Geologic Map of the Malaga 7.5-Minute Quadrangle, Eddy County, New Mexico

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Open-file Digital Geologic Map OF-GM 277

Scale 1:24,000

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Executive Summary

The Malaga quadrangle lies entirely within the Pennsylvanian-Permian Delaware basin along the lower Pecos River south of Carlsbad, New Mexico. The oldest rocks exposed are gypsum breccia deposits belonging to the Ochoan (Upper Permian) Salado Formation, a unit that, where intact, consists of halite and lesser gypsum/anhydrite, polyhalite, potassium-rich salts, and subordinate fine-grained clastic rocks, but has often be subject to intense dissolution and brecciation where occurring close to the surface. Overlying the Salado are the (ascending order) Los Medaños, Culebra Dolomite, Tamarisk, and Magenta Dolomite Members of the Rustler Formation (the highest member, the Forty-niner Member, is not present). The Los Medaños Member is the most extensive member in this area and consists of mudstones and gypsum that is commonly deformed or brecciated. The Culebra Dolomite is a distinctive cream-colored ledge-former that crops out well throughout the quadrangle and commonly well-illustrates the shallow structure of the area. The Tamarisk and Magenta Members are both highly deformed and only locally identifiable; the former, where intact, is dominantly gypsum/anhydrite, while the latter is mainly thinly-bedded arenaceous dolomite. The Ochoan Series is unconformably overlain and inset against by late Cenozoic (middle? Miocene to Middle Pleistocene) Gatuña Formation clastic sedimentary rocks, which consist dominantly of mudstones to fine-grained sandstones with lesser coarser-grained clastic rocks, and in which have developed two mappable caliche horizons. Where feasible, the Gatuña is divided into upper and lower members by an inferred intraformational unconformity, the evidence for which includes an intraformational petrocalcic carbonate horizon of Stage VI morphology that appears to be inset against by and reworked into latter Gatuña conglomerates, which are in turn are overlain by a Stage V petrocalcic carbonate horizon that caps the Gatuña. The Stage VI petrocalcic carbonate horizon is the local top of the lower Gatuña, and is here informally named the Pierce Canyon caliche; the Stage V morphology petrocalcic horizon developed in the top of the upper Gatuña was previously named the Mescalero caliche. Typically the Pierce Canyon caliche lies at higher elevations relative to nearby Mescalero caliche outcrops, but locally the Pierce Canyon caliche is downwarped and underlies upper Gatuña sediments capped by the Mescalero. A distinct component of the upper Gatuña Formation is a set of conglomerates that line the major drainages of the area and are inset into the Pierce Canyon caliche and Ochoan Series strata, and which may be the oldest deposits of the upper Gatuña. However, the mudstones and sandstones of both the upper and lower Gatuña Formation are very similar in appearance, and away from stratigraphic controls (the two caliches and the drainage-lining conglomerates), these outcrops are typically assigned to an undifferentiated Gatuña Formation map unit. The Gatuña is overlain and inset against by unnamed Holocene alluvial and eolian sediments.

Well logs were examined for data on the units underlying the Salado Formation, and the reported formation tops for Permian units as old as Leonardian suggest little tectonic deformation has occurred in the area since the Upper Permian. However, substantial deformation is apparent at the surface, which is inferred to be a consequence of variable dissolution of the evaporite-rich Ochoan Series (Castile and Salado Formations as well as some members of the Rustler Formation). Karst deformation features occurring in the area include outcrop-scale sinkholes and caves and localized syndepositional subsidence of Gatuña Formation sediments; map-scale karst domes and solution troughs; and collapse breccias and 'residues' that result from regional or blanket dissolution. The dissolution is inferred to have most impacted the Salado Formation, and appears to have occurred episodically from Ochoan time through the Middle Pleistocene.

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1. Introduction

1.1. Geologic and geographic setting

The Malaga quadrangle lies in far southeastern New Mexico south of the city of Carlsbad along the Pecos River (Figure 1-1). The quadrangle is named for the town of Malaga, which lies within the quadrangle where US Highway 285 crosses the Black River (Figure 1-2). Relief is generally low, with elevations ranging from about 870 to 960 meters (m) above mean sea level (amsl), and topography is mainly associated with incision of the drainages in the area, including the Pecos and Black Rivers and Salt Draw. However, a number of broad, often closed depressions and low, isolated domal hills are also present, which are likely karst features associated with variable dissolution of underlying evaporite-rich strata, as described in subsequent sections.

Geologically, the study area lies within the Delaware basin (Figure 1-1), one of the three major structural/sedimentologic basins of the Permian Basin oil and gas region of southeastern New Mexico and west Texas. Development of the Delaware basin as a distinct structural entity began in the Pennsylvanian (Hill, 1996), and subsidence continued through at least the Guadalupian (Upper Permian) (Ewing, 1993). The rim of the basin is commonly mapped along the Capitan reef complex (Figure 1-1), which developed in Guadalupian time, although the sedimentologic basin likely extended further Permian-landward in earlier times (cf., Hayes, 1964). Ochoan evaporites, particularly those of the Castile Formation, subsequently filled the basin, and subsequent Ochoan rocks of the Salado, Rustler, and Dewey Lake Formations blanketed the area both within and outside the Capitan reef complex. Of this history, only rocks of the Salado and Rustler Formation are preserved within the quadrangle at the surface today.

Mesozoic strata of the lower Cretaceous rocks at one time covered the area (Lang, 1947), but have subsequently been removed by erosion; whether or not Triassic or Jurassic sediments once buried the study area is not clear. Upper Cenozoic alluvial and eolian sediments later blanketed the region, sediments that are here referred to the lower Gatuña Formation (Powers and Holt, 1993; Hawley, 1993; this report). Later incision and local backfilling by an ancestral Pecos River and its tributaries deposited inset alluvial sediments and sedimentary rocks that are here referred to the upper Gatuña Formation. Gatuña sedimentation along the lower Pecos River valley is strongly influenced by variable dissolution and karst development in the underlying Ochoan strata (cf., Bachman, 1987), and as a consequence deposit preservation is highly variable. However, rocks of the Gatuña are commonly found within the quadrangle along the Pecos and its tributaries as well as along the eastern margin of the study area.

Tectonically, the area has been largely quiescent since Guadalupian time (Powers et al., 1978). However, dissolution of Ochoan evaporites in the shallow subsurface has resulted in substantial localized and regional karst structures that deform the exposed Ochoan and late Cenozoic deposits (Vine, 1960; Bachman, 1980; Bachman, 1987). All of the structure apparent on the Malaga quadrangle is interpreted to be the product of dissolution of subsurface Ochoan deposits, principally of the Salado Formation. Hence, the abundance of ‘structural features’ such as folds and tilted strata shown on the map are inferred to be shallow features lacking deep roots or tectonic underpinnings.

1.2. Methods

Geologic mapping was performed during the years 2017-19 using standard methods (e.g., Compton, 1985). Field mapping was supplemented with remote mapping using 2009-vintage digital stereo aerial imagery using the ERDAS StereoAnalyst extension (Hexagon Geospatial, 2017) to the Esri ArcGIS software package (Esri Inc., 2017). Data was compiled into a geographic information systems (GIS) geodatabase using Esri's ArcGIS software platform. Geologic terms used herein are after Compton (1985), soil terms after Birkeland (1999), carbonate horizon stages after Gile et al. (1966) and Machette (1985), and color notation after Munsell Color (2009). Coordinates reported herein are Universal Transverse Mercator (UTM) coordinates in meters with respect to the North American Datum of 1983 (NAD83), Zone 13S.

Stratigraphic nomenclature follows established names in common usage to the area (cf., King, 1948; Hayes, 1964; Kelley, 1971; Powers et al., 1978; Bachman, 1980; Holt and Powers, 1988; Powers and Holt, 1993; Hawley, 1993; Scholle et al., 2007; Figure 1-3). Hawley (1993) and Pazzaglia and Hawley (2004) imply that the lower Gatuña Formation, as used here, may be a correlative of the Ogallala Formation (e.g., their figures 2 and 10, respectively), given the apparent overlap in ages and similarity in deposits. While I recognize this age correlation, I choose to continue to use the term Gatuña for these rocks, in large part due to the difficulty in accurately referring any single given outcrop to the upper or lower Gatuña based on sedimentologic features alone.

1.3. Acknowledgements

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2. Cenozoic Erathem

2.1. Post-Gatuña Formation deposits

The youngest sediments in the study area are Holocene alluvium and eolian material that lies along active drainages, blankets upland areas and low-gradient slopes, and fills closed depressions. Map units Qtp3, Qtp2, Qtp1, and Qtby, are low terrace and active floodplain silt- and sand-dominated deposits along the Pecos (Qtp_ units) and Black (Qtby) Rivers (Figure 2-1). These deposits are weakly laminated to thinly bedded and bear weak to absent surface soils. Surface soils of the oldest deposits, Qtp1, exhibit darkened A horizons up to 25 cm thick overlying relatively thin Stage I morphology carbonate horizons up to 10 cm thick that are characterized by fine nodules and filaments of carbonate. This level of development suggests a Holocene age for these deposits (cf., table 2 of Machette, 1985). Terrace treads overlying Qtp1 are typically about 5 to 13 m above the historic Pecos River floodplain (Qah). The inset, younger Qtp2 deposit similarly has a thin (circa 5 cm thick) darkened A horizon overlying a salt-enriched horizon characterized by trace very fine nodules and filaments of carbonate ± gypsum salts (Stage I morphology or less). Again, a Holocene age is indicated, and overlying tread heights are typically about 3 to 7 m above the historic Pecos River floodplain. Qtp3 exhibits no significant soil development, and is likely a part of the active floodplain of the Pecos River, being only up to about 4 m above the floodplain directly along the river and often within 2 m of the floodplain. Qtby lies along the Black River, and where examined in outcrop, exhibits no significant soil development, similar to unit Qtp3. However, in places, the tread height overlying these deposits is up to about 8 m above the historic Black River floodplain, and hence the age of the deposits may be diachronous and may include deposits equivalent in age to older Pecos River terrace deposits (Qtp1 or Qtp2). Each of these deposits consists mainly of silts and very fine sands that, where they can be identified, are dominantly of siliceous material. Thin, coarser-grained, lenticular paleochannel fills were observed in some outcrops in the lowest thirds of Qtp1 deposits that consist of medium sands to fine rounded pebbles, with lithologies including quartzite, chert, dolomite, and sandstone. These channel fills may be found in the lower portions of the younger deposits as well, but were not observed in the field. Along ephemeral drainages, an undifferentiated younger alluvial unit, Qay, is mapped that dominantly consists of sands and silts with lesser gravels derived from nearby outcrops of older deposits. No evidence of significant soil development was observed in these deposits.

Much of the study area is blanketed by eolian material (units Qe, Qed) variably reworked into slopewash deposits (Qsw). Generally, the eolian and slopewash material forms low-relief gentle slopes, although dune forms are found in places along the east flank of the Pecos River (unit Qed). These deposits may be very thin, less than 1 m thick, but are often broadly mapped due to these deposits frequently masking the nature of the underlying bedrock or sediment. Where the underlying material can be discerned from sporadic outcrop, the eolian or slopewash material is not mapped. No evidence of significant soil development was observed in these deposits.

Closed depressions are a relatively common geomorphic feature to the study area, and where these depressions have accumulated enough muds and sands to mask the underlying bedrock or sediment, the deposits are mapped as Qdf. The material is dominantly fine-grained and presumably transported mainly by slopewash and eolian processes. No evidence of significant soil development was observed in these deposits.

Small-scale drainages, such as gullies, rills, and first-order ephemeral streams, may end in small alluvial fan deposits of loose sands, muds, and gravels. Where these fans coalesce into mappable extents, they are mapped as Qfy. Fans often grade into alluvium along ephemeral drainages or into depression fills. No evidence of significant soil development was observed in these deposits.

2.2. Gatuña Formation

The Gatuña Formation was originally named and generally described by Lang (Robinson and Lang, 1938) for "an assemblage of rocks of various kinds that were laid down in the (lower) Pecos Valley in post-High Plains time and apparently after the completion of the maximum cycle of erosion of this valley. The deposits are of terrestrial origin and with them began the process of refilling of this valley" (quotation from Hawley, 1993). Lang defined a type area as Gatuña Canyon in the Clayton basin to the north of the study area, and Bachman (1976) subsequently measured a reference section along the north side of Gatuña Canyon. Vine (1963) had previously measured a set of three sections along the north side of Pierce Canyon, a few kilometers east of the Malaga quadrangle, while Powers and Holt (1993) re-measured these sections as well as examined several other outcrops and drill hole core to provide a regional picture of the characteristics of the unit.

Despite this long history of study, the formation is not without controversy. Substantial karst-related deformation of Gatuña deposits, particularly along the Pecos River valley, has resulted in some measure of uncertainty in mapping and correlations, and the deposit as previously measured and mapped appears to include a substantial unconformity (Hawley, 1993). An upper age of Middle Pleistocene has been well established. Bachman (1980) found a volcanic ash in the Gatuña Formation near to Livingston Ridge that Izett and Wilcox (1982) identified as the 0.6 Ma Lava Creek B ash. A caliche commonly found capping the Gatuña Formation (Mescalero caliche of Bachman, 1976) was dated by uranium-series methods by Rosholt and McKinney (1980) to be between 0.57 ± 0.11 (lower part) and 0.42 ± 0.06 Ma (upper part) in age. This caliche is a relict petrocalcic carbonate horizon of Stage V morphology, which is typical of early to middle Pleistocene surfaces in the area (Machette, 1985; Hawley, 1993; Pazzaglia and Hawley, 2004). The Mescalero caliche caps the Gatuña Formation at its type locality (Bachman, 1976), at the measured reference sections along the north side of Pierce Canyon (Vine, 1963; Hawley, 1993), and in many locations on the quadrangle (cf., local geologic mapping by Bachman, 1980; this study).

However, age controls on the lower part of the Gatuña suggest a diachronous base and the potential for a significant intra-formational unconformity. Powers and Holt (1993) report an ash was recovered from deposits mapped as Gatuña southeast of Orla, Texas, the glass of which was K-Ar age dated to 13.0 ± 0.6 Ma, and the chemistry of which suggested correlation to one of two ~13.5 Ma ash layers from a Yellowstone hot spot source. Further, Hawley (1993) indicates that the Gatuña Formation on the south side of Pierce Canyon, across from the sections measured by Vine (1963), is capped by a Stage VI morphology carbonate horizon, comparable to the 'caprock' caliche soil capping the Miocene-early Pliocene Ogallala Formation (for age summary, cf. Pazzaglia and Hawley, 2004). These lines of evidence suggest the base of the Gatuña may be as old as middle Miocene. However, within the section measured by Bachman (1976) are clasts of reworked Stage VI caliche (Bachman, 1974; Powers and Holt, 1993; Hawley, 1993), interpreted to be derived from the Ogallala caprock caliche. This would suggest the base of the Gatuña at its type locality is younger than early Pliocene, and would suggest some period of erosion followed the development of a nearby Stage VI, presumably Mio-Pliocene age caliche, in order to expose the soil and rework the caliche into the Gatuña sediments in Gatuña Canyon. Indeed, Hawley (1993) notes that the northern rim of Pierce Canyon, which is capped by the Stage V Mescalero caliche, is about 21 m (71 ft) lower than the southern rim, which is capped by a Stage VI caliche, suggesting the Middle Pleistocene Mescalero is inset against the Mio-Pliocene soil. Powers and Holt (1993) note the presence of a conglomerate toward the top of the northern Pierce Canyon section that is in slight to pronounced angular unconformity (up to at least 20°) with underlying Gatuña strata, a conglomerate which may be lowermost post-incision sediments. The implication is that the Gatuña Formation, as mapped, encompasses a significant unconformity that separates a lower, Ogallala-age-equivalent, middle? Miocene-early Pliocene Gatuña from an upper, late Pliocene?-middle Pleistocene Gatuña Formation (e.g., figure 2 of Hawley, 1993).

An early goal of mapping along the lower Pecos River valley was to gather more data on the Gatuña Formation sediments in order to better elucidate this hypothesis. Given that only the upper Gatuña Formation appears to be present at its type locality (where reworked caliche conglomerate clasts were observed throughout by Bachman, 1974, and Powers and Holt, 1993), an argument could be made to abandon the use of the term “Gatuña” for the older, Ogallala-equivalent deposits, instead referring these older deposits to a new formation, or perhaps to the Ogallala itself. Some observations presented below, as well as on-going mapping along the Pecos River valley, suggest that this differentiation may be possible. However, at present, there is still ambiguity in many locations as to the age and proper stratigraphic placement of many outcrops of “Gatuña” in this quadrangle, due to a combination of lithologic similarity between the upper and lower Gatuña, of non-continuous deposits as a consequence of subsidence deformation, and overall poor exposure. I, therefore, chose to use a single Gatuña Formation with informal upper and lower members where differentiable, rather than referring to the lower Gatuña Formation sediments as a separate unit. This convention also makes the present work more consistent with older maps of the area.

As mentioned above, Hawley (1993) first indicated that the caliche along the southern, higher rim of Pierce Canyon is of Stage VI morphology and better-developed than the Stage V Mescalero caliche found on the north rim. I use the informal term “Pierce Canyon caliche” for the Stage VI soil horizon found along the south rim, and have mapped it into the Malaga quadrangle (unit Tgpc). At present, the Pierce Canyon caliche is the principal demarcating feature separating the lower (Tg, Tgs) Gatuña Formation from the upper (Qg, Qgs, Qgg, Qgc_) Gatuña; Gatuña strata underlying the Pierce Canyon caliche are of middle(?) Miocene-early Pliocene age, while those overlying or inset against the caliche are of late Pliocene(?) to Middle Pleistocene age. Deposits underlying the Mescalero caliche with an ambiguous relationship to the Pierce Canyon caliche, however, may be of middle(?) Miocene through Middle Pleistocene age. The current work suggests that differences in color and degrees of deformation and cementation may be used as proxies for inferring upper versus lower designations, but in general I am currently hesitant to refer deposits to upper or lower based on color, deformation, and/or cementation without stratigraphic context and instead frequently use an undifferentiated Gatuña Formation map unit (QTg, QTgs). An exception is a set of conglomerates occurring along the flanks of the Pecos and Black Rivers as well as along Salt Draw (units Qgca, Qgcb, Qgcs, respectively). These conglomerates are typically only mildly deformed, and in some areas can be followed up-section into sub-parallel Mescalero caliche (Qgmc) exposures while overlying strongly-tilted Gatuña Formation sandstones and mudstones (e.g., circa 591,850 m E, 3,555,960 m N at the south-central end of the quadrangle). These conglomerates are inferred to be upper Gatuña in age, and indeed may be the lowermost post-incision deposits of the upper Gatuña. Sediments overlying these conglomerates are referred to the upper Gatuña as well. This inference would imply that all tilted sandstones and mudstones beneath the conglomerates are lower Gatuña, but this designation was not made here due to ambiguity as to interpretations and correlations. Because of the commonality of localized, syndepositional, karst-related subsidence deformation throughout the quadrangle, intraformational angular disconformities may be present throughout both the upper and lower Gatuña.

