Geologic Map of the Bitter Lake Quadrangle, Chaves County, New Mexico

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May 2007

New Mexico Bureau of Geology and Mineral Resources
Open-file Digital Geologic Map OF-GM 151

Scale 1:24,000

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ABSTRACT

The Bitter Lake Quadrangle contains the confluence of the Pecos River and the Rio Hondo. The majority of the quadrangle is comprised of Pecos River terraces (the Lakewood terraces, the Orchard Park, and the few, isolated remnants of the Blackdom terrace). The easternmost part of the quadrangle is comprised of bluffs and uplands comprised of Permian gypsum and siliciclastic redbeds immediately east of the Pecos valley, which also underlie the Neogene alluvial deposits covering the remainder of the quad.

Both alluvial valleys consist of multiple Holocene meander belts built atop upper to middle Pleistocene braided alluvial valley fill. The uplands, especially the eastern Permian uplands east of the Pecos and the Orchard Park terrace to the west, are riddled with sinkholes, depressions, and shallow lacustrine deposits, typical of a karstic landscape largely underlain by evaporites. The movement of two Pennsylvanian-Permian regional strike-slip structures, the Y-O Buckle which runs through the eastern part of the quad, and the Six-Mile Buckle, approximately 7.5 km west of the quad, have largely controlled patterns of jointing and weakness within the gypsum between the structures, which, in turn, have produced two distinct orientations of the sinkholes, depressions, and small drainages, either parallel or orthogonal to the structures.

The quadrangle lies within the northern Roswell artesian basin, which, comprised of both a shallow alluvial aquifer and an underlying aquifer within the Permian San Andres formation, have supported extensive agriculture since the late 19th Century. However, within the Bitter Lake quadrangle, ground-water salinities significantly increase from west to east, and high salinity, coupled with presence or absence of gypsum-bearing soils, determine areas of agricultural feasibility here.

OVERVIEW

The Bitter Lake Quadrangle lies in southeast New Mexico on the northeastern outskirts of the city of Roswell. The area covered by the quadrangle, which extends from 33°22'30"N to 33°30'N and 104°22'30"W to 104°30'W, is approximately 158 km^2 (61 mi^2). Elevations range from approximately 1,049 m (3,442 ft) where the Pecos River flows out of the quadrangle to the south to the highest point on the eastern Permian uplands, 1,160 m (3,805 ft). Within the quad, the confluence of the Pecos River and the Rio Hondo occur, alluvial Pecos River terraces cover the majority of the area, and the easternmost bluffs and uplands of the Permian (Guadalupian) Seven Rivers formation (*Psr*) gypsum and siliciclastic redbeds are found east of the Pecos floodplain. A large part of the floodplain, as well as surrounding uplands, falls under the jurisdiction of the Bitter Lake National Wildlife Refuge (BLNWR). Established in 1937 around wetlands within backswamp areas around Bitter Lake and the low-lying westernmost Pecos floodplain, the refuge is a major flyway stop for sandhill cranes, snow geese, and other waterfowl, and supports critical habitat for rare or endangered species, such as the Pecos pupfish, Pecos gambusia, and the Pecos puzzle sunflower.

The BLNWR limits access to the public to a sightseeing loop drive around the southernmost three impoundments, several western bluff overlooks, and three nature trails. Access to the remainder of the refuge within the Bitter Lake quad, including Bitter Lake, the sinkholes north and west of Bitter Lake, and the agricultural farm area south of U.S. Highway 380 requires a research permit for access. Accessibility to the remainder of the quad is quite good via U.S. Highway 380, which traverses the quad from east to west in the southern third of the map, U.S. Highway 70, which cuts across the northwest

corner of the quad, N.M. Route 253, and local surface streets, especially Pine Lodge Road, Red Bridge Road, and River Road.

Notable physiographic features include the north-south oriented Pecos River valley and the east-west oriented Rio Hondo valley, which meet in the southeastern part of the quadrangle. The Pecos valley averages about 2 km in width but exceeds 3 km in the southeastern corner of the quad. The width of the Hondo valley at its mouth's distal edge is approximately 4.5 km, but quickly narrows from ~2 km at the valley-mouth apex to between 0.8 to 1.2 km wide upvalley. Alluvial valley-fill thickness for the Pecos valley increases to the west from 0 m, where the modern Pecos River is incised into *Psr* gypsum (see Figure 1) to approximately 30 m at depth at the base of the western bluffs, while the valley-fill in the Hondo increases quickly from roughly 30-m thick at its mouth to around 45-m thick upvalley (calculated from data from Lyford, 1973). Overall relief for these valleys varies from about 7.5 to 9.2 m along the Hondo margins (and less upvalley), as well as the western bluffs of the Pecos valley, and 70 to 80 m along the bluffs of the eastern Permian uplands. This eastern bluff is known locally as Comanche Hill, at least in the vicinity of U.S. Highway 380, where it climbs the escarpment from the Pecos River. Near these bluffs, numerous spectacular, large, dry, upper to middle Pleistocene sinkholes, most 25-40 m in depth with unknown fill depths, dominate the landscape of the western Comanche Spring quadrangle, immediately east of Bitter Lake.

Figure 1. The modern Pecos River is incised into Seven Rivers formation gypsum in the northeastern part of the quadrangle. Dormant salt cedar (*Tamarix pentandra*), growing along the shore on the right, are approximately 1.5 m in height. Note that the alluvium on top of the gypsum is <1 m in thickness.

Aside from the eastern Permian uplands, the Pecos valley, and the Rio Hondo valley, the majority of the surface area of the quadrangle is comprised of Pleistocene alluvial terraces of the Pecos: the Lakewood, Orchard Park, and Blackdom (from youngest and lowest in the landscape to oldest and highest, respectively). First described in the classic work of Fiedler and Nye (1933), this terrace stratigraphy is still applicable today, although we now recognize 3 terrace levels of the Lakewood, two of which are younger and lower than that of Fiedler and Nye. The Lakewood flanks both the Pecos floodplain, and its tributaries (which include the Rio Hondo as well as Borrendo Creek, a

tributary of the Rio Hondo, as well as its tributaries). The oldest Lakewood terrace deposit is actually cut into the Orchard Park terrace and not into the river valleys.

The Orchard Park terrace covers most of the quadrangle and is a rich, agricultural deposit south of the Hondo valley, but inhospitable to agriculture to the north. Here, its soils are choked with gypsum, its surface is pitted with sinkholes and depressions, and it sits above very saline ground-waters. Its surface is comprised of wide areas of eolian sands, shallow lacustine deposits, and middle Pleistocene Pecos River channels. Finally, situated above the Orchard Park terrace, are 7 isolated high remnants of the Blackdom terrace on the west side of the quadrangle.

One fault, or buckle (the term indicating drag folding and complex lateral and vertical fault movement) crosses the quad from the south-central border to the northeast: the Y-O Buckle. It is only one of several northeast striking faults or buckles that cut across the eastern Pecos slope that primarily date back to Pennsylvanian-Permian time but could have had episodic movement up through the Paleogene (Kelley, 1971). Basically, the Y-O Buckle is a right-lateral strike-slip fault and the next buckle to the west, the Six-Mile Buckle, is a left-lateral strike-slip fault. The Six-Mile Buckle, located about 7.5 km west of the western margin of the Bitter Lake quadrangle, with its reverse, wrenching movement relative to that of the Y-O, greatly influenced the orientation of jointing and zones of weakness within the *Psr* gypsum bedrock between these two structures, which, in turn, greatly influenced patterns of orientation of the Neogene sinkholes, depressions, and minor drainages developed on the Bitter Lake quadrangle.

