Geologic Map of the Chupadera 7.5-Minute Quadrangle, Socorro and Torrance Counties, New Mexico

By

Scott B. Aby[1] and Andrew P. Jochems[2]

[1]Muddy Spring Geology, Dixon, NM 87527
[2]New Mexico Bureau of Geology and Mineral Resources, 801 Leroy Place, Socorro, NM 87801

September 2024

New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 306

Scale 1:24,000

https://doi.org/10.58799/OF-GM-306

This geologic map was funded in part by the USGS National Cooperative Geologic Mapping Program under STATEMAP award number G22AC00601, 2022. Additional support was made possible by the 2023 Technology Enhancement Fund provided by the New Mexico Higher Education Department. Funding is administered by the New Mexico Bureau of Geology and Mineral Resources (Dr. J. Michael Timmons, *Director and State Geologist*; Dr. Matthew J. Zimmerer, *Geologic Mapping Program Manager*).

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

CONTENTS

GEOLOGIC AND GEOGRAPHIC SETTING

The Chupadera 7.5-minute quadrangle is located in central New Mexico east of the Los Pinos Mountains, approximately 6 km south of U.S. Highway 60. The map area includes the headwaters of Chupadera Arroyo, an ephemeral stream that terminates in the internally drained Jornada del Muerto basin some 60 km to the south and a small area in the northwest corner that drains to the Rio Grande.

No perennial water bodies are found in the map area and ephemeral flow is prone to infiltration into poorly consolidated and commonly coarse-grained (i.e. porous) valley-floor deposits. Relatively wet areas are sometimes found upstream of Tertiary dikes, where water apparently pools and rises to the surface. Old homesteads are sometimes found in these locations.

The Chupadera quadrangle was previously mapped at 1:63,360 by Wilpolt et al. (1946) and 1:125,000 by Bates et al. (1947). These authors emphasized the Permian section and prominent Oligocene dikes; the current effort refines these contacts, identifies previously unmapped structures, and delineates Quaternary surficial units in the map area. Surrounding quadrangles mapped at 1:24,000 include Abo (Oviatt, 2010), Becker (Luther et al., 2005), Cerro Montoso (Allen et al., 2014), Rayo Hills (Aby and Jochems, 2022) and Scholle (Scott et al., 2005).

The oldest rocks exposed in the quadrangle are mudstones, gypsum, dolostone and limestones of the Los Vallos Formation. The Los Vallos Formation is comprised, in ascending stratigraphic order, of the Torres, Cañas, and Joyita members. All three members are mapped together on the Chupadera Quadrangle due to poor exposure and the thinness (commonly <15m) of the Joyita Member.

The Torres Member is a lithologically diverse unit consisting of mixed siliciclastic and marine sediments. At least four cycles of mudstone/siltstone-sandstone-dolostone are present, with the latter forming laterally continuous marker beds up to kilometers long. Intervals of gypsum in the Torres commonly exhibit highly contorted textures with intraformational sinkholes evident in places. Depositional environments include coastal plains, mud flats, sabkhas, and shallow-shelf marine settings (Baars, 1962; Lucas et al., 2013b). Fossil-poor and occasionally gypsiferous dolostones indicate deposition under restricted marine conditions. Oligocene dikes and sills, discussed below, have preferentially intruded weakly resistant strata in the Torres Member. The Torres Member is up to approximately 170 m thick on the quadrangle.

The Cañas Member of the Los Vallos Formation is dominated by massive to nodular or laminated, sometimes enterolithic (a small-scale folding thought to be caused by drying of evaporitic sediments) gypsum (Fig. 1) with minor, thin beds of dolostone, siltstone, and mudstone deposited in a hypersaline lagoonal environment (Hunter and Ingersoll, 1981). It usually forms slopes between benches or ridges of the Joyita Member and carbonates capping the Torres Member. The Cañas Member is 30–55 m thick.

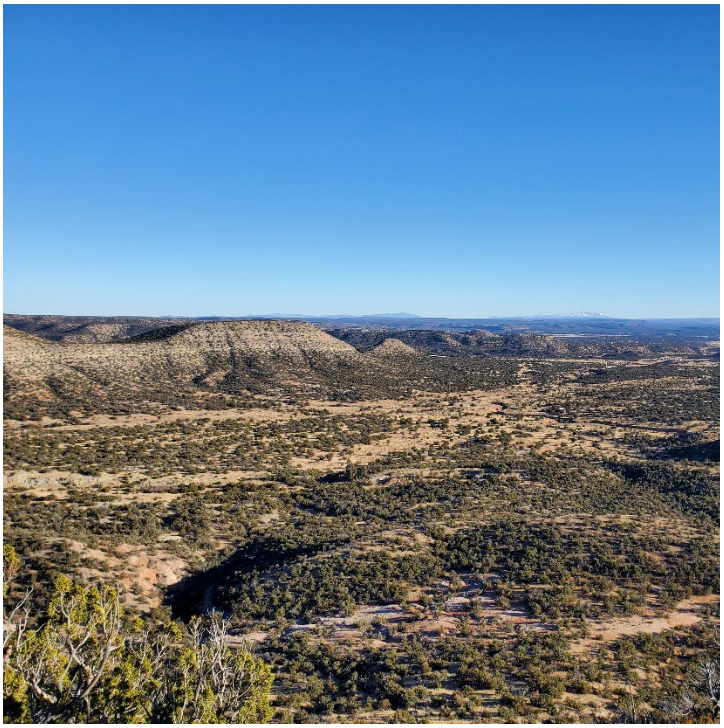

Figure 1—Chupadera Arroyo, looking south. Prominently bedded rock on the left are the San Andres Formation underlain by relatively steep slopes of the slightly darker Glorieta Sandstone. Lowlands in the center are underlain by the Los Vallos Formation.

The Joyita Member comprises siliciclastic beds formed by eolian and fluvial processes. Reddish to reddish yellow siltstones and sandstones were deposited on a large eolian sand sheet that prograded southward during a time of low sea level (Mack and Dinterman, 2002; Lucas et al., 2013b). Abundant gypsum blades and nodules suggest reworking of the Cañas Member. The Joyita is no more than about 15 m thick but is readily distinguished from the overlying Glorieta Sandstone by its dominantly reddish color, presence of gypsum flakes, and litharenitic sandstones. The base of the Joyita Member is defined as the top of the highest gypsum bed in the Cañas Member.

The Glorieta Sandstone (Leonardian) forms bold cliffs and ledges and conformably overlies the Joyita Member of the Yeso with a gradational zone comprised of sandstone and mudstone approximately 1.5–3 m thick (Fig. 2). The Glorieta is dominated by very fine- to fine- or, less commonly, medium-grained, quartz arenites that range from massive to low-angle or trough cross-bedded. Cross-stratification, relative lithologic homogeneity, and the scarcity of fossils in the Glorieta have resulted in competing interpretations of its depositional environment from shallow marine to eolian (e.g., Baars, 1961, 1962, 2000; Kelley, 1971; Milner, 1978; Mack and Dinterman, 2002; Mack and Bauer, 2014). Lucas and others (2013c) suggest that Glorieta sands were initially deposited by eolian processes, either in coastal dunes or on nearshore bars and shoals, and subsequently reworked during sea level rise. The Glorieta reaches a thickness of 70 m.

The San Andres Formation (Upper Leonardian) lies disconformably on the Glorieta Sandstone. The lower part is composed of limestone and dolostone. On the Chupadera quadrangle, there is commonly a 20–40(?)m thick sandstone interval approximately 30–50 m above the base. This sandstone is similar to the Glorieta Sandstone and has been interpreted as a tongue of the Glorieta derived from dune fields and shallow marine nearshore environments during brief episodes of sea level fall (Krainer et al., 2012), although regional relations have not been explored during our mapping. Two sandstone/gypsum intervals are commonly found (separated by 'typical' limestone and dolostone) in the lower San Andres Formation on the adjacent Rayo Hills Quadrangle (Aby and Jochems, 2022) , but the presence of gypsum in the lower San Andres is more variable on the Chupadera Quad.