Gatuña Formation deposits are dominantly light reddish brown to pink (less commonly white, yellow, or pale brown) siltstones to fine sandstones, mudstones, and claystones with rare medium-grained sandstones and conglomerates (map unit QTgs; Figure 2-2). Siltstones to fine sandstones, mudstones, and less common claystones are in very thin to thin planar tabular beds with internal planar or cross laminations or are internally massive. Coarser-grained sandstones and pebble conglomerates are more commonly lenticular or undulatory-tabular bedded, and similarly variably internally cross-stratified or massive. Conglomerate gravels are moderately sorted, clast-supported, and rounded to well-rounded, of lithologies that include quartzites, cherts, sandstones, felsic to intermediate volcanic rocks, and limestones. Deposits are commonly poorly indurated, and often form colluvial slopes. Powers and Holt (1993) indicate that at Pierce Canyon, a few kilometers east of the quadrangle, the total thickness of the Gatuña section is over 90 m (300 ft) thick; cross-section interpretations of the subsurface geology within the quadrangle suggest a thickness of at least 45 m in places.

I tentatively suggest that the majority of the Gatuña Formation deposits on the Malaga quadrangle are lower Gatuña in age, while the upper Gatuña in this area is a more restricted deposit consisting principally of a set of conglomerates inset against older deposits along the Pecos and Black Rivers as well as Salt Draw. Some loose gravels and sands, particularly along the Black River and in the northeast corner of the quadrangle, are also of upper Gatuña age. I further suggest that the Mescalero caliche has accumulated in the top of a combination depositional-erosional surface, in places accumulating in Rustler bedrocks or a thin lag of sediments overlying bedrock. The broad areal distribution of the Mescalero may not be indicative of a broad distribution of upper Gatuña *deposits*. However, I remain uncertain as to the correlation and assignment of many Gatuña outcrops, and my tentative suggestion may yet be disproven by further mapping.

2.2.1. Upper Gatuña Formation

Upper Gatuña Formation deposits, where distinguishable from the lower Gatuña, consist of conglomerates (Qgca, Qgcb, Qgcs), and poorly- to non-cemented sands/sandstones, mud/mudstones, and gravels (Qgs, Qgg), capped in many locations by the Mescalero caliche (Qgmc). The conglomerates are differentiated based on the drainage along which they occur, but each consists of poorly sorted, clast-supported, rounded to well-rounded pebbles, absent to rare cobbles, and trace boulders in thin to thick, lenticular, commonly cross-stratified beds (Figures 2-3 and 2-4). The cementation of these conglomerates is distinguished from that of the Mescalero or Pierce Canyon pedogenic (soil-related) cements by the lack of displacement of gravels, the common preservation of primary depositional features, and the lack of a laminated or tabular-banded uppermost interval; soil development, in contrast, is typically displacive and disruptive, destroying primary sedimentary structures and not uncommonly resulting in matrix-supported textures, and petrocalcic horizons (Stage IV and greater morphologies) are frequently capped by laminated or banded zones. Gravels are dominantly limestone with rare to subequal sandstone, with lesser amounts of Rustler dolomites (absent to rare, though locally common, and mostly Culebra Dolomite, lesser Magenta Dolomite; Figures 2-3C and D), as well as absent to rare clasts of chert, quartzite, and felsic to intermediate volcanic rocks. Very locally, reworked, carbonate-cemented conglomerate is found (Figure 2-3E), which may be reworked from the Pierce Canyon caliche, although the provenance was not established. Rustler dolomite clasts are typically the coarsest gravels, constituting nearly all the cobble- and boulder-sized gravel, and may be derived from nearby outcrops. The conglomerate along the Pecos River (Qgca) is typically coarser-grained, thicker, and more sandstone-rich than the tributary-lining conglomerates (compare Figures 2-3 and 2-4). Conglomerates are typically subhorizontal to only gently deformed (dips commonly less than ~3°), although locally conglomerates are found with dips around 15°-20° associated with local collapse features (cf., Figures 5-2 and 5-3). In places, the conglomerates are in distinct angular unconformity with underlying undifferentiated Gatuña mudstones and sandstones. Conglomerates along the Pecos River are up to 5 m or greater in thickness, while those along tributary drainages are typically only up to about 2 m thick.

Locally overlying the upper Gatuña Formation conglomerates are pink to white to locally reddish brown sandy muds/mudstones, muddy sands/sandstones (unit Qgs), and uncemented gravels (Qgg; Figure 2-5). These are typically very poorly exposed. Evidence suggests that the upper Gatuña is paler colored, less well-cemented, and less deformed than lower Gatuña, at least where the distinction is clear, but only a few clearly-upper and clearly-lower Gatuña outcrops have as-yet been encountered. Thick sections (up to about 6 m thick) of clearly-upper Gatuña are found in the northwest corner of the map area, potentially associated with an ancestral Black River fan, and in the northeast of the map area, where the Pierce Canyon caliche is subsided and overlain by sands (Figures 5-7B and C). Thinner sections are also found at the south-central edge of the quadrangle.

The upper Gatuña section is capped in many locations by the Mescalero caliche (unit Qgmc, Figure 2-6). This caliche is a petrocalcic carbonate horizon of Stage V morphology (Machette, 1985; Hawley, 1993), characterized by a well-cemented zone about 60 to 100 cm thick with an uppermost zone 15 to 30 cm thick of undulatory tabular-banded, nearly pure carbonate cement (Figures 2-6C and D). Locally, fracturing and re-cementation features can be found (Figure 2-6B); however, they are much less common in the Mescalero as compared to the older Pierce Canyon caliche. The cementation of the Mescalero often masks the nature of the parent material in which the carbonate has accumulated. Well-rounded siliceous pebbles can be found in many outcrops, but these may be from a lag rather than a distinct gravel deposit. In the vicinity of Malaga bends, at the tops of some domal hills, Mescalero caliche is juxtaposed against Culebra Dolomite breccias that are well-cemented by similar carbonate accumulations. This suggests that the Mescalero developed at least in places beneath an erosion surface with carbonate accumulating in a variety of sediment as well as bedrock parent materials. However, where the parent material can be determined to be non-Gatuña bedrock, such as in the case of the Culebra Dolomite breccias, bedrock is mapped on the geologic map and not the Mescalero.

2.2.2. Lower Gatuña Formation

The Pierce Canyon caliche (unit Tgpc) and any underlying Gatuña strata (Tg, Tgs) can be unequivocally referred to the lower Gatuña Formation. The Pierce Canyon caliche is a petrocalcic carbonate horizon of Stage VI morphology (Hawley, 1993), characterized by a 3 to 5 m-thick carbonate-impacted zone bearing features that suggest multiple stages of cementation, brecciation, and recementation (Figure 2-7). These features include brecciated bands of nearly-pure carbonate (Figures 2-7A and B), as well as laminations around pebbles and concentrically-laminated pisolites (Figures 2-7C and D). Like the Mescalero caliche, the Pierce Canyon is capped by an undulatory tabular-banded zone of nearly pure carbonate cement (Figure 2-7B) that is as much as 0.5 m thick. Unlike the Mescalero, this zone is commonly fractured, and in the ‘swales’ of undulatory tabular bands can be found thin laminated zones of pure carbonate, potentially reflecting remobilization of carbonate cement from highs to lows along the top of the zone. Carbonate abundance, as well as the degree of fracturing and recementation, decreases down-profile, in places into a more typical conglomerate (Figure 2-7E). The conglomerate consists of poorly sorted, rounded to well-rounded, matrix- to clast-supported pebbles of lithologies that include quartzite, chert, limestone, sandstone, and felsic to intermediate volcanic rocks. Conglomerates are typically massive, however, with primary sedimentary structures presumably destroyed by carbonate accumulation. Gravels are not found in all outcrops of the Pierce Canyon, however, and in many locations, the caliche may be accumulating in lower Gatuña sandstones and mudstones. Unlike with the Mescalero caliche, no examples of the Pierce Canyon caliche accumulating in Rustler bedrocks were identified, suggesting that the older caliche developed in a principally depositional surface.

Commonly underlying the Pierce Canyon caliche are lower Gatuña Formation mudstones and sandstones. The clearly-lower Gatuña deposits are typically darker or stronger colored, better cemented, and/or more deformed as compared to clearly-upper Gatuña deposits, but this possible distinction rests on only a few exposures of clearly-upper and clearly-lower deposits. In the northeast corner of the study area, a well-cemented, brecciated facies of the lower Gatuña is found (Tgs2; Figure 2-8) consisting of brecciated pink to pale brown very fine- to fine-grained sandstones. Brecciation may have been the result of sinkhole collapse subsidence, although no diagnostic features were found.

3. Permian System - Exposed stratigraphy

Cenozoic deposits unconformably lie upon and are inset against Ochoan (Upper Permian) strata of the Salado and Rustler Formations. Older Permian strata are apparent in oil and gas well data from the area, but are not exposed at the surface.

3.1. Rustler Formation

The Rustler Formation was originally named by Richardson (1904) for exposures in the Rustler Hills in Culberson County, Texas, where only about 45 m of the lower parts of what is now considered the Rustler Formation are exposed (Powers and Holt, 1999). The unit was subsequently expanded from a combination of surface mapping and drill core studies to encompass 109 to as much as 150 m of beds (cf., Powers and Holt, 1999). Adams (1944) named the two prominent, continuous dolomite intervals the Culebra Dolomite and the Magenta Dolomite, apparently following informal usage “favored” but not published by W.B. Lang (who is sometimes credited for the names through his Lang, 1938, report), while Vine (1963) introduced the names Forty-niner Member and Tamarisk Member for the overlying and intervening gypsum- and mudstone-dominated intervals (Figure 1-3). The lowermost interval, between the top of the Salado Formation and the base of the Culebra Dolomite, went unnamed until much later, when first Powers and Holt (1990) and subsequently Lucas and Anderson (1994) proposed the names Los Medaños Member and Virginia Draw Member, respectively. Powers and Holt (1990) failed to formally define their ‘Los Medaños Member,’ however, until several years later (Powers and Holt, 1999). Powers and Holt (1999) note that the type section designated by Lucas and Anderson (1994) for their Virginia Draw Member, which is located in the Rustler Hills in the southern Delaware basin, apparently contains a significantly greater proportion of sandstone and limestone than is present in the lowermost member of the Rustler Formation in the northern Delaware basin, where it is principally siltstones and mudstones. The lowermost member of the Rustler Formation on the Malaga quadrangle is dominantly mudstones, as described by Powers and Holt (1999), and hence I use the term Los Medaños Member (unit Prl) for this interval (Figure 1-3). In addition to the Los Medaños, the Culebra Dolomite (unit Prc) is found well-exposed throughout most of the quadrangle, and brecciated outcrops of the Magenta Dolomite (Prm) can be found locally apparently in collapse features along the Pecos River. Poorly exposed gypsiferous mudstones overlying the Culebra or enveloping the brecciated Magenta blocks are inferred to be the Tamarisk Member (Prt), although outcrops of this unit are too poor to assign to the member based on lithology alone. In many locations, particularly along the Pecos River, poorly exposed gypsiferous mudstones of the Rustler are found without stratigraphic context and could be either Los Medaños or Tamarisk; these are mapped as an undifferentiated gypsum and gypsiferous mudstone unit (Prg). No outcrops of the uppermost Forty-niner Member were identified on the quadrangle.

3.1.1. Magenta Dolomite

The Magenta Dolomite is only present on the Malaga quadrangle as subsided breccia blocks in a few small localities along the Pecos River near to Malaga Bends. Where the unit is undisturbed, it consists of 7 to 9 m (Holt and Powers, 1988) of two intervals of light reddish brown arenaceous dolomite to either side of a medial pale yellowish siltstone interval; on this quadrangle, however, the preserved thickness of the unit is nowhere greater than about 2 m. The lower dolomite interval is distinctly undulatory- or wavy-laminated, and consists of crystalline dolomite with common very fine to fine sand grains. The upper interval is very thinly planar tabular bedded, variably internally massive or planar- or cross-laminated, interlayered dolomicrite, arenaceous dolomite, and crystalline dolomite (Figure 3-1).

The medial siltstone interval is also very thinly planar tabular bedded. In some areas, the subsided Magenta is fairly intact, such as in Figure 3-1, but in most places, the dolomite has been brecciated by subsidence into the underlying Tamarisk Member.

3.1.2. Tamarisk Member

The Tamarisk Member is particularly poorly preserved on this quadrangle, most frequently occurring as brecciated or massive light gray nodular gypsum and reddish brown gypsiferous claystones and mudstones (e.g., Figure 5-2C). Holt and Powers (1988) indicate that, where intact, the Tamarisk consists of two anhydrite/gypsum intervals separated by a zone variously dominated by clastic sedimentary rocks or halite and associated evaporite salts (Figure 1-3). The thickness of the intact unit is 30 to 50 m in “normal sections,” with a maximum regional thickness of about 82 m (Holt and Powers, 1988). Within the Malaga quadrangle, the unit has ubiquitously been disturbed by either intraformational dissolution and brecciation or by subsidence/collapse associated with the dissolution of underlying materials, and a preserved thickness of not more than 9 m is interpreted from outcrops and cross-section interpretations. Locally, small unmappable breccia blocks of the Magenta Dolomite can be found subsided into the massive or brecciated Tamarisk deposits. Because of poor exposures and the lack of diagnostic features, outcrops are only referred to the Tamarisk Member (i.e., mapped as unit Prt) if nearby exposures of the Culebra Dolomite can be projected beneath the outcrop with confidence, or if the outcrop bears subsided breccia blocks of the Magenta Dolomite and no breccia of the Culebra. In the absence of stratigraphic controls, poorly exposed massive or brecciated gypsum and mudstones are mapped as the undifferentiated unit, Prg.

3.1.3. Culebra Dolomite

The Culebra Dolomite is a cream-colored to white, vuggy dolomite (Figure 3-2A) that serves as a distinctive marker unit that can be found capping many hills throughout the study area, as well as underlying Gatuña deposits along the eastern margin of the quadrangle. The dolomite interval is up to about 7 to 9 m thick and is typically thin to medium planar tabular bedded, fine-grained, and internally massive, commonly bearing small prismatic to less-commonly spherical vugs 1 to 10 mm in diameter. The interval is commonly folded domally or along linear trends, which is interpreted to be a consequence of variable subsidence related to the dissolution of underlying salts (Section 5; cf., Bachman, 1980). Folded intervals are commonly fractured and locally brecciated. Adjacent to the Mescalero caliche (unit Qgmc) as well as locally where capping isolated domal hills, the Culebra is often found as a breccia with clasts enveloped by carbonate cements, which is interpreted to be pedogenic (soil formation-related, i.e., caliche accumulation; Figure 3-2B). This observation supports that the Mescalero caliche may be accumulating in the top of a combination depositional-erosional surface, rather than a depositional surface alone.

3.1.4. Los Medaños Member

The Los Medaños Member is the most extensive member of the Rustler Formation at the surface on the Malaga quadrangle. Where well-exposed and relatively undisturbed, the unit consists dominantly of reddish yellow, laminated to thinly bedded, poorly indurated silty mudstones, with lesser abundances of pale red, very thinly bedded, calcite-cemented coarse-grained siltstones to very fine-grained sandstones; laminated to thinly bedded, nodular or crystalline, light gray to white gypsum; and trace amounts of thin laminae of waxy reddish yellow claystones (Figure 3-3). However, the unit is typically poorly exposed or highly deformed, and often identified by the presence of contorted gypsum bands at the surface, or by the presence of ripped-up blocks of gypsum along shallow cuts (pipelines, road cuts, etc.). The amount of gypsum present can be highly variable, ranging from laminae or very thin beds (e.g., Figure 3-3A and B) to irregular blocky masses as much as 60 cm across (e.g., Figure 5-5); Powers and Holt (1999) suggest that the abundance of gypsum increases upsection, with the lower roughly half of the unit dominated by mudstones and the upper half including a greater abundance of salts, at least at their type locality to the east of the study area. However, any stretch of good exposure of the Los Medaños interval appears to include at least some gypsum, and as a consequence, I have interpreted that any continuously well-exposed interval that is at least ~5 m thick (stratigraphic thickness) that contains no gypsum is more likely Gatuña Formation than the Los Medaños Member. This convention was applied particularly along a few gully outcrops in the southwestern quarter of the quadrangle, where some ambiguity was encountered; it should be noted that, in this area, in many locations gypsiferous strata were found lower in elevation in the area of the gypsum-free sediments, i.e., the reverse of the pattern described by Powers and Holt (1999). Given the interpretation that the Mescalero caliche is accumulating in a combination depositional-erosional surface, it is possible that some ambiguity results from reworking of Los Medaños sediments into at least the upper Gatuña Formation, making them lithologically similar. In some locations, particularly along the Pecos River, gypsiferous mudstones and gypsum crop out in isolation where the deposits may correlate to either the Los Medaños or Tamarisk Members; in these areas, the outcrops are referred to an undifferentiated Rustler unit (i.e., mapped as unit Prg). Powers and Holt (1999) measured the Los Medaños Member at its type locality to be 34.4 m thick, while Holt and Powers (1988) indicate the interval can be much thicker regionally, up to about 168 m thick to the south and east of the WIPP site. Outcrops, drill hole data, and cross-section interpretations suggest a preserved maximum thickness of about 48 m within the study area.

3.2. Salado Formation

The Salado Formation was initially described by Richardson (1904) as the upper member of the Castile, and subsequently split from the Castile and designated its own formation by Lang (1935). Where it is intact in the subsurface, the unit consists principally (85-90 percent) of rock salt, with lesser anhydrite, polyhalite, and potassium-rich salts, and subordinate sandstone, claystone, glauberite, and magnesite (Jones et al., 1973). The rock salt is composed of white to clear, nearly pure halite and reddish-brown to gray clayey halite in discrete, laterally continuous layers (Jones et al., 1973). Potassium-rich salts are concentrated in the medial McNutt potash zone, which is of regional economic importance as a source of potash ore. The Salado is also the host rock, well in the subsurface, for the Waste Isolate Pilot Plant (WIPP; Powers et al., 1978). However, where closer to the surface, the rock salt is subject to dissolution and can be a source of karst hazards for the area (Johnson, 2005). In the known potassium resource zone, the Salado in the subsurface reaches a maximum thickness of about 610 m (Brokaw et al., 1972), with thicker intervals up to 732 m eluded to by Bachman (1987) for the Delaware basin as a whole.

