

**Geologic Map of the Chaco Canyon 30-Minute x 60-Minute Quadrangle,  
Rio Arriba, San Juan, and Sandoval Counties, New Mexico**

**By**

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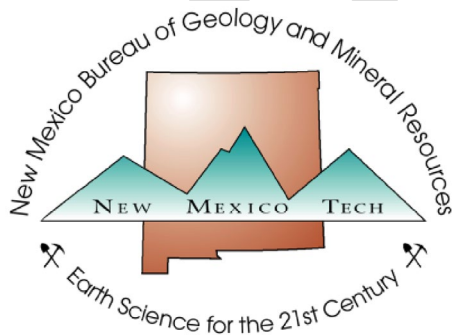
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*Open-File Digital Geologic Map OF-GM 292***

**Scale 1:100,000**

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View looking southeast across *Artemesia tridentata*-dominated Quaternary eolian deposits (map unit Qes) towards Huérfano Mountain (Dził Ná'oodilii), approximately 11 km distant. Huérfano Mountain comprises the Paleocene-aged Nacimiento Formation (map unit P<sub>En</sub>) in its lower half, and the Eocene-aged Cuba Mesa Member of the San Jose Formation (map unit P<sub>Esjc</sub>) in its upper half. Though uplifted approximately 2 km since their deposition, these sedimentary units exhibit gentle dips of 2°, indicating minimal compressive deformation. The fine sand-dominated stabilized eolian deposits in the foreground typify much of the western portion of this quadrangle.

Photograph taken at the northern boundary of Chaco Canyon 30'x60' quadrangle at approximately 36.50°N, 107.91°W (Section 09, Township 26N, Range 10W).

## EXECUTIVE SUMMARY

Located 30 to 135 km southeast of Farmington, New Mexico, the Chaco Canyon 30'x60' Quadrangle occupies key locations for understanding the geologic history of the San Juan Basin. We refine previous mapping which produced a robust geologic map of the bedrock geology of coal-bearing units of the area (Mytton, 1983, and references therein) and focus efforts on (1) accurately mapping surficial units that occupy valley bottoms and plains within the map area and (2) defining and refining member-level designations of the quadrangle's upper two Paleogene units, the Nacimiento Formation and the San Jose formation. The Chaco Canyon 30'x60' Quadrangle includes parts of the Chaco Slope and Central Basin Platform portions of the San Juan Basin, a broken-foreland structural basin formed during the Laramide orogeny. The majority of the quadrangle is located on the southwest limb of the San Juan Basin's synclinal axis, leading to northeast dip directions in bedrock units throughout most of the map area. Late Cretaceous through Eocene siliciclastic sedimentary rocks comprise most of the bedrock in the map area. Four Oligocene trachybasalt dikes cover <1 km<sup>2</sup> in the northeastern map area. Loosely consolidated to unconsolidated Pleistocene deposits exist as sand sheets, stabilized eolian dunes, pediment-capping gravelly sands and sands, and valley-floor alluvium throughout the quadrangle. Holocene deposits include sheetwash alluvium and valley-floor alluvium throughout the map area and minor eolian dunes in the valleys of Escavada Wash and its tributaries.

The depositional history of the Chaco Canyon 30'x60' Quadrangle contains three broadly defined episodes: first, Late Cretaceous deposition of marine, shoreface, and estuarine siliciclastic sediments during the ultimate transgression-regression cycle of the Cretaceous Interior Seaway produced the Menefee Formation, Cliff House Sandstone, Lewis Shale, and Pictured Cliffs Sandstone, all of which are preserved in outcrop in the southwesternmost map area. Second, Late Cretaceous through Eocene deposition of fluvial siliciclastic sediments concurrent with the Laramide Orogeny produced the Fruitland Formation, Kirtland Formation, Ojo Alamo Sandstone, Nacimiento Formation, and San Jose Formation, preserved in broad outcrops across the northern, central, and eastern portions of the map. Finally, Pleistocene and Holocene deposition of eolian sands produced the broad sand sheets which predominate in the western map area, while sheetwash and alluvial processes led to the gravels and sands that comprise the unconsolidated deposits found throughout the quadrangle's valleys and canyon floors. Anthropocene processes in the quadrangle are dominated by incision of

The Continental Divide bisects the quadrangle: 4% of the map area is drained by the Rio Puerco, a tributary to the Rio Grande; 96% of the map area is drained by tributaries to the San Juan River, itself a tributary to the Colorado River.

## INTRODUCTION

This report accompanies the Geologic Map of the Chaco Canyon 30-minute x 60-minute Quadrangle, Rio Arriba, San Juan, and Sandoval Counties, New Mexico (NMBGMR OF-GM 292). Its purpose is to discuss the geologic setting of the map area, to explain the geologic history of the map area, and to identify and explain significant stratigraphic and geomorphic relationships discovered during the course of mapping. This report presents several fundamental geological aspects of the quadrangle, including the geographic and physiographic settings, climate, and previous geological work. Then it describes the geologic map units and their depositional settings by age in greater detail than is possible on the map sheet. The structural geology of the area is discussed. Figures and associated captions are presented at the end of this document.

## MOTIVATION

Superb exposures of Mesozoic and Cenozoic strata along and west of the Continental Divide and of Quaternary surficial deposits in canyons, arroyos, and stabilized dunefields throughout the area allow for the opportunity to reconstruct the geologic history for this area of the Colorado Plateau in New Mexico.

## DESCRIPTIONS OF MAP UNITS

### Quaternary

#### **Anthropogenic units**

**af Artificial fill and disturbed ground** (ca. 0.1 ka to present-day) - Accumulations of clay, silt, and sand from construction of dams in southern map area. Deposits of clay, silt, sand, and pebbles on upstream sides of dams. Disturbed ground and spoils piles from surface lignite mine in the Fruitland Formation in the southern map area. 1-8 m thick.

