Geologic Map of the
Lake McMillan North Quadrangle,
Eddy County, New Mexico.

By

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Open-file Digital Geologic Map OF-GM 167

Scale 1:24,000

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OVERVIEW

The Lake McMillan North 7.5-minute quadrangle lies in southeast New Mexico approximately half way between the cities of Artesia and Carlsbad. The area covered by the quadrangle, which extends from 32°37’30”N to 32°45’N and 104°15’W to 104° 22’ 30”W, is approximately 158 km^2 (61 mi^2). Elevations range from approximately 996 m (3,267 ft) where the Pecos River flows out of the quadrangle to the south across the former bed of Lake McMillan reservoir to the highest point on the eastern Permian uplands, 1,082 m (3,550 ft). Physiographically, the Pecos River alluvial valley runs north to south through the center of the quad, averaging 3.6 km in width and roughly 45 m in depth (calculated from data from Lyford, 1973), and is flanked by Neogene Pecos River alluvial terraces to the west and Permian Artesia Group (Guadalupian) uplands to the east. These uplands are primarily comprised of interbedded dolomites in extensive gypsum-dominated evaporites of the Seven Rivers formation (*Psg, Psda, Psd*), Yates formation (*Py*), Tansill formation (*Pt*), and the upper Permian (Ochoan/Lopingan) Salado formation (*Psl*), which all dip gently to the east. The maximum relief on the quad (225 m) occurs along the McMillan Escarpment, which rises from the floodplain in the southeast, exposing Seven Rivers formation gypsum (*Psg*), capped by the Azotea Tongue of the Seven Rivers formation dolomite (*Psda*).

Three major tributaries draining the eastern flank of the Sacramento Mountains, the Rio Peñasco, Fourmile Draw, and northernmost channels of Seven Rivers flow into the Pecos River from the west on the quadrangle. One major tributary, Chalk Bluff Draw, flows in from the east. The youngest of the Pecos River terraces grade up all of these rivers. During the Pleistocene, both Rio Peñasco and Seven Rivers built large fluviodeltaic fans at their confluences with the Pecos River, which was anastomosing on a braided plain (*Qabp*). Numerous Pleistocene fluviodeltaic channels of these tributaries are mapped on the quad (*Qapc* – Rio Peñasco; *Qasr* – Seven Rivers).

Given that the bedrock terrain either outcropping or underlying all surficial deposits on the quadrangle is predominantly evaporitic, unsurprisingly, karstic depressions and sinkholes riddle the surface on both sides of the alluvial valley. In the eastern Permian uplands several small cave openings (e.g., Turtle Cave) are found, as well as one major perennial spring (Chalk Bluff Spring) (see Figures 1 and 2). The majority of drainage on the quadrangle is subsurface. Depression patterns seen on color digital orthophotographs in the east-central portion of the quad reveal an intriguing glimpse of a subsurface dendritic drainage network some 65 km^2 in size.

The floodplain is dominated by anthropogenic modifications. The Pecos River is channelized within the Kaiser Channel, which up until 1991 flowed into the Lake McMillan Reservoir in the south-central part of the quad (see Figure 3). Finished in 1893, the reservoir extensively leaked into *Psg* deposits throughout its life. The dam was breached and Pecos River interstate stream compact water storage was moved into the newly-constructed Brantley Reservoir several kilometers downstream, which was constructed at a site where the majority of leaking Lake McMillan waters emerged through Major Johnson Springs. Nevertheless, the 98-year reservoir fundamentally altered floodplain geomorphology. A lacustrine plain (~1 m thick) as well as three distinct delta lobes comprised of deposits <1- 2.6 m thick built along the northern shores of the reservoir remain.

Figure 1. Small cave opening in the base of a sinkhole (left of person). Yates formation gypsum is seen at the surface.

Accessibility to and within the quadrangle is quite good. The western third of the quad and the majority of the floodplain are accessed from U.S. Highway 285, which runs north-south just west of the map. The majority of the western alluvial terraces are privately owned and agriculture dominates in the northern and southern sections (Rio Peñasco and Seven Rivers fluviodeltaic plains, respectively). The floodplain is comprised of either U.S. Bureau of Land Management (USBLM) or U.S. Bureau of Reclamation (USBOR) lands. The eastern Permian uplands is predominantly all USBLM land and the oil and gas industry has created an extensive, open road network here. Access is either

Figure 2. View of Chalk Bluff Spring, looking north. Yates formation gypsum is seen in the foreground, higher dolomite-capped Tansill formation hills seen in the distance.

from the north from Chalk Bluff Draw Road which heads south from U.S. Highway 82 at Riverside, or from the south from U.S. Highway 285 via Capitan Reef Road (the Brantley Reservoir exit) to Lake Road, north to Netherlin Road.

