29 m above valley floors. 1.5-2.0 m thick.

High-level piedmont deposits

Qp High-level piedmont deposit, undifferentiated (middle or upper(?) Pleistocene) – Sandy gravel and pebbly sand in thin to medium, tabular to lenticular beds; local cross-stratification in the pebbly sand (very thin to thin, planar to tangential foresets up to 0.8 m tall). Gravel consists of pebbles with 10-20% cobbles and trace-5% boulders. Gravel are clast-supported, subrounded to subangular, and composed predominately of Paleozoic carbonate clasts. Minor debris flows that are matrix-supported and have more cobbles; debris flow matrix is a pale brown to light yellowish brown (10YR 6/3-4), very fine- to very coarse-grained sand with 1-5% silt-clay. Non-debris flow sand is light brownish gray to pale brown (10YR 6/2-3), medium- to very coarse-grained (<15% very fine-fine sand), subrounded to angular (mostly subangular), poorly sorted, and mostly composed of detritus from Paleozoic sedimentary rocks. Non-cemented and moderately consolidated. Base has 1-2 m of scour relief. Top soil generally exhibits calcic horizons having stage III to IV morphology. 1-5 m thick. Subdivided into three geomorphic levels on the east-northeast side of the Mud Springs Mountains, as listed below.

Short— Sandy gravel and pebbly sand in thin to medium, tabular to lenticular beds; locally cross-stratified. Where flanking Mud Springs Mountains, gravel is composed predominately of Paleozoic carbonate clasts. In the northeastern quadrangle, unit is composed primarily of volcanic clasts. Subdivided into three geomorphic levels on the east-northeast side of the Mud Springs Mountains.

Qpl (middle or upper Pleistocene) – Thin piedmont deposit whose associated tread lies a few meters below that of Qpm. 1-3 m thick.

Qpm (middle Pleistocene) – Piedmont deposit whose associated geomorphic surface is relatively extensive and serves as a proxy geomorphic datum. Surface stands 6-27 m above adjacent arroyo floors, the large range due to differential incision of these arroyos. 1-6 m thick. Grades to the Qtc4 or Qtc5 terrace levels along Cuchillo Negro Creek.

Qph (middle Pleistocene) – Piedmont deposit whose associated tread stands 2-7 m above that of Qpm. 1-3 m thick.

Qpc High-level piedmont deposit graded to the Qtc4-Qtc5 terrace levels along Cuchillo Negro Creek (middle or upper(?) Pleistocene) – Sandy gravel similar to unit Qpm in geomorphic position. However, it is composed of volcanic sandy gravel derived from the upper Palomas Formation. 1-3 m thick.

QUATERNARY-TERTIARY BASIN FILL

Palomas Formation

QTp Palomas Formation, undivided (lower Pleistocene to lower Pliocene) – Gravel, sand, and silt (lesser clayey sand and clay-silt) deposited on coalesced fan complexes and by the ancestral Rio Grande in the central Palomas basin. Fossil data (summarized by Morgan and Lucas, 2012), basalt radiometric ages (Bachman and Mehnert, 1978; Seager et al., 1984; Jochems, 2015; Koning et al., 2015, 2016), and magnetostratigraphic data (Repenning and May, 1986; Mack et al., 1993, 1998; Leeder et al., 1996) indicate an age range of ~5.0-0.8 Ma for the Palomas Formation. Where not significantly eroded, the surface soil may be marked by a petrocalcic horizon that is 1-2 m thick and generally exhibits stage IV carbonate accumulation. 40 to >180 m thick. Mapping of the Palomas Formation on this quadrangle builds from earlier sedimentologic and provenance work by Foster (2009) and Mack et al. (2012).

Short—

Gravel, sand, silt, and clay-silt deposited on coalesced fan complexes and by the ancestral Rio Grande. Fossil data, radiometric ages, and magnetostratigraphic data indicate an age range of ~5.0-0.8 Ma. Surface soil may be marked by a 1-2 m thick stage IV petrocalcic horizon. 40 to >180 m thick.

Volcaniclastic units derived from uplands to the west, associated with a piedmont lithofacies assemblage

Upper stratigraphic level

Qpvuc Upper-level, volcaniclastic piedmont deposits, coarse-grained (lower Pleistocene) – Gravelly intervals interbedded with subordinate clayey-silty sand. Stacked gravel bodies constitute >50% of unit (over ~10-20 m vertical scale) and are weakly to well consolidated, non- to weakly calcareous, and imbricated. These gravels consist of clast-supported, subrounded to well rounded (mostly subrounded to rounded), very poorly to poorly sorted, pebbles (50-80%), cobbles (20-50%), and boulders (no more than 5%) in thick to very thick (80-110+ cm), mostly tabular beds. Clast lithologies include intermediate volcanics (55-65%), felsites (30-45%), and Paleozoic sedimentary lithologies (including Abo Formation) and Pliocene basalt (5-15% total). Gravel matrix consists of subangular to rounded, poorly to moderately sorted, vfU-vcU sand composed of 75-85% lithics (volcanic) and 15-25% feldspar+quartz with 30-40% reddish clay bridges and clay chips. Matrix clay gives unit overall colors of dark reddish brown to yellowish red (5YR 3-4/4-6). Occasionally, unit features reddish brown (5YR 5/4), weakly consolidated, non-calcareous clay-silt-very fine sand in massive, tabular beds. These beds constitute 15-20% of unit and contain 5-10% grains of subangular to subrounded sand up to cU in size. Sparse beds (3-5% of unit) consist of strong brown (7.5YR 4/6), weakly consolidated, non-calcareous, weakly planar cross-stratified (foresets <5-6 cm thick) sand in thin (up to 10 cm) lenses. This sand is similar in texture and composition to gravel matrix but with only 10-15% reddish free-grain argillans. Paleosols in unit include stage II calcic horizons with carbonate nodules observed in clayey beds and petrocalcic soils with stage III-IV carbonate accumulation that cap unit in many places. Not mapped north of Cuchillo Negro Creek because most of unit Qpvu there is not overlain by a particularly thick gravel interval. Elsewhere, this unit conformably overlies and partly interfingers with Qpvu. Unit is ~12-37 m thick.

[from Jochems]

Short—

Stacked gravel bodies interbedded with subordinate clayey-silty sand. Gravel constitutes >60% of unit and features matrix with up to 40% clay that imparts dark reddish brown to yellowish red colors (5YR). Local clayey sand beds and sparse sand lenses are reddish brown to strong brown (5-7.5YR). Unit is commonly capped by stage III-IV calcic horizons. 12-37 m thick.

Qpvu Upper-level, volcaniclastic piedmont deposits (lower Pleistocene) – Interbedded silty-clayey fine sand and sandy pebble-cobble intervals. Proportion of fine sediment vs gravelly intervals is 15-50% over vertical scales of 10-20 m. Gravels contain pebbles and subordinate cobbles, and occur in 1-10 m-thick, tabular, laterally extensive intervals. Within these intervals, gravels are in thin to thick, tabular to lenticular beds with local cross-stratification (foresets up to 1 m tall). Gravel are clast- to sand-supported, variably imbricated, subrounded, poorly sorted, and comprised of pebbles with 5-30% fine-coarse cobbles and 1-2% boulders. Estimated clast composition: 15-20% porphyritic intermediate volcanics, 25-30% felsic volcanic rocks, and ~50% fine-grained intermediate volcanic rocks; <2% each of Kneeling Nun Tuff and monzonite. Sand in gravel matrix is reddish brown to light reddish brown (5YR 4-6/3-4) due to 0.5-15% estimated clay content; sand is medium- to very coarse-grained, subrounded, moderately to poorly sorted, and composed of volcanic grains with 20-30% feldspar and quartz. Fine sediment is light brown to light reddish brown (5-7.5YR 6/3-4), well-consolidated, and composed of clayey-silty very fine- to fine-grained sand with minor (1-25%) scattered medium- to very coarse-grained sand and <15% scattered volcanic pebbles. Fine sediment is in medium- to thick, tabular to lenticular to wedge-shaped beds that are internally massive; sparse lenses of reddish brown, weakly to moderately consolidated, poorly sorted, subrounded to rounded, sandy pebble gravel. The fine sediment has subequal or a preponderance of orangish intervals (7.5YR 6/4-6; 5YR 5-6/3-4); orangish colors are commonly due to paleosols with Bw or Bt horizons (15-50 cm thick, commonly overprinted by stage I calcic horizons) as well as possibly higher clay content in the sand matrix. Paleosols are more abundant in this interval compared to underlying units, and exhibit ped development with trace-3% ≤1 mm-wide root casts. Conformably overlies middle-level stratigraphic units across a 10-15 m-thick transitional zone (equivalent to unit QTpvut). 20-30 m thick.

Short—

Fine sand and silty-clayey fine sand interbedded with 15-50% sandy pebble-cobbles. Gravels commonly in laterally extensive intervals 1-10 m thick and contain 0.5-15% clay in their sand matrix. Fine strata are in medium to thick beds and have 50% or greater orangish intervals (commonly due to Bt or Bw horizon development); remainder of fine sediment is tan or light brown. 20-30 m thick.

Middle stratigraphic level

QTpmv -- Middle-level, volcaniclastic piedmont deposits (early to late Pliocene)— Fine sediment interbedded with variable proportions of volcanic gravels derived from western highlands. Fine-grained sediment is typically in medium to thick, tabular beds that are internally massive. Fine strata consists of light brown to light reddish brown (5-7.5YR 6/3) silt, very fine- to fine-grained sand (lesser mL), and clayey-silty very fine- to fine-grained sand; fine beds commonly have 1-20%, scattered, mU-vcU sand grains and trace-15% pebbles—consistent with hyperconcentrated flows; local very thin to thin lenses of pebbly sand and sandy pebbles. Gravelly intervals are 0.5-4 m thick (locally as much as 6 m) and exhibit very thin to medium, tabular to lenticular beds with 1-15% cross-stratification. These intervals are less laterally extensive than those found in Qpvu, and concave-up, buttress-bounded paleochannel forms are more abundant in this unit compared to Qpvu. Gravels are subrounded (mostly) to rounded, moderately to poorly sorted, clast- to sand-supported, and weakly to strongly imbricated. 1-10% matrix-supported, poor to very poorly sorted beds consistent with debris flows; remainder of sediment is primarily deposited by stream-flow processes. Gravels comprised of pebbles with 5-35% cobbles and near Cuchillo Negro Creek is composed of ~50% fine-grained intermediate volcanic rocks (includes basaltic andesites), ~25% felsic volcanic rocks, and 20-25% porphyritic intermediate volcanic rocks; minor lithologic types (each <3%) include Kneeling Nun Tuff, Paleozoic limestone, Abo Formation, and monzonitic intrusions (visual estimation). Near southern quadrangle boundary, a clast count indicates 5% porphyritic intermediate volcanic rock types, 25% fine-grained intermediate volcanic rocks (including basaltic andesites), 10% Kneeling Nun Tuff, 1% lithic tuffs, 1% monzonite intrusives, 50% rhyolites, 2% monzonitic intrusives, 4% granite, and <3%

Paleozoic sedimentary clasts—felsic volcanic rocks are less abundant to the north. Gravel matrix consists of brown to reddish brown (5-7.5YR 5-6/3-4), fU-vcU sand that is subangular to subrounded (most of coarse and very coarse sand is subrounded), moderately to poorly sorted, and predominately composed of volcanic detritus with minor feldspar and <20% quartz; 0-2% clay, with redder (5YR) color are associated with higher clay proportions. We interpret that the gravels were deposited on intra-piedmont gully-mouth fan lobes or within paleochannels—features indicating the latter include limited lateral extents, convex-down basal contacts, cross-stratification, and heavily scoured bases. Gravelly intervals typically have sharp (over 1-3 vertical cm) upper contacts, consistent with avulsion-dominated stream processes. Variable proprtions of paleosols characterized by illuviated clay horizons overlying calcic horizons; these soils are less abundant than observed in Qpvu. Illuviated clay (Bt) horizons are typically reddish brown to yellowish red (5YR 5/6-5/4) and peds are moderately to strongly developed and angular to subangular blocky; there are faint to distinct clay films on ped faces. Calcic horizons are characterized by lighter (whiter) hues and exhibit stage I to II carbonate morphologies. Subunits differentiated based on the proportion of volcanic clast-dominated, gravelly intervals vs. fine-grained deposits. ~60 m thick.

Short—

Fine sediment interbedded with variable proportions of volcanic gravels derived from western highlands. Fine-grained sediment includes silt-fine sand with scattered, minor coarser sand or pebbles; typically in medium to thick, tabular beds that are internally massive. Gravels less laterally extensive, gravel paleochannel forms more common, and paleosols sparser compared to Qpvu unit. ~60 m thick.

QTpvmt Transitional unit at top of middle-level volcaniclastic piedmont deposits (uppermost Pliocene to lower Pleistocene) – Transitional unit locally mapped in the northeastern quadrangle between unit Qpvu and underlying strata, particularly where the transition is thick and underlying strata are fine-grained. Elsewhere, base of unit is difficult to define. Strata are similar to unit Qpvu in terms of gravel proportions, types and textures, and bedding characteristics. However, lowest gravels tend to be finer than overlying gravels. Also, fine-grained sediment has <50% orangish intervals, and paeosols are not as abundant as in unit Qpvu. Interfingers westward with Tpfm. 10-24 m thick.

Short—

Transitional unit locally mapped Qpvu and underlying strata, particularly where the transition is thick and underlying strata are fine-grained. Strata are similar to unit Qpvu in terms of gravel proportions, types and textures, and bedding characteristics. Fine sediment has <50% orangish intervals, and paeosols are not as abundant as in unit Qpvu. Interfingers westward with Tpfm. 10-24 m thick.

QTpvmc Fine-grained deposits with 35-60% gravelly intervals (Pliocene, possibly lowest Pleistocene at its top) – Proportion of gravelly intervals is 35-60%. Grades laterally eastward with unit QTpvm. Conformably overlain by Qpvu and underlain by Tpvl. 35-38 m thick.

QTpvm Fine-grained deposits with 15-40% gravelly intervals (Pliocene, possibly lowest Pleistocene at its top) – Proportion of gravelly intervals is 15-40%. Grades laterally eastward with unit QTpvmf and laterally westward with QTpmvc. Conformably overlain by Qpvu and underlain by Tpvmt or Tplv. 35-50 m thick.

QTpmvf Fine-grained deposits with 5-20% gravelly intervals (Pliocene, possibly lowest Pleistocene at its top) – Proportion of gravelly intervals is 5-20%. Grades laterally eastward with unit Tpfm and laterally westward with QTpmv. Conformably overlain by Qpuv and underlain by Tpvmt. 25-50 m thick.

Tpvmt Transitional unit at the base of the middle stratigraphic level (lower Pliocene)—Proportion of gravelly intervals is 15-50%. Grades laterally eastward with unit Tpvmtf. Northwest of the dam on Cuchillo Negro Creek, poor exposure necessitated lumping this unit with Tpvm. 18-28 m thick.

Tpvmtf Transitional unit at the base of the middle stratigraphic level, fine-grained (lower Pliocene)—Proportion of gravelly intervals is 5-15%. Grades laterally westward with unit Tpvmt. ~30 m thick.

Lower stratigraphic level

Tpvl Coarse volcaniclastic deposits interbedded with 30-60% fine sediment (lower Pliocene) – Sandy gravel interbedded with subequal or subordinate fine sediment (30-60% fine sediment). Sandy gravel is in very thin to medium, tabular to lenticular beds (very thin to thin beds tend to be pebbly; cobbles tend to be in medium, lenticular beds or U-shaped beds). <10% cross-stratification. Gravel are clast- to sand-supported and consist of pebbles with 15-35% cobbles. Clasts are subrounded (mostly) to rounded, poorly sorted, and near Cuchillo Negro Creek is composed of ~50% fine intermediate volcanics, 20-30% porphyritic intermediate volcanic rocks, 25-40% felsic volcanic rocks; <3% each of Paleozoic limestone and Kneeling Nun Tuff (visual estimation of clast%). Near southern quadrangle boundary, a clast count indicates 35% intermediate volcanic rock types (including basaltic andesites), 13% Kneeling Nun Tuff, 7% other tuffs, 1% monzonite intrusives, 2% granite, 2% Precambrian metamorphic rocks, 38% rhyolites, and <2% Paleozoic sedimentary rocks—felsic volcanic rocks are less abundant to the north. Gravel matrix is a pinkish gray to light brown (7.5YR 6/2-3), fine- to very coarse-grained sand (mostly medium- to very coarse-grained) that is subrounded to subangular, poorly to moderately sorted, and composed predominately of volcanic lithic grains with subordinate feldspar and lesser quartz; matrix has 0-2% clay. Intervals with higher matrix clay (0.5-2%) are generally light reddish brown (5YR 6/4). Gravelly sediment is more cemented than the middle interval (10-50% strong cementation by calcium carbonate). Fine sediment is in medium to thick, tabular, internally massive beds and composed of light brown to brown to pink (7.5YR 6-7/3; 5/4) silt to fine-grained sand with minor (trace to 25%) scattered medium to very coarse sand and trace to 20% pebbles. Moderately to well consolidated; sparse paleosols that are similar in character and abundance as those in the middle stratigraphic level. Grades laterally into units Tpal, lower QTps, and lower Tpvlt. 18-25 m thick (up to 30 m where not overlain by Tpvlt).

Short—

Sandy gravel interbedded with 30-60% fine sediment. Sandy gravel is in very thin to medium, tabular to lenticular beds; <10% cross bedding. Fine sediment is in medium to thick, tabular, massive beds; composed of light brown to pink, silt to fine sand with minor (trace to 25%) scattered medium to very coarse sand and trace-20% pebbles. 10-50% strongly cemented; sparse paleosols. 18-25 m thick.

