

Impact of seismic reprocessing with an emphasis on improving static errors corrections on 3-D
land seismic data in Ellis Co., Kansas

by

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Abstract

Seismic datasets play an important role in petroleum exploration and development in the mid- continent. The role of good quality seismic data processing of 3D seismic surveys cannot be underestimated, as it is foundational to the creation of reliable interpretation of seismic data. It is imperative that processing is done properly, as inaccurate data can cause a multitude of problems, from simply unusable data to dry holes drilled due to incorrect placement of seismic reflectors in the subsurface. This research focuses primarily on seismic time corrections “statics” problems with processing, as well as interpreting, a seismic horizon of interest. Specifically, this project investigates the impact of remaining static errors on the fidelity of the geometrical structural seismic attributes (i.e. amplitude) and evaluates the impact on seismic resolution. As this study shows, inaccurate static-correction processing of the seismic data can have a great impact on the overall success of exploratory drilling.

Land seismic data of the midcontinent present unique static time-effects challenges that must be resolved. Among the most prominent are challenges posed by both topographic elevation statics, as elevation differences arising from differentially weathered carbonates and anhydrites in the near-surface, and velocity statics arising from near surface lateral velocity variations. These types of statics need to be removed to improve the overall quality of the processed seismic. When unresolved, these issues have a large negative effects on seismic amplitude and structural fidelity of the post-stack seismic datasets.

This project developed a processing workflow specific to the challenges of seismic datasets in Kansas. An iterative process was used and the processing was highly tailored to deal with the residual statics affecting seismic horizons of rock formations surfaces seen in Kansas. These formations are primarily composed of carbonates and evaporites, and so greatly affect the static solutions needed. Mapped first arrival travel-times were used as the input for travel-time tomographic inversion, creating a velocity model of the near surface. Applying this to the original dataset improves the quality of the seismic cube and removes the obvious topographic imprint present in the original post-stack interpretation. An additional benefit of this workflow was a greatly increased signal-to-noise ratio and significantly improved seismic resolution.

Interpretation of this reprocessed dataset more closely corresponds to well data in the area, giving a high level of confidence in the accuracy of the reprocessing workflow.

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Chapter 1 - Introduction

Seismic datasets play an important role in petroleum exploration in the mid-continent. Companies often spend significant capital on 3-D seismic surveys in order to better understand and characterize the spatial distribution and properties of reservoirs. The role of processing these surveys cannot be underestimated, as this process is foundational to the creation of useable seismic data. It is imperative that processing is done properly, as inaccurate data can cause a multitude of problems, from simply unusable data to incorrect placement of seismic reflectors in the subsurface resulting in dry-holes. While dry-hole analysis is usually completed with such wells, this type of analysis generally focuses on interpretation errors, rather than problems within the seismic dataset itself. This research study focuses primarily on problems with processing, rather than interpreting, the seismic. Specifically, this project investigates the impact of remaining static errors on the fidelity of the geometrical “structural” seismic attributes and on seismic resolution. As this study shows, inaccurate processing of the seismic can introduce artifacts and noise into the dataset, and greatly impact on the overall success of exploratory drilling.

In land seismic datasets especially, inadequate attention is paid to the accurate processing of seismic surveys shot in the area, particularly with static errors corrections. This is problematic, as land data has a number of unique challenges that must be resolved. Among the most prominent of these in Kansas are the challenges posed by differentially weathered carbonates and anhydrites in the near-surface. These present great challenges to correctly modeling and improving statics in the seismic and affect the overall quality of the processed seismic datasets. In incorrectly processed seismic datasets, this issue remains unresolved, and has a large negative effect on the image of the subsurface.

The goal of this project is to apply the fundamentals of seismic data processing to a 3-D dataset in Ellis County, Kansas, in order to develop a processing workflow specific to the challenges of seismic datasets in Kansas. In order to best deal with these problems, an iterative process is used, and the processing was highly tailored to deal with the specific rock formations seen in Kansas. The processing workflow, adopted from Yilmaz (2001), is applied to a field 3-D seismic dataset donated by Stroke of Luck (SOL) Energy and Exploration LLC, with the aim of assessing static errors corrections on the quality of stacking velocity and producing an optimized post-stack seismic data volume. In addition, an interpretation of the reprocessed seismic dataset is compared to the interpretation of the originally processed data in an effort to assess the effectiveness of the reprocessing workflow.

