Technical Memorandum

To:	Samantha Reiter, General Manager – Lone Star Groundwater Conservation District
From:	Michael Keester, PG – LRE Water, LLC. Michael Thornhill, PG – Thornhill Group, Inc.
Date:	December 14, 2021
Project:	LSGCD Subsidence Investigations – Phase 2
Subject:	Review of "Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer" by Kelley and others (2018)

Chapter 36 of the Texas Water Code requires Lone Star Groundwater Conservation District (LSGCD) to consider several factors when developing long-term goals and finding the balance between providing fair and impartial access to groundwater production and conservation of groundwater resources. One of the LSGCD's considerations is the ability to control subsidence within Montgomery County. In order to thoughtfully consider the ability to control subsidence, the District is seeking to develop a robust understanding of the local conditions affect compaction of the subsurface formations which can cause land surface subsidence.

During Phase 1 of the subsidence investigations, Thornhill and Keester (2020) focused on developing an understanding of existing research. During the initial phase, the focus was not so much on the validity or applicability to Montgomery County; rather, it was on compiling existing studies and determining questions that may need further investigation. In Phase 2 of the District's subsidence investigations, the LSGCD technical consulting team has worked collaboratively to investigate two of the most applicable questions.

In this technical memorandum, we document our work related to a review of a subsidence study titled: *Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer* (Kelley and others, 2018). Thornhill and Keester (2020) discussed and summarized this study as part of the Phase I study. However, because information from this study has direct relevance to LSGCD's current and future management of groundwater resources, we conducted a more detailed evaluation of the information provided in the report.

As the report title suggests, Kelley and others' (2018) work focuses on the Jasper Aquifer. As shown on Figure 1, Kelley and others (2018) included all of Brazoria, Fort Bend, Galveston, and Harris counties with portions of the neighboring counties included in the study area. Within Montgomery County, the study area extends to the southern end of Lake Conroe.

Kelley and others (2018) identified their work as an estimate of "the relative risk of subsidence associated with development of brackish groundwater in the Jasper Aquifer of the Gulf Coast Aquifer System within the [Harris-Galveston and Fort Bend Subsidence] Districts." The two objectives of their risk assessment were to:

1. "Assess potential risk of subsidence that may result from development of brackish groundwater resources in the Jasper Aquifer within the [Harris-Galveston and Fort Bend Subsidence] Districts; and
2. Provide the [Harris-Galveston and Fort Bend Subsidence] Districts with guidance regarding the types of activities and data that would benefit the consideration as special provisions to Jasper Aquifer brackish production permits."

To meet the first objective, Kelley and others (2018) developed a numerical model using the MODFLOW code (version not identified). To simulate compaction of the subsurface units, they used the MODFLOW subsidence (SUB) package developed by Hoffman and others (2003). The development of the numerical model of groundwater flow and use of the SUB package is common practice for assessing the potential for compaction and is reasonable approach for addressing the first objective. The numerical model is simply a mathematical representation of the conceptual model of the aquifer. The information developed for the conceptual model dictates the development of the numerical model. Therefore, our work focused primarily on the conceptual model described by Kelley and others (2018).

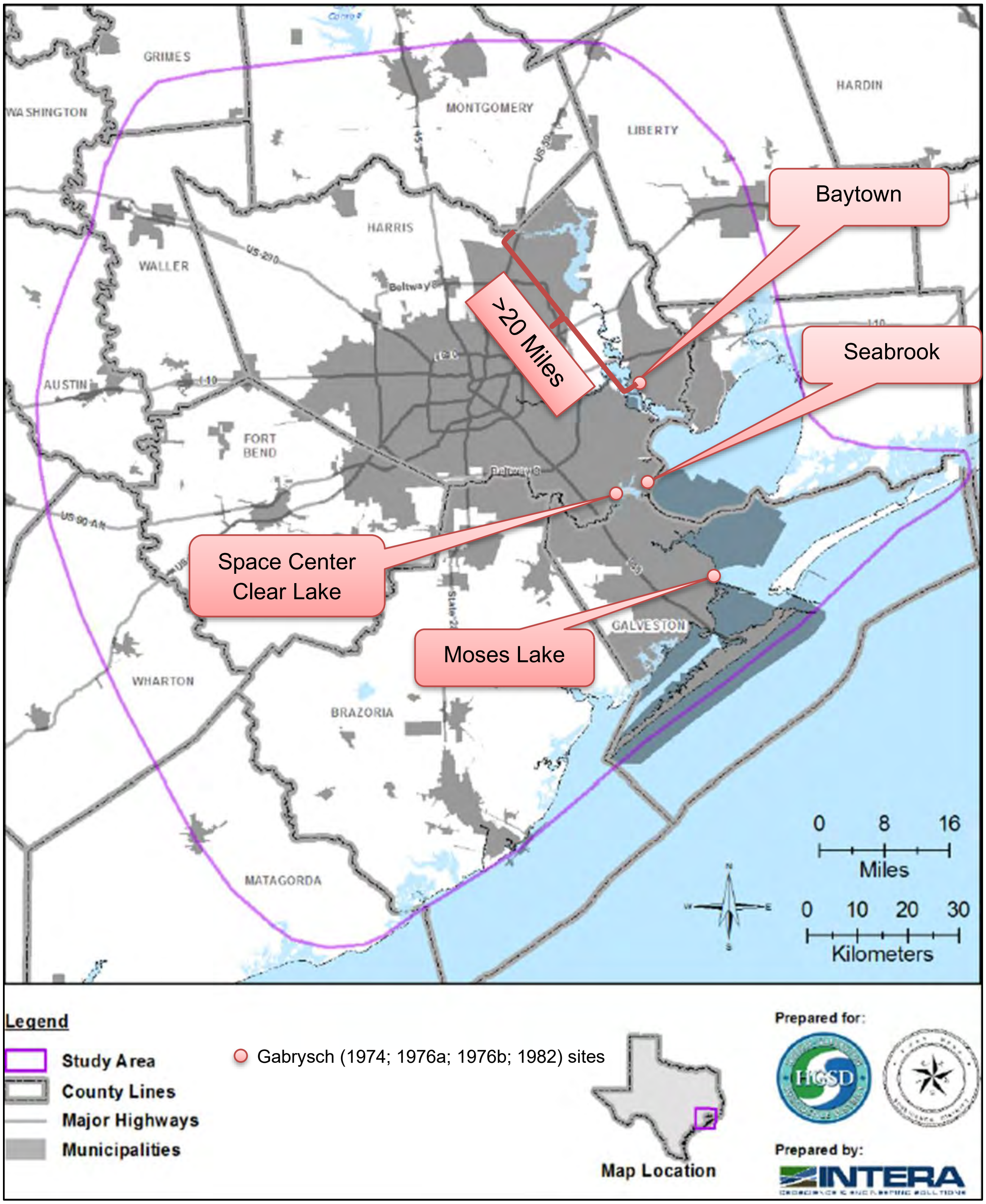

Figure 1. Study area identified by Kelley and others (2018) along with the sites discussed by Gabrysch and Bonnet (1974; 1976a; 1976b) and Gabrysch (1982). Modified from Kelley and others (2018).

Review of Kelley and others (2018) Conceptual Model for Prediction of Compaction in the Jasper Aquifer

Kelley and others (2018) begin their discussion of the conceptual model with a brief introduction to consolidation theory. Their discussion highlights the mathematics behind the numerical model package used to predict compaction and subsidence. Of particular importance to the equations are the following clay bed properties:

- Geostatic stress (σ), hydrostatic stress (u), and effective stress (σ')
- Thickness
- Specific storage
- Vertical hydraulic conductivity
- Preconsolidation stress

Kelley and others (2018) point out that "none of the physical measurements presented [in their report]… have been collected at depths representative of the brackish Jasper Aquifer in the [Harris-Galveston and Fort Bend Subsidence] Districts…. Properties controlling compaction of the brackish Jasper Aquifer should be considered uncertain." To our knowledge the statement would also have been accurate if it more generally referred to the Jasper Aquifer in the Gulf Coast region.

Much of the analyses discussed by Kelley and others (2018) used data obtained and discussed by Gabrysch and Bonnet (1974; 1976a; 1976b). The locations where these data were collected are shown on Figure 1. As shown on Figure 1, the nearest location is more than 20 miles from Montgomery County. Also, the depth from which the data were collected represents the shallower and younger sediments that make up the Chicot and Evangeline aquifers. As such, we agree with Kelley and others (2018) that the application of results from analyses of these data to the Jasper Aquifer is uncertain.

With regard to the first compaction property listed above, geostatic stress is essentially a combination of the weight of the sediments and fluids above a specified depth in the subsurface. The hydrostatic stress is the pressure within the pore space of the sediments above a specified depth in the subsurface. Effective stress is the difference between the geostatic stress and the hydrostatic stress. Terzaghi (1925) identified this relation which allows effective stress within an aquifer to be expressed as (Leake and Galloway, 2007):

$$\sigma' = \sigma - u \tag{1}$$

Commonly, the geostatic stress is considered to be 1.0 pounds per square inch (psi) per foot (ft) of burial (psi/ft). For fresh water, the hydrostatic stress is 0.433 psi/ft which results in an effective stress gradient of 0.467 psi/ft assuming the geostatic stress gradient of 1.0 psi/ft and a water level equal to the depth of burial. These are the stress values used by Kelley and others (2018). However, Tiab and Donaldson (2016) indicate the geostatic gradient in the Gulf Coast region increases with depth being about 0.85 psi/ft near the surface and increasing to 1.0 psi/ft at about 20,000 feet in depth (see Figure 2). They indicate the reason for the curvature of the trend shown on Figure 2 is due to "sediments being younger and more compressible near the surface but being less compressible and more plastic with depth." For depths up to about 2,000 feet, the geostatic stress gradient presented by Tiab and Donaldson (2016) results in an effective stress gradient of about 0.407 to 0.437 psi/ft.

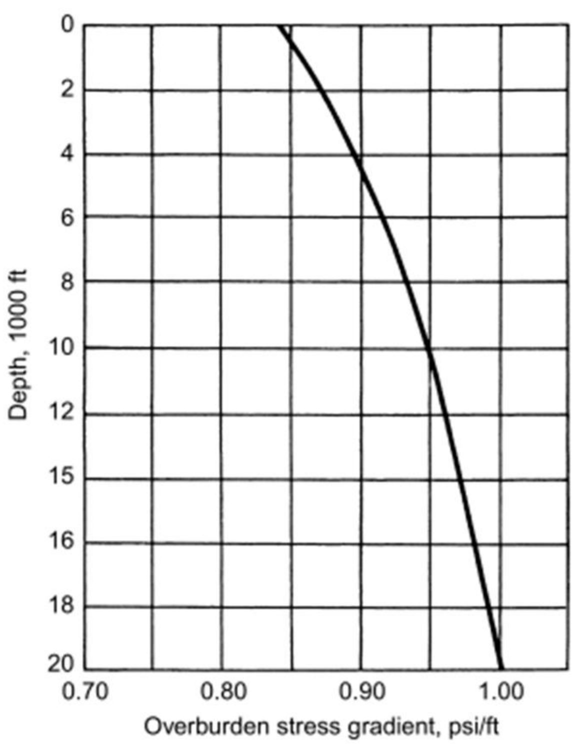

Figure 2. Overburden (geostatic) stress gradient in the Gulf Coast region. Reproduced from Tiab and Donaldson (2016)

The thickness of the clay units also affects compaction of the sediments, particularly the rate of compaction. The local stratigraphy and thickness of clay units will be addressed during a separate task during Phase 2 of the subsidence investigations. Questions related to the stratigraphy and structure of the clay units will be addressed during that task.

Specific Storage

The specific storage (S_s) of aquifer sediments is the volume of water released from or added to storage in a unit volume of aquifer per unit decline or rise in water level (Bear, 1979). The specific storage value may be further defined as the sum of the elastic (S_{ske}) and inelastic (S_{skv}) components (Hoffman and others, 2003) with the inelastic component being approximately 100 times greater than the elastic component (Leake and Prudic, 1991; Young and others, 2006). Due to the difference between the elastic and inelastic components, we can generally assume (as did Kelley and others (2018)) the inelastic specific storage is essentially equal to the total specific storage. Calculation of the specific storage compents is then as follows:

$$S_{skv} \approx S_s = \rho g(\alpha + n\beta) \quad (2)$$

$$S_{ske} = \frac{S_{skv}}{100} \quad (3)$$

where:

$S_{skv} = inelastic\ specific\ storage\ (m^{-1})$ – multiply by 0.3048 to get per foot (ft^{-1})

$S_{ske} = elastic\ specific\ storage\ (m^{-1})$ – multiply by 0.3048 to get per foot (ft^{-1})

$\rho = density\ of\ water\ \left(\frac{kg}{m^3}\right) \cong 1{,}000\frac{kg}{m^3}\ for\ fresh\ water$

$g = gravity\ \left(\frac{m}{s^2}\right) = 9.80665\frac{m}{s^2}$

$a = sediment\ compressibility\ \left(\frac{m^2}{N}\right)$

$n = porosity$

$\beta = water\ compressibility\ \left(\frac{m^2}{N}\right)$

$Units\colon ft = foot;\ m = meter; kg = kilogram; s = second;\ N = Newton = \frac{kg \cdot m}{s^2}$

Kelley and others (2018) state that Gabrysch and Bonnet (1974; 1976a; 1976b) report laboratory measurements of porosity and compressibility for the Baytown, Seabrook, and Moses Lake sites shown on Figure 1. However, these measurements are not actually reported by Gabrysch and Bonnet (1974; 1976a; 1976b); rather, Gabrysch and Bonnet

(1974; 1976a; 1976b) report measurements of void ratio at various levels of pressure for clay samples collected at various depths within the Chicot and Evangeline aquifers. While not stated, we assume Kelley and others (2018) calculated porosity and compressibility from reported data using the following equations:

$$n = \frac{e}{1+e} \tag{4}$$

$$\alpha = \frac{\Delta n}{\Delta \sigma_v'} \tag{5}$$

where:

$e = void\ ratio$

$\sigma_v' = applied\ stress$

The Δ in equation 5 represents a change in the value. That is, compressibility is calculated as the change in porosity divided by the change in applied stress to the sample. We performed the same calculations we assume were performed by Kelley and others (2018) to determine porosity and compressibility from the data reported by Gabrysch and Bonnet (1974; 1976a; 1976b). Our results appeared to agree reasonably well with the results presented by Kelley and others (2018).

One of the requirements Kelley and others (2018) applied to their analysis was to only use measurements of the void ratio where the applied stress was greater than the effective depth of burial. Kelley and others (2018) state that they calculated the effective burial depth “by dividing the pressure applied to the core sample by a geostatic gradient of 0.467 pounds per square inch (psi) per foot of burial depth.” As noted above, the value of 0.467 psi/ft represent the effective stress gradient assuming a geostatic stress gradient of 1.0 psi/ft. We inquired about the reported value and received an email response from Dr. Steve Young on July 28, 2021 that the sentence should read “net effective stress gradient” rather than “geostatic gradient.” As of December 11, 2021 a corrected report had not been posted to the Harris-Galveston Subsidence District website.

For our evaluation of the data, we used the lower and variable geostatic stress gradient identified by Tiab and Donaldson (2016). To calculate the effective burial depth, we followed the same assumptions as Kelley and others (2018) except that the geostatic stress is lower. The following equation illustrates the calculation:

$$Effective\ burial\ depth = \frac{\sigma_v'}{\sigma - u} \tag{6}$$

Using the lower geostatic gradient allows for additional data points to be included in the calculation of porosity and compressibility. Figure 3 and Figure 4 show porosity and compressibility plotted versus effective burial depth. The calculated values reflect the values determined from the Gabrysch and Bonnet (1974; 1976a; 1976b) data. The modeled value reflects the best fit trend line through the data. We selected a logarithmic trend through the data as it provided the best fit through data representing effective burial depths of less than 5,000 feet. Beyond 5,000 feet of depth, the logarithmic trend is not applicable. The equation shown on the chart represents the modeled values.

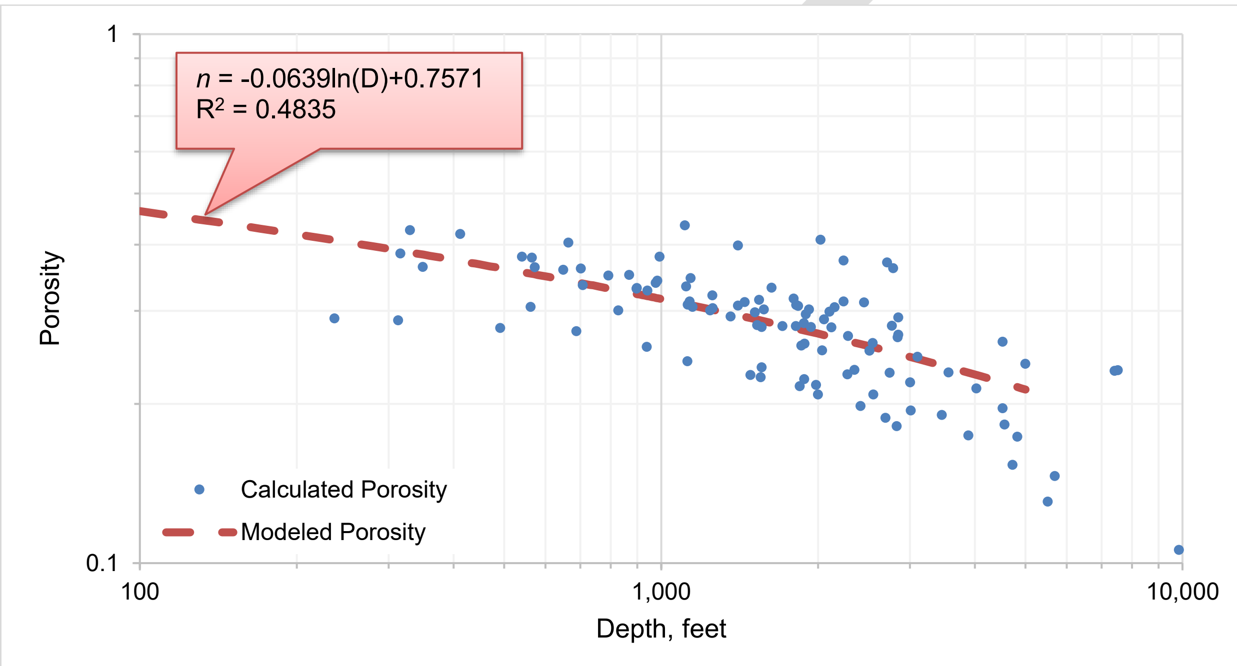

Figure 3. Calculated and modeled porosity with depth based on data reported by Gabrysch and Bonnet (1974; 1976a; 1976b).

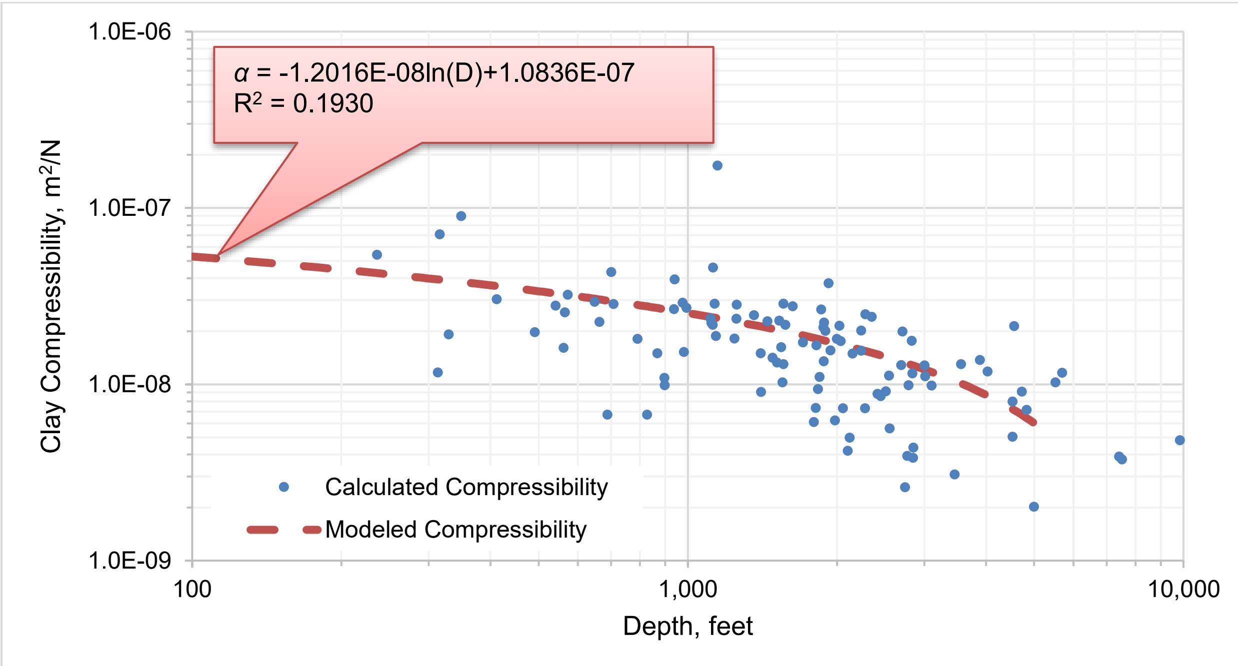

Figure 4. Calculated and modeled clay compressibility with depth based on data reported by Gabrysch and Bonnet (1974; 1976a; 1976b).

Per Equation 2, we also need the compressibility of water to calculate specific storage. Kelley and others (2018) used a constant value of 4.4E-10 m²/N for the compressibility of water. However, the compressibility of water is not a constant value and it varies with the temperature of the water. We can estimate the temperature of water at depth based on the average annual air temperature of 20°C (Long, 2020) and a geothermal gradient of about 9°C per 1,000 feet of depth (Young and others, 2016). We can then use Kell's (1975) equation for the isothermal compressibility of water:

$$\beta = \frac{5.088496\times10^{-10}+6.163813\times10^{-12}t+1.459187\times10^{-14}t^2 +2.008438\times10^{-16}t^3-5.847727\times10^{-19}t^4+4.10411\times10^{-21}t^5}{1+0.01967348t} \quad (7)$$

where

$\beta = isothermal\ compressibility\ (Pa^{-1} \equiv \frac{m^2}{N})$

$t = temperature$ (°C)

Using each of the calculated parameters, we then applied Equation 2 and Equation 3 to calculate the inelastic and elastic specific storage, respectively, for the clay samples. Figure 5 and Figure 6 illustrate the calculated and modeled clay inelastic and elastic specific storage, respectively. Like the porosity and compressibility values, the specific storage values decrease with depth.

All other factors being equal, lower values of clay specific storage result in less predicted compaction. Overall, our modeled values of clay specific storage based on the Gabrysch and Bonnet (1974; 1976a; 1976b) data are similar in magnitude to the modeled values of Kelley and others (2018). Table 1 provides a comparison of our calculated values and those of Kelley and others (2018).

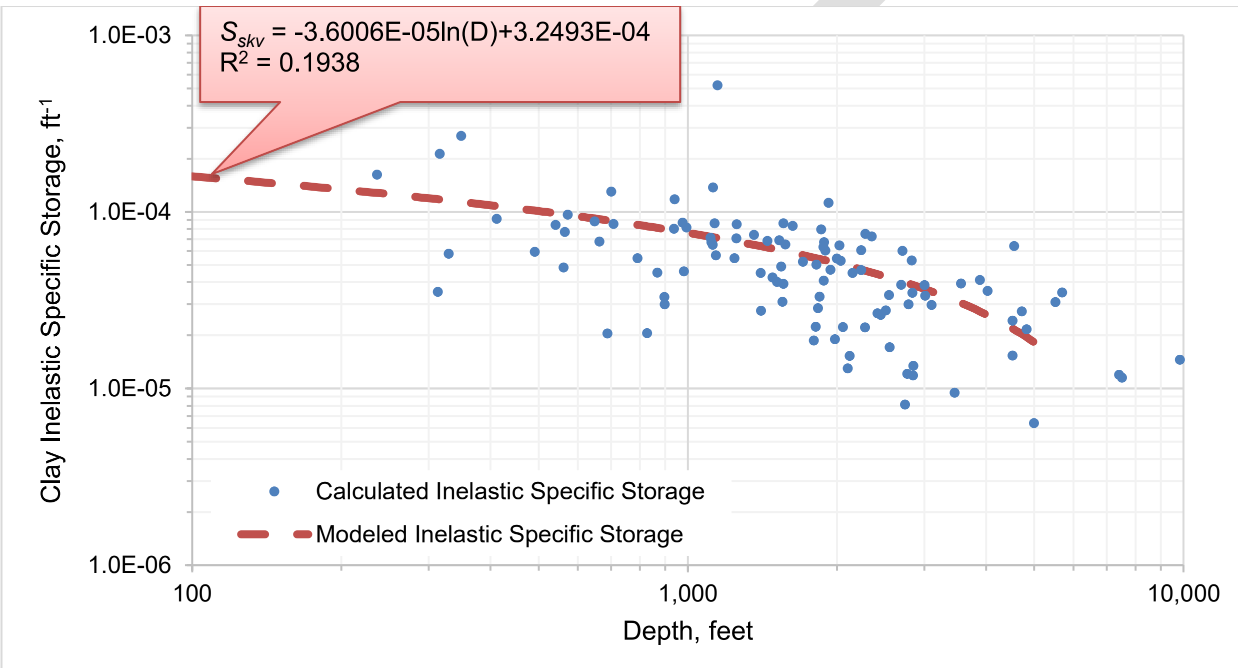

Figure 5. Calculated and modeled clay inelastic specific storage with depth based on data reported by Gabrysch and Bonnet (1974; 1976a; 1976b).

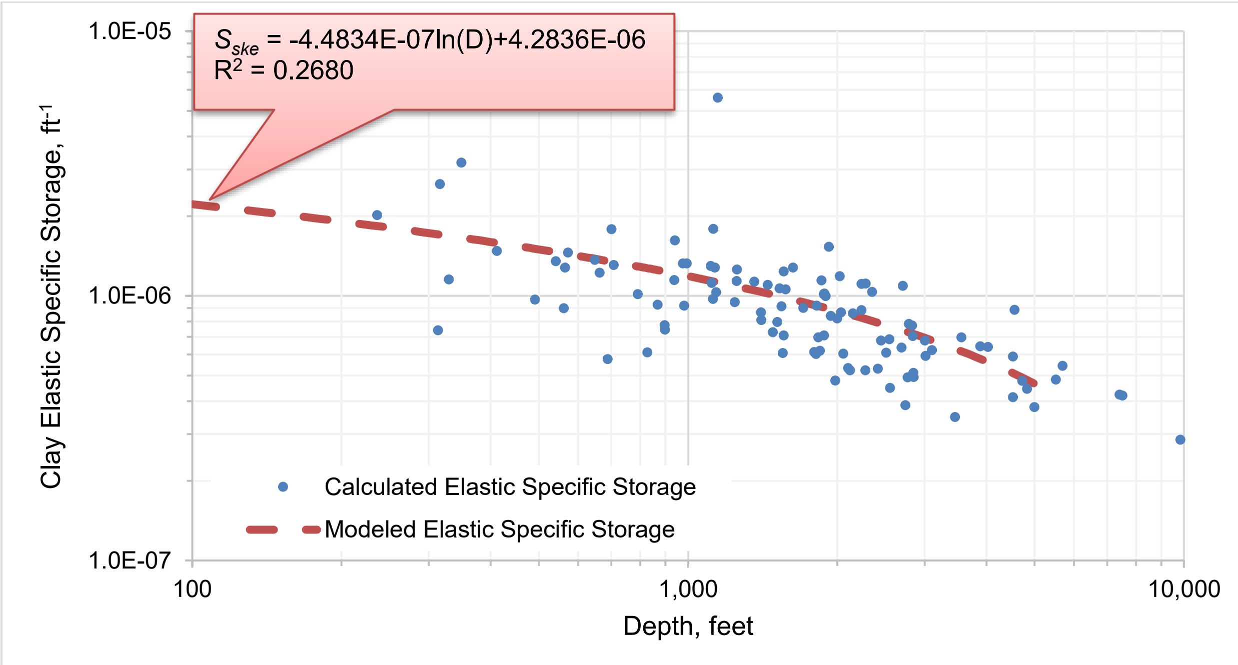

Figure 6. Calculated and modeled clay elastic specific storage with depth based on data reported by Gabrysch and Bonnet (1974; 1976a; 1976b).

Table 1. Comparison of estimated specific storage of clay beds.

Burial Depth (ft)	Clay Inelastic Specific Storage (ft^{-1})			Clay Elastic Specific Storage (ft^{-1})		
	HGSD	LSGCD	Difference	HGSD	LSGCD	Difference
100	3.5E-04	1.6E-04	1.9E-04	4.2E-06	2.2E-06	2.0E-06
250	1.9E-04	1.3E-04	5.9E-05	2.4E-06	1.8E-06	5.7E-07
500	1.1E-04	1.0E-04	1.3E-05	1.6E-06	1.5E-06	8.6E-08
750	8.6E-05	8.7E-05	-7.5E-07	1.3E-06	1.3E-06	-5.4E-08
1,000	7.0E-05	7.6E-05	-6.1E-06	1.1E-06	1.2E-06	-1.1E-07
1,500	5.3E-05	6.2E-05	-8.8E-06	8.7E-07	1.0E-06	-1.3E-07
2,000	4.3E-05	5.1E-05	-8.1E-06	7.5E-07	8.8E-07	-1.2E-07
2,500	3.7E-05	4.3E-05	-6.3E-06	6.7E-07	7.8E-07	-1.0E-07
3,000	3.3E-05	3.7E-05	-4.1E-06	6.2E-07	6.9E-07	-7.7E-08

HGSD = Kelley and others (2018)
LSGCD = This report

The biggest differences are at shallower depths of 500 feet or less. These differences at shallower depths are due to the type of mathematical trend. Using the functions with Microsoft Excel, we applied a logarithmic trend which appears to follow a curved trend in the data whereas Kelley and others (2018) applied a power trend which results in a straight-line on the plots. Also, while both the power and logarithmic trends result in unrealistic porosity values at shallow depths, the logarithmic trend more closely reflects the expected maximum of about 60 percent (Fetter, 1994). For example, the trend line of

Kelley and others (2018) results in a clay porosity of 85 percent at a depth of 10 feet while the logarithmic trend we applied results in a clay porosity of 61 percent for the same depth.

Importantly, the values calculated are for samples collected the Chicot and Evangeline aquifers. While our calculated results for specific storage are similar to those of Kelley and others (2018), like those of Kelley and others (2018) they do not represent samples collected from the Jasper Aquifer. While we are able to determine a trendline through the calculated values on Figure 5 and Figure 6, there is more than an order of magnitude difference in the values for similar depths. This variability should be considered when applying the modeled values to compaction in the Chicot and Evangeline. With the Jasper being an older formation, it is possible the lower bounds of the variability should be considered as a starting point or possibly favored during evaluations using these results.

Vertical Hydraulic Conductivity

The specific storage values of the clay beds control the amount of compaction that can occur under a given amount of stress. However, to determine the rate at which compaction occurs we also need to know the vertical hydraulic conductivity and thickness of the clay beds along with the specific storage. As mentioned previous, we will discuss clay bed thickness in detail in our Task 2 report.

The thickness and vertical hydraulic conductivity of individual clay beds affects the rate at which compaction may occur. When pumping from the aquifer occurs, water will preferentially move through the coarser-grained sediments (that is, sand) causing a pressure (that is, water level) decline in those layers of coarser-grained sediments. The decrease in pressure within the coarser-grained sediment layers creates a pressure gradient between the coarser-grained sediment layers and the finer-grained (that is, clay) sediment layers. This pressure gradient causes water to move from the finer-grained sediment layers into the coarser-grained sediment layers resulting in a decrease in pressure (and increase in effective stress) within the finer-grained sediment layers.

