Groundwater Resources Evaluation Report for Major and Minor Aquifers Beneath University Lands in Andrews, Loving, Ward, Winkler, and Ector Counties, Texas

Prepared for

The University of Texas System
University Lands
Midland, Texas

December 16, 2015

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Mr. T. Neil Blandford was responsible for overall project management, hydrogeolgic analysis, report preparation including all graphics, and the 3D geologic model. The seal appearing on this document was authorized on December 16, 2015.

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- Brant Konetchy and Paul Crossett of LBG-Guyton Associates assisted with well log analysis and geologic interpretations under the direction of Kristie Laughlin
- Farag Botros, PhD, P.E. of Daniel B. Stephens & Associates, Inc. developed the 3D geologic models under the direction of Neil Blandford.
- Andrew Donnelly, P.G. of Daniel B. Stephens & Associates, Inc. assisted with the geology and hydrogeology sections of the report.

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Executive Summary

The Mission of University Lands is to manage and care for the Permanent University Fund (PUF) lands while maximizing the revenue generated for the benefit of Texas higher education. In July 2014, University Lands retained Daniel B. Stephens & Associates, Inc. (DBS&A) to perform hydrological studies of the groundwater resources on selected portions of University Lands; this report presents the results of DBS&A's groundwater resource evaluation for University Lands in Andrews, Loving, Ward, Winkler, and Ector Counties. The purpose of this study was to describe the geologic structure and stratigraphy of the major and minor aquifers on the University Lands to approximately 3,000 feet below ground surface.

University Lands in the Andrews County area are underlain by the Ogallala Aquifer, a designated major aquifer by the Texas Water Development Board (TWDB). University Lands in Loving, Ward, Winkler, Ector, and northern Crane Counties (referenced as the five-county area in this report) are underlain by the Pecos Valley Aquifer, also a major aquifer. The Dockum Aquifer, designated as a minor aquifer, underlies all University Lands in the study area. The Rustler Aquifer, also a minor aquifer, occurs beneath all University Lands in the study area, although the water quality of the Rustler Aquifer is poor, with total dissolved solids (TDS) concentrations greater than 5,000 milligrams per liter (mg/L) in most areas. The Capitan Reef Complex minor aquifer occurs beneath the easternmost portions of University Lands in Ward and Winkler Counties.

Data sources used for the geologic and hydrogeologic analyses documented in this report include geophysical logs, water well driller reports, and water well data obtained from the University Lands well library, geophysical logs, scout tickets, and cable tool driller reports obtained from the Bureau of Economic Geology (BEG) data archives, and driller reports obtained from the TWDB, the Texas Department of Licensing and Regulation (TDLR), and the Texas Commission on Environmental Quality (TCEQ). Well information was collected and screened for the University Lands and immediately adjoining areas. Ultimately, 1,355 data points were used to interpret the geology and hydrogeology of the study area. The results of the geologic analysis are provided through cross sections, geologic unit thickness maps, and three-dimensional (3D) geologic models that can be viewed interactively.

A University Lands water well inventory (database) was compiled from multiple sources including University Lands, the Railroad Commission of Texas, the TDLR, and the TWDB. The database contains 1,113 wells located in the study area. Wells were assigned an aquifer designation based on screen interval or depth using the 3D geologic models constructed as part of this study. The majority of wells are completed in the Ogallala Aquifer (442 wells) or Pecos Valley Aquifer (189 wells). Of the remaining wells that received an aquifer designation, 55 are completed in the Upper Dockum Group, 47 are completed in the Lower Dockum Group (Santa Rosa Formation), and 15 are completed across multiple aquifer units. The TWDB considers all wells completed in the Dockum Group, whether Upper or Lower, to be Dockum Aquifer wells. However, the Lower Dockum Group, which contains the Santa Rosa Formation, is generally more productive than the Upper Dockum Group. Where sufficient information is available, the hydrologic analysis presented in this report differentiates between wells completed in the Upper Dockum Group and the Lower Dockum Group.

Groundwater flow in the Pecos Valley Aquifer is generally to the southeast toward the Monument Draw Trough. Within the trough, groundwater flow is generally to the south-southeast, aligned with the axis of the trough. A cone of depression is evident in the eastern portion of University Lands Block 16 due to pumping of municipal wells. Pecos Valley Aquifer well hydrographs indicate that water levels in the Pecos Valley Aquifer are stable.

Pecos Valley Aquifer well yields are small (0 to 50 gallons per minute [gpm]) in University lands Blocks 17 through 20 and in the western portions of Block 16 and 21, consistent with the limited saturated thickness of the Pecos Valley Alluvium within the structural high west of the Monument Draw Trough. Wells completed in the Monument Draw Trough have significantly larger yields of 200 gpm and higher due to the greater saturated thickness in this area. Water quality of the Pecos Valley Aquifer ranges from fresh (TDS <1,000 mg/L) to moderately saline (TDS 3,001 to 10,000 mg/L).

In Andrews County, groundwater flow in the Ogallala Aquifer is east-southeast. In northeastern Andrews County, groundwater flow is toward a paleochannel present beneath Mustang Draw. Within the paleochannel, the Ogallala Aquifer is thicker and the sediments are more permeable than outside the paleochannel. Groundwater flows toward the paleochannel due to pumping from wells completed in the paleochannel and due to the greater aquifer transmissivity within the paleochannel. Ogallala Aquifer water levels in the Andrews County area are generally stable or increasing.

Ogallala Aquifer well yields are about 100 gpm or less, except in the paleochannel where yields greater than 200 gpm are reported. Water quality in the Ogallala Aquifer ranges from fresh (TDS <1,000 mg/L) to moderately saline (TDS 3,001 to 10,000 mg/L).

There are 102 Dockum Aquifer wells identified in the study area, with an approximately equal split between the Upper Dockum Group and the Lower Dockum Group. There were insufficient data to develop contour maps of Upper or Lower Dockum Group water levels, although observed Dockum Aquifer water levels were compared to water levels in the overlying Pecos Valley or Ogallala Aquifers. Water levels in the Upper Dockum Group are generally similar to those in the overlying Pecos Valley or Ogallala Aquifers, indicating hydraulic connection.

Observed water levels in Lower Dockum (Santa Rosa) wells in Andrews County are approximately 400 to 650 feet lower than those in the overlying Upper Dockum Group and Ogallala Aquifer. Vertical groundwater flow is therefore downward from the Ogallala Aquifer and the Upper Dockum Group into the Lower Dockum Group. Lower Dockum Group water levels are not available in the five-county area.

Dockum Aquifer well yields are generally 50 gpm or less for wells completed in the Upper Dockum Group and 50 to 200 gpm for wells completed the Lower Dockum Group. TDS concentrations of water in the Upper Dockum Group indicate fresh (TDS <1,000 mg/L) to slightly saline (TDS 1,001 to 3,000 mg/L) water. Lower Dockum Group groundwater is slightly saline to moderately saline (TDS 3,001 to 10,000 mg/L) in Andrews County. Insufficient information exists to determine Lower Dockum Group water quality in the five-county area.

The primary conclusions of this study are as follows:

- In the Andrews County area, the majority of wells are completed in the Ogallala Aquifer. In the five-county area, most wells are completed in the Pecos Valley Aquifer.

- Water levels in the Ogallala and Pecos Valley Aquifers are stable.

- With few exceptions, wells not completed in the Ogallala or Pecos Valley Aquifers are completed in the underlying Dockum Aquifer. Dockum Aquifer wells are completed in both the Upper Dockum Group and the Lower Dockum Group.

- Reported well yields and total sand thickness indicate that wells completed in the Lower Dockum Group (which includes the Santa Rosa Formation) are more productive than those completed in the Upper Dockum Group. Based on the same information, the Dockum Aquifer is expected to be more productive in the Andrews County area and Ector County than it is in Loving, Ward, and Winkler Counties.

- Few wells are completed across multiple aquifers.

- The depth to the top of the Dockum Group is less than 300 feet throughout most of the study area. In the Monument Draw Trough in Ward and Winkler Counties, the depth to top of the Dockum Group is greater than 500 feet and can exceed 1,000 feet in places, and the contact between the Pecos Valley Alluvium and the Dockum Group can be hard to identify.

- The difference in water levels between wells completed in the Lower Dockum Group and wells completed in the Upper Dockum Group or the Ogallala Aquifer in Andrews County suggests that the vertical hydraulic conductivity between these wells is low. Groundwater pumping from the Lower Dockum Group should have a negligible effect on water levels in the Ogallala Aquifer.

1. Introduction

In July 2014, University Lands retained Daniel B. Stephens & Associates, Inc. (DBS&A) to perform hydrological studies of the groundwater resources on selected portions of University Lands in west Texas. The University Lands included in the groundwater studies are divided into two areas, referred to as the Northern Area and the Southern Area (Figure 1). This report presents the results of DBS&A's groundwater resource evaluation for University Lands in the Northern Area, which includes University Lands in Andrews, Loving, Ward, Winkler, and Ector Counties. LBG-Guyton Associates, under contract to DBS&A, performed most of the geologic analysis and interpretation presented in this report. The purpose of this study was to describe the geologic structure and stratigraphy of the major and minor aquifers underlying University Lands to a depth of approximately 3,000 feet below ground surface (bgs).

Data sources used for the geologic and hydrogeologic analyses in this report include geophysical logs, water well driller reports, and water well data obtained from the University Lands well library, geophysical logs, scout tickets, and cable tool driller reports obtained from the Bureau of Economic Geology (BEG) data archives, and driller reports obtained from the Texas Water Development Board (TWDB), the Texas Department of Licensing and Regulation (TDLR), and the Texas Commission on Environmental Quality (TCEQ).

Study results are provided in this report in the form of figures, geologic cross sections, and formation thickness maps. In addition, DBS&A constructed interactive three-dimensional (3D) geologic models using Leapfrog Hydro software. The 3D geologic models permit visualization of stratigraphic units, selected details of data points (wells) used to construct the model, and generation of cross sections at locations and orientations selected by the user.

Section 2 of this report provides an overview of the study area. Section 3 provides an overview of the regional geology and hydrogeology. Section 4 describes data sources and analyses. Section 5 presents the study results. Section 6 provides conclusions.

2. Study Area

The study area considered in this report includes portions of 9 counties (Figure 2). University Lands that occur in Loving, Ward, Winkler, Ector, and northern Crane Counties are referred to collectively as the five-county area, and University Lands that occur in Andrews and small portions of three adjacent counties (Gaines, Dawson, and Martin) are referred to collectively as the Andrews County area. Few surface water bodies are present in the study area, and none are of significant size.

The land surface elevation within the study area is approximately 2,500 to 3,500 feet above mean sea level (feet msl) within two physiographic provinces—the High Plains and the Pecos Valley. The Andrews County area and the University Lands in Ector and northern Crane Counties are in the High Plains physiographic province. The High Plains are characterized by a broadly flat to gently rolling plateau generally lacking major drainage systems. The area is covered with numerous shallow depressions, known as playas, which range in depth from a few feet to several tens of feet. The playas drain local watershed areas from less than a square mile to several square miles, resulting in a scarcity of stream drainage systems (Knowles et al., 1984; Ashworth et al., 1991; Peckham and Ashworth, 1993). The only drainage (draw) of appreciable size in the Andrews County area is Mustang Draw. Most of the Andrews County area is located within the Colorado River Basin.

The five-county area is almost entirely located in the Pecos Valley physiographic province, which is characterized by sparsely vegetated rolling uplands with thin sandy soils. These uplands slope south towards the Pecos River, which is the primary surface water feature near the study area and forms the county line between Reeves and Pecos Counties on the south and Ward County on the north (Figure 1). Monahans Draw, an ephemeral tributary to the Pecos River, is the primary surface drainage in the five-county area. The five-county area is in the Rio Grande Basin.

The study area climate is semiarid with hot, dry summers and relatively mild winters. Large fluctuations in daily temperatures are common, with higher temperatures during the daytime and much cooler temperatures at night, relatively low humidity, and irregular rainfall events

(Ashworth et al., 1991). Annual precipitation across the study area ranges from about 17 inches per year (in/yr) in northeastern Andrews County to 11 in/yr in Loving County (Anaya and Jones, 2009). Annual precipitation is highest in the summer and lowest in the winter, and commonly occurs as scattered intermittent thunderstorms (Ashworth et al., 1991; Peckham and Ashworth, 1993; Anaya and Jones, 2009). The high temperatures, low humidity, irregular precipitation, and prevailing winds result in high evaporation rates, with average annual lake evaporation of 72 to 81 in/yr (Ashworth et al., 1991; Peckham and Ashworth, 1993).

3. Overview of Geology and Hydrogeology

This section provides an overview of the regional geologic structure and stratigraphy (Section 3.1) and hydrogeology (Section 3.2) of the study area and adjoining regions based on existing reports.

3.1 Geology

The geology of the study area and adjoining regions is presented in Sections 3.1.1 and 3.1.2.

3.1.1 Structure

Figure 3 illustrates the major structural features underlying University Lands that influenced lithology, depositional patterns, and formation thickness and extent. Stratigraphic units through the base of the Delaware Mountain and Artesia Groups (early to middle Permian) are summarized in Figure 4. The Central Basin Platform and Midland Basin sequence is present on University Lands in the Andrews County area and Ector County. The Delaware Basin sequence is present in Loving, Ward, and Winkler Counties. Figure 4 also illustrates the major and minor aquifers within the stratigraphic units.

The following geologic history and structure descriptions are summarized from Garza and Wesselman (1959), White (1971) and Meyer et al. (2012). Additional information can be obtained from BEG (2015) and SEPM (2015).

The Permian Basin is a sedimentary basin that occurs beneath more than 50 counties in west Texas and southeast New Mexico. Within the study area, the basin is subdivided into the Delaware Basin in the west and Midland Basin in the east. These sub-basins are separated by the structural high known as the Central Basin Platform (Figure 3). During the early to mid-Permian era, the Capitan Reef limestone was deposited along the edge of the Delaware Basin. This created three separate depositional environments: (1) deep-water marine inside the reef, (2) the reef itself, and (3) the shelf (back-reef) deposits outside of the reef. The Capitan Reef accumulated deposits throughout the Permian era, while the Delaware Basin subsided and the

Central Basin Platform experienced uplift. Accumulation of the Capitan Reef deposits was contemporaneous with deposition of the Artesia Group, composed of the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations. The formations of the Artesia Group vary texturally depending on their location relative to the Capitan Reef Complex. The deep water deposits of the Delaware Basin inside the reef generally consist of limestone, shale, and sandstone. The deposits on the shelf outside of the reef consist of limestone and dolomite, which grade laterally outward into limestone, shale, evaporites, and sandstone.

Subsequent to the reef-building period, the Castile, Salado, Rustler, and Dewey Lake Formations were deposited in the Delaware Basin during the late Permian era. The Castile and Salado Formations are evaporites (anhydrite and halite); the Rustler Formation is composed of dolomite and anhydrite. The Dewey Lake Formation (often called the Dewey Lake redbeds) is predominantly siltstone, and marks the end of the Permian. The Castile Formation is not present on the Central Basin Platform. For the purposes of this report, the Rustler, Salado, Castile, and Tansill (Artesia Group) Formations, where they occur, are combined and mapped as a single geologic unit referred to as the undifferentiated Permian evaporites.

A significant period of time and erosion occurred before the terrigenous sediments of the Dockum Group were deposited in the basin. The Cretaceous Antlers Formation sandstones and subsequent marine sequences of transgressive-regressive cycles (Trinity and Fredericksburg Groups) were deposited unconformably on the Dockum Group. This deposition occurred prior to uplift and tilting during the Laramide orogeny of the late Mesozoic and/or early Tertiary era. The Cretaceous units are not laterally continuous throughout the region, and are absent in the study area except for a small region of Antlers Sand subcrop in southern Andrews County.

During the middle Tertiary era, the Trans-Pecos region was transected by a continent-wide belt of volcanism associated with subduction of the Farallon plate beneath the North American plate. Prior to deposition of the Pecos Valley Alluvium, the underlying evaporites of the Castile and Salado Formations began to dissolve and collapse. The collapse of the underlying units ultimately created the Pecos and Monument Draw Troughs, where thick alluvial sequences were deposited. The ridge between the troughs is a remnant of the Salado Formation that has not been removed by dissolution. Dissolution and collapse may have been initiated by the Laramide Uplift of the Central Basin Platform and created hydrogeologic connectivity with the underlying evaporites. However, basal sediments in the Monument Draw Trough in southern Reeves County contain eroded volcanic material, indicating that collapse occurred after the period of extensive volcanism in the Trans-Pecos region. Alternately, perhaps the Monument Draw Trough evolved as a progressive expansion of the trough basin (north to south). The Monument Draw Trough overlies and closely parallels the eastern arc of the Capitan Reef.

Deposition of the Ogallala Formation and Pecos Valley Alluvium occurred during the late Tertiary and Quaternary periods upon eroded topography. The Ogallala Formation consists of fluvial sands and gravels that were deposited in a series of distinct alluvial fan lobes. The Pecos Valley Alluvium fill materials include sand, clay, silt, gravel, and caliche that have been contributed via multiple depositional environments such as valley fill, fluvial, eolian, lacustrine, and dissolution-collapse.

3.1.2 Stratigraphy

A geologic column with corresponding hydrogeologic features is provided in Figure 4. Surface geology was determined from digital versions of the Geologic Atlas of Texas (GAT) sheets for Hobbs (Barnes et al., 1976) and Pecos (Eifler and Barnes, 1976). The surface geology for the five-county and Andrews County areas are provided in Figures 5 and 6, respectively. Sediment and rock of Quaternary, Tertiary, Cretaceous, and Triassic age outcrop within the study area.

The following subsections provide brief descriptions of the geologic units from ground surface through the Permian-age Guadalupian Series rocks.

3.1.2.1 Quaternary Deposits

Thin layers of Quaternary sand and silt Quaternary sediment cover much of the ground surface within the study area. These Quaternary deposits are primarily eolian deposits.

3.1.2.2 Ogallala Formation

The Tertiary Ogallala Formation is primarily composed of coarse-grained fluvial deposits that grade upward into interbedded sands, silts, clays, and gravels (Peckham and Ashworth, 1993). The Ogallala Formation ranges in thickness from 0 to over 800 feet through the state, but is generally less than 200 feet thick in the Andrews County area, with less than 50 feet of net sand (Blandford et al., 2003).

The Ogallala Formation contains a fine- to coarse-grained basal unit, with tan, yellow, or reddish brown moderately to well-sorted quartz sand, interbedded with clay, occasional sandstone, and some gravel (Knowles et al., 1984). These basal units are present in pre-deposition eroded valleys (paleochannels) and are not present at all locations (Knowles et al., 1984; Peckham and Ashworth, 1993). Overlying the basal unit are interbedded, poorly consolidated to unconsolidated sands, silts, and clays with occasional gravels, which were deposited in both fluvial and eolian environments (Peckham and Ashworth, 1993). A caliche layer is commonly found near the surface of the Ogallala deposits, and occasionally a caliche layer is found at depth representative of older soil horizons (Knowles et al., 1984). The top and base of the Ogallala Formation is included in the Andrews County area geologic model.

3.1.2.3 Pecos Valley Alluvium

The Pecos Valley Alluvium underlies the five-county area. This formation consists of discontinuous Tertiary- and Quaternary-age deposits of caliche, clay, silt, sand, gravel, and even boulder-sized material deposited in a variety of settings, including lacustrine, fluvial, eolian, and valley-fill environments (Anaya and Jones, 2009; Meyer et al., 2012). These deposits are unconsolidated to semiconsolidated and undifferentiated, and were unconformably deposited on older formations in several structural basins, including the Pecos Trough to the west and the Monument Draw Trough to the east (Anaya and Jones, 2009; George et al., 2009; Meyer et al., 2012). The lithology and thickness of individual beds within the Pecos Valley Alluvium vary widely over short distances, both laterally and vertically (White, 1971). Clay layers occur frequently in the Pecos Valley Alluvium, but correlation over large distances is difficult (Meyer at al., 2012).

The Monument Draw Trough (Figure 5) consists of a system of linear, deep collapse features, some of which are distinct and relatively isolated from adjacent collapse features. The trough broadens in central Ward County and contains sediments up to 1,000 feet thick in portions of the study area (Figure 5) (White, 1971; Meyer et al., 2012). Outside the trough alluvial sediments are generally 200 feet thick or less (Meyer et al., 2012); a large part of the University Lands in Ward, Winkler, and Loving Counties lie outside the Monument Draw Trough where the Pecos Valley Alluvium is relatively thin (Figure 5). The stratigraphic base of the Pecos Valley Alluvium can be difficult to determine because the basal Pecos Valley Alluvium includes reworked Permian and Triassic redbeds upon which the Pecos Valley Alluvium was deposited, making the basal sediments difficult to discern from the underlying Dockum Group (Meyer et al., 2012). The alluvium stratigraphy is further complicated by the presence of collapse features at depth caused by dissolution of evaporite deposits, and the subsequent infilling with younger material. Meyer et al. (2012) consider different collapse areas within the Monument Draw Trough as individual sub-basins that may have different sediment infill patterns and aquifer properties. The top and base of the Pecos Valley alluvium is included in the five-county area geologic models.

3.1.2.4 Cretaceous Formations

The uppermost Cretaceous rocks throughout most of the Edwards Plateau southeast of the study area are the carbonates of the Washita and Fredericksburg Groups historically referred to collectively as “Edwards and associated limestones” (Barker and Ardis, 1996). Although the Fredericksburg Group outcrops in the study area in Ector County (Figure 5), it is not saturated and is not addressed further.

The Trinity Group within the study area consists of the Antlers Sand, which is a medium-grained sandstone loosely consolidated in places. Estimated thickness in outcrop is 10 feet or less (Barnes et al., 1976), and it is often included with the overlying Ogallala Formation in hydrogeologic studies. The same approach was followed in this report.

3.1.2.5 Triassic Formations

The Dockum Group is a 1,000- to 2,000-foot-thick sequence of sediments deposited in fluvial, deltaic, and lacustrine environments within a closed continental basin or basins, with sediments received from all directions (Ashworth et al., 1991; Bradley and Kalaswad, 2003). The Dockum Group represents the final filling in of several small, adjoining basins, including the Midland Basin (Figure 3) and the Palo Duro and Dalhart Basins farther to the north, all of which are separated by structural highs (Bradley and Kalaswad, 2003). The greatest thicknesses of Dockum Group sediments occur at the centers of the basins, and sediments pinch out along the basin margins. Beds in the Dockum Group are essentially horizontal, with a gentle dip toward the center of the basin (Bradley and Kalaswad, 2003). The top of the Dockum Group is a relatively smooth surface indicative of the final filling of the basin, while the base of the Dockum Group may be irregular, reflecting the structural features that affected deposition (Ewing et al., 2008). Dockum Group rocks were subjected to several episodes of erosion during deposition.

The Dockum Group is composed of non-marine deposits generally consisting of sandstone, siltstone, mudstone, shale, gravel, and conglomerates, deposited in a lacustrine and fluvial depositional system (Ashworth et al., 1991; Ewing et al., 2008). Thicknesses of individual sandstone units within the Dockum Group range from several feet up to about 50 feet. These sandstone units are often lens-shaped, and therefore discontinuous and difficult to correlate in the subsurface (Bradley and Kalaswad, 2003). Sandstone units are typically separated by sandy shale or shale units that range in thickness from about 50 to 100 feet (Ewing et al., 2008).

The Dockum Group stratigraphic nomenclature applied by the TWDB is as follows, from youngest to oldest: the Cooper Canyon Formation, the Trujillo Sandstone, the Tecovas Formation, and the Santa Rosa Formation (Ewing et al., 2008). The Cooper Canyon Formation consists of reddish-brown to orange siltstone and mudstone with some sandstone and conglomerate (Bradley and Kalaswad, 2003). The Trujillo Sandstone is composed of gray, brown, and greenish-gray fine to coarse-grained sandstone and sandy conglomerate with thin interbedded red and grey shale (Bradley and Kalaswad, 2003). The Tecovas Formation is composed of variegated mudstones and siltstones with interbedded fine- to medium-grained sandstone. The Santa Rosa Formation consists of extensive red to reddish brown sandstone and conglomerate (Ashworth et al., 1991; Bradley and Kalaswad, 2003). The Santa Rosa Formation characteristically exhibits several coarsening-upward sequences with significant sand content in the upper portions of the sequences. The term “Santa Rosa” is often used by drillers and others for any sandstone unit in the Dockum Group that produces water.

The Dockum Group is often divided into the Upper Dockum Group, which includes the Cooper Canyon Formation and the Trujillo Sandstone, and the Lower Dockum Group, which includes the Tecovas and Santa Rosa Formations (Bradley and Kalaswad, 2003). Sandstones in the Lower Dockum Group are generally more continuous and have a higher sand percentage than sandstones in the Upper Dockum Group (Ewing et al., 2008). The Dockum Group is present throughout the study area (Figure 4). The top and base of the Upper Dockum Group and the Lower Dockum Group are included in the 3D geologic models.

3.1.2.6 Permian Formations

This section provides an overview of the Permian Ochoan and Guadalupian Series rocks.

3.1.2.6.1 Ochoan Series. The Ochoan Series consists of (from youngest to oldest) the Dewey Lake, Rustler, Salado, and Castile Formations. All of these formations occur within the Central Basin Platform, but the Castile Formation is absent in the Midland Basin. The Rustler, Salado, Castile, and Tansill Formations (discussed in the following subsection) are collectively identified as "undifferentiated evaporites" on the cross sections and the 3D geologic models accompanying this report.

The Dewey Lake Formation is often referred to as the Dewey Lake redbeds. The Dewey Lake Formation consists of interbedded red siltstone and shale (Armstrong and McMillion, 1961).

The Rustler Formation is recognized as a minor aquifer in Texas and locally (e.g., in western Pecos County) provides significant quantities of brackish groundwater; it is reported in places to be cavernous. The Rustler crops out in Culberson County far west of the study area, and is only present beneath the study area at depth. The Rustler Formation unconformably overlies the Salado Formation and has a thickness of 0 to 450 feet. The Rustler Formation consists largely of anhydrite and dolomite, but also has a basal zone of sand, conglomerate, and shale (Armstrong and McMillion, 1961; Brown, 1998).

The Rustler Formation has five to seven members, including, from youngest to oldest, the Forty-Niner Member, the Magenta Dolomite Member, the Tamarisk Member, the Culebra Dolomite Member, the Lower Gypsum and Mudstone Member, and the Siltstone Member. The top Forty-

Niner Member of the Rustler Formation consists of two beds of massive anhydrite and gypsum readily identifiable on geophysical log gamma curves (Ewing et al., 2012). The formation is generally the thickest in the eastern half of its extent, in the middle of the Delaware Basin (Ewing et al., 2012). The top of the Rustler Forty-Niner Member is identified as the top surface of the undifferentiated evaporites in the cross sections and 3D geologic models.

The Salado Formation varies in thickness from less than 100 feet to over 2,200 feet; the northern portion of the Salado in Pecos County is predominantly halite with some anhydrite, and the southern half is more anhydrite with some dolomite. The Castile Formation is up to 2,300 feet thick in Ward County and consists of calcareous anhydrite, halite, and minor amounts of sandstone (White, 1971).

3.1.2.6.2 Artesia Group. The Artesia Group does not occur in the Delaware Basin, and therefore only exists beneath University Lands in the Andrews County area and Ector County (Figure 3). The Artesia Group includes, from youngest to oldest, the Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations. These formations are located along the western margins of the Central Basin Platform northward into the Northwest Shelf and eastward into the Midland Basin (Figure 3). These formations consist of stratigraphically cyclic mixed siliciclastic, carbonate, and evaporite sequences (Nance, 2009). None of the Artesia Group formations outcrop in the study area. The remainder of this section is taken primarily from Nance (2009).

The Tansill Formation is recognized as a predominantly carbonate and evaporite sequence that is overlain by the Salado Formation and underlain by the sandstone beds of the Yates Formation. The Tansill carbonate is primarily dolostone, and the evaporites consist of anhydrite and halite. The Tansill sequence has very low gamma ray log values relative to the underlying Yates sandstones (Nance, 2009). This unit is included with the undifferentiated Permian evaporites on the cross sections and in the 3D geologic models.

The Yates Formation consists of up to 300 feet of thick sandstone sequences with thin carbonate and evaporite interbeds. The sandstone units are typically well-sorted, fine- to very fine-grained sandstone and siltstone. The Yates sandstones have low gamma ray log signatures easily identified from the very low gamma signatures of the overlying Tansill

Formation and the underlying Seven Rivers Formation evaporites (Nance, 2009). The top of the Yates Formation is included in the 3D geologic models.

The Seven Rivers, Queen, and Grayburg Formations form the remainder of the Artesia Group. These formations occur below the Yates Formation at depths of approximately 3,000 feet or greater and are not delineated in this study. The base of the Grayburg Formation (bottom of the Artesia Group) is included in the 3D geologic models.

3.1.2.6.3 Capitan Reef Complex. The Capitan Reef Complex outcrops in the Glass Mountains in southern Pecos County and dips to the north where it occurs deep in the subsurface. The Capitan Reef Complex consists of limestones and dolomites deposited as a reef and reef talus zones around the margin of the Delaware Basin, creating a carbonate barrier between the Delaware and Midland Basins. The Capitan Reef Complex limestones and dolomites interfinger with the Artesia Group formations that occur to the east in the Midland Basin. The geology of the Capitan Reef Complex used in this report is primarily based on the stratigraphic model of Standen et al. (2009). The top and bottom of the Capitan Reef Complex are included in the five-county area 3D geologic model.

3.2 Hydrogeology

The five-county area is underlain by the Pecos Valley, Dockum, and Rustler Aquifers. Part of the five-county area is also underlain by the Capitan Reef Complex Aquifer. The Andrews County area is underlain by the Ogallala, Dockum, and Rustler Aquifers. The following subsections provide an overview of the hydrogeology of the study area and adjoining regions based on existing reports.

3.2.1 Ogallala Aquifer

The Southern Ogallala Aquifer (referred to as the Ogallala Aquifer in this report) is classified as a major aquifer by the state of Texas. The aquifer is composed of saturated gravel, sand, silt, and clay deposits of the Tertiary Ogallala Formation. The Ogallala is one of the most extensively developed aquifers in the state; nearly 95 percent of extracted water is used for irrigated agriculture. Irrigated agriculture is limited in Andrews County, but areas of irrigated agriculture occur north of University Lands in Andrews County and are widespread in Gaines County, as illustrated by the green areas in the aerial photograph background in the figures (e.g., Figure 2). The Ogallala Aquifer also supplies water for municipal, domestic, livestock, and manufacturing users (Blandford et al., 2003, 2008; LBG-Guyton, 2003). Significant development of groundwater from the aquifer began in the 1940s and expanded rapidly during the drought of the 1950s (Blandford et al., 2003).

Beneath the southern margin of the High Plains, including the southeastern portion of the Andrews County study area, the Ogallala Formation is underlain by the Cretaceous-age Antlers Sand. Because these stratigraphic units are difficult to distinguish, and no consistent confining unit separates them, the combined saturated thickness of both units is considered to be the Ogallala Aquifer (Ashworth et al., 1991).

Groundwater production in many parts of the Ogallala Aquifer exceeds groundwater recharge, resulting in consistent, long-term groundwater level declines. However, some areas of the Ogallala Aquifer have experienced stable or increasing water levels (Blandford et al., 2003). Water level data in Andrews County indicate that the aquifer elevation is stable or increasing in some locations (Section 5.2).

Regional groundwater flow in the Ogallala Aquifer tends to follow the regional topography, which is generally to the east-southeast; such is the case in Andrews County (Blandford et al., 2003). Groundwater flow is also influenced by the presence of paleochannels, which occur at drainages eroded on Upper Dockum Group surface prior to deposition of the Ogallala Formation sediments. Because these drainages were topographically low areas prior to infilling by the Ogallala Formation, they are currently areas of thick Ogallala sediments, and consequently greater aquifer thickness. In addition, the Ogallala Formation sediments tend to be coarser and more permeable within the paleochannels than outside the paleochannels, adding to the aquifer production capacity within the paleochannels (Blandford et al., 2003). A significant paleochannel, called the Mustang Draw paleochannel in this report, is approximately commensurate with the surface drainages of Mustang Draw, Monument Draw, and Seminole Draw (Figure 6).

Discharge from the Ogallala Aquifer originally occurred naturally to numerous springs throughout the region. However, as groundwater production from the aquifer has increased over time, groundwater levels in the aquifer have declined, and many springs no longer flow (Hopkins, 1993). In addition, changes in Ogallala Aquifer water levels affect the amount of water exchanged between the Ogallala Aquifer and adjacent, underlying formations (Hopkins, 1993).

Recharge to the Ogallala Aquifer is low, and generally is through the infiltration of precipitation, as well as the vertical movement upward of groundwater from deeper formations. Recent studies in the Central High Plains have indicated that the majority of recharge from precipitation occurs through infiltration in playas, stream drainages, and stock impoundments; minimal recharge occurs outside these areas (Reedy et al., 2003). Precipitation is the only external source of recharge to the aquifer. The recharge rate to the Ogallala Aquifer is variable, with different studies estimating rates of recharge from virtually zero to as high as several in/yr beneath playas (Blandford et al., 2003). Due to the high evaporation rates and slow infiltration rates, only a small portion of water from precipitation results in recharge to the water table (Peckham and Ashworth, 1993). Overall, average estimated recharge rates are nearly zero to almost 1 in/yr (Peckham and Ashworth, 1993).

In some areas groundwater quality in the Ogallala Aquifer is influenced by the upward movement of groundwater from underlying formations. Water quality in the Ogallala Aquifer is generally good, but in the southern portion of the aquifer, including the Andrews County area, Ogallala Aquifer water is more saline due to the upward seepage of groundwater from the underlying Dockum Aquifer (LBG-Guyton, 2003). Ogallala Aquifer water quality in Andrews County is commonly slightly saline, with total dissolved solids (TDS) concentrations of 1,000 to 3,000 milligrams per liter (mg/L) (Ashworth et al., 1991). Other constituents, including chloride, sulfate, fluoride, nitrate, manganese, and selenium, are present at concentrations above drinking water standards in some wells in Andrews County (Ashworth et al., 1991).

The mean hydraulic conductivity of the Ogallala Aquifer is approximately 7 feet per day (ft/d), and ranges from nearly zero to over 1,000 ft/d (Blandford et al., 2003). Higher hydraulic conductivities occur in the coarser-grained deposits present in the paleochannels. Outside the paleochannels, the estimated hydraulic conductivity is generally less than 5 ft/d (Blandford et al., 2003). Average specific yield of the Southern Ogallala Aquifer is generally considered to be 15 percent.

3.2.2 Pecos Valley Aquifer

The Pecos Valley Aquifer is classified as a major aquifer by the state of Texas and is present in the Tertiary- to Quaternary-age sand, gravel, silt, and clay basin-fill deposits of the Pecos Valley Alluvium. The aquifer consists of two hydrologically separate troughs—the Pecos Trough to the west and the Monument Draw Trough to the east. The Monument Draw Trough is similar in extent to the underlying Capitan Reef Complex (Figure 5). University Lands in the five-county area lie at the western margin of the Monument Draw Trough (Figure 5). Most groundwater produced from the Monument Draw Trough is for municipal supply, primarily for cities and towns north or east of the aquifer.

The TWDB maps the Pecos Valley Aquifer into the southwest corner of Andrews County, where it is contiguous with the Ogallala Aquifer. The demarcation between the aquifers is defined as the watershed divide between the Rio Grande and Colorado River Basins. In this study, all saturated Quaternary and Tertiary deposits in southwest Andrews County are considered to be the Ogallala Aquifer (Figure 6).

