GEOLOGIC MAP OF THE CLARK SPRING CANYON 7.5-MINUTE QUADRANGLE, SIERRA COUNTY, NEW MEXICO

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Open-File Geologic Map OF-GM 263

Scale 1:24,000

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EXECUTIVE SUMMARY

The Clark Spring Canyon 7.5-minute quadrangle is located in the southwestern part of the Palomas basin, an east-tilted half graben in the southern Rio Grande rift. The map area includes the eastern piedmont of Sibley Mountain and contains long stretches of the following east-flowing tributaries to the Rio Grande (from north to south): Trujillo Creek, Tierra Blanca Creek, and Berrenda Creek. The oldest rocks exposed in the quadrangle are andesites thought to be Oligocene (to perhaps lower Miocene) in age. Quaternary-Tertiary basin-fill deposits dominate the geology of the quadrangle. Basin-fill that is inferred to correlate to the Miocene Rincon Valley and Hayner Ranch Formations is found along the western margin of the quadrangle where the aforementioned drainages have incised canyons 65-90 m deep. Above these units lie up to 90 m of Plio-Pleistocene gravel, sand, silt, and clay belonging to the Palomas Formation. The Palomas Formation is exposed over approximately 80% of the map area. Younger deposits (middle Pleistocene to Holocene) include alluvial fans and well-defined suites of terraces in the major drainages. The youngest pre-modern deposits have been radiocarbon-dated at ~300-700 cal yr BP. The Palomas Formation and late Quaternary valley fill are most likely to host aquifers.

The units of the Palomas Formation exposed in the quadrangle were deposited on large hanging-wall distributary fan systems emanating from the eastern foothills of the Black Range and the southern Animas Mountains (Sibley Mountain). The Palomas Formation can be subdivided into 6 mostly conformable units. The transitional base of the Palomas Formation (QTplt) consists of ≤14 m of pebbly sand and matrix-supported gravel representing deposition by fluvial and debris-flow processes, respectively. The lower piedmont facies (QTpl) consists of up to 31 m of channel-fill gravels and minor sand. The upper part of this unit is vertically gradational with the middle piedmont facies (QTpm), which is dominated by extra-channel sediment with minor gravels that increase in abundance westward. This unit exceeds 48 m in thickness along the eastern boundary of the map area. The upper piedmont facies (QTpu) includes laterally extensive channel-fills with silt and mud interbeds up to 35 m thick. The upper part of this unit may be laterally gradational with the upper coarse piedmont facies (QTpuc), distinguished by a greater proportion of stacked channel-fill complexes and a capping petrocalcic horizon featuring stage IV carbonate accumulation. The upper coarse facies is as much as 30 m thick and is locally subdivided into inset channel-fills (QTpuci) that may reflect initial incision of the Rio Grande and its tributaries in the latest early Pleistocene.

Structures in the Clark Spring Canyon quadrangle are exceedingly rare. A single small west-down fault was observed in the upper unit of the Rincon Valley Formation (Trvu) along the upper reaches of Montoya Arroyo in the northwest part of the map area. Previous authors have suggested that the northern extension of the west-down Good Sight fault extends through the southeastern portion of the quadrangle, but Palomas Formation beds exposed in this area do not exhibit stratigraphic displacement.

INTRODUCTION

This report accompanies the *Geologic Map of the Clark Spring Canyon 7.5-Minute Quadrangle, Sierra County, New Mexico* (NMBGMR OF-GM 263). Its purpose is to discuss the geologic setting and history of this area, and to identify and explain significant stratigraphic and structural relationships uncovered during the course of mapping.

The Clark Spring Canyon quadrangle is located in the southern part of the Palomas basin in the southern Rio Grande rift (Fig. 1). It is bordered on the west by the Animas Mountains and is characterized by valleys of modest to considerable relief carved by east-flowing tributaries to the Rio Grande. These drainages head in the Black Range to the west. From north to south, they include Trujillo Creek, Tierra Blanca Creek, and Berrenda Creek (Fig. 1). Smaller east-flowing arroyos include Montoya Arroyo in the north and Sibley Canyon and Clark Spring Canyon in the south, the latter a tributary to Berrenda Creek. High interfluves between the major canyons in the quadrangle may underlie the Cuchillo surface, a constructional geomorphic surface with slopes that are typically less than 1-1.5°. The highest location in the quadrangle is 1578 m (~5180 ft) above sea level (asl) south of Trujillo Canyon in section 6, T17S, R6W. The lowest point is 1327 m (~4355 ft) asl where Tierra Blanca Creek exits the quadrangle in section 20, T17S, R5W.

Most of the Palomas basin, including the Clark Spring Canyon quadrangle, has an arid climate. The summer months (June through August) experience mean temperatures of 25.4-27.1° C (77.8-80.8° F). The winter months (December through February) experience mean temperatures of 5.3-7.8° C (41.5-46.1° F). Mean annual

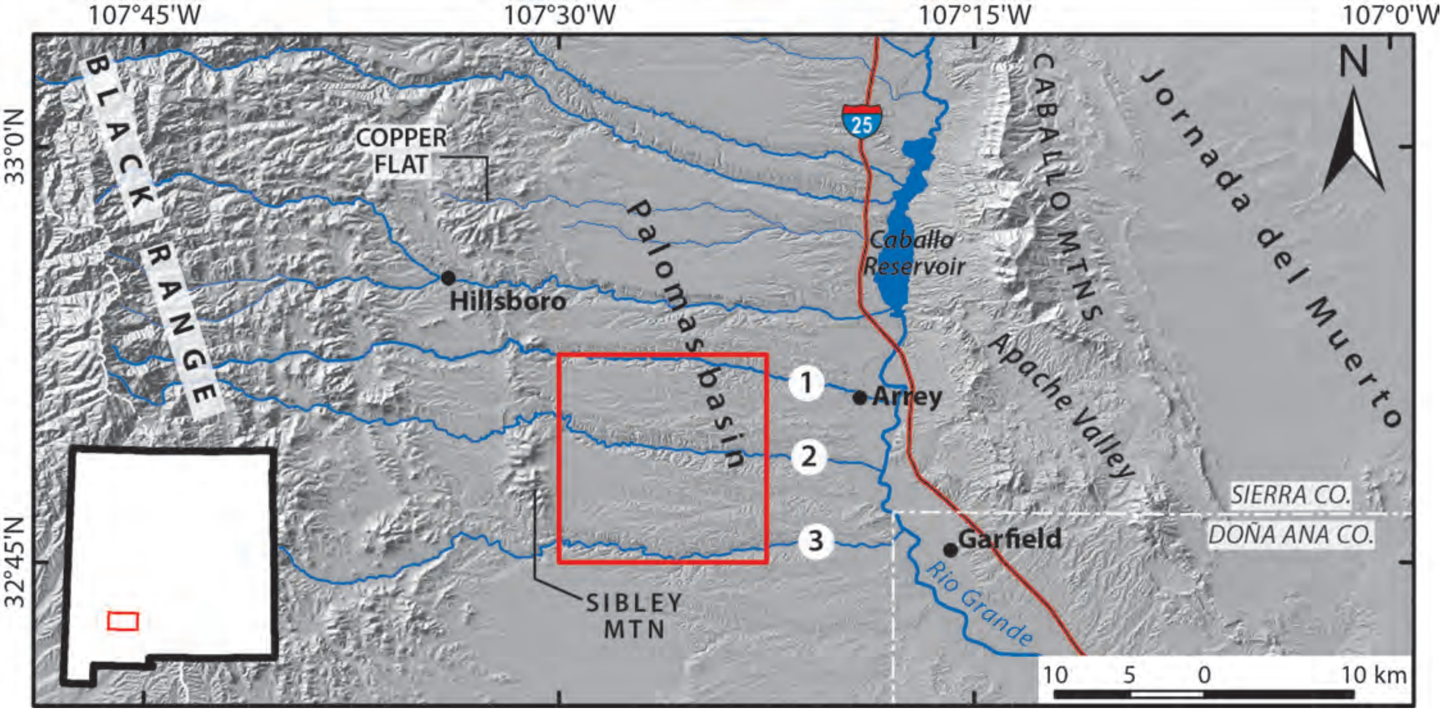

Figure 1. Shaded-relief map showing major physiographic features of the southern Palomas basin and surrounding areas. The basin is bordered on the east by the Caballo Mountains and on the west by the Animas Mountains (including Copper Flat and Sibley Mountain). The Clark Spring Canyon quadrangle is outlined in red. Inset map shows location in southern New Mexico. Major drainages crossing the quadrangle are: (1) Trujillo Creek; (2) Tierra Blanca Creek; and (3) Berrenda Creek.

precipitation is 29.90 cm (11.77 in), over half of which (15.27 cm) falls during the North American monsoon in the months of July through September. All climate data listed above are from the Caballo Dam station (ID# 291286) in the NWS Cooperative network and averaged over the years 1981-2010 (Western Regional Climate Center, 2016).

The geology of the Clark Spring Canyon quadrangle was previously mapped as part of the 1:125,000-scale northwest Las Cruces 1° x 2° sheet by Seager and others (1982). The Jug Canyon quadrangle to the south was mapped by Clemons (1979) at a scale of 1:48,000. Surrounding quadrangles mapped at 1:24,000 scale include Arroyo Cuervo (Jochems, 2017), Caballo (Seager and Mack, 2005), Garfield (Seager and Mack, 1991), Hillsboro (Jochems et al., 2014), the northern part of Lake Valley and the entirety of McClede Mountain (O'Neill et al., 2002a), and Skute Stone Arroyo (Koning et al., 2015).

This report includes a summary of the geologic setting before describing mapped units and their depositional settings by age, oldest to youngest. The structural geology of the area is briefly discussed, as are hydrogeologic implications for mapped basin-fill units. Detailed unit descriptions, radiocarbon age data, and $^{40}Ar/^{39}Ar$ age data are provided as appendices.

GEOLOGIC SETTING

The Clark Spring Canyon 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 southwestern part of the Palomas basin, an east-tilted half-graben containing Miocene through early Pleistocene basin-fill (Figs. 1, 2). The western border (i.e. hanging wall) of the Palomas basin is defined by the Animas Mountains, an east-dipping fault-block composed primarily of Paleozoic sedimentary and Eocene-Oligocene volcanic bedrock. The southern Animas Mountains include Sibley Mountain, which lies directly west of the map area.

Lower to middle Santa Fe Group basin-fill units record earlier phases of extension in the Rio Grande rift. Debris-flow deposits onlap Oligocene volcanic rocks in Berrenda and Tierra Blanca Creeks and suggest an element of paleotopographic relief near the western margin of a wide basin. An ancestral Palomas basin was in place by the late Miocene as indicated by eastward-fining conglomerate and sandstone of the Rincon Valley Formation (Mack et al., 1994a; Seager and Mack, 2003). These facies grade eastward to sandy clay and gypsiferous muds, consistent with interpretations of a large playa lake extending to at

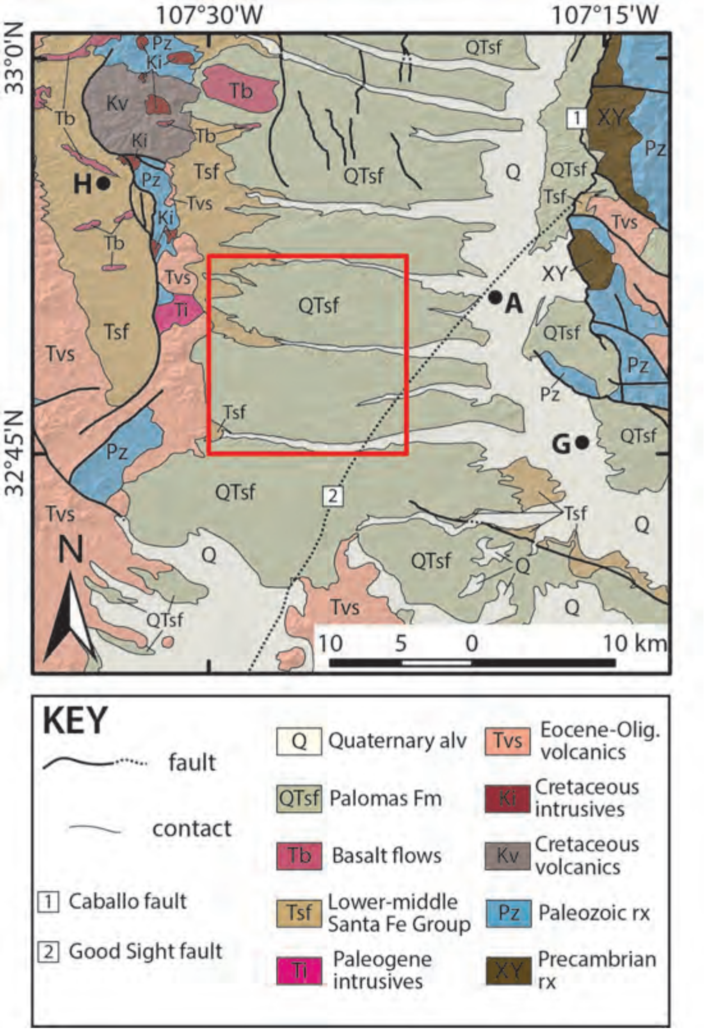

Figure 2. Simplified geologic map of the Palomas basin and vicinity (New Mexico Bureau of Geology and Mineral Resources, 2003). The Clark Spring Canyon quadrangle is outlined in red. Numbers correspond to faults discussed in text (see key). Towns abbreviated as follows: A = Arrey, G = Garfield, H = Hillsboro.

least the latitude of Berrenda Creek (Seager and Mack, 2003).

Plio-Pleistocene basin-fill of the Palomas Formation overlies lower to middle Miocene deposits with angular unconformity or, locally, gradational conformity. A late episode of block-faulting concurrent with deposition of the Palomas Formation resulted in segmentation and narrowing of older basins (Mack et al., 1994a). The Palomas Formation dominates the Clark Spring Canyon quadrangle and is differentiated on the basis of texture, clast lithology, and degree of cementation. This sediment was deposited on a large hanging-wall distributary fan system grading laterally to the ancestral Rio Grande to the east. Thus, piedmont alluvium of the Palomas Formation exposed in the quadrangle was mainly deposited in proximal to medial settings of bajadas with paleoflow oriented primarily toward the east or southeast.

Where preserved, the uppermost Palomas Formation is capped by a gently inclined (≤1.5°) plain known as the Cuchillo surface. This aggradational surface dates to ~0.8 Ma (Mack et al., 1993, 1998; Leeder et al., 1996), and is largely dissected by the large east-flowing drainages and their tributaries in the quadrangle. The Rio Grande and its tributaries began incising into the Palomas Formation in the latest early to middle Pleistocene, alternating with periods of backfilling that resulted in a series of inset terrace deposits distinguished by landscape position, texture, and soil development.

METHODS

Geologic mapping of the Clark Spring Canyon 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 at a scale of 1:12,000.

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 (occasionally moist) samples to Munsell soil color charts (Munsell Color, 2009).

For volcanic 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, i.e. stream terrace, alluvial fan, and valley-floor deposits. Surface characteristics dependent on age include desert pavement development, clast varnish, soil development, and preservation of original bar-and-swale topography. 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

Tertiary volcanic rocks

Two extrusive volcanic units thought to be Oligocene to perhaps early Miocene in age are exposed in or near Tierra Blanca and Berrenda Creeks along the western boundary of the map area. The andesite of Sibley Mountain (Tsa) is found in several steep gullies feeding Tierra Blanca Creek (Fig. 3), where it underlies units Tsmld and Trvl with angular unconformity. It is also onlapped by unit QTpuc. The andesite of Sibley Mountain is correlative with unit Tta of O'Neill and others (2002a) as well as the Pollack quartz latite of Hedlund (1977) and the Bear Springs basalt of Elston (1989). This unit is commonly foliated in the quadrangle (Fig. 3), and its phenocryst content is 3-4% plagioclase, 1-2% hornblende, and trace quartz. Chemical analysis of this unit by O'Neill and others (2002b) indicates that it borders between andesite and trachyandesite. Individual flows are commonly 9-18 m thick.

The andesite of Jaralosa Creek (Tja; Fig. 4) is ~20 m thick in the southwest corner of the quadrangle where it underlies unit Tsmld along Berrenda and Jaralosa Creeks. This unit is correlative with unit Ta1 of O'Neill and others (2002a) and contains phenocrysts of plagioclase (13-15%), pyroxene (2-3%), and quartz (trace). O'Neill and others (2002a, b) suggest that this andesite intrudes Santa Fe Group deposits but field relationships in the map area do not conclusively demonstrate this relationship. Instead, the andesite appears to underlie unit Tsmld with angular unconformity.

Groundmass samples for ^{40}Ar/^{39}Ar dating were collected from the andesites of Sibley Mountain and Jaralosa Creek. These returned ages of 31.54 ± 0.06 and 31.29 ± 0.03 Ma (2σ errors), respectively (Peters, 2016a). These are weighted mean ages from the flattest portion of the spectra, which exhibited evidence of ^{39}Ar recoil, Ar loss, and alteration. As such, we do not consider these to be robust ages. Seager and others (1984) assigned a whole rock K/Ar age of 28.1 ± 0.6 Ma to basaltic andesite flows west of Hillsboro. These flows are likely correlative to the andesite of Sibley Mountain based on texture and phenocryst content. We therefore consider unit Tsa to be late Oligocene in age.

Figure 3. Foliated andesite of Sibley Mountain (Tsa). Hammer for scale is ~25 cm long. Section 18, T17S, R6W.

Quaternary-Tertiary basin-fill

Basin-fill pre-dating the Palomas Formation

Six mapped basin-fill units underlying the Palomas Formation are inferred to have been deposited during the Miocene, representing the middle and lower parts

Figure 4. Andesite of Jaralosa Creek (Tja). Note backpack (white circle) for scale. Section 6, T18S, R6W.

of the Santa Fe Group. The oldest mapped basin-fill consists of debris flow facies of unit Tsmld. This unit is exposed in Trujillo, Tierra Blanca, and Berrenda Creeks near the western quadrangle boundary and may be subdivided into upper coarse and lower fine lithofacies. The lower subunit (Tsmldf) is as much as 15 m thick and consists of pinkish gray to pink (5-7.5YR) clay, silt, and very fine sand mixed with minor sand and pebbles (Fig. 5) that conformably underlies the upper subunit (the subunits also interfinger toward the north). Tsmldf onlaps paleotopographic relief developed on the andesite of Sibley Mountain. The upper subunit (Tsmldc) is over 50 m thick and consists of light reddish brown to light brown or pinkish gray to pink (5-7.5YR), massive, sandy conglomerate and pebbly sandstone (Fig. 5). Trace to 3% clasts of aphanitic, reddish brown, vesicular basalt of unknown age are found in Tsmldc. The provenance of such basaltic clasts is uncertain. Remnants of Pliocene basalt flows are found in the Animas graben between Tierra Blanca Creek and Copper Flat to the north (Seager et al., 1984; O'Neill et al., 2002a; Jochems et al., 2014), but these almost certainly post-date Tsmld. Thus, basaltic clasts in older Santa Fe Group units may have been sourced from now-eroded flows on the eastern margin of the Black Range or could represent relatively uncommon vesicular varieties of Oligocene basaltic andesites.