Tpvlt Transition zone at base of piedmont lithofacies assemblages of the Palomas Formation (lowest Pliocene) – Light reddish brown (5YR 6/3-4) strata in medium to thick, tabular beds, and composed of: 1) siltstone and very fine- to fine-grained sandstone (about 50-70%); and 2) fine- to medium-grained sandstone (~20%), and coarse channel-fills (increasing up-section from 10 to 25% but also decrease laterally to north) Locally in the finer sand are scattered, coarse sand grains. Coarse channel-fills are as much as 2 m thick and consist of thin to medium, tabular beds composed of pebbly sand or sandy pebbles (with as much as 10% cobbles). Pebbles are very fine to medium, subangular to subrounded, and composed predominately of volcanic clasts (mostly rhyolite with 10% tuffs, 10% intermediate volcanics, 1% basaltic andesite, and perhaps trace basalt) together with 1-5% chert and 0-2% granite (both from the Mud Springs Mountains). Proportion of cemented beds increases up-section from 5 to 50%. Cementation is often nodular (5-10 cm across) and probably controlled by bioturbation or burrowing. ~4 m below upper contact lies a 1-2 m thick, lat erally extensive, calcium carbonate bed mixed with 20-40% sand and gravel; its lateral extent and locally porous features suggest it is a travertine. Well consolidated. ~30 m thick. [slightly modified from Jochems and Koning, 2015]

Short—

Light reddish brown (5YR 6/3-4) strata in medium to thick, tabular beds, and composed of: 1) siltstone and very fine- to fine-grained sandstone (about 50-70%); and 2) fine- to medium-grained sandstone (~20%), and 3) coarse channel-fills (increasing up-section from 10 to 25%) composed of pebbly sand or sandy pebbles. Extensive calcium carbonate bed at top of unit. ~30 m thick.

Units derived from Mud Springs Mountains, associated with a piedmont or alluvial fan lithofacies assemblage

Qpxu Deposits with Precambrian-dominated gravels derived from the Mud Spring Mountains (lower Pleistocene) – Moderately to strongly cemented conglomerate composed of granite and minor gneiss; only ~1% Paleozoic carbonate clasts. No bedding observed. Gravel is subangular, very poorly sorted, and comprised of pebbles through fine boulders. >4 m thick. [from Koning]

Qpsu Deposits with sedimentary clast-dominated gravels derived from the Mud Spring Mountains, upper unit (lower Pleistocene)—Interbedded conglomerate and fine sediment that coarsen-upwards in conjunction with a basinward progradation of the associated alluvial fan/piedmont toe. Conglomerate is in 0.5-3.0 m-thick intervals that are laterally extensive and tabular or else wedge-shaped; internal very thin to medium (mostly thin to medium), tabular to lenticular beds. Gravels are clast- to matrix-supported, locally imbricated, and comprised of pebbles with subordinate cobbles and ≤10% boulders. Gravel are angular to subangular, poorly sorted, and composed of Paleozoic carbonate clasts (limestones and dolomites) with very minor clasts of sandstone (<5%), chert (<10%), and granite (<10%, only found south of Mud Springs Mountains). Local cross-bedding up to 2 m thick, with planar foresets. Conglomerate matrix consists of very fine- to very coarse-grained (mostly fine- to very coarse-grained) sand that is very pale brown to light brown to brown (7.5-10YR 6-7/3-4), subrounded to subangular, poorly sorted, and composed primarily of Paleozoic detritus. Coarse sand and pebbly sand occur as thin (<0.5 m) lenses within the conglomerate or in laterally continuous beds up to 2 m thick, the latter being particularly common in the distal position of the piedmont. Gravels typically are well-cemented by calcite. Fine sediment is in medium to thick, tabular to lenticular, internally massive beds and composed of tan silt and very fine- to fine-grained sand; minor coarser, scattered sand grains and up to 20% scattered pebbles (mostly Paleozoic clasts). Burrows are locally abundant in the fine sediment and there are minor, thin to medium lenses of pebbles derived from Paleozoic rocks. Relatively abundant strongly developed calcic paleosols exhibiting stage III to IV carbonate moprhologies (commonly 50-100 cm thick); these are locally overlain by reddish Bt or Bw horizons. This unit conformably progrades over finer-grained units that include Qpvu, QTpsf, and QTpvmf. 10-45 m thick.

Short—

Interbedded conglomerate and fine sediment that coarsen-upwards and conformably progrades over finer-grained units. Gravel composed primarily of Paleozoic carbonate clasts with <5% chert. Fine sediment is in medium to thick, tabular to lenticular, internally massive beds and composed of tan silt and very fine- to fine-grained sand. Common stage III to IV calcic paleosols. 10-45 m thick.

QTpsf Deposits with sedimentary clast-dominated gravels derived from the Mud Spring Mountains, fine-grained (lower Pleistocene to upper Pliocene) – Mapped near the southeast end of the Mud Springs Mountains, this unit consists of light brown (7.5YR 6/3-4) to pink (7.5YR 7/3) silt to fine sand with ≤15% sandy pebble conglomerate beds. Fine sediment is in medium to thick, tabular beds that are internally massive and contain local calcium carbonate nodules. This fine sediment consists primarily of silt and very fine- to fine-grained sand (<15% scattered medium to very coarse sand grains and 0-10% scattered pebbles); up to 20% very thin to thin beds of silty very fine- to very coarse-grained sand; medium and very coarse sand are composed of Paleozoic carbonate and chert detritus. Minor (<15%) sandy pebble conglomerate and pebbly sandstone bodies that are 0.1-1.5 m thick and lenticular; bedding is typically very thin to thin and lenticular. Gravel is composed primarily of Paleozoic limestones and dolostones; 5-15% chert + silicified limestone. <5% cobbles in the gravel fraction. Gravel are subangular to angular, poorly to moderately sorted, and generally poorly imbricated. Sand in the conglomerates is very fine- to very coarse-grained, subangular, and poorly sorted; medium-upper to very coarse sand is composed of carbonate detritus. Trace to 5% greenish mudstone beds. Well consolidated; gravels are typically cemented. Sparser paleosols compared to unit Qpsu. Unit grades laterally away from the Mud Springs Mountains into unit QTptvf. >40 m thick.

Short—

Light brown to pinkish, silt to fine sand with <15% sandy pebble beds. Fine sediment is in medium to thick, tabular beds (internally massive). Up to 20% very thin to thin interbeds of silty very fine- to very coarse-grained sand. Pebbly stratum are 0.1-1.5 m thick and lenticular. Gravel composed primarily of Paleozoic carbonates with 5-15% chert. Sparser paleosols compared to Qpsu. >40 m thick.

QTps Deposits with sedimentary clast-dominated gravels derived from the Mud Spring Mountains (Lower Pliocene to lowest Pleistocene)—Conglomerate grading up-section to interbedded conglomerate and fine sediment, in conjunction with retrogradation of alluvial fan toe. Conglomeratic intervals are in vague, medium to thick, tabular to lenticular beds. Gravel are clast- to matrix-supported, non- to moderately imbricated, and comprised of pebbles and cobbles, with the proportion of cobbles decreasing up-section in conjunction with a decrease in cobble size. Gravel composed of Paleozoic carbonate clasts (mainly limestones) with <5% chert. Conglomerate matrix is pale brown to very pale brown, mostly medium- to very coarse-grained, angular to subrounded, poorly sorted, and composed of Paleozoic detritus. Fine grained sediment is pale brown to very pale brown silt and very fine- to fine-grained sand, with 1-20% scattered medium- to very coarse-grained sand grains and 1-5% thin pebbly beds. Strongly cemented in lower, conglomeratic part of unit; variably weakly to strongly cemented above. Unit interfingers northeastward with units Tpmf and QTpvmf. 20-25 m thick.

Short—

Strongly cemented conglomerate grading up-section to interbedded conglomerate and fine sediment. Conglomeratic intervals are in vague, medium to thick, tabular to lenticular beds. Cobble abundance and size decrease up-section. Fine grained sediment composed of tan silt and very fine- to fine-grained sand, with 1-20% scattered coarser grains + pebbles and 1-5% thin pebbly beds. 20-25 m thick.

Fine-grained strata associated with a marginal basin floor lithofacies assemblage

Tpfm Fine-grained strata with <10% volcaniclastic gravel beds (upper Pliocene, possibly lowest Pleistocene at its top) –Siltstone, very fine- to fine-grained sandstone, and mixed clay-siltstone-very fine-grained sandstone; minor claystone. 1-5% thin to thick, tabular beds of pebble conglomerate; local small-scale cross bedding (<30 cm thick and commonly low-angle foresets); conglomerates mostly composed of volcanic rocks, although near the Mud Springs Mountains there are minor beds composed of Paleozoic sedimentary clasts. Clayey beds are reddish brown (2.5-5YR; a very small percentage are greenish), tabular, and very thin to thick (up to 3 m); these commonly contain vertic and calcic paleosols (latter characterized by calcium carbonate nodules). Siltstone and fine sandstone are in light brown to brown (commonly 7.5YR 5-6/3), tabular beds 0.2-1.5 m thick; these are internally massive or have faint horizontal lamina. Local (<2%) beds of microcrystalline calcite (>95% by volume, rest is sand) have sharp bases and tops and are generally internally massive; a few beds have nodular tops; some beds have root traces in upper 15 cm. Includes very minor (<2%) tongues (<3 m thick) of Tpam. Near the Mud Springs Mountains, a pumiceous bed lying 35-50 m below the top of the unit has been correlated geochemically with a 3.1 Ma pumice bed. This may possibly correlate with a fine white ash mapped north of Cuchillo Negro Creek near Interstate 25, which lies 40 m below the top of the unit and 12 m above (in elevation) the Mud Springs pumice bed. Unit interfingers eastward with unit Tpam and westward with unit Tpvmf. Uppermost strata interfinger with unit Qpvu (Mack et al., 2009). ~110 m thick. [Description modified from Mack et al., 2012].

Short—

Siltstone, very fine- to fine-grained sandstone, and mixed clay-siltstone-very fine-grained sandstone; minor claystone. 1-5% thin to thick, tabular beds of pebble conglomerate. Local beds of microcrystalline calcite (>95% by volume, rest is sand) and very minor (<2%) tongues of Tpam. Pumiceous bed ~35-50 m below top is 3.1 Ma based on geochemical correlation (Mack et al., 2009). 115 m thick.

Axial lithofacies assemblage of the lower to middle Palomas Formation

Tpam Middle axial lithofacies unit (lower to upper Pliocene) – White to light gray (10YR 8/1-7/2) sand interbedded with minor (1-20%) pebbly sand and sandy pebbly conglomerates that are <1 m thick. Strata are cross-stratified (with common trough cross beds 0.1-1.5 m thick) or horizontal-planar laminated to very thinly bedded; local wavy laminations. Pebbles are very fine to very coarse (mostly very fine to coarse; locally trace cobbles up to 10 cm long), subangular to rounded, moderately to poorly sorted, and composed mainly of fine-grained, light-colored volcanic rocks inferred to be felsic. Minor, variable proportions of the following clast types: darker, locally porphyritic intermediate volcanic rocks (0-20%), greenish sandstone (0-1%), limestone (0-5%), granite (10-30%), chert (0-25%), quartzite (0-15%). Also local beds of intra-formational conglomerate composed of reworked calcium carbonate nodules. Sand is fine- to coarse-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, 12-20% orange-colored grains (orange-stained quartz, potassium feldspar, and chert), 0-12% chert, and 10-20% volcanic lithic grains. Locally, sparse (<5%) intra-formational clay-balls up to boulder-size. Sparse (<7%) intervals of fine-grained, thickly bedded (0.5-1.5 m-thick) sediment composed of clay, silt, very fine-grained sand, and clayey-silty very fine-grained sand; pink to reddish brown to brown (very minor green), internally massive, and overprinted by calcic or vertic paleosols; calcic soils have pebble-size calcium carbonate nodules. In the lower 20 m of the unit, cross-stratification is very sparse; rather, very thin to medium, tabular to lenticular beds dominate. Gravely intervals are commonly weakly to strongly cemented, but otherwise this unit is typically non- to weakly cemented. ~110 m thick near cross-section A-A'.

Short—

White to light gray, cross-laminated (common troughs) to horizontal-planar bedded, medium- to coarse-grained sand with ≤20% pebbly beds. Pebbles typically dominated by volcanic rocks but include minor, variable proportions of granite, sedimentary clasts, and chert. Sparse (<7%) intervals of thickly bedded clay, silt, very fine sand, and clayey-silty very fine-grained sand. ~110 m thick to north.

Tpal Lower axial lithofacies unit (lower Pliocene)—Very pale brown to white (10YR 7/3-8/1) sand interbedded with 10-50% gravelly intervals. Sand is horizontal-planar laminated to low-angle cross-stratified (locally massive), and fine- to very coarse-grained (mostly medium- to coarse-grained), subangular to rounded, and quartzo-feldspathic with subordinate lithic grains (% quartz is greater than % feldspar + lithics); lithic grains are typically dominated by felsic volcanic compositions, but in some beds sedimentary compositions dominate. Three allostratigraphic units are recognized near Truth or Consequences, the younger and middle ones occupying unambiguous paleovalleys (see Koning et al., 2018). In the No. 2 Getty West Elephant Butte Federal 3 well, this unit is correlated with pebbly coarse sand at 370-420 ft depths; pebbles and very coarse sand are composed primarily of felsic volcanic rocks with 0-5% orange granite, 0-1% chert, up to 20% potassium feldspar (very coarse sand), 0 to trace quartzite; signs of strong calcium carbonate cementation occur at 460-490 ft. 25 m thick near Truth or Consequences but thickens northwards to 46 m.

Short—

Very pale brown to white (10YR 7/3-8/1) sand interbedded with 10-50% gravelly intervals. Sand is horizontal-planar laminated to low-angle cross-stratified (locally massive), quartzo-feldspathic, and mostly medium- to coarse-grained. Three allostratigraphic units are present near Truth or Consequences, the younger and middle ones occupying unambiguous paleovalleys. 25-46 m, thickening to north.

Tpal3 Lower axial sand unit, youngest allostratigraphic subunit (lower Pliocene)— Sandy gravel and sand filling a 17-19 m deep paleovalley inset into older paleovalley fill (the older paleovalley being filled with unit Tpal2) to the east and unit Tpvlt to the west. Strata are in very thin to thick, tabular to broadly lenticular beds that are locally cross-stratified. Gravel are subrounded to rounded and commonly dominated by coarse to very coarse pebbles and fine to coarse cobbles. Gravel occupies an estimated 25-60% of this unit and cobbles are relatively abundant The contrast in gravel proportions between Tpal3 with the overlying, sandier Tpam unit commonly forms a topographic bench. Gravel assemblage has about equal amounts of felsic vs intermediate volcanic rocks, in addition to notable 10-40% of exotic clasts—mainly quartzite and trace Pedernal chert. Sand in gravel matrix is white to very pale brown (10YR 8/1-2), mostly medium- to coarse-grained, subangular to rounded (mostly subrounded), and well sorted. Variably non-cemented to strongly cemented.17-19 m thick.

Short—

Sandy gravel and sand in a 17-19 m deep paleovalley. Strata are in very thin to thick, tabular to broadly lenticular beds that are locally cross-stratified. 25-60% gravel commonly dominated by coarse to very coarse pebbles and fine to coarse cobbles, and composed of subequal felsic vs intermediate volcanic rocks and 10-40% of exotic clasts—mainly quartzite and trace Pedernal chert. 17-19 m thick.

Tpal2 Lower axial unit, middle allostratigraphic subunit (lower Pliocene)—Sand interbedded with 30-50% gravelly stratum and filling a 17-20 m-deep paleovalley incised in the oldest allostratigraphic unit (Tpal1). Gravel mostly composed of felsic volcanic clasts with minor Paleozoic-Mesozoic sedimentary clasts and 1-3% intermediate volcanic rocks; gravel source areas interpreted to be highlands surrounding the Engle Basin (Koning et al., 2016). The non-gravel fraction consists mainly of fine- to medium-grained sand that is horizontal-planar laminated, cross-laminated (typically <20 cm thick foresets), or massive. In the lower-middle part of the unit, these gravels are 0.1-2 m-thick, typically massive with local low-angle cross-laminations, and composed of very fine to very coarse pebbles with minor (10-20%) cobbles in some beds. In the upper 3 m of the unit, cross-stratification is more pronounced in gravelly sediment and trace exotic clasts appear (Pedernal Chert and quartzite). Unit contains a basal, 3-5 m-thick, coarse conglomerate (abundant coarse cobbles and fine boulders) derived from the Mud Springs Mountains or north of the Caballo Mountains. This conglomerate exhibits 30 to >100 cm-thick beds, typically internally massive, and is clast- to matrix-supported. About 10-15% cross-stratification, with foresets typically ≤50 cm thick but locally occurring as lateral accretion sets 2.0-2.5 m thick. Gravel is comprised of cobbles with slightly lesser to subequal pebbles and 1-20% boulders; gravel is subangular to subrounded and poorly sorted. Gravel composed of Paleozoic sedimentary rocks (mainly carbonates), subordinate greenish sandstone (correlated to the Crevasse Canyon Formation), and ≤20% volcanic rocks and lesser Proterozoic rocks. Clast imbrication indicates a ~200 degree paleoflow direction. Sand is pale brown to very pale brown to light brownish gray (10YR 6/2-4), fine to coarse-grained, subrounded to rounded, poorly to well sorted, and composed of an estimated 40-65% quartz, 10-30% volcanic-dominated lithic grains, and 20-25% feldspar grains—more or less similar to axial sand elsewhere in the lower axial unit. Sand occurs as gravel matrix or in lenses (commonly mixed with pebbles) throughout the unit. 40Ar/39Ar dating of cryptomelane locally precipitated at the top of the unit indicates a minimum age of 4.87±0.05 Ma. Magnetostratigraphic sampling of the sand-dominated upper interval indicates it is all in a reversed chron that we correlate to chron 3n.3r, which indicates an age of 4.9-5.0 Ma. 15-20 m thick, including basal conglomerate.

