Geologic Map of the San Marcial 7.5-Minute Quadrangle, Socorro County, New Mexico

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Open-file Digital Geologic Map OF-GM 287

Scale 1:24,000

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Report for the Geologic Map of the

San Marcial 7.5-Minute Quadrangle, Socorro County, N.M.

Pictured is a view to the north along the east strand of the Little San Pascual Mountain fault zone (left-center of photograph), which separates unconsolidated, sandy sediment on the left from steeply dipping sedimentary rock on the right. In the foreground lies interbedded limestone and fine-grained clastic strata of the Pennsylvanian-age Bar B Formation. To the right (in the foreground), limestone beds are semi-horizontal. But westward (leftward) these beds bend down into the fault. Locally to the left of the fault lies steeply dipping Spears Group volcaniclastic strata (upper Eocene) and Popotosa Formation conglomerates (middle to late Miocene). Thus, the east fault strand is interpreted to be a west-down, normal fault.

INTRODUCTION

This report accompanies the Geologic Map of the San Marcial 7.5-Minute Quadrangle, Socorro County, New Mexico (NMBGMR OF-GM 287). Its purpose is to discuss the geologic setting as well as the stratigraphy and structural geology found on the quadrangle. This report presents several background aspects of the quadrangle, including geographic-tectonic setting, climate, and previous work. It then describes the geologic map units and their depositional settings by age, oldest to youngest and, lastly, the structural geology of the area. Detailed unit descriptions are provided in Appendix 1.

Setting

The San Marcial 7.5-minute quadrangle is unique in that it spans an entire extensional basin of the Rio Grande rift, the southern Socorro basin. The quadrangle lies in southern Socorro County, about 45–50 km (30 mi) south of the city of Socorro. The foot of the Little San Pascual Mountains lies in the northeastern part of the quadrangle, and an alignment of low hills of the southern Chupadera Mountains extends SSW into the northwestern corner of the quadrangle (**FIGURE 1**). In the south-central quadrangle is the imposing Mesa del Contadero, rising 90 m above the Rio Grande floodplain and capped by a basalt flow 3–7 m thick. The main geographic feature of the quadrangle is the Rio Grande, which flows southwesterly through the center of the quadrangle and has a 1.3- to 3.0-km-wide floodplain (0.8–2 mi). The southern boundary of the Bosque del Apache refuge extends southeasterly into the northeast part of the quadrangle. Otherwise the land ownership of the San Marcial quadrangle is private, with almost all of the private ownership falling under a single landowner, the Armendaris Ranch.

The climate is arid, and the vegetation is a mix of riparian woodlands and Chihuahuan scrubland. The annual precipitation is 20 cm (8 inches), most of it falling as monsoonal rainfall in June throughOctober (<https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm7907>). Flora of the Chihuahuan scrubland is characterized by creosote and mesquite. However, in canyon bottoms, the vegetation is more diverse and includes four-wing salt bush, desert willow, and apache plume. The riparian woodlands include tamarisk, cottonwoods, willows, and Russian olives. Grasses, weeds, and tumbleweeds grow where the riparian forest has been cleared.

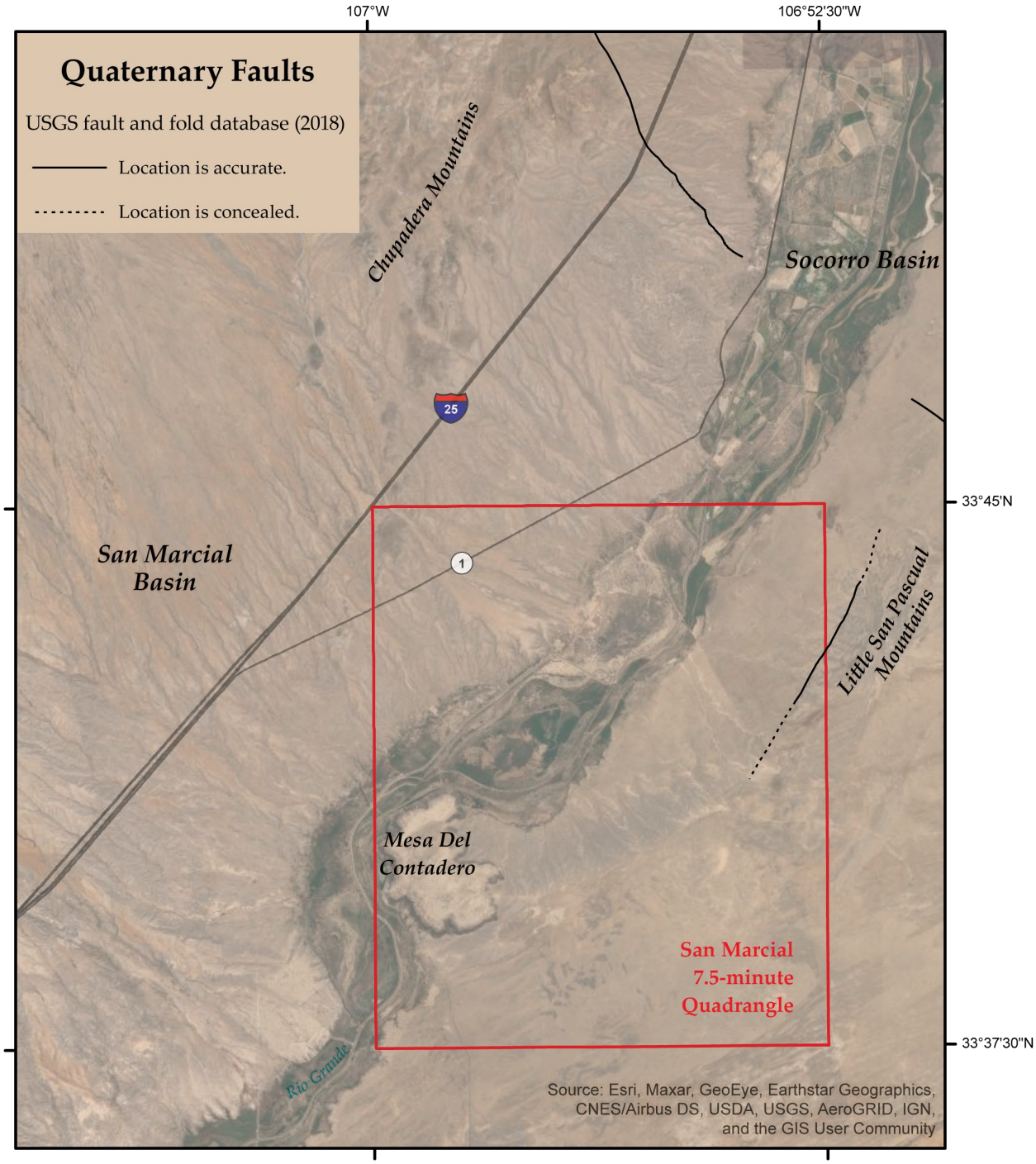

FIGURE 1—Geographic setting of the San Marcial quadrangle.

Measurement and Age Nomenclature

We use metric units for length in this report. An exception is for elevation, where feet are used because the topographic base of the geologic map is contoured in feet. The conversion factor between metric meters and English feet is 3.281 (e.g., 20 feet divided by 3.281 = 6.1 meters); the conversion factor between metric centimeters and English inches is 2.54 (e.g., 10 inches multiplied by 2.54 is 25.4 centimeters). The abbreviation of Ma stands for "millions of years ago," and ka for "thousands of years ago."

Previous Work

Most of the San Marcial quadrangle has not previously been mapped, except near the foot of the Little San Pascual Mountains. This area was included in a larger study of the stratigraphy and structure of the Little San Pascual Mountains (Geddes, 1963a, b). The study concluded that the basic structure of the mountains was a northeast-striking anticline, superimposed by northwest-striking normal faults. It also interpreted that the last movement of the mountain-bounding fault (the Little San Pascual Mountain fault zone) occurred prior to the deposition of what we call the Sierra Ladrones Formation. Interpretation of a gravity profile was interpreted to indicate: (1) at least two large normal faults bounding the eastern margin of the rift basin (Bosque graben), and (2) the rift basin was filled by a minimum of 2,280 m (7,500 ft) of the Santa Fe Group.

Interpretations by Cikoski (2010) and Chamberlin and Cikoski (2010) of geologic relations in the Indian Wells Wilderness quadrangle, which lies due-north of the San Marcial quadrangle, are germane to our effort. There, the basin fill can be subdivided into a lower, tilted sequence (Popotosa Formation, middle to late Miocene) and an upper, lesser-deformed stratigraphic package (Sierra Ladrones Formation). Most of the Popotosa Formation was deposited by west-

flowing piedmont drainages sourced in volcanic terrain northeast of the Little San Pascual Mountains; these strata accumulated in an east–southeast tilted half graben informally called the Bosque graben. This easterly derived piedmont retreated and sometime after 8.5 Ma a western piedmont prograded into the area, depositing sediment on top of the earlier easterly derived piedmont. Although an irregular angular unconformity is present at the common contact between these two piedmont packages, local southward paleocurrents on either side of the contact suggests a somewhat gradual shift towards western piedmont progradation (Cikoski, 2010). Both northeast-striking faults on the eastern basin margin and northwest-striking faults were active syn-depositionally in the late Miocene. Another generation of northwest-striking faults occurred after Popotosa Formation deposition.

MAPPING METHODS

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

map production and layout. Shortened descriptions are presented in the map layout, with detailed versions of the descriptions given in the ArcGIS geodatabase and Appendix 1.

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

STRATIGRAPHY

Although most of the San Marcial quadrangle is covered by the Santa Fe Group or middle to late Quaternary sediment, sedimentary and volcanic bedrock strata are exposed on the flanks of the southern Socorro basin. We discuss the bedrock units in chronologic order, followed by description of the Santa Fe Group and surficial sediment.

Pennsylvanian–Permian Sedimentary Strata

On the footwall (east side) of the Little San Pascual Mountain fault lies a conformable succession of Pennsylvanian–Permian strata that characterizes much of central New Mexico. The lowest unit is the Bar B Formation (IPbb; 270(?) m thick). This late Pennsylvanian unit consists of interbedded limestone and clastic sediment deposited primarily in a low-energy, open marine shelf paleo-environment (Lucas et al., 2017). The limestone occurs in 1–15 m thick intervals, and is composed of micrite, wackestone, and lesser packstone. Within these intervals, the limestone is in medium to very thick, tabular beds. The clastic sediment includes shale, siltstone, and

possible sandstones that collectively form 1–25 m thick intervals. Locally, thick stratiform bodies of chert (likely replacing what was originally limestone) are present.

Above the Bar B lies a 55–60 m thick transitional unit, the Bursum Formation (**Pb**). It is characterized by reddish to maroon siltstone, mudstone, and very fine sandstone interbedded with subordinate light-gray limestone. This sequence is commonly capped by a thick bed of yellowish dolomite. It records a mix of non-marine and marine depositional environments (Lucas et al., 2017).

Above the dolomite lies 220 m of reddish-brown clastic sediment assigned to the Abo Formation. Here, Permian-age mudstones, siltstones, and very fine-grained sandstones are interbeded with minor amounts of very fine- to medium-grained, arkosic sandstones. The mudstones are massive (non- or poorly laminated) and occur in tabular beds. Siltstones and very fine sandstones, on the other hand, are well-laminated. There are 5–10% channel fills (30–100 m wide, 0.3–3 m thick) consisting of very fine- to medium-grained, arkosic sandstone and lesser intra-formational conglomerate. The Abo Formation is universally acknowledged to have been deposited in a largely fluvial paleo-environment (e.g., Kues and Gile, 2004).

The Abo Formation is overlain by the Permian-age Yeso Group, featuring two distinct formations in the San Marcial quadrangle. The Meseta Blanca Formation (also called the Arroyo de Alamillo Formation per Lucas et al., 2005) is 110–130 m thick and comprised of well-bedded (commonly flaggy) siltstone and very fine- to fine-grained, quartzose sandstones (map unit **Pym**). Although primarily reddish brown, the unit on this quadrangle also exhibits yellow or white intervals. Beds are relatively thin (mostly very thin to medium), and internally massive to

horizontal-planar-laminated. Bedding surfaces may feature ripple marks. We did not observe halite casts or herringbone cross-beds on this quadrangle. The Meseta Blanca Formation was deposited on a relatively arid coastal plain, where eolian fine sand was reworked by low-energy fluvial processes. Two previous works have interpreted the sediment in the Mesta Blanca Member to be a consequence of eolian dunes and sand sheets advancing southward onto floodplain, fluvial, and tidal flat deposits (Broadhead et al., 1983; Stanesco, 1991).

The Los Vallos Formation of the Yeso Group (map unit **Pyv**) is 200–230 m thick and comprised of intertonguing: (1) reddish-brown mudstone to siltstone to very fine-grained sandstone; (2) white to yellowish siltstone to fine-grained sandstone; and (3) light-gray limestone-dolomite. Individual tongues are 1–10 m thick. Siltstones and fine-grained sandstones are quartzose, locally clayey, and occur as tabular beds (which are horizontal-planar laminated, massive, or bioturbated). Carbonates occur as thin to thick, tabular beds that form ledges within the softer clastic strata. Compared to carbonates in the overlying San Andres Formation, the ones in the Los Vallos Formation are lighter colored and not as well-bedded nor as fossiliferous. Gypsum or anhydrite seen elsewhere in the Los Vallos Formation was not directly observed on this quadrangle, perhaps due to poor exposure. The Los Vallos Formation was deposited on a low-energy, marginal marine environment that included sabkhas, eolian sand sheets, mud flats, and a shallow-marine shelf (Baars, 1962; Huffman and Condon, 1993; Kues and Giles, 2004).

The San Andres Formation exhibits the following succession (ascending order): a lower limestone tongue (**Psal**, 15–16 m thick); (2) the Glorieta Sandstone (**Pg**, 40 m thick) interbedded with 1–10% limestone beds, and (3) at least 3 m of limestone corresponding to the main body of

the San Andres Formation (**Psa**). Limestone beds of the lower limestone tongue are dark-gray to gray, micritic, and occur in thick, tabular beds. At the base of the tongue is a thick (30–100 cm), tabular bed of white to very pale-brown, fine-grained quartzose sandstone correlative to the Glorieta sandstone. The upper part of the lower tongue has abundant stratiform chert beds; these likely have replaced what was originally limestone. The 40-m-thick Glorieta Sandstone tongue exhibits thick, tabular beds of white to yellowish-tan sandstone; these beds are internally massive. The sand is very fine- to fine-grained, well-sorted, and quartzose. The sandstone is well-cemented by silica, and the intervening 1–10% limestone beds are commonly replaced by stratiform chert or quartz. Above the Glorieta Sandstone, the San Andres Formation consists of thick, tabular beds of packstone limestone that is light-gray (weathering to light-brownish-gray). Bivalves are locally present. The San Andres Formation was deposited in a shallow-marine environment (Kues and Giles, 2004), whereas the Glorieta Sandstone is thought to be eolian (Mack and Bauer, 2014) or perhaps nearshore sand (Baars, 1962).

Stratiform chert and quartz bodies (**Tcq**), 1–15 m thick, are present in carbonate intervals of the Glorieta Sandstone and Bar B, Yeso, and San Andres Formations. The chert is reddish-gray to dark-orange to reddish-brown. The quartz is white and, where crystalline, the crystals are as large as 2 mm. Local geodes are observed that are lined with quartz crystals. At one locality (UTM coordinates: 326223 m E, 3731435 m N, NAD83, zone 13), there is pronounced banding of brownish chert and white quartz (**FIGURE 2**). This unit was mapped where it occupies >50% of outcrop area, with the remainder being limestone, shale, or sandstone. We infer that the localized silica cementation of the Popotosa Formation may be related to this event, and if so unit **Tcq**

would be late Miocene. This silicification event may also be related to precipitation of barite and fluorite(?) in druzy quartz veins, which is observed locally in the Glorieta Sandstone.

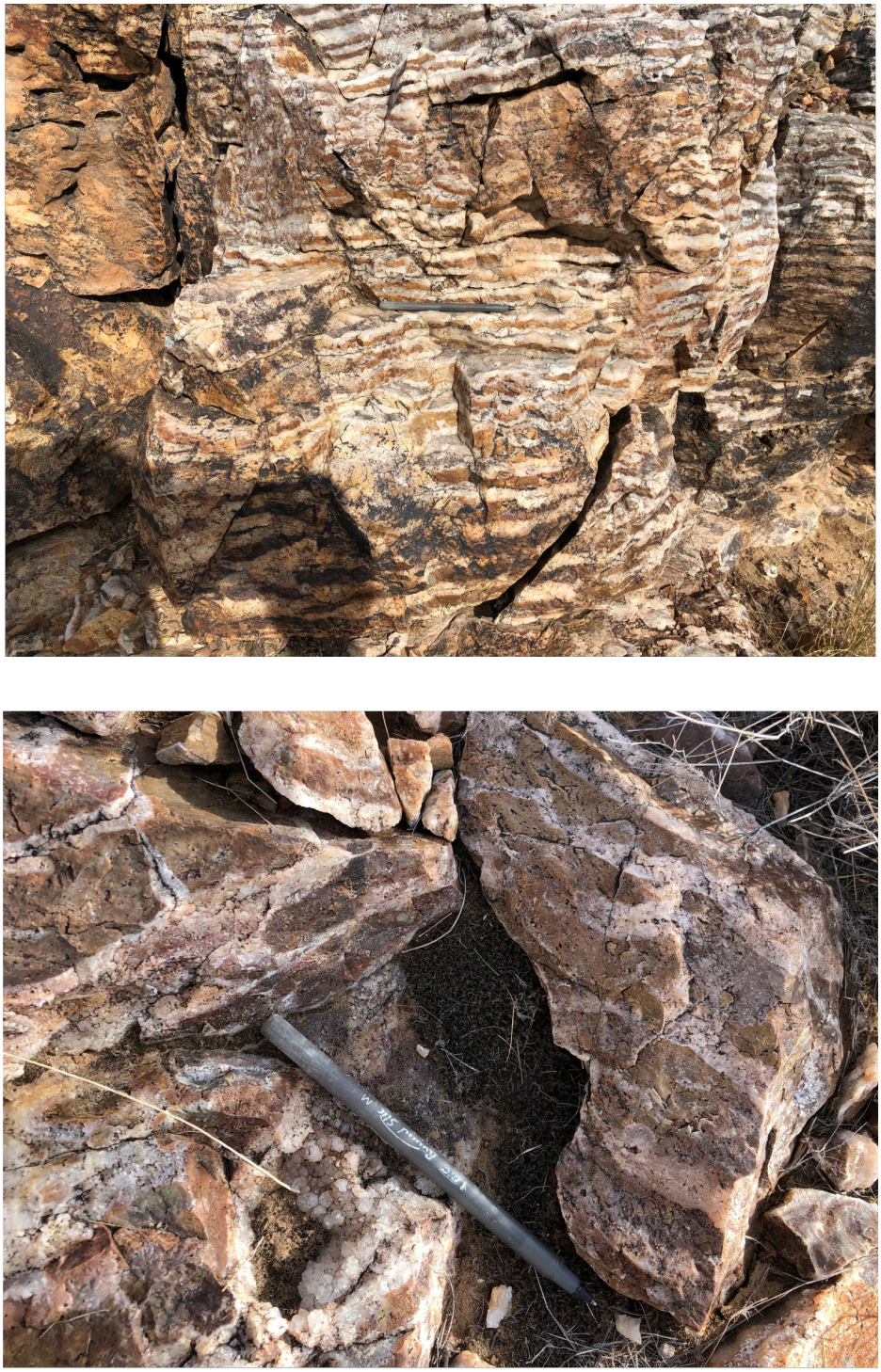

FIGURE 2—Photographs of banded chert found in the foothills of the Little San Pascual Mountains. Pen for scale. The brown chert is intricately interbedded with white quartz, the latter locally forming geodes. In the lower photograph, note how the white quartz locally cross-cuts the brown chert (e.g., above left side of pen), indicating that, at least locally, the quartz post-dates the chert precipitation.

Eocene Non-Volcanic Sedimentary Strata

At the foot of the Little San Pascual Mountains lie scattered exposures of the Baca Formation (**Tb**). This clastic sediment was deposited in the middle Eocene during and immediately following Laramide contractional tectonism (Cather, 2009). The Baca Formation consists of intercalated tongues of: (1) reddish very fine- to fine-grained sand and muddy sand, (2) fine- to medium-grained sand with feldspar and lithic fragments, and (3) fining-upward conglomerates and conglomeratic sandstones. The very fine- to fine-grained sand and muddy sand is reddish-brown and massive; it locally contains 0–10%, scattered, coarser sand grains and 1–3% pebbles. The gray sand is massive to cross-laminated (trough and tangential foresets) and composed of quartz, feldspar and lithic fragments. Gravel in the conglomerates are composed mainly of subrounded-rounded clasts of gray, micritic limestone-dolomites, 1–5% chert, and 1% reddish mudstone–siltstone. Clast size ranges from pebbles (mostly coarse to very coarse) to fine cobbles, with 10% coarse cobbles and 1–5% fine boulders. The gravel matrix consists of reddish, poorly sorted, fine- to very coarse-grained sand with 3–20% (estimated) clay-silt. Beds are thin to thick and lenticular. Measurements of clast imbrication indicate an easterly flow direction. Thus, the corresponding Laramide highland was located west of what is now the Little San Pascual Mountains, consistent with previous interpretations (Cather, 1983).