Above Tsmldc lies the lower unit of the Rincon Valley Formation (Trvl). This 80-m-thick unit includes brown to pinkish gray (7.5YR), well-bedded pebbly sandstone with subordinate pebble-conglomerate interbeds (Fig. 6a), and forms impressive cliffs along Tierra Blanca Creek in sections 7 and 18, T17S, R6W. This unit is typically well-cemented by calcite or opaline silica. Cross-stratification and clast-supported texture in Tierra Blanca Creek suggest that Trvl deposits are mostly fluvial in origin. However, occasional (10-30%) matrix-supported beds in Trujillo Creek could be debris flows. The upper contact of the unit is gradational with the upper unit of the Rincon Valley Formation (Trvu) and is placed at an up-section decrease in reddening, clast-size (typically <15% cobbles), and cementation. Trvu is as much as 52 m thick and consists of pebbly sand with some cross-stratification and lamination as well as imbricated pebble (±cobble) gravel (Fig. 6b). Thin, tabular to lenticular beds are relatively common in Trvu and consistent with deposition in a distal fan setting. Trace to 1% basalt clasts similar to those discussed above were noted in Trvu gravels exposed along Tierra Blanca Creek. In Berrenda Creek, Trvu grades eastward to a fine-grained lithofacies (Trvuf) of reddish brown to yellowish red (2.5-5YR), sandy clay (Fig. 6c). Correlative Rincon Valley Formation beds in the southern Garfield 7.5-minute quadrangle feature siltstone, mudstone, and claystone that is gypsiferous in

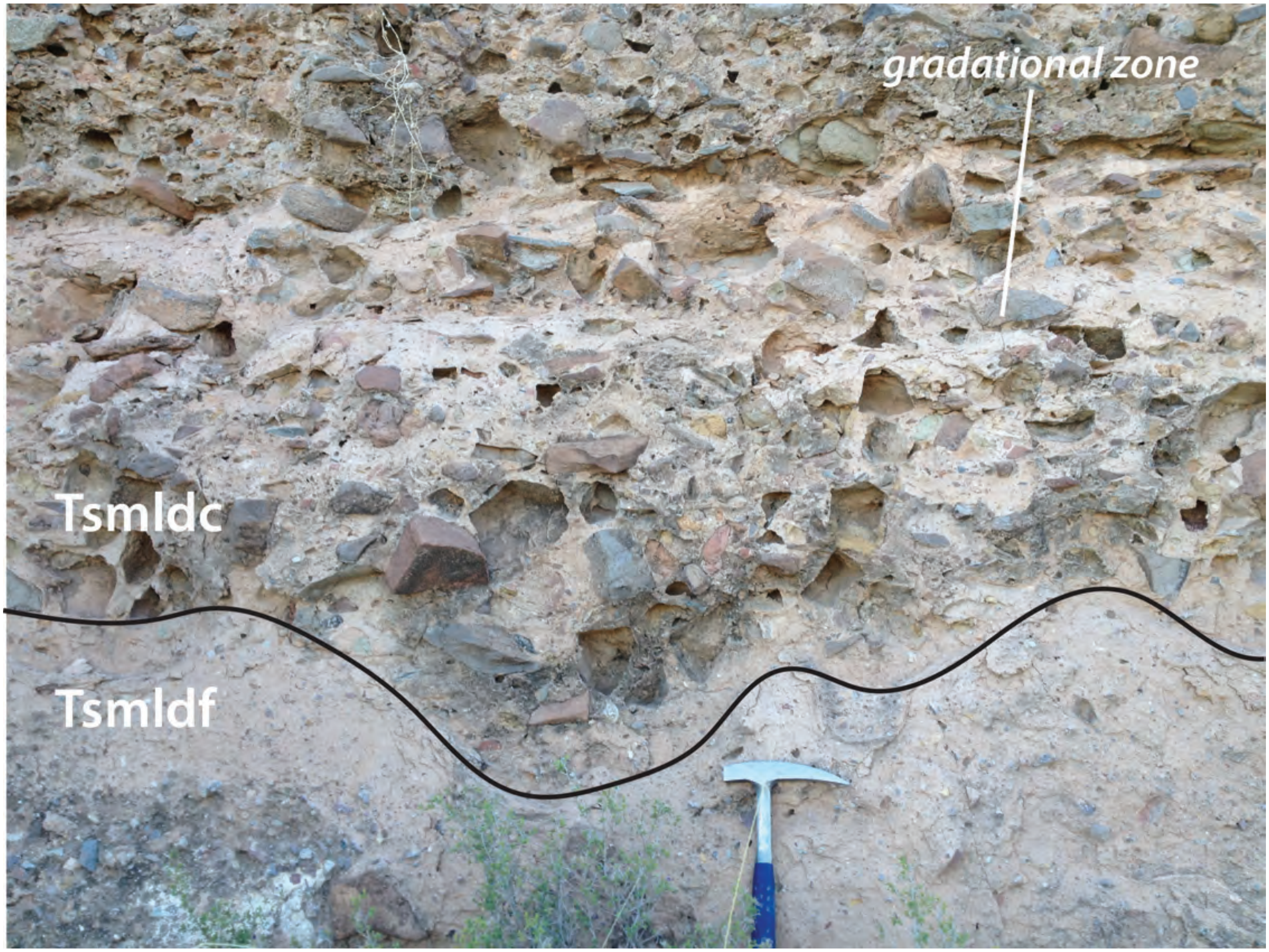

Figure 5. Transitional contact between Tslmdc (top gray gravel) and finer Tslmdf (pink, pebbly silt-clay-very fine sand near the hammer). Photo taken in upper Tierra Blanca Creek. The transition is illustrated by the ~1 m thick intermediary gravel with matrix similar to Tslmdf but clasts similar to Tslmdc. Note the loading structure just above the hammer head. The top of the transition unit (base of Tslmdc) has a scoured lower contact with <10 cm of relief.

places (Seager and Mack, 1991). In the map area, Trvuf beds were probably deposited in an alluvial flat near the western margin of a playa lake. This unit thickens from at least 15 m in the Clark Spring Canyon quadrangle to over 600 m near Hatch (King et al., 1971; Seager, 1995).

Age of basin-fill pre-dating the Palomas Formation

No direct age control exists for Santa Fe Group units predating the Palomas Formation in the Clark Spring Canyon quadrangle. The lower boundary of Tsmld is probably no older than earliest Miocene to latest Oligocene in age based on its nonconformable contact with andesite correlated to an ~28 Ma flow west of Hillsboro (Seager et al., 1984; O'Neill et al., 2002a). Thus, Tsmld and its subunits could correlate to the Hayner Ranch Formation of Seager and others (1971). The age of the lower Hayner Ranch Formation is bracketed by the underlying 27.4-27.0 Ma Thurman Formation in the southern Caballo Mountains (Boryta, 1994; Boryta and McIntosh, 1994).

Pre-Palomas units above unit Tsmld are correlated with the middle to late Miocene Rincon Valley Formation of Hawley and others (1969) and Seager and others (1971). This correlation is based on stratigraphic position, overall reddish color, and laterally gradational relationships with Rincon Valley Formation mapped to the east (Seager and Mack, 1991). In Selden Canyon (between Hatch and Las Cruces) the Rincon Valley Formation interbeds with basalts with K/Ar ages of ~9.6 Ma (Seager et al., 1984). The age of its base is not known but its upper boundary is constrained to be ~5.0 Ma by $^{40}Ar/^{39}Ar$ ages for basalts interbedded with the basal Palomas Formation (Seager et al., 1984; Jochems, 2015; Koning et al., 2015), as well as ~4.9 Ma cryptomelane in a fault zone cutting early

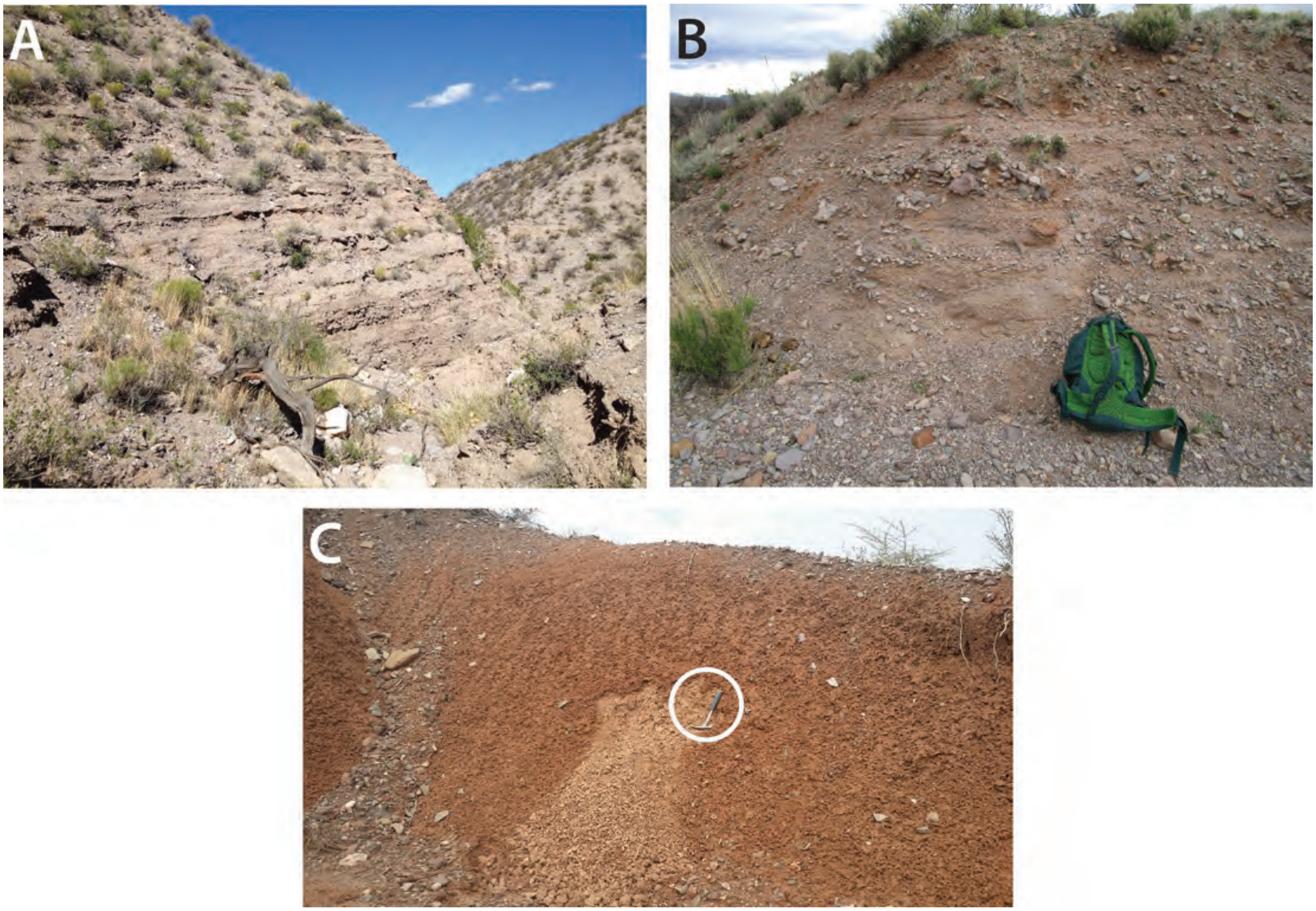

Figure 6. Rincon Valley Formation. (a) Well-cemented, pebbly sandstone of lower Rincon Valley Formation (Trvl) in upper Tierra Blanca Creek. This sediment is in very thin to laminated, horizontal-planar beds. Within the pebbly sandstone are ~25% clast-supported sandy pebbles in very thin to thin, tabular to lenticular beds. Gravel is commonly clast-supported, imbricated, and dominated by subrounded pebbles with only ~10% cobbles. The unit is interpreted to be deposited by stream-flow on an alluvial fan. Only 3% of the unit here consists of matrix-supported, cobbly to fine-bouldery medium, lenticular beds that may be related to debris flow deposition. (b) Upper Rincon Valley Formation (Trvu) on the south slope of Tierra Blanca Creek. Sediment is a pebbly sand in very thin to thin, tabular to lenticular beds; beds are also horizontal-planar laminated or low-angle cross-laminated within 10-30 cm-thick channel fills. In addition, this exposure exhibits 35-45% sandy pebbles in very thin thin, medium beds. Note reddish color. Backpack for scale. (c) Fine-grained lithofacies (Trvuf) showing dry and moist colors. This facies is interpreted as having been deposited in an alluvial flat or playa margin environment. Hammer for scale (white circle) is ~25 cm long. Section 7, T18S, R5W.

Rio Grande deposits in the Truth or Consequences area (Koning et al., 2016).

Basin-fill of the Palomas Formation

Basin-fill of the Plio-Pleistocene Palomas Formation can be subdivided into 6 units in the Clark Spring Canyon quadrangle. The oldest of these, the transitional base of the lower piedmont facies (QTplt), lies conformably and gradationally on the upper unit of the Rincon Valley Formation in Tierra Blanca and Trujillo Canyons. It consists of a thin (≤14 m) band of variably pinkish gray to light brown or reddish yellow to grayish brown (7.5-10YR), pebbly sand and mostly matrix-supported sandy pebble-cobble gravel (Fig. 7a). This gravel may be weakly to moderately cemented by calcite and exhibits 10-50% overprinting by stage I-III calcic horizons. Above QTplt lies similarly colored, sandy pebble channel-fills and minor sand of the lower piedmont facies (QTpl; Fig. 7b). This unit is up to 31 m thick, contains abundant stage II-III calcic horizons, and may also be moderately calcite-cemented. Both units feature fluvially deposited beds as indicated by laminations, low-angle cross-stratification, or imbrication. However, QTplt gravels contain fewer clasts of Paleozoic sedimentary lithologies than QTpl, and these are generally of smaller caliber. QTplt also contains rare clasts of vesicular basalt; these were not noted in QTpl. Finally, matrix-supported gravels representing debris-flow deposits are more common in QTplt than QTpl.

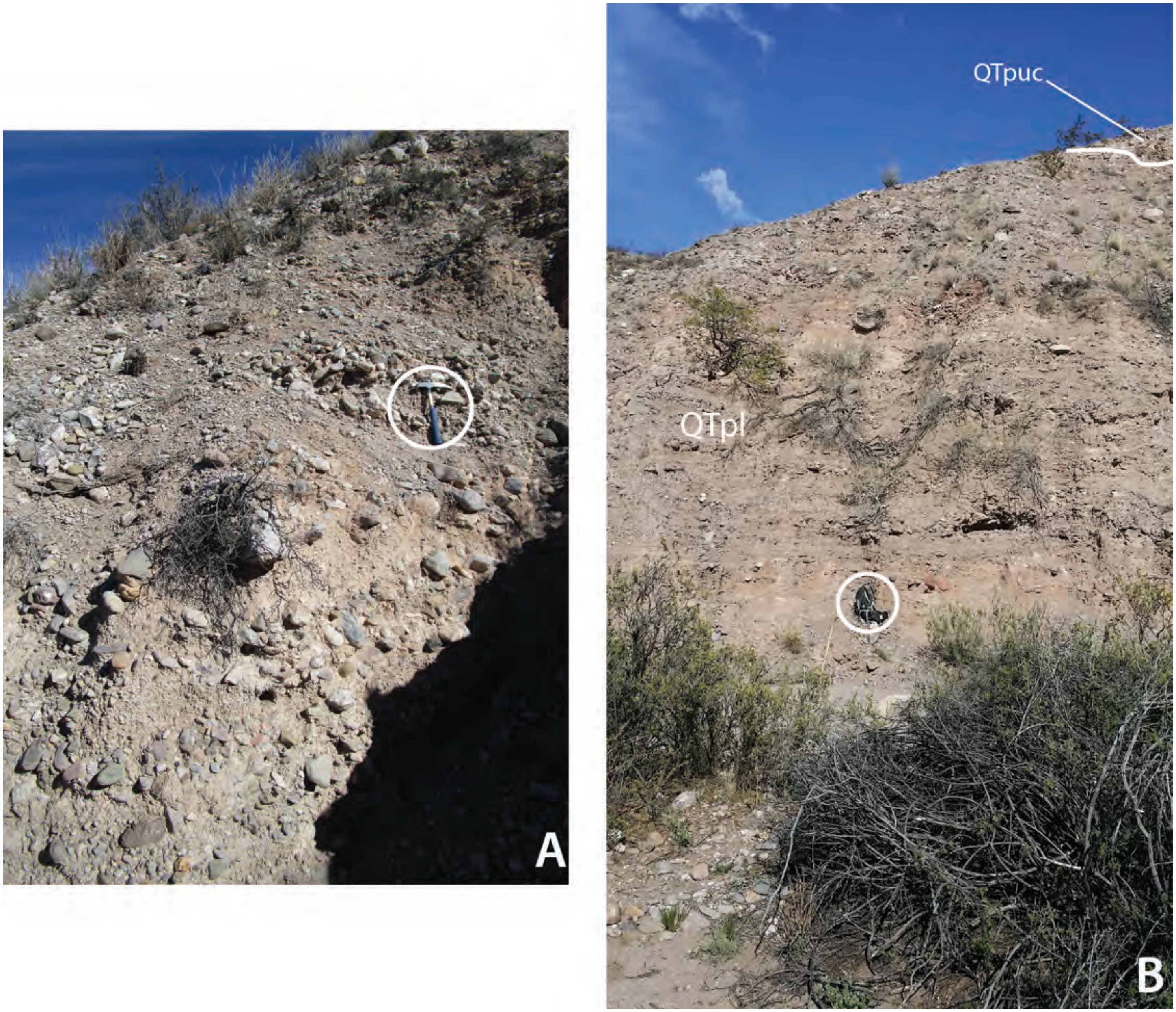

Figure 7. Lower piedmont facies of the Palomas Formation. (a) Lower transitional unit of the Palomas Formation (QTplt) in Trujillo Canyon. Near the hammer (white circle) is the lowest observed dark gray, vesicular, relatively non-altered basalt clasts seen in the Palomas Formation in this particular area (inferred to be Pliocene based on comparison with a dated clast on the north side of the canyon). Note the light orangish hue in the lower part of the photograph. (b) Lower piedmont facies (QTpl) consisting of moderately well bedded, lenticular to tabular, pebbly channel-fills. At upper right of photograph are lowermost beds of coarse QTpuc onlapping unit QTpl. Note backpack (white circle) for scale. Section 8, T18S, R6W.

The upper 3-10 m of unit QTpl grades vertically into the middle piedmont facies (QTpm). The middle piedmont facies includes reddish brown to light brown (5-7.5YR), extra-channel sediment with rare to minor gravel that increases in proportion westward. Silt and mud dominate this unit and are typically massive or poorly stratified. Gravel beds lack clay in their matrix. Paleosols commonly overprint fine-grained beds of QTpm and feature cambic and/or illuviated clay horizons overlying stage I-III calcic horizons with very fine carbonate masses, filaments, and nodules as well as prismatic peds and ped argillans (Fig. 8). This unit is up to 48 m thick and forms badland topography that dominates the eastern 1/3 of the quadrangle.

The upper piedmont facies (QTpu) lies above unit QTpm. The contact between these units is typically sharp and disconformable in the eastern part of the quadrangle (Fig. 9) but more gradual to the west. QTpu is as much as 35 m thick and marked by laterally extensive, occasionally stacked channel-fills with subordinate interbeds of extra-channel silt and mud. Dark reddish brown to reddish

Figure 8. Stacked paleosols in middle piedmont facies of the Palomas Formation (QTpm) along Montoya Arroyo. These buried soils commonly consist of illuviated clay and calcic horizons representing Bt, Btk, and/or K horizons. Stage II-III carbonate accumulation is indicated by carbonate filaments, nodules, and moderate impregnation of surrounding sediment. Paleosols are more common in unit at medial positions within the Palomas basin. Note truck for scale. Section 18, T17S, R5W.

Figure 9. Exposure of contact between upper piedmont facies of the Palomas Formation (QTpu, above) and QTpm (below). Contact occurs at abrupt, slightly wavy scour at base of gray gravel in center-right of photo. Gravel beds in unit QTpu are typically stacked, clast-supported, and well imbricated, and are interpreted as fluvial in origin. Section 6, T17S, R5W.