Short—

Sand with 30-50% gravelly stratum filling a 17-20 m-deep paleovalley. Gravel mostly composed of felsic volcanic clasts with minor Paleozoic-Mesozoic sedimentary clasts and 1-3% intermediate volcanic rocks. Sand is fine- to medium-grained and mostly horizontal-planar laminated to massive. Basal 3-5 m-thick, coarse conglomerate composed of Paleozoic-Mesozoic sedimentary clasts. 15-20 m thick.

Tpal1 Lower axial sand unit, older allostratigraphic subunit (lower Pliocene)— Upward-coarsening unit consisting of sand and pebbly sand interbedded with 30-40% reddish sandy gravels. Sandy gravels are in 0.2-1.0 m-thick intervals that are in vague, very thin, tabular to lenticular beds; local cross-stratification <10 cm thick. Gravels are subangular to subrounded, moderately to poorly sorted, and composed of felsic volcanic clasts with 1-18% intermediate volcanic rocks, 0-13% Paleozoic carbonates, 5-30% green fine- to medium-grained sandstone inferred to correlate to the Crevasse Canyon Formation, 0-3% Proterozoic granite, 0-10% Abo Formation, trace-0.5% McRae Formation sandstone (plagioclase-phyric and similar to clasts seen in the San Jose Member), trace feldspar-bearing porphyry (phenocrysts up to 4 mm long), and 0-1% Proterozoic gneiss. Gravel is exclusively pebble-size in lower 4.5 m of unit, but above contains 1-30% cobbles (mixed with pebbles). Matrix of sandy gravel is typically reddish brown to reddish yellow (5YR 5/3; 5-6/4-6), very fine- to very coarse-grained sand (mostly medium- to very coarse-grained) that is angular to subrounded (mostly subangular), poorly to moderately sorted, and composed quartz and subordinate feldspar + lithic grains; lithic grains dominates in the m-vcU sand fraction and has variable proportions of volcanic, chert, carbonate, and sedimentary rocks; reddish color largely due to 1-25% matrix clay as clast coatings or as chips. Sand and pebbly sand intervals are massive or horizontal-laminated to cross-laminated (<10 cm tall and commonly low-angle foresets). Sand is white (7.5-10YR 8/1), fine- to very coarse-grained (mostly fine- to medium-grained), subrounded to subangular, moderately to well sorted, quartzo-feldspathic sand (quartz>feldspar) with up to 20% volcanic sand grains. However, sandy intervals in lower 4 m of unit are pink to reddish yellow to light reddish brown to light gray (7.5YR 7/3-6; 5YR 6-7/4-6; 7.5YR 7-8/1). Within pebbly sand are local pebble lenses up to 10 cm thick. Minor 0.5-1.5 m-thick intervals composed of very fine sand, silty very fine sand, silt, or clay; these are commonly slightly yellowish-greenish (2.5-5Y 8/1) and in tabular, laminated to thin beds. Near middle of unit is a distinctive ~5 cm-thick, porous travertine marker bed (calcium carbonate mixed with subordinate sand) exhibiting local rhizoliths; internal laminations show local drape forms or flow structures. Unit is moderately to well consolidated and non-cemented or weakly cemented by clays. Where mapped, basal contact seems to be disconformable based on sharp transition to Rincon Valley Formation clayey strata; however, this disconformity may be a local phenomena. Based on similar elevations and reddish colors, this unit likely correlates with unit Tplvt near Interstate 25. Magnetostratigraphic investigations reveal reverse polarity for all of unit except within 2 m of base. We interpret the basal 2 m is part of Chron 3n.4n and thus is slightly older than 5.0 Ma. 14 m thick.

Short—

Upward-coarsening unit consisting of sand and pebbly sand interbedded with 30-40% reddish sandy gravel; reddish colors due to 1-25% clay in gravel matrix. Gravel composition similar to that in mid-upper Tpal2. Sand is white (7.5-10YR 8/1), fine- to very coarse-grained (mostly fine- to medium-grained), and quartzo-feldspathic. Orangish sands in lower 4 m. Disconformable top and base. 14 m thick.

Tpa-swdi Sand-dominated, undivided axial-fluvial deposits covered by slopewash or disturbed (Pliocene) – See descriptions of Tpam and Tpal. Mapped where strongly disturbed by anthrogenic activity or covered by slopewash near urban areas.

Rincon Valley Formation

Trbut Upper Rincon Valley Formation, basin floor lithofacies assemblage near Truth or Consequences (uppermost Miocene) – Very thin to medium, tabular beds of reddish (5-7.5YR hues) very fine- to medium-grained sand, clayey-silty fine sand, siltstone, and silty claystone. Sand is moderately sorted, angular to subrounded, and has relatively low amounts of quartz (typically, % feldspar + % lithic grains > % quartz grains). Clay-silt beds are internally massive and commonly exhibit nodular calcic paleosols. Minor 5-50 cm-thick beds composed of very fine- to very coarse-grained sand, commonly mixed with clay-silt, containing variable percentages of pebbles; these locally fine upward and locally display very thin-thin internal bedding. Pebbles are angular to subangular, poorly to moderately sorted, and composed of Paleozoic sedimentary clasts (i.e., limestone, red siltstone-very fine sandstone of the Abo Formation), greenish fine- to medium-grained sandstones (likely derived from Late Cretaceous strata) together with minor granite, chert, and gneissic clasts. Gravel are both clast- to matrix supported. Paleoflow directions are 150-215 degrees. Well consolidated, with 5% well-cemented, medium to thick layers. 165-180 m (550-600 ft) thick based on interpretations of the Barney Iorio Fee #1 well log [from Koning et al., 2016 and Jochems and Koning, 2015), but only uppermost 10 m is exposed. Strata likely transition down-section to playa clays that are correlative to unit Trplu.

Short—
Very thin to medium, tabular beds of reddish (5-7.5YR hues) very fine- to medium-grained sand, clayey-silty fine sand, and silty clays. Minor 5-50 cm-thick beds of silty-clayey very fine- to very coarse-grained sand with variable amounts of pebbles; pebbles are moderately to poorly sorted and composed of angular to subangular sedimentary clasts plus minor granite, chert, and gneiss. >10 m thick.

TrbuwUpper Rincon Valley Formation, basin floor lithofacies assemblage near Williamsburg (uppermost Miocene, possibly lowermost Pliocene?)—Light reddish brown to yellowish red (5YR 6/4-5/6), very fine- to medium-grained sand, clay-silt, and clayey-silty fine sand in thin to thick, tabular beds (commonly horizontal-planar to ripple-laminated). There are minor (~5%) beds composed of very fine- to very coarse-grained sand with 5% pebbles. The fine texture is consistent with a basin floor depositional environment. Greater than the 6 m of exposed thickness [modified from Jochems and Koning, 2015).

Short—

Light reddish brown to yellowish red (5YR 6/4-5/6), very fine- to medium-grained sand, clay-silt, and clayey-silty fine sand in thin to thick, tabular beds (commonly horizontal-planar to ripple-laminated). There are minor (~5%) beds composed of very fine- to very coarse-grained sand with 5% pebbles. >6 m of exposed thickness.

Trbuc Upper Rincon Valley Formation, basin floor lithofacies assemblage near Cuchillo (upper Miocene) – Interbedded fine, massive sand and coarse sand lenses. Reddish brown to yellowish red (5YR 5/4-6) fine-grained, massive sand constitutes 65-70% of unit and is weakly to moderately indurated, and moderately to strongly calcareous. Sand grains are rounded, well sorted, and composed of 80-90% quartz+feldspar and 10-20% lithics (volcanic) with up to 5% very fine clay chips. This sand occurs in thick (70-100 cm), tabular, internally massive beds. Trace to 2% floating subrounded to rounded, medium to very coarse pebbles concentrated at the tops of red sandy beds consist of Paleozoic carbonates (30-35%), felsic volcanics (15-20%), undivided tuffs (10-15%), ~10% Abo Formation, and 3-6% each of sandstone, Kneeling Nun tuff, Vicks Peak tuff, chert, basalt, and unknown lithologies. Subordinate coarse sandy lenses (30-35%) consist of light brown (7.5YR 6/3-4), moderately well indurated, strongly calcareous and calcite-cemented, subrounded to well rounded, poorly sorted, mU-vcL grains composed of 60-65% quartz, 20-25% feldspar, and 15-20% lithics (volcanic) with no clay. These lenses are thin- to medium-bedded (5-20 cm) and internally massive to vaguely trough cross-stratified. Probably deposited on a basin floor depositional environment on the hanging wall of an actively subsiding Mud Springs fault. Thickness unknown. May be correlative, in part, to units Trplue and Trbut.

Short—
Weakly to moderately indurated, reddish brown to yellowish red (5YR 5/4-6) sand that is internally massive and contains up to 2% floating pebbles of up to 45% Paleozoic lithologies. Subordinate lenses of light brown (7.5YR 6/3-4), calcite-cemented, internally massive to vaguely trough cross-stratified, medium to very coarse sand. Thickness unknown.

Trplu Upper Rincon Valley Formation, playa lithofacies near Elephant Butte (upper Miocene) [cross-section only] – Reddish brown to reddish clay. Described using cuttings logs and down-hole geophysical logs from the No. 2 Getty West Elephant Butte Federal 3 well. Apparent thickness of 236 m where penetrated by this well.

Trpl Lower Rincon Valley Formation, piedmont lithofacies assemblage (lower? to middle Miocene) – Interbedded pebble-cobble conglomerate, massive silt-sand, and massive pebbly sand. Pebble-cobble conglomerate constitutes 30-40% of unit and is pale brown to very pale brown (10YR 6-7/3), moderately well indurated, weakly to moderately calcareous, moderately imbricated, normally graded, and occurs in thick to very thick (50-120 cm), broadly lenticular beds. Gravel consists of clast-supported, subangular to rounded (mostly subrounded to rounded), very poorly to poorly sorted, pebbles (35-75%) and cobbles (25-65%) with trace to 2% boulders up to 40 cm long. Clast lithologies include Paleozoic carbonates (20-25%), undivided tuffs (mostly Kneeling Nun tuff; ~20%), greenish (Mesozoic?) sandstone and siltstone (10-15%), felsic volcanics (10-15%), Abo Formation (10-15%), and less than 10% each of intermediate volcanics, tan sandstone, feldspar porphyry, chert, and petrified wood. Preliminary clast imbrication data suggests southerly paleoflow. Conglomerate matrix consists of very poorly to poorly sorted, subangular to rounded, mL-cU sand (10-20% very coarse sand to granules) composed of 50-60% lithics (volcanic>carbonate), 25-35% quartz, and 15-25% feldspar with no clay. Of subequal percentage to conglomerate is very pale brown (10YR 7/3), silt to fL sand (5-10% fU-mU) in thin to thick (8-60 cm), tabular, internally massive beds. This sediment is well indurated, strongly calcareous, moderately sorted, and subrounded to rounded; sand grains are composed of 70-80% quartz+feldspar and 20-30% lithics (volcanic) with <5% clay chips. Silt-sand contains trace to 3% floating angular to subrounded, fine to very coarse pebbles composed of at least 80% felsic volcanic lithologies. Unit features subordinate (20-30%) beds of pale brown (10YR 6/3) fL-cL sand (up to 3% cU-granules) in thick to thick (5-40 cm), tabular, internally massive beds. This sand is moderately well indurated, strongly calcareous, subrounded to rounded, poorly sorted, and composed of 65-80% quartz+feldspar and 20-35% lithics (volcanic) with no clay. Pale brown sand contains 5-20% subangular to rounded, very fine to coarse pebbles (cobbles in upper 15 cm of some beds) of lithologies similar to conglomerate that sometimes form vaguely imbricated stringers. Probably deposited on a south-sloping piedmont depositional environment on the hanging wall of an actively subsiding Mud Springs fault. Older than unit Trbuc. Probably older than most strata in units Trplue and Trbut. ~10 m exposed, but total thickness is unknown.

Short—
Interbedded pebble-cobble conglomerate, silt-sand, and fine to coarse sand that are pale brown to very pale brown (10YR 6-7/3). Clasts are mostly Paleozoic sedimentary rocks, felsic volcanics, and tuffs with 10-15% green sandstone and siltstone (Mesozoic?). Conglomerates are imbricated and normally graded; silt-sand and sand are internally massive with minor floating pebbles. Thickness unknown.

Trbl Lower Rincon Valley Formation, basin floor lithofacies assemblage near Elephant Butte (lower to middle Miocene) [cross-section only] – Clay, silt, and very fine- to medium-grained sand. Sand is white to light gray to reddish brown; contains subrounded to rounded quartz, chert, and limestone grains. Described using cuttings logs and down-hole geophysical logs from the No. 2 Getty West Elephant Butte Federal 3 well. 113 m apparent thickness where penetrated by this well.

TERTIARY

Igneous rocks

Tb Basalt (lower Pliocene) – Olivine basalt flow and scoria found ~1.5 km southeast of Mud Mountain. Similar in composition to tholeiitic basalt flows elsewhere in region (Bachman and Mehnert, 1978). Dated by McLemore and others (2012) at 5.55+/-0.21 Ma (^{40}Ar/^{39}Ar isochron age) and described as containing numerous xenoliths of limestone, shale, jasperoid, and Proterozoic granite. 11-12 m thick [description modified from Maxwell and Oakman, 1990].

Short—

Olivine basalt flow and scoria found ~1.5 km southeast of Mud Mountain. Similar in composition to tholeiitic basalt flows elsewhere in region (Bachman and Mehnert, 1978). Dated by McLemore et al. (2012) at 5.55+/-0.21 Ma (^{40}Ar/^{39}Ar) and described as containing numerous xenoliths of limestone, shale, jasperoid, and granite. 11-12 m thick [description modified from Maxwell and Oakman, 1990].

Td Basalt dikes (Miocene?)—Basalt dike intruding Lower Permian Abo Formation (Pa) is 0.3-1.2 m wide, vertical, dark olive green and brown; nesophitic texture; highly altered with chalcedony and chlorite in veinlets and cavities, calcite interstitial to feldspar laths, and augite(?) altered to clay, limonite, and chlorite; feldspar laths generally ~0.02 by 0.2 mm; truncated by overlying Palomas Formation. Basalt dike intruding Pennsylvanian Nakaye (₱n) and Bar B (₱b) Formations, adjacent to porphyritic quartz trachyandesite dike (Tqt), is 0.2-0.9 m wide, dark brown; similar to basalt dike intruding

Pa but is more altered and has more interstitial calcite [description modified from Maxwell and Oakman, 1990].

Short—

Basalt dikes intruding Abo (Pa), Nakaye (Pn), and Bar B (Pb) Formations. Dark olive green to brown and nesophitic, with highly altered chalcedony and chlorite in veinlets and cavities, calcite interstitial to feldspar laths, and augite(?) altered to clay, limonite, and chlorite. 0.2-1.2 m wide [description modified from Maxwell and Oakman, 1990].

Tt Porphyritic trachyte (Eocene?)—Dike intruding Pennsylvanian Gray Mesa Formation (Pgm); 1.2-5.5 m wide, light to medium gray, fine grained; bleached and altered zone as wide as 6.1 m on both sides of dike. White rounded quartz phenocrysts 1-2.5 mm in diameter, some with opaque, dark brown reaction rims. White to pink feldspar phenocrysts 7-15 mm in diameter. Feldspar phenocrysts partly altered to clay and calcite; larger grains have myrmekitic cores and granophyric rims; outermost rim poikilitic with inclusions of biotite and randomly oriented euhedral orthoclase and plagioclase crystals. Groundmass is composed of equant grains of orthoclase, quartz, and plagioclase; random biotite and opaques, and interstitial calcite. Called a quartz latite by Maxwell and Oakman (1990), but major oxide analyses in that work suggests a trachyte composition using Le Bas et al. (1986). [Description slightly modified from Maxwell and Oakman, 1990].

Short—

Dike intruding Gray Mesa Formation (Pgm). Light to medium gray. Quartz phenocrysts 1-2.5 mm and feldspar phenocrysts 7-15 mm in diameter. Feldspar phenocrysts partly altered to clay and calcite. Groundmass is composed of equant orthoclase, quartz, and plagioclase with random biotite, opaques, and interstitial calcite. 1.2-5.5 m wide [description slightly modified from Maxwell and Oakman, 1990].

Tr Porphyritic rhyolite (Eocene)—Light pinkish to reddish gray sill intruding Bliss Sandstone (€Ob). Commonly altered and relatively crystal-rich. Phenocrysts include 7-10% fine to medium biotite (euhedral) and 7-10% whitish, very fine to very coarse feldspar (subhedral, equant; occasionally altered to clay). Very fine grained groundmass of feldspar and quartz. K-Ar age of biotite is 40.8+/-1.5 Ma (R.F. Marvin, written commun. to C.H. Maxwell, 1987) [description modified from Maxwell and Oakman, 1990].