COMMENTS TO MAP USERS

This quadrangle map has been Open-filed in order to make it available to the public. The map has not been reviewed according to New Mexico Bureau of Geology and Mineral Resources standards, and due to the ongoing nature of work in the area,

Figure 3. View of the eastern side of former Lake McMillan reservoir, looking south from the McMillan Escarpment (also upper left). Dolomite of the Azotea Tongue of the Seven Rivers formation is seen in the foreground. The levee in the middle distance was constructed in 1908-09, and extended in 1953-54 to prevent the water from reaching the gypsum underlying the dolomite, but during high water levels and occasional breaks in the levee, whirlpools would result in the lake and high rates of leakage occurred.

revision of this map is likely. As such, dates of revision are listed in the upper right corner of the map and on the accompanying report. ***The contents of the report and map should not be considered final and complete until published by the New Mexico Bureau of Geology and Mineral Resources.***

A geologic map graphically displays information on the distribution, nature, orientation, and age relationships of rock and surficial units and the occurrence of structural features such as faults and folds. Geologic contacts are irregular surfaces that form boundaries between different types or ages of units. Data depicted on this geologic map are based on field geologic mapping, compilation of published and unpublished work, and photogeologic interpretation. Locations of contacts are not surveyed, but are plotted by interpretation of the position of a given contact onto a topographic base map; therefore, the accuracy of contact locations depends on the scale of mapping and the interpretation of the geologist. Significant portions of the study area may have been mapped at scales smaller than the final map; therefore, the user should be aware of potentially significant variations in map detail. Site-specific conditions should be verified by detailed surface mapping or subsurface exploration. Topographic and cultural changes associated with recent development may not be shown everywhere.

The cross section is constructed based on exposed geology, and where available, subsurface and geophysical data. Cross sections are interpretive and should be used as an aid to understand the geologic framework and not used as the sole source of data in locating or designing wells, buildings, roads, or other structures. Finally, the views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of either the State of New Mexico or the U.S. Government.

STRATIGRAPHY

As alluded to above, surficial depositional units of the western two-thirds of the Lake McMillan North Quadrangle are late Neogene (the oldest of which, *QTbt*, probably Pliocene) in age. These deposits are underlain by middle Permian Artesia Group (Guadalupian) evaporites and interbedded dolomites, which outcrop in the eastern

Permian uplands. They are inturn overlain by the evaporites of the upper Permian (Ochoan/Lopingan) Salado formation, along the eastern margin of the quad. The Artesia Group consists of series of gypsum beds interfingered with dolomites, and are differentiated into the Tansill (*Pt*), Yates (*Py*), Seven Rivers, and the Queen and Grayburg formations (*Pgq*). The latter two are found only in the subsurface and are undifferentiated here. Beneath these units, wells drill into the San Andres formation (*Psa*) and the Leonardian Yeso formation (*Py*).

Pecos River alluvial valley floor

The majority of the alluvium filling the valley floor was deposited by numerous braided channels of the Pecos River during the upper Pleistocene. These *Qabp* deposits form the basal unit of the valley, upon which Holocene Pecos River meanderbelts would be built. McCraw, *et al*. (2007) mapped 4 Pecos River meanderbelts on the Bitter Lake quadrangle near Roswell, two historic and 2 Holocene in age. In the Lake McMillan North quad, only the most recent meanderbelt, (hmp_4), is thought to be historic.

At the onset of the Holocene, the Pecos River switched from a braided to meandering regime, abandoning its braided surface (*Qabp*) to ultimately build 4 meanderbelts on top of it. Throughout the Holocene north of Fourmile Draw, the river progressed from west to east in its construction of these meanderbelts. Below Fourmile Draw, water continued to flow in old braided channels. Even the most recent meanderbelt (hmp_4) flowed first in old western braided channels before switching to the east.

In the southernmost part of the floodplain lies the former lakebed of Lake McMillan reservoir. As alluded to above, the reservoir, constructed in 1893, constantly leaked into the Seven Rivers formation gypsum. Water flowed through karstic conduits and discharged ~5.6 km downstream into the Pecos River at Major Johnson Springs, the present site of the Brantley Reservoir and the location of a facies change in the Seven Rivers formation to dolomite (*Psd*) (Cox, 1967). By the early 1940s, less than half of the storage capacity of the reservoir remained. According to Cox (1967), consideration of a new dam began as early as 1905. The U.S. Bureau of Reclamation finally began construction of Brantley Reservoir in 1984, and Lake McMillan's dam was breached in 1991.

During the 98-year history of the reservoir, several deltaic systems were created along the northern shore. These systems are subdivided into distributary deposits undifferentiated, distributary channels, and individual delta lobes built by distinct distributary channels. Typical of deltaic deposits, they exhibit a graded sorting ranging from minor pebbles to coarse-grained sand within the distributary channels to fines (silts and clay) at the distal margins of the delta lobes. These deltas were created from four primary sources: (from east to west) eastern tributary unnamed streams debouching from the eastern uplands ($hedl_3$); the main Pecos River channel (both pre- and post-channelization – $hed_{1\text{-}2}$, $hedc_{1\text{-}2}$, $hedl_{1\text{-}2}$), the "West Channel" of the Pecos River (*hwd*, *hwdc*, $hwdl_{1\text{-}3}$), which is predominantly fed by the two main western tributaries of the Pecos River within the Lake McMillan North quadrangle, the Rio Peñasco and Fourmile Draw; and from a cluster of unnamed springs discharging from a former channel of Seven Rivers at the base of the upper Pleistocene Lakewood Terrace (*hsc*, *hsdl*), which carried sufficient flow to actually build a small delta lobe (see Figures 4 -6).

Figure 4. View of a distributary channel (*hwdc*) and distributary delta lobe (*$hwdl_3$*) created by the "western channel" of the Pecos River, looking east. The row of trees seen in the distance line the Kaiser Channel, where the current river flows across the delta plain.