Figure 2—Contact between the Glorieta Sandstone and limestone/dolostones of the San Andres Formation.

Above the Glorieta Sandstone is the San Andres Formation—a sequence of limestone and dolostone capping the ridges and plateaus of Chupadera Mesa. San Andres carbonates formed in an offshore, normal marine setting (Krainer et al., 2012; Brose et al., 2013). High surfaces underlain by the San Andres are erosional and nowhere on the quadrangle is the entire formation exposed. In the eastern uplands of the Chupadera Quadrangle closed depressions formed by karst processes are common. The San Andres is 45–50 m thick in the map area.

No strata of Mesozoic through Eocene age are exposed on the quadrangle. The map area lay just east of the Laramide Montosa uplift (Cather, 1992) in an area of weakly positive topography that was sufficiently high and long-lived to prevent deposition of Cretaceous (Campanian) to Eocene sediments.

Dikes up to 170 m wide intrude The Los Vallos Formation in the western half of the quadrangle. Geochemical analysis indicates that these are monzonitic. They vary from fine-grained and aphanitic to phaneritic with phenocrysts of hornblende, plagioclase, and altered pyroxene and biotite. Thin (generally <1m) sills of this same material are found in the south-central part of the quad, intruded mostly into the Glorieta Sandstone. Where more continuous dikes are present, in the eastern half of the quadrangle, they have not been observed to penetrate the base of the Glorieta.

At least two different orientations, NE–SW and ENE–WSW, are observed among the dikes but cross-cutting relationships are difficult to determine because late Quaternary erosion has been focused in locations where dikes intersect. However, one dike south of the Rayo Hills clearly transitions from NE–SW to ENE–WSW (Aby and Jochems, 2022) and we infer that all dikes are of similar age but with orientations controlled, at least in part, by the spatial distribution of weak versus competent strata within the Yeso Group.

Dikes are particularly prominent in the Torres Member, although they are also observed intruding the Cañas and Joyita members as well as the older Meseta Blanca Formation (Wilpolt and Wanek, 1951). Aldrich and others (1986) obtained a KAr age of 30.0 ± 0.2 Ma from an ENE–WSW dike in the Chupadera quadrangle to the east. Chamberlin and others (2002) noted west-to-east flow fabrics in similar dikes to the south (e.g., Jones Camp dike) and interpreted their origin as a dike swarm emanating from the Socorro-Magdalena caldera cluster approximately 55 km southwest of the map area.

A variety of Quaternary units are found on the Chupadera Quadrangle. These are broadly divided into hillslope/mass-movement, alluvial, eolian and karst deposits. Gradational relationships are recognized between many units. For example, between hillslope and valley-floor units. Coarseness of deposits generally varies according to inferred transport capacity, with eolian and sheetflood deposits consisting of very fine to fine sand, silt and clay (with rare to occasional pebble lags). Alluvial and hillslope deposits are commonly coarser-grained—very fine to coarse sands and pebble-cobble gravels.

Figure 3—Coarse-grained sediments of unit Qfyr. Photo taken at approximately 13S 3796907 373722 NAD83.

Hillslope deposits include debris flows, landslides, colluvium and talus. No geochronological data is available for these deposits but they are presumed to be middle or late Pleistocene to Holocene in age based on laterally gradational relationships with alluvial-fan and valley-floor deposits. Hillslope deposits are primarily mapped where they obscure contacts between Permian bedrock units.

Younger valley fill in the upper Sand Draw and Red Tanks Canyon (Cañada Montosa) drainages on the Rayo Hills Quadrangle returned radiocarbon ages of 3800 to 1470 cal yr BP (Table 2). These deposits feature several buried Stage I or II carbonate horizons (Gile et al., 1966) but surface soils are generally eroded. A historic alluvial-fan deposit prograding onto younger alluvium north of Chupadera Gap on the Rayo Hills quadrangle returned a radiocarbon age of about 140 cal yr BP.

Multiple Pleistocene to Holocene and recent cycles of incision are recognized in Abo Arroyo, a Rio Grande tributary to the north of the map area (Hall et al., 2009; Love and Rinehart, 2016; Rinehart and Love, 2016). At least two or three cycles of incision are evident in the map area. Radiocarbon ages indicate that these episodes took place in the late Holocene after about 3300, 1450, and 150 cal yr BP. Valley- fill in drainages integrated to the Rio Grande returned younger radiocarbon ages, 2250–1600 cal yr BP, than deposits in the internally drained upper Sand Draw (A tributary of Chupadera Arroyo) basin dated at 3800–3350 cal yr BP, despite samples being collected from similar positions below deposit surfaces. The older ages of the Sand Draw deposits broadly correspond to a wet and cold interval inferred from pluvial lake records in southern New Mexico and glacial evidence in the southern Rocky Mountains (Armour et al., 2002; Castiglia and Fawcett, 2006). The most recent episode of incision is likely related to widespread arroyo cutting in historic times (Aby, 2017).

The dominant structures in the quadrangle are a series of NE–SW folds with some anticlines cored by dikes intruding the upper Yeso Group. Larger, kilometer-scale folds are typically upright, gentle to open, and symmetric with a subset of folds that are gently plunging. Smaller folds, ranging from sub-kilometer to outcrop scale, exhibit a wider range of orientations though most are open and upright to slightly incline.

The origin of large anticlines in the map area appears to be related to Oligocene dike intrusion based on spatial coincidence between the two (Bates et al., 1946, p. 40; Cather, 2009). Steeply dipping, sometimes overturned and hydrothermally altered (?) beds are found near the margins of dikes within the Los Vallos Formation.

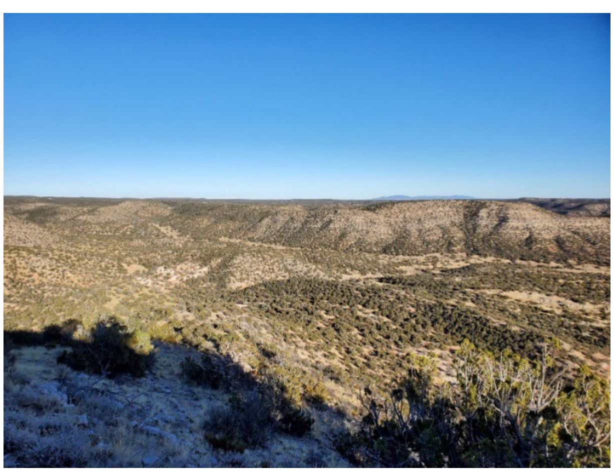

Figure 4—Typical expression of kilometer-scale folds in Glorieta and San Andres Formations.

Groundwater flow in the map area is generally northwest to southeast based on well data and water is derived largely from aquifers in confined sandstones of the Abo and Meseta Blanca Formations or, less commonly, the Torres Member of the Los Vallos Formation. Recharge occurs on the east side of the Los Pinos Mountains several kilometers west of the quadrangle; few if any wells drilled in the map area since the 1980s have encountered artesian conditions.

Yield is typically low, reaching only 20–40 gallons per minute in sandstones of the Abo and Meseta Blanca formations. Water quality data from the quadrangle is limited, but total dissolved solids range from 525 to 3,800 mg/L (Spiegel, 1955). Saline groundwater observed in the Abo and Meseta Blanca aquifers is likely due to seepage from the overlying Los Vallos Formation and perhaps slow rates of lateral flow (Spiegel, 1955).

Several prominent geomorphic surfaces are found in the southwest part of the quadrangle and the southeast part of the adjoining Rayo Hills quadrangle (Aby and Jochems, 2022). These surfaces lie 50–70 m above the modern channels of Sand Draw and Chupadera Arroyo and are associated with thin, coarse-gravel deposits – unit **Qxo** – comprised of strongly varnished, angular to subangular clasts of Glorieta Sandstone. Oviatt (2010, 2011) observed exotic gravel deposits containing rounded clasts of quartzite, chert, and Abo Formation lying 150–200 m above and thus predating the homogenous Qxo pediment gravels.