The Roswell artesian basin has been an extensively studied hydrologic resource since the early 20th Century (e.g., Fiedler and Nye, 1933). Comprised of both a shallow

alluvial aquifer and an underlying aquifer within the Permian San Andres formation, it has supported extensive agriculture within this semiarid basin from early on. While pumping during growing seasons currently lower water table depths in excess of 60 m annually, sufficient rates of recharge from the west off of the Pecos slope keep overall decadal variations relatively low.

Groundwater exhibits significant changes in chemistry across the quadrangle, however. A freshwater-saltwater interface occurs roughly from the northwestern to the southeast-central part of the quad. Here chloride concentrations jump from around 200 ppm to over 7,000 ppm. Thus, ground-water salinity, as well as the distribution of gypsum-bearing soils, clearly determines where agricultural suitability occurs.

Finally, straddling the Pecos floodplain lies the South Bitter Lake Oil Field. Relatively small amounts of both oil and natural gas are still produced from this field, which is primarily producing from the lower part of the Permian San Andres formation. Several well records from this field were utilized to construct the geologic cross section.

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, 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

All surficial depositional units of the Bitter Lake Quadrangle are late Neogene in age with the exception of the eastern Permian uplands and their bluffs, which are comprised of Artesia Group (Guadalupian) Seven Rivers formation gypsum, with redbeds of siltstone, and sandstone (see Figure 2). Underlying *Psr*, seen in well records and the cross section only, are the oldest formations of the Artesia Group, the Grayburg and Queen formations, here undifferentiated (*Pgq*). Below these, are the San Andres formation (Psa) and the Yeso formation (*Py*).

Figure 2. Late afternoon view across Bitter Lake to the eastern Permian bluffs and uplands of the Seven Rivers formation at the eastern edge of the Pecos floodplain. Numerous snow geese can be seen on the lake. At the base of the bluffs on the left, the Lakewood and Orchard Park terraces are evident.

Types of Neogene deposits on the Bitter Lake quad vary widely. Alluvial deposits include floodplain deposits of meander belts (comprised of channel-fill, channel-bar, and point bar deposits), overbank crevasse splay deposits, and low-lying backswamp (slack-water) deposits, all Historic to Holocene in age. These are built upon basal braided stream alluvial deposits, primarily of the Pleistocene. Along floodplain margins, one finds Holocene to upper Pleistocene alluvial fans, inset alluvial terraces (the youngest two Lakewood terrace deposits), and alluvial-colluvial complexes.

The western uplands are comprised of older Pecos alluvial terraces: the oldest (upper to middle? Pleistocene) Lakewood deposit; inset into the predominantly middle Pleistocene Orchard Park terrace, which is an extensive alluvial-eolian complex; and the isolated upper Pliocene (?) to middle Pleistocene alluvial terrace remnants of the Blackdom terrace. Inset within or resting on top of the Orchard Park terrace are two upper to middle Pleistocene Pecos River channel-fill and bar deposits, numerous small stream alluvial deposits (Holocene to upper Pleistocene in age), eolian veneers and small dunes (primarily Holocene), depression-fill complexes comprised of alluvial-, colluvial-, eolian-, and mass wasting-derived deposits (Holocene to upper Pliocene?), sinkholes (Holocene to upper Pliocene?), and shallow lacustrine deposits (Holocene to upper Pleistocene in age).

Pecos River alluvial valley floor

Aside from a thin veneer of undifferentiated alluvium covering Permian Seven Rivers deposits (*Qa/Psr*), the Pecos valley floor consists of four meander belts, a series of depressions which contain Pecos channel alluvium within them, and backswamp

deposits, all atop of braided stream alluvium and Permian bedrock. Described in much further detail within the Description of Map Units section below and based primarily on photogeologic interpretation, the meander belts are divided into two Historic meander belts (the modern one and a 1939-1940 meander belt, based upon the earliest complete aerial photographic coverage of the area by the U.S.D.A. Soil Conservation Service) and two Holocene (upper and lower to middle) meander belts.

The modern meander belt (hmp_2) is constrained in size, largely due to anthropogenic changes to the river. In the early 1950s, two major meander cutoffs (along with other minor channel adjustments) were carried out by the U.S. Bureau of Reclamation to create oxbow lakes out of the large 1940s-era meanders which swept through the BLNWR, thereby increasing open water and wetlands for waterfowl, aquatic plants and fish, and associated wildlife. As a result, the majority of the modern channel through its Bitter Lake reach has since been confined into old braided $Qadp$ channels, and meandering has been hampered (see Figure 3). Modern meander amplitudes are only approximately 0.2-0.6 km in width.

Throughout the upper Holocene, extensive point bar development, with some minor channel bar development has taken place. This has resulted in a series of sweeping meanders, especially through the BLNWR reach, culminating in some of the largest meanders on the entire Pecos River occurring here at this time. The 1939-40 belt (hmp_1) commonly exhibits meanders with amplitudes >1 km in width, the largest on the Bitter Lake quad reaches about 1.8 km in width. Meanwhile, the upper Holocene belt (Hmp_2) may exhibit the largest meander geometries here. While much of this is obscured by more

Figure 3. A view of both the modern Pecos River meander belt in the foreground and a sweeping 1939-40-vintage meander in the upper distance. The lower of the two major 1950s cutoffs occurred just out of the picture to the left.

recent meander belt deposition and/or agriculture, amplitudes are estimated to average about 1 km in width with one amplitude of about 2 km in width.

A series of collapse depressions are found on the southeasternmost part of the Pecos floodplain, which captured the Pecos River for a period of time, creating the lowest inset fluvial deposit of the Pecos floodplain on the Bitter Lake quad. The timing of the collapse or subsidence of the depressions is unknown, but their capture of the Pecos River is constrained to lower Holocene – uppermost Pleistocene, prior to the development of the oldest Holocene meander belt (Hmp_1) and likely during the waning phases of active braided stream ($Qabp$) deposition. This is clear because the tributary Rio

Hondo built two lower to middle Holocene meander belts (Hmh_1 and Hmh_2) across both upper Pleistocene Rio Hondo braided alluvial "deltaic" deposits ($Qabh_1$ and $Qabh_5$) and $Qabp$, into which $Qabh_{1-5}$ drained. An avulsion occurred upstream of the modern U.S. Highway 380 bridge during the middle Holocene, causing Hmp_1 to build out across Hmh_1 and Hmh_2 in the vicinity of the historic Pecos meander belts, thereby cutting these lower Rio Hondo belts off and causing the Rio Hondo to develop Hmh_3 to the south and west.

As to why the Pecos switched from this upper Pleistocene braided regime to a meandering one in the lower Holocene is uncertain. It is unclear whether or not steeper gradients (favoring a braided regime) were present during the upper Pleistocene, but there is evidence that the large amounts of late glacial outwash from the Sacramento Mountains to the west coming down the Rio Hondo (producing the large "deltaic" floodplain mouth fans that built out into the Pecos valley), decreased the gradient of the Pecos floodplain upstream during the waning phases of the Pleistocene, thereby possibly inducing meandering. Easily-erodible banks is a known causal factor for braiding (Fahnestock, 1963); and this is certainly applicable to the Pecos as it flows into outcrop areas of Permian evaporites north of Roswell. Further, a braided regime is facilitated by a greater variability in extremes in discharge (Fahnestock, 1963). This scenario was undoubtedly more common during the upper Pleistocene, when large spring meltwater floods were much more commonplace.