Eocene Volcanic Strata

Volcanic strata consists primarily of intermediate composition volcanic flows, which are interbedded with minor volcaniclastic sediment and one ignimbrite. Most of the intermediate volcanic flows are correlated with the andesite of Willow Springs (Chamberlin and Cikoski, 2010).

These andesites are characteristically plagioclase- and pyroxene-phyric, but within the volcanic package two feldspar-biotite-phyric flows have been mapped.

The plagioclase-pyroxene-phyric andesites (**Twa**) are gray, weathering to a light-brown to brown to reddish-brown, and are variably vesicular. They have 5–10% pyroxene phenocrysts and 10–40% plagioclase phenocrysts (both mostly 0.5–2.0 mm long). The groundmass has abundant plagioclase crystals (≤0.5 mm in size).

The lower and upper biotite-phyric intermediate flows are both highly porphyritic. The lower (**Twabl**) is reddish-gray, varnishing to a dark-reddish-brown. Its phenocrysts include 12–20% feldspar (subhedral, mostly 1–3 mm long but up to 7 mm) and 3–7% biotite (0.1–2 mm long). The upper biotite-phyric lava (**Twabu**) is medium-gray, contains 15–35% feldspar phenocrysts (mostly 1–2 mm, up to 5 mm) and 1–5% biotite phenocrysts (≤1 mm long and bronze-colored). The upper flow forms a ledge that weathers into 5- to 10-cm-thick plates. The lower biotite-phyric intermediate flow returned a $^{40}Ar/^{39}Ar$ plateau age of 35.96 ± 0.02 Ma using biotite (Matt Heizler of the NM Bureau of Geology & Mineral Resources, pers. comm., May 11, 2020).

Locally separating the lava flows are 1–15 m-thick tongues of tan (locally reddish) silt and relatively fine sand (**Tsps**). The sand is mostly very fine- to fine-grained (with minor medium-lower), locally silty, and has sparse pumiceous zones. Locally, there are up to 15% scattered coarse to very coarse sand grains (including pyroxene crystals) and 1–10% scattered, andesitic pebbles. Also, there are 1–10% intervals (mostly <1 m thick) comprised of grayish, very fine- to very coarse-grained, volcanic sand with abundant feldspar and pyroxene grains. The sediment is relatively

massive, and is interpreted as eolian sand reworked by sheetflooding, similar to the fine sediment that caps Plio–Pleistocene lava flows throughout the Rio Grande rift.

The mapped ignimbrite is welded and named the tuff of Battle Mountain (**Ttbm**). It contains biotite and feldspar phenocrysts, is variably eutaxitic, and commonly overlies a black vitrophyre 0.5–2 m thick. The tuff is light-gray to white and weathers to tan, brown, reddish-brown, or purplish colors. The phenocryst assemblage contains 10–25% feldspar (subhedral to euhedral, 0.5–4 mm; probably plagioclase and minor sanidine) and 1–7% biotite crystals (0.1–1 mm); very minor hornblende was also observed. The plagioclase concentration appears to decrease up-section whereas the biotite concentration increases up-section. There is 10% flattened pumice (0.1–1.5 mm), which are locally stretched to form pumice lineations. Lithic xenoliths are lacking to very sparse. The ignimbrite returned an $^{40}Ar/^{39}Ar$ plateau age from biotite of 35.77 ± 0.01 (Matt Heizler of the NM Bureau of Geology & Mineral Resources, pers. comm., May 11, 2020).

Santa Fe Group Basin-fill

The Santa Fe Group can be subdivided into the older Popotosa Formation (Miocene) and younger Sierra Ladrones Formation (Pliocene–Pleistocene). The Sierra Ladrones Formation extends across most of the quadrangle, although it is commonly buried by middle to late Quaternary valley-floor alluvium, terrace deposits, or eolian sand. Most of the upper Sierra Ladrones Formation has been eroded away, particularly near the Rio Grande, but upper strata are preserved near the western and eastern quadrangle borders. A key locality for the geology in the San Marcial quadrangle is Mesa del Contadero. Here, a 818.3 ± 10.6 ka basalt flow (Sion et al., 2020) has preserved the original top of the Sierra Ladrones Formation. The Popotosa Formation, on the other hand, is only exposed near the foot of the Little San Pascual Mountains. Note that

the Popotosa Formation was correlated to the Baca Formation by Geddes (1963a, b). Exposures in the adjacent quadrangle to the east, the Little San Pascual Mountain quadrangle, show a prominent angular unconformity separating the two deposits. The Sierra Ladrones Formation is probably 200–300 m thick. Thicknesses of the Popotosa Formation probably vary widely, depending on location relative to faults and down-dropped fault blocks, with an estimated range of 100–1600(?) m.

Popotosa Formation

Outcrops of the Popotosa Formation can be differentiated into a reddish conglomeratic lithofacies in the east interfingering westward with sandstone. The conglomerate (unit **Tppe**) is in vague, thin to thick, lenticular to tabular beds. The gravel is comprised of pebbles with 10–25% cobbles and trace to 5% boulders. The gravel assemblage is rounded to subrounded, poorly sorted, and composed of Paleozoic limestone, 1–7% chert, and 1–18% sedimentary clasts that include yellowish sandy-silty limestone as well as siltstone to fine sandstone clasts from the Yeso Group and Abo Formation. The presence of these sedimentary clasts indicate that the Yeso and Abo Formation capped the Little San Pascual Mountains when the Popotosa Formation was deposited. The observation that the concentration of Permian-derived clasts decreases and limestone and chert increases up-section indicates a progressive unroofing of these bedrock strata. There are up to 20% sandstone interbeds, where the sand is in medium to thick, wedge-shaped beds and composed mainly of quartz and feldspar with 5–10% dark lithic-mafic grains. The conglomeratic facies is commonly well-cemented by calcium carbonate or locally by silica cement.

To the west of the conglomeratic facies, the sandstone of the Popotosa Formation occurs mostly in thick, tabular beds that are commonly well-cemented by silica (**Tps**). These beds are internally massive or horizontal-planar-laminated. Locally, there are low-angle cross-laminations; elsewhere, burrows or bioturbation are found locally. Colors range from light-gray to pink to red. The sand is mostly fine-grained, subrounded, well-sorted, lacks fines, and is composed of quartz, lesser feldspar, and 1–10% mafic-lithic grains. The sandstone is reddish-brown and cross-stratified in the conspicuous buttes found just south of the northern quadrangle boundary (unit **Tpsx**) 1.2 km east of the Rio Grande floodplain (correlated to the Baca Formation by Geddes, 1963a, b). There, foresets dip steeply to the northeast and typically are >0.5 m tall. We interpret that the cross-stratified sand represents paleo-dunes, which transitioned laterally eastwards into an eolian sand sheet. The sand sheet, in turn, interfingered with gravelly alluvial fans shed from the Little San Pascual Mountains.

The Popotosa Formation is not directly dated on this quadrangle. Dating of a pumice bed and discovery of an oreodont fossil in the quadrangle to the north (Indian Wells Wilderness quadrangle; Chamberlin and Cikoski, 2010; Morgan et al., 2009) indicates a middle to late Miocene age there. We also infer a middle to late Miocene age on this quadrangle based on similar degrees of tilting (6–18°E) and similar cementation as the Popotosa Formation in the Indian Wells Wilderness quadrangle.

Sierra Ladrones Formation

As might be expected in a rift-basin transverse transect, the Sierra Ladrones Formation across the southern Socorro basin on this quadrangle includes a lateral succession of the following facies: gravelly western piedmont facies, a transitional western basin-margin facies (interfingering distal

piedmont-axial-fluvial units), axial-fluvial deposits of the ancestral Rio Grande, a transitional eastern basin-margin facies, and an eastern piedmont facies. The western piedmont facies is derived from the southern Chupadera Mountains, whereas the eastern piedmont facies is sourced from the Little San Pascual Mountains. Aside from minor, localized cementation, the associated map units are typically poorly cemented and non-tilted. Exposed sediment is late Pliocene to early Pleistocene in age, consistent with the discovery of a Blancan fossil assemblage in the axial-fluvial facies in lower Tiffany Canyon (Morgan et al., 2009). Also, a pumice-conglomerate near the foot of the Little San Pascual Mountains (UTM coordinates 324540 m E, 3729293 m N; NAD83, zone 13) is tentatively correlated to the 1.6 Ma Guaje Pumice (based on similar pumice-conglomerates near the village of San Antonio to the north; Cather and McIntosh, 2009); but final geochemical analyses confirming that correlation is pending.

The western piedmont facies (**QTspw**) consists of light-orange to reddish interbedded sand, pebbly sand, and gravel. What is exposed represents the upper part of the unit, which has prograded eastward over the axial-fluvial facies. The sand and pebbly sand is in medium to thick, tabular beds that are internally massive to horizontal-planar laminated. There are subequal to subordinate interbeds of sandy gravel that are in very thin to medium, lenticular to tabular beds that locally exhibit cross-stratification. The gravel is comprised of pebbles with 1–15% cobbles that are subangular to subrounded, poorly sorted, and composed of volcanic rock types (mainly felsic flows or ignimbrites). The sand is fine- to very coarse-grained, mostly subrounded, poorly sorted, and composed of a mix of volcanic grains, feldspar, and minor quartz. Typically, the sand beds contain 1–20% scattered volcanic pebbles and 1–10% out-sized, coarse sand grains. The sand matrix contains 1–15% clay and is relatively well-consolidated as a result. Furthermore, there are

common, weakly developed paleosols featuring subangular blocky peds, weak clay illuviation, and Stage I carbonate morphology.

The distinctive axial-fluvial facies (**QTsa**) lies on either side of the modern Rio Grande floodplain, in the center of the quadrangle. This unit is characterized by light-colored (mostly light-gray to white, 10YR-2.5Y hues), fine- to coarse-grained sand that is cross-laminated, horizontal-planar-laminated to very thinly bedded, or else is massive. The cross-lamination locally exhibits troughs related to streambed dunes of the ancestral Rio Grande. Within the sand are 1–15% pebbly sand layers that are in very thin to medium, lenticular beds. The pebbles are subangular to well-rounded, moderately to poorly sorted, and composed of felsic volcanic rocks, 1–30% intermediate rocks, 1–15% granite, and 0 to trace cherts. There are greater proportions of extra-basinal (exotic) clasts up-section, particularly in the upper 40–50 m of the deposit. This upper, more heterolithic gravel assemblage includes 1–25% chert, 0–15% quartzite, 1–10% quartz, 1–20% Paleozoic limestone, 1–20% reddish siltstone to fine sandstone (from Permian strata), trace to 3% Pedernal Chert, and 0–1% gneiss or schist. There are less than 10% fine-grained floodplain deposits. The axial-fluvial sediment is weakly to moderately consolidated, but near the Little San Pascual Mountains there are 10–50% strongly cemented intervals up to 2 m thick.

Transition zones (basin-margin facies) are mapped along either side of the axial-fluvial depositional tract. On the west side (**QTstw**), the axial sand is interbedded with 30–70% light-orangish to light-brown, thin to thick beds of silt, very fine- to fine-grained sand (locally with scattered coarser sand and pebbles), and clay. This fine sediment is tabular-bedded (internally massive or laminated to very thinly bedded). Locally, 1–5% calcium-carbonate nodules are

present. Contacts between beds are gradational or sharp and mostly planar. The fine-grained sediment includes 1–3 m-thick tongues of piedmont-derived sediment (derived from volcanic terrain to the west), which have <30% gravel and are characterized by: (1) minor to common, very thin to medium, lenticular beds of coarse sand and pebbles composed of volcanic clasts; (2) 1–40% medium to very coarse sand and 0–5% volcanic pebbles scattered in predominately very fine to fine sand; and (3) weak soil development characterized by Stage I carbonate morphology, no visible clay illuviation, and ped development (moderate, medium to coarse, subangular blocky).

The transition zone (basin-margin facies) on the eastern edge of the axial-fluvial depositional tract (**QTste**) is comprised of fine-grained sediment interbedded with minor tongues of sandy gravel derived from the Little San Pascual Mountains. Colors range from pink to light-brown to tan to pinkish white. The fine-grained sediment consists of very fine- to fine-grained sand (locally minor medium sand grains), silt, and silty very fine- to fine-grained sand in medium to thick, tabular (minor broadly lenticular) beds that are internally massive and commonly bioturbated. Locally, some of these predominately fine-grained beds contain minor (<25%), scattered medium to very coarse sand grains and 1–5% scattered pebbles. However, these poorly sorted beds are less common than what is mapped as the eastern piedmont facies. The sandy gravel is in medium to thick, lenticular beds. The gravel is comprised of pebbles with 15–20% cobbles. The clasts are subrounded to subangular, poorly sorted, and composed of 90% Paleozoic limestone and 1–15% locally sourced, angular chert. Weak paleosols are present, mostly in the fine-grained sediment, which exhibit Stage I to II calcic horizons; these whitish paleosol horizons are locally overlain by orangish cambic paleosol horizons with subangular blocky ped structure.

The eastern piedmont facies (**QTspe**) consist of sandy gravel interbedded with subequal (±20%) very fine- to medium-grained sand, silty sand, and silt. Gravelly tongues are 1–4 m thick and exhibit thin to thick, tabular to lenticular beds and 0–10% cross-stratification. The gravel is comprised of pebbles with 1–20% cobbles and 1–5% boulders that are angular to subangular, poorly sorted, and composed of Paleozoic limestone and 0.5–12% angular-subangular chert eroded from Pennsylvanian strata. The finer strata is commonly pinkish-gray to reddish-brown and are in thick, tabular to wedge-shaped beds that are internally massive and commonly bioturbated; there are 1–20% scattered coarse to very coarse sand grains and 1–20% scattered very fine to very coarse pebbles of the aforementioned gravel types. The uppermost part of the unit prograded slightly over the axial-fluvial sand.

Basalt Flows

Two periods of basaltic volcanism occurred on the San Marcial quadrangle. Recent $^{40}Ar/^{39}Ar$ dating has determined that the older episode is 818.3 ± 10.6 ka and the younger episode is 78.1 ± 3.2 ka (Sion et al., 2020). The older basaltic volcanism emanated from a cinder cone corresponding to Mesa Peak on Mesa del Contadero. The cinder cone (unit **Qbucc**) is comprised of black to dark-red, basaltic lapilli (minor ash and bombs up to 20 cm long), welded agglutinate, and local basalt flow lobes. These strata are in tabular, steeply dipping beds. Surrounding this cone, the older flow on Mesa del Contadero (**Qbu**) is 3–7 m thick and consists of a dark-gray to black, vesicular basalt that forms a protective cap on Mesa del Contadero. The lava rock is porphyritic with 7–12% phenocrysts of olivine and 1–2% phenocrysts of pyroxene (both mostly 0.2–1 mm long).

The older, mesa-capping basalt flow overlies hydromagmatic deposits (**Qbuhm**) that are 1–30 m thick, thinning away from Mesa Peak. The hydromagmatic deposits consists of fine- to very-

coarse-grained sand and fine pebbles in horizontal-planar, well-defined laminations. The sand is well-sorted within a lamina and composed of subangular basalt and quartz-rich grains (the latter derived from expulsion of unit **QTsa**). Locally, there are 1–10% cross-laminations up to 10 cm tall, likely representing pyroclastic surge deposits.

The lower basalt flow on the landscape (**Qble**, 78 ka) caps a terrace in the southwestern corner of the quadrangle. The flow is 1–8 m thick and composed of black to very dark-gray, highly vesicular basalt that contains trace to 1% olivine phenocrysts. A thick and extensive eolian sand sheet overlies this basalt.

Terrace Deposits

The terrace deposits on the San Marcial quadrangle are particularly interesting. These formed after incision of the Rio Grande ended Santa Fe Group deposition (i.e., after the emplacement of the Mesa Contadero basalt flow at 818.3 ± 10.6 ka, age from Sion et al., 2020). Recent completion of a terrace study in the Socorro area (Sion et al., 2020), combined with existing and pending age control in the vicinity of San Marcial, are anticipated to increase our understanding of the mid- to late Pleistocene incision/aggradation cycles of the Rio Grande. This report focuses on describing the terrace deposits and their geomorphic positions.

The highest terrace deposits (map units **Qtgh** and **Qtti4**) consist of sandy gravel and minor pebbly sand. The sediment is mostly 3–6 m thick and underlies an extensive geomorphic surface west of the Rio Grande. The strath of the terrace is >2 m above modern grade, and the tread lies 18–10 m above modern grade (decreasing to the west); along Tiffany Canyon, the tread height is 11–13 m. The topsoil exhibits a Stage III to IV petrocalcic horizon. Bedding of gravelly sediment

is very thin to medium and tabular to lenticular; pebbly sand beds are also horizontal-planar-laminated. Within some of the thicker beds is 1–5% cross-stratification. Gravels include pebbles, >5% cobbles, and trace to 3% boulders that are subrounded to subangular, moderately to poorly sorted, and composed of felsic volcanic rocks, 1–10% intermediate volcanic rocks, and 0–1% pebbles reworked from the axial-fluvial unit (**QTsa**). The sand in the gravelly beds is reddish-brown to brownish, mostly medium- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and has 25–40% volcanic-dominated lithic grains, minor feldspar, and up to 10% quartz. There is trace to 3% clay in the sand matrix. Locally there are sand beds 0.5–1 m thick that are internally massive. These sand beds are composed primarily of fine- to medium-grained sand with scattered, coarser volcanic sand grains plus 1–10% scattered pebbles; these sand beds also have 1–5% thin-medium, lenticular beds of sandy pebbles. Local paleosols, up to 60 cm thick, are present that have reddened soil horizons (Bw) overlying calcic horizons exhibiting Stage I to II carbonate morphology.

The next-lowest terrace deposit (**Qtgl** and **Qtti3**) thickens dramatically towards the Rio Grande (from ≈2 m to 10 m) and locally coarsens upwards. Its tread mostly lies 7–10 m above modern grade; the base of the deposit is either buried (near the Rio Grande) or lies 1–5 m above modern grade. The topsoil exhibits calcic horizons with Stage II to III carbonate morphology. The sandy gravel is in very thin to thick, mainly lenticular beds; there is 1–20% local cross-stratification. The gravel includes pebbles with 1–20% cobbles and 0–3% boulders; gravel clasts are subrounded to subangular, moderately to poorly sorted, and composed of felsic volcanic clasts with 2-15% intermediate volcanic rocks, 1-5% chert, and 0% to trace quartzite. The pebbly

sand is mostly horizontal-planar-laminated. The sand is fine- to very coarse-grained and there is only 0–5% clay in the sand matrix.

Two lower, relatively coarse terrace units are present that are most readily recognized in Tiffany Canyon (**Qtti1** and **Qtti2**). Both are composed of sandy gravel comprised of pebbles, 30–50% cobbles, and 1–15% boulders. The higher of these two lower Tiffany Canyon terraces is more extensive. Its tread stands 4–5 m above modern grade and the deposit is 2 m thick. The tread of the lower of these two terraces in Tiffany Canyon is only 2–3 m above grade and the deposit is 1–2 m thick.

Eolian Deposits

Various eolian sand deposits form an extensive surficial unit east (down-wind) of the Rio Grande. The eolian sand is similar in all the deposits, being mostly light-brown to light-yellowish-brown (7.5-10YR 6/4), fine- to medium-grained, subrounded to subangular, well sorted, and composed of quartz, minor feldspar, and 10–20% lithic-mafic grains. Due to bioturbation, minor coarse to very coarse sand and pebbles may be mixed with the fine- to medium-grained sand. The sediment is mostly massive. The upper 10–100 cm is typically loose and has no notable soil development. However, below this loose, upper zone the sediment becomes more consolidated and local buried soils are present. These buried soils are characterized by ped development, Bw horizons (slight reddening), and weak calcic horizons (mostly Stage I). The most common eolian deposit is a 0.2- to 3-m-thick sand sheet (**Qes**) whose surface has various proportions of low coppice dunes (**Qesc**). The coppice dunes are typically developed around small shrubs, cover 10–100% of the surface, and are 0.1–1 m tall. Coppice dunes are massive (due to bioturbation) or exhibit vague cross-laminations.