Bates and others (1947) identified pediment gravel deposits to the north that were later mapped by Scott and others (2005) and Oviatt (2010). The projected grade of these thicker deposits, some containing well-developed pedogenic carbonate, is at least 10's of meters lower than **Qxo** surfaces, although their location in the Abo Arroyo watershed may obscure any relation to Qxo gravel deposits in the Chupadera Arroyo watershed. Abo Arroyo drains to the Rio Grande whereas modern Chupadera Arroyo terminates nearly 50 km to the south in the closed Jornada del Muerto basin.

Qxo surfaces in the Chupadera area parallel modern grade and decrease in elevation from west to east, mimicking dips in the San Andres Formation and Glorieta Sandstone that are locally to the east or east-southeast. Wilpolt and others (1946) observed that strata in the middle part of the Glorieta are less resistant to erosion in places, giving the unit a double-ledged character. Paleo-drainages apparently beveled pediment surfaces on these weaker beds while depositing **Qxo** lag gravels during the Pleistocene. Thus, the pediment surface underlying thin **Qxo** gravel reflects the competing controls of bedrock lithology and baselevel change, both factors in pediment formation that have long been the subject of field and modeling studies in the American Southwest (e.g., Gilbert, 1877; Miller, 1950; Cooke, 1970; Pelletier, 2010).

METHODS

Geologic mapping of the Chupadera quadrangle consisted of traditional field techniques (Compton, 1985) coupled with newer digital approaches. Stereogrammetry software (Stereo Analyst for ArcGIS®, version 16.6.0) permitted accurate placement of geologic contacts using aerial photography obtained from the National Agricultural Imagery Program (NAIP). Planimetric and vertical accuracy of this dataset is approximately 5 m (USDA, 2008).

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

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

ACKNOWLEDGMENTS

Mapping of the Chupadera Quadrangle was funded by the STATEMAP program, which is jointly supported by the U.S. Geological Survey and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR). We thank Dr. J. Michael Timmons Dr. Mathew Zimmerer of NMBGMR for logistical support and coordination. Cartography was provided by the NMBGMR map production group, coordinated by Phil Miller. We are grateful to Ana and Shawn Cain for access to their ranch.

REFERENCES

Aby, S.B. 2017 Date of arroyo cutting in the American Southwest and the influence of human activities, *Anthropocene*, _v 18 p. 76–88.

Aby, S.B. and Jochems, A.P. 2022, Geologic Map of the Rayo Hills Quadrangle Socorro and Torrance Counties, New _Mexico New Mexico Beaurea of Geology and Mineral Resources map OFMG 300.

Aldrich, Jr., M.J., Chapin, C.E., and Laughlin, A.W., 1986, Stress history and tectonic development of the Rio Grande rift, New Mexico: Journal of Geophysical Research, v. 91, p. 6199–6211.

Allen, B.D., Timmons, J.M., Luther, A.L., Miller, P.L., and Love, D.W., 2014, Geologic map of the Cerro Montoso 7.5-minute quadrangle, Socorro County, New Mexico: New Mexico Bureau of Geology and Mineral Resouces, Open-file Geologic Map OF-GM 238, scale 1:24,000.

Armour, J., Fawcett, P.J., and Geissmann, J.W., 2002, 15 k.y. paleoclimatic and glacial record from northern New Mexico: Geology, v. 30, p. 723–726.

Baars, D.L., 1961, Permian strata of central New Mexico: New Mexico Geological Society, Guidebook 12, p. 113–120.

Baars, D.L., 1962, Permian System of Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 46, p. 149–218.

Baars, D.L., 1974, Permian rocks of north-central New Mexico: New Mexico Geological Society, Guidebook 25, p. 167–169.

Baars, D.L., 2000, The Colorado Plateau: A Geologic History: Albuquerque, University of New Mexico

Press, 254 p.

Bates, R.L., Wilpolt, R.H., MacAlpin, A.J., and Vorbe, G., 1947, Geology of the Gran Quivira quadrangle, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 26, 52 p., 9 plates.

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

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

Brose, R.J., Lucas, S.G., and Krainer, K., 2013, The Permian San Andres Formation in central and western New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 213–226.

Castiglia, P.J., and Fawcett, P.J., 2006, Large Holocene lakes and climate change in the Chihuahuan Desert: Geology, v. 34, p. 113–116.

Cather, S.M., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico: New Mexico Geological Society, Guidebook 43, p. 109– 122.

Cather, S.M., 2009, Tectonics of the Chupadera Mesa region, central New Mexico: New Mexico Geological Society, Guidebook 60, p. 127–138.

Chamberlin, R.M., Chapin, C.E., and McIntosh, W.C., 2002, Westward migrating ignimbrite calderas and a large radiating mafic dike swarm of Oligocene age, central Rio Grande rift, New Mexico: Surface expression of an upper mantle diapir?: Geological Society of America, Abstracts with Programs, v. 34, p. 438.

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

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

Hall, S.A., Penner, W., and Ellis, M., 2009, Arroyo cutting and vegetation change in Abo Canyon, New Mexico: Evidence from repeat photography along the Santa Fe Railway: New Mexico Geological Society, Guidebook 60, p. 429–438.

Hunter, J.C., and Ingersoll, R.V., 1981, Cañas gypsum member of Yeso Formation (Permian) in New Mexico: New Mexico Geology, v. 3, p. 49–53.

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

Kelley, V.C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 75 p., 7 plates.

Krainer, K., and Lucas, 2009, Cyclic sedimentation of the Upper Pennsylvanian (Lower Wolfcampian) Bursum Formation, central New Mexico: Tectonics versus glacioeustasy: New Mexico Geological Society, Guidebook 60, p. 167–182.

Krainer, K., and Lucas, S.G., 2013, The Pennsylvanian-Permian Bursum Formation in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 143–160.

Krainer, K., Lucas, S.G., and Brose, R.J., 2012, Reference section of the Lower Permian San Andres Formation, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 395–405.

Kues, B.S., and Giles, K.A., 2004, The late Paleozoic Ancestral Rocky Mountains system in New Mexico: New Mexico Geological Society, Special Publication 11, p. 95–136.

Love, D.W., and Rinehart, A.J., 2016, Uncommon twentieth-century stream behavior of lower Abo Arroyo revealed by flood deposits and historic photographs: New Mexico Geological Society, Guidebook 67, p. 447–457.

Lucas, S.G., and Krainer, K., 2012, The Lower Permian Yeso Group in the Fra Cristobal and Caballo Mountains, Sierra County, New Mexico: New Mexico Geological Society, Guidebook 63, p. 377–394.

Lucas, S.G., Krainer, K., and Colpitts, R.M., Jr., 2005, Abo-Yeso (Lower Permian) stratigraphy in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, p. 101–117.

Lucas, S.G., Barrick, J.E., Krainer, K., and Schneider, J.W., 2013a, The Carboniferous-Permian boundary at Carrizo Arroyo, central New Mexico USA: Stratigraphy, v. 10, no. 3, p. 153–170.

Lucas, S.G., Krainer, K., and Voigt, S., 2013b, The Lower Permian Yeso Group in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 181–199.

Lucas, S.G., Krainer, K., and Brose, R.J., 2013c, The Lower Permian Glorieta Sandstone in central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 59, p. 201–211.

Luther, A.L., Karlstrom, K.E., Scott, L.A., Elrick, M., and Connell, S.D., 2005, Geologic map of the Becker 7.5-minute quadrangle, Valencia and Socorro Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 100, scale 1:24,000.

Mack, G.H., and Bauer, E.M., 2014, Depositional environments, sediment dispersal, and provenance of the early Permian (Leonardian) Glorieta Sandstone, central New Mexico: New Mexico Geological Society, Guidebook 65, p. 261–271.

Mack, G.H., and Dinterman, P.A., 2002, Depositional environments and paleogeography of the Lower Permian (Leonardian) Yeso and correlative formations in New Mexico: The Mountain Geologist,
v. 39, p. 75–88.

Mack, G.H., and Suguio, K., 1991, Depositional environments of the Yeso Formation (Lower Permian), southern Caballo Mountains, New Mexico: New Mexico Geology, v. 13, p. 45–49, 59.