Rio Hondo alluvial valley floor

As alluded to above (and described in detail in the map unit descriptions below), the Rio Hondo also switched from a late Pleistocene braided regime to a Holocene meandering one, building two meander belts out all the way across the entire Pecos floodplain during the lower to middle Holocene (see Figure 4). The Holocene Rio Hondo meander belts are clearly distinguished from any meandering Pecos River deposit by differing lithologies, sediment chararacteristics, and especially meander geometries (Rio Hondo meanders are an order of magnitude smaller than those of the Pecos). In addition to containing a much coarser fraction than the Pecos, clasts of gray and green porphyritic igneous rocks are common, and limestone clasts are larger and more abundant. Soils are typically more loamy and a much darker brown when compared to the reddish brown, poorly sorted deposits of the Pecos.
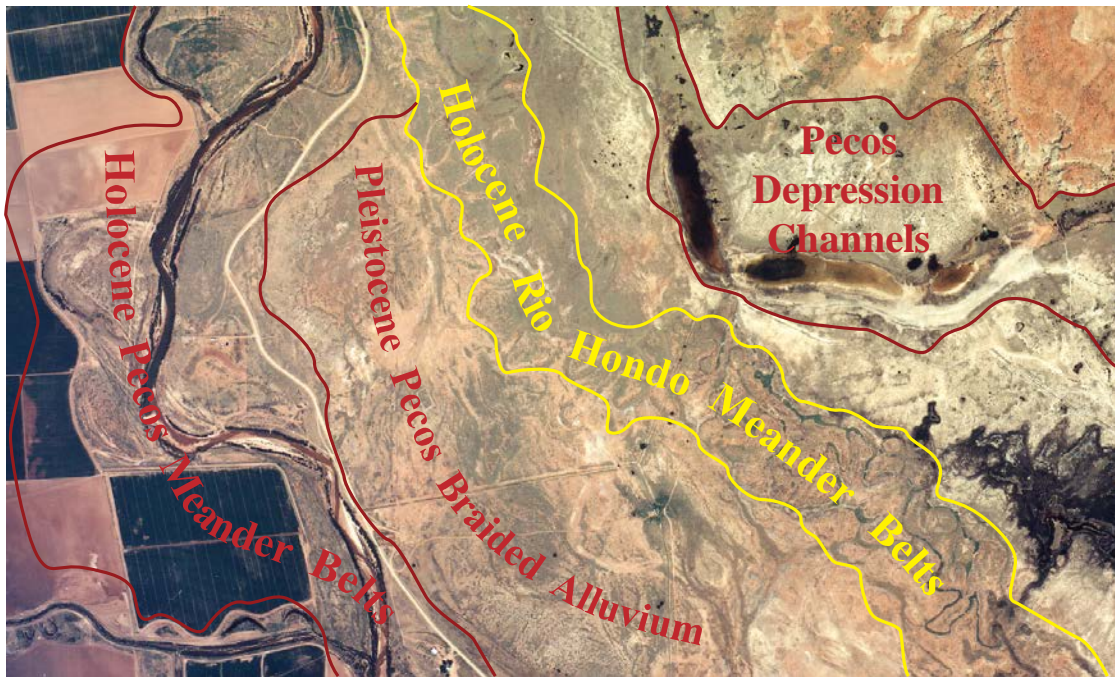

Figure 4. Aerial photographic view of the two earliest Rio Hondo Holocene meander belts (note meander geometries are an order of magnitude smaller than that of the Pecos River) crossing the Pecos floodplain to join the Pecos River in its early Holocene depression-captured channel off of the Bitter Lake quad to the southwest. The Chain

Lakes, occupying the Pecos depression channel (s) (*Qdp*) are in the upper right. The photo is from the Bureau of Land Management and was taken in 1981.

The same characteristics basically apply to the upper Pleistocene "deltaic" valley-mouth fans, each comprised of braided distributaries and overbank deposits. These "deltas" are differentiated based upon height above the Pecos floodplain, degree of channel preservation, degree of deflation, and relative gypsite crust development, into five distinct braided alluvial deposits (*Qabh$_{1-5}$*). With the exception *Qabh$_1$*, the southernmost unit, units *Qabh$_{2-5}$* progressively shift from a northern position adjacent to the Hondo floodplain backswamp (*Qbs*) deposits, southward, approximately to the location of the Holocene Rio Hondo meander belts.

Alluvial terrace deposits

The youngest alluvial terrace, the Lakewood, consists of two valley margin inset terraces, which extend up the Rio Hondo and its tributaries, and an older (upper to middle Pleistocene) terrace deposit inset into the Orchard Park terrace, which commonly exhibits stage III pedogenic carbonate morphology (see Figure 5). Surface tread elevations above the floodplain for these three are: <1-1 m, 1.2-6 m, and 6-9 m, respectively.

The Orchard Park terrace, a large alluvial-eolian complex (*Qoae*), comprises the majority of the surface area on the Bitter Lake quadrangle, in three distinct locations: the northeast corner of the quad, the western two-thirds of the quad north of the Hondo Valley, and the agricultural lands south of the Hondo valley, west of the Pecos floodplain. The northeastern deposit is distinctly different from the other Orchard Park deposits as its largely non-gypsiferous, reddish-brown Pecos alluvium. This deposit could

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actually be an outcrop of the Gatuña Formation (Kelley, 1980; Powers and Holt, 1993) as the lithologic characteristics are essentially identical, but given its roughly parallel proximity to the Pecos floodplain, we map it as *Qoae*.

Figure 5. Exposure of the soil developed in the oldest Lakewood terrace deposit (Qlt_1), in the Rio Hondo valley, displaying a stage III+ pedogenic carbonate morphology (the top of the bk-horizon is at a depth of 28 cm).

The remaining two areas of Orchard Park terrace are separated by the Hondo valley. The southern area lies west of the westernmost gypsiferous soils and saline ground-waters, thus supporting extensive agriculture. North of the Rio Hondo, however,

gypsum-choked soils are common and much of the area falls to the east of the freshwater-saltwater interface (on the saline side). In general, the gypsum content of the soils decreases from the western bluffs above the Pecos valley westward. On the map, the western limit of gypsiferous soils is demarcated with a bold, dashed line, with dots and the small-letter "g." At and near the bluffs, *Qoae* is so choked with gypsum it forms gypsite, an indurated hyper-concentration of gypsum in the soil (Watson, 1983). This material develops from a combination of *in-situ* weathering of gypsum bedrock, as well as eolian and alluvial depositional input of gypsum into the solum (Eswaran and Zi-Tong, 1991).

On this northwestern surface of *Qoae*, in addition to the depression and lacustrine deposits discussed below, two distinct middle (?) Pleistocene Pecos River channels (*Qocp*) traverse from north to south-southwest. Alluvial channel-bar and point bar deposits associated with these Pecos channels (*Qobp*) are present in places. There is some suggestion of fluvial interaction between the channels via *Qa* deposits, and depressions greatly influenced where these channels developed.