Two types of thick eolian sand deposits are found near the base of the Little San Pascual Mountains. The first is an eolian sand ramp (**Qerc**), sloping westward away from the bedrock base of the mountains, that is up to several meters thick. The surface of the sand ramp commonly has coppice and irregular dunes up to 1 m tall. The eolian sand intertongues with gravelly colluvium near the buttress contact with the bedrock. The second type of thick eolian sand deposit is located at the base of the north side of west-trending ridges (underlain by the Santa Fe Group) near the foot of the Little San Pascual Mountain (unit **Qele**). These "lee-side" deposits are 2–12 m thick. Tall arroyo-bank erosion reveals thin to medium, tabular (minor broadly lenticular) beds that are commonly separated by sharp deflation or erosional contacts. The beds are internally massive or else exhibit horizontal-planar-laminations or cross-laminations (tangential, 3–10 cm tall foresets facing northeast). Paleosols appear to be most common in the upper 2 m of the deposit, and are characterized by ped development and extensive burrowing. Below, there are 1–10% paleosols that exhibit calcic horizons with Stage I to II carbonate morphologies. These eolian deposits are interbedded with minor tongues of alluvium (sand and pebbles) shed from the Little San Pascual Mountains. Various types of dunes (coppice, parabolic, transverse, longitudinal, irregular), 0.2–2 m tall, may be found on the surface of these lee-side deposits.

Sand dunes are common in the southeast part of the quadrangle. Here, dune forms include transverse, longitudinal, barchan, parabolic, and irregular. Longitudinal dunes are mostly orientated ≈060 degrees. Barchan dunes are orientated transverse to the 060 degree trend of the longitudinal dunes. Locally, the eastern end (tail) of a barchan dune may curve and merge with a longitudinal dune.

Unit **Qse** is assigned to sheetflood deposits, 1–10 m thick, whose primary constituent is reworked eolian sand. The deposit is massive or locally in medium to thick, tabular beds. Within the sand is trace to 10%, very thin to medium, lenticular beds of sandy pebbles or pebbly sand. The sand is very fine- to coarse-grained (mostly fine- to medium-grained) with 1–10% scattered coarse to very coarse grains and trace to 5% scattered very fine to coarse pebbles. The deposit is generally overprinted by a cumulic sequence of weak paleosols. Pedogenesis is indicated by local burrowing (krotovina), Stage I calcic horizons (1–15% scattered calcium carbonate nodules 0.5–2.0 cm wide and strong HCl effervescence) and ped development that typically lacks notable clay illuviation (peds are moderate, medium to very coarse, subangular blocky, and slightly hard to hard). Minor parts of the surface may be covered by a thin (<20 cm) to thick sheet of eolian sand (see unit **Qes**).

Valley-floor Units

Sediment is typically sandy beneath the Rio Grande floodplain but is coarser on the floors of tributary drainages. Valley-floor sediment includes weakly consolidated to loose, clastic strata that occupies notable portions of the valley floor, including very low-level terraces (<3 m tread height). Beneath the modern Rio Grande floodplain, the sediment is mostly very fine- to medium-grained sand with minor silt and clay beds. Based on historical records of major flooding events, the upper part few meters of the floodplain is <100 years old. Using aerial imagery, we mapped the modern Rio Grande channel (as it existed in 2014) in addition to modern bar deposits, historical channel-splay, and historical scroll-bar deposits. East of the Rio Grande, tributary alluvium is primarily sand with minor gravels. However, tributary alluvium west of the Rio Grande is comprised of sandy gravel, pebbly sand, and sand in variable proportions.

Various allostratigraphic units of Holocene age comprise both valley-floor and flanking alluvial fans in the tributary drainages. These units mainly include younger alluvium, historic alluvium, or modern alluvium. Younger alluvium is assigned to a low-level terrace deposit whose tread stands 0.5–3.0 m above valley floors. The associated geomorphic surface is relatively smooth, lacks bar-and-swale topography (but cobble or boulder bars might still have a subtle expression), and features a desert pavement with high clast density, weak to moderate Av peds, and very weak varnishing of clasts. The topsoil developed on the younger alluvium is characterized by weak calcic horizon(s) with visually detectable Stage I to I(+) carbonate morphologies (clast surfaces partially to wholly covered by $CaCO_3$ coats but the matrix is not whitened; Gile et al., 1966). The sediment consists of interbedded pebbly sand, sand, and sandy gravel. Beds are tabular to lenticular, with ≤10% cross-stratification. Sand outside of gravelly beds is light-brown, mostly fine- to medium-grained, and has up to 20% pebbles. These sand beds are typically massive. The deposit has local buried soils that commonly feature 10–30 cm-thick, weak calcic horizon(s) (Stage I) locally overlain by a 10–5 cm-thick cambic (Bw) horizon or, less commonly, a weak illuviated clay (Bt) horizon. The degree of soil development is consistent with an early to late Holocene age (ca. 100 to 10,000 years before present) based on comparison with Gile et al. (1981).

Historic and modern alluvium differ from the younger alluvium allostratigraphic unit in several respects: (1) they have less sand beds and the sand beds that are present commonly feature internal laminations; (2) their geomorphic surfaces exhibit bar-and-swale topography; and (3) they lack notable topsoil development, with no visible calcium carbonate coats on clast surfaces at a vertical depth of 10–30 cm below ground surface. Historic alluvium underlies treads that are

mostly 0.3–0.7 m above modern alluvium. This alluvium is 1–3 m thick (thickening towards the Rio Grande floodplain), and is inferred to be 10–100 years old (surface lacks historical artifacts associated with the ca. 1880–1930 human occupation of San Marcial). Modern alluvium is relatively sparsely vegetated, sports steep-walled channels, and is inferred to have been active in the past 10 years.

GEOLOGIC STRUCTURE

The southern Socorro basin consists of one (possibly two) half-grabens tilted eastward towards the Little San Pascual Mountains (see Cross Section A–A'). The graben is filled by Santa Fe Group basin-fill, which thickens eastward as the graben floor deepens in that direction. As elaborated above, the Santa Fe Group has two formations: an upper Sierra Ladrones Formation and a lower, more cemented and compacted Popotosa Formation. Recognition of these two units aids in the mapping of faults.

Exposed in the northwestern corner of the quadrangle, on the distal hanging wall ramp, is the upper strata comprising the bedrock floor of the graben. Offset of volcanic strata is attributed to northwest-trending faults. On-going mapping on the Fort Craig quadrangle, where one of these faults is exposed, indicates right-oblique, normal movement consistent with an overall east-west extension direction.

Faults with several hundred meters of inferred throw lie in the center and eastern parts of the San Marcial quadrangle (**FIGURE 3**). A buried, west-down normal fault is inferred under the Rio Grande floodplain to account for apparently shallow bedrock (top at ≈1800 ft depth) under the floodplain in the Bosque del Apache wildlife refuge (Apache 1A oil test well, shown on **FIGURE**

3). The cinder cone that erupted the Mesa del Contadero basalts may be situated on the inferred "floodplain fault," but that is conjecture. The shallow bedrock near the Apache 1A wildcat well is somewhat at odds with the gravity data (**FIGURE 3**) and the several thousand feet of basin fill interpreted under the Rio Grande (Geddes, 1963a, b) If the bedrock high exists, it is likely tilted eastward to a major fault system at the foot of the Little San Pascual Mountains, called the Little San Pascual Mountain fault zone.

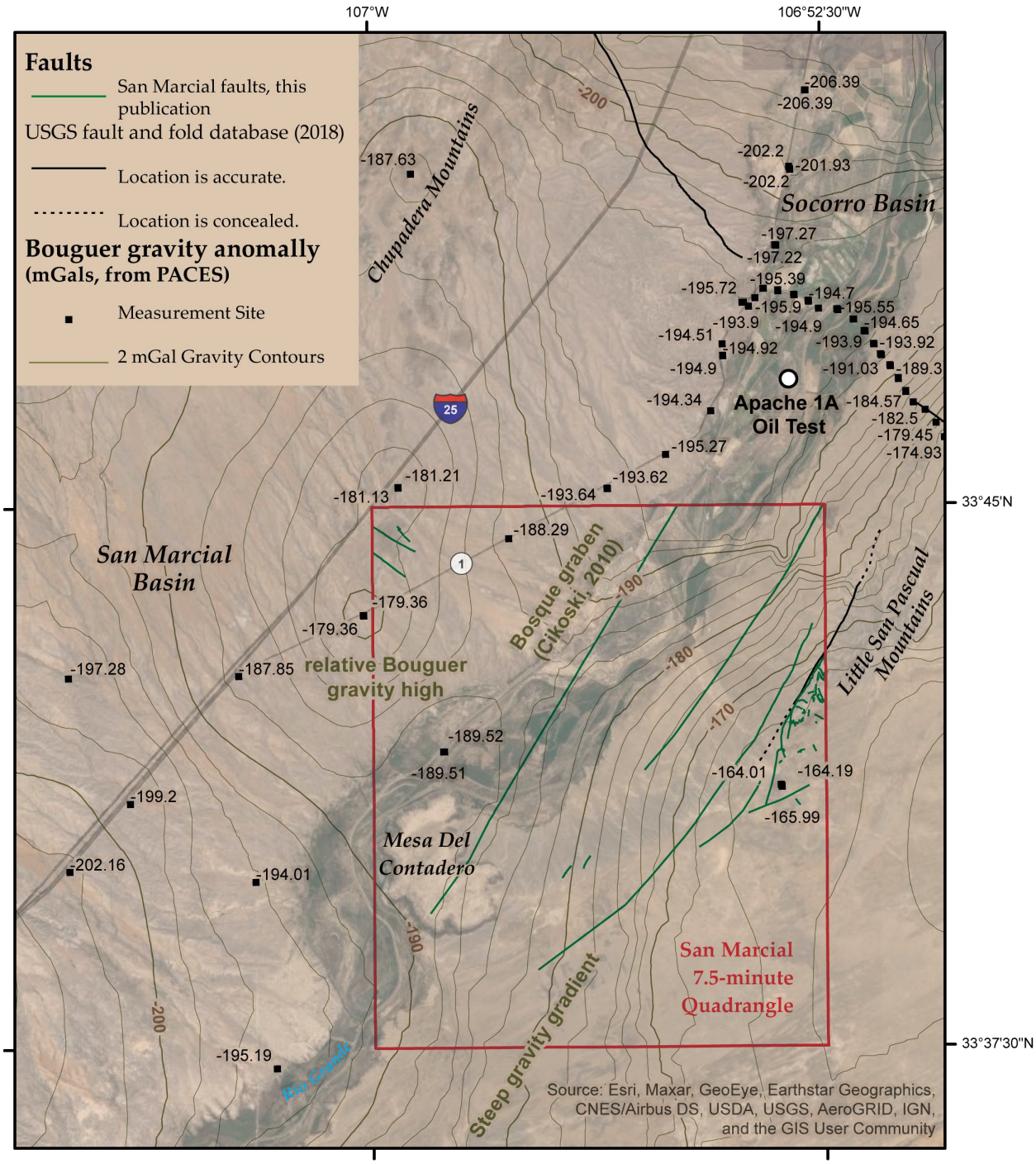

FIGURE 3—Map figure showing fault structures (black and dark-green lines) relative to contouring of Bouguer anomaly gravity data (from PACES database, 2014). Note the gravity highs found in areas corresponding to exposed bedrock, such as the volcanic hills in the northwest corner of the quadrangle and under the Little San Pascual Mountains. There is a gravity low in the area under the Rio Grande floodplain, corresponding to thick basin fill, which according to Geddes (1963a, b) is several thousand feet thick.

The Little Pascual Mountain fault zone is interpreted to have three strands, all of which are normal faults with down-to-the-west throw. The western strand is inferred to coincide with a notable change in slope of the land surface (from 2–3 degrees to 1–1.5 degrees); near the northern quadrangle boundary, this fault juxtaposes the Sierra Ladrones Formation (west side) from variably cemented Popotosa Formation (east side). The central fault strand is mapped using observation of uplifted exposures of Popotosa conglomerate on its footwall, which are unconformably overlain by the Sierra Ladrones Formation. The eastern strand of the Little Pascual Mountain fault zone separates Pennsylvanian–Permian strata from the Santa Fe Group. The Little San Pascual Mountain fault zone projects SSW towards the east side of Mesa del Contadero. We have not observed offset in upper (lower Pleistocene) Sierra Ladrones Formation strata there, but extensive cover by latest Quaternary eolian and sheetflood deposits may cover the fault.

East of the eastern fault strand, in the foothills of the Little San Pascual Mountains, lie several northwest-trending faults that are readily mapped using offset of upper Paleozoic strata. Most kinematic indicators indicate right-lateral, normal-oblique movement. Thus, these faults may be related, in a tectonic sense, to the northwest-trending faults in the volcanic strata on the distal hanging wall ramp. Because the faults that offset the volcanic strata must post-date 35 Ma (see age control below), these northwest-striking faults likely are a product of east-west extension during post-30 Ma Rio Grande rifting. Note that northwest-striking faults are also found in the Popotosa Formation north of the San Marcial quadrangle, where they were active in the middle-late Miocene as well as after ca. 8 Ma (Cikoski, 2010).

The upper Paleozoic bedrock of the foothills of the Little San Pascual Mountains have also been affected by folding. The dominant fold is an anticline-monoline pair that parallels the east strand of the Little San Pascual Mountain fault. We interpret that the folds belong to the same extensional structure as the east strand, representing roll-over onto a buried extensional structure (drape folding) that, with continuing strain, was eventually broken by the east strand of the Little San Pascual Mountain fault. Other folds, affecting the Meseta Blanca Formation of the Yeso Group, are northeast-orientated and commonly tight (locally overturned). At one particularly noteworthy site (UTM coordinates 325651 m E, 3729884 m N) ten tight anticline-synclines lie in a 60-m-wide northeast-trending zone. The projection of this zone of tight folding is not found 500 m to the NE in well-exposed terrain underlain by the Abo Formation. Thus, this particular structure is relatively localized, but undoubtedly involves compressional forces orientated ≈300 degrees.

TECTONIC INTERPRETATIONS

New tectonic interpretations can be made using our mapping of the San Marcial quadrangle, particularly stratigraphic-structural relations along the western front of the Little San Pascual Mountains. There, bedrock strata of the Bar B Formation have been involved in the aforementioned northwest-trending anticline-monocline pair, where folding involves roll-over into the east strand of the Little San Pascual Mountain fault. On the hanging wall are three stratigraphic units (oldest to youngest) separated by unconformities: Spears Group (late Eocene, mostly debris flows), cemented conglomerates of the Popotosa Formation (Miocene, probably middle to late Miocene), and the Sierra Ladrones Formation (lower Pleistocene). The strikes of the Santa Fe Group hanging wall strata and the basal unconformity mostly parallel the NNE trend

of the East strand of the Little San Pascual Mountain fault. The Sierra Ladrones Formation is gently tilted 3 degrees WNW. The Popotosa Formation forms a syncline whose axis parallels the central and east fault strands of the Little San Pascual Mountain fault. The west limb is tilted ≈15 degrees ESE and the east limb is tilted 10–54 degrees WNW (steepening to the east). However, strata of the Spears Group have a N to NW strike, oblique to the trend of the Little San Pascual Mountain fault zone and are either vertical or overturned (overturned beds dipping 70 degrees ENE).

Our interpretation of these observations is as follows. The Popotosa Formation syncline can be explained by footwall flexure of the central fault strand and major drag-folding on the immediate hanging wall of the east fault strand. The fact that this syncline does not notably affect early Pleistocene strata of the Sierra Ladrones Formation means that comparably little deformation has occurred on this structure in the past 2 million years, but notable deformation was occurring in the late Miocene (perhaps the middle Miocene as well). The lack of geomorphic fault scarps bolsters the interpretation of relatively minor middle to late Quaternary motion along the Little San Pascual Mountain fault zone. The oblique strikes and the overturned nature of the Spears Group may indicates two-phases of extension, since the Spears Group is generally acknowledged to post-date Laramide contraction. The latter phase coincides with the one that affected the Popotosa Formation. The earlier one (late Oligocene to early Miocene?) may have involved an earlier rift basin. We speculate that this earlier basin was orientated NNW, perhaps parallel to the NW-striking extensional faults in the San Marcial basin to the west, but has been obscured by the later tectonic basin associated with the Bosque graben and southern Socorro basin. Perhaps this early extensional phase also formed the NW-trending faults as primarily

normal faults, which later experienced right-lateral, normal oblique movement during west-east extensional tectonism. Observation in the Little San Pascual Mountain quadrangle indicates that one northwest-trending fault was highly active since deposition of the Popotosa Formation, but little movement occurred after deposition of early Pleistocene strata. Since there is no control on the trend of the buried "floodplain fault," it is possible that this fault, if it exists, is actually orientated more NNW than shown, and may perhaps be related to this inferred earlier phase of extension—this is speculative and needs to be tested using deep-focused geophysical techniques.

In summary, we infer an earlier phase of extension (late Oligocene to early Miocene?) that formed northwest-orientated faults and resulted in a southwest tilting of the Spears Group. This was followed by east-west extension in the middle to late Miocene. Such a clockwise rotation of the regional extensional axes are consistent with interpretations by Aldrich et al. (1986) and Morgan et al. (1986). The middle to late Miocene tilting formed the Bosque graben and resulted in 100s of meters of throw along the Little San Pascual Mountain fault, further tilting of the Spears Group (resulting in overturned bedding), and a syncline in Popotosa Formation strata between the central and eastern strands of the Little San Pascual Mountain fault. Extension waned after deposition of the uppermost Santa Fe Group (2–1 Ma Sierra Ladrones Formation), and little geomorphic or other field evidence is apparent for late Quaternary motion along this structure.

HYDROGEOLOGIC INFERENCES

The various formations on the San Marcial quadrangle correspond to aquifers where present in the subsurface below the water table. There are few wells on this quadrangle. To our knowledge, there are no pump test data nor has any aquifer study been conducted for the Santa Fe Group, but there is an on-going study of the shallow aquifer underneath the Rio Grande

floodplain by New Mexico Tech. However, observations of outcrop properties of the main map units allows inferences regarding their hydrogeologic character.

Pennsylvanian–Permian strata could transmit groundwater via fracture flow. In carbonate rocks, dissolution could enlarge these fractures and enhance flow rates. In the Little San Pascual Mountains, most fractures have been filled by calcite (or locally, quartz) precipitation. Stratiform dissolution followed by precipitation of chert and quartz also occurred in the limestone strata. Sandstones in Pennsylvanian–Permian strata are well-cemented and would have poor intergranular flow.

Volcanic bedrock is commonly fractured, and sedimentary strata between flows may possibly offer low rates of intergranular flow. Fractures in volcanic bedrock are more open than in Pennsylvanian–Permian strata and may convey groundwater. Enhanced fracturing has locally been observed along fault zones, but in these areas precipitation of quartz or calcite has also been observed. The debris flows of the Spears Group are slightly clayey and probably are poor aquifers, although some sandstone beds may have moderate permeability.

Within the Santa Fe Group, the axial-fluvial unit of the Sierra Ladrones Formation would likely offer the best aquifer and is a reasonable target for groundwater exploration. This unit is >90% sand and pebbly sand that is weakly to moderately consolidated and, where exposed, has <10% moderate-strong cementation except near the Little San Pascual Mountain fault zone, where there are 10-50% strongly cemented intervals up to 2m thick. This unit is as much as 300 m thick in the Socorro area (Chamberlin, 1999), and it is likely 100–300 m thick on this quadrangle. Its saturated extent in the subsurface probably approximately corresponds to its outcrop extent.

The piedmont units of the Sierra Ladrones Formation adjoining the axial-fluvial sand would likely have less yields than the axial-fluvial unit. Wells to the southwest of the quadrangle appear to be screened in the western piedmont facies (e.g., on the Fort Craig and Paraje Well quadrangles), where they likely draw water from sand and sandy gravel bodies. These sand-gravely bodies have 1–20% interstitial clay in outcrops, but observations in the southern San Marcial basin and in the Palomas basin suggest that the proportion of interstitial clay decreases with depth (Jochems, 2015; Jochems and Koning, 2016, 2019; Koning et al., 2015, 2018), which would improve hydraulic conductivity values for these coarser-grained layers in the saturated zone of the western piedmont sediment.

Under the Rio Grande floodplain, an important hydrogeologic phenomenon in the Santa Fe Group and overlying late Quaternary alluvium is up-flow of warmer, saltier water in a southward direction. This is interpreted to be occurring under the southern part of the Bosque de Apache Wildlife Refuge (Barroll and Reiter, 1995), and we infer the same phenomena is likely occurring under much of the floodplain on the San Marcial quadrangle. If the west-down fault under the floodplain really exists, then the higher bedrock on the immediate footwall of the fault, or the fault zone itself, may facilitate this upwelling. West of the fault, a cooler, fresh-water zone may extend to depths of 400–500 ft (122–152 m), as inferred by Barroll and Reiter (1995).

Outcrop observations of the Popotosa Formation indicate higher degrees of cementation and consolidation than the Sierra Ladrones Formation, which would degrade aquifer performance compared to Plio-Pleistocene strata.

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Appendix 1

Description of Map Units

QUATERNARY

Anthropogenic Units

afd Disturbed land and anthropogenic fill

Recent (<100 years old)

Long—

Altered ground and thick accumulations of sediment used as artificial fill for levees, berms, or foundations. Sediment consists primarily of sand with minor pebbles or silty–clayey sand. Variously compacted. 1–6 m thick.