Short—

Light pinkish to reddish gray sill intruding Bliss Sandstone (€Ob). Phenocrysts include 7-10% fine to medium biotite and 7-10% whitish feldspar. Very fine grained groundmass of feldspar and quartz. K-Ar age of biotite is 40.8+/-1.5 Ma (R.F. Marvin, written commun. to C.H. Maxwell, 1987) [description modified from Maxwell and Oakman, 1990].

Tta Trachyandesite sill (Eocene)—Sill intruding lower part of Pennsylvanian Red House Formation (IPr) in southern half of Mud Springs Mountains; exposed for ~3.2 km along strike; 0-27 m thick. Light greenish gray and light to dark olive green and brown; very fine grained, local medium-grained lenses; nesophitic texture, locally plumose. Feldspar laths, 0.02 by 0.02 to 0.2 by 1.0 mm, partly altered to clay; scattered orthoclase and rounded quartz grains 0.2-0.6 mm in diameter; 1-2% total feldspar phenocrysts. Metasomatism partly to completely altered hornblende phenocrysts (5-8%) to actinolite; interstitial material altered to chlorite, which weathers to clay, limonite, and calcite; minor biotite and muscovite. Hornblende $^{40}Ar/^{39}Ar$ age of 43.4+/-0.2 Ma (L.W. Snee, written commun. to C.H. Maxwell, 1989) [description slightly modified from Maxwell and Oakman, 1990].

Short—

Sill intruding Red House Formation (IPr) in southern Mud Springs Mountains. Greenish gray to olive green or brown. Nesophitic. Phenocrysts = 1-2% feldspar, 5-8% hornblende. Interstitial material weathered to clay, limonite, and calcite. Hornblende $^{40}Ar/^{39}Ar$ age of 43.4+/-0.2 Ma (L.W. Snee, written commun. to C.H. Maxwell, 1989). 0-27 m thick [description slightly modified from Maxwell and Oakman, 1990].

Cretaceous

Sedimentary rocks

K Cretaceous strat -- Interpreted and described cuttings logs and down-hole geophysical logs from the No. 2 Getty West Elephant Butte Federal 3 well. 1

Ktmg Undivided Tres Hermanos Formation, Upper Mancos Shale, and Gallup Sandstone (Upper Cretaceous) [cross-section only] – Interbedded sandstones and shales. Basal strata consists of 15 m of very fine-grained, quartz-rich sandstone. Overlying strata comprised of interbedded sandstone and mudstones. Apparent thickness of 46 m where penetrated by the well (140 m thick true thickness using 17° dip).

Kml Lower Tongue of Mancos Shale (Upper Cretaceous) [cross-section only] — Gray shale noted in well cuttings. Underlies a coal-bearing, interbedded shale+sandstone unit tentatively correlated to the Tres Hermanos Formation (Seager and Mack, 2003; Hook et al., 2012). Apparent thickness of 116 m where penetrated by the well (111m true thickness using 17° dip).

Kd Dakota Sandstone [cross-section only]—Fine- to coarse-grained, quartz-rich sand grains that are multicolored. Apparent thickness of 49 m where penetrated by the well (47 m thick true thickness using 17° dip).

Paleozoic

Sedimentary rocks

Psg San Andres Formation and underlying Glorietta Sandstone (lower Permian) [cross-section only]—Tan to gray to brown limestone and local dolomite, interbedded with minor shale, underlain by 40 ft of very fine- to fine-grained, quartzose sandstone correlated to the Glorietta Sandstone. Apparent thickness of 190 m in the No. 2 Getty West Elephant Butte Federal 3 well.

Py Yeso Formation (lower Permian) [cross-section only]— Orange, very fine- to fine-grained, well-sorted sandstone (Meseta Blanca Member, 70 m thick in Caballo Mtns) overlain by an interval of interbedded dolomite, limestone, reddish siltstone-very fine-grained sandstone, and gypsum (Seager and Mack, 2003). Local igneous sills and 250 m apparent thickness in the No. 2 Getty West Elephant Butte Federal 3 well.

Pa Abo Formation (lower Permian)—Reddish brown and grayish red siltstone/mudstone intercalated with sandstone beds that are very fine- to fine-grained, laminar, ripple laminar (including climbing ripples) and/or cross-stratified. Siltstone and mudstone beds contain lenses and nodules of pedogenic calcrete, some with associated rhizoliths. Mudstones may exhibit desiccation cracks on bedding planes. Mostly covered, so two members recognized in the Caballo and Fra Cristobal Mountains by Lucas et al. (2012b) are not distinguished. Locally, fossils of plants (conifers and peltasperms) and vertebrate footprints (mostly of amphibians) are present (DiMichele et al., 2012). 240 m thick (from cross-section).

Short—

Reddish brown and grayish red siltstone/mudstone intercalated with sandstone beds that are laminar, ripple laminar, and/or cross-stratified. Siltstone and mudstone beds contain lenses and nodules of pedogenic calcrete. Locally, fossils of plants (conifers and peltasperms) and amphibian footprints are present (DiMichele et al., 2012). 240 m thick (from cross-section).

Pb Bursum Formation (uppermost Pennsylvanian? to lower Permian)—Interbedded limestone and siliciclastic red beds. Red beds are similar to those of the overlying Abo Formation. The top of the stratigraphically highest marine limestone below red beds lacking marine limestone is the Bursum-Abo contact and is likely a regional unconformity. At a sharp lithologic boundary, red marly shale of the basal Bursum Formation overlies a thick succession of medium-bedded to indistinctly bedded limestone at the top of the Bar B Formation. The top bed of the Bar B Formation displays a karstified surface, indicating subaerial exposure. Locally, a thin carbonate conglomerate bed, overlain by red shale, forms the base of the Bursum Formation. Overlying Bursum strata are shale and siltstone intercalated with beds of limestone and carbonate conglomerate. The limestones range from fossiliferous, bedded wackestones, containing crinoidal debris, brachiopods and, in individual beds, abundant fusulinids (fusulinid wackestone to packstone) to nodular wackestones with abundant marine fossils to pedogenic calcrete. The most common microfacies of the Bursum Formation limestones is wackestone to floatstone; mudstone and packstone are subordinate. A few beds of cross-stratified coarse sandstone/fine-grained conglomerate are composed of various types of carbonate grains (including reworked caliche), and rare chert and quartz grains. One conglomerate unit contains vertebrate bone fragments and rare fragments of reworked marine fossils (bryozoans, brachiopods, echinoderms). The uppermost strata of the Bursum Formation are limestone beds with wavy bed surfaces and shale intercalations, nodular limestone and a 2.6-m-thick, indistinctly nodular-bedded gray limestone interval on top, overlain by red mudstone/siltstone of the Abo Formation. We map the lower contact 20-30 m stratigraphically higher than Maxwell and Oakman (1990). 70-80 m thick.

Short—

Interbedded limestone and siliciclastic red beds. A thin carbonate conglomerate forms the base of the Bursum Formation in places. Overlying strata are shale and siltstone intercalated with beds of limestone and carbonate conglomerate. Limestones locally contain abundant fusulinids. Rare cross-stratified coarse sandstone/conglomerate composed of carbonate, chert, and quartz grains. 70-80 m thick.

IPu **Pennsylvanian(?) strata, undivided (Pennsylvanian?)** — Mapped for slightly hydrothermally altered strata, composed primarily of carbonates, located near downtown Truth or Consequences. Strata interpreted to have been overturned (Maxwell and Oakman, 1990). Also applied to undivided Pennsylvanian strata in the cross-section. 500-525 m thick.

IPbb **Bar B Formation (middle to upper Pennsylvanian)**—Interbedded shale and limestone. Lucas et al. (2016) divided the Bar B Formation in the Mud Springs Mountains into three informal members. The lower member of the Bar B is approximately 85 m thick and is mostly limestone. A distinctive conglomerate bed locally forms the base of the Bar B and is poorly sorted and composed of various types of intraclasts (mudstone, wackestone and packstone) and abundant fragmented fossils, including echinoderms, brachiopods, bryozoans, brachiopod spines, trilobites, *Komia*, a few fusulinids and ostracodes. The lower member of the Bar B Formation is composed of different types of limestone such as indistinctly bedded limestone with some chert, nodular limestone, nodular cherty limestone and wavy bedded limestone with and without chert. Common fossils are crinoids (forming coarse crinoidal packstone), brachiopods, algae, bryozoans, fusulinids and rare solitary corals. Typical microfacies types are wackestone, floatstone, packstone and rudstone, all characterized by a diverse fossil assemblage. Limestone beds are separated by covered intervals, and by thin-bedded, marly limestone and shale. The middle member of the Bar B Formation is 39 m thick and is a distinctive interval of nodular limestone and algal limestone, mostly lacking chert. Microfacies types of the limestone include wackestone, mudstone, packstone and rudstone with a diverse fossil assemblage. Limestone horizons are separated by several covered intervals up to 3.4 m thick. The upper member of the Bar B Formation starts with a 54-m-thick, much covered interval consisting of red mudstone and thin limestone beds where exposed. This interval is overlain by a massive to indistinctly bedded limestone composed of bioclastic wackestone, more red shale and a distinctive polymict conglomerate. The conglomerate is clast-supported and contains abundant chert clasts and different types of limestone clasts in a sandy matrix. It is overlain by cross-stratified sandstone that is well sorted. The sandstone is composed of quartz grains, a few chert grains, micritic carbonate grains, many echinoderm fragments, a few fragmented fusulinid tests and recrystallized skeletons. Above that, wavy bedded fossiliferous limestone (bioclastic wackestone) with crinoids, bryozoans and brachiopods, and cherty nodular limestone, are present. The uppermost 9 m of the Bar B Formation consist of gray, wavy bedded limestone beds (partly algal limestone) containing chert and thin silty intercalations at the base. The top of the Bar B is formed by a massive nodular limestone bed overlain by a gray micritic limestone bed that is bioturbated. Thickness of 178 m (stratigraphic sections) to 280 m (cross-section).

Short—

Interbedded shale and limestone. A conglomerate with carbonate intraclasts and fossil fragments locally forms base of unit. Overlying intervals are: a lower limestone, marly limestone, and shale; middle nodular to algal limestone; and an upper red mudstone, limestone, conglomerate, and sandstone. Common marine fossil assemblages. Thickness: 178 m (stratigraphic sections) to 280 m (cross-section).

IPgm **Gray Mesa Formation (Middle Pennsylvanian)**—Kelley and Silver (1952) introduced the name Nakaye Formation for the succession of dominantly thick-bedded to massive and often cherty limestone that forms a bold escarpment on the western face of the Caballo Mountains. The name refers to Nakaye Mountain in the southwestern part of the Caballos. Maxwell and Oakman (1990) mapped the Nakaye in the Mud Springs Mountains. However, the name Gray Mesa Formation (Kelley and Wood, 1946) was proposed earlier for essentially the same succession of rocks, so we substitute the name Gray Mesa for Nakaye in the Mud Springs Mountains following Lucas et al. (2012a, 2016). In the Mud Springs Mountains, the Gray Mesa Formation is ledge- and cliff-forming gray, dark gray, brown and yellowish orange limestone beds, intercalated gray shale/covered intervals, and a few brown to dark brown sandstone and conglomerate beds. It can be divided into three members named by Thompson (1942): a lower, ~ 30 m thick interval of interbedded limestone, shale and a few sandstone beds (Elephant Butte Member); a middle, ~ 44 m thick limestone interval, many beds very cherty (Whiskey Canyon Member); and an upper, ~ 90 m thick interval of interbedded limestone and shale with a limestone-pebble conglomerate at the base (Garcia Member). The most common limestone microfacies type of the Elephant Butte Member is bioclastic wackestone, which locally grades into packstone and floatstone. Subtypes are phylloid algal wackestone to floatstone and wackestone containing abundant *Komia*. Crinoidal wackestone, fusulinid wackestone-rudstone and bioclastic grainstone are present but rare.

All microfacies are characterized by a diverse fossil assemblage. Sandstone of the Elephant Butte Member is composed mainly of monocrystalline quartz, and subordinately of polycrystalline quartz and rare detrital feldspar grains. The dominant microfacies type of the Whiskey Canyon Member is wackestone, which may grade into floatstone. Rarely, packstone to rudstone is present. All microfacies types contain a diverse fossil assemblage. Larger skeletons are derived from brachiopods, bryozoans, echinoderms, fusulinids and phylloid algae. Smaller fossils include ostracodes, brachiopod spines, gastropods, smaller foraminifers, spicules, completely recrystallized indeterminate skeletons and rare trilobite fragments. The most common microfacies of the limestone in the Garcia Member is wackestone, which locally grades into floatstone (including phylloid algal floatstone), packstone and rudstone, with crinoidal packstone to rudstone being the most common type. Less abundant are mudstone-wackestone and grainstone. All microfacies types are characterized by a diverse fossil assemblage. The most abundant fossils are fragments of echinoderms (dominantly crinoid fragments), bryozoans, brachiopod shells and spines. Locally, abundant phylloid algae and *Komia* are present. Less abundant are fusulinids, smaller foraminifers, ostracodes, spicules, gastropods, bivalves, trilobite fragments and solitary corals. The fine-grained conglomerate to sandstone at the base of the Garcia Member is mixed siliciclastic-carbonate in composition and poorly sorted. It contains abundant angular to subrounded mono- and polycrystalline quartz grains up to 5 mm in diameter, rare chert grains and very rare detrital feldspars. Carbonate grains are up to several cm in diameter and include different types of fossiliferous wackestone, grainstone and mudstone. Fossil fragments are derived from echinoderms, brachiopods, fusulinids and bryozoans. Micritic matrix is present between the nonskeletal and skeletal grains. 160-185 m thick.

Short—

Ledge- and cliff-forming gray, dark gray, brown and yellowish orange limestone beds, intercalated gray shale/covered intervals, and a few brown to dark brown sandstone and conglomerate beds in the upper part. 160-185 m thick.

IPr **Red House Formation (Middle Pennsylvanian)**— Slope-forming gray shale/covered intervals and interbedded diverse lithotypes of gray to dark gray limestone and a few thin sandstone beds. The microfacies of limestone of the Red House Formation include several muddy types, with bioclastic wackestone and packstone containing a diverse fossil assemblage being the most common (Lucas et al., 2016). Other microfacies such as peloidal wackestone, partly containing abundant *Donezella* and other fossils, rudstone and floatstone are subordinate. Rare fusulinid rudstone and phylloid algal floatstone are present. Intercalated sandstone beds are composed mainly of quartz and rare feldspar grains. Maxwell and Oakman (1990) mapped "jasperoid" in the Mud Springs Mountains but did not describe it or explain its significance. As mapped, jasperoid occurs in elongate lenses parallel to bedding in the lower part of the Red House Formation, and also in some of the pre-Pennsylvanian formations. The jasperoid is not a primary depositional feature. At Cuchillo Tank it is a silicified mudstone, which is laminated and contains a few ostracodes and a few-cm-thick layer of wackestone containing abundant small gastropods, subordinate ostracodes and bivalves(?), embedded in silicified micritic matrix. The fossils are totally silicified and defy precise identification. We interpret the jasperoid horizon at Cuchillo Tank as altered strata of the Red House Formation. Note that we agree with Maxwell and Oakman (1986) that the base of the Red House Formation (their "Sandia Formation") in the Mud Springs Mountains, including where it rests on Ordovician strata, is not a fault but instead an unconformable depositional contact (*contra* Kelley and Silver, 1952). Maxwell and Oakman (1986) claimed that the Red House Formation is more than 30-60 m thicker in the southern Mud Springs Mountains because of a within-Red House unconformity. However, the data of Lucas et al. (2016) do not indicate such an unconformity or thickness discrepancy between the northern and southern parts of the range. 56-59 m thick (stratigraphic sections) to 80 m thick (cross-section).

Short—

Slope-forming gray shale/covered intervals and interbedded diverse lithotypes of gray to dark gray limestone and a few thin sandstone beds. Intercalated sandstone beds are composed mainly of quartz and rare feldspar grains. Jasperoid bodies in the Red House Formation consist of silicified mudstone with recognizable, but not identifiable, fossils. Underlain by unconformity. 56-59 m thick (stratigraphic sections) to 80 m thick (cross-section).

Dp Percha Formation (Middle to Upper Devonian)—Devonian strata in the Mud Springs Mountains have been assigned to the Percha, Oñate and Sly Gap formations (e.g., Cooper and Dutro, 1982; Sorauf, 1987; Maxwell and Oakman, 1990) based primarily on age distinctions (biostratigraphy), not on lithology. Invertebrate fossils indicate the lower part of the section is of Middle Devonian age, whereas the upper part is Late Devonian, the real basis for assigning these intervals to the Oñate and Sly Gap formations, respectively. Here the Devonian strata are assigned to one formation-rank lithostratigraphic unit we term the Percha Formation, following Kelley and Silver (1952) and Lucas (2012). These strata are greenish and brownish-yellowish marly shale with intercalated thin, even-bedded limestone beds, nodular limestone beds and limestone nodules dispersed in shale. The lower 16 m of the Percha Formation (assigned by some workers to the Oñate Formation) consist of greenish, brownish-yellowish and rare, reddish marly shale with intercalated thin, even bedded marly limestone beds in the lower part. Marly limestone beds are 0.1-0.2 m thick. In the middle of this unit, small coral colonies (5 cm high, 20 cm wide) and very fossiliferous limestone nodules and lenses (5-10 cm thick) are present in shale that is locally very fossiliferous (brachiopods, crinoids, solitary corals, bryozoans). In the upper part of this unit, thin, wavy to nodular limestone beds are intercalated. These limestone beds are mostly 0.1 m thick, but one nodular limestone bed is 0.3 m thick. The upper 22 m of the Percha Formation (assigned by some workers to the Sly Gap Formation) are greenish, marly shale with small, locally abundant limestone nodules and intercalated nodular limestone (0.3-1.5 m thick) containing brachiopods. Brachiopods are also present in the shale, but much less abundant than in the underlying strata. Only mapped in southern Mud Springs Mountains, where it is 35-40 m thick.

