

Geologic Map of the Bustos Well 7.5-Minute Quadrangle, Socorro County, New Mexico

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*Open-file Digital Geologic Map OF-GM 237***

Scale 1:24,000

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GEOLOGIC SUMMARY OF THE BUSTOS WELL 7.5-MINUTE QUADRANGLE, SOCORRO COUNTY, NEW MEXICO

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INTRODUCTION

The Bustos Well quadrangle contains exposures of rock ranging in age from Pennsylvanian to Holocene. These strata are deformed by numerous faults and folds that range in age Early Cenozoic to Quaternary. Low-angle normal faults are particularly well-developed in the quadrangle.

STRATIGRAPHY

Paleozoic rocks exposed in the quadrangle consist of Pennsylvanian strata (Sandia Formation and Atrasado Formation; the Gray Mesa Formation does not crop out) and Permian strata (Bursum Formation, Abo Formation, Yeso Formation, Glorieta Sandstone, and San Andres Formation). The Yeso Formation is divided into two map units. The lower is the Meseta Blanca Member, and the upper consists of the Torres Member, the Cañas Gypsum Member, and the Joyita Member. The San Andres Formation in the northeast part of the quadrangle near Bordo Atravesado contains unusually abundant gypsum in its middle and upper parts. A thin sequence of orange gypsiferous siltstone locally occurs at the top of the San Andres Formation. These siltstones may pertain to the Artesia Group, but are included in the San Andres Formation for the purpose of mapping.

Triassic strata present in the quadrangle include the Middle Triassic Moenkopi Formation and the Upper Triassic Chinle Formation. Subdivision of the Chinle Formation in the quadrangle is not feasible in most areas. Where it is thin or poorly exposed, the Moenkopi Formation was mapped as part of the Chinle Formation.

Upper Cretaceous strata include the Dakota Sandstone, the lower part of the Mancos Shale, the Tres Hermanos Formation, the D-Cross tongue of the Mancos Shale, the Gallup Sandstone, the Mulatto tongue of the Mancos Shale, and the Crevasse Canyon Formation (mostly the coal-bearing Dilco Member). Because they are commonly thin and/or poorly exposed, the Gallup Sandstone, the Mulatto tongue, and the Crevasse Canyon Formation were mapped as a single unit (**Kuu**).

Paleogene strata consist of the middle Eocene Baca Formation and an overlying succession of middle Eocene–upper Oligocene volcanic and volcanoclastic rocks. The Baca Formation in the quadrangle was deposited in the late Laramide Carthage–La Joya basin by east-flowing fluvial systems that drained the transpressional Sierra uplift to the west (Cather, 2009a). The Baca Formation rests unconformably on Upper Cretaceous strata that range from the Crevasse Canyon Formation in the southeast part of the quadrangle to the Tres Hermanos Formation in the northeast, and the Tres Hermanos and lower part of the Mancos Shale in the southwest. In general, pre-Baca erosion within the quadrangle was deeper to the north and west. Although simple beveling can account for

much of the westward-deepening erosion beneath the Baca, erosion of a footwall block appears to have occurred along a strand of the Ranchito fault system (see cross-section B–B'). There (SE/4 sec. 27, T. 3 S., R. 2 E.), the Baca Formation fills a local paleovalley cut on the lower part of the Mancos Shale. Directly east of this paleovalley, the Baca overlies the Tres Hermanos Formation or the D-Cross tongue of the Mancos Shale and contains large boulders of Proterozoic granite as much as 2.5 m in diameter in its basal part. These are the largest clasts known anywhere in the Baca Formation. The maximum size of clasts in the lower Baca decreases to the north, south, and east of this locality, suggesting the paleovalley was a major point-source for a Baca Formation alluvial fan in this part of the Carthage–La Joya basin. These relationships indicate the west-up normal faults of the Ranchito fault system formed a local margin of the Carthage–La Joya basin during the middle Eocene.

As has been previously noted (Cather and Osburn, 2007; Cather, 2009a), the Baca Formation in the southern Carthage–La Joya basin (including the Bustos Well quadrangle) exhibits an anomalous, inverted unroofing sequence, where the basal Baca contains nearly exclusively of Proterozoic clasts (granite, gneissic granite, schist, and quartzite) that are overlain by increasing proportions of Paleozoic limestone, sandstone, and siltstone clasts upsection. A hypothesis that relates this inverted unroofing succession to detachment faulting is described below.