Milner, S., 1978, Genesis, provenance, and petrography of the Glorieta Sandstone of eastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 165, 25 p.

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

Needham, C.E., and Bates, R.L., 1943, Permian type section in central New Mexico: Geological Society of America Bulletin, v. 54, p. 1653–1668.

Oviatt, C.G., 2010, Geologic map of the Abo quadrangle, Torrance County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 199, scale 1:24,000.

Ramsey, C.B., 2009, Bayesian analysis of radiocarbon dates: Radiocarbon, v. 51, p. 337–360.

Reimer, P.J., and 41 others, 2020, The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP): Radiocarbon, v. 62, p. 757–757.

Rinehart, A.J., and Love, D.W., 2016, Architecture of buried bluff lines: A record of the incising ancestral Rio Grande and Abo Arroyo from the Pleistocene to historical times: New Mexico Geological Society, Guidebook 67, p. 429–438.

Scott, L.A., Elrick, M., Connell, S., and Karlstrom, K., 2005, Preliminary geologic map of the Scholle 7.5-minute quadrangle, Valencia, Torrance, and Socorro Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 099, scale 1:24,000.

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

Spiegel, Z., 1955, Geology and ground-water resources of northeastern Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Ground-water Report 4, 99 p., 2 plates.

Stanesco, J.D., 1991, Sedimentology and depositional environments of the Lower Permian Yeso Formation, northwestern New Mexico: U.S. Geological Survey, Bulletin 1808, p. M1–M12.

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

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

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

Wilpolt, R.H., and Wanek, A.A., 1951, Geology of the region from Socorro and San Antonio east to Chupadera Mesa, Socorro County, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-121, scale 1:63,360, 2 sheets.

Wilpolt, R.H., MacAlpin, A.J., Bates, R.L., and Vorbe, G., 1946, Geologic map and stratigraphic sections of Paleozoic rocks of Joyita Hills, Los Piños Mountains, and northern Chupadera Mesa, Valencia, Torrance, and Socorro Counties, New Mexico: U.S. Geological

Survey, Oil and Gas Investigations Map OM-61, scale 1:63,360, 1 sheet.

TABLES

Table 1—Major-element geochemistry of intrusive rocks in the Rayo Hills 7.5-minute quadrangle.

Sample #	UTM N[a]	UTM E[a]	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SO_3	SiO_2	TiO_2	Total	LOI 1000[b]
22RH-093A	3796214	363079	16.78	4.5	6.69	1.64	3.4	0.07	6.84	0.55	0.03	55.24	1	99.14	2.1
22RH-093B	3796214	363079	17.44	3.95	6.81	1.99	3.24	0.06	6.7	0.65	0.02	55.7	1.1	99.6	1.64

NOTE: All values given in wt %.

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

[b]LOI = loss on ignition.

Table 2—Summary radiocarbon geochronology for Holocene deposits in the Rayo Hills 7.5-minute quadrangle.

Sample #	Lab #[a]	Deposit	Material Dated	UTM N[b]	UTM E[b]	Conventional Age (^{14}C yr BP_{1950})[c]	2σ Calibrated Age Range (cal yr BP_{1950})[d]	Median Age (cal yr BP_{1950})[e]	$\delta^{13}C$ (‰)
22RH-231A	Beta-626858	Qay	charcoal	3793906	371907	3530 ± 30	3894-3714 (0.940) 3708-3699 (0.014)	3800 ± 100	-20.9
22RH-231B	Beta-626859	do.	charcoal	3793906	371907	3140 ± 30	3447-3327 (0.792) 3295-3254 (0.162)	3350 ± 100	-20.8
22RH-520	Beta-626861	Qfh	charcoal	3797629	370482	160 ± 30	286–242 (0.167) 231–164 (0.316) 158–131 (0.098) 118–58 (0.179) 44-0 (0.194)[f]	140 ± 140	-21.4
22RH-521A	Beta-626862	Qay	charcoal	3797726	370311	2250 ± 30	2341–2296 (0.306) 2264-2153 (0.648)	2250 ± 90	-20.3
22RH-521B	Beta-626863	do.	charcoal	3797726	370311	1600 ± 30	1534-1405 (0.954)	1470 ± 60	-21.0
22RH-522	Beta-626864	Qe	charcoal	3799464	367635	2020 ± 30	2047–2020 (0.053) 2007–1872 (0.895) 1848–1844 (0.005)	1950 ± 100	-11.1

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

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

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

[d]2σ calibrated age ranges calculated as relative probability using Bayesian methodology of Ramsey (2009) and IntCal20 calibration curve of Reimer et al. (2020).

[e]Median age reported by averaging entire age range and rounding to nearest 10 yr. Error is difference between median and end values of range.

[f]33-0 cal yr BP range implies possibility of post-1950 age (including modern) indicating the influence of ^{14}C from above-ground nuclear weapons testing.

APPENDIX A

Detailed descriptions of lithologic units on the Chupadera 7.5-minute quadrangle

QUATERNARY

Anthropogenic Units

daf Disturbed land and anthropogenic fill (Recent, <100 years old)—Sand and gravel that has been moved by humans to form berms and dams or has been reworked/remobilized for construction purposes.

Eolian, Hillslope, and Debris-flow Units

Qe Eolian sand (Holocene)—Loose to weakly consolidated, thin- to medium-bedded sand underlying broad sheets. Sand consists of light- to strong-brown or reddish-yellow (7.5YR 5–6/4–6) or yellowish-red (5YR 5/6), internally massive to low-angle planar or ripple cross-laminated, moderately well to well-sorted, subangular to rounded, vfU–fU grains composed of 90–95% quartz and gypsum, 3–5% orange feldspar, and 1–3% lithics (mostly carbonate). Deposit features at least one buried Bw or Bwk horizon up to 0.2 cm thick. A charcoal sample from near the base of one deposit on the adjacent Rayo Hills quadrangle returned a conventional radiocarbon age of 2020±30 ^{14}C yr BP (Aby and Jochems, 2022). Maximum thickness is at least 1.2 m but variable based on location relative to lee-side topography.

Qes Eolian and sheetflood deposits, undivided (Holocene)—Loose to weakly consolidated silty sand and subordinate silt-clay in massive to medium (>12 cm), tabular beds underlying sheets and gently incised surfaces of low to moderate slope. Sand consists of strong brown (7.5YR 4/6), internally massive, well-sorted, vfL–fL grains with 3–5% rounded to well-rounded mL–mU grains composed mostly of quartz (>90%) and trace subangular to rounded granules and fine pebbles of carbonate and sandstone. Silt-clay is yellowish-red (5YR 5/6) to strong-brown (7.5YR 5/6), vaguely laminated (≤0.8 cm), and contains 2–5% floating grains of subangular, fU–mL sand composed of carbonate or dark lithics. Deposit is bioturbated by very fine to coarse roots and medium burrows, including krotovina of sandy material up to 3 cm across. Occasional discontinuous channels incised into the unit typically disappear downstream into low-gradient swales and valley floors. Locally, weak topsoil development is characterized by very fine carbonate coatings indicating stage I carbonate accumulation. Total thickness is at least 1.0–1.5 m.

Qse Sheetflood deposits reworked from eolian sand sheets (Holocene)—Loose to weakly consolidated sand and sandy silt in massive to medium (15–20 cm), tabular to wedge-shaped beds underlying low- to moderate-grade slopes that are commonly rilled or gullied. Sand consists of brown (7.5YR 4/3–4) to strong-brown (7.5YR 4–5/6), crudely horizontal-planar laminated, poorly to moderately well-sorted, subangular to rounded, vfL–fU grains (trace medium grains) composed mostly of quartz. The surface of the deposit features rare to occasional stringers of poorly to moderately sorted, subangular to subrounded (occasionally rounded) pebbles consisting of local lithologies. The base of the deposit may be marked by a thin pebble-gravel where it overlies unit **Qay**. Commonly bioturbated by very fine to very coarse roots and/or burrows. Rare to occasional disseminated gypsum is found near areas of Yeso Group exposure. Topsoil development is characterized by: (A) dark-brown (7.5YR 3/3–4), non-calcareous, sandy to silty A horizons that are 10–40 cm thick; or (B) carbonate filaments indicating stage I carbonate accumulation in the upper 30–35 cm of the deposit. Deposit is 0.5–1.0 m thick in upland areas to perhaps 2.5 m thick near the margins of shallow valleys

Qesa Eolian and subordinate sheetflood and alluvial deposits, undivided (Holocene)—Loose eolian silt to fine-grained sand that has been reworked by alluvial processes in places. See unit descriptions for **Qe**, **Qes**,

Qsae, and **Qse**.