#### **Valley-floor units**

**Qar Modern to historic alluvium (ca. 0.2 ka to present-day)** - Stream-deposited clay, silt, sand, and gravel in valley floors. Mineral composition and grain rounding is influenced by and largely inherited from the bedrock composition of the drainage basin in which the deposit is found; deposits typically have the composition of feldspathic arenite or feldspathic wacke. A typical deposit consists of light yellowish brown, light brown, or light gray poorly consolidated to unconsolidated sand and silty sand with

subordinate pebbly silty sand, sandy silt, and silty clay. Bedforms include crossbedding, ripple crossbedding, ripple laminations, graded bedding, scour-and-fill structures, and plane bedding. Bed thickness varies from laminated (<1 cm) to thick (>30 cm). Reddish brown to light reddish brown paleosols up to 1.3 m thick with columnar peds and root traces are common. Loosely to moderately consolidated; forms vertical faces up to 2 m tall. Distinct contact with underlying units. Gradational contact with surrounding fans and colluvial deposits. Where present in same valley as older alluvium (unit Qay on this map), this unit is inset by 3 - 6 m in a lower geomorphic position. Radiocarbon dates from this unit in Arroyo Chijuilla and Canyon Largo are 2-8 ka. Potsherds from the Pueblo II Period (Pecos Classification; ca. 1 ka) have been found as deep as 3 m below ground level in these deposits. Surface of this unit typically contains grama grass (*Bouteloua sp.*), galleta grass (*Hilaria jamesii*), saltbrush (*Artriplex canescens*), and saltcedar (*Tamarix ramosissima*), with subordinate big sagebrush (*Artemisia tridentata*). Unit includes debris fans, canyon-mouth fans, colluvium, and minor sheetwash alluvium. Since the 19th Century, this deposit has been incised up to 7 m. <8 m thick.

#### Short description:

Light yellowish brown to light brown sand, silt, clay, and gravel in valley floors. Loosely to moderately consolidated. Laminated to thick beds deposited in streams and arroyos with subordinate deposition on floodplains. Distinct contact with underlying units. Gradational contact with surrounding fans and colluvial deposits. Often inset in lower geomorphic position than older alluvium.

**Qea Modern to historic eolian deposits derived from sand-bed arroyos and within valley floors (0.2 ka - present-day)** - Well-sorted coarse silt to medium sand, light yellowish brown to white, unconsolidated. Laminated to thin crossbeds with subordinate horizontal plane beds. Ripples and sand avalanches seen on active deposits. Grains are subrounded to subangular and comprise quartz, feldspars, and lithic fragments. Little to no frosting observed. Deposits have the composition of feldspathic arenite. Includes coppice dunes up to 3 m tall. Frequently reworked by lateral migration of active stream channels in Betonnie Tsosie Wash, Kimbeto Wash, and Escavada Wash. Includes minor amounts of alluvium and sheetwash around active and stabilized dunes. In Kimbeto Wash, Betonnie Tsosie Wash, and Escavada Wash, these deposits are substantial enough to disrupt surface drainage and cause the formation of yazoo channels parallel to the main active channel in those valleys. Includes deflation blowouts up to 300 m in length. Where dunes block surface drainages and in deflation blowouts, includes subordinate palustrine deposits consisting of horizontal plane bedded clay and silt. Dune forms are parabolic and longitudinal, with an average sediment transport azimuth of 069° as determined by

dune morphologies in aerial imagery. Active dunes are 1.5 - 7 m tall. Stabilized dunes typically contain sacaton grass (*Sporobolus sp.*), grama grass (*Bouteloua sp.*), and saltbrush (*Artiplex canescens*). Differentiated from map unit Qes (Eolian sand sheets) by its lower geomorphic position, active dunes, less mature lithologic composition, lighter color, and less-developed soil. <8 m thick.

Short description:

Light yellowish brown to white coarse silt to medium sand making up eolian dunes in valleys. Unconsolidated. Laminated to thin crossbeds and plane beds. Ripples and sand avalanches on active parabolic dunes. Derived from and deposited adjacent to sand-bed arroyos. Includes subordinate alluvium, sheetwash, and palustrine deposits.

**Qao Older alluvium (Pleistocene(?) to early Holocene)** - Clay, silt, sand, and gravel underlying terraces >3 m above active and historic alluvial deposits. Sediment is in laminated to thick tabular to lenticular beds with crossbeds, ripple crossbeds, graded bedding, scour-and-fill structures, and horizontal plane beds. Mineral composition and grain rounding is influenced by and largely inherited from the bedrock composition of the drainage basin in which the deposit is found; deposits typically have the composition of feldspathic wacke with subordinate feldspathic arenite. A typical deposit consists of brown, light brown, or yellowish brown, loosely to moderately consolidated silty sand with subordinate silty clay, pebbly silty sand, and sandy silt, with trace sandy gravel. Reddish brown to light reddish brown paleosols with columnar peds and root traces are common; stage I calcic horizons are present in some of these paleosols. Forms vertical faces up to 4 m tall. Distinct contact with underlying units. Gradational contact with surrounding fans and colluvial deposits. Surface of this unit typically contains the same plant species as map unit Qar, with additional juniper (*Juniperus sp.*), piñon (*Pinus edulis*), big sagebrush (*Artemisia tridentata*), cane cholla (*Cylindropuntia imbricata*), and prickly pear (*Opuntia sp.*). Unit includes debris fans, canyon-mouth fans, colluvium, and minor sheetwash alluvium. Since the 19th Century, this deposit has been incised up to 13 m. Differentiated from map unit Qar (modern to historic alluvium) by higher geomorphic position, slightly finer-grained texture, slightly darker color in outcrop, and different plant community. <14 m thick.

Short description:

Brown to yellowish brown clay, silt, sand, and gravel in terraces >3 m above active and historic alluvial deposits. Loosely to moderately consolidated. Laminated to thick beds deposited in streams and arroyos with subordinate deposition on floodplains. Distinct contact with underlying units. Gradational contact with surrounding fans and colluvial deposits. <14 m thick.

