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

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Open-file Digital Geologic Map OF-GM 276

Scale 1:24,000

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Executive Summary

The Kitchen Cove quadrangle lies along the northwestern margin of the Guadalupian Delaware basin southwest of Carlsbad, New Mexico. The oldest rocks exposed are Guadalupian (upper Permian) carbonate rocks of the Seven Rivers Formation of the Artesia Group, which is sequentially overlain by similar strata of the Yates and Tansill Formations of the same Group. Each of these consists dominantly of dolomitic beds with lesser fine-grained siliciclastic intervals, which accumulated in a marine or marginal-marine backreef or shelf environment. These strata grade laterally basinward (here, eastward) either at the surface or in the subsurface into the Capitan Limestone, a massive fossiliferous "reef complex" that lay along the Guadalupian Delaware basin margin and is locally exposed on the quadrangle at the mouths of Dark Canyon and Kitchen Cove. Marine basinal facies associated with these strata are not exposed but are apparent in oil and gas well records. As the marine environment desiccated in Ochoan (uppermost Permian) time, the basin subsequently filled with evaporite salts and lesser accessory carbonates and clastics of the Castile and Salado Formations, the latter of which overtopped the basin margin to extend onto the shelf. The entire area was then blanketed by the mixed evaporite-carbonate-siliciclastic strata of the Rustler Formation. Of these Ochoan rocks, the lower two members of the Rustler (Los Medaños and Culebra Dolomite Members) are well-preserved on the quadrangle, while a breccia or residue of the more dissolution-prone Castile and Salado Formations crops out locally. These Permian rocks are unconformably overlain by or inset against by late Cenozoic alluvium, including the Late Miocene(?) to Pliocene Gatuña Formation. The Gatuña caps the Culebra Dolomite along the east flank of the Frontier Hills, while a flight of younger alluvial gravels and sands, differentiated based on age inferred from degrees of soil development, are inset against or overlie the Gatuña and older Permian rocks throughout the low-gradient plain that dominates the study area.

Although regionally deformation has been generally modest since the Permian, significant folding is observed throughout the quadrangle affecting the Guadalupian Artesia Group, the Ochoan Rustler Formation, and the late Cenozoic Gatuña Formation. Although this study did not collect the level of detailed data to determine the nature of this deformation, the literature was reviewed and compared to observations made. Folding of the Artesia Group is likely principally the product of syndepositional processes, including syndepositional basinward tilting and collapse of the basin margin, and the development of topographic/bathymetric elements on the shelf associated with paleocurrents. Structure contours for geologic units underlying the Artesia Group generally do not support the existence of large-scale structures affecting the Permian strata here. A slight but consistent deflection of these contours, however, may reflect a small structure that may have affected the geometry of the basin margin in such a way as to concentrate paleocurrents here and promote the development of the paleocurrent-parallel structures observed here.

In contrast, the deformation of the Rustler and Gatuña Formations is likely the product of dissolution of the underlying evaporite-rich Castile-Salado sequence. Linear fold trends observed through the majority of the Frontier Hills may reflect the development of solution-subsidence troughs associated with either the subsurface Capitan reef trend and/or locations of an ancestral Dark Canyon Draw. Domal folds in the southern Frontier Hills may be "karst domes" produced by regional dissolution of the salt sequence down-dropping and folding overlying insoluble materials into domes that then protect the core of the dome from subsequent dissolution. Regional dissolution is also likely the cause of the brecciation of the Castile-Salado 'residue' found locally between the Frontier Hills and the La Cueva Escarpment.

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1. Introduction

1.1. Geologic and geographic setting

The Kitchen Cove quadrangle lies in far southeastern New Mexico immediately southwest of the city of Carlsbad along the eastern flank of the northern end of the Guadalupe Mountains (Figure 1-1). The quadrangle is named for a wide 'cove' in the canyon along Sheep Draw that lies just within the La Cueva Escarpment in the northwestern corner of the quadrangle. The mouth of Dark Canyon lies within the quadrangle, which is incised into the apex of a broad east-opening bend in the trend of the Guadalupe Mountain front and associated Capitan reef complex trend (Figures 1-1 and 1-2). This bend embraces a set of low rounded hills along the base of the Guadalupe Mountains called the Frontier Hills. The eastern half of the quadrangle is dominated by a low-gradient plain that grades gently eastward toward the Pecos River, which passes southeastward from Carlsbad off-quadrangle to the east. U.S. Highway 62-180, also called National Parks Highway, cuts across this plain along the eastern side of the quadrangle, linking Carlsbad to Carlsbad Caverns and Guadalupe Mountains National Parks, which are located off-quadrangle to the southwest. Surface elevations range from about 964 meters (m) above mean sea level (amsl) along Dark Canyon Draw as it enters Carlsbad in the northeastern corner of the quadrangle to a high of about 1,223 m amsl in the southwestern corner within the Guadalupe Mountains.

Geologically, the study area lies in the northwestern sector of 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). In Guadalupian time, which is the oldest time period from which rocks are exposed on the quadrangle, the rim of the basin was defined by the Capitan reef complex (Figure 1-1), which developed at the basin margin and separated the marine Delaware basin from a horseshoe-shaped shelf or backreef environment that surrounded the basin. The reef complex passes along the western side of the quadrangle, mostly in the subsurface although with a few small outcrops occurring along the mouths of Dark Canyon and Kitchen Cove. Shelf or backreef strata of the Artesia Group progrades over the Capitan reef in these exposures and presumably in the subsurface all along the La Cueva Escarpment, and the carbonate facies of these strata uphold the high topography of the Guadalupe Mountains at this latitude. Basin sandstones of the Delaware Mountain Group accumulated along the basin floor below the reef, but are these are not exposed at the surface. As Permian seas retreated in Ochoan time, the Delaware basin first filled with gypsum (Castile Formation) and subsequently the basin, reef, and backreef areas were buried in evaporites of the Salado Formation and the mixed evaporite-carbonate-siliciclastic assemblages of the Rustler and Dewey Lake Formations. The upper portions of the Artesia Group and Capitan reef limestone, remnants of the evaporites of the Castile and Salado Formations, and lower portions of the Rustler Formation crop out within the quadrangle from La Cueva Escarpment through the Frontier Hills.

If Mesozoic strata ever blanketed the area, they have subsequently been stripped by erosion. Lang (1947) reported an occurrence of lower Cretaceous rocks along U.S. 62-180 approximately 7.5 miles south-southwest of Whites City that he as well as Bachman (1980) interpreted to be the remains of a sinkhole-filling breccia, and Hill (2006) describes siliceous gravels lying along the summit plain high in the Guadalupe Mountains as most resembling those found in the Early Cretaceous Trinity Group. This would imply that at least lower Cretaceous strata once covered the area, but the exact extent of this cover is unknown. Uplift of the Guadalupe and Sacramento Mountains in the Cenozoic resulted in broad erosion of the landscape followed by accumulation of the alluvial and eolian sediments of the Ogallala and Gatuña Formations (Powers et al., 1978; Pazzaglia and Hawley, 2004). The late Cenozoic sedimentary record is principally preserved east of the quadrangle (cf., Bretz and Horberg, 1949); however Motts (1962) mapped “older alluvium” along the Frontier Hills that Hawley (1993) later suggested was correlative to the Gatuña Formation. As will be discussed below, this work supports such a correlation as well. Younger alluvial gravels and alluvial and eolian sands are inset against and overlie this “older alluvium,” and underlie the broad plain east of the mountains. This plain has previously been assigned to a single broad geomorphic surface, the Orchard Park plain, which is inset upon by the Lakewood terrace (both terms after Fiedler and Nye, 1933; cf., mapping by Horberg, 1949, and Bjorklund and Motts, 1959). Broadly, this work supports a two-tiered division (here, Qao vs Qay), but I identify subdivisions within these surfaces based on degrees of soil development and sedimentology not mapped previously.

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 karst structures that deform the exposed Ochoan and late Cenozoic deposits, particularly further east by the Pecos River (Vine, 1960; Bachman, 1980; Bachman, 1987). Deformation of Ochoan Series and Gatuña Formation strata exposed within the quadrangle are here interpreted to be the product of dissolution-related subsidence and collapse as well. Folds are also observed in the Artesia Group that have been variously interpreted as post-depositional and tectonic (e.g., Kelley, 1971), shallow-seated syndepositional deformation (e.g., Hunt et al., 2002), or primary features associated with the backreef depositional environment (e.g., Motts, 1972). Subsurface data acquired and interpreted as a part of this work generally suggests a lack of deep-seated structures; 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 platform as well. 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., DeFord and Riggs, 1941; King, 1948; Hayes, 1964; Kelley, 1971; Powers et al., 1978; Bachman, 1980; Holt and Powers, 1988; Powers and Holt, 1993; Hawley, 1993; Powers and Holt, 1999; Scholle et al., 2007; Figure 1-3). Early ambiguity as to the specific definitions of the geomorphic surface terms ‘Orchard Park plain’ and ‘Blackdom plain’ discouraged me from using the terminology of Fiedler and Nye (1933) during mapping, although I discuss correlations and potential correlations between the deposits mapped here to these geomorphic terms below.

1.3. Acknowledgements

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2. Cenozoic Erathem

2.1. Unnamed deposits of the Lakewood terrace

The Lakewood terrace, as mapped and described by Horberg (1949) and Bjorklund and Motts (1959), is underlain by the deposits mapped here as younger alluvium (map unit Qay and its subunits Qay1, Qay1g, Qay2, and Qay2g). These units are differentiated from one another based on a combination of soil development and sedimentary textures. They are largely mapped based on geomorphic criteria (insetting relationships).

Younger alluvial deposits are characterized by the lack of a petrocalcic (cemented) carbonate horizon and differentiated into subunits based on relative age inferred from soil development, sediment color, and geomorphology (Figure 2-1). The younger subunit, Qay2, exhibits no significant surface soil development, being characterized by a rather monotonous brown to yellowish brown coloration to the sand and silt deposits and matrix (Figures 2-1A and B). The deposits are dominantly silts and sands, with rare coarser-grained paleochannel fills of rounded, poorly sorted pebbles, as well as local thin clay layers. Gravel lithologies reflect rocks exposed nearby or upstream (mostly limestones or dolomites, lesser sandstones, and locally Rustler Formation rocks). A coarser-grained subunit, Qay2g (Figure 2-1B), occurs along the larger drainages such as Dark Canyon and Little McKittrick Draws, which is dominated by poorly sorted cobbly pebbles derived from upstream lithologies. Beds in Qay2 and Qay2g are uniformly uncemented and typically poorly structured. The surfaces capping Qay2 deposits typically exhibit bar-and-swale microtopography.

Deposits of the older subunit, Qay1, exhibit weak surface soil development characterized by simple A/Bk horizonation and an overall lighter color as compared to Qay2 (Figure 2-1C). Light brown to pink silty-clayey sands dominate, with slight darkening in the A horizon, and the carbonate horizon is typically characterized by thin, fine filaments and nodules of carbonate (Stage I morphology). Lesser gravels are concentrated in thin pebbly paleochannel fills, with lithologies reflecting those exposed upstream or nearby. Qay1 sands are typically poorly structured and uniformly uncemented. The gravel-rich subunit, Qay1g, locally exhibits somewhat greater soil development (with carbonate horizons of up to Stage II morphology) and may be phreatically cemented by carbonates where overlying shallow bedrock, such as within Dark Canyon (Figure 2-1C). Phreatic cementation is distinguish from pedogenic (soil development-related) carbonate accumulation and cementation by the preservation of primary depositional structures and the lack of gravel displacement as a consequence of the precipitation of carbonates; in contrast, pedogenic carbonate horizons typically have no primary structures preserved and gravels are often visibly displaced, sometimes resulting in matrix-supported textures, as a consequence of soil development (e.g., Figures 2-2 and 2-3). Gravels are commonly cobbly or sandy pebbles, poorly sorted, and rounded, with lithologies reflecting those exposed upstream or nearby (dominantly carbonates with rare sandstones).

Machette (1985) assessed the relationship between carbonate horizon morphology and soil age regionally, and the Stage II or less morphology horizons found in Qay deposits would suggest Holocene to possibly Late Pleistocene ages for these deposits (cf., table 2 of Machette, 1985).

Historic alluvium (Qah) is characterized by a lack of vegetation and the ubiquitous preservation of primary depositional features (e.g., bar and swale topography capping deposits, cross-bedding within deposits).

Younger alluvial deposits were identified in the field based on limited outcrop exposures, then mapped on geomorphic criteria (Qah surfaces have bar-and-swale topography and little vegetation cover, and often are is inset against Qay2 treads; Qay2 treads are inset against Qay1 treads). Where exposures could not be found, where geomorphic controls were lacking, or where the map scale precluded subdivision, undivided units Qay or Qayh were employed. Younger alluvial deposits are typically thin; Bjorklund and Motts (1959) states the Lakewood terrace deposits are less than about 7.5 m thick, and they are frequently thinner particularly where located away from major drainages.

2.2. Deposits of the Orchard Park and Blackdom plains

The Orchard Park plain and Blackdom plains, as mapped and described by Horberg (1949) and Bjorklund and Motts (1959), are underlain by a mix of older alluvium (map unit Qao and its subunits Qao1, Qao2, and Qao2s) and a broad expanse of undivided eolian-alluvial sands that blankets the plain (Qae). Bjorklund and Motts (1959) also appear to extend the Blackdom surface over the oldest late Cenozoic alluvial deposits found on this quadrangle (Tgp), but these are discussed in a subsequent section. The Qao units are differentiated from one another based on a combination of soil development and sedimentary textures. They are largely mapped based on geomorphic criteria (insetting relationships).

Older alluvial deposits are characterized by the presence of a petrocalcic (cemented) carbonate horizon in the surface soil, or by lateral correlation of a deposit lacking a petrocalcic carbonate horizon to a deposit with such a horizon, and are differentiated into subunits based on relative age inferred from the level of development of the carbonate horizon (Figures 2-2 and 2-3). Deposits of the younger subunit, Qao2, are characterized by petrocalcic carbonate horizons exhibiting Stage IV morphology and a relatively restricted thickness, with a well-cemented zone roughly 35 to 60 cm thick that rapidly grades down-section into uncemented sediments (Figure 2-2). Sediments immediately below the cemented horizon are commonly enriched in pedogenic carbonate, but this enrichment decreases down-profile to grade into the unaltered parent material. These Stage IV horizons are characterized by a relatively thin (4 to 20 cm thick) uppermost laminated zone consisting of undulatory tabular laminae 2 to 10 mm thick of nearly pure carbonate cement (Figures 2-2B). Any previously overlying A or B horizons have been stripped by erosion, often replaced by up to 20 cm of eolian or slopewash sands similar to those of map unit Qae. Deposits themselves are dominantly poorly sorted, rounded, cobbly pebble gravels with trace boulders, of lithologies reflecting rocks exposed upstream or nearby (dominantly carbonates with rare sandstones), in massive tabular beds. Subordinate to the gravels are light brown to white massive silty-clayey sand beds (Figures 2-2A and B) that often bear clay films as bridges between and coats around sand grains. Machette (1985) assessed the relationship between carbonate horizon morphology and soil age regionally, and the Stage IV morphology horizons found in Qao2 deposits would suggest a Middle to possibly early Late Pleistocene age for these deposits (cf., table 2 of Machette, 1985).

In several locations, a terrace tread upheld by a thin cobbly pebble layer overlying sands is found above neighboring treads capping outcrops of Qay1 deposits but exhibiting no evidence of a petrocalcic carbonate horizon in the surface soil. At the foot of the Frontier Hills along Elbow Draw, circa 565,415 m E, 3,570,250 m N, one such tread was followed laterally into an outcrop exposed by a drill pad cut that exposed a thin Stage IV petrocalcic horizon developed in a Qao2 deposit. Near the mouth of Little McKittrick Canyon around the south tip of the Hackberry Hills, circa 566,320 m E, 3,580,770 m N, similar treads lacking a petrocalcic carbonate horizon occur that are of comparable height as treads capping exposed Qao2 deposits and surface soils further downstream. This sand-dominated deposit is therefore tentatively correlated to map unit Qao2 despite the lack of a petrocalcic horizon, and mapped as a subunit, Qao2s. These deposits are poorly exposed, but appear to consist dominantly of light brown very fine to fine sands, with subordinate cobbly pebble gravels similar to those seen in Qao2. Common thin carbonate coats on gravels weathering out of terrace tread edges suggest that a weak carbonate horizon of perhaps Stage II morphology may be found developed in these deposits. Otherwise, no significant soil development was observed in these deposits; these may be Qao2 deposits where erosional stripping of the soil continued through the carbonate horizon to completely remove or substantially degrade the soil profile. Alternatively, these may be Qay1-age deposits underlying anomalously high terrace treads.

Deposits of the older subunit of the older alluvium, Qao1, are characterized by petrocalcic carbonate horizons exhibiting Stage V morphology and a thicker carbonate-impacted zone (Figure 2-3). These Stage V horizons are well-cemented over roughly 50 to 110 cm, and are characterized by an uppermost tabular-structured zone that is 25 to 40 cm thick of undulatory tabular bands that are 3 to 10 cm thick and composed of nearly pure carbonate cement (Figures 2-3B and C). Any previously-overlying horizons have been stripped by erosion. Carbonate ubiquitously whitens the matrix of Qao1 gravels, with carbonate-enrichment extending to at least 4 m deep below the top of the carbonate horizon. However, at depth cementation decreases and primary sedimentary structures may be preserved. Deposits consist of poorly sorted, rounded cobbly gravels with trace boulders, of lithologies reflecting rocks exposed upstream or nearby (dominantly carbonates with rare sandstones). Pale pink sand interbeds are present but very rare, and consist of carbonate-engulfed very fine to fine sand grains in massive tabular beds. The Stage V morphology horizon found in the surface soil of Qao1 suggests a Middle Pleistocene age for these deposits (cf., table 2 of Machette, 1985).