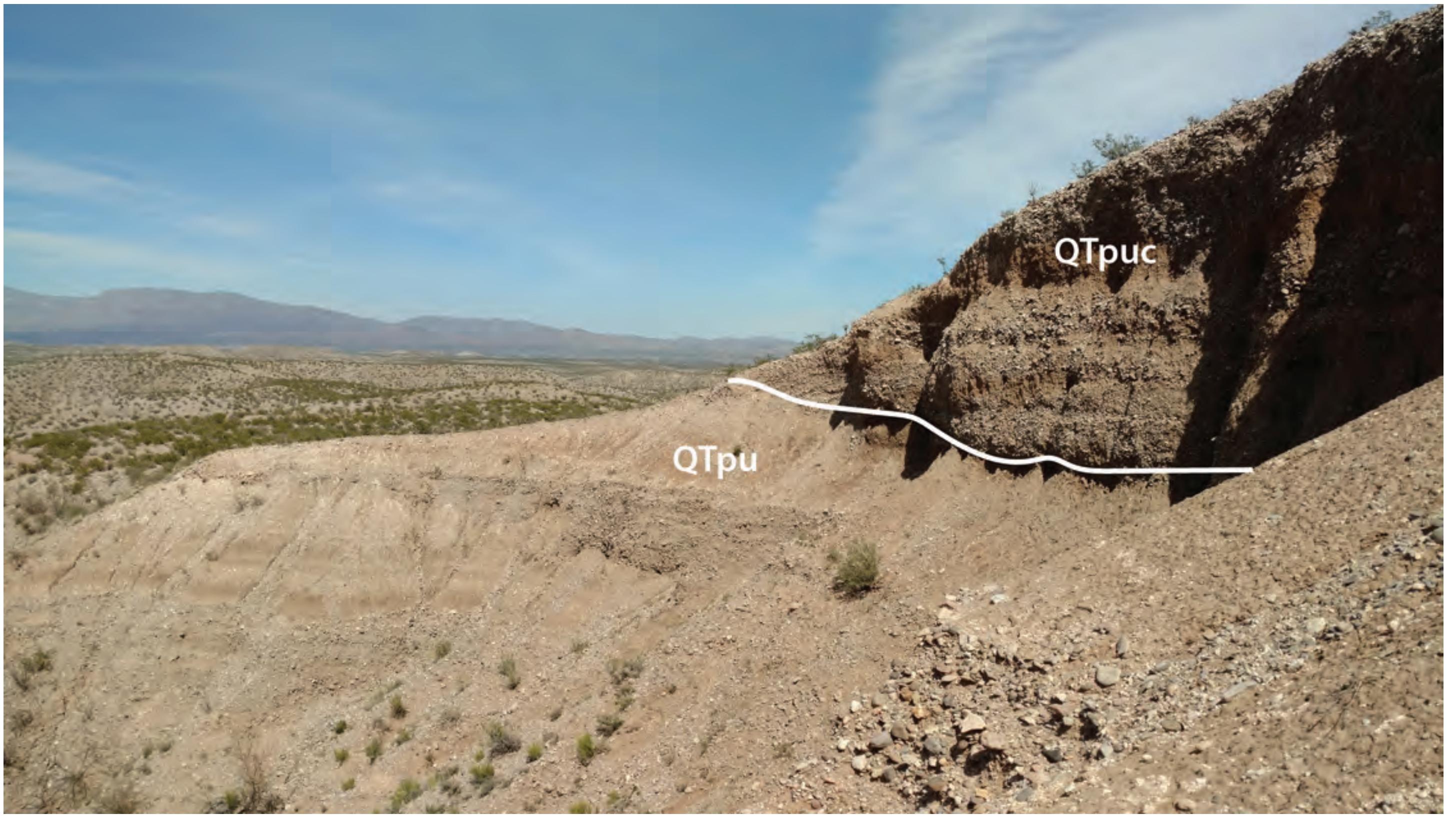

Figure 10. Exposure of contact between upper coarse piedmont facies of the Palomas Formation (QTpuc) and unit QTpu. QTpuc consists of stacked coarse channel fills that are occasionally weakly cemented by reddish clay. Median clast diameter in these deposits is as much as 25 cm. Here, basal QTpuc gravels scour underlying fine-grained sediment of QTpu but the contact may be gradational elsewhere. Section 26, T17S, R6W.

brown or yellowish red colors predominate (5YR), imparted by reddish clay flakes and coats in the matrix of gravel beds. Horizons of illuviated clay and/or stage I to II carbonate accumulation may be observed in fine-grained beds but are less common and more poorly developed than those in unit QTpm. Basal gravels in this unit form ledges or small cliffs whereas extra-channel beds form moderate to steep slopes.

The upper coarse piedmont facies (QTpuc) caps the Palomas Formation and forms a steep cliff on unit QTpu. The contact between these units is typically disconformable but may be laterally gradational south of Tierra Blanca Creek in the center of the map area. QTpuc is up to 30 m thick and contains reddish brown (5YR), stacked channel-fill gravel in greater proportions (>65%) than QTpu (Fig. 10). Median clast diameters in these gravels approach ~25 cm, considerably larger than underlying Palomas Formation units. Like QTpu, reddish clay flakes and coats are common in the gravel matrix and give the unit its reddish hue. QTpuc may be capped by stage IV calcic horizons underlying the constructional Cuchillo surface in the western parts of the quadrangle.

Inset beds of gravel similar to the upper coarse piedmont facies are mapped as unit QTpuci. Their surfaces generally lie 3-7 m below the Cuchillo surface and the underlying deposits are only 3-5 m thick. These deposits could reflect the initial incision of the Rio Grande and its tributaries in the latest early Pleistocene.

Age of the Palomas Formation

As with older Santa Fe Group units, no direct age control has been established for the Palomas Formation in the Clark Spring Canyon quadrangle. However, the unit has been dated elsewhere in the Palomas basin using fossil data (summarized by Morgan and Lucas, 2012), basalt radiometric ages (Bachman and Mehnert, 1978; Seager et al., 1984; Jochems, 2015; Koning et al., 2015, 2016), and magnetostratigraphic data (Repenning and May, 1986; Mack et al., 1993, 1998; Leeder et al., 1996). Together, these data indicate an age range of ~5.0-0.8 Ma for the Palomas Formation.

In the Skute Stone Arroyo quadrangle to the north, basalt clasts in well cuttings of QTplt from Percha Creek yielded whole rock $^{40}Ar/^{39}Ar$ isochron ages of ~5.9 to 5.1 Ma (Peters, 2016b). These samples returned somewhat disturbed age spectra but are generally similar to latest

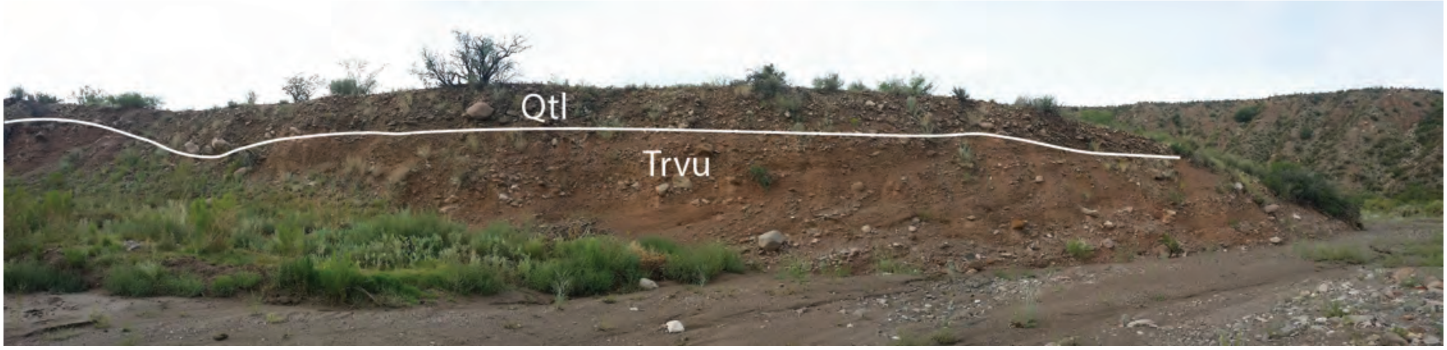

Figure 11. Lower strath terrace deposit (Qtl) on unit Trvu along Jaralosa Creek. Basal strath is shown by white line. The basal parts of terrace fills typically consist of coarse material overlying a scoured contact. These deposits are well imbricated with paleocurrent directions similar to modern stream courses. Younger terrace deposits feature weaker desert pavement, varnishing of surface clasts, and soil development than older deposits. Largest boulders in photo are ~30 cm in diameter. Section 6, T18S, R6W.

Miocene-earliest Pliocene ages for alkaline basalt flows exposed in the Animas graben and Palomas basin. For example, basalt flows near Hillsboro returned K/Ar and ^{40}Ar/^{39}Ar ages of ~4.9-4.4 Ma (Seager et al., 1984; Jochems, unpublished data). We therefore suggest that QTplt in the map area could have a maximum age of at most ~6 Ma and more likely closer to ~5 Ma. A similar interpretation was made by Koning and others (2015). However, we caution that QTplt basalt clasts are similar in appearance to reddish brown, vesicular basalt found in units Tsmldc and Trvu that could have originated from older, now-eroded flows.

If a maximum age of 5 Ma is assumed for QTplt, a broadly estimated maximum age of ~4.5-4.0 Ma may be assumed for QTpl. The upper boundary of QTpl is constrained by the age range of overlying QTpm, which is ~3.8-2.6 Ma (Jochems and Koning, 2015a; Koning et al., 2015). Two lines of evidence exist for this designation. First, a pumice bed in axial-fluvial sediment of the correlative Camp Rice Formation west of Hatch was radiometrically dated at ~3.1 Ma (Mack et al., 1996). This sediment intertongues with fine-grained extra-channel deposits inferred to grade laterally into the middle part of QTpm or equivalent units (Jochems, 2017). Second, QTpm and correlative Camp Rice Formation units feature well-established late early to early late Blancan vertebrate fossils around the Palomas and Hatch-Rincon basins (Morgan et al., 2011; Morgan and Lucas, 2012; Jochems, 2017).

Unit QTpu is thought to be ~2.6-1.8 Ma in age, again based primarily on fossil evidence. The base of QTpu in the Williamsburg quadrangle in the central Palomas basin lies just above the ~2.6-2.0 Ma Kelly Canyon Local Fauna site (Morgan et al., 2011; Morgan and Lucas, 2012). In the same area, upper QTpu beds yielded teeth of the extinct rabbit *Sylvilagus hibbardi* that indicate a late Blancan age of ~2.5-2.0 Ma (G. Morgan, pers. comm., 2014; Jochems and Koning, 2015a).

Stage IV calcic horizons typically cap the upper coarse piedmont facies (QTpuc) where it has not been dissected. These soils underlie the constructional Cuchillo surface, constrained to ~0.8 Ma by magnetostratigraphic data (Mack et al., 1993, 1998; Leeder et al., 1996). Thus, QTpuc is approximately 1.8-0.8 Ma in age, perhaps with a slightly older base (~2.0 Ma?) where it interfingers with upper QTpu beds near Tierra Blanca Creek.

Quaternary deposits (post-Palomas Formation)

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

As many as eight middle to late Pleistocene terraces may be found along the valley margins of Trujillo, Tierra Blanca, and Berrenda Creeks. Three such landforms are observed along smaller tributaries heading in the Palomas basin, such as Montoya Arroyo and Sibley Canyon. Terrace deposits are generally strath deposits 1-7 m thick (Fig. 11), but some fill terraces up to 18 m thick are found along Tierra Blanca Creek. In addition to their inset positions, terrace deposits are distinguished from gravelly sediment in the Palomas Formation by reddish to stronger brown colors (e.g., 5YR 4/4, 7.5YR 4/6), relatively common matrix clay (up to 40%), and larger clast size (up to 70 cm in diameter). Older deposits may have moderate desert pavement, moderate to strong varnish on up to 70% of

Table 1—Summary radiocarbon geochronology for Trujillo Creek samples.

Sample #	**Lab #**[a]	**Deposit**	**Material Dated**	**UTM N**[b]	**UTM E**[b]	**Conventional Age (^{14}C yr BP$_{1950}$)**[c]	**2σ Calibrated Age Range (cal yr BP$_{1950}$)**[d]	**Median Age (cal yr BP$_{1950}$)**[e]	**δ^{13}C (‰)**
CS-25-QayA	Beta-441930	Qah	charcoal	3639717	270834	330 ± 30	472-308 (1.000)	390 ± 80	-26.5
CS-25-Qah	Beta-441929	Qah	charcoal	3639717	270834	390 ± 30	509-427 (0.728) 391-388 (0..004) 379-320 (0.268)	415 ± 95	-27.1
CS-25-QayB	Beta-441931	Qah	charcoal	3639717	270834	770 ± 30	733-669 (1.000)	700 ± 30	-24.2

[a] All samples dated by AMS analysis, Beta Analytic Inc., Miami, FL.

[b] Coordinates given in UTM Zone 13S, NAD83.

[c] Conservative error of ± 30 ^{14}C yr BP$_{1950}$ is given for all samples due to 1σ < 30 ^{14}C yr BP$_{1950}$ in each case.

[d] 2σ calibrated age ranges calculated as relative probability using Calib 7.1 (Stuiver and Reimer 1993) and IntCal13 calibration curve of Reimer et al. (2013).

[e] Median age reported by averaging entire age range and rounding to nearest 5 yr. Error is difference between median and end values of range.

clasts at surface, and surface or buried calcic horizons with up to stage III+ carbonate accumulation. Tread elevations in the major drainages vary from 2 to 47 m above the modern valley floor (typically Qah surfaces). In Trujillo and Tierra Blanca Creeks, tread elevations are notably divergent from the modern valley floor in a downstream direction (i.e. to the east). Older alluvial fan deposits with steep slopes commonly grade to flatter terrace treads.

Valley-floor deposits that postdate terrace gravels include older, younger, and historical alluvium that is latest Pleistocene to Holocene in age. Older valley-floor alluvium (Qao) features pebble-cobble-boulder gravel and pebbly sand with subordinate gleyed to light gray (N 7/ to 10YR) clay-silt and clayey sand (Fig. 12a). These deposits underlie relatively undissected surfaces in the upper parts of the Montoya Arroyo and Sibley Canyon drainages in the western part of the quadrangle. Younger alluvium (Qay) consists of brown (7.5-10YR), relatively fine sand to silty sand interbedded with subequal gravelly beds (Fig. 12b). Soils in this deposit have typically been eroded, but locally a stage I to stage II calcic horizon is found. Historical alluvium (Qah) consists of dark brown to brown (10YR), interbedded sandy silt, pebbly sand, and sandy gravel. It typically has little to no soil development in its top soil (Fig. 12c). Weak stage I calcic horizons are rarely observed. Qah is coarser overall than Qay and exhibits a surface with more distinct bar-and-swale relief. Most of the broad valley-floor surfaces in the larger drainages of the map area are inferred to be Qah treads. Radiocarbon samples from an exposure of historical alluvium in section 34, T16S, R6W returned conventional ages between 330 ± 30 and 770 ± 30 ^{14}C yr BP (Table 1).

Other Quaternary deposits of note include piedmont deposits extending from the Sibley Mountains and landslide deposits. Three generations of piedmont deposits are recognized, including younger piedmont alluvium (Qpy) that grades to unit Qay. The ages of older piedmont alluvium units (Qpo1, Qpo2) are unknown but probably date to the middle to upper Pleistocene because these deposits are clearly inset by Qpy. Piedmont alluvium is dominated by clasts of the andesite of Sibley Mountain with angular to subangular cobbles and boulders indicating short transport distances.

Landslide deposits occur near Berrenda Creek in the southeast corner of the map area (section 7, T18S, R5W and section 12, T18S, R6W). They consist of pebble-cobble-boulder gravel lacking obvious fabric that underlies hummocky topography. Toreva blocks are tilted more steeply toward the valley walls from which they were derived and are elongate parallel to the modern stream course. These deposits were likely formed when beds of lower Palomas Formation piedmont failed on weak muddy deposits of the underlying upper Rincon Valley Formation, perhaps during wet intervals of the late Pleistocene.

In general, middle to late Pleistocene deposits in the Clark Spring Canyon 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 incised during full glacial conditions; (2) aggradation occurred during the transition to interglacial

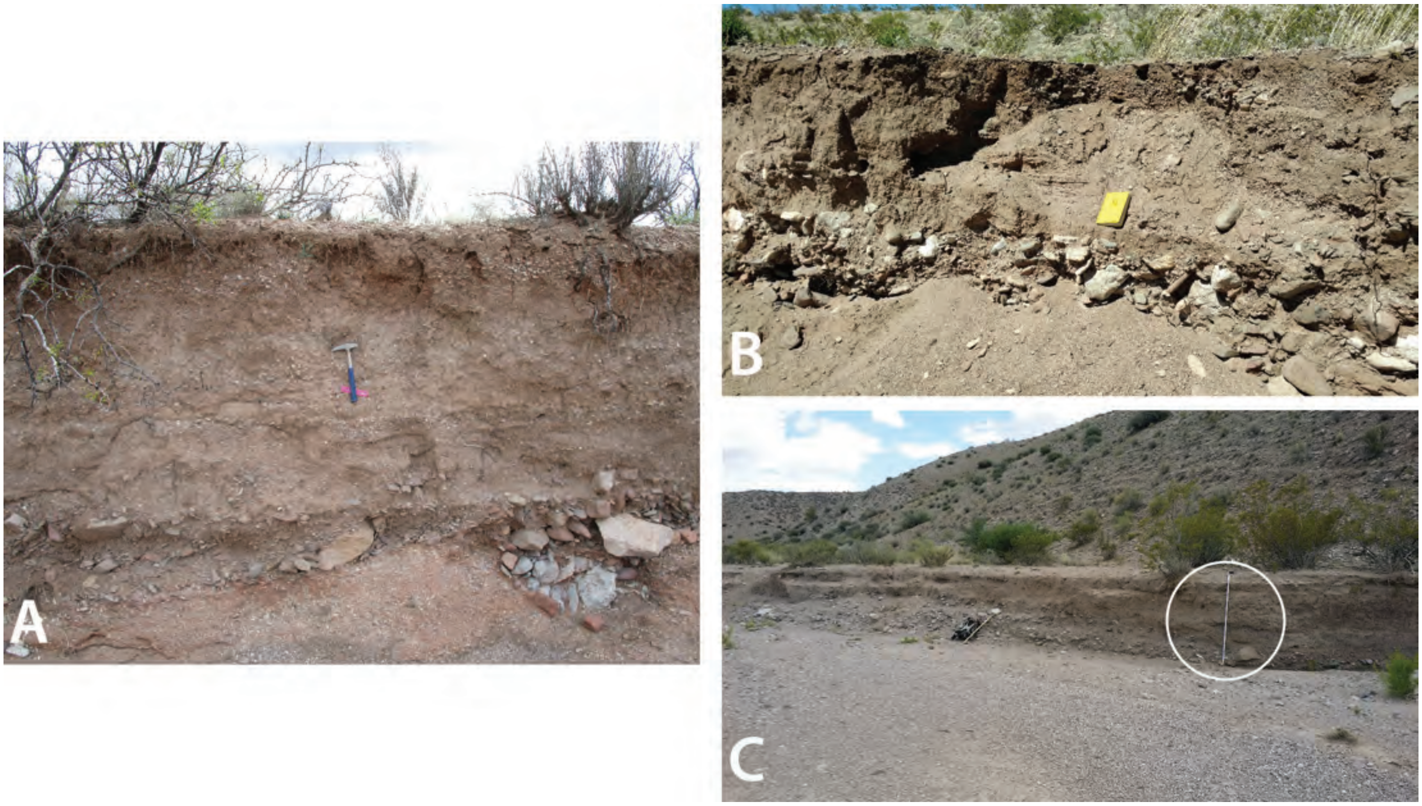

Figure 12. Late Pleistocene to Holocene valley-floor units. (a) Older alluvium (Qao) with a gleyed layer (near hammer head) in Montoya Arroyo. The reddish sediment at the base of the exposure is upper Rincon Valley Formation (Trvu). Above a 1-2 ft-thick basal gravel lies 6 ft of pebbly sand with 25% sandy pebble beds. The gleyed interval consists of silt-clay locally mixed with sand and pebbly sand. (b) Younger alluvium (Qay) in Sibley Canyon. This sediment is brown (7.5-10YR) fine sand and silt with subordinate pebble-cobble gravel. Erosion typically results in poor top soil preservation and coarse lag gravel, but locally A or even stage I to stage II calcic horizons are found. Notebook for scale is 18 cm long. Section 29, T17S, R6W. (c) Historical alluvium (Qah) along Berrenda Creek. These deposits underlie low treads with distinct bar-and-swale relief up to 30 cm. Top soil seldom exhibits soil development but may have a weak stage I calcic horizon in places. Tape for scale (white oval) is 1.5 m tall.

intervals due to decreased water to sediment ratios; and (3) stability ensued for the remainder of the interglacial interval (Gile et al., 1981).