Pecos Valley alluvial terrace complexes

Alluvial terraces of the Pecos River and its tributaries were first described in the classic study of Fiedler and Nye (1933). They recognized 3 terraces: (from lowest to highest) the Lakewood, the Orchard Park, and the Blackdom. The Lakewood terrace, with an elevation of 6 to 9 m above the floodplain, flanked the inset Pecos floodplain and extended up many of its western tributaries. McCraw, *et al.* (2007) further differentiated three distinct, low-lying (upper to middle(?) Pleistocene) "Lakewood terraces." The highest and oldest of which (Qlt_1) would be Fiedler and Nye's original. Surface tread

Figure 5. View of the southern end of delta lobe *hwdl*$_3$. A sense of the relief of the 1.6 m deposit is provided by the pick-axe atop the lobe.

elevations above the floodplain for these three are: <1 - 1.2 m, 1.2 - 6 m, and 6 - 9 m, respectively.

According to Fiedler and Nye (1933), the Orchard Park terrace rises 1.5 - 3 m above the Lakewood terrace and 6 - 10.5 m above the Pecos floodplain. Two levels of this alluvial-eolian complex are recognized here, although not further north in the Roswell area (McCraw, 2008; *McCraw, et al.*, 2007): $QTot_1$ and Qot_2. Consistent with the Orchard Park terrace to the north, many subsidence-related depressions (*Qd*) and

Figure 6. Lush, green vegetation thriving at a former springhead, which had sufficient discharge to build a small delta lobe (*hsdl*). These springs are located at the eastern terminus of one of the Pleistocene channels of Seven Rivers.

collapse-related sinkholes (*Qds*) pit its surface. Pedogenic carbonate increases from stage III in Qot_2 to stage III+ - IV in $QTot_1$.

Kelley (1971) mapped the entire western alluvial terrace complex in the Lake McMillan North quadrangle area as “Quaternary tributary alluvium.” He apparently ignored the high, upland remnants that are found here. These old, Plio- (Mio-?) Pleistocene deposits have troubled geologists, including us, up to this day! As summarized in Hawley (1993), these old, often high (but not always!) alluvial deposits have been mapped as “quartzose conglomerate” (Meinzer, *et al.*, 1923), as well as Ogallala and Gatuña by other workers (see Figure 7). Pedogenic carbonate varies within these deposits from stage IV to VI, indicating antiquity, a ground-water system supersaturated with respect to $CaCO_3$, or both.

Figure 7. Old “quartzose conglomerate,” outcropping on a *QTbt* remnant, approximately 200 m west of the Pecos River floodplain. Clasts of limestone, dolomite, chert, and quartzite are clearly seen. The matrix is primarily micritic.

Since they are comprised of Pecos floodplain alluvial valley-fill, at this time we map these as Blackdom terrace, pushing back the onset of deposition of this unit into the Pliocene (perhaps Miocene?). This obviously needs further work.

Permian bedrock

Artesia Group rocks are backreef equivalents of the Capitan Reef formation, which is exposed along the southeast escarpment of the Guadalupe Mountains southwest of both Carlsbad and the Lake McMillan North quadrangle. The Artesia Group strata are most notable for their dramatic and sometimes abrupt variations in lithofacies north of the Capitan Reef complex (Kelley, 1971). The Group consists primarily of well-bedded dolomite in the near-backreef area of the Guadalupe Mountains. Farther to the north, lithology of the Artesia Group becomes increasingly evaporitic, consisting of interbedded gypsum, reddish-brown mudstone and siltstone, and thin interbeds of dolomite, typical of deposition in a far-backreef intertidal-supratidal-sabkha environment.

Defining formation contacts within evaporitic facies of the Artesia Group is often challenging. Some previous workers (e.g., Motts and Cushman, 1964) have chosen to designate these predominantly gypsum strata as the Artesia *Formation* where the individual units of the Artesia Group are not distinguishable. For consistency with previous geologic mapping in this area (Kelley, 1971; Delher, *et al.*, 2005), we have chosen to break out individual formations in the Lake McMillan North quad, with formation contacts dashed where the precise location of the contact is ambiguous.

Seven Rivers formation

The transition to evaporitic facies within the Seven Rivers formation is almost complete in the vicinity of Lake McMillan North. The unit consists of white to brick-red gypsum, reddish-brown mudstone and siltstone, and thin interbeds of gray lithographic dolomite (*Psg*). The formation is capped by dolomites of the Azotea Tongue (*Psda*), which form a prominent east-dipping cuesta expressed by the McMillan Escarpment along the eastern margin of the old lakebed. Along this cuesta, landslides or slumps are common, where gypsum beds spall or rollover the bluffline (see Figure 8).

Figure 8. Panoramic view of Seven Rivers formation gypsum (*Psg*) “rolling over” the edge of the bluff. Landslides are common along the McMillan Escarpment.

Described by Kelley (1971), the Azotea dolomite serves as a useful marker bed for locating the contact between the Seven Rivers formation and gypsum of the overlying Yates formation (see Figure 9). In this capacity, the Azotea Tongue can be traced along or near the crest of the escarpment as far north as a broad arroyo at approximately 32°40’N, in the northeast quarter of sec. 8, 19S, 27E. At this point the Azotea Tongue dips into the shallow subsurface and is covered by Quaternary fluvial sediments in the arroyo. Farther to the north, the top of the Seven Rivers formation is defined as the top of the uppermost persistent dolomite unit at or near the crest of the McMillan Escarpment (*Psd*).