The decrease in pressure in a finer-grained sediment layer occurs immediately at the interface between that layer and the coarser-grained sediment layer. The decrease in pressure in the finer-grained sediment layer then propagates toward the center of the layer. Assuming consistent hydraulic properties of the layer, as the thickness of the finer-grained sediment layer increases, the time it takes for the pressure decrease to propagate to the center of the layer also increases. The amount of time it takes for full compaction to occur can be expressed as a "time constant" in the compaction calculations (Hoffman and others, 2003). The time constant (τ_0) in Equation 8 represents the amount of time at which about 93 percent of the ultimate clay bed compaction will occur. As illustrated in Figure 7, approximately 50 percent of the compaction occurs relatively rapidly (within about 20 percent of the time constant) and then gradually slows over time.

$$\tau_0 = \frac{\left(\frac{b_0}{2}\right)^2 S_s}{K_v} \quad (8)$$

where:

$b_0 = initial\ thickness\ of\ the\ clay\ bed$

$S_s = specific\ storage\ of\ the\ clay\ bed$

$K_v = vertical\ hydraulic\ conductivity\ of\ the\ clay\ bed$

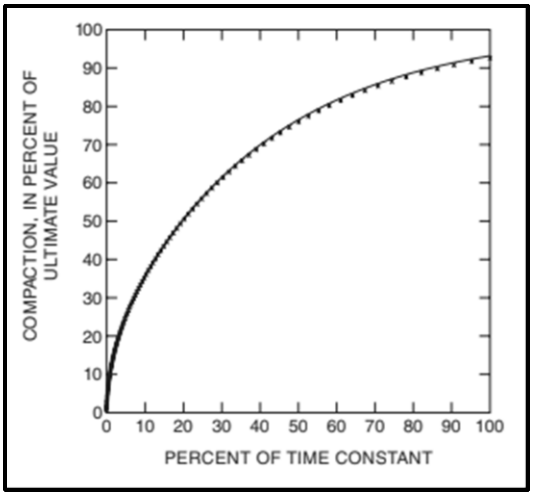

Figure 7. Illustration of compaction as a function of the compaction time constant. Reproduced from Hoffman and others (2003).

Kelley and others (2018) report using vertical hydraulic conductivity values as measured by Gabrysch and Bonnet (1974). However, Gabrysch and Bonnet (1974) only report measured hydraulic conductivity values and do not specify whether those values are horizontal or vertical. Analysis of the data reported by Gabrysch and Bonnet (1974), for samples where the effective stress was greater than the sample depth, provides a range of hydraulic conductivity values from 5.95E-07 to 6.5E-05 feet per day (ft/d). Table 2 provides representative values of the horizontal and vertical hydraulic conductivity of clay.

Table 2. Representative values for horizontal and vertical hydraulic conductivity of clay (Walton, 1987).

Horizontal Hydraulic Conductivity (ft/d)	2.66E-05 – 2.66E-04
Vertical Hydraulic Conductivity (ft/d)	6.52E-09 – 1.33E-07

Comparing the clay hydraulic conductivity results from Gabrysch and Bonnet (1974) to the representative values, the data from Gabrysch and Bonnet (1974) are similar to the representative horizontal hydraulic conductivity values and much greater than the representative vertical hydraulic conductivity. While it is possible that the samples from Gabrysch and Bonnet (1974) are outliers to the representative values, we should not assume the values are measurements of the vertical hydraulic conductivity when they were not reported as such.

All other factors being equal, a lower vertical hydraulic conductivity results in a greater time constant. With vertical hydraulic conductivity as the denominator in Equation 8, each decrease in the order of magnitude in the value causes a corresponding increase in the order of magnitude in the time constant. For example, at a depth of 1,000 feet a 10-foot thick clay bed with a specific storage of 7.74E-05 ft^{-1} (sum of LSGCD values in Table 1) the time constant would be 520 days based on Kelley and others (2018) analysis of the Gabrysch and Bonnet (1974) data (K_v = 3.72E-06 ft/d) but would be more than 14,500 days based on the maximum representative value (K_v = 1.33E-07 ft/d).

To provide a lower bound on their vertical hydraulic conductivity estimates, Kelley and others (2018) used parameters from PRESS models which are used to simulate one-dimensional compaction in the area. These model parameters are lower than the values derived from the Gabrysch and Bonnet (1974) data but remain higher than the maximum representative value for depths less than about 1,500 feet. Nonetheless, in the example above the time constant would increase nearly 2,000 days using the PRESS model vertical hydraulic conductivity. Since the PRESS vertical hydraulic conductivity values are calibrated model parameters for prediction of compaction within the Chicot and Evangeline aquifers, we should exercise caution in assuming the values are a lower bound estimate of the older clays within the deeper formations.

Preconsolidation Stress

Irreversible compaction of subsurface sediments begins when sediments are not fully consolidated and the effective stress is greater than the preconsolidation stress (that is, maximum effective stress). Commonly, the preconsolidation stress is synonymous with the preconsolidation head (that is, water level) of the aquifer (Leake and Prudic, 1991; Hoffman and others, 2003). While a single head value is not necessarily sufficient for calculating the effective stress (Leake and Galloway, 2007), for most analyses it provides a reasonable approximation.

Another way to describe the preconsolidation stress is relative to the amount of drawdown that needs to occur before permanent compaction begins. That is, how much do water levels need to decline before the effective stress is greater than the preconsolidation stress? For the Jasper Aquifer, Kelley and others (2018) conceptualized this “drawdown at preconsolidation stress” to be about 75 feet at ground level and decreasing linearly to zero (0) feet at 870 feet below ground level. That is, they conceptualized that compaction would occur immediately with pressure (that is, water level) decline in sediments at depths at or below 870 feet.

For the drawdown at preconsolidation stress, Kelley and others (2018) indicate the value near land surface (75 feet) is consistent with the Houston Area Groundwater Model (Kasmarek, 2013). In that model, Kasmarek (2013) set the preconsolidation head for the clay units as 70 feet below the starting head (that is, water levels) for the model. These starting heads represented his best estimate of water levels in 1890. Within the model, “for changes in head in which head declines below preconsolidation head, an inelastic response is computed, permanent clay compaction is calculated, and the preconsolidation head is reset to the new head value” (Kasmarek, 2013). That is, per Kasmarek (2013) if the simulated water level declines below the 1890 estimated water level minus 70, then compaction occurs and the new water level becomes the preconsolidation head.

Kelley and others (2018) indicate their conceptualization of drawdown at preconsolidation stress is consistent with current PRESS models. As noted above, the PRESS values are calibrated model parameters for prediction of compaction within the Chicot and Evangeline aquifers and we should exercise caution in assuming the values are applicable to the deeper formations. As Kelley and others (2018) state: “the relationship describing drawdown at preconsolidation stress is very uncertain.”

As discussed by Keester and others (2021), the conceptualization of drawdown at preconsolidation stress by Kelley and others (2018) may be inconsistent with observed water level declines, extensometer measurements, and GPS modeled vertical displacement at the Lake Houston extensometer site (shown on Figure 8). However, Kelley and others (2018) did not consider these data during their analyses.

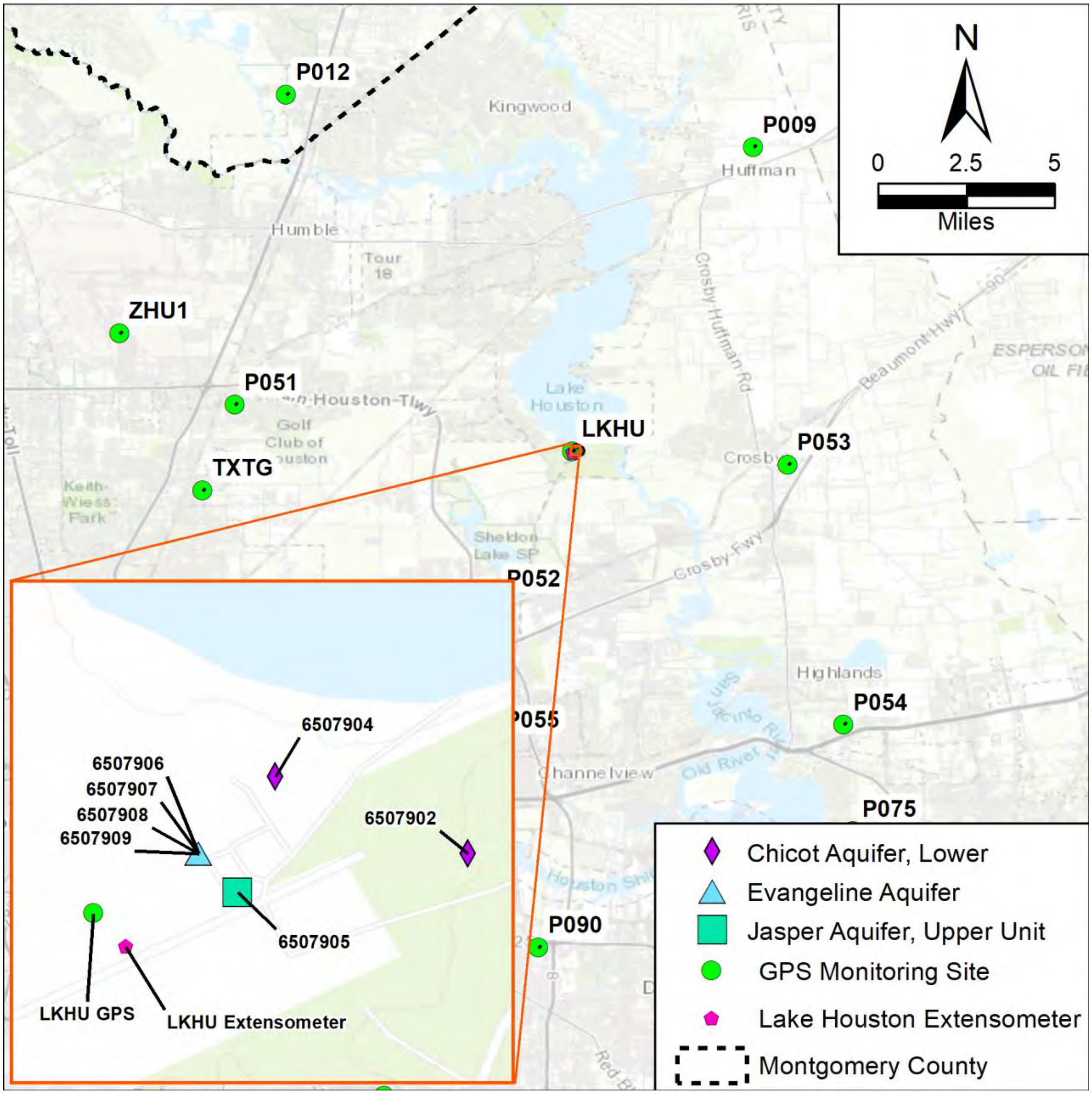

Figure 8. Wells associated with the Lake Houston extensometer site and nearby GPS monitoring sites.

The Lake Houston extensometer was completed in 1980 and the reported cumulative compaction within the Chicot and Evangeline aquifers at the end of 2019 was about 7.5 inches. For sediments below the Evangeline, the Lake Houston extensometer and GPS modeled vertical displacement suggest no measurable compaction occurred. However, during the period of measured compaction in the Chicot and Evangeline aquifers, water levels in the Jasper Aquifer nearly 2,600 feet below ground level have declined by more than 150 feet. Figure 9 illustrates the cumulative compaction of the Chicot and Evangeline aquifers (that is, extensometer data), Jasper Aquifer water level change, and compaction of the formations below the Evangeline (GPS).

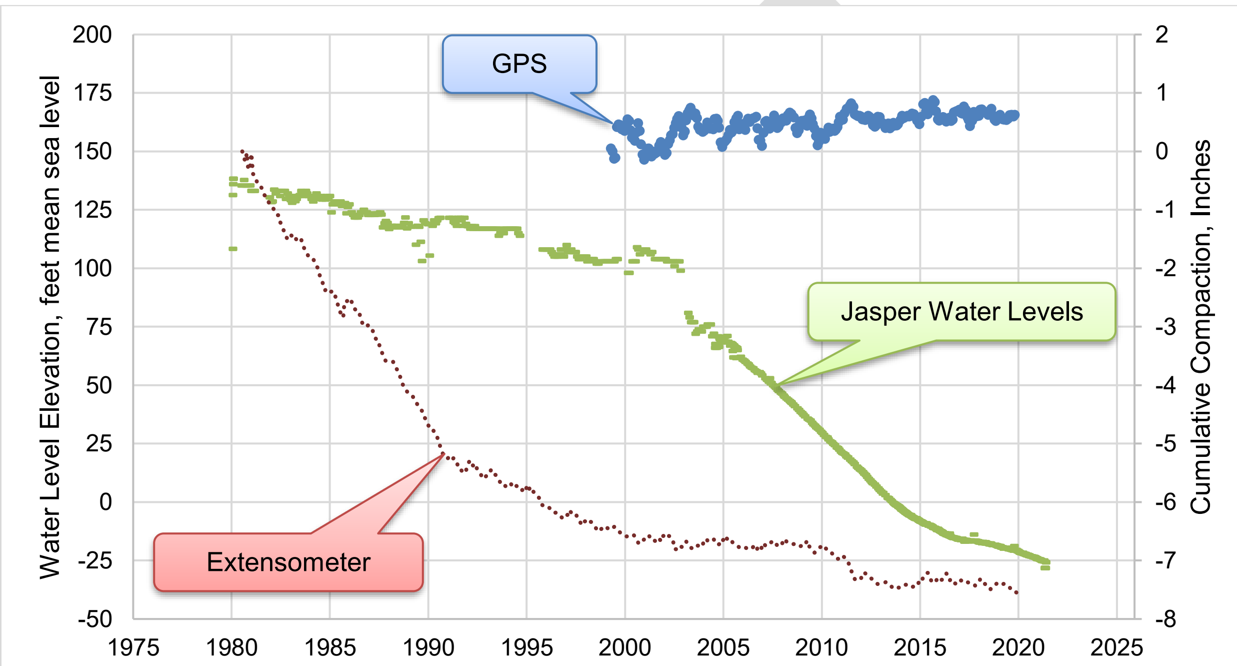

Figure 9. Hydrograph of reported water level measurements from the Lake Houston site Jasper Aquifer monitoring well (TWDB, 2021), reported cumulative compaction of the Lake Houston extensometer (Ramage and Shah, 2019), and GPS modeled vertical displacement of the subsurface units below the Evangeline Aquifer (https://hgsubsidence.org/GPS/).

One possible reason why no measurable compaction occurred in the units below the Chicot and Evangeline aquifers is that the effective stress in the Jasper at the Lake Houston site has not increased to the point where compaction would occur; that is, the water level is still above the preconsolidation head. If the Jasper water level is above the preconsolidation head despite having declined more than 150 feet since 1980 and the depth of the measurement interval being nearly 2,600 feet below ground level, then the drawdown at preconsolidation stress for the Jasper Aquifer as conceptualized by Kelley and others (2018) must be reconsidered. As indicated above, Kelley and others (2018) conceptualized that any drawdown in the Jasper at depths greater than 870 feet would immediately result in inelastic compaction; however, reported data from the Lake Houston site appear to contradict this conceptualization.

Similarly, Gabrysch (1982) noted that deeper layers of the Evangeline at the Clear Lake site (see Figure 1) were not compacting due to water level declines. In his opinion, "Data from the Clear Lake site, where no appreciable compaction of the lower part of the Evangeline aquifer was occurring even though artesian-head declines were occurring, indicate that compaction of the deeper clay layers needs to be excluded in estimating largescale subsidence." Like the Lake Houston site, the lack of observed compaction in the deeper intervals may be due to the water levels not yet declining to preconsolidation head but the observations should be considered and addressed as part of the conceptual model.

Other Considerations

In the conceptual model section of their report, Kelley and others (2018) state that they will review the available data for estimating the properties governing compaction. They identify four properties that are important for their conceptual model of the Jasper Aquifer: specific storage, the thickness of clay beds, the vertical hydraulic conductivity of the clays, and the drawdown at preconsolidation stress. Other interrelated considerations which may influence the conceptualization of compaction and, certainly, the parameterization values and distributions of the factors Kelly and others (2018) identified, derived, or estimated in the Jasper Aquifer include:

- Geometry of geologic units – structural geology maps, model layers, and hydrogeologic cross sections all show that the formations that comprise the Gulf Coast Aquifer System form a "wedge" shape that thickens toward the Gulf of Mexico. Young and others (2012) provide a schematic dip cross section that illustrates older (that is, deeper) beds dipping steeper than the overlying younger beds. Similarly, Popkin (1971) reports that within Montgomery County the Catahoula (which is below the Jasper) dips at 90 feet per mile, while the formations that comprise the Chicot dip at about 10 feet per mile, and intermediate beds dip from between 40 to 85 feet per mile. So far, this study has not discovered any literature that discusses whether variations in geologic dip can affect compaction. Task 2 of Phase 2 of this Subsidence Study will include revised mapping of geologic structure in Montgomery County to confirm formation dips and thicknesses with respect to updated datasets.

  Additionally, the sediments in each formation thicken toward the coast line and generally, depending on the distribution of depositional systems, the clay interbeds become more numerous and total clay thickness and percentages increase toward the Gulf of Mexico. As the geologic units thicken, the arrangement and distribution of sand and clay beds vary. Task 2 of the Phase 2 of this Subsidence Study will include detailed mapping and assessments of the clay and sand layers in each aquifer. Also, the dip, depth and thickness of sands and clays also determine the amount of artesian head reduction that can occur in a particular producing interval. Therefore, updip formations generally have less overall potential for compaction, if all other factors are equal.

- Depositional environments and associated sediment characteristics and lithologies – Young and others (2012) provide a thorough discussion of depositional systems and related facies. For example, lithology of geologic units at land surface is a key factor in the resulting topography. Approximately the northwestern half of Montgomery

County is characterized by topography with rolling hills and incised drainages, while the southeastern part of the county is generally flat and gently sloping toward the coast. Popkin (1971) reports that land surface elevations range from about 45 feet above mean sea level (AMSL) in southeastern parts of the county to about 440 feet AMSL in the northwestern corner. Popkin (1971) also notes that the younger geologic units at land surface form a plain while the older units cropping out farther inland and at higher elevations form cuestas or sand hills. Such features can be important in more precisely delineating depositional distributions and formation characteristics. Also, sediment characteristics such as particle size, roundness, mineral composition, and sorting also factor into compaction characteristics of fine-grained layers. These characteristics vary by deposition setting. Young and others (2012) provided depositional facies definitions and predicted flow characteristics. Reasonable parameterization of models should be based on the most accurate representation of geologic conditions possible. Baker (1979) outlined selected faunal markers for various geologic layers, particularly for the Burkeville Confining System and deeper units. As LSGCD moves into subsequent study phases and collects core samples, such markers should be identified where present in order to accurately determine the geologic layers and aquifer stratigraphy.

- <u>Mineralogy, geochemistry and diagenesis</u> – the properties of clay, mudstones and shale vary greatly depending on the mineralogy and textural characteristics. With respect to clay deposits, the type of clay mineral can affect the compaction characteristics of the interbeds. For example, montmorillonite retains more water than illite which retains more water than kaolinite (Meade, 1964). Kelley and others (2018) note that clays composed of montmorillonite have the highest compressibility.

  Wilson (1962) referring to a field trip stop south of LaGrange, Texas on Highway 71 notes that "…X-ray analyses show that the Catahoula in Central Texas is a calcium-montmorillonite without illite. The Oakville and Fleming clay is sodium-rich, mixed-layer montmorillonite with illite". Gabrysch and Bonnet (1976a; 1976b) report that samples collected from the sites shown on Figure 1 indicate the clays in the Chicot and Evangeline aquifers are a mix of clay minerals with the Baytown and Johnson Space Center sites being predominantly montmorillonite.

  The ionic composition of interstitial fluids (that is, water) and the clay minerals also play a part in the rate of draining of clay porosity and resulting compaction. The American Geological Institute defines diagenesis as "the process involving physical and chemical changes in sediment after deposition that converts it to consolidated rock; includes compaction, cementation, recrystallization, and perhaps replacement as in the development of dolomite (American Geological Institute, 1976). Such factors can only be assessed by detailed sedimentation and geochemistry models, which are beyond the scope of this study, or on a site-by-site basis by collecting core samples of the formations.

- <u>Thickness and distributions of individual clay interbeds</u> – particularly as related to the sand intervals that form primary producing zones for wells in Montgomery County. Kelley and others (2018) provided a general summary comparing and contrasting thicknesses of individual clay beds in the various layers of the Gulf Coast Aquifer System. However, more detailed evaluations are needed to understand the vertical and lateral distributions of clay interbeds and the positioning with respect to producing intervals. Task 2 in Phase 2 of this subsidence study includes interpreting numerous geophysical logs within Montgomery County to delineate the various layers and categorize them as clay, silty/sandy clay, silty/clayey sand, and sand.

- <u>Geologic age of clay layers</u> – Gabrysch (1982) stated, "It is suspected that compressibility of the material is related to the age of sediments and the depth of burial." Similarly, the U.S. Geological Survey did not simulate compaction in the original Northern Gulf Coast groundwater availability model noting that the clay layers in the Jasper and Burkeville "…are geologically older, more deeply buried, and therefore more consolidated relative to the sediments of the Chicot and Evangeline aquifers" (Kasmarek, 2013). Prozorovich (1964) states that geologic age is not a controlling factor with respect to compaction. However, more recently Puttiwongrak and others (2021) concluded that geologic time does affect compaction. As additional information is gathered, particularly subsurface samples, relative importance of various factors can be evaluated.

Along with the parameters discussed by Kelley and others (2018), these additional types of factors must be carefully considered in three-dimensional space when developing concepts and parameters associated with compaction assessments and models. Gabrysch and Bonnet (1976a) note the importance of understanding the variability of distributions and characteristics of clay layers and their properties because the ratio of subsidence to water-level declines "…is not constant in time or uniform in space". Additionally, Gabrysch offers that such variations are "…caused primarily by the difference in total clay thickness, individual clay-bed thickness, and clay characteristics. The depth of the overburden and the amount of load to which the material has been previously subjected must also be considered" (Gabrysch and Bonnet, 1976a).

Conclusions

Our work during this task focused primarily on the conceptual model described by Kelley and others (2018). Since the conceptual model dictates development of the numerical model, it follows that any issues or potential flaws with the conceptual model are also issues or potential flaws with the numerical model. Our review of Kelley and others (2018) revealed questions with their conceptualization of compaction in the Jasper Aquifer.

- Our calculated estimates of inelastic and elastic specific storage of clay samples from Gabrysch and Bonnet (1974; 1976a; 1976b) are similar to those of Kelley and others (2018).
    - Data reported by Gabrysch and Bonnet (1974; 1976a; 1976b) are used to calculate the coefficients needed to determine the inelastic and elastic specific storage of the clay samples. These coefficients (namely, porosity and compressibility) are not reported by Gabrysch and Bonnet (1974; 1976a; 1976b) as stated by Kelley and others (2018).
    - For depths below about 500 feet, differences in the value calculated data increase.
    - Kelley and others (2018) trend through porosity values calculated from the Gabrysch and Bonnet (1974; 1976a; 1976b) data results in unrealistic porosity values for shallow depths.
    - The constant geostatic stress gradient used by Kelley and others (2018) to determine effective burial depth from applied pressure may be too high for the Gulf Coast region.
- Gabrysch and Bonnet (1974) report laboratory measured hydraulic conductivity for four clay samples, but they do not indicate if it is horizontal or vertical hydraulic conductivity.
    - Kelley and others (2018) state the hydraulic conductivity data from Gabrysch and Bonnet (1974) is a measure of the vertical component.
    - The hydraulic conductivity values from Gabrysch and Bonnet (1974) are consistent with representative values of the horizontal hydraulic conductivity of clays.
    - The minimum hydraulic conductivity values from Gabrysch and Bonnet (1974) is about four times greater than the maximum representative value of the vertical hydraulic conductivity of clays.
    - High values for the vertical hydraulic conductivity of the clay results in a shorter time constant for compaction. That is, compaction occurs at a faster rate.

- Kelley and others (2018) conceptualization of drawdown at preconsolidation stress does not appear to be consistent with observed changes in water level and compaction.
    - Observations by Gabrysch (1982) indicated that water level declines in the deep Evangeline Aquifer did not result in appreciable compaction.
    - Observations at the Lake Houston extensometer site indicate there is no discernable compaction of units below the Evangeline Aquifer despite about 150 feet of water level decline in the Jasper Aquifer.
    - Preconsolidation head may be below observed water level declines in the Jasper or the drawdown at preconsolidation stress is greater than conceptualized by Kelley and others (2018).
- Along with burial depth, the age of the sediments may affect the compressibility of the clay layers.
    - It is suspected that younger and shallower materials will compact more easily (Gabrysch, 1982).
    - Chemical reactions within older sediments may allow for increased cementation of the grains.
    - Burial depth increases the effective stress on the sediment grains which increases compaction of the units

With regard to the application of the work by Kelley and others (2018) to the Jasper Aquifer in Montgomery County it is important to remember that the data they used are from more than 20 miles away and are not from the Jasper Aquifer. The data used by Kelley and others (2018) are from younger sediments of the Chicot and Evangeline aquifers. Regarding their analyses, Kelley and others (2018) state that “properties controlling compaction of the brackish Jasper Aquifer should be considered uncertain.”

We recommend users of the Kelley and others (2018) conceptual model of compaction in the Jasper Aquifer carefully consider the conclusions listed above. Revisions to the conceptual model based on our conclusions may result in less predicted compaction in Jasper Aquifer or a slower rate of compaction. While the sediments that make up the formations of the Jasper Aquifer may compact with declining water levels, it is important to appropriately conceptualize the compaction based on the observed data. While the compaction results from a numerical model will remain uncertain, we may reduce the uncertainty through consideration of the available observations.

Geoscientist Seals

This draft technical memorandum is released by the following licensed professional geoscientists in the State of Texas to the Lone Star Groundwater Conservation District for review:

Michael Keester, PG

STATE OF TEXAS
MICHAEL R. KEESTER
GEOLOGY
10331
LICENSED
PROFESSIONAL GEOSCIENTIST

_______________________ Signature

12/14/2021 Date

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ADVANCED GROUNDWATER SOLUTIONS, LLC

TEXAS REGISTERED GEOSCIENCE FIRM 50639

Technical Memorandum

To: Ms. Samantha Reiter, General Manager-
Lone Star Groundwater Conservation District

From: Mr. Christopher Drabek, P.G. – Advanced Groundwater Solutions, LLC.
Mr. James Beach, P.G. – Advanced Groundwater Solutions, LLC.
Mr. Michael Thornhill, P.G. – Thornhill Group, Inc.

Project: LSGCD Subsidence Investigations – Phase 2

Subject: Geologic Structure of the Gulf Coast Aquifer System within Montgomery County

Date: January 10, 2022

Introduction

Task 2 of the Lone Star Groundwater Conservation District (LSGCD) Phase II Subsidence Investigation provides an in-depth evaluation of the subsurface geology of Montgomery County. Work performed as part of this task aims to improve the mapping of the elevation of the top and bottom of the subsurface hydrogeologic formations and to improve the understanding of the thicknesses of sand and clay intervals within the formations in the study area.

For decades a common approach was taken by groundwater professionals towards the delineation of water bearing units of the Gulf Coast Aquifer System (GCAS) in Montgomery and surrounding counties. The delineation of the hydrogeologic units in this study continues that approach, combining an extensive understanding of practical local hydrogeology with geophysical log analysis.

Aquifers and Geology

Gulf Coast Aquifer System

The GCAS is comprised of, from shallowest (youngest) to deepest (oldest), the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, the Jasper Aquifer and the Catahoula Formation. The principal aquifers that provide groundwater in Montgomery County include the Chicot, Evangeline and Jasper aquifers.

Figure 1 shows the outcrop areas and approximate updip extent of the Chicot, Evangeline and Jasper aquifers and the Burkeville Confining Unit within Montgomery County. The aquifer outcrops shown on Figure 1 were adopted from LBG-Guyton Associates (2016). Montgomery County has a surface area of approximately 1,077 square miles. The Chicot Aquifer outcrop is the largest outcrop in the county and has an estimated area of about 798 square miles. The Evangeline Aquifer is located updip from the Chicot Aquifer outcrop and has an estimated area of about 223 square miles. The outcrop of the Jasper Aquifer can be found in the far northwestern part of

Montgomery County and has an estimated area of approximately 24 square miles. The Burkeville Confining Unit is positioned between the outcrops of the Evangeline and Jasper aquifers and has an estimated area of about 32 square miles. The Catahoula Formation outcrop is further north and is not found in Montgomery County.

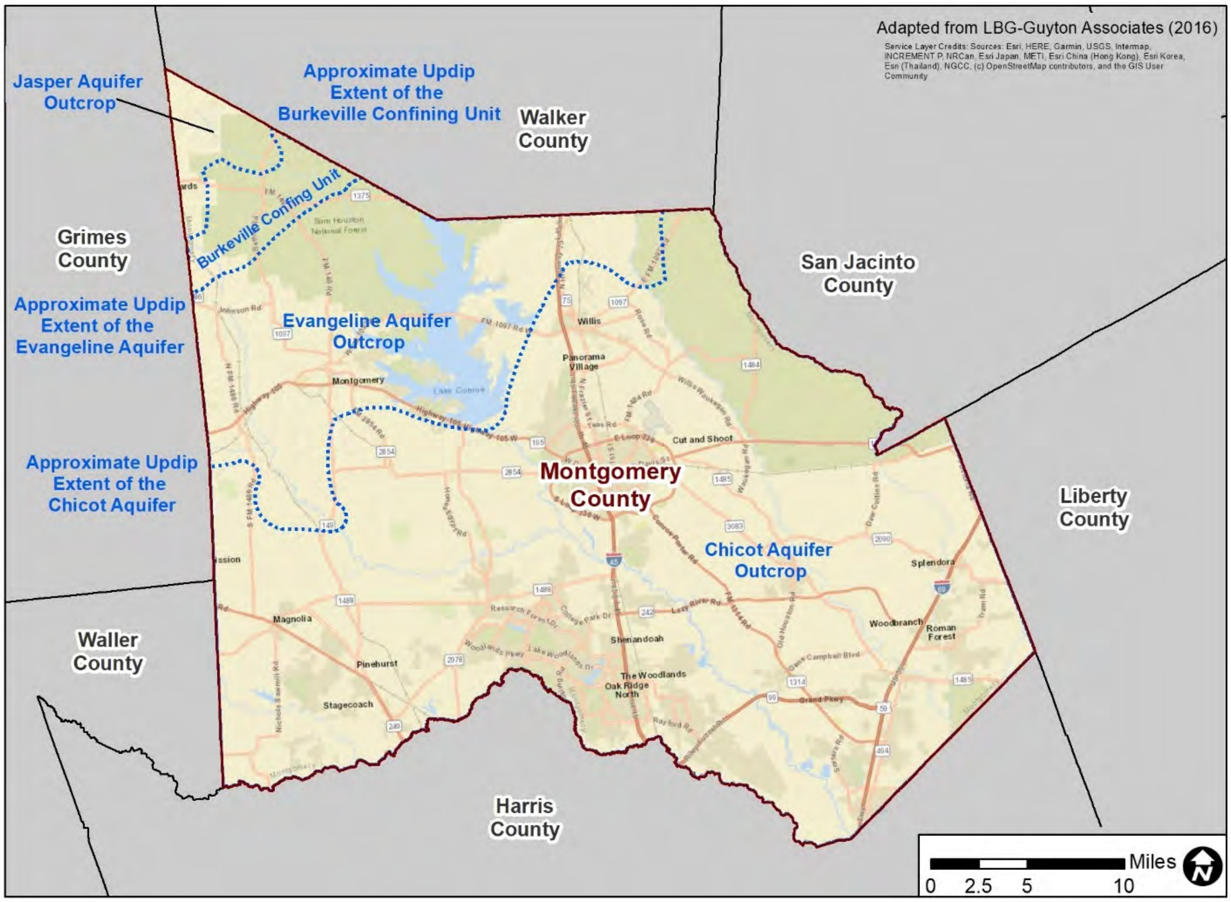

Figure 1. Approximate Aquifer Outcrop Areas (adapted from LBG-Guyton,2016)

The Chicot and Evangeline aquifers consist of unconsolidated and discontinuous layers of sand and clay that are hydraulically connected and are considered a leaky artesian aquifer system. The delineation of the Chicot and Evangeline aquifers can be difficult because an areally extensive confining unit does not exist between the two aquifers. Jorgensen (1975) discusses hydraulic conductivity as a basis for separating the Chicot Aquifer and Evangeline Aquifer in the Houston area. Differences in hydraulic conductivity are thought to cause, in part, differences in water level heads or elevations between the two aquifers. The differences in the static water level heads or elevations are noticeable and can be substantial in some areas, with the static water levels or heads in water wells completed in the Chicot Aquifer being shallower versus the static water levels in water wells completed in the Evangeline Aquifer. There also are differences in lithology, permeability and water quality in the Chicot Aquifer and Evangeline Aquifer. Geophysical logs of the test holes for water wells and oil and gas wells also have been used to estimate the resistivity of sand layers, the thicknesses of sand and clay units and help differentiate the contact of the Chicot and Evangeline aquifers in the greater Houston area.

