GEOLOGIC MAP OF THE

SALADONE TANK 7.5-MINUTE QUADRANGLE,

SIERRA COUNTY, NEW MEXICO

By
Andrew P. Jochems and Daniel J. Koning

May 2016
[Revised January 2017]

New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 259

Scale 1:24,000

This work was supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program (STATEMAP) under USGS Cooperative Agreement G15AC00243 and the New Mexico Bureau of Geology and Mineral Resources.

New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico, 87801-4796

CONTENTS

Note on Private-Land Access in the Saladone Tank Quadrangle

Unlike many 7.5-minute quadrangles in the Palomas basin that contain significant acreages of public land (Bureau of Land Management or State of New Mexico), nearly 75% of land on the Saladone Tank quadrangle is privately owned. We were granted permission to access only a small subset of this land, allowing for field checks of the northern and southeastern parts of the quadrangle. Completion of this geologic map relied heavily on interpretations of aerial photography coupled with projections of units from previous mapping of surrounding quadrangles. We ask that all users of this map obtain permission from local owners before entering their lands.

ABSTRACT

The Saladone Tank 7.5-minute quadrangle features diverse geology, from Paleozoic rocks exposed on either side of a Laramide fault to Eocene-Oligocene volcanic strata to basin-fill that potentially spans much of the temporal evolution of the southern Rio Grande rift. The Chavez Canyon fault was active before ~44 Ma, forming a small intra-uplift block within the northwest-trending Rio Grande uplift. Volcanism from the middle Eocene to late Oligocene records the transition from contractional to extensional tectonics, and lower to upper Santa Fe Group basin-fill records deposition in the Rio Grande rift. Basalts that are likely Pliocene in age constrain the lower boundary of sediments of the Palomas Formation. Palomas Formation deposits reflect continued deposition in the Palomas basin as it attained its modern configuration throughout the Pliocene and Pleistocene. The Rio Grande and its tributaries began to episodically incise after ~0.8 Ma, producing the stepped sequences of terrace and valley-floor deposits observed today.

INTRODUCTION

This report accompanies the *Geologic Map of the Saladone Tank 7.5-Minute Quadrangle, Sierra County, New Mexico* (NMBGMR OF-GM 259). Its purpose is to discuss the geologic setting and history of this area, identify and explain significant stratigraphic and structural relationships, and correlate select map units to regionally mappable units.

The Saladone Tank quadrangle is located in Sierra County in the west-central part of the Palomas basin. Its geographic center is approximately 20 km west-southwest of the city of Truth or Consequences (Fig. 1). The physiography of the map area is diverse with three large drainages crossing the quadrangle. These include Palomas Creek in the northeast and Seco and Las Animas Creeks in the south; the latter two streams parallel one another throughout their Palomas basin reaches. Total local relief is up to 475 m, principally in the Salado Mountains in the northwest. The central and southeastern parts of the quadrangle are dominated by the gently sloping Cuchillo surface. The highest location in the quadrangle, derived from a 10 m digital elevation model (DEM), is 1854 m above sea level (asl) in the Salado Mountains in section 7, T14S, R6W. The lowest point is 1381 m asl where Palomas Creek exits the quadrangle in section 5, T14S, R5W.

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 highs are 55-63° F and average lows are 27-31° F. Average yearly precipitation is 25.5 cm, of which 8.4 cm 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 1951-2012 (Western Regional Climate Center, 2015).

Early geologic mapping and reconnaissance work in the Palomas basin was done by Gordon and Graton (1907), Gordon (1910), and Harley (1934). However, little work has been completed on the Saladone Tank quadrangle. Recent years have seen 1:24,000-scale geologic maps prepared for several of the surrounding 7.5-minute quadrangles: Skute Stone Arroyo to the south (Koning et al., 2015), Williamsburg to the east (Jochems and Koning, 2015a), and Williamsburg NW to the north (Jochems, 2015). In addition, 1:24,000-scale mapping completed by Mayer (1987) covers the northwest corner of the Saladone Tank quadrangle. The geology of the quadrangle is also shown on the 1:100,000-scale map of Harrison and others (1993).

Numerous studies by Greg Mack and Bill Seager (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;

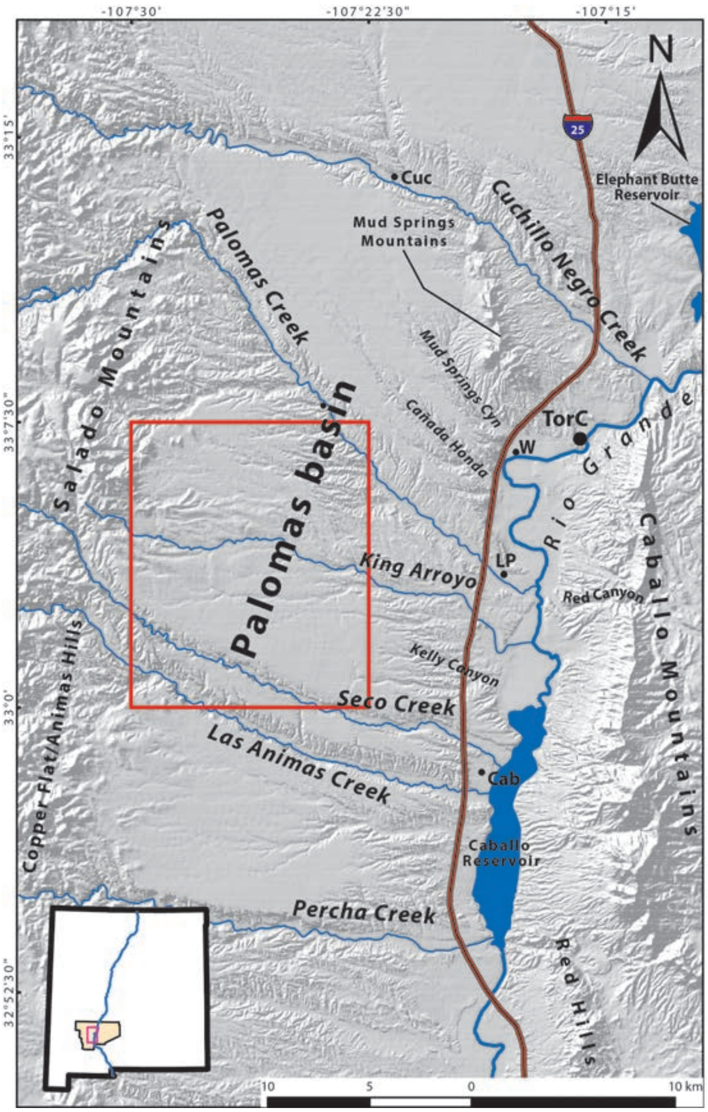

Figure 1. Shaded-relief map showing major physiographic features of the Palomas basin and surrounding areas. The basin is bordered on the east by the Caballo Mountains and on the west by the Animas-Salado uplifts and Sierra Cuchillo (not shown). The Saladone Tank quadrangle is outlined in red. Inset map shows location in Sierra County, New Mexico; blue line is the Rio Grande. Abbreviations for local communities: Cab = Caballo, Cuc = Cuchillo, LP = Las Palomas, TorC = Truth or Consequences, W = Williamsburg.

Mack et al., 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; Mack and Leeder, 1999) and soils and paleoclimate (Mack and James, 1992; Mack et al., 1994a, 2000). Many of these works are referenced in the discussion below on the Palomas Formation.

This report includes a summary of the geologic setting before describing the methods used to complete the geologic map of the quadrangle. Mapped units and their depositional settings are then described by age, oldest to youngest, after which a synopsis of the structural geology of the area is given. Detailed unit descriptions are provided in Appendix A.

GEOLOGIC SETTING

The Saladone Tank 7.5-minute quadrangle is located in the southern Rio Grande rift, a series of *en echelon* basins stretching from northern Colorado to northern Mexico (Chapin and Cather, 1994). The quadrangle includes the west-central part of the Palomas basin, an east-tilted half-graben filled with Miocene through Pleistocene clastic sediment (Figs. 1, 2). The western border (i.e. hanging wall) of the Palomas basin is defined by the Animas Hills and Salado Mountains (Fig. 1), east-dipping fault-block uplifts composed primarily of Paleozoic sedimentary and Eocene-Oligocene volcanic bedrock. The Salado Mountains intersect the northwest corner of the Saladone Tank quadrangle.

Precambrian history is poorly represented in the uplifts bounding the western Palomas basin, and pre-Cenozoic rocks are largely confined to the skyline of the Salado Mountains west of the quadrangle. However, a west-northwest trending Laramide (latest Cretaceous to Eocene) fault interpreted by Lamarre (1974), Mayer (1987), and Seager and Mayer (1988) enters the northwest corner of the quadrangle. This fault, subsequently intruded by an andesite dike, defines the margin of a small intra-uplift block in the northwest-trending Rio Grande uplift. The tectonic history of the Rio Grande uplift is recorded by conglomerate of the Love Ranch Formation (Seager et al., 1986; Seager and Mayer, 1988).

Volcanic rocks that erupted from the Mogollon-Datil volcanic field blanketed the landscape of southwestern New Mexico from the late Eocene through the early Miocene (Chapin et al., 2004). In the Animas Hills and Salado Mountains, these rocks include middle Eocene volcaniclastic units, late Eocene ignimbrites erupted from the nearby Emory caldera, and younger andesitic to rhyolitic lavas likely Oligocene in age (Seager et al., 1984; McIntosh et al., 1991). In addition, thin flows of Pliocene basalt stretch into the Palomas basin from along its western margin, including mesa-forming flows in the central and southern parts of the Saladone Tank quadrangle (Fig. 2).

Crustal extension forming the southern Rio Grande rift began as early as ~35 Ma (Mack et al., 1994b; Mack, 2004a). Basin-fill throughout the rift is characterized

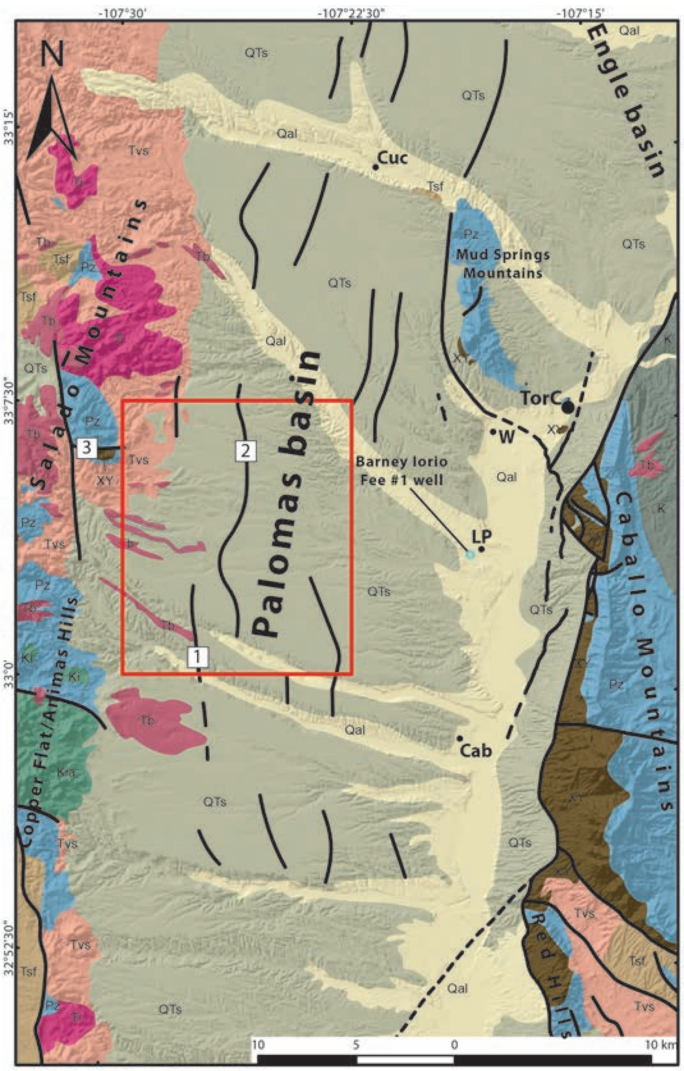

Figure 2. Simplified geologic map of the Palomas basin and vicinity (New Mexico Bureau of Geology and Mineral Resources, 2003). The Saladone Tank quadrangle is outlined in red. Numbers correspond to faults discussed in text: 1 = Saladone Tank fault, 2 = Palomas Creek fault, 3 = Chavez Canyon fault. Unit designations are as follows: Qal = Quaternary alluvium; QTs = Quaternary-Tertiary basin-fill; Tb = Pliocene basalt; Tsf = Santa Fe Group predating the Palomas Formation; Tvs = Eocene-Oligocene volcanic and volcaniclastic, undivided; Ti = Tertiary intrusive; K = Cretaceous sedimentary, undivided; Ki = Cretaceous intrusive; Kia = Cretaceous intrusive/andesite, undivided; Pz = Paleozoic sedimentary, undivided; and XY = Paleo- to Mesoproterozoic, undivided. Abbreviations for local communities as in Figure 1.

by thick accumulations of clastic sediment with minor interbedded volcanic rocks collectively known as the Santa Fe Group (Spiegel and Baldwin, 1963; Kelley, 1977; Hawley, 1978; Chapin and Cather, 1994). We correlate Santa Fe Group deposits predating the Palomas Formation in the Saladone Tank quadrangle to the upper Miocene Rincon Valley Formation of Seager and others (1971) based on lithology and stratigraphic position.

The modern configuration of the Palomas basin began to develop during the latest Miocene and Pliocene (Mack, 2004a), resulting in relatively thick sequences of basin-fill termed the Palomas Formation. In the Saladone Tank quadrangle, the Palomas Formation consists of piedmont deposits containing gravels, sand, silt, and clay deposited on coalesced fan complexes emanating from the eastern Black Range and incipient Animas-Salado uplifts. Palomas Formation beds are capped in many places by a gently inclined (≤1°) plain known as the Cuchillo surface that dates to ~0.8 Ma (Mack et al., 1993, 1998; Leeder et al., 1996; Mack and Leeder, 1999). The Rio Grande and its tributaries began incising into the Palomas Formation after ~0.8 Ma, alternating with periods of backfilling that resulted in a series of inset terrace deposits (Gile et al., 1981; Mack et al., 2006). These morphostratigraphic units are readily identified along Palomas, Seco, and Las Animas Creeks as well as King Arroyo.

METHODS

Geologic mapping of the Saladone Tank quadrangle consisted of traditional field techniques (Compton, 1985) coupled with newer digital approaches. Stereogrammetry software (Stereo Analyst for ArcGIS 10.1, an ERDAS extension, version 11.0.6) permitted accurate placement of geologic contacts using aerial photography obtained from the National Agricultural Imagery Program (NAIP); planimetric and vertical accuracy of this dataset is approximately 5 m (USDA, 2008). Contacts plotted using stereogrammetry were then field-checked where possible (see note on private lands in quadrangle).

Descriptions of individual units were made in the field utilizing both visual and quantitative estimates based on outcrop and hand lens inspection. For clastic sediments, grain sizes follow the Udden-Wentworth scale and the term "clast(s)" refers to the grain size fraction greater than 2 mm in diameter (Udden, 1914; Wentworth, 1922). Descriptions of bedding thickness follow Ingram (1954). Colors of sediment are based on visual comparison of dry samples to Munsell soil color charts (Munsell Color, 2009).

For volcaniclastic, volcanic, and intrusive units, grain or phenocryst size was described following the conventions of Wentworth (1922), Fisher (1961), and White and Houghton (2006). Color was estimated visually on both fresh and weathered surfaces. Other textural terms were assigned according to definitions in Winter (2010; p. 49-52). $^{40}Ar/^{39}Ar$ ages cited for volcanic or intrusive units dated prior to 2008 are scaled upward by 1.3% to account for a revised sanidine monitor age of 28.201 Ma for the Fish Canyon tuff advocated by Kuiper and others (2008).