Holocene incision episodes inferred from radiocarbon ages of valley-floor deposits indicate that down-cutting of east- or 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 climate due to sparser vegetation.

STRUCTURAL GEOLOGY

Unlike most other quadrangles in the Palomas basin, the Clark Spring Canyon quadrangle contains essentially no structures with surface expression. Middle to late Quaternary scarps disrupting the Cuchillo surface are common in the central basin (e.g., Jochems, 2015; Jochems and Koning, 2016) but are not observed here. The upper Palomas Formation is very rarely faulted south of Percha Creek (e.g., Koning et al., 2015), indicating a lack of intrabasin tectonism in the southwestern Palomas basin during and after the early Pleistocene. A very small, west-down normal fault exhibits less than 1 m of throw in unit Trvu in Montoya Arroyo on the border of sections 5 and 6, T17S, R6W. No other faults were recorded during the course of mapping.

Previous workers have inferred a buried, northeast-trending arm of the west-down Good Sight fault south of the Clark Spring Canyon quadrangle (Seager et al., 1982; Mack et al., 1994b). This interpretation is based on a linear zone of steep Bouguer gravity gradient between the latitudes of 32°30’ and 32°40’ west of the modern-day Good Sight Mountains (Fig. 13; Decker and Smithson, 1975; Daggett and Keller, 1982; Daggett et al., 1986; Gilmer et al., 1986). The position of the Good Sight fault in the cross section accompanying the Clark Spring Canyon geologic map is projected from the map

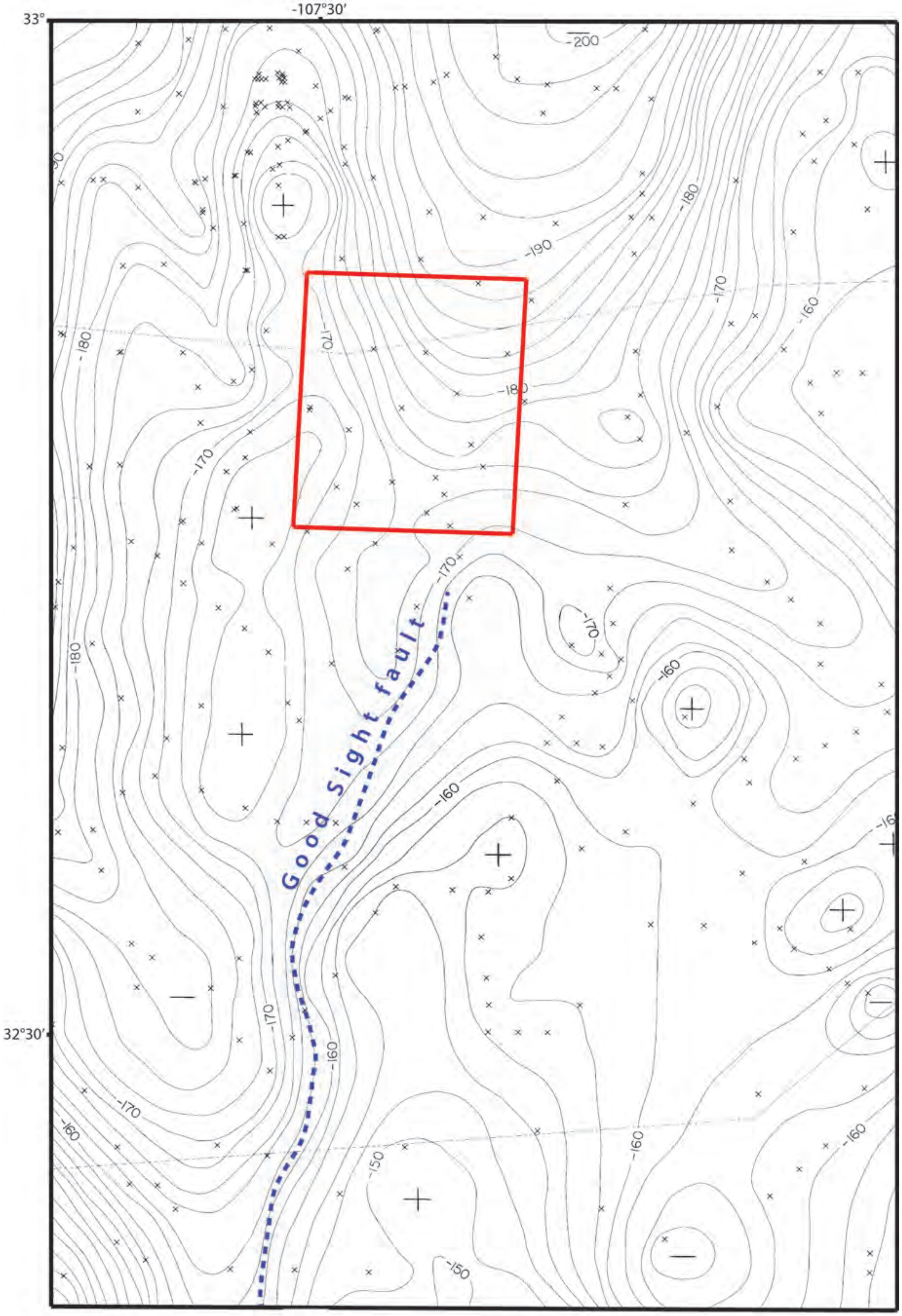

Figure 13. Complete Bouguer gravity anomaly map of southern Palomas and Hatch-Rincon basins and vicinity (modified from Daggett and Keller, 1982). The Clark Spring Canyon quadrangle is outlined in red. Trace of Good Sight fault in blue is interpretation of Seager and others (1982). This inferred fault trace intersects the southeast corner of the map area when projected along strike. Contours in mGals; x's denote locations of gravity measurements.

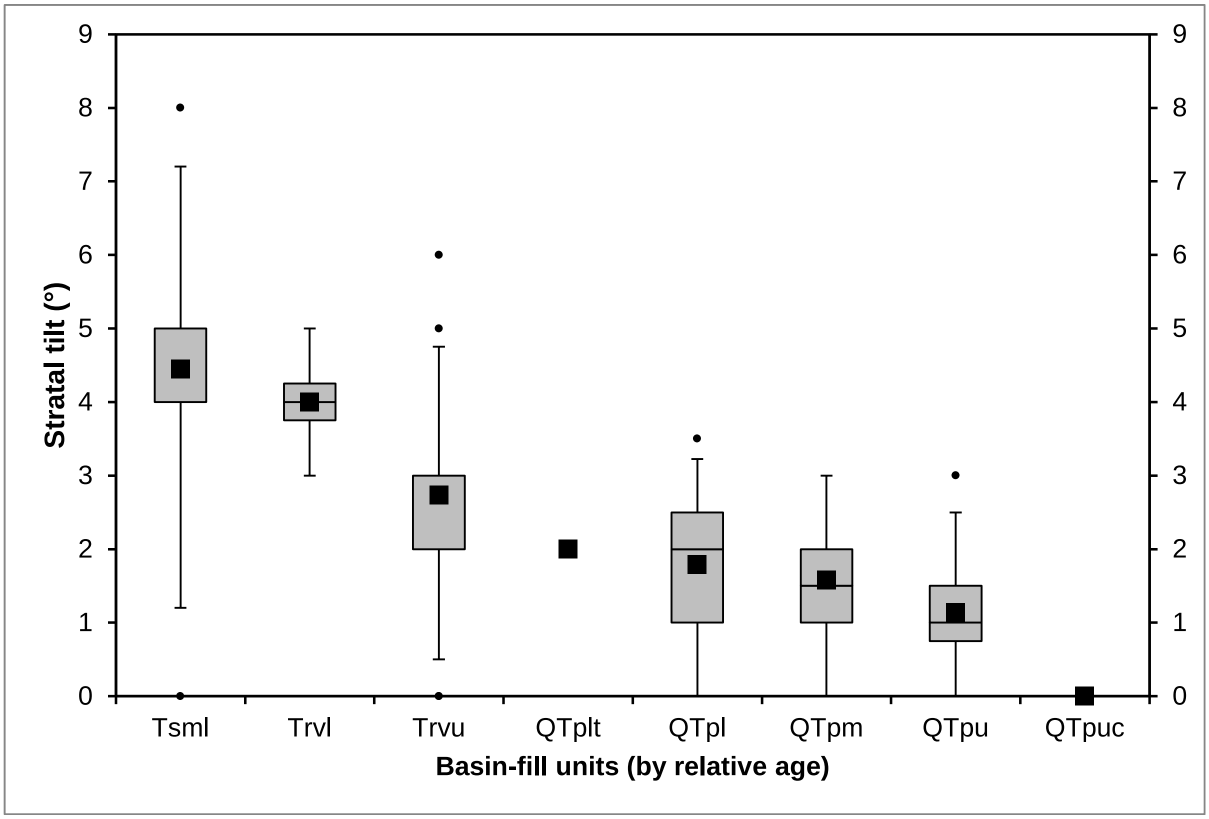

Figure 14. Stratal tilts for late Cenozoic basin-fill units on the Clark Spring Canyon quadrangle. Lines within boxes are medians, ends of boxes are 25th and 75th percentiles, and whiskers are 5th and 95th percentiles. Circles are outlying data. Units listed oldest on left to youngest on right. The following are *n* for each unit: Tsml (9), Trvl (12), Trvu (26), QTplt (1), QTpl (12), QTpm (13), QTpu (11), QTpuc (2).

of Seager and others (1982). Stratigraphic displacement of subsurface units along the fault is schematic. Palomas Formation beds are not disrupted in the vicinity of the inferred trace of the fault. Thus, assuming it continues beneath the southeast corner of the quadrangle, its activity may be locally constrained to the Miocene or earlier.

Because no structure of Plio-Pleistocene age is found in the map area, dips of Palomas Formation strata should primarily represent tilting of the Palomas basin half graben toward its master fault, the west-down Caballo fault. Accordingly, 63% of measured strikes (right-hand rule) are between 340° and 020°, and 93% are between 315° and 045°.

Older basin-fill units typically exhibit greater dip values than the Palomas Formation (Fig. 14). Thus, deposition of basin-fill in this part of the Rio Grande rift was concurrent with tilting of the Palomas half graben. Mean dips for pre-Palomas strata are 2.7-4.4° whereas Palomas beds exhibit mean dips of 2° or less. Figure 14 shows that mean dips consistently decrease with younger basin-fill units, with stratal tilt rates perhaps increasing between the deposition of units Trvl and Trvu (note that unit Tsml includes measurements in upper coarse and lower fine debris flow lithofacies). This interpretation differs with that of Koning and others (2015) for basin-fill units on the Skute Stone Arroyo quadrangle in that relatively constant early to middle Miocene tilting rates are not apparent in the Clark Spring Canyon data. However, a lack of age control for pre-Palomas Formation units may influence the apparent inflection in tilt rates between units Trvl and Trvu.

HYDROGEOLOGY

Aquifers of adequate quantity and quality for domestic, municipal, and agricultural use in the Palomas basin are nearly always found in the Santa Fe Group and younger Quaternary valley fill units. Below, we briefly describe the potential of basin-fill and valley-floor units of the Clark Spring Canyon quadrangle for groundwater resources.

Santa Fe Group units predating the Palomas Formation commonly contain gravels of alluvial origin. However, the intrinsic permeability of these deposits is likely to be affected by matrix- versus clast-supported texture and cementation. Conglomerates in units Tsmldc and Trvl, for instance, are typically well cemented by calcite

Figure 15. Clark Spring found at the contact between units QTpl and Trvuf. Clayey alluvial flat or playa margin sediment of Trvuf acts as an aquitard for groundwater flowing through relatively uncemented pebbly channel-fills of QTpl. Section 7, T18S, R5W.

or silica, potentially hindering groundwater flow. It is possible that cementation in these units decreases toward the east, in which case they could form relatively deep but viable aquifers in the center of the Palomas basin (Koning et al., 2015).

Unit Trvu features weakly cemented, clast-supported gravel with little (<1-7%) interstitial clay and is therefore more likely to effectively transmit fluid. However, it grades eastward to clayey playa (margin) facies of unit Trvuf, an aquiclude or aquitard bearing little or no freshwater (Wilson et al., 1981).

The lower piedmont facies of the Palomas Formation (QTpl) and its transitional base (QTplt) generally consist of pebbly sand and gravel with varying degrees of cementation. Unit QTpl is likely to be a more effective aquifer because of a greater proportion of channel-fill gravels with no matrix clay. Indeed, in the southeast corner of the map area (section 7, T18S, R5W), Clark Spring and Shorthorn Spring emanate from the contact between units QTpl and Trvuf (Fig. 15). The quality of this water is unknown. Extra-channel silt and mud in the middle piedmont facies (QTpm) is unlikely to host aquifers and may act as an aquitard in some cases. However, clast-supported pebbly gravel in this unit lacks matrix clay and may effectively transmit groundwater where saturated. Units QTpu and QTpuc lie above the zone of saturation throughout most of the Palomas basin.

Middle to late Pleistocene valley-floor units have been shown to be high-quality, productive aquifers in the Palomas and Hatch-Rincon basins (Davie Jr. and Spiegel, 1967; Wilson et al., 1981). Well data from these areas suggest that gravels and sands in units Qah and Qay may be saturated as little as 1.5 m below the surface. These units act as hydraulic connections between the surface and units of the underlying Palomas Formation (Davie Jr. and Spiegel, 1967).

There is no permanent population living in the Clark Spring Canyon quadrangle and there are only several wells used for agricultural purposes (i.e. water for livestock). Thus, there is currently low potential for the development of groundwater resources in the map area. Future investigations of local groundwater resources should focus on the lower piedmont facies of the Palomas Formation as well as younger Quaternary valley-floor units as these deposits are most likely to yield high quality water in significant amounts.

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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, UK, Oxford University Press, 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.

Boryta, J.D., 1994, Single-crystal ^{40}Ar/^{39}Ar provenance ages and polarity stratigraphy of rhyolitic tuffaceous sandstones of the Thurman Formation (late Oligocene), Rio Grande rift, New Mexico [M.S. thesis]: New Mexico Institute of Mining and Technology, 95 p.

Boryta, J.D., and McIntosh, W.C., 1993, Single-crystal ^{40}Ar/^{39}Ar provenance ages and polarity stratigraphy of rhyolitic tuffaceous sandstones and sandstones of the Thurman Formation (late Oligocene), Rincon Hills and Caballo Mountains, New Mexico: New Mexico Geological Society Spring Meeting Proceedings, p. 15.

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, v. 291, p. 5–25.

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: New York, John Wiley & Sons, 398 p.

Daggett, P.H., and Keller, G.R., 1982, Complete Bouguer anomaly map of northwest part of Las Cruces 1° x 2° sheet, *in* Seager, W.R., Clemons, R.E., Hawley, J.W., and Kelley, R.E. eds., Geology of northwest part of Las Cruces 1° x 2° sheet: New Mexico Bureau of Mines and Mineral Resources Geologic Map 53.

Daggett, P.H., Keller, G.R., Morgan, P., and Wen, C.L., 1986, Structure of the southern Rio Grande rift from gravity interpretation: Journal of Geophysical Research, v. 91, p. 6157–6167.

Davie Jr., W., and Spiegel, Z., 1967, Geology and water resources of Las Animas Creek and vicinity, Sierra County, New Mexico: New Mexico State Engineer Hydrographic Survey Report, 44 p.

Decker, E.R., and Smithson, S.B., 1975, Heat flow and gravity interpretation across the Rio Grande rift in southern New Mexico and west Texas: Journal of Geophysical Research, v. 80, p. 2542–2552.

Elston, W.E., 1989, Overview of the Mogollon-Datil volcanic field, *in* Chapin, C.E., and Zidek, J. eds., Field excursions to volcanic terranes in the western United States—Volume I, southern Rocky Mountain region: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 43–46.

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.

Hawley, J.W., Kottlowski, F.E., Strain, W.S., Seager, W.R., King, W.E., and LeMone, D.V., 1969, The Santa Fe Group in the south-central New Mexico border region, ^{in} Kottlowski, F.E., and LeMone, D.V., eds, Border Stratigraphy Symposium: New Mexico Bureau of Mines and Mineral Resources Circular 104, 52–76 p.

Hedlund, D.C., 1977, Geologic map of the Hillsboro and San Lorenzo quadrangles, Sierra and Grant Counties, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-900-A, scale 1:48,000.

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.

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 OF-GM 251, scale 1:24,000.

Jochems, A.P., 2017, Geologic map of the Arroyo Cuervo 7.5-minute quadrangle, Doña and Sierra Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 261, 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 OF-GM 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., and Koning, D.J., 2016, Geologic map of the Saladone Tank 7.5-minute quadrangle, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 259, scale 1:24,000.

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.

King, W.E., Hawley, J.W., Taylor, A.M., and Wilson, R.P., 1971, Geology and ground-water resources of central and western Doña Ana County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Hydrologic Report 1, 64 p.

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., The Geology of the Belen Area: New Mexico Geological Society Guidebook 67, p. 459–478.

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, doi: 10.1126/science.1154339.

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.

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., Seager, W.R., and Kieling, J., 1994a, Late Oligocene and Miocene faulting and sedimentation, and evolution of the southern Rio Grande rift, New Mexico: Sedimentary Geology, v. 92, p. 79–96.

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.C., eds., Mogollon Slope, West-Central New Mexico and East-Central Arizona: New Mexico Geological Society Guidebook 45, p. 135–142.

Mack, G.H., McIntosh, W.C., Leeder, M.R., and Monger, H.C., 1996, Plio-Pleistocene pumice floods in the ancestral Rio Grande, southern Rio Grande rift, USA: Sedimentary Geology, v. 103, p. 1–8.

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., Leeder, M., 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.

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.

Morgan, G.S., Sealey, P.L., and Lucas, S.G., 2011, Pliocene and early Pleistocene (Blancan) vertebrates from the Palomas Formation in the vicinity of Elephant Butte Lake and Caballo Lake, Sierra County, southwestern New Mexico, *in* Sullivan, R.M., Lucas, S.G., and Spielmann, J.A., eds., Fossil Record 3: New Mexico Museum of Natural History and Science Bulletin 53, p. 664–736.

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

New Mexico Bureau of Geology and Mineral Resources, 2003, Geologic map of New Mexico: New Mexico Bureau of Geology and Mineral Resources, scale 1:500,000.

O'Neill, J.M., Lindsey, D.A., Hedlund, D.C., Nutt, C.J., and Ratté, J.C., 2002a, Geologic map and cross sections of the McClede Mountain quadrangle and northern part of the Lake Valley quadrangle, Sierra County, New Mexico, *in* O'Neill, J.M., ed., Geologic investigations in the Lake Valley area, Sierra County, New Mexico: U.S. Geological Survey Professional Paper 1644, plate 1, scale 1:24,000.

O'Neill, J.M., Lindsey, D.A., Hedlund, D.C., Nutt, C.J., and Ratté, J.C., 2002b, Geology of the Lake Valley area, *in* O'Neill, J.M., ed., Geologic investigations in the Lake Valley area, Sierra County, New Mexico: U.S. Geological Survey Professional Paper 1644, 1–17 p.

Peters, L., 2016a, ^{40}Ar/^{39}Ar geochronology results from Clark Spring Canyon quadrangle: New Mexico Geochronology Research Laboratory Internal Report NMGRL-IR-928, 9 p.

Peters, L., 2016b, ^{40}Ar/^{39}Ar geochronology results from well cuttings from the Percha Creek well: New Mexico Geochronology Research Laboratory Internal Report NMGRL-IR-933, 14 p.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., and others, 2013, IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP: Radiocarbon, v. 55, p. 1869–1887.

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., 1995, Geologic map of the Hatch quadrangle, Doña Ana County, New Mexico [released 2010]: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 213, scale 1:24,000.