Within the study area, the Burkeville Confining Unit is an aquitard or relatively impermeable layer that is positioned between the Evangeline and Jasper aquifers. The Burkeville Confining Unit can contain fresh to slightly saline water contained in individual sand layers but is considered a confining unit due to its large percentage of silt and clay compared to the Evangeline and Jasper aquifers (Baker, 1979). The sand layers found in the Burkeville are typically thin and are not considered to be hydraulically connected.

While usually recognized as one hydrogeologic unit, the Jasper Aquifer can be divided into two sections, the Upper Jasper and Lower Jasper. Popkin (1971) had classified the Jasper Aquifer in Montgomery County into two units based on lithology, with the upper portion containing a vast sand and the lower part containing mostly interbedded sand and clay. The base of the Lower Jasper Aquifer as discussed by Popkin extends to a deeper elevation than what is considered the base of the Jasper Aquifer today. Baker (1979) classified the Jasper Aquifer as a single hydrogeologic unit and interpreted the base of the Jasper Aquifer at a shallower elevation than Popkin's (1971) base of the Lower Jasper Aquifer. The base of the Jasper Aquifer corresponding to the United Stated Geological Survey (USGS) Source Water Assessment Program (SWAP) Dataset (Strom and others, 2003) gained acceptance in Montgomery County through a LSGCD Groundwater Panel review during the early 2010's as the Catahoula Formation was being explored as an alternative water resource.

The Catahoula Formation is below the base of the Jasper Aquifer and provides a fresh groundwater supply in the north part of Montgomery County where the formation can contain water with a total dissolved solids (TDS) concentration of less than 1,000 milligrams per liter (mg/l). Exploration of the Catahoula Formation as a potential water supply has occurred in a few areas of Montgomery County, but ultimately resulted in the completion of large capacity water wells screening the Jasper Aquifer due to the presence of brackish groundwater in the Catahoula as it gets deeper to the south in the county.

Geology

The geology of the GCAS consists of a complex system of alternating layers of discontinuous sand, silt and clay. The similarities of sediments within each geologic unit can make it difficult to identify the individual geologic units that comprise the hydrogeologic units on geophysical logs. To put the complexity of the GCAS into perspective, it should be noted that site-specific subsurface conditions must be evaluated for each water well that is constructed in the GCAS in the greater Houston area.

Table 1 shows a correlation of the geologic and hydrogeologic units of the GCAS within and near Montgomery County. Table 1 is based on studies completed by Popkin (1971) and Young and Draper (2020). The Chicot Aquifer is composed of the Beaumont, Lissie and Willis formations. The Beaumont and Lissie formations are of Pleistocene age and the Willis Formation is of Pliocene age. The Goliad Sand and part of the Fleming Group (Upper Lagarto Formation) comprise the Evangeline Aquifer. The Burkeville Confining Unit is made up of the Middle Lagarto Formation and can extend into the upper and lower sections of the Lagarto Formation of the Fleming Group. The Jasper Aquifer also belongs to the Fleming Group and includes the Lower Lagarto and Oakville formations. There is some uncertainty as to which geologic formation(s) would encompass the upper and lower sections of the Jasper aquifer. The Catahoula Formation is of Oligocene age. The formations generally outcrop in bands that parallel the Gulf Coast and typically increase in depth and thickness to the south and southeast toward the coast.

Epoch	Hydrogeologic Unit	Geologic Unit		
Holocene	Alluvium			
Pleistocene	Chicot Aquifer	Beaumont Clay		
		Lissie Formation		
Pliocene		Willis Formation		
Miocene	Evangeline Aquifer	Goliad Sand		Upper
				Lower
		Fleming Formation	Lagarto	Upper
	Burkeville Confining Unit			Middle
	Upper Jasper Aquifer			Lower
	Lower Jasper Aquifer		Oakville	
Oligocene	Catahoula		Catahoula	

Table 1. Hydrogeologic and Geologic Units of the Gulf Coast Aquifer System Within and Near Montgomery County (Popkin, 1971; Young and Draper, 2020).

Figure 2 shows the surface geology and the estimated updip extent of the hydrogeologic units in Montgomery County. The updip extent of the Chicot Aquifer generally aligns with the updip extent of the Willis Formation outcrop. The Lissie Formation can be found in the south and southeast parts of Montgomery County. The 2014 Bureau of Economic Geology (BEG) Digital Geologic Atlas of Texas shows the Willis Formation (landward belt) and the Fleming Formation occurring at land surface in the northwest part of the county. The Evangeline Aquifer, Burkeville Confining Unit and Jasper Aquifer are estimated to outcrop in this area. Note that the Willis

Formation (landward belt) shown in the northwest part of Montgomery County on the BEG Digital Atlas of Texas is not included in Table 1.

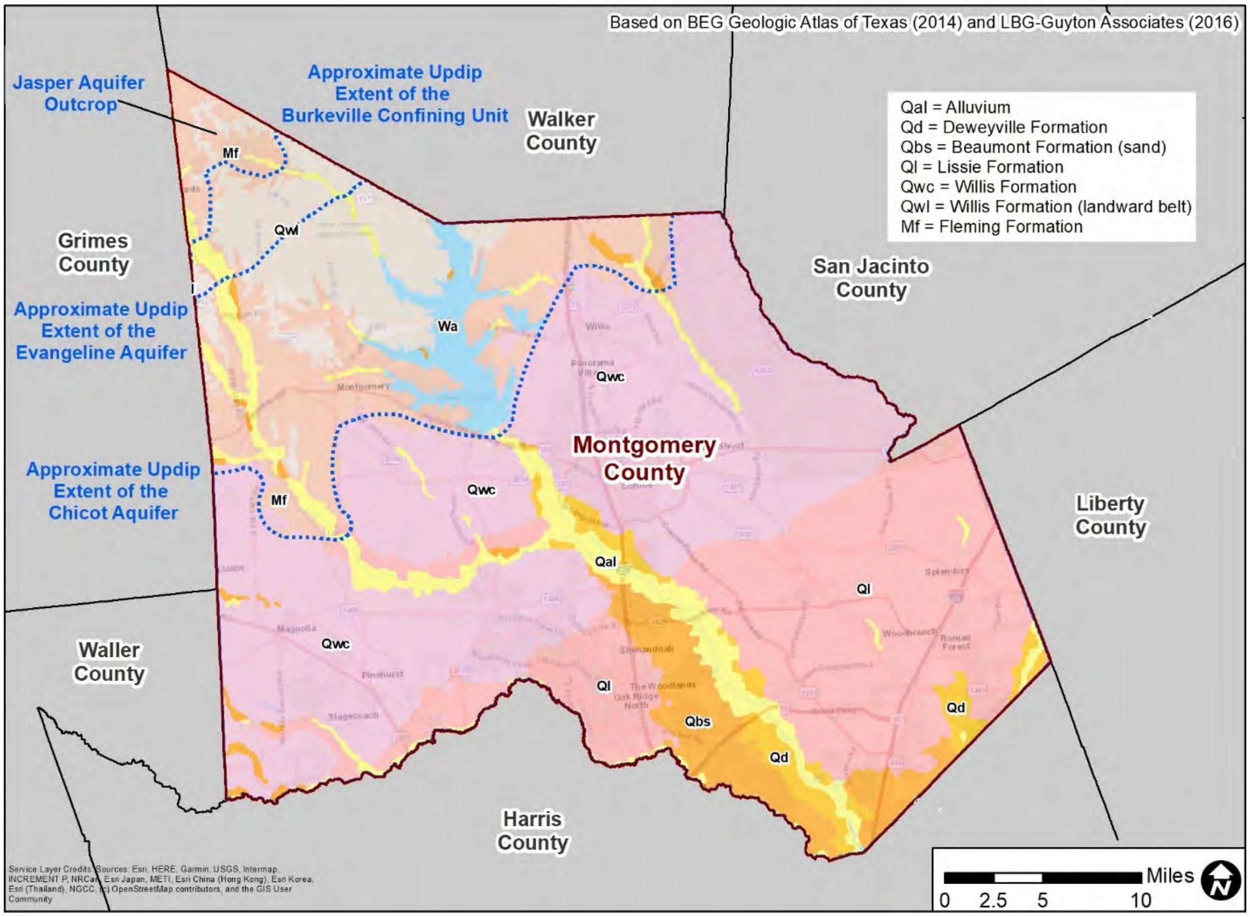

Figure 2. Montgomery County Surface Geology and Approximate Aquifer Outcrop Areas (Based on BEG Geologic Atlas of Texas, 2014; LBG-Guyton, 2016)

Subsurface geologic faults and large oil and gas field locations in the vicinity of Montgomery County are shown on Figure 3. Oil and gas drilling activities are often concentrated at or near these subsurface geologic features. Figure 4 shows the locations of oil and gas well and/or test hole locations in and near Montgomery County based on datasets available for download from the Railroad Commission of Texas (RRC, 2021). It should be noted that this is not a comprehensive location map for all oil and gas wells and/or test holes in this area. The regional dip, subsurface geologic structure, formation thickness and/or groundwater quality may be influenced by geologic structures such as salt domes (Turner Collie & Braden, Inc., 2004).

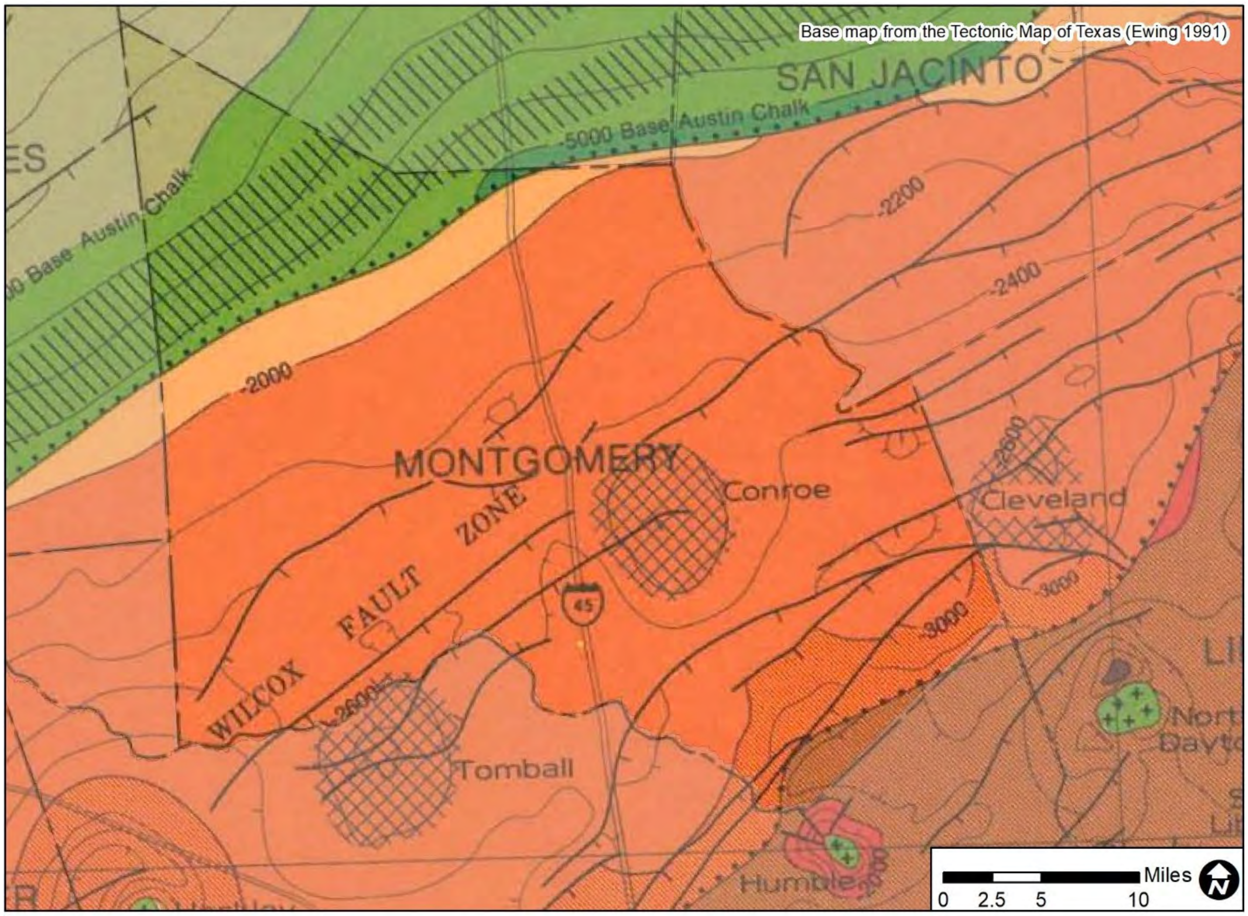

Figure 3. Subsurface Faults and Large Oil and Gas Fields in the Vicinity of Montgomery County (base map from the Tectonic Map of Texas, Ewing, 1991)

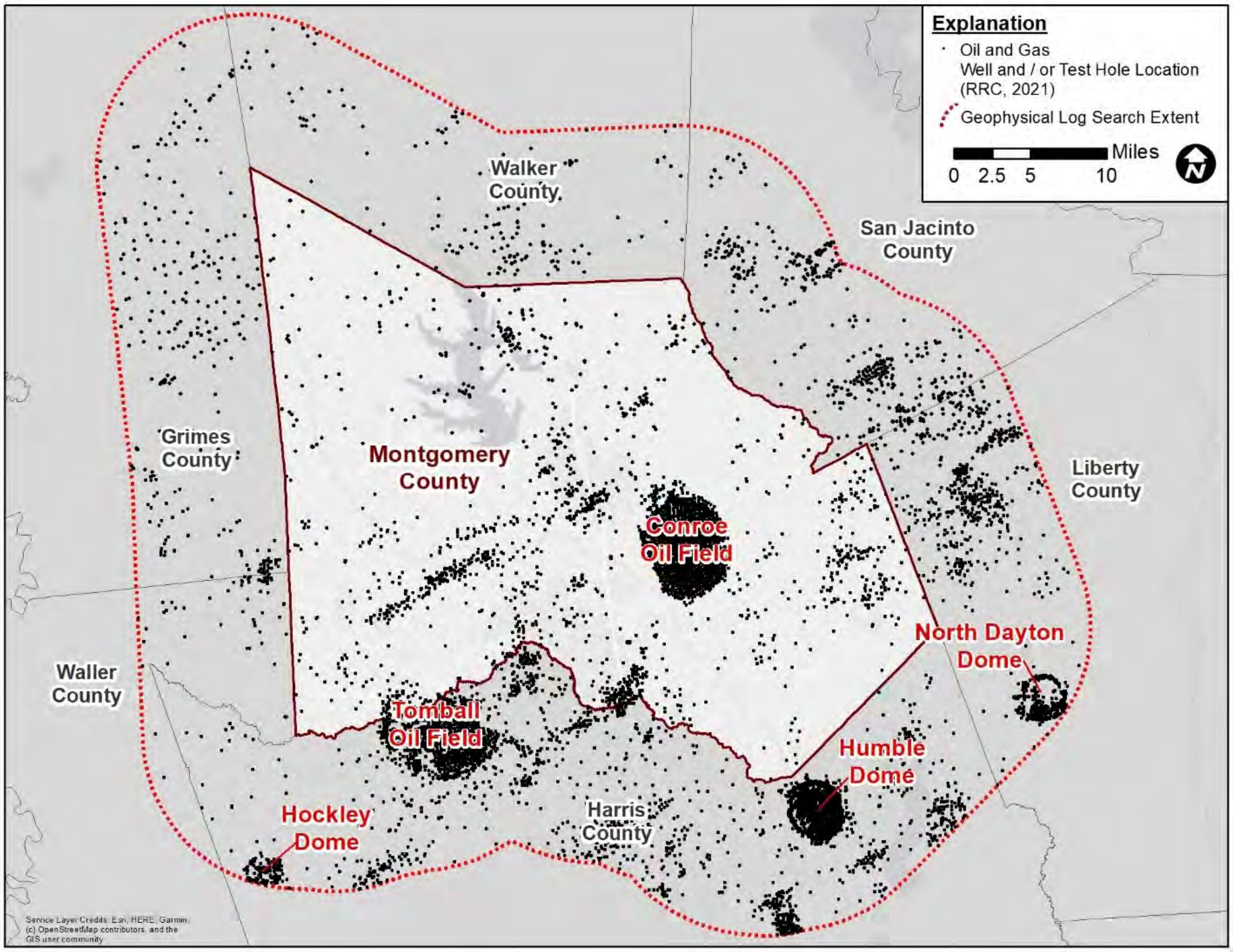

Figure 4. Locations of Oil and Gas Wells or Test Holes (Based on available data from the RRC, 2021).

The Conroe Oil Field is the largest oil and gas field in Montgomery County and is located to the southeast of the City of Conroe. Discovered in 1931, the Conroe Oil Field is located over a deep-seated salt dome that occurs at depths of greater than 5,000 feet (Turner Collie & Braden, Inc., 2004). Other salt domes in the vicinity of the Task 2 study area include the Hockley Dome and Humble Dome in Harris County and the North Dayton Dome in Liberty County as shown on Figure 4.

Geophysical Log Evaluation

One of the goals of Task 2 in the LSGCD Phase II Subsidence Study is to improve the mapping and understanding of the subsurface hydrogeologic formations of Montgomery County. Geophysical logs are an important resource that can be utilized to estimate the depths, thicknesses and composition of the subsurface hydrogeologic units that make up the GCAS.

Geophysical or electric logs are evaluated using the resistivity curves that are shown to the right of the depth scale on the log. These curves measure the resistivity of the sands and clays of the subsurface formations. Clean and coarse sands will have higher resistivity values than fine grained sand, sand intermixed with silt or silt and clay (lowest resistivity values). Resistivity curves also can provide information on the general mineralization or gross water quality of water within subsurface formations. Freshwater sands have higher resistivity values than sands that contain water with more mineralization and higher concentrations of TDS. The properties of resistivity and conductivity are inverses of each other, so higher resistivity equals lower conductivity. As a result, water that contains more dissolved minerals (that is, higher TDS concentration) has a higher electrical conductivity and a lower electrical resistivity than water that has relatively low mineralization or TDS concentration.

Evaluation of spontaneous potential (SP) logs can be another way to assess the quality of the water contained within the subsurface formations. The SP log is normally shown to the left of the depth scale on a geophysical log. The SP curve will show little deflection as the logging tool passes through freshwater sands as freshwater is not that conductive of electricity. The SP curve will show more deflection as the logging tool passes through sands that contain water with higher TDS values.

For this study, the mapping of hydrogeologic units within Montgomery County focused on the Chicot, Evangeline and Jasper aquifers and the Burkeville Confining Unit. The Jasper Aquifer has been divided into upper and lower units. The delineation of the base and total thickness of the Chicot, Evangeline, Burkeville and Upper Jasper is based on geophysical log review. The base of the Lower Jasper Aquifer was established for this study using the USGS SWAP dataset (Strom and others, 2003).

LSGCD currently permits production from the Chicot and Evangeline aquifers as a single combined aquifer. However, it is important to understand the properties and structure of the individual aquifer units, as these two aquifers are often represented as separate layers in groundwater flow models.

Geophysical Log Limitations

Evaluation of geophysical or electric logs is not an exact science and is commonly based on experience and professional opinion, and these opinions regarding the top and bottom of hydrogeologic and geologic units can vary between professionals. Other factors can influence the interpretation of the depth and thickness of subsurface hydrogeologic and geologic formations.

The geophysical log datum is a key component for standardizing the depth scale shown on a log. Often the depth shown on geophysical logs is converted to elevation relative to sea level (rsl) in order to correct for variations in the land surface. The header of the geophysical log may contain the elevation of ground level, Kelly bushing or drill floor, but often one or more pieces of this information is not available.

Acquiring geophysical logs that start shallow enough to include the base of the Chicot Aquifer was a priority consideration in the geophysical log assembly process. Locating logs that start shallow enough to include the base of Chicot Aquifer can be challenging. Often the logs that have a top logged interval showing the base of Chicot Aquifer are relatively older (including from the 1940's) and can potentially be difficult to interpret due to the print quality of the log.

Geophysical Log Data

A total of 146 geophysical logs obtained from public and private sources have been evaluated as part of this study. Most of the geophysical logs reviewed originate from oil and/or gas wells or test holes. The public sources for the geophysical logs include the TWDB Brackish Resources Aquifer Characterization System (BRACS) database (2021) and the Texas Commission on Environmental Quality (TCEQ) Water Well Report Viewer (2021). Geophysical logs also were purchased from a commercial log library in areas where geophysical log coverage was limited or not available from public sources. The search radius for the geophysical logs extends up to 10-miles from Montgomery County in an effort to ensure adequate areal coverage. Figure 5 shows the locations of geophysical logs reviewed as part of this study.

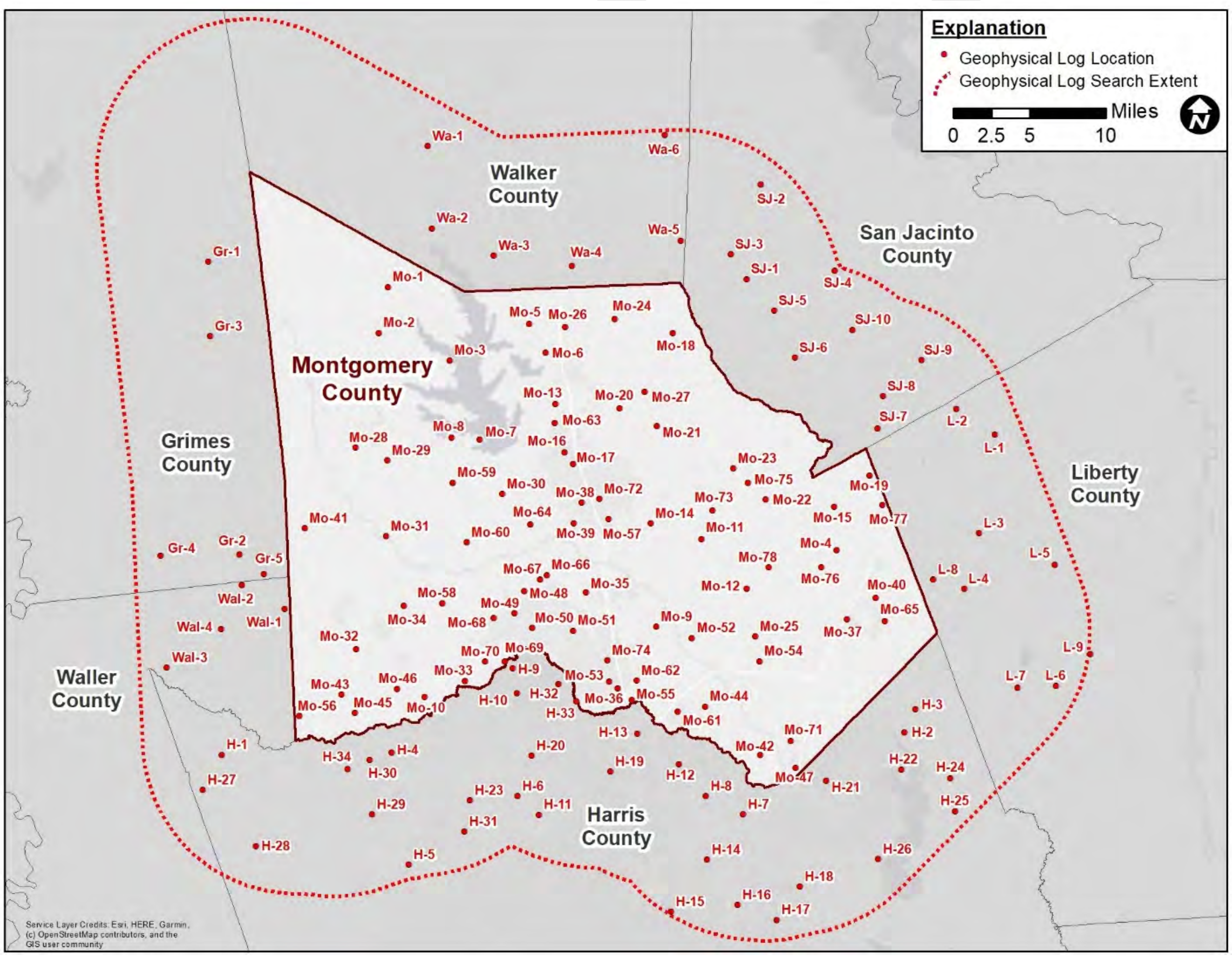

Figure 5. Locations of Geophysical Logs Evaluated for this Study

The datum of the geophysical logs used in this study is based on the land surface elevation. The depth of the hydrogeologic unit selected from the geophysical log has been standardized to account for changes in the land surface elevation by converting the depth of the hydrogeologic unit to elevation rsl. Appendix A includes a table that provides geophysical log data utilized in this study including the: Geophysical Log Number, API Number, State Well Number or Q Number, well or test hole operator and well ID, latitude and longitude, land surface elevation and estimated hydrogeologic unit depth and elevation.

Chicot Aquifer

The Chicot Aquifer is the shallowest hydrogeologic unit occurring in Montgomery County and the aquifer outcrop is present at land surface for approximately 74 percent of the county. A lower amount of groundwater is pumped from the Chicot Aquifer relative to the Evangeline and Jasper aquifers in Montgomery County, with the primary use of the water being for domestic, irrigation (domestic / commercial) and some limited public supply.

Alternating layers of sand, silt and clay and intermittent gravel comprise the Chicot Aquifer. The transition between the Chicot and Evangeline aquifers is not commonly clear and distinct. Historically, many USGS and other scientists, geologists and engineers have used practical hydrogeology concepts, including noticeable differences in lithology, permeability, water levels and water quality combined with geophysical log interpretation to identify the transition between the Chicot and Evangeline aquifers.

Figures 6 and 7 show the estimated elevation of the base of the Chicot Aquifer rsl and the estimated aquifer thickness, respectively. Evaluation of geophysical logs show that the aquifer is increasing in depth and thickness as the aquifer dips to the southeast towards the Gulf of Mexico. The Chicot Aquifer is estimated to dip at a rate of approximately 15 to 25 feet per mile to the southeast based on the geophysical logs used in this study. The base of the Chicot Aquifer is present at land surface in the outcrop area and is estimated to extend to an elevation of about -375 feet rsl in the southeast part of Montgomery County. The thickness of the Chicot Aquifer increases with distance from the estimated updip extent of the aquifer outcrop to an estimated maximum thickness of approximately 470 feet in the southeast part of the county. The average thickness of the Chicot Aquifer in Montgomery County is about 250 feet.

The estimated base of Chicot Aquifer elevation contour map developed for Montgomery County as part of this study appears generally similar to the base of Chicot Aquifer maps shown in Espey, Huston & Associates (1979) and Carr, Meyer and others (1985). The elevation of the base of the Chicot Aquifer is at or near sea level just to the north of the City of Conroe and the elevation of the base of the Chicot Aquifer is approaching -400 feet rsl near the Montgomery / Harris County line in the southeast part of the county in all three (3) studies.