Surface characteristics and relative landscape position were used in mapping middle Pleistocene to Holocene units. Surface processes dependent on age (e.g., desert pavement development, clast varnish, soil development, and preservation of original bar-and-swale topography) were used to differentiate stream terrace, alluvial fan, and valley-floor deposits. Soil horizon designations and descriptive terms follow those of Birkeland and others (1991), Birkeland (1999), and Soil Survey Staff (1999). Stages of pedogenic calcium carbonate morphology follow those of Gile and others (1966) and Birkeland (1999).

STRATIGRAPHY

PALEOZOIC ROCKS

Lower to upper Paleozoic rocks are sparsely exposed on the Saladone Tank quadrangle in sections 6 and 7, T14S, R6W. The oldest exposed units, the Cambro-Ordovician Bliss Formation (€Ob) and the lower Ordovician El Paso Formation (Oep), consist of arkosic conglomerate/sandstone and cherty limestone, respectively (Kottlowski et al., 1956; Mayer, 1987; Mack, 2004b). These rocks were deposited on a stable, epicratonal shelf that was subjected to periodic inundation by shallow, tropical seas (Mack, 2004b). The Bliss Formation is hematitic and marked by its dark color, and has a gradational upper contact with the El Paso Formation. These rocks are located in the hanging wall of the Chavez Canyon fault and are no more than 55 m thick in tandem.

To the north, several exposures of Pennsylvanian rocks are found in the downthrown block of the Chavez Canyon fault. These rocks include shale, limestone, siltstone, and conglomerate of the Red House and Bar-B Formations (IPr and IPb). These units are Morrowan-Atokan and Desmoinesian-Missourian in age, respectively, and reflect early uplift and erosion associated with the ancestral Rocky Mountain orogeny and perhaps glacio-eustatic cyclicity (Soreghan, 1994; Kues and Giles, 2004). Notably, the intervening Gray Mesa Formation (Desmoinesian) is not exposed at the surface due to ~200 m of apparent stratigraphic separation along a north-down normal fault buried by an erosional veneer of Love Ranch Formation sediments (Mayer, 1987). Map data and data from Mayer (1987) indicate that the Red House and Bar-B Formations are approximately 30-80 and 55 m thick in the Saladone Tank quadrangle, respectively.

TERTIARY VOLCANIC AND INTRUSIVE ROCKS

Eocene to Oligocene volcaniclastic and volcanic rocks lie with sharp unconformity on Paleozoic rocks in the Saladone Tank quadrangle. These units record the transition from arc-style to slab roll-back-related volcanism in the Mogollon-Datil volcanic field, including large ignimbrite eruptions and later calc-alkalic volcanism during Rio Grande rift extension (Seager et al., 1984; Chapin et al., 2004).

Rubio Peak Formation

The oldest post-Laramide unit exposed in the Saladone Tank quadrangle is the Rubio Peak Formation (Trp). Although mapped by previous workers as the Palm Park Formation (Lamarre, 1974; Mayer, 1987), the unit is designated the Rubio Peak Formation here because the clasts it contains are compositionally distinct from those in the Palm Park at its type locality in the southern Caballo Mountains, which are primarily andesite-latite (Seager et al., 1971; Seager et al., 1975; Clemons, 1979). In the map area, clasts range in composition from andesite and diorite to rhyolitic tuff. The Rubio Peak Formation in the map area consists primarily of poorly stratified laharic breccias with individual clasts up to 0.6 m in diameter (Fig. 3). Interbedded andesite flows may be present as well (Jochems, 2015), but were not observed in the map area due to restricted access. Ages determined for both lava flows and clasts found in breccia of the Rubio Peak Formation range from 46.3 to 36.7 Ma (Clemons, 1979; Loring and Loring, 1980; McMillan, 2004).

The Rubio Peak Formation and overlying strata are intruded by diorite porphyry (Tad) related to the Garcia Peaks stock to the north. The porphyry is also in fault contact with the Rubio Peak Formation along the border of sections 4 and 5, T14S, R6W. This plagioclase- to hornblende-phyric diorite was dated at 40.35 ± 0.05 Ma by $^{40}Ar/^{39}Ar$ in the Williamsburg NW quadrangle to the north (Jochems, 2015). It is equivalent to units Tqd and Td of Mayer (1987).

Figure 3. Outcrop of laharic breccia of Rubio Peak Formation (Trp). In places, unit contains clasts of andesite or rhyolite up to 0.6 m in diameter. Walking stick for scale (white oval) is 1.5 m tall. Section 5, T14S, R6W.

Eocene ignimbrites

Following deposition of the Rubio Peak Formation and intrusion of the diorite porphyry, local- to regional-scale ignimbrites were erupted from the Mogollon-Datil volcanic field (Chapin et al., 2004). The tuff of Chavez Canyon (Tcc) is the oldest pyroclastic unit found in the Saladone Tank quadrangle, where it fills moderate (10s of m) paleotopography on Rubio Peak or lower Paleozoic strata. It contains up to 6% fine biotite phenocrysts that often exhibit a coppery luster as well as minor to common (10-35%) lithic and pumice lapilli and bombs. The tuff features both unwelded (Tccb) and welded (Tccw) varieties; the latter forms steep cliffs and ledges and is typified by flattening ratios of 1:8 to 1:20 (width:length) in stretched lapilli and vesicles (Fig. 4). A sample of Tccw returned an $^{40}Ar/^{39}Ar$ age on biotite phenocrysts of 37.33 ± 0.06 Ma (L. Peters and W. McIntosh, pers. comm., 2016). Although similar in stratigraphic position to the Sugarlump tuff, this new age implies that the tuff of Chavez Canyon is older by ~1.7 myr. The thickness of the tuff in the map area (up to 204 m) as well as the presence of small bombs of pumice and andesite imply a proximal source.

A local, thin (≤24 m) rhyolitic ash-flow tuff lies with disconformity on the tuff of Chavez Canyon in section 18, T14S, R6W (Fig. 5). This unit is non- to somewhat welded and contains up to 14% phenocrysts of biotite, sanidine, quartz, and hornblende. It is distinguished from the tuff of Chavez Canyon by a paucity of lithic lapilli. It also lacks plagioclase phenocrysts that are observed in the overlying Kneeling Nun tuff. This unit is informally named the tuff of King Arroyo (Tka) here and is equivalent to unit Txl1 of Mayer (1987). McIntosh (1989) suggested a correlation with Bell Top tuff 4 / tuff of Rocque Ramos Canyon; these units have a mean $^{40}Ar/^{39}Ar$ age of 35.41 ± 0.08 Ma and may have erupted from the Emory caldera (Clemons, 1976; Harrison, 1990; McIntosh et al., 1991; Chapin et al., 2004).

The Kneeling Nun Tuff (Tkn) disconformably overlies the Chavez Canyon or King Arroyo tuffs and is characterized by high phenocryst content (30-42% phenocrysts of quartz, biotite, sanidine, and plagioclase). The source of the Kneeling Nun tuff was the Emory caldera to the west and southwest, and its total eruptive volume is thought to have exceeded 900 km^3 (McIntosh et al., 1991). The Kneeling Nun tuff was assigned a mean $^{40}Ar/^{39}Ar$ age of 35.34 ± 10 Ma by McIntosh and others (1991).

Figure 4. Stretched lapilli and pumice fiamme in densely welded Chavez Canyon tuff (Tccw). Pen for scale.

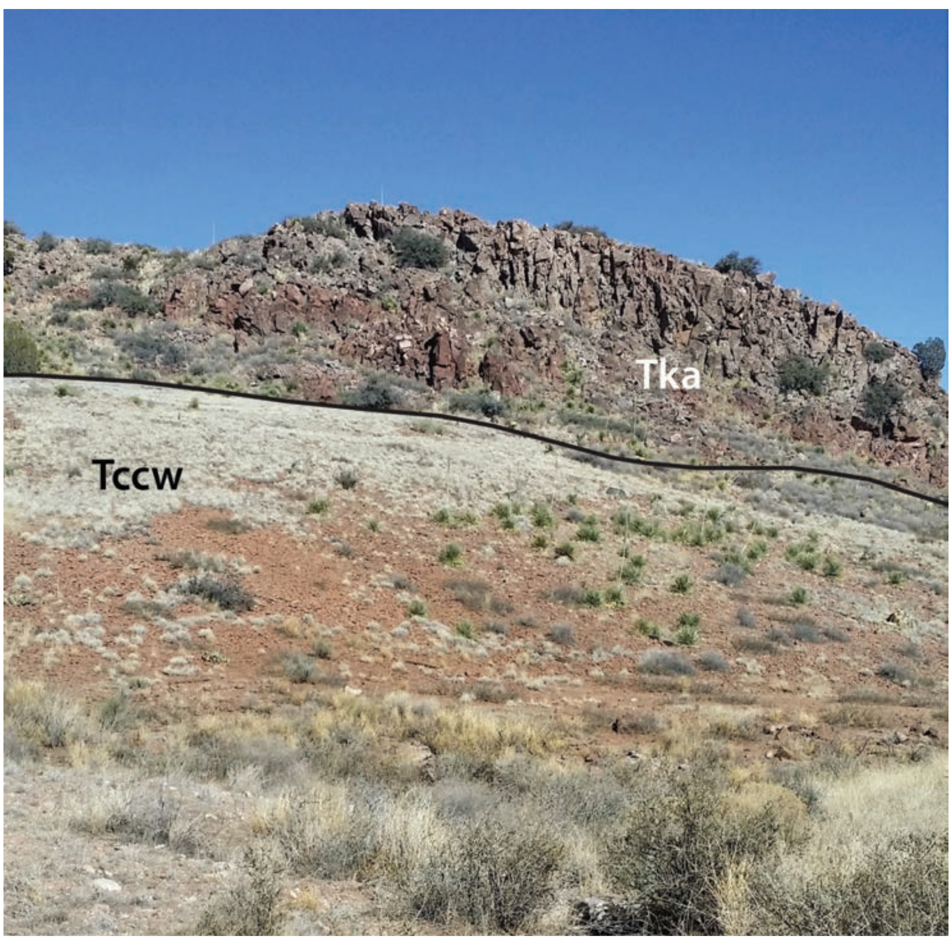

Figure 5. Sharp, disconformable contact between tuff of King Arroyo (Tka) and welded tuff of Chavez Canyon (Tccw). Section 18, T14S, R6W.

Oligocene lavas and Pliocene basalt

Approximately 7 myr of time is missing between the Kneeling Nun tuff and overlying flows of basaltic andesite (Tba) in the Saladone Tank quadrangle. Basaltic andesite exposures are often dark colored and foliated (Fig. 6), and magnification of hand samples reveals sparse to common phenocrysts of plagioclase, pyroxene, and biotite with rare quartz xenocrysts. Such flows are widespread around the Palomas basin and throughout southern New Mexico; correlative units include the Uvas basaltic andesite of Kottlowski (1953), Pollack quartz latite of Jicha (1954), Bear Springs basalt of Elston (1957), and unit T4ba of Seager and others (1982). Radiometric (K/Ar) ages from these units range between 28 and 26 Ma (Clemons, 1979; Seager et al., 1984). Chapin and others (2004) suggest that this widespread unit belongs to the southern Cordilleran basaltic andesite suite of Cameron and others (1989), signifying a transition from contractional deformation to crustal extension associated with the early Rio Grande rift.

Basaltic andesite is overlain by flows of rhyolite (Tr) in sections 8 and 17, T14S, R6W. These flows contain up to ~15% phenocrysts of quartz and sanidine with rare pyroxene. They could be correlative to thin rhyolite bodies interbedded with basaltic andesite in the Hillsboro 7.5-minute quadrangle to the southwest (Jochems et al., 2014). These flows have not been radiometrically dated but likely represent the last pulse of volcanism before the latest Miocene-early Pliocene basaltic extrusions in the area.

Conspicuous but thin (≤5 m) flows of basalt form mesas extending well into the central and southern parts of the quadrangle from the west. These flows contain sparse to occasional phenocrysts of olivine and plagioclase, and exhibit textures common in subaerial, low viscosity lavas such as vesicles concentrated near flow tops (Compton, 1985). Samples collected from basalt flows in surrounding quadrangles have yielded $^{40}Ar/^{39}Ar$ ages between 5.5 and 4.4 Ma (Jochems et al., 2014; Jochems, 2015; Koning et al., 2015).

Figure 6. Strongly foliated basaltic andesite (Tba) dipping toward the southwest. Hammer for scale (white circle) is ~25 cm long. Section 8, T14S, R6W.

QUATERNARY-TERTIARY BASIN-FILL

Basin-fill predating the Palomas Formation

The oldest basin-fill associated with Rio Grande rift extension in the Saladone Tank quadrangle consists of lower Santa Fe Group deposits (Tsl) identified using aerial photography along Las Animas Creek. These beds are typically well-cemented sandstone and conglomerate on the Skute Stone Arroyo quadrangle to the south (Koning et al., 2015). Above them lie light brown to pink (7.5YR 6-7/3) beds of granule to pebble conglomerate of the upper Santa Fe Group predating the Palomas Formation (Tsu). This unit is moderately well exposed in the northwest part of the quadrangle (sections 9 and 17, T14S, R6W), where it includes subordinate beds of reddish clay (Fig. 7). The conglomerates, which lack basalt clasts, represent debris flow facies with lesser proportions of fluvial deposits. Mud beds could represent either overbank facies or playa deposits, although evaporites are not observed. We tentatively correlate these beds to the upper Miocene Rincon Valley Formation of Seager and others (1971) based on their similar lithology and stratigraphic position. Pre-Palomas Formation sediment thickens greatly toward the east from 0 m where Tsu onlaps volcanic rocks with angular unconformity in section 17, T14S, R6W, to a minimum of 640 m in the Barney Iorio Fee #1 well in the central Williamsburg quadrangle (Jochems and Koning, 2015a).

Piedmont facies of the Palomas Formation

Basin-fill stratigraphy of the Saladone Tank quadrangle is dominated by Plio-Pleistocene sediment of the Palomas Formation, the uppermost unit of the Santa Fe Group in the Palomas basin (Lozinsky and Hawley, 1986a,b). The term "Palomas" was first applied to outcrops of upper Santa Fe Group basin-fill by Gordon and Graton (1907), Gordon (1910), and Harley (1934). Lozinsky and Hawley (1986a) formally defined the Palomas Formation. Detailed descriptions of the unit are presented in Lozinsky (1986), Lozinsky and Hawley (1986a,b),

Figure 7. Red mud beds in the upper Santa Fe Group predating the Palomas Formation (Tsu). This unit also features common beds of tan granule and pebble conglomerate. Note 1.5 m tall walking stick for scale (white oval). Section 17, T14S, R6W.

Jochems and Koning (2015a), and Koning and others (2015). Fossil data (summarized by Morgan and Lucas, 2012), radiometric ages (Bachman and Mehnert, 1978; Seager et al., 1984; Jochems, 2015; Koning et al., 2016), and magnetostratigraphic data (Repenning and May, 1986; Mack et al., 1993, 1998; Leeder et al., 1996) indicate an age range of ~5.5-0.8 Ma for the Palomas Formation.

In the Saladone Tank quadrangle, the Palomas Formation consists entirely of piedmont facies derived from hanging wall uplifts along the western margin of the Palomas basin (Figs. 1, 2). The base of the lower piedmont facies of the Palomas Formation (QTpl) is vertically gradational with Tsu over several meters in the northwest part of the quadrangle (Fig. 8), but the contact could be a sharp disconformity elsewhere. The lower piedmont facies are light brownish gray (10YR 6/2) to light gray (10YR 7/1-2) granule-pebble conglomerates with silica or calcite cementation and little to no preservation of paleosols. Planar cross-stratification and imbrication indicate that this unit is mostly fluvial in origin, at least locally. Lower piedmont facies are frequently interbedded with basalt (Tb) throughout the western part of the quadrangle; thus, this unit may be latest Miocene to early Pliocene (~5.5-4.5 Ma) in age if these flows are correlative to dated basalts in surrounding quadrangles (Jochems, 2015; Koning et al., 2015). The lower piedmont facies thickens from 0 to over 60 m toward the east and includes a lower transitional facies identified by Jochems and Koning (2015a) in the Barney Iorio Fee #1 well in the Williamsburg quadrangle.