Short—

Altered ground and thick accumulations of sediment used as artificial fill for levees, berms, or foundations. Sediment consists primarily of sand with minor pebbles or silty–clayey sand. Variously compacted. 1–6 m thick.

Eolian Units

Locally, underlying map units are noted using a backslash (i.e., Qes/underlying unit).

Qe Eolian sand

Late Holocene to recent (modern + historic)

Long—

Undifferentiated wind-blown (eolian), massive sand. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), minor reddish-yellow to strong-brown (7.5YR 6/5–6), fine- to medium-grained, subangular to subrounded, well-sorted, and composed of quartz, minor feldspar, and 3–15% mafic-lithic grains. Less than 10% dunes except for local low mounding around shrubs (<30 cm tall). Loose. 0.2–3 m thick.

Short—

Undifferentiated wind-blown (eolian), massive sand. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), minor reddish-yellow to strong-brown (7.5YR 6/5–6), fine- to medium-grained, subangular to subrounded, well-sorted, and composed of quartz, minor feldspar, and 3–15% mafic-lithic grains. Less than 10% dunes except for local low mounding around shrubs (<30 cm tall). Loose. 0.2–3 m thick.

Qelo Eolian loess

Middle to early Late Holocene

Long—

Pale-brown to light-yellowish-brown (10YR 6/3–4) silt and very fine-grained sand. Massive, bioturbated, and variably burrowed. Drapes hillslopes or overlies planar geomorphic surfaces. May be buried by younger eolian deposits. Minimal pedogenesis or buried soils. 1–5 m thick.

Short—

Pale-brown to light-yellowish-brown (10YR 6/3–4) silt and very fine-grained sand. Massive, bioturbated, and variably burrowed. Drapes hillslopes or overlies planar geomorphic surfaces. May be buried by younger eolian deposits. Minimal pedogenesis or buried soils. 1–5 m thick.

Qes Eolian sand sheet

Middle Holocene to recent (modern + historic)

Long—

Sheet of eolian sand that drapes the land surface. Includes <10% dune forms. Sand is massive, fine- to medium-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, and 10–15% mafic-lithic grains, and 1–20% scattered pebbles due to bioturbation. Paleosols are common in the subsurface and characterized by cumulic calcic horizons (ped development, Stage I carbonate morphology) or a cambic horizon which is underlain by one or more weak calcic horizons (typically Stage I to II). Topsoil has weak ped development, no notable clay illuviation, and a weak Stage I calcic horizon. Loose to weakly consolidated. 0.2–3 m thick.

Short—

Sheet of eolian sand draping the land surface. <10% dune forms. Common paleosols characterized by cumulic calcic horizons (ped development, Stage I carbonate morphology) or a cambic horizon underlain by one or more weak calcic horizons (Stage I to II). Topsoil has weak ped development, no notable clay illuviation, and a weak Stage I calcic horizon. Loose to weakly consolidated. 0.2–3 m thick.

Qele Thick eolian sand on the lee side of topographic slopes

Middle Holocene to recent (modern + historic)

Long—

Thick eolian sand accumulations on the north side of ridges west of the Little San Pascual Mountains. Very thin to medium (mostly thin to medium), tabular (mostly) to broadly lenticular beds. Sharp deflation contacts. Beds are internally massive or exhibit horizontal-

planar-laminations or cross-laminations (tangential, 3–10 cm tall foresets facing northeast). Sand is light-yellowish-brown to light-brown (7.5–10YR 6/4), fine-lower- to medium-lower-grained (≤20% very fine sand and <5% medium-upper-grained sand), subangular to subrounded, well-sorted, and composed of quartz, minor feldspar, and 10–15% mafic-lithic grains. Paleosols are most common in the upper 2 m (marked by ped development and extensive burrowing). Below, there are 1–10%, weakly developed paleosols manifested by calcium carbonate precipitation (Stage I to II) and local ped development. The deposit is interbedded with minor tongues of alluvium characterized by very thin to medium, lenticular beds of Permian- or Pennsylvanian-derived gravel mixed with light-yellowish-brown (10YR 6/4), fine- to very coarse-grained sand. 2–12 m thick.

Short—

Thick eolian sand on north side of ridges west of Little San Pascual Mountains. Very thin to medium (mostly thin to medium), tabular beds. Sharp deflation contacts. Beds are internally massive or exhibit horizontal-planar-laminations or cross-laminations (tangential, 3–10 cm tall foresets facing northeast). Paleosols with Stage I to II carbonate morphology. Minor tongues of alluvium. 2–12 m thick.

Eolian Sand Featuring Dunes

Unless otherwise noted, the sand in these dune deposits is similar to that in unit **Qe** above.

Qed Undifferentiated dune deposits

Late Holocene to recent (modern + historic)

Long—

Various undivided dune forms found along the western foot of the Little San Pascual Mountains. Dunes include parabolic, transverse, longitudinal, and irregular forms 0.2–2 m tall. Dune sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), fine- to medium-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, and 10–20% mafic-lithics. 0.2–3 m thick.

Short—

Various undivided dune forms found along the western foot of the Little San Pascual Mountains. Dunes include parabolic, transverse, longitudinal, and irregular forms 0.2–2.0 m tall. Dune sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), fine- to medium-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, and 10–20% mafic-lithics. 0.2–3 m thick.

Qesc Eolian sand sheet with minor coppice and irregular dunes

Middle Holocene to recent (modern + historic)

Long—

Sheet of eolian sand that drapes the land surface, as in unit **Qes**. On the surface of this sheet are coppice dunes, developed around small shrubs, or irregular dunes. Both cover 10–100% of the surface (over a 50x50 m area) and tend to be 0.05–0.7 m tall, but locally are up to 1 m tall (rarely up to 3 m). Between the dunes is bioturbated, eolian sand with minor pebbles. Dune sand is relatively massive, with local, vague cross-laminations up to 5 cm tall. Sand is light-brown to reddish-yellow to strong-brown (7.5YR 6/3–6), less commonly light-yellowish-brown to very pale-brown (10YR 6–7/4) or yellowish-red (5YR 4–5/6), fine- to medium-grained, subangular-rounded (mostly subangular to subrounded), well-sorted, and composed of quartz, minor feldspar, and 10–20% mafic-lithic grains. Locally, up to 5% scattered pebbles. Loose and no notable topsoil. Local buried soils marked by ped development, Bw horizons with slight reddening, and weak calcic horizons (Stage I, possibly Stage II). The sand sheet is 0.2–3.0 m thick.

Short—

Sheet of eolian sand, as in unit **Qes** but with 10–100% surface coverage by coppice to irregular dunes 0.05–0.7 m tall (locally up to 1 m). Between dunes is bioturbated, eolian sand with minor pebbles. Sand is relatively massive, with local vague cross-laminations up to 5 cm tall; up to 5% scattered pebbles. Loose and no notable topsoil. Local, weakly developed buried soils. 0.2–3 m thick.

Qeled Thick eolian sand on the lee side of topographic slopes, superimposed by dunes

Middle Holocene to recent (modern + historic)

Long—

Unit **Qele** superimposed by various dune forms that include irregular, coppice, parabolic, transverse, and longitudinal. Dunes are loose, 0.2–2 m tall, and lack soil development. Dune deposit is massive to vaguely cross-laminated. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), fine-upper- to medium-lower-grained (locally up to medium-upper-grained), subrounded to subangular, well-sorted, and composed of quartz, 10–25% feldspar, and 10–15% lithic grains (volcanic and chert), and 3–10% mafic grains. Below ≈2 m depth the sediment is equivalent to unit **Qele**. Entire deposit is 2–12 m thick.

Short—

Unit **Qele** superimposed by various dune forms that include irregular, coppice, parabolic, transverse, and longitudinal. Dunes are loose, 0.2–2 m tall, and lack soil development. Dune deposit is massive to vaguely cross-laminated and composed of light-brown, fine-upper- to

medium-lower-grained sand. Below ≈2 m depth the sediment is equivalent to unit **Qele**. Entire deposit is 2–12 m thick.

Qerc Eolian sand ramp with coppice and irregular dunes on the surface

Middle Holocene to recent (modern + historic)

Long—

Sand ramp along foot of Little San Pascual Mountains, superimposed by coppice and irregular dunes up to 1 m tall. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), fine-upper- to medium-lower-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, and 10–15% mafic-lithic grains (mostly chert and volcanic lithics). Loose. Likely intertongues with colluvium and is up to several meters thick.

Short—

Sand ramp along foot of Little San Pascual Mountains, superimposed by coppice and irregular dunes up to 1 m tall. Sand is light-brown to light-yellowish-brown, fine-upper- to medium-lower-grained, subrounded to subangular, well-sorted, and composed of quartz, minor feldspar, and 10–15% mafic-lithic grains. Loose. Likely intertongues with colluvium and up to several meters thick.

Qedl Longitudinal dunes

Late Holocene to recent (modern + historic)

Long—

Eolian sand, as described in the unit **Qe**, forming longitudinal dunes; dunes are orientated ≈60 degrees and are relatively low (<2 m height). Loose and 1–4 m thick.

Short—

Eolian sand, as described in the unit **Qe**, forming longitudinal dunes; dunes are orientated ≈60 degrees and are relatively low (<2 m height). Loose and 1–4 thick.

Qedbl Barchan and longitudinal dunes

Late Holocene to recent (modern + historic)

Long—

Eolian sand, as described in the unit **Qe**, forming barchan dunes and longitudinal dunes. Barchan dunes are orientated transverse to the 60 degree trend of the longitudinal dunes. Locally, the eastern end (tail) of a barchan dune may curve and merge with a longitudinal dune. Dunes are 1–3 m tall. Relatively bare of vegetation. Loose and 1–4 m thick.

Short—

Eolian sand, as described in the unit **Qe**, forming barchan dunes and longitudinal dunes. Barchan dunes are orientated transverse to the 60 degree trend of the longitudinal dunes. Locally, the eastern end (tail) of a barchan dune may curve and merge with a longitudinal dune. Dunes are 1–3 m tall. Relatively bare of vegetation. Loose and 1–4 m thick.

Qedlbc Barchan and longitudinal dunes superimposed by coppice dunes

Late Holocene to recent (modern + historic)

Long—

Eolian sand, as described in the unit **Qe**, forming small coppice dunes developed on longitudinal dunes (**Qedl**) and or on subordinate barchan dunes. Longitudinal and barchan dunes are mostly 1–2 m tall but locally up to 3 m tall. Loose and 1–4 m thick.

Short—

Eolian sand, as described in the unit **Qe**, forming small coppice dunes developed on longitudinal dunes (**Qedl**) and or on subordinate barchan dunes. Longitudinal and barchan dunes are mostly 1–2 m tall but locally up to 3 m tall. Loose and 1–4 m thick.

Qedtlc Transverse, longitudinal, and coppice dunes

Late Holocene to recent (modern + historic)

Long—

Eolian sand, as described in unit **Qe**, forming both linear transverse dunes and longitudinal dunes that are relatively low-lying (<2 m, commonly 0.5–1 m tall). These are commonly superimposed by small coppice dunes. Includes 1–3% large barchan dunes. Loose and 1–3 m thick.

Short—

Eolian sand, as described in unit **Qe**, forming both linear transverse dunes and longitudinal dunes that are relatively low-lying (<2 m, commonly 0.5–1 m tall). These are commonly superimposed by small coppice dunes. Includes 1–3% large barchan dunes. Loose and 1–3 m thick.

Qedpt Irregular, parabolic, and transverse dunes

Late Holocene to recent (modern + historic)

Long—

Fine- to medium-grained sand that forms irregular, parabolic, and transverse dunes ≈0.5–2 m in height. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), mostly fine-upper- to

medium-lower-grained, subrounded to subangular, well-sorted, and composed of quartz, 10–≈20% feldspar, and 15% mafic-lithic grains (including chert). Loose and 1–5 m thick.

Short—

Fine- to medium-grained sand that forms irregular, parabolic, and transverse dunes ≈0.5–2 m in height. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/4), mostly fine-upper- to medium-lower-grained, subrounded to subangular, well-sorted, and composed of quartz, 10–≈20% feldspar, and 15% mafic-lithic grains (including chert). Loose and 1–5 m thick.

Sheetflood Deposits on Gentle Slopes

Locally, underlying map units are noted using a backslash (i.e., **Qs**/underlying unit).

Qse Sheetflood deposits reworking eolian sand

Middle Holocene to recent (modern + historic)

Long—

Sheetflood deposits inferred to have reworked a substantial amount (>70%) of eolian sand. Consists of massive sand commonly overprinted by weak paleosols; also in medium to thick, tabular beds. The unit contains trace to 10% very thin to medium, lenticular sandy gravel or pebbly sand beds. Gravel is comprised of very fine to coarse pebbles Sand is light-brown to reddish-yellow (7.5YR 6/4–6, mostly 7.5YR 6/4) to light-yellowish-brown (10YR 6/4), very fine- to coarse-grained (mostly fine- to medium-grained) with 1–10% scattered coarse to very coarse grains, and trace to 5% scattered very fine to coarse pebbles. Sand is subrounded to subangular, well- to moderately sorted, and composed of quartz, minor feldspar, and 7–10% mafic-lithic grains. Pedogenesis indicated by local burrowing (krotovina), Stage I calcic horizons (1–15% scattered calcium carbonate nodules 0.5–2.0 cm wide and strong HCl effervescence) and ped development that typically lack notable clay illuviation (peds are moderate, medium to very coarse, subangular blocky, slightly hard to hard). Minor parts of the surface may be covered by a thin (<20 cm) to thick sheet of eolian sand (see unit Qes). Weakly to moderately consolidated. 1–10 m thick.

Short—

Sheetflood deposits reworking substantial eolian sand. Composed of massive sand commonly overprinted by weak paleosols. Sand is light-brown (minor reddish-yellow) and mostly fine- to medium-grained; 1–15% scattered coarser sand and pebbles. Pedogenesis indicated by Stage I calcic horizons and ped development that typically lacks clay illuviation. Weakly to moderately consolidated. 1–10 m thick.

Qs Sheetflood deposits

Middle Holocene to recent (modern + historic)

Long—

Sandy sheetflood deposits with minor scattered pebbles. The unit includes minor, very thin to thin, lenticular beds of pebbles. Sand is massive, brown to light-brown to light-yellowish-brown (7.5–10YR 5–6/4), very fine- to coarse-grained (1–10% silt to clay), and moderately to poorly sorted. Weak top soil development exhibiting Stage I carbonate morphology. 1–4 m thick.

Short—

Sandy sheetflood deposits with minor scattered pebbles. The unit includes minor, very thin to thin, lenticular beds of pebbles. Sand is massive, brown to light-brown to light-yellowish-brown (7.5–10YR 5–6/4), very fine- to coarse-grained (1–10% silt to clay), and moderately to poorly sorted. Weak top soil development exhibiting Stage I carbonate morphology. 1–4 m thick.

Hillslope Deposits

Locally, underlying map units are noted using a backslash (i.e., **Qtb**/underlying unit).

Qsc Sheetflood and colluvial deposits, undivided

Late(?) Pleistocene to historic (10 to ≈150 years old)

Long—

Massive, pink to pinkish-white sand that is fine- to medium-grained, subrounded to subangular, and well- to moderately sorted. Sand composed of quartz, minor feldspar, and ≈10% mafic-lithic grains. Scattered in this sand is 5–10% coarse to very coarse sand along with very fine to very coarse pebbles composed of subangular-angular chert and sedimentary clasts. Interbedded in the sand are minor tongues of 10–50 cm thick, channel-fill deposits comprised of clast-supported and imbricated gravel. Gravel are subangular to angular, poorly sorted, and comprised of very fine to very coarse pebbles, 5% cobbles, and 1–3% boulders. Gravel proportion likely increases towards bedrock highs, where gravel tongues probably include massive colluvium. Several meters thick.

Short—

Pink to pinkish-white, fine- to medium-grained, massive sand; contains 5–10%, scattered, coarser sand and pebbles. Unit is 5% tongues of gravelly channel-fill deposits. Gravel are subangular to angular, poorly sorted, and comprised of pebbles, 5% cobbles, & 1–3% boulders. Gravel proportion likely increases towards bedrock highs, where gravel tongues likely include colluvium. Several meters thick.

Qtb Basaltic talus

Late Pleistocene to Holocene

Long—

Basaltic boulders, with lesser cobbles and pebbles, that form a talus apron overlying sand of unit **QTsa**. The talus protects the underlying, relatively loose sand from erosion. 1–3 m thick.

Short—

Basaltic boulders, with lesser cobbles and pebbles, that form a talus apron overlying sand of unit **QTsa**. The talus protects the underlying, relatively loose sand from erosion. 1–3 m thick.

Qcto Older colluvium and talus

Late Pleistocene to Early Holocene

Long—

Angular to subangular, very poorly sorted pebbles through cobles (5% boulders) of unit **Ttbm** that drape unit **Tws** near the western quadrangle boundary.

Short—

Angular to subangular, very poorly sorted pebbles through cobles (5% boulders) of unit **Ttbm** that drape unit **Tws** near the western quadrangle boundary.

Rio Grande Floodplain Units

Long—

Mapped primarily using 2014 aerial imagery from the National Agriculture Imagery Program (NAIP). Features likely formed in the past 100 years, considering the large floods of 1937 and 1941. This work was done independently of Pearce and Kelson (2004), who used aerial photography taken in 1935 and 2001. In contrast, we compared 2014 imagery to aerial photography from 1946 (Army Map Service, 1947).

Short—

Mapped primarily using 2014 aerial imagery from the National Agriculture Imagery Program (NAIP). Almost all features likely postdate the flood of 1941.

Rw14 Water

Modern (<10 years old)

Long—

Flowing or standing water apparent in 2014 digital aerial imagery.

Short—

Flowing or standing water apparent in 2014 digital aerial imagery.

Rcb Rio Grande bar deposits

Modern (<10 years old)

Long—

Unvegetated, longitudinal bars of sand and perhaps minor gravel apparent in 2014 digital aerial imagery.

Short—

Unvegetated, longitudinal bars of sand and perhaps minor gravel apparent in 2014 digital aerial imagery.

Rch Rio Grande channel deposits

≈100 years old to modern (<10 years old)

Long—

Areas of the Rio Grande floodplain with banded surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. These textures mostly parallel the axis of the modern floodplain. The unit is laterally gradational with unit **Rcs** (modified from Cikoski [2018]).

Short—

Areas of the Rio Grande floodplain with banded surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. These textures mostly parallel the axis of the modern floodplain. The unit is laterally gradational with unit **Rcs** [modified from Cikoski (2018]).

Rcs Rio Grande channel-splay deposits

≈100 years old to modern (<10 years old)

Long—

Areas of the floodplain with fanning/distributary surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. Distributary textures commonly can be traced back to current or former locations of the Rio Grande channel. The unit is laterally gradational with unit **Rch** (modified from Cikoski [2018]).

Short—

Areas of the floodplain with fanning/distributary surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. Distributary textures commonly can be traced back to

current or former locations of the Rio Grande channel. The unit is laterally gradational with unit **Rch** (modified from Cikoski [2018]).

Rsb Rio Grande scroll-bar deposits

≈100 years old to modern (<10 years old)

Long—

Areas of the floodplain with scrolled surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. These textures are comprised of tightly parallel, arcuate shapes formed by migration of the river channel.

Short—

Areas of the floodplain with scrolled surface textures (such as vegetation trends) apparent in 2014 digital aerial imagery. These textures are comprised of tightly parallel, arcuate shapes formed by migration of the river channel.

Rau Rio Grande undifferentiated deposits, primarily floodplain alluvium

Historic (10 to ≈150 years old) to modern (<10 years old)

Long—

Areas of the floodplain with non-distinct surface textures. Includes areas of the floodplain that have been artificially disturbed by land management or former agricultural activities such that primary surface textures are unrecognizable (modified from Cikoski [2018]). Consists of sand (mostly very fine- to medium-grained) and lesser silt or clay. Merges downward into unit **Qay**.

Short—

Areas of the floodplain with non-distinct surface textures. Includes areas of the floodplain that have been artificially disturbed by land management or former agricultural activities such that primary surface textures are unrecognizable (modified from Cikoski [2018]). Consists of sand (mostly very fine- to medium-grained) and lesser silt or clay. Merges downward into unit **Qay**.

Valley-floor Units

Many of the valley-floor map units reflect combinations of deposits, such as combined younger alluvium and modern alluvium (**Qaym**). In these combined units, the unit with the largest exposed area is shown first, followed by the unit with the lesser area of exposure. Where modern and historic deposits are subequal (±20%) the resulting map unit is called Recent and abbreviated as **Qar**.