Conformably and gradationally overlying the Baca Formation is the lower Spears Group, a thick succession of intermediate-composition volcanoclastic rocks. The lower Spears is, in turn, overlain by a variety of ignimbrites, lavas, and volcanoclastic deposits, including the Datil Well Tuff, the Rock House Canyon Tuff, the Hells Mesa Tuff, sediments of the upper Spears Group, the Tuff of South Crosby Peak(?), the La Jencia Tuff, the Vicks Peak Tuff, the Lemitar Tuff, and the South Canyon Tuff. Several paleovalley-filling tongues of the La Jara Peak Basaltic Andesite are intercalated within the interval between the lower Spears Group and the base of the Tuff of South Crosby Peak(?).

A thick dacitic lava flow (**Tdd**) appears to fill a north-south trending paleovalley in the footwall of the Bustos fault; the flow is not present east of the fault. The location of its eruption center is unknown. The flow was interpreted as a local dacitic dome by Cather and Osburn (2007), but mapping of the Bustos Well quadrangle demonstrates the dacite had a north-south extent of at least 4 km and thus is better termed a lava flow. In most places the lava overlies the Rock House Canyon Tuff, except locally where it caps a paleovalley filled with Hells Mesa Tuff and the upper Spears Group. A 34.7 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age determination for the dacitic lava (M. Green, written commun., 2012) has now been called into question by its stratigraphic position above the 32.1 Ma Hells Mesa Tuff.

The dacitic lava flow is largely confined to the area of maximum footwall subsidence near the east-down Pinos normal fault. In three places in sec. 26, T. 3 S., R. 2 E., however, the dacite is preserved where it lapped westward onto the footwall of the fault and overlies the Baca Formation or Upper Cretaceous strata. Little or no separation of the dacite by the fault occurred after eruption of the lava. The Pinos fault is apparently

detachment-related (see below) and records ~1.3 km of normal, east-down slip prior to eruption of the dacitic flow. To the east, fanning dips in the upper part of the ignimbrite succession suggest slip was occurring on the listric Bustos fault ~29.7–27.4 Ma (see cross-section B–B').

West of the Bustos fault, the Hells Mesa Tuff and the Tuff of South Crosby Peak(?) are more deeply inset within paleovalleys (~30–60 m deep) than are correlative units east of the fault. In general, most pyroclastic units east of the fault are of broadly tabular geometry and exhibit locally erosional bases with a several meters to a few tens of meters of paleorelief. These relationships suggest the footwall of the Bustos fault was more erosional than the hanging wall, possibly as a result of east-down slip during volcanism.

Quaternary alluvial, eolian, and colluvial deposits occur as thin veneers scattered throughout the quadrangle. Older valley-filling alluvium in the drainage of Cañon Quemado is divided among three units (**Qvo**, **Qvi**, **Qvy**) based on landscape position.

STRUCTURAL GEOLOGY

Introduction

The structural geology of the Bustos Well quadrangle is remarkably complex. The quadrangle contains two examples of early(?) Laramide east-vergent, asymmetrical anticlines. The upper Yeso Formation and superjacent strata are cut by numerous, mostly east-down normal-fault splays that sole downwards into regional, top-east detachment faults. Sub-horizontal detachment faults occur mostly within gypsiferous strata of the upper Yeso Formation, but also are present locally within the Glorieta Sandstone and San Andres Formation. A great variety of small faults and short-wavelength (typically a few tens of meters), open to isoclinal, upright to recumbent folds within the upper Yeso Formation are associated with detachment faulting. These intraformational faults and folds in most cases are not mappable at the present scale.

Detachment faulting appears to have begun during deposition of the Baca Formation in the late Laramide (middle Eocene). Faulting continued (or began again) during and after Oligocene volcanism. Several high-angle normal faults cut pre-Yeso strata in the northwestern part of the quadrangle. These are probably related to Neogene lithospheric extension and rifting. Other parts of the quadrangle may also host rift-related normal faults, but these are often difficult to distinguish from the more numerous detachment-related normal faults.

