Geologic Map of the Pierce Canyon 7.5-Minute Quadrangle, Doña Ana County, New Mexico

By

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Scale 1:24,000

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INTRODUCTION

Located in the lower Pecos River Valley of New Mexico, the Pierce Canyon 7.5-minute quadrangle lies in the northern part of the Delaware Basin, a deep structural sub-basin on the western side of the late Paleozoic Permian Basin (Hills, 1984). The quadrangle extends eastward from the Pecos River in Eddy County near the community of Malaga. Parts of the Malaga Bend another large meander of the Pecos River reach the western portion of the map area (Fig. 1). The lower Pecos River Valley, which drains southwards through Chaves and Eddy counties in southeastern New Mexico, hosts significant agriculture, oil and gas production, potash production, wind energy potential, and recreation/tourism. The Delaware Basin is currently undergoing renewed and rapid growth in exploration and production of hydrocarbons (e.g., Broadhead, 2014, Dunlap, 2018; US EIA, 2019). Resource development and other human activities occur in an area of significant geologic and environmental challenges including limited water supply, karst hazard, and induced seismicity risk (e.g., Lewis, 2012; Bangsund and Johnson, 2013; Land et al., 2018; Lowry et al., 2018; Litherland and Glasgow, 2021). Oil and gas were traditionally produced from conventional reservoir strata, whereas the recent boom focuses on unconventional reservoirs and source rocks (Broadhead, 2014). Sustainable land use, resource management, and hazard mitigation in the region may benefit from more detailed geologic mapping. Hence, ongoing efforts by the NM Bureau of Geology are aimed at preparing 1:24,000-scale geologic maps in the lower Pecos River Valley.

Major tributary drainages that descend east-to-west across the map area – Dog Town Draw, Pierce Canyon, Cedar Canyon, and Wood Draw – presently contain running water only during storm-induced runoff events. Higher interfluvial areas across much of the Pierce Canyon quadrangle exhibit a well-developed, relict carbonate soil horizon that Bachman (1976) called the Mescalero caliche, in reference to the so-called Mescalero plain. The Mescalero plain is a north-south trending geomorphic surface in southeastern New Mexico that extends southward from Fort Sumner to the New Mexico-Texas border between the Pecos River and the High Plains (see Bretz and Horberg, 1949, their Fig. 1). Bachman (1976) speculated that this surface developed during middle Pleistocene time. The age of the surface, associated petrocalcic soil horizon, and underlying alluvial deposits (Gatuña Formation) remain poorly constrained (e.g., Vine, 1963; Rosholt and McKinney, 1980; Powers and Holt, 1993; Hall and Goble, 2012). Entrenchment of the Pecos River and its tributaries have cut a circuitous escarpment into the Mescalero caliche caprock, which locally extends from the vicinity of Pierce Canyon northward to Livingston Ridge along the south side of Nash Draw to the north-northeast of the map area (Figs. 1). Today, this escarpment and the Pecos River floodplain form the most visually distinctive geographic features on the Pierce Canyon quadrangle. A widespread Quaternary eolian sand sheet covers the Mescalero over much of the eastern part of the map are. The walls of Pierce Canyon expose outcrops of striking red sand and mud of the Gatuña Formation the escarpment held up by the Mescalero caliche (Fig. 2).

The landscape is irregularly dotted by small depressions that collect surface runoff and associated sediment. These depressions are one expression of the extensive differential subsidence that has affected the region across a range of scales. This subsidence is caused by dissolution of thick Permian evaporite deposits that underlie the landscape. Widespread solution subsidence in the map area is also suggested by intra-formational unconformities within the Gatuña Formation, steeply tilted blocks of Mescalero caliche and underlying Gatuña Formation, and internally disrupted blocks of down dropped Permian strata (Fig. 3; Vine, 1963; Bachman, 1976). On a larger scale, substantial solution subsidence a short distance to the south of the map area has accommodated accumulations of alluvial valley fills with thickness on the order of 100s of meters (Maley and Huffington, 1953).

Small-scale geologic maps including the area covered by the Pierce Canyon quadrangle were prepared by Hendrickson and Jones (1952), Barnes et al. (1976), and Bachman (1980). More detailed mapping by Vine (1963) was conducted on the Nash Draw 15-minute quadrangle just to the north of the Pierce Canyon quadrangle. Several adjoining 7.5-minute quadrangles to the west have also been recently mapped in more detail (e.g. Cikoski, 2019).

METHODS

Geologic mapping was performed from fall 2020 to spring 2022. Map-unit contacts were delineated using recent-vintage (2005, 2009, 2016) 10-m-resolution color aerial photographs. The workflow involved a combination of field observations and digitization of map and field data into an ArcGIS geodatabase based on the GeMS data standard (USGS NCGMP, 2020). Coordinates reported herein are given as Universal Transverse Mercator easting and northing, in 7meters, using the North American Datum of 1983, zone 13. The classification of surficial deposits is briefly discussed below. Paleozoic bedrock-unit names (cross section) are those historically employed by petroleum geologists operating in the northern Delaware Basin. The subsurface geology portrayed on the cross section was constructed on the basis of oil and gas industry well logs obtained from the New Mexico Oil Conservation Division (OCD) online database. Water-well driller's logs archived by the New Mexico Office of the State Engineer (OSE) provided limited information regarding the distribution of deposits at shallow depth typically not captured in OCD borehole data. The tops of lithostratigraphic intervals (rock formations) were independently identified from the geophysical logs, as operator picks listed in completion reports are somewhat inconsistent.

STRATIGRAPHIC FRAMEWORK

Complete lithologic descriptions and additional information can be found in the appendix at the end of this report, Description of Map Units that accompanies the geologic map, and corresponding attribute table within the GIS database.

Cenozoic Erathem

The bulk of the map area is covered by Quaternary surficial deposits. These deposits are depicted as undivided Neogene-Quaternary deposits (**QTu**) on the geologic cross section. Disturbed ground and artificial fill (**daf**) related to historic anthropogenic activities that significantly obscure surficial geology are limited in extent.

Alluvial, Colluvial, and Eolian Surficial Deposits

Alluvial deposits related to the Pecos River include deposits in active to recently channels and terraces (**Qar**) as well as two broad Holocene alluvial terrace units along the course of the Pecos River (**Qt2**, **Qt1**), which themselves contain several terrace levels. Extensive differential solution subsidence in the region complicates correlation of specific terraces. Other alluvium in the map area consists of locally derived slope-wash deposits and fan and valley floor deposits associated with intermittent streams (**Qae**, **Qa**), which have been variably reworked by eolian processes and are probably recent to uppermost Pleistocene in age.

Extensive upper Pleistocene to modern eolian deposits are found in the map area. Much of the eastern part of the quadrangle is covered by red eolian sand (**Qe**). A variety of eolian dune forms are present but this unit is dominantly surfaced by coppice dunes. The unit is more tan/gray in color where it is thin over underlying caliche. Isolated eolian sand deposits of a lighter yellow to orange color (**Qd**) are found lower in the landscape. These eolian deposits are dominated by coppice dunes and are interpreted to reflect eolian reworking of alluvium.

Clay, silt, and sand transported by slope-wash and eolian processes also accumulate in closed or nearly closed depressions (**Qdf**) resulting from solution subsidence. Colluvial deposits (**Qc**), composed of siliciclastic silt, sand and gravel and debris derived from erosion of caliche are mapped on slopes beneath bluffs where they obscure the underlying geology. These contrast with alluvial-colluvial gravelly deposits (**Qac**) that contain rounded clasts of quartzite, chert, and volcanics together with limestone clasts and pebbles-cobbles of caliche, and mantle the slopes of canyon walls and locally form hummocky mounds. These deposits are interpreted as reworked Gatuña Formation conglomerate and caliche. Another unit of alluvial-colluvial gravel (**Qg**) containing almost no caliche clasts is differentiated that forms low hummocky mounds.