Seager, W.R., and Mack, G.H., 1991, Geology of Garfield quadrangle, Sierra and Doña Ana Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 128, 24 p.

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, 144 p.

Seager, W.R., and Mack, G.H., 2005, Geology of the Caballo and Apache Gap quadrangles, Sierra County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map 74.

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.

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, p. 87–99.

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

Stuiver, M., and Reimer, P.J., 1993, Extended ^{14}C data base and revised CALIB radiocarbon calibration program: Radiocarbon, v. 35, p. 215–230.

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

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

Western Regional Climate Center, 2016, Caballo Dam, New Mexico NCDC 1981-2010 monthly normals: <<http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1286>>. Last accessed November 28, 2016.

White, J.D.L., and Houghton, B.F., 2006, Primary volcaniclastic rocks: Geology, v. 34, p. 677–680.

Wilson, C.A., White, R.R., Orr, B.R., and Roybal, R.G., 1981, Water resources of the Rincon and Mesilla Valleys and adjacent areas, New Mexico: New Mexico State Engineer Technical Report 43, 514 p.

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

APPENDIX A

Detailed descriptions of lithologic units on the
Clark Spring Canyon 7.5-minute quadrangle

QUATERNARY

Hillslope and mass movement units

Qsw Slopewash (Holocene to uppermost Pleistocene) – Clay, very fine sand, and minor silt and fine to coarse sand in very thin, poorly stratified, lenticular beds. Loose and massive. Sand may contain ~5% scattered pebbles. Commonly exhibits cumulic soil development with medium to coarse, sub-blocky peds, illuviated clay, and stage I carbonate morphology. May interfinger with upper Pleistocene fan deposits; otherwise, deposit onlaps fan gravels in most places. 1-2 m thick.

Qtc Talus and colluvium (Holocene to uppermost Pleistocene) – Cobbles and boulders (minor pebbles) lying at the base of steep escarpments or forming aprons flanking upland areas on Tsmld and Tsa in section 18, T17S, R6W. Deposit may exhibit massive or slope-parallel textures. Gravel is very poorly sorted and angular to subangular. Where present, matrix is also very poorly sorted. Thickness unknown but inferred to be <3 m in most places.

Qls Landslide deposit (upper Pleistocene?) – Light brownish to light reddish, sandy pebble-cobble-boulder gravel underlying hummocky topography along Berrenda Creek in section 7, T18S, R5W and section 12, T18S, R6W. Loose with random or massive fabric. No soils observed. Deposit forms toreva blocks that overlie Trvuf and are elongate parallel to the modern stream course. Up to ~15 m thick.

Valley-floor units

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

Qam Modern alluvium (modern to ~50 years old) – Light brownish gray (10YR 6/2) sand and pebble-cobble-boulder gravel in modern channels, troughs, and bars. Loose, non-calcareous, and moderately well imbricated to rippled to (rarely) fluted. Gravel is clast-supported, very poorly to poorly sorted, subrounded to well rounded, and consists of pebbles (60-90%), cobbles (10-30%), and boulders (up to 10%) of >80% volcanic lithologies and up to 10% Paleozoic sedimentary lithologies. Sand consists of poorly sorted, subrounded to rounded, fU-cU grains (5-8% very coarse grains) composed of 50-55% quartz, 30-40% lithics (volcanic>chert), and 10-20% feldspar with little or no clay. Veneers of brown (7.5YR 5/3) silt and clay are occasionally found at channel margins. Maximum thickness approximately 3 m.

Qamh Modern and historical alluvium, undivided (modern to ~700 years old) – Modern alluvium (Qam) and subordinate historical alluvium (Qah). See detailed descriptions of each individual unit.

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

Qah Historical alluvium (~50 to ~700 years old) – Well-defined, interbedded sandy silt, pebbly sand, and sandy gravel in very thin to medium, tabular to lenticular beds. Loose. Sand and pebbly sand is commonly horizontal-planar or gently cross-stratified. Gravel is clast- to matrix-supported, commonly imbricated, poorly to moderately sorted, subrounded (minor subangular), and consists of very fine to very coarse pebbles (60-100%), cobbles (0-30%), and boulders (0-10%) of >80% volcanic lithologies. In sandy gravel beds, sand matrix consists of dark brown to brown (10YR 3-5/3), very poorly to poorly sorted, subrounded to well rounded (minor subangular), fL-cU grains (very fine to medium in floodplain facies) of 60-70% lithics (volcanic), 20-30% quartz, and 10-20% feldspar with no clay. In pebbly sand and sand intervals, sand consists of grayish brown to brown (10YR 5/2-3), poorly to moderately sorted, subrounded (minor subangular), very fine to very coarse grains (very fine to medium in floodplain deposits). Along Berrenda Creek, deposit commonly features brown (10YR 4/3), loose, moderately calcareous, thin- to thick-bedded (6-40 cm), tabular, internally massive, well sorted, sandy silt with 5-10% subrounded, lithic-rich, vfL-fU sand. Top soil characterized by weak to no soil development. Where present, soil is characterized by a weak stage I calcic horizon. Commonly bioturbated by fine to coarse roots and burrows. Surface has distinct bar-and-swale relief (10-30 cm) and very weak clast varnishing in places. These surface characteristics, in addition to relatively distinct bedding and color, distinguish deposit from Qay. Radiocarbon samples from an exposure in section 34, T16S, R6W returned conventional ages between 330±30 and 770±30 ^{14}C yr BP.

	Unit generally overlies a sharp contact with or is inset into Qay. Inferred to be 1.5-4 m thick.
Qahm	Historical and modern alluvium, undivided (modern to ~700 years old) – Historical alluvium (Qah) and subordinate modern alluvium (Qam). See detailed descriptions of each individual unit.
Qahy	Historical and younger alluvium, undivided (~50 years old to lower Holocene) – Historical alluvium (Qah) and subordinate younger alluvium (Qay). See detailed descriptions of each individual unit.
Qar	Recent (historical + modern) alluvium (modern to ~700 years old) – Historical alluvium (Qah) and modern alluvium (Qam) in approximately equal proportions. See detailed descriptions of each individual unit.
Qary	Recent (historical + modern) and younger alluvium, undivided (modern to lower Holocene) – Recent alluvium (Qah + Qam) and subordinate younger alluvium (Qay). See detailed descriptions of each individual unit.
Qay	Younger alluvium (Holocene) – Brown (10YR 4-5/3; 7.5YR 5/2-3), relatively fine sand to silty sand interbedded with subequal to minor gravelly beds in very thin to medium, tabular to lenticular beds. Weakly consolidated. Finer sediment is generally massive within beds but locally occurs in laminated to very thin beds that are horizontal-planar to low-angle cross-stratified. This sand is moderately sorted, subrounded (lesser subangular), and mainly very fine- to medium-grained, locally with minor coarse to very coarse sand and scattered pebbles. Its composition reflects the local source area. In small, steep canyons (drainage area of <1 mi2), sediment is generally a sandy gravel in very thin to thin, tabular to lenticular beds with <10% low-angle cross-bedding. Gravel is commonly clast-supported, poorly to moderately sorted, subrounded, and consists of pebbles and subordinate cobbles of compositions reflecting the local source area. Channel-fill sand consists of poorly sorted, subrounded (minor subangular), fine to very coarse grains composed mostly of lithics (volcanic). Finer sediment typically exhibits cumulic soil profiles characterized by moderate to strong, fine to coarse, subangular, blocky peds, locally with faint evidence of clay illuviation (especially clay bridges). Buried calcic horizons are not usually observed. Erosion typically results in poor top soil preservation and coarse lag gravel, but locally a stage I to stage II calcic horizon is found. Darkened A horizons ~10 cm thick (dark grayish brown, 10YR 4/2) are rare. Surface has very subdued bar-and-swale topography (<20 cm) and weak clast varnish. Compared to Qah, bedding is slightly less distinct and commonly internally massive due to infiltration of fine-grained sediment, bioturbation, and weak cumulic soil development. The deposit also has more fine sand and silty-clayey sand beds and a surface with more subdued bar-and-swale relief than Qah. 1-4 m 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 + Qam). See detailed descriptions of each individual unit.
Qayo	Younger and older alluvium, undivided (Holocene to uppermost Pleistocene) – Younger alluvium (Qay) and subordinate older alluvium (Qao). See detailed descriptions of each individual unit.
Qao	Older alluvium (Holocene to uppermost Pleistocene) – Sandy pebble-cobble and pebble-cobble-boulder gravel, pebbly sand, and clay-silt in laminations to very thin to medium, tabular to lenticular beds. Loose to consolidated and horizontal-planar laminated to planar cross-stratified (foresets 10-40 cm thick). Gravel is clast-supported to open-framework, poorly sorted, subrounded (minor subangular), and consists of pebbles (50-70%), cobbles (25 to >50%), and boulders (3-12%) of volcanic lithologies including up to 1% basalt. Sand consists of yellowish to reddish brown (5YR 4/6 to 5/4), moderately sorted, subangular to subrounded, fU-vcU (<7% vfl-fL) grains dominated by lithics (volcanic) with 1-2% partial clay films. Subordinate (up to 20%) beds in upper 1.2 m of deposit feature gleyed, light brownish gray or light gray (10YR 6/2; 10YR-2.5Y 7/1-2, N 7/) clay-silt with minor sand-pebble interbeds 5-15 cm thick. Surface is typically smooth and undissected. Tread height 2-2.5 m above modern grade. 1-2.2 m thick.

Alluvial fan and piedmont units

Valley-floor alluvial fans

Qfamh	Modern and historical fan alluvium, undivided (modern to ~700 years old) – Modern fan alluvium and subordinate historical fan alluvium (Qfah). Modern fan alluvium is grayish or yellowish brown (10YR 5/2 or 5/4), loose, sandy pebble-cobble gravel graded to Qam or Qah; see description for Qfah.
Qfah	Historical fan alluvium (~50 to ~700 years old) – Brown (7.5-10YR 4-5/3) to pale brown (10YR 6/3), sandy fine pebble gravel interbedded with pebble-cobble gravel in medium to thick (10-60 cm), tabular to lenticular beds. Loose, weakly to moderately calcareous, and massive to well imbricated. Gravel is clast- to matrix-supported and consists of pebbles (50-100%) and cobbles (0-50%) of volcanic lithologies reworked from QTp. Matrix of pebbly gravel consists of very poorly to poorly sorted, subangular to rounded, vfL-cL sand (20-25% very coarse sand to granules) composed of 70-80% lithics (volcanic) and 20-30% quartz + feldspar with 5-15% brownish clay bridges. Matrix of pebble-cobble gravel consists of very poorly to poorly sorted, subangular to rounded, vfU-cL sand composed of 65-75% lithics (volcanic) and 25-35% quartz + feldspar with no clay. Weak A horizons may be observed in the upper 15-20 cm of the deposit. Deposit is bioturbated by very fine to coarse roots and burrows. Surface features bar-and-swale topography with <25 cm of relief. Deposit underlies fans graded to Qah. At least 1.7-2 m thick.
Qfahm	Historical and modern fan alluvium, undivided (modern to ~700 years old) – Historical fan alluvium (Qfah) and subordinate modern fan alluvium. Modern fan alluvium is grayish or yellowish brown (10YR 5/2 or 5/4), loose, sandy pebble-cobble gravel graded to Qam or Qah; see description for Qfah.
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.
Qfar	Recent (historical + modern) fan alluvium (modern to ~700 years old) – Historical fan alluvium (Qfah) and modern fan alluvium in approximately equal proportions. See descriptions for Qfamh and Qfah.
Qfary	Recent (historical + modern) and younger fan alluvium, undivided (modern to lower Holocene) – Recent fan alluvium (Qfar) and subordinate younger fan alluvium (Qfay). See descriptions for Qfamh, Qfah, and Qfay.
Qfay	Younger fan alluvium (Holocene) – Interbedded silt, sand, and sandy gravel in thin to thick (6-33 cm), tabular to broadly lenticular or wedge-shaped beds. Loose to weakly consolidated and moderately to strongly calcareous. Sandy beds may be planar cross-stratified (foresets up to 5 cm thick) or horizontal-planar laminated. Granule-pebble and pebble-cobble gravel consists of clast-supported, imbricated, very poorly to poorly sorted, subangular to rounded clasts of volcanics reworked from QTp. Gravel matrix consists of brown to grayish brown (7.5-10YR 5/2), poorly sorted, subangular to rounded, fU-cU sand composed of 60-70% lithics (volcanic), 20-30% quartz, and 10-20% feldspar with no clay. Finer-grained beds consist of brown to light brown (7.5YR 5-6/3), very poorly to poorly sorted, subrounded to rounded, silt to mU or fL-cU sand composed of 60-90% lithics (volcanic) and 10-40% quartz + feldspar, occasionally with 10-20% floating granules and fine to medium pebbles. Topsoil may feature weak overprinting of upper 8-10 cm by incipient A horizon. Elsewhere, surface overlies a stage I+ calcic horizon or is erosionally stripped. Deposit is bioturbated by fine to very coarse roots and burrows. Surface features subdued bar-and-swale topography with <10-15 cm of relief. Deposit underlies fans graded to Qay. At least 1.5-1.7 m thick.
Qfaym	Younger and modern fan alluvium, undivided (modern to lower Holocene) – Younger fan alluvium (Qfay) and subordinate modern fan alluvium. Modern fan alluvium is grayish or yellowish brown (10YR 5/2 or 5/4), loose, sandy pebble-cobble gravel graded to Qam or Qah; see description for Qfay.
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) alluvial fan deposits, undivided (modern to lower Holocene) – Younger fan alluvium (Qfay) and subordinate recent fan alluvium (Qfar). See descriptions for Qfamh, Qfah, and Qfay.
Qfayo	Younger and older alluvial fan deposits, undivided (Holocene to upper Pleistocene) – Younger fan alluvium

(Qfay) and subordinate older fan alluvium (Qfao). See detailed descriptions of each individual unit.

Qfao Older fan alluvium (lower Holocene to upper Pleistocene) – Reddish brown (5YR 4/4) to brown (7.5YR 4/3-4) or pale brown (10YR 6/3), sandy pebble-cobble-boulder gravel and pebbly sand in medium to very thick (25-140 cm), tabular to lenticular beds. Loose and weakly to moderately calcareous. Gravel is clast- to matrix-supported (35-40 and 60-65%, respectively), massive to variably imbricated, very poorly to poorly sorted, subangular to rounded, and consists of pebbles (50-95%), cobbles (5-30%), and boulders (0-25%) of volcanic lithologies reworked from QTp. Matrix sand consists of poorly sorted, subangular to subrounded, silty, medium to coarse (minor vfL-mU) grains of 60-70% lithics (volcanic), 15-20% quartz, and 15-20% feldspar with up to 25% brownish free-grain argillans. Pebbly sand is similar to gravel matrix. Well-developed topsoil is locally preserved and characterized by a strong calcic horizon (stage II+ to III+) overlain by cambic or illuviated clay horizons. Up to 60-70% of clasts at surface clasts may be varnished. Basal gravels scour underlying units up to 70 cm. Deposit underlies fans graded to Qao, which is often eroded. 1-10 m thick.

Alluvial fans prograding onto terrace deposits

Qf Alluvial fans prograding onto terrace deposits (upper to middle Pleistocene) – Reddish brown (5YR 4-5/3-4) to brown or light brown (7.5YR 5/4 or 6/3), well graded, sandy gravel and pebbly sand in very thin to medium, tabular to lenticular beds. Loose to somewhat consolidated. Gravel is clast- to matrix-supported, occasionally imbricated, poorly sorted, subangular to subrounded, and consists of pebbles (15-50%), cobbles (15-35%), and boulders (1-30%) of mostly volcanic lithologies reworked from QTp. Matrix sand consists of poorly to moderately sorted, subrounded to subangular, mostly medium to very coarse grains dominated (>70-75%) by lithics (volcanic). Up to 10% of beds consist of clayey-silty, very fine- to medium-grained sand with minor, scattered coarser sand and pebbles with ~10% cobbles. Deposit may contain a lower bouldery interval 0.5-2 m thick. This interval generally fines upward to sandy gravel and pebbly sand. Individual fan deposits are distinguished by surface characteristics and relative abundance of soils related to age. (i.e., greater surface clast varnishing and stronger calcic horizons may be present on older deposits). Deposit is graded to upper to middle Pleistocene terrace deposits in larger drainages. 1-7 m thick.

Qfb1 Alluvial fans prograding onto lowermost Berrenda Creek terraces (Qtb1) (uppermost Pleistocene) – Alluvium underlying fan surfaces graded to Qtb1.

Qfb3 Alluvial fans prograding onto middle Berrenda Creek terraces (Qtb3) (upper to uppermost middle Pleistocene) – Alluvium underlying fan surfaces graded to Qtb3.

Qftb1 Alluvial fans prograding onto lowermost Tierra Blanca Creek terraces (Qttb1) (uppermost Pleistocene) – Alluvium underlying fan surfaces graded to Qttb1.

Qftb2 Alluvial fans prograding onto lower Tierra Blanca Creek terraces (Qttb2) (upper Pleistocene) – Alluvium underlying fan surfaces graded to Qttb2. May contain a lower, coarse gravelly layer 0.5-1.5 m thick. Surface has a moderately varnished desert pavement. 1-7 m thick.

Qftb3 Alluvial fans prograding onto middle Tierra Blanca Creek terraces (Qttb3) (upper to uppermost middle Pleistocene) – Alluvium underlying fan surfaces graded to Qttb3.

Qftb4 Alluvial fans prograding onto upper-middle Tierra Blanca Creek terraces (Qttb4) (upper to middle Pleistocene) – Alluvium underlying fan surfaces graded to Qttb4.

Qftb5 Alluvial fans prograding onto upper Tierra Blanca Creek terraces (Qttb5) (middle Pleistocene) – Alluvium underlying fan surfaces graded to Qttb5. Brownish sandy gravel with a boulder-rich base. Overall, gravel consists of well-graded pebbles through cobbles with 20% boulders. 2-6 m thick.

Qftb6 Alluvial fans prograding onto uppermost Tierra Blanca Creek terraces (Qttb6) (middle Pleistocene) – Alluvium underlying fan surfaces graded to Qttb6.

Qft2 Alluvial fans prograding onto lower Trujillo Creek terraces (Qtt2) (upper Pleistocene) – Alluvium underlying fan surfaces graded to Qtt2. Sandy pebbles and pebbly sand in very thin to thin, tabular to lenticular beds; minor (10-15%) medium, lenticular beds of sandy gravel (both matrix- and clast-supported). Approximately 5-10% of beds are clayey-silty (<25% fines), very fine- to medium-grained sand with minor, scattered coarser sand and pebbles with ~10% cobbles. Gravel is mainly clast-supported, imbricated, and comprised of pebbles with 15-20% cobbles and 1-5% boulders. Sand is brown to light brown (7.5YR 5/4 and 6/3), mostly medium- to very coarse-grained, subrounded to subangular, and moderately to poorly sorted. Lower contact is abrupt and slightly wavy. Surface is relatively smooth and weakly to moderately varnished clasts. Relatively common fan deposit. Weakly consolidated.

Qft4 Alluvial fans prograding onto upper-middle Trujillo Creek terraces (Qtt4) (upper to middle Pleistocene) – Alluvium underlying fan surfaces graded to Qtt4.

Qft5 Alluvial fans prograding onto upper Trujillo Creek terraces (Qtt5) (middle Pleistocene) – Alluvium underlying fan surfaces graded to Qtt5. Sediment generally fines upward from a grayish sandy gravel to a redder or browner pebbly sand interbedded with sandy gravel.