Introduction to the Dataset

The study area for this thesis is located in Ellis County, in northcentral Kansas (Figure 1.1). The dataset, provided by SOL, includes a 3-D seismic survey covering 1.9 square miles, as well as 3 wells with Log ASCII Standard (LAS) data from wireline well logs (Figure 1.2). The inline and crossline spacing of the 3-D survey is 82.5 feet, resulting in 97 inlines and 133 crosslines. The original processing report indicates that a seismic datum at 2100 feet and a replacement velocity of 9000 feet/second were used in the static errors correction. A closer look at the data indicates that these values are not representative of the entire survey, and a more in-depth investigation of the statics is needed. The inadequacy of the statics is addressed by this project. In addition, the seismic data have a bandwidth of 10-95 Hertz, with attenuation occurring in the higher frequencies.

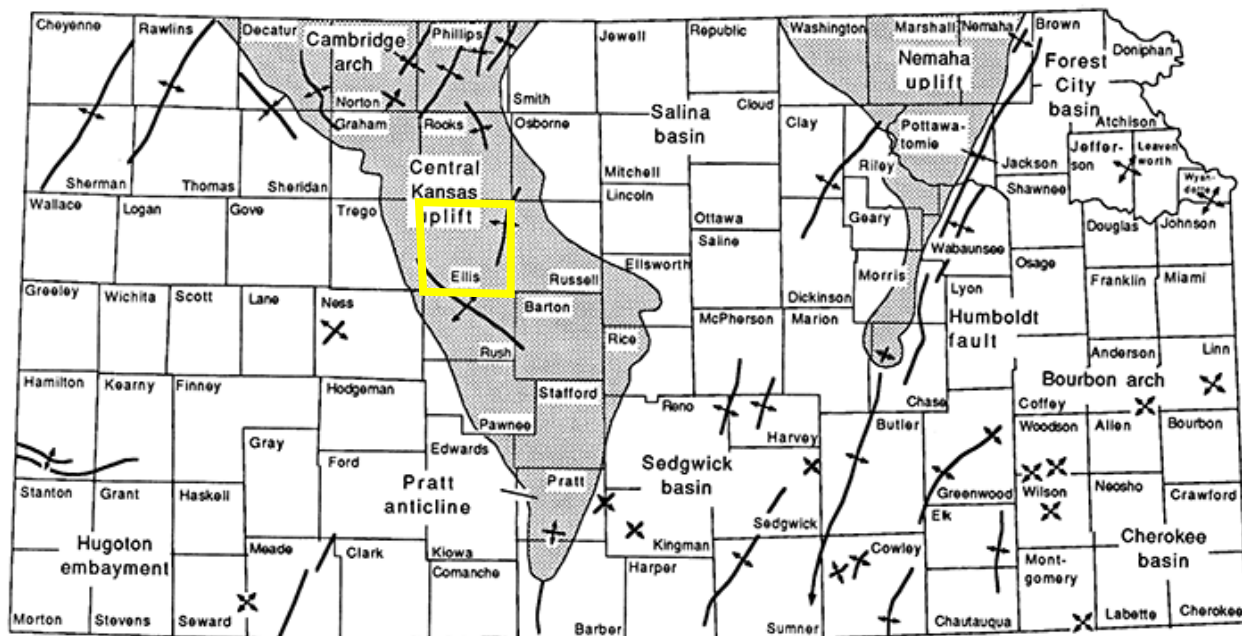


Figure 1.1 shows a map of the different major geologic provinces and structures of Kansas, as well as counties. The study area is located in northcentral Ellis County, outlined in yellow, Note that it is situated directly on the Central Kansas uplift, a broad anticlinal feature trending north-south through central Kansas. Figure modified from Merriam (1963).