Exposures of well-cemented, polymictic, sub- to well-rounded conglomerates are locally present along the modern course of the Pecos River (**Qcc**). Holocene alluvium and terrace deposits are inset against the cemented gravel. These fluvial deposits may be late Pleistocene in age, but their age relative to the Gatuña Formation and Mescalero caliche is uncertain. These outcrops are continuations of exposures mapped by Cikoski (2019) in the Malaga quadrangle to the west, which he interpreted as ancestral Pecos River deposits and a part of the Gatuña Formation. We do not include these deposits within the Gatuña Formation due to differing perspectives on its internal stratigraphy (outlined further below), but an origin as axial stream deposits is likely.

Mescalero Caliche

A well-developed pedogenic carbonate horizon (**Qmc**) is exposed (or shallowly covered) across the western portion of the study area, which Bachman (1976) informally named the Mescalero caliche. It is developed on siliciclastic sediments of the Gatuña Formation and commonly overlain by eolian sand. These overlying eolian deposits are partly correlative with the so-called Mescalero sands (e.g., Bretz and Horberg, 1949; Vine, 1963; Hall and Goble, 2006). Vine (1963) attributed this petrocalcic horizon at Pierce Canyon and Livingston Ridge further north (Fig. 1) to the Pleistocene Mescalero surface of Bretz and Horberg (1949). Bachman (1976) indicated a thickness range of 1 to 4 meters for the Mescalero caliche, noting that carbonate in the upper part of the unit is commonly laminated, pisoliths are less common than in the older (Pliocene) Ogallala caprock, and that pedogenic brecciation and recrystallization is rarely observed. We follow Bachman's (1976, 1980) recognition and informal name for outcrops of this soil horizon in the study area, recognizing that such correlation over large distances is problematic in this region and that soil horizons are not typically differentiated for the purpose of geologic mapping.

The Mescalero caliche is younger than the ca. 0.6 Ma Lava Creek B ash, which is present in underlying deposits (Gatuña Formation) along Livingston Ridge to the north of the map area (Bachman, 1980; Izett and Wilcox, 1982). "Uranium-trend" age estimates obtained during studies at the Waste Isolation Pilot Project site, using an empirically calibrated, open-system age model, suggest a ca. 0.57-0.42 Ma age for the Mescalero caliche and 0.33 Ma age for overlying Berino paleosol deposits (Rosholt and McKinney, 1980). Hall and Goble (2006, 2012) presented optically-stimulated luminescence ages ca. 0.09-0.05 Ma from surficial deposits overlying the Mescalero caliche at three localities on the Mescalero plain, providing what is likely a more reliable minimum age estimate for pedogenesis and development of the Mescalero paleosol.

Previous workers have suggested that some exposures of the paleosol in the study area, notably on the southwestern escarpment of Pierce Canyon, may be equivalent to the Ogallala caprock, older than and distinct from the Mescalero caliche (Hawley, 1993; Cikoski, 2019). This correlation led to a proposed division of the Gatuña Formation into diachronous upper and lower parts. We found little evidence to support the presence of two temporally distinct calcic paleosols in Pierce Canyon that would suggest such a division. The petrocalcic horizon rimming Pierce Canyon can be followed nearly continuously from the mouth of the canyon on its northern wall to the mouth of the canyon on its southern wall, although differential subsidence has caused considerable deformation of what was presumably once a relatively smooth surface (Figs. 2, 4, 5, 6, and 7). We revisited a key outcrop highlighted by Cikoski (2019) just west of the study area, on the Malaga 7.5′-quadrangle, and found no evidence for distinct petrocalcic soil horizons of distinct. There too the effects of subsidence-related warping and displacement of blocks of Gatuña Formation and Mescalero caliche are the cause of the apparent stratigraphic relationships.

Gatuña Formation

The Gatuña Formation was named by Lang (in Robinson and Lang, 1938) for alluvial deposits of mixed lithology dominated by red sand exposed in Gatuña Canyon approximately 40 km north of the Pierce Canyon quadrangle. Lang indicated that the formation is Quaternary in age, accumulating in "post High Plains time," and that in Pierce Canyon it is more than 100 feet thick and may exceed 300 feet at the head of Cedar canyon, but is generally thinner. Usage of the Gatuña Formation name and stratigraphic concept has been informally broadened to include deposits thought to be as old as the Ogallala Formation, extending northward to Guadalupe County, New Mexico and southward to include Pecos valley fills in Texas (see summary in Powers and Holt, 1993).

The age of the Gatuña Formation is poorly documented, with proposed age estimates that vary from as old ca. 13 Ma at its base to as young as ca. 100 ka at its highest levels (Hawley, 1993; Powers and Holt, 1993; Hall and Goble, 2012; S.M. Cather, personal communication, 2021). The main reliable age constraint is the presence of the ca. 0.6 Ma Lava Creek B ash within Gatuña Formation strata along Livingston Ridge on the southern side of Nash Draw (Bachman, 1980; Izett and Wilcox, 1992). At the ash locality, the Gatuña is relatively thin (several meters thick) and, as correctly mapped by Vine (1963), lies on exposed Permian strata. Vine (1963) assigned these Permian strata to the now abandoned Pierce Canyon Redbeds (see further below). The ash bed is present a few meters above the base of the Gatuña Formation at this locality. Assignment of a variety of deposits of uncertain age to the Gatuña Formation in the lower Pecos River Valley and across the border into Texas led Hawley (1993) to suggest a diachronous division into an upper part, conceptually equivalent to Bachman's (1976, 1980) notion of a post-Ogallala unit, and a lower part that is Mio-Pliocene in age and temporally equivalent to the Ogallala Formation. Hawley (1993) stated that an equally valid alternative would be to restrict the term Gatuña to post-Ogallala deposits and assign older valley and depression fills as part of the Ogallala Formation or a new lithostratigraphic unit. Examination of the Gatuña Formation in the field area provides no compelling evidence suggesting such a division, and a Quaternary age assignment for strata exposed beneath the Mescalero caliche in the map area seems reasonable. Nonetheless, we cannot yet exclude the possibility that deposits mapped as Gatuña Formation in the study area may be partly pre-Pleistocene in age, though such a proposition appears highly unlikely.

A descriptive approach to mapping the Gatuña Formation (**QTg** where undivided) is presented herein. For example, in Pierce Canyon, local deposits of conglomerate containing sedimentary (largely carbonate), igneous (porphyry), and metamorphic pebble to cobble-sized clasts (**QTgc**) appear to be inset into reddish-colored Gatuña mud, silt, and sand (**QTgr**). These possibly inset deposits may represent deposition in a former channel of the Pecos River. Elsewhere silt and sand-dominated deposits (**QTgs**) that vary in color from pink, to red, tan and yellow are exposed. The highest levels of Gatuña Formation exposures are often composed of coarser sand to sandy conglomerate (**QTgsc**), which often sit above an intraformational angular unconformity that varies in angular mismatch in as little as tens of meters. Stringers and lenticular beds of pale reddish-gray coarse sand, pebbly sand, and sandy conglomerate (similar to **QTgsc**) are also commonly found intercalated within other Gatuña Formation facies. Intraformational angular unconformities are likely related to solution subsidence during accumulation of these deposits.

Paleozoic Erathem

Permian System

Outcrops of pre-Cenozoic strata are limited in the study area to small exposures of Upper Permian strata. These rocks are variably tilted, deformed, and internally disrupted, interpreted as the result of solution subsidence. At least some of this deformation is likely due to down dropping of blocks when Upper Permian strata sat higher in the landscape than the present day earth's surface. All of the exposures of Permian strata in the map area are probably assignable to the Rustler Formation, although a small exposure of redbed mud to fine sandstone exhibiting distinctive millimeter- to centimeter-wide reduction spots at the mouth of Dog Town Draw is speculatively assigned to the overlying uppermost Permian Dewey Lake Redbeds. The Dewey Lake Redbeds unit (also referred to as the Quartermaster Formation) is dominantly composed of red, terrestrial fine-grained sandstone and mudstone (Vine, 1963). A thickness of 200 feet (61 meters) was measured for the overlying Dewey Lake Redbeds (**Pd**) at the Project Gnome site near the northeastern corner of the map area (Gard, 1968).