Piedmont deposits

Qpy Younger piedmont alluvium (uppermost Pleistocene?) – Reddish brown to brown (5-7.5YR 4/4) sandy pebble-cobble-boulder gravel in thick (35 to >50 cm), tabular to lenticular beds. Loose, very weakly calcareous, well imbricated to internally massive, and normally graded. Gravel is clast-supported, very poorly to poorly sorted, subangular to subrounded, and consists of pebbles (50-80%), cobbles (20-50%), and boulders (5-15%) of andesite derived from the Sibley Mountains. Matrix consists of very poorly sorted, angular to subrounded, fU-vcL sand composed of 85-90% lithics (volcanic) and 10-15% quartz + feldspar with 30-50% free-grain argillans and perhaps occasional clay bridges. Gravel interbeds with subordinate dark brown (7.5YR 3/4), loose, weakly calcareous, thick-bedded (40-50 cm), tabular to wedge-shaped, internally massive, moderately well sorted silt-clay with 5-10% vfL-mL sand grains similar to gravel matrix. Calcareous root traces are somewhat common but no soil development observed. Bar-and-swale topography at surface features less than 10 cm of relief. 1-2.5 m thick.

Qpo Older piedmont alluvium (upper to middle Pleistocene?) – Yellowish red (5YR 4/6), sandy pebble-cobble-boulder gravel in thin to thick (10-60 cm), mostly tabular to vaguely wedge-shaped beds. Loose, moderately to strongly calcareous, and moderately imbricated to massive. Gravel is clast- to matrix-supported (30-40% and 60-70%, respectively), very poorly to poorly sorted, angular to rounded (mostly angular to subrounded), and consists of pebbles (45-55%), cobbles (40-50%), and boulders (5-15%) of gray, flaggy basaltic andesite (70-75%), reddish, aphyric andesite with rare quartz xenoliths (25-30%), and trace whitish gray chert. Matrix consists of poorly to moderately sorted silt to vfU sand (10-20% mL-cU) composed of mostly volcanic lithics (<5-10% quartz + feldspar). Upper 80-100 cm of deposit consists of 35- to 50-cm-thick incipient A horizons, 10-cm-thick Bt horizons with reddish prismatic peds, and 40- to 65-cm-thick stage II calcic horizons with carbonate nodules, masses, and rinds. Surface of deposit is cobbly to bouldery with 50-80% of clasts exhibiting weak to moderate varnish and up to 30 cm of bar-and-swale topography. Deposit is as much as 3.5 m thick. Subdivided into 2 deposits based on landscape position:

Qpo1 Older piedmont alluvium, younger allostratigraphic unit (upper Pleistocene) – Deposit surface is approximately 2-4 m above that of Qpy.

Qpo2 Older piedmont alluvium, older allostratigraphic unit (upper to uppermost middle Pleistocene?) – Deposit surface is approximately 8-9 m above that of Qpy and 4-7 m above that of Qpo1.

Terrace deposits

Terrace deposits of smaller tributaries

Qtg Tributary terrace deposits, undivided (middle to upper Pleistocene) – Reddish brown to brown (5-7.5YR 4/3-4), sandy pebble-cobble-boulder gravel in medium to very thick (10-110 cm), tabular to broadly lenticular beds. Loose to weakly consolidated, non- to moderately calcareous, and moderately or well imbricated to vaguely planar cross-stratified (foresets up to 30 cm thick). Gravel is clast-supported (rarely matrix-supported), very poorly to poorly sorted, subangular to well rounded (mostly subrounded to rounded), and consists of pebbles (50-90%), cobbles (10-45%), and boulders (5-15%) of mostly volcanic lithologies reworked from QTp (<5% each of Paleozoic carbonates, chert, and basalt). Matrix sand consists of very poorly to poorly sorted, subangular to rounded, mL-vcL (minor fU) grains composed of 55-80% lithics (volcanic), 10-35% quartz, and 5-20% feldspar with 5-30% dark reddish free-grain argillans and clay bridges. Contains rare (5%), 15- to 70-cm-thick lenses of moderately calcareous, lenticular, planar cross-stratified (foresets up to 10 cm thick) to horizontal-planar laminated (rare), moderately well sorted, subrounded to rounded, fU-cL sand composed of 60-70% quartz, 20-30% lithics (volcanic), and 10-15% feldspar with no clay. Individual terrace deposits are distinguished by surface characteristics and relative abundance of calcic soils related to age. Older deposits feature moderate to strong varnish on up to 85% of clasts at surface as well as calcic horizons with up to stage II+ carbonate accumulation. 1.2-7 m thick. Subdivided into 3 deposits based on landscape position:

Qtl Lowest tributary terrace deposit (upper Pleistocene) – Terrace tread 3-6 m above valley floor.

Qtm Middle tributary terrace deposit (upper to uppermost middle Pleistocene) – Terrace tread 5-13 m above valley floor.

Qth Upper tributary terrace deposit (middle Pleistocene?) – Terrace tread 8-20 m above valley floor. Also includes high terrace near confluence of Jaralosa and Berrenda Creeks with tread 30-31 m above valley floor.

Terrace deposits associated with Berrenda Creek

Qtb Berrenda Creek terrace deposits, undivided (uppermost to middle Pleistocene) – Reddish brown to yellowish red (5YR 4/4-6) to brown or strong brown (7.5YR 4-5/3-6) to less commonly pinkish gray or light brown (7.5YR 6/2-4), well graded, sandy pebble, pebble-cobble, and pebble-cobble-boulder gravel in medium to very thick (12-130+ cm), lenticular to occasionally tabular beds. Loose to moderately consolidated, non- to strongly calcareous, and non- to moderately cemented by carbonate or clay. Well imbricated to trough or planar cross-stratified (foresets up to 20 cm thick). Gravel is clast-supported (rarely matrix-supported), very poorly to poorly sorted, subangular to well rounded (mostly subrounded to rounded), and consists of pebbles (45-100%), cobbles (0-50%), and boulders (0-20%) up to 45 cm in diameter of subequal proportions of intermediate and felsic volcanic lithologies with 5-15% total of Paleozoic carbonates, chert, and basalt. Matrix sand consists of very poorly to poorly sorted, subangular to rounded, fL-cL grains (up to 20% very coarse sand + granules) composed of 60-85% lithics (volcanic), 15-30% quartz, and 5-20% feldspar with up to 40% reddish or brownish free-grain argillans and/or clay bridges. Some deposits contain lenses of massive to weakly trough cross-stratified, pebbly, vfL-mU sand in upper 2.5 m. Individual terrace deposits are distinguished by surface characteristics and relative abundance of calcic soils related to age as well as color to a lesser extent. Older deposits may have redder (5YR) hues, weak to moderate desert pavement, moderate varnish on up to 70% of clasts at surface, and surface or buried calcic horizons with up to stage III carbonate accumulation. 1.8 to >11 m thick. Subdivided into 6-7 deposits based on landscape position:

Qtb1 Lowermost Berrenda Creek terrace deposit (uppermost Pleistocene) – Terrace tread 3-9 m above valley floor. Subdivided into 2 deposits:

Qtb1a Lowermost Berrenda Creek terrace deposit, younger allostratigraphic unit – Terrace tread 3-4 m above valley floor.

Qtb1b Lowermost Berrenda Creek terrace deposit, older allostratigraphic unit – Terrace tread 5-9 m above valley floor.

Qtb2 Lower Berrenda Creek terrace deposit (upper Pleistocene) – Terrace tread 10-14 m above valley floor.

Qtb3 Middle Berrenda Creek terrace deposit (upper to uppermost middle Pleistocene) – Terrace tread 15-22 m above valley floor.

Qtb4 Upper-middle Berrenda Creek terrace deposit (middle Pleistocene) – Terrace tread 27-33 m above valley floor.

Qtb5 Upper Berrenda Creek terrace deposit (middle Pleistocene) – Terrace tread 35-46 m above valley floor.

Qtb6 Uppermost Berrenda Creek terrace deposit (middle Pleistocene) – Terrace tread 47-51 m above valley floor.

Terrace deposits associated with Tierra Blanca Creek

Qttb Tierra Blanca Creek terrace deposits, undivided (uppermost to middle Pleistocene) – Light brown to brown (7.5YR 6/3 to 10YR 5/3), well graded, sandy pebble-cobble and pebble-cobble-boulder gravel in thick to very thick (50-150 cm), tabular to broadly lenticular beds. Loose to somewhat consolidated, non- to strongly calcareous, and imbricated. Gravel is clast-supported, very poorly to poorly sorted, subrounded, and consists of pebbles (40-60%), cobbles (30-40%), and boulders (20-30%) up to 70 cm in diameter of subequal proportions of intermediate and felsic volcanic lithologies with 1-2% total of Paleozoic carbonates and basalt. Many deposits exhibit upward-fining from 1- to 1.5-m-thick basal layers of bouldery gravel to sandy pebble-cobble gravel. Matrix consists of poorly to moderately sorted, subangular to subrounded, fU-vcU (minor very fine) sand composed principally of volcanic grains. Basal contact is typically scoured and wavy with up to 0.5 m of relief. Individual terrace deposits are distinguished by surface characteristics and relative abundance of calcic soils related to age. Older deposits may have weak to moderate desert pavement, moderate to strong varnish on up to 60% of clasts at surface, and surface or buried calcic horizons with up to stage III+ carbonate accumulation. Elevation of terrace treads is notably divergent from modern floodplain in downstream direction (to east). 1-18 m thick. Subdivided into 6-7 deposits based on landscape position:

Qttb1 Lowermost Tierra Blanca Creek terrace deposit (uppermost Pleistocene) – Terrace tread 3-5 m above valley floor.

Qttb2 Lower Tierra Blanca Creek terrace deposit (upper Pleistocene) – Terrace tread 4-11 m above valley floor. Subdivided into 2 deposits:

Qttb2a Lower Tierra Blanca Creek terrace deposit, younger allostratigraphic unit (upper Pleistocene) – Terrace tread 4-7 m above valley floor.

Qttb2b Lower Tierra Blanca Creek terrace deposit, older allostratigraphic unit (upper Pleistocene) – Terrace tread 7-11 m above valley floor.

Qttb3 Middle Tierra Blanca Creek terrace deposit (upper to uppermost middle Pleistocene) – Terrace tread 10-19 m above valley floor.

Qttb4 Middle Tierra Blanca Creek terrace deposit (middle Pleistocene) – Terrace tread 18-27 m above valley floor.

Qttb5 Upper Tierra Blanca Creek terrace deposit (middle Pleistocene) – Terrace tread 21-39 m above valley floor.

Qttb6 Uppermost Tierra Blanca Creek terrace deposit (middle Pleistocene) – Terrace tread 40-52 m above valley floor.

Terrace deposits associated with Trujillo Creek

Qtt Trujillo Creek terrace deposits, undivided (uppermost to middle Pleistocene) – Reddish brown to light reddish brown (5YR 5-6/4) or brown (7.5YR 4-5/4), well graded, sandy pebble-cobble-boulder gravel in very thin to thick, lenticular to tabular beds. Loose to moderately consolidated, non- to weakly clay-cemented, and imbricated. Less commonly, deposit exhibits trough or planar cross-stratification (foresets up to 60 cm thick) as well as lateral accretion sets up to 1.5 m thick. Gravel is clast-supported, very poorly to poorly sorted, subrounded to rounded, and consists of pebbles (40-70%), cobbles (25-45%), and boulders (3-30%) up to 60 cm in diameter of subequal proportions of intermediate and felsic volcanic lithologies with typically <3-6% each of Paleozoic carbonates and basalt. Matrix consists of poorly to moderately sorted, subrounded (minor subangular), medium to very coarse (<10% silt + very fine to fine) sand composed of mostly lithics (volcanic), subequal proportions of quartz and feldspar, and trace to 10% clay. Subordinate beds include 25-35% pebbly sand in laminated to very thin, tabular beds. Basal contact is typically scoured with up to 1-2 m of relief. Individual terrace deposits are distinguished by surface characteristics and relative abundance of calcic soils related to age. Older deposits may have moderate desert pavement, moderate to strong varnish on up to 65% of clasts at surface, and surface or buried calcic horizons with up to stage

III carbonate accumulation. Elevation of terrace treads is notably divergent from modern floodplain in downstream direction (to east). 1-7 m thick. Subdivided into 6-8 deposits based on landscape position:

Qtt1 Lowermost Trujillo Creek terrace deposit (uppermost Pleistocene) – Terrace tread 2-7 m above valley floor.

Qtt2 Lower Trujillo Creek terrace deposit (upper Pleistocene) – Terrace tread 4-17 m above valley floor.

Qtt3 Middle Trujillo Canyon terrace deposit (upper to uppermost middle Pleistocene) – Terrace tread 10-23 m above valley floor.

Qtt4 Upper-middle Trujillo Creek terrace deposit (middle Pleistocene) – Terrace tread 13-26 m above valley floor. Subdivided into 2 deposits:

Qtt4a Upper-middle Trujillo Creek terrace deposit, younger allostratigraphic unit (middle Pleistocene) – Terrace tread 19-20 m above valley floor.

Qtt4b Upper-middle Trujillo Creek terrace deposit, older allostratigraphic unit (middle Pleistocene) – Terrace tread 21-23 m above valley floor.

Qtt5 Upper Trujillo Creek terrace deposit (middle Pleistocene) – Terrace tread 19-34 m above valley floor. Subdivided into 2 deposits:

Qtt5a Upper Trujillo Creek terrace deposit, younger allostratigraphic unit (middle Pleistocene) – Terrace tread 23-25 m above valley floor.

Qtt5b Upper Trujillo Creek terrace deposit, older allostratigraphic unit (middle Pleistocene) – Terrace tread 29-34 m above valley floor.

Qtt6 Uppermost Trujillo Creek terrace deposit (middle Pleistocene) – Terrace tread 35-47 m above valley floor.

QUATERNARY-TERTIARY

Basin-fill units

QTp Palomas Formation (lower Pleistocene to lowermost Pliocene) – Gravel, sand, silt, and clay deposited on coalesced fan complexes in the west-central Palomas basin. Fossil data (summarized by Morgan and Lucas, 2012), basalt radiometric ages (Bachman and Mehnert, 1978; Seager et al., 1984; Jochems, 2015; Koning et al., 2015, 2016), and magnetostratigraphic data (Repenning and May, 1986; Mack et al., 1993, 1998; Leeder et al., 1996), indicate an age range of ~5.0-0.8 Ma for the Palomas Formation. Where not significantly eroded, the surface soil may be marked by a petrocalcic horizon that is 1-2 m thick and generally exhibits stage IV carbonate morphology. 0 to >90 m thick. Includes 6 subunits:

QTpuc Upper coarse piedmont facies of the Palomas Formation (lower Pleistocene) – Reddish brown (5YR 4-5/4), sandy pebble, pebble-cobble, and pebble-cobble-boulder gravel in medium to thick (35-80 cm), tabular beds. Loose to somewhat consolidated, slightly calcareous to weakly clay-cemented, and internally massive to well imbricated and/or vaguely planar cross-stratified (foresets up to 20 cm thick). Gravel is clast- to matrix-supported (85% versus 15%, respectively), very poorly to poorly sorted, subrounded to rounded, and consists of pebbles (55-95%), cobbles (5-45%), and boulders (trace to 5%). Median clast diameter is ~25 cm. Clast lithologies include intermediate volcanics (40-45%), Paleozoic sedimentary lithologies and chert (15-35%), Kneeling Nun tuff (10-15%), undivided felsic volcanics (2-30%), and trace to 2% each of basalt and volcaniclastic sandstone. Matrix consists of poorly sorted, subrounded, fine to coarse (10% very coarse) sand composed of 60-65% lithics (volcanic>>chert), 20-25% quartz, and 10-15% feldspar with up to 20-25% clay flakes and free-grain argillans. Unit may be capped by stage IV calcic horizon with laminar carbonate. Laterally gradational with upper part of QTpu south of Tierra Blanca Creek. 0-30 m thick.

QTpuci Upper coarse piedmont facies of the Palomas Formation, inset subunit (lower Pleistocene) – Gravel bed(s) as in QTpuc but inset into Cuchillo surface by 3-7 m throughout quadrangle. Individual beds typically 3-5 m thick.

QTpu Upper piedmont facies of the Palomas Formation (lower Pleistocene) – Dark reddish brown to reddish brown (5YR 3-4/4), laterally extensive, occasionally stacked channel fills with subordinate yellowish red (5YR 4-5/6) silt and mud interbeds. Pebbly to cobbly channel-fill gravel is in thick (40-70 cm), lenticular (minor tabular) beds. Loose to weakly consolidated, slightly to moderately calcareous, and weakly clay-cemented. Gravel is clast-supported, well imbricated to occasionally planar cross-stratified (foresets 20-35 cm thick), very poorly to poorly sorted, subrounded to well rounded, and consists of pebbles (60-95%), cobbles (5-35%), and boulders (0-5%). Median clast diameter is ~11 cm. Clast lithologies include intermediate volcanics (30-65%), undivided felsic volcanics (10-40%), Kneeling Nun tuff (10-20%), Paleozoic carbonate and chert (7-15%), and trace to 4% each of basalt, intermediate intrusive lithologies, and volcaniclastic sandstone. Channel-fill matrix consists of very poorly to poorly sorted, subangular to rounded, fine to very coarse sand composed of 70-80% lithics (volcanic>chert + carbonate), 15-20% quartz, and 5-10% feldspar with 1-20% red clay flakes and free-grain argillans. Silt and mud beds are massive/poorly stratified and contain up to 5% very fine to medium sand grains. These beds are commonly overprinted by illuviated clay and/or stage I to II calcic horizons with prismatic peds, ped argillans, root casts coated by manganese oxide, slickensides, and perhaps carbonate nodules and masses. Basal contact taken at base of lowest laterally extensive channel fill or stacked channel fills. Upper part is laterally gradational with QTpuc south of Tierra Blanca Creek. 0-35 m thick.

QTpm Middle piedmont facies of the Palomas Formation (lower Pleistocene to upper Pliocene) – Reddish brown to light brown (5YR 5/4 to 7.5YR 6/3), extra-channel sediment with rare to minor gravel that increases in proportion westward. Loose to weakly consolidated and moderately to strongly calcareous. Silt-sand and sandy mud occur in massive/poorly stratified beds. These finer-grained deposits contain varying amounts of fine to medium (lesser coarse) sand grains typically dominated by lithics (volcanic). Mud beds may be overprinted by cambic and/or illuviated clay and stage I-III calcic horizons with very fine carbonate masses, root casts coated by manganese oxide, prismatic peds, and ped argillans. Gravel is clast-supported, thin- to medium-bedded (8-20 cm), tabular, weakly imbricated, poorly sorted, subangular to rounded, and consists of pebbles (75-90%) and fine cobbles (10-15%). Median clast diameter is ~7 cm. Clast lithologies include intermediate volcanics (40-60%), undivided felsic volcanics (10-30%), Paleozoic carbonate and chert (10-15%), Kneeling Nun tuff (5-15%), and 0-2% each of basalt, intermediate intrusive lithologies, and volcaniclastic sandstone. Gravel matrix consists of brown (7.5YR 5/3-4), moderately sorted silt to very fine sand with 15-25% subrounded to rounded, fine to medium sand grains composed of >90% lithics (volcanic) with no clay. Lower 3-10 m may be vertically gradational with QTpl, particularly along Tierra Blanca and Berrenda Creeks. 0 to >48 m thick.

QTpl Lower piedmont facies of the Palomas Formation (upper to lower Pliocene) – Pinkish to light brownish gray or light brown (7.5-10YR 6/2-3), sandy pebble gravel channel fills and minor sand in thin to medium (3-30 cm), tabular to broadly lenticular beds. Weakly to moderately consolidated, slightly to strongly calcareous and/or calcite-cemented, and moderately imbricated. Channel-fill gravel is clast-supported (rarely matrix-supported), poorly to moderately sorted, subangular to rounded (mostly subrounded), and consists of fine to coarse pebbles of intermediate volcanics (40-60%), undivided felsic volcanics (10-35%), Kneeling Nun tuff (10-20%), Paleozoic sedimentary lithologies and chert (10-15%), and 2-4% each of intermediate intrusive lithologies and volcaniclastic sandstone. Median clast diameter is ~5 cm. Where not replaced by calcite, gravel matrix consists of moderately sorted, subangular to subrounded, silt to very fine (15% fine to coarse) sand composed of 75-80% lithics (volcanic), 10-15% quartz, and 5-10% feldspar with no clay. Gravel coarsens slightly up-section. Subordinate sandy beds consist of internally massive to horizontal-planar laminated (very thin), moderately well sorted, angular to rounded (mostly subangular to subrounded), very fine to fine grains with similar composition to gravel matrix. These beds may contain 1% granules and fine pebbles. Abundant stage II through III+ calcic paleosols, locally with illuviated clay or cambic horizons. Upper 3-10 m may be vertically gradational with QTpm, particularly along Tierra Blanca and Berrenda Creeks. 0-31 m thick.