Qam

Modern alluvium

Modern (<10 years old)

Long—

Loose gravelly sand and sandy gravel forming bars and underlying channels in ephemeral drainages. Sand is predominately medium- to very coarse-grained and brown to grayish-brown (7.5YR 5/4 to 10YR 5/2) to light-gray (10YR 7/2) to pinkish-gray (7.5YR 6–7/2). <15% very fine to fine sand. Sand is medium- to very coarse-grained, subangular to subrounded, very poorly to poorly sorted, and composed of quartz, minor feldspar, and variable proportions of lithic grains (mostly felsic volcanics west of the Rio Grande), and very little or no clay. Sand is well-laminated (horizontal-planar- to cross-laminated). Gravel consists of clast-supported, subangular to rounded, poorly to moderately sorted pebbles with lesser cobbles and minor boulders. West of the Rio Grande, gravel are mostly felsic volcanic clasts with 5–10% intermediate volcanic clasts. East of the Rio Grande, gravel compositions are similar to those in unit **QTpa** (i.e., quartzite, chert, granite, volcanic) or reflect erosion from Pennsylvanian-Permian strata (limestone, dolomite, sandstone, siltstone). Longitudinal and transverse bars are often underlain by pebbles and/or cobbles. No topsoil development. Bar–and-swale topography and sparse to common steep-walled channels characterize the surface, exhibiting up to 0.1–0.6 m of relief. Thickness is probably 0.5–2 m.

Short—

Loose sand and gravel forming bars and underlying channels in ephemeral drainages. Gravel includes pebbles, cobbles, and minor boulders. Sand is brown to grayish-brown to pinkish-gray to light-gray (7.5–10YR) and mostly medium- to very coarse-grained. Bar-and-swale topography (0.1–0.6 m relief), steep-walled channels, and lack of topsoil development characterize the surface. Thickness ≈0.5–2 m.

Qah Historic alluvium

Historic (10 to ≈150 years old)

Long—

Sandy gravel, pebbly sand, and sand that lacks notable topsoil development and features surficial bar-and-swale topography. Gravely sediment is in very thin to medium, tabular to lenticular beds. Sand is massive or laminated (horizontal-planar to wavy). Gravel is dominated by pebbles with minor cobbles; typically clast-supported and exhibiting imbrication; subangular to rounded (mostly subrounded), poorly sorted, and having a composition reflecting the local source area: predominately felsic volcanic rocks west of the Rio Grande; Rio Grande gravel or sedimentary clasts (limestone, sandstone, siltstone, or chert) on east side of river. Sand is

pinkish-gray to light-brown to brown (7.5YR 6/2–3; 5/3) or pale-brown (10YR 6/3), fine- to very coarse-grained, subangular to subrounded, poorly to well-sorted, and has a composition reflective of source area (volcanic-rich on west side of quadrangle, quartz-rich on east side of quadrangle). Draping aforementioned sediment is a relatively common, 1–10 cm thick blanket of brown (7.5YR 5/3), fine-grained sand mixed with variable coarser sand and pebbles. Topsoil lacks ped development and lacks visible signs of calcium carbonate accumulation, although there may be effervescence in hydrochloric acid. Geomorphic surface is commonly about 0.3–0.7 m above the modern channel and sports bar-and-swale topography having 2–10 cm of relief, locally up to 30 cm relief if swales have recently experienced erosion. Weakly consolidated and non-cemented. 1–3 m thick, being thickest near the Rio Grande floodplain.

Short—

Sandy gravel, pebbly sand, and sand whose geomorphic surface exhibits bar-and-swale topography and lacks notable topsoil development. Sediment typically in very thin to medium, tabular to lenticular beds. Sand beds are internally massive or laminated. No visible calcium carbonate accumulation in topsoil. Tread height commonly 0.3–0.7 m. 1–3 m thick, thickening towards Rio Grande floodplain.

Qar Recent (historic + modern) alluvium

Recent (modern + historic)

Long—

Historic alluvium and modern alluvium (**Qam**) in subequal (±20%) proportions. See descriptions of units **Qam** and **Qah**. Weakly consolidated and 0.5–3 m thick.

Short—

Historic alluvium and modern alluvium (**Qam**) in subequal (±20%) proportions. See descriptions of units **Qam** and **Qah**. Weakly consolidated and 0.5–3 m thick.

Qamh Modern and historic alluvium, undivided

Modern (<10 years old) and historic (10 to ≈150 years old)

Long—

Modern alluvium (**Qam**) and subordinate historic alluvium (**Qah**). See detailed descriptions of each respective unit. 0.5–2 m thick.

Short—

Modern alluvium (**Qam**) and subordinate historic alluvium (**Qah**). See detailed descriptions of each respective unit. 0.5–2 m thick.

Qahm Historic and modern alluvium, undivided

Historic (10 to ≈150 years old) and modern (<10 years old)

Long—

Historic alluvium (**Qah**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each respective unit. 0.5–2 m thick.

Short—

Historic alluvium (**Qah**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each respective unit. 0.5–2 m thick.

Qary Recent (historic + modern) and younger alluvium, undivided

Recent (modern + historic) and Early to Late Holocene, respectively

Long—

Recent alluvium (**Qar**) and subordinate younger alluvium (**Qay**). See detailed descriptions of **Qam**, **Qah**, and **Qay**. 0.5–4 m thick.

Short—

Recent alluvium (**Qar**) and subordinate younger alluvium (**Qay**). See detailed descriptions of **Qam**, **Qah**, and **Qay**. 0.5–4 m thick.

Qahy Historic and younger alluvium, undivided

Historic (10 to ≈150 years old) and Early to Late Holocene, respectively

Long—

Historic alluvium (**Qah**) and subordinate younger alluvium (**Qay**). See detailed descriptions of each respective unit. 0.5–4 m thick.

Short—

Historic alluvium (**Qah**) and subordinate younger alluvium (**Qay**). See detailed descriptions of each respective unit. 0.5–4 m thick.

Qay Younger alluvium

Early to Late Holocene

Long—

Interbedded pebbly sand, sand, and sandy gravel; underlies a smooth geomorphic surface (no bar-and-swale topography) standing 0.5–2.0 m above modern grade, whose topsoil shows visible signs of Stage I to I(+) calcium carbonate morphology. Sandy gravel is in clast-supported,

very thin to medium, lenticular (mostly) to tabular beds; ≤10% cross-stratification with planar, very thin foresets. Pebbly sand and sand are in thinly to thickly bedded, lenticular to tabular beds; pebbles are commonly scattered in massive to horizontal-planar-laminated sand. Gravel is comprised of very fine to very coarse pebbles with minor cobbles; gravel are clast-supported, angular-subrounded, poorly to moderately sorted, and composed of volcanic gravel mixed with variable gravel from unit **QTsa**. In the vicinity of Paleozoic bedrock hills, gravel are composed of limestone, very fine- to medium-grained sandstone, chert, or quartz. Sand in sandy gravel is light-brown (7.5YR 6/4) to brown to yellowish-brown (7.5YR 5/4; 10YR 5/3–4), fine- to very coarse-grained (mostly medium- to very coarse-grained), subangular to subrounded, poorly to moderately sorted, and composed of quartz, feldspar, and variable mafic-lithic grains (lithics typically <25%, but dominate the coarse and very coarse sand fraction). Outside of gravelly beds, the sand consists of light-brown to brown to pale-brown to light-yellowish-brown (7.5YR 5–6/4; 10YR 6/3–4; 5YR 4–5/6 where sand is derived from Permian clastics), very fine- to medium-grained (mostly fine to medium) sand with 1–25% scattered coarser sand and very fine to very coarse pebbles (mostly <20% pebbles). Buried soils commonly feature a 10–30 cm-thick, weak calcic horizon (Stage I) locally overlain by a 10–25 cm-thick cambic horizon (Bw; 5–7.5YR 5/6, weak to moderate, subangular blocky peds), or (less commonly) by weak illuviated clay (Bt) +/- thin A horizons. Topsoil characterized by weak ped development (weak to moderate, medium to coarse, subangular blocky and slightly hard) with no clay illuviation and at least one calcic horizon (up to 0.5 m thick) with Stage I to I(+) carbonate morphology. Surface is relatively smooth, lacking bar-and-swale topography (but cobble or boulder bars might still have a subtle expression) and featuring a desert pavement with high clast density but no to very weak varnishing of clasts. Tread is 0.5–3 m above modern grade. May have >1 allostratigraphic subunits. Weakly to moderately consolidated and 1–4 m thick.

Short—

Interbedded pebbly sand, sand, and sandy gravel. Sand outside of gravely beds is light-brown, mostly fine- to medium-grained, and has trace to 20% pebbles. Underlies geomorphic surface w/no bar-and-swale topography, standing 0.5–3 m above modern grade, whose topsoil has calcic horizons with visible Stage I to I(+) calcium carbonate morphology. May have >1 allostratigraphic subunits. 1–4 m thick.

Qayax Younger alluvium deposited by axial river

Early to Late Holocene

Long—

Poorly exposed and loose sand similar in composition and texture to sand in unit **QTsa**, but underlying low (≤3 m above modern grade) terraces that parallel the Rio Grande. Surface lacks bar-and-swale topography, and its topsoil has at least one calcic horizon exhibiting Stage I to I(+) calcium carbonate morphology. 1–4 m thick.

Short—

Poorly exposed and loose sand similar in composition and texture to sand in unit **QTsa**, but underlying low (≤3 m above modern grade) terraces that parallel the Rio Grande. Surface lacks bar-and-swale topography, and its topsoil has at least one calcic horizon exhibiting Stage I to I(+) calcium carbonate morphology. 1–4 m thick.

Qaym Younger and modern alluvium, undivided

Early to Late Holocene and modern (<10 years old), respectively

Long—

Younger alluvium (**Qay**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each unit. 1–4 m thick.

Short—

Younger alluvium (**Qay**) and subordinate modern alluvium (**Qam**). See detailed descriptions of each unit. 1–4 m thick.

Qayr Younger and recent (historic + modern) alluvium, undivided

Early Holocene and recent (modern + historic)

Long—

Younger alluvium (**Qay**) and subordinate recent alluvium (**Qar**). See detailed descriptions of each unit. 1–4 m thick.

Short—

Younger alluvium (**Qay**) and subordinate recent alluvium (**Qar**). See detailed descriptions of each unit. 1–4 m thick.

Qayo Younger alluvium, oldest allostratigraphic unit

Early to Middle Holocene

Long—

Interbedded pebbly sand, sand, and sandy gravel, as described for unit **Qay**, but underlying a relatively high geomorphic surface (2–5 m above modern grade). Gravel is in very thinly to thickly bedded, lenticular beds. Gravel consists primarily of very fine to very coarse pebbles with 1–10% cobbles (notably less than found in older Pleistocene deposits). Gravel is angular to subangular, moderately to poorly sorted, and composed of either: 1) felsic volcanic rocks with roughly 10% intermediate compositions (west of the Rio Grande), or 2) gravel similar to that seen in unit **QTsa** or gravel predominately composed of limestone with minor chert (east of the Rio Grande). Sand outside of gravely beds is light-brown (7.5YR 6/4) or light-brownish-gray to

light-yellowish-brown (10YR 6/2–4), locally reddish-yellow to strong-brown (7.5YR 5–6/5), mostly fine- to medium-grained, and has trace to 20% scattered, coarser sand and pebbles; sand is subangular to subrounded, moderately sorted, and composed of quartz, feldspar, and various lithic grains (mainly volcanics west of the Rio Grande). Matrix of gravelly sediment is light-brownish-gray to light-yellowish-brown (10YR 6/2–4) and consists of very fine- to very coarse-grained sand that is subangular to subrounded, poorly sorted, and mostly a lithic arenite. Weakly consolidated, with <3% clay. Contains notable amounts of sediment reworked from the transitional unit **QTstw** in the northwest part of the quadrangle. Differs from unit **Qtgl** and **Qtti3** by having a lower concentration of cobbles. Tread stands about 1–2 m above adjoining **Qay** treads and 2–5 m above modern grade. Surface lacks bar-and-swale topography and has a weak desert pavement featuring a pebbly clast armor and varnish on ≤10% of surface clasts. Where surface is not eroded, unit may exhibit a >0.5 m thick, brown (7.5YR 4/4) A horizon underlain by a Stage I(+) calcic horizon. 2–6 m thick.

Short—

Highest allostratigraphic unit of younger alluvium (**Qay**). Interbedded pebbly sand, sand, and sandy gravel. Less cobbles than Pleistocene-age alluvium. Underlies a smooth, pebbly geomorphic surface (no bar-and-swale topography), standing 2–5 m above modern grade, with varnish on 0–10% of clasts. Topsoil has Stage I(+) calcic horizons locally overlain by a thick A horizon. 2–6 m thick.

Alluvial Fan Units

Many of the alluvial fan map units reflect combinations of deposits, such as combined younger alluvium and historic alluvium (**Qfyh**). In these combined units, the unit with the largest exposed area is shown first, followed by the unit with the lesser area of exposure. Where modern and historic deposits are subequal (±20%), then the resulting map unit is called Recent and abbreviated as **Qfr**.

Qfm Modern fan alluvium

Modern (<10 years old)

Long—

Similar to unit **Qam** but forms an alluvial fan at the mouths of tributary drainages. See description of unit **Qam**. Weakly consolidated and 0.5–2 m thick.

Short—

Similar to unit **Qam** but forms an alluvial fan at the mouths of tributary drainages. See description of unit **Qam**. Weakly consolidated and 0.5–2 m thick.

Qfh Historic fan alluvium

Historic (10 to ≈150 years old)

Long—

Similar to unit **Qah** but forms an alluvial fan at the mouths of tributary drainages. See description of unit **Qah**. Weakly consolidated and 1–3 m thick.

Short—

Similar to unit **Qah** but forms an alluvial fan at the mouths of tributary drainages. See description of unit **Qah**. Weakly consolidated and 1–3 m thick.

Qfr Recent (historic + modern) fan alluvium

Recent (modern + historic)

Long—

Similar to unit **Qar** but forms an alluvial fan at the mouths of tributary drainages. See description of units **Qah** and **Qam**. Weakly consolidated and 1–3 m thick.

Short—

Similar to unit **Qar** but forms an alluvial fan at the mouths of tributary drainages. See description of units **Qah** and **Qam**. Weakly consolidated and 1–3 m thick.

Qfmh Modern and historic alluvium, undivided

Modern (<10 years old) and historic (10 to ≈150 years old)

Long—

Modern fan alluvium (**Qfm**) and subordinate historic fan alluvium (**Qfh**). Similar to unit **Qamh** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qam** and **Qah**. Weakly consolidated and 1–3 m thick.

Short—

Modern fan alluvium (**Qfm**) and subordinate historic fan alluvium (**Qfh**). Similar to unit **Qamh** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qam** and **Qah**. Weakly consolidated and 1–3 m thick.

Qfhm Historic and modern alluvium, undivided

Historic (10 to ≈150 years old) and modern (<10 years old)

Long—

Historic fan alluvium (**Qfh**) and subordinate modern fan alluvium (**Qfm**). Similar to unit **Qahm** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of units **Qah** and **Qam**. Weakly consolidated and 1–3 m thick.

Short—

Historic fan alluvium (**Qfh**) and subordinate modern fan alluvium (**Qfm**). Similar to unit **Qahm** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of units **Qah** and **Qam**. Weakly consolidated and 1–3 m thick.

Qfhy Younger alluvial fans and slope wash deposits, undivided

Historic (10 to ≈150 years old) and Early Holocene

Long—

Historic fan alluvium (**Qfh**) and subordinate younger fan alluvium (**Qfm**). Similar to unit **Qahy** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of units **Qah** and **Qay**. Weakly consolidated and 1–4 m thick.

Short—

Historic fan alluvium (**Qfh**) and subordinate younger fan alluvium (**Qfm**). Similar to unit **Qahy** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of units **Qah** and **Qay**. Weakly consolidated and 1–4 m thick.

Qfry Recent and younger fan alluvium, undivided

Recent (modern + historic) and Early Holocene

Long—

Recent fan alluvium (**Qfr**) and subordinate younger fan alluvium (**Qfy**). Similar to unit **Qary** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qah**, **Qam**, and **Qay**. Weakly consolidated and 1–4(?) m thick.

Short—

Recent fan alluvium (**Qfr**) and subordinate younger fan alluvium (**Qfy**). Similar to unit **Qary** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qah**, **Qam**, and **Qay**. Weakly consolidated and 1–4(?) m thick.

Qfy Younger fan alluvium

Early to Late Holocene

Long—

Similar to unit **Qay** but forms an alluvial fan at the mouths of tributary drainages. See description of **Qay**. Weakly to moderately consolidated and 1–4(?) m thick.

Short—

Similar to unit **Qay** but forms an alluvial fan at the mouths of tributary drainages. See description of **Qay**. Weakly to moderately consolidated and 1–4(?) m thick.

Qfyh Younger and historic fan alluvium, undivided

Early Holocene and historic (10 to ≈150 years old)

Long—

Younger (**Qfy**) and subordinate historic (**Qfh**) fan alluvium. See detailed descriptions of each unit. Weakly to moderately consolidated and 1–4(?) m thick.

Short—

Younger (**Qfy**) and subordinate historic (**Qfh**) fan alluvium. See detailed descriptions of each unit. Weakly to moderately consolidated and 1–4(?) m thick.

Qfyr Younger and recent fan alluvium, undivided

Early Holocene and recent (modern + historic)

Long—

Similar to unit **Qary** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qay**, **Qah**, and **Qam**. Weakly to moderately consolidated and 1–4(?) m thick

Short—

Similar to unit **Qary** but forms an alluvial fan at the mouths of tributary drainages. See descriptions of **Qay**, **Qah**, and **Qam**. Weakly to moderately consolidated and 1–4(?) m thick.

Qfyo Older allostratigraphic unit of younger fan alluvium

Early to Middle Holocene

Long—

Sand interbedded with minor pebbly beds. Pebbles are mostly very fine to coarse (5–15% very coarse), subrounded to rounded, poorly sorted, and composed of gravel types similar to those in unit **QTsa**. Sand is mostly in medium to thick beds or else massive, light-brown to light-

yellowish-brown (7.5–10YR 6/4) and very fine- to coarse-grained (within a given bed, typically a range of either very fine- to medium-grained or fine- to coarse-grained); well-sorted within a bed or having up to 10% scattered pebbles; 1–3% very thin, lenticular beds of sandy pebbles to pebbly sand. Minor buried soils up to ≈0.5 m thick; these exhibit burrowing features, calcium carbonate accumulation (Stage I to II), and ped development (moderate, coarse to very coarse, subangular blocky), and minor clay illuviation (faint films on ped faces). Topsoil exhibits Stage I or I(+) calcic horizons up to 75 cm thick, with moderately developed, fine to very coarse, subangular blocky peds that are hard to slightly hard; no notable clay illuviation. Tread stands 1–5 m above modern grade, decreasing away from the Rio Grande. 5–7 m thick.

Short—

Sand with minor pebbly beds. Sand is mostly in medium to thick beds or else massive, light-brown to light-yellowish-brown, and very fine- to coarse-grained; up to 10% scattered pebbles and 1–3% very thin, lenticular beds of sandy pebbles to pebbly sand. Minor buried soils with Stage I to II calcic horizons. Topsoil exhibits Stage I or I(+) calcic horizons. Tread height is 1–5 m. 5–7 m thick.

Qfdf Debris flow-dominated fans

Late Pleistocene through Holocene

Long—

Relatively massive sand and basaltic gravel (primarily cobbles and boulders). Gravel is derived from the upper basalt that caps Mesa del Contadero (**Qbu**). Sand is light-colored, fine- to very coarse-grained, subrounded to subangular, and rich in quartz grains (mainly reworked from unit **QTsa**). Weakly consolidated and 1–4 m thick.

Short—

Relatively massive sand and basaltic gravel (primarily cobbles and boulders). Gravel is derived from the upper basalt that caps Mesa del Contadero (**Qbu**). Sand is light-colored, fine- to very coarse-grained, subrounded to subangular, and rich in quartz grains (mainly reworked from unit **QTsa**). Weakly consolidated and 1–4 m thick.