Older alluvial deposits were identified in the field based on limited outcrop exposures, then mapped on geomorphic criteria (tread heights of Qao2 and Qao2s are comparable, and both are inset against Qao1; Qao tread heights lie above adjacent treads capping Qay deposits). Where exposures could not be found, where geomorphic controls were lacking, or where the map scale precluded subdivision, the undivided unit Qao was employed. In outcrops around the Frontier Hills and along the base of the La Cueva Escarpment, older alluvial deposits are typically thin, with Rustler Formation rocks exposed at the bases of several gravel pits, indicating thicknesses of up to about 4 m. However, Bjorklund and Motts (1959) contoured the thickness of the alluvium through much of the quadrangle area, and assigned the majority of the alluvium to their ‘older alluvium,’ which appears largely equivalent to map unit Qao. They indicate that a maximum thickness of 110 m is found along U.S. 62-180 east-southeast of the mouth of Dark Canyon, but this thickness may include some Gatuña Formation conglomerates as well (map unit Tgp). The Gatuña Formation conglomerate is generally not present between the Frontier Hills and the La Cueva Escarpment, and here well records suggest a maximum alluvial thickness of as much as 64 m. Therefore, I suggest that the overall thickness of Qao deposits ranges from 0 to about 64 m or more, and I further suggest that the majority of this thickness is Qao1. Cross-sections by Bjorklund and Motts (1959) show that the subsurface alluvium is dominantly a mix of gravels and sands, and perhaps more sandy than is exposed at the surface.

Much of the Orchard Park plain, as mapped by Horberg (1949), is blanketed by a veneer of eolian silts and sands variously reworked by slopewash, map unit Qae. These sediments are pink to pale brown, and exhibit weak surface soil development characterized by rare fine carbonate nodules (Stage I or less carbonate horizon morphology) occurring below about 30 cm depth. Given the level of soil development, these deposits appear much younger (likely Holocene: cf., table 2 of Machette, 1985) than the older alluvial deposits they blanket. Qae deposits are often thin but in places are as much as 3 m thick.

Comparing my geologic mapping results, including on-going mapping further south on the Black River Village quadrangle (Cikoski, *unpublished mapping*, expected release in 2020), to the maps and descriptions of Horberg (1949) and Bjorklund and Motts (1959), it appears that the deposits of Qae, Qao2, and Qao2s are those associated with the Orchard Park plain, while Qao1 deposits may best be associated with the Blackdom plain. The first of these correlations would indicate that the Orchard Park plain, as mapped, is diachronous, as the levels of surface soil development observed in Qao2 versus Qae indicate substantially different ages, and in fact indicates that the age of Qae is comparable to the age of the inset, Lakewood terrace-underlying Qay deposits. The second of these correlations is currently uncertain, as Bjorklund and Motts (1959) and Motts (1962) map the Blackdom plain as variously overlying deposits of Qao1 and Tgp. Continued mapping to the south may better constrain the surface-deposit association, but at present I believe the association of Tgp with the Blackdom plain is incorrect, and that Qao1 most commonly underlies the Blackdom plain.

Regionally, the Stage V petrocalcic horizons developed in Qao1 deposits are comparable in morphology to the Stage V petrocalcic horizons capping Gatuña Formation strata in Pierce Canyon, east of the Pecos River by the town of Malaga (Mescalero caliche of Bachman, 1980; see also Hawley, 1993). This would suggest that Qao1 is age-correlative with the upper Gatuña Formation (cf., Cikoski, 2019). However, the abundance of limestone in typical Qao1 deposits could enhance the rate of carbonate horizon development as compared to a soil developing in more siliceous sediments, as occurs in Pierce Canyon. More detailed mapping between this quadrangle and the Pecos River is needed to determine the exact correlations.

2.3. Gatuña Formation deposits

The Gatuña Formation was original 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 as referenced in 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 the canyon. Vine (1963) had previously measured a set of three sections along the north side of Pierce Canyon, a few kilometers east of the town of Malaga, 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. In these descriptions, the Gatuña Formation is dominantly sandstones and mudstones with subordinate conglomerate. An ash found in the upper part of the deposit near Livingston Ridge was correlated to the 0.6 Ma Lava Creek B ash (Bachman, 1980; Izett and Wilcox, 1982), while an ash recovered from deposits mapped as Gatuña southeast of Orla, Texas, yielded a K-Ar age of 13.0 ± 0.6 Ma (Powers and Holt, 1993). It is capped by the Mescalero caliche (Bachman, 1976; Bachman, 1980), the age of which is constrained by uranium series methods to be between 0.57 ± 0.11 and 0.42 ± 0.06 Ma (Rosholt and McKinney, 1980). The caliche is of Stage V morphology, which in this area is typically associated with soils of early to middle Pleistocene age

(Machette, 1985; Hawley, 1993; Pazzaglia and Hawley, 2004). Thus, the age data collected on deposits mapped as the Gatuña Formation indicate an age range of Late Miocene to Middle Pleistocene. However, the Gatuña is commonly found in areas underlain by evaporites of the Ochoan Series, and dissolution-related deformation of the Gatuña has inhibited detailed mapping and regional correlation of the unit.

Hawley (1993) examined areas previously established as reference sections for the Gatuña (e.g., Vine, 1963, and Bachman, 1976), and concluded that a substantial unconformity likely exists in the Gatuña as mapped and measured, particularly in the vicinity of Pierce Canyon, approximately 28 km east-southeast of the Kitchen Cove quadrangle. Here, Hawley (1993) noted that along the north side of the canyon, where Vine (1963) measured his multiple reference sections, the formation is capped by the Mescalero caliche, but on the south side of the canyon the same strata are capped by a Stage VI caliche, comparable to the 'caprock' caliche developed in the top of the Miocene-early Pliocene Ogallala Formation. The rim of the south side of the canyon is also notably higher than on the north side. In addition, clasts of reworked conglomerate interpreted to be from the caprock caliche are found in the Gatuña at its type locality (Bachman, 1976; Powers and Holt, 1993). Taken together, a period of intraformational erosion appears to have taken place during Gatuña time, separating a lower and upper Gatuña (Hawley, 1993; Cikoski, 2019), with the lower Gatuña potentially age-correlative to the Ogallala Formation.

On the Malaga quadrangle, approximately 12 km east-southeast of the Kitchen Cove quadrangle, the lower Gatuña Formation is commonly deformed by subsidence related to dissolution of underlying strata, and capped by a well-cemented petrocalcic horizon up to 5 m thick that exhibits a variety of brecciation and recementation features, is capped by a laminated zone of nearly pure carbonate, and bears pisolitic textures and thin concentric laminations around gravels (Cikoski, 2019). Well-cemented alluvial conglomerates occurring along the east flank of the Frontier Hills on the Kitchen Cove quadrangle are similarly deformed, and poor exposures toward the tops of these conglomerates suggest the unit may bear a surface soil with similar features (Figure 2-4). Further, map patterns indicate the Middle Pleistocene Qao1 soil is inset against these conglomerates, constraining the age of the conglomerates to no younger than Middle Pleistocene. I therefore suggest the deformed conglomerates along the Frontier Hills are age-correlative to the Gatuña Formation (likely age-correlative to the lower Gatuña), and belong to a conglomerate-dominated piedmont facies of the Gatuña.

Gatuña piedmont conglomerates (map unit Tgp) consistent of well-cemented, poorly sorted, rounded cobbly pebble conglomerates with trace boulders (Figures 2-4A and B), of mainly carbonate lithologies with lesser sandstones but additionally bearing trace well rounded pebbles of quartzite and chert (Figure 2-4C). Rare interbedded pink sandstones consist of poorly sorted very fine to coarse sand grains of siliceous and carbonate material. Bedding attitudes dip as much as 18° with dip directions to the south (S04W) through northeast (N48E), and map patterns demonstrate that the unit is folded along comparable trends to the underlying Culebra Dolomite. This deformation is likely associated with variable subsidence of the dolomite and conglomerate caused by dissolution of underlying evaporites (discussed in more detail in the Structure section). Although the surface soil for this deposit was not found in good outcrop, poor exposures of the uppermost portions of the deposit in places exhibit brecciation and recementation (Figure 2-4D), laminations are gravels and possible pisolitic textures (Figure 2-4E), and possible planar-tabular laminations (Figure 2-4F), features that suggest a Stage VI morphology carbonate horizon occurs at the top of the deposit. Gravel clast suites and paleotransport directions inferred from clast imbrications indicate the conglomerates are principally derived from the Guadalupe Mountains; the trace quartzite and chert may be derived from siliceous lag gravels preserved high in the Mountains (Hill, 1996; Hill, 2006) or the “Type 2” paleokarst fill found in the Mountains (Koša and Hunt, 2006).

Map patterns indicate that Tgp conglomerates have as much as 25 m preserved thickness. These conglomerates project eastward into the subsurface east of the Frontier Hills, toward where well data from Bjorklund and Motts (1959) indicate a maximum alluvial thickness of about 110 m, and I infer that this thickness is principally a combination of Tgp and Qao alluvium. Given that Qao appears to be as much as 64 m thick between the Frontier Hills and the La Cueva Escarpment (as discussed above), the Tgp portion of the total thickness may be the remainder, or about 46 m. This conjecture is uncertain, however, and on cross-section A-A’ the alluvial deposits are shown as an undivided alluvial unit.

2.4. Uncorrelated deposits

Uncorrelated caliche

An enigmatic and poorly exposed caliche accumulation occurs at the south-central margin of the quadrangle nestled in the Frontier Hills (map unit QTc). It is found along the axis of a synclinal fold deforming the Culebra Dolomite in two locations, where it consists of light gray to white carbonate with internal laminations and local pisolitic textures apparent in up-turned blocks (Figure 2-5). No clastic material was found entrained in this caliche, although very sparse rounded siliceous pebbles were found in the area of the caliche. The pisolitic textures suggest the caliche may be age correlative to the Gatuña conglomerates found along the east flank of the Frontier Hills further north, but the evidence is not particularly strong. The caliche is not likely very thick, perhaps 2 m at most.

Miscellaneous deposits

Small-scale alluvial fans are found in several locations throughout the quadrangle (map unit Qaf). The deposits underlying these fans are poorly exposed, but limited outcrop suggests they may have surface soils bearing carbonate horizons of Stage I through IV morphology; thus they may be associated with a broad range of ages and correlate to any of several more regional alluvial deposits.

Closed depressions, potentially associated with sinkholes, occur as mappable features in a few locations, and where these are filled with sediment the deposit is mapped as Qdf. This material was not found in outcrop, but appears to consist mainly of poorly sorted silts to very fine sands, with lesser clays and coarser material. No evidence of any appreciable surface soil development was observed.

3. Permian System – Exposed stratigraphy

Within the Kitchen Cove quadrangle, Cenozoic deposits unconformably overlie and are inset against Ochoan and Guadalupian (Upper Permian) strata of the Rustler, Salado, and Castile Formations, the Artesia Group, and the Capitan Limestone. Older Permian strata are documented in the subsurface in oil and gas well data.

3.1. Ochoan Series

Ochoan Series strata record a period of gradual desiccation of the sea that had in earlier Permian time occupied the Delaware basin. Early Ochoan strata are dominated by evaporite salts (anhydrite/gypsum and halite of the Castile and Salado Formations), which were followed by deposition of mixed evaporites, carbonates, and siliciclastics (Rustler Formation) and capped by a dominantly siliciclastic interval (Dewey Lake Formation). Ochoan Series strata exposed at the surface on the Kitchen Cove quadrangle are dominantly of the lower portion of the Rustler Formation, with some breccia/residue of the Salado and Castile Formations cropping out between the Frontier Hills and the La Cueva Escarpment.

3.1.1. 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 Kitchen Cove 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 commonly found capping or cropping out along the western flank of the Frontier Hills. Younger Rustler Formation Members are not present at the surface on the Kitchen Cove quadrangle. On cross-section A-A’, I have assumed that late Cenozoic down-cutting prior to deposition of the Gatuña Formation likely extended through all post-Culebra Dolomite members down to the top of the Culebra, as it is the most erosion-resistant member of the Formation. This is consistent with isopach maps by Bachman (1980), which indicate that post-Culebra Members thin westward from the Waste Isolation Pilot Plant (WIPP) site and pinch out circa the Pecos River, over 25 km east of the quadrangle boundary. They are therefore not expected to be present in the Kitchen Cove area, and are not discussed herein.

Culebra Dolomite

Regionally (cf., Holt and Powers, 1988; Holt, 1997) and throughout most of the Kitchen Cove quadrangle the Culebra Dolomite (map unit Prc) is a cream-colored to white fine-grained (commonly microcrystalline) dolomite/dolomicrite that is nearly characteristically highly fractured and commonly bears abundant to rare fine (1 to 10 mm diameter) vugs (Figures 3-2A and B). Beds are commonly planar tabular, thin, and internally massive, although Holt (1997) reports intervals by the WIPP site that bear algal layering, burrows, low-angle cross-laminations, wavy to lenticular bedding, and soft-sediment deformation. The majority of map unit Prc fits this above description.

However, at the north end of the Frontier Hills, circa 568,850 m E, 3,580,120 m N, the dolomite appears to grade laterally into more limey rocks that locally bear original sedimentary structures (Figures 3-2C and D; note that no chemical analyses were performed on these rocks, and the limestone interpretation is based on the preservation of primary features and weathering textures of the outcrop). The limestones are dominantly light brownish gray packstones consisting of moderately sorted, very fine-sand-sized carbonate grains with common (5-15% under hand lens) lime mud, but locally consist of gray to grayish brown mud-rich (50-70%) laminated wackestones (Figure 3-2E). Both packstones and wackestones are thinly tabular bedded with varying degrees of internal cross- and planar-stratification (Figures 3-2C and D). Laminations in the wackestones are typically concentric but irregular (Figure 3-2E). Locally, the limestones are highly internally brecciated (Figure 3-2F).

The limestone interval was only observed at the north end of the Frontier Hills, and, in the literature, the Culebra is nearly ubiquitously described as dolomitic in composition. Sewards et al. (1991) documented and examined rare measureable quantities of calcite in core samples from the WIPP site, but concluded the calcite was in fact the result of dedolomitization of dolomite rather than primary limestone. Previous authors have suggested that the dolomitic composition is a product of early diagenetic alteration (dolomitization) of initially calcium carbonate-dominated sediments as a consequence of a highly saline depositional or early-post-depositional environment (cf., Lowenstein, 1987; Sewards et al., 1991; Holt, 1997). However, Powers and Holt (2000) argue that the overlying and underlying Members of the Rustler Formation exhibit evidence of salinity zonation, with mudstone-dominated mudflat environments along the margins of the Rustler depositional basin grading laterally into halite-dominated saltpan environments toward the center of the basin. If this is the case, then dolomitization of the Culebra may similarly be zoned, and concentrated toward the more saline basin center with lesser dolomitization occurring along the basin margin. The limestone interval occurring in the Kitchen Cove quadrangle may be a rare instance of the original lime being spared dolomitization near the margin of the depositional basin.

Regionally, Holt and Powers (1988) document a thickness range for the Culebra of about 3 to 11 m; within the quadrangle, the preserved thickness is as much as about 9 m.

Los Medaños Member

The Los Medaños Member of Powers and Holt (1999) underlies the Culebra Dolomite throughout the west flank of the Frontier Hills. It is dominated by pale red to reddish yellow mudstones with irregular masses of gypsum and minor brown, very fine- to fine-grained sandstones. The sandstones occur in rare to sparse lenticular intervals that are commonly thin but locally as much as 2 m thick. Overall, the unit is poorly exposed, most commonly apparent at the surface as pale reddish muddy colluvial slopes underlying a Culebra cap. About 25 m of Los Medaños is exposed on the quadrangle, although the base is not exposed, and Powers and Holt (1999) report a thickness of 34.4 m in the type section.

3.1.2. Castile and Salado Formation breccia

The Castile and Salado Formations were originally described by Richardson (1904) and combined in a single Castile Formation unit; Lang (1935) subsequently divided the two, designating the upper halite-dominated interval as the Salado Formation while retaining the original name for the lower gypsum-dominated interval. As both units are dominated by evaporites, both are subject to dissolution and karstification, particularly the halite-dominated Salado Formation. Where intact, the Castile consists of laminated anhydrite and/or gypsum with lesser halite and limestone and minor dolomite and magnesite (Bachman, 1984; Figure 3-3A). The Salado, where less affected by dissolution in the subsurface by the WIPP site, consists principally or rock salt with lesser anhydrite, polyhalite, and potassium-rich salts, and subordinate sandstone, claystone, glauberite, and magnesite (Jones et al., 1973). Westward from the WIPP site, however, the degree of dissolution of the Salado increases as the Formation comes closer to the land surface, and where exposed by the Pecos River and further west the Salado consists of a breccia of gypsum blocks surrounded by an erratic angular matrix of reddish brown gypsum and clay, often described as a "residue" (Jones et al., 1973; Bachman, 1980; Figure 3-3B). Although the degree of dissolution decreases with increasing depth (Brokaw et al., 1972), isopach mapping by Bachman (1980) suggests that no Salado salt is preserved intact beneath the Kitchen Cove quadrangle. Some residual material does appear to be present, however.

The Castile and the remains of the Salado Formation crop out locally at the surface on the quadrangle between the Frontier Hills and the La Cueva Escarpment north of Dark Canyon. Here, low intact outcrops of laminated gypsum (Figure 3-3C) and erratic blocks of gypsum breccia (Figure 3-3D) are sporadically found underlying older alluvial deposits and cropping out along the floors of drainages. Less commonly, reddish clays occur entrained in the erratic gypsum breccia and impart a pink to red color (Figure 3-3E); although the gypsum may be entirely from the Castile Formation, the presence of trace clays suggests the Salado contributed some material to these low outcrops. The base of the Castile-Salado breccia is not exposed.

3.2. Guadalupian Series

The Guadalupian time period takes its name from the Guadalupe Mountains, where some of the most intensely studied Upper Permian stratigraphy is exposed. The Guadalupian Series here has been the focus of over a century of detailed stratigraphic study and continues to yield new insights into the development of backreef-reef-basin environments. King (1948), Newell et al. (1953), and Hayes (1964) are perhaps the most classic publications regarding these strata, and the stratigraphy utilized below largely follows after these works. The history of the nomenclature for this Series is complicated by the long history of study, diverse background of contributors, and the challenging geology; the interested reader is referred to King (1948), Kelley (1971), and Nance (2009a) for historical context, and little of the background will be discussed here. Within the Kitchen Cove quadrangle, only the upper formations of the Artesia Group and the massive facies of the Capitan Limestone are exposed.