QTplt Transitional base of the lower piedmont facies of the Palomas Formation (lower Pliocene) – Pinkish gray to light brown or reddish yellow (7.5YR 6/2-6) to grayish brown (10YR 5/2), pebbly sand

and sandy gravel in very thin to thin, tabular beds or thin to medium, lenticular beds. Rarely, beds are light reddish brown to reddish yellow (5YR 6/4-6). Weak to moderately calcite-cemented. Sandy sediment may exhibit low-angle cross-stratification. Sand is poorly to moderately sorted, subrounded (minor subangular), fine to very coarse (<10% silt and very fine to fine sand) and composed mostly of volcanic grains. Gravel beds constitute 30-50% of deposit and consist of poorly to moderately sorted, subrounded (minor subangular) pebbles (70-80%), cobbles (15-25%), and boulders (trace to 5%). Clast lithologies include intermediate volcanics (40-45%), Kneeling Nun tuff (20-25%), undivided felsic volcanics (15-20%), intermediate intrusive lithologies (<10%), chert (5-10%), and rare (0.5-2%) Paleozoic carbonates and reddish brown, vesicular, altered basalt. Minor medium to thick, lenticular beds contain abundant matrix-supported, poorly sorted cobbles. 10 to 50% overprinting by calcic paleosols (stage I to III carbonate morphology), which increases up-section in Trujillo Creek. Calcic horizons are locally overlain by cambic or illuviated clay horizons. 0-14 m thick.

TERTIARY

Santa Fe Group basin-fill units predating the Palomas Formation

Trv Rincon Valley Formation (upper Miocene) – Gravel/conglomerate and sand/sandstone mostly representing proximal debris flow deposits. Minor clay beds in the southeastern part of the quadrangle may be marginal alluvial-flat facies. The age of the basal Rincon Valley Formation is constrained by an interbedded basalt flow in Selden Canyon dated at ~9.6 Ma (Seager et al., 1984). Its maximum age is constrained by an age of ~5.0 Ma for the lowermost Palomas Formation. Typically underlies the Palomas Formation with angular unconformity. 0 to at least 190 m thick in quadrangle. Includes 3 subunits:

Trvu Upper unit of Rincon Valley Formation (upper Miocene) – Light brown to brown or strong brown (7.5YR 6/3-4; 5/4-6) or reddish brown to reddish yellow or light reddish brown (5YR 4-6/4; 6/3), pebbly sand with <5-40% sandy gravel interbeds. Mostly non- to weakly cemented with 5-20% moderate (0-10% strong) calcite cementation. Pebbly sand and sand are horizontal-planar laminated to thinly bedded (minor lenticular beds) with 1-20% cross-stratification as low-angle cross-laminations or in laminated to very thin, planar foresets up to 30 cm tall. Sand is poorly to moderately sorted, subangular to subrounded, fine to very coarse (mostly medium to very coarse; <15% very fine to fine), and composed mostly of volcanic grains with very little interstitial clay (no more than 1%) except for deposits interpreted as debris flows where clay is up to 7%. Sandy pebbles are in thin to medium, lenticular beds or very thin to thin, tabular beds. Gravel is mostly clast-supported, imbricated, poorly to moderately sorted, subangular to subrounded, and comprised of pebbles with 5-15% cobbles and trace boulders (locally up to 20% cobbles and 1% boulders) that are relatively platy. Clast lithologies include subequal to slightly greater proportions of felsic volcanics (including 1-5% Kneeling Nun tuff and lesser Sugarlump tuff, the latter being noted only in Trujillo Creek) compared to intermediate volcanics. Trace to 0.5% Paleozoic carbonates appear in the upper part of the unit in Trujillo Creek and other lithologies include 0.5% Cretaceous(?) andesites and trace to 1% reddish brown, vesicular basalt. Unit contains ~3-25% poorly sorted, cobble- to coarse-pebble-rich debris flow deposits in medium, lenticular channel fills. Paleosols are very sparse compared with the overlying Palomas Formation; observed paleosols have calcic horizons with up to stage II carbonate morphology. Lower contact is gradational with Trvl and placed where there is an up-section decrease in reddening, clast-size (typically <15% cobbles), and cementation. 0-52 m thick.

Trvuf Upper unit of Rincon Valley Formation, fine lithofacies (upper Miocene) – Reddish brown (2.5YR 4/4) to yellowish red or light reddish brown (5YR 5/6; 6/4), silty to slightly sandy clay in massive or very thick, tabular beds. Loose and non- to somewhat calcareous. May contain 2-10% scattered fine to medium pebbles that are poorly to moderately sorted, angular to subrounded, and consist of volcanic lithologies. In places, 5-10% scattered carbonate masses are present but soil horizonation is not observed. Found in the southeast part of the quadrangle along Berrenda Creek; likely interfingers with coarser Trvu facies to west in subsurface. >15 m thick.

Trvl Lower unit of Rincon Valley Formation (middle or upper Miocene) – Brown to light brown or pinkish gray (7.5YR 5/4 to 6/3; 7/2), well-bedded pebbly sandstone with subordinate (25-35%) sandy pebble-conglomerate interbeds. Well-cemented by calcite and opaline silica. Both pebbly sandstone and conglomeratic beds are locally cross-stratified with planar foresets that dip at low angles (up to 15 cm tall); minor trough- cross-stratification also observed. Pebbly sandstone is horizontal-planar laminated to very thin-bedded, and consists of poorly to moderately sorted, subangular to subrounded, fine to very coarse (<10% finer) grains composed mostly of lithics (volcanic). Conglomerate is in very thin to medium, lenticular beds (minor tabular beds). Gravel is mostly clast-supported, poorly to moderately sorted, subrounded (minor subangular), and comprised of pebbles with 10% cobbles (in Tierra Blanca Creek) to 10-20% cobbles (in Trujillo Creek); 0-1% boulders. Clast lithologies include subequal (±20%) felsites and intermediate volcanic clasts, 5-10% Kneeling Nun tuff, and no Paleozoic carbonates or dark-colored basalts. Unit contains approximately 3-5% (Tierra Blanca Creek) to 10-30% (Trujillo Creek) matrix-supported, poorly sorted, cobbly debris flow deposits in thin to thick, lenticular beds. Paleosols are very sparse. 80 m thick.

Tsmld Santa Fe Group, middle-lower debris flow facies of pre-Palomas Formation basin-fill (middle to lower Miocene) – Debris flow deposits in the lowest exposed Rincon Valley Formation along Tierra Blanca Creek. These deposits are separated from younger strata by a sharp, scoured disconformity (no angularity of bedding across contact; no paleosol observed). At least 60 m thick. Two lithofacies are present that may be merged for the purposes of 1:24,000-scale mapping:

Tsmldc Santa Fe Group, middle-lower debris flow facies of pre-Palomas Formation basin-fill, upper coarse lithofacies – Light reddish brown to light brown (5-7.5YR 6/4) or pinkish gray to pink (5-7.5 YR 7/2-4), sandy conglomerate and minor pebbly sandstone that are mostly massive. In Tierra Blanca Creek, bedding is more distinctive southwards where debris flows occur in medium to thick, lenticular beds. In Trujillo Creek, bedding is medium to thick and tabular. Within relatively massive conglomerate are minor intervals of very thin to medium, lenticular beds of pebbly sandstone and sandy clast-supported pebbles. Conglomerate is moderately to well cemented by calcite and inferred silica. Gravel consists of matrix- to clast-supported, very poorly to poorly sorted, subangular to subrounded, well-graded pebbles through cobbles with lesser boulders. Clast lithologies include 20-35% platy, dark gray, aphanitic andesite correlated to the andesite of Sibley Mountain (Tsa), as well as 1% Cretaceous(?) andesites and trace to 3% aphanitic, reddish brown, vesicular basalts. Largest clasts are up to 0.6 m across. Matrix consists of very poorly to poorly sorted, subangular (minor subrounded), clayey to silty, very fine- to very coarse-grained sand composed of volcanic grains. Occupies most of unit Tsmld on the quadrangle. >50 m thick.

Tsmldf Santa Fe Group, middle-lower debris flow facies of pre-Palomas Formation basin-fill, lower fine lithofacies – Pinkish gray to pink (5-7.5YR 7/2-4) clay, silt, and very fine-grained sand in medium to thick, tabular beds. Internally massive. Contains minor to abundant, scattered fine- to very coarse-gained sand and lesser pebbles that are poorly sorted and subangular to subrounded. Clast composition includes greater proportions of felsic volcanics than Tsmldc (up to 50% including 3% Kneeling Nun and 5-10% other distinctive tuffs). This sediment onlaps paleotopographic relief developed on older volcanic rocks. Conformably underlies Tsmldc across an approximately 1-m-thick gradation. Up to 15 m thick.

Volcanic and intrusive units

Tja Andesite of Jaralosa Creek (lower Miocene? to upper Oligocene) – Dark gray (N 4/) weathering brown (7.5YR 5/3) to dark reddish brown (5YR 3/3), cliff-forming, massive to platy, porphyritic, fine-grained andesite. Phenocrysts include 13-15% plagioclase (up to 0.75 mm, subhedral; thin laths define pilotaxitic texture), 2-3% pyroxene (up to 1.5 mm, anhedral; typically weathered), and trace quartz (1-2 mm, anhedral). O'Neill and others (2002a, b) suggest that this andesite intrudes Santa Fe Group basin-fill along Jaralosa Creek but this relationship was not conclusively established in the field. They identified this rock as an andesite based on geochemical analysis. Thickness likely <20 m.

Tsa Andesite of Sibley Mountain (upper Oligocene) – Very dark gray (7.5YR 3/1) weathering brown (7.5YR 5/3) to yellowish red (5YR 4/6), ledge- to cliff-forming, massive to foliated, aphanitic-porphyritic, fine-grained andesite to trachyandesite flows. Phenocrysts include 3-4% plagioclase (up to 1 mm, subhedral to anhedral; commonly weathered to secondary mineral that is wintergreen in color), 1-2% hornblende (up to 0.75 mm, euhedral; occasionally features oxidation rims), and trace quartz (up to 1.25 mm, anhedral). O'Neill et al. (2002b) identify this rock as bordering between andesite and trachyandesite based on geochemical analysis.

Individual flows commonly 9-18 m thick.

UNITS IN CROSS SECTION ONLY

QTpucu Upper coarse and upper piedmont facies of the Palomas Formation, undivided (lower Pleistocene) – Upper coarse piedmont (QTpuc) and upper piedmont (QTpu) alluvium. See detailed descriptions of each individual unit. 0-40 m thick.

Tsml Santa Fe Group, middle-lower pre-Palomas Formation basin-fill units, undivided (middle to lower Miocene) – Basin-fill alluvium pre-dating the Palomas Formation and likely the Rincon Valley Formation as well. Likely correlative to the Hayner Ranch Formation of Seager (1971). 0 to >600 m thick.

Tvu Volcanic rocks, undivided (Oligocene to Eocene) – Includes Kneeling Nun and Sugarlump tuffs. See O'Neill et al. (2002a, b) for descriptions. At least 320 m thick.

Trp Rubio Peak Formation (Eocene) – Volcaniclastic material and interbedded flows of intermediate volcanics. See O'Neill et al. (2002a, b) for descriptions. Approximately 145-265 m thick.

Pzu Paleozoic rocks, undivided (Paleozoic) – Limestone, dolostone, and minor beds of shale and sandstone. Includes lower (and perhaps upper) Paleozoic strata described by O'Neill et al. (2002a, b). At least 230 m thick.

APPENDIX B

Radiocarbon dating analyses from samples collected on the
Clark Spring Canyon 7.5-minute quadrangle

Samples CS-25-Qah, CS-25-QayA, and CS-25-QayB were collected from Trujillo Creek in section 34, T16S, R6W by Dan Koning.

REPORT OF RADIOCARBON DATING ANALYSES

Mr. Andrew Jochems | Report Date: 7/29/2016

New Mexico Bureau of Geology & Mineral Resources | Material Received: 7/20/2016

Sample Data	Measured Radiocarbon Age	Isotopes Results o/oo	Conventional Radiocarbon Age(*)
Beta - 441927 SAMPLE: 16AC-763A ANALYSIS: AMS-Standard delivery MATERIAL/PRETREATMENT: (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 2465 to 2280 (Cal BP 4415 to 4230) and Cal BC 2245 to 2230 (Cal BP 4195 to 4180) Cal BC 2245 to 2230 (Cal BP 4195 to 4180)	3830 +/- 30 BP	d13C= -22.0	3880 +/- 30 BP
Beta - 441928 SAMPLE: 16AC-763B ANALYSIS: AMS-Standard delivery MATERIAL/PRETREATMENT: (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 2460 to 2270 (Cal BP 4410 to 4220) and Cal BC 2260 to 2205 (Cal BP 4210 to 4155) Cal BC 2260 to 2205 (Cal BP 4210 to 4155)	3830 +/- 30 BP	d13C= -23.1	3860 +/- 30 BP
Beta - 441929 SAMPLE: CS-25-Qah ANALYSIS: AMS-Standard delivery MATERIAL/PRETREATMENT: (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1440 to 1520 (Cal BP 510 to 430) and Cal AD 1575 to 1630 (Cal BP 375 to 320) Cal AD 1575 to 1630 (Cal BP 375 to 320)	420 +/- 30 BP	d13C= -27.1	390 +/- 30 BP
Beta - 441930 SAMPLE: CS-25-QayA ANALYSIS: AMS-Standard delivery MATERIAL/PRETREATMENT: (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1465 to 1645 (Cal BP 485 to 305)	350 +/- 30 BP	d13C= -26.5	330 +/- 30 BP

Results are ISO-17025 accredited. AMS measurements were made on one of 4 in-house NEC SSAMS accelerator mass spectrometers.The reported age is the "Conventional Radiocarbon Age", corrected for isotopic fraction using the d13C. Age is reported as RCYBP (radiocarbon years before present, abbreviated as BP, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C signature of NBS SRM-4990C (oxalic acid) and calculated using the Libby 14C half life (5568 years). Quoted error on the BP date is 1 sigma (1 relative standard deviation with 68% probability) of counting error (only) on the combined measurements of sample, background and modern reference standards. Total error at Beta (counting + laboratory) is known to be well within +/- 2 sigma. d13C values are reported in parts per thousand (per mil) relative to PDB-1 measured on a Thermo Delta Plus IRMS. Typical d13C error is +/- 0.3 o/oo. Percent modern carbon (pMC) and Delta 14C (D14C) are not absolute. They equate to the Conventional Radiocarbon Age. Calendar calibrated results were calculated the material appropriate 2013 database (INTCAL13, MARINE13 or SHCAL13). See graph report for references.

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REPORT OF RADIOCARBON DATING ANALYSES

Mr. Andrew Jochems
Report Date: 7/29/2016

New Mexico Bureau of Geology & Mineral Resources
Material Received: 7/20/2016

Sample Data	Measured Radiocarbon Age	Isotopes Results o/oo	Conventional Radiocarbon Age(*)
Beta - 441931	760 +/- 30 BP	d13C= -24.2	770 +/- 30 BP

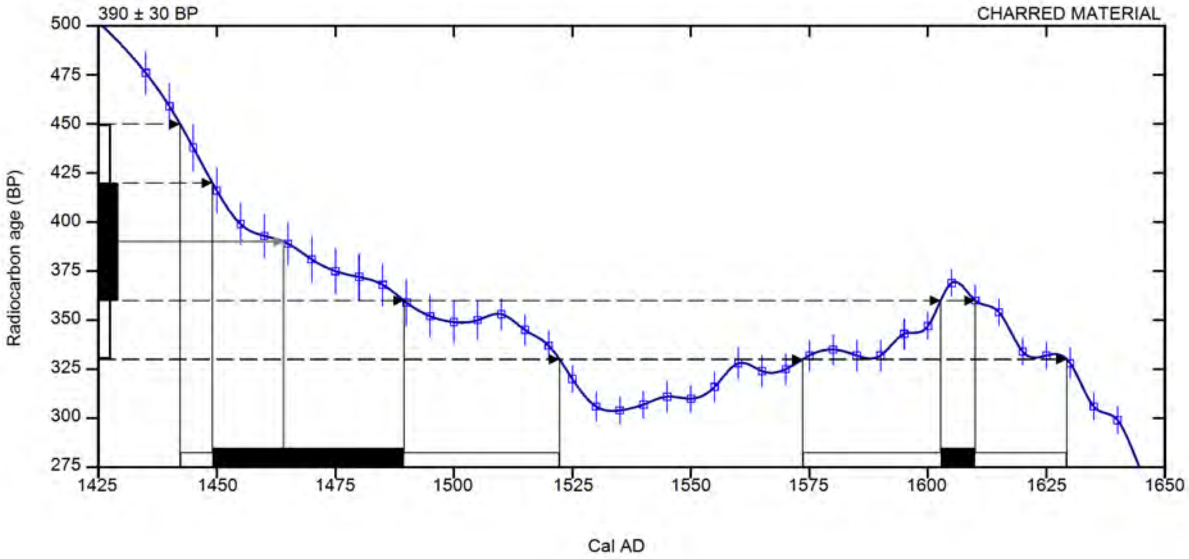
SAMPLE: CS-25-QayB
ANALYSIS: AMS-Standard delivery
MATERIAL/PRETREATMENT: (charred material): acid/alkali/acid
2 SIGMA CALIBRATION : Cal AD 1220 to 1280 (Cal BP 730 to 670)

Results are ISO-17025 accredited. AMS measurements were made on one of 4 in-house NEC SSAMS accelerator mass spectrometers.The reported age is the "Conventional Radiocarbon Age", corrected for isotopic fraction using the d13C. Age is reported as RCYBP (radiocarbon years before present, abbreviated as BP, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C signature of NBS SRM-4990C (oxalic acid) and calculated using the Libby 14C half life (5568 years). Quoted error on the BP date is 1 sigma (1 relative standard deviation with 68% probability) of counting error (only) on the combined measurements of sample, background and modern reference standards. Total error at Beta (counting + laboratory) is known to be well within +/- 2 sigma. d13C values are reported in parts per thousand (per mil) relative to PDB-1 measured on a Thermo Delta Plus IRMS. Typical d13C error is +/- 0.3 o/oo. Percent modern carbon (pMC) and Delta 14C (D14C) are not absolute. They equate to the Conventional Radiocarbon Age. Calendar calibrated results were calculated the material appropriate 2013 database (INTCAL13, MARINE13 or SHCAL13). See graph report for references.