## Surficial units not confined to valley floors

**Qsw Sheetwash alluvium (Pleistocene to Holocene)** - Loose to weakly consolidated clay, silt, sand, and gravel. Includes colluvium on slopes. At foot of slopes, may include mudflows, poorly sorted debris flow deposits, and associated debris flow levees. At the base of slopes, this unit includes locally-derived clay, silt, sand, and mud whose composition and texture is controlled by composition of upslope bedrock outcrops. In these settings, the unit often includes coalesced alluvial sediment aprons that grade upslope into colluvial aprons. Locally contains lag gravel; where this unit is found immediately downslope of outcrops of the Fruitland Formation, Kirtland Formation, Ojo Alamo Sandstone, Nacimiento Formation, or San Jose Formation, the lag gravel frequently contains rounded clasts of crystalline rock and/or petrified wood that are inherited from those Cretaceous and Paleogene units. Where this unit is found on broad upland flats, it consists of alluvial reworked eolian sands. In these settings, it comprises weakly consolidated light brown to light yellowish brown poorly to moderately sorted clay, silt, and sand in poorly expressed very thin to medium horizontal plane beds with trace crossbeds. Grades laterally into adjacent eolian sheet sands (map unit Qes). On surface, dune forms are absent but intermittent drainages often flow parallel to the presumed formed alignment of longitudinal dunes (azimuth of  $060^{\circ} \mp 10^{\circ}$  or  $240^{\circ} \mp 10^{\circ}$ ). Areas of recent deposition host grasses at the surface. Less recently active areas host roughly equal proportions of saltbrush (*Artiplex canescens*) and big sagebrush (*Artemisia tridentata*), with subordinate grasses, Mormon tea (*Ephedra sp.*), broom snakeweed (*Gutierrezia sarothrae*), prickly pear (*Opuntia sp.*), and cane cholla (*Cylindropuntia imbricata*). In upland areas, the contact with underlying unit often is gradational and may be obscured by pedogenic or paleopedogenic alteration. Where found at the base of slope, the lower contact often is distinct and marked by a scour surface. Contacts with adjacent units are gradational. Interfingers with alluvium. Rarely sharply incised; subdued topography is prevalent. 1-6 m thick.

### Short description:

Light brown to yellowish brown poorly to moderately sorted clay, silt, sand, and gravel in poorly exposed very thin to medium beds. Not confined to valleys; in broad upland flats or at the base of slopes. Grades into adjacent colluvium. Interfingers with alluvium. Contains gravel derived from bedrock units upslope. 1-6 m thick.

**Qes Eolian sheet sands (Pleistocene to early Holocene)** - Loose to weakly consolidated sand in broad sheets and stabilized dunes. Younger deposits contain white to pink, well-sorted crossbedded quartz arenitic to feldspathic arenitic (80-95% quartz

in the sand size class) very fine to fine sand in linear or parabolic dunes. Older deposits are more common and consist of light brown, pale brown, and very pale brown loosely consolidated moderately sorted to well-sorted subrounded coarse silt to medium sand in stabilized longitudinal dunes and sand sheets on upland areas. Bedding is disturbed to the point of obscurity in lower portions of the unit. The upper 30 cm of this unit is noneffervescent in hydrochloric acid; lower paleosols within the unit are effervescent. At least 6 paleosols are present in older deposits; these comprise pale brown to strong brown poorly sorted to moderately sorted clay to medium sand, silty sand, sandy silt, and and clayey silt massive horizons with block ped structures and up to stage II pedogenic carbonate horizons with few carbonate nodules and filamental coatings. In general, lower paleosols are darker (lower Munsell color value), finer-grained, and more likely to contain blocky peds, pedogenic carbonate, and thin clay cutans on ped faces. Distinct contact with underlying units, though this contact sometimes is overprinted by a paleosol where Qes overlies Qgs. Stabilized dunes are typified by big sagebrush (*Artemisia tridentata*)-dominated plant communities, with subordinate ricegrass (*Achnatherum hymenoides*), grama grass (*Bouteloua sp.*), saltbrush (*Artriplex canescens*), chamisa (*Ericameria nauseosa*), broom snakeweed (*Gutierrezia sarothrae*), and Mormon tea (*Ephedra sp.*). Pine (*Pinus sp.*) and juniper (*Juniperus sp.*) are nearly entirely absent on this deposit. Generally poorly exposed; well exposed only in active headcuts and construction trenches for pipelines and roads. Average sediment eolian transport azimuth is 061° as determined by dune morphologies in aerial imagery. Stabilized longitudinal dunes are up to 10 m tall. <12 m thick.

#### Short description:

White to light brown moderately to well-sorted coarse silt to medium sand in broad sheets and stabilized dunes. Deposit is located on broad upland flats in western areas of map. Dunes up to 10 m tall. Bedding largely obscured; crossbedding visible in younger portions. Brown paleosols common. Outcrops are rare. Surface typified by *Artemisia tridentata*. <14 m thick.

**Qgs Gravelly sand sheets (Pleistocene)** - Weakly to moderately consolidated gravelly sand in broad sheets capping former pediment surfaces in the drainages of Blanco Wash and Chaco Wash. Primarily light yellowish brown to light brown fine to coarse sand with 2-10% pebbles and trace silt and cobbles. Sand is moderately sorted subrounded to subangular, 50-70% quartz, 25-50% feldspar, and trace to 5% lithics. Gravel is subrounded to very rounded quartzite, chert, dark grey to black petrified wood, yellowish brown to reddish brown petrified wood, crystalline granitic rocks, crystalline gneissic rocks, micrite, and fossiliferous limestone. Pebbles are more abundant lower in the unit. Distinct contact with underlying units is often marked by a



gravel bed 5-30 cm thick. Where visible, the upper contact often is marked by a weakly developed paleosol, discontinuous gravel lenses, and lens-shaped deposits of fine sands interpreted as coppice dunes. Sands in this unit effervesce in hydrochloric acid. The surface of this unit exhibits subdued topography with little steep-sided incision but a relatively mature and interconnected system of small tributary drainages. May include thin surficial deposits of recent eolian sands up to 30 cm thick and coppice dunes up to 2 m high. Surface supports plant community including big sagebrush (*Artemisia tridentata*), grama grass (*Bouteloua sp.*), saltbrush (*Artiplex canescens*), chamisa (*Ericameria nauseosa*), broom snakeweed (*Gutierrezia sarothrae*), and Mormon tea (*Ephedra sp.*). Pine (*Pinus sp.*) and juniper (*Juniperus sp.*) are nearly entirely absent on this deposit. 3-7 m thick.

#### Short description:

Light yellowish brown to light brown gravelly sand with locally-derived pebbles of quartzite, chert, crystalline rock, and petrified wood. Weakly to moderately consolidated. Pebbles decrease in abundance upsection. May contain thin eolian sands and coppice dunes at surface. Upper contact is often marked by paleosol. Subdued surface topography. 3-7 m thick.