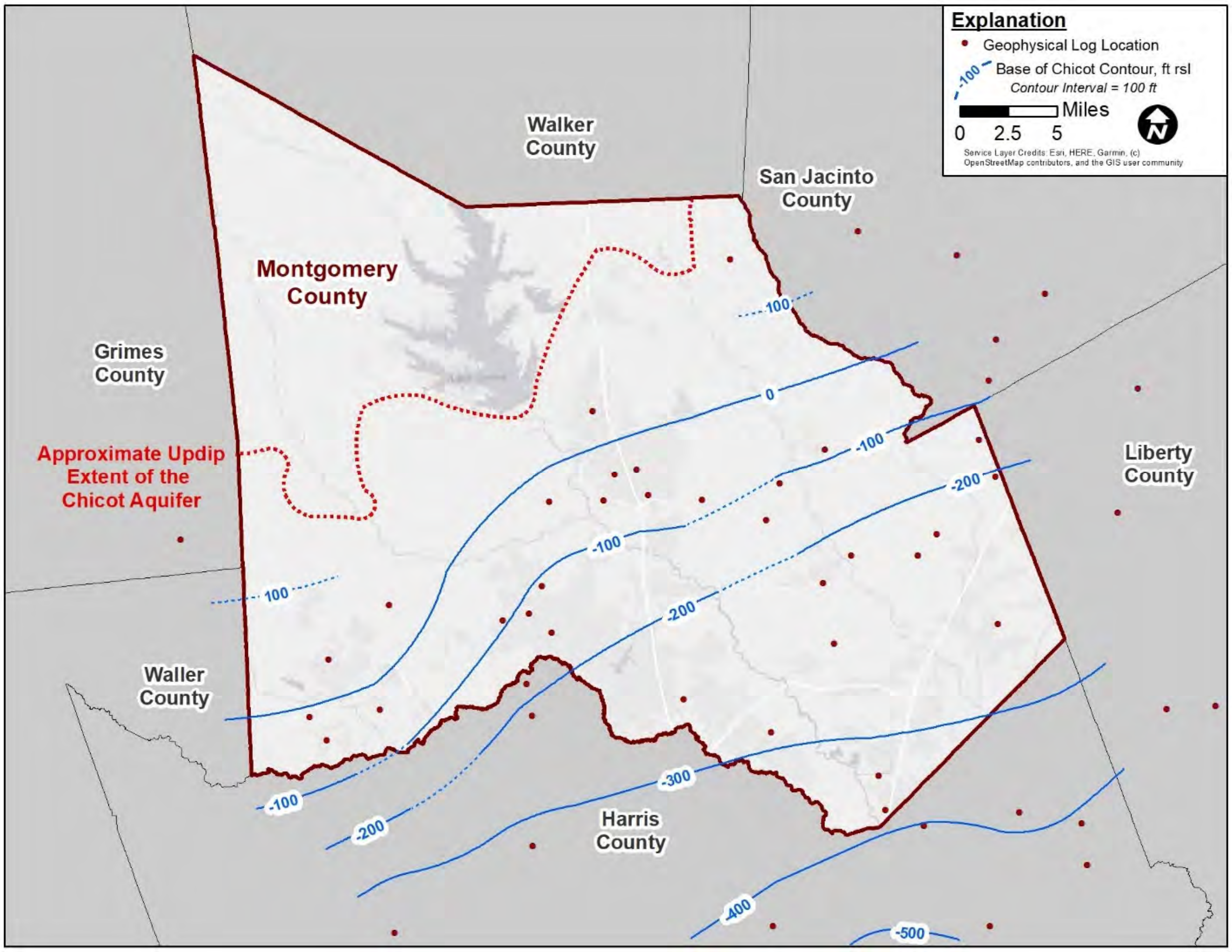

Figure 6. Estimated base of the Chicot Aquifer within Montgomery County

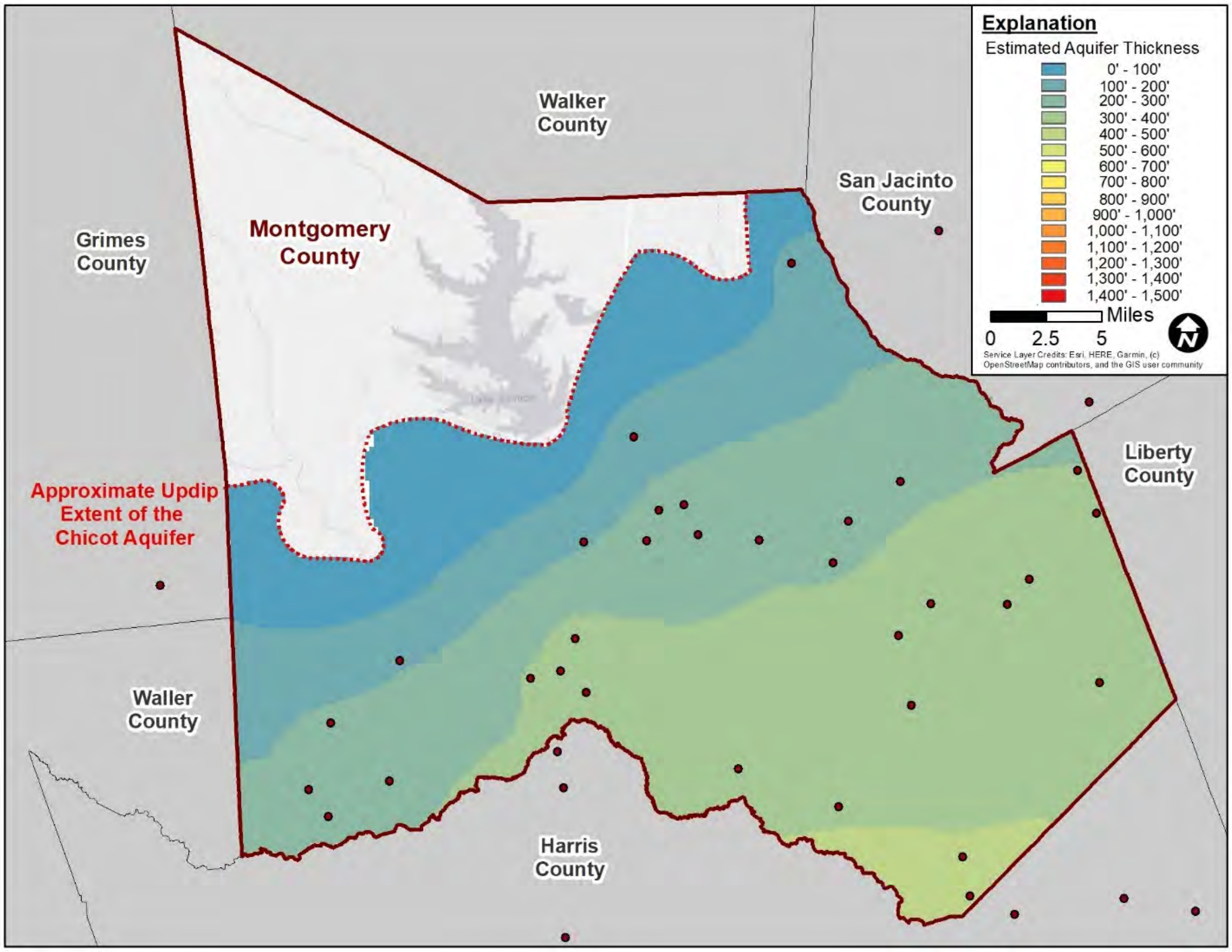

Figure 7. Estimated Thickness of the Chicot Aquifer within Montgomery County

Evangeline Aquifer

The Evangeline Aquifer is positioned below the Chicot Aquifer and above the Burkeville Confining Unit. The aquifer outcrop is present at land surface over approximately 21 percent of Montgomery County. Groundwater pumped from the Evangeline Aquifer is utilized for public supply, commercial, irrigation and industrial uses.

The Evangeline Aquifer is made up of discontinuous layers of alternating sand and clay. Geophysical logs indicate that the Evangeline Aquifer is estimated to dip at a rate of approximately 40 to 50 feet per mile to the southeast in Montgomery County. Figure 8 shows the estimated base of the Evangeline Aquifer, rsl, which is estimated to occur at a depth of about -800 feet rsl in the southwest part of the county and about -1,400 feet rsl in the southeast. The estimated thickness of the Evangeline Aquifer is shown on Figure 9, which increases with distance from the approximate updip extent located in northwest Montgomery County to an estimated maximum thickness of more than 1,000 feet in the southeast part of the county. The average thickness of the Evangeline Aquifer in Montgomery County is about 540 feet.

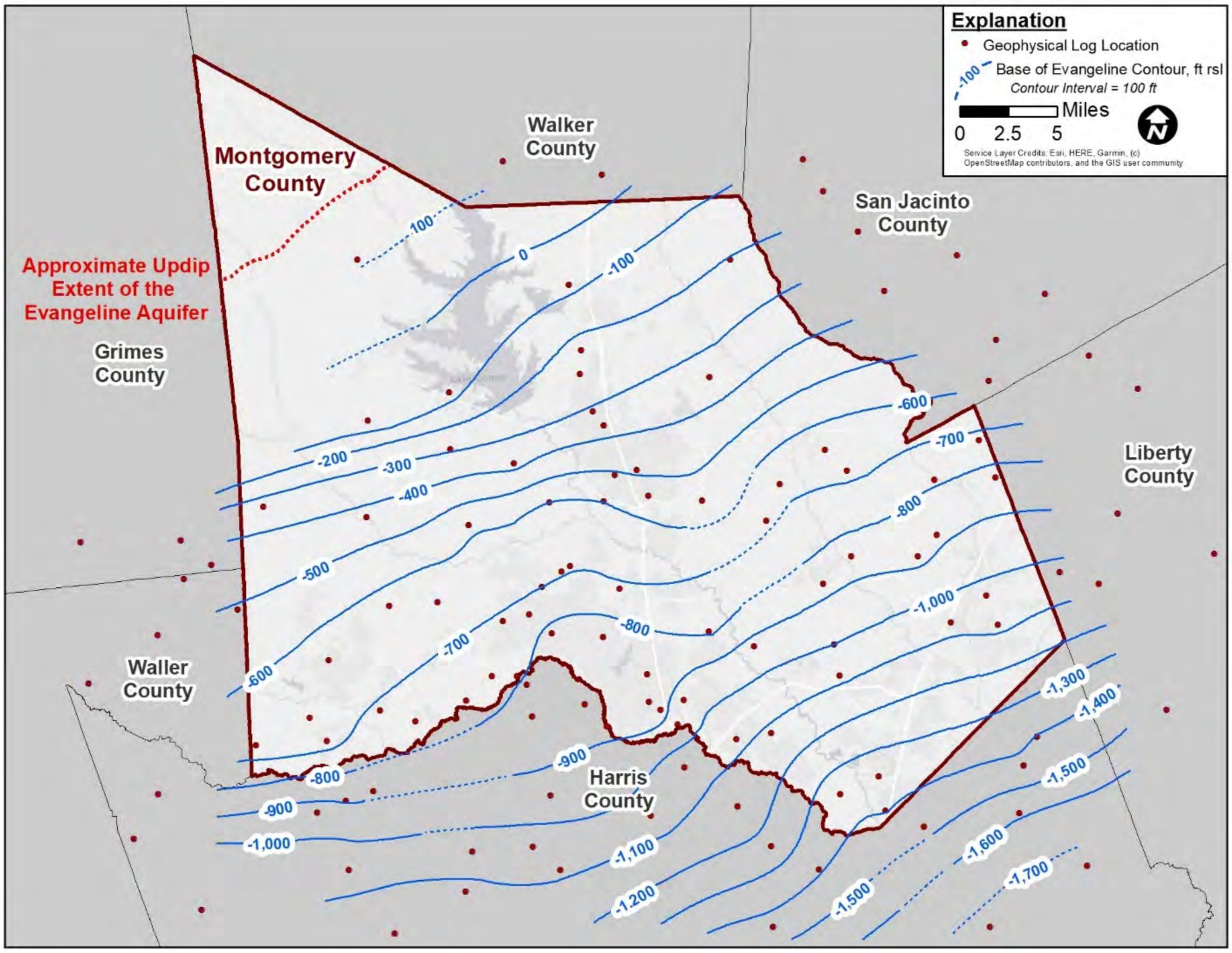

Figure 8. Estimated base of the Evangeline Aquifer within Montgomery County

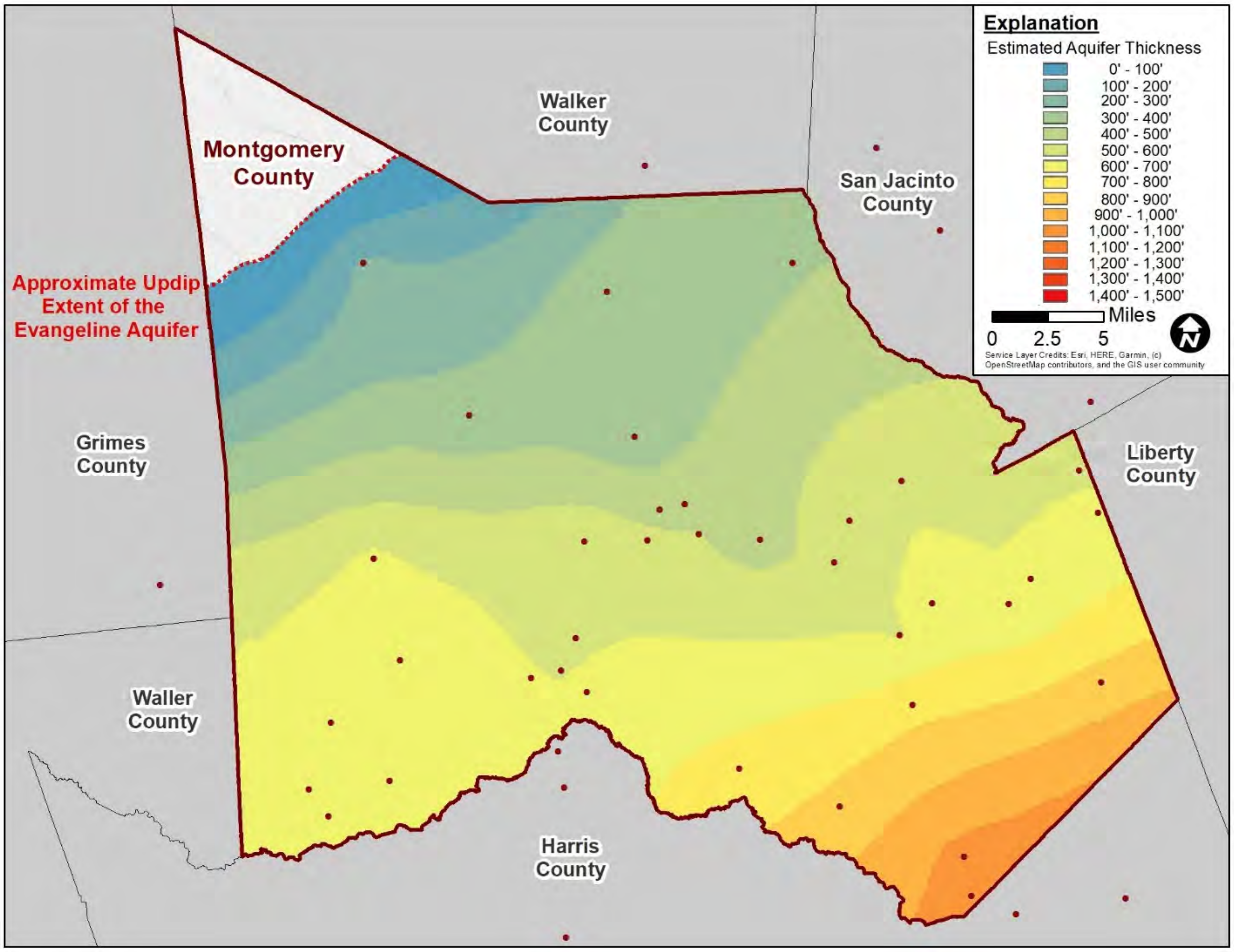

Figure 9. Estimated Thickness of the Evangeline Aquifer within Montgomery County

Burkeville Confining Unit

The Burkeville Confining Unit is vertically positioned between the Evangeline and Jasper aquifers and the outcrop is estimated to be present at land surface over approximately three (3) percent of Montgomery County. The high percentage of clay content in the Burkeville Confining Unit limits movement of groundwater between the Jasper and Evangeline aquifers. Limited sands can occur in the Burkeville and are thought to not be hydraulically connected. In some areas completion of smaller volume domestic wells are possible in the Burkeville Confining Unit; However, the sands of the Burkeville Confining Unit would not be capable of fully supporting a moderate to large capacity water well. It has been noted that in some areas large capacity wells have been constructed with screen set opposite sands in the Burkeville, but the percentage of total well screen in the Burkeville is very small compared to the entire screen interval of the well, which probably is primarily in the shallower Evangeline Aquifer or the upper part of the Jasper Aquifer.

The estimated base of the Burkeville Confining is shown on Figure 10 and the elevation of the base of the formation is estimated to occur at a depth of about -1,100 feet rsl in the southwest part of the county and about -1,870 feet rsl in the southeast. The estimated dip of the base of the Burkeville Confining Unit (equivalent to the top of the Jasper Aquifer) is generally to the southeast at a rate of approximately 40 to 50 feet per mile. The estimated thickness of the Burkeville Confining Unit is shown on Figure 11 and generally increases with distance from the approximate updip extent located in far northwest Montgomery County to an estimated maximum thickness of about 480 feet in the southeast part of the county. The Burkeville Confining Unit thickness is estimated to range from about 200 to 300 feet in a large part of Montgomery County, with an average thickness of the formation estimated to be approximately 240 feet.

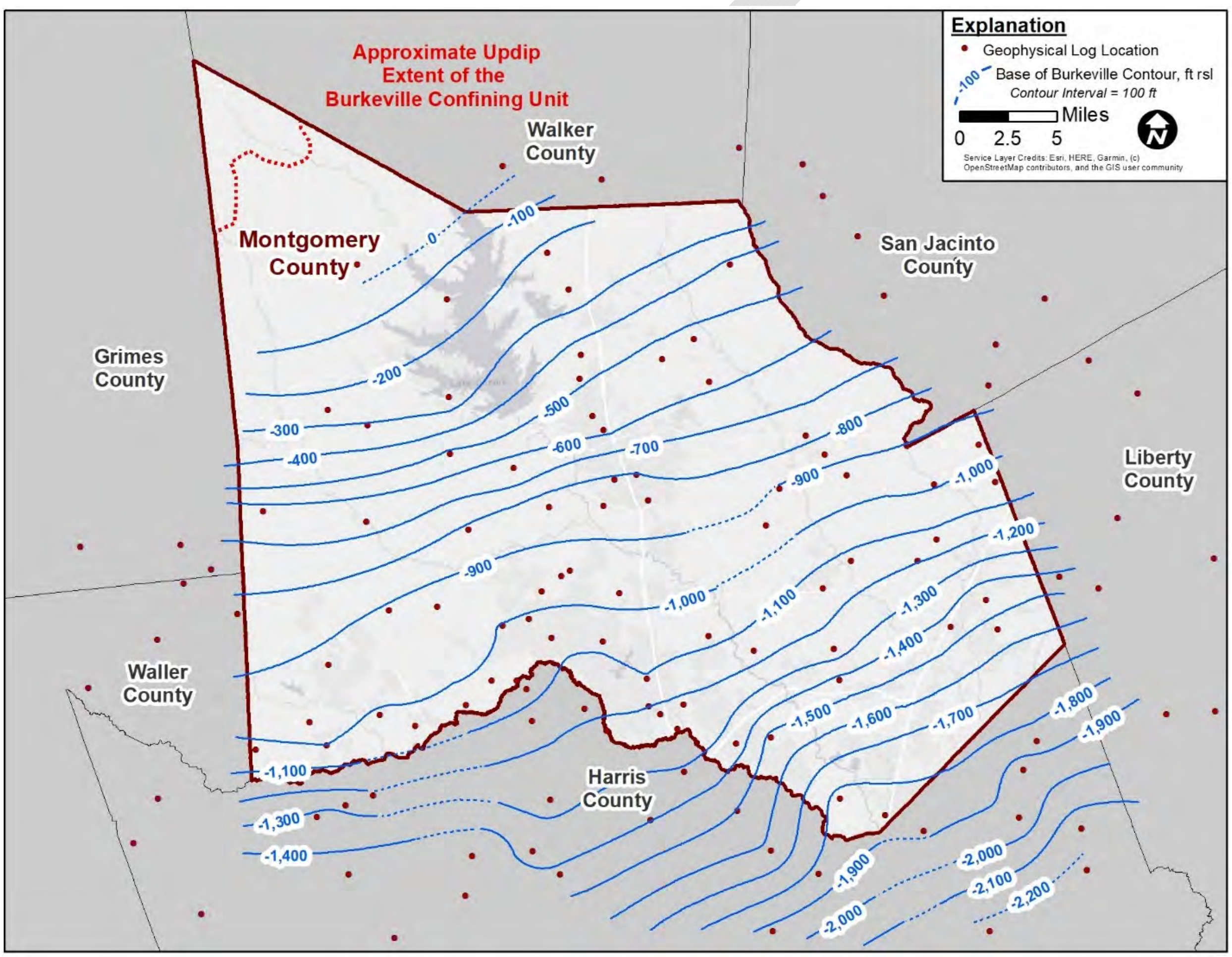

Figure 10. Estimated base of the Burkeville Confining Unit within Montgomery County

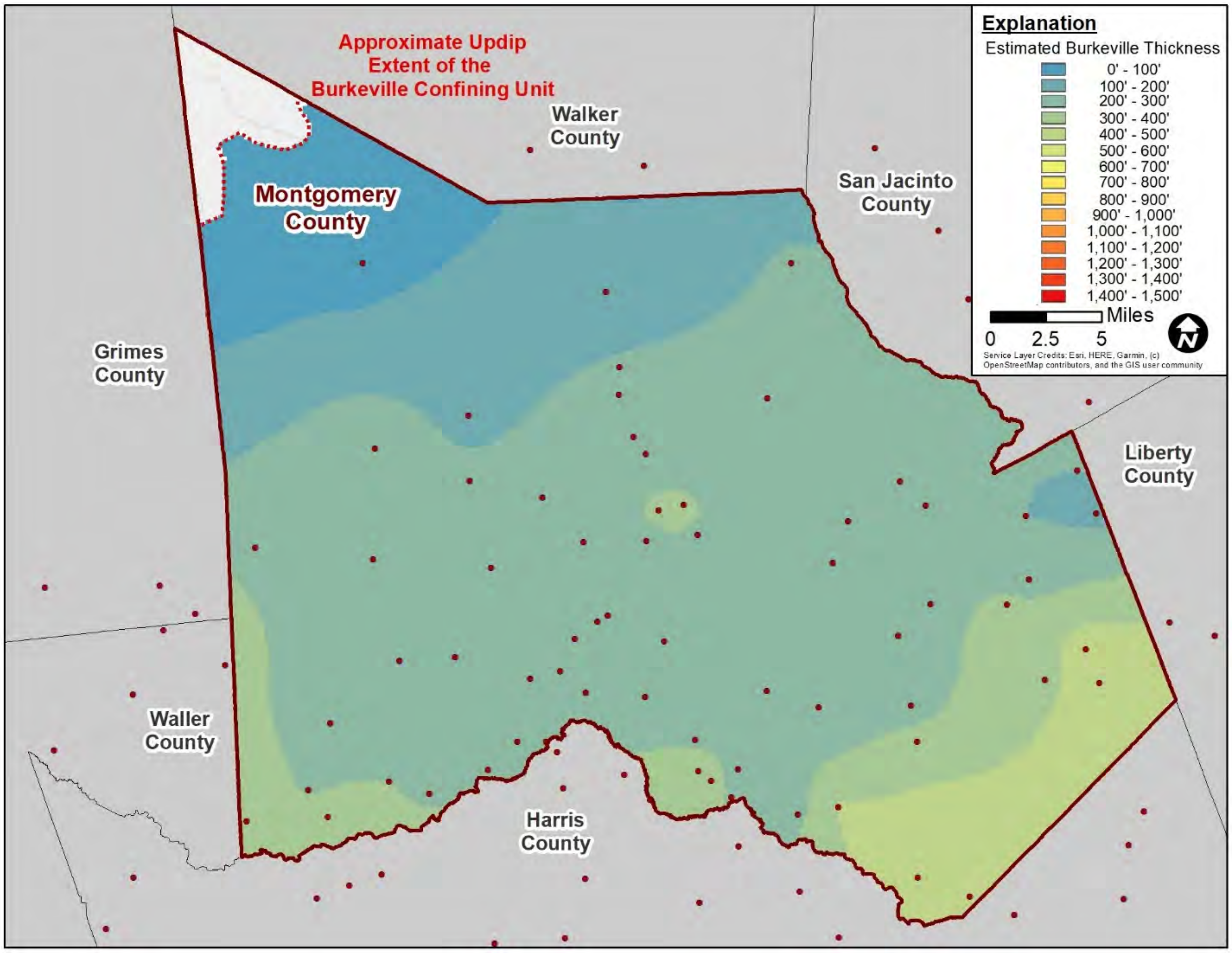

Figure 11. Estimated Thickness of the Burkeville Confining Unit within Montgomery County

Jasper Aquifer

The Jasper Aquifer is also a significant source of groundwater produced in Montgomery County and is positioned between the overlying Burkeville Confining Unit and the underlying Catahoula Formation. Groundwater produced from the Jasper Aquifer is used for public, industrial and other water supply, but also can be used for domestic purposes in the shallower, updip part of the formation. The Jasper Aquifer outcrop is present at land surface in approximately two (2) percent of Montgomery County, the smallest of any hydrogeologic unit in the county.

As the focus of this study is on the principal hydrogeologic units from which groundwater is produced in Montgomery County, the Jasper Aquifer was separated into upper and lower units based on lithology for this discussion. The Upper Jasper Aquifer contains more sand than the Lower Jasper and is the section of the aquifer screened in moderate to large capacity public supply and industrial wells throughout Montgomery County and in parts of north and northwest Harris County. It should be noted that the thicker sands that comprise the Upper Jasper Aquifer can contain brackish groundwater in downdip areas of the formation located in southeast Montgomery

County. The Lower Jasper is made up of mostly interbedded sand and clay and the water contained within the sands can often be of brackish water quality. At the time of this study there has been no development of the brackish groundwater resources available from the Jasper Aquifer. The USGS SWAP dataset corresponding to the base of the Jasper Aquifer (Strom and others, 2003) was used as the base of the Lower Jasper in this study.

Upper Jasper Aquifer

The base of the Upper Jasper Aquifer is estimated to dip at a rate of approximately 50 to 60 feet per mile to the southeast. Figure 12 shows the estimated elevation of the base of the Upper Jasper Aquifer, with the elevation of the base of the Upper Jasper Aquifer estimated to occur at a depth of about -1,500 feet rsl in the southwest and about -2,350 feet rsl in the southeast part of the county. The estimated thickness of the Upper Jasper Aquifer is shown on Figure 13 and increases with distance from the approximate updip extent located in far northwest Montgomery County. The maximum estimated thickness is about 570 feet in the southeast part of the county. The average thickness of the Upper Jasper Aquifer is estimated to be about 390 feet in Montgomery County.

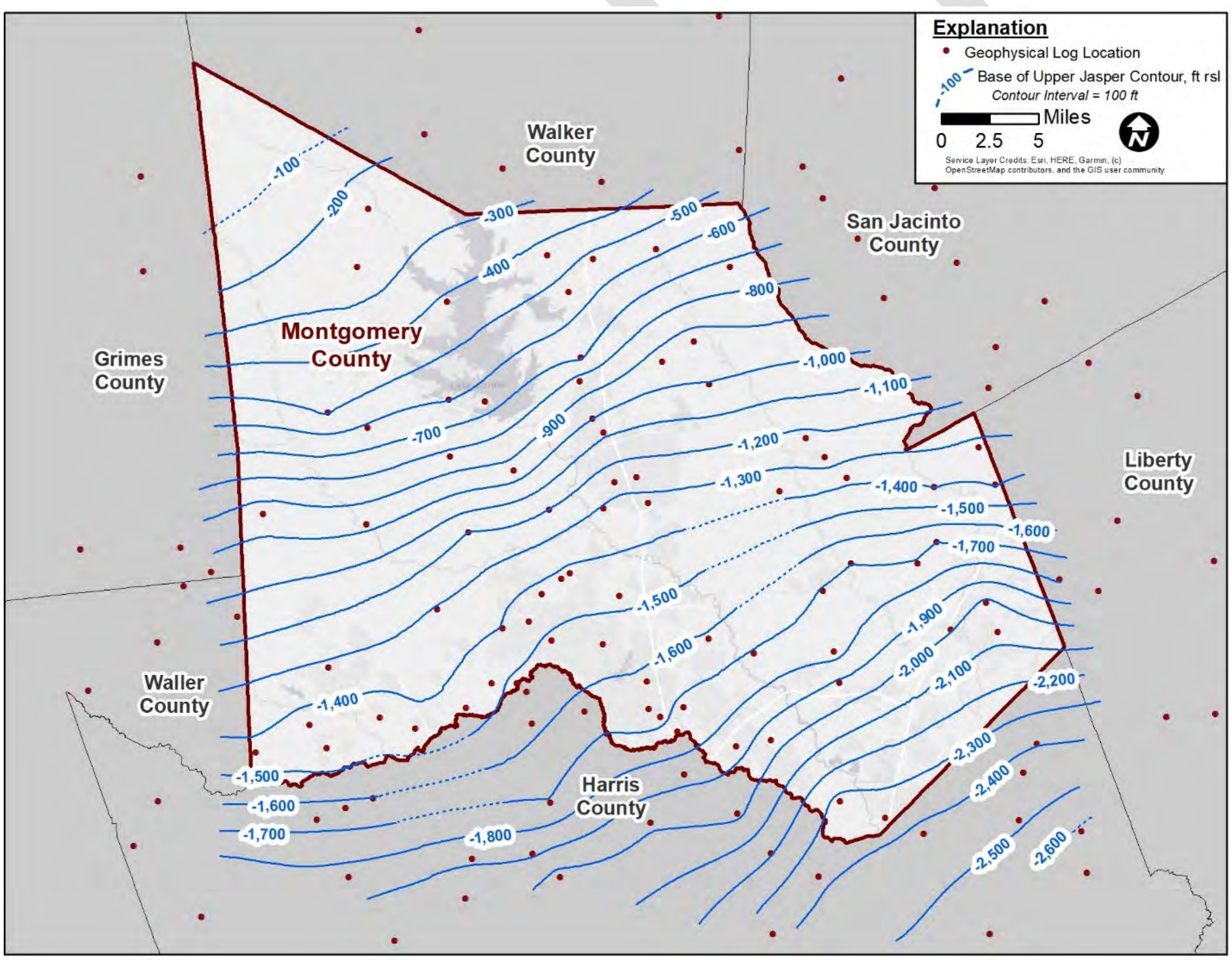

Figure 12. Estimated base of the Upper Jasper Aquifer within Montgomery County

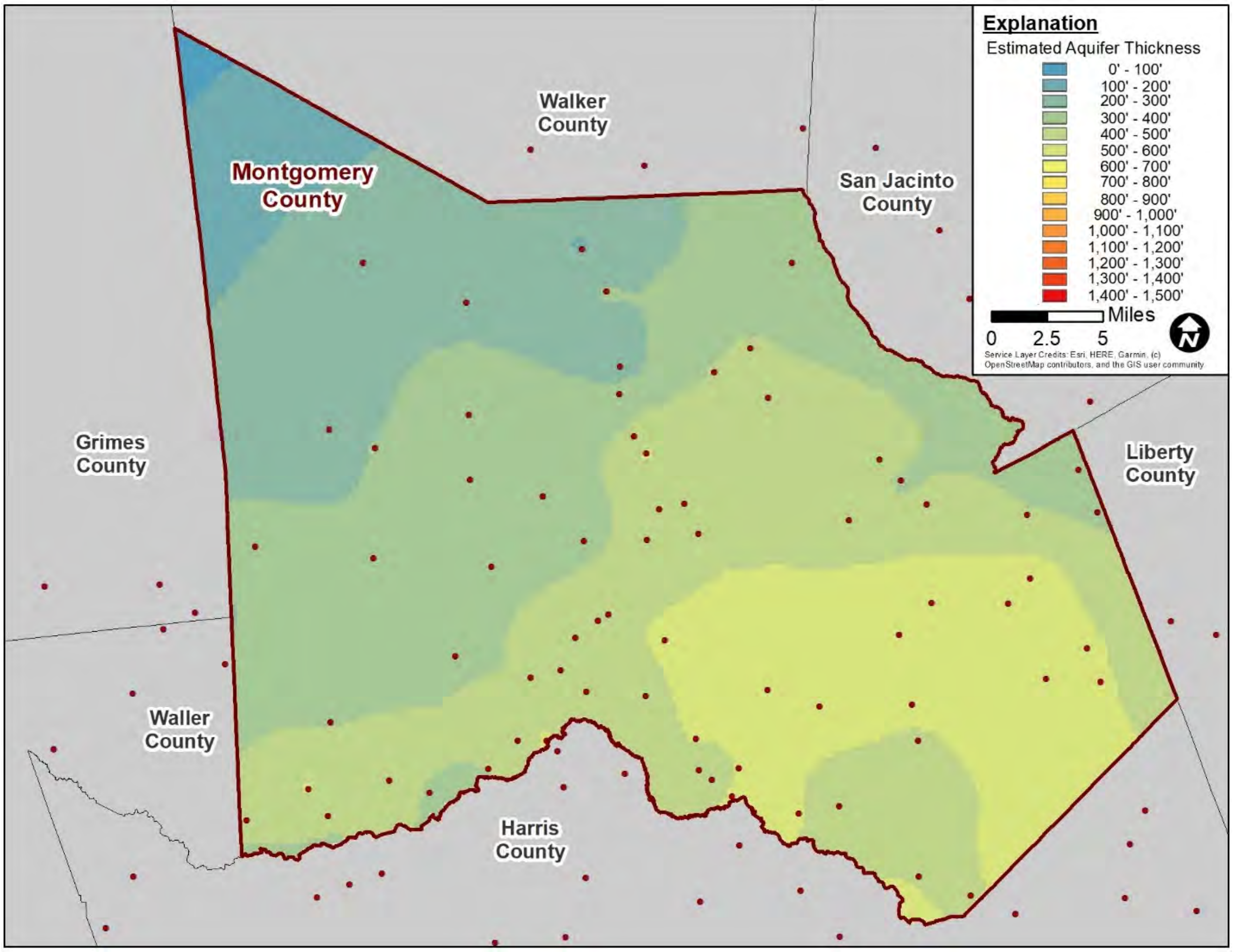

Figure 13. Estimated Thickness of the Upper Jasper Aquifer within Montgomery County

Lower Jasper Aquifer

The base of the Lower Jasper Aquifer was generated from the base of the Jasper Aquifer in the USGS SWAP dataset (Strom and others, 2003) and can be seen on Figure 14. Strom and others (2003) indicate that the SWAP base of the Jasper Aquifer was created using well data from cross sections included in Baker 1979 and 1986. The cross sections included in Baker (1979 and 1986) have limited geophysical log data within Montgomery County.