Finally, Fiedler and Nye (1933) describe the Blackdom terrace in northern Chaves County as isolated erosional terrace remnants 9-15.5 m above the Orchard Park terrace. This perfectly describes the seven isolated high siliciclastic hills we map as Blackdom terrace on the Bitter Lake quadrangle. They are comprised predominantly of chert and quartzite pebbly sand.

Depression, sinkholes, and lacustrine deposits

Depressions and sinkholes are numerous throughout the Bitter Lake quadrangle.

Created by either gradual subsidence (usually leading to depressions - see Figure 6)

Figure 6. A typical depression pitting the surface of the Orchard Park terrace. The eastern Permian uplands are on the skyline.

versus sudden collapse (often leading to sinkhole development) of underlying gypsiferous

carbonate terrane, these complexes consist of unconsolidated, well-sorted, fine-grained

(fine sands to clay) complexes of alluvial, colluvial, eolian, and occasional lacustrine

deposits within closed depressions, often significantly modified by stream erosion and

deposition, playa deposition, deflation, and mass wasting (Hawley, and others, 2004).

Depressions have been forming at least since the middle Pleistocene and quite likely back

into the upper Pliocene. Sinkholes, varying in size from about 2 m^2 to 78 m^2, with depths

often approaching 20 m, are common on the lower two Lakewood terraces on the BLNWR (see Figures 7 and 8), as well as on the upper to middle Pleistocene Orchard Park terrace (see Figure 9).

Figure 7. A small sinkhole on the middle Lakewood terrace (Qlt_2). Note the gypsiferous crust in the foreground.

In the northwestern corner of the quadrangle, numerous, shallow lacustrine deposits are found occupying depressions. One large historic lake, fed by one or more of the Borrendo Springs, was described by Fiedler and Nye (1933) as drying up due to excessive pumping of the artesian aquifer in the early 20th Century. This map is named "Arthur Lake" on the middle 20th Century-vintage U.S. Army Map Service base map,

used by Kelley (1971) on his Plate 2, "*Geology of the Roswell Region*." However, several

local residents, when asked, had never heard of Arthur Lake, and it is not mentioned in

Figure 8. A view of the northern third of Lake St. Francis, one of the largest sinkholes in the BLNWR. A hydrologic monitoring station is seen on the far shore.

Holocene and upper Pleistocene, as lake levels expanded and contracted, water flowed between these shallow basins, giving rise to a somewhat unique lacustrine-alluvial complex deposit (*Qla*). Further work mapping shorelines and coring lacustrine sediments for Holocene paleoecological data are needed here.

Permian bedrock

The bedrock of the Seven Rivers formation (*Psr*), exposed in the bluffs on the easternmost part of the Bitter Lakes quadrangle, is comprised of up to 75% gypsum in the

Figure 9. Small sinkhole developed in the Orchard Park terrace, just west of Bitter Creek in the BLNWR. More than 40 cm of gypsite is exposed in the sinkhole wall.

southern two thirds of the quadrangle. The gypsum content decreases gradually northward, with a concomitant increase in clastic interbeds of siltstone and sandstone.

North of the latitude of the wildlife refuge headquarters, gypsum comprises only about 25% of the unit. Gypsum beds are thin- to thick- to very thick-bedded, and massive to thin-bedded to laminated internally. Red outcrop color is due to surface wash from the clastic interbeds. These clastic layers often contain veins of gypsum. Bedding is irregular and highly variable where gypsum content is high. As gypsum content decreases, bedding becomes thinner and more planar, with less development of collapse features and

slumping is more common. The top of the bluff is often capped by or covered with rubble of medium gray thin- to medium-bedded, crinkly laminated limestone.

STRUCTURE

Named by Merritt (1920) and recognized through this area by Nye (Fielder and Nye, 1933), the Y-O Buckle, along with several other semi-parallel buckles crossing the Pecos slope, were best described by Kelley (1971). Throughout the Bitter Lake quad, the Y-O Buckle remains buried beneath Pecos alluvium. Just to the east of the quad boundary on the Comanche Spring quadrangle, however, the buckle comes out of the alluvium and cuts across the *Psr* bluffs (see Figure 10).

Kelley (1971) maps the Y-O Buckle as a right-lateral strike-slip fault west of Artesia to the south, but indicates its movement is normal and down to the west where it comes out of the Pecos alluvium, east of Bitter Lake. Examination of both surface exposure and well records, which record no vertical offset of strata, lead us to believe that the structure remains a right lateral strike-slip fault here. Furthermore, based upon the apparent right lateral offset of convoluted, monoclinal beds exposed in Figure 11 (just over the hill seen in Figure 10, some 150 m) we suggest a minimum of 25- to 30-m of right-lateral offset here on the Y-O Buckle.

Still another line of evidence exists for right lateral strike-slip along the northernmost Y-O Buckle: the orientation of the majority of sinkholes and depressions west of the structure throughout most of the Bitter Lake quadrangle. The Y-O Buckle strikes N 60° E along the eastern edge of the Bitter Lake quad. The next regional buckle

Figure 10. SW-facing exposure of the Y-O Buckle coming out of the Pecos floodplain alluvium. The outcrop falls just east of the eastern edge of the Bitter Lake quadrangle, within the Comanche Spring quad.

to the west, the Six-Mile Buckle, approximately 7.5 km west of the Bitter Lake quad, is a left lateral strike-slip fault system, or buckle. Its strike changes from about N 62° E at about the latitude of the northern edge of the Bitter Lake quad (33°30'N) to N 45° E, northward. These two essentially opposite movements along these Pennsylvanian-Permian structures, clearly "wrenched" the Permian evaporite facies rocks and controlled the overall pattern of jointing and development of zones of weakness here between these structures. Underlying bedrock collapse or subsidence, leading to surficial depression or sinkhole development, has clearly occurred by in large along these joints and

Figure 11. View to the northwest along strike of the Y-O Buckle on the adjacent Commanche Spring quadrangle. The westward-dipping monoclinal beds in the upper third of the photo are offset from eastward-dipping monoclinal beds in the photo center by approximately 25-30 m. The back of a white Chevrolet full-sized pickup, at least some 60 m distant from the structure lends some sense of scale.

compromised zones. The orientation of most of the sinkholes and depressions on the

Bitter Lake quad trend either N 50° E to N 60° E or along an orthogonal line of N 41°W

to N 45° W.

HYDROLOGY

The Roswell artesian basin is an intensively farmed area in the lower Pecos valley, with a history dating back to the late 19th Century. Agricultural activity in this semiarid region (mean precipitation = ~25 cm/yr) is sustained by irrigation using groundwater from an eastward-dipping, karstic limestone aquifer comprised for the most part of the middle Permian San Andres limestone (and to a much lesser extent in the overlying Grayburg and Queen Formations), and a shallow water table aquifer made up of sand and gravel of the Pecos River floodplain and alluvial terraces. The two aquifers are separated by redbeds and gypsum of the Seven Rivers formation, which serves as a leaky confining unit for the artesian aquifer at depth.

Recharge to the artesian aquifer occurs on the Pecos Slope, west of Roswell, where the San Andres limestone is exposed in outcrop. Some recharge occurs directly via precipitation, but most recharge is derived from underflow and from losing streams such as the Rio Hondo flowing eastward across the Pecos Slope. Groundwater flows eastward (downgradient) through the San Andres and passes beneath the Seven Rivers Formation a few miles west of Roswell, where the San Andres becomes an artesian aquifer. Discharge from the artesian aquifer occurs through solution-enlarged fractures in the overlying Seven Rivers gypsum and manifests itself along both sides of the Pecos River as a discontinuous chain of karst springs, sinkhole lakes and extensive wetlands. The gypsum sinks and springs at BLNWR provide a good example of the nature of the discharge area for the northern artesian basin.