3.2.1. Northwest shelf – Artesia Group

Tait et al. (1962) provided the name Artesia Group to simplify an array of prior names for related strata. The Group, broadly defined, encompasses all Guadalupian backreef strata, and as such is quite diverse regionally. In ascending order, the Group consists of the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations (Figure 1-3). The younger three of these were each coeval with development of the Capitan reef, while the Queen was coeval with the Goat Seep Dolomite (a precursor to the Capitan reef); the Grayburg, initially thought to transition into the Goat Seep as well, in fact underlies the Goat Seep unconformably (Nance, 2009a, and references therein). Each Formation consists of a reef-proximal carbonate-dominated facies and a more distal mudstone-evaporite facies, with the transition shifting basinward from the youngest to the oldest Formation (cf., Motts, 1962). Within the Kitchen Cove quadrangle, however, only the carbonate facies of the Tansill and Yates Formations are well exposed, with the uppermost beds of the Seven Rivers Formation cropping out locally in the southwestern corner.

Tansill Formation

The Tansill Formation was formally defined by DeFord and Riggs (1941) with a designated type section about 2 miles northwest of Carlsbad. It consists dominantly of dolomite with subordinate subarkosic to arkosic siltstone-very fine-grained sandstone, with one particularly thick (~4 m thick) siltstone interval in the upper half of the Formation designated the Ocotillo Silt Member (DeFord and Riggs, 1941; Hayes, 1964; Kelley, 1971; Scholle et al., 2007; Nance, 2009a). This silt member is notable for its lack of erosion resistance, such that it can frequently be located by the presence of a prominent ledge in the slope profile of the Tansill Formation (Motts, 1962), a ledge that is commonly somewhat yellowish in color in aerial imagery from the eroded silt. As a consequence, it forms a natural mappable break, one which I utilize to separate an upper map unit (map unit Patu) from a lower map unit (unit Patl), with the contact at the base of the silt member. The map units are nearly identical lithologically. Each consists of white to light gray, grain-supported dolomitic grainstones, packstones, and lesser wackestones, with rare interbedded pale brown to pink siliciclastic mudstones (Figure 3-4). Dolomite beds are planar tabular; internally massive, planar-laminated, or cross-laminated; and commonly thin but thicken with proximity to the Capitan reef (i.e., closer to the mountain front; Figure 3-4A and Figure 3-5). Overall, beds are rarely pisolitic, but pisolites become more abundant and coarser closer to the reef and locally dominate some beds (Figure 3-4B). Teepee structures (Figure 3-4C) and large molluscan and brachiopod fossils (Figure 3-4D) can be found near to the reef as well. Rarely, silt is found as paleokarst fill or capping carbonate beds (possibly washed in through karst; Figure 3-4E); silt caps and fill are found throughout the unit but are particularly common in the upper map unit. Siltstones/very fine-grained sandstones are very thinly bedded to laminated, and commonly moderately well indurated by carbonate cement (Figure 3-4F). The upper map unit contains a somewhat greater abundance of siliciclastic beds, paleokarst fill, and pisolites than the lower map unit. Thin, siliceous, dark brown-weathering clayey mudstones/claystones/marls are also present in the upper map unit. Both the upper and lower map units transition laterally into massive limestone at the mouths of Dark Canyon and Kitchen Cove as they approach the reef; the transition is gradual but sharp and is used as the functional, mappable contact between the Tansill Formation and the Capitan Limestone (Figure 3-5). The upper Tansill can also be observed to prograde over the Capitan in outcrop (Figure 3-5), such that the mountain front escarpment itself is actually underlain by Tansill strata, contra the mapping of Motts (1962), who mapped Capitan Limestone all along the base of the La Cueva Escarpment. The depositional top of the Tansill is not preserved on this quadrangle; DeFord and Riggs (1941) reports no more than 38 m of Tansill at the type section, while Hayes (1964) and Kelley (1971) report thickness measurements of up to 99 m in the area.

Through the majority of the quadrangle, the Ocotillo Silt Member and the associated pale yellowish underlying ledge are clear and continuous in aerial imagery, and the contact between the upper and lower map units is thus considered a well-defined consistent feature. However, near to the reef and within the La Cueva Escarpment the Member is less clear, and the contact was commonly mapped by projecting the contact along ledges visible on the imagery. An advantage to this approach is that the map pattern well-captures the bedding trends through the near-reef area and well-illustrates the structure; the risk is the possibility of incorrectly correlating lower and upper Tansill strata. A high-resolution, detailed stratigraphic study by Rush and Kerans (2010) documents intraformational unconformities associated with syndepositional reef-front collapses in the reef-proximal Tansill Formation at the mouth of Walnut Canyon, approximately 8 km south of the quadrangle. This collapse truncated a substantial portion of underlying strata, juxtaposing an older sequence (their G27) laterally against strata of a post-collapse on-lapping sequence (their G28). The Ocotillo Silt Member, which occurs at the base of the next youngest sequence (G29), crosses over the collapse contact. Such a collapse feature may not be apparent in aerial imagery, or even readily apparent in ground mapping (cf., figure 6 in Rush and Kerans, 2010). Therefore, projecting the contact along bedding planes toward the reef where the Ocotillo Member ledge is not clearly present may mistakenly result in the map contact crossing a buried, intraformational, collapse-related buttress unconformity. On the other hand, the sequence framework presented by Rush and Kerans (2010) suggests that the post-Ocotillo Tansill beds (i.e., the upper map unit) accumulated in a single sequence without break, suggesting that no such unconformity should be present. Despite the uncertainty, I choose to utilize a projected contact for its utility in illustrating structural trends in the map pattern, but caution that syndepositional intraformational structural complexities may exist in the reef-proximal section of the exposed Tansill Formation.

Yates Formation

The Yates Formation is a relatively siliciclastic-rich interval that conformably underlies the Tansill Formation and is exposed in Dark Canyon, Kitchen Cove, and locally in the northeastern corner of the map area. It takes its name from the Yates oil field in Pecos County, Texas (Gester and Hawley, 1929), and its type section is designated as a particular well (Mear and Yarbrough, 1961); however, the unit has been extensively mapped in the surface and its character at the surface is well-studied (Motts, 1962; Hayes, 1964; Nance, 2009a). Hayes (1964) states the unit is "characterized by very persistent siltstone and sandstone beds which make up one third to two thirds of the formation; the adjacent Seven Rivers and Tansill Formations are predominantly dolomite." These siliciclastic intervals interbed with dolomites that are similar to those observed in the Tansill Formation. The upper contact is well-defined by a particularly thick (up to 2.5 m thick), readily traceable uppermost sandstone band (Figure 3-6A). Down-section, however, the clastic intervals thin and are often poorly exposed, and the lowest, which may be as thin as about 30 cm, can be difficult to identify and trace. Siliciclastics are dominantly very fine-grained sandstones and siltstones in thinly planar bedded, internally planar- or cross-laminated intervals (Figure 3-6B) that are moderately well indurated with carbonate cement. Due to the less erosion-resistant clastic intervals, the unit as a whole tends to form broad rounded slopes underlying the steeper, more ledge-rich slopes of the Tansill Formation. Grains visible under hand lends are dominantly siliceous, although Scholle et al. (2007) and Nance (2009a) reviewed the literature and report that compositions range from kaolinitic and quartzose to arkosic, with the suggestion that the siliciclastics were, at one time, equally arkosic with subsequent variable degradation of the feldspars to clays (Scholle et al., 2007). The dolomite beds exposed within the Kitchen Cove quadrangle resemble those of the Tansill Formation occurring away from the reef. While not exposed in this quadrangle, the Yates transitions laterally into the Capitan Limestone in the subsurface, in similar fashion to the transition observed in outcrop for the Tansill Formation. Within and in the vicinity of the quadrangle, Motts (1962) measured thicknesses of about 80 to 115 m.

Seven Rivers Formation

Originally named by Meinzer et al. (1926), the current definition of the Seven Rivers Formation appears to be implied by its stratigraphic position between the Queen Formation (with a defined type section given by Moran, 1954) and the Yates Formation (as defined by Mear and Yarbrough, 1961) rather than by a surface type section of its own (see historical notes by Kelley, 1971, and Nance, 2009a). Compared to the overlying and underlying Formations, the Seven Rivers is relatively sandstone/siltstone-poor, consisting dominantly of carbonates near to the Captain reef and evaporites and mudstones away from the reef. It is the oldest of the Guadalupian Artesia Group formations to interfinger with the Capitan reef; the Queen Formation, immediately beneath the Seven Rivers, interacted with the Goat Seep Dolomite. The Seven Rivers Formation is only locally exposed in the far southwestern corner of the quadrangle in Mosley, Juniper, and Dark Canyons. Its small exposure presents a potential miscorrelation, as the formation is defined by a lack of interbedded siliciclastics, which, in a limited outcrop area, may be just below the limit of exposure. However, Motts (1962) and Hayes (1957) mapped the Seven Rivers more extensively to the west to northwest and south to southwest of the quadrangle, respectively, providing additional confidence to the interpretation.

In general, the carbonates of the carbonate-dominated facies of the Seven Rivers Formation are comparable to those of the Tansill and Yates Formations (cf., Nance, 2009a, and descriptions by Motts, 1962, Hayes, 1964, and Kelley, 1971). The exposures within the Kitchen Cove quadrangle, however, are quite distinct, so much so that Motts (1972) describe features of the Seven Rivers in this area at some length, suggesting the outcrops may belong to one of his 'shelf domes' (discussed later in the structure section). These outcrops consist of light gray to white micrites to packstones and oolites exhibiting a variety of sedimentary structures (Figure 3-7). Oolites are typically thinly lenticular bedded, cross-laminated, poorly sorted, and "clast-supported," but rich in micritic mud (Figure 3-7A). Micrites, wackestones, and packstones occur in massive, planar-laminated, or internally crenulated medium-thickness tabular beds (Figures 3-7B, C, and D); thin lenticular beds that are variously internally planar-, cross-, or undulatory-laminated (Figure 3-7E); and crenulated thin lenticular beds, each of which bears absent to rare ooids, absent to rare detrital material (Figure 3-7F), and absent to trace vugs as well as clots of sparry calcite that may be vug fill or potentially replaced shells. Motts (1972) also states that isolated thin beds of banded chert and stromatolitic algal mats are present. The interval is syndepositionally faulted, with faults occurring in the lower portions of the outcrop that decrease in offset and tip-out up-section. Motts (1972) reported breccia beds exhibiting "drag folding [occurring] along the periphery of some large blocks and some lenses of breccia[,] and micrite [having] intrusive relations into surrounding blocks, indicating that squeezing and thrusting of the lenses accompanied the slumping" (pg. 715) of the breccia blocks, further suggesting syndepositional deformation of the accumulating carbonate. The interval is thoroughly replaced by dolomitic(?) mud; fresh faces are aphanitic throughout, and the sedimentary features described above can only be observed on weathered faces.

Motts (1972) interpreted the presence of ooids (and pisoids), syndepositional deformation, and weathering textures as evidence for subaerial exposure and erosion associated with a topographically-high dome on the shelf extending Permian landward of the Capitan reef. He provides additional evidence for the presence of these topographically high domes, including map-scale structural patterns and geochemical evidence. I discuss the shelf dome and associated hypotheses more in the structure section; of importance to this portion of the report is that if the sedimentary features of this outcrop are a reflection of a shelf dome, than the outcrops observed on the quadrangle and the description provided should not be expected to continue throughout the quadrangle in the subsurface, but be restricted to the (unknown) extent of the dome. Based on descriptions provided by Motts (1962) and Hayes (1957), I suggest that the Seven Rivers beneath the surface within the quadrangle area away from the hypothesized shelf dome is comparable to the description provided for the Tansill Formation. The base of the unit is not exposed, but Hayes (1957) and Motts (1962) provide thickness estimates of about 80 to 140 m in the area.

3.2.2. Guadalupian reef – Capitan Limestone

The Capitan Limestone was originally named by Richardson (1904) and has subsequently become one of the most classic and thoroughly studied exposed examples of a Permian reef complex. King (1948), Newell et al. (1953), Hayes (1964), Kelley (1971), Hiss (1975b), Hiss (1976), Scholle et al. (2007), and Standen et al. (2009) provide detailed descriptions of the geology, depositional environment and lateral relationships, paleoecology, structure, groundwater hydrology, outcrop features, and a thorough list of follow-up references for the interested reader to pursue for more information on this magnificent feature. Sadly, it barely crops out on the Kitchen Cove quadrangle, occurring only in limited small exposures at the mouths of Dark Canyon and Kitchen Cove (e.g., Figure 3-5).

The Capitan Limestone is the Delaware basin-margin facies of the upper Guadalupian period, grading Permian landward into the Seven Rivers-Yates-Tansill sequence of the Artesia Group and basinward into the Bell Canyon Formation of the Delaware Mountain Group (Figure 1-3). It occupied a dynamic depositional environment (cf., Hunt et al., 2002; Koša and Hunt, 2005; Koša and Hunt, 2006; and Rush and Kerans, 2010), and is frequently divided into two facies: an up-paleo-slope massive facies (‘reef facies’) and a down-paleo-slope breccia facies (‘reef talus facies’), the latter being the product of periodic collapse of the upslope reef. Only the massive facies is exposed on this quadrangle, although even within the massive facies evidence of fracturing and brecciation can be found.

The massive facies of the Capitan Limestone exposed on the Kitchen Cove quadrangle (map unit Pclm) consists of light gray, cream-colored, or white, commonly fossiliferous limestone (Figure 3-8). Fossils include species of calcareous sponges, algae, crinoids, gastropods, brachiopods, pelecypods, and fusulinids (Figure 3-8A; King, 1948; Newell et al., 1953; Hayes, 1964; Scholle et al., 2007). Vuggy porosity is common at the surface (Figure 3-8B), and cavernous porosity is well-documented in parts of the subsurface (e.g., Carlsbad Caverns). It is characteristically massive, with a generally sharp transitional contact with the bedded carbonate facies of the formations of the Artesia Group (Figure 3-5), and it grades both westward into Artesia formations and is overtopped by Artesia formations in both Dark Canyon and Kitchen Cove exposures. Its base is unexposed; isopach mapping by Hiss (1975a) indicates a maximum thickness for the Capitan as a whole within the quadrangle area of about 643 m, while a maximum thickness of about 606 m occurs along cross-section A-A’. It should be noted that Hiss (1975a), Hiss (1976), and Standen et al. (2009) each mapped the Capitan reef complex *aquifer*, which may include portions of the carbonate facies of the formations of the Artesia Group as well as, potentially, the underlying Goat Seep Dolomite. Not surprisingly, the geophysical characteristics of these units are very similar, and distinguishing the units in the subsurface without detailed examination of core would be difficult. Therefore, the subsurface extrapolation shown in cross-section A-A’, with regards to the Artesia Group-Capitan contact, is approximate.

4. Permian System – Subsurface stratigraphy

The New Mexico Oil Conservation Division (NM OCD) database of wells locates 324 active, abandoned, or proposed oil and gas wells within the Kitchen Cove quadrangle. A digital subsurface database built for a larger project on the three-dimensional structure of southeastern New Mexico collected data for 65 of these wells in the quadrangle, some extending over 12,000 ft deep and intersecting rocks as old as Mississippian in age. This dataset was supplemented with 10 additional wells, mostly water wells, from Bjorklund and Motts (1959), Hiss (1976), and Standen et al. (2009), for a total of 75 wells. However, few of these wells contain data on the near-surface Ochoan-Quaternary 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 to extend the cross-section into the Wolfcampian Series.

4.1. Ochoan Series

4.1.1. Castile and Salado Formations

The Castile and Salado Formations once filled the Guadalupian Delaware basin, and, in the case of the Salado, overtopped the margins of the basin (Bachman, 1980). Multiple episodes of basin tilting, uplift, and exposure to aggressive waters (surface and subsurface) has reduced this original thickness of evaporites substantially, however. Today, an eastward thickening of the salt sequence is apparent in the subsurface, as the degree of dissolution decreases eastward as the salts descend to greater depths (Brokaw et al., 1972). The Salado in particular was subject to intense dissolution, and east of the quadrangle a 'dissolution front' can be mapped through the subsurface separating partially dissolved and collapsed Salado 'residue' from underlying intact Salado based on distinctive geophysical log characteristics (Brokaw et al., 1972). Bachman (1980) suggests that no salt from the Salado Formation is preserved as far west as the Kitchen Cove quadrangle, although an unknown thickness of Salado residue may still lie in the subsurface. Intact, bedded anhydrite of the Castile is described in many striplogs and well records for the basin area of the quadrangle, sometimes interbedded with preserved halite, and these have a distinct geophysical log character that would likely allow for accurate delineation of the unweathered Castile interval in the subsurface. However, commonly above the intact Castile, both in well records and geophysical logs, there appears to be a weathered zone that is not readily assignable to either the Castile or Salado Formations, and not uncommonly difficult to differentiate from the overlying Los Medaños Member. Therefore, an undivided Castile-Salado Formation unit was used along cross-section A-A', which includes an unknown but likely highly variable thickness of Castile-Salado breccia overlying intact Castile. The thickness of this interval is estimated to be up to 405 m based on cross-section reconstructions.