### Paleogene

#### **Igneous rocks**

**Pei Intrusive dikes of the Dulce Dike Swarm of Lipman & Zimmerer (2019)** (ca. 25.0 Ma) - Light gray to gray trachybasalt and basaltic trachyandesite dikes intruding Eocene-aged San Jose Formation mudstones and sandstones. Dike orientation is subvertical. Dikes on this quadrangle are up to 2.4 km long. Dike thickness is 1-8 m. Contains phenocrysts of olivine and clinopyroxene. Mica and amphibole present in groundmass.

#### Short description:

Light gray to gray trachybasalt and basaltic trachyandesite dikes intruding Eocene-aged San Jose Formation mudstones and sandstones. Dike orientation is subvertical. Dikes on this quadrangle are up to 2.4 km long. Dike thickness is 1-8 m. Contains phenocrysts of olivine and clinopyroxene. Mica and amphibole present in groundmass.

#### **Siliciclastic rocks**

**PEsjt Tapicitos Member of the San Jose Formation** (Eocene) - Reddish brown, light reddish brown, light reddish gray, and light brown mudstone with subordinate reddish yellow to light red sandstone. Both mudstones and sandstones are slope-formers. Mudstones are moderately to well consolidated non-fissile silty claystones, sandy silty claystones, and siltstones. Bedding is generally obscured by weathering and by the crumbly nates of the units. Sandstones are poorly consolidated medium- to coarse-grained subangular to angular thin- to medium-bedded cross-bedded feldspathic arenites and feldspathic wackes with trace conglomerate lenses. Conglomerates contain subangular to subrounded pebbles of crystalline igneous and metamorphic rocks with subordinate chert, quartzite, and limestone. Sand bodies are 2-30 m thick. Mudstones and sandstones grade laterally and vertically with each other and with the subjacent and adjacent Llaves Member of the San Jose Formation. No known fossils. Upper contact not present in map area. Maximum thickness in map area is approximately 135 m.

Short description:

Reddish brown to light reddish gray non-fissile mudstone and reddish yellow to light red crossbedded feldspathic sandstone with trace conglomerate. Forms slopes. Sand bodies are 2-30 m thick. No known fossils. Interfingers with Llaves Member of the San Jose Formation. Upper contact not present in map area. Maximum thickness 135 m.

**PEsjl Llaves Member of the San Jose Formation** (Eocene) - Reddish yellow, very pale brown, yellow, and brownish yellow crossbedded medium- to very coarse-grained moderately sorted subangular sandstone and conglomerate with lesser reddish brown, yellowish brown, pale olive, and gray mudstone. Mudstone interbeds are laterally discontinuous and 1-5 m thick; rare to 10 m thick. Sand composition is 40-60% quartz, 40-50% feldspar, and trace-15% lithics. Pebbles and rare cobbles include quartzite, phaneritic igneous rocks, felsic- to intermediate-composition gneissic rocks, chert, and trace limestone. Bed thickness ranges from thin to thick. Bottom and top of the Llaves Member in much of the map area are marked by persistent cliff-forming very pale brown to yellow sheet sandstones. Between these two sheet sandstones, there are interbedded sandstones, mudstones, and siltstones forming slopes and small ledges. Intertongues with the underlying Regina Member of the San Jose Formation in upper reaches of Cañada Larga. Intertongues with the Tapicitos Member of the San Jose Formation in far northeastern map area along the Continental Divide in the headwaters of Cañon de los Ojitos and Bear Canyon. Gradational contact with overlying Tapicitos Member of the San Jose Formation. Thickness approximately 95-135 m.

Short description:

Reddish yellow to brownish yellow crossbedded feldspathic sandstone and pebbly sandstone with subordinate reddish brown, pale olive, and gray mudstone. Top and bottom of unit marked by persistent yellow sheet sandstone. Mudstone interbeds are laterally discontinuous. Forms cliffs and high-relief topography. Intertongues with surrounding units. Thickness 95-135 m.

**PEsjr Regina Member of the San Jose Formation (Eocene)** - Light gray, very pale brown, light olive gray, reddish gray, and light yellowish brown mudstone, siltstone, sandy mudstone, and silty mudstone with subordinate white, yellow, and light yellowish brown clayey sandstone, silty sandstone, and sandstone. Lesser amounts of pale brown to yellow feldspathic pebbly sandstone forming prominent cliffs. Mudstones are slope formers and broad, vegetated flats and low hills across wide areas, especially near U.S. Highway 550 and the upper reaches of Cañon Largo. Sandstones are fine- to very coarse-grained moderately sorted angular to subangular feldspathic arenites with subordinate feldspathic wackes. Sand composition is 40-60% quartz, 40-50% feldspar, and 8-15% lithics. The Regina Member generally fines northward in the map area. Pebbles include felsic to intermediate phaneritic rocks, quartzite, felsic- to intermediate-composition gneissic rocks, and chert. Sandstone bedforms include tabular and trough crossbeds, horizontal plane beds, scour-and-fill structures, and massive beds. Contorted beds interpreted as paleoseismites are present in the easternmost map area. The Regina Member contains vertebrate fossils from the Wasatchian North American Stage (ca. 55.4 - 50.3 Ma). Conformable contact with the underlying Cuba Mesa Member of the San Jose Formation. Intertonguing contact with the overlying Llaves Member of the San Jose Formation. In an arcuate northwest-trending path from roughly Deer Mesa in the southern map area through Sisnathyel Mesa, Lybrook, Crow Mesa, to Blanco Mesa in the northern map area, a major regional- to continental-scale drainage divide roughly follows the base of the Regina Member, the streams on the downsection side of the Regina Member flowing south and west into the Rio Puerco, Blanco Wash, and Chaco Wash, and streams on the upsection side flowing north and east into Cañon Largo. Thickness 200-490 m.

Short description:

Light gray, light olive gray, and reddish grey mudstones and silty mudstones with white to yellow feldspathic sandstone and pebbly sandstone. Mudstones are slope-formers. Persistent sandstones can form large cliffs. Fines northward. Conformable lower contact. Intertonguing upper contact. Thickness 200-490 m.