Late Cretaceous(?)–Middle Eocene Contractile Structures

A prominent north-trending, east-vergent anticline with a strike length of ~13 km is present in the central and northern part of the quadrangle, and continues northward into the southwestern part of the Sierra de la Cruz quadrangle (Brown, 1987; Cather and Colpitts, 2012). The east limb of the anticline is locally overturned and, in places, cut by steep reverse faults, thus is likely Laramide in age (but probably pre-middle Eocene, see

below). The central part of the anticline lies unexposed beneath a detached plate of upper Yeso through San Andres strata in the area west of La Montanera. The anticline is truncated by, and does not fold, the overlying detachment, and thus is older. The anticline is truncated southward in the western part of sec. 23, T. 3 S., R. 2 E. by the west-trending, south-down Landing Strip structural zone (named for the landing strip at the Arroyo de las Cañas Ranch, located at the western end of the structural zone). A local, north-trending asymmetrical anticline in the eastern part of sec. 23, T. 3 S., R. 2 E. is the only other contractile structure to which a Laramide origin can be confidently inferred. It is also truncated southward by the Landing Strip structural zone, here interpreted as a lateral ramp in the regional detachment (see below). Each of these asymmetrical anticlines probably developed over the blind tip of a Laramide basement-involved reverse fault that is perhaps similar to the Cañas fault nearby to the west (Cather and Colpitts, 2005). A small thrust fault repeats Mesozoic section in west-central part of section 29, T. 2 S., R. 3 E, but its origin is uncertain.

Middle Eocene–Early(?) Miocene Detachment Faulting

Top-east detachment faulting within the Permian section has been recognized since the 1980s in the region east of Socorro (see summaries in Cather, 2009a; 2009b). Prior to mapping of the Bustos Well quadrangle, it was uncertain whether these faults represented a series of isolated detachments or were part of a regionally interconnected system. This is largely because detachment faults are apparent mostly where fault ramps have caused omission or angular truncation of strata. Where ramps are widely spaced, the continuity of bedding-plane faults through intervening detachment flats is commonly uncertain. Closely spaced exposures of ramps (mostly hanging-wall) in the northern Bustos Well quadrangle (see cross-section A–A' and heavy arrows on map), however, show that a through-going detachment system must be present. These new observations indicate the distribution of detachment faults on adjacent quadrangles is probably more widespread than previously depicted (Cather, 2002; Cather and Colpitts, 2005; Cather et al., 2005; Cather and Osburn, 2007; Cather, 2012). These earlier maps conservatively depicted detachment faults only in proximity to ramps or where significant excision of the section by low-angle faulting was observed.

Consideration of the numerous hanging-wall splays in the northern Bustos Well quadrangle (most are east-down, and each exhibits typically ~100 m or more of normal slip) that sole downwards into the detachment suggests the cumulative slip there on the detachment was at least 1–2 km. The geometry of stratal truncations by fault ramps indicate that upper-plate transport was mostly toward the east, ranging from east-northeast to southeast (upper-plate slip directions based upon ramp geometries are shown by heavy arrows on map).

The amount of top-east slip on the upper plate of the detachment in the southern part of the quadrangle is better constrained than in the north because more complete preservation of the upper plate allows more accurate slip estimates for hanging-wall splays. If cross-section B–B' is a reasonable depiction of the subsurface fault geometry (such cross-sectional depictions are often non-unique in the absence of subsurface data), the

cumulative slip on hanging-wall splays implies at least 5.3 km of cumulative top-east slip on the eastern part of the detachment fault.

An unusually complex area where Triassic and Upper Cretaceous strata and the San Andres Formation lie in fault contact above subhorizontal detachment faults in the upper Yeso Formation is present in the west-central part of sec. 32, T. 2 S., R. 3 E. This area needs to be remapped at a larger scale. The geology is depicted there in the present map is somewhat generalized.

The north-trending, east-down Bustos normal fault can be traced from the Cañon Agua Buena quadrangle to the south (Cather and Osburn, 2007) through the length of the present quadrangle, and into the Sierra Larga region to the north (Cather, 2012). The Bustos fault is strongly listric (Cather and Osburn, 2007) and mapping demonstrates it soles downsection into the upper Yeso Formation (Axen et al., 2012). In the Sierra Larga area, a 34.68 ± 0.11 Ma dike cuts Yeso strata that are tightly folded by early slip on the detachment fault, and the dike itself was subsequently cut by later movement on the fault (Green et al., 2013), indicating episodes of slip both before and after the late Eocene. Fanning dips in hanging-wall volcanic strata in the Bustos Well quadrangle suggest an episode of activity on the fault during the Oligocene (~ 29.7 – 27.4 Ma; see cross-section B–B').

The Ranchito fault system consists of several north-striking normal faults that dip moderately (~ 25 – 35°) to the east, juxtaposing the Permian San Andres Formation with Mesozoic and Paleogene strata on the east. The Ranchito fault system does not cut pre-Yeso beds exposed along its strike north of the west-trending, south-down, Landing Strip structural zone, but rather appears to terminate at this zone. Because the Ranchito fault does not cut pre-Yeso beds, we infer it soles downward into detachment faults in the upper Yeso formation, as does the Bustos fault nearby to the east. Similarly, the above-described Pinos fault cannot be traced into pre-Yeso strata north of the Landing Strip structural zone, and thus is also likely a hanging-wall splay above the detachment fault in the upper Yeso Formation.