A freshwater-saltwater interface is present in the artesian aquifer, extending roughly northwest-southeast beneath the city of Roswell. Chloride concentrations west of the interface are less than 200 ppm (for comparison, EPA secondary standards for chloride concentrations in drinking water are no more than 250 ppm). East of the interface chloride concentrations have been reported as high as 7,000 ppm. In the 1960s, a desalination pilot plant was located a few miles east of Roswell in the south-central area of the Bitter Lakes quad, using saline groundwater derived from a flowing artesian well within the grounds of the plant as feedstock for the desal facility. The pilot plant was originally established as a flash distillation desalination facility, but reverse osmosis techniques were also developed there. The kidney dialysis machine, which also employs reverse osmosis, was a byproduct of research conducted at this plant. Artificial impoundments located ~1.6 km east of the plant, now dry, were apparently used as evaporation ponds for the brine stream from this desal facility.

The Bitter Lake quad lies mostly on the salty side of the freshwater-saltwater interface, as indicated by the limited amount of agricultural activity on this quad, in striking contrast to the dairy farms and lush fields of alfalfa seen in the Roswell North and South quads to the west. Chloride concentrations measured from samples collected in springs and sinkholes at BLNWR range from 1,100 to 3,500 ppm. TDS (total dissolved solids) concentrations range from 3,600 to 9,600 ppm. Many of the springs and sinkholes provide habitat for a number of threatened and endangered species of fish, snails and other small invertebrates. See Land (2005) for a detailed discussion of BLNWR hydrology.

DESCRIPTION OF MAP UNITS

QUATERNARY/NEOGENE

Alluvium, colluvium, eolian, and anthropogenic deposits

daf   **Artificial fill (Historic)** — Disturbed areas, dumped fill, and areas affected by other human disturbances. Mapped where deposits or extractions are areally extensive. Includes impoundment levees in the inundated backswamp (*Qbs*) areas within the Bitter Lake National Wildlife Refuge (BLNWR), the channelized Rio Hondo, North Spring River, and the Hagerman Canal, the BNSF railroad right-of-way, raised roadways along U.S. Highways 380 and 70, the old Desalinization Plant Brine Field, the Roswell Country Club lake, and borrow or gravel pits.

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

Qae   **Valley-slope alluvium with eolian sand (Holocene to upper Pleistocene)** — White (2.5Y8/1) to light gray (2.5Y7/1), unconsolidated to partly consolidated, well-sorted, fine-grained gypsiferous sand, silty sand, and clay along the northeast slope of Lost River. Forms a relatively thin mantle of alluvial slope deposits shed off of the Orchard Park terrace uplands combined with a large eolian component blown out of the Lost River floodplain, which is about 0.5 km wide here. Thicknesses varies from <1 m immediately adjacent to Lost River to 2.5 m downslope of the alluvial terrace (*Qoae*).

Qaf   **Alluvial-fan deposits, undivided (Historic to uppermost Pleistocene)** — Predominantly quartzite, chert, and carbonate cobbles to gravel, often in stringers, in a light reddish-brown (5YR6/4) to reddish brown (2.5YR4/6), unconsolidated, poorly sorted, and coarse- to fine-grained sand to silty sand. These fans are built along the base of the Seven Rivers formation (*Psr*) eastern bluffs and interfinger with and/or spread out onto Pecos floodplain deposits. They are locally incised by small drainages floored with recent alluvium (*Qa*), but these only reach mappable size on the Comanche Spring quadrangle, immediately east of the Bitter Lake quad. Most are stabilized by vegetation and apparently not currently active. Thickness <1 m at their distal margins to 8 (?) m.

Qca   **Colluvium and/or valley-slope alluvium, undifferentiated (Holocene – uppermost Pleistocene)** — Light reddish-brown (5YR6/4) to reddish brown (2.5YR4/6) (eastern *Psr* bluffs), light gray (2.5Y7/1) to pale brown (10YR6/3) (Orchard Park terrace and oldest Lakewood terrace margins), unconsolidated to poorly consolidated, poorly to moderately sorted sand and silty sand, with rubble

blocks of gypsum, sandstone, siltstone, and mudstone, and minor limestone (eastern *Psr* bluffs), and blocks of indurated gypsite along the terrace bluffs. Deposits range from less than 1 m to about 3 m in thickness.

Qe   **Eolian sand, undivided (Holocene – uppermost Pleistocene)** — Very pale brown (10YR8/2) to light brown (7.5YR6/4), unconsolidated, moderately to well-sorted sand, silty sand, and sandy clay. Forms extensive thin sheets and low dunes along the top of the Orchard Park terrace (*Qoae*). Thickness commonly <1 m to about 3 m.

Pecos River alluvial valley floor

Qa/   **Quaternary valley-fill alluvium over Seven Rivers formation, undivided** —
Psr   Light reddish-brown (5YR6/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, pebbly, fine-grained, gypsiferous sand, silty sand, and clay, thinly draped over gypsum, siltstone, and sandstone of *Psr*. Alluvium is <1 m (often <60 cm) in thickness.

Pecos River meander belt alluvial deposits (Historic to lower (?) Holocene) — During the Holocene, the Pecos River built four distinguishable meander belts on top of an upper Pleistocene Pecos River braided alluvial valley-fill deposit (*Qabp*), which is the basal unit of the floodplain. Consisting of channel, channel bar, and point bar deposits, undivided, these meander belt deposits are differentiated based upon aerial photographic work into two older Holocene units and two Historic units: 1) the modern meander belt was mapped from both 2005 digital 1-m resolution, color orthophotography and 1981-vintage color aerial photography produced for the U.S.D.I.- Bureau of Land Management, and 2) a 1939-1940 meander belt was mapped using vintage U.S.D.A. – Soil Conservation Service black and white aerial photography. The 1939-40 meander belt, in places, also incorporates areas where meander migration clearly continued up at least until around 1962, the issue date of the Bitter Lake topographic quadrangle (before photo-revision). All aerial photography was georeferenced and plotted onto the 2005 orthophotography using ArcGIS, to produce a derivative Pecos River channel historical map showing channel migratory change patterns (not included in the open-file report). The historic units are differentiated from the Holocene units by using a lower case "h" on the unit labels.

     hmp$_4$ **Modern meander belt deposits (Historic)** — Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately to well-sorted, occasionally pebbly, coarse- to fine-grained sand in the modern channel and adjacent bar crests, grading to silty sand and sandy clay with distance from the channel. In the early 1950s, two major meander cutoffs (along with other minor channel adjustments) were carried out by the U.S. Bureau of Reclamation to create oxbow lakes out of the large 1940s-era meanders which swept through the BLNWR, thereby increasing open water and wetlands for waterfowl, aquatic plants and fish, and associated wildlife. As a result, the majority of the modern

channel through its Bitter Lake reach has since been confined into old *Qadp* channels, and meandering has been hampered. Modern meander amplitudes are only approximately 0.2-0.6 km in width. This has greatly reduced both channel and overbank deposition, thus the majority of modern meander belt deposits are <1 m thick, but reach about 1.5 m thick in a few places.