Short—

Greenish and brownish-yellowish marly shale with intercalated thin, even-bedded limestone beds, nodular limestone beds and limestone nodules dispersed in shale. Small coral colonies and fossiliferous limestone nodules and lenses are found in the lower 16 m. Only mapped in southern Mud Springs Mountains, where it is 35-40 m thick.

Om Montoya Group (Upper Ordovician)—The Montoya is treated in the literature as either a group or a formation; we treat it as a group because its subdivisions are mappable at a scale of 1:24,000 in the Mud Springs Mountains. The most widely used stratigraphic subdivisions come from Kelley and Silver (1952), who also treated the Montoya as a group and divided it into four formations (ascending): Cable Canyon, Upham, Aleman and Cutter. Entwistle's (1944) older term Second Value Dolomite is sometimes used to combine the Cable Canyon and Upham (as members) where those units cannot be mapped separately (Pratt, 1967; Hayes and Cone, 1975). Maxwell and Oakman (1990) did this in the Mud Springs Mountains, mapping the Cable Canyon and Upham together as Second Value, and we adopt that usage here. We should also note that Entwistle's (1944) other subdivisions of the Montoya have priority over Kelley and Silver's (1952). Thus, the Par Value and Raven members of Entwistle are the same units as the Aleman and Cutter (respectively) of Kelley and Silver. Kelley and Silver (1952) argued that Entwistle's type sections of these units were inadequate due to structural complications and mineralization. Hayes and Cone (1975, p. 52) disagreed, but they used Kelley and Silver's terminology because it was much more widely used than the terminology of Entwistle. We follow suit and use Kelley and Silver's (1952) named subdivisions of the Montoya Group—Cable Canyon, Upham, Aleman and Cutter Formations. 110-150 m thick, thinning to NE.

Short—

The Montoya is treated in the literature as either a group or a formation; we treat it as a group because its subdivisions are mappable at a scale of 1:24,000 in the Mud Springs Mountains. We use Kelley and Silver's (1952) named subdivisions of the Montoya Group—Cable Canyon, Upham, Aleman and Cutter Formations. 110-150 m thick, thinning to NE.

Omc Cutter Dolomite—Above a thin, basal bed of carbonate conglomerate, light gray, mostly medium bedded, partly laminated, partly bioturbated dolomite with rare chert and rare limestone beds. A massive chert horizon (1.5 m thick) is present in the lower part. Covered intervals are up to 5.7 m thick. 40-45 m thick

Oma Aleman Formation—Mostly gray to dark gray, medium- to thick-bedded cherty dolomite containing abundant chert nodules, chert lenses and thin chert layers. A few covered intervals (0.7-0.8 m thick) present in upper part of unit. In the lower and middle part of the formation, some beds contain abundant silicified brachiopods and few gastropods. 39-46 m thick (stratigraphic sections) to 95 m thick (cross-section).

Omsv Second Value Dolomite—The Second Value Formation is gray, sandy dolomite that is generally cherty (Upham Member: 17-19 m thick) above brown to dark yellowish brown quartz sandstone and pebbly sandstone (Cable Canyon Member, 6 m thick). The Upham Member base consists of thick-bedded gray sandy dolomite containing a few small chert nodules. It grades upward into thick-bedded dolomite with crinoidal debris and intercalated cherty dolomite with chert nodules up to about 30 cm in diameter. The Cable Canyon Member forms a distinct unit of uniform lateral thickness composed of brown and dark yellowish brown, massive and cross-stratified, pebbly sandstone and sandstone containing rounded to well-rounded quartz grains with diameters up to 1 cm. The contact with the underlying McKelligon Limestone is very sharp and erosive, whereas the contact with the overlying Upham Member is more gradational. Sandstone is moderately sorted and commonly has a bimodal grain-size distribution with smaller grain-size ranging from 0.1 to 0.5 mm and a larger grain size population ranging from 0.5 to 2 mm. Most grains are rounded, and some are well rounded. Grains are dominantly monocrystalline quartz and rare polycrystalline quartz. Detrital feldspars, mica and rock fragments are absent, so the sandstone has a high textural and compositional maturity. 20-25 m thick.

Short—

Gray, sandy dolomite that is generally cherty above brown to dark yellowish brown quartz sandstone and pebbly sandstone. Dolomite may contain limestone debris. Sandstone is massive to cross-stratified and forms a sharp, erosive contact on the underlying McKelligon Limestone. 20-25 m thick.

El Paso Group (Lower Ordovician)—There have been three different schemes of lithostratigraphic nomenclature applied to the El Paso Group strata in the Mud Springs Mountains (Kelley and Silver, 1952; Hayes and Cone, 1975; Clemons, 1991). Kelley and Silver (1952, see especially fig. 3), in their classic study of the geology of the Caballo Mountains, divided the El Paso Group there and in the Mud Springs Mountains into two formations that they named: lower, Sierrite Limestone and upper, Bat Cave Formation. However, Hayes and Cone (1975) did not use these names and instead assigned the El Paso Group section in the Mud Springs Mountains to the Hitt Canyon Formation overlain by the McKelligon Limestone, units named by Flower (1964) and Harbour (1972) in the Franklin Mountains near El Paso, Texas. Hayes and Cone (1975) divided the Hitt Canyon Formation into three informal members—lower sandy member, middle member and upper sandy member. They equated the Sierrite Limestone of Kelley and Silver (1952) to the lower sandy member and the lower part of the middle member and considered the Bat Cave Formation to be equivalent to the upper part of the middle member, the upper sandy member and the lower part of the McKelligon Limestone. Clemons (1991) treated the El Paso as a formation-rank unit, dividing it into the (ascending order) Hitt Canyon, Jose, McKelligon and Padre members. He only recognized the lower three members in the Mud Springs Mountains (Clemons, 1991, table 1). Mack (2004) used the stratigraphic nomenclature of Clemons (1991). Lucas et al. (2012a) presented both the lithostratigraphic nomenclature of the El Paso Group used by Kelley and Silver (1952) and Hayes and Cone (1975) in a road log to a fieldtrip in the Mud Springs Mountains. We assign the El Paso Group to the Hitt Canyon and McKelligon formations, following Hayes and Cone (1975). 142-180 m thick, thinning to NE.

Short—

There have been three different schemes of lithostratigraphic nomenclature applied to the El Paso Group strata in the Mud Springs Mountains (Kelley and Silver, 1952; Hayes and Cone, 1975; Clemons, 1991). We assign the El Paso Group to the Hitt Canyon and McKelligon formations, following Hayes and Cone (1975). 142-180 m thick, thinning to NE.

Oem McKelligon Limestone—The McKelligon Limestone is 30-77 m thick and composed mostly of medium-bedded, subordinately thick-bedded to massive, commonly bioturbated limestone. Thin- to thick-bedded cherty and bioturbated limestone and bedded dolomitic limestone/dolomite are intercalated. A thin stromatolite bed is developed near the base. In the Mud Springs Mountains, the McKelligon forms a prominent cliff at the top of the Bat Cave Formation of Kelley and Silver (1952). 30 m thick near Mud Mountain.

Short—

Medium-bedded, subordinately thick-bedded to massive, commonly bioturbated limestone. Thin- to thick-bedded cherty and bioturbated limestone and bedded dolomitic limestone/dolomite are intercalated. A thin stromatolite bed is developed near the base. 30 m thick near Mud Mountain.

Oeh Hitt Canyon Formation—Upper part consists of massive, partly dolomitized limestone with columnar stromatolites up to about 0.5 m high, oolitic limestone that is partly cross-stratified and dolomitized, bedded limestone (grainstone, packstone) with rare chert, indistinctly bedded dolomitic limestone, indistinctly bedded to massive bioturbated limestone and bedded, bioturbated limestone. Also present are gray bioturbated limestone with flaser bedding, thin-bedded limestones, thin-bedded cherty limestone, massive limestone beds with columnar stromatolites and thrombolites (1.1 and 1.4 m thick), and medium-bedded crinoidal limestone beds that are partly cross-stratified. A few thin shale intervals (0.3-0.6 m thick) and covered intervals that probably represent shale (0.3-1.3 m thick) are also present. Lower part consists of brownish, dolomitic siltstone-sandstone with common ripple lamination and rare small-scale cross-stratification and horizontal lamination, and common bioturbation. Rare, thin chert lenses are intercalated. Individual units are up to 5.3 m thick and partly separated by thin shale layers. Intercalated beds consist of bedded and crossbedded limestone containing abundant crinoidal and other fossil debris. 102-112 m thick.

Short—

Partly dolomitized to bedded limestone with columnar stromatolites and rare to occasional chert in upper part. Sparse shale or covered intervals are present. Lower part consists of dolomitic, laminated siltstone-sandstone intercalated with bedded, fossiliferous limestone and rare chert lenses. 102-112 m thick.

€Ob **Bliss Sandstone (upper Cambrian to lower Ordovician)**—Alternating, mostly dark brown to black-colored pebbly sandstone, sandstone, siltstone, shale and rare, thin, fossiliferous (crinoid debris, bryozoans) carbonate (limestone, dolomite) beds. Sedimentary structures in the sandstone beds are horizontal lamination, ripple lamination, trough crossbedding and rare herringbone crossbedding. Some sandstone and siltstone beds appear massive and are bioturbated. The sandstone contains abundant quartz, and, in the upper part of the formation, greenish glauconitic sandstone (glaucarenite) beds are present. Individual siltstone-sandstone intervals are 0.2-1 m thick, rarely up to 2.8 m thick, and covered intervals are 0.1-3.6 m thick. Carbonate beds are 0.2-0.3 m thick. A thin siltstone horizon in the uppermost part of the formation (3-4 m below the top) contains well preserved dendroid graptolites. Iron oolite beds, which are intercalated in the lower part of the Bliss Formation in the Caballo and the Fra Cristobal Mountains, are absent in the Mud Springs Mountains, although a few iron ooids are present in sandstone in the lower part of the formation. In the Mud Springs Mountains, the Bliss Formation can be divided into two, member-level lithostratigraphic units that can also be recognized in the Caballo and Fra Cristobal Mountains: (1) a lower member dominated by crossbedded and bioturbated quartz-rich sandstone; and (2) an upper member with numerous beds of ripple-laminated glaucarenite and some coarse carbonate beds. The lower member contains brachiopods, trilobites and a *Skolithos*-dominated ichnoassemblage. The upper member yields numerous graptolites and a *Palaeophycus*-dominated ichnoassemblage. Previously published conodont and trilobite biostratigraphy in the Caballo Mountains indicates that most or all of the lower member is late Cambrian (Sunwaptan) in age, whereas most or all of the upper member is early Ordovician (Skullrockian) in age (Taylor and Repetski, 1995). Thus, the Cambrian-Ordovician boundary is stratigraphically high in the lower member. The upper member graptolite assemblage is dominated by *Rhabdinopora flabelliformis* (Eichwald), which confirms its Early Ordovician age. 45-55 m thick.

Short—

Alternating dark brown sandstone, siltstone, shale and rare, fossiliferous carbonate beds. Sandstone sedimentary structures include horizontal or ripple lamination and trough or rare herringbone cross-stratification. Greenish glauconitic sandstone and dendroid graptolites are present in the upper part of the formation. Sparse iron ooids are present in sandstone in the lower part. 45-55 m thick.

PRECAMBRIAN

pCu Precambrian rocks, undivided (Meso- to Paleoproterozoic) – Whitish gray to purplish white meta-sandstone, reddish gray quartzite, dark gray and brown quartz or quartz-biotite schist (up to 15%), dark green to black amphibolite schist and gneiss, and intercalated pink to reddish granite and granite-gneiss. Meta-sandstone occurs in thin to thick, sometimes wavy beds with occasional cross-stratification and contains medium to coarse, poorly sutured grains of quartz. Granite contains abundant coarse potassium feldspar crystals and exhibits hypidiomorphic granular texture. Discontinuous layers of possible amphibolite schlieren are observed in one location west of Mud Mountain. Locally, pegmatitic to aplitic dikes cut the granite. Forms the core of the Mud Springs Mountains and is only exposed in limited outcrops along the western face of the range.

Short—

Meta-sandstone, quartzite, quartz or quartz-biotite schist, amphibolite schist and gneiss, and intercalated granite and granite-gneiss. Locally, pegmatitic to aplitic dikes cut the granite. Forms the core of the Mud Springs Mountains and is only exposed in limited outcrops along the western face of the range.

MISCELLANEOUS CROSS-SECTION UNITS

Tsf Undivided Santa Fe Group underlying middle Palomas Formation (uppermost Oligocene to lower Pliocene) [cross-section only] —Sand, gravels, and clayey-silty sands that underlie the middle Palomas Formation. Correlative in part to units Tplv, Tpvlt, Tpal3, Tpal2, Tpal1, Trbuc, Trbuw, Trbut, Trplu, and Trpl.

Tv-Pz Undivided pre-Santa Fe Group strata (Cambrian to Oligocene?)— Primarily dolomites and limestone rocks in the lower to middle parts, possibly overlain by a thin interval of sandstone and shales correlative to the Cretaceous, which in turn is overlain by an unknown thickness of Oligocene-Eocene volcanic rocks. Mapped to the west of the Mud Springs Mountains.

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APPENDIX 2. STRATIGRAPHIC SECTIONS OF EARLY RIO GRANDE DEPOSITS

DESCRIPTION OF REVISED SOUTH POPLAR STREET STRATIGRAPHIC SECTION.

Location: Section 33, T13S, R4W, Cuchillo 7.5-minute quadrangle.

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Sand textures are abbreviated as follows: very fine-lower, vfL; very fine-upper, vfU; fine-lower, fL; fine-upper, fU; medium-lower, mL; medium-upper, mU; coarse-lower, cL; coarse-upper, cU; very coarse-lower, vcL; very coarse-upper, vcU. The term "clast(s)" refers to the grain size fraction greater than 2 mm in diameter. Descriptions of bedding thickness follow Ingram (1954).

The section comprises revised measurements from the South Poplar St. Stratigraphic Section measured by Andy Jochems on March 24, 2015. The base of the section described below approximately corresponds to 15.5 m in the South Poplar St. section as shown in Figure 3 of Koning et al. (2016).

Revised portion of South Poplar St. section (SP-R). This section consists of axial-fluvial facies of the Palomas Formation. Approximately 1.90-2.05 m of gravelly sediment were previously included with medium-grained sand beds in unit Tpal2 just below unit Tpal3. Measured in SW1/4 of Section 33, T13S, R4W, Sierra County, New Mexico. Measured and described by Andy Jochems on September 26, 2017, using an abney level, Jacob's staff, and tape measure.

Unit	Description	Thickness (cm) (Unit)	(Total)
	AXIAL-FLUVIAL DEPOSITS OF THE PALOMAS FORMATION, THIRD AGGRADATIONAL UNIT (Tpal3), EM PETROFACIES		
RSP-11	**Sandy pebble-cobble conglomerate—**Well-cemented, planar cross-stratified pebble-cobble conglomerate with abundant clasts of intermediate volcanic lithologies. Tpal3 also has lenses and interbeds of horizontally laminated sandstone. THREE PMAG SAMPLES TAKEN OVER AN ESTIMATED HORIZONTAL DISTANCE OF 20 METERS: SP-8A (~13.9 m height, on ENE side), SP-8B (13.9 m height, 3-7 m WSW of SP-8A), and SP-8C (~13.7 m height, 10 m west of sample SP-8B). UTM coordinates of samples (NAD83, zone 13): SP-8A is located at 289,039 m E, 3,668,165 m N; SP-8B is located at 289,037 m E, 3,668,163 m N; SP-8C is located at 289,033 m E, 3,668,164 m N.		
	Total section	>2.2 m thick	
	AXIAL-FLUVIAL DEPOSITS OF THE PALOMAS FORMATION, SECOND AGGRADATIONAL UNIT (Tpal2), LV PETROFACIES		
RSP-10	**Pebble gravel**—As subunit SP-R8 but light brownish gray (10YR 6/2) and planar cross-stratified (foresets up to 20 cm thick). Scours subunit SP-R2 by up to 50 cm.	1105	1165
RSP-9	**Pebble gravel**—As subunit SP-R8 but composed entirely of pebbles. Becomes mostly matrix-supported and massive in upper 30 cm. Scoured up to 50 cm by subunit SP-R3.	1035 1.45	1105
RSP-8	**Pebble-cobble gravel and sand**— Weakly consolidated, clast-supported, medium- to thick-bedded (20-60 cm), moderately imbricated to trough cross-stratified, sandy pebble-cobble gravel. Clasts are subangular to rounded, very poorly sorted, and consist of 60-70% pebbles and 30-40% cobbles. Visually estimated clast lithologies include	960	1035