The middle piedmont facies (QTpm) is found in the northeast part of the quadrangle and is characterized by pinkish (7.5YR), fine-grained sand and sandy silt with subordinate channel-fills and reddish (5YR) mud. Internally massive beds containing scattered coarse sand grains and pebbles are interpreted as hyperconcentrated flow deposits (Mack and Leeder, 1999; Mack et al., 2002). Elsewhere, well sorted, fine-grained beds likely represent eolian deposits or overbank sediment where horizontal-planar lamination is observed. In the Williamsburg quadrangle to the east, fossils collected by previous workers from correlative beds include *Paramylodon*, a small ground sloth, and the horse *Nannippus* (Tedford, 1981; Morgan and Lucas, 2012). The co-occurrence of these species suggests a late Blancan (~3.0-2.6 Ma) North American Land Mammal age for the upper part of this unit (Morgan et al., 2008; Morgan and Lucas, 2012). The unit is up to 53 m thick along the eastern border of the quadrangle.

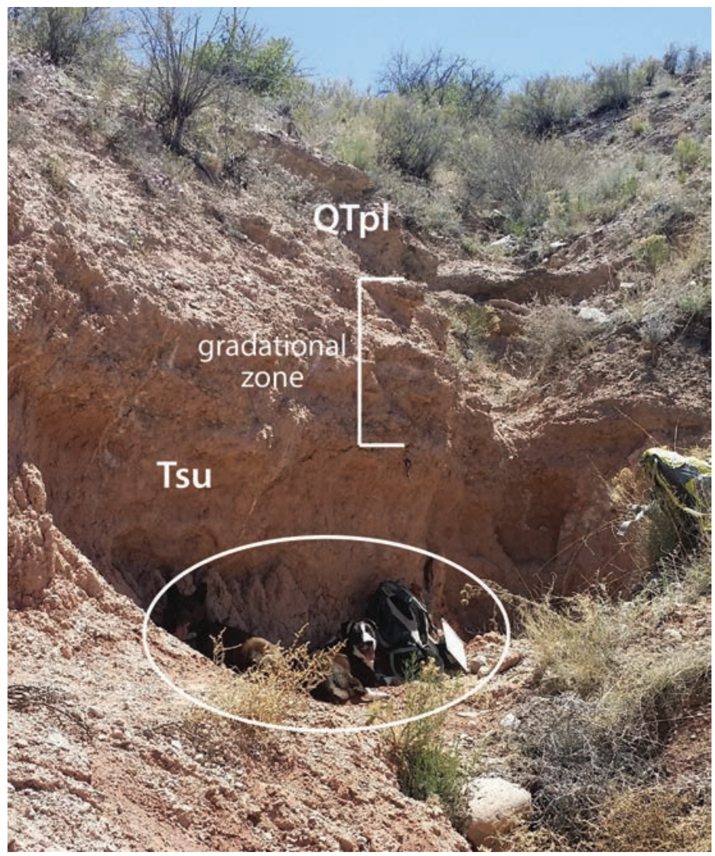

Figure 8. Vertically gradational contact between reddish Tsu deposits below and gray pebble conglomerate of the lower piedmont facies of the Palomas Formation (QTpl) above. Note dogs and backpacks for scale (white oval). Section 17, T14S, R6W.

The middle piedmont facies has a laterally gradational, interfingering contact with a transitional unit (QTpt) in the northeastern corner of the quadrangle (Fig. 9). This relatively thin (6-25 m) unit consists of light brown (7.5YR 6/3), well cemented, sandy pebble-cobble conglomerate

Figure 9. Interfingering contact between middle (QTpm) and transitional (QTpt) piedmont facies of the Palomas Formation. Light colored beds are silts and fine sands of the middle piedmont facies, whereas bedded gravels belong to the transitional unit. Section 8, T14S, R5W.

and pebbly sandstone (Fig. 10). The unit generally lacks paleosols. Common trough cross-stratification and channel forms up to 7 m across indicate that this unit was fluvially deposited.

The upper western piedmont facies (QTpu) consists of clay-silt, sandy silt, fine to coarse sand, and pebbly to cobbly channel-fills (Fig. 11A). These deposits exhibit a variety of colors but are most often yellowish red (5YR 4-5/6) to strong or light brown (7.5YR 4-5/6; 6/4). Buried Bk horizons with stage II carbonate development are common (Fig. 11B). This unit has a mostly conformable contact with the underlying middle or transitional piedmont facies, although the contact could locally be disconformable along buried channels. The unit is distinguished by its redder colors, common channel-fills and muddy beds, a greater proportion of basalt clasts (≤5%), and free-grain argillans found in nearly all gravels. The diverse lithofacies observed in this unit likely represent both channel and extra-channel sediments deposited along avulsing drainages in the middle reaches of large hanging wall alluvial fans. The upper piedmont facies features more abundant and thicker (up to 0.8 m) calcic horizons (stage II-III) near its top, and has a laterally gradational with the upper coarse piedmont facies in the northern part of the quadrangle. In the Williamsburg quadrangle, the lower contact of correlative piedmont beds lies immediately above the Kelly Canyon Local Fauna site, estimated to be ~2.6-2.0 Ma in age (Morgan et al., 2011; Morgan and Lucas, 2012). Magnetostratigraphic and additional paleontologic data from the Las Palomas area suggests that the upper piedmont facies spans the interval of ~2.5-1.8 Ma (Mack et al., 1993, 1998; Leeder et al., 1996; Seager and Mack, 2003; Jochems and Koning, 2015a). The unit is as much as 28 m thick along the eastern border of the Saladone Tank quadrangle.

The upper coarse piedmont facies of the Palomas Formation (QTpuc) dominates the southeastern corner of the quadrangle and is characterized by beds of reddish brown (5YR) to brownish (7.5YR) pebble-cobble-boulder

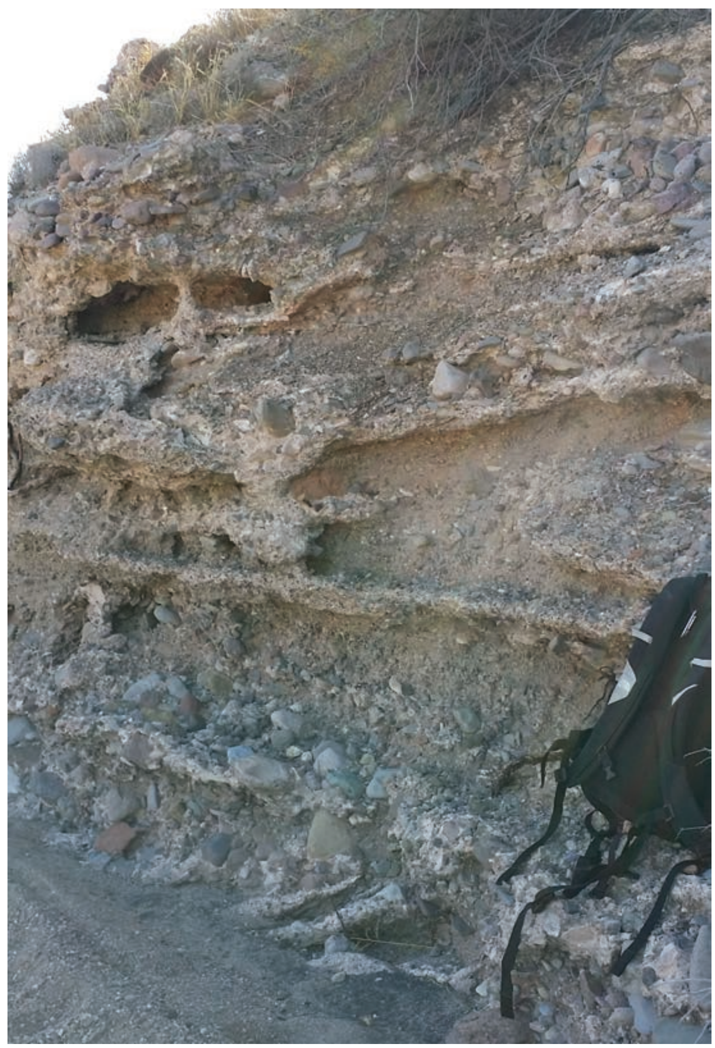

Figure 10. Well stratified gravels of the transitional piedmont facies of the Palomas Formation (QTpt). Individual beds range from pebbly to cobbly in texture. Note backpack for scale. Section 1, T14S, R6W.

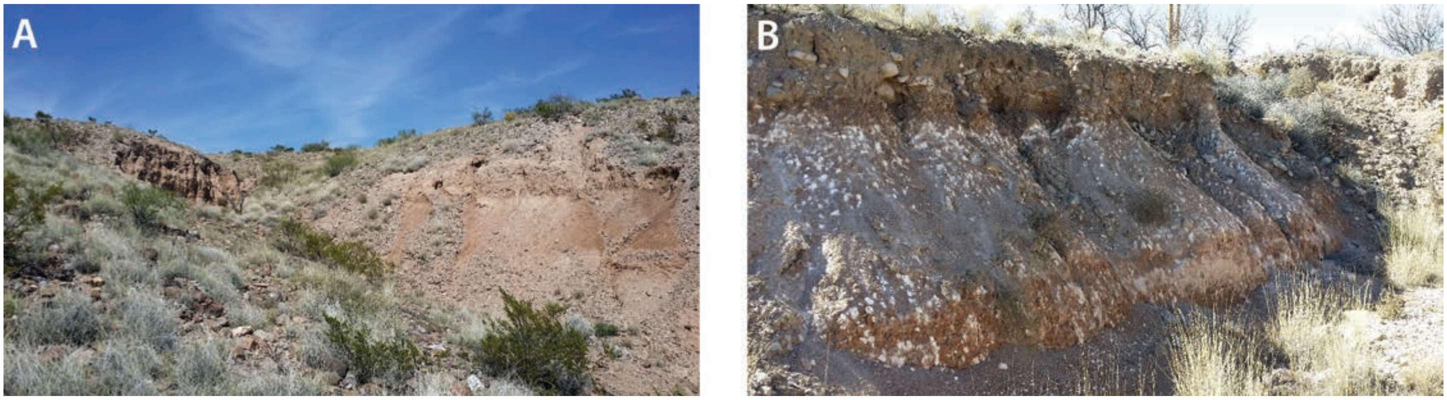

Figure 11. Upper piedmont facies of the Palomas Formation (QTpu). (A) Gravel, silt, and mud beds in the upper piedmont facies. Unit is mostly dominated by reddish (5YR) hues but beds may be lighter brown (7.5YR) as well. Section 12, T14S, R6W. (B) Stage II calcic horizon developed in reddish, muddy parent material of QTpu. Exposure is capped by thin pediment gravel (not mapped) overprinted by ~20 cm-thick A and ~30 cm-thick illuviated clay (Bt) horizons. Section 12, T14S, R6W.

Figure 12. Upper coarse piedmont facies of the Palomas Formation (QTpuc), southeast corner of quadrangle. Note clipboard (white circle) for scale.

gravel and pebbly sand (Fig. 12). Reddish hues are derived primarily from an abundance of clay flakes, bridges, and free-grain argillans (Fig. 13). The unit is typically strong brown (7.5YR 4-5/6) in the northwestern corner of the quadrangle. Gravel beds are clast- to matrix-supported, often well imbricated, and contain up to 10% clasts of jasperoid/chert, Paleozoic sedimentary lithologies, and basalt. Gravels may be clay-cemented and locally feature lateral accretion sets. Sandy beds may be horizontal-planar to cross-laminated. Like QTpu, the upper coarse unit is mostly fluvial in origin with significant proportions of debris flow deposits in places. Cambic-argillic and calcic (Bk to K) horizons are found throughout the unit. Together with QTpu (in places), QTpuc underlies the Cuchillo surface, marked by a petrocalcic horizon that is 1-2 m thick where not significantly eroded. This

Figure 13. Upper coarse piedmont facies of the Palomas Formation (QTpuc) with abundant interstitial clay. Pen for scale.

surface soil generally exhibits stage III to IV carbonate morphology (Seager and Mack, 2003; McCraw and Love, 2012), and is correlative to the Jornada I and La Mesa surfaces of the Camp Rice Formation in the Rincon and Mesilla basins to the south (Gile et al., 1981). The age of the youngest coarse upper piedmont is constrained by magnetostratigraphy to ~0.8 Ma (Mack et al., 1993, 1998; Leeder et al., 1996; Mack and Leeder, 1999). The upper coarse piedmont is at least 52 m thick where Seco Creek exits the southeastern corner of the quadrangle.

QUATERNARY HISTORY (POST-PALOMAS FORMATION)

Deposition of the Palomas Formation ceased ~0.8 Ma (Lozinsky and Hawley, 1986a,b; Mack et al., 1993, 1998; Leeder et al., 1996; Mack and Leeder, 1999), after which the Rio Grande and its tributaries began incising and eventually forming the modern network of arroyos and stream valleys. Valley-margin deposits are typified by inset stream terraces and, in places, alluvial fans graded to those deposits. Valley-floor deposits include low-lying terraces adjacent to modern stream courses.

Larger drainages such as Palomas, Las Animas, and Seco Creeks typically feature 2-6 inset surfaces along a given reach. The highest and oldest inset surfaces along Seco Creek include three elongate surfaces with little or no underlying gravels that can be distinguished from Palomas Formation beds. These surfaces are termed the upper, middle, and lower Seco Creek surfaces (Qsu, Qsm, and Qsl). Lying 47-64 m above modern grade, they probably represent the earliest middle Pleistocene incision of Seco Creek.

Terrace deposits along major drainages on the Saladone Tank quadrangle are distinguished from Palomas Formation gravels by their inset position as well as browner colors (e.g., 7.5YR 4-5/4; 10YR 4-5/3), greater proportions of basalt clasts (up to 20%), and varying degrees of desert pavement development, clast varnishing, and soil development. For example, older high terrace deposits (Qth) feature stage III+ calcic horizons whereas younger low terrace deposits (Qtl) have little or no soil development (Fig. 14). Although such surficial characteristics are useful criteria for correlating terraces along a given drainage, they may fail where terrace treads have been subject to erosion that has removed soils and obscured original desert pavement and clast varnishing. Where present, strong calcium carbonate accumulation (stage II or greater) is indicative of surfaces that have been stable on a timescale of 10^4 to 10^5 yr (Gile et al., 1966; Birkeland, 1999). Terrace treads (upper surface) range from as little as 2-9 m above modern grade (Qta1, Qtl) to as much as 110 m above modern grade (Qta5).

Figure 14. Lower terrace deposit (Qtl) along Cañon de las Canalejas in section 13, T14S, R6W. Thin, dark brownish gravel above strath (white line) on reddish upper piedmont facies of the Palomas Formation (QTpu) lacks significant soil development due to relatively young age (late Pleistocene) and erosion. Walking stick for scale (black rectangle) is 1.5 m tall. Note that deposit is not mapped at 1:24,000 scale due to limited spatial extent.

Broad piedmont surfaces are subtly inset into the upper coarse alluvium of the Palomas Formation in the northwest part of the quadrangle. These surfaces are underlain by Qpo gravels that are graded to Qtl terraces along King Arroyo and its tributaries. This piedmont alluvium is reddish brown to brown (5-7.5YR 4/4) and dominated by clasts of tuff of Chavez Canyon; it is readily identified from aerial photographs in sections 5, 19, and 20, T14S, R6W. These deposits probably resulted from enhanced hillslope erosion during the late Pleistocene. In places, the surfaces of these deposits are nearly concordant with the Cuchillo surface formed on uppermost deposits of the Palomas Formation, but are distinguished by a lack of calcic soils, strong reddish color, and relatively dense growth of creosote bush (*Larrea tridentata*).