4.2. Guadalupian Series

4.2.1. Delaware Mountain Group

Originally named by Richardson (1904) and elevated to group status by King (1942), the Delaware Mountain Group (cross-section unit Pd) consists dominantly of arkosic to subarkosic very fine- to fine-grained sandstones and siltstones with lesser detrital carbonate interbeds that accumulated in the Delaware basin through the Guadalupian epoch (Nance, 2009b). The Group is subdivided into three Formations (in ascending order, the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations) on a combination of lithologic and faunal evidence; however, the data available for the wells along cross-section A-A’ were not sufficient to subdivide the group into its formations with confidence. The exception is the Lamar Limestone Member of the Bell Canyon Formation (unit Pdl), a member with distinct geophysical character that often caps the Delaware Mountain Group and was mapped along the cross-section (note though that as mapped on the cross-section the Lamar Limestone may include overlying sandstones that properly belong to the Reef Trail Member of Wilde et al., 1999). 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. Well records collected as a part of this study suggest an overall Delaware Mountain Group thickness of about 979 to 1,060 m beneath the majority of the quadrangle, thinning to about 670 to 727 m in the northwestern corner of the quadrangle. Well records suggest a relatively thick Lamar Member here, with a thickness of about 36 to 60 m beneath the quadrangle.

4.3. Pre-Guadalupian Series

4.3.1. 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; well logs collected for this study from within the quadrangle extent report a unit thickness of about 1,005 to 1,224 m here.

4.3.2. Wolfcampian Series

Exposed Wolfcampian strata in southeastern New Mexico (Hueco Limestone) belong to the shelf or platform facies of the Wolfcamp Series. Subsurface data indicates this facies grades laterally basinward across a broad transition zone into a basinal facies that likely underlies the Kitchen Cove quadrangle (Hayes, 1964). Hayes (1964) reports that wells drilled approximately 5 to 6.5 km south of the Kitchen Cove quadrangle in Sections 26 and 29, T 24 S, R 26 E (Union Crawford 1-26 and Gulf Estill 1-AD, respectively), encountered between 454 and 527 m of gray, black, or brown shale interbedded with finely crystalline, rarely cherty, brownish limestone underlying the Bone Spring Limestone. In contrast, the well record and striplog for the Western Oil McKittrick Federal 1 in Section 25, T 22 S, R 25 E, in the far northwestern corner of the quadrangle, reports Wolfcampian strata from about 2,440 to 2,894 m depth (454 m thick), which reportedly consist of interbedded gray to dark brown limestone and white to dark gray very fine-grained sandstone.

Regional references describing the basinal Wolfcamp Series in the northern Delaware basin generally suggest the unit consists of interbedded limestones and shales to siltstones as well. 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). The overall consensus of regional and local well log descriptions thus appears to be that the Wolfcamp Series basinal facies consists of interbedded limestones and shales and siltstones to potentially very fine-grained sandstones.

Well records from within the quadrangle extent report Wolfcamp Series thicknesses from about 153 to 462 m, generally thinning to the northwest (Permian landward).

5. Structure

5.1. Structural setting

The Kitchen Cove quadrangle lies in the northwestern sector of the Pennsylvanian-Permian Delaware basin, which overprints an older, broader, Ordovician to Pennsylvanian Tobosa basin (Hill, 1996). Subsidence of the 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, the area has been largely tectonically quiescent. Episodic subaerial periods exposed latest Permian (Ochoan) evaporite-rich strata to aggressive waters that dissolved salts and induced karstic deformation, however. During late Cenozoic Basin and Range development, the region was tilted gently eastward, uplifting and exposing the Guadalupe Mountains, which shed detritus eastward. Continued dissolution of evaporites later deformed the alluvial sediments as well as older strata within the Delaware basin area.

Some debate exists as to the relative importance of tectonic deformation versus primary sedimentary features versus syndepositional deformation in controlling the observed structures of Guadalupian strata. Kelley (1971) generally preferred tectonic deformations, included a mountain-front fault system (his Barrera and Carlsbad faults) along the base of the Guadalupe Mountains and a nearby fold belt, his Carlsbad folds. Hayes and Bachman (1979) examined the evidence for Kelley’s faults, however, and argued against their presence, while Motts (1972) provided comparisons of the domal folds through the Carlsbad area to shelf domes and topography/bathymetry observed in modern platform settings and argued these folds were principally primary depositional features. The origin of basinward folding of Artesia Group strata all along the margin of the Capitan reef is similarly debated, with competing theories giving varying weights to primary depositional topography (e.g., King, 1948) versus syndepositional deformation (e.g., Hunt et al., 2002; cf., Rush and Kerans, 2010, and references therein for discussion). This study did not collect the level of detailed data necessary to definitely argue for one theory or another, and it seems that each of these factors contributes in some way to the observed structure.

Less debate exists as to the cause of observed folding of the Ochoan Series and late Cenozoic alluvium. Research further east, southeast, and south of the quadrangle documents substantial deformation of these rocks as a consequence of subsidence and collapse caused by dissolution of underlying evaporite salts on a variety of spatial scales, from individual sinkholes to outcrop-scale subsidence to regional brecciation and the development of deep “solution troughs” accumulating hundreds of meters of syndeformational sediment (cf., Olive, 1957; Bachman, 1980; Gustavson, 1986; Bachman, 1987; Meyer et al., 2012; Land et al., 2018; Cikoski, 2019). Folds are observed throughout the Frontier Hills on the Kitchen Cove quadrangle deforming both Rustler and Gatuña Formation deposits, indicating at least some deformation occurred as young as Pliocene time, and the most likely explanation is dissolution-related subsidence and collapse. A significant consequence of this interpretation is that the variety of structures mapped through the Frontier Hills should not be expected to have deep roots extending below the Ochoan Series; deformation should be limited to the dissolution-affected region near the land surface.

5.2. Reef-margin structures

Broad, commonly arcuate anticlines and synclines through the Kitchen Cove and greater Guadalupe Mountains reef margin area have been documented by numerous previous authors (cf., Motts, 1962; Kelley, 1971; Motts, 1972; Hunt et al., 2002; Koša and Hunt, 2006; Figure 5-1). Limiting discussion to those structures occurring directly within or near to the quadrangle, these include 1) a set of broad west-northwest/east-southeast-trending syncline-anticline pairs observable in the trend of the Guadalupe Mountains front (e.g., Dark Canyon syncline and McKittrick Hill anticline on Figure 5-1); 2) smaller scale, generally northwest/southeast-trending anticlines that often manifest as elongate rounded hills and ridges (e.g., Hackberry Hills anticlinal dome, 'current-oriented mounds' of Motts, 1972) and associated synclines; 3) a broad, persistent anticlinal hinge zone paralleling the reef margin about 2.5-3 km Permian landward that tilts upper Artesia Group strata basinward near to the reef; 4) short wavelength and less persistent anticline-syncline pairs that parallel the reef margin and are located basinward of the persistent anticline (e.g., closely-spaced, paralleling anticlines and synclines at the south-central margin of the quadrangle); and 5) map-scale joints parallel to the reef margin. In addition, Motts (1972) documents 6) numerous small domes superimposed on these larger structures (his 'shelf domes'). Most of these features are likely genetically related, complicating the following discussion. Figure 5-1 shows many of these features on a regional scale.

Basinward tilting of the Artesia Group, the short wavelength reef margin-parallel folds, and the reef margin-parallel jointing (numbers 3, 4, and 5 above) are all likely the product of syndepositional deformation of the Artesia Group as a consequence of basinward slumping of the Capitan reef platform margin (Newell et al., 1953; Hunt et al., 2002; Koša and Hunt, 2005; Koša and Hunt, 2006; Rush and Kerans, 2010). Although some previous authors have interpreted the basinward dips of the Artesia Group as primary, depositional dips (e.g., King, 1948, and others referenced in Rush and Kerans, 2010), the most recent work by E. Koša, D. Hunt, and others is quite detailed and convincing. They document syndepositional basinward fault slip and progressive rotation of geopetals in the areas of Slaughter and Walnut Canyons, to the southwest of this quadrangle, that extends up to 6 km Permian landward of the reef margin. Several of the faults documented by Koša and Hunt (2005) and Koša and Hunt (2006) tip-out into reef-paralleling fold sets, and these could produce the short wavelength anticlines and synclines observed particularly at the south end of this quadrangle. Koša and Hunt (2005) and Koša and Hunt (2006) also document numerous syndepositional passive dilational fractures with little or no offset, which are essentially the reef margin-parallel joints mapped here. Rush and Kerans (2010), meanwhile, documented intraformational collapse of the basin margin, constrained by fusulinid data and high resolution sequence stratigraphy. Current research strongly supports that the basin margin was a dynamic location with a long, syndepositional history of basin margin steepening, basinward tilting, reef margin-parallel fracturing, and periodic collapse, and the three reef margin-paralleling features mapped on the Kitchen Cove quadrangle likely belong to this style of deformation.

The broad west-northwest-trending folding (#1 above) may then be simply an 'artifact' of the geometry of the reef margin. Bends in carbonate platform margins are not uncommon (Figure 5-2), and strata slumping basinward along a curvilinear margin would result in anticlines and synclines at bends in the margin geometry. Such folds should be expected to trend away from the basin margin at a high angle, as is seen with the Dark Canyon syncline and McKittrick Hill anticline (Figure 5-1), and decrease in magnitude away from the margin. As slumping was syndepositional (Newell et al., 1953; Hunt et al., 2002; Koša and Hunt, 2005; Koša and Hunt, 2006; Rush and Kerans, 2010), these folds would be as well, which is consistent with the observations of Motts (1972) for these synclines and anticlines to be Guadalupian topographic/bathymetric lows and highs, respectively.

Motts (1972) devoted significant discussion to the northwest-trending anticlines and synclines (#2 above), which he interpreted to be, and described as, ‘current-oriented mounds and adjacent synclines’ (Figure 5-1). He discusses sedimentologic and geochemical evidence to support that these mounds and adjacent synclines were syndepositional paleotopographic highs and lows, respectively, and suggested that the synclines were channels through which water was transferred between the backreef and marine basin environments, and that the mounds (anticlines) were constructed in part by biohermal growth. In particular, he compares the features to bathymetric features observed at the closure of the “Tongue of the Ocean” in the Great Bahama Bank, and also mentions the Thousand Islands (Kepulauan Seribu) and Great Barrier Reef as potential modern analogues. Figure 5-3 shows the three suggested potential modern analogues for visual comparison to the patterns mapped by Motts (1972) (Figure 5-1). In each case, elongate topographic/bathymetric mounds are found oriented parallel to the dominant oceanic currents. At the head of the Tongue of the Ocean, these currents appear to be controlled by the shape of the basin margin focusing water flow. With the Torres Strait, flow is similarly controlled by topography/bathymetry, although in this instance flow is more tightly controlled by the shoreline. In the Kepulauan Seribu, the current is controlled by east-west currents driven by the southern Pacific monsoon (Jordan, 1998). In some instances, particularly in the Kepulauan Seribu, the topographic highs support the development of current-elongated patch reefs (Jordan, 1998), consistent with Motts’ interpretation of biohermal growth partially constructing the anticlines/mounds. Alternatively, Kelley (1971) interprets the mounds (a component of his Carlsbad folds) to be tectonic in origin, arguing that the limited extent of the mounds (which are not observed further south of what is shown on Figure 5-1) and coincidence of this extent with the bends in the mountain front trend support that both the mountain front trend and the domes are a product of some tectonic forcing. However, as shown by the structure contours on Figure 5-1, there does not appear to be substantial deformation of the underlying Pennsylvanian strata through this area.

Motts (1972) also describes small domes superimposed on the larger structures (#6 above, ‘shelf domes’ on Figure 5-1). According to his description, they are composed principally of carbonate mud with subordinate pisolitic/oolitic beds, with evidence of syndepositional brecciation and recementation and subaerial weathering, and suggests the features are similar to features found around Florida and the Bahamas. Motts (1972) in particular suggests that the pisolites and brecciation may be related to the development of a mature caliche profile, and suggests that the outcrops of Seven Rivers Formation observed in the southwestern corner of the study area may belong to one of these domes. The oolites and brecciation I observed in these outcrops do not particularly well resemble the features I have observed in well-developed caliche profiles previously (shown, for example, in photos in Cikoski, 2019), but I admit I have not observed a caliche developed in carbonate mud previously. However, I do agree that the cross-laminated lenticular bedding and presence of ooids could reflect a slightly topographically higher environment of deposition, while the syndepositional deformation could be a product of slumping of this environment. Presumably, Kelley (1971) considered these domes a constituent of his Carlsbad folds and hence a principally tectonic feature, although he does not discuss them specifically.

Structural contours published by Meyer (1966) for the tops of strata of several ages in the Pennsylvanian as well as the top of the Wolfcampian generally do not support the existence of any large tectonic structures of Permian or younger age underlying the study area (cf., Figure 5-1, which shows the top of the Cisco [uppermost Pennsylvanian] contours; contours on the tops of other Series are similar). Although the Huapache monocline clearly offsets these strata, this feature is well southwest of the study area. This lack of underlying structure would generally not support any strong structural controls on the deformation observed at the surface. However, these structure contours do consistently show a slight deformity in the area of the bend in the trend of the Capitan reef complex. Contours typically strike north-northeast through the area, but, in the vicinity of the northeastern corner of the quadrangle and trending generally west-northwest/east-southeast, there is a slight offset of this overall regional trend that occurs beneath the area of domal folding and the 'elbow bend' in the trend of the Capitan reef complex (Figure 5-1). South of this trend, 'current-oriented mounds' and 'shelf domes' have not been observed (Kelley, 1971; Motts, 1972). These observations could be genetically related, in that the slight deformation observed in the Pennsylvanian structure contours could have affected the geometry of the basin margin, potentially causing the elbow bend in the reef trend and creating a flow-focusing geometry as seen at the head of the Tongue of the Ocean (Figures 5-2A and 5-3A). The focused flow then results in the development of current-oriented mounds and associated shelf domes. The structural deformation and the reef trend do not perfectly collocate, but the dynamic shelf environment may have modified the initial geometry caused by the deformation. This hypothesis would be generally consistent with the known underlying structure, the evidence for syndepositional development of these mounds and domes, the geometry of the 'current-oriented mounds,' the known restricted extent over which these mounds occur, and the geometry of the Capitan reef and basin margin. In addition, the hypothesized structural trend would project into a set of arcuate anticlines and synclines located 10 to 20 km Permian landward from the reef margin that are subparallel to the reef margin trend (green dashed anticlinal folds on Figure 5-1). The arcuate geometry of these folds may have been affected by the hypothesized underlying structure.

5.3. Delaware basin structures – karst deformation

Broadly, two forms of deformation occur at the surface on the quadrangle within the Delaware basin: dissolution and brecciation of the lower Ochoan evaporite-dominated Castile and Salado Formations, and irregular folding of the Rustler and Gatuña Formations. Regionally, both such structures have been documented previously (Bachman, 1980; Bachman, 1987). The first of these, dissolution and brecciation of the Castile and Salado, is associated with regional or blanket dissolution of halite particularly in the Salado Formation. Previous authors have documented dissolution of the Salado as early as syndepositionally during Salado (Ochoan, upper Permian) time (Johnson, 1993), and it is anticipated that any period of regional subaerial exposure and erosion could have resulted in further dissolution of the sequence (Bachman, 1980). This includes several time periods in the Mesozoic and early Tertiary (Bachman, 1980; Lambert, 1983) and undeniably includes the late Cenozoic, as a consequence of eastward tilting and uplift of the basin (Hill, 1996). Widespread dissolution of the Salado sequence preferentially removed the halite portion of the sequence, while leaving behind a mass of gypsum blocks surrounded by an erratic matrix of gypsum and clay, often referred to as a residue (Jones et al., 1973; Powers et al., 1978; Bachman, 1980; Figure 5-4). This residue is exposed in places between the Frontier Hills and the La Cueva Escarpment north of Dark Canyon (Figure 3-3E). Isopach mapping by Bachman (1980) indicates that no rock salt remains in the Salado sequence in this area. In contrast, about 600 m of salt is commonly present further east by the Eddy County-Lea County line (Bachman, 1980). Assuming at least this thickness was once present underlying the Rustler Formation at least up to the present-day Guadalupe Mountain front, a substantial degree of subsidence of the overlying strata must have taken place. This subsidence is also inferred to have caused the deformation of the Rustler Formation described below.

The typically underwhelming exposures along the Frontier Hills (e.g., Figure 3-1) masks a substantial amount of deformation of both the Permian Rustler Formation strata as well as the Tertiary Gatuña Formation conglomerates. The rarity of good outcrop limits the ability to accurately map deformational trends, but local bedding measurements and walked-out contacts tend to support a set of northeast-trending folds from Dark Canyon north with a few southeast-trending folds at the southern end of the quadrangle. Folding may, at least in part, be associated with the location of the buried Capitan reef, as well as Quaternary drainage patterns. Maley and Huffington (1953), Hiss (1976), and Ewing et al. (2012), among others, describe a structural trough overlying the Capitan Limestone along the eastern side of the Delaware basin between Belding, Texas, and the San Simon swale in New Mexico (Belding-San Simon trough), along which Rustler strata are documented to have been down-dropped and an unusually large thickness of Cenozoic fill is present (e.g., Maley and Huffington, 1953; Meyer et al., 2012). Some of these authors (Maley and Huffington, 1953; Hiss, 1976) attribute the presence of the trough to subsurface removal of salts immediately adjacent to the limestone, as a consequence of undersaturated waters within the limestone coming into contact with the salts. As the Captain reef is known to at least locally have cavernous porosity, it would, presumably, have the capacity to deliver significant volumes of undersaturated water to the salt/limestone contact as well as transport the subsequently-saturated waters away. The Capitan extent in the subsurface, as mapped by Standen et al. (2009), shows the limestone extending basinward of the Guadalupe Mountain front by as much as 1.5 km within the Kitchen Cove quadrangle extent, although more commonly about 600-700 m, in the subsurface west of the Frontier Hills (e.g., Figures 1-1 and 5-1). Groundwater flowing through this subsurface limestone could preferentially remove salts beneath the valley between the Guadalupe Mountains and the Frontier Hills, and this preferential dissolution could have caused some of the northwestward tilting observed at the north end of the Frontier Hills, and possibly caused the down-dropping of Gatuña Formation conglomerates observed as an isolated elongate hill just east of the mouth of Dark Canyon (circa 563,070 m E, 3,572,500 m N) that appears inset against Rustler outcrops further east in the Frontier Hills. Subsurface dissolution along the Capitan would likely not explain the fold axes located further from the mountain front, however. Instead, dissolution along Quaternary drainages may be responsible for preferential linear dissolution here. Subparallel to the Belding-San Simon trough, but located basinward of the Capitan reef, is the Balmorhea-Pecos-Loving (BPL) trough, a structurally similar feature that is also filled with an unusually large thickness of Cenozoic sediments (Maley and Huffington, 1953; Hiss, 1976; Meyer et al., 2012). Being basinward of the reef, however, its origin is likely not the result of preferential dissolution along the reef trend; instead, Bachman (1987) hypothesized that the BPL trough is the product of an ancestral Pecos River trend. In this model, the ancestral Pecos River system carries undersaturated water into the area, which travels in part through the subsurface beneath the river where it traverses across and dissolves the underlying salts, and also carries the subsequently-saturated waters out of the area as well. In similar fashion, an ancestral Dark Canyon Draw may have paralleled the modern draw and caused preferential dissolution along the eastern side of the Frontier Hills, resulting in additional linear preferential subsidence patterns and folding of the Rustler and Gatuña Formation strata basinward of the Capitan Limestone extent.