Unit	Description	Thickness (cm) (Unit)	(Total)
	40% Paleozoic sedimentary rocks, 30% Cretaceous sedimentary rocks, 20% felsic volcanics, and 10% intermediate volcanics; also trace to 2% quartzite pebbles. Matrix consists of brown (10YR 4-5/3), subangular to subrounded, poorly sorted, mL-vcL sand composed of 65% quartz, 20% lithic (volcanic+sedimentary), and 15% feldspar grains with little apparent clay. Exhibits up to 85 cm of scour into basal sand lens and underlying massive sand. Sand lens at base is up to 15 cm thick and consists of grayish brown (10YR 5/2), loose, low-angle cross-stratified, subangular to rounded, moderately sorted, mU-cU sand (3% very coarse) composed of 70% quartz, 15% feldspar, and 15% lithic grains. It features 20-85% disseminated flakes/particles of dark-colored material that could be manganese oxide. *Dan Koning mainly described below, Andy Jochems described strata above.*		
RSP-7c	**Sand in uppermost part**—10YR 6-7/2 (mostly 7/2), massive, mL-cL (mostly mL-mU; ≤5% fL-fU and <5% cU), subrounded to subangular (more subrounded than below), and well sorted. Sand contains 18-20% orange-colored grains, 10-15% volcanic grains, and 1-5% mafic grains. Upper contact is a pronounced scour (at least 10 cm of scour relief). Sand sample SP-SS-8 taken at 938-948 cm. DESCRIBED AT 938-948 CM. FOUR PMAG SAMPLES TAKEN OVER 3-4 M HORIZONTAL DISTANCE: SP-7A (903-910 cm on the right), SP-7B (900-906 cm, taken ~0.5? m left of SP-7A), SP-7C (900-906 cm, taken 130 cm left of SP-7B), and SP-7D (881-891 cm. taken 170 cm left of SP-7C). Pmag sample SP-7C UTM coordinates: 289,041 m E, 3,668,170 m N (NAD83, zone 13). Sand here is 10YR 7/2, mL-cL, subangular to subrounded, well sorted, and contains 15-17% orange-colored grains and 10% light-colored volcanic grains. FIVE PMAG SAMPLES TAKEN OVER 2-3 M HORIZONTAL DISTANCE: SP-6A (770-780 cm height), SP-6B (770-780 cm, taken 30 cm left of SP-6A), SP-6C (763-773 cm, taken 70 cm left of SP-6B), SP-6D (760-770 cm, taken 70 cm left of SP-6C), and SP-6E (750-760 cm, taken ~1? m left of SP-6D). Pmag sample UTM coordinates: 289,042 m E, 3,668,173 m N (NAD83, zone 13). The sand here is 10YR 7/2, fU-cU, subrounded to subangular, low-moderately sorted, and composed of 20% orange-colored grains and 12-15% volcanic grains. **Sand in upper part**—2.5Y 8/1, massive, mL-mU sand (≤5% cL-cU and ≤5% fL-fU), subangular to subrounded, well sorted, and contains 20% orange-colroed grains and 10-15% felsic volcanic grains. Sand sample SP-SS-6 taken at 730-738 cm. DESCRIBED AT 730-738 CM.	682	960
RSP-7up	**Two thin lens of pebbles within the sand of SR-R7. Not described.**	678	682
RSP-7b	**Sand in middle part**—2.5Y 8/1, massive, mL-cL, subangular to subrounded, high-moderate to low-well sorted sand containing 20% light-colored volcanic grains, 20% orange grains. FIVE PMAG SAMPLES TAKEN OVER 1.5 CM HORIZONTAL DISTANCE: SP-5UA (620-630 cm, on right), SP-5UB (620-630 cm, 80 cm to left of SP-5UA), and SP-5UC (620-630 cm, taken 70 cm to left of SP-5UB). Sand sample SP-SS-5U taken at 650-670 cm.	615	678
RSP-7mp	**Sandy pebbles**—Similar to that described below for SR-R7lp, but relatively massive.	590	615
RSP-7lp	**Sandy pebbles**—Pale brown to light yellowish brown (10YR 6/3-4), low angle cross-stratified to horizontal-planar laminated sandy pebbles occurring as a lense in SR-R7. Pebbles are very fine to very coarse, subangular to subrounded, poorly to moderately sorted, and composed of felsic volcanic rocks with 10% yellowish vf sandstone-	569	585

Unit	Description	Thickness (cm) (Unit)	(Total)
	siltstone. One cobble of quartzite and one cobble of green K sandstone. At top is reddish brown, claystone rip-ups. Sand is mL-vcU, subangular to subrounded, moderately sorted, lithic arenite.		
RSP-7a	**Sand in lower part**—White (10YR-2.5Y 8/1), laminated (horizontal-planar to low-angle cross-stratified 1-3 cm-thick), mL-mU sand (≤10% fL-fU and 5% cL-cU), subangular (mostly) to subrounded, and well sorted. Top contact is scoured and sharp, ranging from 569 cm to 590 cm. Lower contact sharp and planar. @566 cm: very thin lens of pebbly sand. Pebbles are very fine and composed of felsic volcanic rocks. THREE PMAG SAMPLES TAKEN OVER 1 M HORIZONTAL DISTANCE: Sample SP-5LA (557-567 cm, on right), SP-5LB (557-567 cm, 30 cm left of SP-5LA), and SP-5LC (559-569 cm, taken 50 cm to left of SP-5LB). Sand sample SP-SS-5L taken at 580 cm. These samples are located just below the pebble lens of SR-R7lp. Pmag sample UTM coordinates: 289,045 m E, 3,668,170 m N (NAD83, zone 13). FIVE PMAG SAMPLES TAKEN OVER ~1-1.5 M HORIZONTAL DISTANCE: SP-4AA (534-545 cm height, on right), SP-4A (532-542 cm, in center), SP-4B (519-532 cm, in center, below SP-4A), and SP-4C (519-532 cm, to left of SP-4B). Sand sample SP-SS-1 taken at 524 cm. Pmag sample UTM coordinates: 289,043 m E, 3,668,169 m N (NAD83, zone 13).	512	569
RSP-6	**Greenish silt-clay**—Mansell color of 2.5Y 7/3. Sharp base and top. Found at top of incised gully.	494	512
RSP-5	**Cobble-bearing sandy pebbles**—Massive, very fine to very coarse pebbles with 15-20% cobbles and fine boulders. Cobbles and fine boulders are composed of sandstone, Abo Formation, and 10% felsic volcanic clasts. Pebbles are mostly felsic volcanic clasts with 25-35% altered Paleozoic limestone (altered to a soft, powdery clast) and 5% Abo Fm. No bedding seen. Sand is 7.5-10YR 6/4, fU-vcU (mostly mU-vcU), angular to subrounded (mostly subangular), poorly sorted, and lithic-rich; estimate trace-15% clay in sand matrix. Upper contact is sharp. Did not note lower contact except that it was planar. @458 cm: Imbrication of 5 clasts give 115-140 degree paleoflow.	265	494
RSP-4	**Sandy pebbles**—Massive, vf-vc pebbles dominated by felsic volcanic lithologies. Pebbles are subangular to angular and moderately sorted. Sand concentration increases up-section. Sand is 7.5YR 7-8/1, mU-vcU, subangular(m)-subrnded, and moderately sorted. No obvious bedding. Lower contact corresponds with a scour that ranges in height from 212 to 233 cm. Imbrication in lower 10-20 cm indicates southward paleoflow.	233	265
RSP-3	**Sand**—7.5-10YR 8/1, fL-mU (mostly mL-mU) sand that is subrounded to subangular, well sorted, and composed of 15-20% orange-colored grains & 5% volcanic rocks. Horizontal-planar laminated. Top contact ranges from 212 cm to 233 cm because it corresponds with a scour. SP-R5 SIX PMAG SAMPLES TAKEN: SP-3a and SP-3aa (190-202 cm); SP-3B (197-212 cm); SP-3C (197-212 cm, in front); SP-3D and SP-3E (197-212 cm, in back). Samples taken over 1 m horizontal spacing just above head of gully. Pmag sample UTM coordinates: 289,049 m E, 3,668,169 m N (NAD83, zone 13).	182	233
RSP-2	**Sandy pebbles**—Vague to moderately exposed, 1-15 cm-thick, lenticular beds; also local low-angle cross-stratification (laminations to very thin beds). No consistent imbrication. Pebbles are very fine to coarse, subangular to subrounded, low-moderately sorted, and composed of felsic-dominated volcanic lithologies. Sand is white to pinkish gray (7.5YR 8/1-7/2). Described in gully. @172-182 cm: Pebble size coarsens to very fine-coarse. @160-170 cm: 80% of clasts consist of granules composed of 2/3 felsics and 1/3	29	182

Unit	Description	Thickness (cm) (Unit)	(Total)
	intermediate volcanic rocks. @ 145-155 cm: Sporadic MnO coats.		
RSP-2su	**Sand lens within sandy pebbles of SP-R2.** Lens of fL-cL sand that is massive to low-angle x-stratified. Sand is white (7.5YR 8/1), fL-cL, subrounded-rounded, poorly to moderately sorted, and composed of 80% qtz, 10-15% feld, 5-10% volcanic-dominated lithic grains. 3-5% vc sand to vf pebble-size grains composed mainly of felsic volcanic rocks. Trace orange clay. Described in gully.	130	135
RSP-2sl	**Sand lens within sandy pebbles of SP-R2**— Large lens of sand present just south of gully axis. Sand is horizontal-planar laminated, white (7.5YR 7/1), fU to mU (mostly fU to mL), subangular to subrounded, well sorted, has 20% orange-colored grains, and 5-7% volcanic grains. Sand occurs as a lense within sandy pebbles described in SP-R2. Described just to south of gully. PMAG SAMPLES SP-2A, SP-2B, AND SP-2C TAKEN BETWEEN 68 AND 80 CM. SAND SAMPLE SP-SS-2 TAKEN AT 74-76 CM.	45	80
RSP-1	**Sand**—fU to cL (mostly mL-mU) sand that is horizontal-planar laminated, with cross-lamination in upper 10 cm. Sand is light gray to pinkish gray (7.5YR 7/1-2), fU to cL (mostly mL-mU), subangular to subrounded, low-well sorted, and had 20% orange-colored grains. Moderately consolidated and non-cemented. Described in gully. PMAG SAMPLES SP-1A, 1B, 1C, AND 1D TAKEN BETWEEN 0 AND 12 CM. SAND SAMPLE SP-SS-1 TAKEN AT 10-12 CM. Pmag sample UTM coordinates: 289,049 m E, 3,668,172 m N (NAD83, zone 13). **Base of section at UTM coordinates: 289,049 m E, 3,668,172 m N (NAD83, zone 13). Section above is ubiquitously weakly to moderately consolidated and weakly cemented.** **AXIAL-FLUVIAL DEPOSITS OF THE PALOMAS FORMATION, SECOND AGGRADATIONAL UNIT (Tpa2cl), LS PETROFACIES**	0	29
SP -7	**Gravel** – Similar to unit **P-6** but lacks sand lenses.	2.10	9.20
SP -6	**Gravel and sand** – Very pale brown (10YR 7/3), massive to weakly imbricated, very poorly sorted, angular to rounded, pebble-cobble-boulder gravel interbedded with massive to horizontally laminated (thin) sand. Clasts consist of 40% pebbles, 40% cobbles, and 20% boulders (maximum intermediate axis ~30 cm) of ~55% Paleozoic sedimentary lithologies and 25% Cretaceous sandstone; the remainder includes Precambrian intrusive/metamorphics or Tertiary volcanics. Imbricated clasts imply a SSW paleocurrent direction (mean = 202°, n = 46). Sand occurs in lenses throughout unit and is moderately well sorted, subrounded to rounded, vfU-mL and consists of 65% quartz, 25% feldspar, and 10% lithic grains. Lenses commonly contain mud rip-ups. In some gravel beds, sandy matrix is poorly sorted, subrounded to well rounded, vfU-cU and consists of 55% quartz, 30% feldspar, and 15% lithic grains. Photo: 20150324_170324: Units P-5 and P-6 (1.5 m Jacob's staff for scale). *Base of unit at 289070 m E, 3668141 m N.* **RINCON VALLEY FORMATION**	1.25	7.30
SP -5	**Clay** – Reddish brown (5YR 4-5/4) and massive. Pedoturbated; common carbonate nodules and masses denote Bk horizon/paleosol. Contains single interbed of pink (7.5YR 7.3), massive silt.		
SP -4	**Silt** – Pink (7.5YR 7/3) and massive.		
SP -3	**Clay** – Reddish brown (5YR 4-5/4) and massive. Contains rare carbonate masses.		
SP -2	**Silt, sand, and gravel** – 5-12 cm beds of light reddish brown to light brown (5-7.5YR 6/4) to pinkish white (7.5YR 8/2), interbedded silt, sand, and granule-pebble gravel. Silt contains ~10% clay. Sand is mostly replaced by calcite, but is very fine- to fine-grained where intact. Gravel consists of clast-supported granules (85%) and pebbles		

Unit	Description	Thickness (cm) (Unit) (Total)
	(15%); clasts are mostly Paleozoic sedimentary and Precambrian intrusive/metamorphic lithologies.	
	Covered interval; likely silt and clay.	
SP -1	**Pebble gravel and silt** – 15-45 cm beds of light reddish brown (5YR 6/4), sandy, pebble gravel grading up into sandy silt in the upper 20 cm. Pebbles are poorly to moderately sorted, subangular to subrounded, and consist of ~70% Paleozoic sedimentary lithologies and ~15% Precambrian granite and metamorphics; the remainder include Cretaceous sandstone, chert, and Tertiary volcanic rocks. Weakly imbricated pebbles imply a SSW paleocurrent direction (mean = 213°, n = 55). Sand is very poorly sorted, subangular to subrounded, vfU-cL, and consists of 65% lithic, 20% feldspar, and 15% quartz grains. Deposit has rare carbonate cement.	
	Base not exposed. ***Base of stratigraphic section at 289095 m E, 3668125 m N.***	

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DESCRIPTION OF UPPER JUNIPER STREET STRATIGRAPHIC SECTION. SECTION 33, T13S, R4W, CUCHILLO 7.5-MINUTE QUADRANGLE.

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Sand textures are abbreviated as follows: very fine-lower, vfL; very fine-upper, vfU; fine-lower, fL; fine-upper, fU; medium-lower, mL; medium-upper, mU; coarse-lower, cL; coarse-upper, cU; very coarse-lower, vcL; very coarse-upper, vcU. The term “clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Descriptions of bedding thickness follow Ingram (1954).

The section comprises measurements in lower axial-fluvial facies of the Palomas Formation and was measured by Andy Jochems on December 1, 2017. At ~2.6 m is a 1-cm-thick travertine bed that caps the Juniper Street section measured by Dan Koning on November 21, 2017.

Upper Juniper St. section (UJ). This section consists of axial-fluvial facies of the Palomas Formation. Measured in NE¼SE¼SW¼ of Section 33, T13S, R4W, Sierra County, New Mexico. Measured and described by Andy Jochems on December 1, 2017, using an abney level, Jacob's staff, and tape measure.

Unit	Description	Thickness (cm) (Unit)	(Total)
	Total section	>11.25 m thick	
	AXIAL-FLUVIAL FACIES OF THE PALOMAS FORMATION **Petrofacies 2 (Tpal2)**		
UJ-17	**Pebble-cobble gravel and sand**—Grayish brown to brown (10YR 5/2-3), weakly imbricated, pebble-cobble gravel and subordinate white (10YR 8/1), massive to horizontal-planar laminated sand. Moderately to strongly calcareous. Clasts consist of very poorly to poorly sorted, subangular to rounded pebbles (80-90%) and cobbles (10-20%). Gravel matrix consists of poorly sorted, rounded to well rounded, fL-cU sand grains comprised of 60-70% quartz, 20-25% lithics (volcanic>sandstone+carbonate), and 10-20% feldspar with no clay. Massive to laminated sand occurs in thin beds in upper part of exposure. Loose to weakly consolidated. Broadly scoured base. Sand sample from lower 30 cm of unit. Clast count (875-905 cm, n=123): 19% felsic volcanics, 15% intermediate volcanics, 15% undivided tuffs, 14% Pz carbonates, 11% Mz sandstone, 10% Mz vf sandstone+siltstone, 7% Abo Formation, 4% quartzose sandstone, 2% chert+jasperoid, 2% granite, 2% quartzite, <1% vein quartz, <1% other	>250	>1125
UJ-16	**Pebble-cobble gravel**—Reddish brown to light reddish brown (5YR 5/4-6), weakly to moderately imbricated, pebble-cobble gravel. Non-calcareous. Clasts consist of very poorly sorted, subangular to rounded pebbles (60-90%) and cobbles (10-40%). Gravel matrix consists of very poorly sorted, subangular to subrounded, vfU-vcL sand grains comprised of 55-65% quartz, 30-35% lithic (sandstone+carbonate>volcanic), and 5-15% feldspar with 20-30% reddish clay chips and bridges. Moderately well consolidated (clay-cemented). Strongly scoured base. Clast count (705-730 cm, n=137): 27% Mz sandstone, 17% intermediate volcanics, 15% undivided tuffs, 12% felsic volcanics, 9% Abo Formation, 9% Mz vf sandstone+siltstone, 4% Pz carbonate, 4% quartzose sandstone, 2% granite, <1% basalt, <1% chert+jasperoid Mean size of largest observed clasts (730 cm, n=17): 13 x 9 cm	180	875