Many studies have either documented or described a westward thinning of the Salado and interpreted the thinning to be the consequence of progressive, if irregular, dissolution of the Salado as it approaches the land surface in the regionally up-dip (westward) direction (cf., Brokaw et al., 1972; Powers et al., 1978; Bachman, 1980). Dissolution preferentially removes the rock salt constituent of the Salado, while hydration alters the anhydrite to gypsum. These processes alter and distort the unit considerably, such that where the unit is exposed at the surface it little resembles the Salado at depth (e.g., Figure 3-4). On a broad scale, dissolution varies with depth below the land surface, such that a ‘dissolution front’ exists at depth below which the Salado is intact and above which the Salado has been heavily disturbed by dissolution. Jones et al. (1973) describe the material above the front as a consisting of “clay with crudely interlayered seams of broken and shattered gypsum and fine-grained sandstone.” The contact between the intact and leached Salado is distinct in geophysical logs, and Brokaw et al. (1972) contoured the contact in the subsurface through an area mostly to the north and northeast of the Malaga quadrangle, showing it to contain numerous irregular pits, hills, and troughs. One such pit appears to occur at the east margin of the quadrangle at the border of T 24 S and T 25 S, that may continue southward along the east margin of the quadrangle.

At the surface, only the leached Salado Formation ‘residue’ is found in outcrop (unit Ps; Figure 3-4). On the Malaga quadrangle itself, the Salado occurs at the surface only as low outcrops of white to light gray, nodular or laminated gypsum breccia blocks surrounded by irregularly-oriented, variably weathered, red to reddish brown, crystalline gypsum matrix with lesser incorporated waxy reddish-brown clays (Figures 3-4C and D). Only a handful of outcrops were identified, all along the Pecos River in the vicinity and upstream of Malaga bend, in an area of particularly strong karst deformation. In each instance, the Salado outcrop is located in the core of a karst dome (*sensu* Bachman, 1980) overlain by domally-folded Rustler Formation strata; these domes are likely not the product of uplift but instead of subsidence of surrounding materials as a consequence of regional dissolution (cf., Bachman, 1980, 1987). Intact Salado Formation is found nowhere exposed on the quadrangle, nor is the base of the Salado exposed. Isopach contouring by Bachman (1980) suggests the unit may be as much as 300 m thick along the eastern margin of the quadrangle, generally thinning southward and westward. Cross-section interpretations suggest the Salado may be as thin as 180 m along the southern margin of the quadrangle.

Examined oil and gas well data suggest that the contacts separating units underlying the Salado are of low relief; for example, along cross-section A-A’ each contact below the Salado is essentially a straight line of ~1° apparent dip eastward. In contrast, bedding planes measured at the surface in the Gatuña and Rustler Formations dip as steeply as about 50° with dip directions to all azimuths. The implication is that accommodation for the tilting of Rustler and Gatuña beds must take place within or above the Salado Formation. Well data for this interval is sparse, but I infer the majority, if not all, of the deformation to be accommodated by the variable dissolution of and subsidence into the Salado Formation, as illustrated in cross-section A-A’. The erratic hills, pits, and troughs in the dissolution front separating intact Salado from leached Salado residue (Brokaw et al., 1972) support this interpretation. In fact, I note that Brokaw et al. (1972) locate an elevational low in this surface along the eastern margin of the Malaga quadrangle just north of a trough inferred to lie at the east end of cross-section A-A’; their mapping does not extend this far south, but it is possible that this structural low extends southward into the cross-section line. Subsidence into the Salado may be much more erratic than is depicted on the cross-section line, but the lack of dense subsurface control precludes mapping this contact in detail.

4. Permian System – Subsurface stratigraphy

The New Mexico Oil Conservation Division (NM OCD) database of wells locates 590 active, abandoned, or proposed oil and gas wells within the Malaga quadrangle. A digital subsurface database built for a larger project on the three-dimensional structure of southeastern New Mexico collected data for 211 of these wells in the quadrangle, some extending over 15,000 ft deep and intersecting rocks as old as the Ordovician Montoya Formation. However, few of these wells contain data on the near-surface Salado-Rustler-Gatuña interval. In so far as this project is concerned with studying, mapping, and interpreting surface geologic materials, I chose to concentrate subsurface projections and interpretations along a line with good shallow subsurface control, despite this line having less well control for deeper strata. Nevertheless, good well control was available along the cross-section line for units as old as the Wolfcampian.

4.1. Castile Formation

The Castile Formation (cross-section unit Pc) was named by Richardson (1904) and subsequently re-defined by Lang (1935) to its current usage. Where intact, the Castile consists of laminated anhydrite and gypsum with lesser halite and limestone, and minor dolomite and magnesite (Bachman, 1984). Regionally, the unit is as much as 640 m thick, but on the average, the unit thickness is about 460 to 520 m thick (Bachman, 1984). Isopach mapping (Bachman, 1980) and well controls within the Malaga quadrangle indicate a thickness of about 445 to 525 m here, generally thickening eastward.

4.2. Delaware Mountain Group

Originally named by Richardson (1904) and elevated to group status by King (1942), the Delaware Mountain Group consists dominantly of arkosic to subarkosic, very fine- to fine-grained sandstones and siltstones, with lesser detrital carbonates, that accumulated in the Delaware basin through the Guadalupian Epoch (Nance, 2009). The Group is subdivided into three Formations on a combination of lithologic and faunal evidence. The lowest formation, the Brushy Canyon Formation (cross-section unit Pdbr), is considerably coarser grained than the overlying two younger formations, although the grain sizes remain dominantly fine sand-sized, and no clastic carbonates interbed with the Brushy Canyon (King, 1942; Nance, 2009). King (1942) reports than the Brushy Canyon appears to pinch out laterally at least along the western margin of the Delaware basin, rather than grading into a preserved reef, marginal, or shelf facies, as is seen with the younger two formations. The middle formation, the Cherry Canyon Formation (Pdcc), is finer grained than the underlying Brushy Canyon, and contains several interbedded detrital carbonate intervals, with three persistent intervals having named member status: in ascending order, the Getaway, South Wells, and Manzanita Limestone Members (King, 1942). King (1942) reports that the sandstone interval beneath the lowest persistent limestone, the Getaway Limestone, can be followed out of the Delaware basin to underlie younger basin-margin facies, but that the Getaway and South Wells thicken, while the intervening sandstones thin and pinch out, toward the western margin of the basin, where each limestone interval transitions into the Goat Seep Dolomite, a reef or basin-margin facies. The youngest of the formations, the Bell Canyon Formation (Pdbc), is lithologically similar to the underlying Cherry Canyon, except that the interbedded detrital carbonate beds are rarer but thicker and more laterally persistent (King, 1942). King (1942) named four persistent limestone members while King and Newell (1956) added a fifth, the McCombs; in ascending order, the members are the Hegler, Pinery, Rader, McCombs, and Lamar Limestone Members, and the lowest (Hegler) and highest (Lamar) generally bracket the unit, although as much as 6 m of additional

Bell Canyon sandstones in places overlie the Lamar (King, 1942; King, 1948; these beds were later named the Reef Trail Member by Wilde et al., 1999). The Lamar Limestone (Pdl) has a distinctive geophysical character and was included in cross-section A-A’ as well (although as shown on the cross-section the member may include beds of the Reef Trail Member). King (1948) reports thicknesses of 305 to 350 m (Brushy Canyon), 305 to 390 m (Cherry Canyon), 204 to 317 m (Bell Canyon), and 5 to as much as 46 m (Lamar Limestone) at the surface for the units shown on cross-section A-A’. Cross-section interpretations constrained by well logs indicate thicknesses of 470 to 490 m (Brushy Canyon), 360 to 405 m (Cherry Canyon), 240 to 270 m (Bell Canyon), and about 10 m (Lamar) for these units beneath the Malaga quadrangle.

4.3. Bone Spring Limestone

Named by Blanchard and Davis (1929) for exposures in Bone Canyon below Bone Spring on the west side of the Guadalupe Mountains, the Bone Spring Limestone consists of dark gray or brownish gray to black, thinly bedded, locally cherty limestone with lesser black to dark brown shale and dark brown shaly limestone (King, 1948; King, 1965; Hayes, 1964). Hayes (1964) reports thicknesses in nearby wells as ranging from 948 to nearly 1,036 m; cross-section interpretations constrained by well logs indicate a thickness of at least 965 m beneath the Malaga quadrangle.

4.4. Wolfcampian Series

Basinal Wolfcamp-age strata are rarely, if ever, exposed at the surface, and few publications synthesizing what data is available for the Wolfcamp within the northern Delaware basin appear to be readily available. Hayes (1964) reports that a well drilled approximately 10 km west of the Malaga quadrangle in Section 31, T 24 S, R 27 E (Humble Wiggs 1), encountered about 533 m of gray, black, or brown shale interbedded with finely crystalline, rarely cherty, brownish limestone underlying the Bone Spring Limestone. Tyrell (1966) describes “Wolfcamp” strata of the western Delaware basin as consisting of three subdivisions: a lowermost detrital unit of variable character and thickness, a medial sequence of “lime-shale-lime,” and an uppermost unit apparently equivalent to the “3rd Bone Spring Sand” interval, although current usage appears to correlate the “3rd Bone Spring Sand” with the Dean Formation and well within the Leonardian Series (cf., Hamlin and Baumgardner, 2012; Hennefent et al., 2015; Ward, 2017; EIA (U.S. Energy Information Administration), 2018). Hennefent et al. (2015), in passing, describes the Wolfcamp in the Delaware basin as consisting of “polymictic breccias fining upward into massive skeletal packstone, laminated wackestone, and organic silty mudrock…and local very fine-grained, feldspathic and calcareous sands” (“Wolfcamp D”) overlain by “sandy limestone and dolomitic siltstones grading upward to nonorganic, dolomitic, silty mudstones capped by thin organic laminae” (“Wolfcamp C”) with “limestones fining upward into calcareous siltstone and silty mudrock” (“Wolfcamp A”) at the top of the “Wolfcamp Formation,” although they do not provide a reference for this description. In the Midland Basin, the Wolfcamp Series is commonly described as a “two-rock-type” system of interbedded shale and limestone (e.g., Flamm, 2008; Ward, 2017). Hence, the overall consensus is that the Wolfcamp Series basinal facies consists of interbedded shales and limestones. A few wells report the tops of Pennsylvanian units at depth in the Malaga area, and these suggest a thickness for the Wolfcamp of about 453 to 566 m below the quadrangle. However, such deep data was generally too rare to continue the cross-section to the top of the Pennsylvanian with confidence.

5. Structure

5.1. Structural setting

The Malaga quadrangle lies in the northern portion of the Pennsylvanian-Permian Delaware basin, which overprints an older, broader Ordovician to Pennsylvanian Tobosa basin (Hill, 1996). Subsidence of the Delaware basin was particularly strong in the Wolfcampian through Guadalupian time (Ewing, 1993), and greater than 4,570 m of Permian strata may lie below the surface in the basin (Oriel et al., 1967). Following the Permian, structural development has been nearly non-existent. A gentle regional eastward tilting of the area following the Permian is apparent (cf., Broadhead and Gillard, 2005), which is often attributed to Cenozoic Basin and Range development, although several authors note that uplift may have occurred in Triassic or earliest Cretaceous time as well (e.g., Ewing, 1993). Regardless of timing, the regional geologic setting for the rocks exposed on the Malaga quadrangle is one of prolonged subsidence and sedimentation in the Permian, followed by a long period dominated by erosion or non-deposition, and a period of eastward tilting and uplift of mountains to the west that renewed sedimentation in the late Cenozoic (deposition of the lower Gatuña / Ogallala). Despite this simple regional structural setting, the surface geology is complexly deformed, as a consequence not of tectonic structures but of karst/dissolution-related, localized subsidence and collapse.

5.2. Tectonic structures

No tectonic structures (faults, deep-seated folds) were identified at the surface on the Malaga quadrangle. All structures (mapped folds, strata tilting, steep fault-like contact trends) occurring at the surface are inferred to be the product of karst deformation. As illustrated in cross-section A-A', well data does not support the presence of substantial structures deforming the pre-Ochoan Permian strata underlying the area. Structural contours of the top of the Bone Spring Limestone by Broadhead and Gillard (2005) similarly suggest a lack of significant structures at depth for explaining deformation of upper Permian or younger strata.

5.3. Karst structures

In contrast to the paucity of shallow tectonic structures, the Malaga quadrangle holds a plethora of karst structures from outcrop to regional scale. Bachman (1987) describes the variety of karst features observed in the Permian evaporites of southeastern New Mexico, and his paper and references therein were a crucial guide to studying the deformation apparent on the quadrangle. In fact, Bachman (1980) produced a 'geologic sketch map' of the karst features at Malaga bend, which served as an early point-of-reference for this present work. Research presented by Land et al. (2018) also provided an early introduction to the geology and karst features of the quadrangle, as well as provided a window into the subsurface of features occurring along U.S. Highway 285.

5.3.1. Sinkholes and caves

Outcrop-scale subsidence features are common to the study area (cf., Land et al., 2018). These range from centimeter- or decimeter-scale 'divots' in gypsiferous strata (Figure 5-1A) to cover-collapse sinks, where unconsolidated sediment washes into an underlying cavity (Figure 5-1B), to man-sized sinkholes leading to legitimate, man-enterable, if often shallow, caves (Figure 5-1C). Land et al. (2018) identified over 30 sinkhole or potential sinkhole features along Highway 285, ranked the potential for each to be associated with a larger feature at depth (following the methods of Veni (1999)) then performed electrical resistivity surveys along the higher-ranked features as well as at bridge abutments and piers. Sinkhole and potential sinkhole features were in either the Los Medaños Member of the Rustler Formation or were cover collapses or soil pipes affecting Quaternary eolian or alluvial material. In most cases, the resistivity surveys did not support deep roots to the sinkhole features observed at the surface, with high-resistivity zones (interpreted to be air-filled cavities) rarely extending deeper than about 4.6 m below ground surface, although there were a few possible exceptions (Land et al., 2018). Land et al. (2018) suggested that this lack of deep roots may be a product of the heterolithologic nature of the Los Medaños Member; although the Los Medaños does include substantial soluble gypsum, the member also includes significant clastic layers that would not be affected by dissolution. Such a juxtaposition could limit the growth or size of cavity development. However, this present work shows that the Salado Formation can be at the surface within the Malaga quadrangle area and in many places is likely within 50 m of the land surface, given that the Culebra Dolomite frequently crops out throughout the study area and that the underlying Los Medaños Member here is nowhere interpreted to be more than about 48 m thick. I suggest that some of the potential cavities observed in the resistivity surveys published by Land et al. (2018) may, in fact, be developed in the Salado Formation, and as a consequence may be larger cavities than those observed in the overlying Los Medaños Member of the Rustler Formation.

As many of the 30+ potential sinkhole features were later assessed as either minor features or not karst-related, and because many features overlap at this map scale, I only show 15 of the potential features mapped by Land et al. (2018) as subsidence features on the Malaga quadrangle geologic map. Features interpreted to be unlikely to overlie a larger sinkhole were excluded. I additionally mapped more subsidence features that I observed either on the ground or could confidently determine were subsidence features from air photo interpretation. In all, 91 small-scale subsidence features were mapped on the Malaga quadrangle. Not surprisingly, the majority (~66%) are mapped on the Los Medaños Member, while ~19% are mapped on depression fills (map unit Qdf). The remainder are mainly on alluvial or eolian units and are likely cover-collapse sinkholes. Following the results of Land et al. (2018), I suggest that the majority of these surface sinkholes likely do not continue into deep roots. However, I do caution that some may be expressions of deeper cavities in the Salado Formation.

5.3.2. Localized subsidence features and collapse breccias

Subsidence and/or collapse of younger strata or deposits into older units as a consequence of localized dissolution is apparent at the outcrop scale in several locations, but best expressed in a broad outcrop of map unit Qgca overlying undifferentiated Gatuña mudstones/sandstones (QTgs) and gypsum breccia of the Tamarisk Member of the Rustler Formation (Prt) circa 592,000 m E, 3,556,185 m N, along the Pecos River at a set of distinct bends along cross-section A-A’ near the south end of the quadrangle (Figure 5-2). From south to north along the outcrop, QTgs mudstones and sandstones are juxtaposed against Prt gypsum breccia along a poorly-exposed but clearly steeply-dipping contact (Figures 5-2A and B) that is interpreted to be a collapse/subsidence contact across which QTgs strata was down-dropped to be inset against Prt. The base of Qgca crosses this contact, truncating the contact as well as QTgs bedding and the Prt breccia. Where Qgca overlies QTgs, the contact is undulatory but this is likely due mainly to erosional channeling of the contact. Where Qgca overlies Prt gypsum breccia, the contact can be quite irregular (Figures 5-2C and D), likely as a consequence of the syndepositional variable dissolution of the gypsum breccia by ancestral Pecos River stream water. In places, the Qgca bedding is draped along the contact (Figures 5-2A, C, and D), indicating syndepositional subsidence of the Qgca gravels. At the far north end of the outcrop, draped conglomerate beds can be followed into a section of massive pebbly sandstone (Figure 5-2D), likely the product of a collapse event that destroyed sedimentary structures and accumulated an unstructured mass of sands, as opposed to the slower subsidence suggested by the folded bedding. Similar outcrops of Qgca subsided into Rustler Formation gypsum and mudstones were encountered circa 593,430 m E, 3,559,275 m N at the east-central margin of the quadrangle on the east bank of the Pecos River, where a low dome of Rustler Formation is found underlying Qgca conglomerates that thicken to either side of the dome, with bedding planes that are draped along the margins of the dome. At the north end of the quadrangle on the east flank of the Pecos River (circa 590,000 m E, 3,567,750 m N), Qgca conglomerate, Culebra Dolomite, and Los Medaños deposits are all variably subsided around outcrops of Salado Formation residue (Figure 5-3).

Numerous closed depressions, some large enough to be named (e.g., Willow Lake, Queen Lake, Mexican Lake, and Horseshoe Lake), occur throughout the quadrangle that may be surface expressions of localized subsidence. Most of these depressions are lined with depression fill or slopewash sediments (map units Qdf and Qsw), concealing the exact nature of the depression. However, the relatively common abundance of mapped sinkhole features (~19% of mapped sinkhole features as described in the preceding section) within the depression fill map unit (Qdf) suggests that at least locally cavities or subsidence-related brecciation is not uncommon beneath the floors of these depressions. Where resistant units (particularly the Culebra Dolomite, less commonly the Mescalero caliche) occur along the flanks of these depressions they not uncommonly form dip slopes dipping toward the depression, suggesting the depression and its immediate flanks have been let down by dissolution-related subsidence. Many of these depressions occur within the Los Medaños Member of the Rustler, and dissolution may have occurred in either the Los Medaños or the underlying Salado Formation.