Figure 9. Outcrop of Azotea Tongue dolomite (*Psda*) at the top of the Seven Rivers formation. This dolomite is a useful marker bed, differentiating the Yates formation (foreground, upper bluff in the distance on the right) from the underlying Seven Rivers formation.

Yates formation

In the Lake McMillan North area the Yates formation is composed of white to occassionally reddish-brown gypsum with interbeds of reddish-brown mudstone and siltstone and thin, lithographic dolomite. As described above, the contact with the underlying Seven Rivers Formation is not always well-defined and is probably transitional in the northern part of the mapped area. Yates strata are exposed in a subdued outcrop belt trending approximately south-to-north east of the Seven Rivers bluffs along the eastern margin of old Lake McMillan and the Pecos River. Lithologies of the Yates and Seven Rivers Formations are nearly identical and are very difficult to distinguish on the ground. However, Yates strata appear to contain fewer mudstone-siltstone interbeds, imparting a higher reflectivity to the unit expressed as lighter tones on black and white air photos, in contrast with the slightly darker outcrop of the Seven Rivers Formation. Thick dolomite units such as the Azotea Tongue are not present in the Yates, thus the Yates outcrop is more subdued and rarely forms prominent escarpments.

Tansill formation

The Tansill formation in the mapped area consists of interbedded gypsum and dolomite. The unit is capped by a thick, persistent dolomite bed with a tan-to-brown, hackley appearance in outcrop that forms prominent buttes and cuestas east of the McMillan Escarpment. Gypsum units are poorly exposed, and thin dolomite beds within the Tansill cap isolated buttes west of the main outcrop belt.

Salado formation

The Salado outcrop belt occurs along the eastern edge of the Lake McMillan North quad. In the subsurface of the Delaware Basin, the Salado Formation consists of almost 2,000 ft of massive halite and argillaceous halite, with lesser amounts of anhydrite and polyhalite. Rare amounts of potassium salts (sylvite and langbeinite) occur in the McNutt potash zone in the central part of the formation (Cheeseman, 1978). Clastic material makes up less than 4% of the Salado. Because of the soluble nature of Salado rocks, the unit is very poorly exposed in outcrop, consisting of an insoluble residue of reddish-brown siltstone, occassional orange-red gypsum, and greenish and reddish clay in chaotic outcrops (Kelley, 1971). In most areas the Salado outcrop is covered by a thin veneer of pediment gravels and windblown sand. Contact with the underlying Tansill Formation is obscure and very rarely exposed.

STRUCTURE

Structural geology of the Lake McMillan North quad is not complex. Regionally, Artesia Group strata dip gently to the east at approximately 1° (~100 ft/mile). However, the dip of these strata is enhanced on Lake McMillan North to approximately 12° east, due to the proximity of the Artesia-Vacuum Arch, discussed below. Localized folding occurs in many areas, often as very small-scale folds and undulations in dolomite beds of the Yates and Seven Rivers Formations. These features are almost certainly non-tectonic folds, the result of localized subsidence associated with subsurface dissolution of gypsum.

In the subsurface, the Artesia-Vacuum Arch extends east-northeast beneath the Pecos Valley. The arch is almost completely covered by post-Permian beds, although Kelley (1971) reports that the plunging south limb is expressed by Yates and Tansill strata near Chalk Bluff Draw. The effects of the arch are clearly seen in the cross section accompanying this map. The Artesia-Vacuum Arch controls production from Permian and Pennsylvanian reservoirs in the Empire Abo field and other oil and gas reservoirs over a distance of almost 75 miles into Lea County. Measureable surface manifestations of the arch are practically non-existent, apart from Kelley's (1971) observations of dipping strata in Chalk Bluff Draw.

HYDROLOGY

Lake McMillan North is located near the southern end of the Roswell Artesian Basin, where gypsum beds of the Artesia Group serve as a leaky confining unit for groundwater stored in vuggy to cavernous carbonates of the underlying Grayburg and San Andres Formations. In the early history of development of the artesian aquifer, many wells flowed to the surface, with yields as high as 5,700 gpm (Welder, 1983). Although decades of intensive pumping have caused substantial declines in hydraulic head, some wells still display strong artesian flow (Land and Newton, 2008). As recently as the 1940s, wells in the vicinity of Lake McMillan flowed to the surface, with water levels reported up to 40 feet above ground level (U.S. Geological Survey, 2007). In part because of upward artesian flow from the underlying aquifer, caves, sinkholes and solution-enlarged fissures are very common in gypsum outcrops along the eastern margin of the Pecos River (Stafford, *et al*., 2008). Large slump blocks are present along the McMillan Escarpment due to dissolution and sapping processes in Seven Rivers gypsum strata at the base of the escarpment.

DESCRIPTION OF MAP UNITS

NEOGENE

Alluvium, eolian, and anthropogenic deposits

daf — **Disturbed land and/or artificial fill —** Dumped fill and areas affected by human disturbances, mapped where deposits or extractions are areally extensive. Especially notable are the numerous constructed oil and gas well pads. Also includes the U.S. Bureau of Reclamation's Kaiser Channel of the Pecos River, the Lake McMillan containment levee, and levees adjacent to the Rio Peñasco.