Groundwater in the Pecos Valley Aquifer occurs under unconfined or semiconfined conditions. The semiconfined conditions occur due to the presence of interbedded clays and silts within the Pecos Valley Alluvium. The saturated thickness of the Pecos Valley Aquifer exceeds 800 feet in the Monument Draw Trough (Meyer et al., 2012). White (1971) uses the term “Allurosa” Aquifer in reference to the combined water-producing portions of the Pecos Valley Alluvium and the underlying Santa Rosa Formation, which is common within the Monument Draw Trough.

Recharge of the Pecos Valley Aquifer occurs through the infiltration of precipitation, irrigation return flow, and seepage from irrigation ditches and canals (White, 1971). The only source of recharge in the study area is precipitation. Most of the precipitation either evaporates or is transpired, and significant recharge only occurs during infrequent significant rainfall events

(Garza and Wesselman, 1959). Within Winkler and Ward Counties, recharge is the highest beneath a series of sand dunes that extend from southeast New Mexico into Winkler and Ward Counties approximately along the eastern margin of the Monument Draw Trough (Garza and Wesselman, 1959; White, 1971).

Prior to significant pumping, groundwater discharge from the Pecos Valley Aquifer was to the Pecos River south of the study area. With the onset of significant groundwater pumping in the 1940s, water levels in the aquifer began to decline, although water levels have partially recovered since the 1970s due to reduced pumping (Garza and Wesselman, 1959; Anaya and Jones, 2009). Groundwater levels in the study area are currently generally stable.

Wells completed in the Monument Draw Trough can yield in excess of 1,000 gpm, while wells in the thinner portions of the alluvium can produce between 100 and 300 gpm (Garza and Wesselman, 1959). Aquifer properties are variable throughout the aquifer. White (1971) noted that aquifer transmissivities in Ward County range from 1,470 to 32,100 square feet per day (ft^2/d), with hydraulic conductivities of 25 ft/d to about 300 ft/d. However, he also noted that hydraulic conductivities were less than about 50 ft/d in 80 percent of the tests, and the highest transmissivity and hydraulic conductivity estimates were significantly higher than those of the other tests. Specific capacities ranged from 0.3 to 173 gallons per minute per foot (gpm/ft), with the most permeable deposits and highest-capacity wells producing from Pecos River gravel deposits near Barstow and Grandfalls south of the study area (White, 1971). Anaya and Jones (2009) noted that the geometric mean of hydraulic conductivity for the Pecos Valley Aquifer is approximately 8.6 ft/d, resulting in transmissivity estimates as high as 14,000 ft^2/d. Aquifer properties determined from pumping tests in the Pecos Valley Aquifer in Winkler County show transmissivities of approximately 3,300 ft^2/d in areas where the alluvium was at least 600 feet thick (Garza and Wesselman, 1959).

Groundwater quality in the Pecos Valley Aquifer is variable due to natural conditions and anthropogenic sources. Water quality in the Monument Draw Trough is generally fresh (TDS <1,000 mg/L) to slightly saline (TDS 1,000 to 3,000 mg/L) (LBG-Guyton, 2003). TDS concentration tends to increase with increasing depth (White, 1971). Within Ward County, nearly one-half of the reported groundwater quality samples were fresh, approximately one-quarter were slightly saline, and the remaining one-quarter were moderately saline (White, 1971). Groundwater quality in Winkler County shows similar trends to those in Ward County—fresh groundwater overall, particularly in the Monument Draw Trough, and slightly to moderately saline groundwater in other areas of the county (LBG-Guyton, 2003). It should be noted that most water wells in Ward and Winkler County tend to be shallow in relation to the aquifer thickness, and therefore do not yield groundwater from the higher TDS portions of the Pecos Valley Aquifer at depth.

3.2.3 Dockum Aquifer

The Dockum Aquifer is classified as a minor aquifer by the state of Texas. Dockum Aquifer is the term used for all of the water-bearing units in the Triassic Dockum Group (Bradley and Kalaswad, 2003). The Dockum Group is present across a large part of the state, from the Panhandle region to the Trans-Pecos region. Maps of the Dockum Aquifer prepared by the TWDB do not include portions of the aquifer that have an estimated downdip water quality of 5,000 mg/L TDS or greater (Bradley and Kalaswad, 2003).

The Dockum Group is typically divided into the Upper Dockum, consisting of the Cooper Canyon Formation and the Trujillo Sandstone, and the Lower Dockum, consisting of the Tecovas Formation and the Santa Rosa Formation (Figure 4). Geologic descriptions of these formations are provided in Section 3.1.2. The Upper and Lower Dockum Groups occur throughout the study area, except that the Upper Dockum Group may be absent in portions of the Monument Draw Trough (White, 1971). Groundwater is obtained from both units, although production capacity in generally higher in the Santa Rosa Formation of the Lower Dockum Group (Bradley and Kalaswad, 2003).

Water in the Dockum Aquifer in the study area occurs under confined conditions. Water level maps constructed during development of the Dockum Aquifer groundwater availability model (GAM) indicate an overall southerly to southeastern movement of groundwater in the aquifer prior to significant groundwater development (Ewing et al., 2008). Regional hydrographs in Dockum Aquifer wells vary, with some hydrographs indicating distinct water level declines over time and others showing stable water levels or only small declines (Bradley and Kalaswad, 2003). There are no Dockum Aquifer well hydrographs within the study area. The regional direction of groundwater flow for more recent periods has remained to the south or southeast, altered locally by pumping centers (Ewing et al., 2008).

Recharge to the Dockum Aquifer occurs from infiltration of precipitation or other sources of water in the outcrop areas, or from cross-formational flow from adjacent aquifers. Because the study area is far removed from the nearest outcrop area, Dockum Aquifer recharge within or near the study area, as well as induced groundwater flow that occurs in response to groundwater production, is from cross-formational flow from adjacent aquifer units above or below the Dockum Group. Similarly, Dockum Aquifer discharge that does not occur to wells will occur as cross-formational groundwater flow to adjacent aquifers.

The primary groundwater-producing unit in the Dockum Aquifer is the basal Santa Rosa Formation, synonymous with the Santa Rosa Sandstone. Locally, any water-bearing sandstone in the Dockum Group is often referred to as the “Santa Rosa,” a practice that has led to confusion in the literature regarding which geologic unit is actually the Santa Rosa Sandstone (Bradley and Kalaswad, 2003). Well yields in the Dockum Aquifer vary widely. Reported well yields range from as low as 0.5 gpm in Mitchell County to as high as 2,500 gpm in Winkler County (Bradley and Kalaswad, 2003). White (1971) documents specific capacities of less than 5 gpm/ft in Ward County for wells east of the Monument Draw Trough that were producing primarily from the Santa Rosa Formation (White, 1971). Bradley and Kalaswad (2003) report that mean specific capacities of Dockum Aquifer wells range from 0.14 to 25 gpm/ft, with an overall mean of about 4 gpm/ft. Ewing et al. (2008) report that analyses of multiple aquifer test results indicate hydraulic conductivities ranging from 1 to 100 ft/d, averaging between 20 and 30 ft/d. They also noted significant variability in hydraulic conductivity over short lateral distances in the Lower Dockum Group, and that hydraulic conductivity decreased with increasing depth. Reported storage coefficients range from about 4×10^{-5} to 2×10^{-3}, with mean estimates of approximately 1×10^{-4} or 2×10^{-4} (Bradley and Kalaswad, 2003; Ewing et al., 2008).

Two Santa Rosa wells drilled for the City of Kermit produced between 1,200 and 1,900 gpm of water, with transmissivities estimated at 3,340 ft^2/d and a storage coefficient of 0.0003 (Garza and Wesselman, 1959). However, Garza and Wesselman (1959) believed that the highly productive zone of the Dockum Group was probably not extensive, and note that yields in most of the other Santa Rosa Formation wells were significantly lower.

Water quality in the Dockum Aquifer ranges from fresh (TDS <1,000 mg/L) in outcrop areas and a few other areas at the edges of the depositional basin to brines with over 50,000 mg/L TDS in the middle of the basin (Ewing et al., 2008; LBG-Guyton, 2003). Beneath the Andrews County area, the Dockum Aquifer contains slightly to moderately saline groundwater (TDS 1,000 to 10,000 mg/L). Upward movement of groundwater from the Dockum Aquifer in this area has led to poorer water quality in the overlying Ogallala Aquifer than occurs in most other areas. In Ector County, Dockum wells produce groundwater with TDS concentrations between 2,000 and 7,000 mg/L and sulfate and chloride concentrations up to 2,500 mg/L from wells that are 430 to 710 feet deep (Knowles, 1952). Water quality from the Dockum Aquifer in Winkler County is generally better in the west than the east, with the lowest TDS concentrations detected near the town of Kermit (Garza and Wesselman, 1959). In the eastern half of the county, the Dockum has TDS concentrations of 1,000 to 4,000 mg/L. Water produced from the Dockum Aquifer in Winkler County is typically hard and can be high in sulfate and fluoride (Garza and Wesselman, 1959).

The presence of uranium minerals in the Dockum Group has long been recognized, and is the source of some radiological constituents (radium-226 and -228) reported in some Dockum Aquifer groundwater samples (Bradley and Kalaswad, 2003; McGowen et al., 1979). The concentrations of some trace metals, including antimony, beryllium, cadmium, lead, mercury, selenium, and thallium, were reported to exceed drinking water regulatory limits in several counties (Bradley and Kalaswad, 2003).

3.2.4 Rustler Aquifer

The Rustler Aquifer is classified as a minor aquifer by the TWDB. Few studies have been performed on the hydrogeology of the Rustler Aquifer because of the small quantities of groundwater it produces and because sufficient quantities of better quality water can typically be produced from shallower aquifers (Ewing et al., 2012). Groundwater in the Rustler Aquifer primarily occurs in solution openings in dissolved limestone, dolomite, and gypsum, which results in highly variable well yields and poor water quality. The Rustler Aquifer extent as mapped by the TWDB does not include Andrews County or most of the five-county study area (it does include some University Lands in southeastern Loving County and western Ward County). The Rustler Formation does, however, occur beyond the aquifer extent mapped by the TWDB (including the remainder of the study area), but these additional regions are not considered part of the aquifer by TWDB due to poor water quality. Where groundwater is produced from the Rustler Aquifer, it is typically used for irrigation, livestock, domestic, and tertiary oil recovery.

Limestone and dolomite zones within the Rustler Formation can be cavernous and highly productive. However, highly productive wells are sporadic and located close to low-productivity wells (White, 1971). Ewing et al. (2012) identify two independent flow systems within the Rustler Aquifer. One is a system of recharge in the Rustler outcrop area and discharge to the Pecos River and cross-formational flow to adjacent aquifers where the aquifer is shallow. A second flow system is indicated farther downdip, with water coming in from the Tessey Limestone. Existing data imply that these two systems are not connected.

Within the study area, groundwater in the Rustler Aquifer occurs under confined conditions and recharge is from cross-formational flow (LBG-Guyton, 2003). Rustler Aquifer water also discharges to adjacent formations. Limited water level data indicate that groundwater flow in the Rustler Aquifer is to the southeast in the Loving and Winkler Counties area and to the south in Ward and Crane Counties, toward a potentiometric low near the Pecos River. Discharge from the Rustler Aquifer in this area may be to the overlying Edwards-Trinity (Plateau) Aquifer and ultimately to the Pecos River (Ewing et al., 2012).

Relatively few wells have been completed in the Rustler Aquifer. Ewing et al. (2012) report that only 95 wells completed in the Rustler Aquifer were identified in Texas, with 63 of these wells falling within the TWDB Rustler Aquifer boundary (primarily in Pecos and Reeves Counties). Consequently, little is known about the hydraulic properties of the Rustler Aquifer. Well yields are highly variable, with wells capable of producing almost no groundwater and wells that can produce over 4,000 gpm (Ewing et al., 2012). Garza and Wesselman (1959) report that production from the Rustler Aquifer is sporadic in Winkler County, with some wells producing up to 800 gpm from the formation where it is 300 to 500 feet thick. Storage coefficient estimates for the Culebra Dolomite Member of the Rustler Formation range from 1.5×10^{-5} to 5.7×10^{-4} (Ewing et al., 2012).

Overall water quality in the Rustler Aquifer is poor, with most wells yielding saline to brine water. Fresh groundwater is found only in a limited area near the Rustler Formation outcrop in Culberson County. Brown (1998) indicated that Rustler Aquifer wells produced groundwater with TDS concentrations between 1,000 and 5,000 mg/L, and an average aquifer-wide TDS concentration of approximately 2,800 mg/L. Clear water quality patterns have not been identified, but in general groundwater produced from the upper Rustler is of better quality than groundwater produced from the lower Rustler, which can be saline with TDS concentrations of over 10,000 mg/L (LBG-Guyton, 2003). Rustler Aquifer groundwater is primarily a sodium and chloride water (White, 1971).

Trace metals concentrations are generally insignificant in groundwater produced from the Rustler Aquifer, with only iron and manganese concentrations elevated above the drinking water standard in a few wells (Brown, 1998; Ewing et al., 2012). Naturally occurring radioactivity was also detected in many wells (Brown, 1998).

3.2.5 Capitan Reef Complex Aquifer

The Capitan Reef Complex Aquifer is classified as a minor aquifer by the state of Texas and is present in the porous limestones and dolomites of the Capitan Reef and related formations. This aquifer occurs beneath portions of University Lands Blocks 16 and 21 in Ward and Winkler Counties, respectively, and borders the eastern edge of block 17 (Figure 5). The Capitan Reef Complex Aquifer is composed of up to 2,000 feet of massive, cavernous limestone and dolomite. The aquifer forms a 7- to 10-mile-wide horseshoe shape essentially rimming the Delaware Basin. The eastern side of the aquifer is present beneath University Lands in Winkler, Ward, and Pecos Counties, and ultimately terminates in the Glass Mountains to the south in Brewster County where the Capitan Reef Complex outcrops (Figure 3). The Capitan Reef Complex Aquifer is not extensively developed in Texas, and is virtually undeveloped in the study area. In Ward and Winkler Counties, most groundwater produced from the aquifer is used for tertiary oil recovery (LBG-Guyton, 2003).

Well depths vary from shallow in the mountain areas where the formation outcrops to over 4,000 feet in Ward and Winkler Counties. In the downdip portion of the aquifer, groundwater is under significant confining pressure. Due to the cavernous nature of the Capitan Reef Complex rocks, well yields can be high. Limited data and information exist on the aquifer hydraulic properties (White, 1971; LBG-Guyton, 2003). LBG-Guyton (2003) indicates that transmissivities of the Capitan Reef Complex Aquifer average approximately 5,350 ft^2/d, but may be as high as 16,040 ft^2/d. Storage coefficients are estimated to be 1×10^{-3} to 1×10^{-4} (LBG-Guyton, 2003).

The quality of groundwater produced from the Capitan Reef Complex Aquifer is also highly variable. Fresh groundwater is generally present in and near the outcrop areas in the Glass Mountains in Brewster and Pecos Counties and the Guadalupe, Delaware, and Apache Mountains in Culberson County to the west (LBG-Guyton, 2003). Recharge from precipitation occurs on outcrops along the Guadalupe Mountains and recharge by infiltration occurs in the Glass Mountains (Richey and Wells, 1985). In the downdip areas, including Ward and Winkler Counties, moderately saline to saline groundwater is produced, including some deep wells in Ward County producing groundwater with TDS concentrations in excess of 10,000 mg/L (Brown, 1997; LBG-Guyton, 2003). The eastern side of the Capitan Reef Complex, which includes the study area, produces groundwater that is notably warmer and has higher concentrations of all dissolved analytes relative to those observed for the western side of the aquifer, primarily in Culberson County (Brown, 1997). Naturally occurring radioactivity was detected in several deep wells in northern Pecos, Ward, and Winkler Counties, including gross alpha, gross beta, radium-226, and radium-228 (Brown, 1997). Groundwater produced from the deepest parts of the aquifer is corrosive and used only for secondary oil recovery.

4. Data Sources and Analysis

Data sources used for the geologic and hydrogeologic analysis contained in this report include scanned geophysical logs from the University Lands geophysical log library, University Lands water well data, geophysical logs, scout tickets, and cable tool driller reports obtained from BEG data archives, driller reports from the TWDB groundwater database (TWDB, 2015b), and driller reports submitted to the TDLR and the TCEQ. Well information was collected and screened for the study area (Figure 2) and a 2-mile buffer surrounding the University Lands tracts. Ultimately, 1,355 data points were used to interpret the geology and hydrogeology of the study area (Figure 8).

The goal of the geologic data analysis was to identify geologic formations that are known or potential aquifer units within approximately 3,000 feet of the land surface. Based on the project scope of work and additional discussions with University Lands, surfaces were evaluated for the following geologic formations and material types (Figure 4):

- Bottom of the Pecos Valley Alluvium or the Ogallala Formation (top of Dockum Group). Where Trinity Group sand exists below the Ogallala Formation, it is included with the Ogallala Formation.

- Bottom of Upper Dockum Group (top of Lower Dockum Group)

- Bottom of Santa Rosa Formation (top of Dewey Lake Formation, also base of Dockum Group).

- Combined section of Permian evaporitic formations undifferentiated in this report. The undifferentiated evaporite section includes, where present, the Rustler, Salado, Castile, and Tansill Formations. This section begins with the top of anhydrite of the Forty-Niner Member of the Rustler Formation, and ends at the top of the Yates Formation within the Artesia Group, the Capitan Reef Complex, or the Delaware Mountain Group, depending on location.

- Bottom of Artesia Group, where it exists.

- Where the Capitan Reef Complex is present in Ward and Winkler Counties, its top surface is mapped in the cross sections. The base of the 3D geologic model in these counties is the top of the Delaware Mountain Group.

In some instances additional formations were identified and entered into the database (e.g., Seven Rivers and Grayburg Formation tops in the Artesia Group). These additional picks are not represented in the 3D geologic models or the cross sections.

Data sources used in the analysis are summarized in the following subsections.

4.1 Geophysical Logs

Geophysical logs used in the study were obtained from three sources, as described in the following subsections.

4.1.1 University Lands Geophysical Logs

The University Lands geophysical log library contains approximately 8,000 logs in the study area. Initial log selection was conducted randomly in each county; if a log was not useful for the required analysis, another was selected.

For each selected log, initial data acquisition consisted of recording top of log elevation, elevation of the bottom of surface casing, total depth, log type, year drilled, and existing formation picks marked on the log. An objective of this step was to compile more logs than needed for the final analysis so that logs with unsuitable data could be omitted from the study. Initially, over 1,100 University Lands geophysical logs were selected. Approximately 100 of these logs were subsequently omitted from the study due to unsuitable log intervals or data quality limitations.

Next, the dataset was mapped to determine data density and spatial distribution. Ultimately, after thinning data clusters and removing questionable logs, approximately 570 logs remained in the study. Formation picks on these logs were recorded to depths of 3,000 to 5,000 feet, depending on the well location. Typically, formation tops were picked on the gamma log.

4.1.2 BRACS Study Geophysical Logs

The TWDB Pecos Valley Alluvium Brackish Resources Aquifer Characterization System (BRACS) study (Meyer et al., 2012) characterized geologic structure and brackish water resources in the Pecos Valley Aquifer. The BRACS study area included the five-county area and the southwestern corner of Andrews County.

Over 1,400 geophysical logs and nearly 1,700 water well reports were used in the BRACS study. Nearly 200 geophysical logs with formation tops picked for the study are located within the study area; ultimately, 113 BRACS logs were incorporated into this study. BRACS data were omitted in select locations where the BRACS formation picks conflicted with picks on logs selected from the University Lands library. The BRACS data included formation picks for top of the Pecos Valley Alluvium, Dockum Group, Dewey Lake Formation, Rustler Formation, Yates Formation, and Bell Canyon Formation (top of Delaware Mountain Group). At select locations, formation picks were recorded to the Precambrian. The top of the Lower Dockum Group was interpreted where practical on the BRACS geophysical logs.

4.1.3 BEG Geophysical Logs

The BEG maintains a geophysical log library with API number, location coordinates, and geophysical log top and bottom elevations. A total of 26 logs were selected from this library to infill areas lacking well control.

4.2 Water Well Driller Reports

Water well reports were compiled from University Lands, TDLR, TWDB, the TCEQ, and published reports. Collectively, 125 state well reports were used for this study. Screened intervals, total depths, and top of the Dockum Group data were extracted from these water well reports. These data were used to infill the 2-mile buffer zones.

A total of 19 water well geophysical logs and driller reports from the University Lands well library supplemented areas lacking well control and provided additional data points in areas with drilling activity. These water well geophysical logs are recorded in uncased boreholes and provide high-resolution information useful for accurate formation picks.

4.3 Confidence Ranking for Formation Picks

Each well (data point) was assigned a formation pick confidence estimate to assist with interpretation reliability. The confidence ranking scale ranges from 1 to 5, with 1 representing the lowest confidence and 5 representing the highest confidence. The interpretation reliability attribute for a well location can be considered when using surfaces provided as part of this study. For example, if there is a cluster of wells with confidence values of 2 or 3, then the surface should be considered more “interpretive” and may benefit from refinement as additional well information becomes available.

Confidence levels for formation picks were assigned as follows. Using the five shallowest surfaces in any given area, a value of 1 was assigned where a pick was determined, and a 0 was assigned where a pick of a formation top could not be determined. Summing these values for the five shallowest surfaces at each location resulted in scores ranging from 1 to 5. Logs with scores of 1 or 2 were considered to have low confidence values, logs with scores of 3 and 4 were considered to have moderate confidence values, and logs that scored 5 were considered to have a high confidence value. Using this ranking system, 54 logs scored low, 226 logs scored moderate, and 433 logs scored high confidence values.

5. Results

This section provides the results of study, focusing first on the geology (Section 5.1) and then the hydrogeology (Section 5.2).

5.1 Geology

The geologic interpretations are presented in cross sections, geologic unit thickness maps, and 3D interactive geologic models. The cross sections and geologic unit thickness maps for the five-county and Andrews County areas are provided in Appendices A and B, respectively. The 3D models for each of these areas are provided in Appendix C.

5.1.1 Five-County Area

The surface geology for the five-county area is provided in Figure 5. Geologic cross sections and geologic unit thickness maps are provided in Appendix A. The surface geology is primarily composed of Quaternary alluvium and dune sands. There is limited outcrop of the Fredericksburg and Trinity Groups immediately east of University Lands Block 35 in Ector County (Figure 5). Study results for each of the major geologic units are described in the following subsections.

5.1.1.1 Pecos Valley Alluvium

The Pecos Valley Alluvium is present at the surface in the five-county area. The alluvium was deposited on an erosional surface (top of the Dockum Group), and therefore exhibits significant local variability. In addition, significant solution collapse has formed large coalescing depressions within the Monument Draw Trough, and relatively isolated solution collapse features are present in some locations (Section 3.2).

The Pecos Valley Alluvium generally dips from west to east and is relatively thin in eastern Loving, western Winkler, and western Ward Counties (University Lands Blocks 18, 19 and 20), where it varies in thickness from less than 50 feet to approximately 220 feet (cross sections A-A’, B-B’, and C-C’ in Appendix A). The alluvium thickens eastward toward the edge of the

Monument Draw Trough. In University Lands Block 17, the alluvium thickens to over 700 feet (cross section E-E’ in Appendix A). Some of the larger solution collapse features near the western extent of the Monument Draw Trough are present in the west-central portion of Block 17. In these features, the Pecos Valley Alluvium is about 1,000 feet thick. These features are best viewed in the 3D geologic model, but they can be discerned as the darker (greater thickness) areas along the western edge of Block 17 in Figure A-10 (Appendix A).

In Block 21, solution collapse features aggregated to form the regional structural collapse zone of the Monument Draw Trough. The thickness of Pecos Valley Alluvium in the easternmost portion of Block 21 exceeds 1,000 feet at most locations (cross sections A-A’, B-B’, and F-F’ in Appendix A), and the maximum alluvium thickness is nearly 1,700 feet (Figure A-10 in Appendix A). In University Lands Block 16, the Pecos Valley Alluvium thickness varies from 450 feet to nearly 1,200 feet (cross section C-C’ and Figure A-10 in Appendix A).

In University Lands Block 35 in Ector County, the alluvium thickness ranges from approximately 50 to 150 feet.

5.1.1.2 Dockum Group

The Dockum Group generally dips from northwest to southeast (cross sections A-A’ and B-B’ in Appendix A). Within the Monument Draw Trough in University Lands Block 16, the Upper Dockum Group is thin (cross sections C-C’ and E-E’ in Appendix A).

The thickness of the Upper Dockum Group increases from west to east (Figure A-11 in Appendix A), with the exception of University Lands Block 16 as noted above. In Loving and Ward Counties, the thickness of the Upper Dockum ranges from 30 to 130 feet, with an average thickness of about 80 feet. In Winkler County University Lands tracts, the Upper Dockum Group thickness ranges from about 100 feet to over 350 feet, with an average thickness of about 240 feet. In the north-central portion of Block 21, the Upper Dockum Group thickness approaches 900 feet within a limited area (Figure A-11 in Appendix A).

Thickness of the Lower Dockum Group increases from northwest to southeast across the University Lands in Loving, Ward, and Winkler Counties (Figure A-12 in Appendix A). On

University Lands in Loving and Winkler Counties, the thickness of the Lower Dockum Group ranges from about 55 to 500 feet. The Lower Dockum Group thickness is greater in Ward County, ranging from about 330 feet to nearly 1,100 feet in limited areas (Figure A-12).

In University Lands Block 35 in Ector County, the thickness of the Upper Dockum Group ranges from about 45 feet to nearly 100 feet, and the thickness in the Lower Dockum Group ranges from about 430 to 710 feet.

5.1.1.3 Rustler Anhydrite and Other Evaporites

The Rustler Formation and other undifferentiated Permian evaporites occur beneath the entire five-county area. The thickness of the undifferentiated Permian evaporites is greatest (nearly 4,500 feet) west of the Monument Draw Trough, and is least (approximately 1,000 to 1,500 feet) within the trough (cross sections B-B’ and C-C’ and Figure A-14 in Appendix A). The undifferentiated Permian evaporites are approximately 1,300 feet thick in Ector County (cross section H-H’, Appendix A).

5.1.1.4 Artesia Group

In the five-county area, the Artesia Group occurs only in University Lands Block 35 in Ector County, where the top of the Artesia Group is relatively flat-lying and occurs at about 2,500 feet bgs (cross section H-H’ in Appendix A).

5.1.1.5 Capitan Reef Complex

The Capitan Reef Complex underlies the eastern three-quarters of University Lands Block 16 in Ward County and the eastern one-third of Block 21 in Winkler County (Figure 5). The depth to the top of the Capitan Reef Complex below University Lands Block 16 ranges from about 3,250 feet to 3,550 feet on the eastern edge of the block (cross sections C-C’ and G-G’ in Appendix A). In University Lands Block 21, the depth to the Capitan Reef Complex ranges from approximately 3,100 to 3,300 feet (cross sections A-A’, B-B’, and F-F’ in Appendix A). The thickness of the Capitan Reef Complex ranges from 0 to more than 2,100 feet (Figure A-15 in Appendix A).

5.1.2 Andrews County Area

The surface geology for the Andrews County area is provided in Figure 6. Geologic cross sections and geologic unit thickness maps are provided in Appendix B. The surface geology is primarily Quaternary alluvium, dune sands, and Ogallala Formation along Mustang Draw and its tributaries and larger depressions. Small outcrops of Dockum Group and Cretaceous sediments occur along the western margin of Shafter Salt Lake in central Andrews County adjacent to University Lands Block 14. The Lower Dockum Group and older rocks in this area exhibit relatively uniform geology with near-horizontal bedding, consistent with their location within the Central Basin Platform and the western margin of the Midland Basin (Figure 3). The thicknesses of the Dockum Group, the Dewey Lake Formation, and the Artesia Group increase from west to east as the Central Basin Platform transitions into the Midland Basin (Figure 3). The top of the Dockum Group is an erosional surface on which the Ogallala Formation was deposited. The top of the Dockum Group and the thickness of the Ogallala Formation therefore have greater variability than the other geologic units.

Study results for the major geologic units are described in the following subsections.

5.1.2.1 Ogallala Formation

The base of the Ogallala Formation was determined from the well logs analyzed in this study in combination with the base of aquifer map used in Blandford et al. (2003). The base of the Ogallala Formation generally dips to the east-southeast across Andrews County, ranging from 3,250 feet msl in the west to about 2,750 feet msl near the Andrews-Martin County line. The Ogallala Formation ranges in thickness from about 50 feet to as high as approximately 300 feet in the center of the Mustang Draw paleochannel in University Lands Blocks 4 and 5 (cross sections J-J’, K-K’, and L-L’ and Figure B-13 in Appendix B).

5.1.2.2 Dockum Group

In Andrews County, the top of the Dockum Group dips from west to east, with the highest elevations in Block 12 at approximately 3,250 feet msl. The lowest elevation of the top of the Dockum Group occurs in Block 6 along the Andrews-Martin County line at 2,750 feet msl. The elevation change of this surface across Andrews County from west to east is about 500 feet.

The base of the Upper Dockum is highest in southwestern Andrews County with an elevation of approximately 3,000 feet msl in Block 11. The top of the Upper Dockum Group dips to the northeast, where the lowest elevations of about 2,300 feet msl occur in Block 6; this represents a total elevation change across Andrews County of about 700 feet (cross sections J-J', K-K', and L-L' in Appendix B). The highest elevation of the base of the Dockum Group occurs in southern Andrews County in Block 11. The surface dips southwest to northeast, with the lowest elevations present in Block 7 in northeast Andrews County (cross section S-S' in Appendix B).

The Upper Dockum Group is thickest (up to 700 feet in University Lands Block 13) in the northern half of Andrews County. The thinnest occurrences of the Upper Dockum Group (between 120 and 200 feet thick) are present in the southern portions of University Lands Blocks 9, 10, and 11 in southern Andrews County (Figure B-14 in Appendix B).

Review of the cross sections and thickness maps in Appendix B indicates that at many locations, the thickness of the Lower Dockum Group is approximately twice that of the Upper Dockum Group. The Upper Dockum Group generally thickens from west to east, and is thickest (over 1,300 feet) in Block 9 in southern Andrews County and in Block 5 in northern Andrews County. The Lower Dockum Group is thinnest, approximately 800 to 1,000 feet, in Blocks 11 through 14 in western Andrews County (Figure B-15 in Appendix B).

5.1.2.3 Rustler Anhydrite and Other Evaporites

The top of the Rustler Anhydrite and associated undifferentiated Permian evaporites slopes gently from west to east into the Midland Basin (cross sections K-K', L-L', and M-M' in Appendix B). The thickness of the Rustler Formation and other undifferentiated Permian evaporites ranges from about 925 feet in eastern Andrews County to over 1,300 feet in western Andrews County (Figure B-17 in Appendix B).

5.1.2.4 Artesia Group

The top of the Artesia Group is relatively flat-lying and occurs at about 3,000 feet bgs in Andrews County (cross sections in Appendix B). The thickness of the Artesia Group ranges from about 1,200 feet in western Andrews County to over 2,000 feet in eastern Andrews County (Figure B-18 in Appendix B).

5.2 Hydrogeology

This section presents available hydrogeologic data, analysis, and interpretations for the study area. Much of the analysis presented in this section is derived from information in the University Lands water well database described in Section 5.2.1. Water quality is presented in accordance with the categories used by the TWDB based on TDS concentrations in mg/L, where fresh water has TDS concentrations of 0 to 1,000 mg/L, slightly saline water has TDS concentrations of 1,000 to 3,000 mg/L, moderately saline water has TDS concentrations of 3,000 to 10,000 mg/L, and very saline water has TDS concentrations of 10,000 to 35,000 mg/L.

5.2.1 University Lands Water Well Database

5.2.1.1 Database Construction

The water well database is a compilation of water well data from multiple sources including University Lands water well applications, University Lands water well GIS shapefiles, the Railroad Commission of Texas, the TDLR, and the TWDB (TWDB, 2015a). Combination of these data sources produced many duplicate records (records for the same well that appear in more than one dataset). The files were analyzed and compared with each other during a process of deduplication. The well count for the entire database is 3,766 wells, of which 1,113 wells are located in the study area (324 in the five-county area and 789 in the Andrews County area).

5.2.1.2 Aquifer Designations

Water wells were assigned an aquifer, or multiple aquifers, by comparing the well attribute data to GIS-based aquifer surfaces extracted from the 3D geologic models described in Section 5.1. Attribute data include screen interval(s), well depth, and aquifer designation assigned in the TWDB groundwater database. Within ArcGIS, each well was assigned a value for the depth of each aquifer at the well location. These depth values were then compared to the well's attribute data to identify the aquifer from which the well produces.

Because not all wells have each of these attributes, aquifer designations were assigned to each well based on hierarchal criteria. The screened intervals were used first to calculate whether the top of a well's screen and the bottom of a well's screen are in a particular aquifer. There were 380 wells with screened interval data in the water well database within the study area. Of these wells, 129 were in the five-county area and 251 were in the Andrews County area.

There are 364 wells that have no screen interval data but have well depth values. These wells were assigned an aquifer based on their depth only. Finally, there were 33 wells that have no screen interval and no well depth value, but have a TWDB aquifer code attribute. For these wells, the TWDB aquifer designation was used to assign the well to the corresponding aquifer designation used in the University Lands water well database. For example, "Antlers Sand" in the TWDB aquifer codes was assigned to "Trinity Group" in the University Lands water well database.

The majority of wells were assigned aquifer designations of Ogallala (442 wells) or Pecos Valley (189 wells). Of the remaining wells that received an aquifer designation, 55 are completed in the Upper Dockum Group, 47 are completed in the Lower Dockum Group, and 15 are completed across multiple aquifer units. Scenes can be selected in the 3D geologic models that illustrate water well depths and, where available, screen intervals.

5.2.2 Pecos Valley Aquifer

The Pecos Valley Aquifer is the first aquifer that occurs beneath University Lands in the five-county area. Wells completed in the Pecos Valley Aquifer are illustrated in Figure 8. Most of the wells in the eastern portion of University Lands Block 16 are municipal supply wells completed in the Monument Draw Trough. Although Pecos Valley Alluvium is present beneath the Ector County portion of the study area (University Lands Block 35), the alluvium is generally not saturated.

The depth to water under University Lands in the five-county area generally ranges from approximately 50 to 150 feet bgs. Saturated thickness ranges from 0 to more than 1,500 feet, reflecting the variability of the base of alluvium (Meyer et al., 2012). The greatest saturated thickness occurs within the Monument Draw Trough (Figure 5). Limited saturated thickness occurs west of the Monument Draw Trough, where relatively thin alluvial sediments overlie the structural high that separates the Monument Draw Trough and Pecos Troughs of the Pecos Valley Aquifer (cross sections A-A', B-B', and D-D' in Appendix A).

A potentiometric surface (water level) map for the Pecos Valley Aquifer is provided in Figure 9. Due to limited observed water level data, measurements from a range of water elevation measurement dates were used to develop the map. Groundwater flow in the Pecos Valley Aquifer beneath University Lands Blocks 17 through 21 is generally to the southeast toward the Monument Draw Trough. Within the trough, groundwater flow is generally to the south-southeast, aligned with the axis of the trough. A local cone of depression is evident in the eastern portion of Block 16 due to pumping from municipal supply wells.

Pecos Valley Aquifer well hydrographs within or near University Lands in Ward, Winkler, and Loving Counties are also illustrated in Figure 9. The hydrographs indicate that water levels in the Pecos Valley Aquifer are generally stable. Two wells in the Monument Draw Trough show early water level declines of about 25 feet (well 46-24-705) and 40 feet (well 46-32-912), but currently have stable or increasing water levels.