5.3.3. Karst domes and mounds

Bachman (1980) differentiates between and describes separately three karst features that each result in low rounded hills: karst domes, karst mounds, and breccia chimneys. No examples of the last of these, breccia chimneys, were observed on the Malaga quadrangle, and no clear examples of karst mounds were identified either. Karst domes, however, are a ubiquitous feature of the quadrangle, so much so that Bachman (1980) included a high-resolution map of a part of the Malaga quadrangle near Malaga bend in his publication as an exemplary location of this particular karst feature. Karst domes are characterized by a capping, erosion- and dissolution-resistant layer or horizon that dips radially away from a central location, such that the capping layer is folded into a true structural dome (Bachman, 1980; Bachman, 1987; Figure 5-4). Bachman (1980) interpreted the karst domes to be the product of regional dissolution, wherein the capping layer is gradually let-down by the subsurface removal of salts from beneath the flanks of the dome, draping the dome around a core that is then preserved from later dissolution by the presence of the erosion- and dissolution-resistant dome cap. The cores of these domes may be readily soluble or otherwise unstable rocks, but the presence of the capping layer encompassing the unstable rock protects the soluble rocks from further dissolution. This mechanism is entirely deflational, in that it relies entirely on the removal of material from the subsurface to result in an otherwise positive structural element. It is also an inherently shallow mechanism; were the removal of material occurring at significant depth, then the development of a local resistant cap would have no effect on deflation and no dome would be created or preserved.

On the Malaga quadrangle, most domes are roughly circular in plan view, and a quick measure of the diameters of the domes on the geologic map, as topographically-defined, shows the domes to be dominantly about 150 to 250 m in diameter. A north-northeast/south-southwest-elongate Mescalero caliche dome centered approximately at 593,800 m E, 3,557,800 m N (Figure 5-4B) is the largest dome preserved in the map area, with a long axis of ~1,000 to 1,100 m and a short axis of ~400 to 500 m. No domes capped by Culebra of comparable size to this large dome were observed, suggesting there is possibly a relationship between maximum dome size and age of the deformed strata, with maximum size decreasing with the age of capping strata; however, the sample size supporting this relationship is presently quite small. Preserved domes are particularly common between Malaga bend and the southeastern corner of the quadrangle, and many isolated arcuate ridges of Culebra Dolomite throughout the map area may be remnants of eroded domes.

The material encased within the dome may be brecciated or intact. In places, the material underlying the capping layer does not also dip radially away from the central point. Along the margins of the large elongate Mescalero caliche-capped karst dome discussed above (Figure 5-4B), I measured radially outward dips of the Mescalero caliche of 6 to 9°, with subhorizontal trends toward the interior of a mapped concentric hinge zone. In contrast, along the southwest margin of the dome, the underlying undifferentiated Gatuña sandstones and mudstones are exposed and exhibit dips of 7 to 21° that are consistently to the northeast, contra the ~9° southwestward dip of the overlying caliche. In most cases, the core of the dome is either not well enough exposed or too brecciated to evaluate the conformity of underlying and overlying layers.

Alternative hypotheses to explain the karst domes typically invoke at least some measure of salt flowage (cf., Vine, 1960; Kelley, 1971). Bachman (1987), however, argues that the depth of burial of the Salado Formation in this area has not been sufficient to generate the pressures needed to cause salt flowage. Some previous authors have also suggested the domes on the Malaga quadrangle may share an origin with the deep-seated breccia chimney hills that occur further north in the vicinity of the shared corners of T20S R30E, T20S R31E, T21S R29E, and T21S R30E (note that the ranges for T20S and T21S are shifted relative to one another). Vine (1960) and Bachman (1980) studied these hills and concluded at least some do have deep-seated origins and are breccia chimneys, but, as described below, Bachman (1980) argues that such features are unlikely to occur away from the subsurface Capitan reef. No evidence was found as a part of this study to support a deep-seated origin for the karst domes found here, nor was the rheology and burial history of the Salado Formation found within the study area investigated. However, no data contrary to Bachman’s hypothesis was found, either.

Karst dome formation appears to span at the very least much of the Pleistocene, and possibly has older origins. Clearly, the Mescalero caliche is deformed by this process, indicating that dome formation has occurred following the Middle Pleistocene. In contrast, some Culebra-capped domes along the north flank of Salt Draw are buried by subhorizontal Mescalero caliche (Figure 5-4C), indicating some karst mound development must predate the development of the caliche. An additional line of evidence for pre-Mescalero dome formation is the relative sizes and preservations of Culebra-capped domes as compared to Mescalero-capped domes. No Culebra-capped dome was found greater than about 350 m in diameter and many isolated arcuate Culebra outcrops are likely remnants of highly eroded Culebra-capped domes, and in contrast, Mescalero-capped domes have dimensions upwards of 1,100 m by 500 m and were generally not found as arcuate remnants. The smaller sizes and more commonly eroded nature of the Culebra-capped domes may reflect an older age of regional dome development that affected the Culebra but predated the Mescalero caliche.

Karst mounds, as defined by Bachman (1980), are low rounded hills of collapse breccia, such as shown in Figure 5-5, a mound from the Red Bluff quadrangle to the south of the study area. Bachman (1980) hypothesized that these breccia mounds are the remnants of collapse features, wherein younger material collapsed into a cavity in soluble strata, the soluble strata subsequently eroded away, and a mound of collapse breccia is left behind as a low isolated hill. He stressed, however, that he interprets these features as shallow features without deep roots, and supports this assertion with limited drill hole data. This is in sharp contrast to the origin of breccia chimneys, described below. I observed no comparable, isolated mounds of breccia such as shown in Figure 5-5 on the Malaga quadrangle, although I note that some breccias that do occur on the quadrangle, such as the Tamarisk Member gypsum breccia in Figure 5-2C, could evolve into a karst mound with erosional removal of the overlying conglomerate.

Bachman (1980) discusses breccia chimneys at length due to their importance as reflections of deep-seated dissolution and collapse processes. No breccia chimneys are thought to be present on the Malaga quadrangle, but a description of them is included here for the sake of completeness. Breccia chimneys are vertical cylindrical fissures filled with collapse breccia that may extend vertically through hundreds of meters of strata. A drill hole into a breccia chimney to the north of the study area in Section 35 of T 20 S, R 30 E (Hill A of Vine, 1960, and Bachman, 1980) reached a total depth of 258 m without encountering the base of the breccia, while a second breccia chimney about 2 miles to the east-southeast (Hill C of the same references) appears to extend into underground potash mine workings (Bachman, 1980). Both features overlie the Captain reef trend, apparently at the location of a submarine canyon complex carved into the reef, and Bachman (1980) interprets that this unique location resulted in enhanced dissolution of the Salado Formation at its base where it lay on top of the Capitan (no Castile Formation would have been present as this is outside the Guadalupian Delaware basin), dissolution that resulted in a deep-seated cavity that stoped upwards and eventually collapsed, filling with a thick section of collapse breccia. Bachman (1980) further interprets that similar deep-seated breccia chimneys are not likely to be found within the Guadalupian Delaware basin.

5.3.4. Solution troughs

Solution troughs are linear or curvilinear bands of enhanced dissolution that may be relatively small-scale features (such as the solution-subsidence troughs described by Olive, 1957) or be regional features that can be traced for tens of miles (salt-solution troughs of Hiss, 1976). Some of these larger features are filled with significant thicknesses of Cenozoic fill; Bachman (1987), for example, observed sediment thicknesses as much as 357 m in well data from wells drilled in the Balmorhea-Pecos-Loving (BPL) trough of Hiss (1976), and Meyer et al. (2012) report Cenozoic fill thicknesses up to about 530 m in solution troughs in Texas in the greater lower Pecos Valley area. These features are thought to be associated with groundwater flowing through joints and fractures (Olive, 1957), through the underlying Capitan reef (Maley and Huffington, 1953), or associated with the trends of ancestral river systems (Bachman, 1987) preferentially dissolving salts along the groundwater flow path. As the material is removed from the subsurface, a trough is formed either as a single collapse event of a roof into an underlying cavity (e.g., Olive, 1957) or progressively as overlying materials subside into the thinned area (e.g., Bachman, 1987). The BPL trough, which consists of a curvilinear trend of numerous coalescing lens-shaped structural basins (Hiss, 1976), can be traced along a roughly north-northwest-south-southeast trend just east of the study area on the east side of the Pecos River (Hiss, 1976; Bachman, 1987; Ewing et al., 2012).

Relatively small scale solution troughs appear to cause synclinal folds in the trend of the Mescalero caliche and the Qgca conglomerate in the southeastern corner of the quadrangle east of the Pecos River (e.g., Figure 5-6). At least two such synclines are present trending northeast-southwest that can be traced for a few hundred meters. One can be observed plunging southwest, toward the Pecos River. A subparallel anticlinal northwest-facing hinge line further north (circa 593,200 m E, 3,557,050 m N) may as well be the southeast side of a solution trough, with the opposing side of the trough removed by erosion. A subparallel low anticlinal ridge (circa 593,100 m E, 3,557,940 m N) may be the product of two parallel solution troughs to either side of the ridge leaving an anticline in between. In fact, the elongate nature of the large Mescalero caliche dome discussed in preceding sections (centered circa 593,800 m E, 3,557,800 m N and shown in Figure 5-4B) may be the result of solution troughs to either side of the dome. These subparallel troughs and hinge lines could be reflecting subsurface groundwater flow paths, wherein groundwater likely flowing southwestward toward the Pecos River is preferentially dissolving salts along the flow path to cause linear subsidence of the surface strata. Working further north and east of the study area, Brokaw et al. (1972) identified two northeast-southwest-oriented, southwest-plunging “groundwater troughs” in their water table/potentiometric surface contour map that similarly would indicate southwest-directed flow along discrete linear northeast-southwest paths. The northern of these troughs trends south-southwest past Laguna Grande de la Sal east of Loving to enter the Malaga quadrangle area at the northeastern corner of the quadrangle, essentially directing groundwater into the area of Malaga bend (Brokaw et al., 1972). The southern trough, which Brokaw et al. (1972) does not continue up to the Malaga quadrangle boundary, could project west-southwest from where they mapped the trough into the southeastern corner of the quadrangle, beneath the set of hypothesized solution troughs described here.

Larger scale solution troughs may control depositional patterns of the Gatuña Formation. A continuous band of Gatuña mudstones and sandstones along Salt Draw that exhibit inconsistent dip angles and dip directions may be the product of filling a solution trough, with the erratic dips being a product of tilting during subsidence into the trough. In the far southeastern corner of the quadrangle, along cross-section A-A’, Gatuña Formation mudstones and sandstones are juxtaposed against the Culebra Dolomite across both a moderately-westward-dipping depositional contact and a steeply-eastward-dipping insetting contact. The former is apparent in map patterns and the comparable bedding angles measured in Gatuña outcrops (21° to S64W and 26° to S54W) directly overlying Culebra Dolomite (12° to S74W). The latter contact is apparent in a sudden truncation of Culebra Dolomite along a trend dipping 51° to N86E, with Gatuña rocks occurring just east of the truncation; further south, map patterns also show the Gatuña Formation juxtaposed against Rustler Formation strata across a steep contact. Further east, the Rustler is not found in outcrop, apparently buried beneath a relatively thick fill of Gatuña Formation strata. In fact, the striplog for the Neil H. Wills #1 Superior-Federal well (API number 30-015-03722) located at the eastern end of cross-section A-A’ shows approximately 46 m of clastic sediments overlying a dolomite interval that in turn appears to overlie gypsum at 67 m depth (although the lithologic symbol used on the striplog for the inferred gypsum interval is ambiguous, consisting of a set of disconnected, undescribed ‘plus’ [+] symbols; regardless, it is clearly not halite/rock salt nor anhydrite, both of which occur deeper along the log and are illustrated with distinctly different patterns). This interval is presumably the Gatuña Formation over the Culebra and Los Medaños Members of the Rustler Formation. In most tectonic settings, these relationships would be readily explained by a small north- to north-northwest-striking normal fault, but in the evaporite section of the Delaware Basin, a more likely explanation is solution subsidence. In fact, the top of the Delaware

Mountain Group, well constrained by well logs here, consistently falls along the regional ~1° eastward dipping structural trend along cross-section A-A' with no apparent offset, suggesting the insetting relationship observed in the Gatuña and Rustler Formations is a product of shallower processes. Hence, I interpret instead that the contact is the margin of a north- to north-northwest-trending solution trough that filled with Gatuña Formation sediments. Dissolution could have occurred in either the gypsiferous section of the Los Medaños Member or in the Salado Formation. I infer, however, that the majority of the dissolution occurred in the Salado Formation, as shown in cross-section A-A'. That this trough trend is at a high angle to the synclines and current groundwater flow patterns discussed previously suggests that this trough formed under a different hydrologic regime than today. As at least the western margin of this proposed trough is overlain by upper Gatuña Pecos River conglomerates (map unit Qgca), the trough is possibly the result of a former position of an ancestral Pecos River (as suggested, at a larger scale, for the BPL trough by Bachman, 1987), although the majority of the Gatuña here is mudstones and sandstones and not conglomerates.

5.3.5. Regional dissolution

Regional or 'blanket' dissolution of the Ochoan evaporites has been documented by numerous previous authors (e.g., Brokaw et al., 1972; Jones et al., 1973; Bachman, 1980). Although most of this discussion revolves around the generally east-to-west thinning of the Salado Formation, Bachman (1980) also documented generally east-to-west thinning of the gypsum-rich Tamarisk Member of the Rustler Formation as well. This helps explain why the preserved thickness of the Tamarisk Member is no more than 9 m on the Malaga quadrangle despite Holt and Powers (1988) indicating that the Tamarisk Member is typically 30 to 50 m thick further east by the WIPP site. Regional dissolution, coupled with the development of local protective carapaces of solution- and erosion-resistant layers, formed the karst domes described in preceding sections occurring throughout the quadrangle. Regional dissolution is also interpreted to have caused the development of Salado Formation 'residue' breccias (e.g., Figure 3-4C; Jones et al., 1973) exposed locally along the Pecos River.

In both the northeastern and southeastern corners of the quadrangle, the Pierce Canyon is exposed and dips toward the latitudinal centerline of the quadrangle to plunge into the subsurface (although whether or not the Pierce Canyon continues beneath the surface in between these exposures is unknown). The geometry of this deformation is in part a large scale trough, as the two outcrops dip toward each other, and in part a pair of large scale karst domes, as each exhibits some radial-outward dipping patterns. Air photo examination of the surrounding quadrangles suggest that caliche becomes subhorizontal east of the quadrangle, and I suggest the deformation is best viewed as the product of an embayment, of sorts, in the regional dissolution pattern, wherein the eastward-propagating dissolution front has advanced somewhat further between Malaga bend and the southern margin of the quadrangle to cause a broad, westward-plunging, scallop-shaped deformation pattern that does not extend far east of the quadrangle boundary.

The Pierce Canyon caliche exposure in the northeastern corner of the quadrangle deserves particular discussion as it can be followed southward across an east-northeast-trending anticlinal hinge line where it descends to be buried by upper Gatuña sands capped by subhorizontal to gently-dipping Mescalero caliche (Figure 5-7). This exposure indicates that a period of dissolution and deformation occurred after the development of the Pierce Canyon caliche in the early Pliocene and development of the Mescalero caliche in the Middle Pleistocene. It is also one of the few places where the two caliches can be seen adjacent to one another and their relative relationships can be observed in outcrop.

Finally, within Pierce Canyon itself, subhorizontal Pierce Canyon caliche is found overlying lower Gatuña Formation sandstones that are dipping up to at least 20° (Powers and Holt, 1993; Hawley, 1993), indicating some tilting occurred prior to the development of the Pierce Canyon in the Pliocene. The scale of this tilting is unknown but appears to affect much of the canyon, and hence is suggested to be a regional feature.

5.3.6. Timing of dissolution and deformation

The discussion above indicates that dissolution and subsidence-related deformation occurred at least from before the development of the Pierce Canyon caliche (to deform lower Gatuña Formation sandstones below the subhorizontal caliche) in the Pliocene through to following the development of the Mescalero caliche in the Middle Pleistocene. Although no evidence is present on the quadrangle for earlier periods of dissolution, Bachman (1980) presents evidence for dissolution in the Triassic, while Johnson (1993) presents evidence for syndepositional dissolution of Salado salts in Ochoan time at least along the eastern margin of the Delaware basin. Paleogeography suggests that the area was above sea level and presumably subject to erosion during the Jurassic as well (Bachman, 1980), a situation that would be amenable to dissolution and deformation, although there is no record of this time period preserved in the area. Although the rate of dissolution and degree of deformation has likely varied substantially with climate and landscape evolution, it seems likely that dissolution of evaporites and associated deformation of overlying materials has occurred sporadically during many time periods from the Ochoan on to the present. Note, though, that the presence of relatively small sinkholes in alluvial and eolian material is not necessarily an indicator that rapid dissolution is creating new subsurface cavities today, as these sinks could be ‘cover collapse’ sinkholes, wherein unconsolidated material overlying an existing cavity is rapidly subsided into the existing cavity. This cavity may have formed at a much earlier time period than the cover collapse.