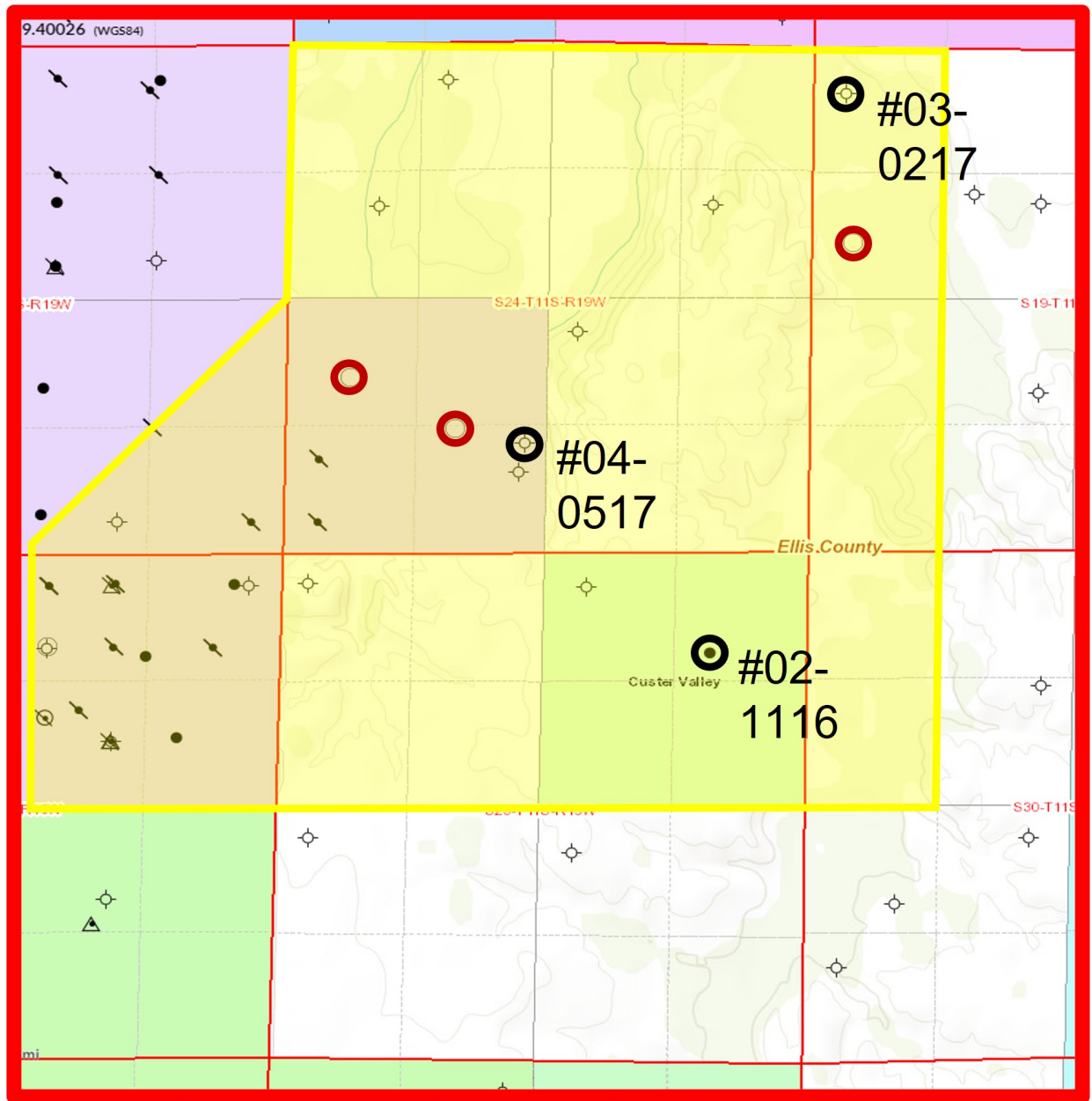


Figure 1.2 is a zoomed in look at the study area. The seismic survey, shown in yellow, is located in the northcentral portion of Ellis County, in Township 11 South and Range 19 West and Township 11 South and Range 18 West. It spans approximately 1.9 square miles, primarily in Sections 24 and 25 of T11S R19W. SOL drilled six wells (red circles), for which LAS wireline well logs were provided for three wells (black circles): Custer Valley #02-1116, Custer Valley #03-0217, and Custer Valley #04-0517. There are 24 additional wells within the boundary of the seismic survey, some of which have information available in the Kansas Geological Survey's database.