Reported yields from wells completed in the Pecos Valley Aquifer are presented in Figure 10. Reported yields are generally approximate estimates provided by the driller. Reported well yields can be influenced by many factors other than aquifer properties, including well diameter and pump capacity. As indicated in Figure 10, Pecos Valley Aquifer well yields are small (0 to 50 gpm) in University Lands Blocks 17 through 20, and in the western portions of Blocks 16 and 21. This is consistent with the limited saturated thickness of the Pecos Valley Alluvium within the structural high west of the Monument Draw Trough. Wells completed in the Monument Draw Trough (eastern portions of University Lands Blocks 21 and 16) achieve significantly larger well yields of 200 gpm and higher due to the greater saturated thickness in this area.

Sand units equal to or greater than 15 feet thick within the saturated portion of the Pecos Valley Aquifer were tabulated for selected oil and gas well geophysical logs. Estimated total sand thickness ranges from 0 feet in Loving County to over 1,000 feet near the center of the Monument Draw Trough.

Pecos Valley Aquifer TDS concentrations are shown in Figure 11. As illustrated in the figure, water quality ranges from fresh (TDS <1,000 mg/L) to moderately saline (TDS 3,001 to 10,000 mg/L). Groundwater in the Monument Draw Trough is generally more saline along the western side of the trough and with increasing depth.

5.2.3 Ogallala Aquifer

The Ogallala Aquifer is the first aquifer that occurs beneath University Lands in the Andrews County area. Wells completed in the Ogallala Aquifer are shown in Figure 8.

An Ogallala Aquifer potentiometric surface map is provided in Figure 9. Groundwater flow is to the east-southeast. In northeastern Andrews County, groundwater flow is locally toward the Mustang Draw paleochannel (Figure 6 and Figure B-13 [Appendix B]). Groundwater flows toward this feature due to municipal water supply wells completed in the paleochannel (Figure 9).

Ogallala Aquifer well hydrographs within or near the Andrews County area are also provided in Figure 9. Observed water levels in the Andrews County area are generally stable (wells 27-51-701 and 27-45-901) or increasing (wells 27-35-701 and 27-45-201). Well 27-39-903, located near the Mustang Draw paleochannel (Figure B-13 in Appendix B), has experienced a long-term decline of about 40 feet. The general pattern of greater water level decline within and near paleochannels, and less decline outside of paleochannels, is consistent with other regions of the Southern High Plains (Blandford et al., 2003).

Reported yields from wells completed in the Ogallala Aquifer are presented in Figure 10. Reported yields are generally approximate estimates provided by the driller, although pumping tests are required for water wells completed on University Lands. Reported well yields can be influenced by many factors other than aquifer properties, including well diameter and pump capacity. As indicated in Figure 10, Ogallala Aquifer well yields are fairly small (100 gpm or less), with the exception of the northern portion of University Lands Block 4, where well yields greater than 200 gpm are reported. These higher-yield wells are completed in the Mustang Draw paleochannel (Figure B-13 in Appendix B). Yields from wells completed in paleochannels are generally greater than those completed elsewhere in the Ogallala Aquifer due to the greater saturated thickness and the more permeable nature of the sediments (Blandford et al., 2003).

The TDS concentrations of groundwater in the Ogallala Aquifer are shown in Figure 11. As illustrated in the figure, water quality ranges from fresh (TDS <1,000 mg/L) to moderately saline (TDS 3,001 to 10,000 mg/L).

5.2.4 Dockum Aquifer

The depth to the top of the Dockum Group from ground surface is presented in Figure 12, and is dependent on the ground surface elevation and the thickness of the overlying Ogallala Formation (Andrews County area) or Pecos Valley Alluvium (five-county area). The depth ranges from less than 100 feet outside of the Mustang Draw paleochannel in the Andrews County area and outside the Monument Draw Trough in the five-county area, up to 1,500 feet or more within the Monument Draw Trough (Figure 12).

The water well database contains 102 water wells completed in the Dockum Aquifer, with the distribution approximately equal between the Upper Dockum Group and the Lower Dockum Group. The well locations are shown in Figure 13. Sufficient water level data were not available to prepare Dockum Group potentiometric surface maps for the five-county area or for the Andrews County area. However, observed water levels for Dockum Aquifer wells were compared to water levels in the overlying aquifer. In the five-county area, only water levels from wells completed in the Upper Dockum Group were available. Comparison of Upper Dockum Group water levels with the water level contours provided in Figure 9 for the Pecos Valley Aquifer indicates that in University Lands Blocks 18, 19, and 20 the water levels are similar. Two Upper Dockum Group wells located close together in the north-central portion of Block 17 have water levels about 40 to 50 feet higher than those in the Pecos Valley Aquifer, indicating that vertical groundwater flow is upward from the Upper Dockum Group into the Pecos Valley Aquifer. The pattern of upward flow moving from west to east in University Lands Blocks 17 and 21, approaching the Monument Draw Trough, may be a regional pattern; however, insufficient data exist to verify this pattern at other locations.

In the Andrews County area, water level elevations in wells completed in the Upper Dockum Group in the southwestern (Blocks 9, 10, and 11) and northeastern (Blocks 4 and 6) portions of the county are similar to those observed in nearby Ogallala Aquifer wells. Upper Dockum Group wells in these areas are completed in the upper (shallower) part of the Upper Dockum Group, and appear to be hydraulically connected to the Ogallala Aquifer, as evidenced by the similar water levels.

Lower Dockum Group wells are present in University Lands Blocks 3, 4, 7, and 10 in northeastern Andrews County. Water levels in these wells are approximately 400 to 650 feet lower than those in the overlying Upper Dockum Group and Ogallala Aquifer. A Lower Dockum Group well in the northeastern quarter of Block 10 in south-central Andrews County also indicates a Lower Dockum Group water level about 400 feet lower than that of the Ogallala Aquifer. The direction of vertical groundwater flow in the Andrews County area is therefore downward from the Ogallala Aquifer and Upper Dockum Group into the Lower Dockum Group. These observations indicate that the overall vertical hydraulic conductivity between the Lower Dockum Group wells and the overlying (shallower) wells is low; otherwise, the large difference in water levels would not exist. Groundwater pumping from Lower Dockum Group wells will therefore have only small effects on water levels in the Ogallala Aquifer.

The reported yields from wells completed in the Dockum Aquifer are provided in Figure 14. Reported well yields can be influenced by many factors other than aquifer properties, including well diameter, well screen placement, and pump capacity. Reported yields for wells completed in the Upper Dockum Group are 50 gpm or less. Wells completed in the Lower Dockum Group generally have higher yields than those completed in the Upper Dockum Group, ranging from 50 to 200 gpm. Based on existing data, Lower Dockum Group well yields of 100 to 200 gpm are common within and near University Lands Blocks 3, 7, and 11. In University Lands Block 9, well yields are lower at 50 to 100 gpm (Figure 14).

The total sand interval thicknesses for the Upper and Lower Dockum Group are presented in Figures 15 and 16, respectively. The values provided in these figures were determined by identification of sand intervals 15 feet thick or greater on University Lands geophysical logs at the indicated locations. For the most part, the total sand thickness within the Upper Dockum

Group is 50 feet or less in the five-county area, but is generally greater than 100 feet in Andrews County (Figure 15). In the five-county area, total sand thickness in the Lower Dockum Group is generally 25 to 100 feet, but can locally be 10 to 25 feet. In the Andrews County area, Lower Dockum sand thickness exceeds 100 feet at all well locations (Figure 16).

TDS concentrations in groundwater from wells completed in the Upper and Lower Dockum Group are illustrated in Figures 17 and 18, respectively. TDS concentrations of Upper Dockum Group water are fresh to slightly saline (Figure 17). Lower Dockum Group groundwater is slightly to moderately saline in Andrews County (Figure 18).

5.2.5 Groundwater Volume Estimates

Approximate estimates of the volume of groundwater beneath the University Lands in the study area were made for the Upper and Lower Dockum Group. These estimates are based on the thicknesses and extenta of these geologic units as rendered in the 3D geologic models.

The estimated groundwater volume of Upper and Lower Dockum Group sediments was multiplied by an effective (drainable) porosity of 1 percent (0.01) to estimate the volume of groundwater. Although individual sand units in the Dockum Group likely have higher effective porosity than 1 percent (perhaps 5 to 10 percent), 1 percent effective porosity was selected to account for the high percentage of low-permeability strata in the Dockum Group. The volume estimates assume that the Dockum Group sediments are saturated at all locations beneath University Lands.

In the study area, the Upper Dockum Group contains approximately 1.6 million acre-feet of groundwater and the Lower Dockum Group contains approximately 4.3 million acre-feet of groundwater. Of the total estimated volume, 83 percent is in the Andrews County area and the remainder is in the five-county area. Note that 1 acre-foot is equivalent to 325,851 gallons, or about 7,758 barrels. *These volume estimates are approximate and are not indicative of recoverable groundwater in any area.* Recoverable groundwater depends on numerous factors, including aquifer depth, aquifer hydraulic properties, depth to the potentiometric surface under pumping conditions, and groundwater quality relative to its intended use.

6. Conclusions

The primary conclusions of this study are as follows:

- In the Andrews County area, the majority of wells are completed in the Ogallala Aquifer. In the five-county area, most wells are completed in the Pecos Valley Aquifer.

- Water levels in the Ogallala and Pecos Valley Aquifers are stable.

- With few exceptions, wells not completed in the Ogallala or Pecos Valley Aquifers are completed in the underlying Dockum Aquifer. Dockum Aquifer wells are completed in both the Upper Dockum Group and the Lower Dockum Group.

- Reported well yields and total sand thicknesses indicate that wells completed in the Lower Dockum Group (which includes the Santa Rosa Formation) are more productive than those completed in the Upper Dockum Group. Based on the same information, the Dockum Aquifer is expected to be more productive in the Andrews County area and Ector County than it is in Loving, Ward, and Winkler Counties.

- Few wells are completed across multiple aquifers.

- The depth to the top of the Dockum Group is less than 300 feet throughout most of the study area. In the Monument Draw Trough in Ward and Winkler Counties, the depth to the top of the Dockum Group is greater than 500 feet and can exceed 1,000 feet in places, and the contact between the Pecos Valley Alluvium and the Dockum Group can be hard to identify.

- The difference in water levels between wells completed in the Lower Dockum Group and wells completed in the Upper Dockum Group or the Ogallala Aquifer in Andrews County suggests that the vertical hydraulic conductivity between these wells is low. Groundwater pumping from the Lower Dockum Group should have a negligible effect on water levels in the Ogallala Aquifer.

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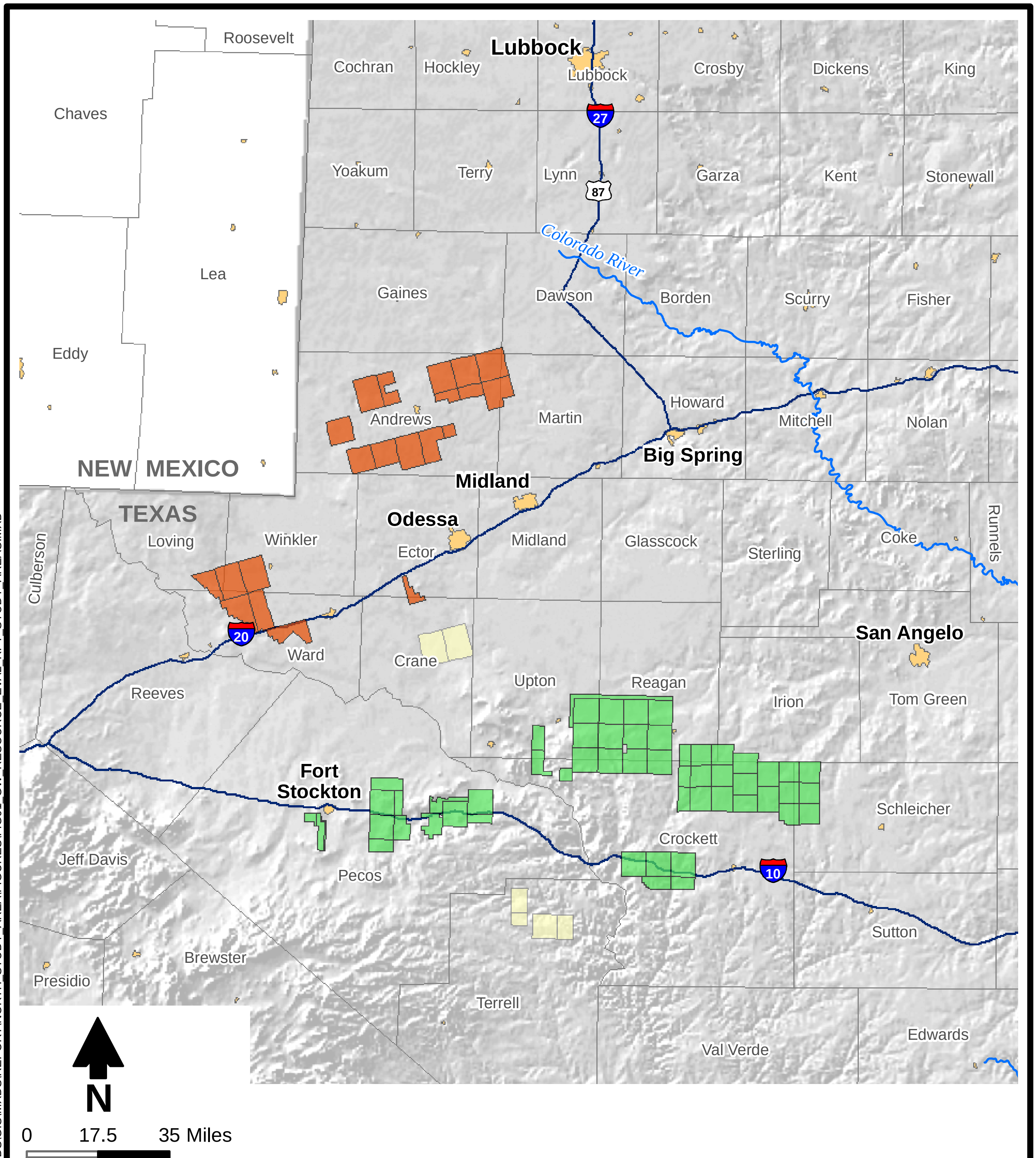
Figures



Explanation

- University Lands (Northern study area)
- University Lands (Southern study area)
- Other University Lands
- Urban area
- County

UNIVERSITY LANDS

Groundwater Resource Evaluation Report Study Areas

Daniel B. Stephens & Associates, Inc.

11/13/2015 JN WR14.0154

Figure 1

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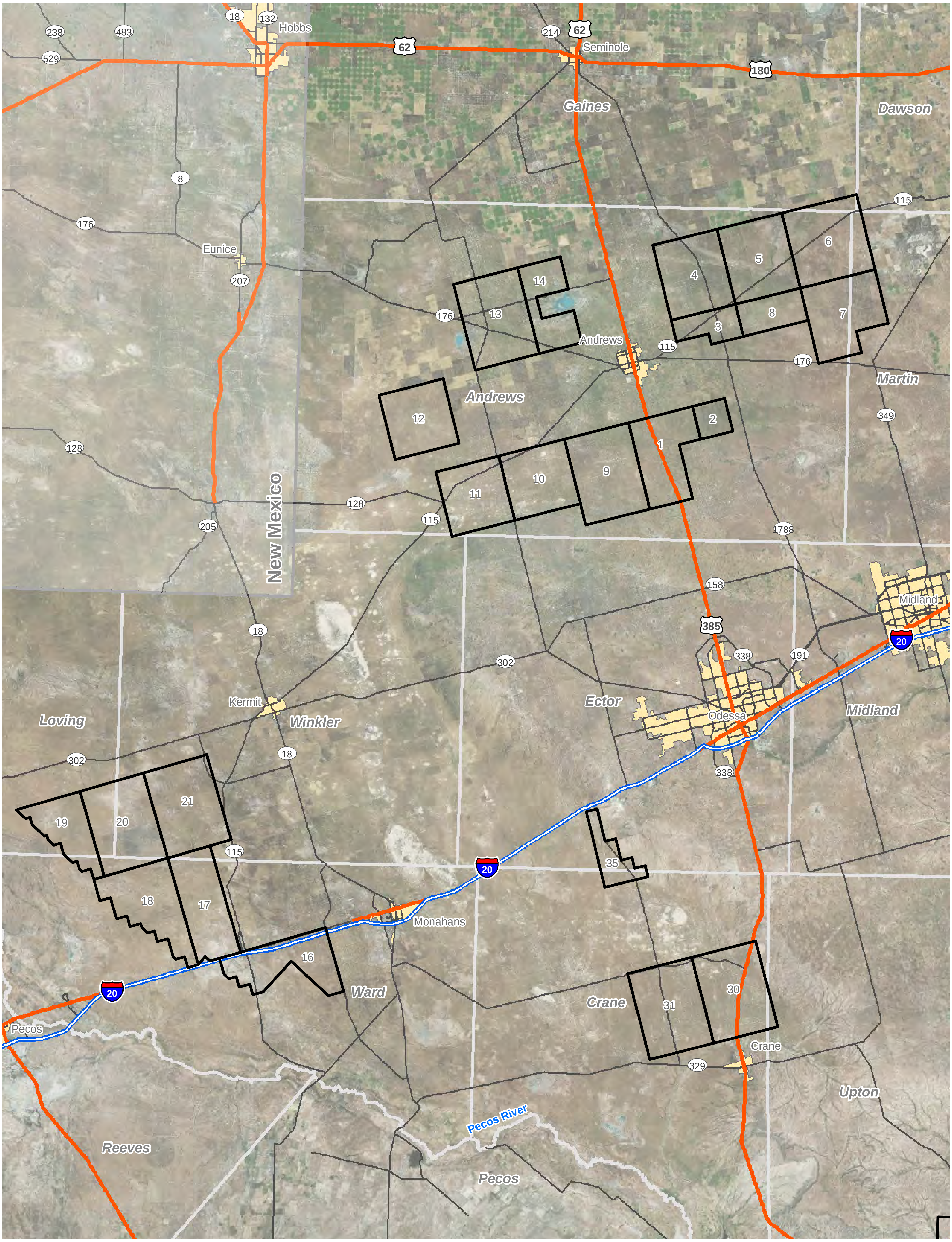


Note: North Study Area does not include University Lands Blocks 30 and 31 in Crane County.

N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

Figure 2

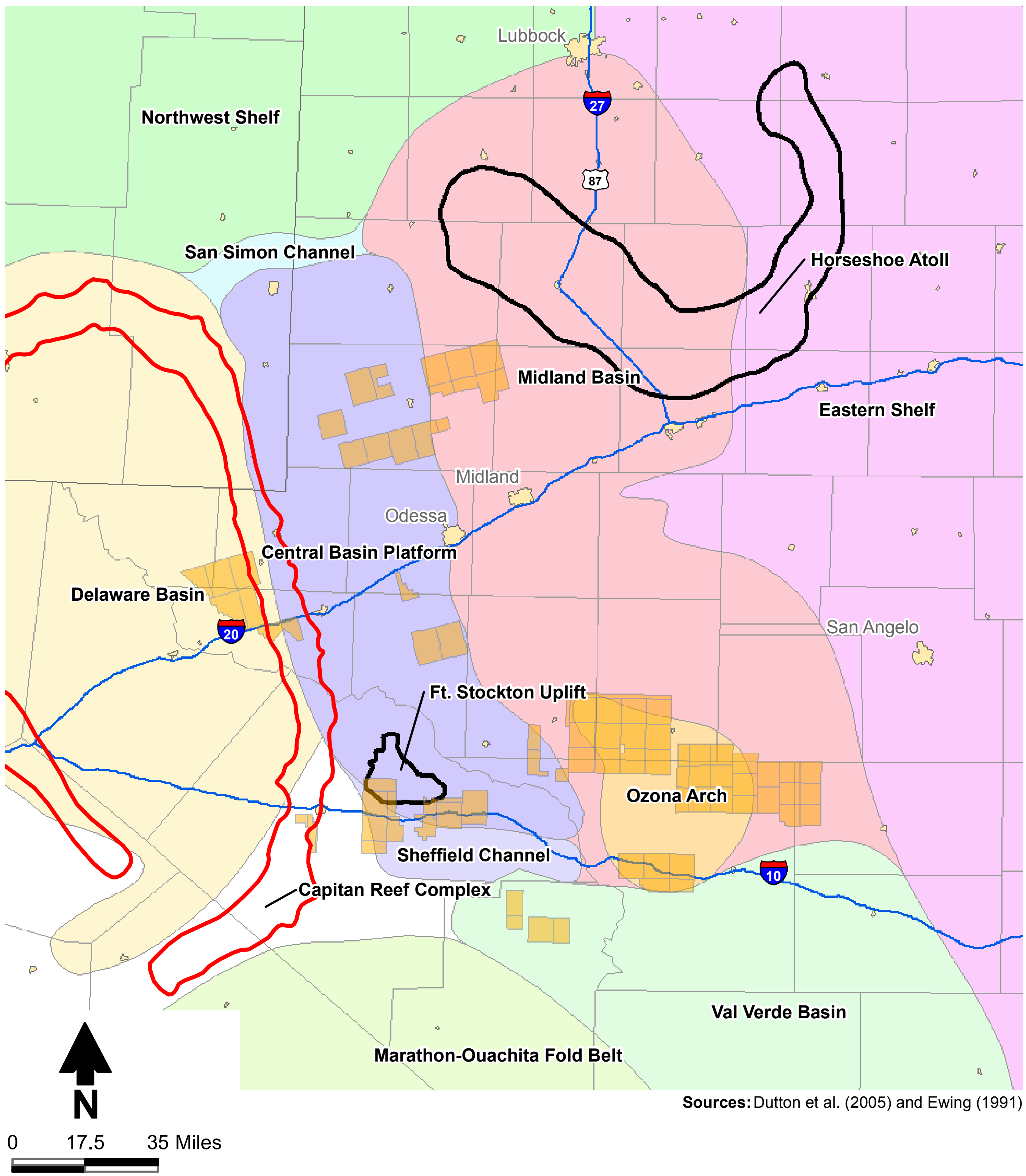
Daniel B. Stephens & Associates, Inc.

12/11/2015

JN WR14.0154

UNIVERSITY LANDS

Northern Study Area



Sources: Dutton et al. (2005) and Ewing (1991)

Explanation

- Capitan Reef Complex
- University Lands
- Ewing geologic feature
- Urban area
- County

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West Texas Regional Geologic Structure

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Figure 3

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG03_WEST_TEXAS_REGIONAL_GEOLOGY.MXD

Period	Group/Series	Formation: Central Basin Platform and Midland Basin		Formation: Delaware Basin		Aquifer
Quaternary		Sheet sand and windblown sand		Sheet sand and windblown sand		Above the water table (not saturated)
Tertiary	Late Pliocene to Miocene	Ogallala or Pecos Valley Alluvium		Pecos Valley Alluvium		Ogallala or Pecos Valley – major aquifers
Cretaceous	Fredericksburg Group	Fort Terrett		Fort Terrett		Edwards-Trinity (Plateau) – major aquifer
Cretaceous	Trinity Group	Antlers Sand		Antlers Sand		Only Antlers Sand saturated – in hydraulic communication with Ogallala where it occurs
Triassic	Dockum Group	Cooper Canyon Trujillo Sandstone		Cooper Canyon Trujillo Sandstone		Upper Dockum* – minor aquifer primarily a confining unit, but sand layers do provide water to wells
Triassic	Dockum Group	Tecovas Santa Rosa		Tecovas Santa Rosa		Lower Dockum* – minor aquifer (Santa Rosa)
Permian	Ochoan Series	Dewey Lake		Dewey Lake		Confining unit
Permian	Ochoan Series	Rustler		Rustler		Rustler – minor aquifer
Permian	Ochoan Series	Salado		Salado Castile		Confining unit
Permian	Guadalupian Series	Artesia Group	Tansill Yates Seven Rivers Queen Grayburg	Capitan Reef or Delaware Mountain Group	Bell Canyon Cherry Canyon Brushy Canyon	Capitan Reef – minor aquifer

* Dockum Aquifer is the term used for any water-producing rocks in the Dockum Group, although the Lower Dockum Group is the most productive unit (Bradley and Kalaswad, 2003).

Figure 4

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Geologic Column and Corresponding Aquifer Units

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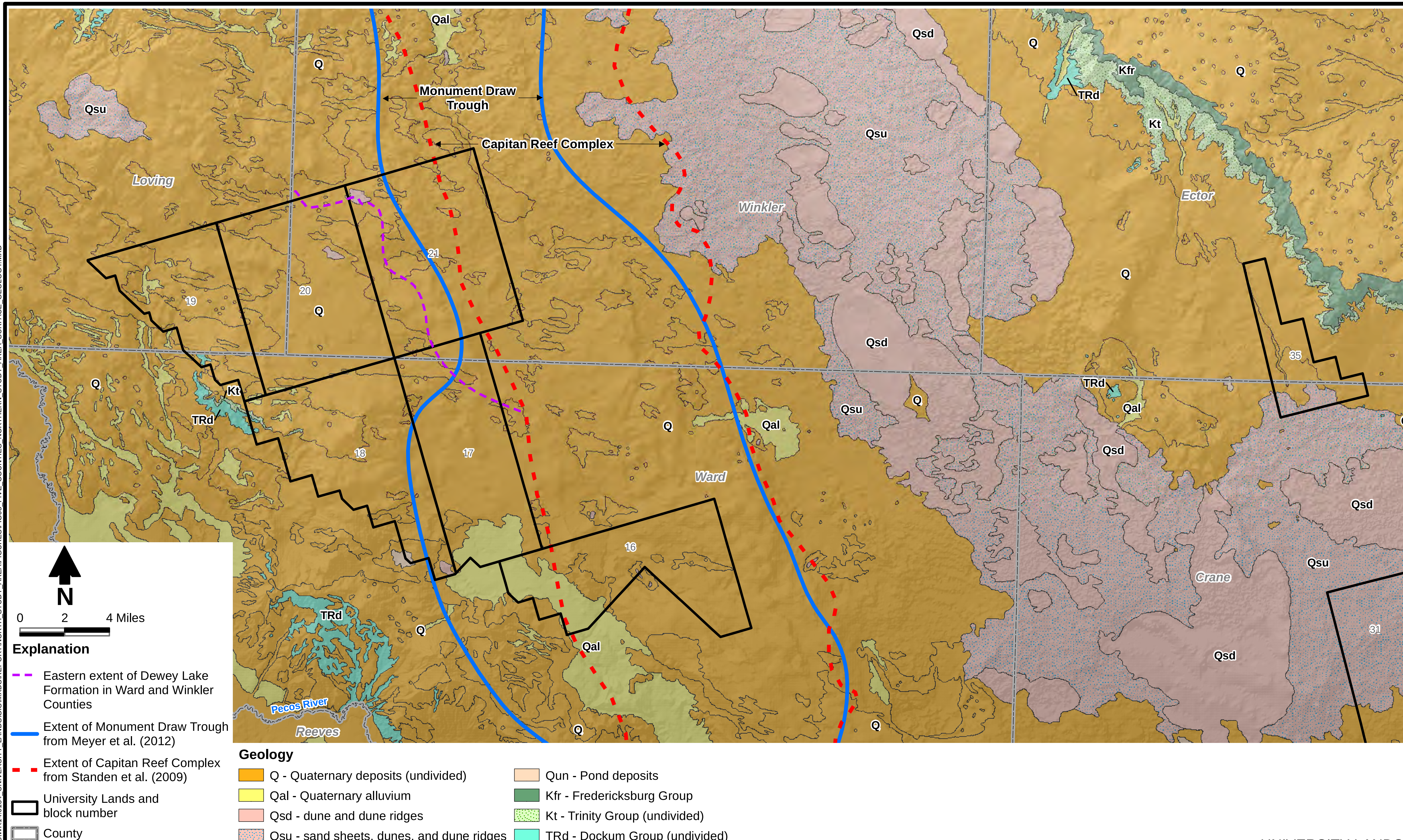

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG05_FIVE_COUNTIES_NORTHERN_STUDY_AREA_SURFACE_GEOLOGY.MXD

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Five-County Area Surface Geology

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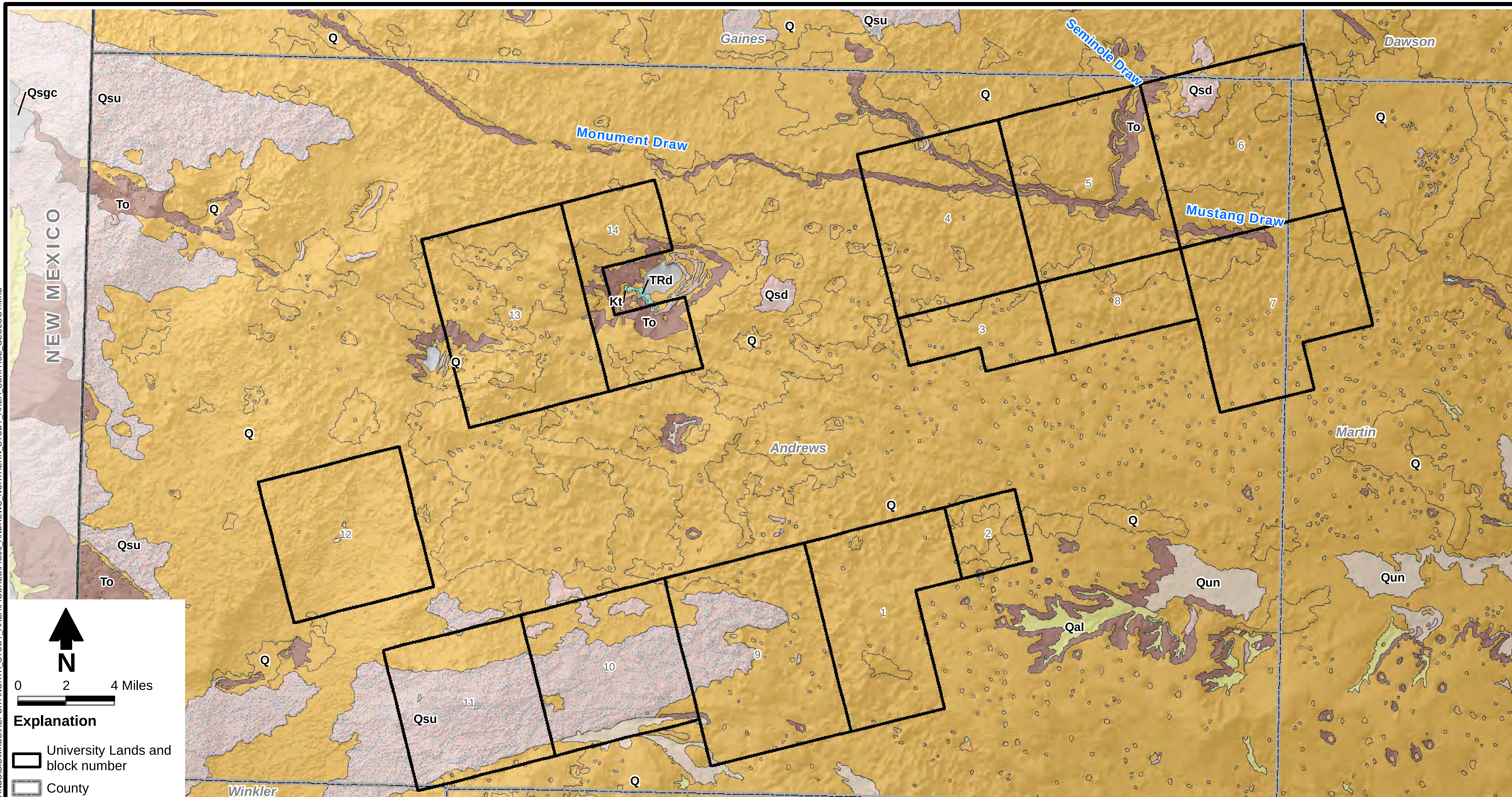
Figure 5



Explanation

University Lands and block number

County

Geology

Q - Quaternary deposits (undivided)

Qal - Quaternary alluvium

Qsd - dune and dune ridges

Qsgc - Colluvial deposits

Qsu - sand sheets, dunes, and dune ridges

Qun - Pond deposits

To - Ogallala Formation

Kfr - Fredericksburg Group

Kft - Fort Terrett Formation (Fredericksburg Group)

Kt - Trinity Group (undivided)

TRd - Dockum Group (undivided)

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG06_ANDREWS_NORTHERN_STUDY_AREA_SURFACE_GEOLOGY.MXD

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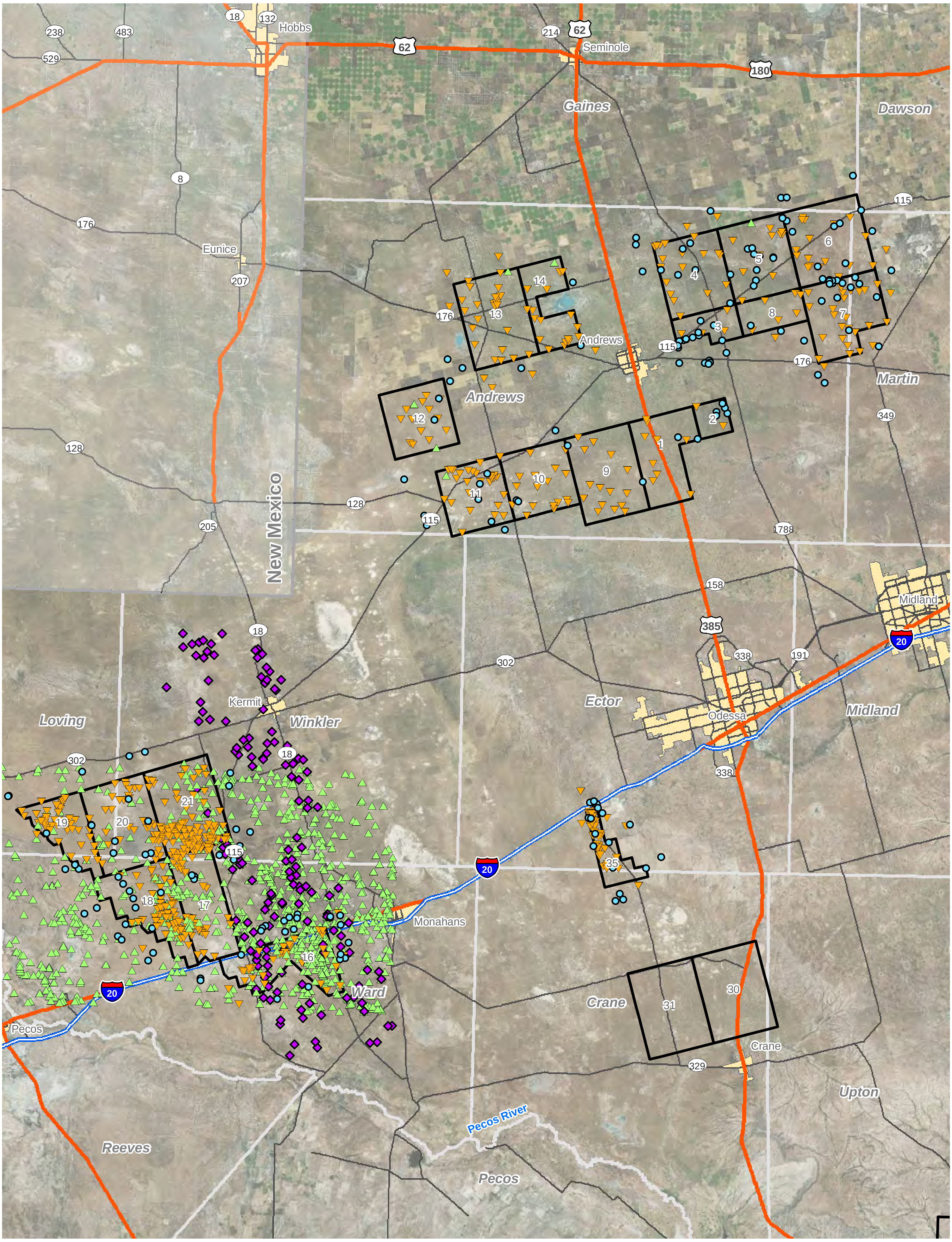
Andrews County Area Surface Geology