These observations imply the Ranchito fault system, the Pinos fault, and the Landing Strip structural zone all are kinematically linked to regional top-east detachment faulting the upper Yeso Formation. If so, the Ranchito and Pinos faults represent largely dip-slip, hanging-wall splays that join the detachment down-dip (see cross-section B–B'). The Landing Strip structural zone appears to represent a south-facing lateral ramp on the detachment. Faults associated with the Landing Strip structural zone are only exposed in a few places. No kinematic indicators were noted on these faults, but sinistral-oblique slip might be expectable where the Landing Strip structural zone locally juxtaposes the upper plate of the detachment against the rocks of the lower plate.

The previously described spatial association between a Baca-filled paleovalley developed within the Ranchito fault system, and anomalously coarse, proximal fan deposits in the Baca Formation directly down depositional dip to the east, strongly suggest the Ranchito fault system formed a local margin of the late Laramide Carthage–La Joya basin. This

implies at least part of the Carthage–La Joya basin owes its origin to half-graben development linked to regional top-east detachment faulting during the middle Eocene.

The Ranchito, Pinos and Bustos faults may have developed sequentially from west to east. The Ranchito fault system was active during Baca sedimentation in the middle Eocene. The Pinos fault cuts the 34.4 Ma Rock House Canyon Tuff and possibly the 32.1 Ma Hells Mesa Tuff, but does not appreciably offset the dacite lava where it laps westward across the fault (the dacite is being redated; it is younger than the 32.1 Ma Hells Mesa Tuff but older than the 29.7 Ma Tuff of South Crosby Peak(?)). Fanning of dips in volcanic strata in the hanging wall of the Bustos fault suggests slip was occurring ~29.7–27.4 Ma. Alternatively, the apparent age progression may be simply an artifact of incomplete exposure.

SYNTHESIS

What follows is a plausible model to explain the development of detachment faulting in the Quebradas region east of Socorro. Most of the critical observations that contribute to this model are derived from the Bustos Well quadrangle. We seek to incorporate the following observations:

- 1) Close spacing of exposed fault ramps in the northern Bustos Well quadrangle indicates that detachment faults in the Permian section are part of a regionally linked system.
- 2) East-directed Laramide basement-involved faulting along the flank of the Sierra uplift extended at least as far east as the central Bustos Well quadrangle, as shown by the presence of east-vergent anticlines. This suggests a basement wedge underlies much of the Quebradas area to the west.
- 3) Detachment faulting is younger than early(?) Laramide contractile folding.
- 4) Slip occurred on the detachment, before and after intrusion of a late Eocene dike in the Sierra Larga at 34.68 ± 0.11 Ma (Green et al., 2013). Pre-dike deformation may correspond to an episode of middle Eocene slip (syn-Baca Formation) manifested by basin-margin development along the Ranchito fault system. Post-dike slip may have begun (or continued) during the Oligocene, as shown by fanning dips in volcanic strata of the hanging wall of the Bustos fault and deeper incision of paleovalleys on the footwall. The overlap of a dacitic lava flow onto the footwall of the Pinos fault in the Bustos Well quadrangle will further constrain the timing of late-phase detachment faulting (redating of the flow is now underway). The dacite is not appreciably cut by the Pinos fault. Faulting must have continued after the end of volcanism on the Bustos fault, as volcanic units are now separated ~1.5 km across it.
- 5) The Baca Formation of the southern Carthage–La Joya basin exhibits an anomalous, inverted unroofing sequence where the base of the unit is dominated

by Proterozoic clasts and gives way to mostly Paleozoic detritus upsection.

A Model for the Development of Detachment Faulting East of Socorro

During the Laramide orogeny, but prior to deposition of the Baca Formation in the middle Eocene, west-up basement faulting along the east flank of Sierra uplift extended at least as far east as the central part of the map area. Blind reverse faults produced two asymmetrical, east-vergent anticlines in the quadrangle. We suggest the anticlines mark the east edge of a subsurface basement wedge, similar to that proposed for the Nacimiento uplift in northern New Mexico (Pollock et al., 2004). This wedge may be responsible for much of the anomalous structural elevation of the east flank of the Socorro Basin.