Qa — **Quaternary tributary alluvium and valley-fill alluvium, undifferentiated (Historic to uppermost Pleistocene) —** Brown (7.5YR4/2) to pinkish gray (7.5YR6/2) (*tributaries*) to light reddish-brown (5YR 6/4) to reddish brown (2.5YR4/6) (*Pecos floodplain valley-fill*), unconsolidated, moderately sorted, pebbly sand, silt, and clay. Varies considerably in thickness from <1 to 3 m in tributaries and up to 10-12 m in the floodplain.

Qaf — **Alluvial-fan deposits, undivided (Historic to uppermost Pleistocene) —** Predominantly carbonate gravels to pebbles, often in stringers, in a brown (7.5YR4/2) to pinkish gray (7.5YR6/2), unconsolidated, poorly sorted, and coarse- to fine-grained sand to silty sand. These fans are built by tributaries along the base of both the eastern bluffs and the western floodplain margin, and interfinger with and/or spread out onto Pecos floodplain deposits. Thicknesses vary considerably from <1 m for small fans (as well as larger fans at their distal margins) up to ~8 m at the apices of fans built by large tributaries (e.g., Chalk Bluff Draw).

Qae/ Py, Pt, or Psl — **Quaternary alluvial and eolian deposits, undifferentiated (upper Pleistocene to Holocene) —** Pinkish gray (7.5YR6/2) to light reddish-brown (5YR 6/4), unconsolidated, well-sorted, fine-grained sand, silt, and clay in a thin (<1-1.5 m, usually <60 cm) mantle draped over either the Yates formation (*Py*), the Tansill Formation (*Pt*), or the Salado formation (*Psl*).

Pecos River alluvial valley floor

(Historic map unit labels are given a lower case "h" *to differentiate them from Holocene map units.)*

Pecos River meanderbelt alluvial deposits (Historic to lower Holocene) **—** At the onset of the Holocene, the Pecos River switched from a braided regime to a meandering one, and proceeded to build four distinguishable meanderbelts on top of the basal, upper Pleistocene Pecos River braided alluvial valley-fill (*Qabp*). Consisting of channel, channel bar, point bar, and natural levee deposits, undivided, these meanderbelts are differentiated based upon cross-cutting relationships observed in the field, as well as aerial photographic work into an historic unit (hmp_4) and three older Holocene units ($Hmp_{1\text{-}3}$). These older Holocene units are only found north of Fourmile Draw, and reveal a pattern of progressive meanderbelt shifting from west to east across the floodplain.

hmp_4 **Historic meanderbelt deposits (Historic to upper Holocene) —** Occasional pebbles of dolomite, limestone, sandstone, chert, and quartzite in a very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately to well-sorted, coarse- to fine-grained sand in the former modern channel and adjacent bar crests, grading to silty sand and sandy clay with distance from this channel. The meanderbelt was abandoned following the channelization of the Pecos River into the Kaiser Channel during the mid 20th Century. In the south half of the quad, hmp_4 is divided. Probably in the 1800s, the river shifted across valley to the west and built a small meanderbelt atop of braided stream *Qabp* deposits, prior to shifting back to the eastern valley margin. Meanderbelt thicknesses commonly range from 1 to 5 m.

Hmp_3 **Young meanderbelt deposits (upper Holocene) —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, occasionally pebbly (dolomite, limestone, sandstone, chert, and quartzite), coarse- to fine-grained sand, silty sand, and sandy clay. Unit lies immediately west of hmp_4 in the center of the floodplain. Thickness 2-5 m.

Hmp_2 **Older Holocene meander belt deposits (upper to middle Holocene) —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, occasionally pebbly (dolomite, limestone, sandstone, chert, and quartzite), coarse- to fine-grained sand, silty sand, and sandy clay. Unit lies immediately west of Hmp_3. Thickness 3-5 m.

Hmp_1 **Old Holocene meander belt deposits (lower to middle Holocene) —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, occasionally pebbly (dolomite, limestone, sandstone, chert, and quartzite), coarse- to fine-grained sand, silty sand, and sandy clay. Unit lies immediately west of Hmp_2. Thickness 3-5 m.

Hafp **Holocene Rio Peñasco fan and backswamp deposits (middle to upper Holocene) —** Occasional carbonate, chert, and quartzite pebble stringers in brown (7.5YR4/2) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted sand, silty sand, and sandy clay nearest to the mouth of the Rio Peñasco, grading downvalley to sheetflood and overbank silt and clay with distance from the mouth. Thickness <1 to 3 m.

Hcr **Holocene crevasse splay deposits (middle to upper Holocene) —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, graded sand and silty sand closest to the channel bank breached by the crevasse to sandy clay at the distal margins. Thickness <1 to 2 m.

Qbs **Floodplain alluvial backswamp deposits (upper Pleistocene to Historic) —** Light reddish-brown (5YR6/4) to very dark gray (7.5YR3/1), unconsolidated, well-sorted, silty sand, sandy clay, and clay in low-lying, poorly drained areas along the eastern margin of the floodplain. These areas commonly received only fine-grained, slack-water flood deposition, prior to channelization. Thicknesses range from 3-15 (?) m.