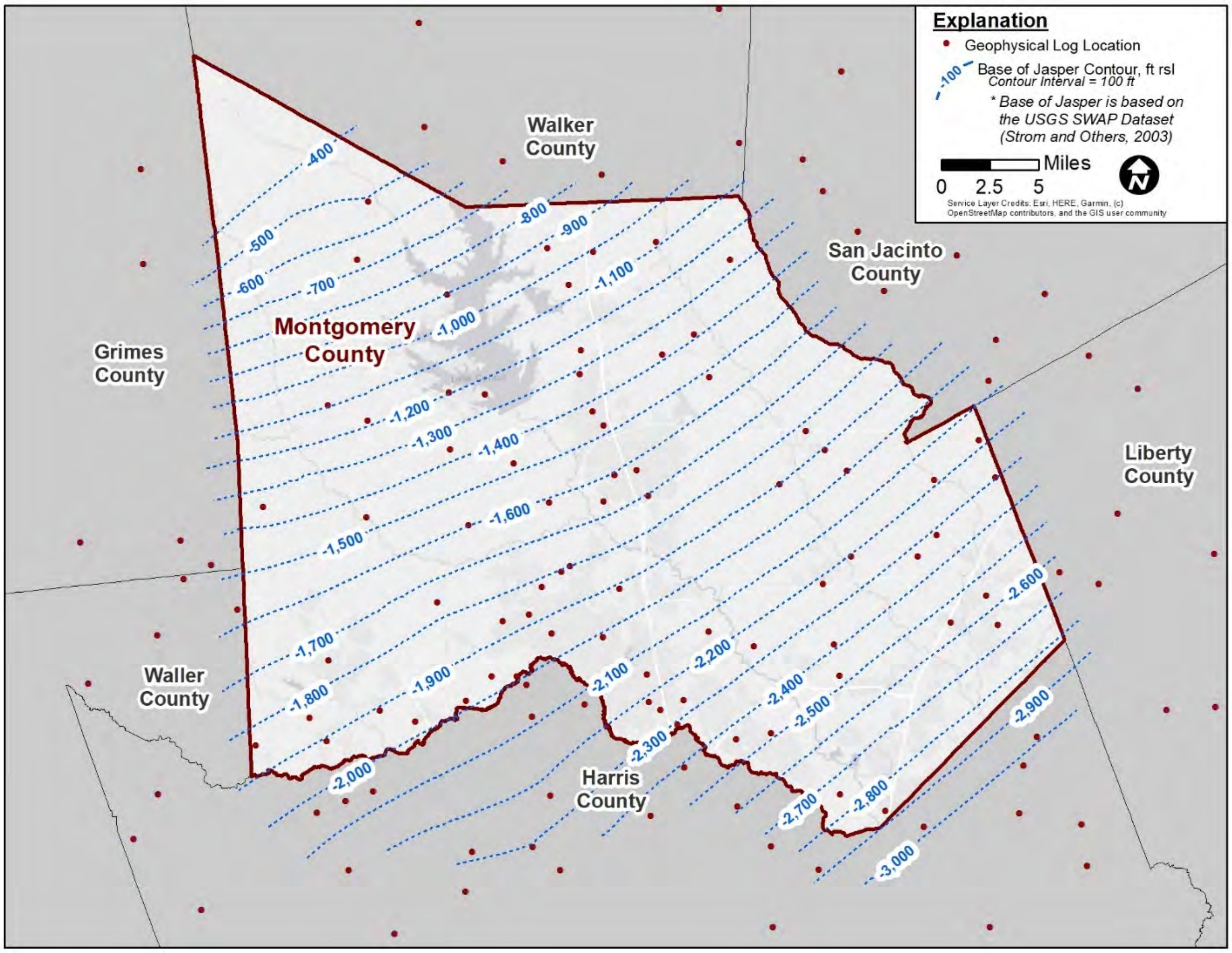

Figure 14. Estimated base of the Lower Jasper Aquifer within Montgomery County Based on the USGS SWAP Dataset (Strom and others, 2003)

The estimated dip of the base of the Lower Jasper Aquifer is at rate of approximately 50 to 60 feet per mile to the southeast. The elevation of the base of the Upper Jasper Aquifer is estimated to occur at a depth of about -2,000 feet rsl in the southwest part of the county and about -2,900 feet rsl in the southeast part.

Figure 15 shows the approximate thickness of the Lower Jasper Aquifer as defined by the difference between the estimated base of the Upper Jasper (as defined in this study) and the base of the Jasper Aquifer as defined by the USGS SWAP Dataset (Strom and others, 2003). The estimated thickness of the Lower Jasper Aquifer in Montgomery County ranges from approximately 100 feet in the northwest part of the county to approximately 900 feet in the east part of the county, with an average thickness of about 500 feet.

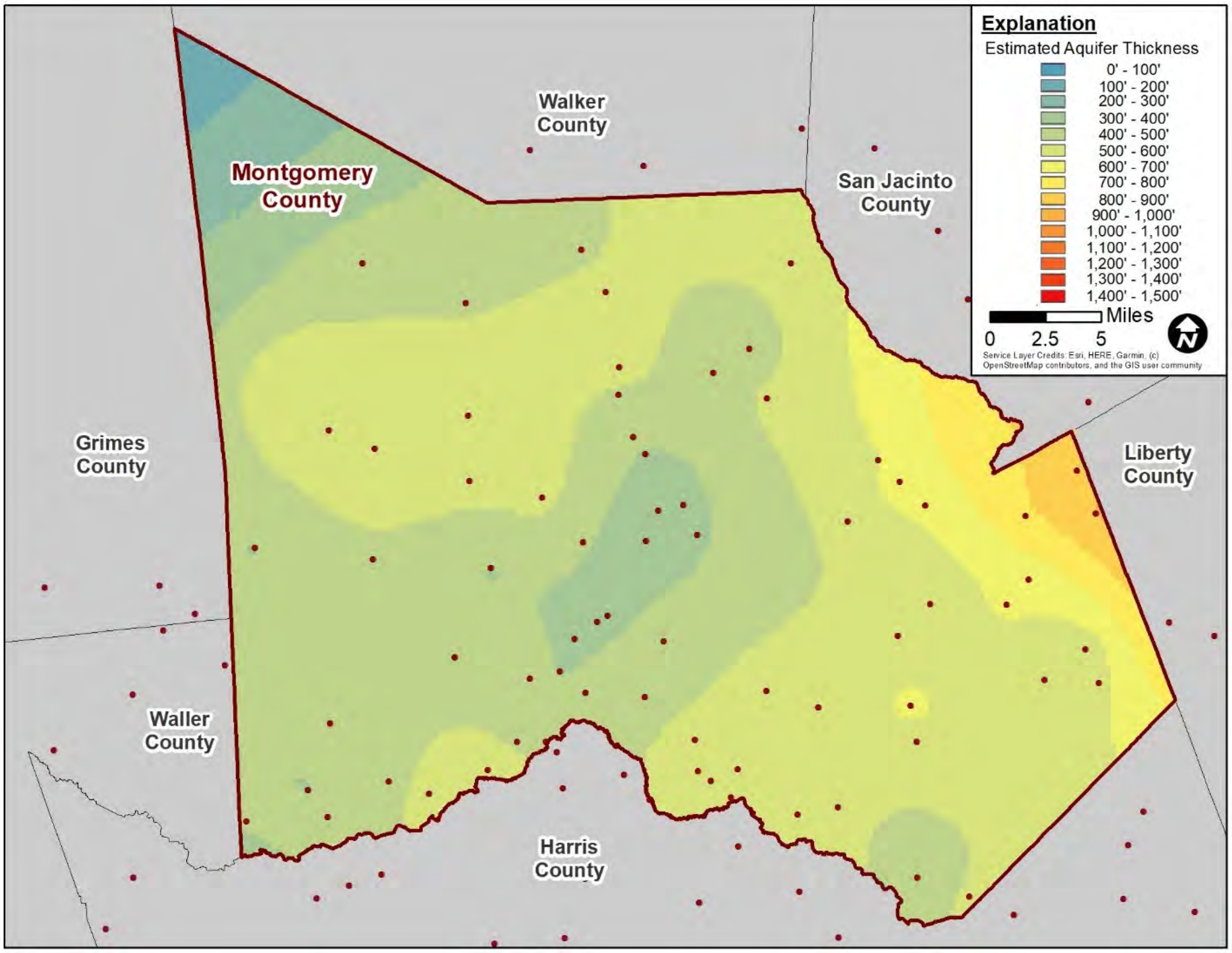

Figure 15. Estimated Thickness of the Lower Jasper Aquifer within Montgomery County as the difference between the base of the Upper Jasper as defined as part of this study and the base of the Jasper Aquifer as defined by the USGS SWAP Dataset

Combined Jasper Aquifer

Figure 16 shows the estimated thickness of the Jasper Aquifer (combined upper and lower units) based on the difference between base of the Burkeville Confining Unit as delineated in this study and the base of the Jasper Aquifer depicted by the USGS SWAP Dataset. Please note that the thickness comparison using the base of the Jasper Aquifer as defined by the USGS SWAP Dataset provides a general estimate of the total thickness of the Jasper Aquifer using the surface that was accepted as the base of the Jasper by LSGCD in the early 2010's. The total thickness of the Jasper Aquifer is estimated to range from about 150 feet in the outcrop area in the northwest part of Montgomery County to an estimated maximum thickness of approximately 1,280 feet in the east part of the county. The estimated average thickness of the Jasper Aquifer (combined upper and lower units) is approximately 890 feet.

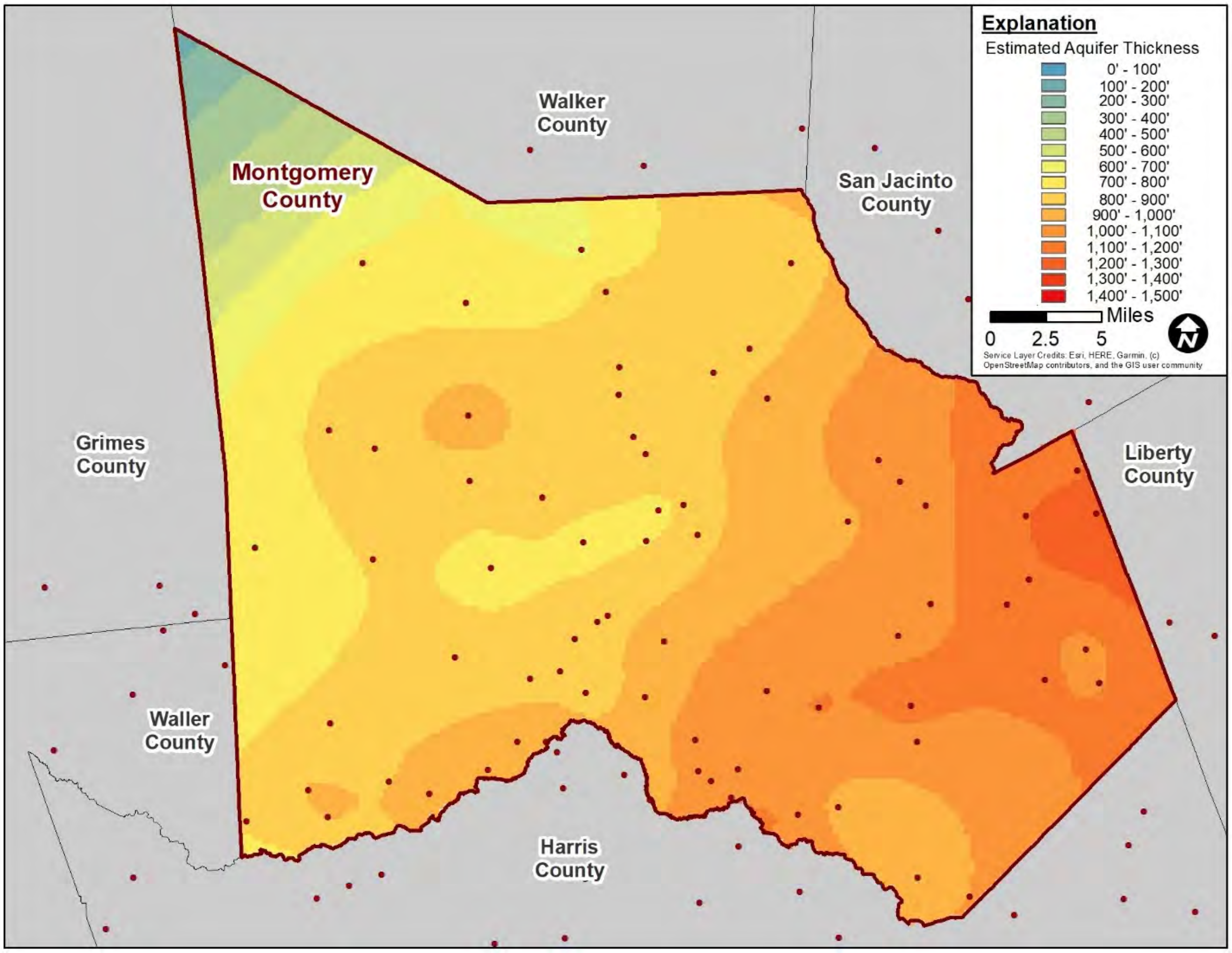

Figure 16. Estimated Total Thickness of the Jasper Aquifer within Montgomery County as the difference between the base of the Burkeville Confining Unit as defined in this study and the base of the Jasper Aquifer as defined by the USGS SWAP Dataset

The estimated thickness of the Jasper Aquifer (combined upper and lower units) based on Popkin (1971) has a substantially greater thickness relative to the estimated thickness using the USGS SWAP Dataset. An estimated thickness for the total Jasper Aquifer based on Popkin (1971) was developed using data assembled for the 2004 LSGCD Groundwater Resources Management Information Report for Montgomery County (Turner Collie & Braden, Inc., 2004). Estimated total Jasper Aquifer thicknesses based on the Popkin (1971) methodology range from approximately 1,490 feet to approximately 3,040 feet in Montgomery County, with an average thickness of about 2,100 feet.

Typical Geophysical Logs

A series of 16 typical geophysical logs have been developed within Montgomery County and areas to the east and southeast of the county boundary to demonstrate the selection of the base of the hydrogeologic units in this study. Figure 17 shows the location of the geophysical type logs and reduced copies of the geophysical logs are included in Appendix B. It should be noted that the estimated bases of the hydrogeologic units are shown in depth below land surface on the geophysical logs in Appendix B.

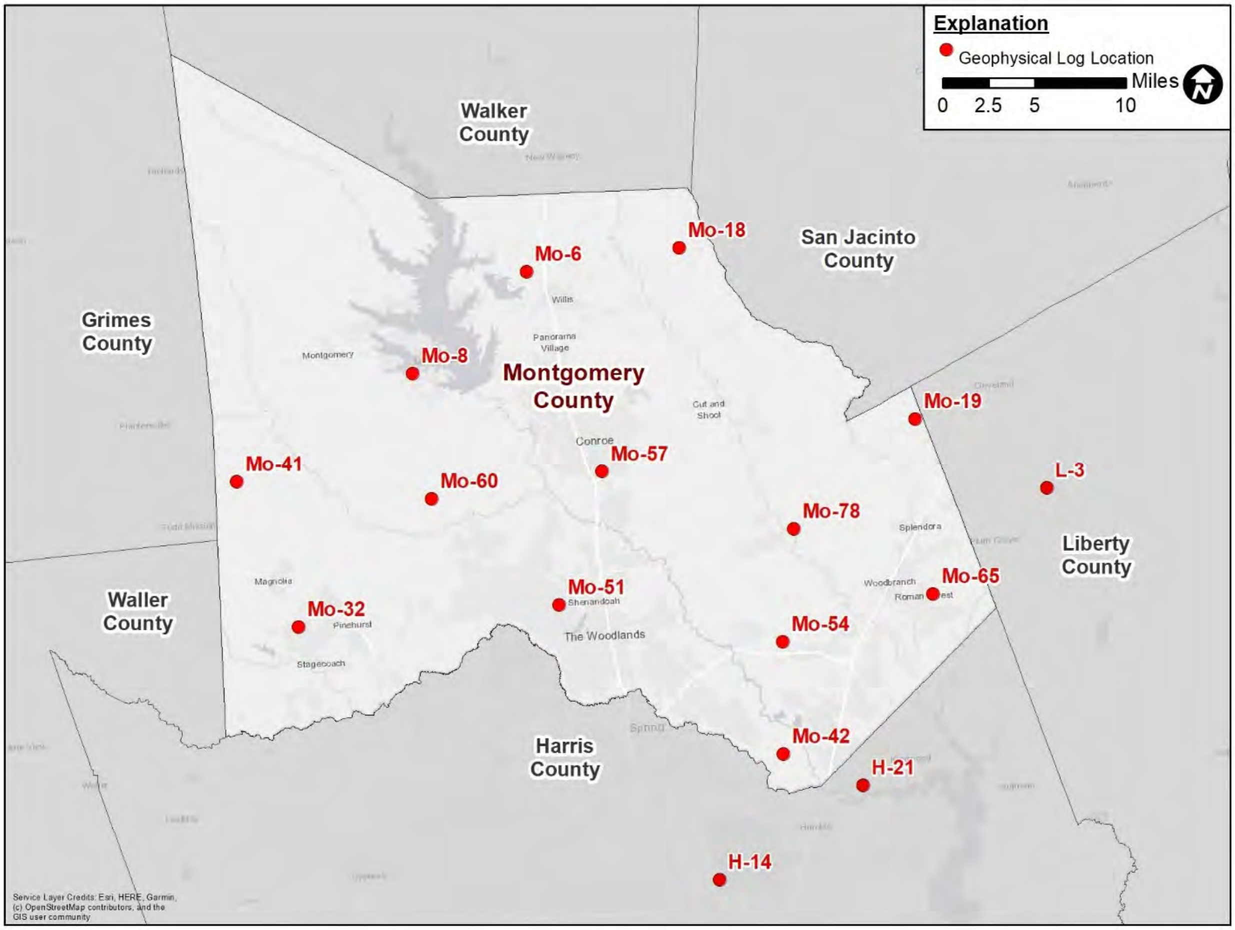

Figure 17. Typical Geophysical Log Locations

The geophysical logs in Appendix B show the estimated base of the Chicot, Evangeline and Upper Jasper aquifers and Burkeville Confining Unit developed for this study, the base of the Jasper Aquifer according to the USGS SWAP Dataset (Strom and others, 2003) and the base of the Lower Jasper Aquifer identified by Popkin (1971).

In this study, the base of the Chicot Aquifer is generally estimated to occur at the base of shallow sands that which have higher resistivity values and limited clay content. The higher resistivity values of the Chicot Aquifer often coincide with lower TDS concentrations in water collected and analyzed from water wells completed in the Chicot Aquifer relative to that of the water samples collected from wells completed in the Evangeline Aquifer.

Also, it should be noted that the base of the Lower Jasper as estimated by Popkin (1971) is significantly deeper than the USGS SWAP base of Jasper estimate that gained acceptance in the early 2010's. In north Montgomery County, some of the sands that are screened in wells completed in the Catahoula Formation were considered to be part of the Lower Jasper according to the base of Lower Jasper / Jasper Aquifer estimated by Popkin (1971).

Gulf 2023 Groundwater Flow Model

In an effort to improve future groundwater availability models of the GCAS, additional stratigraphic and lithologic data beyond the existing Chicot, Evangeline and Jasper aquifers and Burkeville Confining Unit data was developed by Young and others (2012). A lithostratigraphic approach, as defined by Young and others (2012), involves interpolating formation lithologies from geophysical logs and correlating the lithologies between additional geophysical logs (Young and other, 2012). A chronostratigraphic approach and sequence stratigraphy was utilized by Young and others (2012) to identify clay-dominated flooding surfaces of the same age and subsequently subdivide the Chicot, Evangeline and Jasper aquifers and Burkeville Confining Unit into sub-aquifer layers.

As a result of the work performed by Young and others (2012) the Chicot, Evangeline and Jasper aquifers and the Burkeville Confining Unit of the GCAS were subdivided into 10 subunits as follows:

- Chicot Aquifer: 1) Beaumont Clay; 2) Lissie Formation; 3) Willis Formation;
- Evangeline Aquifer: 4) Upper Goliad; 5) Lower Goliad; 6) Upper Lagarto;
- Burkeville Confining Unit: 7) Middle Lagarto;
- Jasper Aquifer: 8) Lower Lagarto; 9) Oakville Formation; and 10) Catahoula Formation

Young and Draper (2020) updated the extent of the Burkeville Confining Unit and the base of the Chicot Aquifer to support the development of the Gulf 2023 groundwater model. The Gulf 2023 groundwater model is a six-layer groundwater flow model that is currently being developed by the USGS for the Harris-Galveston Subsidence District. The following layers are assigned to the Gulf 2023 model: Layer 1 – Alluvium and Beaumont Clay; Layer 2 – Chicot Aquifer; Layer 3 – Evangeline Aquifer; Layer 4 – Burkeville Confining Unit; Layer 5 – Jasper Aquifer; and Layer 6 – Catahoula Formation.

Young and Draper (2020) updated the subdivided formations defined by Young and others in 2012 by adjusting the base of the Chicot Aquifer (top of the Evangeline Aquifer), the top of the Burkeville Confining Unit (base of the Evangeline Aquifer) and the base of the Burkeville Confining Unit (top of Jasper Aquifer) to support the Gulf 2023 model.

Regarding the updated Burkeville Confining Unit utilized in the Gulf 2023 model, Young and Draper (2020) state:

> "Because the Burkeville unit defined by Baker (1979) is a lithostratigraphic unit that is not bounded by isochronous boundaries and exists across the Upper, Middle and Lower Lagarto formations, it cannot be accurately represented by any single chronostratigraphic formation defined by Young and others (2010, 2012). To create a "lithostratigraphic-based" Burkeville Unit from the clays and sand sequences generated by Young and others (2010, 2012), we correlated the sand and clay sequences in the Upper, Middle and Lower Lagarto Formations based on a lithostratigraphic approach. This approach provides a practical integration of the lithostratigraphic and chronostratigraphic approaches to represent the conceptualization by Baker (1979) of the Burkeville Confining Unit."

Young and Draper (2020) indicated that the Willis Formation (base of Chicot Aquifer) was primarily updated to incorporate additional geophysical logs into the analysis, increasing the number of logs used to estimate the base of the Willis Formation from 290 logs to 650 logs with stratigraphic picks. Young and Draper (2020) state:

> "At each geophysical log, the location of the base of the Willis was selected to represent a transition from the sand-rich basal Chicot Aquifer (Willis Formation) to the sand-poor top of the Evangeline. In most of the logs, the adjustment to the previous picks by Young and others (2010, 2012) was less than 100 feet."

Gulf 2023 Hydrogeologic Surface Comparison

The base of the geologic units (with hydrogeologic equivalents) developed by Young and others (2012) and the updated picks of the hydrogeologic units based on Young and Draper (2020) are shown on the typical geophysical log examples included in Appendix B, where available. Hydrogeologic picks approximated from Young and Draper (2020) are noted as the 'Gulf 2023 Dataset' and the geologic formation picks approximated from Young and others (2012) labeled 2012 and include the hydrogeologic unit where applicable.

The picks shown on the geophysical logs in Appendix B were based on common API numbers for geophysical logs used in the Task 2 study and the above referenced reports. The appendices included with Young and others (2012) and Young and Draper (2020) provide the geophysical log API number, datum and the estimated elevation of the hydrogeologic/geologic unit. The geophysical log datum and hydrogeologic/geologic unit elevation were used to convert the elevation of the base of the hydrogeologic/geologic unit to depth below land surface for a cleaner presentation of the picks on the geophysical logs.

Based on a limited number of geophysical logs common between this study and Young and others (2012), the base of the hydrogeologic units selected by Young and others (2012) appears to be generally deeper in the subsurface in the southeast part of Montgomery County relative to this study. The Burkeville Confining Unit/Middle Lagarto as defined in Young and others (2012) include sand intervals that are considered to be part of the Upper Jasper Aquifer in this study. It should be noted that a number of large capacity water wells in Montgomery County that screen sands of the Upper Jasper Aquifer would have been included as part of the Burkeville Confining Unit based on the chronostratigraphic formation picks of Young and others (2012).

Modifications to the Young and others (2012) dataset by Young and Draper (2020) to support the Gulf 2023 model included adjustments to the top and bottom of the Burkeville Confining Unit and the base of the Chicot Aquifer. Young and Draper (2020) used a lithostratigraphic based approach to adjust the Burkeville Confining Unit elevations, which yielded formation picks that are generally similar to the picks defined in this study for most parts of Montgomery County.

A chronostratigraphic approach was utilized by Young and Draper (2020) to update the base of Chicot Aquifer in support of the Gulf 2023 model. The base of the Chicot Aquifer as defined by Young and Draper (2020) is generally deeper than the base of Chicot Aquifer defined in this study and previous work by others and becomes increasingly deeper in the southeast part of Montgomery County. The depth of the estimated base of Chicot Aquifer (Young and Draper, 2020) exhibits larger increases in depth in parts of Liberty and Harris counties based on geophysical logs reviewed within the search area of this study.

The estimated depth of the base of the Chicot Aquifer as defined by Young and Draper (2020) can be significantly deeper in parts of northeast and east Harris County than defined in previous studies. The estimated base of the Chicot Aquifer developed by Young and Draper (2020) can reach depths that are approximately twice as much as previous depth estimates in areas of Harris County.

Gulf 2023 Observation Well Designations

The differences between the estimated aquifer elevations developed in support of the Gulf 2023 model by Young and Draper (2020) and work performed by others can be illustrated by plotting the observation wells used in the development of the USGS 2021 Water-Level Altitude Map Series and highlighting the observation wells that will receive new aquifer designations based on the Gulf 2023 model.

In May 2021, LSGCD received provisional water level data in tabular form that was collected and provided by the USGS (2021b). The provisional table included a column that displayed the newly assigned aquifer designation based on the Young and Draper (2020) dataset. The original aquifer designations available from the USGS National Water information System Web Interface Groundwater Levels for Texas (2021a) were added to the table to allow a comparison of the original and newly assigned aquifer designations. At the time of this study (January 2022), the

USGS water level data appears to still be provisional and unpublished. It is our understanding that the USGS is planning to update the official aquifer designations of observation wells in the greater Houston area next year based on the Gulf 2023 model surfaces.

Figure 18 shows the USGS observation well locations with a newly assigned aquifer designation based on the elevations developed by Young and Draper (2020). Based on the provisional data provided by the USGS in May 2021, it is estimated that approximately 36% (165 out of 458) of the water wells included in the USGS observation program will experience a change in aquifer designation in Montgomery and Harris counties.

Prior to the adoption of the new approach taken in the delineation of the hydrogeologic units for the Gulf 2023 model, a large number of the wells in the USGS observation program had been developed and evaluated over several decades by experienced local USGS technical staff. In addition, the previous/current USGS aquifer data and designations have been reviewed and generally accepted by groundwater engineers, hydrogeologists and consultants with decades of local experience in the greater Houston area, based on assessment of site-specific geophysical logs, well material setting sheets and construction data and well pumping test data. Reassignment of the observation wells may affect conceptual understanding of groundwater flow in the GCAS and ultimately how that flow is simulated in the Gulf 2023 model.

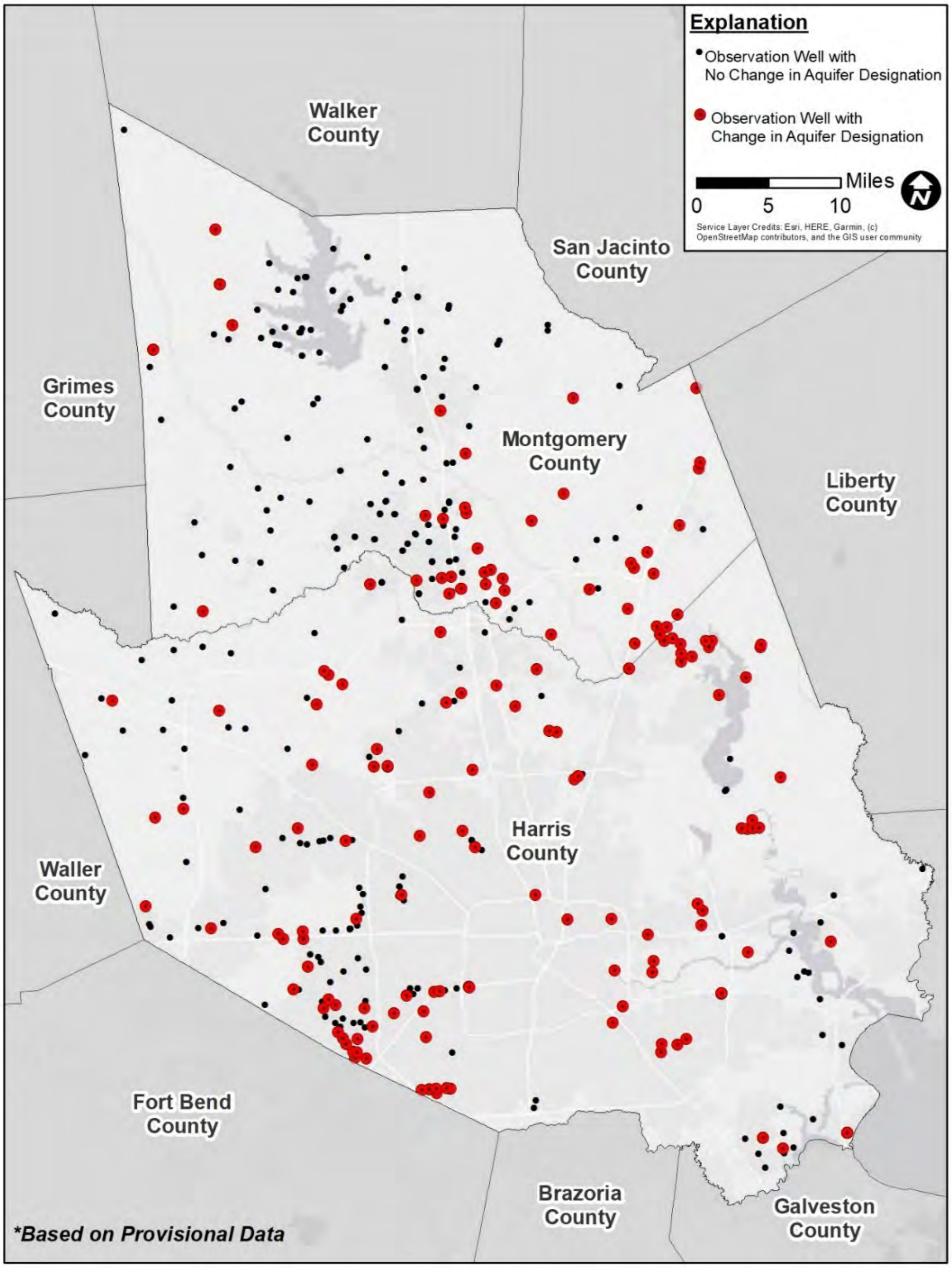

Figure 18. USGS Observation Wells that will be Assigned a New Aquifer Designation based on the Gulf 2023 Groundwater Flow Model (based on provisional data provided by the USGS in May 2021).