Younger valley-floor deposits lie well below most terraces, flanking arroyos throughout the study area (Fig. 15). Like terraces, surface characteristics of these deposits may imply relative age, with illuviated clay and stage I calcic horizons observed in soils capping younger alluvium (Qay) and bar-and-swale topography better preserved in historical alluvial deposits that lack well-developed soils (Qah). Alluvial fan deposits (units Qfah, Qfay) emanating from side gullies and ravines commonly interfinger with or prograde over valley-floor deposits. Modern alluvium (Qam) in ephemeral drainages is marked by sandy pebble to cobble gravel forming pronounced bar-and-swale topography.

Radiocarbon ages acquired from Cañada Honda in the Williamsburg quadrangle and along Las Animas Creek in the Skute Stone Arroyo quadrangle provide temporal constraints for valley-floor deposits. Ages range from approximately 11000 to 2500 calibrated years before present (cal yr BP) for Qfay and Qay deposits, respectively, to as young as ~150 cal yr BP for Qah sediment deposited by Las Animas Creek (Jochems and Koning, 2015b).

Climatic drivers for middle to late Quaternary deposits

In general, middle to late Pleistocene deposits in the Saladone Tank quadrangle and throughout the Palomas basin formed during periods of climatic fluctuation related to glacial-interglacial cycles. One model proposes that terrace formation in the southern Rio Grande rift occurs in three stages: (1) the Rio Grande and the lower valleys of its tributaries incise during full glacial conditions; (2) aggradation occurs during the transition to interglacial intervals due to decreased water to sediment ratios; and (3) stability ensues for the remainder of the interglacial

Figure 15. Younger alluvium (Qay) along a tributary to Cañon de las Canalejas in section 11, T14S, R6W. Deposit is characterized by brown color, fine texture (silt-sand), and weak to moderate soil development, including Bw, Bt, or stage I calcic horizons. Note backpack for scale.

interval (Gile et al., 1981).

Holocene incision episodes inferred from radiocarbon ages of valley-floor deposits indicate that down-cutting of east-southeast-draining arroyos in the Palomas basin may have occurred during periods of enhanced summer monsoon, whereas Rio Grande incision may have been more sensitive to winter precipitation in its headwaters (Mack et al., 2011; Jochems and Koning, 2015b). Incision during summer monsoons may be enhanced by overall arid climates.

STRUCTURAL GEOLOGY

Major faults on the Saladone Tank quadrangle include a Laramide fault, pre-Pliocene normal faults, and a series of intrabasin faults crossing the central and eastern portions of the map area.

The west-northwest trending Chavez Canyon fault enters the quadrangle in section 7, T14S, R6W. This Laramide (latest Cretaceous to Eocene) fault was first mapped by Lamarre (1974) and Mayer (1987). The fault is intruded by an andesite dike that cuts the topography at a steep angle; thus, the fault is likely reverse with a steep southern dip (Seager and Mayer, 1988). Biotite separate collected from the dike returned a K/Ar age of 43.7 ± 1.7 Ma. The fault defines a small intra-uplift block in the northwest-trending Rio Grande uplift, the syn- to post-tectonic history of which is recorded by coarse conglomerate of the Love Ranch Formation containing cobbles and boulders of lower Paleozoic strata (Seager et al., 1986; Seager and Mayer, 1988). The Rubio Peak Formation rapidly thins until it pinches out toward the uplifted block of this fault, which exhibits nearly 400 m of stratigraphic separation (Mayer, 1987; Seager and Mayer, 1988).

A number of faults buried by the Palomas Formation and younger sediment are found in the northwest corner of the quadrangle. These high-angle (~70° to near vertical) structures commonly trend east-northeast, though at least one structure trends toward the southeast (Fig. 16). Additionally, a strong component of right-lateral slip (rake < 10°) is observed on one steeply dipping normal fault that cuts the Chavez Canyon tuff in section 7, T14S, R6W. Several north-south trending faults are found to the east (sections 8-9 and 16-17, T14S, R6W), where they cut upper Santa Fe Group deposits but are buried by lower piedmont facies of the Palomas Formation, constraining their activity to the late Miocene or earlier.

Figure 16. Shear planes (a and b) in oblique-slip fault truncating unwelded Chavez Canyon tuff (Tccb). Near-vertical planes trend northwest-southeast, nearly perpendicular to dominant northeast trends in faults cutting volcanic rocks. Slickenlines on shear surfaces define a minor component of right-lateral slip. Note 1.5 m tall walking stick above letter "a" for scale. View is to southeast. Section 7, T14S, R6W.

Outcrop patterns of volcanic rocks offset by one such fault in sections 8 and 17, T14S, R6W, indicate a possible component of left-lateral slip.

Numerous short (2-12 km), north-south trending normal faults cut the lower to upper piedmont facies of the Palomas Formation in the eastern half of the quadrangle (Fig. 17). These faults are commonly high-angle (55° to vertical) and seldom exhibit oblique components of slip. They include the Palomas Creek fault, Cuchillo Negro fault zone, and unnamed faults on the Cuchillo Plain of

Figure 17. Normal faults (arrows) in transitional piedmont facies of the Palomas Formation (QTpt). Shear planes in faults cutting the Palomas Formation often exhibit strong post-rupture carbonate development and rotated clasts. Note backpack in front of fault for scale (black circle). View is to north-northwest. Section 12, T14S, R6W.

Machette and others (1998). These faults form 2-10 m high scarps that generally face east in the northern part of the quadrangle and west in the southern part. Most of these faults are likely middle Pleistocene in age, though some may have ruptured as recently as ~250-100 ka based on the morphology of their scarps (Machette, 1987).

An additional fault delineated using aerial photography and unpublished subsurface data (J. Hawley, pers. comm., 2015) is the Saladone Tank fault in the south-central part of the quadrangle. This fault forms a conspicuous scarp between the upper coarse piedmont facies of the Palomas Formation and a basalt flow capping the interfluve between Seco and Las Animas Creeks. Although Machette (1987) shows this fault as having west-down motion, we note that it must have an east-down geometry because of the disappearance of the basalt flow in that direction. The absence of this flow and underlying Tsu deposits on the hanging wall of the fault indicates at least 63 m of apparent stratigraphic separation. Thus, the Saladone Tank fault may be partly responsible for increasing accommodation space for the thick (>50 m) sequence of upper Palomas Formation sediments in the southeastern part of the quadrangle.

KEY STRATIGRAPHIC AND STRUCTURAL RELATIONSHIPS

Restricted access to the southwestern part of the Saladone Tank quadrangle precludes interpretations about the history of early rift-fill exposed along Seco and Las Animas Creeks. However, some general observations may be offered regarding thickness and coarsening trends in the Palomas Formation and their implication for the local structure of the Palomas basin.

Palomas Formation thickness and coarsening trends

Initially thought to be 100-131 m thick (Lozinsky and Hawley, 1986a), our work suggests that the Palomas Formation thickens from 0 m where it onlaps the eastern Salado Mountains in the Saladone Tank quadrangle to over 350 m in the Williamsburg quadrangle to the east. This range is based on the measured thicknesses of piedmont units in Truth or Consequences city wells and the west Williamsburg stratigraphic section, as well as projections of exposures in the Saladone Tank quadrangle to the Barney Iorio Fee #1 well in the central Williamsburg quadrangle (Jochems and Koning, 2015a). The eastward thickening of piedmont facies derived from

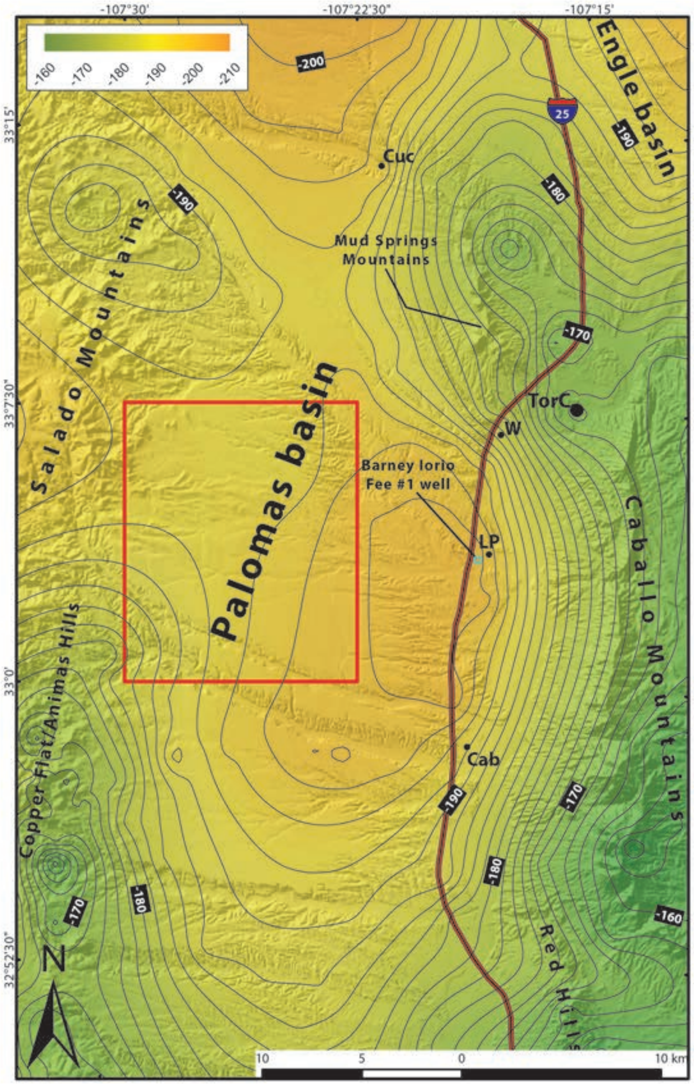

Figure 18. Complete Bouguer-anomaly gravity map of Palomas basin and surrounding uplifts. Saladone Tank quadrangle is outlined in red. Note that deepest part of the basin coincides with a low gravity anomaly located near Las Palomas (LP) and the Barney Iorio Fee #1 well (blue circle). Data from Kucks and others (2001). Reduction density = 2.67 gm/cc; sea level datum. Contour interval = 2 mGal. Abbreviations for local communities as in Figure 1.

the hanging wall of the Palomas basin is consistent with the overall thickening of the Santa Fe Group eastward toward the modern Rio Grande (Gilmer et al., 1986).

The Palomas Formation also exhibits an upward-coarsening trend from the QTpl-QTpm contact that is observed throughout the Palomas basin (Koning et al., 2015; Jochems, 2015). This pattern may be the result of tectonic tilting, the large size of hanging wall catchments, or paleoclimatic drivers in the surrounding mountain ranges. The latter may have promoted conditions favorable for high erosion rates in headwater areas, such as increased discharges capable of transmitting coarser detritus into the basin (Mack et al., 2012). Changes in such conditions with climatic shifts, such as glacial-interglacial transitions, have been well-documented (Bull, 1991), and have been invoked for similar coarsening trends observed in rift-fill packages elsewhere in New Mexico (Koning et al., 2002). Accommodation space created along Neogene normal faults may account for locally thick sequences of coarse basin-fill.

Geophysical interpretation of west-central Palomas basin structure

Gravity data indicates that the northern part of the Saladone Tank quadrangle overlies a structural "saddle" in the Palomas basin (Fig. 18; Kucks et al., 2001). This observation is apparently corroborated by the relatively thin (<30 m?) sequence of basin-fill in the area due east of the Salado Mountains, where upper Santa Fe Group gravels wedge out atop volcanic rocks. The dramatic thickening of basin-fill units toward the east coincides with decreasing Bouguer-anomaly gravity values toward the deepest part of the Palomas basin, located just west of the Rio Grande (Fig. 18; Gilmer et al., 1986). As noted above, Plio-Pleistocene slip along at least one fault (the Saladone Tank fault) may have helped create accommodation space for a thick sequence of basin-fill in the southeast part of the quadrangle.

ACKNOWLEDGMENTS

Mapping of the Saladone Tank quadrangle was funded by the STATEMAP program, which is jointly supported by the U.S. Geological Survey and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR). We thank Dr. J. Michael Timmons of NMBGMR for logistical support. We are grateful for land access provided by Las Palomas Land & Cattle Company (caretakers Mr. Jonathan Beaty and Mr. John Walker). Sincere thanks are due to Dr. John Hawley, NMBGMR emeritus, for generously sharing unpublished resources with us.

REFERENCES

Bachman, G.O., and Mehnert, H.H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283–292.

Birkeland, P.W., 1999, Soils and geomorphology: Oxford University Press, New York, 448 p.

Birkeland, P.W., Machette, M.N., and Haller, K.M., 1991, Soils as a tool for applied Quaternary geology: Utah Geological and Mineral Survey Miscellaneous Publication 91–3, 63 p.

Bull, W.B., 1991, Climatic Geomorphology: Oxford University Press, Oxford, 326 p.

Cameron, K.L., Nimz, G.J., Kuentz, D., Niemeyer, S., and Gunn, S., 1989, The southern cordilleran basaltic andesite suite, southern Chihuahua, Mexico: A link between Tertiary continental arc and flood basalt magmatism in North America: Journal of Geophysical Research, v. 94, p. 7817–7840.

Chapin, C.E., and Cather, S.M., 1994, Tectonic setting of the axial basins of the northern and central Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America Special Paper 29, p. 5–25.

Chapin, C.E., McIntosh, W.C., and Chamberlin, R.M., 2004, The late Eocene-Oligocene peak of Cenozoic volcanism in southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 271–293.

Clemons, R.E., 1976, Geology of the east half Corralitos Ranch quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 36, scale 1:24,000.

Clemons, R.E., 1979, Geology of Good Sight Mountains and Uvas Valley, southwest New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 169, 32 p.

Compton, R.R., 1985, Geology in the field: John Wiley & Sons, New York, 398 p.

Elston, W.E., 1957, Geology and mineral deposits of Dwyer quadrangle, Grant, Luna, and Sierra Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 38, 86 p.

Fisher, R.V., 1961, Proposed classification of volcaniclastic sediments and rocks: Geological Society of America Bulletin, v. 72, p. 1409–1414.

Gile, L.H., Peterson, F.F., and Grossman, R.B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347–360.

Gile, L.H., Hawley, J.W., and Grossman, R.B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—Guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.

Gilmer, A.L., Mauldin, R.A., and Keller, G.R., 1986, A gravity study of the Jornada del Muerto and Palomas basins, *in* Clemons, R.E., King, W.E., Mack, G.H., and Zidek, J., eds., Truth or Consequences region: New Mexico Geological Society, Guidebook 37, p. 131–134.

Gordon, C.H., 1910, Sierra and central Socorro Counties, *in* Lindgren, W., Graton, L.C., and Gordon, C.H., eds., The Ore Deposits of New Mexico: U.S. Geological Survey Professional Paper 68, p. 213–285.

Gordon, C.H., and Graton, L.C., 1907, Lower Paleozoic formations in New Mexico: Journal of Geology, v. 15, p. 91–92.

Harley, G.T., 1934, The geology and ore deposits of Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 10, 220 p.

Harrison, R.W., 1990, Cenozoic stratigraphy, structure, and epithermal mineralization of north-central Black Range, New Mexico, in the regional framework of south-central New Mexico [Unpublished PhD dissertation]: Socorro, New Mexico Institute of Mining and Technology, 386 p.

Harrison, R.W., Lozinsky, R.P., Eggleston, T.L., and McIntosh, W.C., 1993, Geologic map of the Truth or Consequences 30 x 60 minute quadrangle: New Mexico Bureau of Mines and Mineral Resources Open-File Report 390, scale 1:100,000.

Hawley, J.W., ed., 1978, Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, 241 p.

Ingram, R.L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geological Society of America Bulletin, v. 65, p. 937–938.

Jicha, H.L., Jr., 1954, Geology and mineral deposits of Lake Valley quadrangle, Grant, Luna, and Sierra Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 37, 93 p.

Jochems, A.P., 2015, Geologic map of the Williamsburg NW 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map 251, scale 1:24,000.

Jochems, A.P., and Koning, D.J., 2015a, Geologic map of the Williamsburg 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map 250, scale 1:24,000.