The folds along the south end of the quadrangle may have a different cause. The southernmost Frontier Hills that lie within the quadrangle boundary appear to be deformed by a set of domal folds that coalesce to create a set of synclinal troughs in between. These domes may be examples of karst domes as described by Bachman (1980). Karst domes are a product of local preservation of soluble material in a region of blanket dissolution. As the regional dissolution front passes and removes soluble material, the overlying strata are let down, and if this down-dropped material is insoluble it may form a protective cap that shelters local pockets of soluble material from further dissolution. The end result is a structural dome, capped by the insoluble strata, with a core of more soluble material that upholds the dome shape. Such features have been studied by Bachman (1980) in the area of Malaga bend, and are present throughout the Malaga quadrangle to the east-southeast (e.g., Cikoski, 2019).

At the south end of the quadrangle between the Frontier Hills and the Guadalupe Mountain front is a single map-scale depression of note. Although the Castile is a minor part of the surface geology of this quadrangle, further south the unit crops out extensively, and along the south margin of the quadrangle the Castile is likely close to the surface. Stafford (2013) and Stafford et al. (2018), and references therein, discuss at length numerous processes that can result in sizeable subsurface cavities and caves in the Castile through the Gypsum Plain, located mostly south of the quadrangle. I suggest that this depression is the surface manifestation of one of these cavities. The depression itself is likely a cover-collapse sinkhole. Cover-collapse sinkholes occur when a sediment bridge overlying a cavity is suddenly disrupted, often during a large rain event, and rapidly subsides into the underlying cavity. If this is the case, additional cavities may lie beneath the surface in this area.

6. Figures

1. Introduction

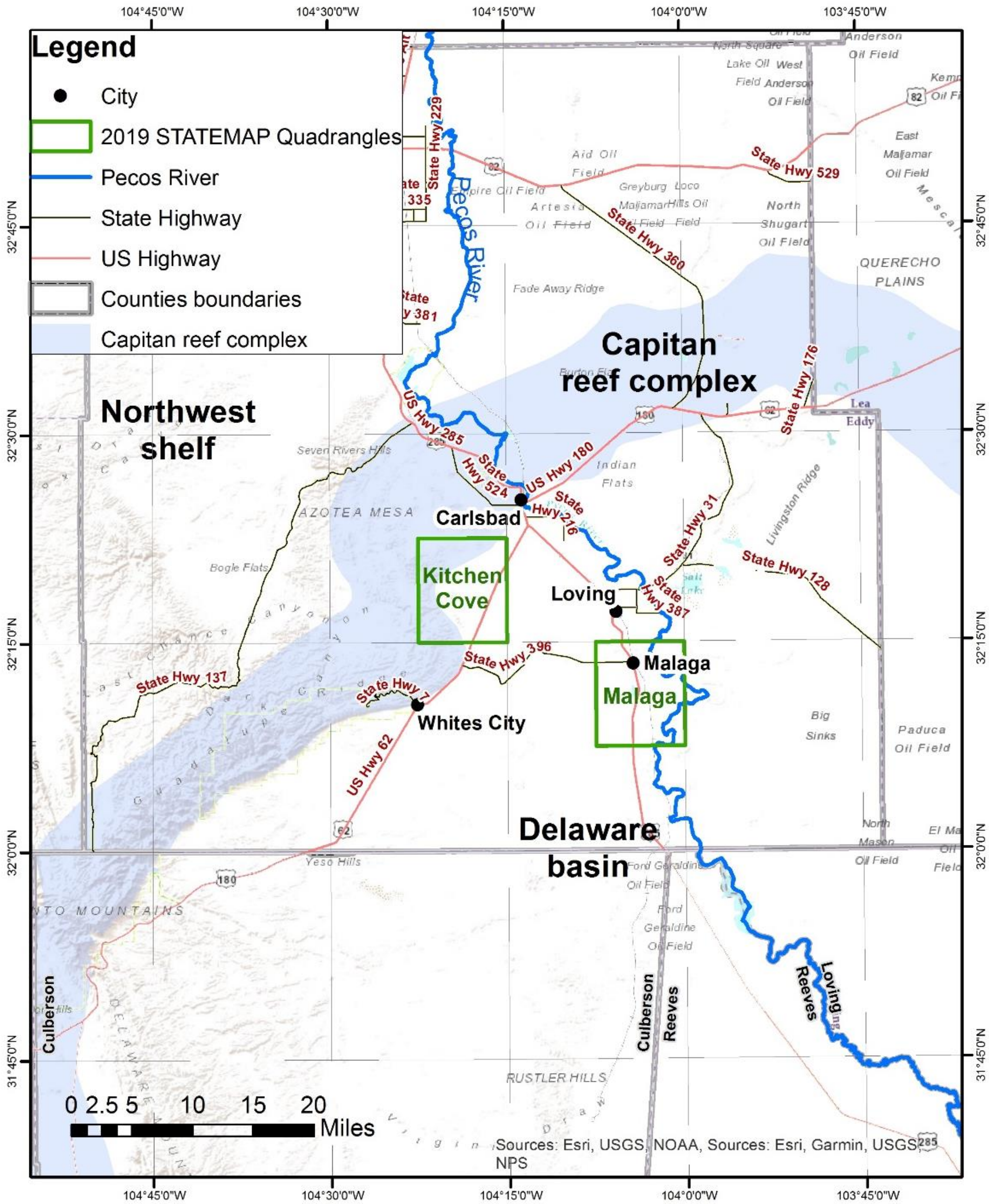


Figure 1-1: Geographic location of the study area. Capitan reef complex extent from Standen et al. (2009).

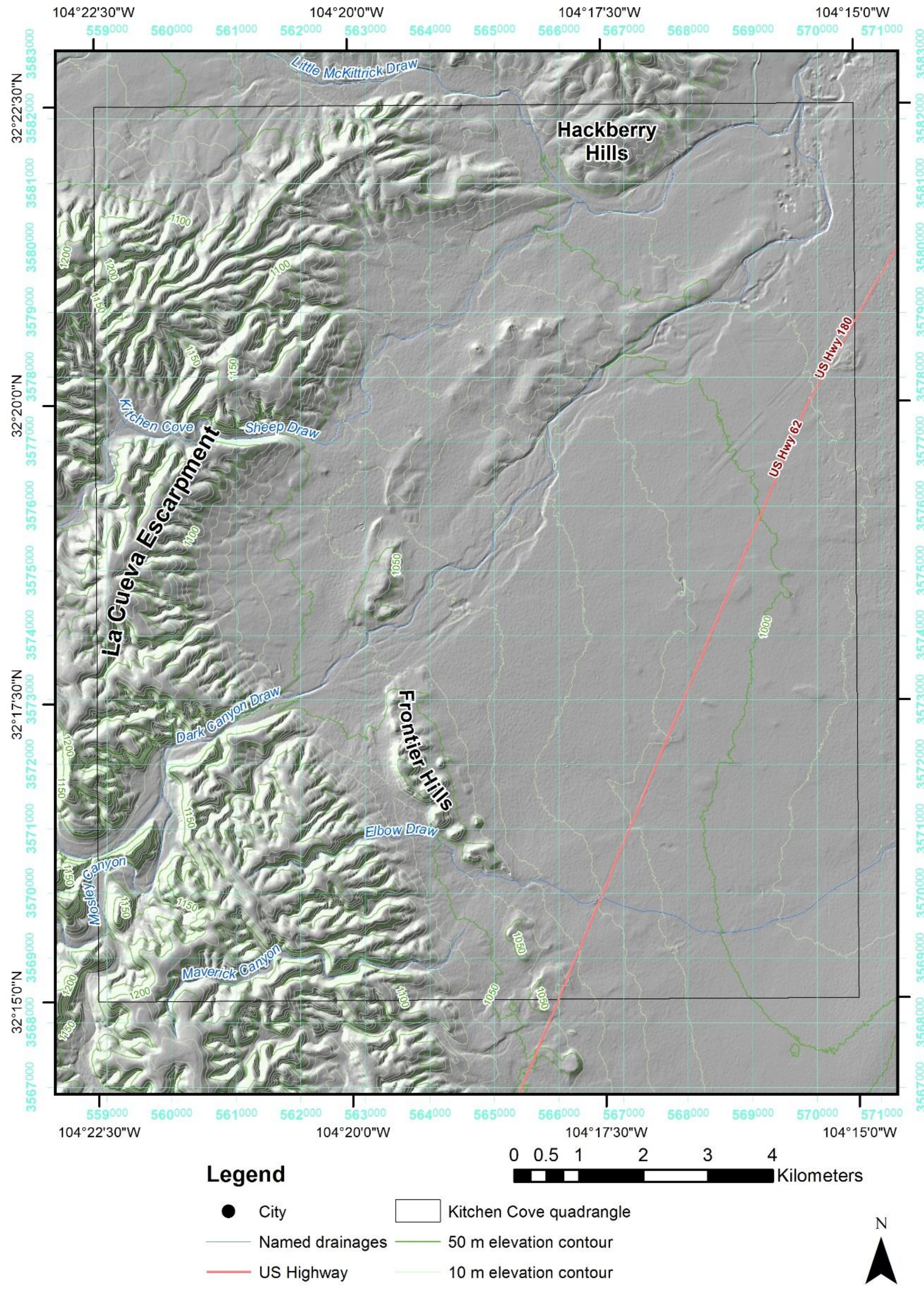
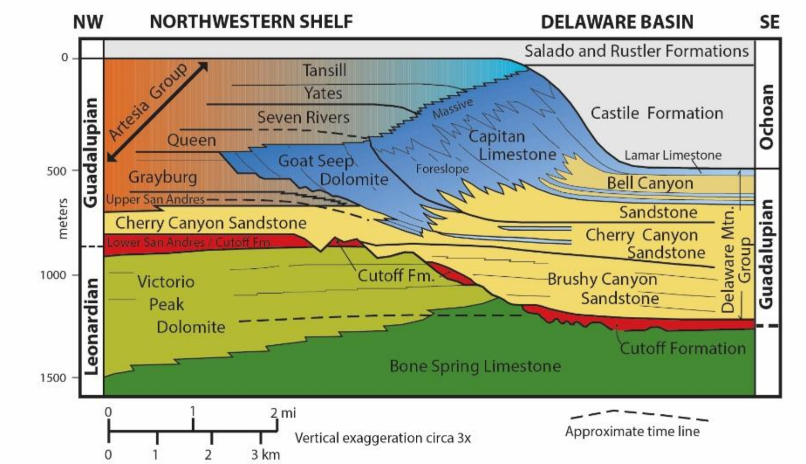
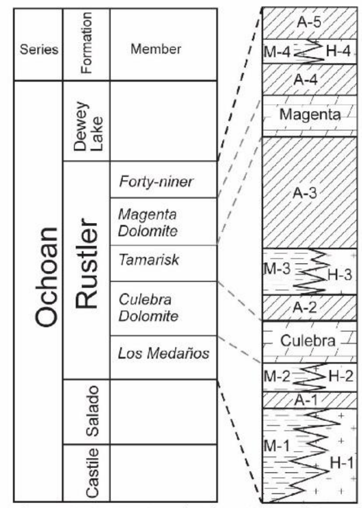


Figure 1-2: Topography and geographic features of the Kitchen Cove quadrangle. Processed from digital terrain models from Intermap Technologies (2008).



Classic depiction of the stratigraphy of the Permian strata exposed in the Guadalupe Mountains. Modified from Scholle et al. (2007). Abbreviations: Fm. = Formation, Mtn. = Mountain. Note that in cross-section A-A': the Formations and most Members of the Delaware Mountain Group are combined (unit Pd); the Castile and Salado Formations are combined (Pcs); the massive and foreslope members of the Capitan Limestone (plus the Goat Seep Dolomite, if present) are combined (Pclu); and the Victorio Peak and Cutoff Formations, if present, are combined with the Bone Spring Limestone (Pbs).



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

Figure 1-3: Permian stratigraphic nomenclature. Late Cenozoic deposits are largely unnamed. Alluvial conglomerates capping the Rustler Formation along the Frontier Hills are correlated to the Gatuña Formation, as discussed in the text.

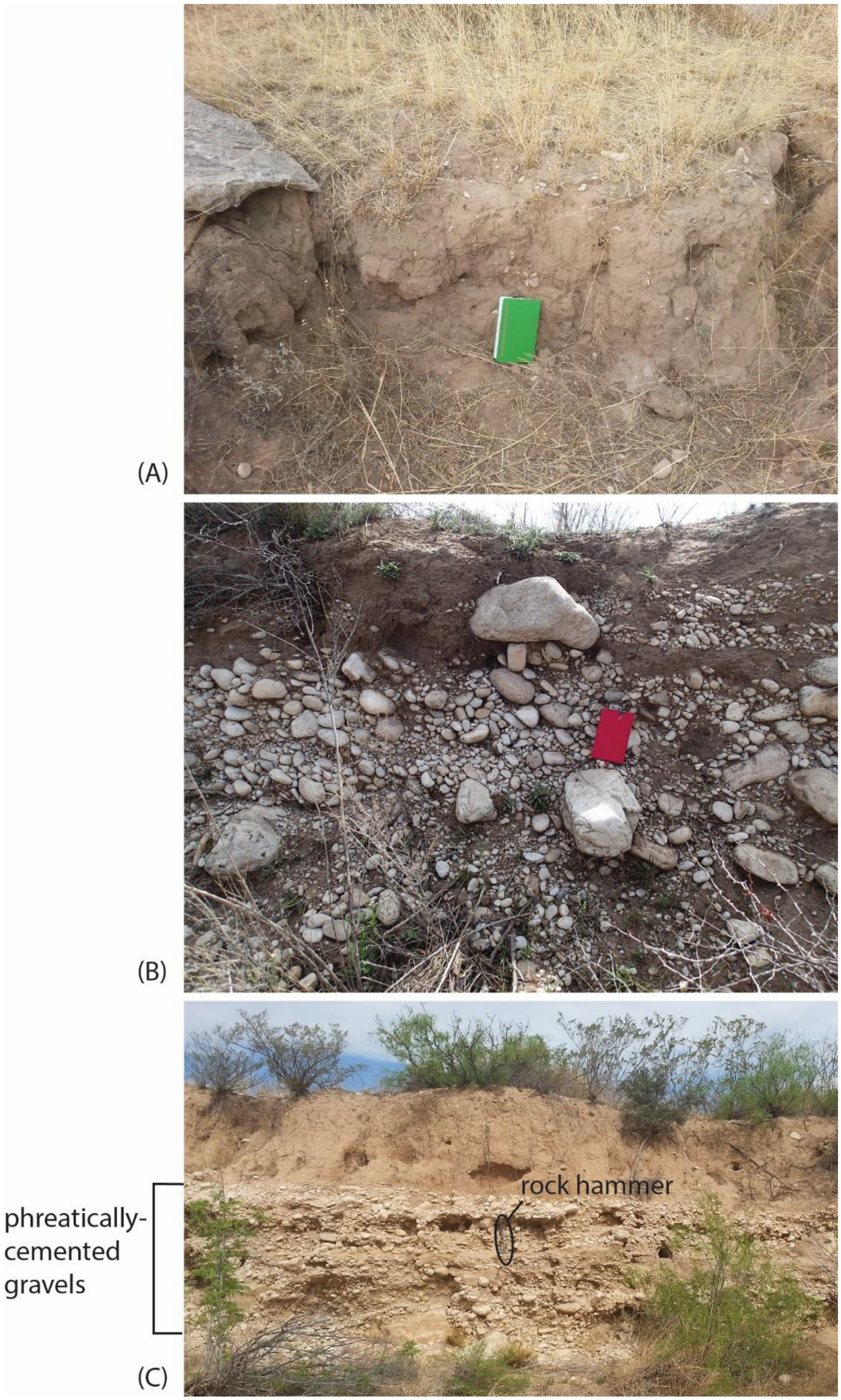


Figure 2-1: Outcrops of Qay deposits. (A) Qay2 silts and sands. (B) Qay2g gravels. (C) Qay1g, here consisting of Qay1 silts and sands overlying phreatically-cemented gravels.

Figure 2-2: Outcrops of Qao2 deposits. (A) Qao2 pedogenic carbonate-cemented conglomerate overlying silty-clayey sands. (B) Close-up of the Stage IV petrocalcic carbonate horizon developed in the Qao2 deposit. (C) Gravel-dominated Qao2 deposits. (D) Close-up of Qao2 Stage VI petrocalcic carbonate horizon developed in Qao2 gravels.