Qabp **Pecos River braided alluvial deposits (upper Pleistocene to lower Holocene) —** Gravels and pebbles of dolomite, limestone, sandstone, chert, and quartzite in a reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), unconsolidated, poorly to moderately sorted, coarse- to fine-grained sand, silty sand, sandy clay, and clay. Braided channels and bars typify the surface of *Qabp*. While mostly buried by Holocene meanderbelt deposition in the northern part of the quad, large areas of *Qabp* are still exposed in the western and south-central areas of the floodplain surface. Thicknesses vary (based upon Lyford, 1973) from about 5 to 30 m.

Historic Lake McMillan

Lake McMillan was impounded in 1893 and due to its location up against the eastern bluffs, comprised of highly fractured Seven Rivers formation gypsum (*Psg*), significantly leaked from the onset. Water flowed through karstic conduits and discharged ~5.6 km downstream into the Pecos River at Major Johnson Springs, the present site of the Brantley Reservoir and the location of a facies change in the Seven Rivers formation to dolomite (*Psd*) (Cox, 1967). A levee was constructed in 1908-09, and extended in 1953-54 to prevent the water from reaching the gypsum, but during high water levels and occasional breaks in the levee, whirlpools would result in the lake and high rates of leakage occurred. By the early 1940s, less than half of the storage capacity of the reservoir remained. According to Cox (1967), consideration of a new dam began as early as 1905. The U.S. Bureau of Reclamation finally began construction of Brantley Reservoir in 1984, and Lake McMillan's dam was breached in 1991. Nevertheless, its existence fundamentally changed the surficial geology of this part of the Pecos Valley.

hl **Lake McMillan lacustrine deposits —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. Thickness <1-1.5 m.

hl/hmp$_4$ **Lake McMillan lacustrine deposits over Pecos River channel deposits —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay, thinly *hmp$_4$* deposits. Thickness <1 m.

Historic Lake McMillan deltaic deposits

During the 98-year history of the reservoir, several deltaic systems were created along the northern shore. These systems are subdivided into distributary deposits undifferentiated, distributary channels, and individual delta lobes built by distinct distributary channels. Typical of deltaic deposits, they exhibit a graded sorting ranging from minor pebbles to coarse-grained sand within the distributary channels to fines (silts and clay) at the distal margins of the delta lobes. These deltas were created from four primary sources: (from east to west) eastern tributary unnamed streams debouching from the eastern uplands (*hedl*$_3$); the main Pecos River channel (both pre- and post-channelization – *hed*$_{1-2}$, *hedc*$_{1-2}$, *hedl*$_{1-2}$), the "West Channel" of the Pecos River (*hwd*, *hwdc*, *hwdl*$_{1-3}$), which is predominantly fed by the two main western tributaries of the Pecos River within the Lake McMillan North quadrangle, the Rio Peñasco and Fourmile Draw; and from a cluster of unnamed springs discharging from a former channel of Seven Rivers at the base of the upper Pleistocene Lakewood Terrace (*hsc*, *hsdl*), which carried sufficient flow to actually build a small delta lobe.

East channel (main Pecos River) delta system

hed$_1$ **Early phase east channel distributary deposits, undifferentiated —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. Thickness <1-1.5 m.

hedc$_1$ **Early phase east channel distributary channel deposits —** Minor carbonate pebbles in a reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), coarse- to fine-grained sand and silt overlying Holocene valley fill deposits. Channel bifurcated into a minor northeastern distributary and a main south-flowing distributary. Thickness 1-2 m.

hedl$_1$ **Early phase east channel delta lobe deposits —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. Northeastern delta lobe continued to be active during late phase east channel delta building while the main southern delta lobe was abandoned. Thickness <1-1.5 m.

hed$_2$ **Late phase east channel distributary deposits, undifferentiated —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. Thickness <1-1.5 m.

hedc$_2$ **Late phase east channel distributary channel deposits —** Minor pebbles in a reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), coarse- to fine-grained sand and silt overlying Holocene valley fill deposits. Channel bifurcated into an eastern distributary (which overrode and buried parts of *hed*$_1$ and *hedc*$_1$) and a southern distributary. The eastern distributary likely built first and was probably active concurrently during construction of the southern delta, but was abandoned following the creation of the Kaiser Channel. Thickness 1-2 m.

hedl$_2$ **Late phase east channel delta lobe deposits —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. The eastern margin of the southern delta lobe cut into and eroded the distal part of *hedl*$_1$. Thickness <1-1.5 m.

hedl$_3$ **Late phase east channel delta lobe deposits —** Reddish brown (2.5YR4/6) to light reddish-brown (5YR6/4), well sorted, minor pebbles and fine-grained sand, silt, and clay overlying Holocene valley fill deposits, built along the eastern margin of the Pecos floodplain, primarily fed by unnamed tributaries flowing off of the eastern Permian uplands and down along the eastern levee. Thickness <1-1 m.