The Rustler formation consists largely of marginal marine red and yellow siliciclastic mudstone, gypsum, fine-grained sandstone, and carbonate mudstone (including the Magenta and Culebra members). A number of poorly exposed, low, hummocky outcrops near the mouth of Wood Draw expose variously deformed beds of carbonate, red and yellow mudstone, brown sandstone, and gypsum. Some of the exposures appear to be capped by caliche in that area. On the north side of Pierce Canyon, a large block of the Rustler Formation was identified by Vine (1963) as probably belonging to the Magenta member (Fig. 3). Strata at this outcrop are tilted about 25 degrees to the north-northwest and consist of a 1 to 2 meter thick bed of recrystallized carbonate mudstone, overlain by a several-meter succession of thinly bedded to laminated carbonate mudstone and siliciclastic mud, followed by redbed mudstone with at least one, thin lenticular bed of carbonate mudstone. Vine (1963) measured 72 ft (22 m) of Gatuña Formation sand, mud and gravel overlying the tilted block of Rustler at this locality. The redbed mudstone beneath the Gatuña Formation is similar in appearance to the outcrop mapped as Dewey Lake Redbeds, but is too small to map separately at 1:24,000 scale. Based on log interpretations, about 110 meters of Rustler Formation (**Pr**) remains beneath the land surface in the vicinity of the line of section shown on the geologic map.

SUBSURFACE GEOLOGY

Subsurface Neogene-Quaternary Alluvial Fill

The overall Late Cenozoic removal of Mesozoic rocks from the Delaware Basin and downcutting by the Pecos River system has been complicated by subsidence associated with dissolution of Permian evaporites, and it is generally recognized that local Neogene alluvial deposits may potentially be present in the subsurface. Thus, these and all other relatively young deposits are labeled **QTu** on the cross section (undivided Neogene-Quaternary valley fill). The thickness of unit **QTu** (i.e. depth to bedrock) depicted on the cross section is generally poorly constrained. Geophysical borehole logs examined for this project rarely provide useful information for the upper few hundreds of feet beneath the land surface, and the distribution of water-well logs is generally sparse and in some cases the lithological logs are difficult to interpret.

Examination of logs in the vicinity of the map area and the distribution of Permian bedrock outcrops examined in the field indicate that fill thicknesses are highly variable. For example, water-well logs in the vicinity of the Pecos River east of the map area, indicating the presence of sand and gravelly fills 60 m or more beneath the land surface, are commonly located in proximity to nearby outcrops of the Rustler Formation. No attempt was made to capture this variability on the cross section. The depth to bedrock along the eastern end of the cross section is similarly generalized, and assumes that no Triassic rocks (Santa Rosa Sandstone) remain above Permian Dewey Lake strata in that area. A water-well log near the eastern end of the cross section (OSE well number C-03893) reports “sand” and “sandy clay” to a depth of 600 feet. Less than 2 km north-northeast of the northeastern corner of the map area, only 92 feet of fill

(Gatuña Formation and overlying alluvium) were logged at the Project Gnome site (Gard, 1968).

Paleozoic Erathem

Paleozoic sedimentary rocks underlying the map area have received considerable study resulting in a substantial literature spanning more than 100 years. More complete discussion and literature citations concerning Paleozoic strata underlying the Delaware Basin are presented in Hill (1996). Rock-unit names depicted on the cross section are listed below.

Permian System

Approximately 3500 meters of Permian marine strata underlie the study area beneath the Rustler Formation. The Upper Permian (Lopingian) Salado (**Ps**) and Castile (**Pc**) Formations consist largely of evaporites, with mainly halite in the Salado and anhydrite in the underlying Castile. These deposits accumulated in an increasingly restricted marine environment within the Delaware Basin outboard of the Capitan Reef and Northwest Shelf toward the close of the Permian (Hayes, 1964). Widespread dissolution of the evaporites present in these two formations is responsible for differential land subsidence occurring in the basin today. Dissolution of Salado halite is especially pronounced, and the unit varies in thickness from approximately 200 to 500 meters along the line of the cross section. Based on sonic and other geophysical logs it appears that much of the halite in the Castile Formation, particularly the two lower members (Halite I and II), remains intact beneath the map area, and the formation ranges from approximately 450 to 550 meters in thickness along the cross section. The Castile-Salado sequence is underlain by fine-grained siliciclastic sedimentary strata and lesser carbonates of the middle Permian (Guadalupian) Delaware Mountain Group (Hayes, 1964). The Delaware Mountain Group is composed of the Bell Canyon (**Pbc**), Cherry Canyon (**Pcc**), and Brushy Canyon (**Pbrc**) Formations, which total approximately 1150 meters in thickness beneath the study area. Lower Permian

(Cisuralian) strata of the Bone Spring (~990 m) and Wolfcamp (~550 m) formations are composed of carbonate, siliciclastic mud, and some sandy intervals (King, 1948).

Pennsylvanian Subsystem

Marine and marginal marine strata of Pennsylvanian age are approximately 780 meters thick in the study area. The youngest Pennsylvanian rocks are composed of interbedded carbonate and siliciclastic sediment assigned to the upper Pennsylvanian Canyon and overlying Cisco formations (ℙcc). These strata are underlain by carbonate, shale, and sandstone of the Atoka Formation and overlying Strawn group (ℙsa), which are in turn underlain by lower Pennsylvanian strata of the Morrow Formation (ℙm). The Morrow Formation contains thick sequences of relatively coarse fluvial-deltaic sand in the lower two thirds of the unit (Hayes, 1964; Broadhead, 2017).

Mississippian Subsystem

The oldest unit shown on the cross section consists largely of fine-grained siliciclastic sedimentary strata (shale) assigned to the Barnett Formation (Mb). The Barnett overlies older Mississippian carbonate rocks for a combined thickness of about 190 meters in the map area. These strata overlie Mississippian to Cambrian carbonate and siliciclastic strata deposited within the broader southern and eastern Laurentian continental margin, which themselves overlie Precambrian basement rocks of probable Mesoproterozoic Grenville province affinity (Hills, 1984).

STRUCTURE

The study area, lying within the larger Delaware Basin province, has been largely tectonically quiescent since the Paleozoic, with the observed deformation of Permian and Cenozoic deposits attributed to solution subsidence and the attendant removal of material within Upper Permian strata. At a regional scale, an overall dip of about one degree to the east is indicated in the map area by depths to the top of the Delaware Mountain Group determined from well logs. This broad eastward dip of pre-Cenozoic strata is attributed to the effects of either Cenozoic extension or Mesozoic tectonism

(Ewing, 1993; Cikoski, 2019). The Tobosa Basin, the predecessor of the Delaware Basin, gradually subsided during the early Paleozoic, accumulating a relatively complete sequence of lower to middle Paleozoic strata (Hill, 1996). Collision of Gondwana beginning in the early Carboniferous led to segmentation of the Tobosa Basin into the uplifts and basins associated with the Permian Basin (e.g., Diablo and Central Basin platforms, Delaware and Midland basins; Hills, 1984). Regional uplift of western North America during the late Cretaceous-Paleogene Laramide orogeny resulted in little internal deformation of strata in the Delaware Basin. Paleogene-Neogene crustal extension resulted in faulting, range uplift, and basin subsidence to the west (e.g., Salt Basin graben, uplift of the Guadalupe Mountains; Kelley, 1971).

Thus, observed deformation in the northern Delaware Basin is largely attributed to dissolution and removal of salt in the Salado and Castile formations, resulting in significant differential subsidence of the land surface. The effects of solution subsidence are expressed as a wide variety of features at multiple scales including: meter- to kilometer-scale, small amplitude closed depressions; up to 100 meter-scale down dropping of Permian strata from previously higher structural levels; up to 100s of meters of warping and down dropping of the Mescalero caliche surface resulting in features that resemble karst domes and mounds (Figs. 5, 6, 7; Bachman, 1980); variable angularity of intraformational unconformities within the Gatuña Formation of up to 10s of degrees over 10s of meters to kilometers; and angular mismatch between more steeply rotated Gatuña Formation strata and the overlying Mescalero caliche surface of up to 10s of degrees. The study area sits along the larger Balmora-Pecos-Loving trough of Hiss (1976).