Summary of Clay Layer Thickness Based on Geophysical Log Analysis

It has long been understood that most compaction in sediments occurs in layers dominated by clay. Therefore, the thickness of clay layers within aquifers is one key in understanding the amount of subsidence that may occur in areas of groundwater withdrawal. The USGS has produced maps showing cumulative clay thickness for the Chicot, Evangeline and Jasper aquifers across the Houston Area including the entirety of Montgomery County (Kasmarek and Robinson, 2004). Similarly, LSGCD published maps showing the clay thickness for the geologic units that comprise the Chicot, Evangeline and Jasper aquifers, and the Burkeville Confining Unit, all based on GIS operations utilizing datasets by Young and others (2012) (see Thornhill and Keester, 2020).

The USGS conducted some of the definitive work relating to the depth of burial and the compressibility of clay layers in the Chicot and Evangeline aquifers in selected areas of southern Harris County and Galveston County, noting, "The time lag between loading and ultimate consolidation is dependent upon the thickness and permeability of the clay bed" (Gabrysch and Bonnet, 1976). Similarly, INTERA noted the relationship between the fluid-pressure reductions in groundwater producing zones (i.e., sands), the thickness of individual clay beds (sometimes called interbeds), the vertical hydraulic conductivity of the clay layers and the time it takes for compaction to occur (Kelley and others, 2018). Figure 19, reproduced from Kelley and others (2018) illustrates the relationship of the positioning and thickness of clay interbeds and the compaction of a clay layer between aquifer sand zones (i.e., producing zones). INTERA also provided a summary of individual clay-bed thicknesses for selected logs across much of the Houston area including the southern part of Montgomery County from about Lake Conroe to the southern county border (see Kelley and others, 2018).

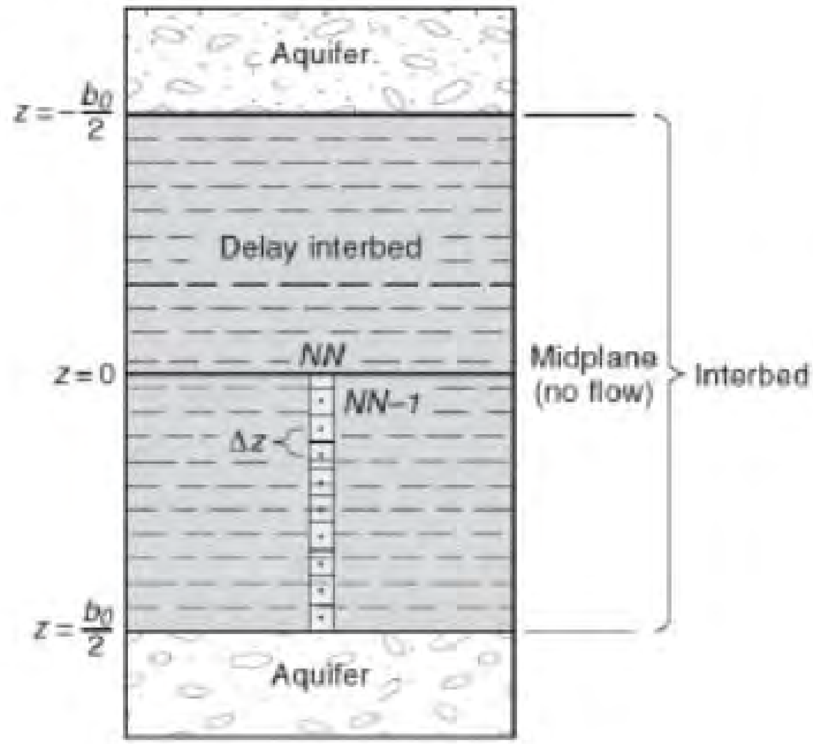

Figure 19. Illustration of the Relationship between the Aquifer Sands and Clay Interbed (reproduced from Kelley and others, 2018).

Work Conducted

There has been no study that has focused on log analysis to determine clay-bed thicknesses and distributions relative to producing intervals (i.e., sands) across all of Montgomery County. Therefore, the work for this section was focused on assessing the distribution and thickness of the clay layers within the formations that comprise the GCAS in Montgomery County. Also, while total clay thickness is important, understanding the vertical and horizontal distributions of clay layers relative to sand zones that are typically screened in water wells within Montgomery County and the region is key. The relationships between the thicknesses of clay layers and the positioning with respect to well-screen intervals can impact the total amount and rate of compaction. Therefore, the work included:

- Obtaining the available geophysical logs for the study area;
- Analyzing the applicable geophysical logs and making picks categorized as sand, silty or clayey sand, silty or sandy clay and clay. For this evaluation to date, zones were categorized as either being "clay" or "sand";

- Evaluating the clay layers for the Chicot, Evangeline and Jasper aquifers, as well as for the Burkeville Confining Unit, with respect to total clay thickness, and average clay-layer thickness; and,

- Selecting potential high production sand intervals and evaluating the clay layers within the interval that would likely be screened in a well, and determining the number of clay interbeds, the total clay thickness, the minimum and maximum clay-bed thicknesses, and average interbed thickness.

Due to the age of the logs available, the clay picks were primarily based on induction (i.e., resistivity) log signatures, although spontaneous potential curves were also assessed. Because of the log resolution, some thicker sequences of clays are likely comprised of multiple layers of thinner beds which cannot be distinguished based on log interpretation alone.

Results of Log Analysis

Figure 20 provides a histogram illustrating the clay-bed thickness distribution by hydrologic unit in Montgomery County. The histogram shows that most clay layers are relatively thin with the Evangeline and Burkeville having generally thicker clay layers than the Chicot and Upper Jasper units.

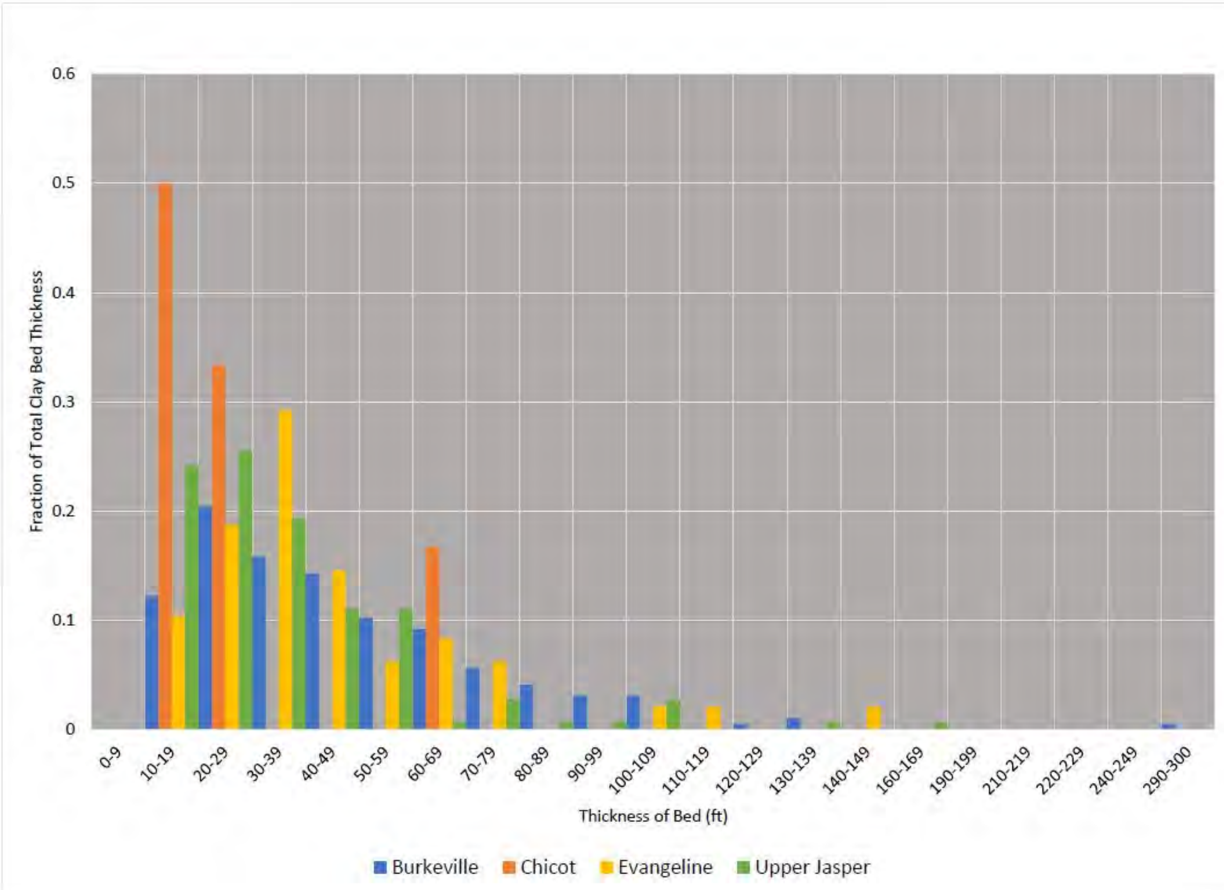

Figure 20. Distribution of Clay Bed Thickness by Hydrogeologic Unit for Montgomery County.

Appendix C provides summary tables characterizing sand and clay layers for seven (7) log sites at locations in Montgomery and Harris counties shown on Figure 21. Comparing original cumulative clay thicknesses presented by Kasmarek and Robinson (2004) with the elevations of this study show that the total clay thickness for the Chicot and Evangeline aquifers are relatively comparable to those determined from the seven (7) logs analyzed for this study. However, since Jasper production within Montgomery and northern Harris counties is almost exclusively limited to the Upper Jasper Aquifer, the clay layers likely affected by depressurization and potential compaction are likely much thinner than the clay thickness of the entire Jasper. Comparing original GAM cumulative clay thickness for the Jasper aquifer as presented by Kasmarek and Robinson (2004) with clay-interbed thicknesses for the seven (7) log sites shows that the GAM Jasper clay thicknesses are 2.3 to 4.9 times thicker than the clay interbeds within likely targeted fresh and brackish groundwater zones in the Upper Jasper.

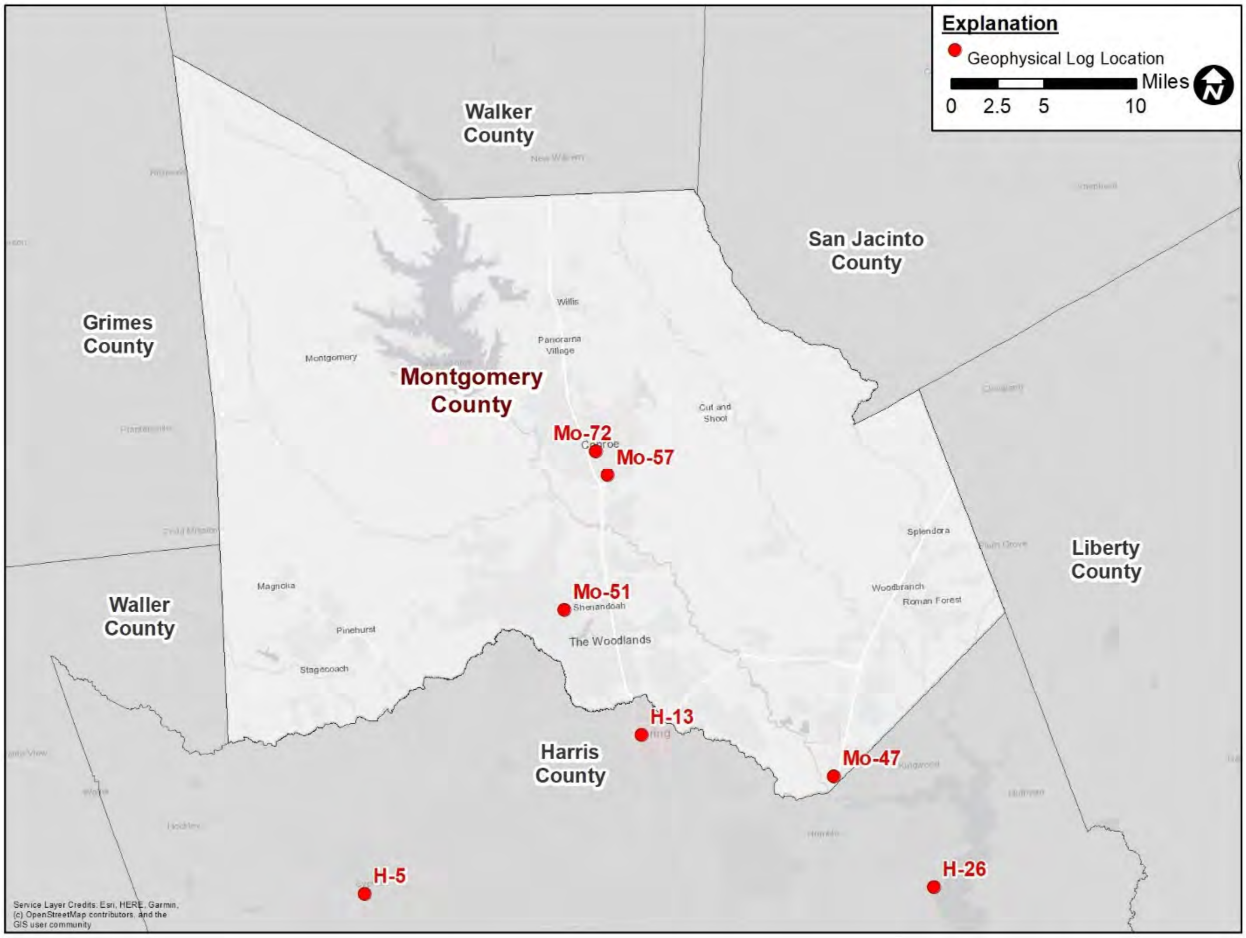

Figure 21. Geophysical Logs Used to Characterize Sand and Clay Layers

Similarly, when considering likely potential target intervals for screening large-capacity water wells the Upper Jasper Aquifer exhibits less cumulative clay and less percentage clay in the targeted producing interval than does the Evangeline Aquifer.

The distribution and thickness of clay layers is critical to understanding the hydraulics, mechanics, magnitude, and timing of compaction and resulting subsidence. Understanding these distributions as related to zones targeted for large-capacity pumping should also be a consideration for future studies and modeling efforts. The information compiled from the log analyses and identifying clay and sand layers will be critical in planning subsequent work including planning drilling, logging and coring efforts.

Summary

- The geology of the GCAS is made up of a complex system of alternating layers of discontinuous sand, silt and clay that increase with depth and thickness while dipping generally south and southeast toward the Gulf of Mexico. It can be difficult to identify the individual geologic units on geophysical logs due to the similarities of sediments within each geologic unit. Historically, the sub-aquifers of the GCAS in Montgomery County and the greater Houston area have been classified by hydrogeologic units and include from shallowest (younger) to deepest (older) the Chicot Aquifer, Evangeline Aquifer, Burkeville Confining Unit, Jasper Aquifer and the Catahoula Formation.

- The principal aquifers that provide groundwater to Montgomery County are the focus of this study and include the Chicot, Evangeline and Jasper aquifers. A limited amount of groundwater is produced from the Catahoula Formation in the north part of Montgomery County but the Catahoula was not discussed at length in this report.

- In this study the Jasper Aquifer was divided into two units based on lithology, the Upper Jasper and the Lower Jasper. The upper part of the Jasper Aquifer can have relatively thick sand beds with moderate electrical resistivity values that typically contain freshwater and are capable of supporting moderate to large capacity water wells in most parts of Montgomery County. The lower part of the Jasper Aquifer contains mostly interbedded sand and clay and the sands contain water with brackish quality, based on relatively low electrical resistivity values. At the time of this study, no wells have been completed in the brackish portion of the Jasper Aquifer. It is our understanding that all registered and permitted wells with the LSGCD that are designated as the Jasper Aquifer are completed in the sands that comprise the upper part of the aquifer.

- Geophysical logs were evaluated to improve the understanding of the depth, thickness and composition of the principal aquifers within Montgomery County. Elevation estimates relative to sea level were developed and mapped for the base of the Chicot, Evangeline and Upper Jasper aquifers and the Burkeville Confining Unit based on the evaluation of many geophysical logs. The base of the Lower Jasper / Jasper Aquifer in this study was defined using the USGS SWAP Dataset (Strom and others, 2003) developed for the base of the Jasper Aquifer, which gained acceptance in Montgomery County during the early 2010's as the Catahoula Formation was being explored as an alternative water resource. It should be noted that the base of the Lower Jasper as defined by Popkin (1971) is substantially deeper than the base of the Jasper Aquifer as defined by the USGS SWAP Dataset (Strom and others, 2003).

- The base of aquifer and confining unit surfaces developed as part of this study provide a general reference for the approximation of the tops and bottoms of the hydrogeologic units in Montgomery County. Site specific conditions may vary from the surfaces developed using the evaluated geophysical logs.

- Young and Draper (2020) used an approach combining the chronostratigraphic and lithostratigraphic methodology to update the hydrogeologic units in support of the development of the Gulf 2023 groundwater flow model. This new combined approach resulted in a generally deeper base of the Chicot Aquifer in Montgomery and surrounding counties compared to the base of Chicot Aquifer as defined in this study and previous work. The lithostratigraphic based approach to adjust the Burkeville Confining Unit elevations yielded formation picks that are generally similar to the picks defined in this study for most parts of Montgomery County. While the Gulf 2023 model will have hydrogeologic surfaces that are delineated differently, the hydrogeologic and subsidence parameters assigned to each model layer will likely influence the performance of the model and its ability to simulate observed aquifer conditions as much or more than the hydrogeologic surfaces developed for the model.

- Because the Jasper production within Montgomery and northern Harris counties is almost exclusively limited to the Upper Jasper aquifer, the clay layers likely affected by depressurization and potential compaction are likely much thinner than the cumulative clay thickness of the entire Jasper. Comparing original GAM cumulative thickness for the Jasper aquifer as presented by Kasmarek and Robinson (2004) with clay-interbed thicknesses for the seven (7) log sites shows that the GAM Jasper thicknesses are 2.3 to 4.9 times thicker than the clay interbeds within likely targeted fresh and brackish water zones in the Upper Jasper. Similarly, when considering likely potential target intervals for screening in large-capacity water wells the Upper Jasper aquifer in almost every case exhibits less cumulative clay and less percentage clay in the interbeds of the targeted producing interval than does the Evangeline Aquifer.

- The distribution and thickness of clay layers is critical to understanding the hydraulics, mechanics, magnitude and timing of compaction and resulting subsidence. Understanding these distributions as related to zones targeted for large-capacity pumping should also be a consideration for all future studies and developing parameters for modeling efforts. The information compiled from the log analyses and identifying clay and sand layers will be critical in planning subsequent work including planning of drilling, logging and coring efforts.

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APPENDIX A

Geophysical Log Data

Geophysical Log Number	API Number, State Well Number and / or Q Number	Company	Well	Latitude	Longitude	Land Surface Elevation (feet)	Base of Chicot Depth (feet, bls)	Base of Evangeline Depth (feet, bls)	Base of Burkeville Depth (feet, bls)	Base of Upper Jasper Depth (feet, bls)	Base of Chicot Elevation (feet, rsl)	Base of Evangeline Elevation (feet, rsl)	Base of Burkeville Elevation (feet, rsl)	Base of Upper Jasper Elevation (feet, rsl)	SWAP Base of Jasper Elevation (feet, rsl)
Mo-1	4233901886	THE PURE OIL CO. & W.T. MORAN CORP.	CENTRAL COAL & COKE 3	30.5159	-95.6830	191	--	--	--	445	--	--	--	-254	-507
Mo-2	4233900966	RED BANK OIL CO.	CENTRAL COAL & COKE	30.4727	-95.6947	334	--	220	280	550	--	114	54	-216	-665
Mo-3	Q-41 / 6036403	STRUM & WOMACK	FOSTER #2	30.4441	-95.6180	191	--	--	335	610	--	66	-144	-419	-905
Mo-4	4233901799	E.L. KURTH TRUSTEE	SOUTHLAND PAPER MILLS 4	30.2492	-95.2027	123	390	1,005	1,260	1,825	-267	-882	-1,137	-1,702	-2,320
Mo-5	Q-197 / 6036304	C.W. CHICK HANSLIP	CRAWFORD #1	30.4756	-95.5294	290	--	--	538	730	--	--	-248	-440	-927
Mo-6	4233900868	SUPERIOR OIL CO AND CARLTON L. SPEED JR.	JAMES SYKES B 1	30.4477	-95.5122	284	--	360	510	820	--	-76	-226	-536	-1,059
Mo-7	4233900980 / 6044101	T. J. WOOD	FULTZ #1	30.3682	-95.5885	210	--	--	--	860	--	--	--	-650	-1,249
Mo-8	4233900979 / 6043304	F. A. CALLERY	WEISINGER 1	30.3707	-95.6197	264	--	330	500	860	--	-66	-236	-596	-1,197
Mo-9	4233930630	CYPRESS ENERGY DEV.	HARPER B. / 1	30.1842	-95.4035	117	--	910	1,190	1,730	--	-793	-1,073	-1,613	-2,149
Mo-10	4233901142	STABLE OIL CO.	JOLKE #1	30.1260	-95.6601	167	--	900	1,190	1,580	--	-733	-1,023	-1,413	-1,970
Mo-11	4233930951	WHITING PETROLEUM CORPORATION	RHODES, W.S. 1801A	30.2653	-95.3500	159	280	810	1,090	--	-121	-651	-931	--	-1,969
Mo-12	4233901930	HUMBLE OIL AND REFINING CO	KATHRYN M. HINES 1	30.2161	-95.3030	124	400	995	1,280	1,835	-276	-871	-1,156	-1,711	-2,224
Mo-13	4233900901	SUNRAY - MIDCONTINENNT OIL CO.	MARGARET SYKES #1	30.3985	-95.5042	339	--	580	790	1,025	126	-241	-451	-686	-1,253
Mo-14	Q-152	HUMBLE OIL REFINING CO.	SO TEX DEV CO 80-A	30.2822	-95.4048	210	290	745	--	--	-80	-535	--	--	-1,810
Mo-15	4233900032	J. A. GRAY	FOSTER LBR. CO. #1	30.2905	-95.2032	123	--	910	1,110	1,520	-135	-787	-987	-1,397	-2,185
Mo-16	4233900097	OHIO OIL CO.	ANDERSON #1	30.3525	-95.4961	203	180	510	780	1,200	23	-307	-577	-997	-1,428
Mo-17	4233900101	COX & CAL-MON OIL CO.	FOSTER #2	30.3413	-95.4872	235	--	600	810	1,320	-5	-365	-575	-1,085	-1,478
Mo-18	4233900045	PHILLIPS PETR. CO.	FRASER #1	30.4613	-95.3718	345	165	550	765	1,070	180	-205	-420	-725	-1,269
Mo-19	4233900013	AMERADA PETR. CO.	FOSTER LUMBER CO. #1	30.3187	-95.1627	155	305	950	1,150	1,480	-150	-795	-995	-1,325	-2,180
Mo-20	4233900082 / 6037803	MORRIS K. WOMACK	HUNT #1	30.3925	-95.4337	265	--	--	815	1,220	87	--	-550	-955	-1,386
Mo-21	4233900079	MORRIS K. WOMACK ETAL	HUTCHINGS SEALY NBT #1	30.3742	-95.3940	253	--	585	825	1,250	--	-332	-572	-997	-1,520
Mo-22	4233900504	CURTIS HANKAMER	FORMAN #1	30.3001	-95.2780	165	--	830	1,100	1,540	-110	-665	-935	-1,375	-1,997
Mo-23	4233900502	W. F. NEWTON	MARSH - RICE UNIVERSITY #1	30.3310	-95.3120	208	--	--	962	1,440	-64	-652	-754	-1,232	-1,826
Mo-24	4233900056	MCCRAY G. / 1	COPANO TRANS	30.4768	-95.4349	272	--	--	--	850	--	--	--	-578	-1,087
Mo-25	4233901713	STANDARD OIL OF TEXAS	DOROTHY ANDERSON 1	30.1707	-95.2957	120	350	1,120	1,360	1,880	-230	-1,000	-1,240	-1,760	-2,388
Mo-26	4233900059	SPILLER J.B. / 1	KINSALA & NEWTON	30.4715	-95.4897	330	--	--	--	860	--	--	--	-530	-1,009
Mo-27	4233900066	ROSE K.G. / 1	THE MORAN CORP.	30.4067	-95.4056	244	--	--	780	1,200	--	--	-536	-956	-1,388
Mo-28	Q-44 / 6043101	O. C. GARVEY AND TODD	MARTIN #1	30.3649	-95.7250	261	--	--	535	760	--	--	-274	-499	-1,094
Mo-29	4233900993	F. A. CALLERY	MARY LENA CASTLE #1	30.3519	-95.6911	393	--	425	700	1,010	--	-32	-307	-617	-1,185
Mo-30	Q-362	FISH OIL AND GAS CO.	BERKLEY & HOGG #1	30.3158	-95.5663	231	--	600	850	1,170	--	-369	-619	-939	-1,476
Mo-31	4233930484	SOUTHLAND ROYALTY COMPANY	GEORGE MITCHELL #1	30.2799	-95.6954	183	--	620	840	1,160	--	-437	-657	-977	-1,463
Mo-32	4233901881	HUMBLE OIL & REFINING CO.	J. W. LEWIS ET AL #1	30.1743	-95.7328	261	220	920	1,190	1,580	41	-659	-929	-1,319	-1,753
Mo-33	4233901102	MITCHELL & MITCHELL	NEIDRAL #1	30.1399	-95.6155	149	--	900	1,180	1,580	--	-751	-1,031	-1,431	-1,982
Mo-34	4233901046	THE GRAY WOLFE CO	PAN-AM 3	30.2131	-95.6788	249	190	885	1,180	--	59	-636	-931	--	-1,712
Mo-35	Q-222 / 6053105	BASSETT S. WINMILL	F.M. YOST ETAL	30.2190	-95.4792	185	--	890	1,140	1,650	--	-705	-955	-1,465	-1,916
Mo-36	4233901420	COFFEE C W	LATZER-LAYTON UNIT 1	30.1271	-95.4482	134	--	1,020	1,370	1,820	--	-886	-1,236	-1,686	-2,251
Mo-37	4233901846	F. S. CROCKETT	BUCK WILLIAMS #1	30.1834	-95.1941	107	--	1,180	1,538	2,100	-333	-1,073	-1,431	-1,993	-2,553
Mo-38	4233900162	HUMBLE OIL AND REFINING CO	O. C. COX 1	30.3043	-95.4794	179	220	690	1,025	1,450	-41	-511	-846	-1,271	-1,607
Mo-39	4233900199	HUMBLE OIL AND RRG. CO	B. D. GRIFFIN B-1	30.2848	-95.4895	160	240	760	1,020	1,470	-80	-600	-860	-1,310	-1,655
Mo-40	4233930558	INDEPENDENT EXPL.	MCCLAIN / 1	30.2021	-95.1622	105	--	1,140	1,600	2,130	--	-1,035	-1,495	-2,025	-2,559
Mo-41	4233930072	GLENN H. MCCARTHY	SAUNDERS GREGG ET AL 1	30.2906	-95.7842	318	--	670	940	1,275	--	-352	-622	-957	-1,352
Mo-42	4233901732	W. O. HEINZE	BENDER #1	30.0586	-95.2960	78	--	1,450	1,920	2,415	-372	-1,372	-1,842	-2,337	-2,748
Mo-43	4233901014	STANOLIND OIL AND GAS CO	H. C. NICHOLS 1	30.1317	-95.7511	229	240	880	1,170	1,680	-11	-651	-941	-1,451	-1,846
Mo-44	4233901739	MOBIL OIL COMPANY	BENDER ESTATE FARM 1	30.1065	-95.3535	100	390	1,220	1,630	2,060	-290	-1,120	-1,530	-1,960	-2,486
Mo-45	4233930521	ALLIED PRODUCTION CORP.	JOHN BIRCH	30.1137	-95.7374	219	230	880	1,220	1,640	-11	-661	-1,001	-1,421	-1,909
Mo-46	4233901079	COAST CO	PITTS AND LYLES 1	30.1351	-95.6901	216	240	930	1,230	1,685	-24	-714	-1,014	-1,469	-1,910
Mo-47	4233901728	D B OIL COMPANY	CLEVELAND W D / 1	30.0448	-95.2575	104	460	1,500	1,970	2,450	-356	-1,396	-1,866	-2,346	-2,868
Mo-48	4233901109	MOBIL OIL CORPORATION	INA ARCENAUX 1	30.2228	-95.5462	194	340	900	1,170	1,630	-146	-706	-976	-1,436	-1,824
Mo-49	4233930003	THE MORAN CORPATION COLUMBIA DRILLING CO.	M AND M MINERALS 1	30.2024	-95.5583	187	320	895	1,190	1,670	-133	-708	-1,003	-1,483	-1,876
Mo-50	4233901954	CYPRUS OIL COMPANY	CHASE MANHATTAN 4	30.1877	-95.5394	173	325	1,015	1,260	1,680	-152	-842	-1,087	-1,507	-1,943
Mo-51	4233901879	ASSOCIATED OIL AND GAS COMPANY	BLANCHE FOLEY EST 1	30.1835	-95.4949	165	--	1,035	1,250	1,730	-145	-870	-1,085	-1,565	-2,012
Mo-52	4233901721	WHIFFEN ESTATES INC.	C. A. WHITE #1	30.1719	-95.3650	100	--	1,035	1,250	1,810	--	-935	-1,150	-1,710	-2,256
Mo-53	4233901779	WILEY CORP.	WILEY #1	30.1337	-95.4575	121	--	930	1,320	1,750	--	-809	-1,199	-1,629	-2,216
Mo-54	4233901718	HUMBLE OIL & REFINING CO.	W. M. WICKIZER	30.1471	-95.2921	120	--	1,200	1,550	2,040	-311	-1,080	-1,430	-1,920	-2,474
Mo-55	4233901743	CORLEY & GEISELMAN	HARVEY P. / 1	30.1156	-95.4337	105	--	1,020	1,310	1,820	--	-915	-1,205	-1,715	-2,309
Mo-56	4.2339E+13	FLEMMING #1	DAVID B. MACDANIEL	30.1128	-95.7983	243	--	890	1,265	1,670	--	-647	-1,022	-1,427	-1,841
Mo-57	4233900202	HUMBLE OIL AND REFINING	GRAND LAKE GAS UNIT 2 WELL 1	30.2875	-95.4508	169	220	720	1,010	1,495	-51	-551	-841	-1,326	-1,706