Adjacent to the study area are two oil fields, which have collectively produced millions of barrels of oil (Kansas Geologic Society). These are the Riverview oil field to the east, and the Solomon oil field to the west. Both fields produce from the Arbuckle Formation, which is the target formation in the study area. The production from these adjacent fields suggests that the study area has the potential to yield productive wells, although the wells drilled in the area have been deemed nonproductive. This is due to the wells either missing the productive zone, or due to insignificant oil shows. Arbuckle production in this area is controlled by structural position, and thus it is likely that an inadequate static correction in the seismic processing of the dataset contributed to poor well placement, and that with proper attention to seismic detail, this field could be productive.

Statement of Problems and Objectives

An examination of the interpretations of the original processed seismic data by SOL shows that the Metz 3-D seismic dataset has significant problems. This is shown in Figure 1.3, a structure-contour map of the top of the Arbuckle Formation, with the well locations overlain. Several offset wells, none of which were productive, were drilled on an apparent structural high interpreted from the dataset. This lack of production is surprising, given that wells drilled on similar structures in the same target formation in fields directly adjacent have produced collectively nearly half a million barrels of oil. Further investigation into the seismic shows that the apparent structure is not present but is an artifact created by incorrect processing in the seismic dataset. The apparent structural high is clear on this map, but a cross sectional view shows that this is inconsistent with the Arbuckle Formation tops from the wireline well logs. The Arbuckle Formation is encountered in the wells much lower across the apparent high and much

higher along the flanks of the apparent structure than the interpreted seismic shows (Table 1.1).

Thus, it is evident that there is a problem with the seismic data.

