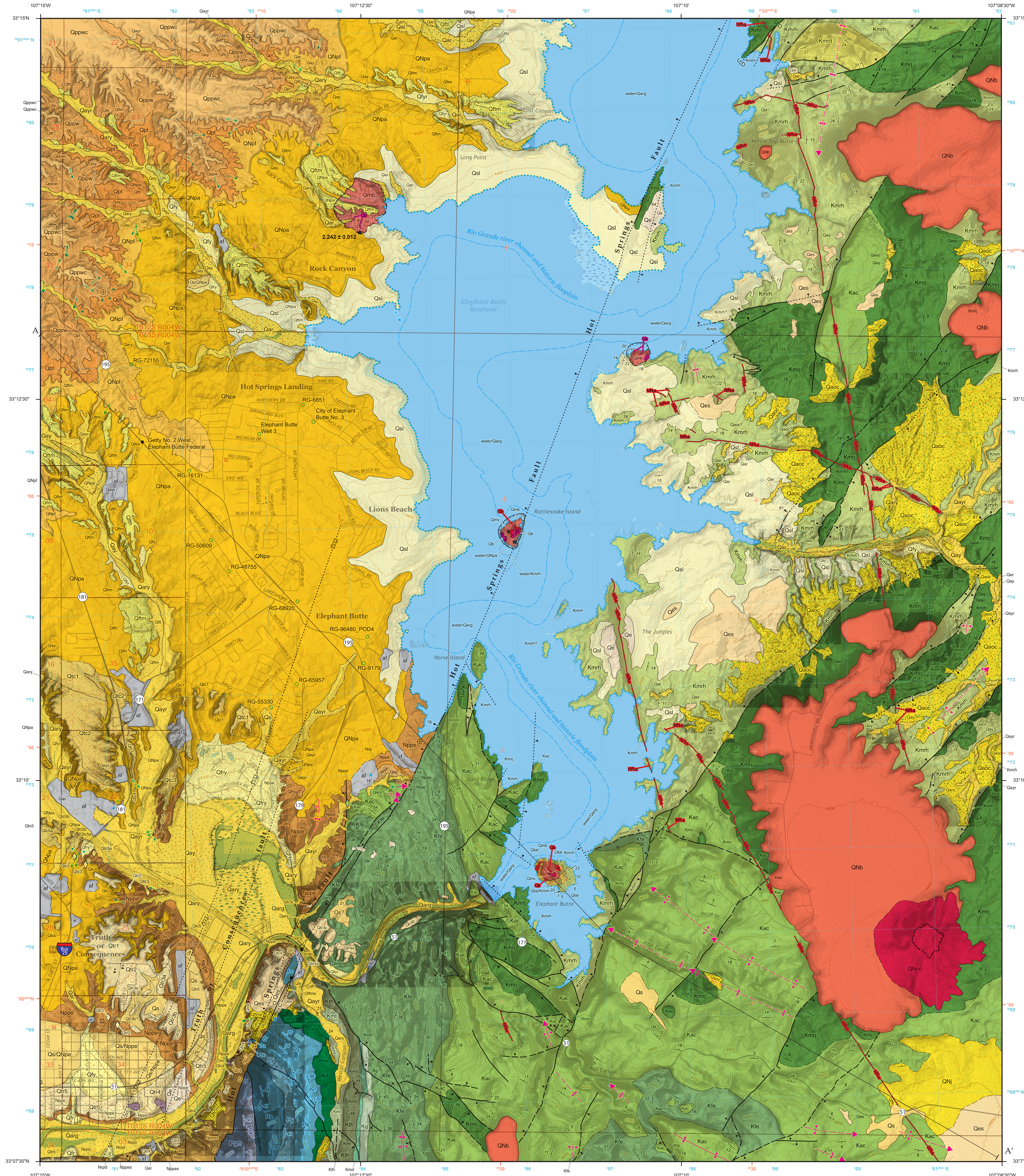


North American Datum of 1983 (NAD83)
Projection and 1,000-meter grid: Universal Transverse Mercator, Zone 13S, shown in blue.
10,000-foot ticks: New Mexico Coordinate System of 1983 (West Zone), shown in red.

Digital base map data.....U.S. Geological Survey, 2019
Contours and hillshade.....IFSAR 4.5 m Digital Terrain Model, 2007

1:24,000

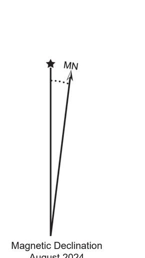
1 0.5 0 1 Mile

1,000 0 1,000 2,000 3,000 4,000 5,000 6,000 7,000 Feet

1 0.5 0 1 Kilometer

Contour Interval 20 Feet
North American Vertical Datum of 1988

Quadrangle Location



Magnetic Declination
August 2024
7° 51' East
At Map Center

New Mexico Bureau of Geology and Mineral Resources Geologic Map 84

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This and other STATEMAP quadrangles are available for free download in both PDF and ArcGIS formats at:

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

April 2026

by
Daniel J. Koning[1], Richard P. Lozinsky[2], and Bruce E. Cox[3]

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Comments to Map Users

A geologic map displays information on the distribution, nature, orientation, and age relationships of rocks and deposits, and the occurrence of structural features. Lithologic and fault contacts are irregular surfaces that form boundaries between different ages or types of units. Data depicted on this geologic map may be based on any of the following: field geologic mapping, a compilation of published and unpublished work, and/or photogeologic interpretation. Locations of contacts are not surveyed but are plotted by relative position on a topographic or orthophotographic base map; therefore, the accuracy of contact locations depends on the scale of mapping and the geologist's interpretation.

Resizing this map would cause the details of the map to be misrepresented and result in erroneous interpretations. Using this product at a scale different than originally intended requires verification of site-specific conditions with detailed surface mapping or subsurface exploration. Topographic and cultural changes may not be shown due to recent development. Cross sections are constructed based on the author's interpretations of geologic mapping and available geophysical and subsurface (drill hole) data.

Cross sections should be used to understand the map area's general geologic framework and not be the sole source of information for locating or designing wells, buildings, roads, or other human-made structures.

Point symbols can be set to rotate around a point of observation using their azimuth values. The point of observation can be one of three possibilities: the trailing end—or tail—opposite the arrowhead or other ornamentation of the symbol; the midpoint—or center of the symbol; or the head of the symbol. See the symbol codes described in the GIS data (FGDC_Symbols nonspatial table) for attributes that describe the azimuth measurement convention and the location of the point of observation for each symbol.