Qfo Older fan deposits

Middle to Late Pleistocene

Long—

Thick alluvial fan deposits that fill paleovalleys and are buttressed against slopes east of the Rio Grande. May have more than one allostratigraphic unit, but if so they could not be confidently recognized. Sediment consists of two lithofacies. The first is massive sand with minor (1–15%) scattered pebbles (similar to those in unit **QTsa**) and 0.5–3% very thin, lenticular, sandy-pebble

to pebbly-sand beds. Sand is pale-brown (10YR 6/3) to light-brown (7.5YR 6/3–4) to brown (7.5YR 5/4), and either: 1) moderately to well-sorted and very fine-lower- to medium-grained (locally silty), or 2) moderate to poorly sorted and very fine- to very coarse-grained. Common weakly developed paleosols characterized by ped development, minor calcium carbonate accumulation (Stage I), and no notable clay illuviation. Ped development is weak to strong, coarse to very coarse, and subangular blocky. The second lithofacies is more common further away from the Rio Grande. It consists of channel-fills up to 0.7 m deep; these are filled by lenticular-bedded sandy pebbles (with 0.5–1% cobbles); gravel are subrounded to rounded, moderately to poorly sorted, and composed of volcanic rocks with 2–10% quartzite, 12–15% chert, 15–20% granite, 1–2% quartz, and trace to 5% siltstones–fine sandstones; sand with the pebbly beds is strong brown (7.5YR 5/6) to light-yellowish-brown (10YR 6/4), medium- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and composed of quartz, lesser feldspar, 15–20% orange-colored grains (potassium feldspar or chert), & 10–15% other lithic grains. Near the Rio Grande floodplain, this map unit includes subordinate, laterally extensive, axial tongues composed of pale-brown (10YR 6/3), fine-upper- to coarse-upper-grained sand with 5–10% very coarse grains and 1–15% pebbles that are scattered or in very thin to thin, lenticular beds (locally as thick as 55 cm). Pebbles are very fine to very coarse, subangular to subrounded, moderately to poorly sorted, and composed of similar gravel types as seen in unit **QTsa**; sand in the pebbly beds is light-yellowish-brown (10YR 6/4), fine-upper- to very coarse-upper-grained, subrounded, and poorly sorted. Sand in these tongues is pale-brown to brown (10YR 5–6/3) or light-gray to very pale-brown (10YR 7/2–3), laminated to very thin, horizontal-planar (mostly) to low-angle cross-laminated (facing south), subangular to subrounded, well- to moderately sorted, and similar in composition to sand in unit **QTsa** (e.g., composed of quartz, clear (vitreous) feldspar, 15% orange-colored microline-orthoclase and orange-colored chert, and 10–13% dark mafic-lithics). Entire unit is loose to weakly consolidated. 1–18 m thick.

Short—

Thick alluvial fan deposits filling paleovalleys and buttressed against paleoslopes east of Rio Grande. May have more than one allostratigraphic unit. Consists of: 1) massive sand with 1–15% pebbles (scattered or in lenses), common weakly developed paleosols (Stage I calcic horizons); and 2) pebbly sand channel fills. Unit includes thick tongues of axial sand with minor pebbles. 1–18 m thick.

Terrace Units

Qtti1 Lowest terrace along Tiffany Canyon, discontinuous

Late Pleistocene

Long—

Sandy gravel in clast-supported, lenticular beds; underlies a tread standing 2–3 m above modern grade. Gravel is comprised of pebbles, 50% cobbles, and 1–15% boulders composed of felsic to intermediate volcanic rocks. Gravel is mostly clast-supported, very poorly sorted, and subangular to subrounded (pebbles also angular). Matrix consists of strong brown (7.5 YR 4/6) to reddish-brown (5YR 5/4), medium- to very coarse-grained sand. Sand is angular to subrounded, poorly sorted, and composed of 5–20% quartz and feldspar, 80-95% felsic volcanic rocks, ≈1–3% clay, Scoured base with 0.3–0.4 m of scour relief. Geomorphic surface exhibits a weak to moderate desert pavement: ≈95% surface-clast density and moderate clast varnish, and weakly to moderately developed Av peds; 15% cobbles on the surface. Moderately consolidated. 1–2 m thick.

Short—

Sandy gravel in clast-supported, lenticular beds; tread stands 2–3 m above modern grade. Gravel comprised of pebbles, 50% cobbles, and 1–15% boulders composed of felsic to intermediate volcanic rocks. Matrix consists of strong-brown to reddish-brown, medium- to very coarse-grained sand. Geomorphic surface exhibits a weak to moderate desert pavement. Moderately consolidated. 1–2 m thick.

Qtti2 Second-from-lowest terrace along Tiffany Canyon, discontinuous

Late Pleistocene

Long—

Sandy gravel that is grayish and clast-supported. Vague, medium to thick, lenticular beds. Gravel consists of pebbles with ≈35% cobbles and 5–7% fine boulders. Moderately consolidated. Sharp, scoured lower contact. Tread stands 4–5 m above modern stream grade. 2 m thick.

Short—

Sandy gravel that is grayish and clast-supported. Vague, medium to thick, lenticular beds. Gravel consists of pebbles with ≈35% cobbles and 5–7% fine boulders. Moderately consolidated. Sharp, scoured lower contact. Tread stands 4–5 m above modern stream grade. 2 m thick.

Qtti3 Middle terrace along Tiffany Canyon, continuous

Middle(?) or Late Pleistocene

Long—

Sandy gravel underlying the lower extensive terrace in Tiffany Canyon. Cobbly sediment is in medium to thick, lenticular beds and pebbly sediment is in laminated to medium, lenticular to tabular beds. Minor beds of coarse sand which are 15–20% cross-stratified (planar, laminated to very thin foresets up to 60 cm tall). Gravel comprised of very fine to very coarse pebbles with 15–20% cobbles and 1–3% boulders; mostly clast-supported. Gravel are subrounded (minor rounded) and moderately to poorly sorted within a bed. Sand is brown to reddish-brown (5-7.5YR 4/4) to light-reddish-brown (5YR 6/3) and fine- to very coarse-grained, subangular to subrounded (medium to very coarse sand is more rounded), poorly sorted, and a volcanic lithic arenite with 1–5% clay. Moderate to well- consolidated and weakly cemented by clay. Geomorphic surface exhibits a moderate desert pavement: >95% surface-clast density, variably varnished clasts, mostly weakly varnished with 20% being moderately to strongly varnished, weak Av peds. Tread lies 7–9 m above modern grade. Correlative to unit **Qtgl**. 2–5 m thick.

Short—

Sandy gravel underlying the lower extensive terrace in Tiffany Canyon, correlative to unit **Qtgl**. Cobbly sediment is in medium to thick, lenticular beds and pebbly sediment is in laminated to medium, lenticular to tabular beds. Gravel includes pebbles, 15–20% cobbles and 1–3% boulders. Sand is brown to reddish-brown and fine- to very coarse-grained. Tread lies 7–9 m above modern grade. 2–5 m thick.

Qtti4 Upper terrace along Tiffany Canyon, continuous

Middle to Late(?) Pleistocene

Long—

Sandy gravel underlying higher extensive terrace along Tiffany Canyon, correlative to unit **Qtgh**. Gravel is poorly sorted, mostly clast supported (subordinate sand supported), and comprised of pebbles and cobbles with 1–3% boulders. Gravel composed of volcanic rocks (mostly felsic, minor intermediate) that are angular to subrounded. Matrix consists of very fine to very coarse sand, poorly sorted and composed of volcanic lithic grains, minor feldspar, and 10% quartz. Topsoil carbonate horizon exhibits a Stage II(+) to III(+) carbonate morphology. Locally contains finer-grained beds ≈0.5–1 m thick; these are internally massive, contain ≈3–5% clay, and composed of light-brown (7.5YR 6/4), fine- to medium-grained sand with scattered, coarser, volcanic sand grains. Moderately consolidated. Moderately developed desert pavement. Tread height is 11–13 m. Deposit is ≈6 m thick.

Short—

Sandy gravel underlying higher extensive terrace along Tiffany Canyon, correlative to unit **Qtgh**. Gravel comprised of pebbles and cobbles with 1–3% boulders. Matrix consists of very fine to very coarse sand. Topsoil carbonate horizon exhibits a Stage II(+) to III(+) carbonate morphology. Moderately consolidated. Moderately developed desert pavement. Tread height is 11–13 m. Deposit is ≈6 m thick.

Qtg Gravelly terrace deposit west of Rio Grande, undifferentiated

Late Pleistocene

Long—

Sandy gravel that is clast-supported and weakly consolidated. Gravel consists of very fine to very coarse pebbles with minor cobbles. Gravel is subrounded, poorly sorted, and composed of felsic-dominated volcanic clasts. Sand is brown (7.5YR 5/4), fine- to very coarse-grained, subrounded to subangular, poorly sorted, and has 0.5–3% clay in matrix. Geomorphic surface exhibits a weak to moderate desert pavement, with high clast density, weak varnish, and moderate Av peds. Tread height of 3–6 m. East of the Rio Grande, unit applied to high-level sandy gravel to gravelly sand (pebbles and cobbles), composed of basalt clasts from Mesa del Contadero and river gravel from unit **QTsa**, that caps ridges ≈10–20 m above modern grade. 0.5–3 m thick.

Short—

Sandy gravel comprised of pebbles and minor cobbles. Gravel is clast-supported, subrounded, and poorly sorted; composed of felsic-dominated volcanic clasts (west of Rio Grande), or basalt clasts and reworked **QTsa** gravel (east of Rio Grande). Sand is brown, fine- to very coarse-grained, and has 0.5–3% clay in matrix. Tread height of 3–6 m (west of Rio Grande) or 10–20 m (east of Rio Grande). 0.5–3 m thick.

Qtgl Lower gravelly terrace deposit west of Rio Grande

Middle(?) or Late Pleistocene

Long—

Pebbly sand and sandy gravel, locally exhibiting a coarsening-upward trend. Sandy gravel is in very thin to medium, lenticular beds (minor tabular and very minor U-shaped beds [maximum paleo-channel depth of 50 cm]); 1–20% cross-stratification (foresets up to 20 cm tall, planar, and very thinly bedded to laminated). Gravel consists of very fine to very coarse pebbles with 1–20% cobbles that are clast-supported, subrounded to subangular, and moderately to poorly sorted within a bed. Clast imbrication indicates paleoflow parallel to that of modern drainages. Gravel composed of felsic volcanic clasts with 2–15% intermediate volcanic rocks, 1–5% chert clasts, and trace quartzite. Pebbly sand is mostly horizontal-planar-laminated (minor very thinly bedded); 1–5% cross-laminations with planar foresets up to 30 cm tall. Sand in pebbly

sand strata is light-yellowish-brown to very pale-brown to light-gray (10YR 6–7/4; 7/2-3), pinkish- to light-brown (7.5YR 6/2–3), or reddish-brown (5YR 5/4), and fine- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and composed of about subequal quartz and feldspar with 20–50% volcanic lithic grains; 0–1% clay in matrix. Weakly to moderately consolidated. Tread surface has a weakly to moderately developed desert pavement (moderate to strong clast armor and weakly varnished clasts). Top soil has calcic horizons weaker than Stage III(+). Tread height is typically 7–10 m, but locally lower due to erosion. 2–10 m thick.

Short—

Pebbly sand and sandy gravel, locally coarsening upwards. Sandy gravel is mostly in very thin to medium, lenticular beds; pebbly sand is mostly horizontal-planar-laminated; 1–20% cross-stratification. Gravel consists of pebbles with 1–20% cobbles. Sand is fine- to very coarse-grained; 0–1% clay in matrix. Tread has a weak to moderate pavement and stands 7–10 m above modern grade. 2–10 m thick.

Qtgh Higher gravelly terrace deposit west of Rio Grande

Middle to Late(?) Pleistocene

Long—

Sandy gravel and minor pebbly sand underlying an extensive geomorphic surface west of the Rio Grande. Deposit consists of sandy gravel with lesser pebbly sand in very thin to medium, tabular to lenticular beds; pebbly sand beds are also horizontal-planar-laminated; 1–5% cross-stratification with planar foresets. Gravel are comprised of very fine to very coarse pebbles with 5–10% cobbles and trace to 3% boulders; cobbles may be particularly abundant (30–40%) near its base. Gravel are subrounded to subangular, moderately to poorly sorted within a bed, clast-supported (minor sand-supported) and imbricated. Gravel are composed of felsic-dominated volcanic clasts, 1–10% intermediate volcanic clasts, and 0–1% pebbles reworked from unit **QTsa**. Sand in gravelly beds is reddish-brown to brown to dark-brown (5-7.5YR 3–5/3–4) to light-brown (7.5YR 6/4), fine- to very coarse-grained (mostly medium- to very coarse-grained); subrounded to subangular, moderately to poorly sorted within a bed, and composed of quartz, feldspar, and 25–40% volcanic-dominated lithic grains; trace to 3% clay in sand matrix. Local weathering or oxidation of underlying sand. Very minor sand beds up to 1 m thick; sand is fine- to medium-grained and has 10% scattered very fine to very coarse pebbles and 3–5% thin to medium, lenticular beds of sandy pebbles. Local paleosols up to 60 cm thick having reddened (Bw) horizons overlying calcic horizons (Stage I to II). Strath is typically >2 m above modern grade. Tread is smooth and exhibits a moderately developed desert pavement: 15–25% well-varnished clasts (rest are moderately to weakly varnished) and moderate to high surface-clast density. Topsoil contains a Stage III to III(+) petrocalcic horizon >0.5 m thick. Tread stands 18 m

(near Rio Grande) to 10 m (near western border of quadrangle) above modern grade. Weakly to moderately consolidated. Thickness range of 1–12 m, but mostly 3–6 m.

Short—

Thick deposit underlying an extensive geomorphic surface west of Rio Grande. Consists of sandy gravel with lesser pebbly sand. Gravel comprised of pebbles, 5–10% cobbles and trace to 3% boulders. Strath and tread typically are >2 m and 10–18 m above modern grade, respectively. Topsoil contains a Stage III to III(+) petrocalcic horizon >0.5 m thick. Thickness range of 1–12 m, but mostly 3–6 m.

Quaternary Volcanic Units

Qble Lower basalt outcrops within eolian sand

Late Pleistocene

Long—

Mapped where small, subordinate basalt outcrops occur within thick eolian sand accumulations. Eolian sand as in unit **Qe**. Basalt is black to very dark-gray (N 2.5/–3/), highly vesicular, and contains trace to 1% olivine phenocrysts. Late Pleistocene age based on unpublished $^{40}Ar/^{39}Ar$ data (Matt Zimmerer, personal comm., June 7, 2019). 1–8 m thick.

Short—

Mapped where small, subordinate basalt outcrops occur within thick eolian sand accumulations. Eolian sand as in unit **Qe**. Basalt is black to very dark-gray (N 2.5/–3/), highly vesicular, and contains trace to 1% olivine phenocrysts. Late Pleistocene age based on unpublished $^{40}Ar/^{39}Ar$ data (Matt Zimmerer, personal comm., June 7, 2019). 1–8 m.

Qbucc Cinder cone, source for upper basalt capping Mesa del Contadero

Early to Middle Pleistocene

Long—

Black to dark-red, basaltic cinder (primarily lapilli with minor ash and dense bombs up to 20 cm long) and welded agglutinate interbedded with localized basalt lobes that are dense or, less commonly, vesicular to scoriaceous; strata are in steeply dipping beds. Basalt contains 7–8% phenocrysts of olivine and pyroxene that are mostly 0.2–1.0 mm, but 1–3% are 1–2 mm (primarily pyroxene); phenocrysts are commonly altered to iddingsite. Strata form a 25 m tall cinder cone, corresponding to Mesa Peak, on the northeast side of Mesa del Contadero.

Short—

Black to red, basaltic cinder (primarily lapilli with minor ash and bombs up to 20 cm) and welded agglutinate interbedded with localized basalt lobes. Basalt contains 7–8% phenocrysts of

olivine and pyroxene. Strata are in steeply dipping, tabular beds that underlie a 25 m tall cinder cone, corresponding to Mesa Peak, on the northeast side of Mesa del Contadero.

Qbu Upper basalt capping Mesa del Contadero

Early to Middle Pleistocene

Long—

Dark-gray to black, vesicular basalt containing 8–12% phenocrysts of olivine and 1–2% phenocrysts of pyroxene; phenocrysts are 0.2–1 mm long, with trace up to 1.5 mm long. 3–7 m thick.

Short—

Dark-gray to black, vesicular basalt containing 8–12% phenocrysts of olivine and 1–2% phenocrysts of pyroxene; phenocrysts are 0.2–1 mm long, with trace up to 1.5 mm long. 3–7 m thick.

Qbuhm Hydromagmatic deposits underlying the upper basalt capping Mesa del Contadero

Early to Middle Pleistocene

Long—

Horizontal-planar, well-defined laminations consisting of fine- to very coarse-grained sand and subordinate very fine to medium pebbles (1–15% coarse to very coarse pebbles); 1–10% cross-laminations up to 10 cm tall. Strata are grayish-brown to olive-gray to light-yellowish-brown to pale-brown (2.5–5Y 5/2–7/3). Sparse thicker beds up to 50 cm (tabular). Sand is well- to moderately sorted within a lamina and composed of a mix of subangular basalt and quartz-dominated sand (latter similar to that in **QTsa**). Pebbles are composed primarily of subangular basalt with trace to 5% axial-fluvial types (similar to those in **QTsa**); Trace to 1% fine cobbles of basalt; sparse sag-forming bombs are up to 20 cm across. Strata commonly exhibit fining-upward trends over 5–30 cm intervals. Weakly to moderately well-consolidated. 1–30 m thick, thinning away from the cinder cone constituting Mesa Peak.

Short—

Horizontal-planar, well-defined laminations of fine- to very coarse-grained sand and fine pebbles. Contains 1–10% cross-laminations up to 10 cm tall. Strata are grayish-brown to olive-gray to pale-brown. Sand is well-sorted within a lamina and composed of of subangular basalt and quartz-dominated sand (similar to sand in **QTsa**). Pebbles primarily of basalt with trace to 5% **QTsa** types. 1–30 m thick.

QUATERNARY–TERTIARY

Basin-fill Units

Long—

Basin-fill units collectively belong to the Santa Fe Group. The upper Santa Fe Group is called the Sierra Ladrones Formation, consistent with nomenclature used in the Socorro Basin to the north. To the south and west of the quadrangle, STATEMAP work is using the age-equivalent term Palomas Formation for these strata. The Sierra Ladrones Formation is relatively non-cemented and little deformed (tilted <3°). The lower Santa Fe Group is called the Popotosa Formation, which is relatively cemented and deformed. Where exposed, the contact between these two formations corresponds to an unconformity. However, near the Rio Grande, where the basin-fill is thickest, the contact may be conformable.

Short—

These units collectively belong to the Santa Fe Gp. In the Socorro Basin to the north the upper Santa Fe Gp. is called the Sierra Ladrones Fm. South and west of the quadrangle, STATEMAP work is using the age-equivalent term Palomas Fm. The lower Santa Fe Gp is called the Popotosa Fm. An unconformable contact exists between these two formations. The contact may be conformable near the Rio Grande.

Sierra Ladrones Formation

QTspw Western piedmont facies

Early Pliocene to Early Pleistocene

Long—

Variably clayey, interbedded sand and gravel that progrades over the upper tongue of axial-fluvial sediment west of the Rio Grande (see cross section A–A'). Colors are typically reddish-yellow to light-brown to brown (7.5Y reddish-brown to strong brown to yellowish-red to light-reddish-brown (5–7.5YR 4-6/4–6). Sediment consists of fine- to very coarse sand and pebbly sand in medium to thick, tabular beds (internally massive to horizontal-planar-laminated); hosting variable (but typically subordinate) tongues of sandy gravel that exhibit very thin to medium, lenticular (minor tabular) beds or is cross-stratified. Gravel comprised of pebbles with 1–15% cobbles; subangular to subrounded, poorly sorted, and composed of felsic-dominated volcanic rock types. Sand is fine- to very coarse-grained (<20% very fine sand), subrounded (mostly) to subangular, poorly to very poorly sorted, and composed of a mix of volcanic grains, feldspar, and quartz. Typical observations in sand include 1–20% scattered volcanic pebbles and 1–10% out-sized, coarse sand grains. Contains 1–15% clay. Common weakly developed paleosols characterized by ped development (weak to strong, fine to coarse, and subangular blocky), weak clay illuviation manifesting faint to distinct coats on few to many ped faces, and calcium carbonate precipitation (1–15% nodules, effervescence in hydrochloric acid, local whitening). 2–≈150 m thick.

Short—

Orangish to reddish, clayey, interbedded sand and gravel prograding over unit **QTsa**. Consists of fine to very coarse sand and pebbly sand in medium to thick, tabular beds; hosting variable (subequal to subordinate) tongues of sandy gravel that exhibit very thin to medium, lenticular (minor tabular) beds or is cross-stratified. Weak paleosols with illuviated clay and calcic horizons. 2–150 m thick.

QTstw Western margin, piedmont-axial transition zone

Early Pliocene to Early Pleistocene

Long—

Light-colored, medium-grained sand interbedded with subequal (±20%) light-orange fine-grained sediment, mapped on west side of the Rio Grande. Light-colored sediment correlates to unit **QTsa** (axial sand) and consists of 35–65% tongues (few to several m thick) of loose axial sand with minor pebbly intervals. Axial grained sand is light-gray (10YR 7/2), fine- to coarse-grained (mostly medium-grained), subangular to subrounded, well-sorted, and composed of quartz, 15–30% feldspar, 12–15% orange-stained quartz or chert, and 10–12% dark-colored lithics & mafics. Axial gravel consists of very fine to very coarse pebbles (trace cobbles) that are subrounded to rounded, poorly sorted, and composed of felsic volcanic clasts with 20% granite and gneiss, 10% quartzite, 10% intermediate volcanic rocks, ≈5% quartz, and <5% each of Paleozoic limestone, vesicular mafic lava, chert, and Abo Formation clasts. Fine-grained sediment consists of light-orangish to light-brown, thinly to thickly bedded silt, very fine- to fine-grained sand, silty fine sand, and clay. Fine-grained sediment is tabular-bedded; beds are internally massive or laminated to very thinly bedded. Silt and fine sand colors include yellowish-red to reddish-yellow to strong brown (5–7.5YR 5–6/6), pinkish-gray (5–7.5YR 7/2), and light-brown (7.5YR 6/3–4). Clay is reddish-brown to light-reddish-brown (5YR 5–6/3). Locally, 1–5% calcium-carbonate nodules are present. Contacts between beds are gradational or sharp and mostly planar. Fine-grained sediment includes 1–3 m-thick tongues of piedmont-derived sediment (derived from volcanic terrain to the west), which have <30% gravel and are characterized by: 1) minor to common, very thin to medium, lenticular beds of coarse sand and pebbles composed of volcanic clasts; 2) 1–40% medium to very coarse sand and 0–5% volcanic pebbles scattered in predominately very fine to fine sand; and 3) weak soil development characterized by Stage I carbonate morphology, no visible clay illuviation, and ped development (moderate, medium to coarse, subangular blocky). Weakly to moderately consolidated (fine-grained sediment) to loose (axial sand) and no to weak effervescence in HCl. Bottom of unit not seen, but thickness is likely 5–20 m.