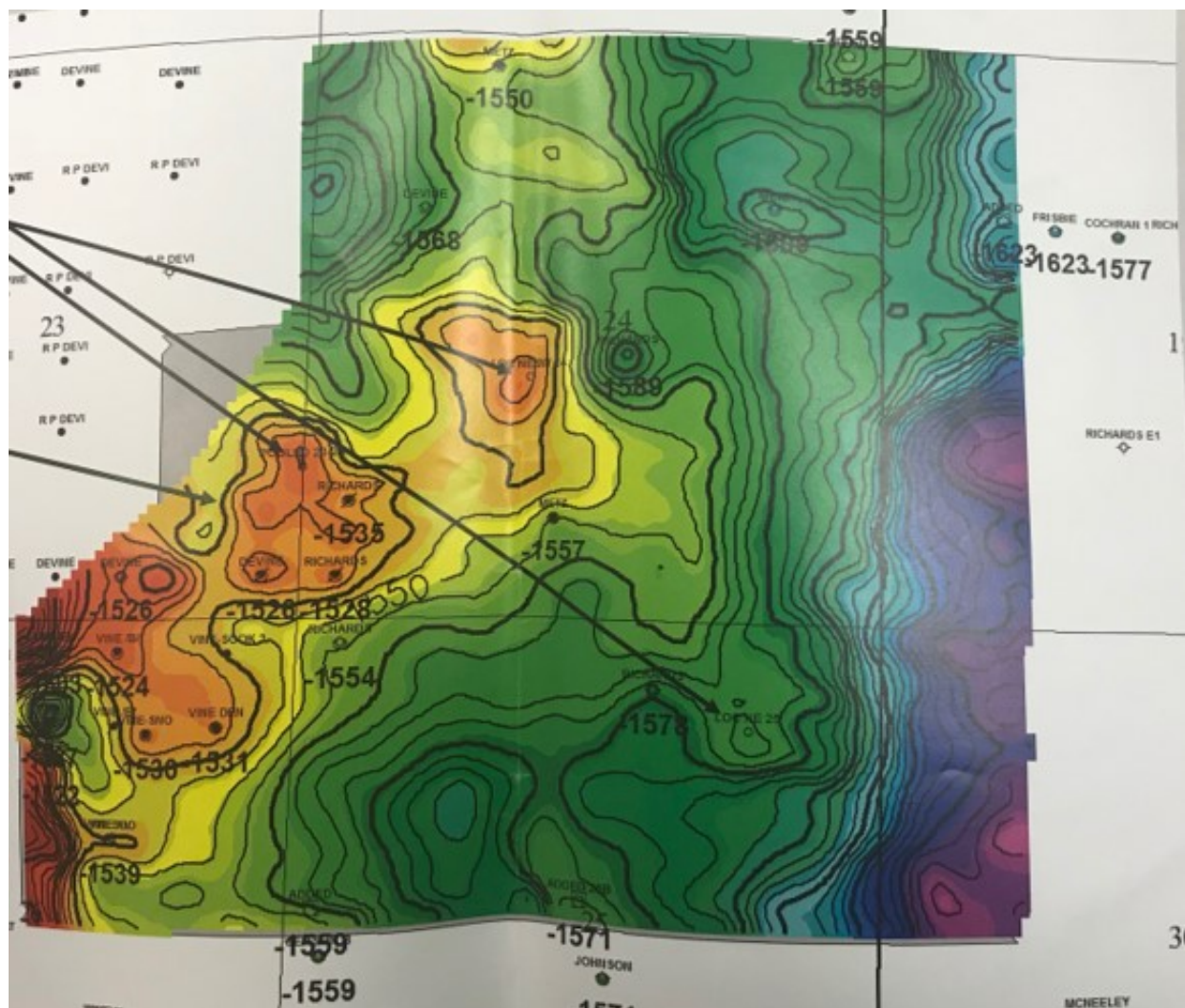


Figure 1.3 displays the structure-contour map on the top of the Arbuckle Formation originally interpreted from the seismic dataset, as provided by SOL. Warmer colors represent shallower depths and cooler colors represent deeper depths. Some of the wells have the depth of the Arbuckle posted beneath them. The contour interval is 5 feet. There is an apparent structural high in the west to central portion of the study area, with a relief of approximately 140 feet. This interpreted structure-contour map was used by SOL to determine well locations for the Custer Valley wells.

Top of Arbuckle Formation Depths, Subsea (feet)			
Well Number	#02-1116	#03-0217	#04-0517
Expected Depth	-1570	-1580	-1540
Actual Depth	-1571	-1566	-1554

Table 1.1 shows the disparity between the depths of the top of the Arbuckle Formation expected based on the original seismic interpretation and the depths where the Arbuckle was encountered in the wells. For the Custer Valley #02-1116 well, there is little difference between the expected and actual depths. The Arbuckle Formation was encountered nearly 14 feet higher than expected in the #03-0217 well, and 14 feet lower than expected in the #04-0517 well. This is noteworthy, as it does not support the interpretation of an apparent structural high in this area.

Additional evidence of adverse impact on amplitude and time of seismic events is provided by the low correlation coefficient (0.5) of the “best” well-to-seismic tie achieved in a preliminary study based on the contractor processed seismic data (Figure 1.4). The porosity-sonic log versus gamma ray-sonic log relationships (Figure 1.5) imply seismic amplitude dependence on lithology and reservoir quality, suggesting that a good quality statics correction may have a large positive impact on amplitude corrections.