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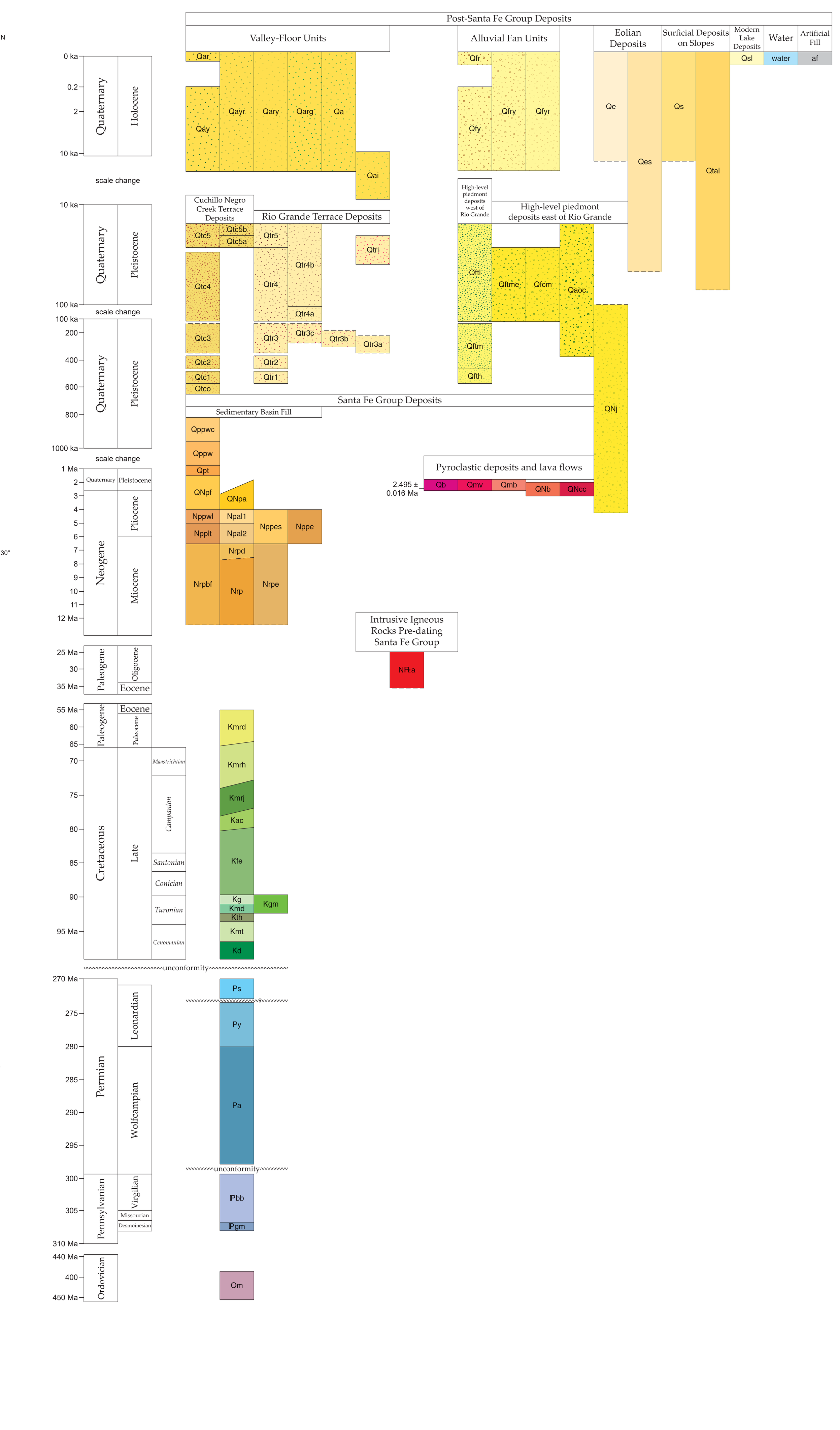
The views and conclusions in these map documents are those of the authors and should not be interpreted as necessarily representing the official policies, expressed or implied, of the State of New Mexico or the U.S. Government.

Correlation of Map Units



Explanation of Map Symbols

Contact—Identity and existence are certain or questionable where queried. Location is accurate where solid, approximate where dashed or concealed where dotted.

Gradational contact—Identity and existence are certain. Location is accurate where solid and approximate where dashed.

Fault (generic; vertical, subvertical, or high-angle; or unknown or unspecified orientation or sense of slip)—Identity and existence are certain where solid. Location is accurate where solid, approximate where dashed, and concealed where dotted.

Normal fault—Identity and existence are certain and questionable where queried. Location is accurate where solid, approximate where dashed, and concealed where dotted. Ball and bar on downthrown block.

Reverse fault—Identity and existence are certain. Location is accurate where solid and concealed where dotted. Rectangles on upthrown block.

Strike-slip fault, left-lateral offset—Identity and existence are certain. Location is concealed. Arrows show relative motion.

Beach

Shoreline cliff—Identity and existence are certain. Location is accurate. Hachures point down cliff.

Indefinite or unsurveyed shoreline, Rio Grande river channel and historic floodplain.

Anticline—Identity and existence are certain. Location is accurate where solid, approximate where dashed, and concealed where dotted. Large arrowhead shows direction of plunge.

Syncline—Identity and existence are certain or questionable where queried. Location is accurate where solid and approximate where dashed. Large arrowhead shows direction of plunge.

Rim of volcanic crater—Identity and existence are certain. Location is accurate where solid and approximate where dashed. Hachures point into crater.

Dike—NRa—Identity and existence are certain. Location is accurate where solid and approximate where dashed. For the full map unit description, refer to the Description of Map Units.

Ring dike—Qb—Identity and existence are certain. Location is accurate where solid. For the full map unit description, refer to Description of Map Units.

Fault showing local up/down offset—U is on the upthrown block, and D is on the downthrown block.

Inclined fault—Showing dip value and direction.

Strike-slip fault (in cross section)—Plus, away from observer; dot, toward observer.

Horizontal bedding.

60 Inclined bedding—Showing strike and dip.

63 Overturned bedding—Showing strike and dip.

37 Approximate orientation of inclined bedding—Showing approximate strike and dip.

29 Subsurface attitude determined from 3-pt-problem methodology; this methodology uses the elevation of a specific stratum in wells (based on well interpretation).

Paleocurrent direction.

Paleocurrent direction determined from imbrication.

Paleocurrent direction determined from cross-beds.

2.447 ± 0.057 Radiometric sample locality—Showing age.

RG-55330 Water well, type unspecified.

Getty No. 2 West Elephant Butte Federal Oil well

A–A' Cross section line and label.

Description of Map Units

POST-SANTA FE GROUP DEPOSITS

Water

water **water (modern)**—Liquid water occupying Elephant Butte Lake. Annual surface-elevation changes are as much as 15 m. Maximum depth during investigation is ≈170 ft (≈50 m). Representative shoreline elevation shown on map is 4380 ft. A highstand of 4441 ft occurred in June 1942 and the lake was near this level (≈full capacity) from the mid-1980s through 2000, allowing development of notable shoreline deposits (Qsl).

Artificial Fill

af **Artificial fill (recent (0–100 years))**—Thick accumulations of sand with minor gravel and silt–clay from construction activities related to terracing, roads, levees or dams. The fill is 1–10 m thick.