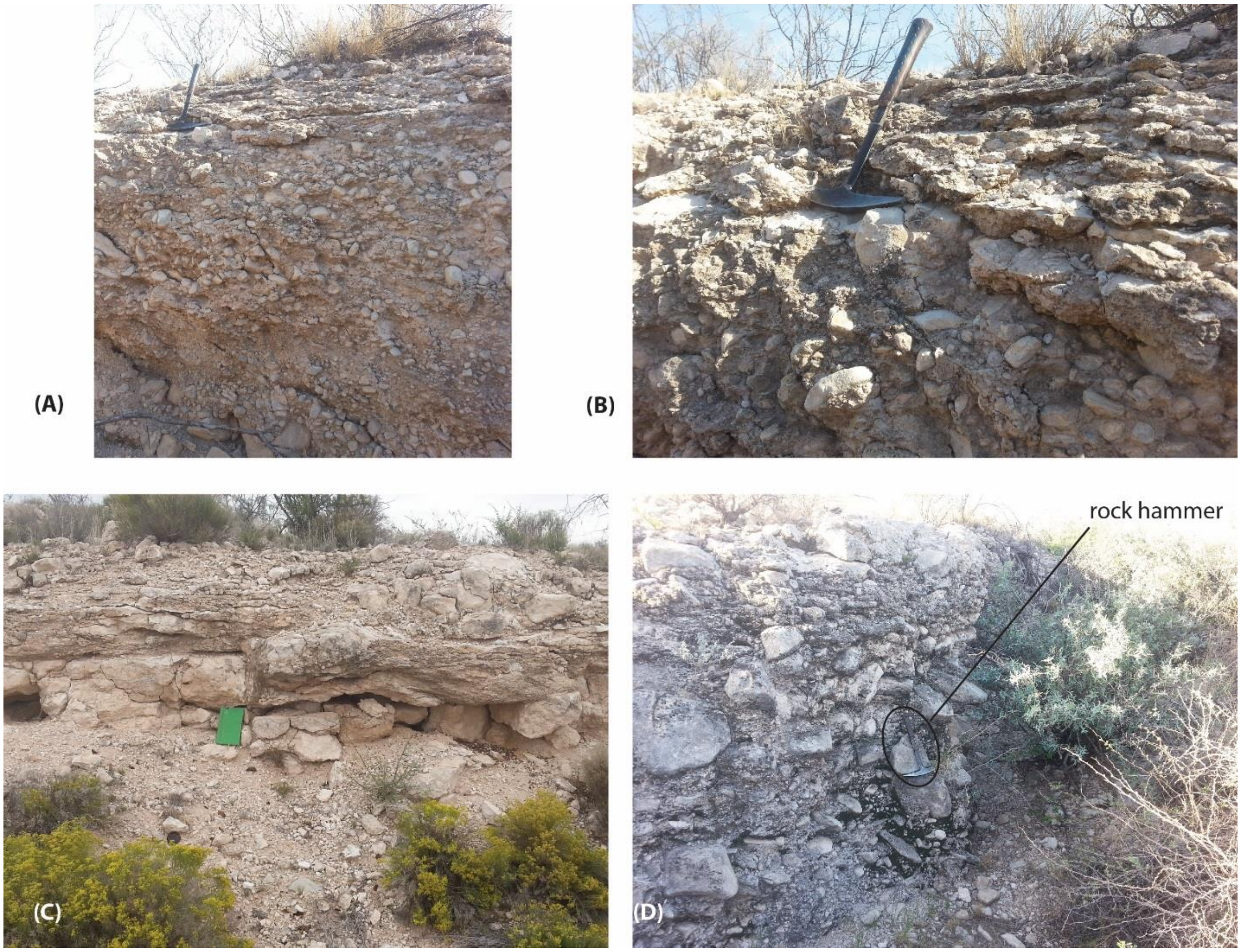


Figure 2-3: Outcrops of Qao1 deposits. (A) Qao1 in a gravel pit, showing depth of carbonate accumulation and cementation. (B) Close-up of the undulatory tabular banded zone capping the petrocalcic carbonate horizon. (C) Exposure of the petrocalcic carbonate horizon developed in Qao1 deposits. (D) Exposure highlighting the depth of cementation in Qao1 deposits.

Figure 2-4: Outcrops and features of Tgp deposits. (A) Outcrop of conglomerates mapped as Tgp. (B) Close-up of conglomerate beds of unit Tgp. (C) Trace siliceous pebbles found in Tgp. (D) Extensive brecciation of Tgp found in the upper portions of the deposit, possibly related to soil development. (E) Concentric laminations around gravels and possible pisolites in thoroughly carbonate-cemented upper portions of Tgp. (F) Brecciation and possible laminations. (G) Well-cemented upper portions of Tgp.

Figure 2-5: Features of the uncorrelated caliche unit, QTc. (A) Typical exposure of QTc. (B) Close-up of pisolitic texture locally appearing on weathered faces of the caliche.

3. Permian System

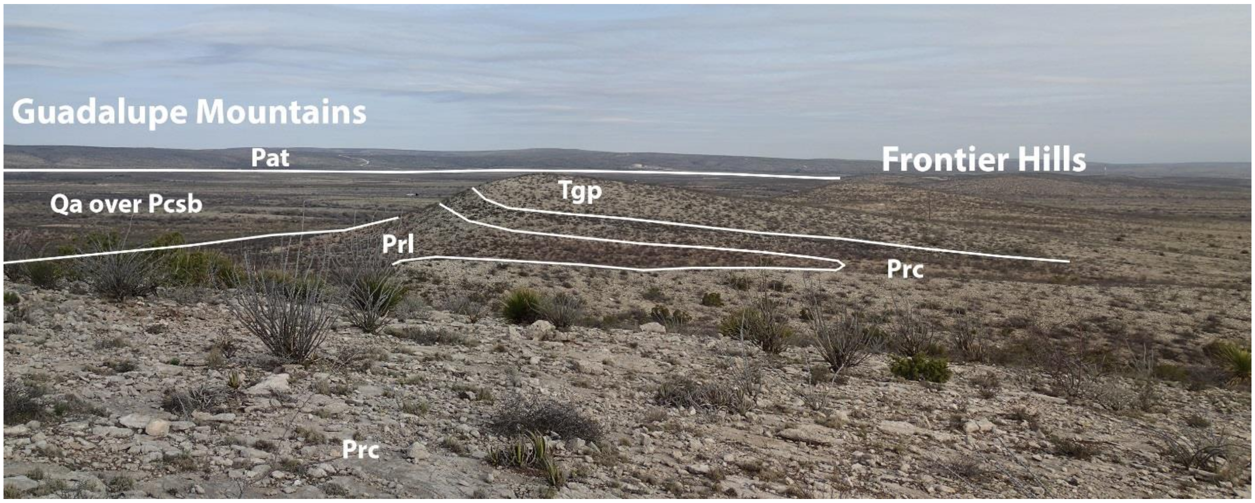


Figure 3-1: View of the Frontier Hills. Circa Dark Canyon Draw and further north, Gatuña Formation conglomerates rest on the Culebra Dolomite, with the Los Medaños Member occurring as pinkish or reddish brown slopes beneath. The valley between the Frontier Hills and the Guadalupe Mountains are dominantly alluvium overlying Castile-Salado breccia deposits. View is looking north.

Figure 3-2: Outcrops and features of the Culebra Dolomite. (A) Typical outcrop, showing typical bedding and fracturing of the Culebra. (B) Close-up, showing the abundant small vugs that often pockmark Culebra beds. (C) Outcrop of the limey facies. (D) Cross-stratification preserved in the limey facies. (E) Concentric, if irregular, laminations in the limey facies. (F) Brecciation of the limey facies.

Figure 3-3: Outcrops of Castile and Salado Formations and associated breccias. (A) Intact, laminated to thinly bedded Castile Formation gypsum, exposed on the Black River Village quadrangle to the south. (B) Salado Formation 'residue,' exposed east of the quadrangle circa 573,390 m E, 3,564,730 m N (Stop 2-8 of Chaturvedi, 1980). Note large blocks of gypsum right of hammer, surrounded by erratic reddish brown clay-gypsum matrix. (C) Low outcrop of seemingly intact Castile on the Kitchen Cove quadrangle. (D) Unaligned gypsum crystals in Castile-Salado breccia outcrop. (E) Pinkish Castile-Salado breccia. Pink color comes from pale reddish brown clays incorporated in the gypsum.

Figure 3-4: Outcrops and features of the Tansill Formation. (A) Typical outcrop expression of the carbonate facies of the Tansill Formation. (B) Large pisolites observed locally throughout the Tansill but particularly common closer to the Capitan reef. (C) Teepee structures found proximal to the Capitan reef. Note that bedding is undisturbed above the teepees. (D) Shell fragments, found close to the Capitan reef margin. (E) Silt capping a carbonate bed. Silt may have been washed in between beds along karst features. (F) The Ocotillo Silt Member in outcrop.

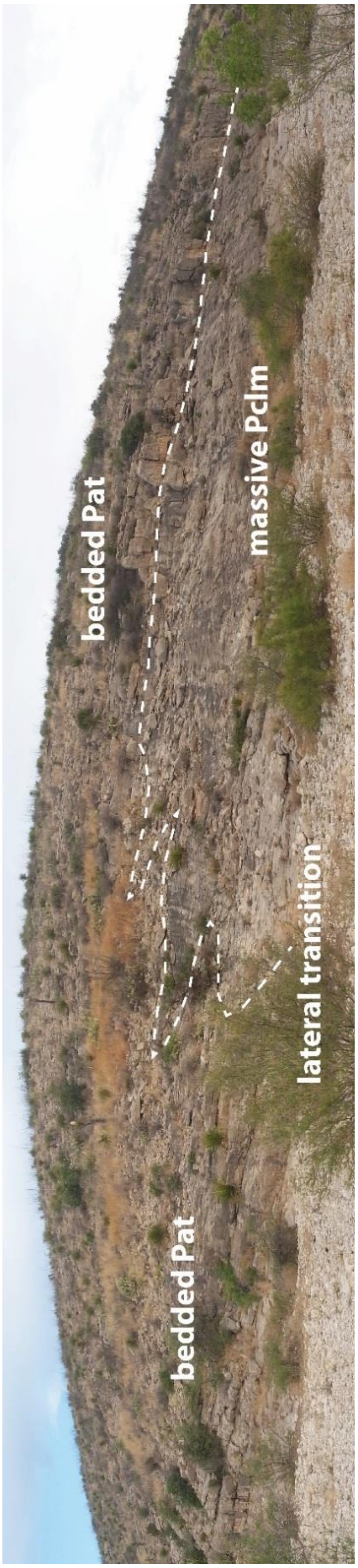


Figure 3-5: The Capitan Limestone-Tansill Formation transition in outcrop along the north flank of Dark Canyon. Bedded upper Tansill beds transition into massive Capitan limestones at stream level laterally, and overtake the Capitan vertically as well.

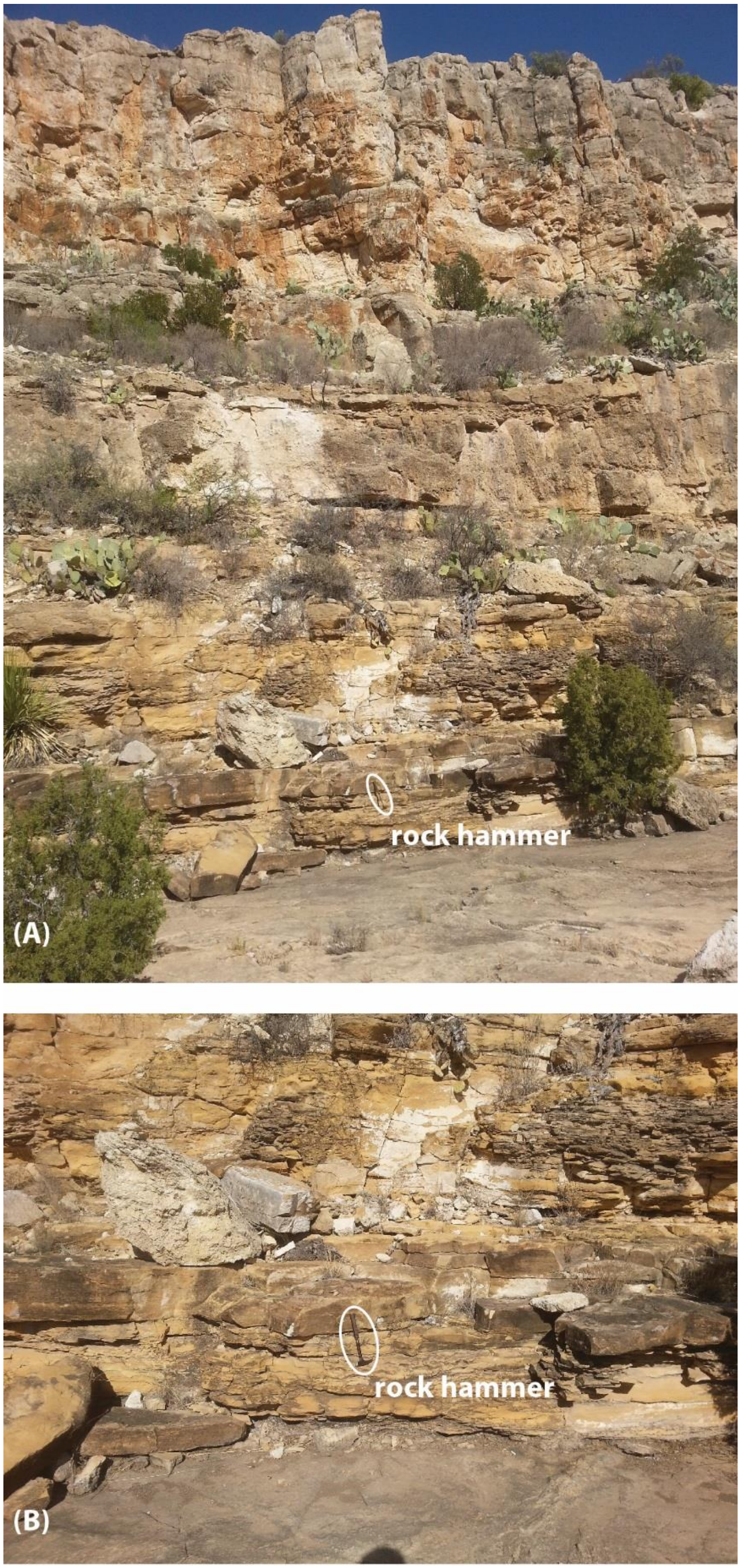


Figure 3-6: Outcrops of the Yates Formation. (A) Contact between the Yates and Tansill Formations. The thick sandstone/siltstone interval at the base of the outcrop is the highest Yates clastic layer, which defines the contact between the two formations. (B) Close-up of the highest Yates sandstone/siltstone interval.

Figure 3-7: Features of the Seven Rivers Formation exposed on the Kitchen Cove quadrangle. (A) Oolite beds. (B) Massive micrites with rare detrital material and oolites. (C) Thinly bedded micrite to packstones with variable amounts of clastic or oolitic material. (D) Crenulated textures in thinly bedded carbonates. (F) Lenticular micrites, possibly from syndepositional deformation. (F) Clastic detritus in a packstone or wackestone.

Figure 3-8: Features of the Capitan Limestone. (A) Fossils encased in lime mud. (B) Vugs. (C) Local brecciation.