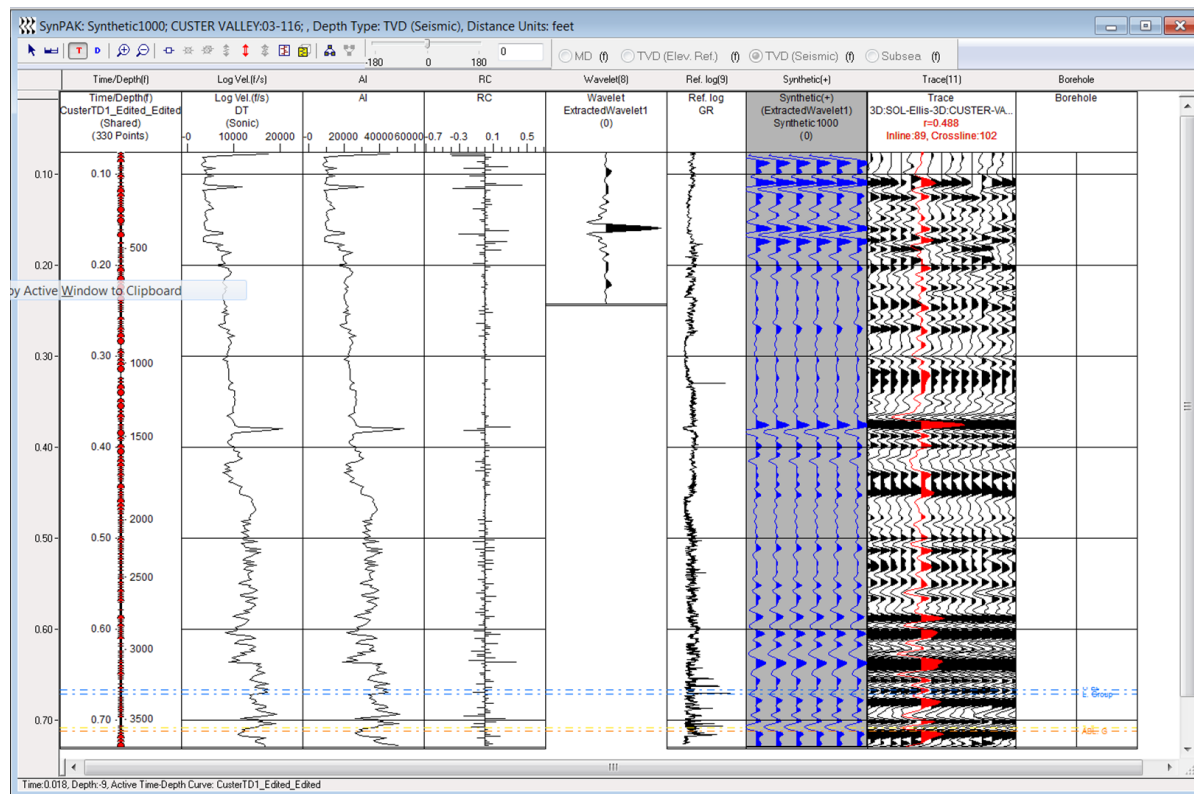


Figure 1.4 shows an example well-to-seismic tie between the originally processed seismic dataset and the Custer Valley #02-1116 well data. From left to right the window shows

shared time-depth points, sonic interval transit time (DT), acoustic impedance (AI), RC, the extracted wavelet, gamma ray (GR), the generated synthetic seismic amplitude, the originally processed seismic dataset (from Inline 89 and Crossline 102) and the borehole caliper log. As can be seen, there is a low correlation between the synthetic amplitude and the original amplitude (using original processing). The correlation coefficient is less than 0.5 ($r=0.488$), showing that there is a disconnect between the modeled amplitudes using well log data and the amplitude of the originally processed seismic dataset provided by SOL.