Figure 6

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG07_DATA_SOURCES_FOR_GEOLOGIC_ANALYSIS.MXD



N

0 4.5 9 Miles

Explanation

- Water well drillers report
- BRACS database (Meyer et al., 2012)
- Oil and gas geophysical log
- Oil and gas geophysical log / Capitan study
- University Lands and block number
- Urban area
- County

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Data Sources for Geologic Analysis

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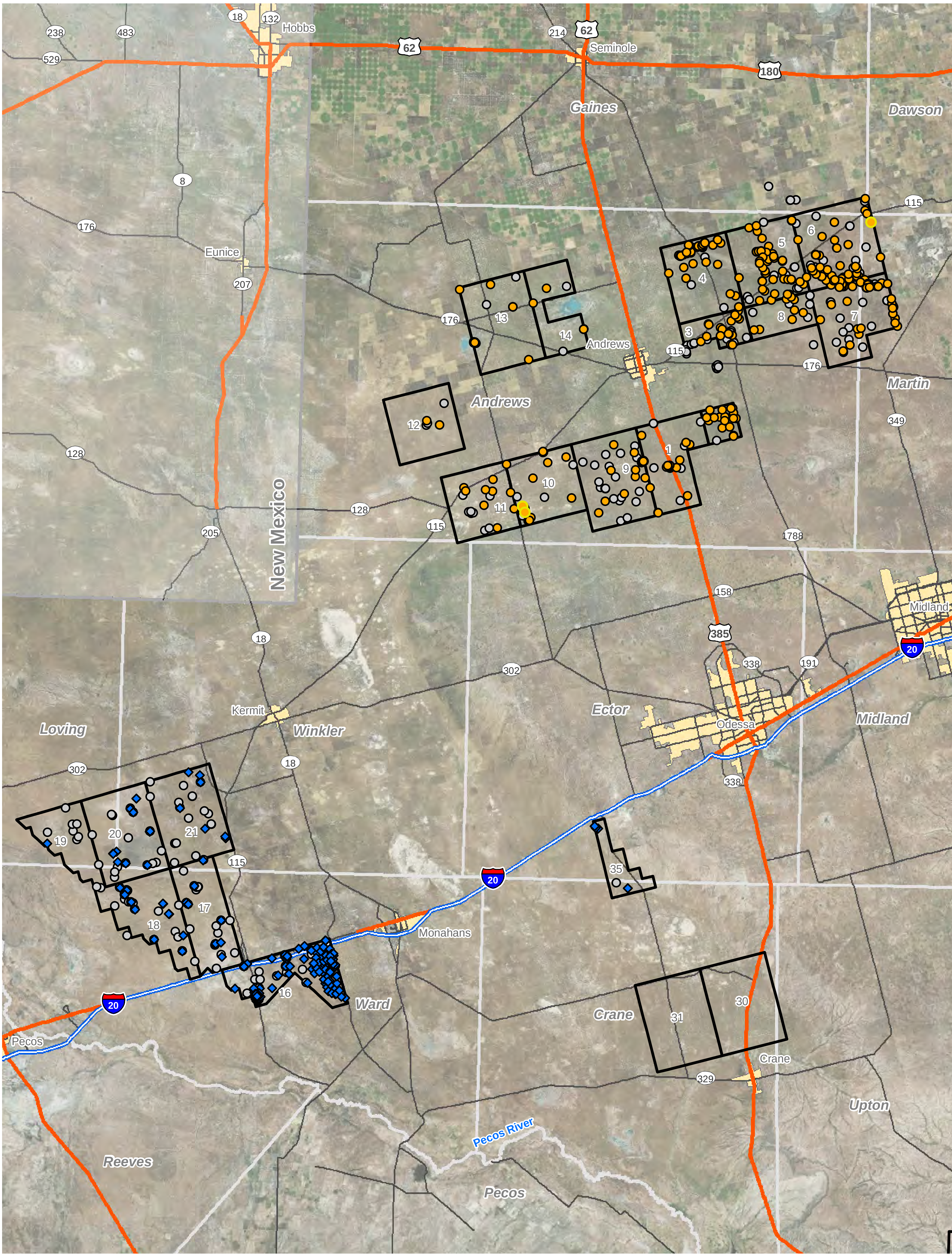
Figure 7



N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

Well completed in the Ogallala aquifer

Well completed in the Pecos Valley aquifer

Well with no aquifer designation

Well completed according to University Lands Groundwater Management Plan (2013)

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Wells Completed in the Ogallala and Pecos Valley Aquifers

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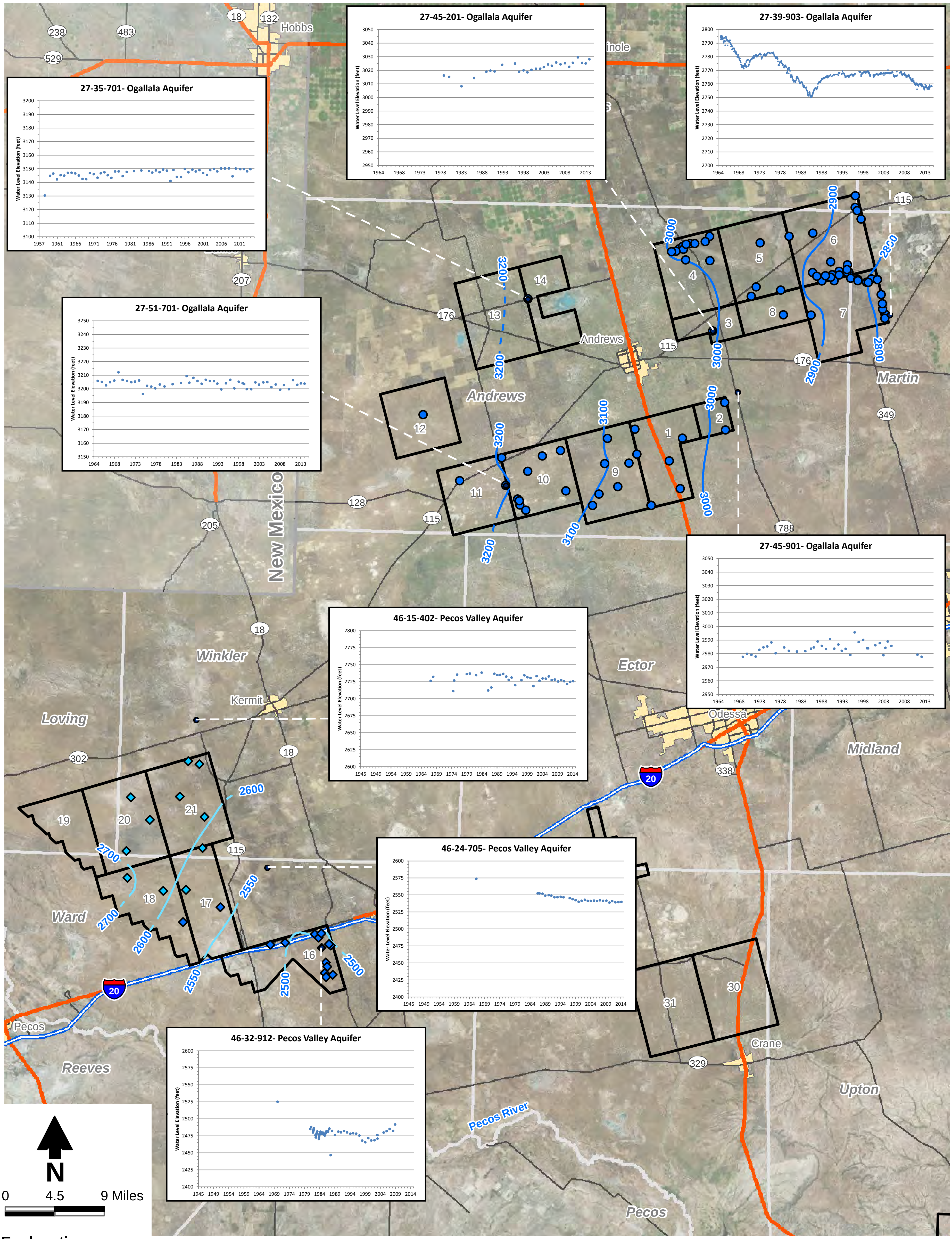
Figure 8



Explanation

- Well completed in the Ogallala Aquifer
- Well completed in the Pecos Valley Aquifer (pre 1/1/2000)
- Well completed in the Pecos Valley Aquifer (post 1/1/2000)
- Ogallala Aquifer water level elevation contour (ft msl), dashed where inferred
- Pecos Valley Aquifer water level elevation contour (ft msl), dashed where inferred
- University Lands and block number
- Urban area
- County

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Ogallala and Pecos Valley Aquifer Potentiometric Surface

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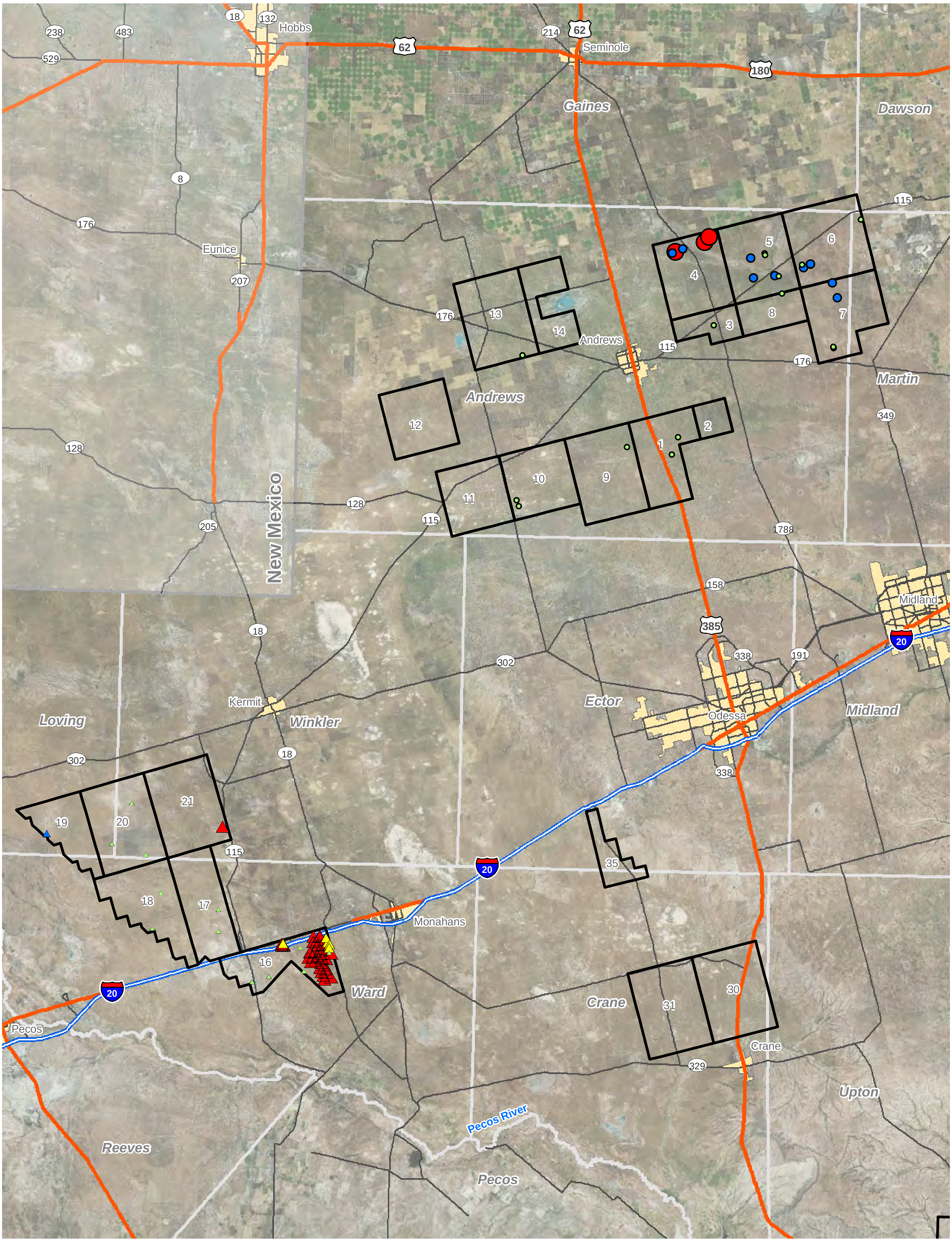

N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

Well yield (gpm)

Well completed in the Ogallala Aquifer	*Well completed in the Pecos Valley Aquifer*
0 - 50	0 - 50
51 - 100	51 - 100
101 - 200	101 - 200
>200	>200

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Yield of Wells Completed in the Ogallala and Pecos Valley Aquifers

Figure 10

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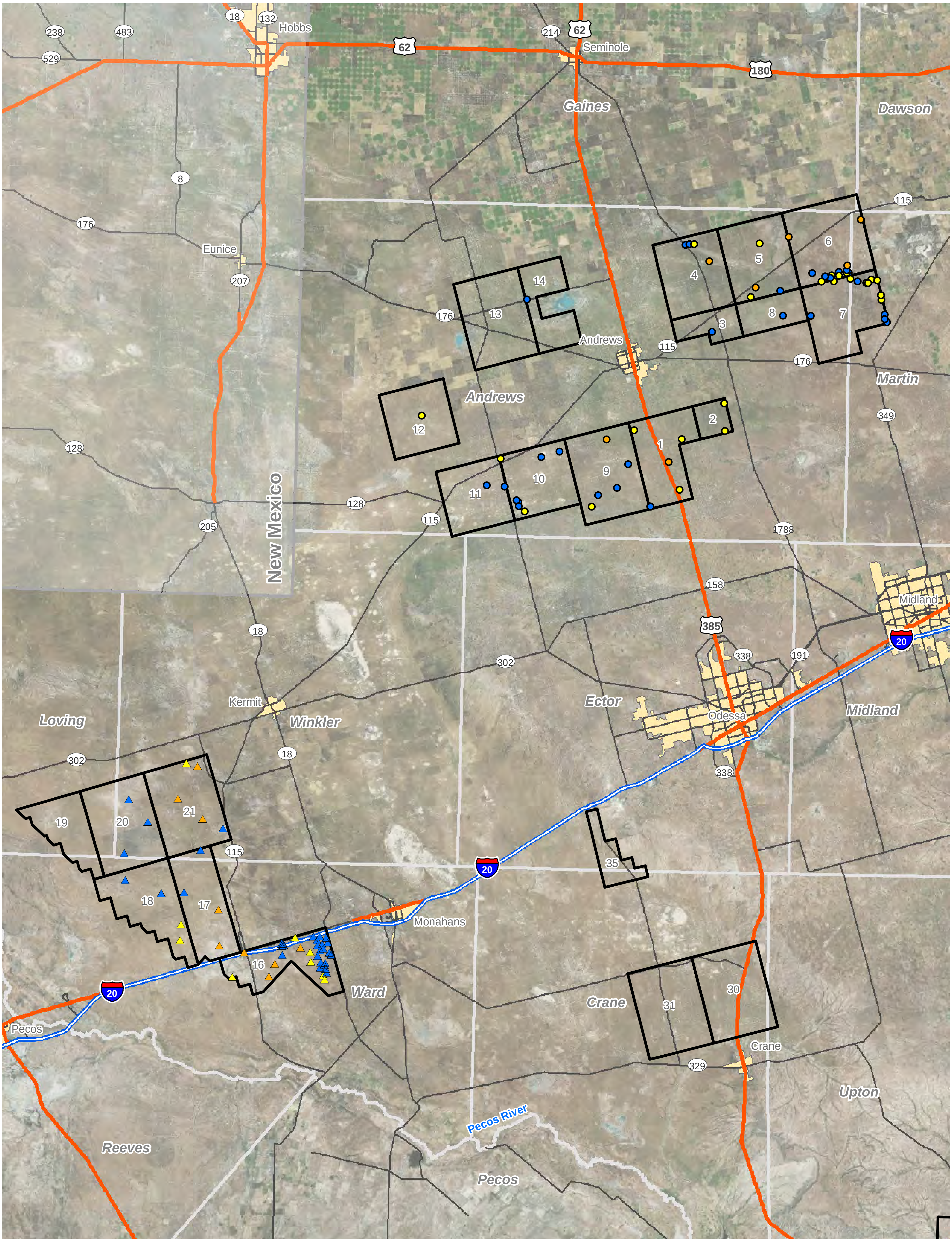

N
0 4.5 9 Miles

Explanation

University Lands and block number
Urban area
County

TDS in groundwater (mg/L)

Well completed in the Ogallala Aquifer
- 0 - 1,000
- 1,001 - 3,000
- 3,001 - 10,000
- > 10,000

Well completed in the Pecos Valley Aquifer
- 0 - 1,000
- 1,001 - 3,000
- 3,001 - 10,000
- > 10,000

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TDS of Ogallala and Pecos Valley Aquifer Wells

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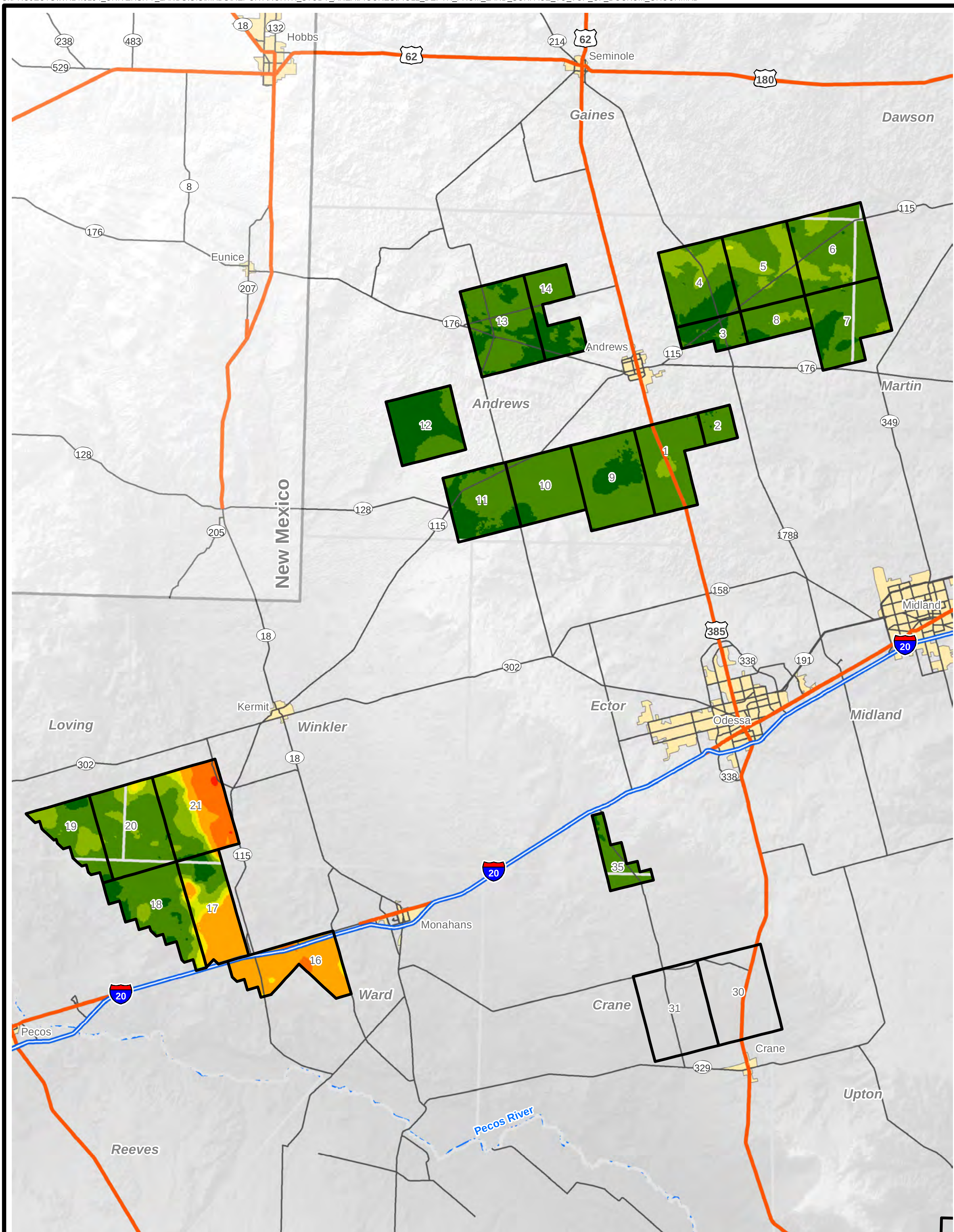
Figure 11

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG12_DEPTH_FROM_LAND_SURFACE_TO_TOP_OF_DOCKUM_GROUP.MXD



N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

Depth to top of Dockum Group (ft)

- < 100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 1,000
- 1,000 - 1,500
- > 1,500

Figure 12

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Depth from Land Surface to Top of Dockum Group

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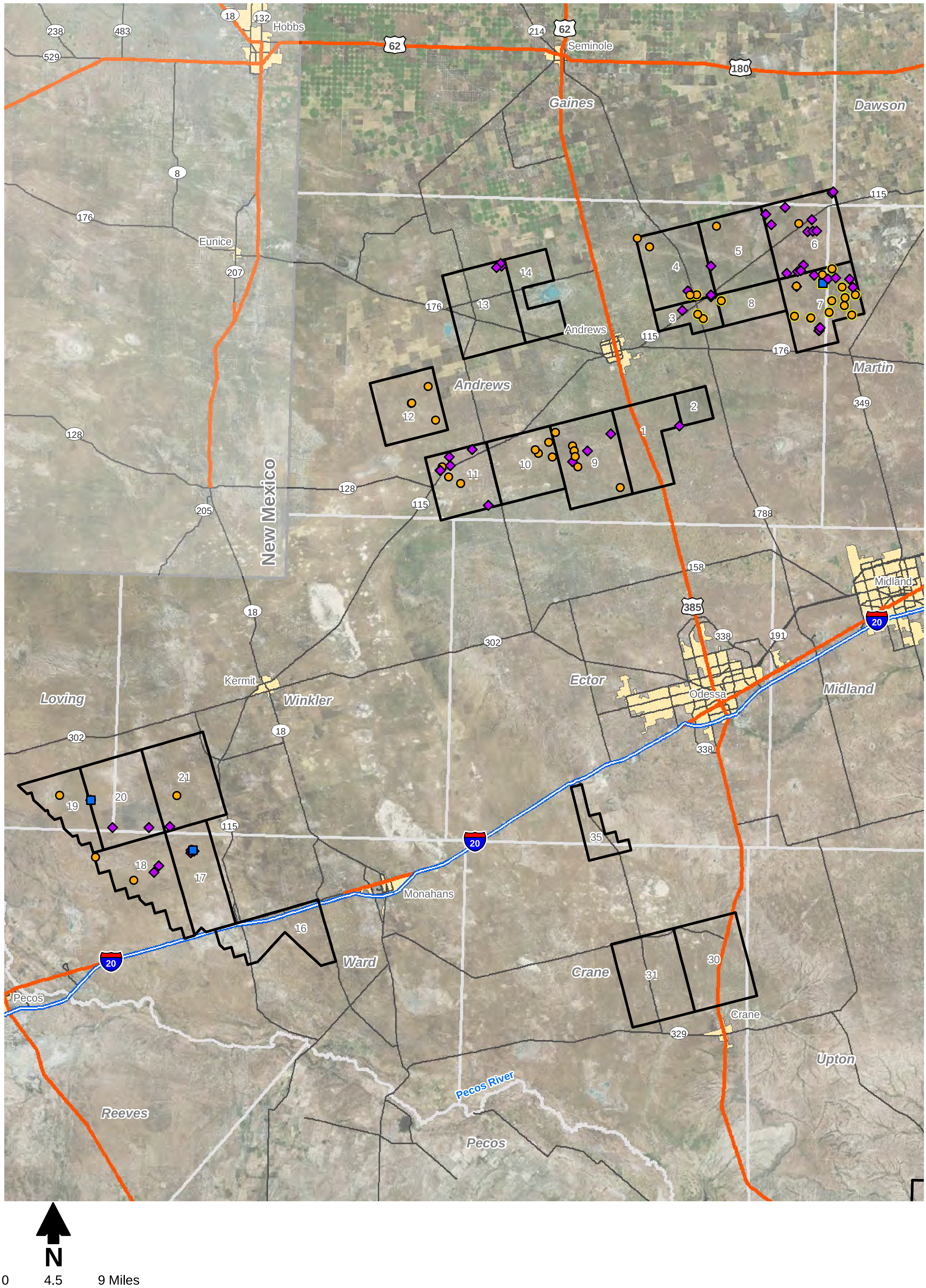
S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG13_WELLS_COMPLETED_IN_THE_DOCKUM_AQUIFER.MXD



Explanation

University Lands and block number

Urban area

County

Well completed in Upper Dockum Group

Well completed in Upper and Lower Dockum Group

Well completed in Lower Dockum Group

Well completed according to University Lands Groundwater Management Plan (2013)

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Wells Completed in the Dockum Group

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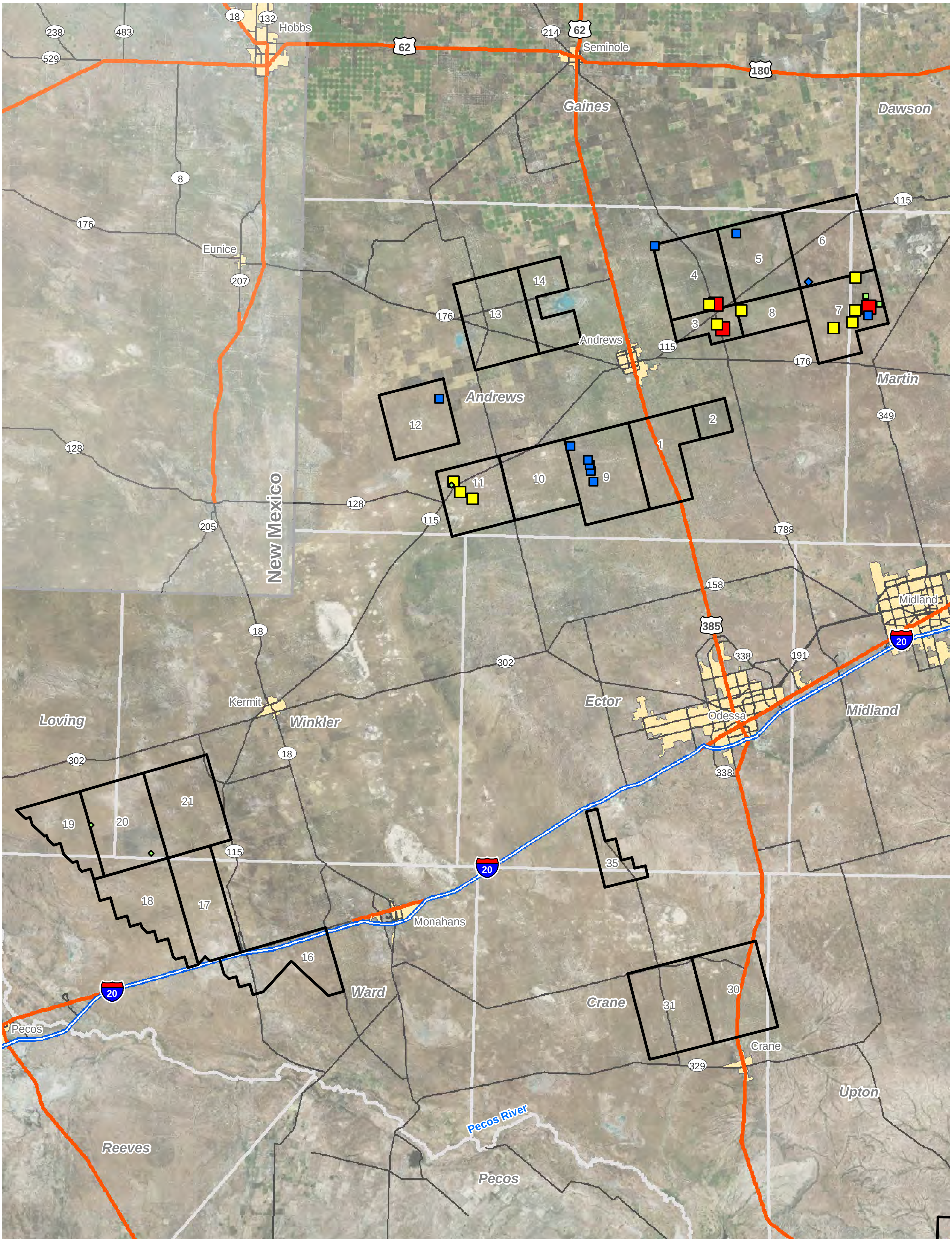
Figure 13

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG14_YIELD_OF_WELLS_COMPLETED_IN_DOCKUM_GROUP.MXD



N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

Well yield (gpm)

Well completed in the Upper Dockum Group	*Well completed in the Lower Dockum Group*
0 - 50	0 - 50
51 - 100	51 - 100
101 - 150	101 - 150
> 150	> 150

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Yield of Wells Completed in the Dockum Group

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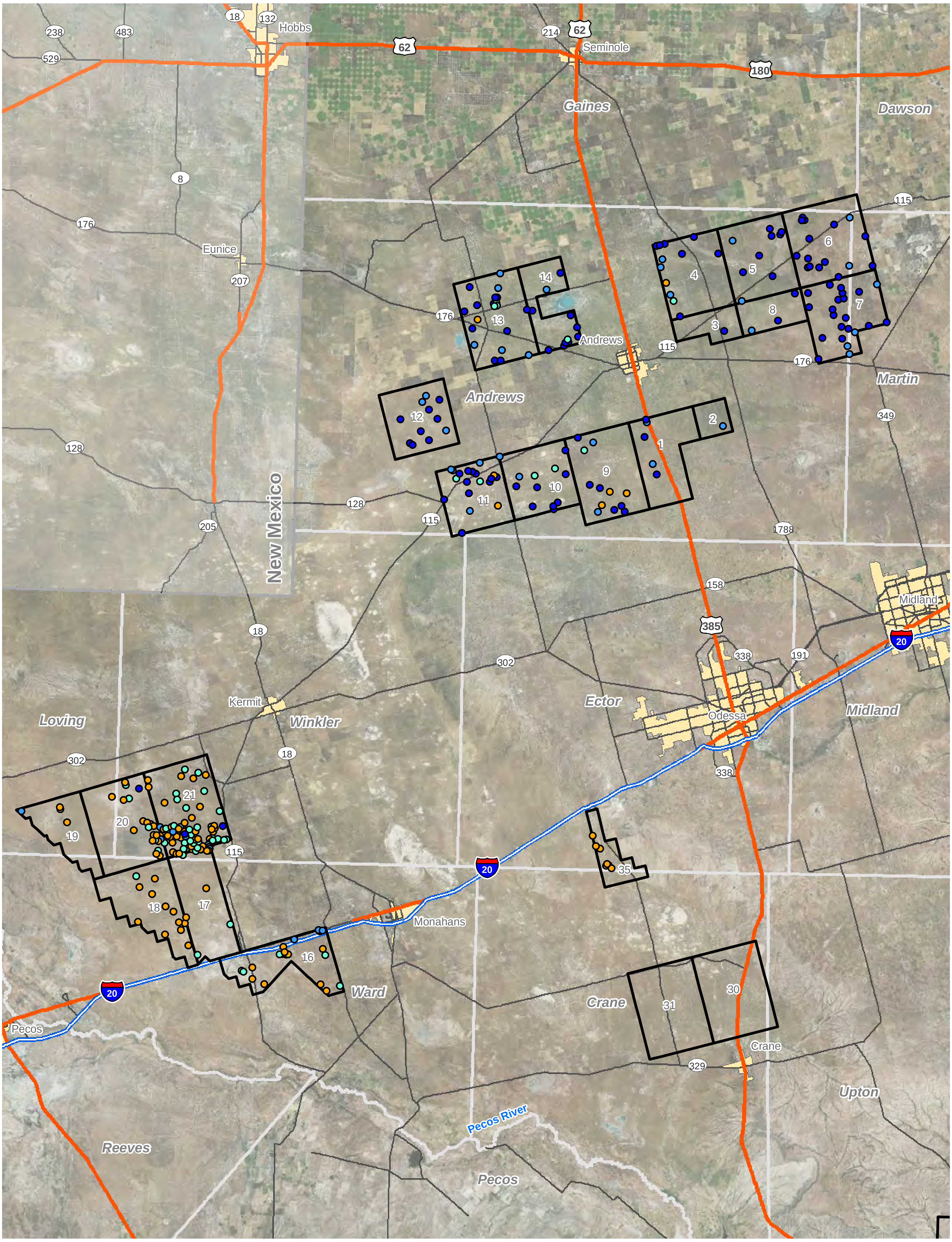
Figure 14

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG15_TOTAL_SAND_INTERVAL_THICKNESS_UPPER_DOCKUM_GROUP.MXD



Explanation

University Lands and block number

Urban area

County

Total sand interval thickness (feet)

- 10 - 25
- 26 - 50
- 51 - 100
- >100

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Total Sand Interval Thickness for the Upper Dockum Group

Figure 15

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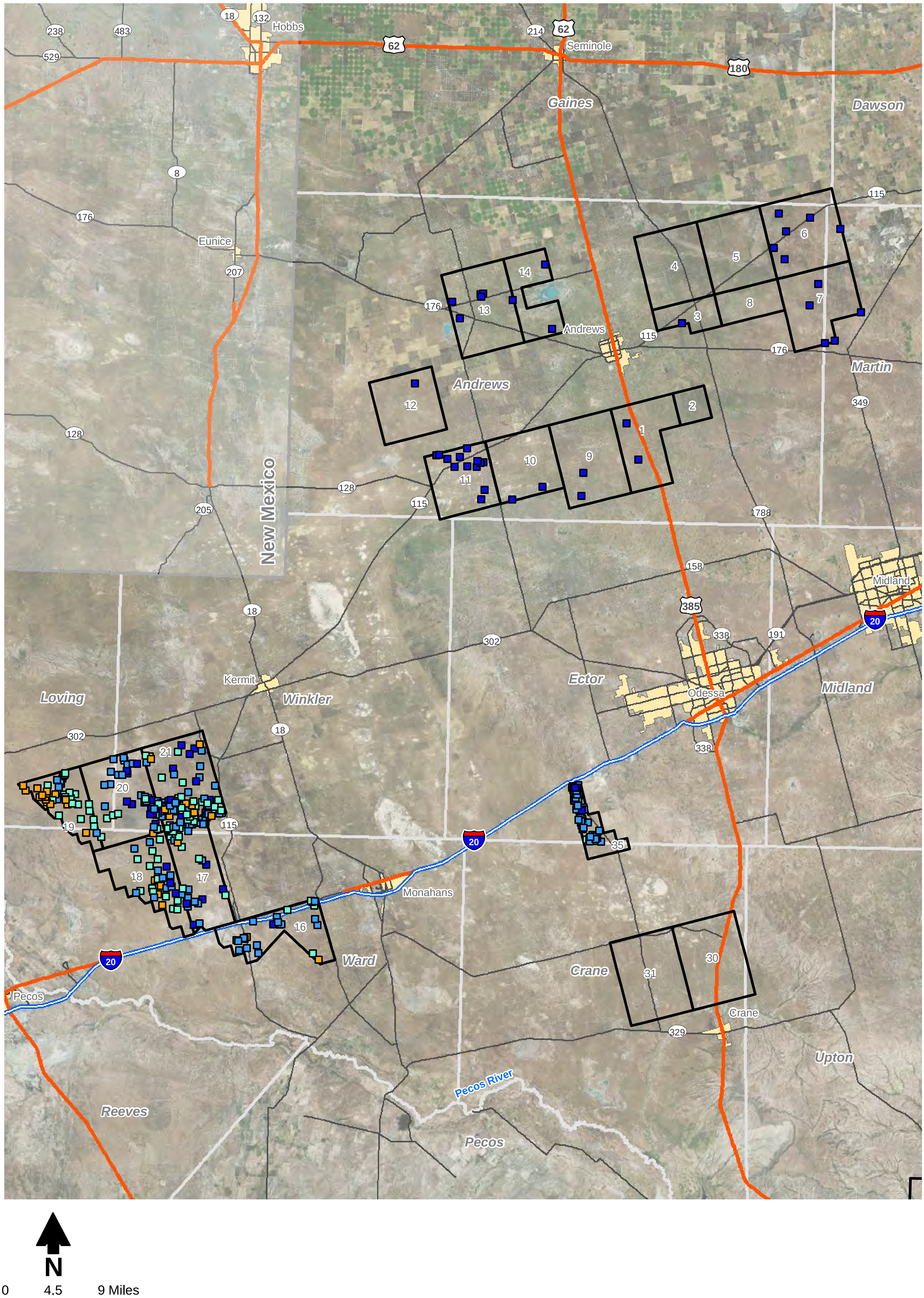
S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG16_TOTAL_SAND_INTERVAL_THICKNESS_LOWER_DOCKUM_GROUP.MXD