**PEsjc Cuba Mesa Member of the San Jose Formation** (Eocene) - White to yellow, rusty-weathering sandstone, pebbly sandstone, and trace conglomerate with lenses of light gray to reddish gray mudstone and silty mudstone. Sandstones are medium- to very coarse-grained moderately sorted angular to very angular feldspathic arenites. Sand composition is 40-55% quartz, 45-55% feldspar, and 5-15% lithics. Pebbles include phaneritic igneous rocks, quartzite, gneissic rocks, chert, and trace limestone. Sandstone bedforms include tabular crossbeds, horizontal plane beds, scour-and-fill structures, contorted beds, and massive beds. Contorted beds in the eastern map area near Mesa de Cuba are interpreted as paleoseismites. Silicified trees are common in the lower portions. Molds of trees are common throughout, especially in bases of sandstone beds overlying mudstones. Sandstones form prominent and continuous cliffs. Mudstones are lens-shaped, slope-formers, discontinuous over kilometers, and may grade into sandstones over meters. Contains vertebrate fossils from the Wasatchian North American Stage ( 55.4 - 50.3 Ma). The Cuba Mesa Member generally thins and fines westward in the map area. Disconformable to slightly angular unconformable with the underlying Nacimiento Formation. Conformable contact with the overlying Regina Member of the San Jose Formation with minor intertonguing with the Regina Member in the southeastern map area from roughly Arroyo Chijuilla to Torreon Wash. Thickness 50 m in western map area to 235 m in east.

Short description:

White to yellow rusty-weathering sandstone with lenses of light gray to reddish gray mudstone. Sandstones are cliff-forming and crossbedded. Silicified trees and molds of trees common. Thins and fines westward in map area. Disconformity and angular unconformity at base. Conformable and intertonguing at top. Thickness 50 - 235 m.

**PEne Escavada Member of the Nacimiento Formation** (Paleocene) - White to gray sandstone and mudstone. Sandstones are very fine- to medium-grained poorly to moderately sorted angular to subrounded (primarily subangular) feldspathic arenites and feldspathic wackes. Sandstone beds are rarely visible; those observed are thin to medium horizontal plane beds and tabular crossbeds. Mudstones include silty claystone, clayey siltstone, and clayey sand siltstone. Bedding is difficult to observe in Escavada Member mudstones. Laterally extensive highly resistant 5-30 cm-thick silicified volcanic ashes are common. These beds include vertical burrows of 8-20 mm diameter, rare root traces, uneven bases, and sharp tops. Typically forms slopes and steep badlands beneath the overlying cliffs of the Cuba Mesa Member of the San Jose Formation. The Escavada Member lacks age-diagnostic fossils. Magnetostratigraphy suggests a Tiffanian North American Stage (60.2 - 56.8 Ma) age. Conformably overlies older members of the Nacimiento Formation Disconformable with overlying San Jose

Formation; a slight (2-5°) angular unconformity exists atop the Escavada Member in the southeastern map area. Thickness 50-90 m in north-central map area, thinning to 20-30 m in southeast.

Short description:

White to gray sandstone and mudstone with silicified volcanic ash beds. Bedding difficult to observe except in highly resistant silicified beds. Conformable lower contact. Disconformity or slight angular unconformity at top. Thins southeastward. 20-90 m thick.

**Penoe Ojo Encino Member of the Nacimiento Formation** (Paleocene) - Gray, pale red, light reddish brown, pale olive, and very dark gray mudstones with white to yellow sandstones. Can be subdivided into three lithologic categories: mudstones, isolated sandstones, and a basal pebbly sandstone (Penistaja Bed).

Mudstones: Mudstones predominate and are variegated hues of red, green, almost black, and gray. Mudstone lithology includes non-fissile clay, silty clay, and minor sandy silty clay. Bedding in mudstones is obscured by modern weathering and by pseudoslickenlines from expanding clays. Mudstones contain smectite, montmorillonite, and trace kaolinite. Mudstone outcrops are frequently unvegetated to sparsely vegetated slope-formers and exhibit popcorn weathering at the surface. Carbonized root traces are present but not common.

Isolated sandstones: Isolated sandstones make up approximately 30% of the Ojo Encino Member and contain very fine- to medium-grained poorly to moderately sorted angular to subrounded sands with abundant silt. Sand composition is 45-60% quartz, 20-40% feldspar, and trace-25% lithics. Bedding is laminated to medium, with tabular and trough crossbeds, graded beds, crevasse-splay deposits, and horizontal plane beds. Carbonized wood and plant debris are present in isolated sandstones. Forms slopes and small discontinuous cliffs. Isolated sandstones are 2-10 m thick.

Basal sandstone (Penistaja Bed of Williamson & Lucas (1992)): The Penistaja Bed is a continuous cliff-forming very pale brown to light gray pebbly sandstone. Sand composition is fine- to coarse-grained moderately to well-sorted angular to subrounded (predominantly subangular) calcareous feldspathic arenite. Brown cannonball concretions up to 50 cm in diameter are common. Bedforms include trough crossbeds, epsilon crossbeds with clay drapes, and horizontal plane beds. Disconformable lower contact is marked by a scoured gravel layer. The Penistaja Bed is present from the

southeastern map area westward to approximately the Continental Divide at Encino Wash. Thickness 15-60 m.

The age of the Ojo Encino Member is well constrained by biostratigraphy and dated ashes to the Torrejonian North American Stage (63.3 - 60.2 Ma). It intertongues to the northwest with the Tsosie Member of the Nacimiento Formation. It disconformably overlies the older Arroyo Chijuillita Member of the Nacimiento Formation. It is conformably overlain by the younger Escavada Member of the Nacimiento Formation. Thickness 90-122 m.

Short description:

Variegated red, green, gray, and black mudstones and white to yellow sandstones with thick, continuous cliff-forming yellow basal sandstone (Penistaja Bed). Mudstones form steep slopes and badlands with little vegetation and popcorn weathering. Sandstones are weakly consolidated and form slopes and discontinuous cliffs. Thickness 90-122 m.