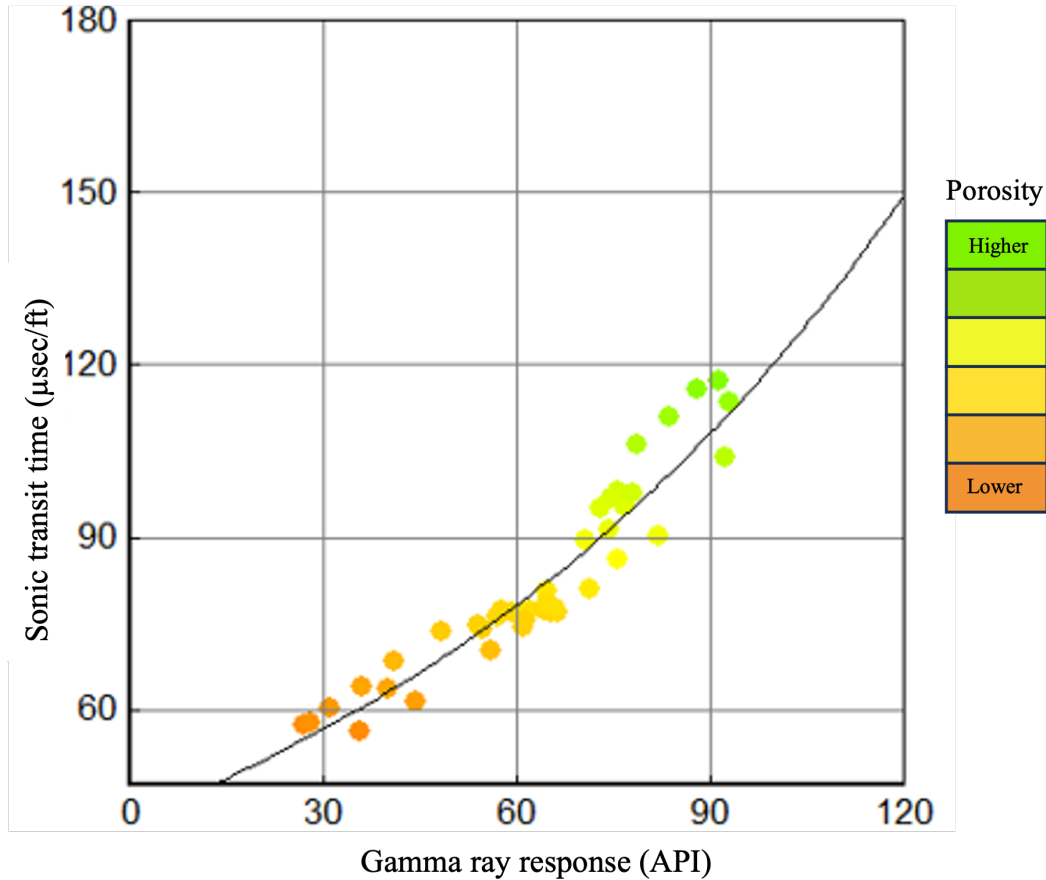


Figure 1.5 shows a crossplot of the sonic transit time values (y-axis) and gamma ray values (x-axis). Warmer colors (orange) denote lower porosity while cooler colors (green) denote higher porosity. As indicated, porosity increases along the best fit curve. The relationship between sonic transit time and gamma ray response is important, as it shows a strong correlation between these two measurable responses and implies that lithology (evidenced by gamma ray response) and reservoir quality represent controls on seismic amplitude.

A comparison of structure maps of different formation boundaries with the surface topography can further illuminate this problem. As Figure 1.6 shows, the topography of the

dataset is comprised of wide, flat areas that are deeply incised by drainage channels. These drainage channels cut through the stratigraphy, exposing several different formations at the surface (Figure 1.7). This results in rapid changes in elevation over very short distances. In addition, there is a meander channel of the Saline River that crosses the northern portion of the study area. The floodplain of the Saline River here is broad and flat, representing a topographic low in the area. Comparing this topography to time-structure maps of different formations as interpreted in the seismic data (Figure 1.3; Figure 1.8) shows that there is similar structure in all the maps. The apparent structural high seen in the Arbuckle and Stone Corral formations directly correlates to the higher elevation in the topographic map. It is unlikely that the subsurface directly correlates to the surface topography given that the depositional and structural history of the area consists of many iterations of inland sea encroachment, uplift and surficial exposure. Therefore, it is inferred that there are severe issues with the near-surface statics corrections applied to the dataset.