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -27.1 o/oo : lab. mult = 1)

Laboratory number	**Beta-441929 : CS-25-QAH**
Conventional radiocarbon age	**390 ± 30 BP**
Calibrated Result (95% Probability)	**Cal AD 1440 to 1520 (Cal BP 510 to 430)** **Cal AD 1575 to 1630 (Cal BP 375 to 320)**
Intercept of radiocarbon age with calibration curve	Cal AD 1465 (Cal BP 485)
Calibrated Result (68% Probability)	Cal AD 1450 to 1490 (Cal BP 500 to 460) Cal AD 1605 to 1610 (Cal BP 345 to 340)



Database used

INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

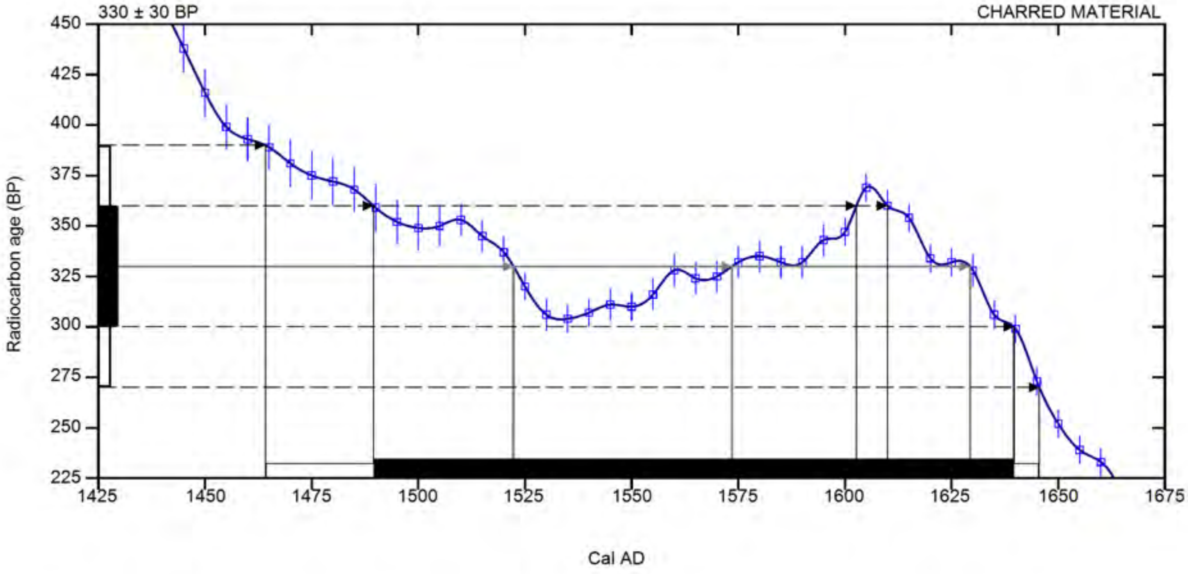
References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -26.5 o/oo : lab. mult = 1)

Laboratory number	**Beta-441930 : CS-25-QAYA**
Conventional radiocarbon age	**330 ± 30 BP**
Calibrated Result (95% Probability)	**Cal AD 1465 to 1645 (Cal BP 485 to 305)**
Intercept of radiocarbon age with calibration curve	Cal AD 1520 (Cal BP 430) Cal AD 1575 (Cal BP 375) Cal AD 1630 (Cal BP 320)
Calibrated Result (68% Probability)	Cal AD 1490 to 1640 (Cal BP 460 to 310)



Database used

INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

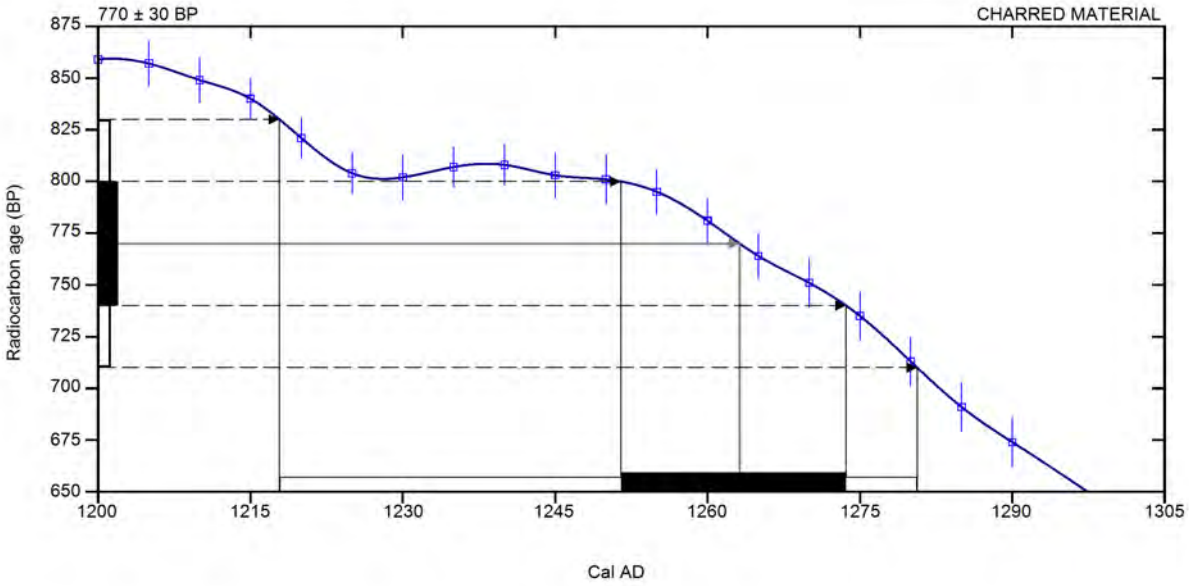
References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24.2 o/oo : lab. mult = 1)

Laboratory number	**Beta-441931 : CS-25-QAYB**
Conventional radiocarbon age	**770 ± 30 BP**
Calibrated Result (95% Probability)	**Cal AD 1220 to 1280 (Cal BP 730 to 670)**
Intercept of radiocarbon age with calibration curve	Cal AD 1265 (Cal BP 685)
Calibrated Result (68% Probability)	Cal AD 1250 to 1275 (Cal BP 700 to 675)



Database used

INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

APPENDIX C

$^{40}Ar/^{39}Ar$ dating analyses from samples collected on the
Clark Spring Canyon 7.5-minute quadrangle

Samples 15CSC-796-AJ and 15CSC-809-AJ were collected from the andesites of Jaralosa Creek (Tja) and Sibley Mountain (Tsa), respectively. Samples collected in section 6, T18S, R6W and section 18, T17S, R6W, respectively, by Andy Jochems.

$^{40}Ar/^{39}Ar$ Geochronology Results

By

Lisa Peters

MAY 10, 2016

Prepared for
Andy Jochems
NMBGMR/NM Tech
Socorro, NM 87801

NEW MEXICO GEOCHRONOLOGY RESEARCH LABORATORY (NMGRL)

CO-DIRECTORS	LABORATORY TECHNICIAN
DR. MATTHEW T. HEIZLER	LISA PETERS
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Internal Report #: NMGRL-IR-928

Introduction

Two fine-grained andesites from Clark Spring Canyon were submitted for dating by Andy Jochems of the NMBMMR. Groundmass concentrates were prepared and analyzed.

^{40}Ar/^{39}Ar Analytical Methods and Results

The groundmass concentrate was prepared by treating crushed material with dilute HCl and then removing the phenocrysts. The mineral separate and monitors (Fish Canyon tuff sanidine, 28.201, Kuiper et al., 2008) were loaded into aluminum discs and irradiated for 8 hours at the USGS TRIGA reactor in Denver Colorado.

The groundmass was step-heated with a Photon Machines Diode laser and was analyzed with a Thermo Helix MCPlus mass spectrometer. Abbreviated analytical methods for the dated sample are given in Table 1. The age results are summarized in Table 1 and the argon isotopic data are given in Table 2.

Both samples (15CSC-796-AJ and 15CSC-809-AJ) yielded disturbed hump-shaped age spectra. The low apparent ages in the early heating steps rise over the initial 30% of the age spectra from 23.98±0.63 Ma to 31.87±0.01 Ma for 15CSC-796-AJ and 11.96±0.82 Ma to 33.04±0.02 Ma for 15CSC-809-AJ. Over the remainder of the spectra, the ages drop and then level off. A weighted mean age is calculated from the more concordant final three steps of each age spectra (31.29±0.03 Ma, 15CSC-796-AJ and 31.54±0.06 Ma, 15CSC-809-AJ). The data was evaluated with the inverse isochron technique but neither sample was found to be isochronous.

Discussion

We have assigned the weighted mean ages calculated from the age spectra (31.29±0.03 Ma, 15CSC-796-AJ and 31.54±0.06 Ma) as our preferred estimates of the eruption or intrusion ages for these samples. The humped-shape of these age spectra are highly suggestive that the samples has undergone ^{39}Ar recoil during the irradiation of the sample. Recoil can be a problem for multiphase samples such as biotite that is partially altered to chlorite, or groundmass concentrates, especially those that are somewhat altered to clay because the ^{39}Ar produced at the reactor recoils or jumps from the high-K phases to the low-K phases, thus raising the ages of the low-K phases and lowering the ages of the high-K phases (Figure 3). In samples that are suspected of having undergone recoil, the integrated age is often assigned as our best estimate of the sample's age. For these samples, however, the young apparent ages in the early heating steps that are correlated to low radiogenic yields indicate that they may have undergone some alteration and associated Ar loss. As both age spectra have a nearly flat portion of ~30% or greater at the end of the spectra, we have decided to assign the ages calculated from these portions of the spectra as our best estimate of the ages. We do caution that our confidence in the errors assigned to these ages is not high and that the ages themselves should be used with caution.

References Cited

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.

Min, K., Mundil, R., Renne, P. L., and Ludwig, K.R., 2000, A test for systematic errors in $^{40}Ar/^{39}Ar$ geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite: Geochimica et Cosmochimica Acta, v. 64, p. 73-98.

Taylor, J.R., 1982. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements,. Univ. Sci. Books, Mill Valley, Calif., 270 p.

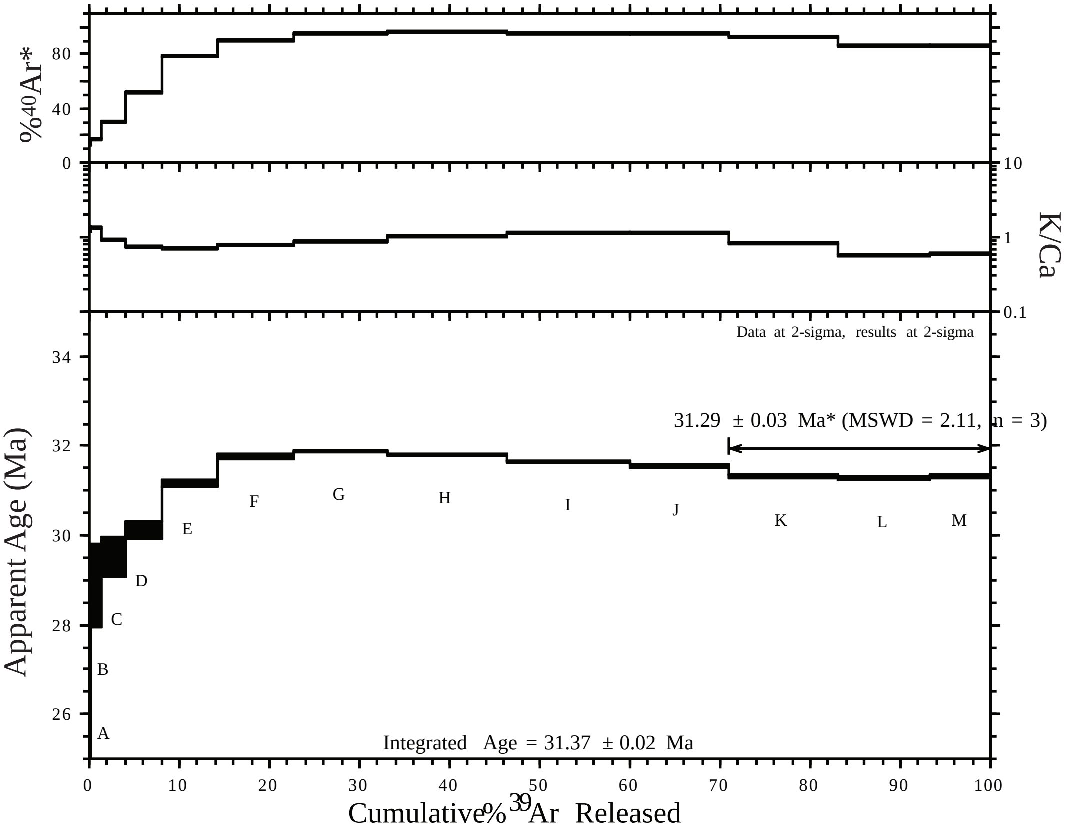
Table 2. ^{40}Ar/^{39}Ar analytical data.

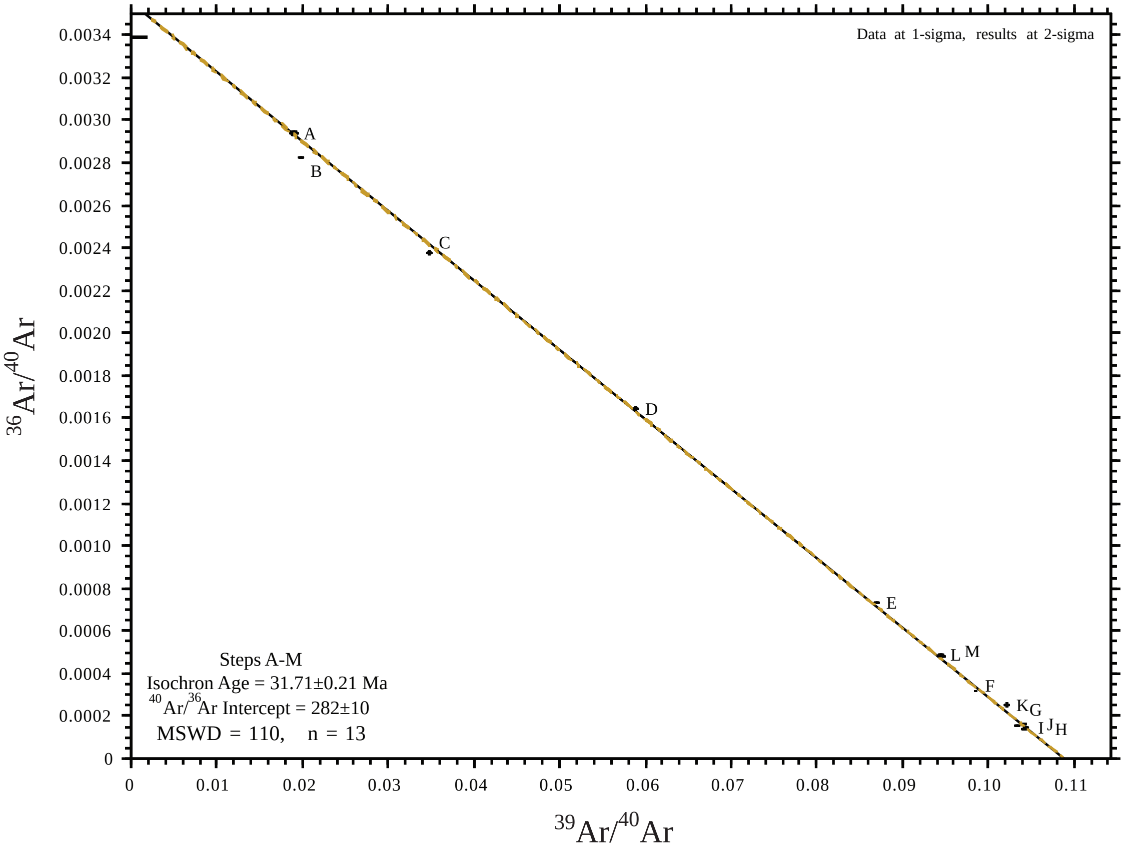
	ID	Power	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar	^{39}Ar$_K$	K/Ca	^{40}Ar*	^{39}Ar	Age	±1σ
		(Watts)			(x 10^{-3})	(x 10^{-15} mol)		(%)	(%)	(Ma)	(Ma)
	15CSC-809-AJ, Groundmass, 19.28 mg, J=0.0019021±0.02%, IC=0.9993722±0.0027589, NM-288J, Lab#=65451-01, Argus VI										
X	A	0.5	57.50	1.053	183.2	0.8	0.48	6.0	0.2	11.96	0.82
X	B	0.8	60.32	1.387	190.6	3.0	0.37	6.8	1.1	14.24	0.62
X	C	1.3	42.19	1.055	121.8	8.1	0.48	14.9	3.6	21.79	0.38
X	D	1.6	23.85	0.8010	52.54	12.3	0.64	35.1	7.3	28.96	0.17
X	E	1.9	13.14	0.7650	13.07	18.5	0.67	71.1	12.9	32.23	0.05
X	F	2.2	10.73	0.6685	4.058	24.4	0.76	89.3	20.3	33.04	0.02
X	G	2.6	9.912	0.5959	1.533	31.6	0.86	95.9	29.9	32.79	0.02
X	H	3.0	9.531	0.5400	0.6105	41.2	0.94	98.6	42.3	32.40	0.01
X	I	3.5	9.367	0.5064	0.4771	33.5	1.0	98.9	52.5	31.97	0.01
X	J	4.0	9.332	0.5497	0.6462	18.6	0.93	98.4	58.1	31.69	0.04
	K	6.0	9.417	0.9440	1.276	29.7	0.54	96.8	67.1	31.46	0.02
	L	10.0	9.469	0.9061	1.337	69.2	0.56	96.6	88.1	31.56	0.01
	M	15.0	9.449	0.9478	1.281	39.4	0.54	96.8	100.0	31.56	0.01
	Integrated age ± 2σ			n=13		330.2	0.67	K2O=3.46		31.43	0.03
	Plateau ± 2σ steps K-M			**n=3**	**MSWD=17.85**	**138.319**	**.551±0.027**		**41.9**	**31.54**	**0.06**
	Isochron±2σ steps A-M			n=13	MSWD=1075.50		^{40}Ar/^{36}Ar=	280±30		32.04	0.66
	15CSC-796-AJ, Groundmass, 21.2 mg, J=0.0019024±0.02%, IC=0.9993722±0.0027589, NM-288J, Lab#=65452-01, Argus VI										
X	A	0.5	52.03	0.4133	152.7	1.2	1.2	13.3	0.3	23.98	0.63
X	B	0.8	50.02	0.3985	141.1	3.9	1.3	16.7	1.4	28.87	0.47
X	C	1.3	28.59	0.5586	68.00	10.2	0.91	29.9	4.2	29.50	0.22
X	D	1.6	16.95	0.6951	28.04	14.6	0.73	51.4	8.1	30.11	0.10
X	E	1.9	11.49	0.7407	8.531	22.9	0.69	78.5	14.3	31.14	0.04
X	F	2.2	10.15	0.6609	3.390	31.0	0.77	90.6	22.7	31.74	0.02
X	G	2.6	9.665	0.5705	1.609	38.6	0.89	95.5	33.2	31.87	0.01
X	H	3.0	9.588	0.5033	1.417	48.8	1.0	96.0	46.4	31.78	0.01
X	I	3.5	9.574	0.4551	1.513	50.8	1.1	95.7	60.1	31.62	0.01
X	J	4.0	9.594	0.4369	1.657	40.6	1.2	95.3	71.1	31.54	0.01
	K	6.0	9.781	0.6207	2.569	44.3	0.82	92.7	83.1	31.31	0.02
	L	10.0	10.56	0.8807	5.347	38.1	0.58	85.7	93.4	31.25	0.02
	M	15.0	10.54	0.8535	5.225	24.4	0.60	86.0	100.0	31.29	0.03
	Integrated age ± 2σ			n=13		369.5	0.84	K2O=3.52		31.37	0.02
	Plateau ± 2σ steps K-M			**n=3**	**MSWD=2.11**	**106.782**	**.684±0.270**		**28.9**	**31.29**	**0.03**
	Isochron±2σ steps A-M			n=13	MSWD=114.13		^{40}Ar/^{36}Ar=	282±10		31.71	0.21

Notes:

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interfering reactions.
Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties.
Integrated age calculated by summing isotopic measurements of all steps.
Integrated age error calculated by quadratically combining errors of isotopic measurements of all steps.
Plateau age is inverse-variance-weighted mean of selected steps.
Plateau age error is inverse-variance-weighted mean error (Taylor, 1982) times root MSWD where MSWD>1.
Plateau error is weighted error of Taylor (1982).
Decay constants and isotopic abundances after Minn et al., (2000).
symbol preceding sample ID denotes analyses excluded from plateau age calculations.
Weight percent K_2O calculated from ^{39}Ar signal, sample weight, and instrument sensitivity.
Ages calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 28.201 Ma
Decay Constant (LambdaK (total)) = 5.463e-10/a
Correction factors:
$(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ = 0.0006752 ± 0.000002
$(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ = 0.0002653 ± 0.0000003
$(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ = 0.012
$(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ = 0.00697 ± 0.0004

15CSC-796-AJ Groundmass Concentrate





15CSC-809-AJ Groundmass Concentrate