Eolian Deposits

Qe **Eolian sand (recent to middle Holocene)**—Windblown sand on the leeward side of topographic highs. Sand is light-brown to light-yellowish-brown (7.5–10YR 6/3–4), mostly massive, well-sorted, fine- to medium-grained, and quartzo-feldspathic. Commonly vegetated, with little or no soil development. The sediment is deflated from the Rio Grande floodplain or Palomas Formation (i.e., QNpa). The deposit is weakly consolidated and 1–5 m thick.

Qes **Eolian sand sheets (late Pleistocene(?) to Holocene)**—Sand and silty sand forming a sheetlike deposit. The sand is pale-brown to light-yellowish-brown (10YR 6/3–4), massive, well-sorted, fine- to medium-grained, and quartzo-feldspathic. Weakly developed soils with weak to moderate ped development and CaCO3 precipitation. Some coppice dunes are present on the surface. Sands are loose to weakly consolidated. The unit is generally less than 4 m thick.

Surficial Deposits on Slopes

Qs **Sheet flood deposits (recent to middle Holocene)**—Sheetflood deposits with a high proportion of quartzo-feldspathic sand input via eolian processes or reworking of QNpa. The sediment is massive and variably overprinted by weakly developed, calcic soils (Stage I carbonate morphology). The sand is very fine- to fine-grained, with minor medium- to very coarse-grained sand and scattered pebbles. The deposits are weakly consolidated and 1–5 m thick.

Qtal **Talus deposits (Holocene to late Pleistocene)**—Accumulation on steep hillslopes of angular to subangular blocks of basalt, primarily boulder-size, that weather from columnar basalt flanking the central vent breccia of maars. The proportion of sandy matrix is variable. It is mapped only on Elephant Butte. The deposit thickness is greater than 3 m.

Valley-Floor Units

Qa **Alluvium, undivided (Holocene to late Pleistocene)**—Sand, gravelly sand, and sandy gravel occupying valley-floor positions. Includes units Qar and Qay (described below), but these could not be differentiated due to anthropogenic disturbance. The deposit is 1–10 m thick.

Qarg **Alluvium of the Rio Grande (recent to late Pleistocene)**—Alluvium underlying the Rio Grande floodplain and in the active channel. Floodplain deposits consist of sand, silt, and clay. The active channel has sandy pebbles and cobbles that are subrounded to rounded and composed of diverse lithologies (including quartzite, sandstone, chert, and volcanic rocks). The sand is fine- to coarse-grained and quartzo-feldspathic. The deposit thickness is 10–20 m.

Qar **Recent alluvium of ephemeral drainages (recent (modern to historic))**—Loose sand and gravel (pebbles, minor cobbles) that form bars and underlie channels in ephemeral drainages. The sand is light-gray to brown to grayish-brown and mostly medium- to very coarse-grained. Bar-and-swale topography, steep-walled channels, sparse vegetation, and lack of topsoil development characterize the surface. The deposit overlies and inset into Qay. The deposit is ≈0.1–2 m thick.

Qay **Younger alluvium (late Holocene to latest Pleistocene)**—Interbedded pebbly sand, sand, and sandy gravel that underlies a smooth geomorphic surface (no bar-and-swale topography) typically 1–3 m above the modern grade. The sand is brown, fine- to very coarse-grained, and weakly consolidated. The topsoil on maximum aggradation surface (mapped separately) has Stage I to II calcium carbonate morphology. The deposit extends under Qar and is 1–30(?) m thick.

Qayr **Younger alluvium and subordinate younger alluvium (recent to latest Pleistocene)**—Unit that combines younger alluvium underlying low-level terraces and small tributary alluvial fans (Qay) with subordinate recent alluvium (Qar), the latter occurring primarily in incised drainages. See detailed descriptions of units Qay and Qar. This deposit is <30 m thick.

Qary **Recent alluvium and subordinate younger alluvium (recent to latest Pleistocene)**—Recent deposits (Qar) underlying recently reworked drainage floors flanked by slightly older sediment (Qay) underlying low-level terraces and small tributary alluvial fans. See detailed descriptions of units Qar and Qay. This deposit is <30 m thick.

Qai **Intermediate alluvium (early Holocene to latest Pleistocene)**—Sandy gravel and pebbly sand; the topsoil exhibits a weak cambic horizon (20–30 cm thick) and a Stage II calcic horizon (>15 cm thick). Sand is fine- to very coarse-grained and pebbles are subrounded, poorly sorted, and volcanic. Tread height is ≈2 m above adjoining valley floor. Qai is differentiated from Qay primarily based on its slightly more developed topsoil. The deposit is 1–3 m thick.

Modern Lake Deposits

Qsl **Lake shoreline deposits (recent)**—Loose sand, gravelly sand, and gravel along the margin of Elephant Butte Lake. Sediment is principally reworked from underlying deposits (Cretaceous strata, Santa Fe Group, and post-Santa Fe Group). There are common small benches (generally less than a few meters wide) created by wave erosion and nearshore currents. The unit is <30 years old (postdates high lake levels of the mid-1990s).

Alluvial Fan Units

Qfr **Recent fan alluvium (0 to 100 years old)**—Small alluvial fans at the mouth of low-order drainages on the southern border of the Rio Grande floodplain near Truth or Consequences. Bar-and-swale topography, steep-walled channels, sparse vegetation, and lack of topsoil development characterize the surface. Probably less than 2 m thick and overlies Qfy.

Qfy **Younger fan alluvium (Holocene to latest Pleistocene)**—Gravelly sediment underlying small alluvial fans. It is composed mainly of sandy gravel and gravelly sand in very thin to medium, tabular to broadly lenticular beds. The sand is brownish and medium- to very coarse-grained. The thin topsoil (tens of centimeters) has a Stage I to I+ carbonate morphology. The deposit has a smooth geomorphic surface with weak desert pavement and is 2–5(?) m thick.

Qfyr **Younger fan alluvium and subordinate recent alluvium (recent to latest Pleistocene)**—Gravelly sediment underlying small alluvial fans at the mouths of low-order drainages. Consists mainly of Qfy with subordinate Qar, the latter being inset below smooth, slightly elevated geomorphic surfaces associated with Qfy (exhibiting weak desert pavement development). See descriptions of Qfy and Qar. This deposit is 2–5(?) m thick.

Qfry **Recent alluvium and subordinate younger fan alluvium (recent to latest Pleistocene)**—Gravelly sediment underlying small alluvial fans at the mouths of small, low-order drainages. Consists mainly of unit Qar with subordinate Qfy deposits. Qar deposits are inset below smooth, slightly elevated geomorphic surfaces associated with Qfy (exhibiting weak desert pavement development). See descriptions of Qar and Qfy. This deposit is 2–5(?) m thick.