The literature for the Delaware basin contains different ideas concerning the timing of salt dissolution. Some researchers (e.g., Bachman, 1976) suggest that solution subsidence occurred repeatedly over a broad span of geologic time. Regionally, solution subsidence may have occurred repeatedly over a broad span of time, beginning as early as Permian depositional timing (e.g., Kosa and Hunt, 2006). It is clear that dissolution of Permian evaporites is ongoing, as indicated by subsidence-related deformation of comparatively young Quaternary deposits (Figs. 5, 6, 7; e.g., Land et al., 2018). This differential deformation has complicated the depositional record of the lower Pecos River Valley. Better chronology of the alluvial valley fill in this region is certainly a worthy challenge and would go a long way toward resolving some of the stratigraphic problems that exist.

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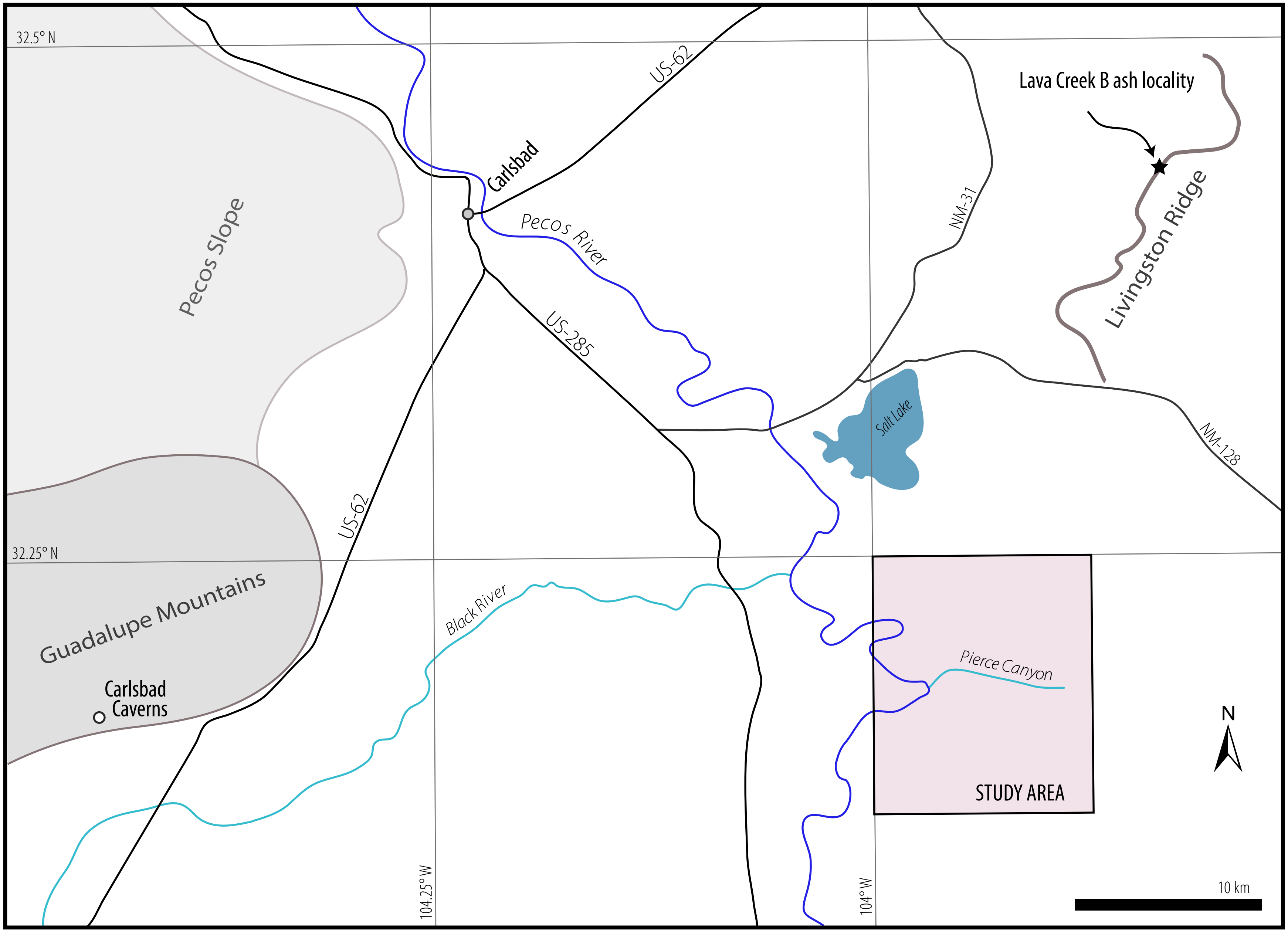

Figure 1—Geographic context for the Pierce Canyon 7.5′ quadrangle.

Figure 2—View looking southeast at the east wall of Pierce Canyon from the canyon floor at 13S 600573mE 3561649mN NAD83. The canyon floor is Quaternary alluvium with small coppice dunes formed through eolian reworking of the surface. The butte in the background is capped by a continuous petrocalcic horizon interpreted as the Mescalero caliche, which is developed on top of the Quaternary(?) Gatuña Formation siliciclastic strata that are variably exposed in the canyon walls.

Figure 3—View looking north at the north wall of Pierce Canyon towards its western end from the canyon floor at 13S 597544mE 3562820mN NAD83. Quaternary alluvial deposits form the canyon floor in the proximal foreground. In the background, the butte is capped by a continuous petrocalcic horizon interpreted as the Mescalero caliche developed on top of Quaternary(?) Gatuña Formation siliciclastic strata. Of note is the mound in the midground interpreted as the tilted block of Permian Rustler Formation overlain by Gatuña Formation as described by Vine (1963).