Short—

Light-colored, medium-grained, axial sand interbedded with 30–70% orange to light-brown, thin to thick beds of silt, very fine- to fine-grained sand (locally with scattered coarser sand and

pebbles), and clay. Fine sediment is tabular-bedded (internally massive or laminated to very thinly bedded). Includes 1–3 m-thick tongues of piedmont lithofacies with <30% gravel (unit **QTspw**). 5–20 m thick.

QTsa Axial-fluvial facies

Early Pliocene to Early Pleistocene

Long—

Light-colored, clean, fine- to coarse-grained sand that is cross-laminated (also very thinly bedded; common trough forms; measured foresets being up to 0.5 m tall), horizontal-planar-laminated to very thinly bedded, or massive. Color is light-gray (2.5Y–10YR 7/1–2) or pale-brown to light-brownish-gray (10YR 6/2–3) or white (2.5Y–10YR 8/1). Contains 1–15% pebbly, medium- to very coarse-grained sand in lenticular, very thin to medium beds (internally horizontal-planar-laminated to low-angle cross-stratified). Pebbles are very fine to very coarse, subangular to well-rounded, moderately to poorly sorted, and composed of felsic volcanic rocks (locally with high percentages of Hells Mesa Tuff), 1–30% intermediate volcanic rocks, 1–15% granite, 1–25% chert, 0–15% quartzite, 1–10% quartz, 1–20% Paleozoic limestone, 1–20% reddish siltstone to fine sandstone (from Permian strata), trace to 3% Pedernal Chert, and 0–1% gneiss or schist; local zones contain high concentrations of cobbles composed of Hells Mesa Tuff, likely derived from upstream fan-toe cutting. Clast diversity and proportion of exotic clasts decreases down-section. Sand ranges from fine- to coarse-grained, but most commonly is fine-upper- to medium-upper-grained; subrounded to subangular (minor rounded), moderate to well-sorted, and composed of quartz, minor (10–30%) clear (vitreous) feldspar (plagioclase and sanidine), 5–20% orthoclase-microline and granite fragments, and 5–20% chert, volcanic lithic grains, and mafic grains. Local mud or clay rip-up clasts (commonly green to brown) up to 25 cm diameter. Sand deposited in paleochannels or fluvial lobes by the ancestral Rio Grande. <10% fine-grained, tabular-bedded strata consisting of light-brown (7.5YR 6/4) silt, very fine- to fine-grained sand, or silty–clayey fine sand; less common reddish-brown to dark-reddish-brown (5YR 4/3–4) clay–silt; these fine strata are in medium to thick, tabular, internally massive beds that are locally bioturbated or pedogenically modified; interpreted as floodplain lithofacies. Weakly to moderately consolidated, but near the Little San Pascual Mountains there are 10–50% strongly cemented intervals up to 2 m thick. Base not exposed. 20 to possibly as much as 250 m thick.

Short—

Light-colored (10YR–2.5Y), fine- to coarse-grained sand that is cross-laminated (common trough forms), horizontal-planar-laminated to very thinly bedded, or massive. Unit has 1–15% pebbly beds with exotic clasts (e.g., 1–15% quartzite and 10–25% chert, decreasing down-section). Deposited in paleochannels or lobes by the ancestral Rio Grande, <10% fine-grained, floodplain deposits. 20–250(?) m thick.

QTsage Axial-fluvial facies with gravel assemblage mainly sourced from the eastern piedmont

Late Pliocene to Early Pleistocene

Long—

Poorly exposed sand, similar to that observed in unit **QTsa**, mixed with minor pebbles and cobbles (95% pebbles vs 5% cobbles) composed of Paleozoic carbonates, 1–5% chert, 1–20% Permian siltstones and sandstones, trace to 10% volcanic rocks, 1% granite, and 0 to trace amounts of quartzite. Gravel are subangular to subrounded (chert may be rounded to subrounded) and poorly sorted. May erode to form SSW-trending topographic ridges. 2–10 m thick.

Short—

Poorly exposed sand, similar to that in unit **QTsa**, mixed with pebbles and cobbles (95% pebbles vs 5% cobbles) composed of Paleozoic carbonates, 1–5% chert, 1–20% Permian siltstones and sandstones, trace to 10% volcanic rocks, 1% granite, and trace quartzite. Gravel are subangular to subrounded (chert may be rounded to subrounded) and poorly sorted. May form SSW-trending ridges. 2–10 m thick.

QTste Eastern margin, piedmont-axial transition zone

Pliocene to Early Pleistocene

Long—

Fine-grained sediment interbedded with minor tongues of sandy gravel. Fine-grained sediment consists of very fine- to fine-grained sand (locally minor medium-grained lower sand), silt, and silty very fine- to fine-grained sand in medium to thick, tabular (minor broadly lenticular) beds that are internally massive and commonly bioturbated. Locally has minor (<25%), scattered medium to very coarse sand grains and 1–5% scattered pebbles; these poorly sorted beds are less common than unit **QTspe**. Exhibits colors of very pale-brown to pink (7.5–10YR 7/3), light-brown (7.5YR 6/3), or pinkish-gray to pinkish-white (7.5YR 7–8/2). Local fining-upward trends. Sandy gravel is in medium to thick, lenticular beds that are clast-supported and comprised of pebbles with 15–20% cobbles; gravel are subrounded to subangular, poorly sorted, and composed of 90% Paleozoic limestone with 1–15% relatively angular, locally sourced chert. Sand in the channel fills is brownish, medium- to very coarse-grained, subrounded to subangular, moderately to poorly sorted, and composed of Paleozoic carbonate lithic grains, 15–30% quartz, and 15–30% feldspar. Weak paleosols, mostly in the fine-grained sediment, manifested by Stage I to II calcic horizons locally overlain by orangish cambic horizons; moderate, medium-coarse, subangular blocky ped structure. Moderately to well-consolidated. Locally strongly cemented. 5–40 m thick.

Short—

Pink to pinkish-white, very fine- to fine-grained sand, silty sand and silt in medium to thick, tabular beds (internally massive & bioturbated). <25%, scattered, coarser sand grains and 1–5% pebbles. Minor tongues of sandy gravel (pebbles, 15–20% cobbles; composed of limestone and minor chert) that are medium to thick and lenticular. Paleosols with Stage I to II calcic horizons. 5–40 m thick.

QTspe Eastern piedmont facies

Pliocene to Early Pleistocene

Long—

Interbedded sandy gravel interbedded with subequal (±20%) very fine- to medium-grained sand, silty sand, and silt. Gravelly tongues are 1–4 m thick and exhibit thin to thick, tabular to lenticular beds and 0–10% cross-stratification (very thin to thin, planar foresests up to 40 cm tall). Gravel is clast- to sand-supported and comprised of very fine to very coarse pebbles, 1–20% cobbles, and 1–5% boulders; it is moderately imbricated, angular to subangular, poorly sorted, and composed of Paleozoic limestone, 0–20% siltstone and very fine- to fine-grained sandstone (from Permian strata), and 0.5–12% angular to subangular chert eroded from Pennsylvanian strata. Sand matrix of gravelly sediment is light-gray to pinkish-gray (5–7.5YR 7/2) to pink (5YR 7/3), fine- to very coarse-grained, and subanguar to subrounded; fine-lower- to medium-lower-grained sand is mainly composed of quartz and feldspar, but medium-upper- to very coarse-upper-grained sand is composed of lithic grains. Fine sediment consists of silt, silty fine sand, and very fine-lower- to medium-lower-grained in thick, tabular to wedge-shaped beds that are internally massive and commonly bioturbated (large burrow forms); 1–20% scattered medium-upper- to very coarse-upper-grained sand, and 1–20% scattered very fine to very coarse pebbles of aforementioned gravel types. Fine sand is pinkish-gray to reddish-brown (5YR 7/2–5/4), subangular, moderately sorted, and composed of quartz, feldspar, and 1–5% dark mafic-lithic grains. Interfingers with, and partly progrades over, axial-fluvial sediment of unit **QTsa**. Weakly to well-consolidated and poorly to moderately cemented by calcium carbonate. 2–50 m thick.

Short—

Interbedded sandy gravel and very fine- to medium-grained sand. Gravelly tongues exhibit thin to thick, tabular to lenticular beds and 0–10% cross-stratification. Gravel comprised of angular to subangular pebbles, 1–20% cobbles, 1–5% boulders; composed of Paleozoic limestone, 0–20% Permian clastics, and 0.5–15% chert. Fine sediment has 1–20% scattered coarse sand, and 1–20% pebbles. 2–50 m thick.

Popotosa Formation

Tppe Gravelly eastern piedmont facies

Middle to Late Miocene

Long—

Strongly cemented conglomerate derived from Little San Pascual Mountains. Vague, thin to thick, lenticular to tabular beds. Gravel are rounded to subrounded, poorly sorted, and composed of Paleozoic limestone, 1–7% chert (locally rounded to well-rounded), 0–10% of a yellowish, silty to sandy limestone, 1–8% very fine to fine sandstone to siltstone (from Permian strata, mostly reddish). Gravel are clast- to sand-supported, moderately well-imbricated, and comprised of very fine to very coarse pebbles, 10–25% fine to coarse cobbles, and trace to 5% boulders. In up-section direction, gravel size increases and the concentration of Permian-derived clasts decreases. Gravel matrix consists of grayish to reddish, fine- to very coarse-grained (mostly coarse- to very coarse) sand that is angular to subrounded (mostly subangular), poorly sorted and a lithic arenite. Fine-lower- to medium-lower-grained sand is a mix of Paleozoic detritus and quartz and feldspar grains, and coarser sand is composed of Paleozoic lithic grains (mostly limestone) and trace to 5% chert. Local (up to 20%) sandstone interbeds that are medium to thick-bedded, wedge-shaped, and internally massive; these consist of either very fine- to medium-grained, subrounded to subangular, moderately to well-sorted sand; minor, very thin to medium, lenticular beds of sandy pebbles–pebbly sand; sand is reddish-yellow (5–7.5YR 6/6), and composed mainly of quartz and feldspar with 5–10% dark mafic-lithic grains. Upper strata possibly time-correlative to the lower Sierra Ladrones Formation. Well-cemented by calcium carbonate; local silica cementation. 10–1,600(?) m thick.

Short—

Conglomerate, composed mainly of limestone clasts; subrounded to rounded and comprised of pebbles, 10–25% fine to coarse cobbles, and trace to 5% boulders. Vague, thin to thick, lenticular to tabular beds. Local (up to 20%) sandstone interbeds. Upper strata possibly time-correlative to the lower Sierra Ladrones Fm. Well-cemented by calcium carbonate; local silica cementation. 10–1,600(?) m thick.

Tps Sandstone

Early(?) to late Miocene

Long—

Well-sorted sandstone in thin to thick (mostly thick), tabular beds. Beds are internally massive, horizontal-planar-laminated, or exhibit local, low-angle cross-laminations; local burrowing and bioturbation. Sand is pinkish-gray to light-gray to pink (7.5YR 7/2–3; 10YR 7/2) or red to dark-red (2.5YR 3–4/6); sand is very fine-upper- to medium-lower-grained (mostly fine-lower- to fine-upper-grained), subrounded (minor subangular), well-sorted, lacks fines, and composed of

quartz, 20–45% feldspar, and 1–10% mafic-lithic grains; trace to 0.5% distinctly orange grains that may be potassium feldspar or chert. Commonly well-cemented by silica and outcrops are strongly varnished. 10–1,600(?) m thick.

Short—

Well-sorted sandstone in thin to thick (mostly thick), tabular beds (internally massive, horizontal-planar-laminated, or locally low-angle cross-laminated). Sand is light-gray to pink to red, mostly fine-grained and subrounded, lacks fines, and composed of quartz, 20–45% feldspar, and 1–10% mafic-lithic grains. Commonly well-cemented by silica and outcrops are strongly varnished. 10–1,600(?) m thick.

Tpsx Cross-stratified sandstone

Middle to Late Miocene

Long—

Well-sorted, reddish-brown (5YR 3–5/3; 2.5YR 4/4), fine-grained sandstone that is cross-stratified. Cross-stratification occurs within very thick, tabular beds. Foresets dip steeply to NE and are typically >0.5 m tall. Grains are fine-lower- to fine-upper-grained (<10% very fine-upper-grained and <10% medium-lower-grained), rounded to well-rounded, and composed of quartz, minor feldspar, and 5–15% mafic-lithic grains. Well-cemented by hematite (locally nodular) and possibly silica (no HCl effervescence). Eolian depositional environment. >30 m thick.

Short—

Well-sorted, reddish-brown, fine-grained sandstone that is cross-stratified within very thick, tabular beds. Foresets dip steeply to NE and >0.5 m tall. Grains are mostly fine-lower- to fine-upper-grained, rounded-well rounded, and composed of quartz, minor feldspar, and 5–15% mafic-lithic grains. Well-cemented by hematite (locally nodular) and possibly silica. Eolian depositional environment. >30 m thick.

Tpsc Sandstone and conglomerate

Early to Late Miocene

Long—

Cross section only. Sandstone inferred to be interbedded with volcanic-gravel conglomerate and conglomeratic sandstone. Conglomerates may be tuff-dominated or andesite-dominated. Correlates with Popotosa-age units in the Indian Well Wilderness quadrangle to the north (Chamberlin and Cikoski, 2010). Possibly 1,300 m thick.

Short—

Cross section only. Sandstone inferred to be interbedded with volcanic-gravel conglomerate and conglomeratic sandstone. Conglomerates may be tuff-dominated or andesite-dominated. Correlates with Popotosa-age units in the Indian Well Wilderness quadrangle to the north (Chamberlin and Cikoski, 2010). Possibly 1,300 m thick.

Precipitate Rocks

Qtrv Travertine

Late or Middle(?) Pleistocene

Long—

Laminated to very thin, tabular beds of calcium carbonate. Rock is light-gray (10YR 7/1), variably vuggy (has cavities), and has local root traces (as vertical tubules ≤1 mm wide or as horizontal, bifurcating roots up to 2 cm wide). Locally interbedded with minor (up to 30%) very thin to medium, tabular beds of sandy, very fine to very coarse-grained pebbles that are clast- to sand-supported and imbricated (giving a westward flow direction). Pebbles are angular to subangular and composed of Paleozoic carbonates and minor reddish siltstones to fine sandstones (eroded from Permian strata). The sand in the gravel beds is fine-lower to very coarse-upper-grained (mostly very coarse), angular to subangular, and poorly sorted; coarse to very coarse sand grains are composed of Paleozoic limestone-dolomite, fine to medium grains are limestone-dolomite and feldspar and quartz. Up to ≈6 m thick.

Short—

Laminated to very thin, tabular beds of calcium carbonate. Rock is light-gray, variably vuggy, and has local root traces (up to 2 cm wide). Locally interbedded with minor (up to 30%) very thin to medium, tabular beds of sandy pebbles; pebbles are angular to subangular and composed of Paleozoic carbonates and minor Permian siltstones to sandstones; westward paleoflow. Up to ≈6 m thick.

Tqc Quartz and chert bodies

Oligocene to Miocene

Long—

White to grayish, crystalline to microcrystalline quartz (≤2 mm crystal size) and reddish-gray to dark-orange to reddish-brown chert; occurs as stratiform bodies within the Yeso, Glorieta Sandstone, or San Andres Formations. Appears to have replaced original limestone beds. Deposits are typically massive, but locally occur as 1–5 centimeter-scale, tabular bands of alternating quartz and chert, with quartz locally exhibiting penetrative relations (e.g., veinlets) with the chert and thus seems to be younger. Chert is dark-orange to reddish-brown to reddish-gray. Quartz is white and, where crystalline, the crystals are as large as 2 mm. Local geodes

lined with quartz crystals. Mapped where unit occupies >50% of outcrop area, with the remainder being limestone, shale, or sandstone. 1–15 m thick.

Short—

White to grayish, crystalline to microcrystalline quartz (≤2 mm crystal size) and reddish-gray to dark-orange to reddish-brown chert. Occurs as stratiform bodies that replaced original limestone. Deposits are typically massive, but locally occur as 1–5 centimeter-scale, tabular bands of alternating chert and quartz. Local geodes. Mapped where unit occupies >50% of outcrop area. 1–15 m thick.

Eocene–Oligocene Volcanic and Volcaniclastic Rocks

Note that volcaniclastic strata are assigned to the Spears Group, and ignimbrites younger than 32–33 Ma is included in the Mogollon Group (per Cather et al., 1994). The andesite flows mapped on this quadrangle, in addition to the tuff of Battle Mountain, belong to the Datil Group (per Cather et al., 1994).

Ttm Undivided tuffs of the Mogollon Group

Early to Late Oligocene

Long—

Cross section only. Various rhyolitic ignimbrites that are partially to densely welded, phenocryst-poor to phenocryst-rich (1–40%), and have a phenocryst assemblage (mostly 0.5–3 mm) dominated by sanidine and quartz, with variable (but typically <1%) plagioclase and trace to 1% biotite. Unit most likely includes the phenocryst-poor (≤5%) and densely welded La Jencia and Vicks Peak Tuffs, both exhibiting strongly flattened pumices, but may possibly include the stratigraphically higher and more crystal-rich Lemitar and South Canyon Tuffs. Unit may be restricted to paleovalleys. 1–120(?) m thick, but thickness is highly uncertain.

Short—

Cross section only. Various rhyolitic ignimbrites; partially to densely welded with 1–40% phenocrysts (mostly 0.5–3 mm) dominated by sanidine and quartz with variable (typically <1%) plagioclase and trace to 1% biotite. Most likely includes the phenocryst-poor (≤5%) and densely welded La Jencia and Vicks Peak tuffs; possibly the Lemitar and South Canyon tuffs. Thickness uncertain; 1–120(?) m.

Twabu Upper biotite-bearing andesite flow

Late Eocene

Long—

Medium-gray lava with 15–35% plagioclase phenocrysts (subhedral and 0.5–5 mm, mostly 1–2 mm long) and 1–5% biotite phenocrysts (an- to subhedral, ≤1 mm long and bronze-colored). Forms a ledge that weathers into 5–10 cm-thick plates. 40–50 m thick.

Short—

Medium-gray lava with 15–35% plagioclase phenocrysts (subhedral and 0.5–5 mm, mostly 1–2 mm long) and 1–5% biotite phenocrysts (an- to subhedral, ≤1 mm long and bronze-colored). Forms a ledge that weathers into 5–10 cm-thick plates. 40–50 m thick.

Ttbm Tuff of Battle Mountain

Late Eocene

Long—

Biotite- and feldspar-phyric, welded and foliated tuff. Tuff is variably eutaxitic and commonly overlies a black vitrophyre 0.5–2 m thick. Rock is light-gray to white (5R 7–8/1), weathering to tan, brown, reddish-brown, and purplish colors. Phenocryst assemblage contains 10–25% feldspar (subhedral to euhedral, 0.5–4 mm; probably plagioclase and minor sanidine) and 1–7% biotite crystals (0.1–1 mm); very minor hornblende. Plagioclase concentration decreases up-section whereas biotite increases. ≈10% flattened pumice (0.1–1.5 mm), which are locally stretched to form pumice lineations. Unit may correlate to tuff of Chupadera Wilderness, but that tuff is moderately lithic rich whereas this one lacks lithic grains. Pending $^{40}Ar/^{39}Ar$ dating of this tuff will test this hypothesized correlation, since the tuff of Chupadera Wilderness conformably overlies the 33.9 Ma Blue Canyon Tuff (Chamberlin and Cikoski, 2010). 18 m thick.

Short—

Welded and foliated tuff; variably eutaxitic and overlies a 0.5–2 m thick, black vitrophyre. Phenocrysts include 10–25% feldspar (0.5–4 mm, probably plagioclase and minor sanidine) and 1–7% biotite crystals (0.1–1 mm); very minor hornblende. ≈10% flattened and locally stretched pumice. May correlate to 33.7–33.9 Ma tuff of Chupadera Wilderness (see Chamberlin and Cikoski, 2010). 18 m thick.