Jochems, A.P., and Koning, D.J., 2015b, Holocene stratigraphy and a preliminary geomorphic history for the Palomas basin, south-central New Mexico: New Mexico Geology, v. 37, no. 4, p. 77–88.

Jochems, A.P., Kelley, S.A., Seager, W.R., Cikoski, C.T., and Koning, D.J., 2014, Geologic map of the Hillsboro 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 242, scale 1:24,000.

Kelley, V.C., 1977, Geology of the Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 33, 60 p.

Koning, D.J., Connell, S.D., Pazzaglia, F.J., and McIntosh, W.C., 2002, Redefinition of the Ancha Formation and Pliocene-Pleistocene deposition in the Santa Fe embayment, north-central New Mexico: New Mexico Geology, v. 24, no. 3, p. 75–87.

Koning, D.J., Jochems, A.P., and Cikoski, C.T., 2015, Geologic map of the Skute Stone Arroyo 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 252, scale 1:24,000.

Koning, D.J., Jochems, A.P., Morgan, G.S., Lueth, V., and Peters, L., 2016, Stratigraphy, gravel provenance, and age of early Rio Grande deposits exposed 1-2 km northwest of downtown Truth or Consequences, New Mexico, *in* Frey, B.A., Karlstrom, K.E., Lucas, S.G., Williams, S., Zeigler, K., McLemore V., and Ulmer-Scholle, D.S., eds., Geology of the Belen Area: New Mexico Geological Society Guidebook 67, p. 459-478.

Kottlowski, F.E., 1953, Tertiary-Quaternary sediments of the Rio Grande valley in southern New Mexico, *in* Kottlowski, F.E., ed., Guidebook of southwestern New Mexico: New Mexico Geological Society Guidebook 4, p. 144–148.

Kottlowski, F.E., Flower, R.H., Thompson, R.L., and Foster, R.W., 1956, Stratigraphic studies of the San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 1, 132 p.

Kucks, R.P., Hill, P.L., and Heywood, C.E., 2001, New Mexico aeromagnetic and gravity maps and data: A web site for distribution of data: U.S. Geological Survey Open-File Report 01–0061.

Kues, B.S., and Giles, K.A., 2004, The late Paleozoic Ancestral Rocky Mountains system in New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 95–136.

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008, Synchronizing rock clocks of Earth history: Science, v. 320, p. 500–504.

Lamarre, A.L., 1974, Fluorite in jasperoid of the Salado Mountains, Sierra County, New Mexico: Significance to metallogeny of the western United States [Unpublished M.S. thesis]: London, Ontario, University of Western Ontario, 134 p.

Leeder, M.R., Mack, G.H., and Salyards, S.L., 1996, Axial-transverse fluvial interactions in half-graben—Plio-Pleistocene Palomas Basin, southern Rio Grande rift, New Mexico, USA: Basin Research, v. 12, p. 225–241.

Loring, A.K., and Loring, R.B., 1980, K/Ar age of middle Tertiary igneous rocks from southern New Mexico: Isochron/West, Bulletin of Isotopic Geochronology, no. 28, p. 17–19.

Lozinsky, R.P., 1986, Geology and late Cenozoic history of the Elephant Butte area, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 187, 39 p.

Lozinsky, R.P., and Hawley, J.W., 1986a, The Palomas Formation of south-central New Mexico—A formal definition: New Mexico Geology, v. 8, no. 4, p. 73–82.

Lozinsky, R.P., and Hawley, J.W., 1986b, Upper Cenozoic Palomas Formation of south-central New Mexico, *in* Clemons, R.E., King, W.E., Mack, G.H., and Zidek, J., eds., Truth or Consequences Region: New Mexico Geological Society Guidebook 37, p. 239–247.

Machette, M.N., 1987, Preliminary assessment of Quaternary faulting near Truth or Consequences, New Mexico: U.S. Geological Survey Open-File Report 87–652, 41 p.

Machette, M.N., Personius, S.F., Kelson, K.I., Haller, K.M., and Dart, R.L., 1998, Map and data for Quaternary faults and folds in New Mexico: U.S. Geological Survey Open-File Report 98–521, 443 p.

Mack, G.H., 2004a, Middle and late Cenozoic crustal extension, sedimentation, and volcanism in the southern Rio Grande rift, Basin and Range, and southern Transition Zone of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 389–406.

Mack, G.H., 2004b, The Cambro-Ordovician Bliss and lower Ordovician El Paso formations, southwestern New Mexico and west Texas, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 35–44.

Mack, G.H., and Seager, W.R., 1990, Tectonic control on facies distribution of the Camp Rice and Palomas Formations (Pliocene-Pleistocene) in the southern Rio Grande rift: Geological Society of America Bulletin, v. 102, no. 1, p. 45-53, doi: 10.1330/0016-7606(1990)102<0045: TCOFDO>2.3.CO; 2.

Mack, G.H., and James, W.C., 1992, Calcic paleosols of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift: Sedimentary Geology, v. 77, p. 89–109.

Mack, G.H., and Leeder, M.R., 1999, Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande Rift: Journal of Sedimentary Research, v. 69, no. 3, p. 635-652.

Mack, G.H., Salyards, S.L., and James, W.C., 1993, Magnetostratigraphy of the Plio-Pleistocene Camp Rice and Palomas Formations in the Rio Grande rift of southern New Mexico: American Journal of Science, v. 293, p. 49–77.

Mack, G.H., James, W.C., and Salyards, S.L., 1994a, Late Pliocene and early Pleistocene sedimentation as influenced by intrabasinal faulting, southern Rio Grande rift, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift: Structure, Stratigraphy, and Tectonic Setting: Geological Society of America Special Paper 291, p. 257–264.

Mack, G.H., Nightengale, A.L., Seager, W.R., and Clemons, R.E., 1994b, The Oligocene Goodsight-Cedar Hills half graben near Las Cruces and its implications to the evolution of the Mogollon-Datil volcanic field and to the southern Rio Grande rift, *in* Chamberlin, R.M., Kues, B.S., Cather, S.M., Barker, J.M., and McIntosh, W.S., eds., Mogollon Slope, West-Central New Mexico and East-Central Arizona: New Mexico Geological Society Guidebook 45, p. 135-142.

Mack, G.H., Salyards, S.L., McIntosh, W.C., and Leeder, M.R., 1998, Reversal magnetostratigraphy and radioisotopic geochronology of the Plio-Pleistocene Camp Rice and Palomas Formations, southern Rio Grande rift, *in* Mack, G.H., Austin, G.S., and Barker, J.M., eds., Las Cruces Country II: New Mexico Geological Society Guidebook 49, p. 229–236.

Mack, G.H., Cole, D.R., and Treviño, L., 2000, The distribution and discrimination of shallow, authigenic carbonate in the Pliocene-Pleistocene Palomas Basin, southern Rio Grande rift: Geological Society of America Bulletin, v. 112, no. 5, p. 643–656.

Mack, G.H., Leeder, M., and Salyards, S.L., 2002, Temporal and spatial variability of alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas half graben, southern Rio Grande rift, New

Mexico, USA, *in* Renaut, R.W., and Ashley, G.M., eds., Sedimentation in Continental Rifts: SEPM Special Publication 73, p. 165–177.

Mack, G.H., Seager, W.R., Leeder, M.R., Perez-Arlucea, M., and Salyards, S.L., 2006, Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA: Earth-Science Reviews, v. 77, p. 141–162.

Mack, G.H., Leeder, M.R., and Carothers-Durr, M., 2008, Modern flood deposition, erosion, and fan-channel avulsion on the semiarid Red Canyon and Palomas Canyon alluvial fans in the southern Rio Grande rift, New Mexico, U.S.A.: Journal of Sedimentary Research, v. 78, no. 7, p. 432–442, doi: 10.2110/jsr.2008.050.

Mack, G.H., Dunbar, N., and Foster, R., 2009, New sites of 3.1-Ma Pumice beds in axial-fluvial strata of the Camp Rice and Palomas Formations, southern Rio Grande rift: New Mexico Geology, v. 31, p. 31–37.

Mack, G.H., Leeder, M.R., Perez-Arlucea, M., and Durr, M., 2011, Tectonic and climatic controls on Holocene channel migration, incision and terrace formation by the Rio Grande in the Palomas half graben, southern Rio Grande rift, USA: Sedimentology, v. 58, p. 1065–1086, doi: 10.1111/j.1365-3091.2010.01195.x.

Mack, G.H., Foster, R., and Tabor, N.J., 2012, Basin architecture of Pliocene-lower Pleistocene alluvial-fan and axial-fluvial strata adjacent to the Mud Springs and Caballo Mountains, Palomas half graben, southern Rio Grande rift, *in* Lucas, S.G., McLemore, V.T., Lueth, V.W., Spielmann, J.A., and Krainer, K., eds., Geology of the Warm Springs Region: New Mexico Geological Society Guidebook 63, p. 431–446.

Mayer, A.B., 1987, Structural and volcanic geology of the Salado Mountains-Garcia Peaks area, Sierra County, New Mexico [Unpublished M.S. thesis]: Las Cruces, New Mexico State University, 61 p.

McCraw, D.J., and Love, D.W., 2012, An overview and delineation of the Cuchillo geomorphic surface, Engle and Palomas Basins, New Mexico, *in* Lucas, S.G., McLemore, V.T., Lueth, V.W., Spielmann, J.A., and Krainer, K., eds., Geology of the Warm Springs Region: New Mexico Geological Society Guidebook 63, p. 491–498.

McIntosh, W.C., 1989, Ages and distribution of ignimbrites in the Mogollon-Datil volcanic field, southwest New Mexico: A stratigraphic framework using $^{40}Ar/^{39}Ar$ dating and paleomagnetism [Unpublished Ph.D. dissertation]: Socorro, New Mexico Institute of Mining and Technology, 313 p.

McIntosh, W.C., Kedzie, L.L., and Sutter, J.F., 1991, Paleomagnetism and $^{40}Ar/^{39}Ar$ ages of ignimbrites, Mogollon-Datil volcanic field, southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 135, 79 p.

McMillan, N.J., 2004, Magmatic record of Laramide subduction and the transition to Tertiary extension: Upper Cretaceous through Eocene igneous rocks of New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The Geology of New Mexico: A Geologic History: New Mexico Geological Society Special Publication 11, p. 249–270.

Morgan, G.S., Sealey, P.S., and Lucas, S.G., 2008, Late Pliocene (late Blancan) vertebrate faunas from Pearson Mesa, Duncan Basin, southwestern New Mexico and southeastern Arizona: New Mexico Museum of Natural History and Science Bulletin, v. 44, p. 141–188.

Morgan, G.S., and Lucas, S.G., 2012, Cenozoic vertebrates from Sierra County, southwestern New Mexico, *in* Lucas, S.G., McLemore, V.T., Lueth, V.W., Spielmann, J.A., and Krainer, K., eds., Geology of the Warm Springs Region: New Mexico Geological Society Guidebook 63, p. 525–540.

Munsell Color, 2009, Munsell soil color book: X-Rite, Grand Rapids, MI.

Repenning, C.A., and May, S.R., 1986, New evidence for the age of lower part of the Palomas Formation, *in* Clemons, R.E., King, W.E., Mack, G.H., and Zidek, J., eds., Truth or Consequences region: New Mexico Geological Society Guidebook 37, p. 257–260.

Seager, W.R., and Mayer, A.B., 1988, Uplift, erosion, and burial of Laramide fault blocks, Salado Mountains, Sierra County, New Mexico: New Mexico Geology, v. 10, no. 3, p. 49–53.

Seager, W.R., and Mack, G.H., 2003, Geology of the Caballo Mountains, New Mexico: New Mexico

Bureau of Geology and Mineral Resources Memoir 49, 136 p.

Seager, W.R., Hawley, J.W., and Clemons, R.E., 1971, Geology of San Diego Mountain area, Doña Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 97, 38 p., 2 pl., scale 1:24,000.

Seager, W.R., Clemons, R.E., and Hawley, J.W., 1975, Geology of Sierra Alta quadrangle, Sierra and Doña Ana Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 102, 56 p., 1 sheet, scale 1:24,000.

Seager, W.R., Clemons, R.E., Hawley, J.W., and Kelley, R.E., 1982, Geology of northwest part of Las Cruces 1° x 2° sheet, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 53, scale 1:125,000.

Seager, W.R., Shafiqullah, M., Hawley, J.W., and Marvin, R.F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of America Bulletin, v. 95, no. 1, p. 87–99.

Seager, W.R., Mack, G.H., Raimonde, M.S., and Ryan, R.G., 1986, Laramide basement-cored uplift and basins in south-central New Mexico, *in* Clemons, R.E., King, W.E., and Mack, G.H. eds., Truth or Consequences Region: New Mexico Geological Society Guidebook 37, p. 123–130.

Soil Survey Staff, 1999, Soil taxonomy: U.S. Department of Agriculture Handbook 436, 869 p.

Soreghan, G.S., 1994, Stratigraphic responses to geologic process: Late Pennsylvanian eustasy and tectonics in the Pedregosa and Orogrande basins, ancestral Rocky Mountains: Geological Society of America Bulletin, v. 106, p. 1195–1211.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey Water-Supply Paper 1525, 258 p.

Tedford, R.H., 1981, Mammalian biochronology of the Late Cenozoic basins of New Mexico: Geological Society of America Bulletin, v. 92, p. 1008–1022.

Udden, J.A., 1914, The mechanical composition of clastic sediments: Geological Society of America Bulletin, v. 25, p. 655–744.

USDA, 2008, Natural Agricultural Imagery Program (NAIP) information factsheet: U.S. Department of Agriculture, 2 p.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377–392.

White, J.D.L., and Houghton, B.F., 2006, Primary volcaniclastic rocks: Geology, v. 34, no. 8, p. 677–680.

Winter, J.D., 2010, Principles of igneous and metamorphic petrology: Pearson/Prentice Hall Upper Saddle River, New Jersey, 702 p.

APPENDIX A

Detailed descriptions of lithologic units on the Saladone Tank 7.5-minute quadrangle

QUATERNARY

Hillslope and valley-floor units

daf Disturbed or artificial fill (modern) – Sand and gravel that has been moved by humans to form berms and dams.

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 in poorly stratified/massive beds. Unconsolidated and weakly to moderately calcareous. Sand consists of very poorly to poorly sorted, angular to subrounded, vfU to cU grains with 80-90% lithic (volcanic), 10-15% quartz, and 5-10% feldspar grains. Fine to medium pebbles are angular to subangular and composed of tuff and rhyolite (65-75%), basaltic andesite and intrusive andesite/diorite (25-35%), and scarce chert and Paleozoic carbonates. Gravel comprises 15-30% of unit by volume. Deposit may be overprinted by 30-50 cm thick Bt horizons with 15% scattered sand grains as described above. Typically 1-1.5 m (3.3-5 ft) thick but may be as much as 3 m (10 ft) thick.

Qsc Slopewash and colluvium (upper Pleistocene to Holocene?) – Silt, sand, and gravel in poorly stratified deposits underlying aprons extending off of basalt flows north of Las Animas Creek. Unit not described in field due to restricted access but is readily identified in aerial photography. Perhaps similar to unit Qasc but lacking soils. Likely <3 m (10 ft) thick.

Qam Modern alluvium (modern to ~50 years old) – Grayish brown (10YR 5/2), sandy gravel lining valley floors. Gravel is imbricated, very poorly to poorly sorted, subangular to well rounded, and consists of 60-90% pebbles, 10-40% cobbles, and 0-10% boulders. Matrix consists of very poorly to poorly sorted, subrounded to well rounded (minor subangular), vfU-cL sand composed of 40-55% lithic (volcanic+chert), 30-35% quartz, and 15-25% feldspar grains with trace proportions of clay. Local surface relief of up to 1.5 m (5 ft) between channels and bars; channels are commonly 4-6 m (13-20 ft) wide in larger drainages. Maximum thickness approximately 3 m (10 ft).

Qamh Modern and historical alluvium, undivided (modern to ~600 years old) – Modern alluvium (Qam) and subordinate historical alluvium (Qah). See detailed descriptions of each individual unit.