4. *Permian System – Unexposed*

5. Structure

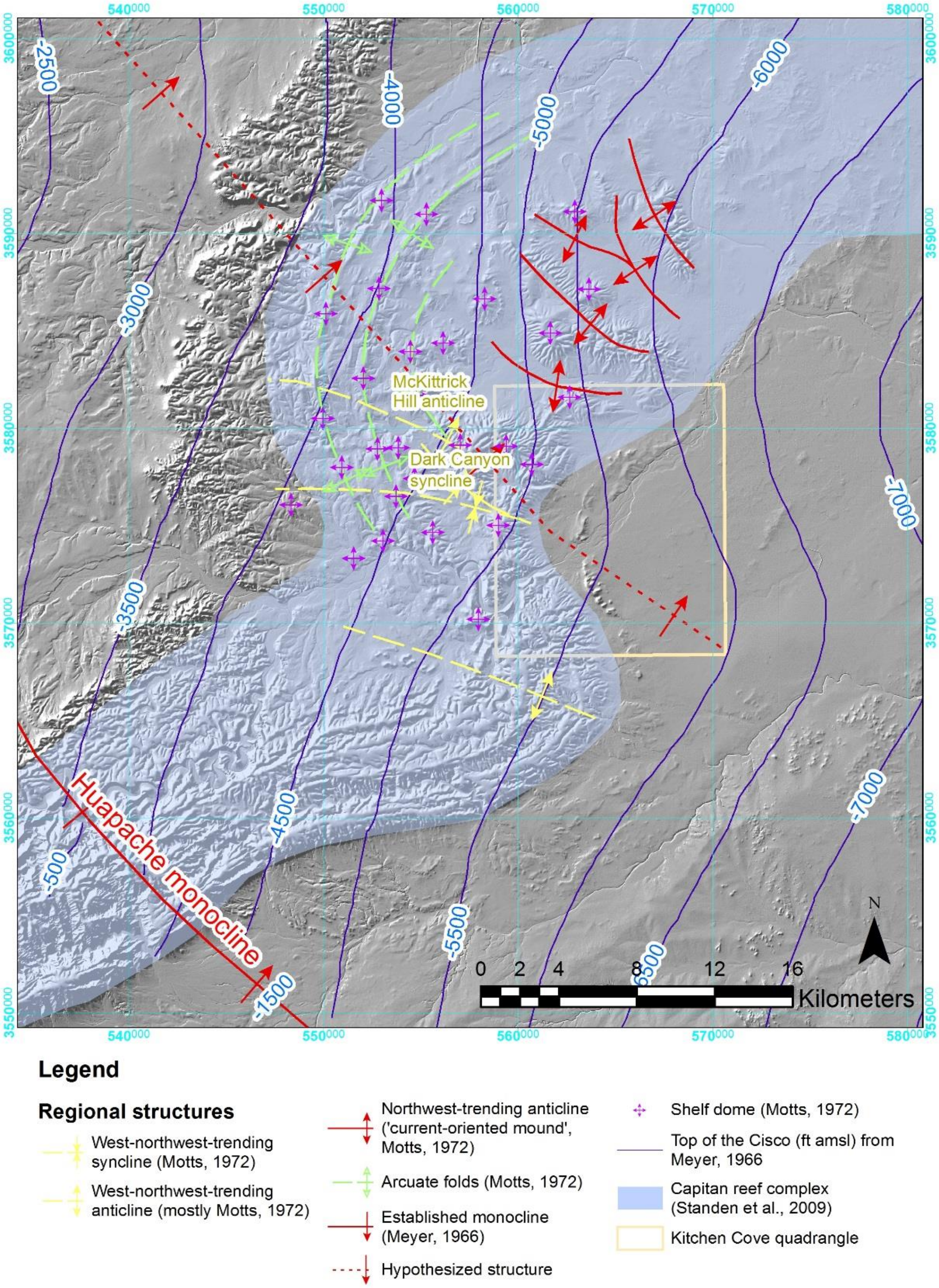
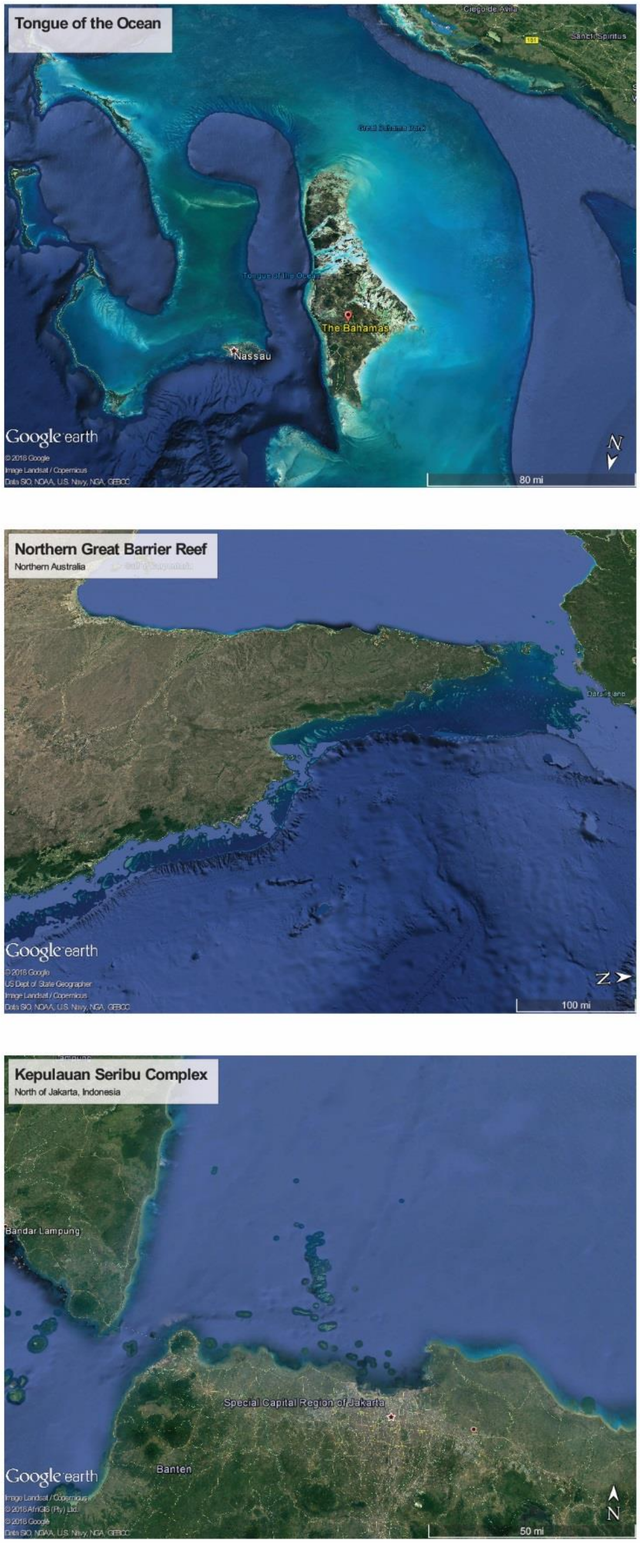


Figure 5-1: Regional structural trends. Mostly adapted from Motts (1972), with top of Cisco (uppermost Pennsylvanian) contours and the Huapache monocline adapted from Meyer (1966), and the extent of the Capitan reef in the subsurface from Standen et al. (2009). Southernmost, unnamed west-northwest-trending anticline was interpreted for this report based on topographic and geologic map trends by the author.



(A)

(B)

(C)

Figure 5-2: Regional settings of hypothesized modern analogues to the domal structures observed in the Artesia Group north of Dark Canyon. (A) "Tongue of the Ocean" in the Great Bahama Bank by Andros Island. This location was discussed explicitly by Motts (1972) as a potential analogue. (B) Great Barrier Reef of northern Australia. (C) Kepulauan Seribu complex, also called the Thousand Islands, north of Jakarta, Indonesia. Options (B) and (C) were not discussed in detail by Motts, but suggested as locations for further investigation. All images courtesy of Google (2015).

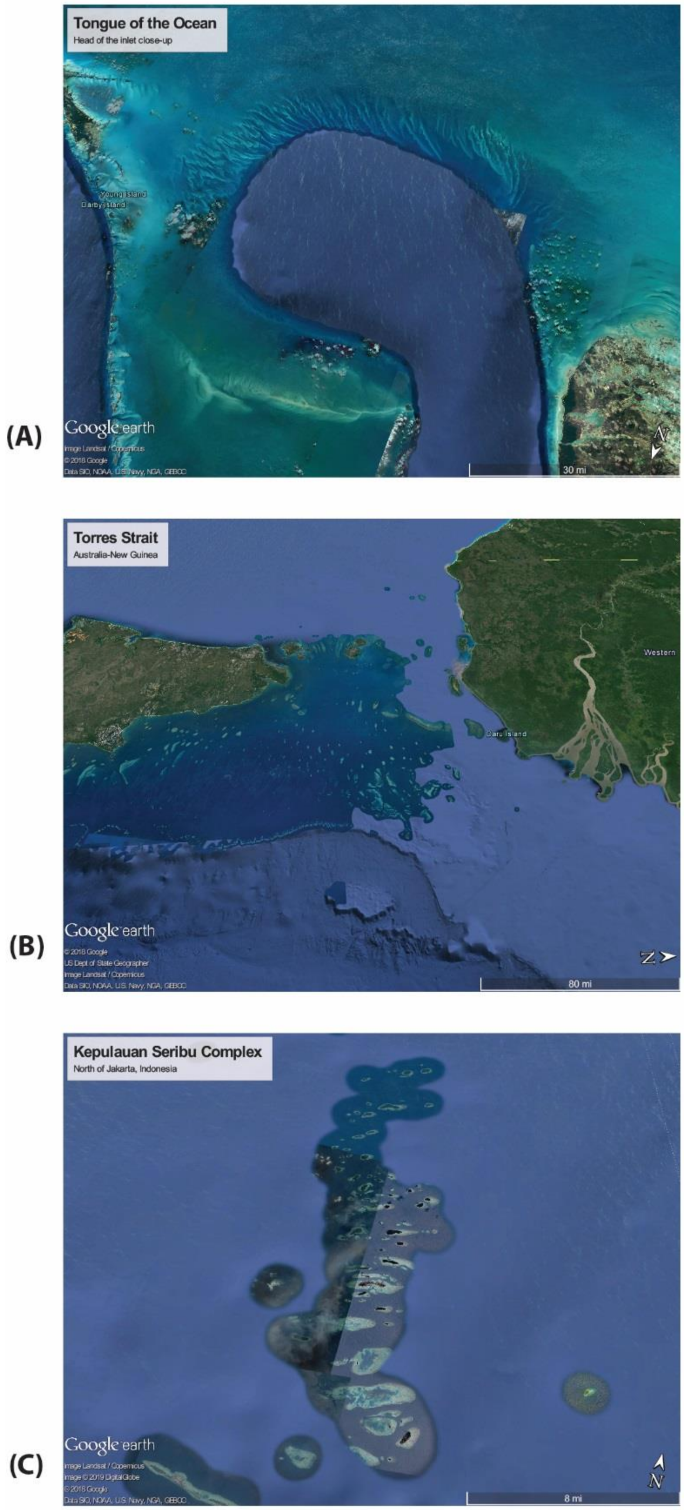


Figure 5-3: Images of potential current-oriented mound modern analogues. (A) Potential 'current-oriented mounds' developed at a horseshoe-shaped bend at the end of the Tongue of the Ocean, Great Bahama Bank. (B) Current-elongate domes developed in the Torres Strait (the Torres Strait Islands) where the northern Australian continental shelf merges with the southern New Guinea shelf. Larger islands are cored by igneous rocks. (C) Current-elongate patch reef domes of the Kepulauan Seribu, north of Jakarta, Indonesia. Note that some, particularly toward the south, consist of rings of shallow concentric reefs that encompass a central lagoon, rather than being entirely subaerially exposed. All images courtesy of Google (2015).

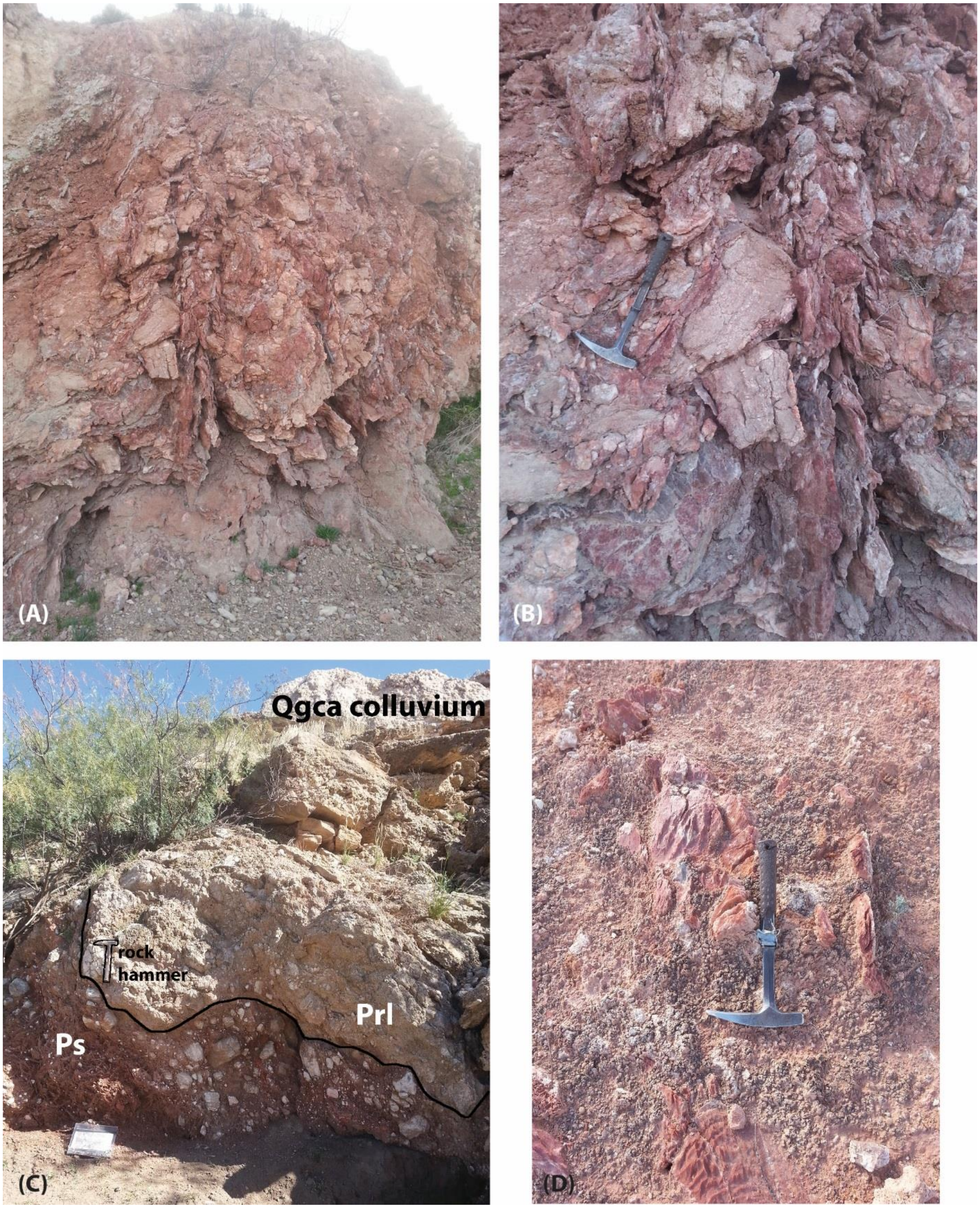


Figure 5-4: Outcrops of the Salado Formation residue. (A) Tall outcrop of Salado Formation breccia at circa 573,390 m E, 3,564,730 m N (Stop 2-8 of Chaturvedi, 1980); rock hammer is just right of and below the center of the photo. (B) Close up of gray laminated gypsum blocks surrounded by erratic reddish brown matrix. (C) Outcrop of Salado 'residue' along the Pecos River in the north center of the Malaga quadrangle circa 589,950 m E, 3,567,750 m N. Unit Qgca there is a conglomerate facies of the upper Gatuña Formation (Cikoski, 2019). (D) Weathered low outcrops of Salado residue circa Malaga bend on the Malaga quadrangle.

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8. Map unit descriptions

Unit	Full Name	Age	Description
	Description of Map Units		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		
	Artificial deposits		
af	Artificial fill	Historic	Variously compacted sands, gravels, and muds emplaced by anthropogenic means. Only mapped where the deposit is of significant aerial extent, thickness, or masks underlying geologic relationships. 0 to perhaps 10 m thick.
	Alluvial deposits		
Qa	Undivided Quaternary alluvium	Middle(?) Pleistocene to Historic	Cross-section only. May include areas of any or all of the Quaternary alluvial deposits described below. Well logs suggest unit thickness may be as much as 64 m.
QTa	Undivided Quaternary-Tertiary alluvium	Late Miocene(?) to Historic	Cross-section only. May include areas of any or all of the Quaternary or Gatuña Formation alluvial units described below. Well data from Bjorklund and Motts (1959) suggest an on-quadrangle alluvium thicknesses of as much as 110 m.
Qaf	Small-scale fan alluvium	Middle(?) Pleistocene to Holocene	Generally thin veneers of alluvial gravels and sands deposited as small, coalescing alluvial fans by low-order tributary drainages. Sediments are poorly sorted and of compositions reflective of upstream rock or sediment types. Surface soil characteristics are highly variable, but often include carbonate horizons with Stage I to IV morphology. Deposits are poorly exposed, but thicknesses likely 0 to perhaps 3 m.
Qah	Historic alluvium	Historic	Poorly or unvegetated sandy gravels along active drainage channels. Deposits are dominantly poorly sorted, rounded pebbles to trace boulders of mainly limestone/dolomite lithologies with lesser amounts of material derived from other upstream-exposed units. Most deposits are matrix-poor and loose, and exhibit no evidence of appreciable soil development. Locally overtops the treads of low terraces along the channel flanks. Map unit includes small unmappable Qay terrace deposits and anthropogenically-emplaced material along active and abandoned gravel pit operations. Deposits are 0 to perhaps 4 m thick.
Qayh	Historic and undivided younger alluvium	Holocene	Gravels, sands, and muds within and along narrow active drainage channels. Used where historic alluvium and younger terrace deposits cannot be mapped separately with accuracy at the map scale, and is dominated by historic alluvium that often overtops the low treads of adjacent terrace alluvium. Terrace alluvium is mainly of Qay2/Qay2g type. Deposits are 0 to perhaps 4 m thick.
Qay	Younger alluvium, undivided	Late Pleistocene? to Holocene	Undifferentiated Holocene alluvial sands, muds, and gravels. Deposits are principally like those of Qay2 and/or Qay1, and less commonly like Qay2g, Qay1g, and/or Qah. This undivided map unit is used where map scale, poor exposure, and/or a lack of differentiating features precludes subdivision. Deposits are 0 to perhaps 7 m thick.

Qay2	Younger subunit of the younger subunit	Late Holocene	Brown to yellowish brown fine sands to silts and lesser clays and gravels along active drainage channels and swales or underlying low terraces with no appreciable surface soil development. Most deposits are massive to laminated, poorly sorted, sandy silts to silty sands with trace rounded pebbles derived from nearby alluvial gravel deposits. Rare paleochannel fills of poorly sorted, rounded, clast-supported pebbles occur as thin lenticular ribbon-shaped interbeds. Map unit also includes lesser historic alluvium, commonly consisting of cobbly pebble gravel deposits along active drainage channels with common bar-and-swale topography and little to no vegetation. Sand and silt colors of 10YR 5/3-5/4 were measured. Deposits are 0 to perhaps 5 m thick.
Qay2g	Gravel-dominated deposits of the younger subunit of the younger alluvium	Late Holocene	Gravels and lesser brown to yellowish brown sands and trace muds underlying low terraces exhibiting no appreciable surface soil development. Deposits are mostly found along the flanks of larger drainage channels, and consist dominantly of poorly sorted, rounded to well-rounded, cobbly pebbles and trace boulders, of mainly limestone/dolomite lithologies with rare sandstone and Culebra Dolomite clasts as well as trace reworked conglomerate clasts and well-rounded siliceous pebbles (chert, quartzite), in thick to medium, clast-supported, unconsolidated, uncemented, massive planar tabular or broadly lenticular beds. Irregular sand beds as much as 40 cm thick but commonly pinching out laterally are up to 40% of outcrops, typically becoming more abundant up-section, and consist of poorly sorted, well-rounded to rounded, very fine to fine grains of principally siliceous material and carbonate lithics. Sand colors of 10YR 5/3-5/4 were measured. Deposits are 0 to perhaps 5 m thick.
Qay1	Older subunit of the younger alluvium	Late Pleistocene? to Holocene	Dominantly light brown to pink alluvial sands with lesser gravels underlying terraces bearing surface soils characterized by weak A/Bk soil horizonation. Sands are mostly poorly sorted, silty-clayey, fine- to less commonly medium-grained, predominantly of carbonate lithics, and occurring in massive intervals that bear trace pebbles and surround thin pebbly paleochannel fills. Gravels are predominantly poorly sorted sandy pebbles consisting of limestone/dolomite lithologies and rare sandstone clasts in poorly structured lenticular beds. Surface soils most commonly consist of a darkened A horizon overlying sands with thin, fine filaments and fine nodules of carbonate (Stage I carbonate horizon morphology). Sand colors of 7.5YR 6/3 to 7/4 were measured. Deposits are 0 to perhaps 7 m thick.
Qay1g	Gravel-dominated deposits of the older subunit of the younger alluvium	Late Pleistocene? to Holocene	Dominantly gravels with lesser light brown to pink sands underlying terraces with surface soils characterized by A/Bk soil horizonation. Gravels are dominantly poorly sorted, rounded to well-rounded, cobbly and/or sandy pebbles of mainly limestone/dolomite lithologies with rare sandstone and Culebra Dolomite clasts, in medium-thickness, massive to cross-stratified lenticular beds. Sands are like those described for Qay1, occurring mostly as massive tabular or irregular interbeds surrounded by or capping gravel deposits. Locally, such as along Dark Canyon, variable amounts of phreatic carbonate cements the gravel beds. Surface soils most commonly consist of a darkened sandy A horizon overlying a carbonate horizon exhibiting Stage I to Stage II morphology. Sand colors of 7.5YR 6/3 to 7/4 were measured. Deposits are 0 to perhaps 7 m thick.