By early Eocene time, widespread Proterozoic exposures existed on the Sierra uplift to the west, but subsidence and sedimentation had not yet begun in the southern Carthage–La Joya basin. Instead, transport systems caused bypass of Proterozoic detritus beyond the study area to the east. During the middle Eocene, a topographic slope driven by structural growth of the basement wedge may have become sufficient to initiate top-east gravity sliding on slip planes within the weak gypsiferous (and possibly halite-bearing; Green et al., 2013) beds of the upper Yeso Formation. Development of mostly east-down normal-fault splays in the hanging wall of the detachment caused half-grabens to develop in which clastic detritus of the Baca Formation began to be deposited. Clasts were initially dominated by Proterozoic lithotypes derived from the Sierra uplift. Proterozoic clasts were increasingly supplanted by Paleozoic lithotypes as footwalls were incised due to falling base levels driven by subsidence of adjacent half-grabens.

It is unclear if detachment slip and associated half-graben development continued during middle to late Eocene deposition of the lower Spears Group. But fanning dips, footwall onlap of the dacitic lava, and increased erosion depth on the footwall of the Bustos fault suggest deformation was occurring during the subsequent Oligocene ignimbrite flare up. Synvolcanic detachment faulting may have been caused by gravity-driven spreading of the volcanic field (e.g., Borgia et al., 2000; Le Corvec and Walter, 2009). The locus of Spears age volcanism was centered on the Sierra uplift, now foundered to form the Socorro Basin of the Rio Grande rift (Cather, 1990). Ignimbrite volcanism was geographically much more widespread. If volcanic spreading drove top-east detachment faulting in the Quebradas region, it might be expectable that top-west faulting occurred in the region west of the Socorro Basin. In fact, detachment faulting in the upper Yeso Formation has recently been noted near Yellow Mountain, north of Riley, New Mexico (D. Scholle, written commun., 2013). Although clearly top-west, detachment faulting in this region is essentially unstudied, so its timing and origin are not known.

Detachment faulting may have been accompanied by sequential west-to-east development of hanging-wall splays. Extension associated with detachment faulting in the Quebradas region may have been compensated by intra-Yeso contractile folding and faulting in the broad Prairie Spring and Chupadera anticlines to the east (Cather, 2009b). A kinematic link to the more-distant Chupadera anticline has yet to be demonstrated.

The timing of the end of detachment faulting is poorly constrained, other than it must post-date the youngest volcanic unit in the quadrangle (27.4 Ma). During the middle to late Miocene culmination of rifting (Chapin and Cather, 1994), deformation by rift-related normal faults was probably sufficient to disrupt the detachment and prevent further regional slip on the fault.

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PRELIMINARY GEOLOGIC MAP OF THE BUSTOS WELL 7.5' QUADRANGLE,
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DESCRIPTION OF UNITS

CENOZOIC ERATHEM

NEOGENE

Middle(?) Pleistocene–Holocene

Qal Alluvium (Holocene) — Sand, gravel, and mud in, and adjacent to, modern arroyo channels. Alluvium is typically at or near the grade of modern channels. 0–10 m thick.

Qc Colluvium and talus (upper Pleistocene–Holocene)— Gravelly deposits of poorly sorted colluvium and talus blocks on, or adjacent to, steep slopes. 0–5 m thick.

Qae Eolian deposits (upper Pleistocene–Holocene) — Eolian sand and loessic silt locally reworked by alluvial processes. Deposits are stabilized by vegetation in most areas. Includes intercalated alluvial deposits and thin, discontinuous eolian veneers on stable upland surfaces. 0–5 m thick.

Qvy Younger piedmont alluvium (upper Pleistocene) — Gravel, sand, and minor mud deposited at low elevations (less than about 5 m) above modern stream grade. Alluvium is representative of deposition in a variety of piedmont environments, including alluvial fans, paleovalley and arroyo fills, strath terraces, fill terraces, and pediment surfaces. 0–15 m thick.

Qvi Intermediate-age piedmont alluvium (upper? Pleistocene) — Gravel, sand, and mud deposited at intermediate elevations (about 5–10 m) above modern stream grade. Range of depositional environments is similar to Qvy. 0–10 m thick.

Qvo Older piedmont alluvium (middle? Pleistocene) — Gravel, sand, and mud deposited at higher elevations (more than about 10 m) above modern stream grade. Range of depositional environments is similar to Qvy. 0–15 m thick.

PALEOGENE

Upper Eocene–Oligocene

Tsc South Canyon Tuff — Light gray to light purple, densely welded, crystal-poor to moderately crystal-rich rhyolite ignimbrite. Crystals are mostly sanidine and quartz; lithic fragments are common. About 150–250 m thick. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 27.4 Ma (all $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported here are from McIntosh et al., 1991, except where noted).