DRAFT

Geophysical Log Number	API Number, State Well Number and / or Q Number	Company	Well	Latitude	Longitude	Land Surface Elevation (feet)	Base of Chicot Depth (feet, bls)	Base of Evangeline Depth (feet, bls)	Base of Burkeville Depth (feet, bls)	Base of Upper Jasper Depth (feet, bls)	Base of Chicot Elevation (feet, rsl)	Base of Evangeline Elevation (feet, rsl)	Base of Burkeville Elevation (feet, rsl)	Base of Upper Jasper Elevation (feet, rsl)	SWAP Base of Jasper Elevation (feet, rsl)
Mo-58	4233901039	ACCO-ROBERTS & MURPHY COMPANY	M ROBERTS ESTATE / 1	30.2143	-95.6370	220	--	840	1,140	1,530	--	-620	-920	-1,310	-1,764
Mo-59	4233901887	SOCONY MOBIL OIL COMPANY	SEALY-SMITH FOUNDATION / 1	30.3282	-95.6204	227	--	530	750	1,060	--	-303	-523	-833	-1,365
Mo-60	4233930199	LADD PET. CORP.	SEALY & SMITH FDTN. / 2	30.2711	-95.6073	195	--	780	1,030	1,400	--	-585	-835	-1,205	-1,600
Mo-61	4233901734	JACK W. FRAZIER	BENDER #1	30.1029	-95.3838	104	--	1,180	1,450	1,960	-282	-1,076	-1,346	-1,856	-2,439
Mo-62	4233930730	FIRST MATAGORDA CORP	BENDER ESTATES A-2	30.1339	-95.4274	112	360	1,095	1,340	1,850	-248	-983	-1,228	-1,738	-2,267
Mo-63	4233900902	B. B. BURKE	FERGERSON #1	30.3805	-95.5057	307	--	550	790	1,150	100	-243	-483	-843	-1,315
Mo-64	4233900934	HUMBLE O&R CO.	HUMBLE O&R CO.	30.2857	-95.5367	167	190	775	1,010	1,370	-23	-608	-843	-1,203	-1,613
Mo-65	4233901849	ATLANTIC REFINING COMPANY	FOSTER LBR. CO 1	30.1799	-95.1533	105	340	1,180	1,660	2,180	-235	-1,075	-1,555	-2,075	-2,650
Mo-66	4233901113	DAVID L. GORDON	MCMAHAN H.M. / 1	30.2372	-95.5209	182	--	880	1,120	1,610	--	-698	-938	-1,428	-1,802
Mo-67	4233901105	D.L. GORDON TRUST	D.L. GORDON TRUST	30.2334	-95.5288	190	--	880	1,130	1,610	--	-690	-940	-1,420	-1,808
Mo-68	4233930494	AIKMAN PETROLEUM INC	AIKMAN PETROLEUM INC	30.1983	-95.5812	216	310	930	1,220	1,620	-94	-714	-1,004	-1,404	-1,864
Mo-69	4233930097	BINTLIFF DAVID C	BINTLIFF DAVID C	30.1569	-95.5709	160	--	915	1,160	1,680	--	-755	-1,000	-1,520	-1,991
Mo-70	4233901101	SIMONTON & TALLEY	SIMONTON & TALLEY	30.1575	-95.5924	162	--	910	1,180	1,640	--	-748	-1,018	-1,478	-1,963
Mo-71	6062604	LAYNE TEXAS COMPANY	KINGWOOD PLACE #1	30.0706	-95.2620	85	410	1,450	--	--	-325	-1,365	--	--	-2,779
Mo-72	4233900154	HUMBLE OIL AND REFINING COMPANY	CONROE TOWNSITE OIL UNIT 97 1	30.3070	-95.4602	209	218	695	1,010	1,470	-9	-486	-801	-1,261	-1,629
Mo-73	4233900742 / 6046504	HUMBLE OIL & REFINING CO.	MARY A. EMORY #5	30.2921	-95.3369	164	275	855	1,080	1,540	-111	-691	-916	-1,376	-1,903
Mo-74	4233901423	C.W. COFFEY ETAL	BALDWIN BROS #1	30.1540	-95.4586	145	--	980	1,250	1,760	-250	-835	-1,105	-1,615	-2,156
Mo-75	4233901872	TEXACO INCOROATED	B.D. GRIFFIN 1	30.3165	-95.2964	194	280	870	1,070	1,440	-86	-676	-876	-1,246	-1,907
Mo-76	4233901801	E. L. KURTH AND S. W. HENDERSON JR.	SOUTHLAND PAPER MILLS 8	30.2336	-95.2202	119	390	990	1,315	1,830	-271	-871	-1,196	-1,711	-2,333
Mo-77	4233900019	AMERADA PETROLEUM CORPORATION	H. A. GODEJOHN 1	30.2901	-95.1502	155	360	995	1,170	1,550	-205	-840	-1,015	-1,395	-2,297
Mo-78	4233901604 / 6054302	ATLANTIC REFG. CO	SO. TEX. DEVELOPMENT 1	30.2358	-95.2777	130	340	990	1,260	1,830	-210	-860	-1,130	-1,700	-2,207
Wa-1	Q-50	M. H. MARR AND THE MORAN CORRPORATION	KATIE WARD NO 1	30.6477	-95.6329	345	--	--	--	190	--	--	--	155	-122
Wa-2	4247130016	MORAN CORPORATION, THE	CENTRAL COAL AND COKE 9	30.5698	-95.6318	211	--	--	--	390	--	--	--	-179	-394
Wa-3	4247130010	THE MORAN CORP.	CENTRAL COAL & COKE A-2	30.5419	-95.5653	352	--	220	322	564	--	132	30	-212	-617
Wa-4	4247100046	R.W. RAMEY AND TEXMO OIL CO.	TOMY KMEICIK 1	30.5287	-95.4799	349	--	300	370	630	--	49	-21	-281	-818
Wa-5	4247130232 / Q-91	GETTY OIL CO	T.W. KEELAND 1	30.5484	-95.3592	353	--	--	325	770	--	--	28	-417	-990
Wa-6	4247130011	PLACID OIL COMPANY	GIBBS BROS. #2	30.6492	-95.3718	340	--	--	--	240	--	--	--	100	-623
Gr-1	4218530369	ARCO EXPLORATION	CHARLIE ASHORN 1	30.5465	-95.8792	359	--	--	--	190	--	--	--	169	8
Gr-2	4218530009	LONE STAR PRODUCING CO	GOFORTH 1	30.2681	-95.8569	317	120	700	975	1,260	197	-383	-658	-943	-1,392
Gr-3	4218530028	VICTORY PETROLEUM CO.	WILLIAM BLEVINS #1	30.4756	-95.8801	375	--	--	--	370	--	--	-999	5	-317
Gr-4	4218500117	ATLANTIC REFINING CO	E. R. SANDERS 1	30.2695	-95.9437	324	--	610	860	1,040	--	-286	-536	-716	-1,162
Gr-5	4218530056	CHARLES B. MARINO	COWAN-ZOLLMAN 1-6	30.2488	-95.8310	306	--	730	1,090	1,350	--	-424	-784	-1,044	-1,467
SJ-1	4240700031	MIDLAND PRODUCTION CORP AND WOLF'S HEAD	HILL ESTATE 1	30.5096	-95.2884	376	--	535	750	1,010	--	-159	-374	-634	-1,283
SJ-2	4240730059	GLEN ROSE CORP	CENTRAL COAL AND COKE C-1	30.5985	-95.2685	312	--	--	--	830	--	--	--	-518	-1,010
SJ-3	4240730086	HOUSTON PETROLEUM CO	BROWDER-SCOTT UNIT 1	30.5338	-95.3049	273	--	350	455	820	--	-77	-182	-547	-1,160
SJ-4	4240730453	HOUSTON PETROLEUM COMPANY	U.S.A. 1	30.5140	-95.1913	254	--	--	--	865	--	--	--	-611	-1,483
SJ-5	4240730017	CONTINENTAL OIL CO	GIBBS BROTHERS AND COMPANY 1	30.4784	-95.2597	266	95	545	715	995	171	-279	-449	-729	-1,461
SJ-6	4240730018	CONTINENTAL OIL COMPANY	DRUCILLA MAYS, ET AL #1	30.4331	-95.2394	235	--	600	800	1,090	--	-365	-565	-855	-1,665
SJ-7	4240700271	ATLANTIC REFINING CO	R. L. WHITE 1	30.3626	-95.1519	180	255	750	1,010	1,370	-75	-570	-830	-1,190	-2,066
SJ-8	4240700214	AMERADA PETR. CORP AND MID-STATES OIL CORP.	CENTRAL COAL COKE CORP 1	30.3930	-95.1444	151	175	670	900	1,180	-24	-519	-749	-1,029	-1,988
SJ-9	4240700246 / Q-8	MAGNOLIA PETROLEUM COMPANY	HINCHLIFF-SIMS #1	30.4257	-95.1002	187	200	630	900	1,160	-13	-443	-713	-973	-1,962
SJ-10	4240700156 / Q-130	AMERADA PET. CO	FOSTER LBR. CO A-1	30.4572	-95.1749	253	210	560	770	1,012	43	-307	-517	-759	-1,780
L-1	42229105456	WILSON - BROACH CO.	C. M. HIGHTOWER #1	30.3517	-95.0232	156	315	840	1,185	1,460	-159	-684	-1,029	-1,304	-2,349
L-2	4229100008	MILES PRODUCTION CO	HINCHLIFF MRS M P / 1	30.3780	-95.0643	214	--	810	1,030	1,360	--	-596	-816	-1,146	-2,183
L-3	4229105018	HUMBLE OIL AND REFINING COMPANY	B. E. QUINN B-1	30.2592	-95.0455	123	370	1,040	1,310	1,680	-247	-917	-1,187	-1,557	-2,622
L-4	4229131549	GUARDIAN OIL COMPANY	FRIENDSWOOD 1	30.2073	-95.0648	130	--	1,200	1,650	1,970	--	-1,070	-1,520	-1,840	-2,754
L-5	4229102431	ACORN OIL CO.	C.C. BERRY 1	30.2259	-94.9641	115	--	1,260	1,710	2,025	0	-1,145	-1,595	-1,910	-2,909
L-6	4229102483	THE TEXAS CO.	R.B. BALDWIN C-4	30.1114	-94.9689	82	450	--	2,040	2,490	-368	--	-1,958	-2,408	-3,279
L-7	4229132387	ANSCHUTZ EXPLORATION CORPORATION	STORSSER FARMS INC. #1	30.1110	-95.0113	80	420	1,640	2,065	2,510	-340	-1,560	-1,985	-2,430	-3,185
L-8	4229130349	ANDERSON T G	BALDWIN EST / 1	30.2175	-95.0983	89	--	1,120	1,510	1,875	--	-1,031	-1,421	-1,786	-2,647
L-9	4229105450	CENTAUR PETR CORP	M R SCOTT ETAL 1 / 1	30.1399	-94.9297	97	--	1,755	2,400	2,590	--	-1,658	-2,303	-2,493	-3,284
Wal-1	4247330066	STARR OIL & GAS CO.	WILLIAM M. RICE INSTITUTE	30.2147	-95.8099	280	--	790	1,110	1,420	--	-510	-830	-1,140	-1,569
Wal-2	4247330379	HIGH CHAPPARAL OIL COMPANY	COWAN-ZOLLMAN-HIGH CHAPPAR	30.2390	-95.8554	290	--	740	1,080	1,330	--	-450	-790	-1,040	-1,473
Wal-3	4247300029	C. W. WEAVER	STEGER #1	30.1635	-95.9410	300	--	910	1,100	1,480	--	-610	-800	-1,180	-1,522
Wal-4	4247300037	STARR OIL & GAS COMPANY	WILLIAM M. RICE INSTITUTE / 1	30.1977	-95.8802	283	--	785	1,140	1,460	--	-502	-857	-1,177	-1,523
H-1	4220107892	AL A. BROWN	W. P. THOMPSON #1	30.0789	-95.8848	245	--	1,010	1,360	1,800	9	-765	-1,115	-1,555	-1,816
H-2	4220101024	J. M. FLAITZ & R. B. MITCHELL	HAMILTON ESTATE / 1	30.0740	-95.1367	59	--	1,480	2,020	2,510	--	-1,421	-1,961	-2,451	-3,027

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Geophysical Log Number	API Number, State Well Number and / or Q Number	Company	Well	Latitude	Longitude	Land Surface Elevation (feet)	Base of Chicot Depth (feet, bls)	Base of Evangeline Depth (feet, bls)	Base of Burkeville Depth (feet, bls)	Base of Upper Jasper Depth (feet, bls)	Base of Chicot Elevation (feet, rsl)	Base of Evangeline Elevation (feet, rsl)	Base of Burkeville Elevation (feet, rsl)	Base of Upper Jasper Elevation (feet, rsl)	SWAP Base of Jasper Elevation (feet, rsl)
H-3	4220101022	S. & H. OIL & ROYALITY	W. M. ALLAUN	30.0953	-95.1241	105	--	1,510	1,950	2,500	-391	-1,405	-1,845	-2,395	-2,988
H-4	Q-222 / 6059503	THE TEXAS COMPANY	J.E. WILSON #1	30.0749	-95.6986	206	--	1,090	1,420	1,810	--	-884	-1,214	-1,604	-2,061
H-5	4220132375	CARNEGIE FINANCIAL CORP	J A KITZMANN 1A	29.9681	-95.6851	147	550	1,360	1,760	2,150	-403	-1,213	-1,613	-2,003	-2,375
H-6	4220100858	SLICK OIL CORPORATION	PAUL H. JACKSON 1	30.0288	-95.5628	143	480	1,190	1,485	2,030	-337	-1,047	-1,342	-1,887	-2,306
H-7	4220101017	STARR OIL & GAS COMPANY	LEANDER WALKER / 1	30.0030	-95.3174	91	--	1,480	1,920	2,470	--	-1,389	-1,829	-2,379	-2,878
H-8	4220101014	ALLDAY & TAYLOR	#1 DULANEY	30.0217	-95.3572	74	--	1,310	1,690	2,270	-426	-1,236	-1,616	-2,196	-2,740
H-9	4220100717	SOUTHERN UNION GAS COMPANY	WM. HOLDREITH 1	30.1500	-95.5629	135	310	990	1,190	1,645	-175	-855	-1,055	-1,510	-2,018
H-10	4220100794	R.W. RAMEY	W.T. JONES #2	30.1263	-95.5593	166	390	992	1,315	1,740	-224	-826	-1,149	-1,574	-2,083
H-11	4220100882	R. D. SIMONTON	HIEDAN 1	30.0104	-95.5402	130	--	1,212	1,565	2,170	-510	-1,082	-1,435	-2,040	-2,413
H-12	4220100964	FALCON SEABOARD DRILLING COMPANY	HUGO LEMM / 1	30.0529	-95.3851	104	--	1,230	1,608	2,080	--	-1,126	-1,504	-1,976	-2,589
H-13	4220131542	HAMMAN OIL & REFINING COMPANY	R. D. SMITH / 1	30.0836	-95.4293	117	--	1,200	1,430	1,990	--	-1,083	-1,313	-1,873	-2,412
H-14	4220102972	UNION PRODUCING COMPANY	DEUTSER 1	29.9615	-95.3589	70	500	1,510	2,000	2,450	-430	-1,440	-1,930	-2,380	-2,918
H-15	4220102680	TEXAS STATE DRILLING COMPANY	FLEMING 1	29.9134	-95.4005	57	510	1,690	2,150	2,340	-453	-1,633	-2,093	-2,283	-2,973
H-16	4220103001	J. BRIAN EBY	CLAUD B. HAMILL 1	29.9171	-95.3277	66	570	1,680	2,190	2,510	-504	-1,614	-2,124	-2,444	-3,116
H-17	4220132052	MARSHALL, A.B.	MARSHALL, A.B. FEE 25	29.9015	-95.2854	70	600	1,760	2,290	2,575	-530	-1,690	-2,220	-2,505	-3,254
H-18	4220102983	MCDANNALD OIL CO.	MCDANNALD FEE 1	29.9321	-95.2583	70	610	1,740	2,260	2,585	-540	-1,670	-2,190	-2,515	-3,216
H-19	4220100991	SOHIO PETROLEUM COMPANY	H. KOTHMAN / 1	30.0484	-95.4604	110	--	1,145	1,510	2,095	--	-1,035	-1,400	-1,985	-2,453
H-20	4220132489	DAN A. HUGHES COMPANY	WRIGHTSTONE UNIT / 1	30.0668	-95.5458	149	--	1,090	1,415	1,855	--	-941	-1,266	-1,706	-2,234
H-21	4220107603	HUMBLE OIL AND REFINING COMPANY	FOSTER LUMBER CO 2	30.0315	-95.2249	70	475	1,540	1,950	2,500	-405	-1,470	-1,880	-2,430	-2,978
H-22	4220101032	HUMBLE OIL AND REFINING COMPANY	FOSTER LUMBER COMPANY 1	30.0388	-95.1419	52	410	1,645	1,965	2,535	-358	-1,593	-1,913	-2,483	-3,127
H-23	4220100709	GORDON STREET INC	FINGER / 1	30.0269	-95.6154	148	--	1,200	1,690	2,030	--	-1,052	-1,542	-1,882	-2,281
H-24	4220101065	PLACID OIL COMPANY	MRS. D.F. SMITH 1	30.0284	-95.0890	80	500	--	2,260	2,700	-420	--	-2,180	-2,620	-3,269
H-25	4220132265	ARKLA EXPLORATION CO	THARP ESTATE 2	29.9972	-95.0856	67	500	1,800	2,310	2,715	-433	-1,733	-2,243	-2,648	-3,368
H-26	4220102720	CHARLES B. WRIGHTSMAN	HARRIS COUNTY LAND AND IMPRO	29.9548	-95.1717	59	550	1,855	2,310	2,620	-491	-1,796	-2,251	-2,561	-3,321
H-27	4220131572	DURANGO EXPLORATION	RAINES 1	30.0463	-95.9069	247	--	1,260	1,530	1,950	--	-1,013	-1,283	-1,703	-1,861
H-28	4220104295	J. F. CORLEY	WARREN RANCH / 1	29.9914	-95.8508	201	--	1,450	1,865	2,275	--	-1,249	-1,664	-2,074	-2,076
H-29	4220100476	CARNES W. WEAVER	KITZMANN / 1	30.0169	-95.7225	169	--	1,210	1,600	2,010	--	-1,041	-1,431	-1,841	-2,186
H-30	4220100090	M. E. ANDREWS & KIRBY SOUTHWORTH DRILLING	A. A. FROENAIEN #1	30.0686	-95.7228	211	--	1,100	1,490	1,840	-89	-889	-1,279	-1,629	-2,048
H-31	4220103517	M. P. S. PRODUCTION COMPANY	JOYCE BURG / 1	29.9972	-95.6226	143	--	1,270	1,765	2,140	-308	-1,127	-1,622	-1,997	-2,368
H-32	4220100809	RAMEY & MOSBACHER	PEDEN ET AL #1	30.1336	-95.5133	128	--	982	1,310	1,770	-252	-854	-1,182	-1,642	-2,128
H-33	422010078	HARRELL OIL COMPANY	HILDERBRANDT G. / 1	30.1164	-95.4948	112	--	990	1,340	1,815	--	-878	-1,228	-1,703	-2,203
H-34	4220130640	MCCORMICK OIL & GAS CORP.	GERALD O. NICHOLS ET AL / 1	30.0608	-95.7479	216	--	1,200	1,550	1,880	--	-984	-1,334	-1,664	-2,036

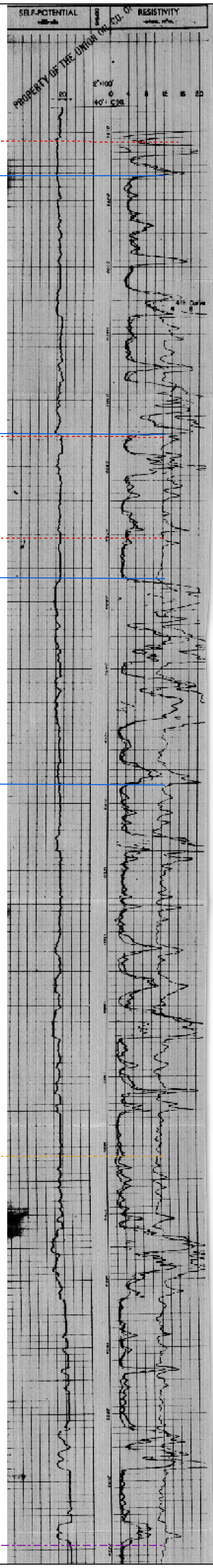
APPENDIX B

Typical Geophysical Logs

Mo-18
Phillips Petroleum Company
Fraser #1
42-339-00045

Approximate Base of Chicot
(Gulf 2023 Dataset)

Estimated Base of Chicot



Estimated Base of Evangeline

Approximate Base of Evangeline
(Gulf 2023 Dataset)

Approximate Base of Burkeville
(Gulf 2023 Dataset)

Estimated Base of Burkeville

Estimated Base of Upper Jasper

Approximate Base of Jasper
(SWAP Dataset)

Approximate Base of Lower Jasper
(Popkin 1971)

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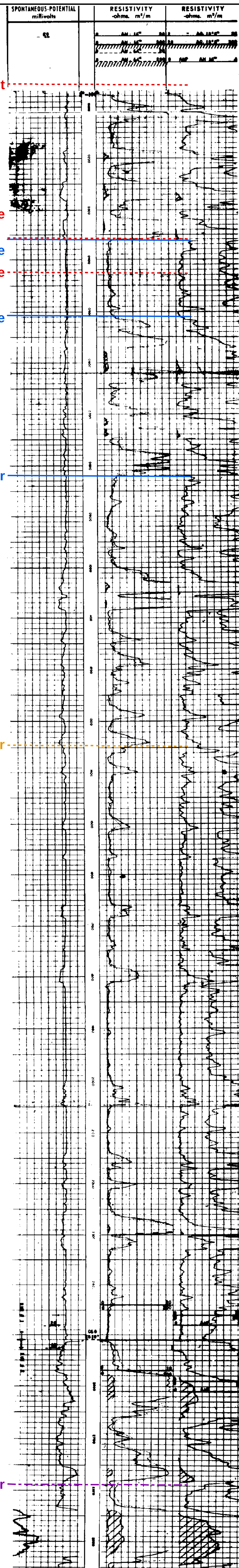
Mo-6
Superior Oil and Speed Jr.
James Sykes B1
42-339-00868



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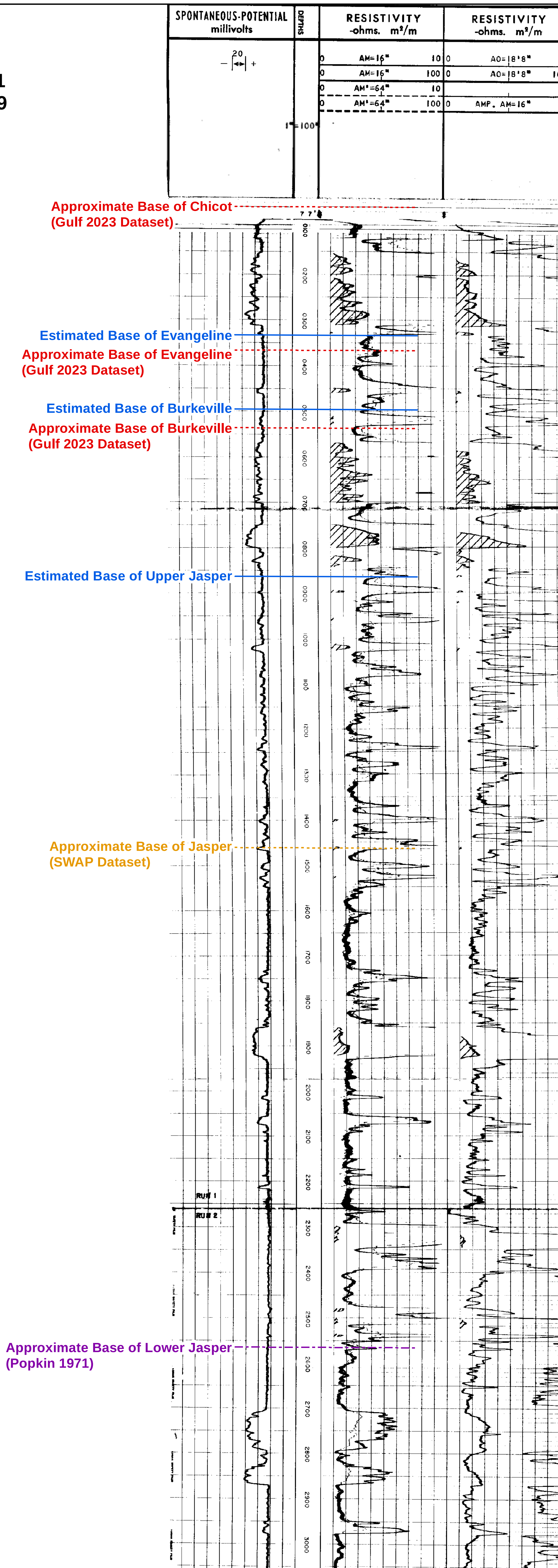
Mo-8
F. A. Callery
Weisinger #1
42-339-00979



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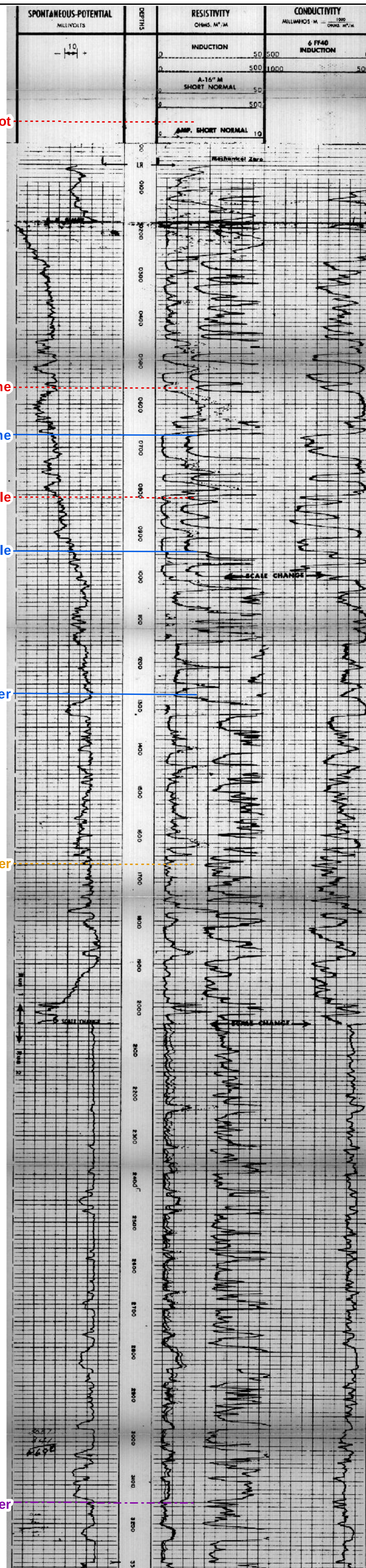
Mo-41
Glenn H. McCarthy
Saunders Gregg et al #1
42-339-30072



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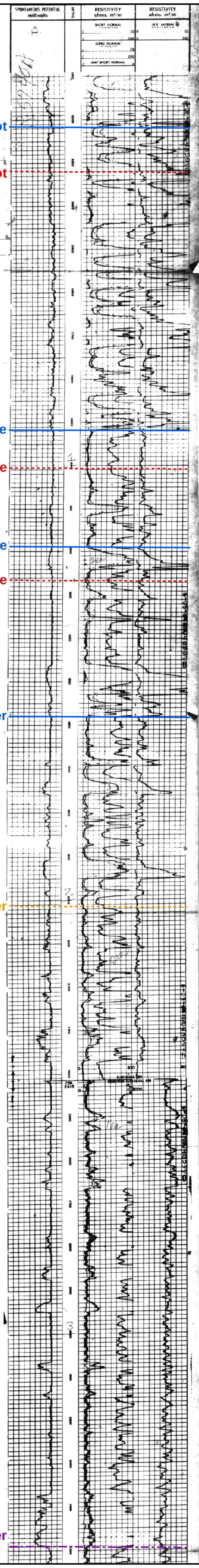
Mo-32
Humble Oil & Refining Company
J.W. Lewis et al #1
42-339-01881



Estimated Base of Chicot

Approximate Base of Chicot
(Gulf 2023 Dataset)

Estimated Base of Evangeline

Approximate Base of Evangeline
(Gulf 2023 Dataset)

Estimated Base of Burkeville

Approximate Base of Burkeville
(Gulf2023 Dataset)

Estimated Base of Upper Jasper

Approximate Base of Jasper
(SWAP Dataset)

Approximate Base of Lower Jasper
(Popkin 1971)

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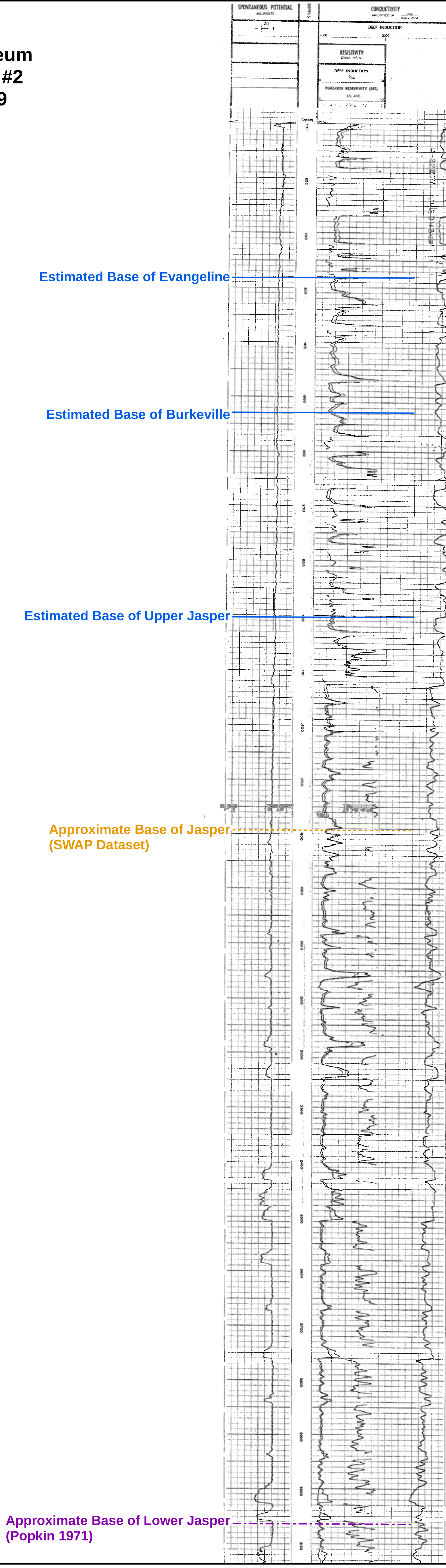
Mo-60
Ladd Petroleum
Sealy Smith #2
42-339-30199