Explanation

University Lands and block number

Urban area

County

Total sand interval thickness (feet)

- 10 - 25
- 26 - 50
- 51 - 100
- >100

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Total Sand Interval Thickness for the Lower Dockum Group

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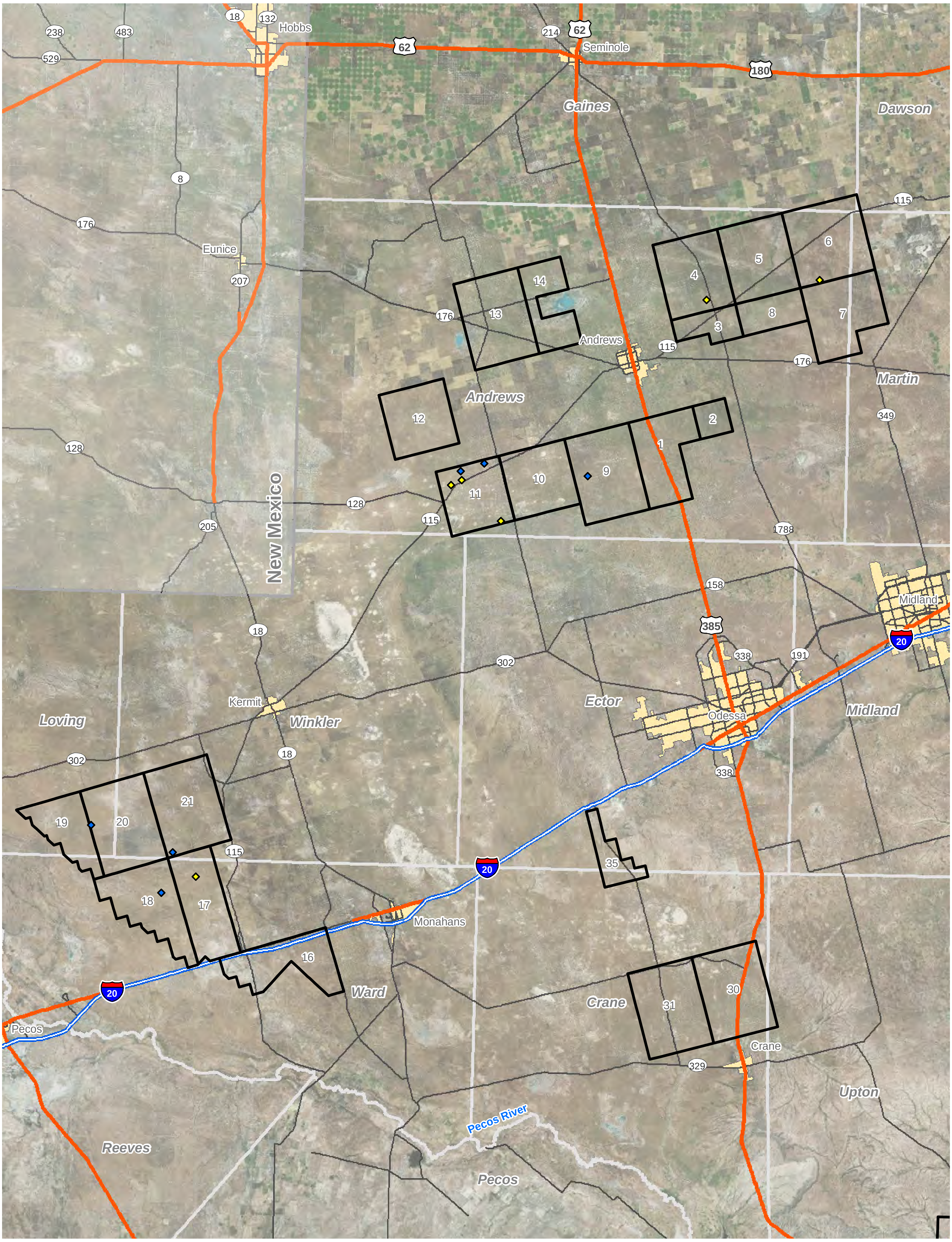
Figure 16

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG17_TDS_OF_UPPER_DOCKUM_GROUP_WELLS.MXD



Explanation

University Lands and block number

Urban area

County

TDS in groundwater (mg/L)

- 0 - 1,000
- 1,001 - 3,000
- 3,001 - 10,000
- > 10,000

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TDS of Upper Dockum Group Wells

Figure 17

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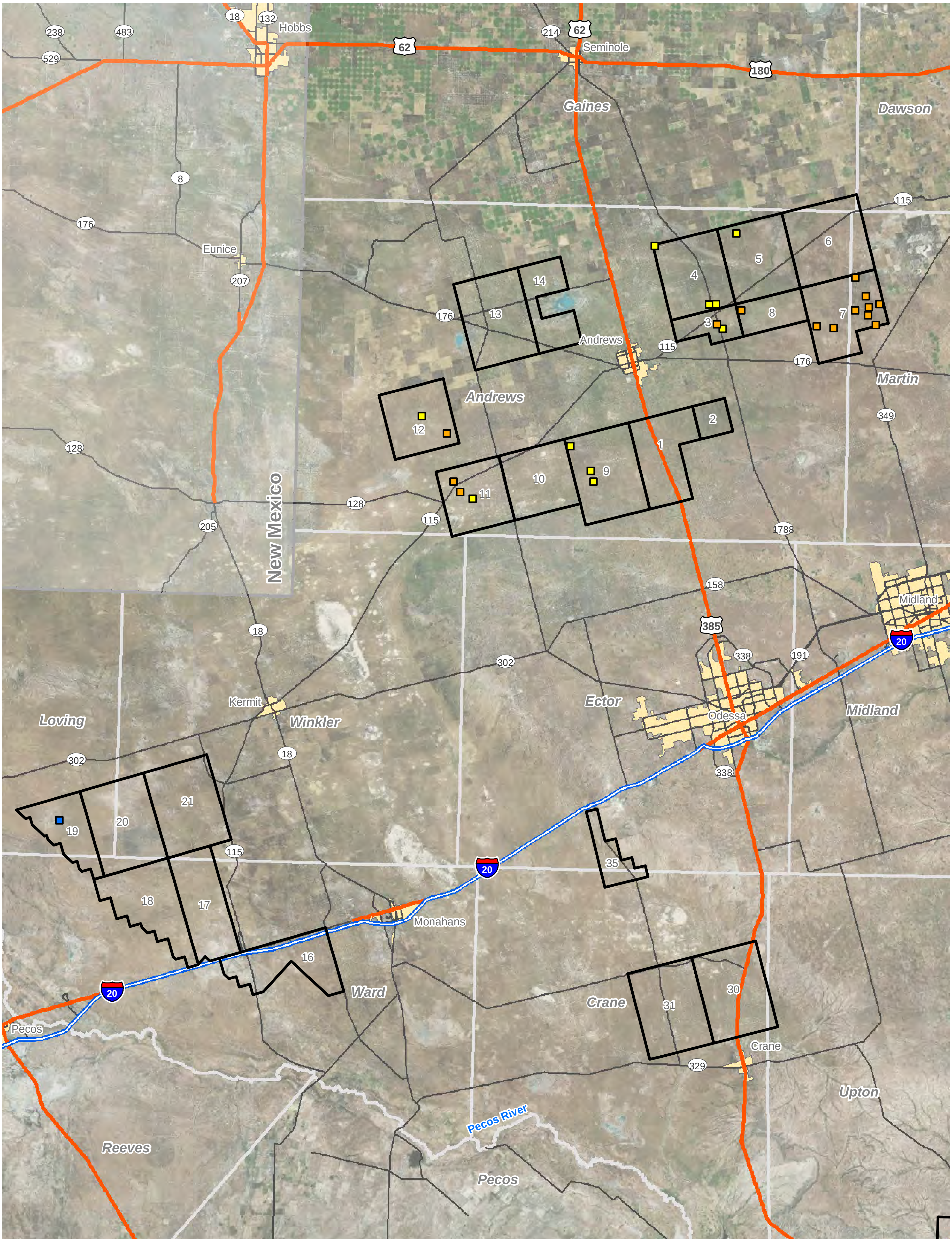
S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\FIGURES\FIG18_TDS_OF_LOWER_DOCKUM_GROUP_WELLS.MXD



N

0 4.5 9 Miles

Explanation

University Lands and block number

Urban area

County

TDS in groundwater (mg/L)

0 - 1,000

1,001 - 3,000

3,001 - 10,000

> 10,000

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TDS of Lower Dockum Group Wells

Figure 18

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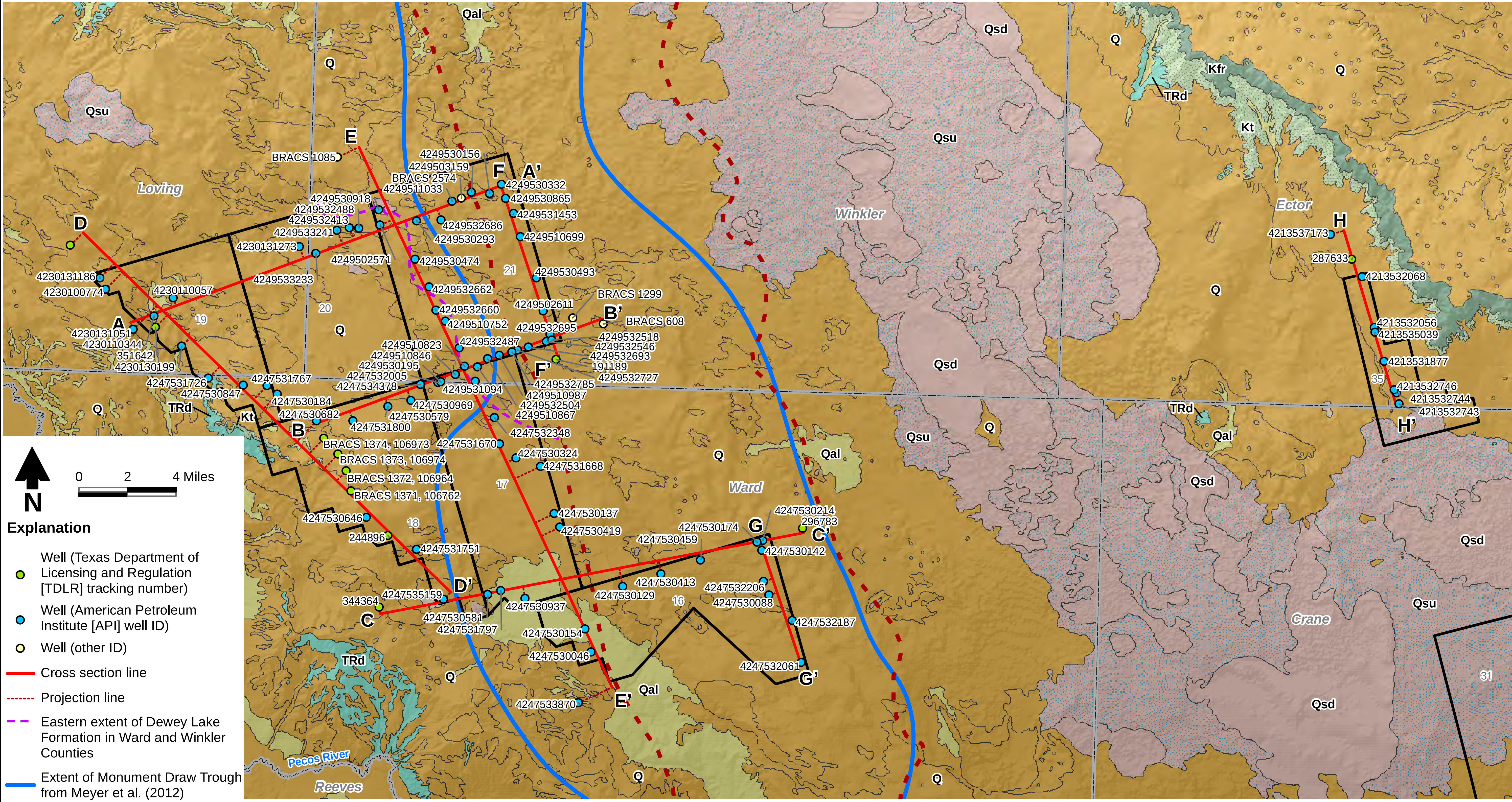
JN WR14.0154

Appendix A

Geologic Cross Sections and Unit Thickness Maps for Five-County Area



Explanation

- Well (Texas Department of Licensing and Regulation [TDLR] tracking number)
- Well (American Petroleum Institute [API] well ID)
- Well (other ID)
- Cross section line
- Projection line
- Eastern extent of Dewey Lake Formation in Ward and Winkler Counties
- Extent of Monument Draw Trough from Meyer et al. (2012)
- Extent of Capitan Reef Complex from Standen et al. (2009)
- University Lands and block number
- County

Geology

- Q - Quaternary deposits (undivided)
- Qal - Quaternary alluvium
- Qsd - dune and dune ridges
- Qsu - sand sheets, dunes, and dune ridges
- Qun - Pond deposits
- Kfr - Fredericksburg Group
- Kt - Trinity Group (undivided)
- TRd - Dockum Group (undivided)

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-01_FIVE_COUNTIES_NORTHERN_STUDY_AREA_SURFACE_GEOLOGY.MXD

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Five-County Area Surface Geology (A-A' Through H-H')

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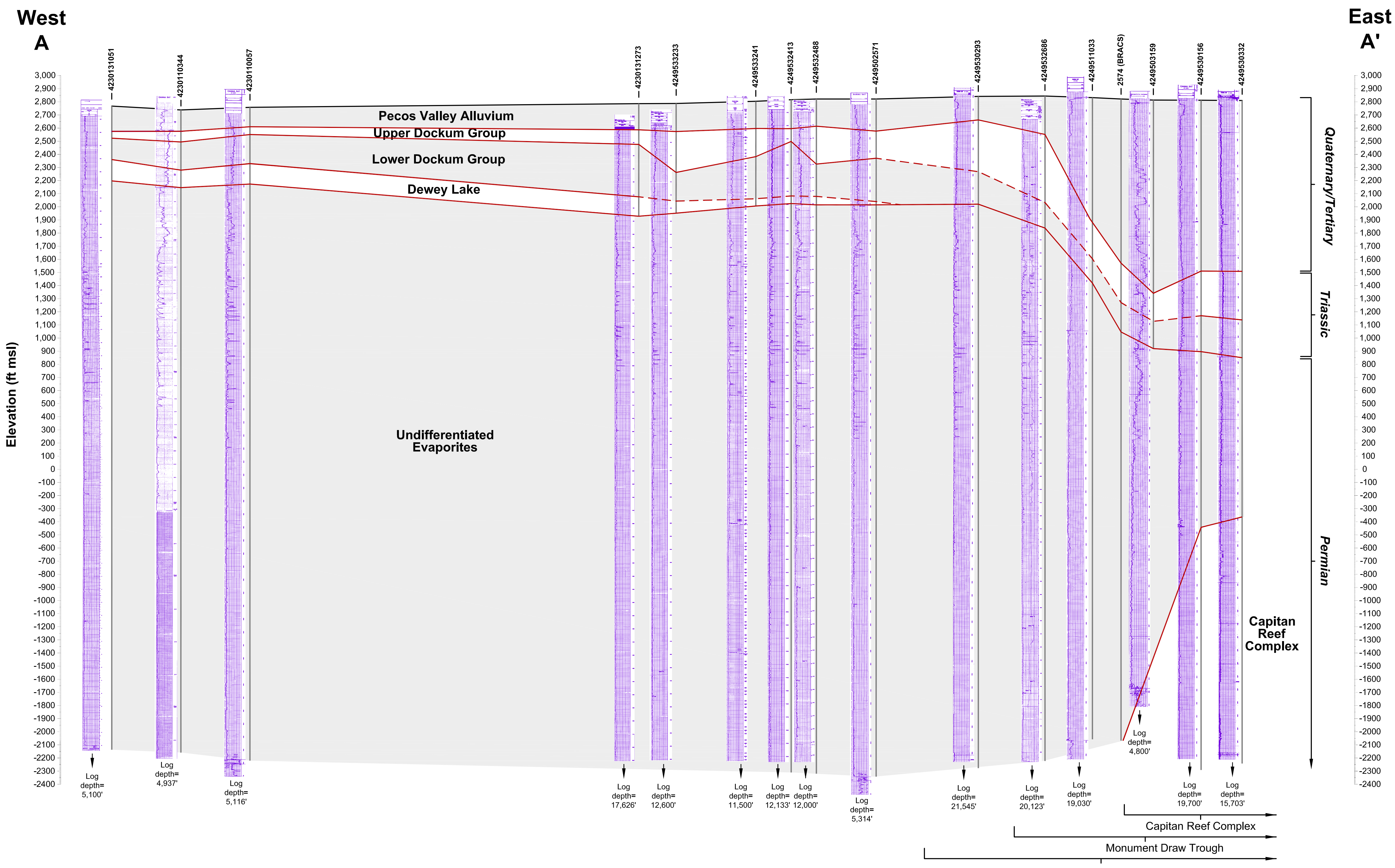
JN WR14.0154

Figure A-1



0 8,000 ft

10X vertical exaggeration

Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4230131051) or Brackish Resources Aquifer Characterization System (*BRACS*), (e.g. 2574 BRACS).

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West to East Geologic Cross Section A-A'

Figure A-2

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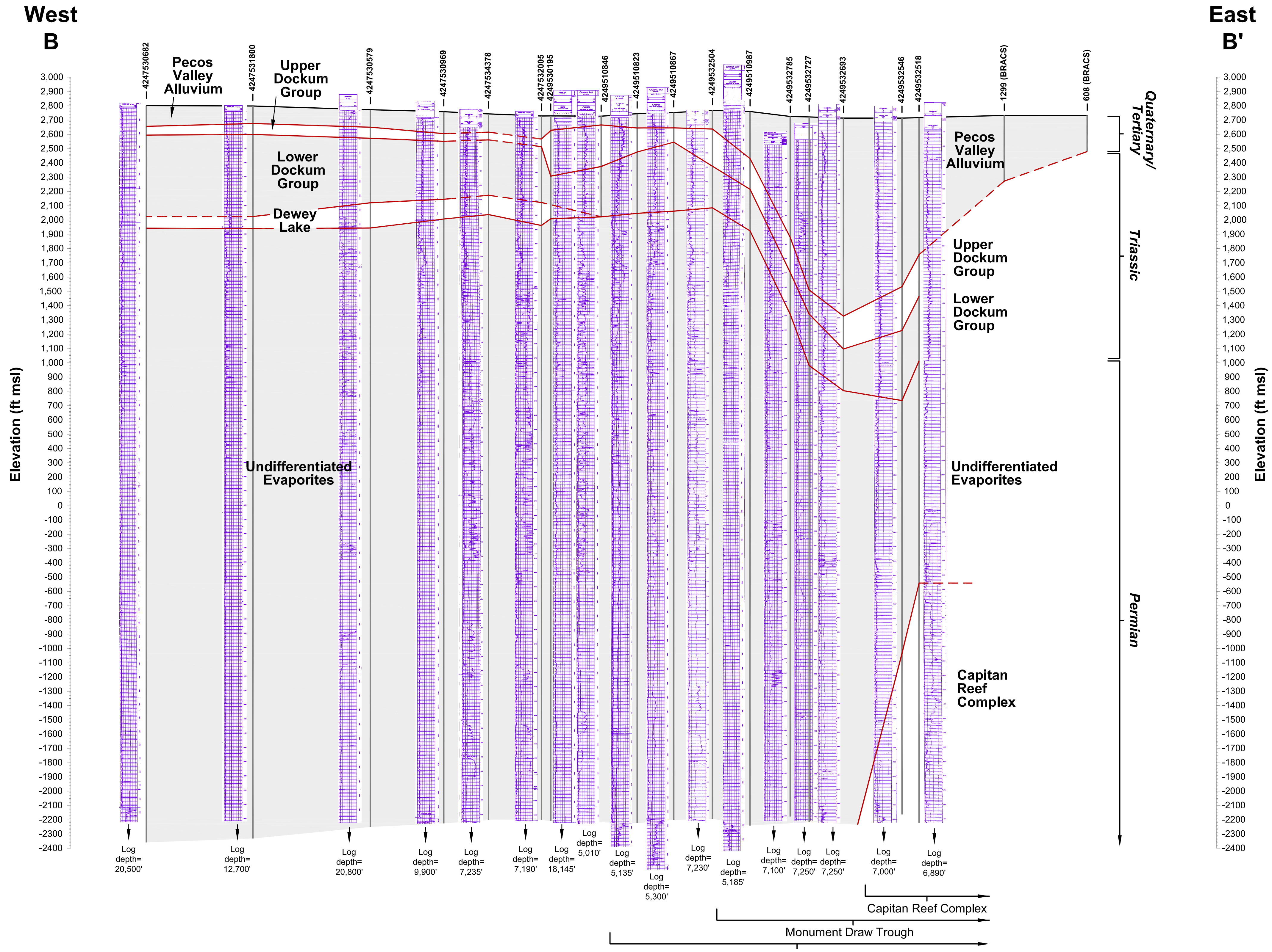
S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-02_GUYTON_Cross_Sec_A-A'.dwg



Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4247530682) or Brackish Resources Aquifer Characterization System (*BRACS*), (e.g. 608 BRACS).

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West to East Geologic Cross Section B-B'

Figure A-3

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-03_GUYTON_Cross_Sec_B-B'.dwg

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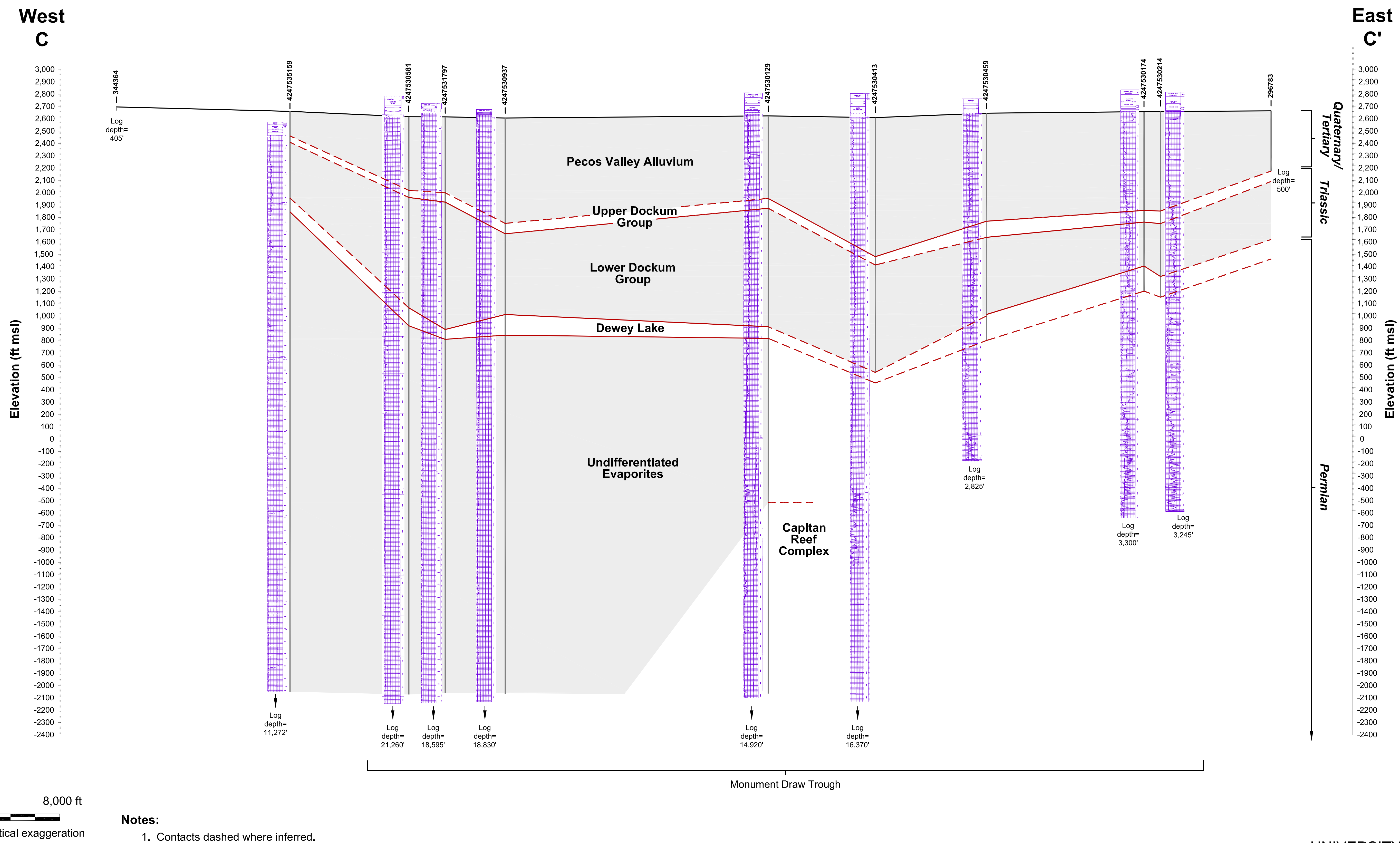

Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4247535159) or TDLR (e.g. 344364).

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-04_GUYTON_Cross_Sec_C-C'.dwg

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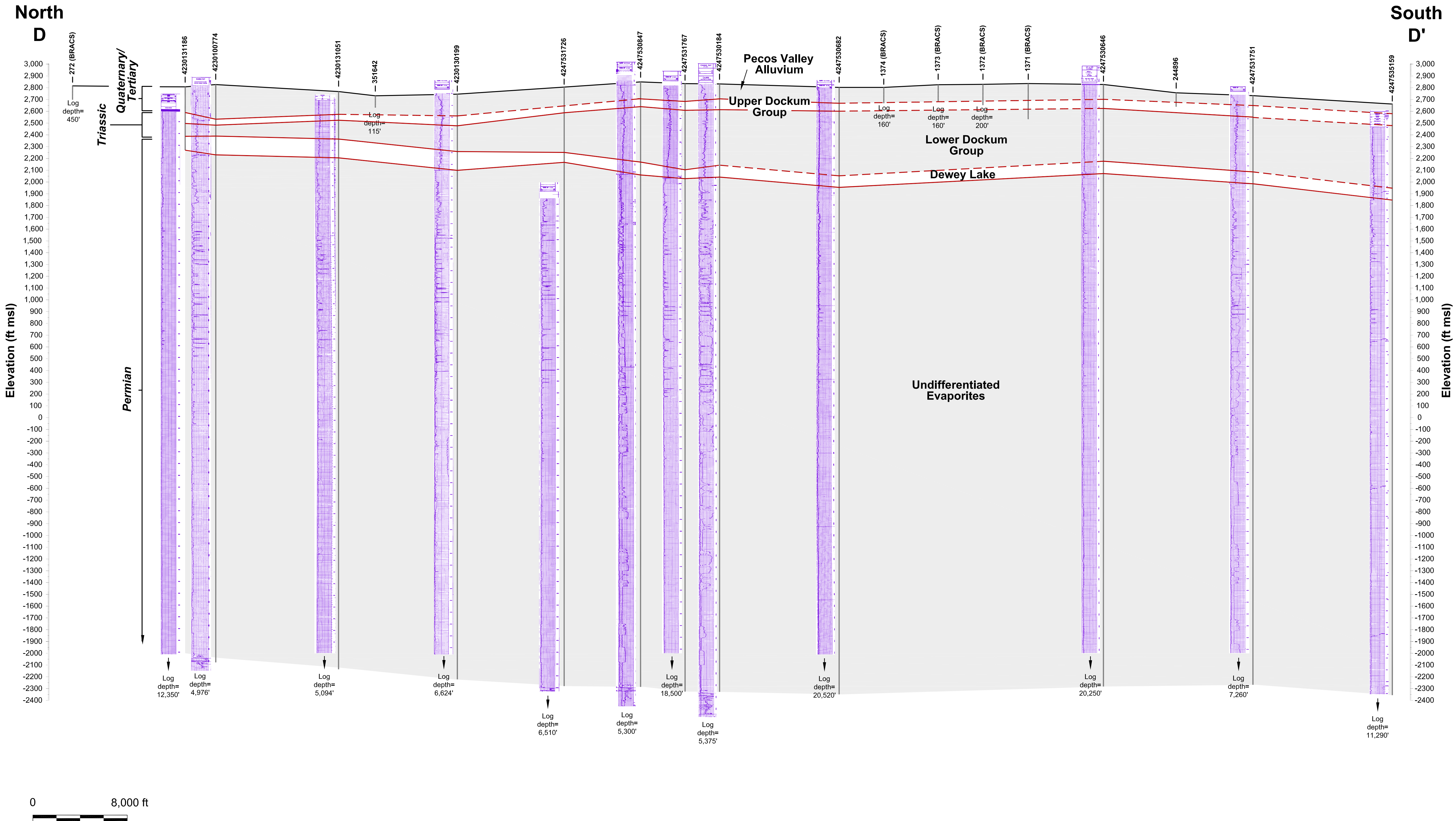
UNIVERSITY LANDS
West to East Geologic Cross Section C-C'

Figure A-4



Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4230131186), TDLR (e.g. 351642), or Brackish Resources Aquifer Characterization System (*BRACS*), (e.g. 272 BRACS).

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North to South Geologic Cross Section D-D'

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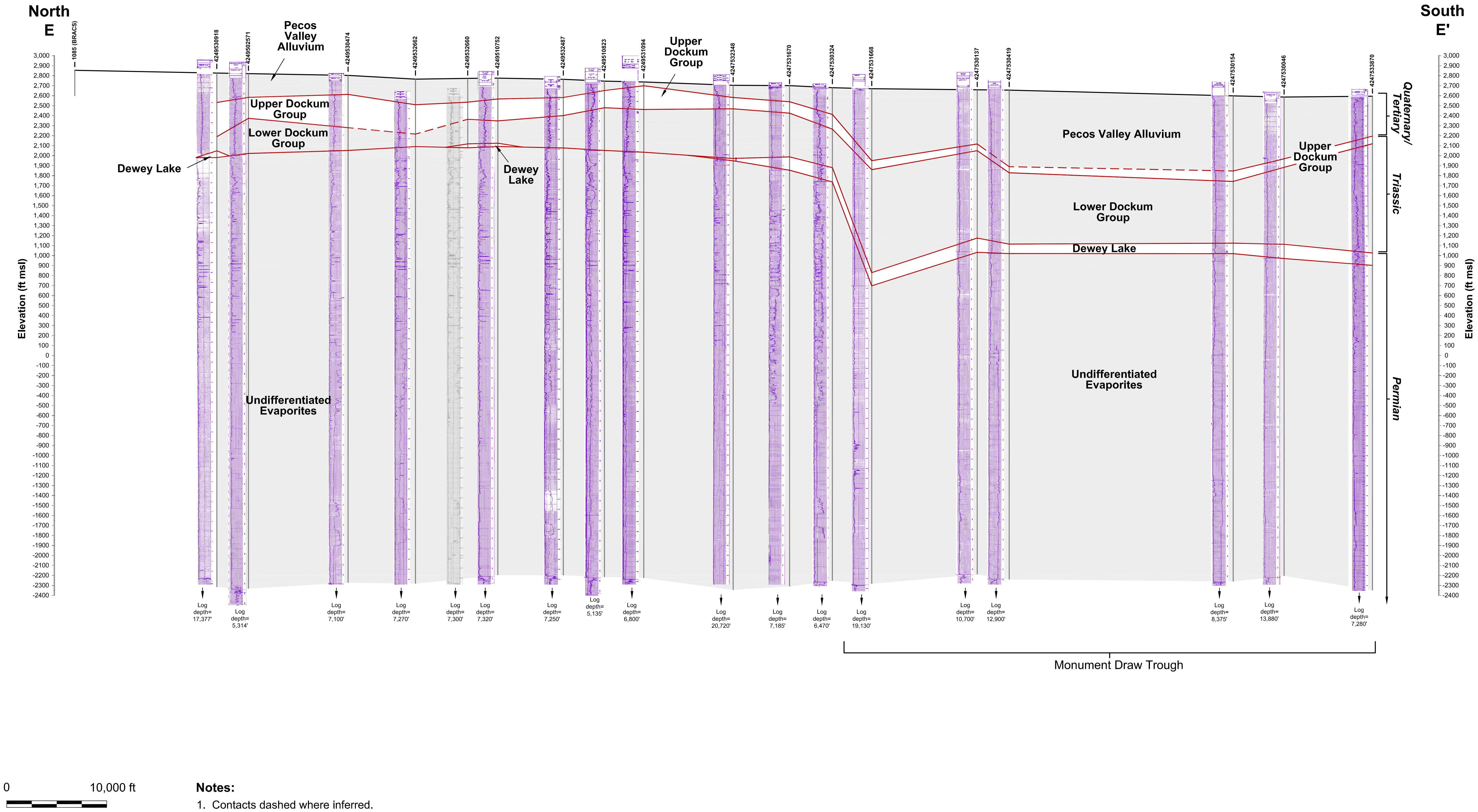
JN WR14.0154

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-05_GUYTON_Cross_Sec_D-D'.dwg

Figure A-5



Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4249530918) or Brackish Resources Aquifer Characterization System (*BRACS*), (e.g. 1085 BRACS).