High-level piedmont deposits west of Rio Grande

Qftl **Lower unit (late Pleistocene)**—Sandy pebbles, pebbly sand, and fine-grained sand to silty-clayey fine-grained sand with minor pebbles. Finer grained sediment may be pedogenically altered (Stage I carbonate morphology, weak to moderate peds with faint clay films). The geomorphic surface is 4–6 m above the modern grade, its topsoil has Stage I+ to II calcic horizons, and it exhibits weak to moderate clast varnishing. The deposit is several meters thick.

Qftm **Middle unit (middle Pleistocene)**—Sandy gravel and gravelly sand in very thin to medium, lenticular to tabular beds. The sediment underlies a tread 12–13 m above the modern grade and is at same geomorphic level as Qtc2. Gravel is composed of volcanic-dominated pebbles with minor cobbles. Sand is brownish and mainly medium- to very coarse-grained. The topsoil has Stage II to III+ carbonate morphology. The deposit is <5 m thick.

Qfth **Higher unit (middle Pleistocene)**—Gravelly sediment similar to Qftm (as described above) underlying terrace deposits a few meters above the surface of adjoining Qftm. The deposit lies at the same geomorphic level as the Qtc1 terrace deposit and is a few meters thick.

High-level deposits east of Rio Grande

Qfcm **Fan deposit flanking western Caballo Mountains (late to middle Pleistocene)**—Sandy gravel, gravelly sand, and sand in fans at the mouths of ephemeral streams draining the western Caballo Mountains. Typically overlies Qtr4 terrace deposit. Gravel is angular to subangular, poorly sorted, and composed of sandstone, limestone, and siltstone. Clast composition varies depending on the bedrock exposed in a given drainage. The deposit is 2–15 m thick.

Qftme **Fan and terrace deposits associated with Mescal Canyon (late to middle Pleistocene)**—Sandy gravel, gravelly sand, and sand in medium to thick, broadly lenticular to tabular beds. This sediment underlies high-level terraces of Mescal Canyon and its alluvial fan at the north end of the Caballo Mountains; tread heights are 25–32 m above the modern grade. The well-graded pebbles through boulders are composed of sandstone, siltstone, and limestone clasts. The deposit is 2–11 m thick.

Qaoc **Older alluvium in Cutter Sag (late to middle Pleistocene)**—Deposits east of Rio Grande underlying fan-terraces and minor stream terraces that are >3 m above the modern grade. Sediment consists of sand, clayey–silty sand, and gravel. The gravel is subangular and composed of sandstone and siltstone eroded from local Cretaceous units. Sand include quartz, feldspar, and sedimentary and volcanic lithic grains. The deposit is 1–5(?) m thick.

QNj **Surficial deposits in the Jornado del Muerto (Pleistocene)**—Pale-red to buff silt and sand with pebble and cobble interbeds. Clasts are angular to rounded and poorly sorted and include sandstone, quartzite, granite, limestone, and a variety of volcanic types. Capped by weak to strong calcic soils. The unit is generally <6 m thick.

Cuchillo Negro Creek Terrace Deposits

Weakly to moderately stratified and weakly consolidated sand and gravel. Terraces occur at five main levels above the present base level, with one (1) denoting the oldest (highest) level and progressively higher numbers indicating progressively younger (lower) deposits. Similar numbers in Cuchillo Negro Creek vs. Rio Grande terrace labels indicate the same geomorphic level. Weakly consolidated. The older two deposits are thicker than the younger deposits.

Qtc5 **Lower terrace deposit (late Pleistocene)**—Gravelly terrace deposit whose tread lies 9–14 m above younger valley fill alluvium. The deposit includes two subunits (Qtc5b and Qtc5a) whose treads are separated by ≈2 m. Inferred to represent two stratigraphic units, but the associated buttress unconformity has not been confirmed. The deposit is 2–4 m thick.

Qtc5b **Lower subunit of lower terrace deposit (late Pleistocene)**—Sandy pebbles and cobbles underlying 1–2 m of finer sediment. Lower gravel consists of pebbles through coarse cobbles and 10% fine boulders, and composed mainly of dark intermediate volcanic rocks (minor felsics). Upper 1–2 m is mostly very fine- to medium-grained sand. The tread lies 9–11 m above the modern grade. Topsoil carbonate morphology is less than Stage III. The deposit is 3–4 m thick.

Qtc5a **Upper subunit of lower terrace deposit (late Pleistocene)**—Sandy pebbles through cobbles and 1–10% fine boulders; similar to gravelly sediment in unit Qtc5. The terrace tread lies 12–14 m above younger alluvium in Cuchillo Negro Creek and ≈2 m above the tread of Qtc5. The terrace deposit correlates with Qtc3a of Koning et al. (2018). The unit is 2–3 m thick.

Qtc4 **Lower-middle terrace deposit (early-late Pleistocene)**—The deposit is approximately similar to that of Qtc3. Gravel consists of subrounded pebbles with 10–15% cobbles. The tread is ≈22 m above the unincised valley floor of Cuchillo Negro Creek. Both tread and strath lie 4–5 m below the respective tread and strath of Qtc3, and so Qtc4 appears to be a separate cut-and-fill event that postdates Qtc3. The deposit is ≈5 m thick.

Qtc3 **Upper-middle terrace deposit (middle Pleistocene)**—Sandy gravel and subequal gravelly sand in very thin to medium, lenticular to tabular beds. Gravel is clast-supported, subrounded, and a volcanic-dominated suite of pebbles, 10–20% cobbles, and 1–2% boulders. Sand is mostly coarse- to very coarse-grained and reddish-brown. The terrace tread is 27–28 m above the modern grade and has a moderately varnished desert pavement. The deposit is ≈5 m thick.

Qtc2 **Lower-upper terrace deposit (middle Pleistocene)**—Sandy gravel and subordinate gravelly sand in lenticular to tabular beds. Gravel is subrounded, mostly composed of intermediate-composition volcanic rocks, and consists of pebbles, 20–40% cobbles, and 1–2% boulders. The tread lies ≈29–30 m above Qay in Cuchillo Negro Creek. The unit correlates with Qftm of this work and Qtc4 of Koning et al. (2018). The unit is weakly consolidated and 5–10 m thick.

Qtc1 **Upper terrace deposit (middle Pleistocene)**—Sandy gravel in very thin to medium, tabular to lenticular beds. Gravel is mostly composed of intermediate-volcanic rocks and consists of pebbles, 10–40% cobbles, and 0–1% boulders. Sand is reddish-brown and mostly medium- to very coarse-grained. The tread lies ≈9 m above the Qtc2 tread, 48–49 m above Cuchillo Negro Creek. The deposit correlates to Qfth and is 9–10 m thick, tapering northward.