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7. Figures

1. Introduction

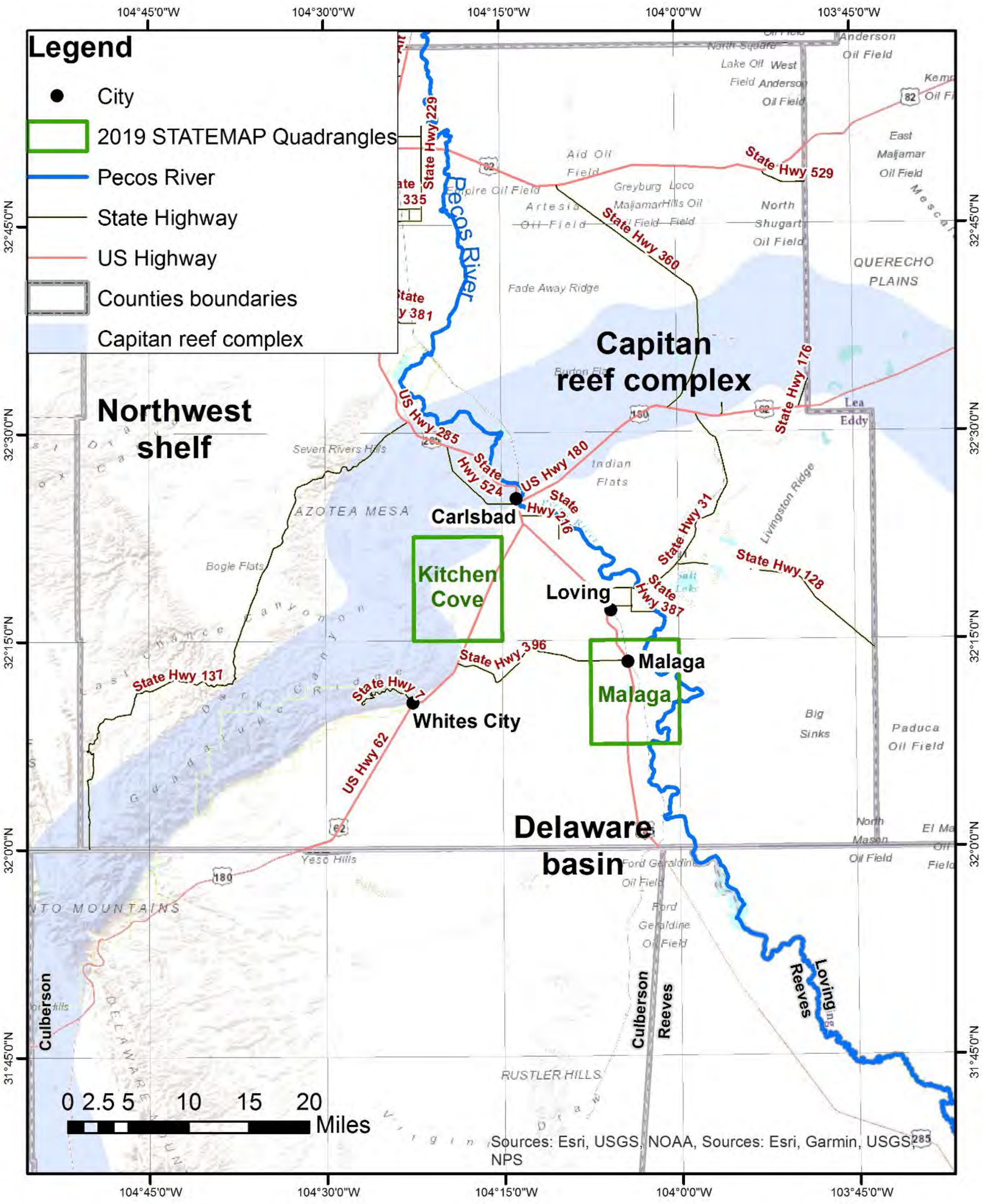


Figure 1-1: Geographic location of the study area. Capitan reef complex extent from Standen et al. (2009).

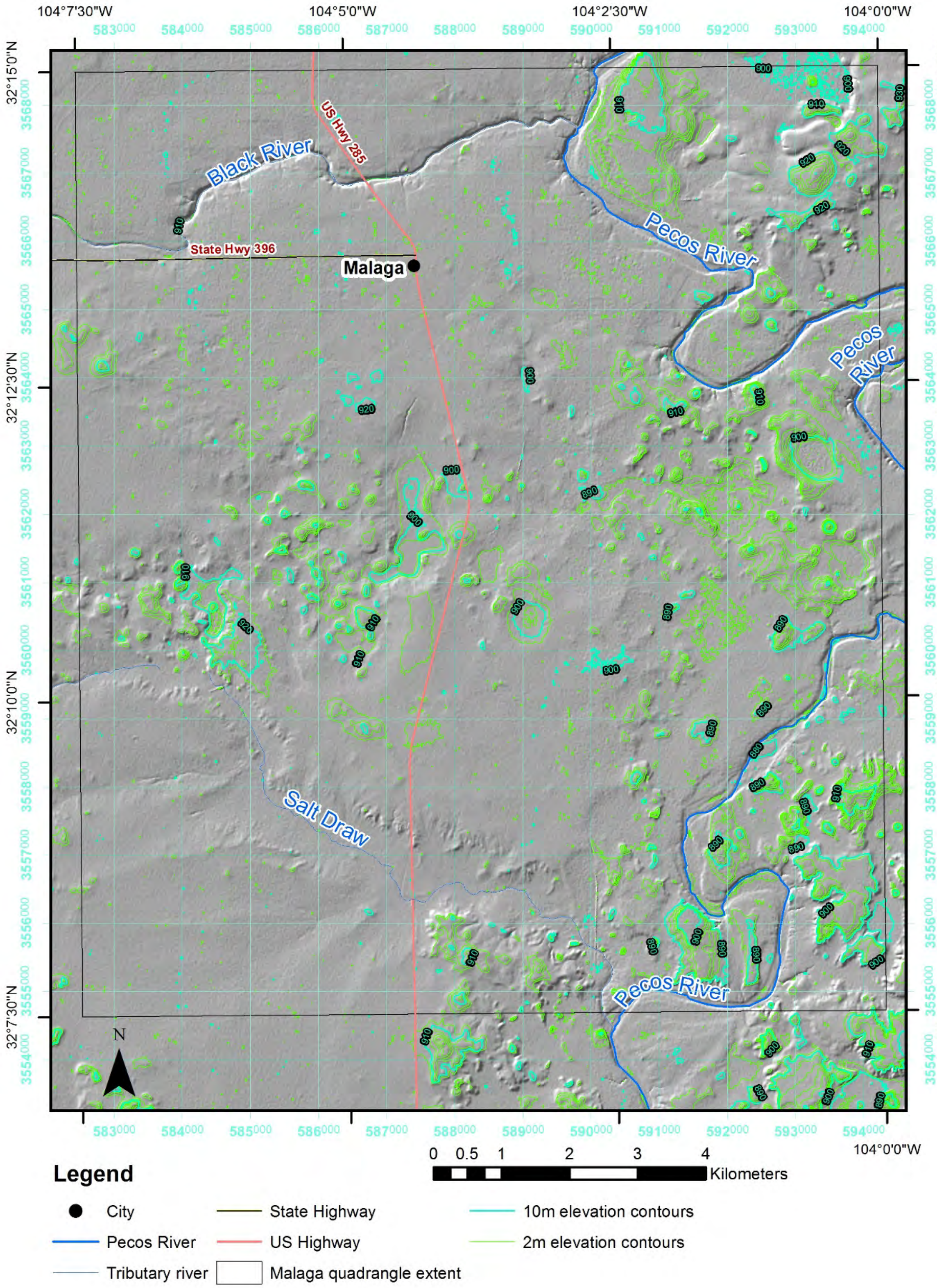
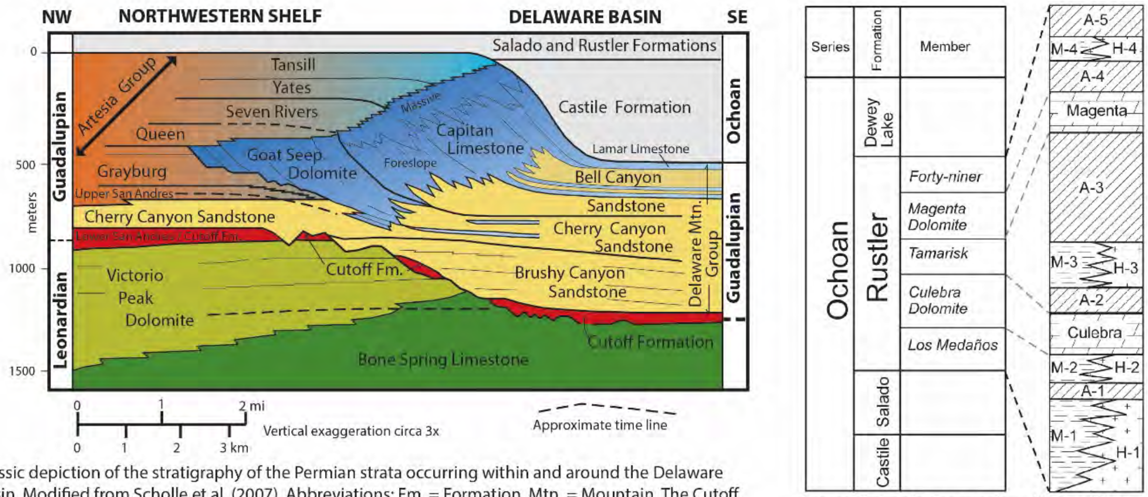


Figure 1-2: Topography of the Malaga quadrangle. Processed from digital terrain models from Intermap (Intermap Technologies, 2008).



Classic depiction of the stratigraphy of the Permian strata occurring within and around the Delaware basin. Modified from Scholle et al. (2007). Abbreviations: Fm. = Formation, Mtn. = Mountain. The Cutoff Formation, if present, is combined with the Bone Spring Limestone. The Wolfcamp Series underlies the Bone Spring Limestone.

Ochoan Series stratigraphy, from Holt and Powers (1988). The Dewey Lake Formation and Forty-niner Member are not found on the Malaga quadrangle. Lithologic abbreviations: A - Anhydrite (gypsum at the surface); H - Halite; M - Mudstone.

Figure 1-3: Permian stratigraphic nomenclature. All late Cenozoic deposits underlying the Mescalero caliche are referred to the Gatuña Formation; younger deposits are unnamed.

2. Cenozoic Erathem

Holocene alluvium along the Black River (Qtby)

Holocene alluvium along the Pecos River (surface soil developing in Qtp1)

Holocene alluvium along the Pecos River (lower Qtp1)

Figure 2-1: Outcrops of Holocene alluvium along the Black and Pecos Rivers.

(A)

Typical light reddish brown mudstones and sandstones, at the south-central end of the Malaga quadrangle

(B)

Mudstones and sandstones on the north flank of Pierce Canyon, capped by the Mescalero caliche

Figure 2-2: Typical exposures of the undifferentiated Gatuña Formation mudstones and sandstones.

Figure 2-3: Features of the upper Gatuña Formation conglomerate along the Pecos River. (A) At a distance and (B) close up, showing hollowed-out pebbles. (C) Showing a local abundance of cobbles of the Culebra Dolomite and (D) a boulder of Magenta Dolomite. (E) A reworked, carbonate-cemented pebble conglomerate clast.

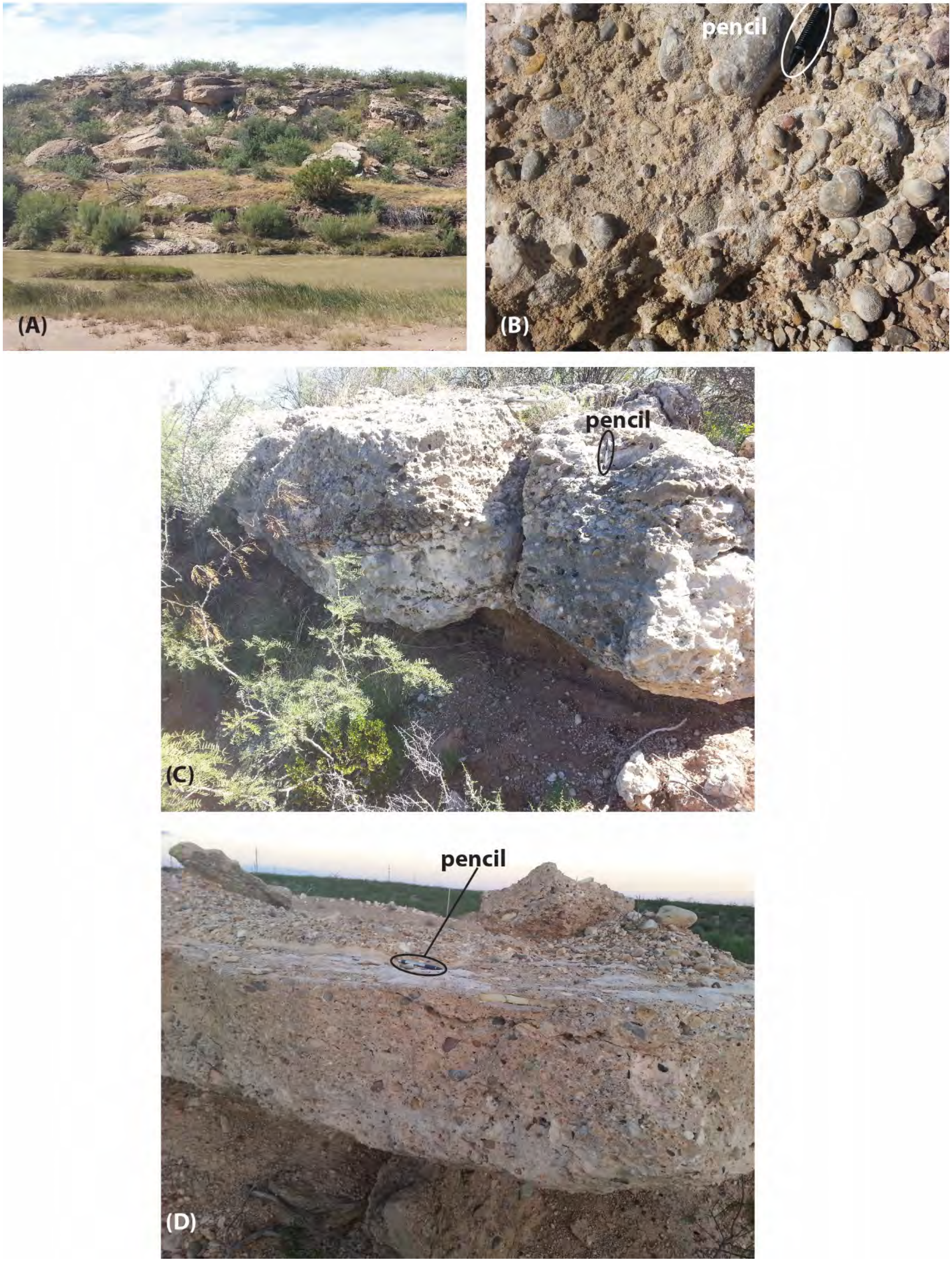


Figure 2-4: Outcrops of upper Gatuña Formation conglomerates along the Black River and Salt Draw. (A) Typical outcrops along the Black River. (B) Close-up view of pebbles in the conglomerate along Black River; note that the pebbles remain in contact and are not displaced. (C) Outcrops of the conglomerate along Black River overlying uncemented Gatuña Formation deposits. (D) Outcrop of the conglomerate along Salt Draw; note the preservation of cross-bedding.

Figure 2-5: Gravel pit exposure of uncemented upper Gatuña Formation gravels.

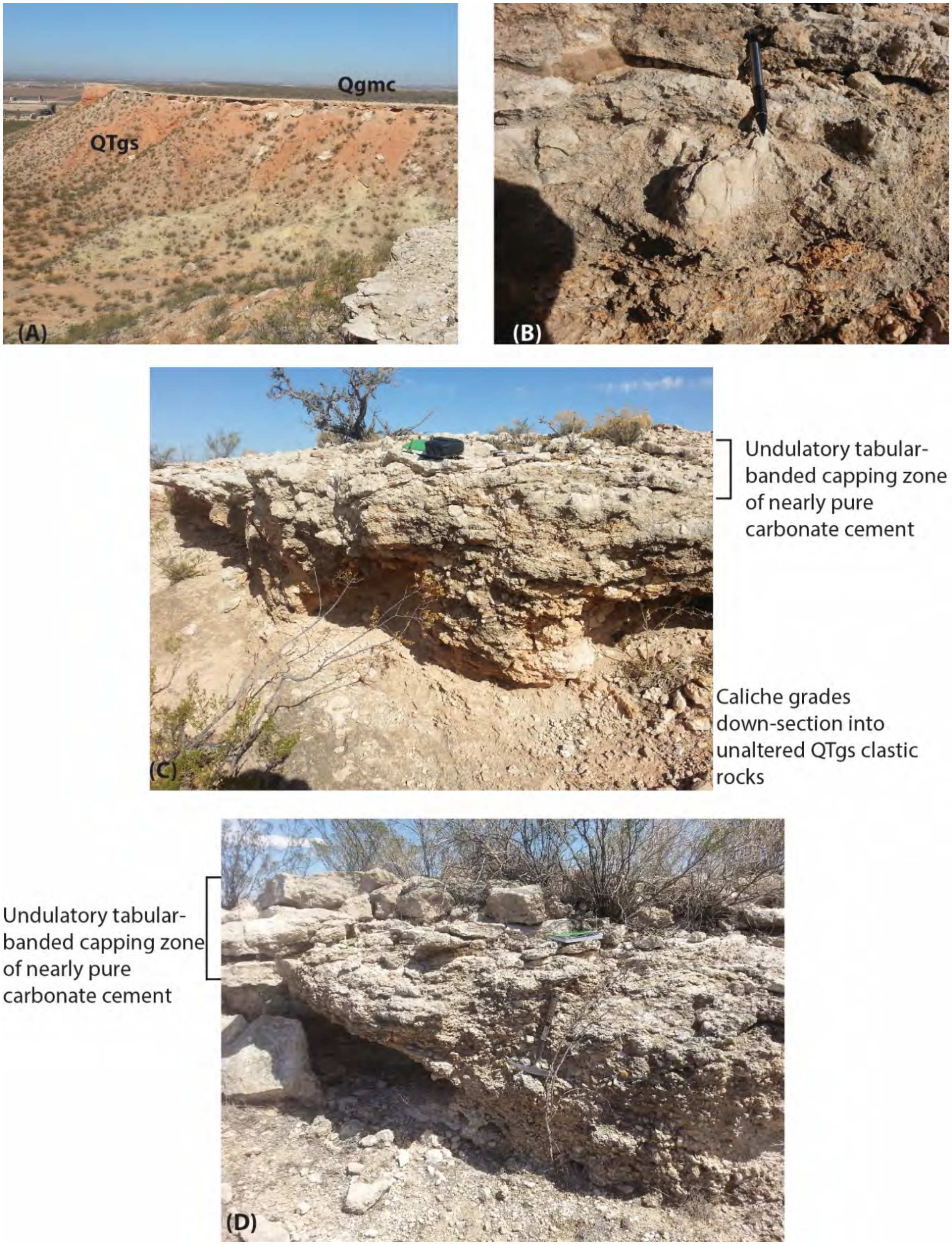


Figure 2-6: Features of the upper Gatuña Formation Mescalero caliche. (A) Mescalero caliche (Qgmc) capping a section of undifferentiated Gatuña Formation mudstones and sandstones (QTgs) along the north flank of Pierce Canyon. (B) Re-cemented fracture developed in the caliche. (C) and (D) Typical exposures of the caliche, showing undulatory tabular-banded capping zone grading down-section into non-caliche-cemented Gatuña sedimentary rocks (in C), locally with abundant pebbles (in D).

Figure 2-7: Features of the lower Gatuña Formation Pierce Canyon caliche. (A) Typical outcrop of thick, brecciated caliche. (B) The upper portion of brecciated caliche, including an undulatory tabular-banded capping zone that is similarly brecciated. (C) Thin laminae of carbonate surrounding pebbles. (D) Pisolites (at pencil tip). (E) Locally, the Pierce Canyon grades down-section into well-cemented siliceous pebbles conglomerate. (F) "Egg cup" cavity left by the dissolution of pebbles from the caliche.

Figure 2-8: Boulder of well-cemented, brecciated sandstone of the lower Gatuña Formation (map unit Tgs2).