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-06_GUYTON_Cross_Sec_E-E'.dwg

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North to South Geologic Cross Section E-E'

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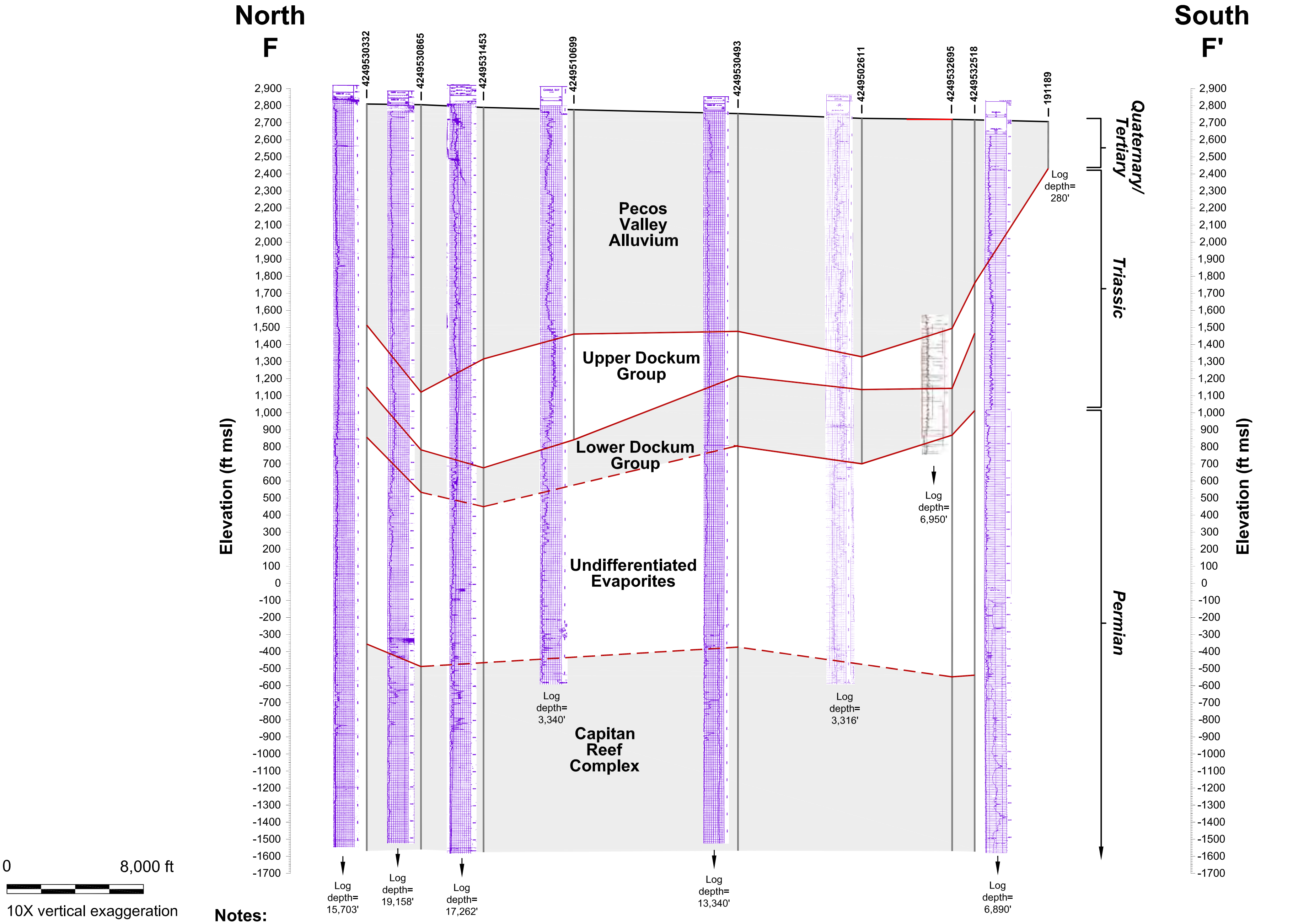
JN WR14.0154

Figure A-6

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-07_GUYTON_Cross_Sec_F-F'.dwg



Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4249530332) or TDLR (e.g. 191189).

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North to South Geologic Cross Section F-F'

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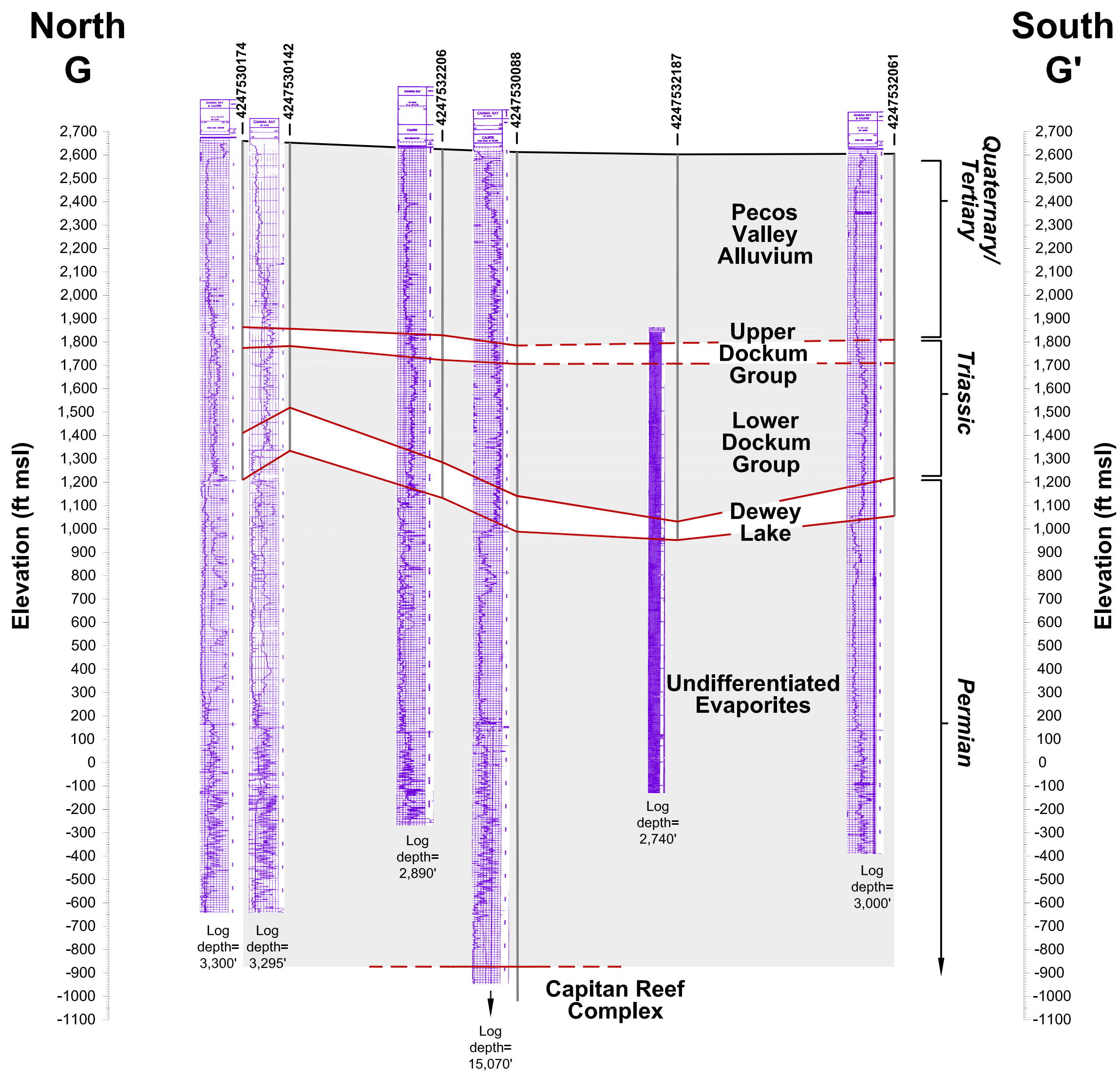
Figure A-7

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigA-08_GUYTON_Cross_Sec_G-G'.dwg



0 8,000 ft

10X vertical exaggeration

Notes:

1. Contacts dashed where inferred.
2. API well identifier (e.g. 4247530174).

Figure A-8

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11/17/2015 JN WR14.0154

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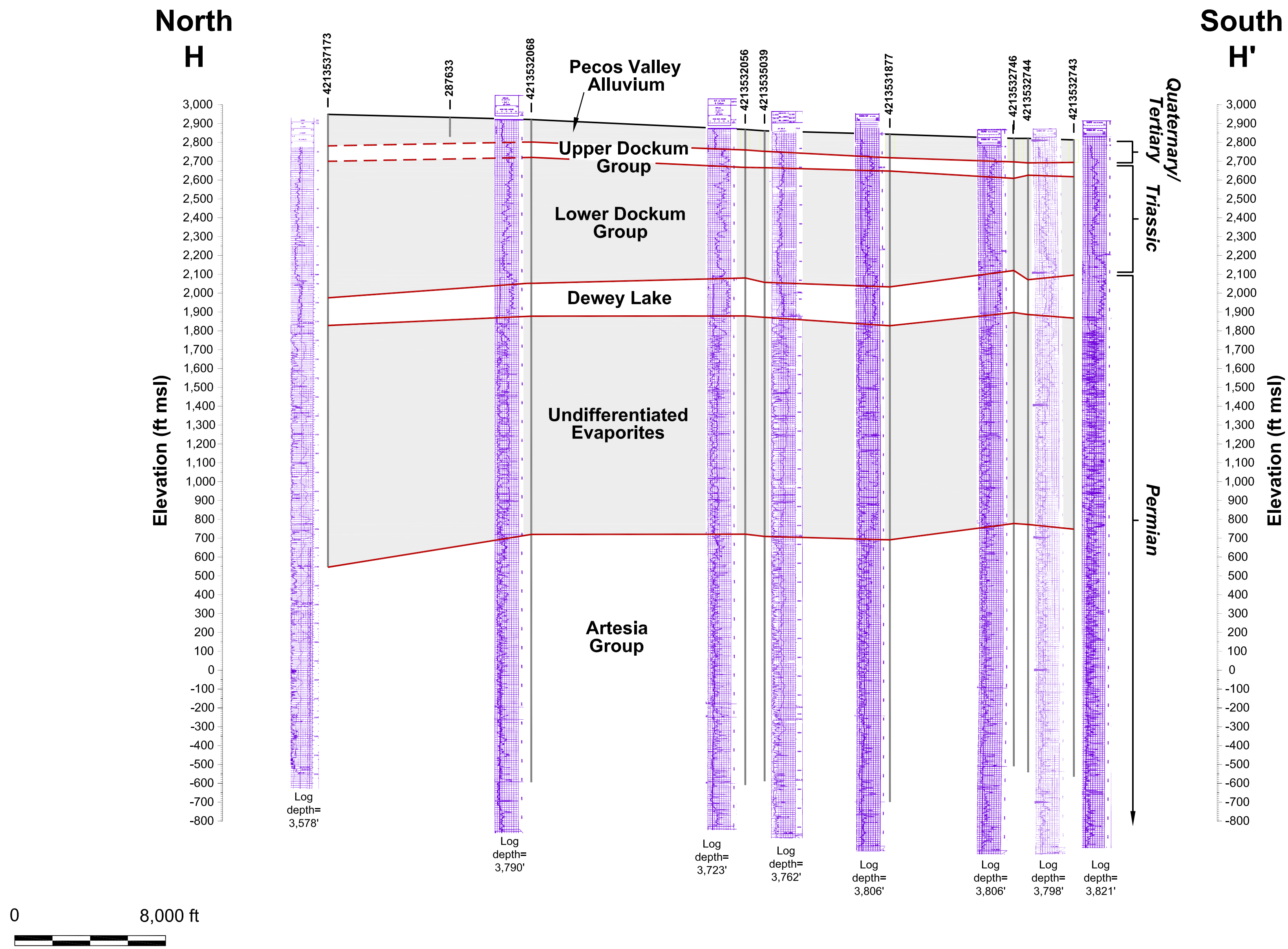
North to South Geologic Cross Section G-G'



Notes:

1. Contacts dashed where inferred.
2. Well identifiers are API (e.g. 4213537173) or TDLR (e.g. 287633).

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North to South Geologic Cross Section H-H'

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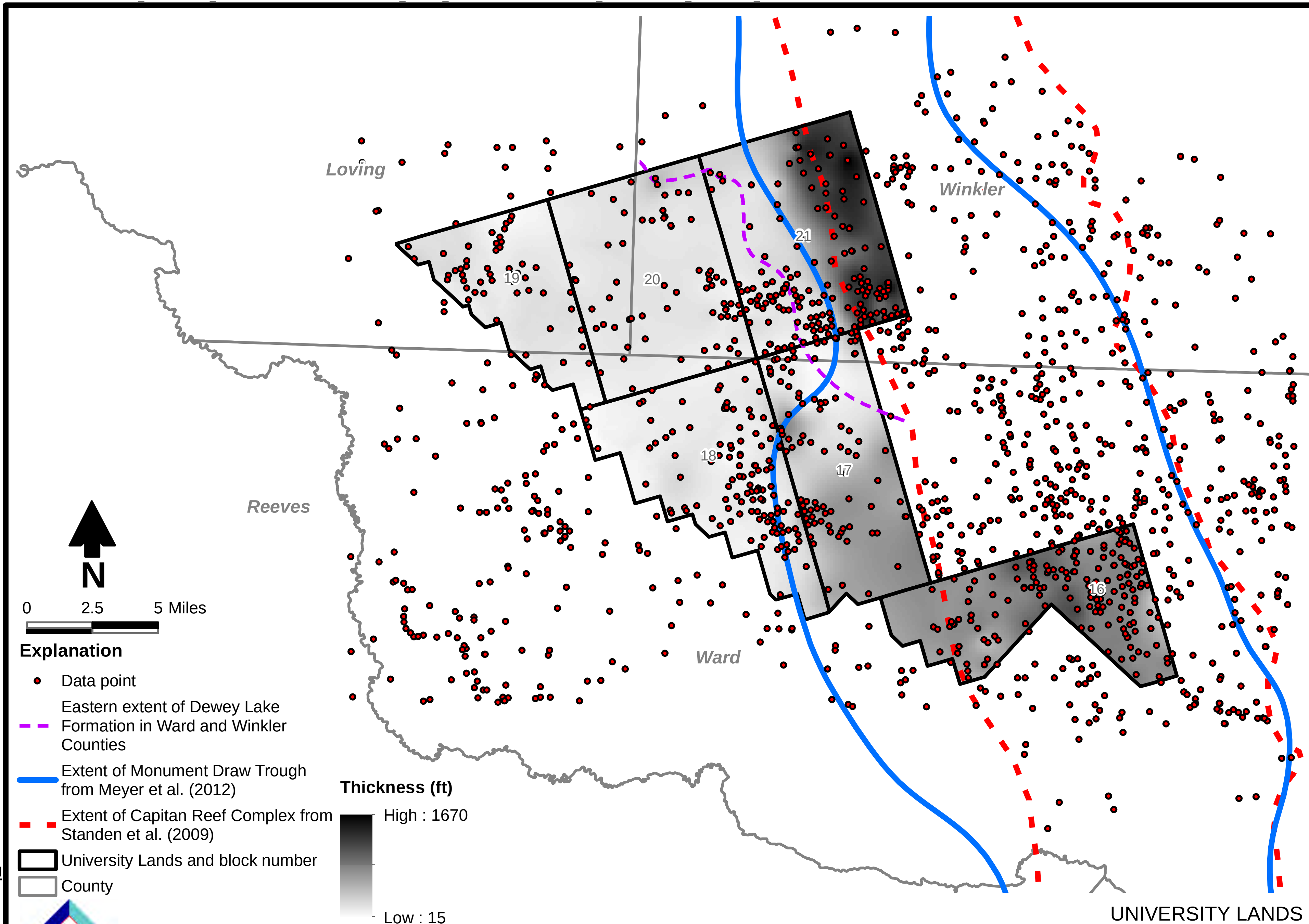
JN WR14.0154

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-10_WARDWINKLER_THICKNESS_ALLUVIUM.MXD



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Thickness of Pecos Valley Alluvium

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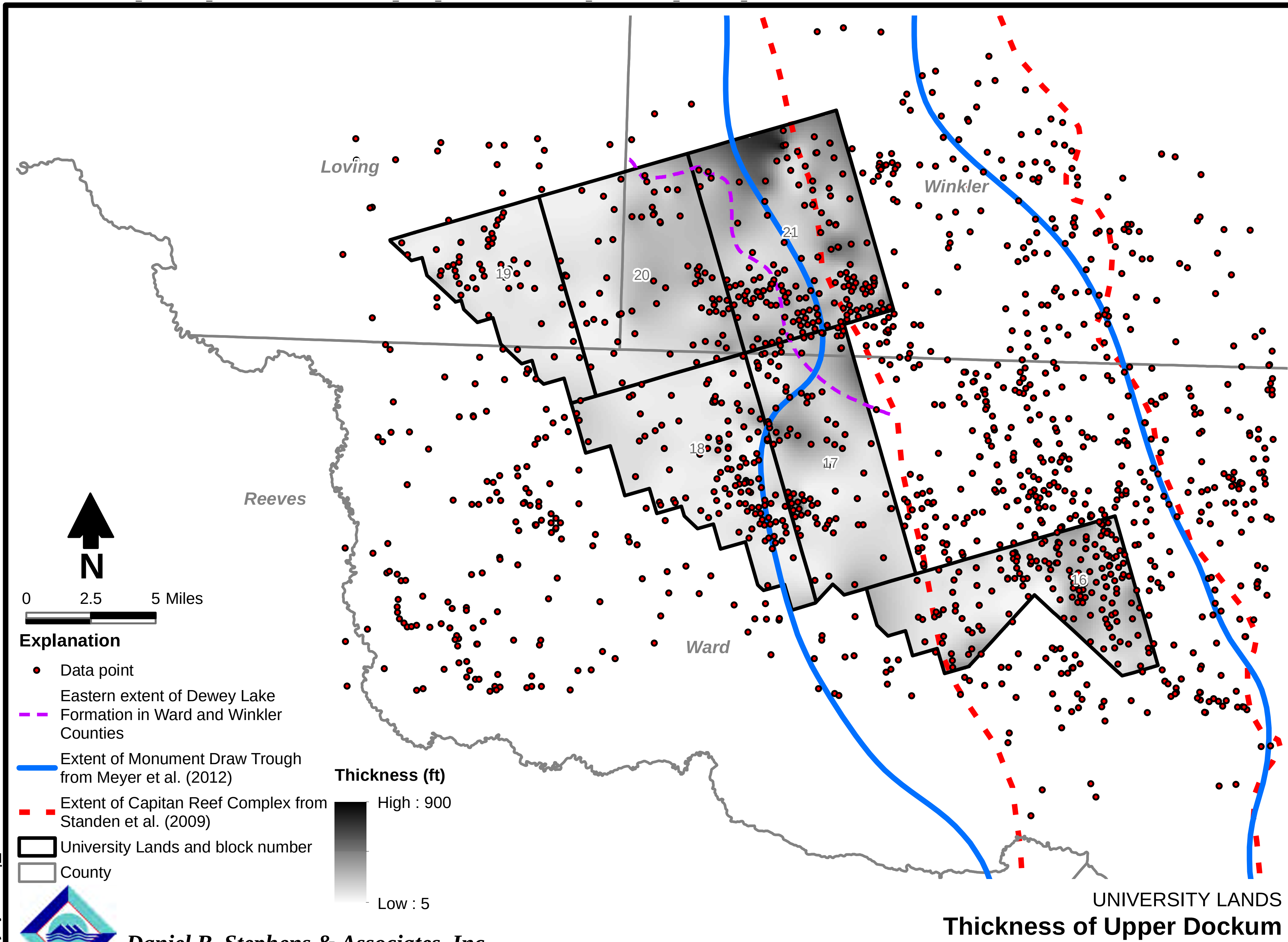
12/14/2015

JN WR14.0154

Figure A-10

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-11_WARDWINKLER_THICKNESS_UPPERDOCKUM.MXD



UNIVERSITY LANDS
Thickness of Upper Dockum

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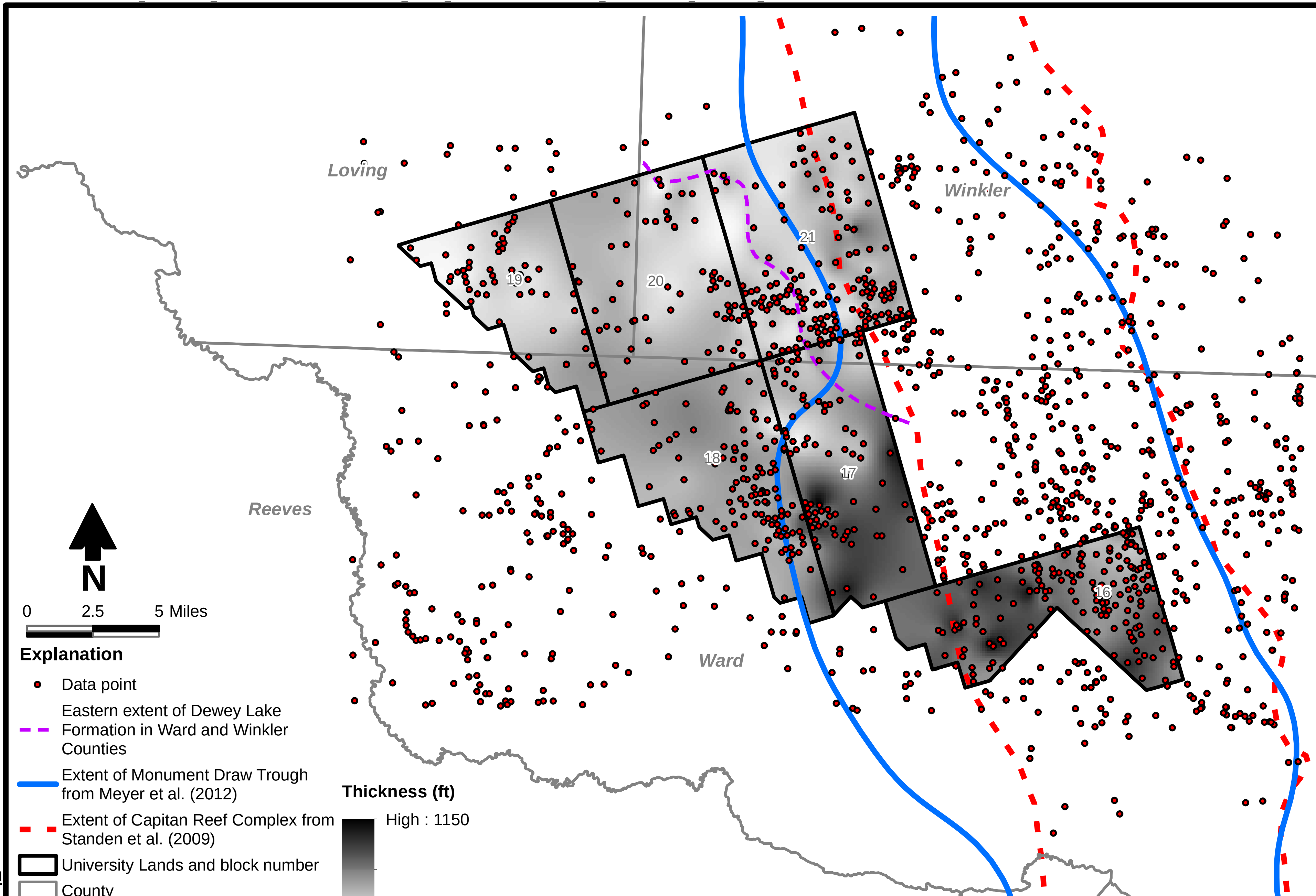
12/14/2015
JN WR14.0154

Figure A-11

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-12_WARDWINKLER_THICKNESS_LOWERDOCKUM.MXD



UNIVERSITY LANDS

Thickness of Lower Dockum

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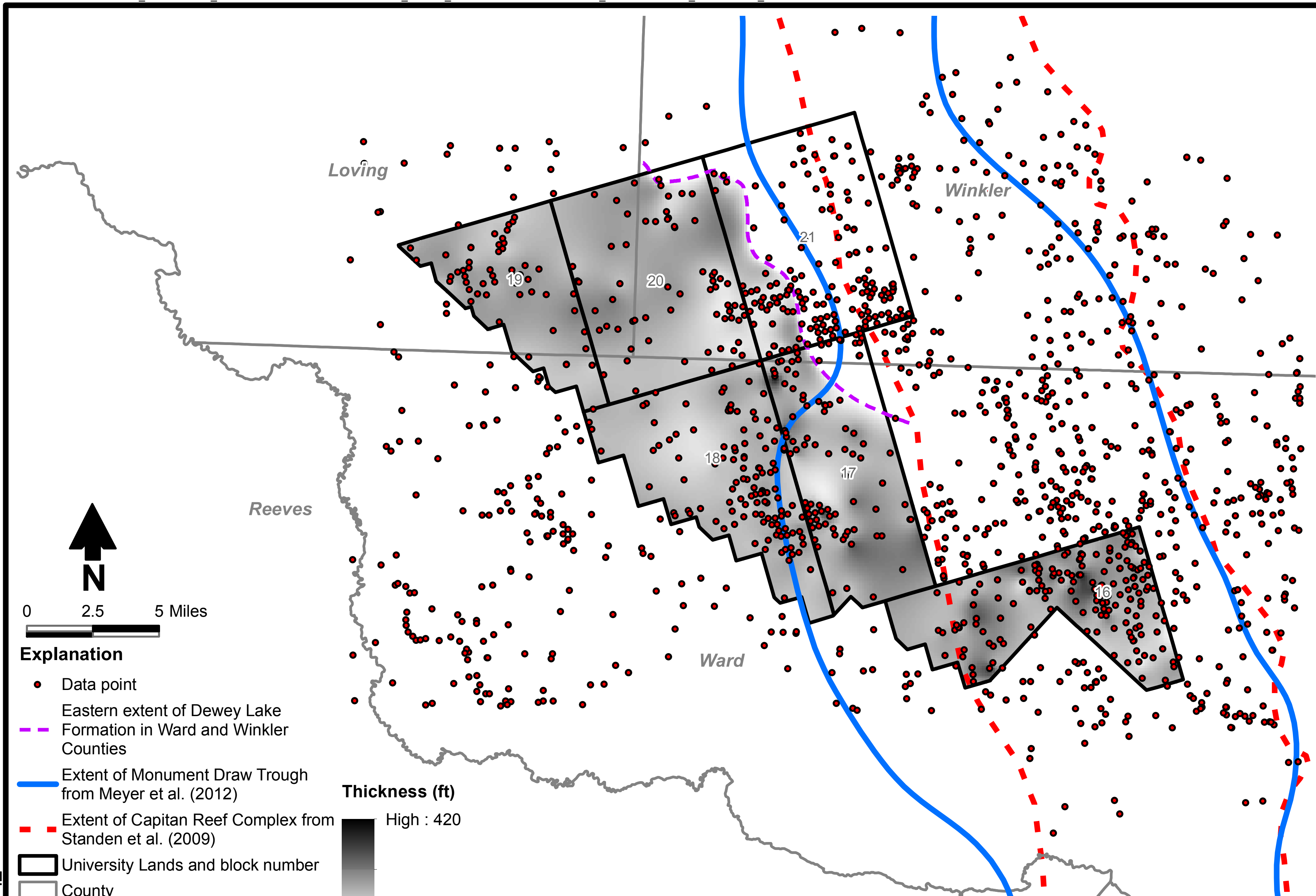
12/14/2015

JN WR14.0154

Figure A-12

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-13_WARDWINKLER_THICKNESS_DEWEYLAKE.MXD



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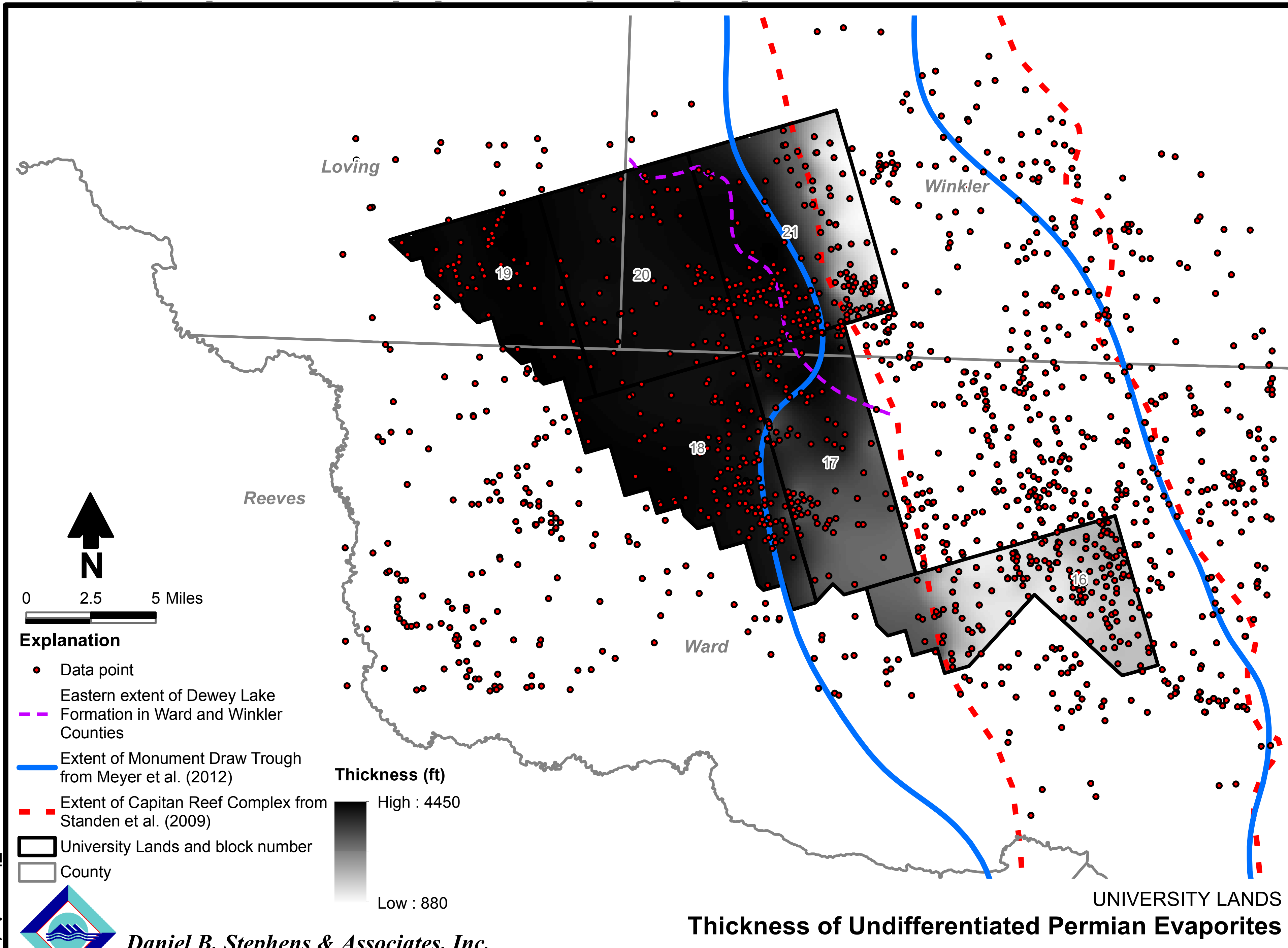
Thickness of Dewey Lake Formation

Figure A-13

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-14_WARDWINKLER_THICKNESS_EVAPORITES.MXD



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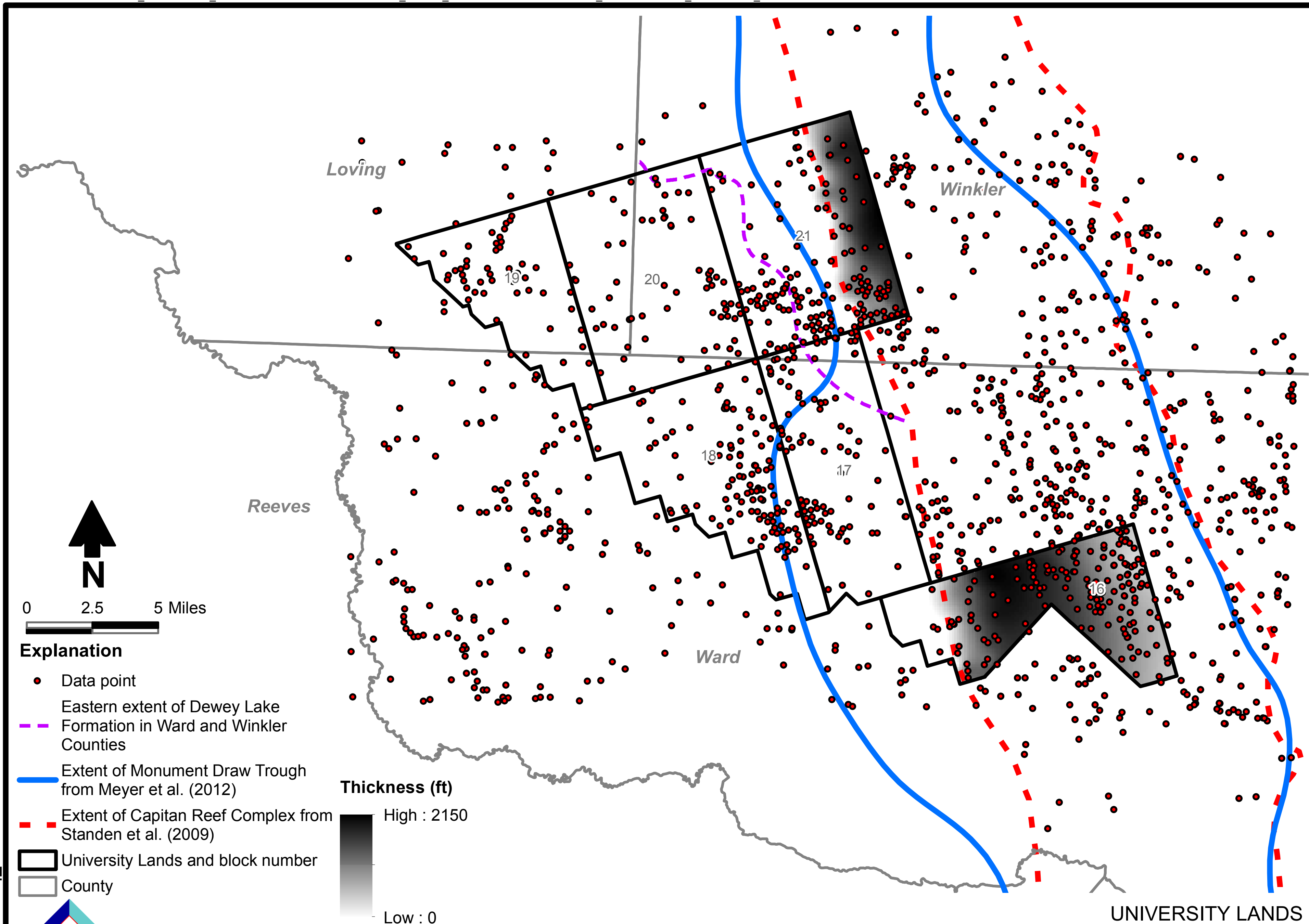
Thickness of Undifferentiated Permian Evaporites

Figure A-14

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGA-15_WARDWINKLER_THICKNESS_CAPITAN.MXD



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Thickness of Capitan Reef Complex