**Pent Tsosie Member of the Nacimiento Formation** (Paleocene) - (Formerly within the Ojo Encino Member of the Nacimiento Sandstone of Williamson (1996); proposed as "Tsosie Member" by Cather et al. (2019)). White to light yellowish brown sandstones and light gray, gray, and grayish brown mudstones. Sandstones are in 10-35 m-thick channel complex bodies with crossbeds, laterally accreted beds, preserved channel margins, and point-bar deposits. Sand composition is fine- to coarse-grained, moderately sorted, subangular to subrounded. Conglomerate present only as intraformational mudstone rip-up clasts. Mudstones are drab-colored and separate the more prevalent sandstone complexes. Sandstones host sparse shrub and small tree plant communities. Mudstones are largely unvegetated and form badlands topography with popcorn weathering. The Tsosie Member is entirely or largely Torrejonian in age, though its base may extend into the late Puercan North American Stage (66.0 - 63.3 Ma) (Cather et al., 2019). Intertongues with the adjacent Kutz and Ojo Encino Members of the Nacimiento Formation. Intertongues with and conformably overlies the Arroyo Chijuillita Member of the Nacimiento Formation. Conformably overlain by the Escavada Member of the Nacimiento Formation. Thickness 65-130 m.

Short description:

White to light yellow brown sandstones in channel complexes separated by drab light gray to grayish brown mudstones. Sandstone channel complexes are 10-35 m thick. Conformable to intertonguing lower contact. Conformable upper contact. Intertongues with adjacent units. Thickness 65-135 m.

**Penk Kutz Member of the Nacimiento Formation** (Paleocene) - (Formerly the “main body” of the Nacimiento Formation of Williamson (1996); proposed as “Kutz Member” by Cather et al. (2019)). White, gray, light brown, gray, grayish green, and light reddish brown sandstone and mudstone. Reddens upward. Sandstone bodies are 2-35 m thick with laminated to very thick beds, crossbeds, crevasse splay deposits, laminations, and horizontal plane beds. Sandstones are fine- to coarse-grained poorly to moderately sorted angular to subrounded with trace pebbles of chert and crystalline rocks. Sandstone composition is 45-60% quartz, 20-40% feldspar, and trace-25% lithics. Brown cannonball concretions up to 2 m diameter present. Sandstone induration varies; forms both slopes and cliffs. Mudstones include non-fissile claystone, silty claystone, sandy silty claystone, siltstone, and sandy siltstone. Many mudstone layers can be traced laterally for kilometers. Pseudoslickenlines, root traces, and paleosols are present in mudstones. Mudstone induration varies; generally forms steep badlands topography with popcorn weathering at surface. The Kutz Member outside the map area contains an ash dated at  $65.49 \pm 0.06$  Ma (Cather et al., 2019). The lower 3040 m of the Kutz Member contains Puercan (66.0 - 63.3 Ma) fossils. The middle and upper Kutz Member contains Torrejonian (63.3 - 60.2 Ma) fossils (Williamson, 1996). Conformably overlies the Ojo Alamo Sandstone. Intertongues with the adjacent Tsosie Member of the Nacimiento Formation. Conformably overlain by the Escavada Member of the Nacimiento Formation. Relationship with the Arroyo Chijuillita Member of the Nacimiento Formation is poorly understood. Thickness 300-370 m.

Short description:

White, gray, light brown, gray, and light reddish brown sandstones and mudstones. Highly variable lithologic composition from claystone to sandstone. Reddens upward. Induration varies; generally forms steep badlands with small discontinuous cliffs. Conformable with underlying and overlying units. Thickness 300-370 m.

**Penac Arroyo Chijuillita Member of the Nacimiento Formation** (Paleocene) - White to light gray and pinkish gray sandstone and yellowish gray to dark reddish brown mudstone. Sandstones are very fine- to medium-grained moderately to well-sorted subangular to subrounded clay-cemented feldspathic arenites and feldspathic wackes. Sandstone bodies are 1-5 m thick and contained laminated to medium horizontal plane beds and crossbeds. May contain cannonball concretions up to 1 m diameter. Sandstones are weakly to moderately indurated and form steep slopes and small discontinuous cliffs. Mudstones are slightly calcareous to noncalcareous slope formers. Very dark gray to black discontinuous lignites up to 20 cm thick are common. The base of the Arroyo Chijuillita Member contains Puercan fossils (66.0 - 63.3 Ma). At Mesa de

Cuba in the southeasternmost map area, the upper half of the Arroyo Chijuillita Member contains Torrejonian fossils (63.3 - 60.2 Ma) (Williamson, 1996). Base is conformable with the underlying Ojo Alamo Sandstone. Top is disconformable with the overlying Ojo Encino Member of the Nacimiento Formation. Intertongues to the northwest with the adjacent Tsosie Member of the Nacimiento Formation and possible the Kutz Member of the Nacimiento Formation. Thickness 30-130 m.

Short description:

White, light gray, and reddish gray sandstone and yellowish gray to dark reddish brown mudstone. Sandstones are weakly to moderately indurated 1-5 m thick isolated bodies. Mudstones are slope formers and commonly contain thin discontinuous lignite. Conformable lower contact. Disconformable upper contact. Intertongues with adjacent units. Thickness 30-130 m.

**PE<sub>n</sub> Nacimiento Formation, undivided** (Paleocene) - Only shown in cross section. Includes all members of the Nacimiento Formation described above.

**PE<sub>oa</sub> Ojo Alamo Sandstone** (Paleocene) - Note: we use the term Ojo Alamo Sandstone *sensu* Baltz (1967); since this definition includes only one proposed member (the Kimbeto Member *sensu* Powell (1973)), we do not name members within the Ojo Alamo Sandstone here. Very pale brown to yellowish brown sandstone and conglomerate with subordinate pale brown to brown and dark gray mudstones. Sandstones are fine- to coarse-grained moderately sorted angular to subrounded micaceous feldspathic arenites. Sandstone composition is 32-60% quartz, 26-45% feldspar, and 8-36% lithics. Pebbles are subangular to well-rounded chert, purplish quartzite, intermediate composition phaneritic igneous rocks, petrified wood, and limestone. Intraformational mud clasts up to 60 cm diameter are present at the base of some sand bodies within the Ojo Alamo Sandstone. Sandstone bedforms include horizontal plane beds, tabular and epsilon crossbeds, graded beds, and scour-and-fill structures. Bed thickness ranges from medium to very thick. Moderately to strongly cemented with clay and silica. Typically forms prominent outcrops. Mudstones within the Ojo Alamo Sandstone in the map area are discontinuous lenses up to 100s of m in width. They include sandy claystone, silty claystone, and organic shale lenses with preserved plant material. The unit generally fines upward. Contains petrified logs up to 2 m diameter at 30 m length. In outcrop, the Ojo Alamo Sandstone in the map area often is marked by juniper (*Juniperus sp.*) and piñon (*Pinus edulis*) trees, ricegrass (*Achnatherum hymenoides*), grama grass (*Bouteloua sp.*), and a decrease in abundance of other grasses and shrubs relative to surrounding units. Disconformably overlies the



Kirtland Formation. Conformably overlain by the Nacimiento Formation. Thickness 5 - 120 m.