hmp_3 **1939-1940 meander belt deposits (Historic)** — Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately to well sorted, coarse- to fine-grained gypsiferous sand in the Historic channel and adjacent bar crests, grading to silty sand and sandy clay with distance from these older channels. Throughout the upper Holocene, extensive point bar development, with some minor channel bar development has taken place. This has resulted in a series of sweeping meanders, especially through the BLNWR reach, with meander amplitudes >1 km in width common, the largest reaching about 1.8 km in width. In terms of estimating thicknesses of this meander belt, the Holocene meander belts, and the braided Pleistocene deposits, we consider a valley-fill thickness map based upon interpretations of data from numerous wells throughout the Roswell artesian basin by Lyford (1973). This map depicts the valley fill thickness dropping from approximately 30 m at the base of the western Orchard Park terrace bluffs to < 1 m just west of the modern channel. Based upon this fact that the meander belts are built on a wedge of Pleistocene braided alluvial valley fill, present at the surface aside hmp_2 and buried with a ~30-m base alongside the western bluffs, the thickness of hmp_1 ranges from <1 m to 3-10 m where it overlies Holocene meander belts, and up to15 m where it buries *Qabp*.

Hmp_2 **Younger Holocene meander belt deposits (Historic to upper Holocene)** — Very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, moderately to well sorted, occasionally pebbly, coarse- to fine-grained sand, silty sand, and sandy clay. Meander geometries are similar to hmp_1, and while much of this is obscured by more recent meander belt deposition and/or agriculture, amplitudes are estimated to average about 1 km in width with one amplitude of about 2 km in width. Thickness 3-10 m.

Hmp_1 **Older Holocene meander belt deposits (upper Holocene to lower (?) Holocene)** — White (2.5Y8/1) to light gray (2.5Y7/1) in the northern part of the quad, very pale brown (10YR 7/4) to reddish brown (2.5YR4/6) in the south, unconsolidated, well sorted, fine-grained, gypsiferous (especially in the north) sand, silty sand, and sandy clay. Meander geometries are significantly smaller with meander amplitudes averaging only 0.5 km in width. It appears that this meander belt was first to develop, switching the river from flowing in a braided, coarser-grained *Qabp* floodplain into a small meandering stream, which probably co-existed with active *Qabp* channels throughout much of the lower Holocene. The northern segment is older than those deposits located at the mouth of the Rio Hondo, whose timing is constrained to the middle Holocene, as discussed below. Nevertheless, the northern segment is also younger as it has

been active throughout much of the Holocene, acting as a yazoo stream flowing into the backswamp (*Qbs*) of and surrounding Bitter Lake. Thickness <1 to 3 m.

Qdp　**Pecos River channel alluvium occupying coalescing depressions (middle Holocene to uppermost Pleistocene)** — Light reddish-brown (5YR 6/4) to reddish brown (2.5YR4/6), unconsolidated, well sorted, fine-grained, gypsiferous sand, silty sand, and clay thinly draped over the floor of depressions developed primarily in gypsum. Forms the lowest inset fluvial deposit of the Pecos floodplain. The timing of the collapse or subsidence of the depressions is unknown, but their capture of the Pecos River is constrained to lower Holocene – uppermost Pleistocene prior to *Hmp₁* development and probably in the waning phases of active *Qabp* deposition. This is clear because the tributary Rio Hondo built two lower to middle Holocene meander belts (*Hmh₁ and Hmh₂*) across both upper Pleistocene Rio Hondo braided alluvial "deltaic" deposits (*Qabh₁ and Qabh₅*) and *Qabp*, into which *Qabh₁₋₅* drained. *Hmh₁ and Hmh₂* are clearly distinguished from any meandering Pecos River deposit by differing lithologies, sediment chararacteristics, and especially meander geometries (Rio Hondo meanders are an order of magnitude smaller than those of the Pecos), and are clearly visible in aerial photos completely crossing the Pecos floodplain to the eastern margin, where it joined the Pecos in its *Qdp* channel on the Bottomless Lakes quadrangle southeast of the Bitter Lake quad. While *Qdp* flows could have occurred concurrently in the depression channel(s) and parts of *Hmp₁*, it was not until an avulsion occurred upstream during the middle Holocene, which caused *Hmp₁* to build out across *Hmh₁* and *Hmh₂* in the vicinity of the historic meander belts, thereby cutting these lower belts off and causing the Rio Hondo to develop *Hmh₃* to the south and west. Pecos River alluvium is very thin in these channels (<1 to 2 m thick) and very little bank or bar formation occurred while *Qdp* was active. The shallow, saline Chain Lakes now occupy *Qdp*.

Qabp　**Pecos River braided alluvial deposits (lower Holocene to upper Pleistocene)** — Light reddish-brown (5YR6/4) to reddish brown (2.5YR4/6), unconsolidated, poorly to moderately sorted, pebbly coarse- to fine-grained sand, silty sand, sandy clay, and clay. Braided channels and bars typify the surface of *Qabp*. As discussed above, the thickness of *Qabp* is greatest on the western margin of the floodplain, although buried, varies from 10 - 20 m. Large areas of *Qabp* are found on the floodplain surface in the center and eastern margins of the valley, here the thickness varies from 3 m to <1 m.

Qbs　**Floodplain alluvial backswamp deposits (Historic to upper Pleistocene)** — *Pecos floodplain*: light gray (2.5Y7/1) to very dark gray (7.5YR3/1), unconsolidated, well-sorted, gypsiferous silty sand, sandy clay, and clay in low-lying, poorly drained areas surrounding Bitter Lake and the impoundments along the western margins. *Rio Hondo floodplain*: light brownish gray (10YR6/2) to dark yellowish brown (10YR3/4), unconsolidated, well-sorted, gypsiferous silty sand, sandy clay, and clay in low-lying, poorly drained areas below the northern bluffs of the oldest Lakewood terrace (*Qlt₁*). Both areas commonly only receive fine-grained, slack-water flood deposition, although several springs discharge into the

Pecos *Qbs*. The Rio Hondo *Qbs* area occupies the lowest inset area in its floodplain, and is probably the result of scour from a Pleistocene Rio Hondo channel. Thicknesses range from 3-15 (?) m in the Pecos floodplain and are unknown in the Rio Hondo floodplain, but probably 3 m or less.

Rio Hondo alluvial valley floor

Qah   **Quaternary valley-fill alluvium within the Rio Hondo, undivided (Historic to upper Pleistocene)** — Cobbles and gravels of chert, quartzite, gray and green porphyritic igneous rocks, and limestone in brown (10YR5/3) to dark yellowish brown (10YR3/4), unconsolidated, poorly to moderately sorted, coarse- to fine-grained sand, silty sand, silt (largely calcareous), sandy clay, and clay. While clasts and coarse-grained sediment are common, these deposits are typically found between meander belts and older Pleistocene channel deposits, and are thus finer-grained. According to Lyford (1973), the valley fill beneath the Hondo valley in the Bitter Lake quadrangle increases from about 30 m in thickness at the mouth to over 45 m quickly upvalley. Thicknesses of *Qah* are estimated to be 10-25 m.