3. Permian rocks

Figure 3-1: Outcrop of the Magenta Dolomite.

Figure 3-2: Outcrops of the Culebra Dolomite. (A) Intact Culebra, exhibiting tabular bedding and abundant fine vugs. (B) Internally-brecciated Culebra, recemented by carbonate.

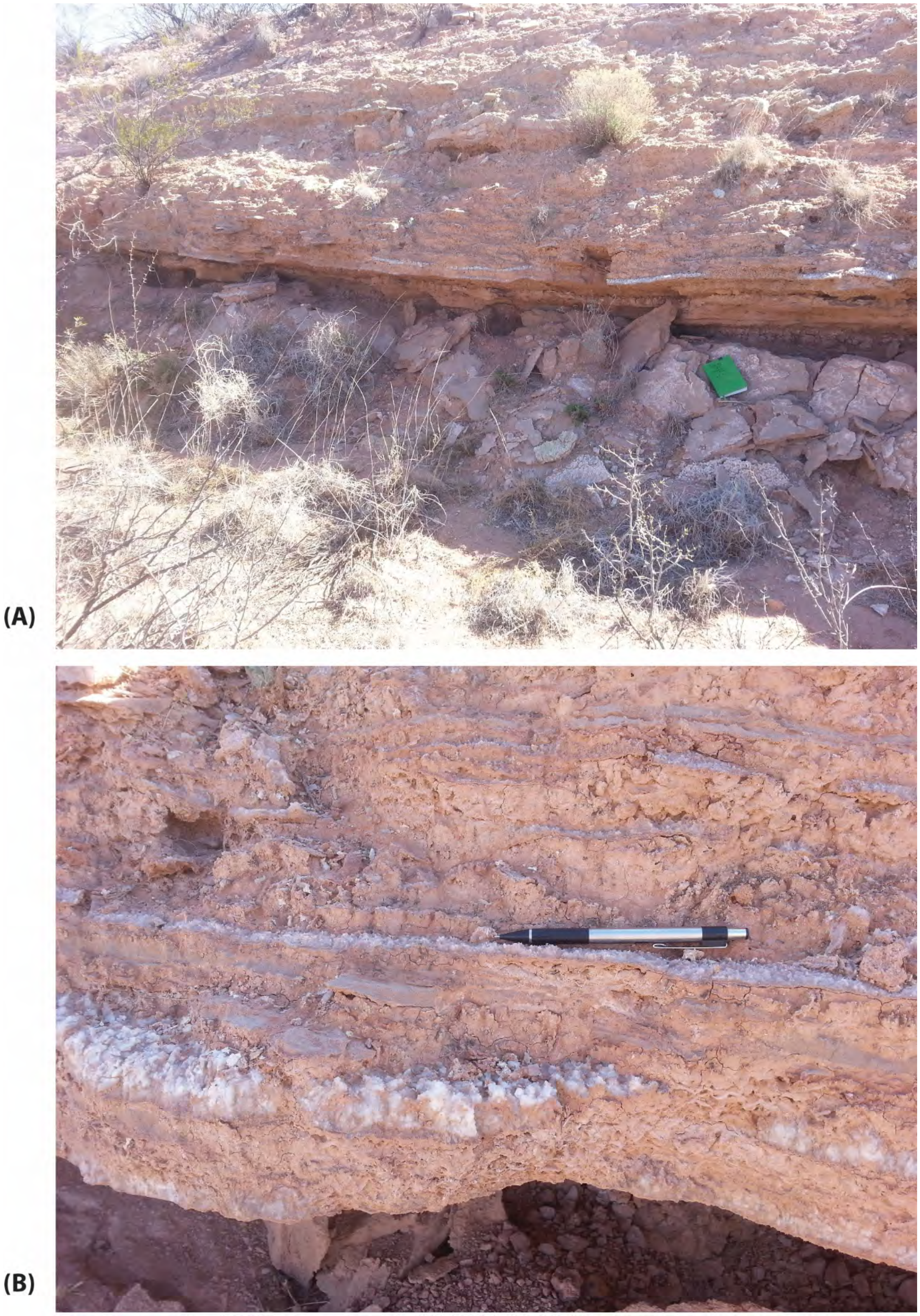


Figure 3-3: Typical outcrop of undeformed Rustler Formation Los Medaños Member.

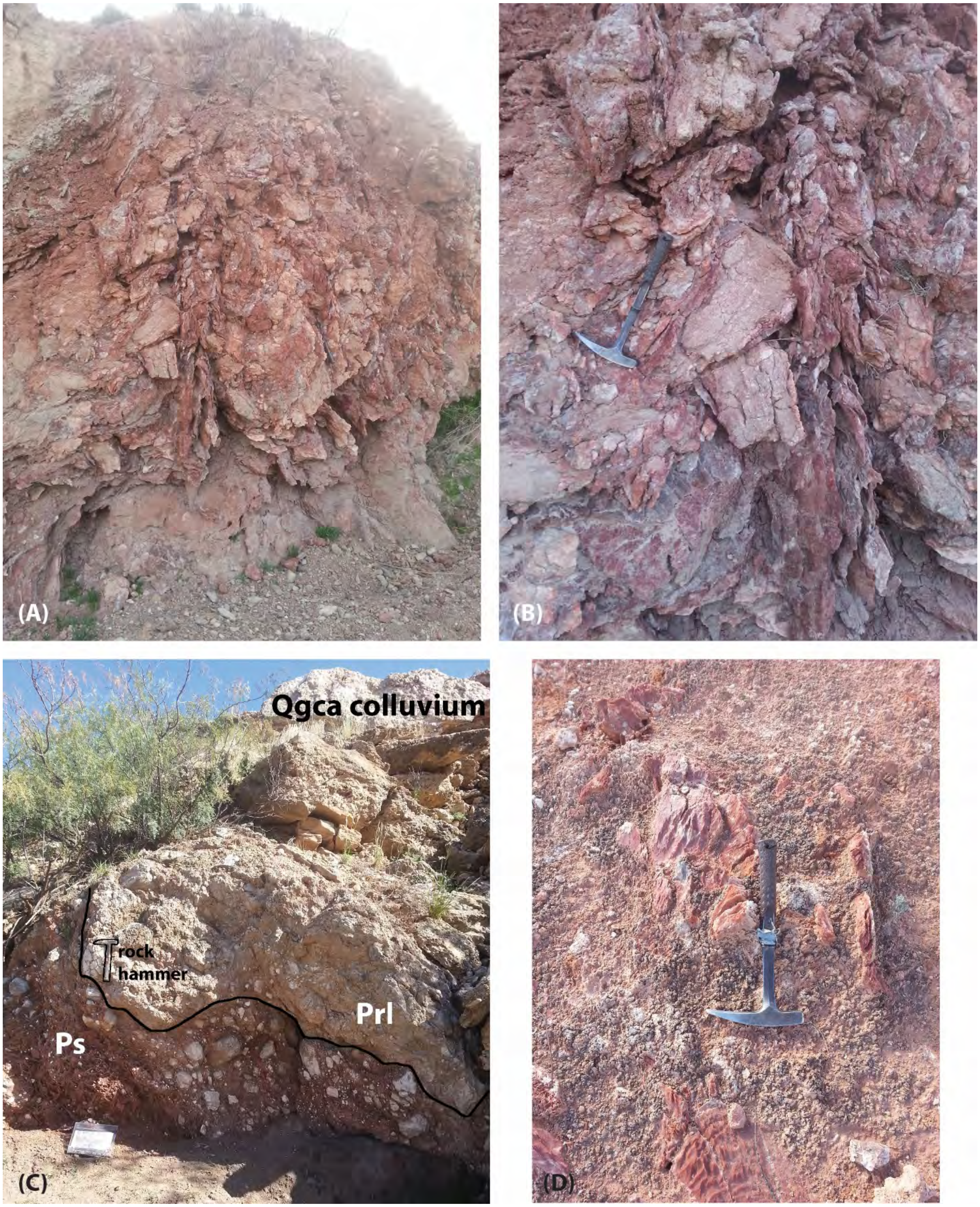


Figure 3-4: Outcrops of the Salado Formation. (A) Tall outcrop of Salado Formation breccia ~5.6 miles west of the quadrangle circa 573,390 m E, 3,564,730 m N (Stop 2-8 of Chaturvedi, 1980); rock hammer is just right of and below the center of the photo. (B) Close up of gray laminated gypsum blocks surrounded by erratic reddish brown matrix. (C) Outcrop of Salado 'residue' along the Pecos River in the north center of the quadrangle circa 589,950 m E, 3,567,750 m N. (D) Weathered low outcrops of Salado residue circa Malaga bend.

4. Unexposed Permian rocks
5. Structure

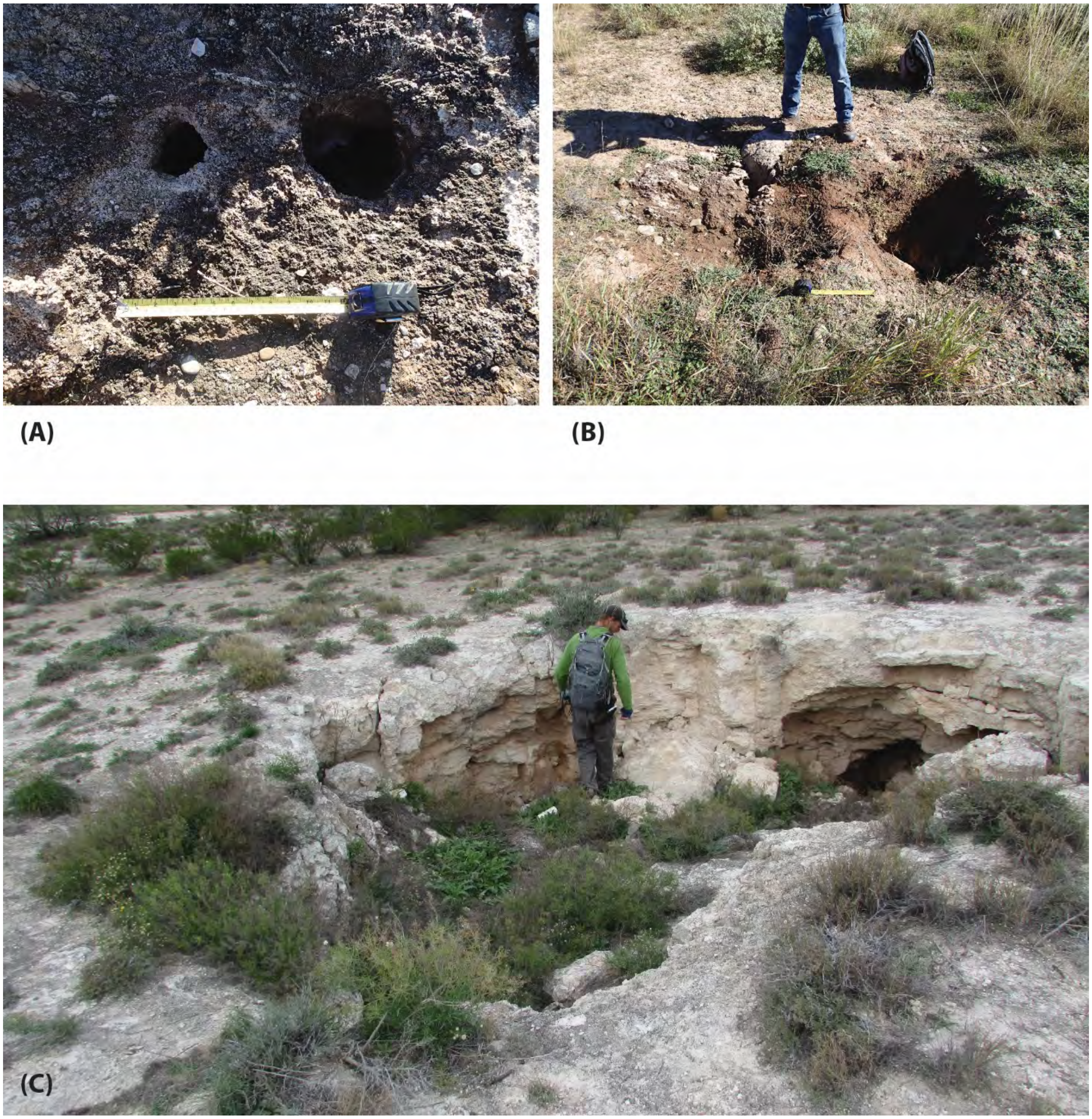


Figure 5-1: Examples of sinkhole features mapped by Land et al. (2018) along U.S. Highway 285. (A) Small cavities dissolved into/weathered out of Los Medaños Member gypsum. (B) Cover-collapse sinkholes with Los Medaños Member gypsum bedrock locally exposed in the walls of the sinkhole. (C) Large sinkhole in Los Medaños Member gypsum with a man-enterable cave in one corner.

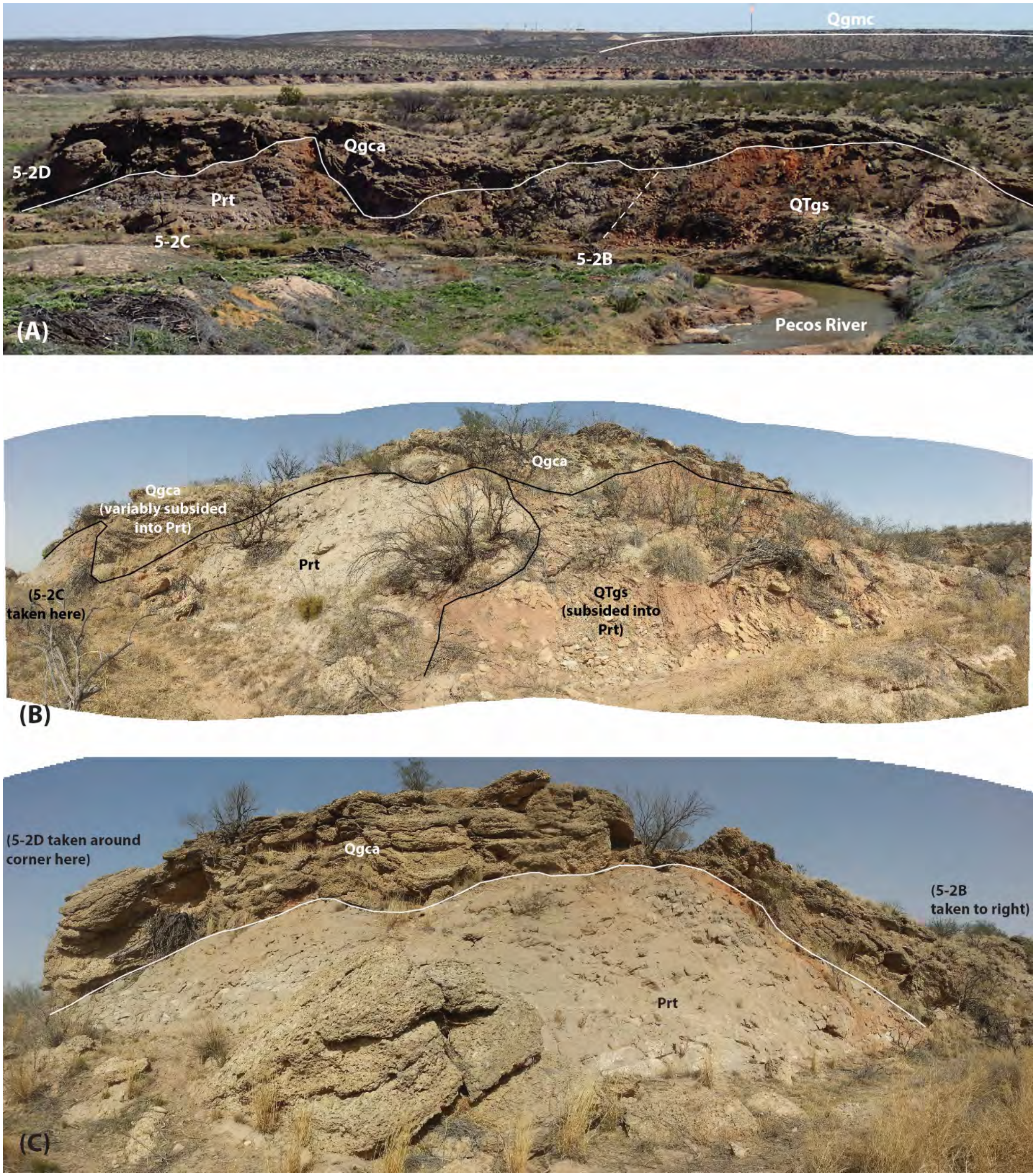


Figure 5-2: Outcrop of subsided upper Gatuña Formation conglomerate along the Pecos River. (A) Outcrop from a distance, locating photos (B) through (D). (B) South side of the outcrop, showing QTgs clastic rocks juxtaposed against Tamarisk Member gypsum breccia, with both overlain by the upper Gatuña conglomerate. (C) Upper Gatuña conglomerate variably subsided into Tamarisk Member gypsum breccia. (D) [next page] Close-up photo of upper Gatuña conglomerate bedding 'draped' over subsided contact and projecting into massive pebbly sands.


bedding slumps into subsidence feature from right to left (south to north)
Qgca
representative bedding planes
Qgca
massive pebbly sands
Qgca
contact
Prt (mostly concealed)
(D)

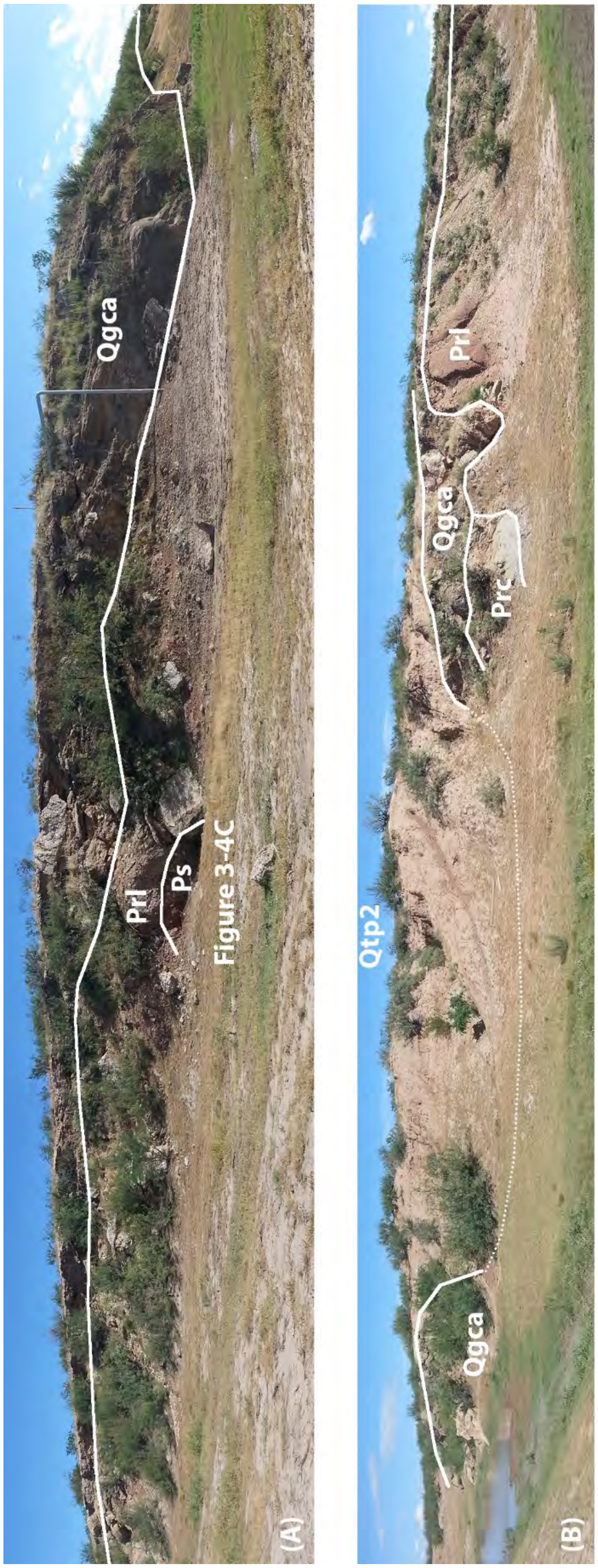


Figure 5-3: Outcrops of deformed upper Gatuña Formation conglomerates overlying deformed Culebra Dolomite, Los Medaños Member gypsum and mudstones, and Salado Formation breccia, all buried by Holocene alluvium. (A) Southern panorama. (B) Northern panorama.