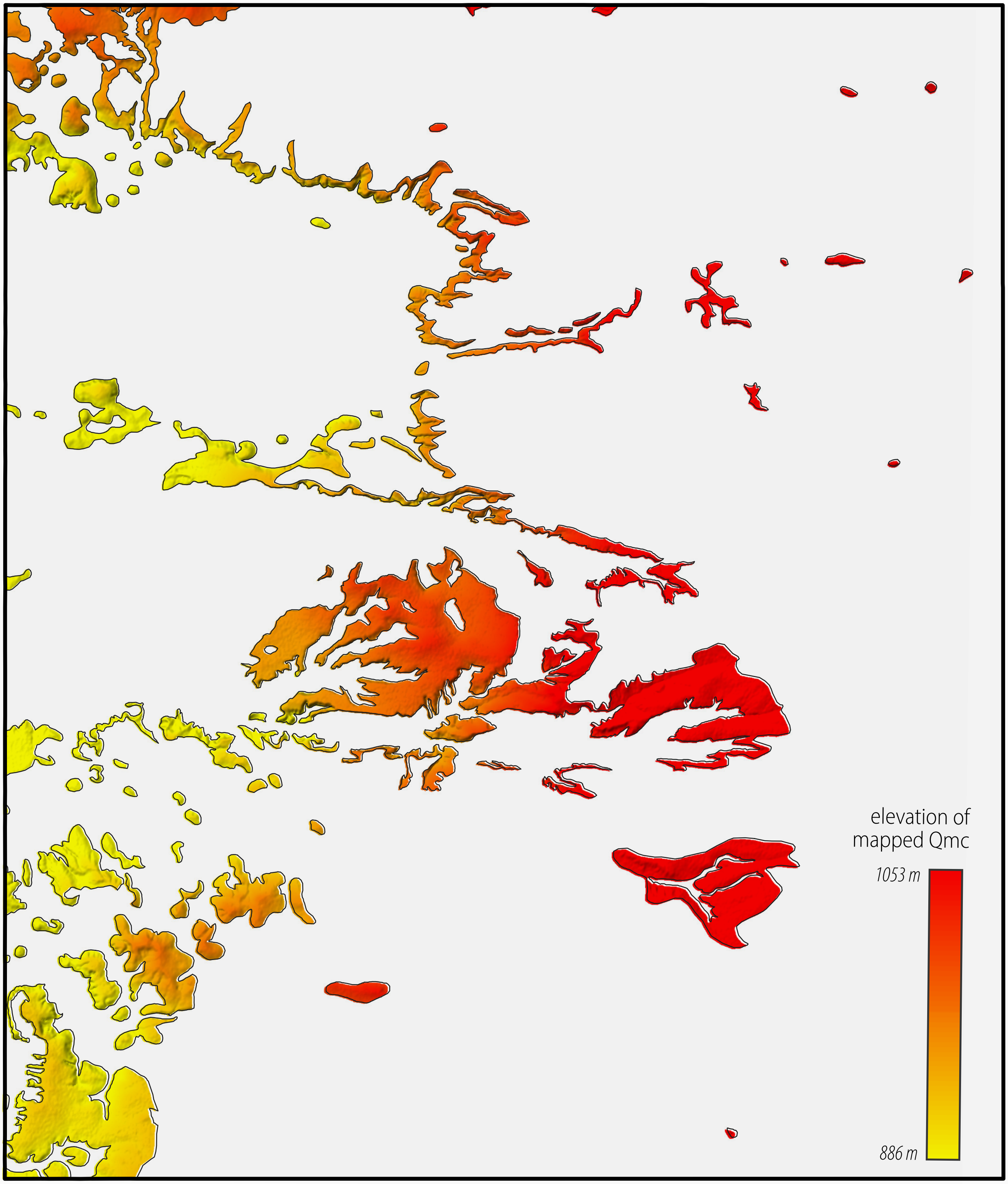

Figure 4—Elevation of areas mapped as **Qmc** within the Pierce Canyon quadrangle, highlighting the highly the variable elevation, over 150 m of relief, and sloping of the Mescalero caliche surface. This variability is interpreted to represent deformation due solution subsidence that has occurred since formation of the Mescalero caliche surface. The image itself is the result of clipping the digital elevation model (DEM; Intermap Technologies, 2008) to the **Qmc** map unit polygons. The clipped DEM was standard deviation stretched along a yellow to red color gradient, then multiplied by a hillshade derived from the clipped DEM to accentuate the finer structure of the warped surface. Figure extent is same as map area extent, but at 1:65,000 scale.

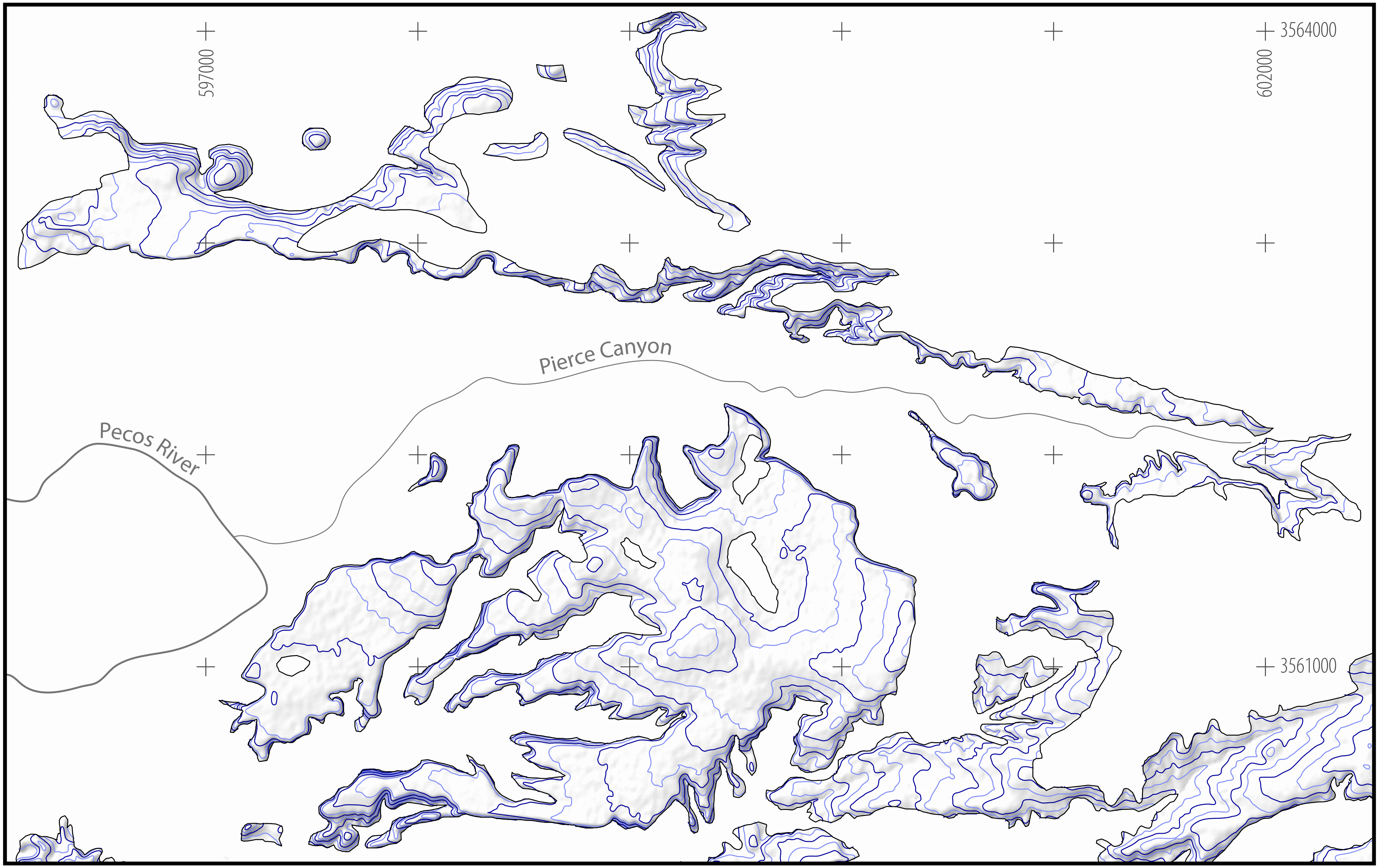

Figure 5—Elevation of areas mapped as **Qmc** in the north and south rims of Pierce Canyon, displayed as contours that emphasize the variations in elevation rather than the absolute range of **Qmc** surface elevations as in Figure 4. Underlying hillshade accentuates these variations. Bold dark blue contours are 5 m intervals, with intervening light blue contours giving 2.5 m intervals. UTM coordinates given in NAD83 zone 13, map at 1:24,000 scale.

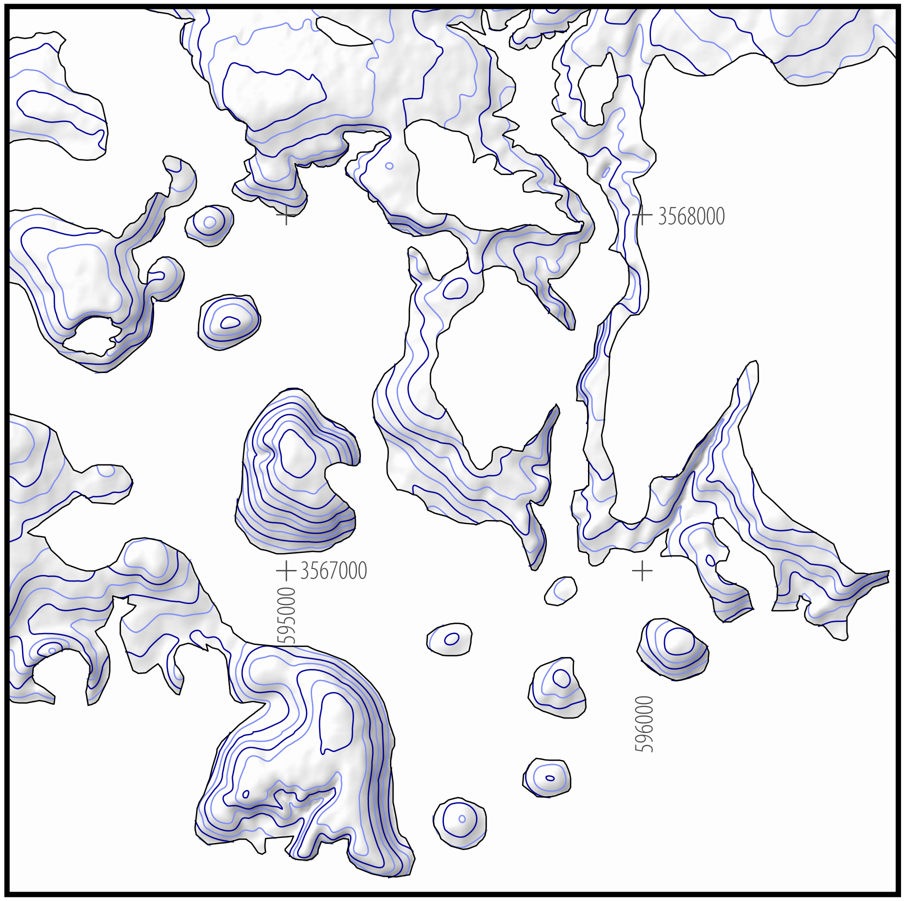

Figure 6—Elevation of areas mapped as **Qmc** in the northwestern corner of the map area, displayed as contours that emphasize the variations in elevation and underlain by a hillshade layer. Coordinate system and scale same as Figure 5.