Rio Hondo meander belt alluvial deposits (Historic to lower (?) Holocene) — Cobbles and gravels of chert, quartzite, gray and green porphyritic igneous rocks, and limestone in brown (10YR5/3) to dark yellowish brown (10YR3/4), unconsolidated, moderately sorted, coarse- to fine- grained sand, silty sand, silt (largely calcareous), and sandy clay. While meander geometries are essentially identical between all three Hondo meander belts, *Hmh$_1$* certainly exhibited the widest lateral migration (although not necessarily widest meander amplitude).

Hmh_3 **Modern (pre-channelization) meander belt deposits (Historic to upper Holocene)** — Responding to an avulsion of the Pecos River in the middle Holocene which shifted flow back to the west-central part of the floodplain into the *Hmp$_1$* deposit, *Hmh$_3$* after leaving the Hondo floodplain was forced to turn south and build a course over the top of the oldest and lowest Rio Hondo braided alluvial "deltaic" deposit (*Qabh$_1$*). Upstream of this southerly diversion, *Hmh$_3$* basically built up on top *Hmh$_2$*. It was abandoned in the early 20th Century with the construction of the Hagerman Canal and the channelized Rio Hondo. Thickness 1-3 m.

Hmh_2 **Young meander belt deposits (middle Holocene)** — As described above, the two oldest Hondo meander belts (*Hmh$_1$ and Hmh$_2$*) built up on top of both upper Pleistocene Rio Hondo braided alluvium (*Qabh*) and upper Pleistocene Pecos braided alluvium. In the Pecos floodplain, *Hmh$_2$* built up on top *Hmh$_1$*, but in the Hondo floodplain, it built a new meander belt north of *Hmh$_1$* until it reached the vicinity of the present-day Hagerman Canal diversion, where it crossed over *Hmh$_1$* and flowed to the south, over *Qabh$_1$*. Thickness 1-3 m.

Hmh_1 **Older Holocene meander belt deposits (middle Holocene to lower (?) Holocene)** — In the Hondo floodplain, *Hmh$_1$* flowed primarily along the southern margin (mapped where not totally obscured by agriculture), probably

in upper Pleistocene channels. At the mouth of the floodplain, its course was clearly influenced by the youngest upper Pleistocene channels within $Qabh_5$. Thickness 1-3 m.

Rio Hondo braided alluvial deposits (lower Holocene to upper Pleistocene) — Cobbles and gravels of chert, quartzite, gray and green porphyritic igneous rocks, and limestone in brown (10YR5/3) to dark yellowish brown (10YR3/4), unconsolidated, poorly to moderately sorted, coarse- to fine- grained sand, silty sand, silt (largely calcareous), sandy clay, and clay. Upvalley from the mouth of the Hondo floodplain, these braided deposits are probably all buried (if exposed, they are undiscernable due to agriculture). They undoubtedly fill the entire base of the inset valley and are probably 15 to 30 m thick. As these upper Pleistocene braided stream channels carrying glacial outwash from the Sacramento Mountains discharged out into the Pecos floodplain, they built a series of "deltaic" valley-mouth fans, each comprised of braided distributaries and overbank deposits. These "deltas" can be differentiated based upon height above the Pecos floodplain, degree of channel preservation, degree of deflation, and relative gypsite crust development into five distinct braided alluvial deposits. With the exception $Qabh_1$, the southernmost unit, units $Qabh_{2-5}$ progressively shift from a northern position adjacent to the Hondo floodplain Qbs deposits, southward approximately to the location of the Holocene Rio Hondo meander belts.

$Qabh_5$ **Youngest braided valley-mouth alluvial-fan deposits (uppermost Pleistocene**) — Clearly defined channels on the second-lowest $Qabh$ surface, some still active, including a large, main, "Pleistocene-sized" channel (i.e., very high meander wavelengths and amplitudes compared to Holocene Rio Hondo channels), overridden in places by Hmh_{1-2}. Bar and swale deposits exhibit minor gypsite crust development. $Qabh_5$ spreads out laterally both north and south at the margin of Pecos alluvial deposits (both braided and meandering) due to the fact that it accommodates Holocene to modern flows from older $Qabh$ valley-mouth fan channels. Thickness <1 to about 15 m.

$Qabh_4$ **Younger braided valley-mouth alluvial-fan deposits (upper Pleistocene**) — Surface slightly higher, channels less defined and more braided (multiple, smaller channels) with more extensive gypsite at the surface than $Qabh_5$. The 2005 orthoimagery shows approximately the eastern quarter of this deposit with a distinctly redder surface, in a semi-arcuate shape, suggesting a possible short-lived Hmp_2 occupation of this lowland. Thickness <1 to about 15 m.

$Qabh_3$ **Young braided valley-mouth alluvial-fan deposits (upper Pleistocene**) — Highest $Qabh$ deposit suggesting formation during periods of massive outwash deposition. Large areas choked with gypsite crust, minor channel remnants remain. Thickness ~3 to 20 m.

$Qabh_2$ **Older braided valley-mouth alluvial-fan deposits (upper Pleistocene**) — Lower, northernmost $Qabh$ deposit exhibiting large areas choked with gypsite crust, few channel scars remaining, and wide areas of extensive deflation. Often undergoes modern flooding. Thickness ~2 to 10 m.

Qabh$_1$ **Oldest braided valley-mouth alluvial-fan deposits (upper to middle (?) Pleistocene)** — Lowest-lying, yet most extensive braided alluvial-fan deposit. Greatly modified by agriculture on it eastern margin adjacent to and within the Pecos floodplain. Only an occasional channel remnant remains. Overriden by *Qabh$_5$*, *Hmh$_3$*, and *Hmp$_2$*. Thickness ~2 to 30 m.

Alluvial terrace deposits

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 western tributaries. We now recognize three distinct low-lying (upper to uppermost middle(?) Pleistocene) "Lakewood terraces," the highest and oldest of which would be Fiedler and Nye's original. Surface tread elevations above the floodplain for these three are: <1-1 m, 1.2-6 m, and 6-9 m, respectively. We differentiate these terraces by their location either in the Pecos valley or in the tributary valleys of the Rio Hondo and Borrendo Creek, and its tributaries. All of the Pecos valley Lakewood terrace deposits vary between: 1) the west side, with light gray (2.5Y7/1) to very pale brown (10YR7/4) to reddish brown (2.5YR4/6), unconsolidated, well-sorted, medium- to fine-grained gypsiferous sand, silt, and sandy clay, and 2) the east side, made up of light reddish-brown (5YR6/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, pebbly, fine-grained, gypsiferous sand, silty sand, and clay. As for the tributary Lakewood terrace alluvial deposits, they're 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. 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 to middle 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. On the Bitter Lake quadrangle, it consists of an alluvial-eolian complex (*Qoae*), with many subsidence-related depressions (*Qd*) and collapse-related sinkholes (*Qds*) pitting its surface. Furthermore, many of these depressions

are artesian-spring fed, and supported shallow lakes (Ql, Ql_2, and Ql_1) prior to 20$^{\text{th}}$ Century pumping of the artesian aquifer. Given their shallow nature, water often flowed from basin to basin, giving rise to an unusual "hybrid" lacustrine-alluvium map unit (Qla).