Unit	Description	Thickness (cm) (Unit)	(Total)
	Mean paleocurrent direction from imbrication (730 cm, n=51): 124°		
	AXIAL-FLUVIAL FACIES OF THE PALOMAS FORMATION **Petrofacies 1 (Tpal1)**		
UJ-15	**Interbedded gravel, sand, and mud**—Strongly interbedded unit. Gravel is in lenses of very poorly sorted, subrounded to rounded pebbles or pebbles (80-90%) and cobbles (10-20%) with a reddish yellow (5YR 6/6) matrix containing 15-25% clay films. Sand is horizontal-planar laminated and in 10-15-cm-thick, tabular beds; sand composition is similar to unit UJ-13. Mud is as described in unit UJ-8 (likely rip-ups). Loose to moderately consolidated. Scoured base.	66	695
	Clast count (665-685 cm, n=125): 22% undivided tuffs, 18% felsic volcanics, 18% Mz sandstone, 16% intermediate volcanics, 6% quartzose sandstone, 5% Mz vf sandstone+siltstone, 4% Abo Formation, 4% granite, 4% Pz carbonate, 3% chert+jasperoid, <1% vein quartz		
	Mean paleocurrent direction from imbrication (675 cm, n=46): 102°		
UJ-14	**Pebbly sand**—Similar to sand of unit UJ-13 but with volcanic lithics more abundant than sedimentary and chert lithics. Trough cross-stratified and pebbly (subrounded to rounded, fine) in lower 25 cm. Horizontal-planar to rarely cross-laminated in upper 35 cm. Weakly consolidated. Mostly planar base.	60	629
	Sand sample from 30 cm below top of unit.		
UJ-13	**Pebbly sand and pebble gravel**—Light brownish gray (10YR 6/2), planar cross-stratified (foresets up to 7 cm thick), pebbly sand interfingering with pebble gravel. Upper 15 cm consists of coarser (up to very coarse) pebble gravel and discontinuous interbeds of red (2.5YR 6/6), massive, non-calcareous mud (likely rip-ups). Non- to weakly calcareous. Sand consists of very poorly sorted, subangular to rounded, fU-vcL grains comprised of 60-65% quartz, 25-30% lithics (chert+carbonate+Mz sedimentary>volcanic), 5-15% feldspar, and no clay. 15-25% pebbles are present in sand. Gravel consists of poorly to moderately sorted, subangular to rounded, fine to medium (few coarse) pebbles with matrix similar to sand described above. Loose to weakly consolidated. Basal scour up to 5 cm.	60	569
	Clast count (525-555 cm, n=135): 23% undivided tuffs, 21% felsic volcanics, 18% intermediate volcanics, 12% Mz sandstone, 5% chert+jasperoid, 5% Pz carbonate, 4% granite, 4% quartzose sandstone, 2% Abo Formation, 2% Mz vf sandstone+siltstone, 1% quartzite, <1% vein quartz, <1% other (mud rip-up)		
	Mean size of largest observed clasts (525-555 cm, n=13): 5 x 4 cm		
	Mean paleocurrent direction from imbrication (525-555 cm, n=33): 131°		
UJ-12	**Sand**—White (10YR 8/1), horizontal-planar laminated sand. Non-calcareous. Sand consists of moderately sorted, rounded, fU-mU grains comprised of 70-80% quartz, 15-20% feldspar, and 5-15% lithics (chert, few volcanic) with no clay. Moderately consolidated. Basal scour of 3-4 cm.	34	509
	PALEOMAG SAMPLES UJ-12-1, UJ-12-2, AND UJ-12-3 TAKEN 5-15 cm BELOW TOP OF UNIT. Sample UTM coordinates: 289445 m E, 3668102 m N (NAD83, zone		

Unit	Description	Thickness (cm) (Unit)	(Total)
	13). Sand sample from middle 10 cm of unit.		
UJ-11	**Sandy pebble gravel**—White (10YR 8/1), moderately imbricated, sandy pebble gravel. Very weakly calcareous. Pebbles are very poorly sorted, subangular to rounded, and fine to very coarse. Matrix sand consists of poorly sorted, subangular to rounded, vfU-mU grains comprised of 65-70% quartz, 15-20% feldspar, and 10-20% lithics (volcanics≈orangish chert) with no clay. Loose. Basal scour up to 8 cm. Clast count (450-475 cm, n=146): 24% intermediate volcanics, 21% felsic volcanics, 17% Mz sandstone, 14% undivided tuffs, 7% Mz vf sandstone+siltstone, 4% chert+jasperoid, 4% quartzose sandstone, 3% granite, 2% Abo Formation, 2% Pz carbonate, <1% quartzite, <1% vein quartz, <1% other (breccia) Mean size of largest observed clasts (450-475 cm, n=12): 5 x 3 cm Mean paleocurrent direction from imbrication (450-475 cm, n=41): 143° ***Units UJ-11 and above are in footwall of southwest-down normal fault, whereas units UJ-10 and below are in hanging wall. Beds in hanging wall have an apparent dip of 6-7° toward 355°, whereas footwall beds are near-horizontal lying. Apparent stratigraphic displacement across fault is approximately 1 m.***	25	475
UJ-10	**Sand**—Light brown to pink (7.5YR 6-7/4), massive (likely bioturbated), slightly clayey sand. Pink (5YR 7/3) in upper 50 cm; siltier in lower 15 cm. Very weakly calcareous. Sand consists of moderately well sorted, subrounded to rounded, vfL-fL grains comprised of 45-50% quartz, 30-40% feldspar, and 10-25% lithics (chert) with 10-20% clay flakes and bridges. Moderately consolidated. Diffuse, mostly planar base. Sand sample from lower 20 cm of unit.	133	450
UJ-9	**Sandy silt**—White (2.5Y 8/1-2), horizontal-planar to vaguely cross-laminated, sandy silt. Very weakly calcareous. Sand consists of 10-20% subrounded to rounded, vfL-fL grains comprised of 50-60% quartz and 40-50% feldspar+lithics (orangish chert>mafics). Weakly to moderately consolidated. Basal scour up to 6 cm.	41	317
UJ-8	**Mud**—White (2.5Y 8/2), massive mud with pale red (10R 7/3) mottles. Non-calcareous and slightly (≤5%) sandy. Sand consists of subangular to rounded, lithic grains of uncertain composition due to small size. Moderately to moderately well consolidated. Planar base.	17	276
UJ-7	**Travertine**—Thin bed of travertine occasionally exhibiting flow structures.	1	259
UJ-6	**Sand**—White (10YR 8/1), horizontal-planar to cross-laminated sand. Non- to very weakly calcareous. Sand consists of moderately well sorted, subrounded to well rounded, fU-mU grains of 80-90% quartz, ~10% feldspar, and ~10% lithics (mafics, chert) with no clay. Sand contains sparse, subrounded to rounded, fine pebbles of mostly volcanic lithologies. Moderately consolidated. Basal scour up to 10 cm.	106	258
UJ-5	**Silt-clay**—Pink (5YR 7/4), massive silt-clay. Weakly consolidated. Mostly planar base with rare, low-amplitude scours.	12	152
UJ-4	**Pebbly sand**—Similar to sand of unit UJ-6 but with rare, 1-2-cm-thick pebble lags.	47	140

Unit	Description	Thickness (cm) (Unit)	(Total)
	Pebble lithologies are mostly volcanic, but granite and petrified wood are also observed. Basal scour of 2-4 cm.		
UJ-3	**Sand**—Pinkish gray to light brown (7.5YR 6/2-3), planar cross-stratified sand. Non-calcareous. Sand consists of poorly sorted, subangular to rounded, mL-cU grains comprised of 70-80% quartz, 15-20% lithics (volcanic>sandstone+carbonate), and 10-15% feldspar with no clay. Pervasive staining by MnOx and FeOx minerals. Loose. Planar base.	5	93
UJ-2	**Sandy pebble gravel**—Light reddish brown (5YR 6/4), weakly to moderately imbricated, sandy pebble gravel. Non-calcareous. Pebbles are very poorly to poorly sorted, subrounded to rounded, and fine to very coarse. Gravel matrix consists of very poorly sorted, subangular to rounded, vfU-cL sand grains comprised of 75-85% quartz and 15-25% feldspar+lithics (sandstone, carbonate, chert, volcanic) with 15-20% pinkish clay chips and films. Loose to weakly consolidated. Basal scour of 1-5 cm. Clast count (70-80 cm, n=115): 31% felsic volcanics, 30% intermediate volcanics, 20% undivided tuffs, 6% Mz sandstone, 5% Pz carbonates, 4% Mz vf sandstone+siltstone, 2% chert+jasperoid, <1% other (intrusive)	23	88
UJ-1	**(Pebbly) sand**—Similar to sands of units UJ-4 and UJ-6. NOTE 1: Only 65 cm of this unit is exposed in roadcut; therefore, its total thickness is uncertain. **Base of section at UTM coordinates: 289444 m E, 3668068 m N (NAD83, zone 13).**	65	65

References

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DESCRIPTION OF WEST JUNIPER STREET STRATIGRAPHIC SECTION. SECTION 33, T13S, R4W, CUCHILLO 7.5-MINUTE QUADRANGLE.

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Sand textures are abbreviated as follows: very fine-lower, vfL; very fine-upper, vfU; fine-lower, fL; fine-upper, fU; medium-lower, mL; medium-upper, mU; coarse-lower, cL; coarse-upper, cU; very coarse-lower, vcL; very coarse-upper, vcU. The term “clast(s)” refers to the grain size fraction greater than 2 mm in diameter. Descriptions of bedding thickness follow Ingram (1954).

West Juniper Street stratigraphic section (MJ). This section consists of early(?) axial-fluvial facies of the Palomas Formation. The presence of orangish hues, finer sand, and volcaniclastic beds with >90% fine-grained felsites suggests a separate lithologic unit than the Poplar Street stratigraphic section. Measured in SE1/2 of NE1/4 of SE1/4 of SW1/4 of Section 33, T13S, R4W, Sierra County, New Mexico. Measured and described by Dan Koning on November 22, 2017, using an abney level, Jacob's staff, and hand-held GPS unit.

Unit	Description	Thickness (cm) (Unit)	(Total)
	OLDEST ALLOSTRATIGRAPHIC UNIT OF FLUVIAL-AXIAL SAND **Top of West Juniper St. stratigraphic section, in UTM coord (NAD83): 289,449 m E, 3,668,062 m N. (waypoint 171201_405)**		
WJ-7	**Sandy gravel**—Vague, thin, tabular to lenticular beds whose gravel are well-imbricated. Imbrication of TRC-24 is likely from this unit. Gravel are subangular to subrounded and composed (visual estimation) of fine-grained felsites, 15% greenish f- to m-gr (Mesozoic) sandstone, 3% altered Paleozoic carbonates, 3-5% very fine- to fine-grained sandstone + siltstone, 1% Abo Fm clasts, 0.5% feldspar pophyry. Intra-formational rip-up of green siltstone-claystone (coarse cobble) and a reddish clay (fine boulder size). Gravel is mostly comprised of vf-vc pebbles but does have 3-4% fine cobbles composed of sedimentary clasts. Sand is reddish brown (5YR 5/3), vfU-vcU, angular-subrounded, poorly sorted, and quartz-poor (even in fL-mL size fraction). MnO stains are present and there is much oxidation and discoloration; clasts seen abnormally darkened, probably due to alteration. Well consolidated and weakly cemented by clay. **Sand sample taken 40 cm above base of unit.**	90	520
WJ-6b	**Sand and pebbly sand with ~15% sandy pebble beds**—Massive to vaguely horizontal-planar laminated; also local low-angle cross-laminations; sandy pebbles are in very thin to thin (up to 10 cm-thick), lenticular beds. Pebbles are vf-c (minor vc) and subangular. Pebbly sand has 10-20% vf-c, subangular to subrounded pebbles. Sand and pebbly sand is white (7.5YR 8/1), fL-mL (quartzo-feldspathic and angular) with 10-15% mU-vcU volcanic sand grains. **PALEOMAGNETIC SAMPLES: WJ-6b-3 is on south nose of the knob (top of sample lies 10-13 cm below the base of WJ-7); WJ-6b-2 (top of sample lies 10-20 cm below the base of WJ-7), and WJ-6b-1 at the top of the south wall of the gully that follows the fault (top of sample lies 107 cm above the contact of unit 6a/5b). Sand sample taken 5 cm below the paleomagnetic sample WJ-6b-3. Photo of WJ-6b-3 site: TRC_24_pmag_6b_03_ph. Photo of WJ-6b-2 site: TRC_24_pmag_6b_02_ph_01 and _ph_02. PHoto of WJ-6b-1 site: TRC_24_pmag_6b_01_ph_01 to _ph_03.** **Sample GPS locations (UTM NAD83): WJ-6b-1 (waypoint 171201_411): 289,452 m E, 3,668,063 m N; WJ-6b-2 (waypoint 171201_410): 289,451 m E, 3,668,061 m N; WJ-6b-3 (waypoint 171201_409): 289,448 m E, 3,668,062 m N.**	90	460
WJ-6a	**Subequal sandy pebbles and pebbly sand**—Very thin to thin, lenticular beds. Pebbles are mostly up to 5 cm long, but 0.5% of clasts are out-size: 9x6 cm and 8x6 cm (both are rhyolites), and 12x5 cm (meta-siltstone?). Pebbles are subangular to subrounded, low-moderate to poorly sorted. Estimated pebble composition: mostly fine-grained felsites with 3% altered, yellow Pz carbonates, 5% intermediate volcanics, 0.5% McRae Fm volcanics or volcaniclastic sandstne (plag-phyric4 m of unit and matches what is seen in the San Jose Creek Mbr), 3-5% green Mz sandstone, 1% gray	50	370

Unit	Description	Thickness (cm) (Unit)	(Total)
	intermediate volcanic clasts comparable to those seen in TRC-51, and trace feldspar-bearing porphyry (phenocrysts up to 4 mm long). Sand is pink to reddish yellow (7.5YR 7/4-6), poorly sorted, and fL-mL (subangular and quartzo-feldspathic) to mU-vcU (subrounded volcanic lithic grains). Moderately consolidated. Lower contact is abrupt and wavy (2 cm of relief) or gradational over 10 cm vertical distance. Sample TRC-24 was taken from this interval.		
WJ-5	**Sand—** Fining-upward sand that can be divided into two subunits on the NE side: **Subunit 5b (NE side only):** Silty-clayey, light reddish brown to pink (5YR 6-7/4), very fine- to medium-grained sand that is horizontal-planar laminated to massive. 1% clay rip-ups that are reddish brown, rounded, and up to 6-8 mm in diameter. Basal contact is gradational over 5 cm. 30 cm thick. **Subunit 5a:** Horizontal planar-laminated with local cross-laminations (3-4 cm tall and fills shallow paleo-channels). Sand is pink (5-7.5YR 7/3-4), mL-mU grading upward to fU-mL, subangular, well sorted, and quartzo-feldspathick with only 1-4% lithic grains. Near top is 3 cm-long reddish brown clay rip-ups. Near pmag site WJ-5a-4, sand is mL and horizontal-planar laminated; 1% light reddish clay lamina (horizontal - planar) 0.5-1.0 cm thick and interbedded within the sand. **PALEOMAGNETIC SAMPLES TAKEN AT 250 CM: WJ-5a-1 (60 cm below 5b top, 20 cm above 5a base), WJ-5a-2 (50 cm below 5b top, 35 cm above 5a base, separated from WJ-5a-1 by 1 m horizontal distance), WJ-5a-3 (60 cm below 5b top, 30 cm above 5a base, separated from WJ-5a-2 by 2.5 horizontal distance), and WJ-5a-4 (SW end of know; top of sample is 28 cm below WJ-6a base). Pmag samples taken at UTM coordinates: 289,455 m E, 3,668,060 m N (NAD83, zone 13). Sand sample taken 15 cm above base of subunit. Photos of outcrop: TRC_24_WJ_05_ph_01 to _ph_4. Photos of pmag samples: Photos TRC_pmag_5a_01to03_ph_01 to _ph_04; also TRC_pmag_5a_04_ph_01 to _ph_02.** 70 cm thick.	100	320
WJ-4	**Sandy pebbles**—Vague, very thin to thin, lenticular beds. Pebbles are very fine to very coarse, angular to subrounded (mostly subangular), poorly sorted, and composed (based on visual estimation) of fine-grained felsites, 5% green Mesozoic sandstone, trace schist, and trace chert. A single imbricated clast indicates a 220 degree paleoflow direction. Sand is light reddish brown to reddish yellow (5YR 6/4-6), vfL-vcU (mostly fU), subangular to subrounded (mostly subangular), poorly sorted, and has composition dependent on grain size (based on visual estimation): 1) vfL-mL sand is predominately quartz-feldspathic; 2) mU-vcU sand is composed of volcanic lithic grains. Basal contact is a scour with ~2 cm of relief. **Sand sample upper 10 cm of unit. Photos TRC_24_WJ_04_ph_01 and _02.**	25	220
WJ-3	**Sand with 5-10% scattered pebbles**—Horizontal-laminated with local 1-3 cm-deep scours. The pebbles are mostly up to 3 cm long and include fine-grained felsites, 1-5% crystal-rich tuffs, 15% Mesozoic green sandstone, 10% altered Paleozoic carbonates. One 10x6 cm, rounded, rip-up clast of light purple-pink siltstone-vf sandstone (intra-formational). 1-3% reddish brown clay rip-ups up to 1 cm long. Sand is pink to reddish yellow (5YR 7/4-6), fU-mU, subrounded-subangular, well sorted, and quartzo-feldspathic with 10% lithic grains. Basal contact is a scour with >7 cm of relief. Orangish color or sand due to oxidation. **Sampled sand in basal 10 cm of exposure. Photos TRC_24_WJ_03_ph_01 and 02.**	45	195
WJ-2	**Interbedded pebbly sand w/ 15% sandy pebbles—Pebbly sand** is horizontal-planar laminated (up to 1 cm-thick) or cross-laminated (with tangential foresets up to 6 cm tall); contains 15% scattered pebbles up to 3 cm long. Sand is pink (5YR 7/4, lesser 2.5YR 7/4), vfL-vcU (mostly mL-mU), subangular, poorly sorted, and quartz-feldspathic with 15-20% volcanic grains + lesser lithics. **Sandy pebbles** are in: 1) medium, lenticular beds or U-shaped channel fills, or 2) in tangential, 1 cm-thick foresets, up to 7 cm tall, that are intimately interbedded in the pebbly sand. A sandy pebbly channel fill in the NE part of the exposure is 25 cm thick and internally massive. Pebbles are up to 3 cm long, angular to subrounded (mostly subangular), low-	30	150