Tl Lemitar Tuff — Pink, densely welded, moderately crystal-rich rhyolite ignimbrite. Crystals are sanidine, plagioclase, quartz, and biotite; lithics are minor. Thickness is about 0–110 m. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 28.0 Ma.

Tvp Vicks Peak Tuff — Light gray, moderately welded, crystal-poor rhyolite ignimbrite. Thickness ~110 m. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 28.6 Ma.

Tlj La Jencia Tuff — Pink to gray, densely to moderately welded, crystal-poor, rhyolitic ignimbrite that exhibits compound cooling. Upper part of unit is prominently flow-banded. Crystals are mostly sanidine and quartz; lithics are typically sparse. Thickness ~140 m. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 28.9 Ma.

Tcp Tuff of South Crosby Peak(?) — light gray, poorly welded, moderately crystal-rich ignimbrite. About 30–50 m thick. $^{40}\text{Ar}/^{39}\text{Ar}$ age is ~29.7 Ma.

Tlp La Jara Peak Basaltic Andesite — Aphanitic to slightly porphyritic mafic flows and associated breccias of mostly basaltic andesite composition. Phenocrysts are mostly plagioclase and clinopyroxene. In the quadrangle, the unit occurs as several tongues 0–80 m thick intercalated within the stratigraphic interval between the lower Spears Formation and the base of the Tuff of South Crosby Peak(?).

Tsu Upper Spears Group — Dark- to medium-gray volcanoclastic sandstone and conglomerate. Debris-flow breccias are locally present. Clast lithotypes are mostly dark gray basaltic andesite (plagioclase- and clinopyroxene-bearing) but also andesite-dacite (plagioclase- and amphibole-bearing) and ignimbrite clasts. 0–120 m thick. Spears Group terminology used as defined by Cather et al. (1994).

Tid Andesite to basaltic andesite dike — Mafic to intermediate-composition dike ~5–10 m wide in southeastern part of quadrangle. Commonly exhibits greenish alteration. Probably represents an intrusive equivalent of the La Jara Peak Basaltic Andesite.

Tdd Dacite extrusive rocks — Medium brownish gray, plagioclase and amphibole-bearing lava. Composed of a single flow 0–90 m thick with an autobrecciated base. The flow yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 34.7 Ma (M. Green, written commun., 2012), but this is anomalously old based on the age of underlying 32.1 Ma Hells Mesa Tuff.

Thm Hells Mesa Tuff — Brownish pink, crystal-rich, densely welded rhyolitic ignimbrite. Crystals are sanidine, quartz, and biotite; lithics are sparse. Exposed as erosional remnants within paleovalleys. 0–15 m thick. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 32.1 Ma.

Trh Rock House Canyon Tuff — Light gray, crystal-poor rhyolitic ignimbrite. Phenocrysts are mostly sanidine with rare quartz, biotite, and hornblende(?). Poorly to

moderately welded. Contains local zones of abundant flattened pumice. About 90–150 m thick. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 34.4 Ma

Tdw Datil Well Tuff — Medium brownish gray, crystal-rich rhyolitic ignimbrite. Crystals are mostly sanidine with subordinate plagioclase and minor quartz, biotite, and pyroxene(?). Lithic-rich and pumice-poor. 0–50 m thick. $^{40}\text{Ar}/^{39}\text{Ar}$ age is 35.5 Ma.

Tsl Lower Spears Group — Medium- to light-gray volcanoclastic sandstone, conglomerate, debris-flow breccia, and minor mudstone. Clasts are dominated by plagioclase- and amphibole-bearing andesite and dacite. Non-volcanic clasts are locally present above transition with underlying Baca Formation. Thickness is ~760 m. Age range is ~39–36 Ma (Cather et al., 1987). Usage of the term Datil Group is after Cather et al. (1994).

Middle Eocene

Tbpg Baca Formation (middle Eocene) — Fluvial red-bed sandstone, conglomerate, and minor mudstone deposited in piedmont environments. Sandstone is commonly cross-bedded; conglomerate contains pebbles, cobbles and boulders of Paleozoic and Proterozoic lithotypes. Clasts are dominantly (>90%) Proterozoic lithotypes (granite, gneissic granite, schist, and quartzite) near the base of the unit. Paleozoic clast types (limestone sandstone, siltstone) increase in abundance upsection in most areas. About 300 m thick. Granite boulders as much as 2.5 m in diameter are present in the southwestern part of the quadrangle. Nomenclature after Cather et al. (2013).