Figure A-15

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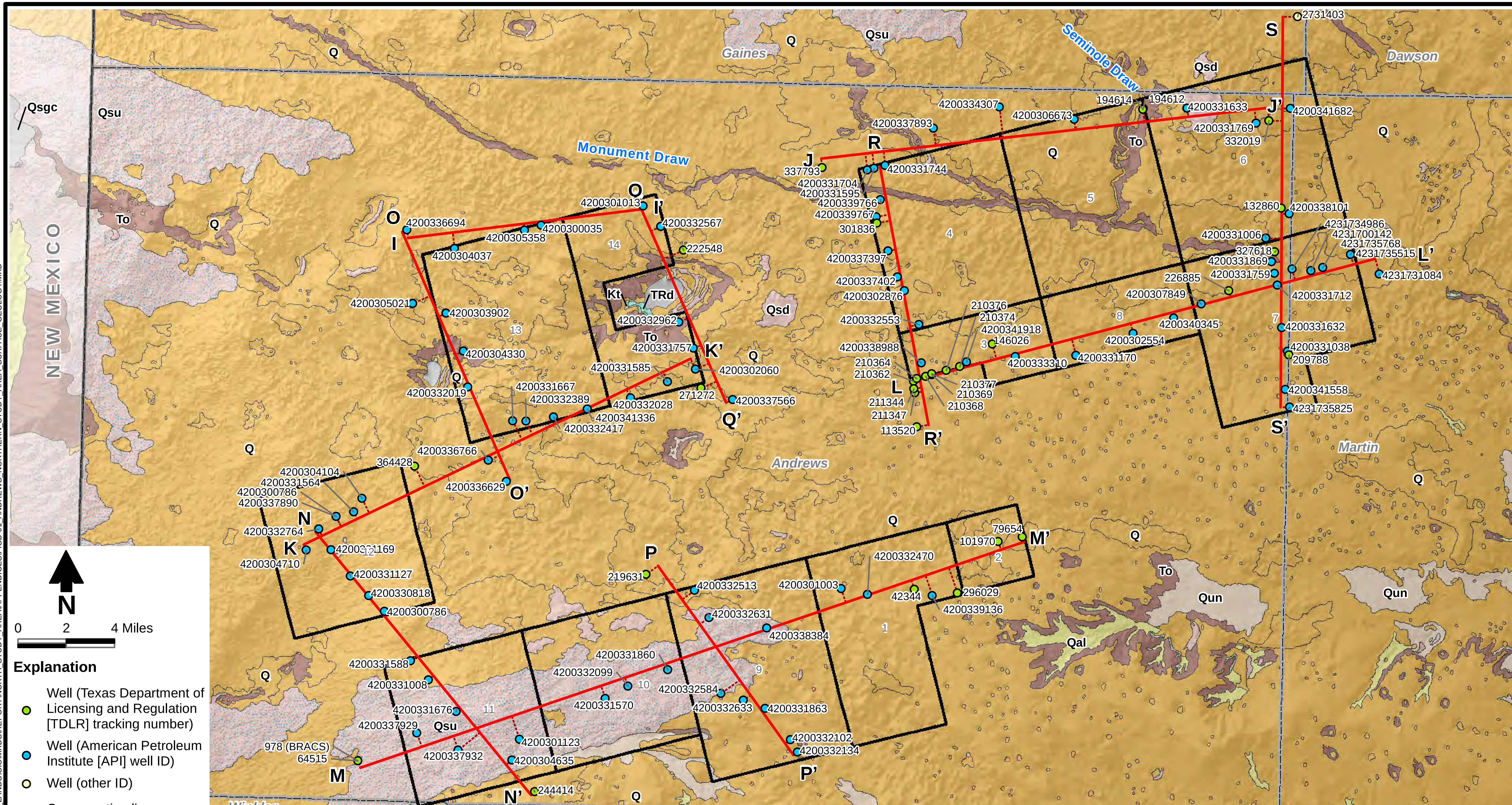
Appendix B

Geologic Cross Sections and Unit Thickness Maps for Andrews County Area



Explanation

- Well (Texas Department of Licensing and Regulation [TDLR] tracking number)
- Well (American Petroleum Institute [API] well ID)
- Well (other ID)
- Cross section line
- Projection line
- University Lands and block number
- County

Geology

- Q - Quaternary deposits (undivided)
- Qal - Quaternary alluvium
- Qsd - dune and dune ridges
- Qsgc - Colluvial deposits
- Qsu - sand sheets, dunes, and dune ridges
- Qun - Pond deposits
- To - Ogallala Formation
- Kfr - Fredericksburg Group
- Kft - Fort Terrett Formation (Fredericksburg Group)
- Kt - Trinity Group (undivided)
- TRd - Dockum Group (undivided)

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-01_ANDREWS_NORTHERN_STUDY_AREA_SURFACE_GEOLOGY.MXD

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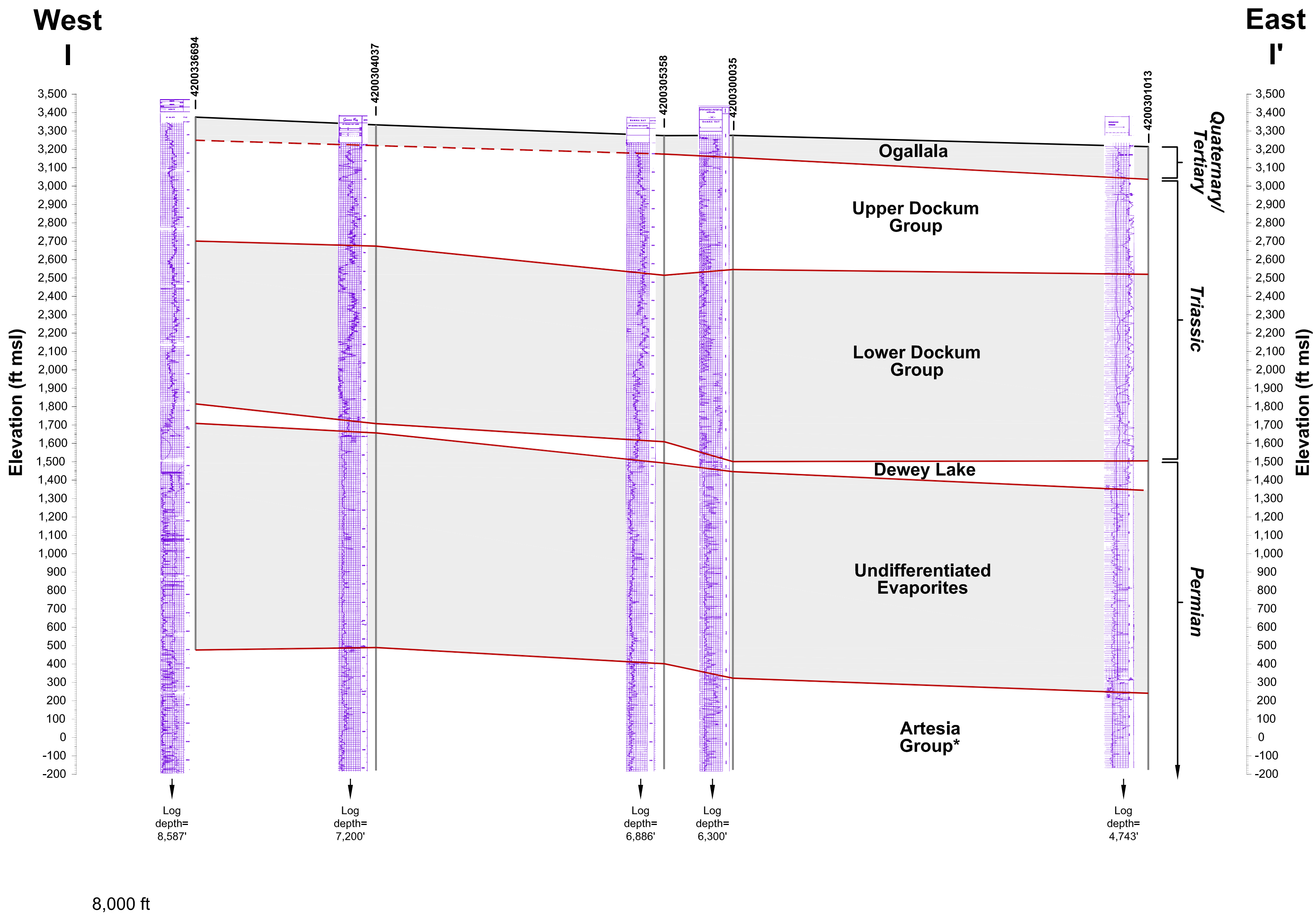
Andrews County Area Surface Geology (I-I' Through S-S')

Figure B-1

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-02_GUYTON_Cross_Sec_I-I'.dwg



Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. API well identifier (e.g. 4200336694).

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West to East Geologic Cross Section I-I'

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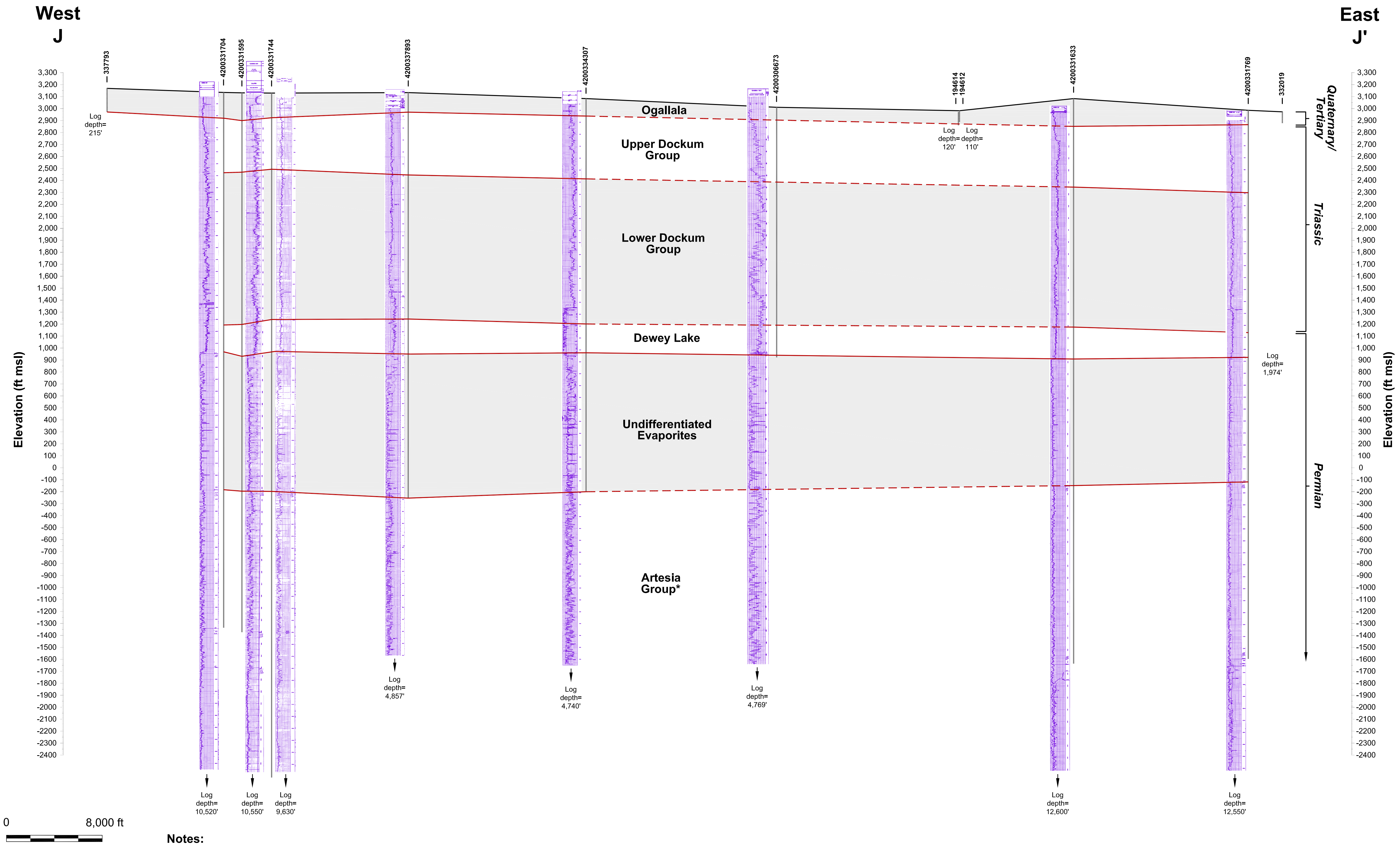
Figure B-2



Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200331704) or TDLR (e.g. 337793).

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-03_GUYTON_Cross_Sec_J-J'.dwg

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West to East Geologic Cross Section J-J'

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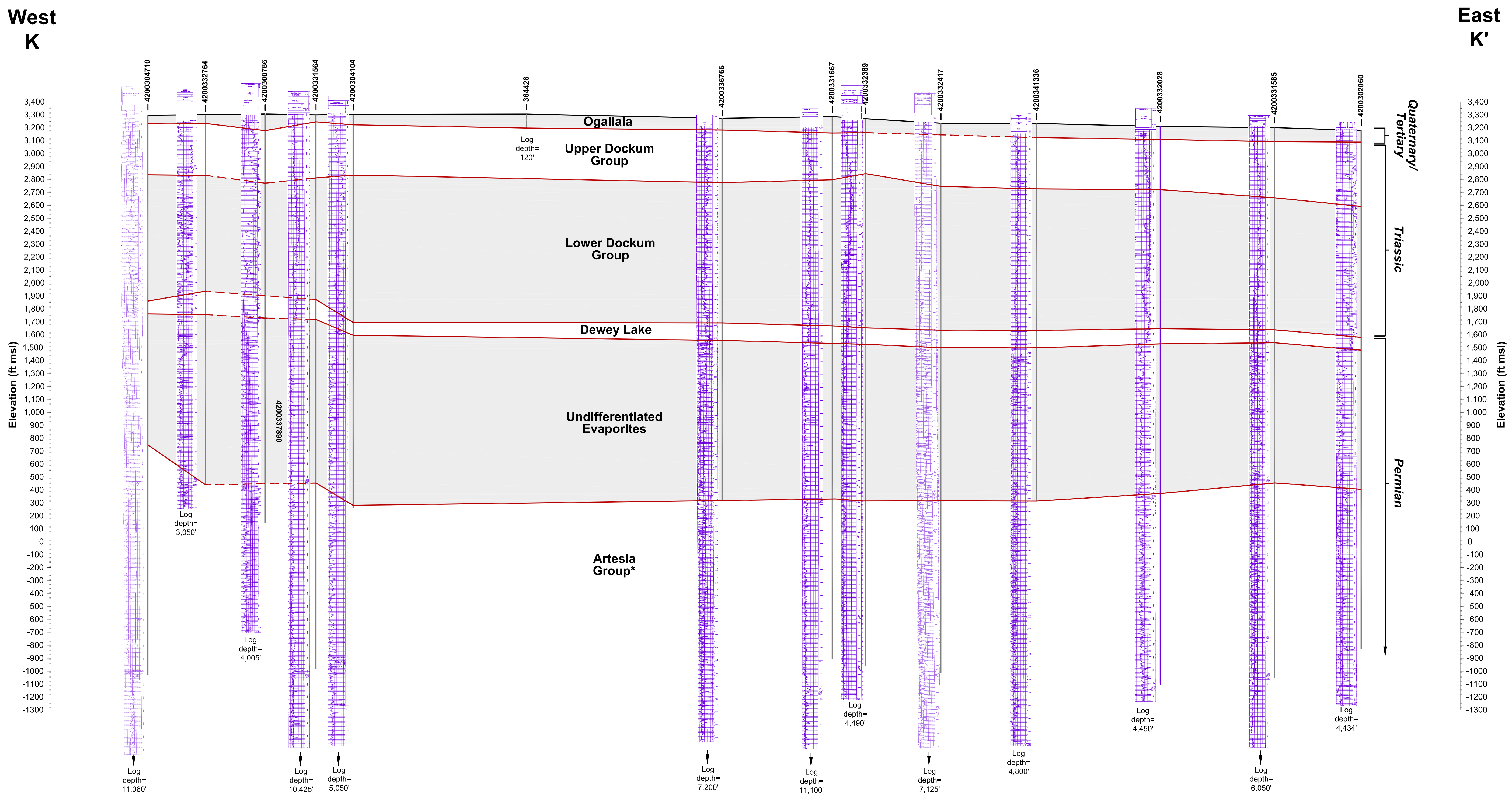
Figure B-3



0 8,000 ft

10X vertical exaggeration

Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200304710) or TDLR (e.g. 364428).

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-04_GUYTON_Cross_sec_K-K'.dwg

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West to East Geologic Cross Section K-K'

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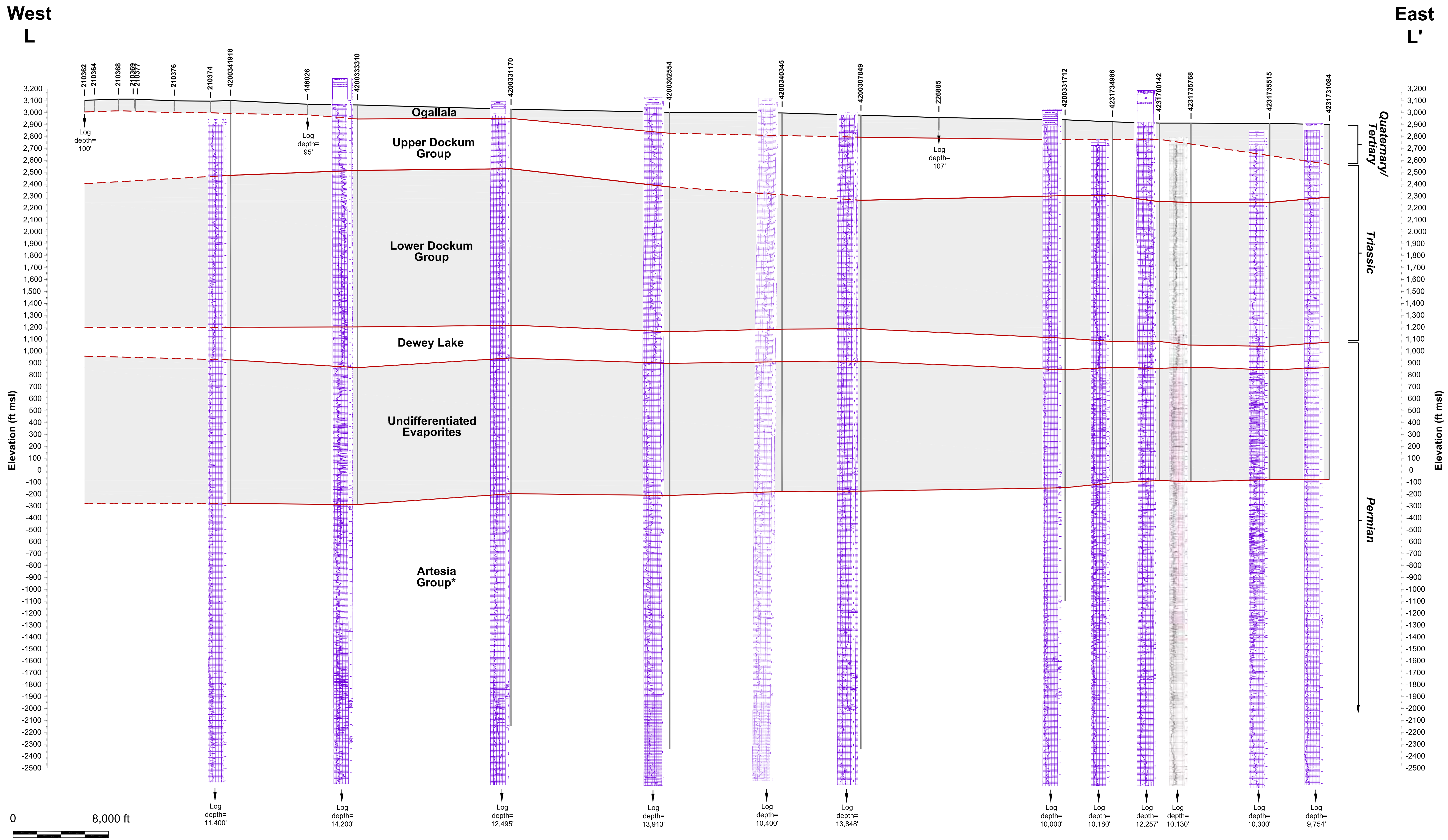
Figure B-4



10X vertical exaggeration

Notes:
1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200341918) or TDLR (e.g. 210362).

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-05_GUYTON_Cross_sec_L-L'.dwg

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West to East Geologic Cross Section L-L'

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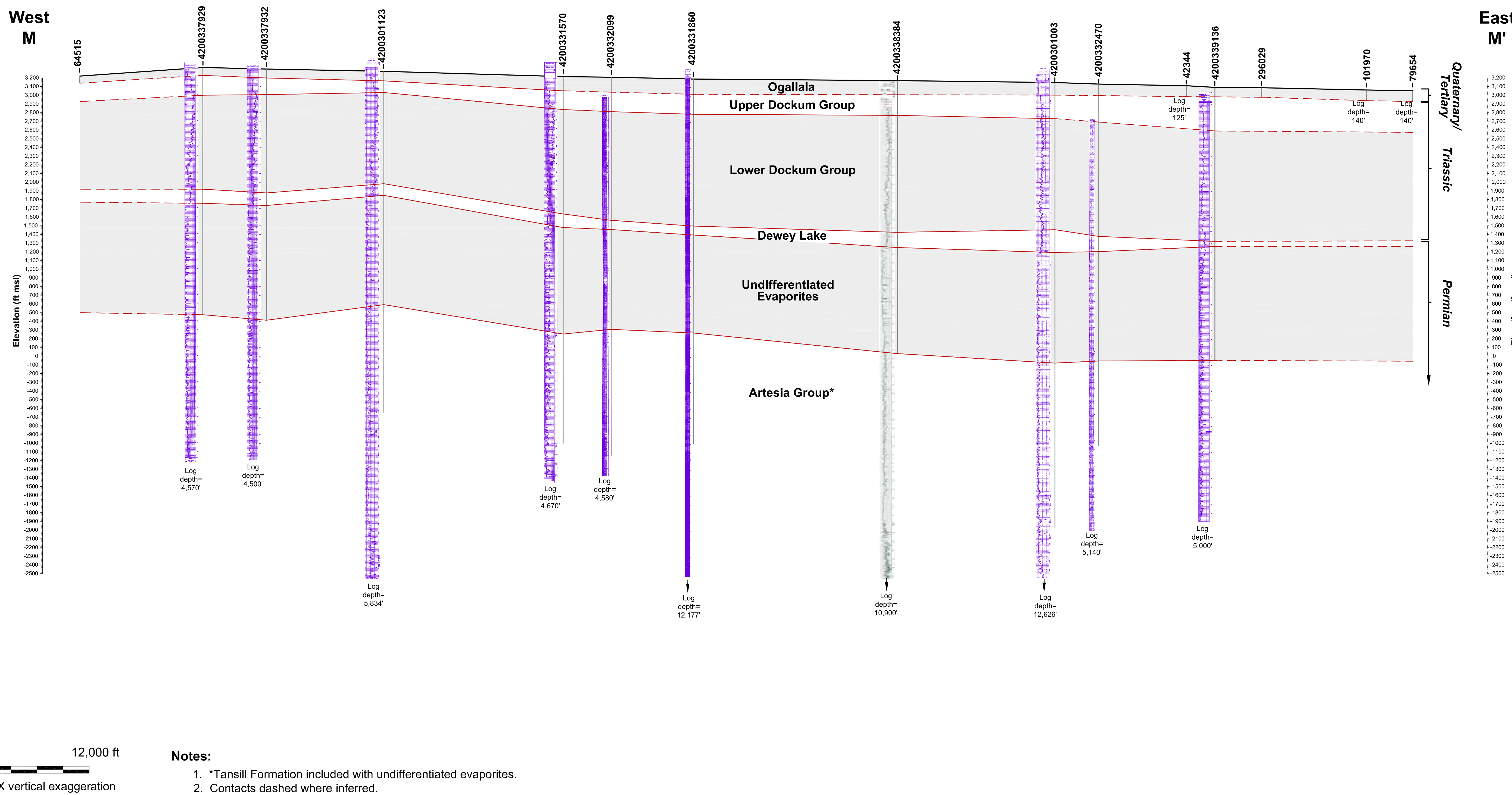
Figure B-5



Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200337929) or TDLR (e.g. 64515).

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West to East Geologic Cross Section M-M'

Figure B-6

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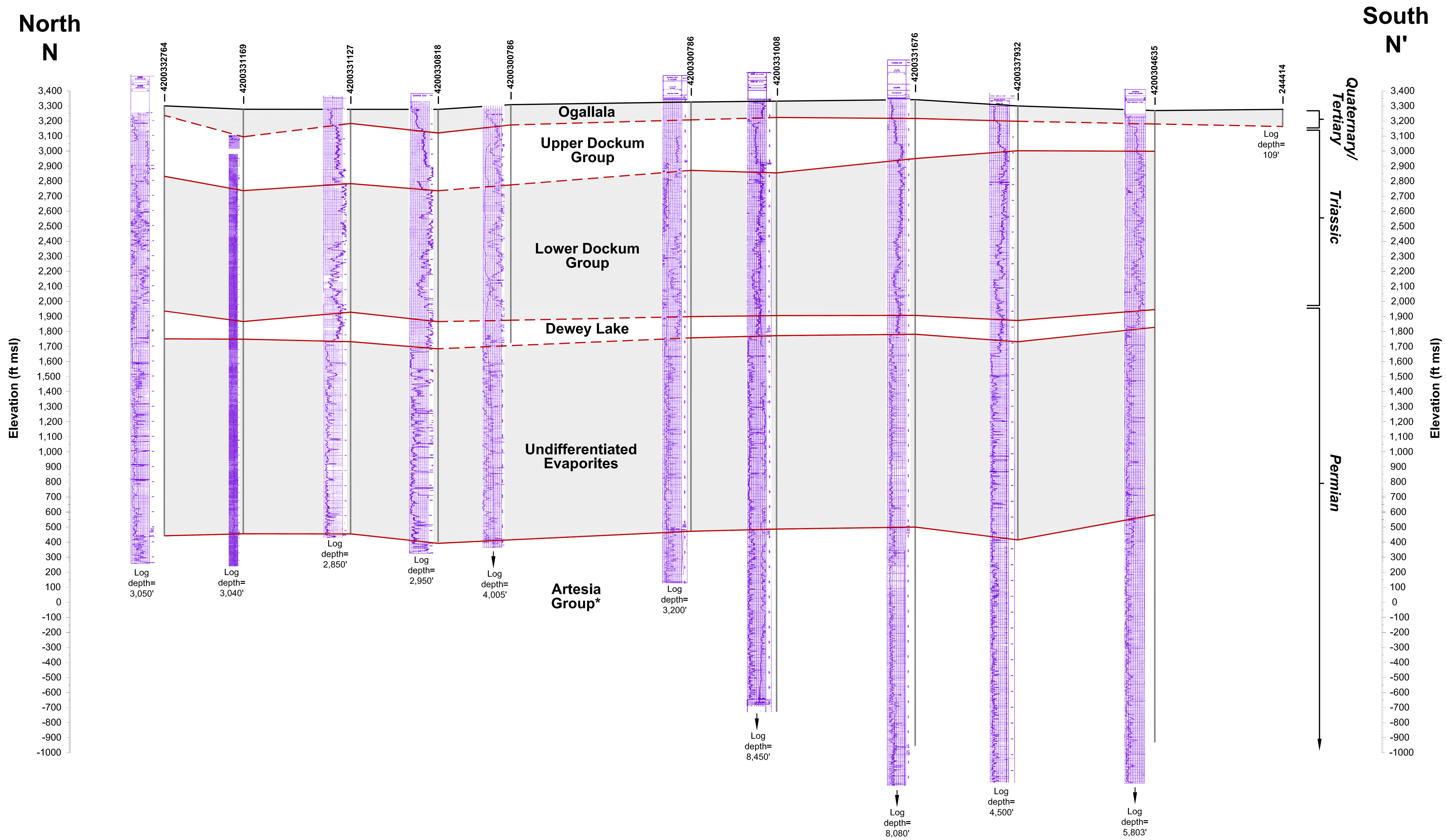
S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-06_GUYTON_Cross_sec_M-M'.dwg



0 8,000 ft

10X vertical exaggeration

Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200332764) or TDLR (e.g. 244414).

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West to East Geologic Cross Section N-N'

Figure B-7

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-07_GUYTON_Cross_sec_N-N'.dwg

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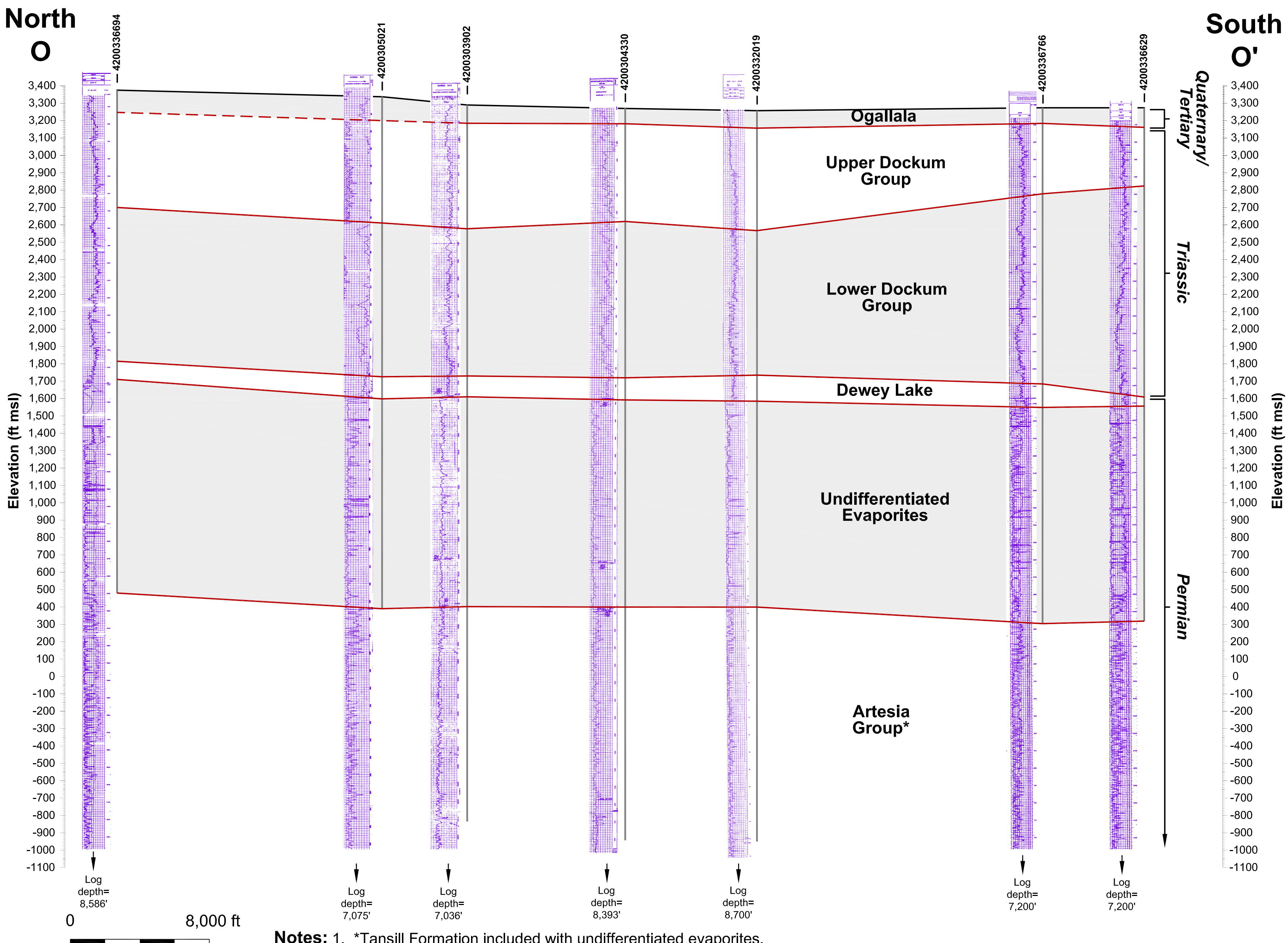
JN WR14.0154

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-08_GUYTON_Cross_sec_O-O'.dwg



10X vertical exaggeration

Notes:
1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. API well identifier (e.g. 4200336694).

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North to South Geologic Cross Section O-O'

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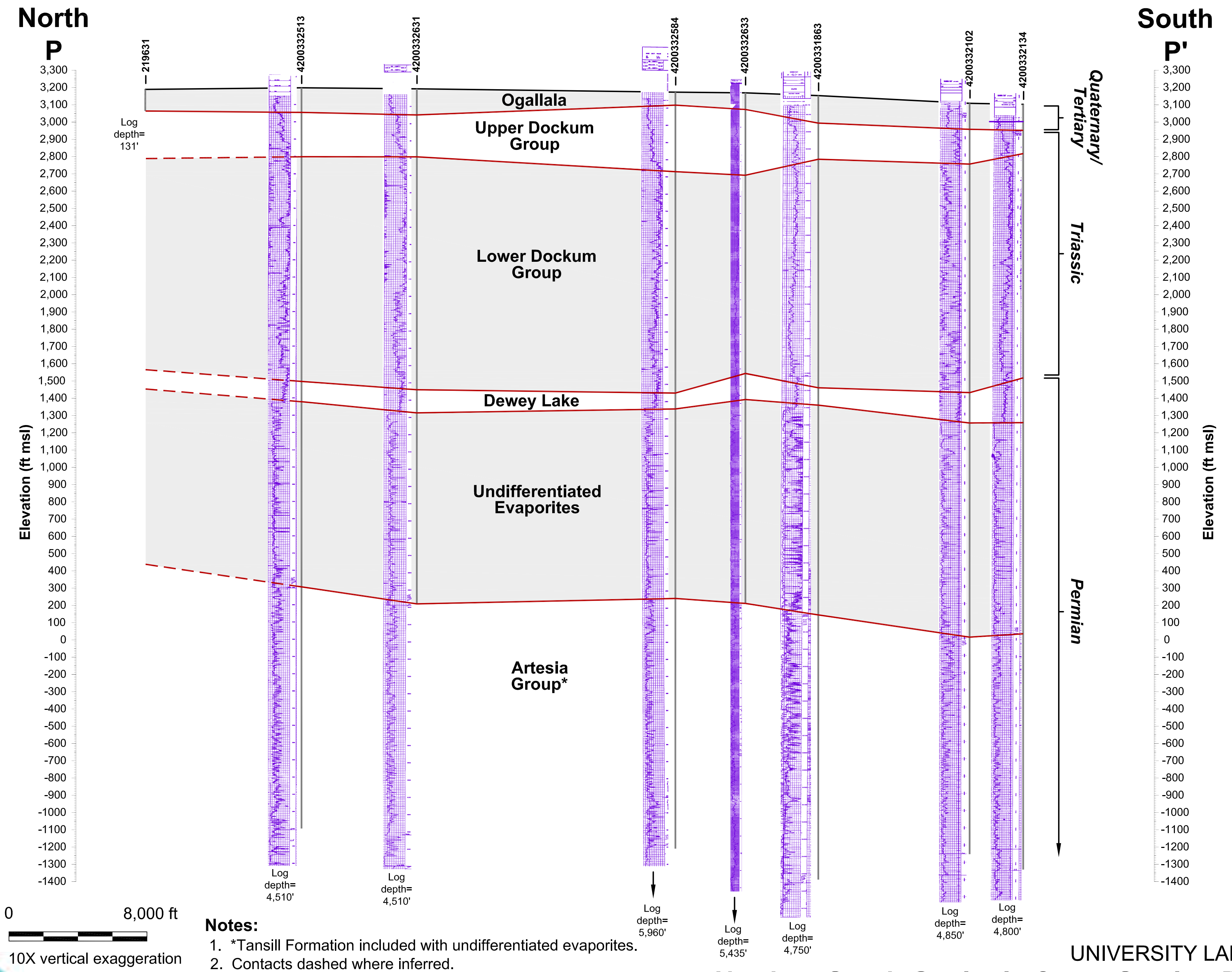
Figure B-8

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-09_GUYTON_Cross_sec_P-P'.dwg



Notes:
1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200332513) or TDLR (e.g. 219631).