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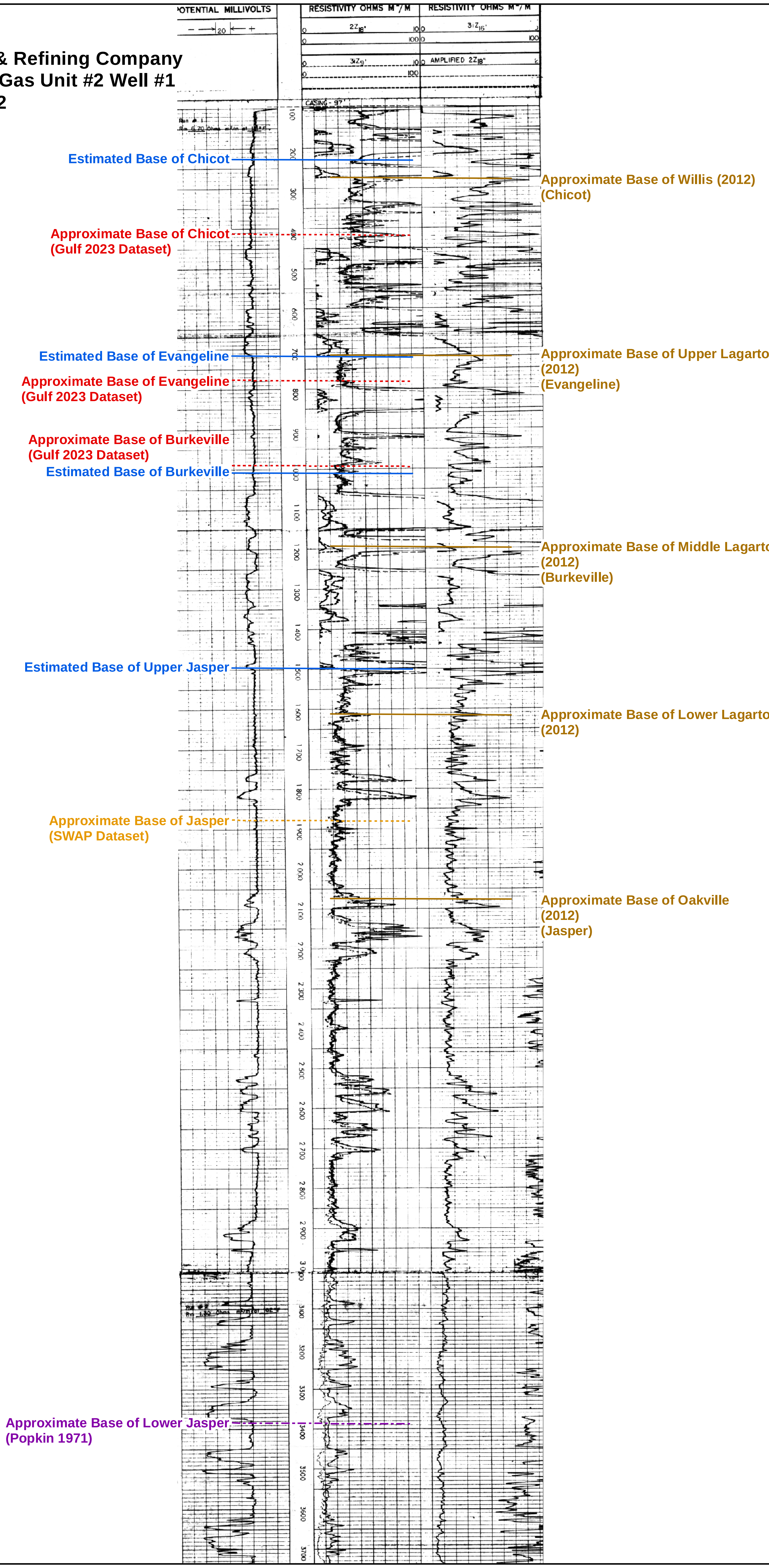
Mo-57
Humble Oil & Refining Company
Grand Lake Gas Unit #2 Well #1
42-339-00202



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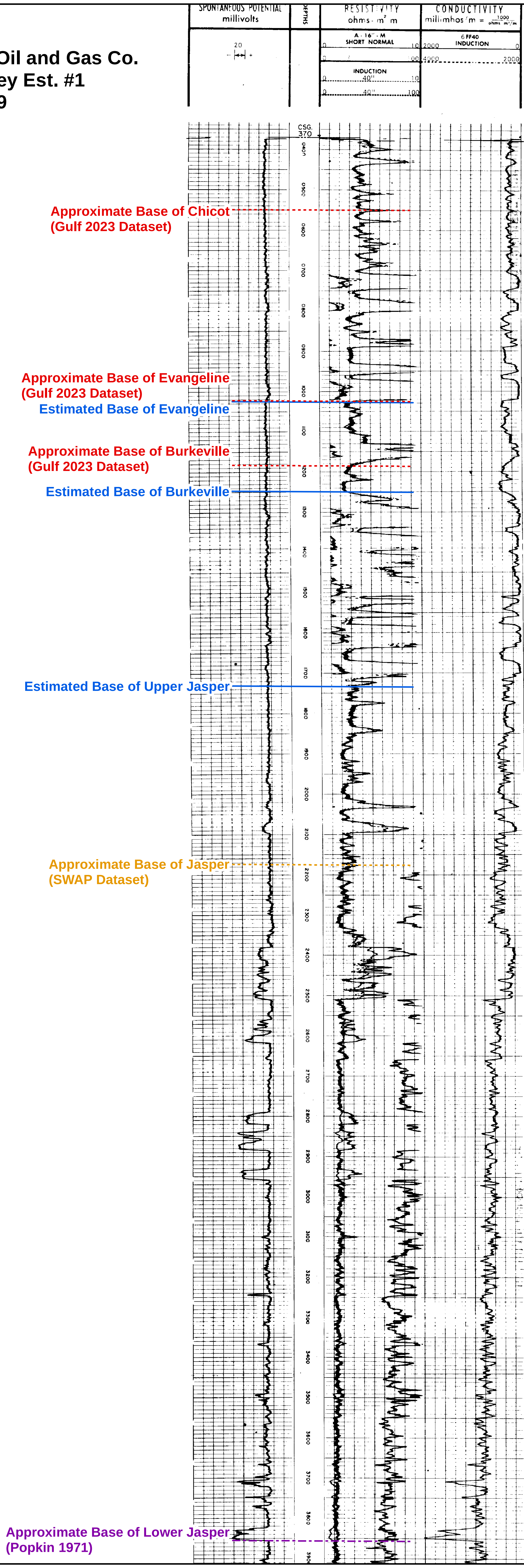
Mo-51
Associated Oil and Gas Co.
Blanche Foley Est. #1
42-339-01879



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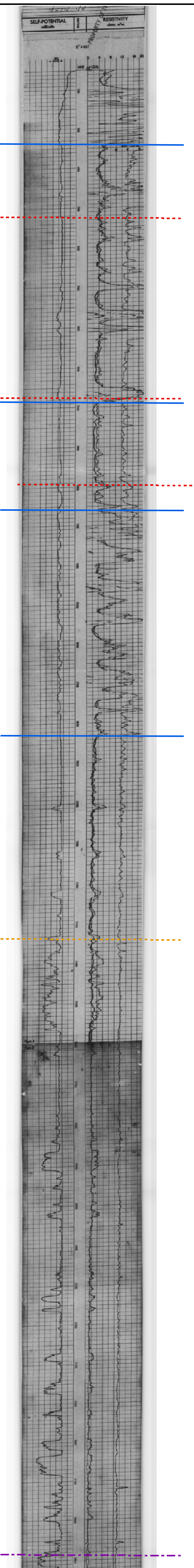
Mo-78
Atlantic Refining Company
S. Texas Development #1
42-339-01604



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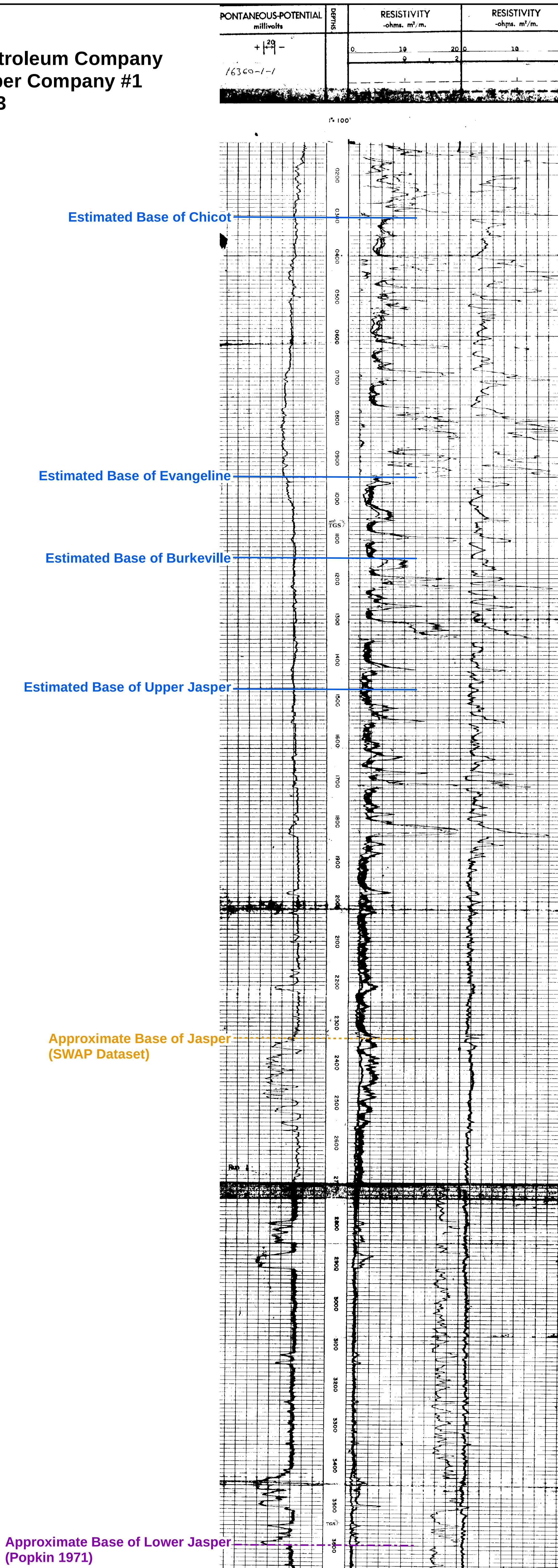
Mo-19
Amerada Petroleum Company
Foster Lumber Company #1
42-339-00013



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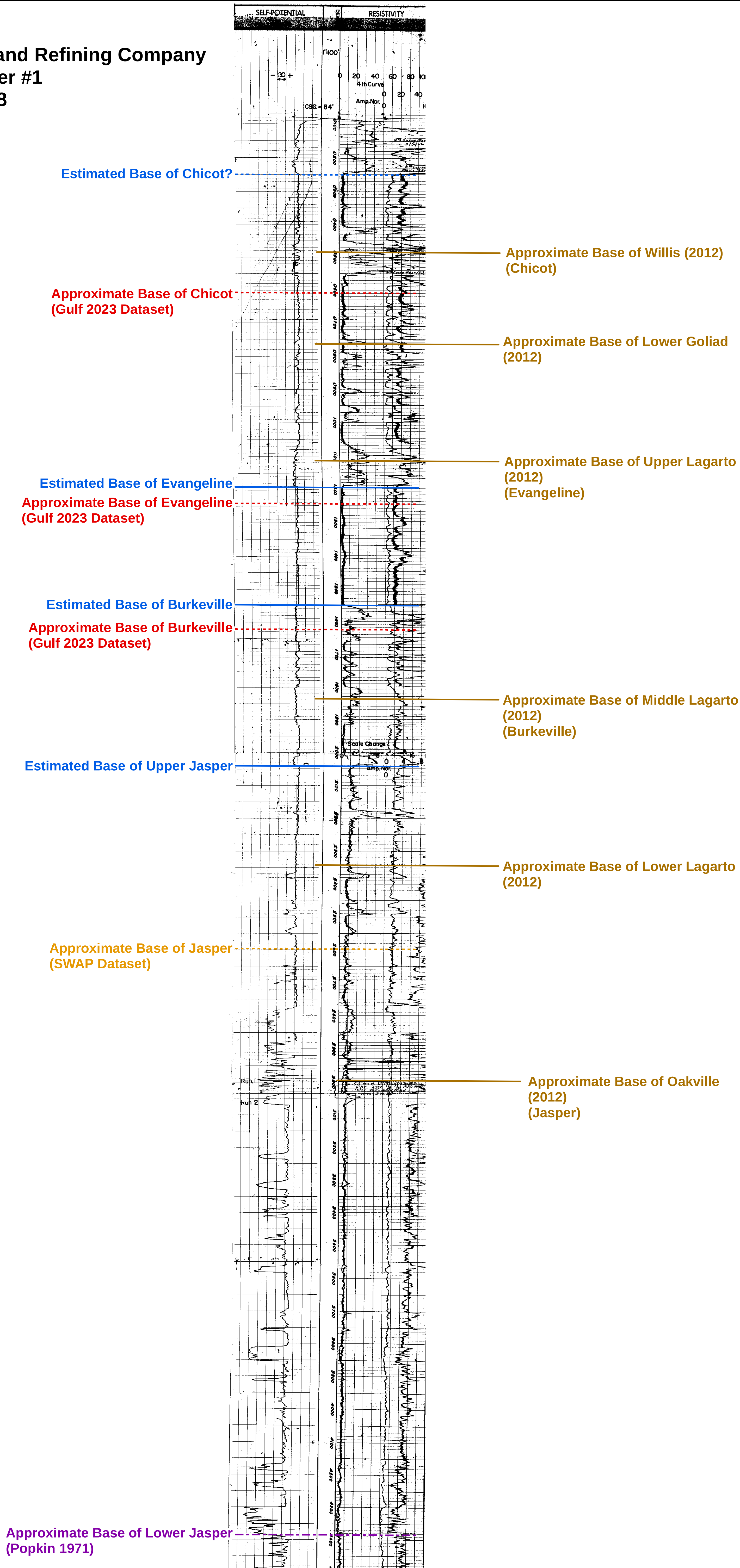
Mo-54
Humble Oil and Refining Company
W.W. Wickizer #1
42-339-01718



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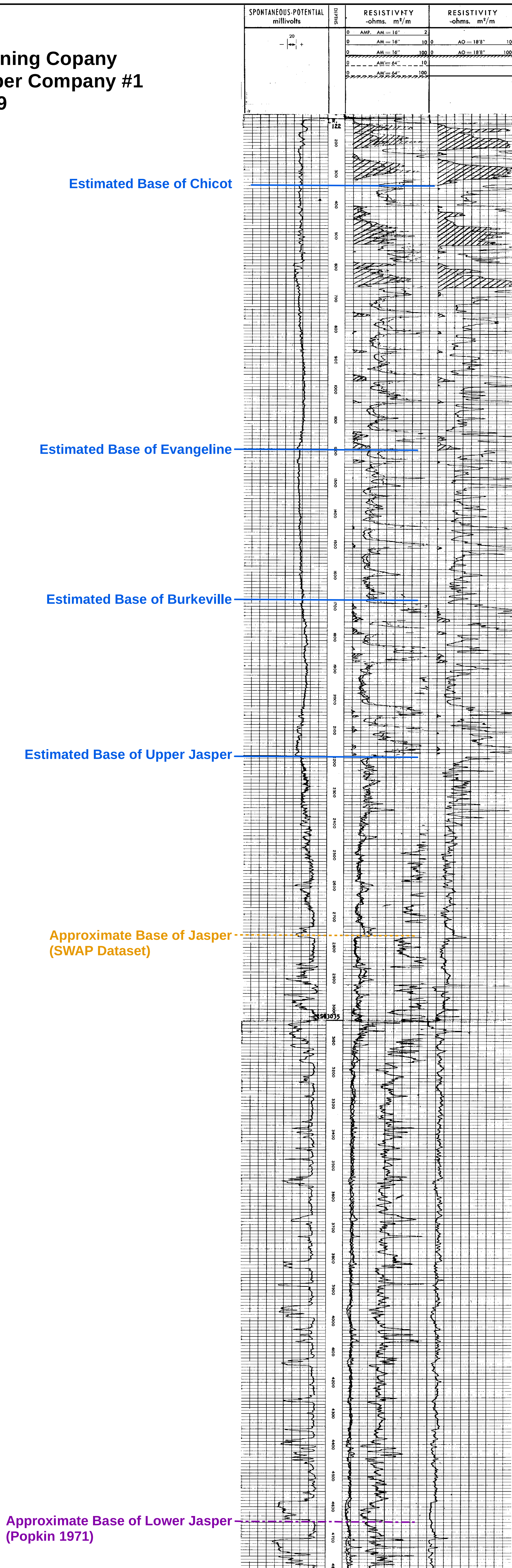
Mo-65
Atlantic Refining Copany
Foster Lumber Company #1
42-339-01849



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Bender #1
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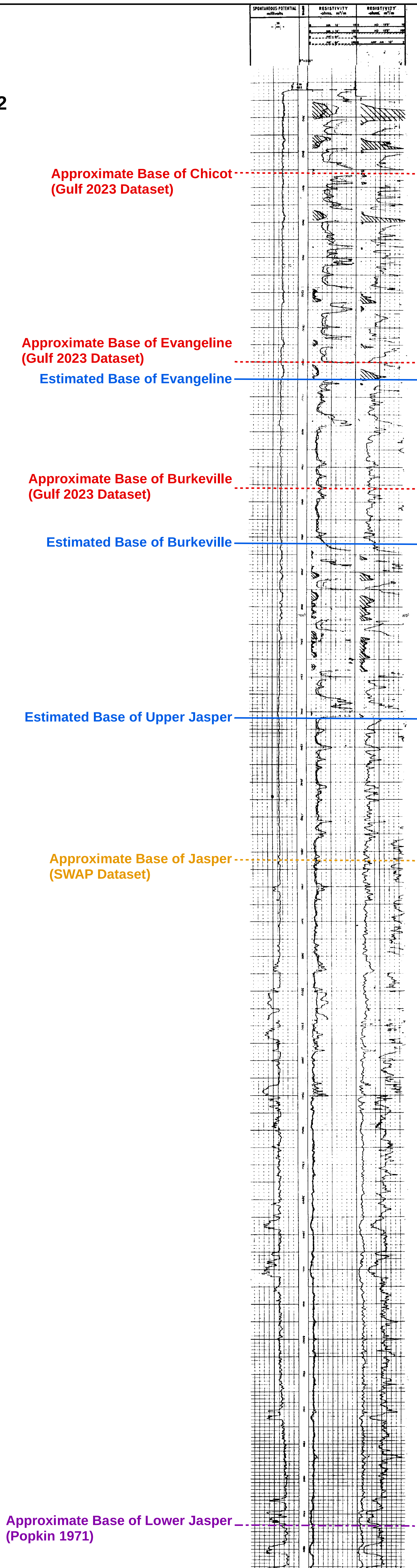

DRAFT

L-3
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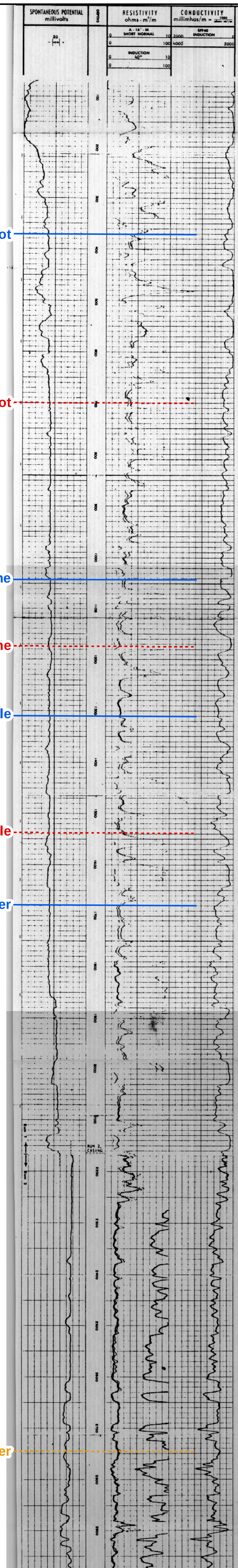
B.E. Quinn #B-1
42-291-05018



Estimated Base of Chicot

Approximate Base of Chicot
(Gulf 2023 Dataset)

Estimated Base of Evangeline

Approximate Base of Evangeline
(Gulf 2023 Dataset)

Estimated Base of Burkeville

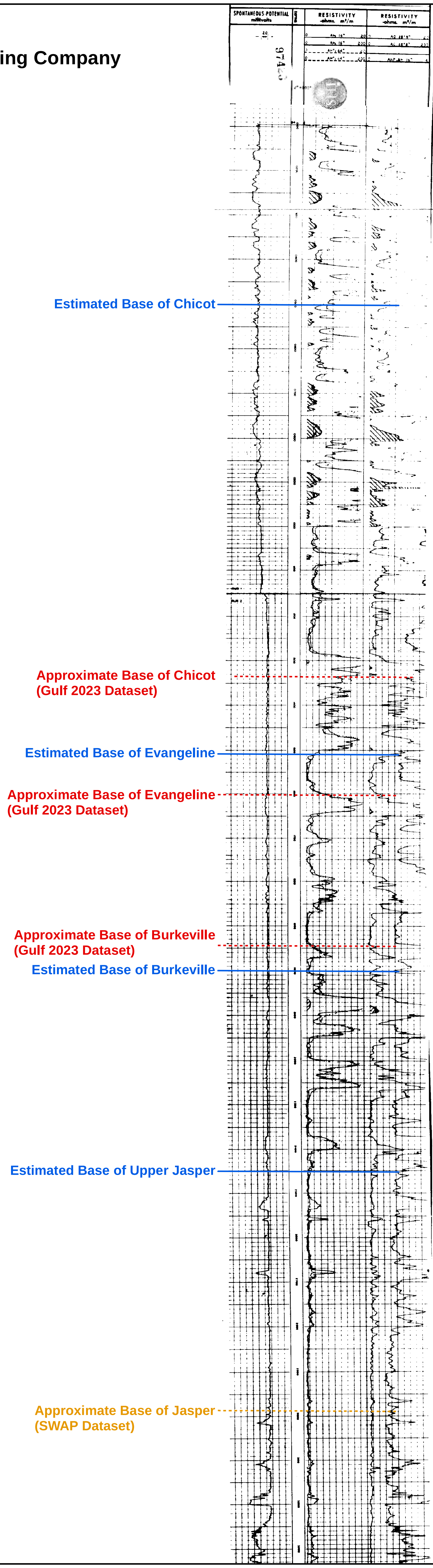
Approximate Base of Burkeville
(Gulf 2023 Dataset)

Estimated Base of Upper Jasper

Approximate Base of Jasper
(SWAP Dataset)

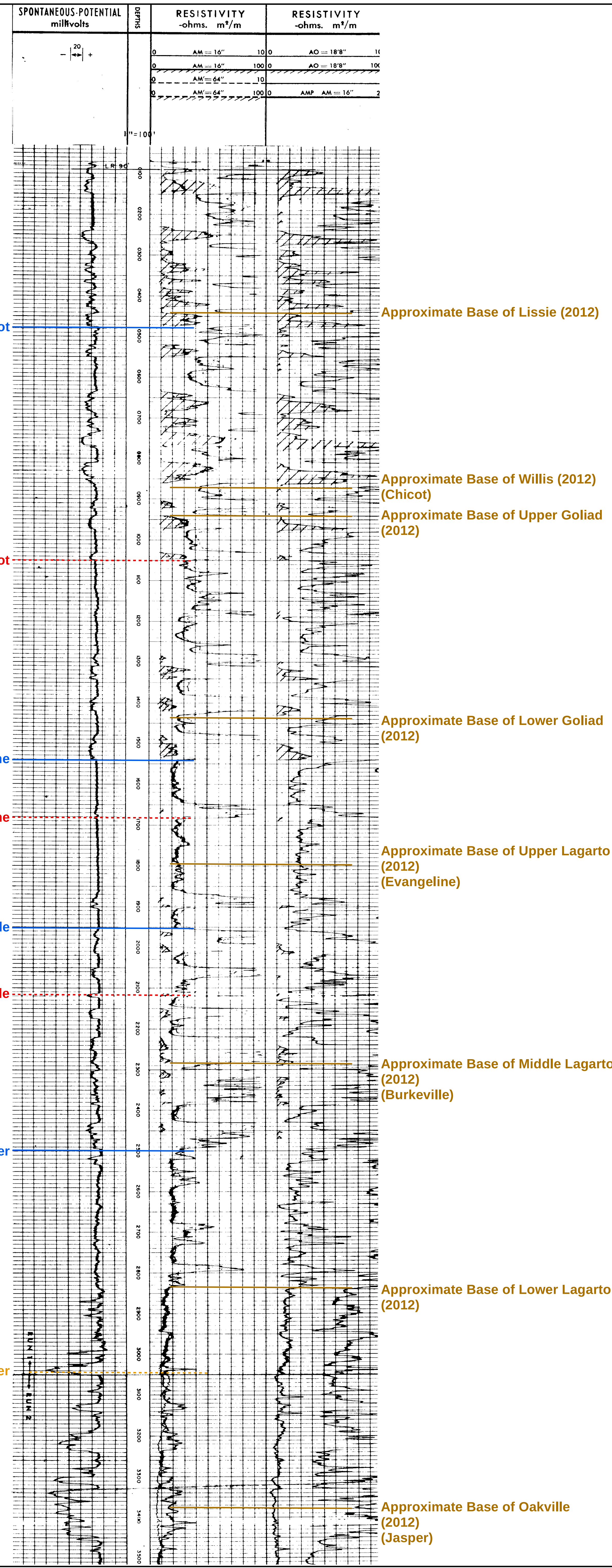
DRAFT

H-14
Union Producing Company
Deutser #1
42-201-02972



DRAFT

H-21
Humble Oil & Refining Company
Foster Lumber Company #2
42-201-07603



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APPENDIX C

Clay Layers Summary

Appendix C - 1
Clay Layers Summary
Geophysical Log: Mo-47

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Inverval			
Total Interval Thickness	>387 feet*	1,040 feet	470 feet	480 feet
Total Clay Thickness	>199 feet	650 feet	56 feet	162 feet
Total Sand Thickness	>188 feet	390 feet	414 feet	318 feet
Percent Clay	~51 percent	63 percent	88 percent	34 percent
Percent Sand	~49 percent	37 percent	12 percent	66 percent
	Potential High Producing Interval			
Number of Producing Intervals	1	1	0	1
Producing Interval Thickness	240 feet	400 feet	NA	480 feet
Net Clay Thickness	92 feet	180 feet	NA	162 feet
Net Sand Thickness	148 feet	220 feet	NA	318 feet
Percent Clay	38 percent	45 percent	NA	34 percent
Percent Sand	62 percent	55 percent	NA	66 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	6	8	NA	8
Minimum Thickness	5 feet	5 feet	NA	5 feet
Maximum Thickness	30 feet	110 feet	NA	55 feet
Average Thickness	15 feet	23 feet	NA	20 feet

Appendix C - 2
Clay Layers Summary
Geophysical Log: Mo-51

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	UTD*	>665 feet*	233 feet	475 feet
Total Clay Thickness	UTD*	>447 feet*	185 feet	128 feet
Total Sand Thickness	UTD*	>218 feet*	48 feet	347 feet
Percent Clay	UTD*	~67 percent*	21 percent	27 percent
Percent Sand	UTD*	~33 percent*	79 percent	73 percent
	Potential High Production Intervals			
Number of Producing Intervals	UTD*	1	0	1
Producing Interval Thickness	UTD*	312 feet	NA	475 feet
Net Clay Thickness	UTD*	143 feet	NA	128 feet
Net Sand Thickness	UTD*	169 feet	NA	347 feet
Percent Clay	UTD*	46 percent	NA	27 percent
Percent Sand	UTD*	54 percent	NA	73 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	UTD*	4	NA	9
Minimum Thickness	UTD*	10 feet	NA	3 feet
Maximum Thickness	UTD*	68 feet	NA	30 feet
Average Thickness	UTD*	36 feet	NA	14 feet

Appendix C - 3
Clay Layers Summary
Geophysical Log: Mo-57

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	UTD*	500 feet	290 feet	485 feet
Total Clay Thickness	UTD*	245 feet	200 feet	150 feet
Total Sand Thickness	UTD*	255 feet	90 feet	335 feet
Percent Clay	UTD*	49 percent	69 percent	31 percent
Percent Sand	UTD*	51 percent	31 percent	69 percent
	Potential High Production Intervals			
Number of Producing Intervals	UTD*	1	0	1
Producing Interval Thickness	UTD*	270 feet	65 feet	435 feet
Net Clay Thickness	UTD*	110 feet	63 feet	100 feet
Net Sand Thickness	UTD*	160 feet	2 feet	335 feet
Percent Clay	UTD*	41 percent	97 percent	23 percent
Percent Sand	UTD*	59 percent	3 percent	77 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	UTD*	6	1	4
Minimum Thickness	UTD*	5 feet	2 feet	5 feet
Maximum Thickness	UTD*	44 feet	2 feet	40 feet
Average Thickness	UTD*	18 feet	2 feet	25 feet

Appendix C - 4
Clay Layers Summary
Geophysical Log: Mo-72

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	UTD*	477 feet	315 feet	460 feet
Total Clay Thickness	UTD*	277 feet	236 feet	155 feet
Total Sand Thickness	UTD*	200 feet	79 feet	305 feet
Percent Clay	UTD*	58 percent	25 percent	34 percent
Percent Sand	UTD*	42 percent	75 percent	66 percent
	Potential High Production Intervals			
Number of Producing Intervals	UTD*	1	0	1
Producing Interval Thickness	UTD*	115 feet	NA	350 feet
Net Clay Thickness	UTD*	16 feet	NA	90 feet
Net Sand Thickness	UTD*	99 feet	NA	260 feet
Percent Clay	UTD*	14 percent	NA	26 percent
Percent Sand	UTD*	86 percent	NA	74 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	UTD*	4	NA	5
Minimum Thickness	UTD*	2 feet	NA	3 feet
Maximum Thickness	UTD*	8 feet	NA	40
Average Thickness	UTD*	4 feet	NA	18 feet

Appendix C- 5
Clay Layers Summary
Geophysical Log: H-5

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	550 feet	810 feet	400 feet	390 feet
Total Clay Thickness	>146 feet	528 feet	346 feet	209 feet
Total Sand Thickness	>404 feet	282 feet	54 feet	181 feet
Percent Clay	~27 percent	65 percent	86 percent	54 percent
Percent Sand	~73 percent	35 percent	14 percent	46 percent
	Potential High Production Intervals			
Number of Producing Intervals	1	1	0	1
Producing Interval Thickness	290	275 feet	NA	220 feet
Net Clay Thickness	93 feet	139 feet	NA	84 feet
Net Sand Thickness	197 feet	136 feet	NA	136 feet
Percent Clay	32 percent	51 percent	NA	38 percent
Percent Sand	68 percent	49 percent	NA	62 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	7	10	NA	7
Minimum Thickness	2 feet	2 feet	NA	3 feet
Maximum Thickness	32 feet	39 feet	NA	40 feet
Average Thickness	13 feet	14 feet	NA	12 feet

Appendix C - 6
Clay Layers Summary
Geophysical Log: H-26

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	<550 feet	1,305 feet	455 feet	310 feet
Total Clay Thickness	>132 feet	580 feet	390 feet	113 feet
Total Sand Thickness	>418 feet	725 feet	65 feet	197 feet
Percent Clay	~24 percent	44 percent	86 percent	36 percent
Percent Sand	~76 percent	56 percent	14 percent	64 percent
	Potential High Production Intervals			
Number of Producing Intervals	1	2	0	1
Producing Interval Thickness	350 feet	1,170 feet	NA	285 feet
Net Clay Thickness	91 feet	525 feet	NA	98 feet
Net Sand Thickness	259 feet	663 feet	NA	187 feet
Percent Clay	26 percent	45 percent	NA	34 percent
Percent Sand	74 percent	55 percent	NA	66 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	7	22	NA	5
Minimum Thickness	3 feet	2 feet	NA	2 feet
Maximum Thickness	25 feet	60 feet	NA	70 feet
Average Thickness	13 feet	30 feet	NA	20 feet

Appendix C - 7
Clay Layers Summary
Geophysical Log: H-40

	Chicot Aquifer	Evangeline Aquifer	Burkeville Confining Layer	Upper Jasper Aquifer
	Total Aquifer Interval			
Total Interval Thickness	UTD*	UTD*	230 feet	560 feet
Total Clay Thickness	UTD*	UTD*	161 feet	313 feet
Total Sand Thickness	UTD*	UTD*	69 feet	247 feet
Percent Clay	UTD*	UTD*	70 percent	56 percent
Percent Sand	UTD*	UTD*	30 percent	44 percent
	Potential High Production Intervals			
Number of Producing Intervals	UTD*	1	0	1
Producing Interval Thickness	UTD*	390 feet	NA	470 feet
Net Clay Thickness	UTD*	92 feet	NA	263 feet
Net Sand Thickness	UTD*	298 feet	NA	207 feet
Percent Clay	UTD*	24 percent	NA	56 percent
Percent Sand	UTD*	76 percent	NA	44 percent
	Clay Interbed Characteristics			
Number of Clay Interbeds	UTD*	6	NA	7
Minimum Thickness	UTD*	2 feet	NA	8 feet
Maximum Thickness	UTD*	62 feet	NA	115 feet
Average Thickness	UTD*	15 feet	NA	38 feet