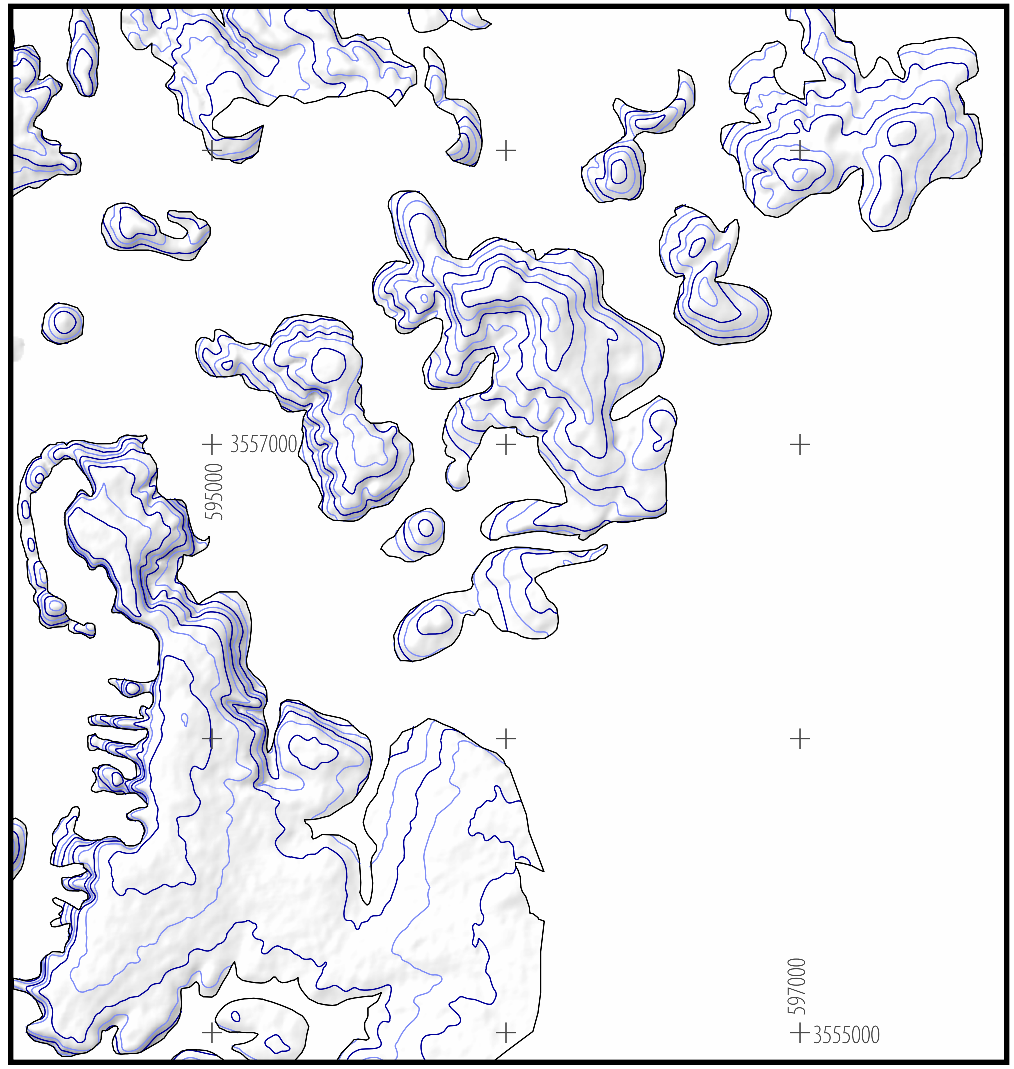

Figure 7—Elevation of areas mapped as **Qmc** in the southwestern corner of the map area, displayed as contours that emphasize the variations in elevation and underlain by a hillshade layer. Coordinate system and scale same as Figure 5.

Appendix: Description of Map Units

CENOZOIC ERATHEM

Holocene Series

Anthropogenic Units

daf—**Disturbed ground and artificial fill (Historic to Modern)**—Compacted gravels, sands, and muds underlying dams, roads, areas of intensive agriculture, and other artificial constructions. Only mapped where extensive or concealing underlying geologic relations. Deposit thicknesses are 0 to about 10 m.

Short description—Areas where intensive anthropogenic activities obscure the nature of the underlying geology.

Alluvial Deposits

Qar—**Modern, historic, and younger (recent) alluvial deposits (Holocene to Modern)**—Unvegetated or poorly vegetated sands, muds, and gravels along active drainage channels or underlying low terraces, including some of the youngest and lowest terraces along the Pecos River. Mapped deposits may include areas submerged beneath water on aerial imagery. Deposits are unconsolidated, and no evidence of significant soil development was observed. Deposit thicknesses are 0 to 4 m.

Short description—Younger to modern alluvial deposits.

Qae—**Alluvially reworked eolian deposits (Holocene to Modern)**—Alluvially reworked red Qe eolian sand, reworked by eolian processes in channel floors. Channel walls include exposures of cemented gravel and variably indurated sands with variable proportions of pebbles. Subangular to rounded pebbles dominantly consist of Qmc caliche, except a single locality containing red-brown mudstone clasts immediately adjacent to Pipeline Road in the northern central portion of the quadrangle.

Short description—Alluvial deposits derived from eolian sands.

Qa—**Alluvium (Holocene)**—Alluvial sands, muds, and gravels exposed in canyon floors, minor alluvial fans, and drainages. Deposit characteristics vary with the nature of the materials exposed up-gradient and underlying the deposit. Deposits are unconsolidated with no evidence of significant soil development observed. Deposit thicknesses are 0 to 7 m. Includes active channels and **Qar** where these deposits are too small to map at this scale.
Short description—Alluvial deposits.

Pecos River Terrace and Floodplain Deposits

Qt2—**Younger terrace deposits (Holocene)**—Brown, thinly laminated silts and very fine sands exhibiting very weak surface soil development. Sands are dominantly siliceous. Deposits are up to 4 m thick.
Short description—Younger Pecos River terrace deposits.

Qt1—**Older terrace deposits (Holocene)**—Brown, thinly bedded silts and lesser silty very fine-grained sands overlying light brown silty sands with trace pebbly channel fills, and bearing a surface soil characterized by a Stage I morphology carbonate horizon. Deposits overall are as much as 8 m thick.
Short description—Oldest Pecos River terrace deposits.

Eolian Deposits

Qe—**Eolian sheet sand (Holocene)**—Windblown fine, distinctive red-brown sands underlying dune fields and wind-sculpted hummocky terrain. Locally color varies to pale-yellow and grey-white. They are principally exposed in a large eolian sand sheet, covered by coppice dunes and other dune-forms, occupying most of the western half of the quadrangle. Deposits are loose with no evidence of notable soil development observed. Up to 10 m thick.
Short description—Eolian sheet sands and dunes.

Qd—**Eolian dune deposits (Holocene)**—Windblown, orange- to tan-yellow silts and sands. Generally expressed as areas of significant coppice dunes forming on top of, and likely derived from alluvial deposits. Rarely form more complex dune forms. More isolated deposits than, and distinct in color from **Qe**. No evidence of notable soil development was observed. **Qd** deposits are generally less than 2 m thick, with local variations as thick as 8 m.