Short description:

Very pale brown to yellowish brown sandstone and conglomerate with brown and gray mudstone lenses. Sandstones are fine- to coarse-grained feldspathic arenites with pebbles of chert, crystalline rocks, petrified wood, and limestone. Abundant petrified wood. Marked by piñon and juniper at the surface. Disconformity at base. Conformable with overlying Nacimiento Formation. Thickness 5 - 120 m.

## Cretaceous

### **Siliciclastic rocks**

**Kk Kirtland Formation** (Late Cretaceous; Campanian-Maastrichtian?) - White and very pale brown to dark gray and pale olive mudstone and siltstone with minor dark grayish brown to black coal beds and lenses of light gray sandstone. Sandstones are very fine to medium grained moderately to well-sorted subangular to subrounded feldspathic arenites to feldspathic litharenites. Sandstones contain 21-65% quartz, 17-48% feldspar, and 4-53% lithics. Weakly to moderately indurated. Forms slopes, vegetated flats, and steep badlands topography. Abundant Campanian (83.6 - 72.1 Ma) vertebrate fossils constrain the age of the Kirtland Formation, and the base of the Formation is dated at  $75.02 \pm 0.13$  Ma (Fowler, 2017). The upper Kirtland Formation northwest of the quadrangle is known to host Maastrichtian (72.1 - 66.0 Ma) vertebrate fossils and palynomorphs; it is unknown whether these Maastrichtian strata continue onto the quadrangle. Conformable lower contact with underlying Fruitland Formation. Disconformable upper contact with the overlying Ojo Alamo Sandstone. Thickness 150-170 m.

Short description: White, pale brown, gray, and pale olive mudstone and siltstone with minor coal and light gray sandstone lenses. Weakly to moderately indurated. Forms slopes, vegetated flats, and badlands. Abundant Campanian-aged vertebrate fossils. Thickness 150-170 m.

**Kkf Farmington Sandstone Member of the Kirtland Formation** (Late Cretaceous; Campanian) Light yellowish brown to yellowish brown sandstone with interbedded light gray to very pale brown mudstones. Sandstone is fine- to medium-grained poorly to well sorted, subangular to subrounded clay-cemented feldspathic wacke. Well

indurated and forms resistant but discontinuous cliffs. Mudstone is silty claystone and sandy claystone, less resistant, and forms rounded low-relief outcrops between sand bodies. Constrained by dated ashes to between  $74.11 \pm 0.62$  Ma and  $73.37 \pm 0.28$  Ma (Sullivan and Lucas, 2003). Member pinches out to the southeast near Tsun-je-zhin approximately 7 km east of the western map boundary. Thickness in the quadrangle is 9-30 m.

Short description:

Light yellowish brown to yellowish brown sandstone with interbeds of light gray to very pale brown mudstones. Sandstones are well indurated feldspathic wackes and form discontinuous cliffs. Mudstones are less resistant and form rounded low-relief outcrops between sand bodies. Thickness 9-30 m.

**Kf Fruitland Formation** (Late Cretaceous; Campanian) - Variegated gray, yellowish gray, and yellowish brown sandstone, siltstone, and mudstone, with dark brown to black carbonaceous shale and coal. Coal beds are often marked by reddish yellow oxidized zones in the overlying and underlying strata. Sandstones are lens-shaped and 0.5-14 m thick, very fine- to medium-grained moderately to well-sorted subangular to subrounded quartz arenites, subfeldspathic arenites, quartz wackes, and subfeldspathic wackes. Sandstone composition is 86-97% quartz, 1-10% feldspar, and 1-5% lithics. Bedforms include horizontal plane beds, crossbeds, and ripple laminations. Ironstone concretions are common in Fruitland Formation sandstones. Multistoried sand bodies are better indurated and form benches. Isolated sandstones are weakly indurated and form slopes. Mudstones include silty claystone, sandy claystone, and clayey siltstone. Mudstones are carbonaceous and have carbonized plant material and roots. Mudstones are generally poorly indurated and form slopes. Indurated reddish yellow mudstones associated with coals form steeper outcrops. Palynomorphs suggest a late Campanian age (Lucas et al., 2006). Conformable and intertonguing upper and lower contacts. Thickness within the quadrangle varies from 20-80 m.

Short description:

Gray, yellowish gray, and yellowish brown sandstone, siltstone, and mudstone with dark brown to black carbonaceous shale and coal. Coal beds often marked by reddish yellow oxidized zones of "clinker" in surrounding beds. Sandstones are more quartz-rich than all overlying Cretaceous and Paleogene units. Weakly to moderately indurated. Forms slopes and badlands. Thickness 20-80 m.

**Kpc Pictured Cliffs Formation** (Late Cretaceous; Campanian) - Very pale brown, pale brown, and yellow sandstone with thin interbeds of light gray to light yellowish brown siltstone and subordinate gray shale. Sandstones are discontinuous over 100s to 1000s of m in bodies that are 4-12 m thick. Sandstones are very fine- to fine-grained well-sorted subrounded quartz arenites, subfeldspathic arenites, quartz wackes, and subfeldspathic wackes; arenites predominate. Sandstones are often organic-rich, interbedded with siltstones, and heavily burrowed by *Ophiomorpha*. Bedforms include wavy beds, flaser beds, ripple crossbeds, herringbone crossbeds, and horizontal plane beds. In most of the map area, the Pictured Cliffs Formation contains the stratigraphically highest occurrence of *Ophiomorpha*. Sandstones are moderately to well-indurated and form 3-10 m-tall cliffs in the eastern outcrop area, and steep slopes and broad outcrops in the area between Escavada Wash and Chaco Wash and west of Kimbeto Wash. Represents the final regression of the Cretaceous Interior Seaway from northwestern New Mexico. Conformable and intertonguing upper and lower contacts. Thickness 12-24 m.