Qah Historical alluvium (~50 to ~600 years old) – Brown, yellowish brown, light brownish gray, and pale brown (10YR 5/3-4; 6/2-3), gravelly sand and sandy pebble and pebble-cobble gravel in very thin to medium, tabular to broadly lenticular beds. Unconsolidated, weakly calcareous, and occasionally planar cross-stratified with foresets 10-15 cm (4-6 in) thick. Gravel is clast-supported, imbricated, poorly to moderately sorted, subangular to rounded, and includes 50-95% pebbles, 5-50% cobbles, and up to 3% boulders. Matrix consists of very poorly to moderately sorted, subrounded to rounded, silty, fL-vcL sand composed of 50-60% lithic (volcanic+chert>>carbonate), 25-30% quartz, and 15-20% feldspar grains with trace proportions of clay. Heavily bioturbated by fine to coarse roots with no obvious soil development. Weak to moderate bar-and-swale topography is preserved with 10-50 cm (4-20 in) of local relief. Deposit flanks modern drainage courses and is inset into younger alluvium (Qay). Correlative deposits along Las Animas Creek in the Skute Stone Arroyo 7.5-minute quadrangle returned convention radiocarbon ages of 110 ± 30 and 180 ± 30 ^{14}C yr BP (Jochems and Koning, 2015b). Tread height up to 1.5 m (5 ft) above modern grade. 3-5 m (10-16 ft) thick.

Qahm Historical and modern alluvium, undivided (modern to ~600 years old) – Historical alluvium (Qah) and subordinate modern alluvium (Qam). See detailed descriptions of each individual unit.

Qary Recent (historical + modern) and younger alluvium, undivided (modern to lower Holocene) – Recent alluvium (Qah and Qam, undivided) and subordinate younger alluvium (Qay). See detailed descriptions of each individual unit.

Qay Younger alluvium (Holocene) – Brown (7.5YR 5/4; 10YR 4-5/3), pebbly silt, sand, and sandy pebble-cobble gravel in thin to thick, tabular to broadly lenticular or wedge-shaped beds. Unconsolidated and weakly to somewhat calcareous. Gravel is clast- to matrix-supported, occasionally imbricated, very poorly to poorly sorted, angular to rounded, and composed of 60-90% pebbles, 10-40% cobbles, and up to 5% boulders of mostly reworked volcanic clasts. Sand consists of poorly to well sorted, angular to rounded, vfL-mU grains composed of 55-70% lithics (volcanic), 25% feldspar, and 5-20% quartz. Illuviated clay horizons (Bw or Bt) overlying stage I calcic horizons may be observed in upper 0.5-0.8 m (1.6-2.6 ft) with discontinuous carbonate coats on 60-75% of clasts where present. Deposit is strongly bioturbated by burrows and fine to very coarse roots. Bar-and-swale topography mostly obliterated. Deposit is inset into older terraces (e.g. Qtu) and inset by historical alluvium (Qah), and is better preserved in lower (first to second) order streams. Fan sediment graded to correlative deposits in the Williamsburg 7.5-minute quadrangle returned convention radiocarbon ages of 2480 ± 30 and 9590 ± 30 ^{14}C yr BP (Jochems and Koning, 2015b). Tread height 1.7-2 m (5.6-6.6 ft) above modern grade. >2-4 m (6.6-13 ft) thick.

Qaym Younger and modern alluvium, undivided (modern to lower Holocene) – Younger alluvium (Qay) and subordinate modern alluvium (Qam). See detailed descriptions of each individual unit.

Qayh Younger and historical alluvium, undivided (~50 years old to lower Holocene) – Younger alluvium (Qay) and subordinate historical alluvium (Qah). See detailed descriptions of each individual unit.

Qayr Younger and recent (historical + modern) alluvium, undivided (modern to lower Holocene) – Younger alluvium (Qay) and subordinate recent alluvium (Qah and Qam, undivided). See detailed descriptions of each individual unit.

Alluvial fan and piedmont units

Qfam Modern fan alluvium (modern to ~50 years old) – Light brownish gray to pale brown (10YR 6/2-3), sandy pebble and pebble-cobble gravel. Unconsolidated, weakly calcareous, and vaguely ripple cross-stratified to internally massive. Gravel is clast- to matrix-supported, occasionally imbricated, poorly sorted, subangular to rounded (minor well rounded), and consists of 70-90% pebbles, 10-30% cobbles, and <10% boulders of mostly reworked volcanic clasts. Matrix consists of very poorly to poorly sorted, subangular to rounded, fU-mU sand (10-15% silt + cL-vcL sand) composed of 60-70% lithic (volcanic), 15-30% quartz, and 10-15% feldspar grains with no clay. Subordinate (up to 10-15%) deposits of brown (7.5YR 4-5/4), unconsolidated, weakly calcareous, massive, poorly to moderately sorted, subangular to rounded, silt to fU sand (up to 5% mL-cU) comprised of similar grains as primary matrix; contains 10-20% fine to medium pebbles. Deposit is found in small channels and lobes on low-relief fans entering larger arroyos, and forms small bars and levees with 10-50 cm (4-20 in) of fresh bar-and-swale topography. Thickness unknown but likely no more than 2 m (6.6 ft).

Qfar Recent fan alluvium (modern to ~600 years old) – Modern fan alluvium (Qfam) and historical fan alluvium (Qfah) in approximately equal volumetric proportions. See detailed descriptions of each individual unit.

Qfamh Modern and historical fan alluvium, undivided (modern to ~600 years old) – Modern fan alluvium (Qfam) and subordinate historical fan alluvium (Qfah). See detailed descriptions of each individual unit.

Qfah Historical fan alluvium (~50 to ~600 years old) – Brown (7.5YR 4-5/4), sandy pebble-cobble gravel in thin to thick, tabular beds. Unconsolidated, calcareous, and normally graded. Gravel is mostly clast-supported, weakly to moderately imbricated, poorly sorted, subangular to rounded, and consists of 75-95% pebbles and 5-25% cobbles of felsites (55-60%), basaltic andesite and intrusive andesite/diorite (30-35%), chert and Paleozoic sedimentary clasts (5-10%), and Tb (3-6%). Matrix consists of poorly sorted, subangular to rounded, silt to mL sand composed of 80% lithics (volcanic), 10% quartz, and 10% feldspar grains with trace to 2% free-grain argillans. Subordinate beds of light brown (7.5YR 6/3-4), unconsolidated, calcareous, moderately well sorted, silt to vfU sand in thin, tabular, internally massive beds, with texture similar to gravel matrix except size. Deposit surface features slightly varnished clasts, 5-20 cm (2-8 in) of relict bar-and-swale relief, and little to no soil development. 1.5-3 m (5-10 ft) thick.

Qfahm Historical and modern fan alluvium, undivided (modern to ~600 years old) – Historical fan alluvium (Qfah) and subordinate modern fan alluvium (Qfam). See detailed descriptions of each individual unit.

Qfahy Historical and younger fan alluvium, undivided (~50 years old to lower Holocene) – Historical fan alluvium (Qfah) and subordinate younger fan alluvium (Qfay). See detailed descriptions of each individual unit.

Qfary Recent (historical + modern) and younger fan alluvium, undivided (modern to lower Holocene) – Recent fan alluvium (Qfah and Qfam, undivided) and subordinate younger fan alluvium (Qfay). See detailed descriptions of each individual unit.

Qfay Younger fan alluvium (Holocene) – Brown (7.5YR 5/3-4), sandy pebble-cobble gravel in thick to very thick beds. Unconsolidated, strongly calcareous, and mostly internally massive. Gravel is clast- to matrix-supported, moderately imbricated, very poorly sorted, subangular to rounded, and consists of 65-80% pebbles and 20-35% cobbles of felsites (60-65%), basaltic andesite and intrusive andesite/diorite (25-30%), chert and Paleozoic sedimentary clasts (10-15%), and Tb (2-5%). Matrix consists of poorly sorted silt to fL sand with 20-30% very poorly sorted, subrounded to rounded, fU to vcU sand composed of 80-85% lithic (volcanic), 10-15% quartz, and 5-10% feldspar grains. Subordinate beds (12-15% of unit by volume) include brown (7.5YR 4/3), unconsolidated, strongly calcareous sand in thin to medium, internally massive beds. This sediment consists of moderately sorted, subangular to rounded, vfU to mU sand with 85-90% lithic (volcanic>carbonate), 5-10% quartz, and 5-10% feldspar grains with 12-20% scattered, subangular to subrounded, fine to medium pebbles. Deposit commonly features a moderately developed A horizon in upper 20-25 cm (8-10 in), with 2-3 buried Bw or Btk (stage I carbonate morphology) horizons each 15-25 cm (6-10 in) thick. Correlative deposits in the Williamsburg 7.5-minute quadrangle returned convention radiocarbon ages of 2480 ± 30 and 9590 ± 30 ^{14}C yr BP (Jochems and Koning, 2015b). >2-3.5 m (6.6-11.5 ft) thick.

Qfayh Younger and historical fan alluvium, undivided (~50 years old to lower Holocene) – Younger fan alluvium (Qfay) and subordinate historical fan alluvium (Qfah). See detailed descriptions of each individual unit.

Qfayr Younger and recent (historical + modern) fan alluvium, undivided (modern to lower Holocene) – Younger fan alluvium (Qfay) and subordinate recent fan alluvium (Qfah and Qfam, undivided). See detailed descriptions of each individual unit.

Qfo Older fan alluvium (middle to upper Pleistocene?) – Brown (7.5YR 5/3-4) sand, gravelly sand, and sandy pebble and pebble-cobble-boulder gravel in massive or thin to thick, vaguely lenticular to perhaps tabular beds. Weakly to moderately consolidated, weakly carbonate-cemented, and overall reverse graded. Gravel constitutes the upper 0.8-1.8 m (2.6-6 ft) of lower deposits and is comprised of 50-60% pebbles, 30-35% cobbles, and 10-15% fine boulders. Gravel matrix consists of poorly sorted, subrounded (minor subangular), medium- to very coarse-grained sand. Finer-grained beds consist of silty, very fine- to fine-grained sand with minor medium- to very coarse-grained sand and 10-20% scattered pebbles. Internal contacts may be vertically gradational over 1 m (3.3 ft) or slightly scoured with up to 20 cm (8 in) of relief. Lower deposits graded to Qtl exhibit stage I-II calcic horizons up to 60 cm (24 in) thick, whereas higher deposits feature reddish brown illuviated clay horizons (Bw or Bt) overlying stage III calcic horizons that are 20 and 30-40 cm (8 and 12-16 in) thick, respectively. Deposit surface may exhibit desert pavement with a moderate clast armor and moderately varnished clasts. 3-4 m (10-13 ft) thick.

Qpo Piedmont alluvium (middle to upper Pleistocene?) – Reddish brown to brown (5-7.5YR 4/4), sandy pebble-cobble-boulder gravel in medium to thick, tabular beds. Unconsolidated, moderately calcareous, mostly internally massive, and vaguely reverse graded. Gravel is clast- to matrix-supported, weakly imbricated, very poorly sorted, subangular to rounded, and consists of 60-85% pebbles, 15-30% cobbles, and 5-10% boulders of over 85% volcanic lithologies. Matrix consists of poorly sorted, subangular to rounded, silt to mL sand (20-25% mU-cL) composed of 75-90% lithic (volcanic), 5-15% quartz, and 5-15% feldspar grains. Deposit features A and Bw horizons in upper 30-45 cm (12-18 in). Varnish observed on 15-25% of clasts at surface. >1.7-10 m (5.6-33 ft) thick.

Terrace units

Terrace deposits of Las Animas Creek

Qta Terrace deposit of Las Animas Creek, undivided (Pleistocene) – Sandy gravel deposits underlying terraces. Clasts are dominated by volcanic lithologies, typically including 5-15% Tb, and may be coated by Mn oxides. Locally subdivided into 5 deposits in quadrangle [descriptions modified from Koning et al., 2015; tread heights estimated from photogrammetric analysis due to restricted access]:

Qta1 Lowest terrace deposit of Las Animas Creek (upper Pleistocene) – Brownish cobble-boulder gravel in basal ~1 m (3.3 ft) overlain by pebbly sand. Gravel is very poorly sorted and subrounded. Tread height 5-10 m (16-33 ft) above the valley floor. 2 m (6.6 ft) thick.

Qta2 Lower-middle terrace deposit of Las Animas Creek (uppermost middle to upper Pleistocene) – Reddish brown, brown, and strong brown (5YR 4-5/; 7.5YR 4-5/4-6), sandy gravel in thin to thick, mostly lenticular beds. Loose to moderately consolidated and non-cemented. Gravel is typically clast-supported, imbricated, and consists of very poorly to poorly sorted, subrounded to rounded, subequal pebbles and cobbles with subordinate boulders. Matrix is poorly to moderately sorted, subangular to subrounded, medium to very coarse sand with <0.5-5% clay. Tread height 15-20 m (49-66 ft) above the valley floor. 1-8 m (3.3-26 ft) thick.

Qta3 Middle terrace deposit of Las Animas Creek (middle Pleistocene) – Brown, strong brown, and dark brown (7.5YR 5/4-6; 7.5YR 3/3), sandy gravel and gravelly sand in vague, thin to thick, lenticular beds. Gravel is clast-supported, very poorly to moderately sorted, subrounded to rounded, and consists of subequal pebbles and cobbles with subordinate boulders. Matrix is poorly to moderately sorted, subrounded to subangular, medium to very coarse sand with 1-5% clay. Tread height 30-40 m (98-131 ft) above the valley floor. 1.5-3 m (5-10 ft) thick.

Qta4 Upper-middle terrace deposit of Las Animas Creek (middle Pleistocene) – Pinkish gray or brown (7.5YR 6/2; 4/4), locally strong brown (7.5YR 5/6) or yellowish brown (10YR 5/4), sandy gravel in very thin to thick, tabular to lenticular beds with local lateral accretion cross-stratification up to 1 m (3.3 ft) thick. Well consolidated and weakly cemented by clay. Gravel is clast- to matrix-supported, well imbricated, very poorly to poorly sorted, mostly subrounded, and contains subequal pebbles and cobbles with subordinate boulders. Matrix is poorly to moderately sorted, mostly subrounded, fine to very coarse sand with <3% clay. May be locally overprinted by an argillic soil horizon (moderate to strong ped development, argillans on ped faces) and/or a strong (stage III to IV) calcic horizon. Tread height 45-55 m (148-180 ft) above the valley floor. 1-4 m (3.3-13 ft) thick.

Qta5 Uppermost terrace deposit of Las Animas Creek (middle Pleistocene) – Sandy gravel in vague, medium to thick beds. Gravel is clast-supported, commonly imbricated, and contains pebbles, cobbles, and boulders that include 10-20% Tb clasts. Local intervals, about 1 m (3.3 ft) thick, are dominated by pinkish gray to pink (7.5YR 7/2-3), bioturbated silt and very fine- to fine-grained sand mixed with 1-5% scattered pebbles. Topsoil commonly has a strong (stage III+ to IV) calcic horizon. Tread height 90-110 m (295-361 ft) above the valley floor. 0.5-3 m (1.6-10 ft) thick.

Terrace deposits of Palomas Creek

Qtp Terrace deposit of Palomas Creek, undivided (Pleistocene) – Sandy gravel deposits underlying fill and strath terraces. Clast compositions are dominated by diorite and volcanic lithologies derived from the eastern Black Range and Garcia Peaks, with subordinate Paleozoic sedimentary lithologies. Locally subdivided into 2 deposits in quadrangle [descriptions modified from Jochems (2015) and Jochems and Koning (2015)]:

Qtp2 Lower-middle terrace deposit of Palomas Creek (upper Pleistocene) – Brown (7.5-10YR 4/3), sandy pebble-cobble gravel in thick to very thick, tabular beds with occasional sand lenses. Unconsolidated and weakly to moderately calcareous. Gravel consists of poorly to moderately sorted, subrounded to well rounded pebbles and cobbles with no more than 3% boulders. Matrix contains up to 5% free-grain argillans. Deposit contains few preserved soils (likely eroded). Varnish on 20-30% of clasts at surface. Tread height 12-20 m (39-66 ft) above the valley floor. 2-5 m (6.6-16 ft) thick.