Qtco **Uppermost terrace deposit (middle Pleistocene)**—Sandy gravel that is clast-supported and in poorly defined, tabular to lenticular, very thin to medium beds. The unit caps buttes whose tops are ≈55 m above Cuchillo Negro Creek. Gravel is clast-supported, subrounded and consists of pebbles (mostly very coarse) with 25–30% cobbles. A calcic topsoil with Stage III carbonate morphology is preserved locally. The deposit is 2–3 m thick.

Rio Grande Terrace Deposits

Weakly to moderately stratified sand and gravel with sparse silt lenses. Gravel clasts are up to 30 cm, subrounded to rounded, poorly to moderately sorted, and composed of volcanic rocks, quartz, granite, sandstone, and metamorphic clasts. Terraces occur at five main levels above the present base level, with one (1) denoting the oldest (highest) deposit and increasing numbers progressively indicating progressively younger (lower) deposits. The deposits are weakly consolidated.

Qtr5 **Lower terrace deposit (late Pleistocene)**—Poorly bedded, imbricated sandy gravel consisting of ≈60% pebbles and ≈40% cobbles. Clasts are composed of intermediate volcanic rocks, subordinate felsic volcanic rocks, 5–10% quartzite and quartz, and 5–10% granite. Pale-brown to light-gray sandy matrix. Stage I+ carbonate morphology in topsoil. The tread height is 8–14 m above the modern grade, increasing upstream. The deposit is 1.5–3 m thick.

Qtri **Intermediate terrace deposit between Qtr4 and Qtr5 (late Pleistocene)**—Medium- to thick-bedded and well-imbricated. Contains up to 15% boulders. Light-yellowish-brown (10YR 6/4) sandy matrix. Sandy pebble lenses are common and ≤25 cm thick. The topsoil has a 35 cm thick Stage II+ calcic horizon. The tread height is 19–21 m above the modern grade. The unit may correlate to Qtr4 of Jochems and Koning (2014), whose description is used here. The deposit is ≈3 m thick.

Qtr4 **Upper-middle terrace deposit (early-late Pleistocene)**—Clast-supported, sandy gravel in tabular to lenticular beds and subordinate gravelly sand. Stage II+ to III carbonate morphology in the upper 0.5–1 m. The tread height is 23–26 m and the strath has several meters of relief. The deposit correlates to Qtr5 of Jochems and Koning (2014) and is generally several meters (up to 25 m) thick. It is locally subdivided into two subunits (Qtr4a and Qtr4b).

Qtr4b **Lower subunit of the upper-middle terrace deposit (early-late Pleistocene)**—The tread height is 23–26 m above the modern grade of the Rio Grande.

Qtr4a **Upper subunit of the lower-middle terrace deposit (early-late Pleistocene)**—The tread height is 25–30 m above the modern grade of the Rio Grande.

Qtr3 **Upper-middle terrace deposit (middle Pleistocene)**—Poorly exposed sandy gravel, mainly coarse to very coarse pebbles and fine cobbles. Gravel is rounded to subrounded and composed of volcanic rocks, sedimentary clasts, quartzite, chert, and granite. The tread height is 42–48 m above the modern grade of the Rio Grande. Qtr3 is not mapped stricto sensu but divided into three subunits based on the tread height.

Qtr3c **Lower subunit of the upper-middle terrace deposit (middle Pleistocene)**—The tread height is 42–43 m above the modern grade of the Rio Grande. The deposit is a few meters thick.

Qtr3b **Middle subunit of the upper-middle terrace deposit (middle Pleistocene)**—The tread height is ≈44 m above the modern grade of the Rio Grande. The deposit is a few meters thick.

Qtr3a **Upper subunit of the upper-middle terrace deposit (middle Pleistocene)**—The tread height is 46–48 m above the modern grade of the Rio Grande. The deposit is a few meters thick.

Qtr2 **Lower-upper terrace deposit (middle Pleistocene)**—The deposit is approximately similar to that of Qtr1. The tread height is 49–52 m above the modern grade of the Rio Grande. The deposit is a 1–4 m thick.

Qtr1 **Uppermost terrace deposit (middle Pleistocene)**—Poorly exposed, mesa-capping, sandy gravel. Clasts are mainly rounded to subrounded (minor subangular) and poorly sorted. The gravel consists of pebbles, 5–15% cobbles, and 1–3% fine boulders. The clasts are composed of felsic to intermediate volcanic rocks with 10–20% quartzite, 10–15% chert, and 3% granite. The tread is 58–59 m above the modern grade of the Rio Grande. The deposit is 3–4 m thick.

SANTA FE GROUP DEPOSITS

Pyroclastic Deposits and Lava Flows

Qmb **Maar-related, breccia deposits (earliest Pleistocene)**—Brownish sandstone and slightly silty to clayey sandstone with proportionally variable, scattered basaltic and pumiceous lapilli. Sand has a high proportion of detritus from the Palomas Formation (QNpa) and McRae Group. The strata are in well-defined, relatively thin, tabular to slightly wavy beds and conformably underlain by flat-bedded, base surge sediments. The deposit is greater than tens of meters thick.

Qmv **Maar-related vent facies (earliest Pleistocene)**—Clast-supported, basalt breccia that accumulated inside of volcanic vents. It is an autobreccia probably formed from interaction with groundwater. Basalt clasts are vesicular and matrix between clasts is a chilled, fine-grained magma that is locally flow-foliated. This unit occurs as vertical bodies that likely extend downwards at least several meters.

Qb **Maar-related, basaltic lavas (earliest Pleistocene)**—Very dark-gray to black, basaltic rocks extruded from structurally controlled vents into the ancestral Rio Grande valley. Columnar basalt, pillows, and hyaloclastite are common at each volcanic center. Xenoliths include Cretaceous sediments, Precambrian metamorphics, and mantle-derived olivine xenoliths. Basalt ring dikes occur at Elephant Butte and Rattlesnake Island.

QNcc **Cinder cone deposits (earliest Pleistocene to latest Pliocene)**—Slightly reddish basaltic lapilli and scoria, inferred to have steeply inclined bedding. Spatter and agglutinate is abundant near the crater rim and within the crater. Deposit thickness of ≈30 m.

QNb **Basalt flows (earliest Pleistocene to latest Pliocene)**—Mesa-capping, basaltic lavas. This extrusive rock contains very dark-gray to black, aphanitic groundmass with sparse phenocrysts up to 2 mm long composed of olivine and plagioclase. Mostly ʻaʻā lava with minor pāhoehoe. Columnar and platy jointing is well expressed. The flows are 3–23 m thick.

Sedimentary Basin Fill

Palomas Formation

Upper Palomas Formation

Qppwc **Western piedmont deposits, upper coarse unit (early Pleistocene)**—Sandy gravel in thin to medium, lenticular to tabular beds. Gravel is mainly clast-supported and pebbles with 10–20% cobbles, and is composed of felsic to intermediate volcanics. To the north, the upper 2–6 m of deposit has abundant Vicks Peak Tuff clasts. Sand is medium- to very coarse-grained and contains 1–10% clay chips and coatings. The unit is typically 2–6 m thick, and up to 15 m thick.