Qao	Older alluvium, undivided	Middle to Late(?) Pleistocene	Alluvial gravels bearing surface soils characterized by Stage IV or V morphology petrocalcic carbonate horizons. Commonly subdivided based on the level of soil development. The undivided map unit is used where map scale, poor exposure, or a lack of differentiating features precludes subdivision. Deposits of Qao are like those of Qao1 and/or Qao2.
Qao2	Younger subunit of the older alluvium	Middle to Late(?) Pleistocene	Alluvial gravel and lesser light brown to white sand deposits bearing surface soils characterized by Stage IV morphology petrocalcic carbonate horizons. These carbonate horizons typically consist of a 4 to 20 cm-thick laminated top consisting of undulatory laminations 2 to 10 mm thick with common entrained alluvial gravels, which overlies a 30 to 40 cm-thick carbonate-cemented zone that grades down-profile into uncemented gravels and/or sands. Any previously overlying A or B horizons have been stripped. Deposits dominantly consist of poorly sorted, rounded, cobbly pebble gravels and trace boulders, of mainly limestone/dolomite lithologies with rare sandstone clasts. Sands are mainly poorly sorted, silty-clayey, subangular to rounded, very fine to medium grains of mainly carbonate lithics occurring in thick massive intervals. Sand colors of 7.5YR 6/4-8/4 were measured. Clay films are found below the carbonate horizon as rare to common bridges between grains and as gravel coats. Deposits are locally capped by up to 20 cm of eolian or slopewash sands similar to those of unit Qae. Gravel deposits are 0 to perhaps 5 m thick.
Qao2s	Sand-dominated deposits of the younger subunit of the older alluvium	Middle to Late(?) Pleistocene	Alluvial sand and lesser gravel deposits underlying surfaces that occur at comparable levels to surfaces capping Qao2 deposits. Deposits are poorly exposed but appear to consist principally of light brown, moderately sorted, siliceous, variably silty, very fine to fine sands in massive beds. A sand color of 7.5YR 6/4 was measured. Gravels are poorly sorted, rounded to well-rounded cobbly pebbles and trace boulders, of mainly limestone/dolomite lithologies with rare sandstone clasts and trace well-rounded siliceous pebbles, occurring in thick lenticular or ribbon-shaped beds that pinch out laterally into sand intervals. No preserved surface soil was found in outcrop for this unit; however, along the edges of terrace treads there are commonly thin carbonate coats completely encircling gravels as well as rare float of carbonate-cemented gravels, suggesting a minimum Stage II carbonate soil horizon is or was at one point present. Deposits 0 to perhaps 5 m thick.

Qao1	Older subunit of the older alluvium	Middle Pleistocene	Alluvial gravel deposits bearing surface soils characterized by Stage V morphology petrocalcic carbonate horizons. These carbonate horizons typically consist of a 25 to 40 cm-thick tabular-structured top zone consisting of undulatory bands of dominantly carbonate cement that are 3 to 10 cm thick, which overlies a carbonate-cemented zone 30 to 70 cm thick, with cementation decreasing down-profile; engulfing, but only weakly cementing, carbonate continues below the well-cemented zone to at least 4 m depth. Any previously overlying A or B horizons have been stripped. Deposits dominantly consist of poorly sorted, rounded, cobbly pebble gravels and trace boulders, of mainly limestone/dolomite lithologies with rare sandstone clasts. Sand beds are very rare, and typically consist of carbonate-engulfed very fine to fine sand grains in medium to thick, moderately cemented, massive, tabular, pale pink beds; a sand color of 9.5YR 7/2 was measured. Deposits are locally capped by up to 20 cm of eolian or slopewash sands similar to those of unit Qae. Gravels and soil may correlate to the Upper Gatuña Formation of Cikoski (2019). In outcrop, gravel deposits are 0 to about 4 m thick; well logs suggest thicknesses may be up to 64 m or more.
Tgp	Gatuña Formation, piedmont facies	Late Miocene(?) to Pliocene	Alluvial conglomerates and rare sandstones along the east flank of the Frontier Hills. Deposits dominantly consist of cobbly pebble gravels and trace boulders, of mainly limestone/dolomite lithologies with lesser sandstone clasts and trace well-rounded quartzite and chert, in medium to thick, moderately well-cemented, clast-supported, often cross-stratified, lenticular beds. Pink sandstone interbeds are rare, and consist of poorly sorted, rounded, grain-supported, very fine to coarse grains of siliceous and carbonate lithologies, in thick, generally poorly cemented, massive, tabular beds. Sand bed colors of 7.5YR 7/3-7/4 were measured. No complete exposure of a surface soil was found. Partial exposures suggest a well-cemented near-surface zone exhibiting smooth, micritic cement textures; brecciation and recementation features; thin concentric laminations around gravels; and a level of induration that typically causes fractures to traverse through gravels rather than around gravels. This near-surface zone could be a poorly exposed Stage VI carbonate horizon. Deposits are 0 to at least 25 m thick; well records suggest thicknesses may exceed 46 m.
	Miscellaneous deposits		
Qae	Alluvial and eolian sediment	Holocene	Pink to pale brown piedmont-blanketing slopewash and windblown silts and fine sands. Dominantly silts, with lesser very fine sands and trace pebbles, in massive deposits. A silt color of 7.5YR 7/3 was measured. Surface soils are weak and characterized by rare fine carbonate nodules up to 2 mm across occurring throughout deposits below about 30 cm depth (Stage I or less carbonate horizon morphology). Deposits are commonly thin but can be as much as 3 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 likely 0 to perhaps 2 m thick.

Qca	Undivided colluvium and alluvium	Holocene	Uncemented sands and gravels transported by gravitational or unconfined alluvial mechanisms. Mapped only where concealing underlying geologic relationships, principally between map unit Tgp and underlying Rustler Formation strata. Sediments are mainly derived from upslope Tgp deposits, and hence consist of similar assemblages of gravels and sands. Deposits are 0 to perhaps 1 m thick.
QTc	Uncorrelated caliche	Pliocene(?)	"Deposits" of pure(?) carbonate cement along the east flank of the Frontier Hills. No entrained sediments or bedrock blocks were found in these caliche zones. Caliche is poorly exposed, but upturned blocks reveal common laminations 1 to 6 mm thick with local pisolitic textures. Caliche is white to light gray (7.5YR 7/1 was measured), very well-indurated, and locally fractured or jointed. Caliche is 0 to perhaps as much as 2 m thick.
	Permian System		
	Ochoan Series		
Pr	*Rustler Formation*	Ochoan (Upper Permian)	
Prc	Culebra Dolomite Member of the Rustler Formation	Ochoan (Upper Permian)	Cream-colored to white, ledge-forming, conspicuously vuggy dolomite, locally grading laterally into light yellowish to grayish brown limestone. Dolomite beds are thin, planar tabular, very fine-grained, and commonly internally massive. Abundant to rare vugs are fine in size (1 to 10 mm in diameter) and distinctive to the unit. Limestones are mainly fine-grained, carbonate mud-rich packstones and lesser wackestones, in thin tabular beds that are locally internally cross-, planar-, or concentrically-laminated. Unit is locally highly fractured, with fractures variously filled with caliche/carbonate cement, particularly adjacent to map units Tgp and QTc. Measured colors range from white for dolomite outcrops to mainly 2.5Y 6/3 and locally 2.5Y 5/1-5/2 and 10YR 6/6 for the limestones. Preserved unit thickness is up to about 6 to 9 m.
Prl	Los Medaños Member of the Rustler Formation	Ochoan (Upper Permian)	Pale red to reddish yellow mudstones, isolated masses of gypsum, and rare brown sandstones. Mudstones are laminated, weakly indurated, and very poorly exposed, and often only apparent as reddish brown silts and clays in colluvial slopes. Sandstones occur as typically thin but locally thick lenticular intervals of very fine- to fine-grained, cross-laminated, very thinly bedded siliceous sandstones interlayered with lesser light brown siltstones. Gypsum occurs as irregular white to light gray masses generally cropping out of otherwise colluvial slopes. Colors of 5YR 6/6-7/6 (mudstones) and 2.5Y 7/4 (sandstones) were measured. The base of the unit is unexposed. The exposed unit thickness is up to 25 m, while Powers and Holt (1999) report a thickness of 34.4 m in the type section.
	Castile and Salado Formations, undivided	Ochoan (Upper Permian)	

Pcsb	Breccia of Castile and Salado Formation rocks	Ochoan (Upper Permian)	Irregular breccia blocks and outcrops of mainly Castile Formation lithologies with subordinate Salado Formation residue. Breccia blocks are up to 1 m across and consist of erratic mixtures of principally gypsum with lesser selenite and clay. Some blocks and outcrops bear subparalleling laminations that may be remnant bedding planes, while other blocks consist of discordant, unaligned crystalline material with irregular thin bands of clays. Blocks and outcrops are principally white to gray (circa 2.5Y to 10YR 7-8/1-2 was measured), less commonly pink to red (5YR 6/4 and 10R 6/8 and 4-5/6 was measured), with redder colors more common to clay-enriched blocks. Deposits are poorly exposed, and breccia unit thickness is poorly constrained; at depth, the breccia grades into intact gypsum and anhydrite below the depth of weathering and dissolution, but the depth of this transition was not determined. Maximum total thickness of Castile and Salado deposits is around perhaps 405 m.
Pcs	Castile and Salado Formations, undivided	Ochoan (Upper Permian)	Cross-section only. Includes Castile-Salado breccia and intact Castile Formation at depth. Cross-section interpretations indicate a maximum thickness of approximately 405 m.
	Guadalupian Series		
Pcl	*Capitan Limestone*	Guadalupian (Upper Permian)	
Pclm	Massive facies of the Capitan Limestone	Guadalupian (Upper Permian)	Light gray, weathering medium gray, massive fossiliferous limestone. Conspicuous fossils include calcareous sponges and fragments of brachiopod and gastropod shells and crinoids. Commonly vuggy, locally brecciated or fractured, with breccia and fractures recemented by carbonate mud. Grades laterally westward and vertically up-section into the Tansill Formation at the surface, and into the Yates and Seven Rivers Formations in the subsurface. Contact is placed along the transition from bedded Artesia Group to massive Capitan carbonates. Base unexposed.
Pclu	Undivided Capitan reef complex	Guadalupian (Upper Permian)	Cross-section only. In the subsurface, the Capitan reef complex may include areas of the massive facies of the Capitan Limestone (map unit Pclm), areas of Capitan Limestone talus slope breccia (cf., Newell et al., 1953, and Hayes and Koogle, 1958), and potentially areas of Goat Seep Dolomite, a precursor to the Capitan Limestone (Newell et al., 1953; Hiss, 1975; Standen et al., 2009). King (1948) reports a thickness range of 300 to 600 m at the surface, and as much as 820 m in the subsurface. Well data from Hiss (1975) and Standen et al. (2009) indicate the on-quadrangle thickness ranges from about 315 to 643 m, decreasing to 0 m within the Guadalupian Delaware basin.
Pa	*Artesia Group*	Guadalupian (Upper Permian)	

Pat	*Tansill Formation*	Guadalupian (Upper Permian)	Principally white to light gray thinly bedded dolomite grainstones to packstones, with local interbedded siltstones/mudstones in the upper portion. Typically subdivided into lower and upper map units, with the contact placed along a conspicuous and continuous ledge developed along the base of a siltstone interval in the Ocotillo Silt Member of DeFord and Riggs (1941). Both map units consist principally of grainstones and packstones in tabular beds 10 to 40 cm thick that are variously internally massive, planar-laminated, or cross-laminated. Rarely, beds are pisolitic, and locally bear paleokarst-filling silt or are capped by silt. Near to the Capitan Limestone, pisolites become more common, beds thicken, and mollusc and brachiopod fossils as well as tepee structures are found. Interbedded mudstones, more common in the upper map unit, are pale brown to pink, dominantly siltstones, tabular, very thinly bedded to laminated, and commonly moderately well-indurated by carbonate cement. Colors of 2.5Y 8/1, 6/1, and 7/2 to 10YR 8/1 (dolomites) as well as 2.5Y 7/4 to 8/3 (siltstones) were measured. Preserved unit thickness is about 80 to 90 m.
Patu	Upper map unit of the Tansill Formation	Guadalupian (Upper Permian)	White to light gray thinly bedded dolomite grainstones to packstones with rare mudstones overlying a conspicuous and continuous ledge in the Ocotillo Silt Member. Principally consists of dolomites as described above; mudstones are rare but occur at several stratigraphic levels (particularly at the base) and paleokarst-filling silt is more common than in the underlying lower map unit. Pisolitic beds are overall rare, but are common just above the basal contact and near to the Capitan Limestone. The top of the unit is not preserved on the quadrangle.
Patl	Lower map unit of the Tansill Formation	Guadalupian (Upper Permian)	White to light gray thinly bedded dolomite grainstones to packstones below a conspicuous and continuous ledge in the Ocotillo Silt Member. Principally consists of dolomites as described above; mudstones are a trace element of the map unit and silt as paleokarst fill is more rare than in the overlying upper map unit. Pisolites are generally only found near to the Capitan Limestone.
Pay	*Yates Formation*	Guadalupian (Upper Permian)	Interbedded white to light gray dolomite grainstones to packstones and lesser pale brown siltstones to very fine-grained sandstones. Dolomites are comparable to those described for the Tansill Formation. Clastic rocks are subordinate to dolomites, and occur in 0.3 to 2.5 m-thick intervals of thinly planar bedded, internally planar- or cross-laminated, very fine-grained sandstones and undulatory-laminated siltstones. Beds are moderately well-indurated by carbonate cements, but generally erode more readily than the interbedded carbonates and are often poorly exposed. Colors of 10YR 7/3-7/4 (sandstones) and 10YR 6/6-7/6 (siltstones) were measured for the clastic intervals. Unit thickness is about 80 to 90 m.

Pas	*Seven Rivers Formation*	Guadalupian (Upper Permian)	A distinctive interval of light gray to white micrites to packstones and oolites, tentatively assigned to the Seven Rivers Formation based on mapping by Motts (1962). Oolites are typically thinly lenticular-bedded, cross-laminated, poorly sorted, "clast-supported," and micritic mud-rich. Micrites, wackestones, and packstones are variously structured, including: massive, planar-laminated, or internally crenulated medium-thickness tabular bedding; planar-, cross-, or undulatory-laminated thin lenticular bedding; and crenulated thin lenticular bedding, all bearing absent to rare ooids, absent to rare detrital carbonate, and absent to trace clots of sparry carbonate that could be either filled vugs or replaced shells. The interval is thoroughly replaced by carbonate mud; ooids and sedimentary structures are only apparent on weathered faces, while fresh faces are uniformly light gray (circa 10YR 7/2, weathering to circa 7.5YR 7/2 or 10YR 8/1) carbonate mud in which structures and clasts are not apparent. The lower part of the exposed interval is variously brecciated and intraformationally faulted; faults do not extend upsection to the top of the unit. The base of the unit is unexposed; Motts (1962) reports thickness estimates of 80 to 140 m for the Seven Rivers Formation, while cross-section A-A' suggests an on-quadrangle preserved thickness of up to about 55 m.
	Delaware Mountain Group	Guadalupian (Upper Permian)	
Pd	Delaware Mountain Group, undivided	Guadalupian (Upper Permian)	Cross-section only. Dominantly arkosic to subarkosic very fine- to fine-grained sandstones and siltstones, with minor detrital carbonates (King, 1948). Cross-section interpretations, constrained by well logs, suggest a unit thickness of about 979 to 1,060 m thick along cross-section A-A'; well logs report thinner sections in the northwest corner of the quadrangle, where the thickness is about 670 to 727 m.
Pdl	Lamar Limestone Member of the Bell Canyon Formation of the Delaware Mountain Group	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 but thickening westward to as much as 46 m thick at the surface closer to the Guadalupe Mountains. Cross-section interpretations constrained by well logs suggest the unit may be thicker still in the subsurface here, with a maximum thickness of about 60 m, thinning eastward to about 36 m. This thickness may include beds of the Reef Trail Member overlying the Lamar Limestone.
	Leonardian and Wolfcampian series		
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. Well logs report a unit thickness of about 1,005 to 1,224 m here.

Pw	Wolfcampian Series	Wolfcampian (Lower Permian)	Cross-section only. Hayes (1964) suggests the unit consists of subequal amounts of gray, black, or brown shale and finely crystalline, rarely cherty, brownish limestone in wells drilled about 5 to 6.5 km south of this quadrangle (Union Crawford 1-26 and Gulf Estill 1-AD in Sections 26 and 29 of T24S, R26E), where the series is about 454 to 527 m thick. A striplog for the Western Oil McKittrick Federal 1 (Section 25 of T22S, R25E, in the northwestern corner of the quadrangle) suggests the series consists of interbedded gray to dark brown limestone and white to dark gray very fine-grained sandstone; here the unit is reported to be 454 m thick. Additional well logs in the quadrangle area report thicknesses from about 153 to 462 m, appearing to generally thin northward and westward.