Qsae Sheetflood, alluvial, and subordinate eolian deposits, undivided (Holocene)—Loose, silty to coarse-grained sand on low- to moderate-grade slopes that are more commonly incised than those underlain by unit **Qesa** and coarser than unit **Qsea**. Nearly all eolian sand has been reworked by alluvial processes. Some gravel may be present. See unit descriptions for **Qe**, **Qes**, and **Qse**.

Qsea Sheetflood and subordinate eolian and alluvial deposits, undivided (Holocene)—Loose, silty sand on low- to moderate-grade slopes that are more commonly incised than those underlain by unit **Qesa**. Nearly all eolian sand has been reworked by alluvial processes. See unit descriptions for **Qe**, **Qes**, **Qsae**, and **Qse**.

Qsc Sheetflood and colluvial deposits, undivided (Upper? Pleistocene to Holocene)—Loose to weakly consolidated, silty sand and pebble (rare cobble) gravel underlying moderate-grade slopes at the base of bedrock uplands. See unit descriptions for **Qse** and **Qct**

Qsec Sheetflood deposits reworked from eolian sand sheets and colluvial deposits, undivided (Upper? Pleistocene to Holocene)—Loose to weakly consolidated sand, silty sand-and-pebble (rare cobble) gravel underlying moderate-grade slopes at the base of bedrock uplands. See unit descriptions for **Qse**, **Qsc**, and **Qct**.

Qct Colluvium and talus, undivided (Upper? Pleistocene to Holocene)—Loose, poorly sorted, angular to subrounded cobble-boulder gravel forming aprons or mantles at the foot slopes of bedrock uplands. Deposit is <5 m thick.

Qls Landslide deposits (Upper Pleistocene to Holocene)—Weakly consolidated gravel in massive to poorly defined, thick or very thick, wedge-shaped beds. Gravel is mostly matrix-supported, internally massive to chaotically bedded and/or slope-parallel, very poorly sorted, angular to subangular clasts and consists of 40–70% pebbles, 30–40% cobbles, and 5–20% boulders primarily derived from the Glorieta Sandstone or San Andres Formation. Matrix sand consists of brownish-yellow to yellow (10YR 6/6–8, 7/6), non-calcareous, very poorly to poorly sorted, angular to subrounded, vfU–mU grains (5–10% cL sand to granules) composed of subequal proportions of quartz and lithics (sandstone, siltstone, and carbonate) and up to 5% orange feldspar. Locally features a surface soil with stage II carbonate accumulation (clast coatings) that is poorly exposed but presumed to occur in the upper 1.0–1.5 m of the deposit. Deposit is at least 4.0 m thick.

Qdy Younger debris-flow deposits (Holocene)—Loose to weakly consolidated, reverse-graded, silty to pebbly sand and pebble-cobble gravel in massive or thick, tabular to broadly lenticular beds. Sand consists of strong-brown to reddish-yellow (7.5YR 5–6/6–8), weakly calcareous, moderately sorted, subangular to rounded, vfL–mL grains composed of 85–90% quartz, 5–10% lithics (dark mafics or iron-oxide flakes derived from the Glorieta Sandstone and subordinate sandstone and carbonate), and up to 5% feldspar. Gravel is internally massive to weakly or moderately imbricated, poorly to moderately sorted, angular to rounded, and consists of 60–90% pebbles, 10–30% cobbles, and 0–10% boulders of Glorieta Sandstone, Iron-oxide concretions derived from the limestone/dolostone of the Glorieta, and San Andres Formations. Gravel matrix is similar to sandy beds. Stage II carbonate accumulation (clast coatings) is observed in the upper 0.4–0.6 m of the deposit. Maximum thickness is 8.5 m.

Qdyr Younger and recent debris-flow deposits, undivided (Holocene)—Younger (**Qdy**) and subordinate recent (modern + historical) debris-flow deposits. The following description is for recent debris-flow deposits that are not mapped separately in the quadrangle: loose to moderately consolidated gravel in massive or medium to thick (15–35 cm), lobate to snout- or fan-shaped beds. Gravel is open-framework to matrix-supported, internally massive to imbricated, very poorly to poorly sorted, mostly angular to subrounded, and consists of 45–95% pebbles, 5–45% cobbles, and 0–25% boulders of sandstone, siltstone, and carbonate. Open-framework texture is more common in modern deposits. Matrix consists of brown (7.5YR 5/4) to strong-brown or reddish-yellow (7.5YR 5/6–8, 6/8) to yellowish-brown (10YR 5/4), very poorly to poorly sorted, angular to rounded silt to cL sand composed of 60–80% quartz, 10–30% lithics (carbonate, sandstone, siltstone, and minor dark mafics or iron-oxide flakes derived from the Glorieta Sandstone), and 5–10% orange feldspar. Historical deposits (~50 to ~200 years old) may feature an upper sandy gravel comprised of loose pebbles, cobbles, and boulders in massive to medium, lobate to broadly lenticular beds. Gravel in this bed are clast- to matrix-supported and internally massive to moderately imbricated. Clasts consist of 60–80% pebbles, 10–25% cobbles, and 10–15% boulders of sandstone, carbonate, and siltstone. The upper gravel matrix consists of brown to strong-brown (7.5YR 4/4–6), moderately calcareous, very poorly to poorly sorted, subangular to subrounded, fL–vcL sand of similar composition to the lower gravel matrix but with common fine, disseminated charcoal fragments. No topsoil is preserved on recent deposits, which form bar-and-swale topography of 0.4 (historical) to 2.0 m (modern) and are frequently capped by open-framework boulder trains. Deposit is at least 1.4–2.0 m thick.

Qdo Older debris-flow deposits (Middle? to upper Pleistocene)—Very weakly consolidated gravel in massive, wedge-shaped beds. Gravel are clast- to matrix-supported, internally massive to vaguely imbricated, very poorly to poorly sorted, angular to subrounded (minor rounded), and consist of 45–60% pebbles, 25–30% cobbles, and 10–30% boulders of San Andres Formation carbonate and Glorieta Sandstone. Bedding is indistinct and clast-supported texture is more common than matrix-supported. Matrix consists of brown to light-brown (7.5YR 5–6/4), strongly calcareous, poorly sorted, subangular to rounded, silt to mL sand (<5% mU sand). Where discernible, sand grain lithologies include at least 95% quartz with the remainder composed of sandstone, carbonate, feldspar, and micas. Deposit surface does not commonly feature notable bar-and-swale topography. Deposit is at least 2.0–5.0 m thick.

Qdoy Older and younger debris-flow deposits, undivided (Middle? Pleistocene to Holocene)—Older (**Qdo**) and subordinate younger (**Qdy**) debris-flow deposits. See detailed descriptions of each individual unit.

Qdfy Younger debris-flow and alluvial-fan deposits, undivided (Holocene)—Unit mapped where younger debris-flow (**Qdy**) and alluvial-fan (**Qfy**) deposits are highly gradational. See detailed descriptions of each individual unit.

Valley-floor Units

Qam Modern alluvium (Modern to ~50 years old)—Loose sand and sandy gravel forming longitudinal bars and underlying channels in modern, ephemeral-stream courses. Gravel are very poorly to moderately sorted, subangular to well-rounded, and consist of 55–90% pebbles, 10–35% cobbles, and 0–10% boulders of local lithologies. Sand consists of light-brown (7.5YR 6/4) to light-yellowish-brown (10YR 6/4), very poorly to poorly sorted, subangular to well-rounded, fL–cL (trace to 3% very coarse) grains composed of 80–85% quartz, 10–15% lithics, and 5–10% feldspar. Surface characterized by bar-and-swale topography exhibiting up to 0.5 m of relief. Maximum thickness is 2.0–2.5 m.