Unit	Description	Thickness (cm) (Unit)	(Total)
	moderate to high-poorly sorted, and composed (visual estimation) of fine-grained felsites, 1% feldspar porphyry (phenocrysts up to 3 mm long), 1% crystal-rich tuffs, 5% intermediate volcanic rocks (similar to those seen in TRC-51), 5% Mesozoic sandstone, and trace chert; no obvious imbrication. Pebble sizes (axb axes in cm): 2.5x22.2, 3.0x2.1, 2.3x1.8, 2.3x1.8, 2.5x1.5, 2.8x2.5, 3.0x1.8 cm. The sand in this 25 cm-thick channel fill is light reddish brown to reddish yellow (5YR 6/4-6), mL-vcU, subangular to subrounded, moderately to poorly sorted, and quartzo-feldspathic with 15% volcanic lithic grains. Basal contact not exposed. Well consolidated and weakly cemented. **Sand sample from 120-128 cm. Photos TRC_24_WJ_02_ph_01 [shows SW pebble channel fill margin] and TRC_24_WJ_02_ph_02 [south side of exposed unit, showing x-laminations and very thin beds of pebbly sand].**		
	Artificial fill and no exposure	90	120
WJ-1	**Sandy Pebbles—**Sandy pebbles in vague, very thin to thin, lenticular to tabular beds. Pebbles are subangular to subrounded, low-moderately sorted, and composed of fine-grained felsites with 5-10% green fine- to medium-grained sandstone (probably Mesozoic) and trace rounded rhyolite. Orangish discoloration throughout. Sand is yellowish red (5YR 4-5/6), fU-vcU, angular to subrounded (mostly subangular), poorly sorted, and apparently dominated by lithic grains and feldspar (based on hand lens inspection). Well consolidated because of clay. Basal and top contacts are not exposed. Pebble sizes (axb axes, in cm): 3.5x2.5, 7.1x4.2, 3.8x3.2, 5.0x4.3, 4.0x1.5, 438x3.3, 4.0x3.6, 3.0x1.6. **Photos TRC_24_WJ_01_ph_01 and TRC_24_WJ_01_ph_02**	30	30
	Base of section at UTM coordinates: 289,457 m E, 3,668,057 m N (NAD83, zone 13). Section above is ubiquitously weakly to moderately consolidated and weakly cemented. This location corresponds to the exposure exhibiting MJ-1 and MJ-2.		

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DESCRIPTION OF MIDDLE JUNIPER STREET STRATIGRAPHIC SECTION. SECTION 33, T13S, R4W, CUCHILLO 7.5-MINUTE QUADRANGLE.

Grain sizes follow the Udden-Wentworth scale for clastic sediments (Udden, 1914; Wentworth, 1922) and are based on field estimates. Sand textures are abbreviated as follows: very fine-lower, vfL; very fine-upper, vfU; fine-lower, fL; fine-upper, fU; medium-lower, mL; medium-upper, mU; coarse-lower, cL; coarse-upper, cU; very coarse-lower, vcL; very coarse-upper, vcU. The term "clast(s)" refers to the grain size fraction greater than 2 mm in diameter. Descriptions of bedding thickness follow Ingram (1954).

Middle Juniper Street stratigraphic section (MJ). This section consists of early(?) axial-fluvial facies of the Palomas Formation. The presence of orangish hues, finer sand, and volcaniclastic beds with >90% fine-grained felsites suggests a separate lithologic unit than the Poplar Street stratigraphic section. Measured in SE1/4 of NE1/4 of SE1/4 of SW1/4 of Section 33, T13S, R4W, Sierra County, New Mexico. Measured and described by Dan Koning on November 22, 2017, using an abney level, Jacob's staff, and hand-held GPS unit.

Unit	Description	Thickness (cm) (Unit)	(Total)
	OLDEST ALLOSTRATIGRAPHIC UNIT OF FLUVIAL-AXIAL SAND **Top of Middle Juniper stratigraphic section, in UTM coord (NAD83): 289,460 m E, 3,668,097 m N.**		
MJ-9 (MJ-L)	**Silt and very fine sand**—Light greenish gray (10Y 8/1), silt and vfL-vfU sand that is massive. Minor CaCO3-filled rhizoliths 1 mm wide and 10 mm vertical (exposed). Minor orangish mottling, especially in lower 20 cm. In middle of the graben (UTM coord: 289,455 m E, 3,668,086 m N, wpt 22), only the lower 60 cm of the unit is reduced; above lies silt and vfL-vfU sand that is redder (5-7.5YR 7/3) which grades upward into vfL-fL sand. This unit is all massive. Total thickness in middle of graben is 1.5 m. Lower contact is sharp; upper contact is deeply scoured. **Photo taken at wpt 22: TRC_52_MJ_09.** @ wpt 22 (UTM coord: 289,455 m E, 3,668,086 m), 3-6 m west of the East fault, this unit also underlies Unit MJ-8 (extending to 35 cm below the base of Unit MJ-8). **Photos TRC_52_graben_08_and_09_ph_01 and TRC_52_graben_08_and_09_ph_02.**	150	866
MJ-8 (MJ-K)	**Travertine marker bed**—Within a 5 cm interval are 1-3 cm-thick beds of sand+CaCO3. Locally abundant rhizoliths and porosity. Local drapes. This is a laterally extensive marker bed, extending across the entire exposure and across the eastern fault. It continues westward to the West Juniper Street stratigraphic section. **Two photos taken of travertine. At top of strat section (east of East fault) is TRC_MJ_08_ph_01 and TRC_MJ_08_ph_01. At wpt 22 (UTM coord: 289,455 m E, 3,668,086 m), in the graben west of the East fault, a photo was taken of a vein: TRC_MJ_08_ph_03.**	5	716
MJ-7 (MJ-J)	**Pebbly sand fining upward to sand—**Horizontal-planar laminated sand. Sand is white (10YR 8/1), fU-mL, clean, subrounded-subangular, well-sorted, and quartzo-feldspathic with 20% orange-red grains and 10% dark lithic+mafic grains. **Sampled sand.** Internal subdivisions as follows (in ascending order): 1) lowest 30 cm that is locally pebbly (but also locally sandy in horizontal-planar to low-angle cross-laminations); upper 10 cm interval is softer and has locally abundant rip-ups of 2.5-5YR 7/6 clay. 2) 30-60 cm above base is fU-mL sand, as described above, that is interbedded with local very thin lenses of vf-vc, fine-grained felsite pebbles. 3) 60-115 cm above base is the sand described above. 4) 115-120 cm above the base is orangish, clayey-silty sand. 5) 120-130 cm above the base is sand as described above. 6) 130-132 cm above the base is 2.5YR 8/3 clay. 7) 133-140 cm above the base is sand as described above. Note that subunits 4 through 7 grade laterally westward to light green silt to fU sand, as seen on the western gully wall **PMAG SAMPLES COLLECTED IN GULLY 90 CM ABOVE THE BASE OF**	140	711

Unit	Description	Thickness (cm) (Unit)	(Total)
	MJ-7, IN SUBUNIT #3. J1 TAKEN ON THE WEST WALL (80 cm below MJ-6 upper contact) , J-2 TKEN ON THE NORTH SIDE OF GULLY (55 cm below MJ-6 upper contact), AND J-3 TAKEN ON THE EAST WALL (55 cm below MJ-6 upper contact). UTM COORDINATES OF SAMPLES (NAD83): 289,460 m E, 3,668,097 m N. **Photo with watch taken of middle Pmag sample site (whose top is just to the right of the watch). Photo TRC_52_MJ_07. Note that subunit 4 base lies ~15 cm above the top of this sample. Photo**		
MJ-6 (MJ-H and MJ-I)	**Fining-upward interval of sandy gravel and pebbly sand**—Lower part is more gravelly, ~40 cm thick, and its contact with the overlying, lesser-gravelly, upper part is indistinct. Lower part consists of very thin to thin, lenticular to tabular beds of sandy pebbles with local cobbles. Maximum clast sizes: 8x5 cm (Mz fine- to medium-grained sandstone), 16x9 cm (reddish brown, very fine sandstone = Abo Fm), 9x6 cm (very fine- to fine-grained, green sandstone, and 7x6 cm (green siltstone). Gravel comprised of very fine to very coarse, subangular to subrounded, moderately sorted, fine-grained felsites with 5% Abo Fm clasts and 10% green fine- to medium-grained sandstone; one Vicks Peak Tuff clast is 45x30 mm and another fine-grained felsite is 60x37 mm. The sand is white (5Y 8/1), mL-vcU, subrounded to subangular, and moderately sorted; the mL-mU sand fraction is quartzo-feldspathic. Lower contact is scoured with 10-20 cm of scour relief. Upper part is less gravelly, ~50 cm thick, and its contact with the underlying, more-gravelly, lower part is indistinct. It consists of pebbly sand that is low-angle cross-laminated. Other than a thin pebble beds (described below), the pebbles only comprise 7-10% of the unit. Pebbles are very fine to coarse, subangular to subrounded, moderately sorted, and composed of fine-grained felsites with 5-10% sandstone-siltstone clasts of inferred Mesozoic-late Paleozoic age. Sand matrix is pink (7.5YR 7/3) with 15% streaks (<=1 cm thick) of strong brown (7.5YR 5/6), mL-vcU, subrounded to subangular, and moderately sorted; mL-mU sand is quartzo-feldspathic. @523-533 cm, there is a lenticular sandy pebble bed; pebbles composed mainly of fine-grained felsites.	90	571
MJ-5c	**Silt and very fine sand**—Seems to fill a paleochannel that overlies unit MJ-5b and MJ-5b. Light green color (5Y 8/1). Thickness measurement taken where this unit overlies MJ-5a. Presumably it is 24 cm thick where if overlies unit MJ-5b.	15	481
MJ-5b (MJ-G)	**Interval of numerous inset channel fills of sand and pebbles -- eastern fining upward channel fill**— Paleochannel is 86 cm deep (i.e., has a 86 cm-tall buttress on its NW side). Lower 55 cm is composed of light red (2.5YR 6/6) sandy pebbles that are very fine to coarse, subangular to subrounded, and moderately sorted. Pebbles are composed of fine-grained felsites with one plag-dominated, fine-grained sandstone (San Jose Fm?) and trace medium-grained green sandstone (Mesozoic age), trace intermediate volcanic rocks (similar as those noted in TRC-51). Above lies (in ascending order): 1) 5 cm of sand (white, vfL-fL(m) with minor fU), and quartzo-feldspathic); 2) 5 cm of very fine to fine pebbles (like that described in lower 55 cm); 3) 21 cm of sand (white, vfL-fL(m) with minor fU), and quartzo-feldspathic) that has internal laminations that "onlap" NW paleochannel margin. Lower contact is scoured. Described at UTM coord (NAD83): 289,472 m E; 3,668,087 m N. Description lies 2 m east of description for MJ-5a. Photo **TRC_52_MJ_4b_and_5b**; Photo **TRC_52_MJ_5b. Sand sampled ~20 cm above the base of subunit.**	86	466
MJ-5a (MJ-G)	**Interval of numerous inset channel fills of sand and pebbles -- western channel fill**—Lower subunit (30 cm thick) consists of light reddish brown to reddish yellow (5YR 6/4-6) sandy pebbles grading upward into pebbly sand; pebbles are up to 3 cm long; lower contact is scoured with 7 cm of relief. Upper subunit (65 cm thick) consists of white (10YR-2.5Y 8/1), fU, well-sorted, sand. Sand is quartz-rich and	95	475

Unit	Description	Thickness (cm) (Unit)	(Total)
	contains 5-7% mafic + volcanic grains; sand is horizontal-planar laminated to low-angle cross-laminated (1-2 cm thick foresets); At top of upper subunit is a discontinuous, 6 cm-thick bed of sandy pebbles; **sampled sand in middle of upper subunit**. Sharp, concave-up contact separates the lower and upper subunits (4 cm of relief). Photos **TRC_52_MJ_05_and_04**; Photo **TRC_52_MJ_5a**		
MJ-4b (MJ-F)	**Very fine sand and silty very fine sand**—Vaguely horizontal-planar laminated, white (2.5Y 8/1), vry fine sand and silty very fine sand. 5% horizontal-planar lamina of silt and clay. 15% reddish discoloration. Sand is quartzo-feldspathic. Lower contact is sharp and has 7-8 cm of relief. Described at UTM coord (NAD83): 289,472 m E; 3,668,087 m N. **Photo TRC_52_MJ_4b_and_5b;** Photo **TRC_52_MJ_4a_and_4b. Photo TRC_52_MJ_5_and_4.**	95	380
MJ-4a (MJ-E)	**Interbedded fine sand and silt, clay, and silty very fine sand**—Very thin to thin, tabular to irregular beds of: 1/3 orangish (2.5YR 7/4) to light green silt-clay and silty very fine sand; and 2/3 white (10YR 8/1) vfL-fL (minor fU), well sorted, quartz-rich sand. The lowest thin bed is fU-mL and has 15% orange-colored grains. Described at UTM coord (NAD83): 289,475 m E; 3,668,087 m N. **Sampled this lowermost sand. Photo TRC_52_MJ_4;** Photo **TRC_52_MJ_4a_and_4b**	40	285
	Artificial fill and no exposure	120	245
MJ-3 (MJ-D)	**Sand with 10% pebble beds—**Sand is horizontal-planar laminated and pink (7.5YR 7/3), fL-mL, subrounded to subangular, well sorted, and quartz-feldspathic with 10% sediment+volcanic lithic grains. Sandy pebbles have a matrix similar to the sand just described; pebbles are very fine to coarse, subrounded to subangular, low-moderately sorted. Clast composition and imbrication data are on Iphone (TRC-52) are from the lower (70-74 cm) and upper (98-101 cm) pebble beds. Three out-sized clasts: 10x5 cm (mL green sandstone); 8x7 cm (welded tuff that may be South Park Tuff because it is crystal-rich); 12x8 cm (silicified fine-grained volcanic rock). **Sampled sand.** Described at UTM coord (NAD83): 289,476 m E; 3,668,086 m N. **THREE PMAG SAMPLES TAKEN WITHIN 2 M OF EACH OTHER. D-1 IS ON THE WEST, D-2 IS IN THE MIDDLE, AND D-3 IS ON THE EAST.** Three photos taken: **TRC_52_MJ_03_ph_01 through TRC_52_MJ_03_ph_03.** @98-101 cm: Sandy pebble bed. @70-74 cm: Sandy pebble bed.	50	125
	Artificial fill and no exposure	25	75
MJ-2b (MJ-C)	**Sandy pebbles inset into unit MJ-2a**—Manganese-cemented sandy pebble conglomerate. Deposit fills two paleochannels 30-40 cm deep. These paleochannels exhibit laminations to very thin beds that are parallel to the lower, scoured contact. Pebbles are up to 62 mm long and composed of fine-grained felsites with trace to 1%, green-brown [siltstone-very fine sandstone and fine- to medium-grained sandstone]. Measured pebble sizes: 5.5x3.3, 6.2x3.5, 3.2x2.3, 3.3x3.0, 2.8x1.5, 2.3x2.2, 3.9x2.3, 4.0x3.7. Non-cemented sand is pink (5YR 7/4), mL-vcU, subrounded to subangular, moderately sorted, and quartzo-feldspathic with 20% felsic volcanics.	36	50
MJ-2a (MJ-B)	**Sand—**Sand is cross-laminated, with tangential foresets >=6 cm thick. Lower half of unit is composed of fL-fU sand, but uper half of unit is composed of fU-mU sand. Both are white to light gray (7.5YR 7-8/1), subrounded to well sorted, and quartz-feldspathic with 20% orange grains and 7-10% volcanic+mafic grains. **Photo TRC_52_1to3. Sampled sand.**	38	50
MJ-1 (MJ-A)	**Sandy Pebbles—**Exposed in a 25 cm-tall road cut. Pebbles are up to 3 cm long, subangular, moderately sorted, and composed wholly of fine-grained felsites (much fine-grained welded tuffs); trace yellowish-green, feldspar megacrystic rock (feldspars up to 6 mm long) and trace green sandstone (inferred to be Mesoazoic). Measured pebble sizes (axb cm): 2.0x1.6, 2.5x2.0, 2.0x1.5, 2.5x1.3, 2.8x2.0, 2.3x1.2, 2.3x1.9, 3.0x2.2. Matrix is light reddish brown (5YR 6/3-4) fU to mL, quartzo-feldspathic sand with 50% volcanic mU-vcU grains; subrounded to subangular and poorly sorted.	12	12

Unit	Description	Thickness (cm) (Unit)	(Total)
	Upper contact is sharp and planar and its location varies between 5 and 12 cm above the base of the exposure.		
	Base of section at UTM coordinates: 289,478 m E, 3,668,080 m N (NAD83, zone 13). Section above is ubiquitously weakly to moderately consolidated and weakly cemented. This location corresponds to the exposure exhibiting MJ-1 and MJ-2.		
	No exposure	-100	-100
	Rincon Valley Formation		
	Silt and clay— Light reddish yellow to light red (2.5YR 6/4-6) silt and clay. Place upper contact at the UTM coord (NAD83): 289,485 m E; 3,668,074 m N). Unit described at the following two locales (UTM coord, NAD83): 289,499 m E, 3,668,078 m N; 289,493 m E, 3,668,075 m N.		

References

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