Qtp3 Middle terrace deposit of Palomas Creek (middle to upper Pleistocene?) – Brown to light brown (7.5YR 5-6/3), sandy pebble-cobble gravel in thin to thick, broadly lenticular beds with occasional cross-stratification. Unconsolidated and very weakly calcareous. Gravel consists of well imbricated, poorly to moderately sorted, subrounded to well rounded pebbles and cobbles. Deposit features stage I+ calcic horizons with 50% of clasts coated up to 80% by carbonate rinds. Varnish on 40-50% of clasts at surface. Tread height 27-30 m (89-98 ft) above the valley floor. 1.4-3 m (4.6-10 ft) thick.

Terrace deposits in other drainages

Qtu Terrace deposit, undivided (Pleistocene) – Reddish brown (5YR 4/3-4) to dark brown (7.5YR 3/3-4), sandy pebble-cobble-boulder gravel in medium to very thick, tabular to broadly lenticular beds. Unconsolidated, weakly to moderately calcareous, and occasionally trough cross-stratified. Gravel is clast-supported, well imbricated, very poorly sorted, subangular to well rounded (mostly rounded to well rounded), and composed of 25-70% pebbles, 30-50% cobbles, and 5-25% boulders of felsites (40-70%), basaltic andesite and intrusive andesite/diorite (30-45%), Tb (5-15%), and chert and Paleozoic sedimentary clasts (3-5%). Matrix consists of very poorly to poorly sorted, subangular to well rounded, silty, vfL-vcL sand composed of 60-70% lithic (volcanic>chert), 15-25% quartz, and 5-20% feldspar grains with 5-15% free-grain argillans and flakes that give the deposit its color. Subordinate beds consist of brown (7.5YR 4/4), strongly calcareous, massive, moderately sorted, sandy silt in unconsolidated, medium, broadly lenticular beds containing 10-20% mL-vcU grains of sand and 5-8% fine to medium pebbles. Stage I-II calcic horizons are commonly observed in the upper 60 cm (24 in) of the deposit. Varnish observed on 5-30% of clasts at surface. Tread height 1.7-3.5 m (5.6-11.5 ft) above modern grade. 1-3.1 m (3.3-10.2 ft) thick. Locally subdivided into 4 deposits in quadrangle:

Qtl Lower terrace deposit (upper Pleistocene) – Brown (7.5YR 5/2-4; 4/3) or grayish brown (10YR 5/2), sandy pebble-cobble-boulder gravel in vague, medium, lenticular beds. Gravel is mostly clast-supported, imbricated, poorly sorted, subrounded pebbles through coarse cobbles with 15-25% fine boulders. Clasts are locally stained orange by iron oxides. Matrix is poorly to moderately sorted, subrounded (minor subangular), medium- to very coarse-grained (minor fL-fU) sand composed of mostly lithic (volcanic) grains with <1% clay. Surface is smooth and consists of weakly to strongly varnished clasts (pebbles). Overall, tread lies 5-9 m (16-30 ft) above the valley floor. 1-2 m (3.3-6.6 ft) thick. This subunit can be further divided into two individual terrace deposits separated by 1-2 m (3.3-6.6 ft):

Qtl1 Lower Qtl terrace deposit – Qtl gravel underlying terraces with treads 5-6 m (16-20 ft) above the valley floor.

Qtl2 Higher Qtl terrace deposit – Qtl gravel underlying terraces with treads 6-9 m (20-30 ft) above the valley floor.

Qtm Middle terrace deposit (middle to upper Pleistocene) – Brown (10YR 5/3), sandy pebble-cobble and pebble-cobble-boulder gravel in poorly stratified beds. Weakly consolidated. Gravel consists of poorly sorted, subrounded, well-graded pebbles and cobbles with 10-30% boulders. Matrix is poorly sorted, subangular to subrounded, fine- to very coarse-grained (cL-vcU in places) sand with local accumulations of manganese. Locally, the entire sediment profile is overprinted by an illuviated (Bw or Bt) clay horizon. Tread is eroded, with bouldery paleochannel fills exhibiting positive relief (up to 10-20 cm [4-8 in]). Moderate varnishing of clasts at surface. Overall, tread lies approximately 20 m (66 ft) above the valley floor. 1-2 m (3.3-6.6 ft) thick. This subunit can be further divided into three individual terrace deposits separated by 1-2 m (3.3-6.6 ft):

Qtm1 Lowest Qtm terrace deposit – Qtm gravel underlying terraces approximately 18-20 m (59-66 ft) above the valley floor.

Qtm2 Middle Qtm terrace deposit – Qtm gravel underlying terraces approximately 20-23 m (66-76 ft) above the valley floor.

Qtm3 Highest Qtm terrace – Qtm gravel underlying terraces approximately 23-25 m (76-82 ft) above the valley floor

Qth High terrace deposit (middle Pleistocene) – Brown (7.5YR 4/4) sandy gravel in vague, thin to medium beds. Gravel consists of clast- to matrix-supported, poorly sorted, mostly subrounded (subordinate rounded), well-graded pebbles, cobbles, and 15-35% fine to coarse boulders dominated by volcanic lithologies (particularly crystal-poor rhyolite, andesite, and basaltic andesite with subordinate tuffs and Tb). Matrix is moderately sorted, subrounded, mostly mU-vcU sand dominated by lithic (volcanic) grains with approximately 10% free-grain argillans. Overall, tread lies approximately 30 m (98 ft) above the valley floor. 0.5-4 m (1.6-13 ft) thick. This subunit can be further divided into three individual terrace deposits separated by 1-2 m (3.3-6.6 ft) and distinguished by surface and soil characteristics:

Qth1 Lowest Qth terrace deposit – Qth gravel underlying terraces approximately 27-30 m (89-98 ft) above the valley floor. Surfaces exhibit moderate clast varnishing.

Qth2 Middle Qth terrace deposit – Qth gravel underlying terraces approximately 30-33 m (98-108 ft) above the valley floor. Surfaces have been eroded to such an extent that cobbly paleochannels form positive topographic relief (10-15 cm [4-6 in]). These deposits feature moderately developed desert pavement (poor clast armor) and weak to moderate varnishing of pebbles and cobbles at the surface. Qth2 deposits also feature moderate Av peds in a surface soil that includes an illuviated clay or cambic horizon (Bt or Bw) underlain by a strong calcic horizon.

Qth3 Highest Qth terrace deposit – Qth gravel underlying terraces approximately 33-36 m (108-118 ft) above the valley floor. Surfaces exhibit a moderate desert pavement with moderately varnished clasts (mostly pebbles). These deposits feature a preserved topsoil with a yellowish red (5YR 4-5/6) argillic/calcic horizon underlain by a stage III+ calcic horizon (K) that is approximately 1 m (3.3 ft) thick. The argillic horizon exhibits weak, medium, subangular blocky ped development with common, distinct argillans on ped faces and coarse sand grains. Weak to moderate Av peds are found at the surface.

Qtvh Very high terrace deposit (middle Pleistocene) – Poorly exposed sandy gravel. Surface has a moderate- to well-developed desert pavement (moderate clast armor); surface clasts are pebble-dominated and weakly to well-varnished. Underlying soil has very poor to poor Av peds. Tread height approximately 40 m (130 ft) above valley floor. Likely 1-2 m (3.3-6.6 ft) thick.

QUATERNARY-TERTIARY

Basin-fill

QTp Palomas Formation (uppermost Miocene to lower Pleistocene) – Gravel, sand, silt, and clay deposited on coalesced fan complexes in the west-central Palomas basin. Fossil data (summarized by Morgan and Lucas, 2012), radiometric ages (Bachman and Mehnert, 1978; Seager et al., 1984; Jochems, 2015; Koning et al., in press), together with magnetostratigraphic data (Repenning and May, 1986; Mack et al., 1993, 1998; Leeder et al., 1996; Seager and Mack, 2003), indicate an age range of ~5.5-0.8 Ma for the Palomas Formation. Where not significantly eroded, the surface soil is marked by a stage IV petrocalcic horizon that is 1-2 m (3.3-6.6 ft) thick. More information on this horizon and the constructional surface developed on the Palomas Formation, the Cuchillo surface, can be found in McCraw and Love (2012). 0 to >194 m (0 to >635 ft) thick. Includes 5 subunits in quadrangle:

QTpuc Coarse gravel of the upper piedmont facies of the Palomas Formation (lower Pleistocene) – Sandy pebble-cobble-boulder gravel and pebbly sand in thin to thick, tabular to broadly lenticular beds. Gravel beds are typically thin to medium and lenticular. Sandy beds may exhibit internal horizontal-planar laminations and cross-laminations (mostly planar foresets up to 15-20 cm [6-8 in] high). Loose to moderately consolidated and strongly carbonate-cemented or weakly clay-cemented. Unit is typically strong brown (7.5YR 4-5/6) in the northern part of the quadrangle, but varies from reddish brown to light reddish brown to yellowish red (5YR 5-6/4; 5/6) or brown or light brown to strong brown (7.5YR 5-6/4; 5/6) in the south. Gravel is clast- to matrix-supported, moderately well imbricated, poorly to moderately sorted, subangular to rounded, and includes 60-95% pebbles, 10-40% cobbles, and 10-30% boulders of basaltic andesite and intrusive andesite/diorite (40-65%), felsites (20-50%), jasperoid/chert and Paleozoic sedimentary clasts (<3-5%), and Tb (trace to 5%). The proportion of boulders increases westward in the southern part of the quadrangle. Gravel matrix consists of poorly sorted, subrounded (minor subangular), medium- to very coarse-grained sand (<25% very fine to fine) composed of 60% lithic (volcanic+chert), 25% feldspar, and 15% quartz grains with 3-20% orangish free-grain argillans. Locally, matrix may be pinkish gray (7.5YR 6/2). Unit contains rare (<5%) lenses of pebbly, fU-cU sand. Deposit exhibits internal scour contacts with up to 1.5 m (5 ft) of relief where coarser channel gravels have cut into underlying pebble gravel or sand. Rare to minor (1-20%) beds include: (A) 30-50 cm (12-20 in) thick lenses of matrix-supported debris-flow gravel with abundant cobbles and boulders; and (B) light brown 7.5YR 6/3-4 (minor 5-7.5YR 5/6), 30-170 cm (12-70 in) thick, tabular to lenticular, internally massive beds of extra-channel sediment consisting of clayey-silty vfL-fU sand with scattered mL-vcU sand and pebbles. The latter commonly feature cambic-argillic paleosol horizons in their upper 20-30 cm (8-12 in) characterized by strongly developed, coarse, angular blocky peds, with variable clay illuviation on ped faces. Other strata include channel-fills with lateral accretion sets (thinly bedded planar foresets that are 10-120 cm [4-48 in] tall); these strata are subequal to clast-supported beds in the southeast part of the quadrangle but increase in abundance toward the west. Stage IV pedogenic carbonate (Bk and K horizons) is observed in the upper 1.6-3 m (5.2-10 ft) of the unit, where 80-90% of clasts are coated by carbonate rinds up to 1 mm thick and some horizons are completely plugged with laminar carbonate. Unit is laterally gradational with QTpu in the northern part of the quadrangle and thickens significantly southwards from 3 to >52 m (10 to >170 ft).

QTpu Upper piedmont facies of the Palomas Formation (lower Pleistocene) – Yellowish red (5YR 4-5/6) to strong or light brown (7.5YR 4-5/6; 6/4), silty mud, sandy silt, and subordinate pebble-cobble gravel in medium to thick, tabular to lenticular beds (less commonly in wedge-shaped and wavy beds). Loose to somewhat consolidated, weakly to strongly carbonate-cemented, and typically massive with rare sand lenses exhibiting tangential cross-stratification with foresets up to 8 cm (3 in) thick. Gravel beds constitute 30-40% of unit by volume and are clast-supported and crudely to moderately imbricated. Unit features rare (up to 1%) lenses of open-framework pebble-cobble gravel. Clasts are mostly poorly sorted, subangular to rounded, and consist of 45-90% pebbles, 10-50% cobbles, and 2-10% boulders. Clast lithologies are mostly extrusive volcanics (>80% felsites and intermediate volcanics), but may also include up to 5% each of jasperoid/chert, Paleozoic carbonate, Tad, and Tb. Sand constitutes 5-20% of units by volume and is poorly to moderately sorted, subangular to subrounded, and fine- to coarse-grained; grains consist of 60-70% lithics (volcanic>>chert), 15-20% feldspar, and 10-15% quartz. Individual sandy silt beds with 5-10% red free-grain argillans occasionally grade downward into clayey silt. Buried Bk horizons (stage II carbonate morphology) are observed in places and distinguished by abundant carbonate nodules and fragments. Unit is laterally gradational with QTpuc in the northern part of the quadrangle, where it features more abundant and thicker (up to 0.8 m [2.6 ft]) calcic horizons near its top. Its basal contact with QTpt or QTpm is disconformable. 0-28 m (0-92 ft) thick, thickening to the east.

QTpt Transitional piedmont facies of the Palomas Formation (Pliocene to lower Pleistocene) – Light brown (7.5YR 6/3) sandy pebble-cobble conglomerate and pebbly sandstone in medium to thick, tabular beds. Moderately well consolidated, moderately to strongly calcareous, and commonly trough cross-stratified. Gravel is clast-supported, imbricated, very poorly to moderately sorted, mostly subrounded, and consists of 40-90% pebbles, 10-60% cobbles, and up to 5% boulders of basaltic andesite and intrusive andesite/diorite (50-60%), felsites (30-40%), and chert and Paleozoic sedimentary clasts (<10%). Sandy matrix and sandstones consist of 70% lithic (volcanic+chert), 15% feldspar, and 15% quartz grains. Carbonate cement is massive and fine-grained in highest ledges in section, and either massive or sparry in lower intervals. No evidence of soil horizonation/pedogenesis, indicating that unit was deposited mostly in stream channels. Unit features abundant channel forms up to 0.7 m (2.3 ft) deep and 6-7 m (20-23 ft) across. Forms prominent ledges. Unit has a laterally gradational, interfingering contact with QTpm in the northeast corner of the quadrangle (sections 5 and 8, T14S, R5W). 6-25 m (20-82 ft) thick, thickening to the east.

QTpm Middle piedmont facies of the Palomas Formation (Pliocene to lower Pleistocene) – Pinkish white to pink (7.5YR 8/2-3), very fine to fine-grained sand, silty fine sand, and sandy silt in thin to thick (mostly medium to thick), tabular beds that are internally massive to horizontal-planar laminated. Colors are occasionally reddish brown (5YR 5/4) in more clay-rich facies. Poorly to moderately consolidated and perhaps weakly cemented by calcium carbonate. Scattered (up to 15%) medium to very coarse sand grains and pebbles are locally observed; unit contains <25% clayey beds. Channel-fill gravel is typically minor (<10-15% of unit by volume) but occasionally exposures are comprised of up to 60-65% very fine to very coarse pebbles with <20% cobbles and no more than 5% boulders; clasts are poorly to moderately sorted, subrounded to rounded, and composed of felsites, basaltic andesite, and intrusive andesite/diorite. Channel-fills may be moderately to strongly carbonate-cemented and feature matrix material consisting of light brown (7.5YR 6/3-4), poorly sorted silt to vfU sand with 10-20% fL to cU sand composed of 70% lithic (volcanic), 15% quartz, and 15%

feldspar grains with no clay observed. Unit has a laterally gradational, interfingering contact with QTpt in the northeast corner of the quadrangle (sections 5 and 8, T14S, R5W). 0-53 m (0-175 ft) thick, thickening to the east (maximum thickness from Jochems and Koning, 2015a).