MESOZOIC ERATHEM

UPPER CRETACEOUS

Kuu Undivided Upper Cretaceous strata consisting of the Gallup Sandstone (Lower Coniacian), Mulatto tongue of the Mancos Shale (Middle Coniacian), and Crevasse Canyon Formation (Coniacian–Santonian?)— Gallup Sandstone is fine grained, gray to yellowish gray, regressive coastal barrier-island sandstone and mudstone. About 5–15 m thick. Mulatto tongue of the Mancos Shale is drab marine shale about 30 m thick that is intercalated within the lower Crevasse Canyon Formation about 50 m stratigraphically above the top of the Gallup sandstone. Crevasse Canyon Formation (mostly the Dilco Member) is drab to gray sandstone, mudstone, and coal deposited in coastal plain and fluvial settings. Thickness is as much as 300 m. Typically poorly exposed.

Kmd D-Cross Tongue of the Mancos Shale (Upper Middle Turonian–Lower Coniacian) — Noncalcareous, medium gray, marine shale. About 90 m thick with a sharp basal contact and a gradational upper contact. Fossils *Prionocyclus wyomingensis* (Meek) and *Scaphites warreni* Meek and Hayden, *Prionocyclus novimexicanus* (Marcou), *Forresteria* sp., *Lopha sannionis* (White), and sparse *Ostrea elegantula* White.

Kth Tres Hermanos Formation (Middle Turonian) — Sandstone and shale unit that forms a regressive-transgressive wedge of nearshore marine and non-marine deposits that is about 80 m thick with a gradational base and a sharp top. Consists of three unmapped members, in ascending order: Atarque Sandstone Member (lower Middle Turonian) — Regressive coastal barrier sandstones that weather light gray to dark brown or buff. Lower sandstones are transitional with underlying shale and constitute a 5–7 m thick, ridge-forming unit that has very fossiliferous lenses and concretionary sandstone bodies with *Pleuriocardia* (*Dochmocardia*) *pauperculum* (Meek) and *Gyrodes* spp. Uppermost bed is commonly a brackish water coquina of *Crassostrea soleniscus* (Meek). Carthage Member (middle Middle Turonian) — Marine, marginal marine, and non-marine sandstone and shale slope-forming unit ~60 m thick; lower two-thirds contains thin, fine grained sandstone beds of paludal-lacustrine or crevasse splay origin and discontinuous, cross-bedded channel sandstones. The upper third contains marine shale with fossiliferous concretions and *Prionocyclus hyatti* (Stanton). Fite Ranch Sandstone Member (upper Middle Turonian) — Highly bioturbated, coastal barrier sandstone that coarsens upward from very fine grained to fine grained. Sandstones are light gray, but weather light to dark brown and constitute a 10–12 m thick ridge-forming unit with sharp top and gradational base. Contains *Lopha bellaplicata novamexicanum* Kauffman.

Kml Lower part of the Mancos Shale (Middle Cenomanian–Lower Turonian) — Calcareous to noncalcareous gray marine shale with minor, thin sandstone beds near base and top. Sharp basal contact and gradational upper contact. Calcareous shale in upper part of unit contains abundant *Pycnodonte newberryi* (Stanton). Thin sandstones in basal 15 m contain common *Ostrea beloiti* Logan. About 135 m thick.

Kd Dakota Sandstone (Middle Cenomanian) — Gray to yellow, fluvial to marginal marine medium to coarse-grained sandstone and minor mudstone. No body fossils have been found in the Dakota. About 5–20 m thick.

TRc Chinle Formation (Upper Triassic) — Red, gray and maroon fluvial mudstone with subordinate sandstone, limestone-pebble conglomerate, and limestone. Forms slopes and valleys. Locally includes Moenkopi Formation. About 200 m thick. Formation-rank nomenclature after Cather et al. (2013).

TRm Moenkopi Formation (Middle Triassic) — Red-brown, brown, and buff continental mudstone, sandstone and minor conglomerate. Locally mapped as part of the Chinle Formation where thin or poorly exposed About 10–30 m thick.

PALEOZOIC ERATHEM

PERMIAN

Psa San Andres Formation (Permian, Leonardian) — Interbedded limestone, dolostone, and gypsum. Limestone is brownish-black, pale yellowish-brown and medium gray, and ranges from wackestone to grainstone. Dolostone is brownish-gray to olive-gray, and locally gypsiferous. Bedded gypsum is abundant in the middle and upper

part of the San Andres in the northeastern part of the quadrangle. Gypsum is white to light gray, laminated to massively bedded. Thickness is ~200 m. Locally includes 5–15 m of orange gypsiferous siltstone at the top of the unit that may be correlative with the Permian Artesia Group.