On the Bitter Lake quadrangle, the Orchard Park terrace comprises the majority of the surface area, in three distinct locations: the northeast corner of the quad, the western two-thirds of the quad north of the Hondo Valley, and the agricultural lands south of the Hondo valley, west of the Pecos floodplain. The northeastern deposit is distinctly different from the other Orchard Park deposits as its largely non-gypsiferous, made up of light reddish-brown (5YR 6/4) to reddish brown (2.5YR4/6), unconsolidated, moderately sorted, pebbly, medium- to fine-grained sand, and silty sand. This deposit could actually be an outcrop of the Gatuña Formation (Kelley, 1980; Powers and Holt, 1993) as the lithologic characteristics are essentially identical, but given its roughly parallel proximity to the Pecos floodplain, we map it as *Qoae*.

The remaining two areas of Orchard Park terrace are separated by the Hondo valley. The southern area lies west of the westernmost gypsiferous soils and saline ground-waters, and again, supports extensive agriculture. It is comprised of very pale brown (10YR7/4) to reddish brown (5YR4/4), unconsolidated, moderately sorted, coarse- to fine- grained sand, silty sand, silt, and sandy clay. The northern area, however, is predominantly gypsiferous with saline ground-waters. It is comprised of white (2.5Y8/1) to light gray (2.5Y7/1) to very pale brown (10YR 7/4), unconsolidated, well sorted, fine-grained, gypsiferous sand, silty sand, and sandy clay. In general, the gypsum content of the soils decreases from the western bluffs above the Pecos valley westward. At and near the bluffs, *Qoae* is so choked with gypsum it forms gypsite, an indurated hyper-concentration of gypsum in the soil (Watson, 1983). This material develops from a combination of *in-situ* weathering of gypsum bedrock, as well as eolian and alluvial depositional input of gypsum into the solum (Eswaran and Zi-Tong, 1991).

On this northwestern surface of *Qoae*, in addition to the depression and lacustrine deposits discussed below, two distinct middle (?) Pleistocene Pecos River channels (*Qocp*) traverse from north to south-southwest. Alluvial channel and point bar deposits associated with these Pecos channels (*Qobp*) are present in places. There is some suggestion of fluvial interaction between the channels via *Qa* deposits, and depressions greatly influenced where these channels developed.

Qoae　**Orchard Park terrace alluvial and eolian deposits, undivided (upper to middle Pleistocene)** — Thickness 15 to 45 m.

Qocp　**Orchard Park terrace ancestral Pecos River alluvial channel deposits (upper to middle Pleistocene)** — Thickness ~2 to 15 m.

Qobp　**Orchard Park terrace ancestral Pecos River alluvial point and channel bar deposits (upper to middle Pleistocene)** — Thickness 1-2 m.

Qbt　**Blackdom Terrace alluvial deposits (lower Pleistocene to upper Pliocene)** — Fiedler and Nye (1933) describe the Blackdom terrace in northern Chaves County as isolated erosional terrace remnants 9-15.5 m above the Orchard Park terrace.

This perfectly describes the isolated high hills we map as Blackdom terrace on the Bitter Lake quadrangle. They are comprised predominantly of chert and quartzite gravel in yellowish brown (10YR5/4) to reddish brown (5YR5/4), unconsolidated, moderately sorted, coarse- to fine-grained, occasionally gypsiferous, sand and silty sand. Thickness 15 to 30(?) m.

Depressions, sinkholes, and lacustrine deposits

Qd **Quaternary depression fill, primarily caused by subsidence (Historic to middle Pleistocene)** — Unconsolidated, well-sorted, fine-grained (fine sands to clay) complexes of alluvial, colluvial, eolian, and occasional lacustrine deposits within closed depressions created by either gradual subsidence or sudden collapse followed by gradual subsidence of underlying gypsiferous carbonate terrane. These complexes are often significantly modified by stream erosion and deposition, playa deposition, deflation, and mass wasting. 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)** — *Eastern bluffs*: boulders, slump blocks, gravel, sand, silt, and clay filling dry sinkholes derived from local collapse of *Psr*. Thickness unknown, probably 1-5 m for smaller sinks, quite likely several tens of meters for the larger ones (predominantly on the Commanche Spring quad to the east). *Western terraces*: occasional cobbles, gravel, and slumped gypsite blocks in a fine-grained sandy clay matrix. Most are submerged beneath the water table. Thickness <1 to 5 (?) m.

Ql **Quaternary lacustrine deposits, undivided (lower Holocene (?) to upper Pleistocene)** — Unconsolidated, well-sorted, fine-grained silty sands, silt, and clay deposited primarily by pluvial lakes fed by artesian springs. These deposits surround the lower Holocene lacustrine units, and may have a significant alluvial component in their composition. Thickness 1-2 m.

Ql$_2$ **Young Quaternary lacustrine deposits (predominantly Historic to lower (?) Holocene)** — greenish gray (Gley1, 5/5GY) to greenish black (Gley1, 2.5/5GY), unconsolidated, well-sorted, fine-grained silty sands, silt, and clay deposited by lakes fed by artesian springs. Occupies lowest, wettest landscape positions. Thickness 1-3 m.

Ql$_1$ **Older Quaternary lacustrine deposits (Historic to upper Pleistocene)** — greenish gray (Gley1, 5/10Y) to gray (5YR5/1), unconsolidated, well-sorted, fine-grained silty sands, silt, and clay deposited by lakes fed by artesian springs. Occupies area surrounding *Ql$_2$*, and is inundated less frequently. Thickness 1-3 m.

Qla **Quaternary lacustrine and alluvial deposits, undivided (Historic to upper Pleistocene)** — Pinkish gray (5YR6/2) to gray (5YR5/1), unconsolidated, well-sorted, fine-grained silty sands, silt, and clay. Usually lacustrine, but when water

levels are sufficiently high, fluvial action occurs depositing alluvium, especially along the margins of this unit. Thickness 1-3 m.

PALEOZOIC

Pemian Artesia Group

Psr   **Seven Rivers Formation (Guadelupian - upper Permian)** – White to pale gray gypsum, brick red, pale red, to orange very fine sandstone, siltstone, and mudstone, and minor limestone. Exposed in bluffs along the east bank of the Pecos River. Gypsum comprises up to 75% of the unit in the southern two thirds of the quadrangle. Gypsum content decreases gradually northward, with concomitant increase in clastic interbeds. North of the latitude of the wildlife refuge headquarters, gypsum comprises only about 25% of the unit. Gypsum beds are thin- to thick- to very thick-bedded, and massive to thin-bedded to laminated internally. Red outcrop color is due to surface wash from the clastic interbeds. These clastic layers often have veins of gypsum. Bedding is irregular and highly variable where gypsum content is high. As gypsum content decreases, bedding comes thinner and more planar, with less development of collapse features and slumping. Top of the bluff is often capped by or covered with rubble of medium gray thin- to medium-bedded, crinkly laminated limestone. Thickness: Top not exposed; at least 75 m based on cross-section.

Pqg   **Queen and Grayburg Formations, undivided (Guadelupian - upper Permian)** – Cross section only. Completely covered by terrace deposits or stripped.

Other Pemian Sedimentary Rocks

Psa   **San Andres Formation (middle to upper Permian)** – Light to dark gray and bluish gray limestone and dolomite. Limestones and dolomites range from thin to very thick bedded, and are carbonate mudstones, wackestones, and grainstones. Freshly broken surfaces are darker gray than weathered surfaces and often fetid. Silty and sandy beds are common. Presumably the upper Bonney Canyon member of Kelley (1971). Thickness unknown.

Py   **Yeso Formation (lower to middle Permian) –** Cross section only.

Pa   **Abo Formation (lower Permian) –** Cross section only.

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