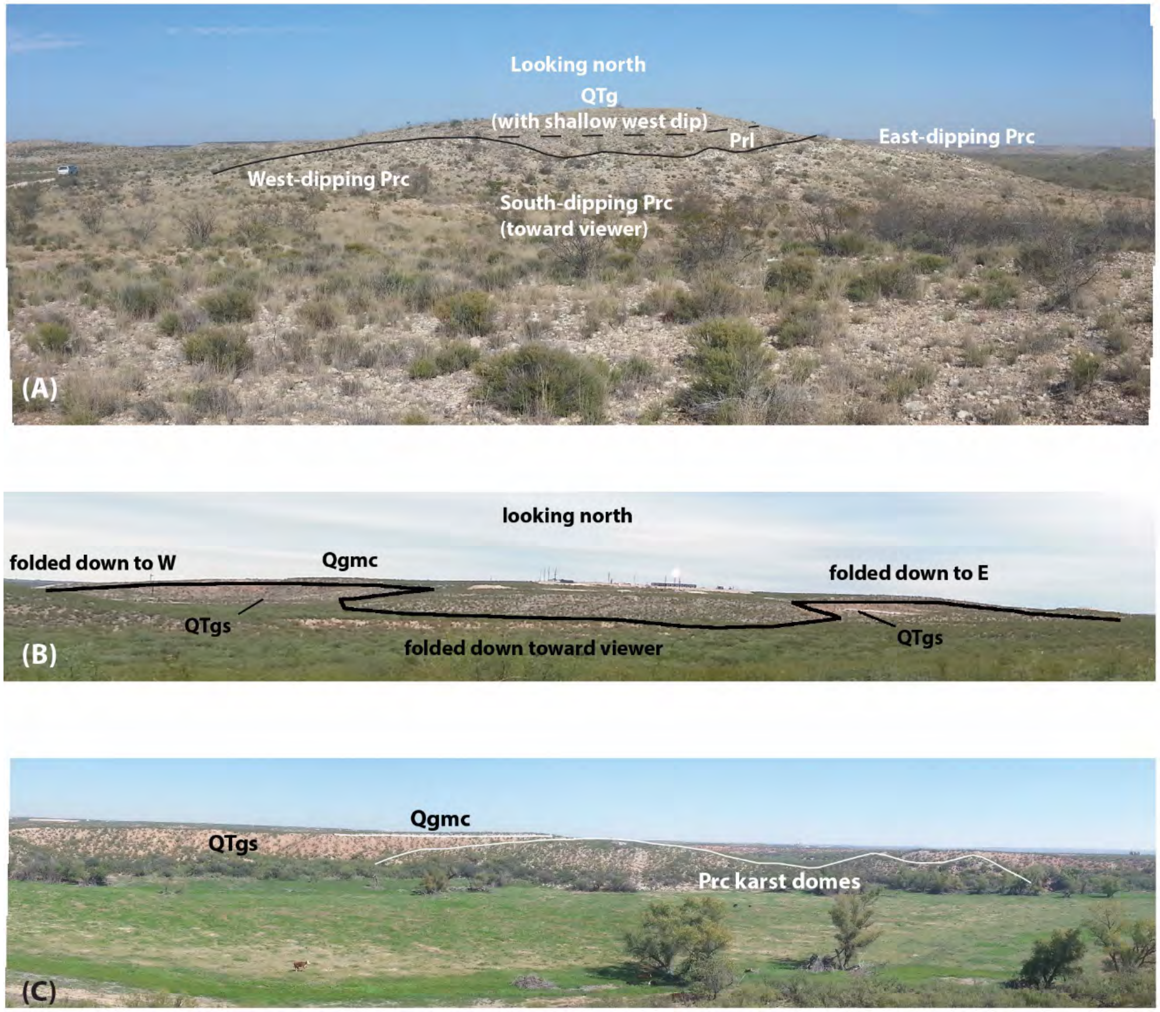


Figure 5-4: Photos of karst domes. (A) Karst dome formed by Culebra Dolomite surrounding Los Medaños Member deposits, capped by subhorizontal Gatuña Formation (from the Red Bluff quadrangle to the south). Truck at the left end of photo for scale. (B) Large karst dome capped by Mescalero caliche draped over undifferentiated Gatuña Formation deposits. Oil well infrastructure at center of photo for scale. (C) Culebra Dolomite karst domes on the northeast side of Horseshoe Lake, buried by Gatuña Formation sediments and capped by subhorizontal Mescalero caliche.

Figure 5-5: Karst mound of gypsum breccia, exposed on the Red Bluff quadrangle to the south.

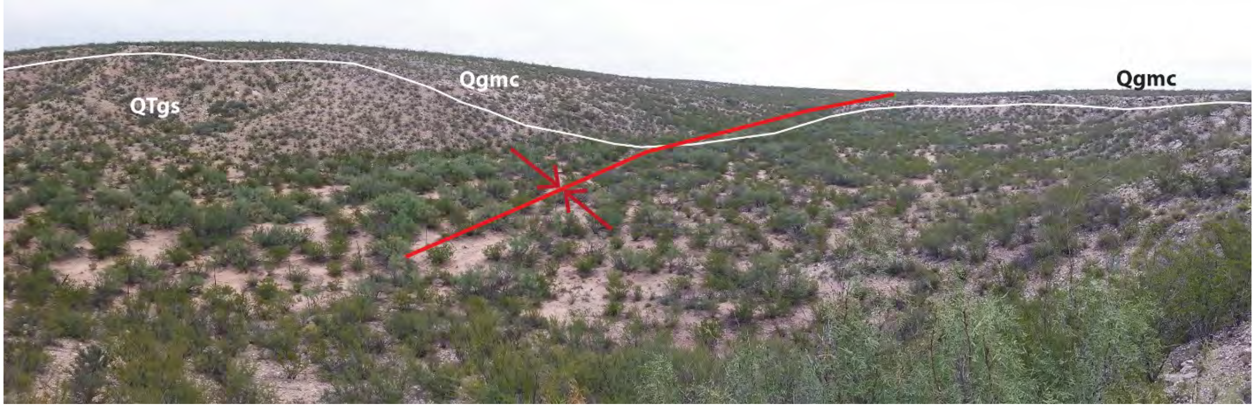


Figure 5-6: Synclinal fold in the Mescalero caliche interpreted to overlie a solution trough.

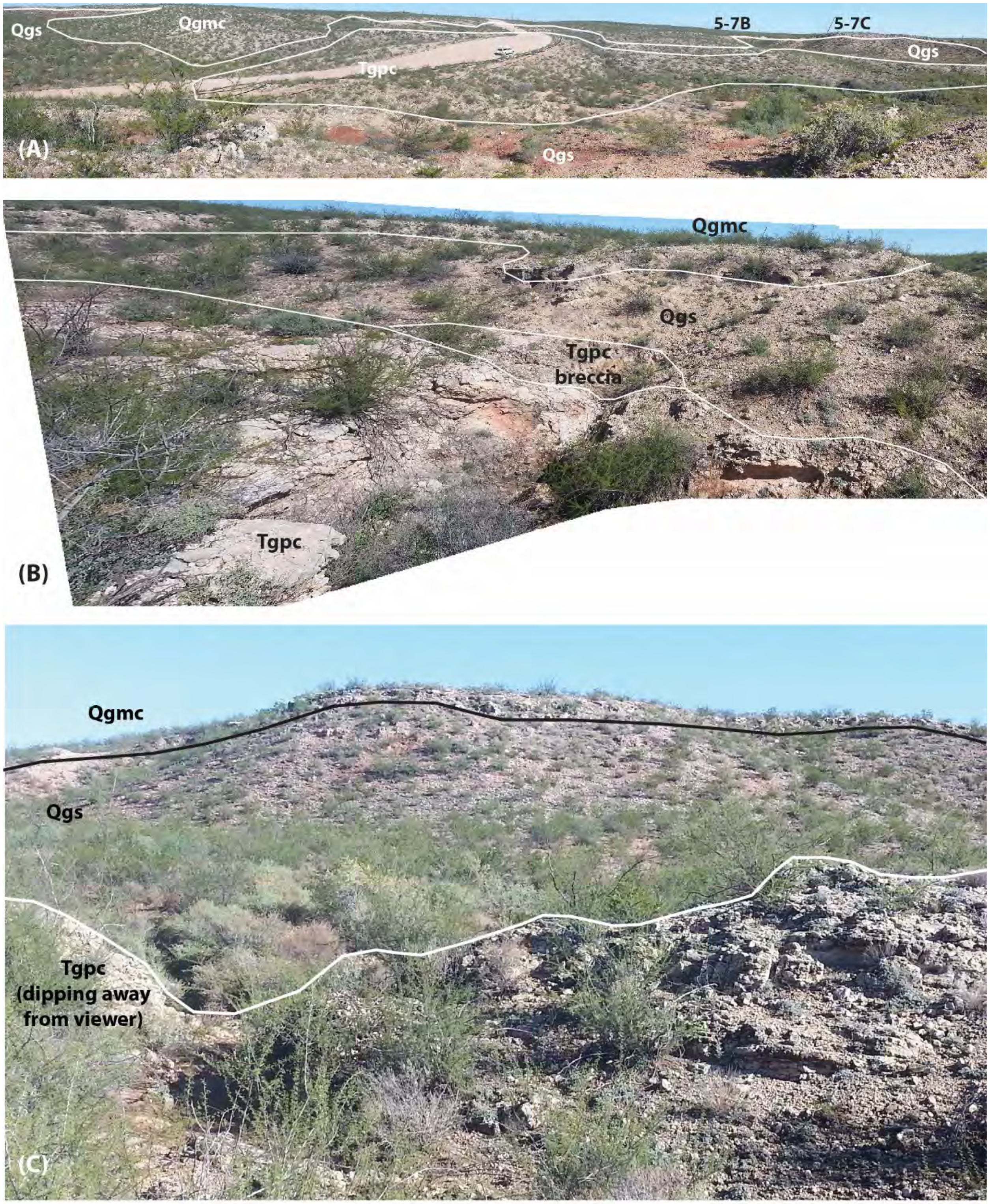


Figure 5-7: Folded Pierce Canyon caliche underlying upper Gatuña Formation sediments and the Mescalero caliche. (A) Overview of the outcrop area, looking north from circa 594,020 m E, 3,566,430 m N. Approximate locations of photos (B) and (C) are shown. (B) Close-up panorama of the Pierce Canyon caliche folded down to the east to plunge beneath upper Gatuña Formation sediments capped by the Mescalero caliche. The Pierce Canyon is locally brecciated at the contact. (C) Photo looking east, down the dip of the Pierce Canyon caliche, circa 593,965 m E, 3,566,655 m N. The Pierce Canyon here dips about 35° eastward, while the Mescalero is commonly subhorizontal.

8. Map unit descriptions

Map unit	Name	Age	Description
			Geologic terms after Compton (1985), soil terminology after Birkeland (1999), carbonate horizon stages after Machette (1985), and color notation after Munsell Color (2009).
	Cenozoic Erathem		
	Anthropogenic units		
af	Artificial fill	Historic	Compacted gravels, sands, and muds underlying dams, roads, and other artificial constructions. Only mapped where extensive or concealing underlying geologic relations. Deposit thicknesses 0 to about 10 m.
dg	Disturbed ground	Historic	Areas where anthropogenic activities obscure the nature of the underlying geology. Principally locates areas of active intensive agriculture, where terracing, tillage, and/or crop cover obscures the underlying deposits.
	Miscellaneous deposits		
Qe	Eolian deposits	Holocene	Slope-blanketing windblown very pale brown silts and fine sands variably reworked by slopewash transport. Deposits are loose and poorly exposed. No evidence of notable soil development was observed. A sediment color of 10YR 7/3 was measured. Deposits are 0 to perhaps 2 m thick.
Qed	Dune deposits	Holocene	Windblown fine sands underlying dune fields and wind-sculpted hummocky terrain. Deposits are loose and poorly exposed. No evidence of notable soil development was observed. Deposits are 0 to 6 m thick.
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. Surface soils were not observed in outcrop, but no evidence of significant soil development was found. Deposits are 0 to perhaps 2 m or more thick.
	Generic alluvial deposits	Late Pleistocene? to Historic	
Qa	Alluvium, undivided	Late Pleistocene? to Historic	Cross-section only. Undivided alluvial deposits along active drainage systems. May include terrace deposits Qtp1, Qtp2, and Qtp3, fan alluvium Qfy, and/or younger and historic alluvium Qay and Qah.
	Confined alluvial deposits	Holocene	
Qah	Historic alluvium	Historic	Unvegetated or poorly vegetated sands, muds, and gravels along active drainage channels. Includes areas submerged beneath water on aerial imagery. Deposits are unconsolidated, and no soil development is apparent. Deposit thicknesses are 0 to perhaps 2 m.
Qay	Younger alluvium	Holocene	Sands, muds, and gravels underlying low terraces and floodplains along active drainage channels. Includes historic alluvium that cannot be mapped separately at this scale. Deposits are unconsolidated, and no evidence of significant soil development was observed. Deposit thicknesses are 0 to perhaps 4 m.

	Unconfined alluvial deposits	Holocene	
Qfy	Fan alluvium	Holocene	Sands, muds, and gravels underlying coalescing alluvial fans emanating from low-order drainages. Deposit characteristics vary with the nature of the materials exposed up-gradient. Deposits are unconsolidated and poorly exposed. No evidence of significant soil development was observed. Deposit thicknesses are 0 to perhaps 4 m.
Qsw	Slopewash alluvium	Holocene	Sands, muds, and trace gravels transported by slopewash and eolian processes and blanketing low-gradient slopes. Deposit characteristics vary with the nature of the materials exposed up-gradient and underlying the deposit. Deposits are unconsolidated and poorly exposed. No evidence of significant soil development was observed. Deposit thicknesses are 0 to perhaps 4 m.
Qtp	*Pecos River terrace and floodplain deposits*	Holocene	
Qtp3	Youngest terrace/floodplain deposits	Late Holocene and Historic	Brown thinly-laminated silts and very fine sands exhibiting no surface soil development. Sands are dominantly siliceous. Terrace treads are up to 4 m above the Pecos River channel, and are likely flooded in large flood events. Deposit thicknesses are up to perhaps 4 m.
Qtp2	Younger terrace deposits	Late Holocene	Brown thinly-laminated silts and very fine sands exhibiting very weak surface soil development. Sands are dominantly siliceous. Surface soils are characterized by a thin (circa 5 cm thick) darkened A horizon and trace very fine nodules and stringers of carbonate ± gypsum in underlying sediments. Terrace tread heights are typically 3 to 7 m above the Pecos River channel. A fresh sand color of 7.5YR 5/4 and an A horizon color of 10YR 5/3 were measured. Deposits are 0 to perhaps 4 m thick.
Qtp1	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. Upper brown silts and silty sands are as much as 6 m thick in thin planar tabular beds with massive or planar-laminated internal structure. Lower light brown sands are massive and coarser grained, bearing rare medium to very coarse grains, granules, and trace fine pebbles. Paleochannel fills are lenticular, very thin to thin, internally massive, and consist of rounded pebbles to coarse sands with lithologies including quartzites, cherts, dolomites, and sandstones. Surface soil is characterized by a darkened A horizon up to about 25 cm thick overlying a thin (up to about 10 cm thick) Stage I carbonate horizon characterized by fine nodules and filaments of carbonate. Terrace tread heights are typically 5 to 13 m above the Pecos River channel. Colors of 7.5YR 5/3 and 7.5YR 6/4 were measured for the upper silts and sands and the lower sands, respectively. Deposits overall are as much as 8 m thick.
	Tributary terrace deposits	Holocene	
Qtby	Young terrace and floodplain deposits along the Black River	Late Holocene	Dark brown to dark yellowish brown weakly laminated very fine to fine sands with no appreciable surface soil development. Sands are moderately well-sorted and rounded, and principally of limestone lithics with subordinate to subequal siliceous material. Colors of 10YR 3/3 to 4/3 were measured. Terrace tread heights are as much as 8 m above the Black River channel. Deposits are as much as 10 m thick.