Pg Glorieta Sandstone (Permian, Leonardian) — White to very pale orange, fine- to medium-grained, friable to well-indurated, crossbedded quartzarenite. Has scattered coarse, well-rounded, frosted quartz grains, especially in the lower half of the unit. Thickness is ~70 meters.

Pyu Upper Yeso Formation (Permian, Leonardian) — Interbedded siltstone, gypsum, dolomitic limestone, sandstone, and shale. About 200 m thick. Consists of three unmapped members (in ascending order): the Torres, Cañas Gypsum, and Joyita Members. The upper two members are locally cut out by low-angle normal faults. Torres Member—Interbedded pale to moderate reddish-brown, grayish-pink or grayish-red, fine- to medium-grained quartzose sandstone, white to light gray gypsum thin layers and lenses of dolomitized oolitic limestone, and pale yellowish-brown to olive black limestone that ranges from carbonate mudstone to peloidal or oolitic packstone and grainstone and are locally sparsely fossiliferous, dolomitic, and argillaceous. Thickness is ~160 meters. Cañas Gypsum Member—Interbedded very light gray to white laminated to nodular-mosaic gypsum and minor, thin very fine-grained silty sandstone and a thin, fetid, gypsiferous calcareous mudstone and limestone. Thickness is 0–24 meters. Joyita Member—Pale reddish-brown to moderate reddish-orange, friable and calcareous, fine- to very fine-grained quartzose sandstone with scattered displacive halite casts and clay flakes on bedding surfaces. The upper beds display low-angle cross beds and ripple cross-laminations. Thickness is 0–30 meters. Nomenclature after Cather et al. (2013).

Pyl Lower Yeso Formation (Permian, Leonardian) — The Meseta Blanca Member constitutes the lower Yeso Formation. The Meseta Blanca Member is interbedded very pale orange, pinkish-gray and moderate reddish-brown, very fine- to medium-grained quartzose sandstone, are very light gray to dark reddish-brown siltstone and are dark reddish-brown to grayish-red, slope forming mudstones and shales. Thickness is ~90 m. Top of the unit is placed at the base of the lowermost marine limestone in the Torres Member of the upper Yeso Formation. Base of unit is gradational in many places with the underlying Abo Formation. Nomenclature after Cather et al. (2013).

Pa Abo Formation (Permian, Leonardian) — Interbedded dark reddish brown mudstone and shale, and grayish red to dark reddish brown siltstone, sandstone and, locally, thin conglomerate and rare limestone. Thickness is ~200 meters.

Pb Bursum Formation (Permian, Wolfcampian) — Interbedded medium dark gray to grayish red mudstone, medium gray to brownish black, peloidal, fossiliferous, and locally dolomitic limestone, and grayish orange pink to grayish orange, fine to very coarse-grained, lenticular and trough cross-bedded sandstone. About 60 m thick.

PENNSYLVANIAN

IPma Atrasado Formation of Madera Group (Desmoinesian, Missourian, and Virgilian) — marine and paralic interbedded brownish-gray arkosic sandstone, greenish-gray to gray mudstone, and light gray limestone. Approximately 250 m thick. Nomenclature after Cather et al. (2013).

IPmg Gray Mesa Formation of Madera Group (Desmoinesian) — Medium-gray, fossiliferous, commonly cherty, marine limestone, greenish-gray mudstone, and minor sandstone. Subsurface only. About 50 m thick regionally. Nomenclature after Cather et al. (2013).

IPs Sandia Formation (Atokan) — Continental and marine, Arkosic to quartzitic light brown sandstone, greenish-gray mudstone, and medium gray limestone. 90–175 m thick.

EXPLANATION OF MAP SYMBOLS

Contact between geologic units. Dashed where approximately located; dotted where concealed.

Fault showing direction (arrow) and amount of dip of fault plane. Dashed where approximately located; dotted where concealed. Bar and ball on downthrown block of steep faults. Square teeth on upper plate of moderate- to low-angle normal faults (younger over older); triangular teeth on upper plate of low-angle thrust faults (older over younger).

Arrow showing approximate direction of motion of upper-plate of low-angle normal fault, based on geometry of truncation of strata in hanging-wall ramp by fault.

Anticline showing trace of axial plane and plunge direction. Dashed where approximately located, dotted where concealed.

Syncline showing trace of axial plane and plunge direction. Dashed where approximately located, dotted where concealed.

Strike and dip of bedding.

Vertical bedding.

Breccia

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