Qah Historical alluvium (~50 to ~200 years old)—Loose, sandy gravel in thick (0.3–0.9 m), lenticular beds. Gravel are clast-supported, moderately to well-imbricated, very poorly to poorly sorted, subrounded to well-rounded, and consist of 45–65% pebbles, 15–30% cobbles, and 5–25% boulders of local lithologies, primarily carbonates and Glorieta Sandstone. Matrix consists of brown to light-brown (7.5YR 5–6/4), weakly calcareous, angular to subrounded, vfL–mU sand composed of 80–85% quartz, 10–15% lithics (sandstone, siltstone, carbonate, and subordinate dark mafics or iron-oxide flakes derived from the Glorieta Sandstone), and up to 5% feldspar. Gravel occasionally underlies low-angle to horizontal-planar laminated sand that is similar to gravel matrix and is often mantled with eolian and/or sheetflood deposits. Deposit is commonly bioturbated by very fine to very coarse roots and may feature a well-developed A horizon in the upper 0.2 m. Surface characterized by bar-and-swale topography exhibiting up to 0.35 m of relief. Tread height is 0.6–1.6 m above modern grade. Deposit is at least 0.8–1.6 m thick

Qar Recent (historical + modern) alluvium (Modern to ~200 years old)—Historical (**Qah**) and modern alluvium (**Qam**) in approximately equal proportions. See detailed descriptions of each individual unit.

Qamh Modern and historical alluvium, undivided (Modern to ~200 years old)—Modern (**Qam**) and subordinate historical (**Qah**) alluvium. See detailed descriptions of each individual unit.

Qahm Historical and Modern alluvium, undivided (Modern to ~200 years old)—Historical and subordinate modern alluvium. See detailed descriptions of each individual unit.

Qay Younger alluvium (Holocene)—Loose to weakly consolidated, silty to slightly clayey sand in medium to very thick (0.2–1.4 m), tabular to broadly lenticular beds underlying broad surfaces that are occasionally deeply incised throughout the quadrangle. Sand consists of light- or strong-brown to reddish-yellow (7.5YR 6/4–6) to dark-yellowish-brown (10YR 3/6, 4/4), moderately to strongly calcareous, mostly massive, poorly to moderately well-sorted, subangular to well-rounded, vfL–mL grains (0–5% subangular to rounded mU–cU grains) composed of 75–95% quartz, 5–15% feldspar, and 5–10% lithics (carbonate and sandstone). Sandy beds contain 0–10% matrix-supported (rare clast-supported), poorly to moderately sorted, mostly subangular to subrounded granules to pebbles (rare cobbles) of local lithologies. Less common are beds of weakly consolidated pebble-cobble (rare pebble-cobble-boulder) gravel in thin to very thick (4 cm to 1.2 m), lenticular beds. Gravel are moderately well-imbricated, poorly to moderately sorted, subangular to rounded, and consist of 90–95% pebbles and 5–10% cobbles of local lithologies with matrices similar to sandy intervals. Deposit is commonly bioturbated by very fine to very coarse roots and contains rare to common charcoal fragments. Buried Bw or Bt horizons are indicated by rare to occasional clay argillans on larger grains and prismatic ped structures. Diffuse carbonate coatings in the upper part of the deposit indicate stage I to II carbonate accumulation. Occasionally mantled by sheetflood and reworked eolian sediment. Charcoal samples from deposits on the adjacent Rayo Hills quadrangle returned conventional radiocarbon ages of 1600±30 to 3530±30 ^{14}C yr BP (Aby and Jochems, 2022). Deposit is 3.5–10.0 m thick.

Qayi Younger alluvium, inset subunit (Holocene)—Sediment similar to but underlying a cut-fill terrace inset 4–5 m into younger alluvium (**Qay**). Deposit is up to 6.0 m thick.

Qahy Historical and younger alluvium, undivided (Holocene)—Historical (**Qah**) and subordinate younger alluvium (**Qay**). See detailed descriptions of each individual unit.

Qayh Younger and historical alluvium, undivided (Holocene)—Younger (**Qay**) and subordinate historical alluvium (**Qah**). See detailed descriptions of each individual unit.

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

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

Qao Older gravelly alluvium (Middle to Upper Pleistocene)—Poorly exposed, weakly imbricated pebble-cobble gravel. Clasts consist of 65–95% pebbles and 5–35% cobbles. Matrix consists of strong-brown (7.5YR 4–5/6), strongly calcareous, poorly to moderately sorted, subangular to rounded, silty vfL–mL sand (3–5% mU–cL sand) composed of 85–90% quartz, 10–15% lithics (sandstone and dark mafics and/or iron-oxide flakes derived from the Glorieta Sandstone), and trace to 3% feldspar. Unconsolidated gravel features stage IV carbonate accumulation (K horizon with laminations) at least 0.4 m thick at its surface. A conglomerate in massive to medium or thick, lobate to tabular beds is found in upper Sand Draw in the eastern part of the adjacent Rayo Hills quadrangle. The conglomerate is brown to slightly reddish-gray (weathering white to pinkish-white), well-indurated, calcite-cemented, matrix-supported, and internally massive. Clasts consist of poorly sorted, subangular to rounded pebbles (90–97%), cobbles (3–10%), and trace small boulders of Glorieta Sandstone (55–65%), carbonate (35–45%), and a few percent monzonite clasts. The conglomerate matrix consists of very poorly sorted, subrounded to rounded, fU–vcU sand (2–5% granules) composed of 85–95% quartz, 5–15% lithics (sandstone and carbonate), and trace to 3% feldspar. Smaller (fine to medium) sand grains in the matrix exhibit a frosted appearance. Total thickness unknown but at least 4.0–5.0 m.

Alluvial-fan and piedmont Units

Qfh Historical fan alluvium (~50 to ~200 years old)—Loose to weakly consolidated gravel in medium to thick (35–65 cm), wedge-shaped beds. Gravel are clast-supported, internally massive or weakly to moderately imbricated, very poorly sorted, angular to subrounded, and consist of 45–55% pebbles, 40–45% cobbles, and 10–15% boulders. Matrix consists of light brown (7.5YR 6/3–4) to yellowish or light-yellowish-brown (10YR 5–6/4), moderately calcareous, very poorly to poorly sorted, subangular to subrounded, vfL–cL sand (trace to 12% cU sand to granules) composed of 45–80% quartz, 10–45% lithics (sandstone and dark mafics and/or iron-oxide flakes derived from the Glorieta Sandstone), and 5–15% orange feldspar with occasional fine-grained, disseminated charcoal. Topsoil features a 0.1–0.2 m thick A horizon where not eroded. Surface characterized by bar-and-swale topography exhibiting up to 0.2 m of relief. A charcoal sample from the Rayo Hills quadrangle returned a conventional radiocarbon age of 160±30 ^{14}C yr BP (Aby and Jochems, 2022). Maximum thickness is 3.2 m.

Qfhm Historical and modern fan alluvium, undivided (Modern to ~200 years old)—Historical (**Qfh**) and subordinate modern fan alluvium. See detailed descriptions of each individual unit.

Qfy Younger fan alluvium (Holocene)—Loose to weakly consolidated, silty to pebbly sand and gravel in massive or medium to thick, wedge-shaped to lobate beds. Sand consists of light-brown to reddish-yellow (7.5YR 6/4–6), strongly calcareous, internally massive, poorly sorted, angular to rounded, vfL–mU grains (trace to 3% cU grains to granules) composed of 80–85% quartz, 10–15% lithics (dark mafics and/or iron-oxide flakes derived from the Glorieta Sandstone and subordinate sandstone), 5–10% orange feldspar, and 5–10% gypsum. Gravel are internally massive to weakly or moderately imbricated, very poorly to poorly sorted, mostly angular to subrounded, and consist of 55–80% pebbles, 10–30% cobbles, and 10–15% boulders of Glorieta Sandstone, iron-oxide concretions derived from the Glorieta, and carbonate. Underlying sand may contain stringers of such gravel. Surface soil may contain Bw or Bt horizons up to 0.3 m thick overlying Bk horizons (stage I to II carbonate accumulation) but the latter are typically eroded. Deposit contains rare to occasional charcoal fragments. Surface characterized by bar-and-swale topography exhibiting up to 0.2 m of relief. Deposit is 3.9–4.4 m thick.