Tsps Spears Group, silt and fine sand

Late Eocene

Long—

Tan (locally reddish) and massive, silt and very fine to fine sand. Sand is very fine-lower- to medium-lower-grained (mostly very fine- to fine-grained) and locally silty; sparse pumiceous zones. Sand is subangular and apparently composed of feldspar with 20% dark grains (volcanic lithics and pyroxene). Locally, there is up to 15% scattered coarse to very coarse sand (including pyroxene crystals) and 1–10% scattered, andesite pebbles. Contains 1–10% intervals (mostly <1 m thick) comprised of grayish, very fine- to very coarse-grained, volcanic sand with abundant feldspar and pyroxene grains. Weakly to moderately consolidated and poorly exposed. Occurs as 1–15-m thick tongues within Willow Spring andesite flows. Interpreted as eolian sand reworked by sheetflooding, locally mixed with minor volcaniclastic sand and ash fall. Only the >10 m thick tongues are shown on map. Up to 15 m thick.

Short—

Tan (locally reddish) and massive, silt and very fine to fine sand occurring as 1–15 m-thick tongues within unit **Twa**. Sand is subangular and apparently composed of feldspar with 20% dark grains (volcanic lithics and pyroxene). Locally, up to 15% scattered coarse to very coarse sand (including pyroxene crystals) and 1–10% andesite pebbles. Interpreted as eolian sand reworked by sheetflooding.

Twa Andesite of Willow Springs

Late Eocene

Long—

Gray (N\5–6), pyroxene- and plagioclase-phyric andesite. Weathers to a light-brown to brown to reddish-brown (5–7.5YR 5–6/4). Variably vesicular (1–30% vesicles). Phenocryst assemblage: 1) 0.5–10% (mostly 5–10%) pyroxene (anhedral to subhedral and 0.2–5 mm, mostly 0.2–2 mm); 2) 10–40% plagioclase (euhedral to subhedral and 0.2–5 mm, mostly 0.5–2 mm). Groundmass has abundant plagioclase crystals (≤0.5 mm in size). Minor (1–10%) tongues of reddish breccia or sandstone. ≈300 m thick.

Short—

Gray, pyroxene- and plagioclase-phyric andesite, weathering to a light-brown to brown to reddish-brown. Variably vesicular. Phenocryst assemblage: 0.5–10% (mostly 5–10%) pyroxene (anhedral to subhedral, mostly 0.2–2 mm); 10–40% plagioclase (euhedral to subhedral, mostly 0.5–2 mm). Groundmass has abundant plagioclase crystals (≤0.5 mm). Includes 1–10% tongues of reddish breccia or sandstone. ≈300 m thick.

Twabl Lower biotite-bearing andesite flow

Late Eocene

Long—

Ledge-forming, highly porphyritic lava. Reddish-gray fresh color (2.5YR 5/1–2), varnishing to a dark-reddish-brown (2.5–5YR 4/4) to light-maroon to light-gray. Phenocrysts include 12–20% plagioclase (subhedral & 0.5–7 mm long, mostly 1–3 mm) and 3–7% biotite (sub- to euhedral, 0.1–2 mm long,). Lower contact is indistinct; it was drawn at the base of the ledge. Within 2 m above the base there are both pyroxene (5–7%) and biotite (5–7%) phenocrysts. Top and base of flow is vesicular; flow brecciation observed at flow top. 14 m thick.

Short—

Ledge-forming, highly porphyritic lava. Reddish-gray, varnishing to a dark-reddish-brown to light-maroon to light-gray. Phenocrysts include 12–20% plagioclase (subhedral & 0.5–7 mm, mostly 1–3 mm) and 30–7% biotite (sub- to euhedral, 0.1–2 mm). Both pyroxene (5–7%) and biotite (5–7%) phenocrysts observed within 2 m above base. Top and base of flow is vesicular; flow breccia at top. 14 m thick.

Tspa Spears Group volcaniclastic strata intertonguing with the andesite of Willow Springs

Late Eocene to Early Oligocene

Long—

Cross section only. Tongues of volcaniclastic conglomerate, conglomeratic sandstone and sandstone that are inferred to intertongue with andesite flows correlative to the andesite of Willow Springs. See descriptions for units **Tsp** and **Twa**. Uncertain inferred thickness of 700–750 m.

Short—

Cross section only. Tongues of volcaniclastic conglomerate, conglomeratic sandstone and sandstone that are inferred to intertongue with andesite flows correlative to the andesite of Willow Springs. See descriptions for units **Tsp** and **Twa**. Uncertain inferred thickness of 700–750 m.

Tsp Spears Group volcaniclastic strata, undivided

Late Eocene to Early Oligocene

Long—

Weak-red (10R 5/4), thick-bedded conglomeratic sandstone and sandstone. Conglomeratic beds are internally massive. Sandstone beds are relatively tabular and massive to laminated (horizontal-planar- to low-angle cross-laminated) and composed of clayey (1–20% estimate),

very fine- to fine-grained sand with minor scattered coarser sand (volcanic lithics); sand is angular to subangular (mostly subangular). Gravel ranges from pebbles to boulders (up to 45x37 cm) that are typically matrix-supported in exposed areas, consistent with deposition by lahar or debris flows. Lower conglomeratic beds feature subrounded to rounded, intermediate volcanic clasts with 30–40% Paleozoic limestone, 5% orange granite, and 5% reddish-brown fine sandstones-siltstones (Permian). Higher conglomeratic beds are dominated by intermediate volcanic rocks. In subsurface of western quadrangle (description from Chamberlin and Cioski, 2010): unit consists of andesitic conglomerates and conglomeratic sandstones dominated by varicolored andesitic clasts; conglomerates are mostly clast-supported; also likely includes sparse conglomeratic intervals composed of hornblende-plagioclase dacitic clasts. Conformably overlies Baca Formation or unconformably overlies Pennsylvanian strata. Thickness poorly constrained; inferred to be 190–250 m thick.

Short—

Weak-red, thick-bedded conglomerate, conglomeratic sandstone and sandstone. Gravel is mainly intermediate volcanic (with sedimentary clasts near base) and ranges from pebbles to boulders; associated beds are matrix-supported and massive, consistent with lahar or debris flow deposition. Sandstone beds are variably clayey and relatively tabular (internally massive to laminated). 190–250 m thick.

Eocene Sedimentary Rocks, Non-volcanic

Tb Baca Formation

Middle Eocene

Long—

Thick alluvial fan deposits that fill paleovalleys and are buttressed against slopes east of the Rio Grande. May have more than one allostratigraphic unit, but if so they could not be confidently recognized. Sediment consists of two lithofacies. The first is massive sand with minor (1–15%) scattered pebbles (similar to those in unit **QTsa**) and 0.5–3% very thin, lenticular, sandy-pebble to pebbly-sand beds. Sand is pale-brown (10YR 6/3) to light-brown (7.5YR 6/3–4) to brown (7.5YR 5/4), and either: 1) moderately to well-sorted and very fine-lower- to medium-grained (locally silty), or 2) moderate to poorly sorted and very fine- to very coarse-grained. Common weakly developed paleosols characterized by ped development (weak to strong, coarse to very coarse, subangular blocky), minor calcium carbonate accumulation (Stage I), and no notable clay illuviation. The second lithofacies is more common further away from the Rio Grande. It consists of channel-fills up to 0.7 m deep; these are filled by lenticular-bedded sandy pebbles (with 0.5–1% cobbles); gravel are subrounded to rounded, moderately to poorly sorted, and composed of volcanic rocks with 2–10% quartzite, 12–15% chert, 15–20% granite, 1–2% quartz, and trace to 5% siltstones–fine sandstones; sand with the pebbly beds is strong brown (7.5YR 5/6) to light-yellowish-brown (10YR 6/4), medium- to very coarse-grained, subrounded to

subangular, moderately to poorly sorted, and composed of quartz, lesser feldspar, 15–20% orange-colored grains (potassium feldspar or chert), & 10–15% other lithic grains. Near the Rio Grande floodplain, this map unit includes subordinate, laterally extensive, axial tongues composed of pale-brown (10YR 6/3), fine-upper- to coarse-upper-grained sand with 5–10% very coarse grains and 1–15% pebbles that are scattered or in very thin to thin, lenticular beds (locally as thick as 55 cm). Pebbles are very fine to very coarse, subangular to subrounded, moderately to poorly sorted, and composed of similar gravel types as seen in unit **QTsa**; sand in the pebbly beds is light-yellowish-brown (10YR 6/4), fine-upper- to very coarse-upper-grained, subrounded, and poorly sorted. Sand in these tongues is pale-brown to brown (10YR 5–6/3) or light-gray to very pale-brown (10YR 7/2–3), laminated to very thin, horizontal-planar (mostly) to low-angle cross-laminated (facing south), subangular to subrounded, well- to moderately sorted, and similar in composition to sand in unit **QTsa** (e.g., composed of quartz, clear (vitreous) feldspar, 15% orange-colored microline-orthoclase and orange-colored chert, and 10–13% dark mafic-lithics). Entire unit is loose to weakly consolidated. 1–18 m thick.

Short—

Meter-scale, intercalated tongues of: 1) reddish-brown, massive, very fine- to fine-grained sand and silty–clayey fine sand (0–10%, scattered, coarser sand grains and 1–3% pebbles); 2) gray, fine- to medium-grained sand with feldspar and lithic fragments; and 3) fining-upward conglomerates and conglomeratic sandstones; gravel composed mainly of subrounded Paleozoic carbonates. 20–40 m thick.

PALEOZOIC

Note that Paleozoic strata thin westward in the subsurface due to erosion of a Laramide-age highland.

Psa San Andres Formation, main body above Glorieta Sandstone tongue

Leonardian

Long—

Thick, tabular beds of a packstone limestone. Limestone is light-gray (fresh) weathering to light-brownish-gray (10YR–2.5Y 6/2). Local bivalves. Top not exposed. >3 m thick.

Short—

Thick, tabular beds of a packstone limestone. Limestone is light-gray (fresh) weathering to light-brownish-gray (10YR–2.5Y 6/2). Local bivalves. Top not exposed. >3 m thick.

Pg Glorieta Sandstone Tongue within the San Andres Formation

Leonardian

Long—

Thick, tabular beds of white to yellowish-tan sandstone. Sand is very fine- to fine-grained, well-sorted, and quartzose. Beds are internally massive. Fresh colors are typically whitish to very pale-brown. Weathered colors are pale-brown to very pale-brown (10YR 6–7/3, 8/2). Well-cemented by silica (no to very weak effervescence in HCl). Contains 1–10% limestone interbeds that are commonly replaced by stratiform, microcrystalline to crystalline quartz or chert. 40 m thick.

Short—

Thick, tabular beds of white to yellowish-tan sandstone. Sand is very fine- to fine-grained, well-sorted, and quartzose. Beds are internally massive. Fresh colors are typically whitish to very pale-brown. Weathered colors of pale-brown to very pale-brown. Well-cemented by silica. 1–10% limestone interbeds commonly replaced by stratiform quartz or chert (unit Tqc). 40 m thick.

Psal Lower San Andres Formation below the Glorieta Sandstone tongue

Leonardian

Long—

Dark-gray (N4/, 2.5Y 4/1) to gray (2.5Y 5/1), micritic limestone in thick, tabular beds. Weathered faces are pale-brown to light-gray (10YR 6/3–7/2). At base is a thick, tabular bed of Glorieta Sandstone (not mapped); this sandstone is internally massive, white to very pale-brown (weathering to a grayish-brown), fine-grained, well-sorted, and quartzose. Upper part of unit has abundant stratiform chert beds that likely replaced limestone. 15-–16 m thick.

Short—

Dark-gray to gray, micritic limestone in thick, tabular beds. Weathered faces are pale-brown to light-gray. At base is a thick, tabular bed of Glorieta Sandstone that is internally massive, white to very pale-brown (weathering to a grayish-brown), fine-grained, well-sorted, and quartzose. Upper part of unit has abundant stratiform chert beds that likely replaced limestone. 15–16 m thick.

Pyv Yeso Group, Los Vallos Formation

Leonardian

Long—

Intertonguing reddish-brown mudstone to siltstone to very fine-grained sandstone, white to yellowish siltstone to fine-grained sandstone, and light-gray limestone-dolomite. Individual tongues are 1–10 m thick. Mudstones to very fine sandstones are reddish brown (2.5–5YR 4–5/4) and internally massive. Siltstones to fine-lower-grained sandstones are quartzose and yellowish red (5YR 4–5/6) or pale-brown to yellow (2.5Y 8/3–6, 2.5Y 7/6, 5Y 8/3), locally clayey; these are laminated to very thinly bedded (mostly horizontal-planar-laminated, minor wavy laminated) or internally massive and bioturbated. Limestone-dolomite is in 1–10 m thick intervals exhibiting thin to thick, tabular bedding. These carbonates occupy 5–20% of the formation, are micritic, and light-gray (2.5Y 7/1–2) to light-brownish-gray (2.5Y 6/2) (fresh and weathered color); compared to those in unit **Psa**, the limestones in this unit have a lighter color and are not as well-bedded nor as fossiliferous. Fine-grained strata erode readily, but limestone-dolomite commonly form ledges. ≈200–230 m thick.

Short—

Intertonguing reddish-brown mudstone to siltstone to very fine-grained sandstone, white to yellowish siltstone to fine-grained sandstone, and light-gray to light-brownish-gray limestone-dolomite. Individual tongues are 1–10 m thick. Clastic sediment is well-sorted, quartzose, and internally horizontal-planar-laminated to massive. Carbonates are thin to thick, tabular-bedded. ≈200-230 m thick.

Pym Yeso Group, Meseta Blanca Formation

Leonardian

Long—

Also called Arroyo de Alamillo Formation. Reddish-brown (2.5YR 4/4; minor white or yellow), well-bedded (commonly flaggy) siltstone and very fine- to fine-grained sandstone. Beds are very thin to medium (minor thick), tabular, and internally massive to horizontal-planar-laminated. Local ripple marks on bedding surfaces. Sand is very fine- to fine-grained, well-sorted, and quartzose. Minor poorly bedded, relatively massive, reddish clayey siltstone to very fine sandstone. 110–130 m thick.

Short—

Also called Arroyo de Alamillo Fm. Reddish-brown (minor white or yellow), well-bedded siltstone & very fine- to fine-grained sandstone. Beds are very thin to medium (minor thick), tabular, and internally massive to horizontal-planar-laminated. Local ripple marks on bed

planes. Sand is well-sorted & quartzose. Minor poorly bedded, reddish, clayey siltstone to very fine sandstone. 110–130 m thick.

Pa Abo Formation

Wolfcampian

Long—

Reddish-brown (2.5YR 4/4) mudstones, siltstones, and very fine-grained sandstones interbedded with minor very fine- to medium-grained sandstone. Mudstones are chunky (non- or poorly laminated) and in tabular beds. Siltstones and very fine-grained sandstones are in medium to thick beds that are well-laminated (horizontal-planar to ripple-marked to wavy). Contains 5–10% channel fills having 30–100 m widths, 0.3–3 m thicknesses, and consisting of very fine- to medium-grained, arkosic sandstone and lesser intra-formational conglomerate. In the latter, clasts are very fine to coarse pebbles that are subangular to subrounded, poorly sorted, and grain-supported; sand is mostly medium- to very coarse-grained, subangular, and composed of limestone. Sandstones exhibit cross-laminations (up to 10 cm tall, common trough forms) and are pinkish-gray to brown to reddish-gray to brown (5–7.5YR 5–6/2) or reddish-brown to weak-red (2.5YR–10R 4–5/3), weathering to reddish-brown (5YR 5/3). Sand is angular to subangular, well-sorted, and composed of quartz with subordinate feldspar. 220 m thick.

Short—

Reddish-brown mudstones, siltstones and very fine-grained sandstones interbedded with minor very fine- to medium-grained sandstones. Mudstones are chunky and in tabular beds. Siltstones and very fine-grained sandstones are in medium to thick, well-laminated beds. Includes 5–10% channel fills with very fine- to medium-grained, arkosic sandstone and minor intra-formational conglomerate. 220 m thick.

Pb Bursum Formation

Early Wolfcampian

Long—

Reddish to maroon (Mansell colors of weak-red to reddish-brown, 2.5YR 4/2–3) siltstone, mudstone, and very fine sandstone interbedded with subordinate light-gray limestone. Limestone is commonly a micrite to packstone, and thin to thick, tabular-bedded. Very minor intra-formational conglomerates composed of very fine to medium, limestone pebbles. Contains 1–5% thick, tabular beds of sandstone that are rusty-colored to light-brown and horizontal-planar-laminated. Stratigraphic interval commonly capped by a thick bed of yellowish dolomite. Age from Lucas et al. (2017). 55–60 m thick.

Short—

Reddish to maroon siltstone, mudstone, and very fine sandstone interbedded with subordinate light-gray limestone (micrite to packstone in thin to thick, tabular beds). Very minor intra-formational conglomerates. Includes 1–5% thick, tabular beds of brownish horizontal-planar-laminated sandstone. Commonly capped by a thick bed of yellowish dolomite. Age from Lucas et al. (2017). 55–60 m thick.

IPu Pennsylvanian strata, undivided

Atokan to Virgilian

Long—

Cross section only. Consists of Red House Formation and probably Gray Mesa Formation; possibly includes the Bar B Formation. Uncertain due to lack of subsurface data. 200–600 m thick.

Short—

Cross section only. Consists of Red House Formation and probably Gray Mesa Formation; possibly includes the Bar B Formation. Uncertain due to lack of subsurface data. 200–600 m thick.

IPbb Bar B Formation

Late Desmoinesian to late Virgilian

Long—

Interbedded limestone with subequal (±20%) clastic sediment. The limestone occurs in intervals 1–15 m thick, where bedding is medium to very thick and tabular. Limestone is light-gray (lesser-gray or brownish-gray) and chert-poor (≤5% chert nodules, up to ≈40 cm or in stringers), and composed of micrite, wackestone, and lesser packstone. Local tannish-gray dolomitic limestone. Clastic sediment occurs in 1–25 m thick intervals and is non- to poorly exposed; likely consists of shale, siltstone, and possible sandstones. 270(?) m thick (age & thicknesses from Lucas et al., 2017).

Short—

Interbedded limestone with 30–70% clastic sediment. Limestone is in 1–15 m thick intervals having medium to very thick, tabular beds. Limestone is grayish, has ≤5% chert, and composed of micrite, wackestone, and lesser packstone. Poorly exposed clastic sediment (probably shale and siltstone; possible sandstones) in 1–25 m thick intervals. 270(?) m thick (age & thicknesses from Lucas et al., 2017).

IPgm Gray Mesa Formation

Late Atokan to Desmoinesian

Long—

Cross section only. Comprised of three members (ascending order): Elephant Butte (45 m of limestone with 40% [shale and covered intervals]); Whiskey Canyon (37 m of mostly ledge-forming, cherty limestone intervals up to 12 m thick); and Garcia (87 m of alternating limestone and covered intervals, with its lower 5 m being a cross-stratified sandstone). 170 m thick (from Lucas et al., 2017).

Short—

Cross section only. Comprised of three members (ascending order): Elephant Butte (45 m of limestone with 40% [shale and covered intervals]); Whiskey Canyon (37 m of mostly ledge-forming, cherty limestone intervals up to 12 m thick); and Garcia (87 m of alternating limestone and covered intervals, with its lower 5 m being a cross-stratified sandstone). 170 m thick (from Lucas et al., 2017).

IPrh Red House Formation

Atokan

Long—

Cross section only. Yellowish to brownish, intercalated limestone, shale, and sandstone. Lower interval (>42 m) consists of sandstone, pebbly sandstone, shale, and limestone. The middle interval (≈45 m) is dominated by shale with a few thin limestone beds. The upper interval (≈53 m) consists of interbedded limestone and thin shale intervals. >200 m thick [from Lucas et al., 2017].

Short—

Cross section only. Yellowish to brownish, intercalated limestone, shale, and sandstone. Lower interval (>42 m) consists of sandstone, pebbly sandstone, shale, and limestone. The middle interval (≈45 m) is dominated by shale with a few thin limestone beds. The upper interval (≈53 m) consists of interbedded limestone and thin shale intervals. >200 m thick (from Lucas et al., 2017).

PRECAMBRIAN

p€u Precambrian rocks, undivided

Meso-(?) to Paleo-proterozoic

Long—

Cross section only. Schist, amphibolite, felsic porphyry, and granite. Highly variable thicknesses of lithologic types. Protoliths for schist and amphibolite were arkosic sandstones and muddy siltstones, with minor interbedded volcanic flows; these were later intruded by granite (synthesized by Richard Chamberlin [in Chamberlin and Cikoski, 2010] from Kent [1982] and Bowring et al. [1983]).

Short—

Cross section only. Schist, amphibolite, felsic porphyry, and granite. Highly variable thicknesses of lithologic types. Protoliths for schist and amphibolite were arkosic sandstones and muddy siltstones, with minor interbedded volcanic flows; these were later intruded by granite (synthesized by Richard Chamberlin [in Chamberlin and Cikoski, 2010] from Kent [1982] and Bowring et al. [1983]).