QTpl Lower piedmont facies of the Palomas Formation (Pliocene) – Light brownish gray (10YR 6/2) to light gray (10YR 7/1-2) granule-pebble conglomerate in thin to thick, mostly tabular beds. Beds may be vaguely planar cross-stratified with foresets up to 30 cm (12 in) thick. Moderately to strongly consolidated and weakly calcite- to strongly silica-cemented. Gravel consists of clast-supported, imbricated, very poorly to moderately sorted, subangular to subrounded granules (30-50%), pebbles (35-80%), and cobbles (5-15%); cobbles increase to perhaps 25% in upper part of unit. Clasts are typically composed of 55-60% felsites (0% Tccw clasts increasing to as much as 60% in upper part) and 40-45% intermediate lithologies (mostly Tba), but isolated hills comprised of the unit in the northwest part of the quadrangle are dominated by felsites and Tb. Matrix consists of very poorly to poorly sorted, subangular to subrounded, mL-vcL sand composed of 70-80% lithic (volcanic), 15-20% feldspar, and 10-15% quartz grains. Matrix may be reddish yellow (7.5YR 6-7/6) where unit is strongly cemented in northern part of quadrangle. Unit has a vertically gradational basal contact with Tsu in the northwest corner of the quadrangle (section 17, T14S, R6W), but may form a sharp disconformity elsewhere. Unit is interbedded with Tb throughout the western part of the quadrangle. 0-61 m (0-200 ft) thick, thickening to the east (maximum thickness from Jochems and Koning, 2015a).

Tsu Upper Santa Fe Group deposits predating the Palomas Formation (upper Miocene) – Light brown to pink (7.5YR 6-7/3), sandy granule to pebble conglomerate in medium to thick, tabular to lenticular beds. Moderately consolidated, moderately calcareous, and internally massive to weakly imbricated. Cemented by either silica or calcite. Gravel is clast- to matrix-supported, very poorly to moderately sorted, angular to subrounded, and comprised of granules (30-50%), fine to medium (<15% coarse) pebbles (25-40%), cobbles (5-15%), and boulders (<5%) consisting of basaltic andesite (50-60%), felsites (40-50%), and trace pumice. Matrix consists of poorly to moderately sorted, subangular to subrounded, vfL-cU sand composed of 70-85% lithic (volcanic), 10-15% quartz, and 10-15% feldspar grains with up to 25% chalky carbonate powder (silt fraction). Locally, unit also includes beds of reddish clay with 10-15% vfU-mL sand and strong argillic soil development in upper 30-40 cm (12-16 in); carbonate nodules and tubules as well as prismatic peds with manganese coatings and slickensides are found in these paleosols. Unit is disconformably to gradationally overlain by QTpt. Likely correlative to the Rincon Valley Formation of Seager and others (1971). 0-326 m thick (0-1070 ft), thickening to the east (maximum thickness from Jochems and Koning, 2015a).

Tsl Lower Santa Fe Group (Oligocene to middle Miocene) – Relatively well-cemented Santa Fe Group consisting of volcaniclastic sandstone and conglomerate. Correlative to the Hayner Ranch Formation and possibly to the Thurman Formation (Seager et al., 1971; Seager et al., 1982). Described using exposures on the Skute Stone Arroyo quadrangle to the south (Koning et al., 2015). Estimated to be as much as 1100 m (3609 ft) thick in the southeastern part of the quadrangle using cross-section on Skute Stone Arroyo quadrangle (Koning et al., 2015).

Tlr Love Ranch Formation (Eocene) – Light red bouldery conglomerate, siltstone, and shale. Boulders may be up to 2 m (6.6 ft) in diameter and consist of sandstone and carbonates from the Bliss and El Paso Formations, respectively. Maximum thickness approximately 100 m (330 ft) [description from Mayer (1987)].

TERTIARY

Intrusive units

Tim Mafic dike (upper Eocene) – Black, aphanitic mafic material in a dike cutting Tccw in the western part of the quadrangle. Features 5% total phenocrysts of coarse to very coarse plagioclase and fine hornblende. Also contains rare gabbroic xenoliths <2 cm (0.8 in) in diameter.

Ti Undivided intrusive lithologies (middle Eocene?) – Dikes, sills, and small stocks or plugs of unknown lithology that form prominent ledges, buttes, or lineaments. Identified using aerial photography due to restricted access.

Tad Diorite porphyry stock (middle Eocene) – Medium gray to bluish gray weathering brownish gray to orange tan, non-vesicular, porphyritic, very fine- to medium-grained intrusive diorite. Groundmass is plagioclase-rich. Possible seriate texture. Phenocrysts include 8-14% plagioclase (0.5-2 mm with 1% outsized crystals up to 5mm; subhedral, equant to tabular; rare seritization), 5-10% hornblende (1-2 mm; subhedral to euhedral; prismatic; 2-3% pseudomorphs of earthy clay or biotite), and 2-7% biotite (microphenocrysts up to 1.5 mm; euhedral, platy; rarely glomeroporphyritic and commonly altered to Fe oxides). Quartz present in trace amounts. Forms small cliffs, ledges, and steep slopes. A sample from the Garcia Peaks in the Williamsburg NW 7.5-minute quadrangle to the north yielded an $^{40}Ar/^{39}Ar$ age of 40.35 ± 0.05 Ma (Jochems, 2015). Equivalent to units Td and Tqd of Mayer (1987).

Tia Biotite andesite dike (middle Eocene) – Light to dark gray, porphyritic, fine- to coarse-grained andesite dike. Groundmass of feldspar and brown glass. Phenocrysts include 35% plagioclase (euhedral-subhedral, tabular) and ~15-20% biotite (subhedral, equant to prismatic). Trace minerals include acicular hornblende, quartz, and magnetite. Intrudes entire length of Chavez Canyon fault. Biotite separate dated by K-Ar method at 43.7 ± 1.7 Ma (Lamarre, 1974) [description modified from Mayer (1987)].

Volcanic and volcaniclastic units

Tb Basalt flows (lower Pliocene) – Black to very dark gray, dense to strongly vesicular or scoriaceous, aphanitic to aphanitic-porphyritic, fine-grained basalt. Up to 10% of vesicles are filled by calcite in upper parts of flows. Phenocrysts include 3-6% olivine (up to 1 mm; subhedral; commonly glomeroporphyritic) and 2-4% plagioclase (up to 1.5 mm; subhedral to euhedral; commonly as fine laths). May contain 3-5% disseminated magnetite. Forms ledges capping high mesas. 4.5-5 m (15-16.5 ft) thick.

Tr Aphanitic-porphyritic rhyolite (upper Oligocene) – Light reddish gray to light purplish brown weathering light reddish brown, non-vesicular, aphanitic-porphyritic, medium-grained (trace to 1% coarse) rhyolite. Phenocrysts include 3-5% quartz (1.5-3 mm; anhedral; occasionally shattered, often embayed), 2-5% sanidine (2.5-6 mm; anhedral to subhedral, equant to tabular; glomeroporphyritic or cumulophyric with pyroxene), and 2-3% pyroxene (<0.5-2 mm; anhedral to subhedral, stubby/equant to tabular; occasional celadonite pseudomorphs). Forms gentle to moderate slopes. 0-53 m (0-174 ft) thick.

Tba Basaltic andesite (upper Oligocene) – Medium to dark gray weathering light gray to light brownish gray, thinly foliated (5-8 cm [2-3 in]) to massive, non- to moderately vesicular, aphanitic-porphyritic, fine- to medium-grained basaltic andesite. Vesicles commonly filled by calcite forming amygdales up to 2.5 cm (1 in) in diameter. Alternatively, amygdales may be filled with acicular zeolite. Phenocrysts include 1-12% plagioclase (up to 2 mm with sparse megacrysts up to 7 mm; subhedral to euhedral, equant to tabular), 2-4% pyroxene (1-2 mm with sparse megacrysts up to 5 mm; anhedral to subhedral, equant; common celadonite pseudomorphs surrounded by Fe oxide reaction rims), and trace to 4% biotite (0.5-1.5 mm; euhedral). Contains <3% disseminated magnetite and trace phenocrysts of quartz xenocrysts. Unit also contains trace lithic fragments of mafic material up to 1.5 cm (0.6 in) across. Forms cuestas, ledges, and gentle to moderate slopes. Lithologically similar and likely correlative to the Uvas Basaltic Andesite of Kottlowski (1953) and Bear Springs Basalt of Elston (1957); radiometric ages from these units range between 28 and 26 Ma (Clemons, 1979; Seager et al., 1984). 26-230 m (85-755 ft) thick.

Tkn Kneeling Nun Tuff (upper Eocene) – Pinkish gray or tan weathering light orange brown, non-vesicular, unwelded, porphyritic, fine- to coarse-grained, rhyolitic crystal tuff. Phenocrysts include 8-14% quartz (0.5-2.5 mm; anhedral to subhedral, occasionally equant; commonly shattered), 10-12% biotite (<0.5-1.5 mm; euhedral, tabular to platy or as books), 7-10% sanidine (1-3 mm; euhedral, tabular; chatoyant), 5-6% plagioclase (2-6 mm; anhedral to subhedral, equant to tabular, rarely skeletal; occasional seritization), and trace to 2% hornblende (up to 1 mm; subhedral to euhedral, prismatic to acicular). Contains 2-3% lithic fragments of reddish, plagioclase-phyric andesite and pumice as well as rare fragments of Tccw up to 2.5 cm (1 in) in diameter. $^{40}Ar/^{39}Ar$-dated at 35.34 ± 0.10 Ma (McIntosh et al., 1991). 5-68 m (16-225 ft) thick.

Tka Tuff of King Arroyo (upper Eocene) – Weak red to medium purplish brown weathering reddish brown, massive to weakly foliated, non- to slightly vesicular, unwelded to somewhat welded, porphyritic, fine- to medium-grained, rhyolitic ash flow tuff. Phenocrysts include 5-6% biotite (microphenocrysts to 1 mm; subhedral to euhedral, platy to tabular; rare cumulophyric texture with sanidine), 2-4% sanidine (1-3 mm; subhedral to euhedral, tabular; chatoyant), 1-3% quartz (1-2.5 mm; anhedral to subhedral, equant), and trace to 1% hornblende (up to 1 mm; euhedral, prismatic to acicular). Contains trace lithic fragments up to 3 cm (1.2 in) in diameter of dark purple, aphanitic rhyolite and white pumice. Flattening ratios suggested by vesicles range from 1:4 to 1:6 (width:length). Forms small cliffs and ledges. Equivalent to unit Txl1 of Mayer (1987) and possibly Bell Top tuff 4 /Tuff of Rocque Ramos Canyon with an $^{40}Ar/^{39}Ar$ age of 35.41 ± 0.08 Ma (Clemons, 1976; Harrison, 1990; McIntosh et al., 1991). 4-24 m (13-79 ft) thick.

Tcc Tuff of Chavez Canyon (middle to upper Eocene) – Dusky red weathering red to pale red, massive, non-vesicular, porphyritic-aphanitic, fine- to medium-grained lithic tuff. Phenocrysts include biotite and hornblende with subordinate plagioclase and quartz. Contains lapilli of rhyolitic to andesitic material and pumice. Includes small exposures of pinkish white, vitric tuff with scattered (<3%) phenocrysts of biotite and glass shards, and abundant dark reddish brown pumice. Forms cliffs, ledges, and steep slopes. Biotite from a sample of welded tuff of Chavez Canyon returned an $^{40}Ar/^{39}Ar$ age of 37.33 ± 0.06 Ma (L. Peters and W. McIntosh, pers. comm., 2016). 21-204 m (69-669 ft) thick (Mayer, 1987). Locally subdivided into welded and non-welded varieties:

Tccw Tuff of Chavez Canyon, welded unit – Medium to dark reddish brown, massive, non- to slightly vesicular, moderately to densely welded, porphyritic-aphanitic, fine- to medium-grained lapilli tuff. Phenocrysts include 4-6% biotite (up to 1 mm with occasional out-sized phenocrysts up to 2.5 mm; subhedral to euhedral, platy to equant; coppery luster), trace to 3% quartz (up to 1.5 mm; anhedral), 1-2% hornblende (1-2.5 mm; euhedral, prismatic), and trace-2% plagioclase (up to 1.5 mm; anhedral to subhedral, tabular). Contains 15-35% lapilli and small bombs of weak to pale red pumice and gray to dark purple, plagioclase-phyric andesite up to 0.8 cm (0.3 in) in diameter. Flattening ratios suggested by stretched lapilli and vesicles typically range from 1:8 to 1:20 (width:length), though they may be as low as 1:5 in larger lapilli. Biotite from a sample of this unit returned an $^{40}Ar/^{39}Ar$ age of 37.33 ± 0.06 Ma (L. Peters and W. McIntosh, pers. comm., 2016). 61-160 m (200-525 ft) thick.

Tccb Tuff of Chavez Canyon, unwelded unit – Light bluish gray weathering light tannish gray to light gray, medium- to very thick-bedded to massive, slightly vesicular/axiolitic, unwelded, aphanitic-porphyritic, medium- to coarse-grained lapilli tuff. Phenocrysts include 1-3% biotite (microphenocrysts to 1 mm; subhedral to euhedral, platy; coppery luster) and trace to 1% hornblende (up to 1.5 mm; euhedral, prismatic). Plagioclase and quartz are present in trace amounts. Contains 10-25% lapilli to fine blocks (3 mm to 7.5 cm) of light pinkish purple pumice and aphanitic rhyolite, porphyritic (biotite+hornblende) rhyolite and tuff, and plagioclase-phyric andesite up to 2.2 cm (<1 in) in diameter. 12-44 m (39-144 ft) thick.

Trp Rubio Peak Formation (Eocene) – Light gray with occasional yellowish red zones, weakly to somewhat consolidated, moderately clay-cemented (subordinate calcite cement), matrix-supported, massive and poorly stratified, poorly sorted laharic breccia. Clasts consist of angular to subrounded coarse pebbles (70-80%), cobbles (15-20%), and boulders (5-15%); the latter may be up to 0.5 m (1.6 ft) in diameter. Clast lithologies are limited to 3 types: light gray to light tan quartz diorite (Tad); purplish gray hornblende-phyric andesite; and dark reddish brown, porphyritic tuff with sanidine and biotite phenocrysts. Matrix consists of poorly sorted, angular to subrounded, vfU-cU sand-sized grains of quartz (40-50%), hornblende and biotite (35-40%), and feldspars (15-20%); roughly 20% of grains are essentially intact phenocrysts. Up to 75% of matrix material is replaced by clay in some intervals. 0-533 m (0-1750 ft) thick (Mayer, 1987).

PALEOZOIC

ℙb Bar-B Formation (Pennsylvanian; Desmoinesian to Missourian) – Limestone and mudstone with subordinate shale and conglomerate. Limestone is typically thin-bedded and nodular with brachiopods, bryozoans, crinoids, and gastropods. Mudstone is red, calcareous, and interbeds with chert to quartz-rich pebble conglomerate in the upper part of the unit. 55 m (180 ft) thick [description from Mayer (1987)].

ℙr Red House Formation (Pennsylvanian; Morrowan to Atokan) – Shale and subordinate limestone, siltstone, and conglomerate. Shale is black, red, or green and fissile. Limestone features lacy chert near top of unit and contains forams and phylloid algae among other fossils. Conglomerate in the upper part of the unit is cross-stratified and quartzose. 30-80 m (98-262 ft) thick [description from Mayer (1987)].

Oep El Paso Formation (lower Ordovician) – Limestone that is locally sandy with minor silicified sandstone near top. Maximum thickness 30-35 m (100-115 ft) in quadrangle [description from Mayer (1987)].

€Ob Bliss Formation (upper Cambrian to lower Ordovician) – Arkosic pebble conglomerate grading upward to arkosic, oolitic, or quartzose sandstone. Commonly iron-rich and locally glauconitic. Maximum thickness 20 m (66 ft) in quadrangle [description from Mayer (1987)].

UNITS IN CROSS-SECTION ONLY

p€u Proterozoic rocks, undivided (Paleo- to Mesoproterozoic?) – Granite, muscovite schist, and metadiorite. Aplitic granite comprises as much as 65% of Proterozoic lithologies exposed southwest of quadrangle. [description from Mayer (1987)].