Qppw **Western piedmont deposits (early Pleistocene)**—Fine-grained strata (very fine- to fine-grained sand, clayey-silty fine-grained sand, silt, and clay) intertonguing with 15–30% gravelly bodies. Fine strata are in 0.1–2.0 m thick, tabular beds and internally massive to vaguely horizontally laminated; slightly redder (commonly 5YR) compared to Qpt. Gravels are subrounded and composed of felsic to intermediate volcanic rocks. The deposit is ≈20 m thick.

Middle Palomas Formation

Qpt **Upper transitional zone (early Pleistocene)**—Brownish (7.5YR) transition between Qppw and QNpf. Strata are mainly composed of very fine- to fine-grained sand, silt, and clay in medium to thick, tabular beds with 1–5% authigenic carbonates. Contains 10–35% gravelly bodies that are relatively tabular and mostly 0.5–2 m thick. Gravel is pebble-rich and volcanic; the matrix is a clay-free, fine- to very coarse-grained sand. Deposit is ≈3–10 m thick.

QNpf **Fine-grained strata (early Pleistocene to late Pliocene)**—Fine-grained, light-brown (7.5YR), tabular-bedded strata with <5% gravelly bodies. Beds are medium to thick and internally massive. Sediment is silt, very fine- to fine-grained sand, silt-clay, and subordinate clay to clayey fine-grained sand. Paleosols (1–10%) exhibit Bt over Bk horizons. Local shallow-groundwater authigenic carbonates, including nodules and tabular bodies. The deposit is 10–90 m thick.

QNpa **Sandy axial-fluvial deposits (early Pleistocene to early Pliocene)**—Light-colored sand and 1–15% pebbly sand. Pebble composition is mostly felsic volcanic rocks and intra-formational clasts with 5–20% granite, 3–30% greenish sandstone, 1–5% chert, 1–2% reddish Permian clasts, and 1–20% intermediate volcanic rocks; pebbles in uppermost strata have 15–20% chert and 1–5% quartzite. Sand is medium- to coarse-grained and quartzo-feldspathic. The deposit is ≈100 m thick.

Lower Palomas Formation

Nppwl **Western piedmont deposits, lower unit [cross section only] (early Pliocene)**—Sandy gravel interbedded with subequal(?) fine-grained sediment. Sandy gravel is in tabular to lenticular beds; <10% cross bedding. Fine-grained sediment is in medium to thick, tabular, massive beds; composed of light-brown to pink, silt to fine-grained sand with minor (trace to 25%) scattered medium to very coarse sand and trace-20% pebbles. 10-50% strongly cemented; sparse paleosols. Deposit is ≈40 m thick.

Npplt **Transition zone at base of western piedmont deposits [cross section only] (latest Miocene to earliest Pliocene)**—Light-reddish-brown (5YR 6/3–4) strata in medium to thick, tabular beds, and composed of: 1) siltstone and very fine- to fine-grained sandstone (about 50-70%); and 2) fine- to medium-grained sandstone (≈20%), and 3) coarse channel-fills (increasing up-section from 10 to 25%) composed of pebbly sand or sandy pebbles. Deposit is ≈30 m thick.

Npal1 **Coarse axial-fluvial facies of the lower Palomas Formation, upper unit [cross section only] (earliest Pliocene)**—Whitish, coarse- to very coarse-grained sand with abundant conglomeratic tongues. Very coarse-grained sand and pebbles are subangular to subrounded and composed of felsic volcanic rocks, with sedimentary clasts increasing to the south. Coarse-grained sand is composed of quartz, 33–50% volcanic grains, 5–20% probable potassium feldspar, 1–5% granite, and 1% chert. Deposit is 45–50 m thick in the Getty West Elephant Butte No. 2.

Npal2 **Coarse axial-fluvial facies of the lower Palomas Formation, lower unit [cross section only] (earliest Pliocene to latest Miocene)**—Upward coarsening, slightly reddish white sand with pebbles. Sand is mostly coarse to very coarse and has 10–15% very fine to fine pebbles composed of felsic volcanic rocks, but sedimentary clasts become more common to the south. The sand is subrounded to subangular and composed of fine-grained felsic volcanics, 1–5% Mesozoic sandstone, and 1–3% quartz. The unit is 30 m thick in Getty West Elephant Butte No. 2.

Nppe **Eastern piedmont deposits (early Pliocene to latest Miocene)**—Yellowish- to slightly greenish-brown, sandy conglomerate and conglomeratic sandstone. These strata are in very thin to medium-thick, tabular to lenticular beds, with ≈5–10% cross-stratification. Clasts are composed of 50% greenish sandstone, 10–45% light-gray limestone, and 1–5% reworked Permian strata. Minor pebbly, very fine- to fine-grained sand tongues. The deposit is up to 180 m thick.

Nppes **Southern fan deposits of the eastern piedmont deposit (latest Miocene to early Pliocene)**—Sandy conglomerate and gravelly sandstone in thin to thick, relatively tabular beds that are internally massive. Gravel is mostly subangular, poorly sorted, and composed of reddish siltstone–very fine-grained sandstone (to north) and carbonate clasts (to south). Interfingers northward with Nppe. The sand is silty-clayey and very fine- to very coarse-grained. The deposit is well cemented and >45 m thick.

Rincon Valley Formation

Nrpbf **Distal piedmont and basin floor deposits [cross section only] (late Miocene)**—Clayey very fine- to fine-grained sand that likely becomes more conglomeratic to the west. In its basal portion, where penetrated by the Getty West Elephant Butte No. 2 well, the sand is mostly composed of rounded quartz grains and is subrounded to rounded and well sorted. The deposit is ≈107 m thick where penetrated by the well, but inferred to be ≈300 m to west.

Nrpd **Playa-lacustrine and deltaic deposits (late Miocene)**—Interbedded clay, silt, and very fine- to fine-grained sand. Reddish-brown to brown clay and yellowish-brown silt are in very thin to medium, tabular beds and massive to horizontally laminated. Quartz-rich, light-colored sand tongues are very fine- to fine-grained and increase upsection, exhibiting intricate inter-stratification with clayey sand and silt micro-laminae. The deposit is >15 m thick.

Nrp **Playa-lacustrine deposits (late Miocene)**—Reddish-brown to reddish clay in the Getty West Elephant Butte No. 2 well, where it has an apparent thickness of 217 m. Where exposed to near the Hot Springs fault, this clay occurs in a ≈7 m-thick tongue within eastern piedmont sediment and locally exhibits mm-scale, sand-filled fractures (desiccation cracks), slickenside faces and CaCO3 nodules.

Nrpe **Eastern piedmont deposits (late Miocene)**—Medium to thick, tabular to lenticular beds of sandstone and conglomeratic sandstone. Sandstone is fine- to medium-grained, with 15% coarse- to very coarse-grained sand composed of volcanic grains. Gravel is composed of plagioclase-phyric intermediate volcanic rock with 5% green siltstone to fine-grained sandstone. The gravel matrix is a light-yellowish-brown, muddy, very fine- to fine-grained sand. The unit is ≈350 m thick.