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North to South Geologic Cross Section P-P'

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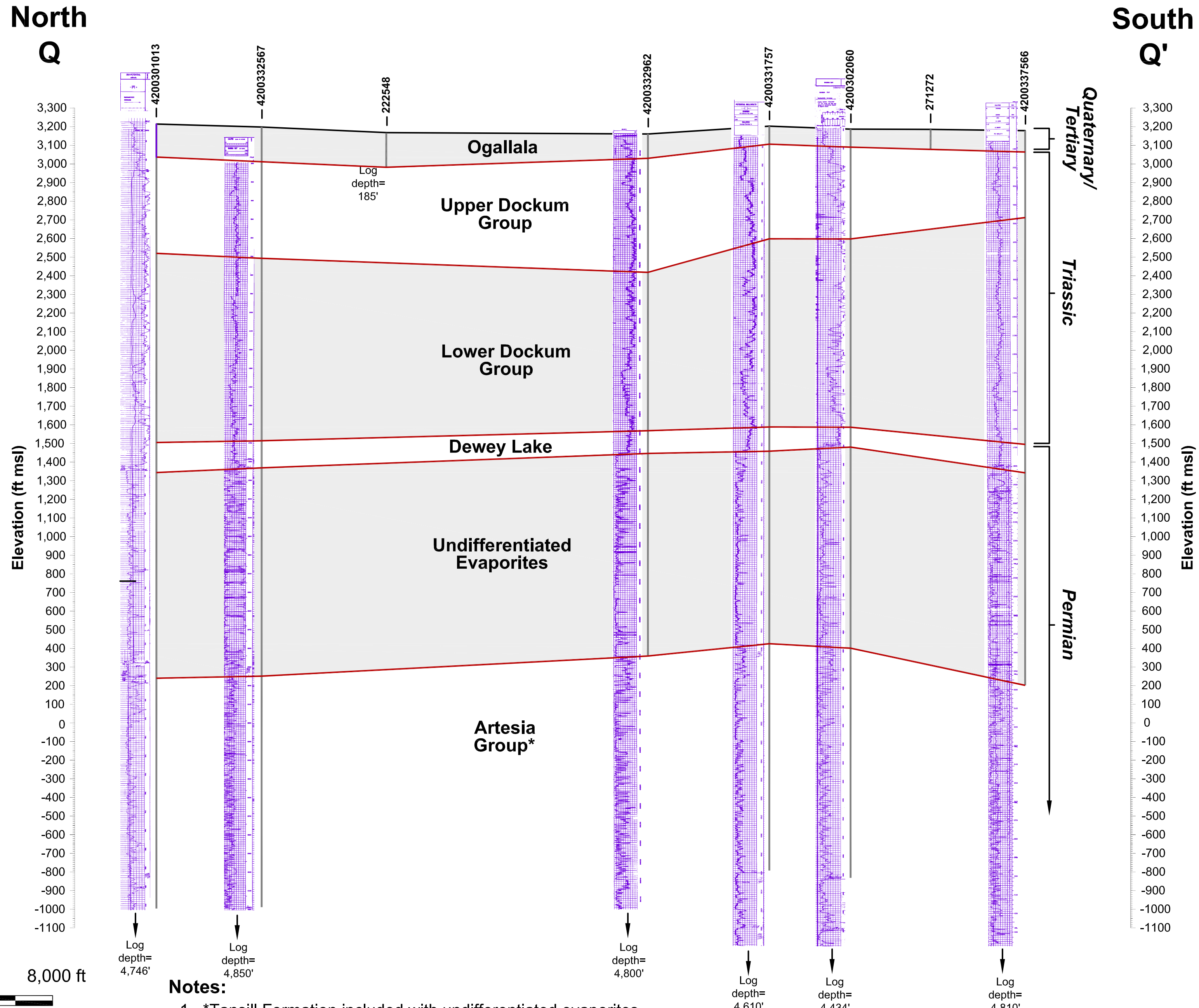
Figure B-9

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-10_GUYTON_Cross_sec_Q-Q'.dwg



0 8,000 ft

10X vertical exaggeration

Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200301013) or TDLR (e.g. 222548).

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North to South Geologic Cross Section Q-Q'

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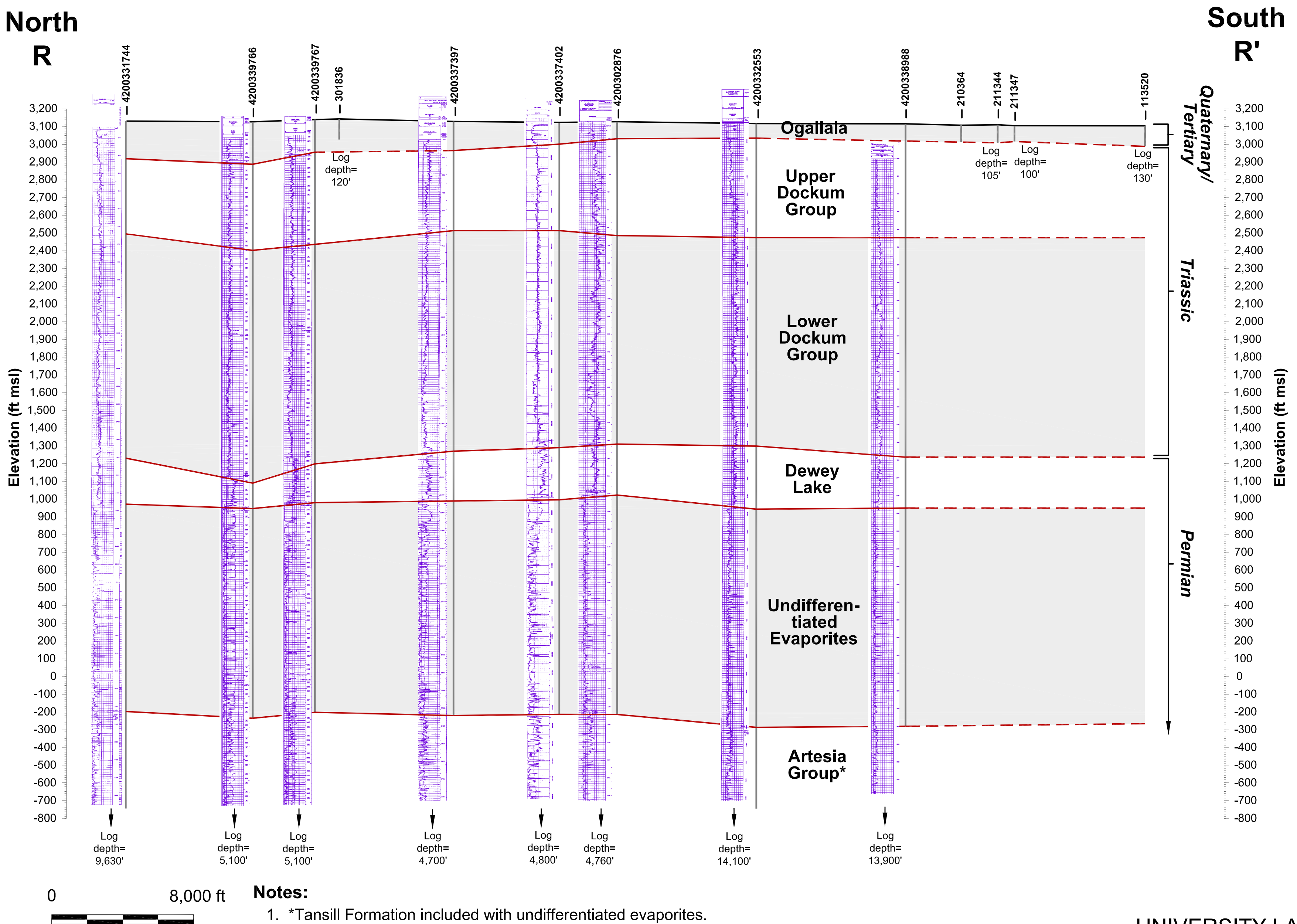
Figure B-10

S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-11_GUYTON_Cross_sec_R-R'.dwg



Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200331744) or TDLR (e.g. 301836).

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North to South Geologic Cross Section R-R'

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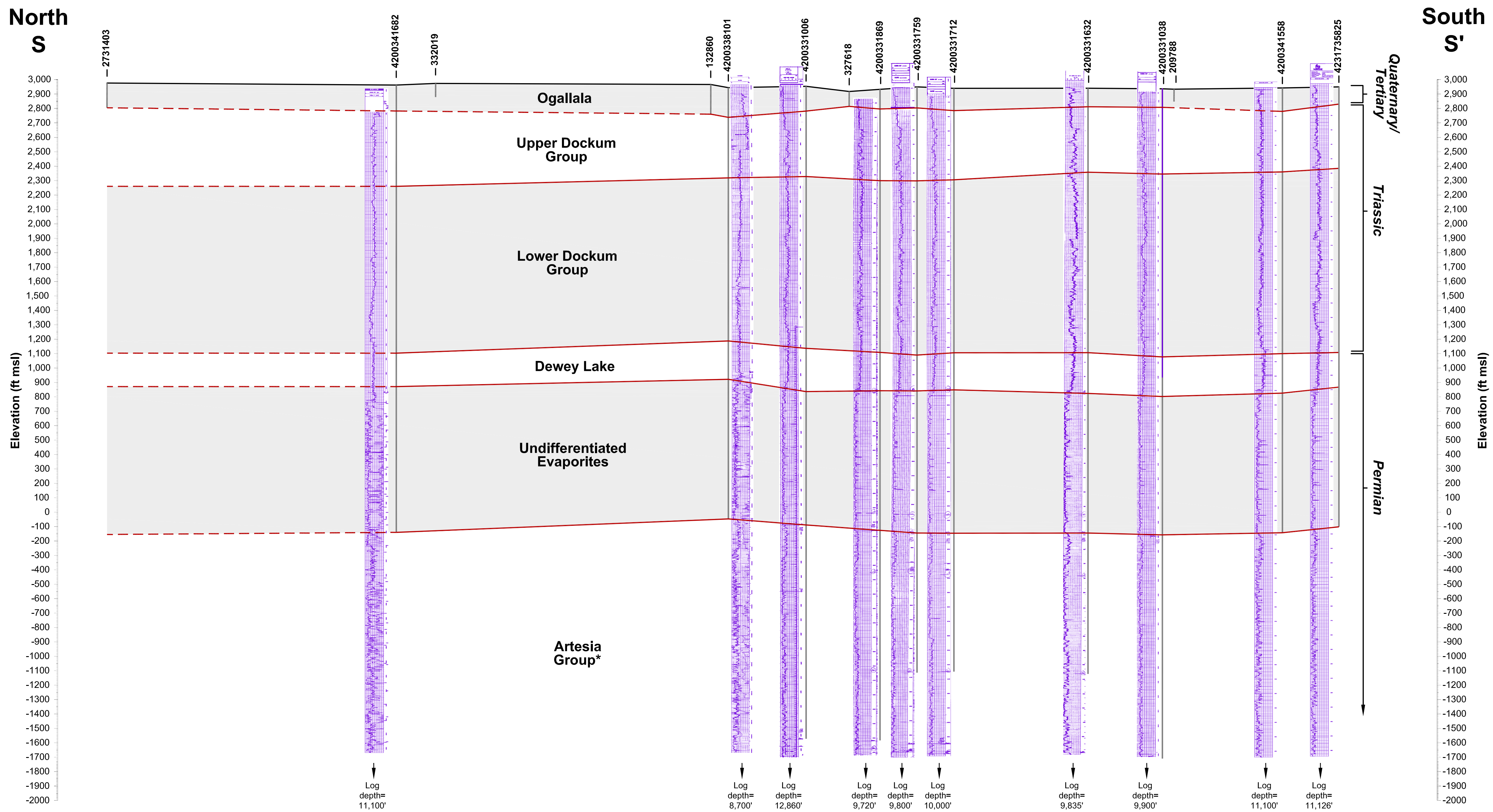
Figure B-11



0 8,000 ft

10X vertical exaggeration

Notes:

1. *Tansill Formation included with undifferentiated evaporites.
2. Contacts dashed where inferred.
3. Well identifiers are API (e.g. 4200341682) or TDLR (e.g. 2731403).

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North to South Geologic Cross Section S-S'

Figure B-12

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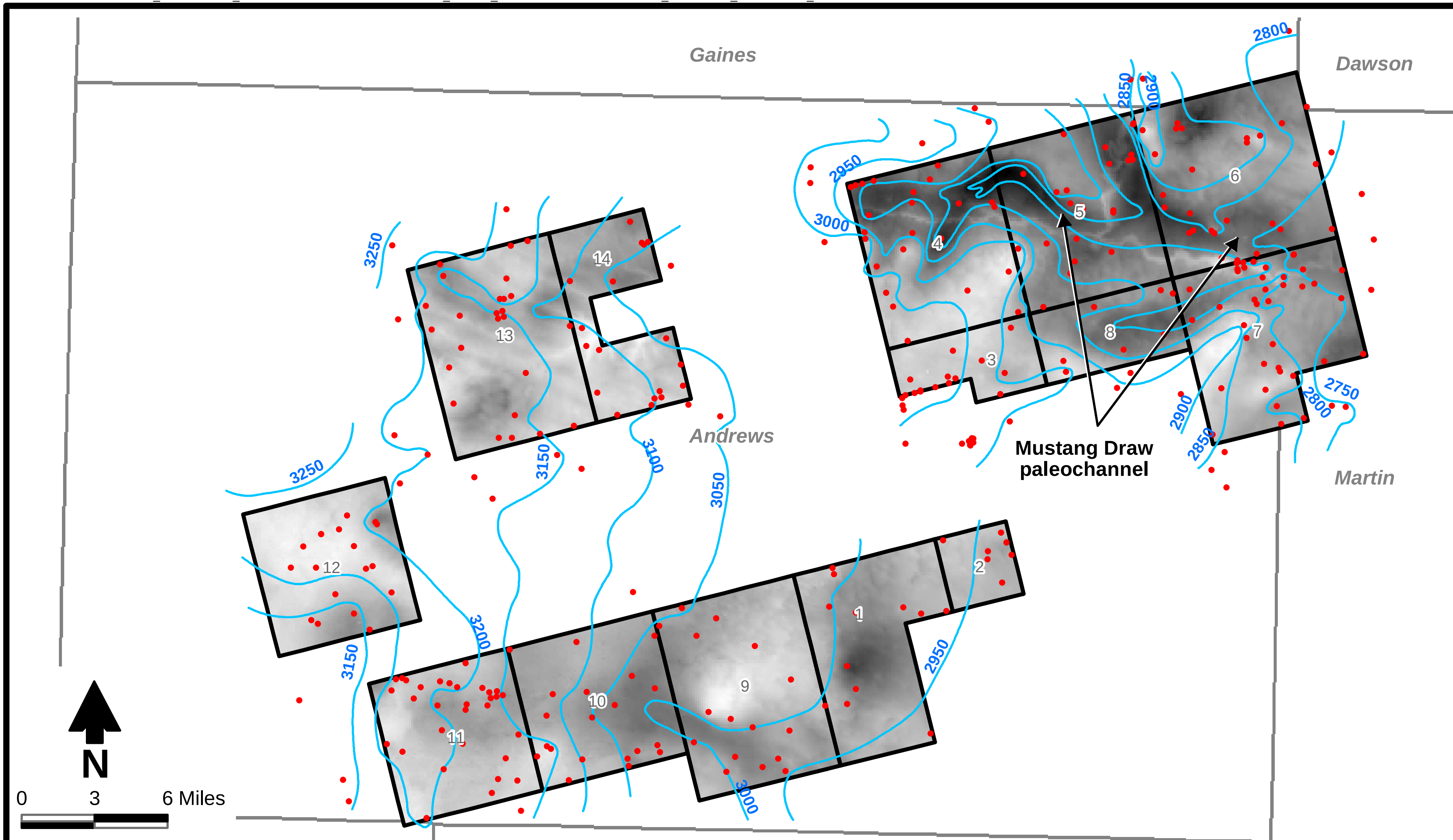
S:\Projects\WR14.0154_University_Lands\VR_Drawings\FigB-12_GUYTON_Cross_sec_S-S'.dwg

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-13_ANDREWS_THICKNESS_OGALLALA.MXD



Explanation

- Data point
- University Lands and block number
- County
- Elevation of base of Ogallala contour (ft)

Thickness (ft)

High : 310

Low : 45

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Thickness of Ogallala Formation

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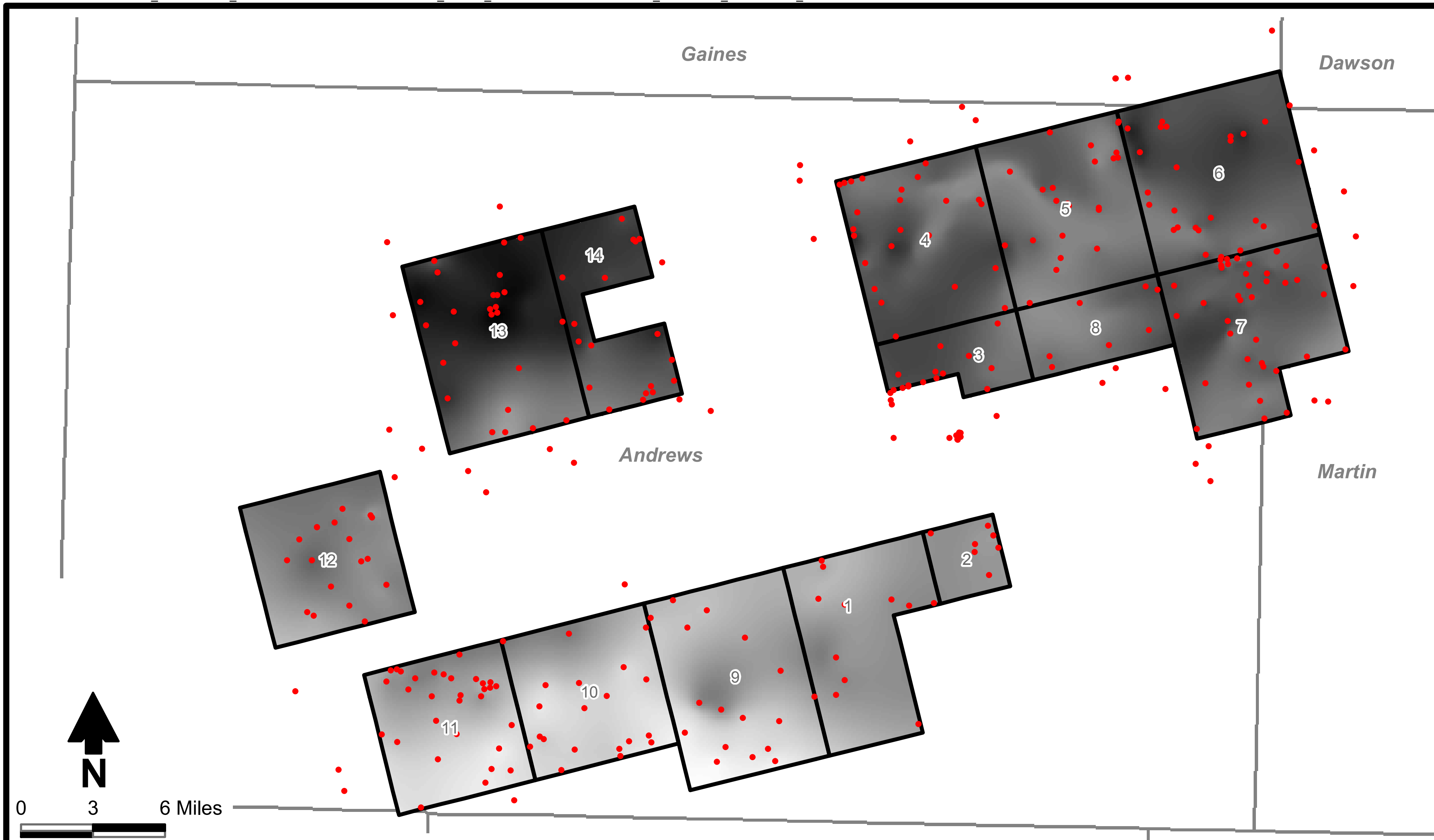
Figure B-13

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-14_ANDREWS_THICKNESS_UPPERDOCKUM.MXD



Explanation

- Data point
- University Lands and block number
- County

Thickness (ft)

High : 700

Low : 115

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Thickness of Upper Dockum

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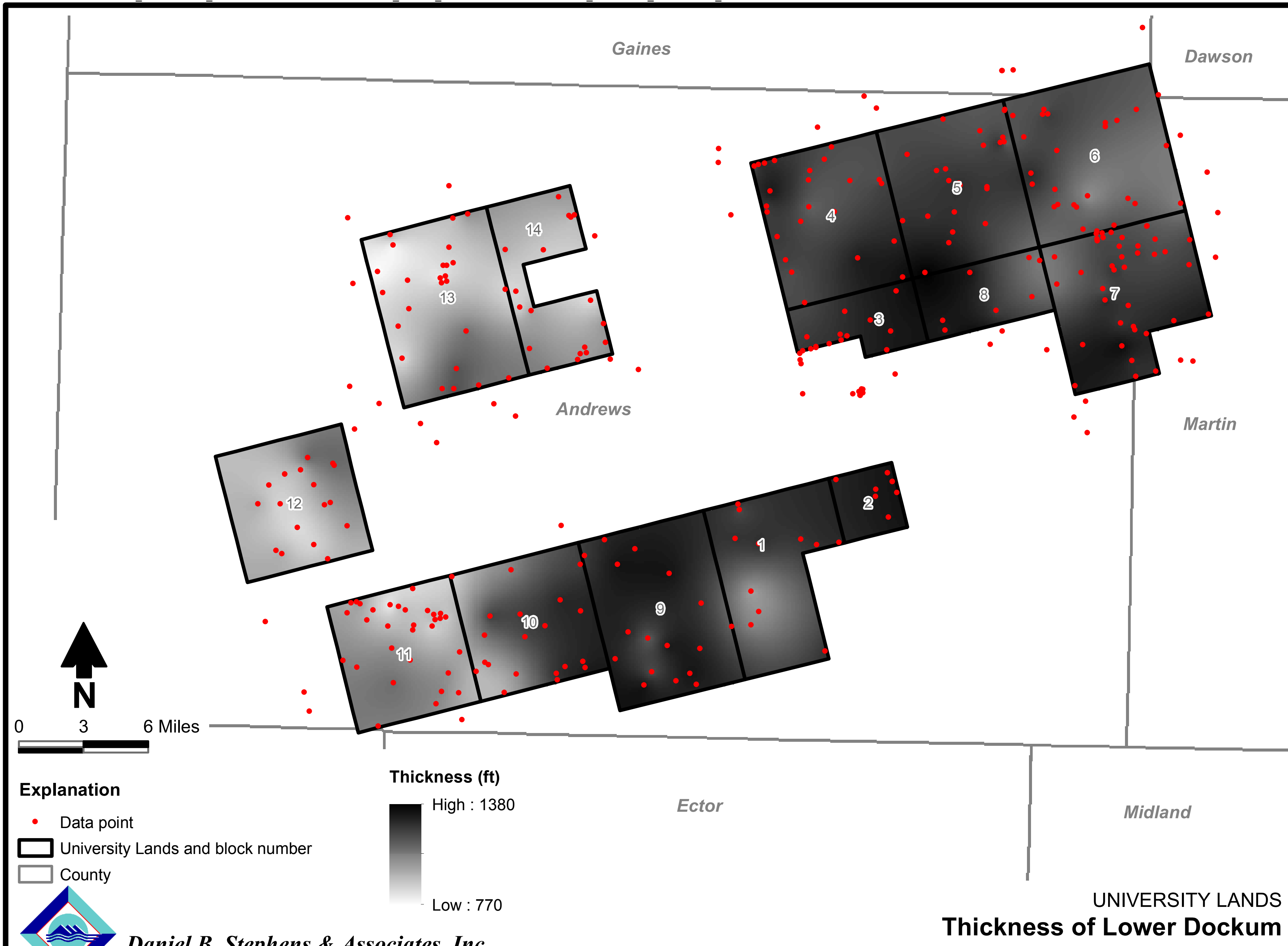
Figure B-14

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-15_ANDREWS_THICKNESS_LOWERDOCKUM.MXD



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Thickness of Lower Dockum

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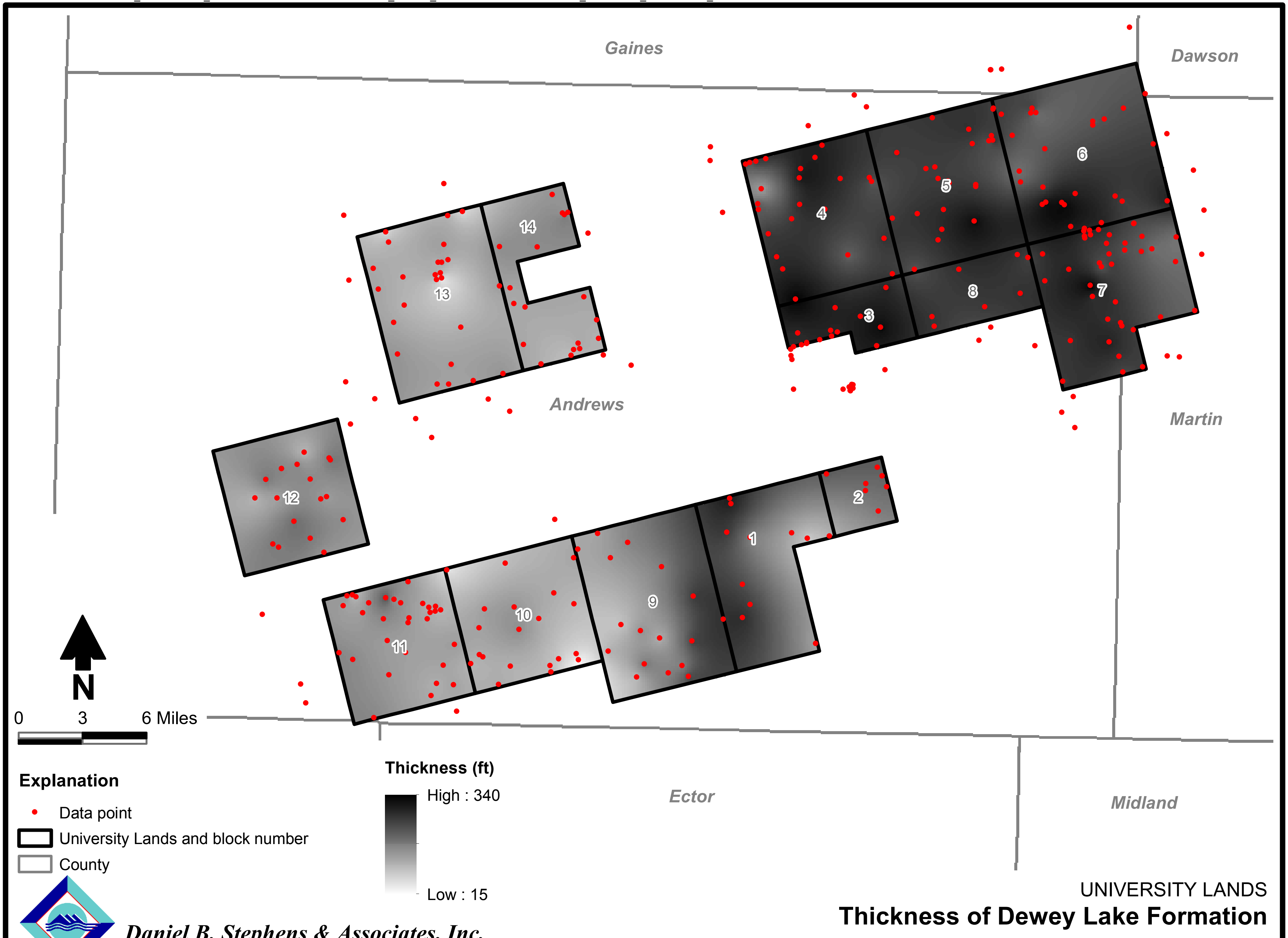
Figure B-15

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-16_ANDREWS_THICKNESS_DEWEYLAKE.MXD



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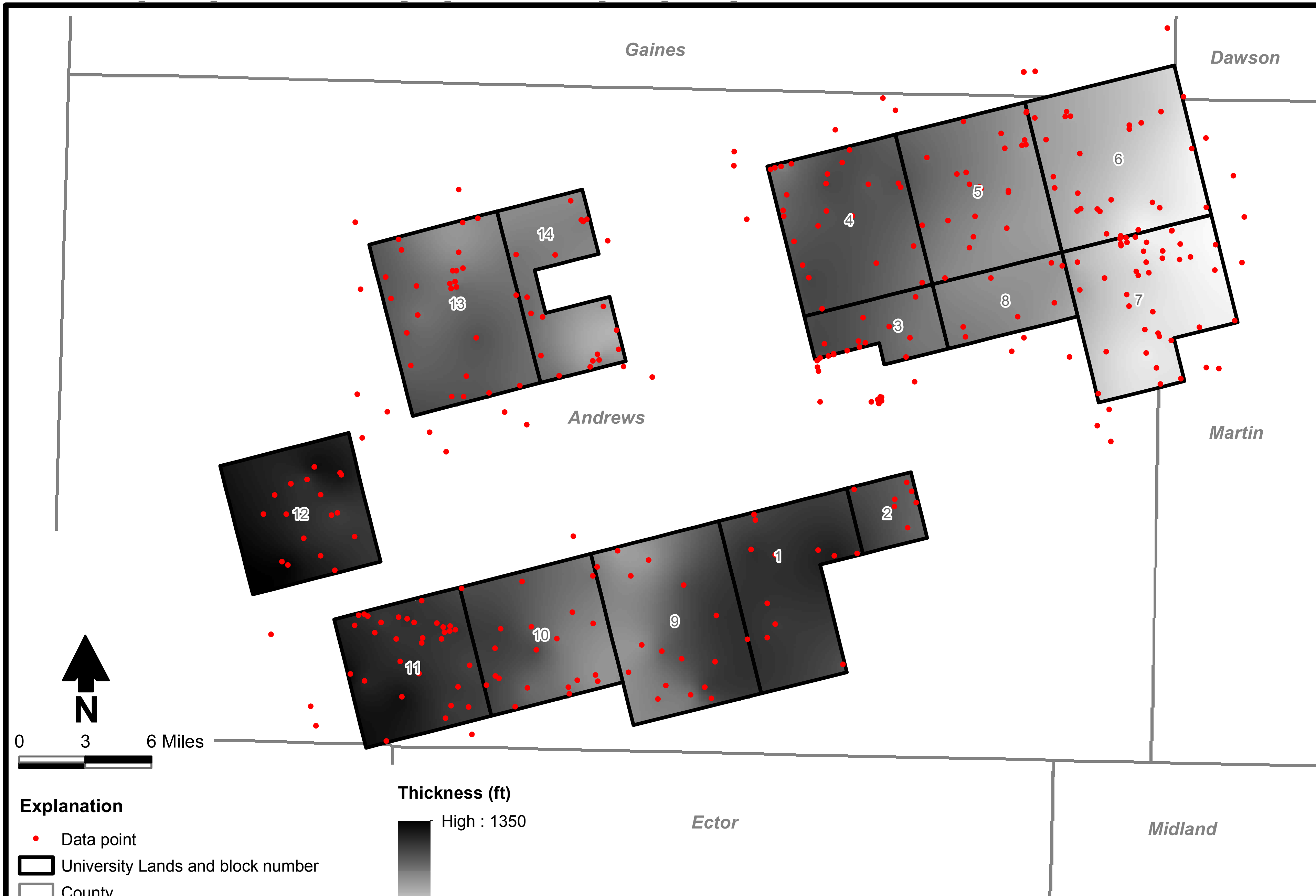
UNIVERSITY LANDS
Thickness of Dewey Lake Formation

Figure B-16

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-17_ANDREWS_THICKNESS_EVAPORITES.MXD



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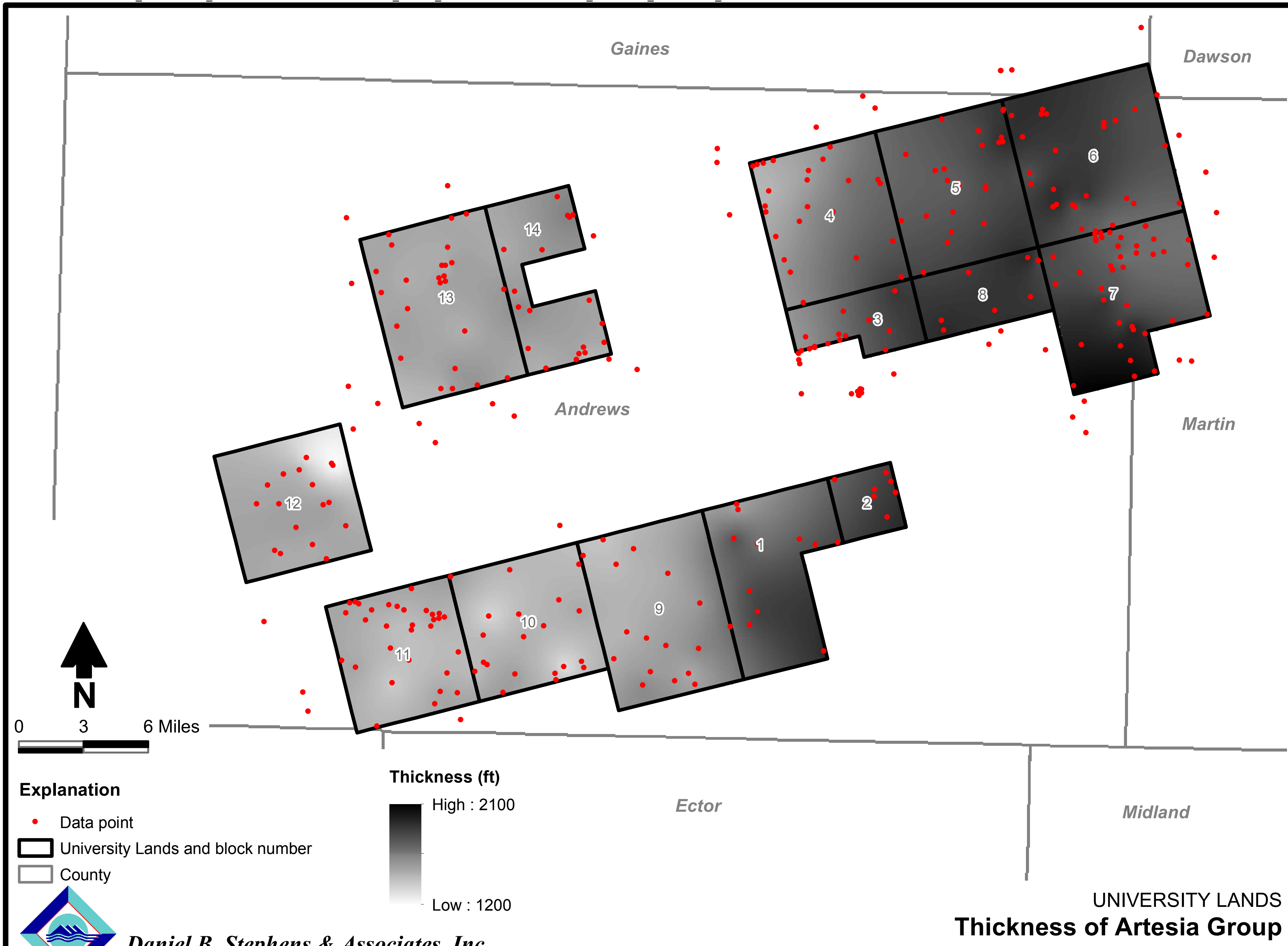
UNIVERSITY LANDS
Thickness of Undifferentiated Permian Evaporites

Figure B-17

S:\PROJECTS\WR14.0154_UNIVERSITY_LANDS\GIS\MXDS\REPORT\NORTH_STUDY_AREA\APPENDICES\FIGB-18_ANDREWS_THICKNESS_ARTESIAGROUP.MXD



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Thickness of Artesia Group

Figure B-18

Appendix C

Three-Dimensional Geologic Models

This appendix has been provided separately to University Lands.