Short description:

Very pale brown to yellow sandstone with thin interbeds of light gray to light yellowish brown siltstone and subordinate gray shale. Sandstone bodies are 4-12 m thick, crossbedded, and typically quartz-rich. *Ophiomorpha* burrows common. Forms small cliffs, broad surface outcrops, and steep rounded slopes. Conformable contacts. Thickness 12-24 m.

**Kl Lewis Shale** (Late Cretaceous; Campanian) - Upper part light olive gray, olive gray, and dark gray calcareous sandy shale and silty shale with pale brown to light brown sandstone interbeds up to 1.5 m thick. Becomes sandier upsection and grades into the overlying Pictured Cliffs Formation. Middle part light gray to dark olive gray claystone, shale, and silty claystone with thin to medium light brown sandstone beds and trace concretionary limestone and marls. Lower part very pale brown to light yellowish brown sandstone, silty sandstone, and clayey sandstone with abundant light gray to gray mudstone and shale interbeds; becomes clayier upsection. Forms slopes. Generally outcrops poorly, best exposed beneath cliffs of overlying Pictured Cliffs Formation and in steep arroyo walls. In most of its outcrop area, the Lewis Shale forms broad flats and low-relief hills supporting grasses and small shrubs. Contains Campanian marine invertebrate fossils, particularly in thin limestone interbeds of the middle part. May contain *Ophiomorpha* burrows in sandy intervals, particularly near the base and top. Gradational upper and lower contacts. Outcrop thickness 30-35 m. Thickens northeastward in subsurface to >450 m.

Short description:

Upper part gray sandy shale and light brown sandstone. Middle part gray shale with minor sandstone, limestone, and marl. Lower part light brown sandstone fining into sandy shale. Forms flats and low hills; outcrops poorly. Gradational upper and lower contacts. Outcrop thickness 30-35 m; thickens northeastward in subsurface to >450 m.

**Kch Cliff House Sandstone** (Late Cretaceous; Campanian) - Upper part white to brownish yellow sandstone with shark teeth, gastropods, bivalves, and rare ammonites. Upper unit often includes a capping brown to dark brown well-cemented sandstone with death assemblage of broken marine invertebrates. Middle part sandstones similar to upper part but with abundant light gray to grayish brown shale interbeds. The fossil bivalve *Inoceramus* is more common in the middle part; *Ophiomorpha*, shark teeth, and ammonites also are present. Lower part very pale brown to brownish yellow sandstone with crossbeds, ripple laminations, abundant *Ophiomorpha nodosa* burrows and rare shark teeth, bivalve, and ammonite fossils. Sandstones are fine- to coarse-grained moderately to well-sorted subrounded with lenticular beds, horizontal plane beds, crossbeds, and massive beds. Upper and lower parts are well indurated and form vertical cliffs. Lower and upper sandstone is highly fractured by joints parallel to cliff faces. Middle part forms slopes. Conformable and intertonguing contacts. Thickness in outcrop 100-112 m. Thins northeastward in subsurface to 30 m.

Short description:

Upper and lower white to brownish yellow sandstones with *Ophiomorpha*, shark teeth, ammonite, and bivalve fossils. Middle unit contains sandstone with interbedded light gray to grayish brown shale; *Inoceramus* common. Sandstones form prominent cliffs. Middle unit forms gentle slope between sandstone cliffs. Conformable contacts. Outcrop thickness 100-112 m; thins in subsurface to 30 m.

**Kmf Menefee Formation, undivided** (Late Cretaceous; Campanian) - Pale brown to light yellowish brown sandstone with interbeds of light olive gray to grayish green and brown carbonaceous mudstone and siltstone. Sandstones are moderately indurated, 0.5-3 m thick, fine- to coarse-grained moderately sorted subrounded to subangular with crossbeds, laminations, and wavy and flaser bedding. Mudstones and siltstones are carbonaceous and contain thin discontinuous lignite layers. Silicified trees present. Rare turtle, fish, crocodile, dinosaur, palm, and conifer fossils. Sandstones form small cliffs; mudstones form slopes and recessive outcrops beneath sandstone caps. Generally fines upward. Conformable and intertonguing upper contact. Lower contact does not outcrop on the quadrangle. Outcrop thickness on the quadrangle about 150 m. Thickness in subsurface in the quadrangle about 500 m in south, thinning northeastward to about 150 m near northern map boundary.

Short description:

Pale brown to light yellowish brown sandstone with interbeds of light gray to grayish green and brown carbonaceous mudstone and siltstone. Sandstones up to 3 m thick and form small cliffs. Mudstones form slopes. Silicified trees present; rare vertebrate and leaf fossils. Conformable upper contact. Lower contact not present in quadrangle. Outcrop thickness 150 m.

**Kmfm Mudstone tongue of the Menefee Formation** (Late Cretaceous; Campanian) - Gray to dark gray mudstone and siltstone, dark gray to black carbonaceous shale, and minor thin beds of oxidized and iron-stained lignite with dark grayish brown to yellowish brown sandstone lenses. Sandstone composition similar to main body of Menefee Formation. Exists as a thin tongue extending and pinching out to the northeast from a thicker tongue to the southwest off the quadrangle. Outcrops only on West Mesa and South Mesa in the far southwest of the quadrangle. Forms steep slope between the sandstone cliffs of the lower Cliff House Sandstone. Thickness 0-25 m.

Short description:

Gray to dark gray mudstone and siltstone, dark gray to black carbonaceous shale, and thin orange and dark brown lignite and dark grayish brown to yellowish brown sandstone lenses. Exists as thin tongue extending northeast onto South Mesa and West Mesa. Forms slope. Thickness 0-25 m.

**Kpl Point Lookout Sandstone** (Late Cretaceous) - Only shown in cross section. Does not outcrop on quadrangle. Thickness in subsurface about 120 m.

**Km Mancos Shale** (Late Cretaceous) - Only shown in cross section. Does not outcrop on quadrangle. Includes Graneros Shale Member, Greenhorn Limestone Member, and Carlisle Shale Member. Thickness in subsurface about 1600 m.

**Kd Dakota Sandstone** (Early Cretaceous-Late Cretaceous) - Only shown in cross section. Does not outcrop on quadrangle. Thickness in subsurface about 150 m.

## Jurassic

## Siliciclastic rocks

**Jm Morrison Formation** (Late Jurassic) - Only shown in cross section. Does not outcrop on quadrangle.

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