INTRUSIVE IGNEOUS ROCKS PRE-DATING SANTA FE GROUP

NRa **Andesite dikes (Miocene to Eocene)**—Gray, fine- to medium-grained, porphyritic andesite that weathers brown or dark-gray. Phenocrysts are mainly plagioclase. Dikes are up to 8 m thick and have steep dips.

PALEOGENE TO CRETACEOUS STRATA

McRae Group

Note that we follow Lucas et al. (2019) in raising the McRae to Group status and within the McRae use the following as formation-rank terms: Double Canyon, Hall Lake, and José Creek.

Kmrd **Double Canyon Formation (McRae Group) (latest Cretaceous to earliest Paleocene)**—Light-colored succession of interbedded mudstone, siltstone, sandstone, and conglomerate. Fine-grained strata lack red colors and contain thin sandstone beds. Pebbly strata are commonly cross-stratified and clasts are composed of granitic and volcanic rocks, chert, and mudstone rip-ups. Sand is fine- to coarse-grained. Silicified logs and stumps are locally present. The deposit is >130 m thick.

Kmrh **Hall Lake Formation (McRae Group) (Maastrichtian to late Campanian(?))**—Reddish-brown mudstones with subordinate, lenticular sandstone tongues and sparse conglomeratic beds. Mudstones exhibit blocky structure and contain calcic paleosols. Sandstones are massive, horizontally laminated, or cross-bedded. Sand is fine- to very coarse-grained. Volcanic gravel clasts dominate, but granite, chert, quartzite, and quartz increase upsection. The deposit is ≈700 m thick.

Kmrj **Jose Creek Formation (McRae Group) (late Campanian)**—Grayish to brown sandstones with 35–50% olive to brownish-gray siltstones to mudstones; the latter contain interbeds of very fine- to fine-grained sandstone. Mudrocks are massive and have paleosols. Sandstones exhibit cross-bedding and horizontal laminations. Conglomeratic bodies increase and coarsen southwards and dominated by porphyritic andesite clasts. Contains petrified wood. The unit is 120–200 m thick.

CRETACEOUS STRATA

Terrestrial strata between McRae Group and Gallup Sandstone

Kac **Ash Canyon Formation (Campanian)**—Ledge-forming, tan to brown, medium- to coarse-grained sandstone and pebbly conglomerate interbedded with subordinate olive-gray mudstone. Pebbles are subrounded and composed mainly of chert and quartz. Petrified wood is common. We follow Lucas et al. (2019) in elevating this unit to formation-rank status. The deposit is ≈360 m thick.

Kfe **Flying Eagle Canyon Formation (Campanian to Coniacian)**—Ledge-forming, fine- to medium-grained, gray to brown sandstones interbedded with siltstones and mudstones, sensu Lucas et al. (2019). The sandstones are sheetlike, lenticular or ribbonlike and 2–8 m thick. The mudstones are gray to olive gray and interbedded with thin, very fine- to fine-grained sandstones that exhibit horizontal laminations, ripple marks, or are massive. Strata are 300–340 m thick.

Marine, Nearshore, and Coastal-margin Strata

Kgm **Undivided Gallup Sandstone and D-Cross Tongue of the Mancos Shale [cross section only] (late Turonian)**—Sandstone and shale lying above the Tres Hermanos Formation, as interpreted in the Getty West Elephant Butte No. 2 well. These strata correlate to the D-Cross Tongue of the Mancos Shale and the overlying Gallup Sandstone. The map unit may include lowest strata of Flying Eagle Canyon Formation (Kfe). Strata are 90–110 m thick.

Kg **Gallup Sandstone (late Turonian)**—Light-colored, tabular-bedded sandstones that are mainly very fine- to fine-grained (minor fine- to medium-grained beds). In the lower part of the unit, fine-grained sandstones are interbedded with gray, silty shales. Sandstones are horizontally laminated, trough cross-bedded, ripple-laminated, bioturbated, or massive. Sparse bivalves, plant debris, and shark teeth are present. The unit is 40 m thick.

Kmd **D-Cross Tongue of Mancos Shale (late Turonian)**—Shale in the lower 30 m transitioning upward to interbedded silty shale, siltstone, and sandstone. Shale is mostly grayish and, in its lower part, calcareous. Sandstone intervals are up to 8 m thick and trough cross-bedded (most common), horizontally laminated, planar cross-bedded, or massive. There are distinct limestone concretions. The unit is 50 m thick and its top contact is gradational.

Kth **Tres Hermanos Formation (middle Turonian)**—A ≈75 m thick succession divided into a basal sandstone (Atarque Member), a medial carbonaceous mudstone-dominated interval (Carthage Member), and an upper sandstone (Fite Ranch Member). The Atarque Member is 13–14 m of sandstone and minor shale; sandstone is trough cross-bedded, horizontally laminated, or massive. The Carthage Member is composed of non-fissile mudstone and siltstone and is 50 m thick.

Kmt **Tokay Tongue of Mancos Shale (early Turonian to late Cenomanian)**—Dark-gray, calcareous shale and siltstone with some sandstone. Intercalated limestone is common ≈60 m above the base of the unit and assigned to the Bridge Creek Limestone. Silty shale and siltstone increase upsection above this stratum. Sandstones in the upper part are commonly hummocky cross-stratified or horizontally laminated. Contains numerous bentonite beds. Strata are ≈150–160 m thick.

Kd **Dakota Sandstone (middle Cenomanian)**—Medium-bedded, white to buff, medium- to coarse-grained sandstone with a 15–20 m thick medial, grayish, sandy shale. Sandstone is mostly medium-grained, subrounded, and a quartz arenite with minor chert grains; variably pebbly and cross-stratified to horizontal laminated. The upper sandstone unit is ≈5 m thick and contains burrows of *Ophiomorpha* and *Thalassinoides*. The unit is 30–40 m thick.

PALEOZOIC STRATA

Permian Strata

Ps **San Andres Formation (early Guadalupian to late Leonardian)**—About 30 m of thin- to medium-bedded limestone forming a hogback. This is overlain by ≈200 m of thin- to medium-bedded, fossiliferous, chert-poor limestone and dolomite interbedded with yellow to red, very fine- to medium-grained sandstone, along with local beds of gypsum. The upper contact is an unconformity. Correlates to the upper Yeso Formation of Seager (2015). Strata are ≈230 m thick.

Py **Yeso Group (Leonardian)**—The Yeso Group includes the Arroyo de Alamillo and Los Vallos Formations (sensu Lucas and Krainer, 2012). The Arroyo de Alamillo consists mainly of orange (minor white to light-green), very fine- to fine-grained, well-sorted sandstone with local ripple marks, salt casts, and burrows. The Los Vallos Formation contains interbedded dolomite, limestone, siltstone to very fine-grained sandstone, and gypsum. The unit is 180–210 m thick.