Qfyh Younger and historical fan alluvium, undivided (Holocene)—Younger (**Qfy**) and subordinate historical fan alluvium (**Qfh**). See detailed descriptions of each individual unit.

Qfyr Younger and recent (historical + modern) fan alluvium, undivided (Holocene)—Younger and subordinate recent (historical + modern) fan alluvium. See detailed descriptions of **Qfh** and **Qfy**. Modern fan alluvium consists of loose, clast-supported to open-framework, sandy pebble-cobble-boulder gravel. This gravel forms bars, lobes and underlying braided channels.

Qpo Older piedmont alluvium (Middle? to Upper Pleistocene)—Thin pebble-cobble and pebble-cobble-boulder gravel occurring as small remnants or capping low-gradient ridges. Clasts are 40–60% pebbles, 20–45% cobbles, and 10–20% boulders of Glorieta Sandstone and carbonate. Surface soils are commonly eroded. Deposit is <2.4–3.0 m thick.

Qxo Older pediment gravels (Middle? to Upper Pleistocene)—Pebble-cobble and pebble-cobble-boulder lag gravels overlying erosional surfaces formed on the Glorieta Sandstone in the southwest part of the quadrangle. Clasts are angular to subangular and commonly feature strong varnish. Gravel deposits are associated with erosional or pediment surfaces formed on less resistant strata in the middle part of the Glorieta. The slopes of the surfaces are generally parallel to modern grade, indicating that these upland geomorphic features formed in the ancestral drainages of Sand Draw and Chupadera Arroyo. Pediment surfaces are 50–70 m above modern grade. Gravel deposits are 0.8–2.0 m thick.

Karst-Fill Units

Qkf Karst-fill deposits (Holocene) —Silt-clay, sand, and minor gravel-filling karst-related collapse features (dolines) in the central and eastern parts of the quadrangle. Deposit is likely similar to units **Qesa**, **Qsae**, and **Qsea** but better stratified and lacking flow-related sedimentary structures. Deposit is perhaps up to 6–8 m thick.

Qamkf Karst-fill deposits modified by alluvial and/or mass movement processes (Holocene)—Similar to unit **Qkf** but exhibiting evidence of alluvial or mass-movement reworking such as flow or slump structures. Deposit may be similar to units **Qah**, **Qay**, **Qesa**, **Qsae**, and/or **Qsea**. Deposit is perhaps up to 6–8 m thick.

TERTIARY

Heading 3: Intrusive Units

Ti Intrusive monzonite (Lower Oligocene)—Medium- to whitish- or very light-gray, weathering to medium- or dark-gray, non-vesicular, massive, aphanitic to phaneritic monzonite intruding weakly consolidated strata of the Torres Member of the Los Vallos Formation or as thin sills in the lower Glorieta Sandstone in the south-central part of the quadrangle. Spheroidal weathering is common. Where phaneritic, phenocrysts include 20–30% hornblende (medium- to coarse-grained, subhedral to euhedral prisms), 10–15% plagioclase (fine- to medium-grained, anhedral to subhedral), trace to 1% biotite (fine-grained, subhedral), and trace quartz (fine- to medium-grained, anhedral). Bates et al. (1947) noted the presence of orthoclase, pyroxene, and magnetite in some samples. Hornblende and biotite are commonly altered to greenish or yellowish, powdery secondary minerals. Aphanitic margins contain trace to 1% very fine-grained, equant phenocrysts inferred to be biotite based on their shape and luster and feature occasional to common splotches of very pale-green, grainy alteration minerals forming diffuse boundaries with the groundmass. Some dikes contain occasional xenoliths, up to 7 cm in diameter, of mafic material with subequal plagioclase, pyroxene phenocrysts, and rare biotite. Whole-rock geochemistry indicates a monzonitic composition (55.2–55.7 wt% SiO_2, 8.3–8.8% $Na_2O + K_2O$). Aldrich et al. (1986) obtained a K-Ar age of 30.2±2.0 Ma from a dike in section 29, T01N, R06E. Dikes are commonly 45–75 m in width. A relatively thick sill mapped previously (Wilpolt et al., 1946) at a small scale in the south-central part of the map, was not found, but rather many thin (.3–3m(?)) sills of Ti were identified within the Yeso Formation and Glorieta Sandstone. These sills are noted with map unit points in the south-central part of the map. No doubt, additional thin sills are present that could not all be mapped at 1:24,000 scale. On the cross sections, we confine these sills to the Yeso Group, as these intrusions are confined to the Yeso in surface exposures. Chamberlin and others (2002) noted west-to-east flow fabrics in similar dikes to the south (e.g., Jones Camp dike) and interpreted their origin as a dike swarm emanating from the Socorro-Magdalena caldera cluster approximately 55 km southwest of the map area. It is likely that intrusion of these dikes caused deformation within the Yeso Group, although the exact nature of this deformation is unknown.

PALEOZOIC

Psa San Andres Formation (Lower Permian)—Light- to medium- or brownish-gray, thin- to thick-bedded, internally massive to horizontal-planar or ripple-laminated, featureless to vuggy, slightly fossiliferous, and/or bioturbated limestone, dolomitic or gypsiferous limestone, and dolostone. Fossils, (very fine crinoids and shell fragments), bioturbation (bedding-plane-parallel burrows up to 4 cm in diameter), oncoids up to 22-cm-long and 10 cm in diameter, and trace to occasional disseminated chert occur in the upper 10 m of exposure. Limestone may emit a slightly oily odor when struck. Wackestone, floatstone, and rudstone are recognized from the San Andres Formation (Brose et al., 2013). In the lower part, limestone and dolostone are interbedded with sandstone, gypsum and minor shale, mudstone, and sandstone. Two distinct gypsum/sandstone sequences are traceable across nearly all exposed outcrops in the western half of the adjacent Rayo Hills quadrangle and scattered gypsum lenses(?) are present in some outcrops on the Chupadera quadrangle. Gypsum is white to light- or medium-gray, poorly to moderately indurated, massive to vaguely medium- or thick-bedded, and internally massive to laminated. Sandstones are similar to those of the upper Glorieta Sandstone and on this quadrangle seem (based on relatively poor exposures) to form a 10–20 m(?) thick interval approximately 30(?) m above the base of the San Andres Formation. Mudstone is grayish-purple to reddish-brown, very poorly to moderately indurated, non- to strongly calcareous, internally massive, and silty to gypsiferous. The San Andres Formation caps mesas and plateaus with an upper erosional surface (Brose et al., 2013). Exposures of the San Andres Formation are generally poor due to abundant blocky limestone rubble covering the surface, especially in the uplands in the northern and eastern parts of the quadrangle. No doubt, this poor exposure conceals details of the structure in this area. Some relatively steeply dipping beds in this area have been tilted by karst processes. Bedding attitudes that are shallow and down*slope* should be viewed with caution as slabby beds are often displaced by erosion and in areas of poor exposure it is difficult to tell these displaced slabs from intact beds. Unit is 45–50 m thick.