QTg	<u>*Gatuña Formation*</u>	Late Miocene to Middle Pleistocene	
QTgs	Undifferentiated siltstone/sandstone-dominated Gatuña Formation	Late Miocene to Middle Pleistocene	Light reddish brown to pink, to less commonly white, yellow, or pale brown, variously gypsiferous siltstones to fine-grained sandstones, mudstones, claystones, rare medium-grained sandstones, and trace pebble conglomerates. Dominantly very thinly to thinly planar tabular-bedded siltstones to very fine-grained sandstones and mudstones that are internally massive or planar- or cross-laminated. Coarser-grained sandstones and pebble conglomerates are more commonly in undulatory-tabular or lenticular beds, but similarly very thinly to thinly bedded. Claystones are typically thinly planar laminated. Pebbles are moderately sorted and rounded to well rounded, and lithologies include quartzites, cherts, sandstones, felsic to intermediate volcanic rocks, and limestones. Colors circa 5YR 6/4 dominate; overall, color measurements include 2.5YR to 7.5YR 6/3-6/4 (mudstones, sandstones); 5YR to 7.5YR 7/3 (sandstones); 2.5YR to 5YR 5/4 (claystones); 5YR 8/2-8/3 (mudstones, sandstones); rarely 2.5Y 7/3-8/3 (mudstones); and trace stronger colors up to 10YR 6/8-7/8. Undifferentiated map unit QTgs is used where the assignment of an outcrop to the upper or lower Gatuña is unclear. Deposit thicknesses are difficult to assess due to common subsidence-related deformation, but cross-section interpretations suggest thicknesses may be as much as 45 m.
Qg	Upper Gatuña Formation	Lower(?) to Middle Pleistocene	Dominantly pink to white sandy muds/mudstones and muddy fine-grained sands/sandstones, with lesser conglomerates and gravels, that overlie or are inset against the Pierce Canyon caliche and underlie the Mescalero caliche. As compared to lower Gatuña mudstones and sandstones, the upper Gatuña mudstones and sandstones tend to be 1) lighter colored, 2) less well-cemented, 3) less deformed (commonly subhorizontal), and 4) overall thinner. Assignment to the upper Gatuña is most clear where an outcrop overlies the Pierce Canyon caliche or overlies or interfingers with upper Gatuña conglomerates or gravels (units Qgca, Qgcb, Qgcs, and Qgg). Elsewhere, assignment is tentative, and the undifferentiated unit QTg is commonly used in lieu of a specific assignment.
Qgmc	Mescalero caliche	Middle Pleistocene	Petrocalcic soil horizon exhibiting Stage V carbonate horizon morphology. This horizon is characterized by a 15-30 cm thick planar- or undulatory-tabular-structured zone at the top that is composed predominantly of carbonate cement often with only trace incorporated parent material. Tabular bands are 0.5 to 3 cm thick each. Below the tabular zone is 60 to 100 cm of massive cemented carbonate, with cementation decreasing and the abundance of incorporated parent material increasing down-profile. Recemented fractures and degradational features are found locally but are rare. Most commonly, the caliche is cementing poorly sorted, well-rounded pebble gravels, with lithologies including quartzite, chert, limestone, sandstone, and trace granite and volcanic rocks, and pebble gravels locally extend up to 2 m below the caliche. Pebble gravels are not ubiquitous, however, and in many locations, the caliche may be forming in fine-grained bedrock or sediment (e.g., Prl or QTgs/Qgs). Carbonate-cemented Prc breccia found in the vicinity of the Mescalero caliche further suggests the caliche locally extends into bedrock. Caliche zone is typically 0.5 to 1.75 m thick.

Qgs	Sand- and mud-dominated facies	Lower(?) to Middle Pleistocene	Pink to white and locally reddish brown sandy muds/mudstones, muddy sands/sandstones, and lesser pebble gravels/conglomerates overlying or inset against the Pierce Canyon caliche; interfingering with or overlying upper Gatuña gravels/conglomerates; or otherwise exhibiting upper Gatuña Formation characteristics. Generally weakly cemented and poorly exposed. Muds/mudstones are poorly sorted, commonly clayey and sandy, less commonly gypsiferous, and occur in poorly-expressed planar tabular mostly medium-thickness beds. Sands/sandstones are generally subordinate to muds, very fine to fine-grained (locally coarser-grained where adjacent to conglomerates), commonly muddy/clayey and poorly sorted but locally clean and moderately sorted, and dominantly of siliceous material with subordinate to locally subequal limestone lithics. Fine rounded pebbles of chert, quartzite, and felsic-intermediate volcanic material are a trace component of both mud/mudstone and sand/sandstone beds. Rare gravel/conglomerate beds are comparable to those of Qgg and Qgc units. Colors of 5YR 7/4 and 8/2-8/3, 7.5YR 7/4, 10YR 8.5/1, and less commonly 7.5YR 6/3 and 2.5YR-5YR 4/4 were measured, with white (carbonate) mottling locally occurring adjacent to Qgmc or Qgc conglomerates. Deposit bases are typically unexposed, but thicknesses are 0 to perhaps 6 m.
Qgg	Gravel-dominated facies	Lower(?) to Middle Pleistocene	Uncemented to poorly cemented siliceous pebble gravels underlying or in proximity to the Mescalero caliche. Gravels are poorly to very poorly sorted, rounded to well rounded, clast-supported pebbles with absent to rare cobbles of lithologies including chert, quartzite, felsic to intermediate volcanics, limestone, and lesser Culebra Dolomite, in cross-stratified, lenticular, medium-thickness beds, with a matrix of pink to white, poorly sorted, fine- to medium-grained siliceous sands. A matrix color of 5YR 8.5/2 was measured. Deposits are typically poorly exposed, and their presence and extent often inferred from the occurrence of low, rounded mounds or hills mantled by siliceous pebbles. Deposits are typically <1 to 1.5 m thick, but locally may be as much as 6 m thick.
Qgc	Conglomerate-dominated facies	Lower(?) to Middle Pleistocene	Well-cemented pebble conglomerates and rare sandstones underlying, grading up-section into, or in proximity to the Mescalero caliche. Carbonate cementation is ubiquitous to these units, but does not exhibit pedogenic features such as destruction of primary sedimentary structures, displacing of grains and gravels, down-section variability in cementation, or tabular/laminated banding at the tops of cemented horizons. Conglomerate-dominated deposits commonly occur inset against older rocks along major drainages, and are subdivided based on drainage association.

Qgca	Conglomerates along the Pecos River	Lower(?) to Middle Pleistocene	Pink to pinkish white well-cemented coarse pebble conglomerates and lesser sandstones occurring along the Pecos River. Gravels consist of poorly sorted, rounded to well rounded pebbles with trace to rare cobbles and trace to absent boulders, of mainly limestone with subordinate to subequal sandstone, and additional lithologies including rare to minor Culebra Dolomite, rare to minor chert and quartzite, and trace each of felsic to intermediate volcanic rocks, Magenta Dolomite, and reworked pebble conglomerates, in cross-stratified, lenticular, medium-thickness beds. Conglomerate clasts include siliceous pebbles cemented by white carbonate and are interpreted to be reworked from lower Gatuña outcrops. Cobbles and boulders are nearly all Culebra Dolomite, presumably derived from proximal outcrops. Rare interbedded sandstones and conglomerate bed matrices consist of poorly sorted, rounded, locally clayey, very fine to coarse grains of dominantly siliceous material with subordinate limestone lithics, with clay as gravel-coating films and as a constituent of the cement. Sandstones occur as cross-stratified lenticular thin beds. Conglomerate and sandstone beds are moderately well to very well indurated by a ubiquitous grain-enveloping carbonate cement. Sandstone and conglomerate matrix colors of 5YR 7/3-7/4 and 8/2, 2.5YR 8/2-8/3, and 7.5YR 7/3 were measured. Conglomerates locally interfinger with poorly-cemented sands/sandstones and muds/mudstones of unit Qgs. Deposits are as much as 5 m or greater in thickness.
Qgcb	Conglomerates along the Black River	Lower(?) to Middle Pleistocene	Light gray to light pinkish gray limestone pebble conglomerates and lesser pebbly sandstones occurring along the Black River. Conglomerates consist of poorly to very poorly sorted, clast-supported, rounded pebbles with absent to rare cobbles and trace boulders, of mainly limestone with rare to minor sandstone and trace to rare chert and quartzite, in cross-stratified lenticular medium to thick beds. Conglomerate matrix and interbedded pebbly sandstones consist of poorly sorted, rounded, grain-supported, medium to very coarse grains of mainly limestone lithics with minor sandstone lithics and siliceous material. Beds are well to very well indurated, with a ubiquitous grain-enveloping, often sparry carbonate cement. Deposits are as much as 2 m thick.
Qgcs	Conglomerates along Salt Draw	Lower(?) to Middle Pleistocene	Pink pebble conglomerates and lesser sandstones occurring along Salt Draw. Conglomerates consist of poorly sorted, clast-supported, rounded to well-rounded pebbles with trace cobbles, of lithologies including common limestone, sandstone, quartzite, and chert; absent to rare felsic to intermediate volcanics; and absent to trace granite, in cross-stratified thin to thick lenticular beds. Rare sandstones and conglomerate matrix consist of poorly sorted fine to coarse rounded grains of mainly quartz and siliceous lithics. Conglomerate and sandstone beds are moderately well to very well indurated by a ubiquitous grain-enveloping locally sparry carbonate cement. Sandstone and conglomerate matrix colors of 2.5-5YR 8/3 were measured. Deposits are as much as 2 m thick.
Tg	Lower Gatuña Formation	Late Miocene to Pliocene	Dominantly light reddish brown mudstones and sandstones, with lesser conglomerates, that underlie the Pierce Canyon caliche. As compared to upper Gatuña mudstones and sandstones, the lower Gatuña mudstones and sandstones tends to be 1) darker colored, 2) better cemented, 3) moderately to strongly deformed or tilted, and 4) overall thicker. Assignment to the lower Gatuña is most clear where an outcrop underlies the Pierce Canyon caliche. Elsewhere, assignment is tentative, and undifferentiated unit QTg is commonly used in lieu of a specific assignment.

Tgpc	Pierce Canyon caliche	Pliocene	(New informal name) Petrocalcic soil horizon exhibiting Stage VI carbonate horizon morphology. This horizon is characterized by a diverse array of cementational, degradational, brecciation, and recementational features that extend 3.5 to 5 m below the top of the horizon, grading down-profile into more banal cemention. A typical profile bears a conspicuously undulatory-tabular-structured uppermost zone up to 0.5 m thick with tabular bands 3 to 30 cm thick of nearly pure carbonate cement. Fracturing and recementation of these bands is common, and thin laminae of pure cement commonly occurs in the swales or low areas in undulations. Concentrically-laminated structures are locally apparent in weathered faces, either as pisolites or as laminae around carbonate-engulfed gravels. Below the tabular zone lay a cemented/fractured/recemented zone 3 to 5 m thick, with carbonate abundance generally decreasing down-profile. Most often, the caliche is cementing poorly sorted, well-rounded pebble gravels of lithologies including quartzite, chert, limestone, sandstone, and volcanic rocks, and well-cemented pebble conglomerates directly underlying the caliche zone are included in the Tgpc map unit. In some locations, where gravel clasts are rare or unapparent, the caliche may be forming in Tgs mudstones and sandstones. Caliche zone is typically 3.5 to 5 m thick.
Tgs	Sandstone- and mudstone-dominated facies	Late Miocene to Pliocene	Light reddish brown, and less commonly pink, yellow, or pale brown, variously gypsiferous siltstones to fine-grained sandstones, mudstones, claystones, and rare medium-grained sandstones and trace pebble conglomerates underlying the Pierce Canyon caliche. Deposits are similar to those described for map unit QTgs, but with age constrained to upper Tertiary by the level of soil development in the overlying caliche zone.
Tgs2	Well-cemented subunit	Late Miocene to Pliocene	Pink to locally pale brown well-cemented sandstones. Sandstones are laminated to very thinly bedded and locally brecciated, and consist of poorly sorted, rounded, very fine to fine grains of dominantly siliceous material, cemented by fine-grained calcitic material. Rare pale brown sandstones tend to be thicker bedded with a sparry calcitic cement, and bear redoximorphic mottling characterized by clots of orange staining <1 mm across. Colors of 5YR 7/3 (pink) and 2.5Y 7/3 (pale brown) were measured. The base of the unit is not exposed; deposit thickness is up to at least 10 m.
	Permian System		
	Ochoan Series	Ochoan (Upper Permian)	
Pr	*Rustler Formation*	Ochoan (Upper Permian)	

Prm	Magenta Dolomite	Ochoan (Upper Permian)	Light reddish brown to pink arenaceous dolomites with a medial pale yellowish siltstone interval. Lower dolomite is distinctly undulatory- or wavy-laminated crystalline dolomite with common very fine to fine sand grains. Upper dolomite is interlayered dolomicrite, arenaceous dolomite, and crystalline dolomite in very thin, planar tabular beds that are variously internally massive or planar- or cross-laminated. Fresh colors of 5YR 6/3, 2.5YR 6/4, and 7.5YR 7/3 were measured for these rocks. Medial siltstone is also very thinly planar tabular bedded. Most often, the Magenta Member occurs as breccia blocks subsided into the underlying Tamarisk Member that are variously internally brecciated. Holt and Powers (1988) report a unit thickness of 7 to 9 m; local outcrops are no more than 2 m thick in this area, however.
Prt	Tamarisk Member	Ochoan (Upper Permian)	Brecciated to massive light gray nodular gypsum and reddish brown gypsiferous claystones/mudstones. Poorly exposed and often identified by the presence of gypsum and gypsiferous muds in colluvial/residuum slopes overlying the Culebra Dolomite or bearing breccia blocks of the Magenta Dolomite. A claystone color of 2.5YR 5/4 was measured. Holt and Powers (1988) report a thickness of about 30 to 50 m in 'normal sections,' with a maximum regional thickness of about 82 m; local outcrops and cross-section interpretations suggest a preserved thickness of no more than 9 m here, however.
Prc	Culebra Dolomite	Ochoan (Upper Permian)	Cream-colored to white, ledge-forming, conspicuously vuggy dolomite. Dolomite beds are thin, planar tabular, fine-grained, and internally massive. Abundant to rare vugs are fine in size (1 to 10 mm in diameter) and distinctive to the unit. Unit is locally highly fractured, with fractures variously filled with caliche/carbonate cement, particularly adjacent to map unit Qgmc. Preserved thickness up to about 7 to 9 m.
Prl	Los Medaños Member	Ochoan (Upper Permian)	Interlayered mudstones, sandstones, and gypsum. Reddish yellow, laminated to thinly bedded, poorly indurated silty mudstones dominate. Pale red, very thinly bedded, moderately indurated, sparry calcite-cemented coarse-grained siltstones/very fine-grained sandstones and laminated to thinly bedded, nodular or crystalline, moderately indurated gypsum beds are both rare and approximately subequal in abundance. Gypsum also occurs as irregular masses up to 60 cm in diameter. Trace thin laminae of waxy claystones are the least common lithology. Colors of 5YR 6/6-7/6 (mudstones, claystones) and 2.5YR 7/2-7/1 (siltstones/very fine-grained sandstones) were measured. Unit is generally poorly exposed and often identified by abundant reddish muds with trace irregular gypsum masses in colluvial/residuum slopes. Unit is locally highly deformed/brecciated, and may incorporate brecciated blocks of Prc that subsided into the unit. The base of the unit is only exposed in deformed outcrops; Powers and Holt (1999) report a thickness of about 34.4 m in the type section, while cross-section interpretations suggest a thickness of about 48 m in this area.
Prg	Gypsiferous mudstone members, undivided	Ochoan (Upper Permian)	Undivided Prl and Prt. This map unit is used where poor exposure and unclear stratigraphic location precludes assigning a deposit to a specific map unit.

Ps	Salado Formation	Ochoan (Upper Permian)	In outcrop, map unit consists of nodular to laminated white to light gray gypsum breccia blocks surrounded by an erratic, variably weathered, red to reddish-brown crystalline gypsiferous matrix bearing waxy reddish-brown clays. The matrix is dominantly gypsum and clay (Brokaw et al., 1973; Jones et al., 1973); colors of 10R 5/4-5/6 were measured. The base of the unit is unexposed here; isopach maps by Bachman (1980) suggest the Salado Formation unit may be as much as 300 m thick along the eastern margin of the quadrangle, generally thinning southward and westward. Cross-section interpretations suggest the Salado may thin to about 180 m or less in the southwest corner of the quadrangle. Deformation of surface geologic units is inferred to be accommodated dominantly by the variable dissolution of and subsidence into the Salado, as depicted in cross-section A-A'.
Pc	Castile Formation	Ochoan (Upper Permian)	Cross-section only. Observations to the west on the Black River Village quadrangle suggest that the intact Castile consists of laminated white to light gray gypsum and anhydrite. Isopach maps by Bachman (1980) suggest the unit generally thickens from southwest to northeast from about 445 to 505 m thick.
	Guadalupian Series	Guadalupian (Upper Permian)	
Pd	*Delaware Mountain Group*	Guadalupian (Upper Permian)	Cross-section only. Dominantly arkosic to subarkosic, very fine- to fine-grained sandstones and siltstones, with minor detrital carbonates.
Pdl	Lamar Limestone Member of the Bell Canyon Formation	Guadalupian (Upper Permian)	Cross-section only. The uppermost detrital carbonate of the Delaware Mountain Group provides a distinct marker horizon in geophysical logs. King (1942) reports the limestone is gray to black, fine-grained, thinly bedded to thinly laminated, and 5 to 10 m thick at its type locality, thickening to as much as 46 m thick closer to the Guadalupe Mountains. Well logs suggest a thickness of about 10 m in the subsurface here. May include the overlying Reef Trail Member of the Bell Canyon Formation.
Pdbc	Bell Canyon Formation	Guadalupian (Upper Permian)	Cross-section only. Dominantly arkosic to subarkosic, very fine-grained sandstones and siltstones, with minor detrital carbonates. King (1948) reports unit thicknesses from 204 to 317 m; well logs suggest a thickness of about 240 to 270 m here.
Pdcc	Cherry Canyon Formation	Guadalupian (Upper Permian)	Cross-section only. Dominantly arkosic to subarkosic, very fine-grained sandstones and siltstones, with minor detrital carbonates. King (1948) reports unit thicknesses from 305 to 390 m; well logs suggest a thickness of about 360 to 405 m here.
Pdbr	Brushy Canyon Formation	Guadalupian (Upper Permian)	Cross-section only. Dominantly arkosic to subarkosic, fine-grained sandstones. King (1948) reports a unit thickness of 305 to 350 m; well logs suggest a thickness of 470 to 490 m here.
	Lower Permian strata	Lower Permian	

Pbs	Bone Spring Limestone	Leonardian (Lower Permian)	Cross-section only. King (1948) and Hayes (1964) suggest the unit consists dominantly of brownish gray to black, thinly bedded, rarely cherty limestone with lesser black to dark brown shale and dark brown shaly limestone. King (1948) reports a thickness of about 952 m was encountered in a well near El Capitan, while Hayes (1964) reports that nearly 1,036 m was encountered in a well about 10 km west of the quadrangle (Humble Wiggs 1 in Section 31, T 24 S, R 27 E). Well logs suggest a unit thickness of at least 965 m here.
Pw	Wolfcampian Series	Wolfcampian (Lower Permian)	Cross-section only. Hayes (1964) suggest the unit consists of subequal amounts of gray, black, or brown shale and finely crystalline, rarely cherty, brownish limestone in a well about 10 km west of the quadrangle (Humble Wiggs 1 in Section 31, T 24 S, R 27 E), where the Series is about 533 m thick. Well logs from within the quadrangle extent suggest the Series is between about 453 and 566 m thick here.