Pa **Abo Formation (middle to late Wolfcampian)**—The unit consists of brick-red, reddish-brown, or purplish mudstone (blocky-textured), shale, siltstone, and fine-grained sandstone. Siltstones and very fine-grained sandstones are commonly in thin (<1 m) beds with ripple marks or horizontal laminae. Very fine- to fine-grained sandstones occupy paleochannels or form sheetlike bodies. Sparse limestones and thin (<0.5 m) beds of intraformational conglomerate. The unit is ≈150 m thick.

Pennsylvanian Strata

IPbb **Bar B Formation (late Desmoinesian to late Virgilian)**—The unit consists of interbedded limestone, dolomite, shale, and (in upper 50 m) conglomerate. Shale is more abundant than in the Gray Mesa Formation, is gray to purplish-gray, and forms slopes. Limestone is gray, tan, and orange and forms ledges 1–5 m thick; some beds locally have abundant marine fossils, burrow traces, and chert. The upper contact is at the top of the highest limestone bed. The unit is 119 m thick.

IPgm **Gray Mesa Formation (Desmoinesian)**—Usage of Gray Mesa follows Lucas et al. (2012a). It consists of ledge-forming limestone (1–15 m thick beds) separated by thinner covered slopes. Limestones are commonly gray, bioturbated, fossiliferous packstones. Dark-gray or black chert is very common. Grainstones are less common. Covered intervals correspond to thin-bedded limestones and reddish, green, or gray shale. The unit is 190 m thick.

Ordovician Strata

Om **Montoya Formation (Late Ordovician)**—Dark-brown, medium- to coarse-grained, basal sandstone overlain by thinly bedded to massive, gray dolomite with scattered brown chert nodules and lenses. The unit is 110 m thick.

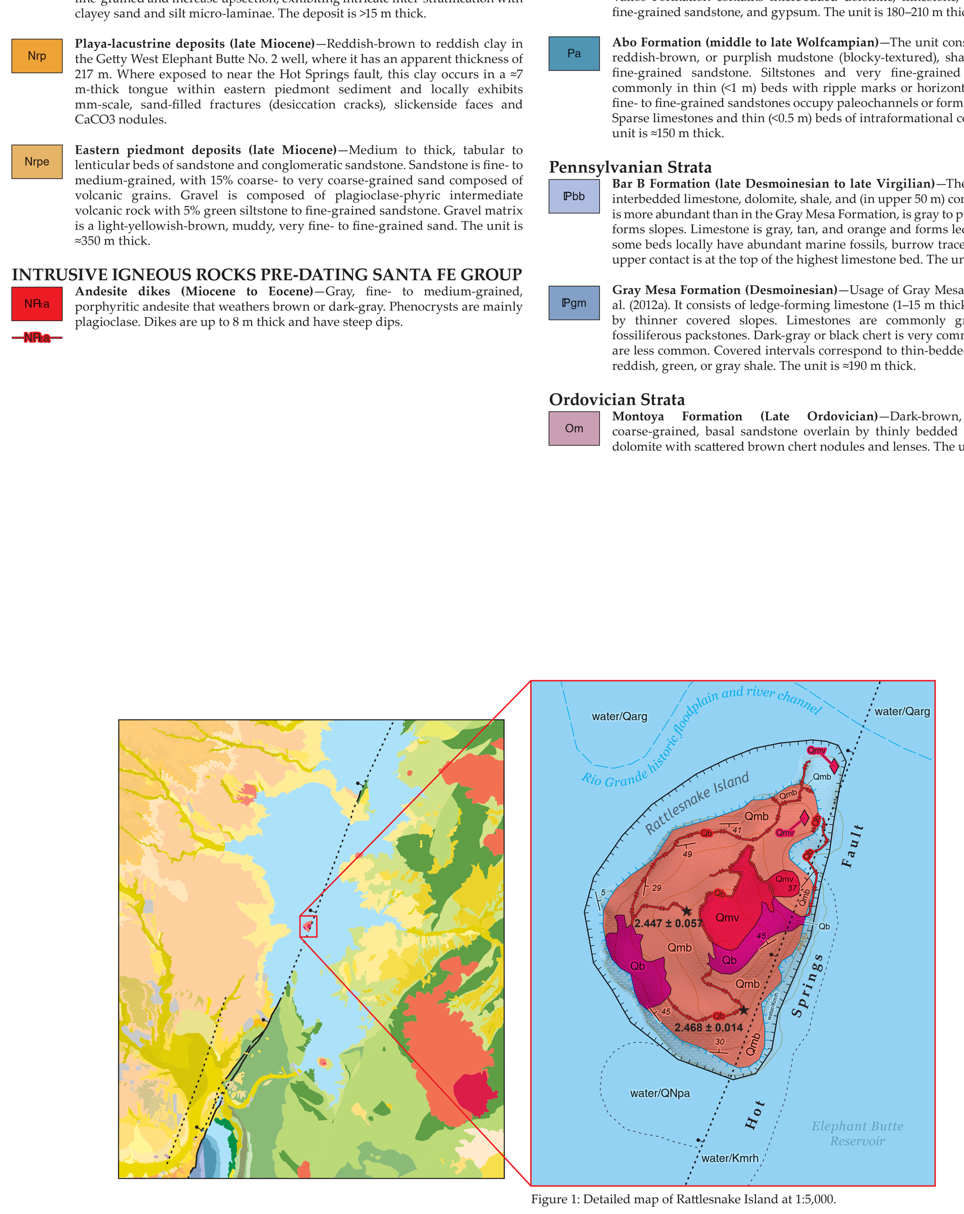
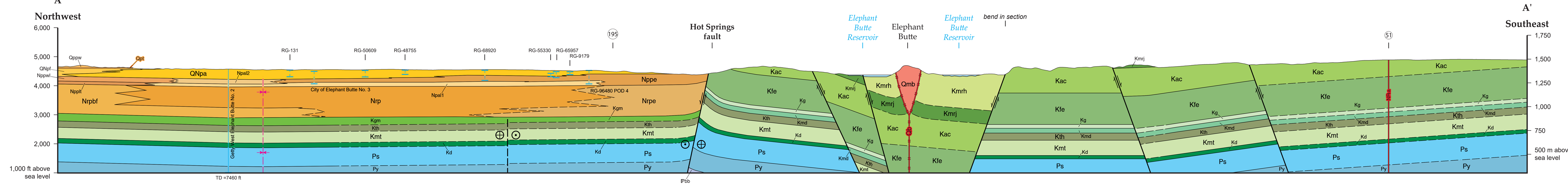


Figure 1: Detailed map of Rattlesnake Island at 1:5,000.

Geologic Cross Section A–A'

(no vertical exaggeration)