West channel delta system

hwd **West channel distributary deposits, undifferentiated — —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), well sorted, fine grained sand, silt, and clay overlying uppermost Pleistocene - Holocene valley fill deposits. Thickness <1-1 m.

hwdc **West channel distributary channel deposits —** Minor pebbles in a very pale brown (10YR7/4) to reddish brown (2.5YR4/6), coarse- to fine-grained sand and silt overlying uppermost Pleistocene - Holocene valley fill deposits. These channels occupied older braided channels (*Qabp* channels) and distributary channel bifurcation rarely occurred until reaching active delta lobes. Thickness 1-1.5 m.

hwdl$_{1\text{-}3}$ **West channel delta lobe deposits —** Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), well sorted, fine grained sand, silt, and clay overlying Holocene valley fill deposits. Three distinct delta lobes were built concurrently from different distributaries. Delta lobe *hwdl$_2$* is the largest and was built by the majority of the West Channel(s) discharge. Thickness <1-1.5 m.

Lakewood Terrace spring delta system

hsc **Lakewood Terrace spring conduit channels —** Very pale brown (10YR7/4), well sorted, fine grained sand, silt, and clay deposited from discharge from at least 5 unnamed springs debouching from the base(?) of the Lakewood Terrace. Overlies Holocene valley margin deposits. Thickness <1-3 m.

hsdl **Lakewood Terrace spring delta lobe —** Very pale brown (10YR7/4), well sorted, fine grained sand, silt, and clay. Thickness <1-2.5 m.

Pecos Valley western tributaries and terrace complexes

Qapc **Quaternary channel alluvium of the Rio Peñasco (upper Pleistocene to middle Holocene) —** Gravels and pebbles of dolomite, limestone, sandstone, chert, and quartzite in dark yellowish brown (10YR3/4) to very pale brown (10YR7/4), unconsolidated, moderately to well-sorted, sand, silty sand, and sandy clay. During the uppermost Pleistocene, the Rio Peñasco built a braided fluviodeltaic fan at its Pecos River floodplain mouth, not unlike other major western tributaries. While fan surface thicknesses remained low, insufficient to become mappable units (and are thus here mapped as Lakewood terraces), the fan channels do form distinct deposits. Thickness 1 to 3 m.

Qasr **Quaternary channel alluvium of Seven Rivers (upper Pleistocene to middle Holocene) —** Gravels and pebbles of dolomite, limestone, sandstone, chert, and quartzite in dark yellowish brown (10YR3/4) to very pale brown (10YR7/4), unconsolidated, moderately to well-sorted, sand, silty sand, and sandy clay. Seven Rivers, a western tributary of the Pecos River, has occupied numerous fan channels in proximity to its mouth (hence, the name). Currently, the main channels turn south, west of Lake McMillan North, and flow into Brantley Reservoir on the Lake McMillan South quad. However, from the upper Pleistocene to the late Holocene, several channels flowed across Lakewood terraces, east of Lakewood on the Lake McMillan North quad, and flowed into the "Western Channel" of the Pecos River. One such channel provided sufficient ground-water flow to build a small delta into Lake McMillan (*hsc, hsdl*). Thickness 1 to 3 m.

Lakewood terrace alluvial deposits (upper to middle Pleistocene) — Alluvial terraces of the Pecos River and its tributaries were first described in the classic study of Fiedler and Nye (1933). They recognized 3 terraces: (from lowest to highest) the Lakewood, the Orchard Park, and the Blackdom. The Lakewood terrace, with an elevation of 6 to 9 m above the floodplain, flanked the inset Pecos floodplain and extended up many of its tributaries. Following McCraw, *et al.* (2007), three distinct, low-lying (upper to uppermost middle(?) Pleistocene) "Lakewood terraces" are recognized. The highest and oldest of which (Qlt_1) would be Fiedler and Nye's original. Surface tread elevations above the floodplain for these three are: <1-1.2 m, 1.2-6 m, and 6-9 m, respectively. They are comprised of occasional gravels and pebbles, brown (10YR5/3) to dark yellowish brown (10YR3/4), unconsolidated, moderately sorted, coarse- to fine- grained sand, silty sand, silt and sandy clay. Pedogenic carbonate increases from stage I to stage II+ (occasionally III) from Qlt_3 to Qlt_1. Mostly non-gypsiferous.

Qlt$_3$ **Youngest Lakewood terrace alluvial deposits (upper Pleistocene) —** Thickness <1 to 1 m.

Qlt$_2$ **Young Lakewood terrace alluvial deposits (upper Pleistocene) —**Thickness 1.5 to 5 m.

Qlt$_1$ **Older Lakewood terrace alluvial deposits (upper to middle Pleistocene) —** Thickness ~2 to 9 m.

Orchard Park terrace alluvial deposits (upper Pliocene (?) to upper Pleistocene) **—** According to Fiedler and Nye (1933), the Orchard Park terrace rises 1.5-3 m above the Lakewood terrace and 6-10.5 m above the Pecos floodplain. Two levels of this alluvial-eolian complex are recognized here, although not further north in the Roswell area (McCraw, 2008; *McCraw, et al.*, 2007): *$QTot_1$* and *Qot_2*. Consistent with the Orchard Park terrace to the north, many subsidence-related depressions (*Qd*) and collapse-related sinkholes (*Qds*) pit its surface.

It is comprised of gravels and pebbles of dolomite, limestone, sandstone, chert, and quartzite in a very pale brown (10YR7/4) to reddish brown (5YR4/4), unconsolidated, moderately sorted, coarse- to fine- grained sand, silty sand, silt, and sandy clay. Pedogenic carbonate increases from stage III in *Qot_2* to stage III+ - IV in *$QTot_1$*.