Short description—Isolated eolian sand dune deposits.

Miscellaneous Deposits

Qdf—**Depression Fill (Holocene)**—Silts, sands, and clays accumulating in closed or nearly closed depressions. Dominantly slopewash- and eolian-transported muds and very fine sands, with trace coarser material, up to 2 m thick.

Short description—Silts, sands, and clays accumulating in closed or nearly closed basins.

Qc—**Colluvium (Holocene)**—Colluvial deposits covering slopes below rims of **Qmc** in canyon walls. Composed of silt to medium sand with pebbles to boulders of **Qmc** caliche.

Short description—Slope-blanketing colluvial deposits.

Qg—**Alluvial-colluvial gravel (Holocene)**—Alluvial and colluvial gravel consist of sub- to well-rounded quartzite, chert, volcanics, and limestone pebbles. Generally forms low, hummocky mounds thought to represent weathering and reworking of **QTg** conglomerates. Differentiated from **Qac** by a conspicuous lack of caliche clasts derived from **Qmc**.

Short description—Alluvial and colluvial gravel lacking caliche clasts.

Qac—**Alluvial-colluvial deposits (Holocene)**—Alluvial and colluvial gravel consisting of sub- to well-rounded pebbles-cobbles of caliche, quartzite, chert, volcanics, and limestone. Generally covers slopes in canyon walls or forms gentle, hummocky mounds thought to represent reworking of **QTg** conglomerates and **Qmc**. Differentiated from **Qg** by the presence of abundant **Qmc** caliche clasts.

Short description—Alluvial and colluvial gravel including caliche clasts.

Pleistocene Series

Qcc—Cemented conglomerates along the Pecos River (upper Pleistocene)—Well-cemented pebble to cobble conglomerates and rare interbedded sandstone lenses. Carbonate cementation is ubiquitous in these units, but does not exhibit pedogenic features. Conglomerates consist of carbonate, siliceous, and volcanic clasts supported by a carbonate cement matrix.

Short description—Well cemented conglomerates exposed along the Pecos River, sitting above terrace surfaces, with carbonate, siliceous, and volcanic pebbles in a carbonate matrix.

Mescalero Caliche

Qmc—Mescalero caliche (Upper Pleistocene)—Relict calcic soil horizon exhibiting Stage IV+ pedogenic carbonate morphology, with a durable, discontinuously preserved upper horizon of laminated carbonate up to a few decimeters thick. Below the laminated caprock is up to 4 meters (typically 1 to 3 meters) of clastic alluvium engulfed by white to gray carbonate. The carbonate becomes softer and earthier with depth. The relative proportion of parent material also increases with depth. Pedogenic brecciation and recrystallization structures are rare. Unit is relatively resistant to erosion and forms vertical cliffs along bluff lines. Commonly, the paleosol formed in sand and rounded gravelly deposits (Gatuña Formation), which include clasts of limestone, quartzite, chert, sandstone, and porphyritic igneous rock; in other areas it formed in finer-grained deposits, and locally appears to be present immediately above Rustler Formation strata. Over much of the map area the Mescalero caliche is overlain by windblown sand and/or surface alluvium.

Short description—Relict, well-developed, cliff-forming carbonate soil horizon developed in gravelly and finer-grained deposits of the Gatuña Formation.

Gatuña Formation

QTg—Undivided Gatuña Formation (Miocene-Pliocene? to Pleistocene)—The Gatuña Formation generally consists of pale-red sand and mud, with stringers and locally thick lenticular beds of reddish-gray pebbly sand to conglomerate. According to some reports thickness generally varies from a few meters to 10 meters or more, reaching up to 100 meters in the Pierce Canyon/Cedar Canyon area. The unit is capped by a well-developed calcic paleosol (Qmc) in the map area. The base of the Gatuña Formation is poorly exposed in the map area. Near the mouth of Wood Draw surface exposures of the Rustler Formation are overlain by Mescalero caliche presumably developed in thin Gatuña deposits. A few meters of Gatuña Formation deposits were observed to overlie the Permian Rustler Formation at the surface. Given the single tephrochronology datum and observed field relationships, we prefer a Pleistocene age for the entire Gatuña Formation but cannot rule out that the formation is partly upper Neogene.

Short description—Dominantly pale-red sand and mud, with stringers and lenticular beds of reddish-gray pebbly sand to conglomerate.

QTgc—Conglomerate-dominated facies of the Gatuña Formation (Miocene-Pliocene? to Pleistocene)—Well-cemented pebble conglomerates and rare sandstones underlying, grading up-section into, or in proximity to the Mescalero caliche. Conglomerates consist of poorly sorted, clast-supported, rounded to well-rounded pebbles with trace cobbles, of lithologies including common limestone, sandstone, quartzite, chert, felsic to intermediate volcanics, and absent-to-trace granite.

Short description—Conglomerate-dominated facies of the Gatuña Formation.

QTgr—Mud and sand-dominated facies of the Gatuña Formation (Miocene-Pliocene? to Pleistocene)—Dominantly light reddish brown mudstones and sandstones with lesser conglomerates of the Gatuña Formation that underlie caliche in the western portion of the map area. Compared to other Gatuña mudstones and sandstones, these deposits tend to be darker colored, better cemented, and generally thicker.

Short description—Mud and sand-dominated facies of the Gatuña Formation.

QTgs—Sand-dominated facies of the Gatuña Formation (Miocene-Pliocene? to Pleistocene)—Pink to tan to grey, thin-thick bedded, fine-grained sandstones of the Gatuña Formation, locally interbedded with minor, thin mud-silt and pebble conglomerate layers. Uncommonly include yellow, thin-bedded sandstone layers in the western portion of Cedar Canyon. Occasionally overlain across a variably angular intraformational unconformity by 0.1-3 meters of subhorizontal, medium-bedded to massive, grey to white sandstones and sandy conglomerates (e.g., **QTgsc**).

Short description—Sand-dominated facies of the Gatuña Formation.

QTgsc—Sandy-conglomerate facies of the Gatuña Formation (Miocene-Pliocene? to Pleistocene)—Medium bedded to massive sandy pebble conglomerate, interbedded with thin to thick bedded, white to grey to tan sandstones, of the Gatuña Formation underlying, grading up-section into, or in proximity to the Mescalero caliche. Conglomerates consist of poorly sorted, rounded to well rounded, matrix-supported pebbles, with rare cobbles, of limestone, chert, quartzite, and mafic to felsic volcanics.

Short description—Sandy-conglomerate facies of the Gatuña Formation.

Undivided Cenozoic Deposits

QTu—Undivided Neogene-Quaternary deposits (Neogene to Modern)—Cross section only. Undivided Cenozoic deposits, including Quaternary surficial deposits, the Gatuña Formation, and possible subsurface Neogene alluvial fill. Well logs suggest a maximum thickness of approximately 160 m along the eastern end of the cross section, and 100 m in the vicinity of the Pecos River.

Short description—Cross section only. Undivided Cenozoic deposits, including Quaternary surficial deposits and the underlying Gatuña Formation.

PALEOZOIC ERATHEM

Permian System

Ochoan Series (Upper Permian)

Pd—Dewey Lake Redbeds (Ochoan)—Red, laminated to thinly bedded coarse siltstone and fine-grained subarkosic sandstone. Planar, ripple, and larger-scale cross sets are common, as are greenish-gray reduction spots and zones in some exposures. Unit is exposed to the north of the map area in the vicinity of Nash Draw, where it stratigraphically overlies the Permian Rustler Formation and underlies the Triassic Santa Rosa Formation. Along the eastern end of the cross section the unit is estimated to be ~50 m thick and overlain by late Cenozoic alluvial-fill deposits. However, intervening remnants of basal Triassic strata may be present. Dewey Lake strata may be exposed in the map area near a small gully cut near the mouth of Dog Town Draw.
Short description—Red, laminated, coarse siltstone and fine-grained sandstone.