Pg Glorieta Sandstone (Lower Permian)—White to yellowish white or very pale pinkish, poorly to moderately indurated, strongly calcareous, massive or thin- to thick-bedded, tabular to lenticular, internally massive to horizontal-planar laminated to low-angle planar or tangential cross-stratified, moderately to well-sorted, subangular to rounded, quartzose, vfL-fU sandstone. Up to 5–10% feldspar and lithics (dark mafics and/or iron-oxide flakes) may be present in some sandstone bodies. Iron oxide stains and concretions up to 20 cm in diameter are occasionally observed in the upper 37 m of the unit. Rare siltstones are gray to dark greenish gray, slightly calcareous, lenticular, and massive. Sandstones are interbedded with thin siltstones and dark purplish gray, non-calcareous, massive to ripple-laminated mudstones in the lower 2 m of the unit, suggesting a gradational contact with the underlying Joyita Member of the Los Vallos Formation. Forms prominent cliffs and ledges below slopes of the lower San Andres Formation. Wilpolt and others (1946) observed that strata in the middle part of the Glorieta are less resistant to erosion in places, giving the unit a double-ledged character. Landscape degradation during the Pleistocene apparently took advantage of these weaker beds with paleo-drainages beveling pediment surfaces on the Glorieta and depositing associated lag gravels (**Qxo**) in the southwest part of the quadrangle. The Glorieta Sandstone is up to 70 m thick.

Pyv Los Vallos Formation of the Yeso Group (Lower Permian)—Interstratified limestone, dolostone, gypsum, mudstone, siltstone, and sandstone. The Joyita Member forms the upper approximately 12 m of the unit and consists of interstratified siltstone and sandstone with rare mudstone and neither gypsum nor carbonates present. Mudstones and siltstones are light-reddish or reddish-yellow-brown to maroon, poorly indurated, non- to slightly calcareous, massive or thin-bedded, internally massive to low-angle planar laminated (rare), and commonly gypsiferous. Sandstones are yellowish white to reddish brown, poorly to moderately well-indurated, non- to strongly calcareous, massive or thin- to thick-bedded, tabular, internally massive to low-angle planar cross-stratified, moderately well- to well-sorted, and subangular to rounded. Sand grains are vfL–fU and composed of 75–90% quartz, trace to 15% orange feldspar, and 3–7% lithics (dark mafics) with occasional reworked gypsum flakes. The Cañas Member forms an interval approximately 30–55 m thick below the Joyita Member and consists of whitish to grayish, poorly to moderately well-indurated, massive or wavy/thin- to medium-bedded, internally massive to nodular or laminated gypsum that is enterolithic in places. Mudstones and siltstones are as described above in the Joyita Member and commonly underlie covered slopes. A dolostone marker bed near the stratigraphic center of the Cañas Member is medium to dark-gray, moderately indurated, wavy/thin-bedded, internally massive, and gypsiferous. The Torres Member forms the lower 168 m or more of the unit and consists of most of the lithologies described above. Carbonates in the Torres Member are medium to dark or brownish gray, moderately to well-indurated, very thin- to very thick-bedded, tabular to broadly lenticular, internally massive to horizontal-planar or ripple-laminated to brecciated dolomite or, rarely, dolomitic limestone. These are largely non-fossiliferous, slightly to very vuggy, and may emit a fetid or oily scent when struck. Wackestone, grainstone, and rudstone are recognized from the Torres Member, and four to six dolomite intervals may be traced over 100s of meters or more (Lucas et al., 2013). Torres Member gypsum is whitish to dark gray to mottled (red-yellow-gray), very poorly to well-indurated, massive or thin- to medium-bedded, internally massive or nodular to wavy laminated, and occasionally sandy with up to 5–7% grains of subangular to rounded, vfU–mL sand composed of at least 10% lithics (dark mafics) and feldspar. Mudstone and siltstone are light red or brownish red, very poorly to poorly indurated, non- to slightly calcareous, massive or thin-bedded, internally massive to vaguely ripple-laminated, and commonly gypsiferous. Sandstone in the Torres Member is yellowish, weakly calcareous, moderately well-sorted, and dominantly fine-grained with common gypsum flakes. Up to 235 m thick. Outcrop patterns and the highly deformable nature of gypsum indicate local thickness variations which are indicated schematically on the cross sections.

Notes on Cross sections

Structure shown on the cross sections is derived from available bedding attitudes available in limited outcrops. Particularly in the eastern half of the quadrangle exposures are extremely limited. Rather than including schematic structures in this area (and some others) we have chosen to show the broad outlines of structure from available data and the general gentle eastward dip of Permian strata indicated by outcrop patterns. In particular, it is not possible to define the exact nature of deformation within the Yeso Group gypsum and mudstones. Multiple lines of evidence and observation indicate decimeter-scale thickness variations in most units and thicknesses shown on the cross sections are drawn at “average” values except where outcrop patterns indicate specific local variations.

Units shown only on cross sections

PERMIAN AND PENNSYLVANNIAN

Pym Meseta Blanca Formation of the Yeso Group (Lower Permian)—Composed of 80–95% quartz, 2–20% feldspar (plagioclase and minor potassium feldspar), and trace to 3% lithics (dark mafics and mica). Less common are intervals of reddish-brown, moderately indurated, calcite-cemented, thin- to medium-bedded, tabular to lenticular, ripple cross-stratified (asymmetric), very well-sorted, arkosic vfL–vfU sandstone.

Induration and texture impart a metaquartzite-like appearance to some intervals (Lucas et al., 2013). Siltstones containing halite pseudomorphs low in the unit are common elsewhere (Lucas et al., 2013) but not well-exposed in the map area. The lower contact with the Abo Formation is gradational and has not been strictly defined. We have mapped this contact at the approximate level where lighter-red/orangish sandstones of the Meseta Blanca predominate over generally darker-red sandstones and relatively thick, brick-red mudstones of the Abo Formation. In the north-central quadrangle, the unit is commonly mantled by 1–2 m of alluvial material that is not mapped due to its thin and discontinuous nature. Unit is approximately 97 m thick in the west-central part of the quadrangle.

Pa Abo Formation (Lower Permian)—Interbedded dark-reddish-brown to pale-red or dark-purplish-brown to maroon siltstone and very fine- to medium-grained sandstone. Sandstones are moderately indurated, non- to weakly calcareous, thin- to medium-bedded, internally massive or vaguely horizontal-planar to low-angle planar cross-laminated, well- to very well-sorted and arkosic. Contains trace to 2% subangular to subrounded, fL–cL sand grains composed of quartz, feldspar, dark mafics, and/or mica. Unit is moderately well-exposed in the northwestern part of the quadrangle with a maximum thickness of approximately 235 m.

P/IPb Bursum Formation (Upper Pennsylvanian to Lower Permian)—Light-brown sandstone, gray, fossiliferous limestone, and minor intraformational (limestone-clast) conglomerate beds. Approximately 76 m thick (Scott et al., 2005; Allen et al., 2014).

IPa Atrasado Formation (Upper Pennsylvanian)—Cross section only. Gray, thin- to thick-bedded, fossiliferous limestone and intervening intervals dominated by greenish-gray to reddish-brown siliciclastic mudstone, siltstone, and calcareous shale. Cross-stratified to planar-laminated, silty sandstone to pebbly sandstone in thick, lenticular channel fills are common. Unit is 180–240 m thick (Allen et al., 2014).

IPg Gray Mesa Formation (Middle Pennsylvanian)—Cross section only. Medium- to thick-bedded, fossiliferous, cherty limestone and siliciclastic deposits consisting of mudstone, shale, and sandstone. Unit is approximately 120 m thick (Allen et al., 2014).

IPs Sandia Formation (Middle Pennsylvanian)—Cross section only. Greenish-gray, reddish-brown, and yellowish mudstone to silty or sandy shale and calcareous shale; yellowish- and reddish-brown, gray, and greenish-gray planar-laminated and cross-stratified sandstone to pebble conglomerate; and gray to brownish-gray fossiliferous limestone and sandy limestone. Unit is approximately 70 m to more than 100 m thick (Allen et al., 2014).

PROTEROZOIC

Xu Paleoproterozoic rocks, undivided (Paleoproterozoic)—Cross section only. Chiefly the lower member of the Sevilleta Metarhyolite, described by Allen et al. (2014) as medium-gray to black, dense, finely banded metarhyolite with minor white mica, oxides, epidote, and biotite. Speckled with 1.0–2.5 mm white feldspar crystals that have been sericitized