Qot_2 **Younger Orchard Park terrace alluvial-eolian complex (middle to upper Pleistocene)** — Thickness 5 to 45 m.

$QTot_1$ **Older Orchard Park Terrace alluvial deposits (upper Pliocene (?) to lower Pleistocene)** — Thickness 5 to 45 m.

Blackdom terrace alluvial deposits (Pliocene to lower Pleistocene) — Kelley (1971) mapped the entire western terrace complex as Quaternary tributary alluvium. Fiedler and Nye (1933) describe the Blackdom terrace as isolated erosional terrace remnants 9-15.5 m above the Orchard Park terrace, and early Pleistocene in age. In many places these high, upland remnants have been mapped as "quartzose conglomerate" (Meinzer, *et al.*, 1923), as well as Ogallala and Gatuña by other workers, as summarized in Hawley (1993). Since they are comprised of Pecos floodplain alluvial valley-fill, at this time we map these Blackdom terrace, pushing back the onset of deposition of this unit into the Pliocene (perhaps Miocene?). This obviously needs further work.

These depostis are comprised predominantly of dolomite, limestone, chert, and quartzite gravels and pebbles in a yellowish brown (10YR5/4) to reddish brown (5YR5/4), unconsolidated, moderately sorted, coarse- to fine-grained, sand and silty sand. Occasionally the matrix has lithified and the deposits resemble "quartzose conglomerate." Pedogenic carbonate varies from stage IV to VI.

QTbt **Blackdom Terrace alluvial deposits (Pliocene to early Pleistocene)** — Thickness 15 to 30 (?) m.

Quaternary depression fill and sinkhole deposits

Qd **Quaternary depression fill, undifferentiated (middle Pleistocene to Holocene)** — Unconsolidated, well-sorted, fine-grained (fine sands to clay) complexes of alluvial, colluvial, eolian, and occasional lacustrine deposits within closed depressions. Colors variable. Depressions are created by either gradual subsidence or sudden collapse followed by gradual subsidence of underlying gypsiferous carbonate terrane. These complexes, often significantly modified by stream erosion and deposition, playa deposition, deflation, and mass wasting, commonly "mimic" on the surface, subterranean drainage through karstic conduits. A striking example of this can be seen in the dendritic pattern of depressions in the northeast to east-central part of the quad in the eastern Permian uplands. Depression fills have been active since the middle Pleistocene and are usually 1-3 m thick but can reach thicknesses in excess of 30 m.

Qds **Quaternary sinkhole deposits, primarily caused by collapse (Historic to middle Pleistocene) —** Complexes of unconsolidated, well- to poorly-sorted, coarse- to fine-grained sands to clay, alluvial, colluvial, eolian, and occasional lacustrine deposits within closed depressions. Colors variable. Thickness <1 to 3 m.

PALEOZOIC

Psl **Salado formation, mixed silty gypsiferous facies (Ochoan / Lopingan) —** Basal light gray dolomite grading upward into interbedded mixed gray silty dolomite, siltstone and gypsum, and yellowish sandstone with sublitharenite and orange-red chert grains. Thickness ~ 30 m.

Permian Artesia Group

Pt **Tansill formation, mixed silty gypsiferous facies (Guadelupian) —** Basal light gray dolomite grading upward into interbedded mixed gray silty dolomite, siltstone and gypsum, and yellowish sandstone with sublitharenite and orange-red chert grains. Thickness 2 to 50 m.

Py **Yates formation, mixed gypsiferous facies (Guadelupian) —** Very light gray, massive to vesicular gypsum interbedded with pink dolomite, green to white and orange to red siltstone and minor sandstone. Folded into domes and basins on a meter to several decimeter scale. Forms caverns, like Turtle Cave. Outcrop exposures poor. Forms low relief strike valley east of the Seven Rivers Formation bluffs. Thickness increases westward from 2 to 50 m.

Psda **Seven Rivers formation, dolomitic facies (Azotea Tongue of Kelley, 1971) (Guadelupian) —** Light gray to yellowish to pink, thinly to thickly bedded, vesicular to massive dolomite interbedded with pink dolomitic siltstone, yellowish sandstone and thin beds of milky gypsum. Thickness 2 to 20 m.

Psd **Seven Rivers formation, dolomitic facies (Guadelupian) —** Light gray to yellowish to pink, thinly to thickly bedded, vesicular to massive dolomite interbedded with pink dolomitic siltstone, yellowish sandstone and thin beds of milky gypsum. Thickness 1 to 3 m.

Psg **Seven Rivers formation, gypsiferous facies (Guadelupian) —** White to gray, occasionally yellow to red massive gypsum interbedded with thin- to medium-bedded, light gray dolomite and red gypsiferous siltstone, often containing gypsum nodules, and yellowish sandstone, which often exhibit soft sediment deformation.

Commonly fractured, occasionally forming caverns, with many low amplitude folds varying in scale from meters to kilometers. Thickness unknown.

Pgq **Queen and Grayburg formations (Guadelupian) —** Cross section only.

Lower Permian Formations

Psa **San Andres formation —** Cross section only.

Pay **Yeso and Abo formations, undifferentiated —** Cross section only.

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