Pr—Rustler Formation (Ochoan)—Red, yellow and gray mudstone, gypsum, fine-grained sandstone, and carbonate. Two widespread carbonate intervals named the Culebra (lower in the section) and Magenta members are recognized as stratigraphic markers to subdivide this lithologically heterogeneous formation into members. Unit is present in the subsurface throughout the map area. It is overlain by Cenozoic alluvial deposits or by the Permian Dewey Lake Formation in the eastern part of the map area. Underlain by the halite-dominated Salado Formation, the Rustler Formation has been variably deformed by solution subsidence and collapse. Based on borehole logs up to 110 meters of Rustler strata are present along the cross section. Several poorly exposed outcrops near the mouth of Wood Draw expose variously deformed, broken tilted blocks of carbonate, red and yellow mudstone, brown sandstone, and gypsum.
Short description—Mudstone, gypsum, fine-grained sandstone, and carbonate.

Ps—**Salado Formation (Ochoan)**—Cross-section only. Largely halite with economically important potash zones, several named anhydrite beds, and minor amounts of siliciclastic mud and fine sand. Dissolution of Salado halite beneath the map area is readily apparent from examining well logs, and unit thickness (~200 to 500 m along the cross-section) changes abruptly. Exposures of variously deformed deposits, consisting mainly of red mud and gypsum, including secondary selenite, have been referred to as "Salado residue" in some reports (e.g., Gard, 1968). Based on lithology, such deposits may represent collapsed Rustler strata, resulting from the dissolution of underlying Salado halite.

Short description—Cross section only. Largely halite; contains several named anhydrite beds and minor amounts of siliciclastic sediment.

Pc—**Castile Formation (Ochoan)**—Cross section only. Finely crystalline, pale-gray calcium sulfate, interlaminated with brown to dark-gray calcite. The unit contains a thin, basal laminated limestone, and relatively thick halite intervals that provide a basis for dividing the formation into members. The Castile Formation underlies the Salado Formation and, unlike the Salado Formation, is restricted to the Delaware Basin proper (i.e. was not deposited on the surrounding marine shelf). Based on geophysical logs much of the halite in the Castile Formation, particularly in the two lower members (Halite I and II), remains intact in the map area. The thickness ranges from approximately 450 to 550 meters along the cross section, and is underlain by the Bell Canyon Formation.

Short description—Cross section only. Interlaminated anhydrite and calcite, halite, and minor limestone and siliciclastic sediment.

Guadalupian Series (Middle Permian)

Delaware Mountain Group

Pbc—**Bell Canyon Formation (Guadalupian)**—Cross section only. Predominately buff to brown, fine-grained, subarkosic sandstone and siltstone, with some shale intervals.

Siltstone and fine sandstone are commonly finely laminated and carbonaceous. The unit contains named carbonate intervals, which thicken and grade into the Capitan Formation along the margin of the Delaware Basin. The uppermost named limestone, the Lamar, is readily apparent on gamma-ray logs. The top of the Bell Canyon Formation is at the top of a siliciclastic interval (Reef Trail Member) that overlies the Lamar limestone beds. The Bell Canyon is approximately 290 m thick in the map area.
Short description—Cross section only. Dominantly subarkosic, very fine-grained sandstone and siltstone, with minor carbonate beds.

Pcc—**Cherry Canyon Formation (Guadalupian)**—Cross section only. Predominately buff to brown, fine-grained, subarkosic sandstone and siltstone, with some shale intervals. Siltstone and fine sandstone are commonly finely laminated and carbonaceous. The unit contains named carbonate intervals, which thicken and grade into the Capitan Formation along the margin of the Delaware Basin. The top of the Cherry Canyon Formation is placed at the base of the lowest carbonate interval (Hegler) in the Bell Canyon Formation. The Cherry Canyon Formation is approximately 375 m thick in the map area based on log picks.
Short description—Cross section only. Dominantly subarkosic, fine-grained sandstones and siltstones, with minor carbonate beds.

Pbrc—**Brushy Canyon Formation (Guadalupian)**—Cross section only. Tan and brown sandstone and siltstone, with shale beds in the lower part. The unit may contain thin beds of gray-brown carbonate and coarse-grained siliciclastic deposits near its base. Sandstone and siltstone are commonly laminated. The contact between the Cherry Canyon and Brushy Canyon formations was historically chosen in outcrop at a lithologic change between comparatively coarse-grained sandstone beds in the Brushy Canyon and finer-grained deposits beneath the Getaway limestone interval of the Cherry Canyon Formation. Neutron density-porosity logs show a distinct, laterally traceable log response compatible with such a change. The contact between siliciclastic deposits at the base of the Brushy Canyon Formation and uppermost Bone Spring carbonate mud is readily identified on gamma-ray logs. The Brushy Canyon Formation is approximately 485 m thick in the map area.

Short description—Cross section only. Dominantly subarkosic sandstone and siltstone with coarser sandstone, shale intervals and minor carbonate in the lower part.

Cisuralian Series (Lower Permian)

Pbs—**Bone Springs Formation (Cisuralian)**—Cross section only. Dark gray to brown, thinly bedded carbonate mudstone, with varying amounts of intercalated dark gray calcareous shale. Contains three regionally recognized sandy intervals (first, second and third Bone Spring sands) consisting of light gray to tan, fine-grained sand with micaceous, shale or calcareous intervals (the stratigraphic position of the lower and upper sandy intervals are indicated on the cross section). The Bone Spring Formation is up to 990 m thick in the map area.

Short description—Cross section only. Carbonate mudstone, subordinate shale and sandstone.

Pw—**Wolfcampian Series (Cisuralian)**—Cross section only. Greenish gray, brown and black calcareous and carbonaceous shale, with some carbonate and siliciclastic sand. The top of the Wolfcamp lies beneath the third Bone Spring sand; the base of the unit was chosen on wireline-logs at the top of a sequence of alternating shale and carbonate beds assigned to the Upper Pennsylvanian Canyon-Cisco interval. Approximately 540 m thick in the map area.

Short description—Cross section only. Calcareous and carbonaceous shale with beds of carbonate and sandstone.

Pennsylvanian Subsystem

IPcc—**Cisco Formation and Canyon Group undivided (Upper Pennsylvanian)**—Cross section only. Interbedded carbonate and shale, with some sandy siliciclastic intervals likely present. Gamma-ray logs suggest carbonate and shale beds alternate on a scale of one to several meters. The unit's base is placed at the top of a prominent carbonate interval assigned here to the top of the Strawn Formation. The Cisco-Canyon interval is approximately 130 m thick in the map area.

Short description—Cross section only. Interbedded carbonate and shale, with lesser amounts of coarser siliciclastic sediment likely present.

IPsa—**Strawn and Atoka Formations undivided (Middle (Lower-Upper?) Pennsylvanian)**—Cross section only. Interbedded carbonate, sandstone, and shale. Phylloid algal mounds are reported in the Strawn interval to the southeast of Carlsbad, NM, where the unit has been targeted for oil and gas production. The underlying Atoka Formation in the Delaware Basin contains carbonate beds, sandstone, shale, and calcareous shale. The base of the Strawn-Atoka interval is chosen on gamma-ray and resistivity logs at the top of the upper Morrow carbonate interval. Approximately 240 m thick in the map area.

Short description—Cross section only. Interbedded carbonate, sandstone and shale.

IPm—**Morrow Formation (Lower Pennsylvanian)**—Cross section only. The upper third of the Morrow Formation consists of carbonate and calcareous shale, together with fine- to medium-grained sandstone and shale. The underlying middle and lower Morrow intervals are dominantly fine- to coarse-grained sandstone, with lesser shale. Approximately 410 m thick beneath the map area.

Short description—Cross section only. There is carbonate and intercalated shale in the upper part of the formation, with sandstone and lesser shale and carbonate in the lower two-thirds of the formation.

Mississippian Subsystem

Mb—Barnett Formation (Upper Mississippian)—Cross section only. Shale and silty shale with lesser fine-grained sandstone and siltstone. The Barnett Formation is approximately 75 m thick in the map area, and overlies older Mississippian carbonate strata.

Short description— Cross section only. Shale and silty shale with lesser fine-grained sandstone and siltstone.