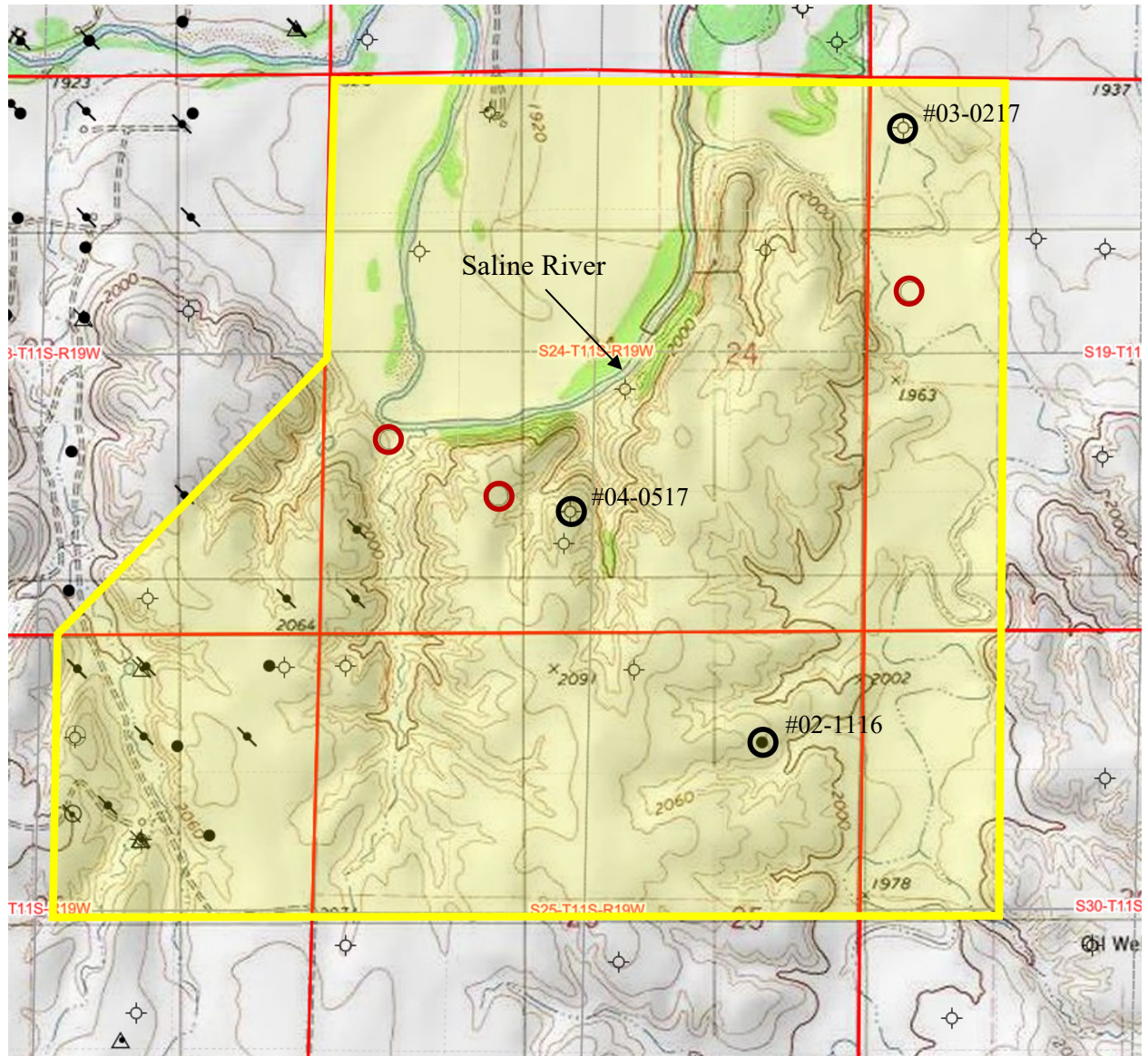


Figure 1.6 shows the topography of the study area. There is a large, flat topographic high in the west and central portion of the survey (shown in yellow), that is deeply incised by drainage channels. There is also a large meander channel of the Saline River that crosses through the north of the study area. The topographic relief between these features is high, and the steep gradient at the drainage channels has great impact on the behavior of seismic waves in the near-surface.

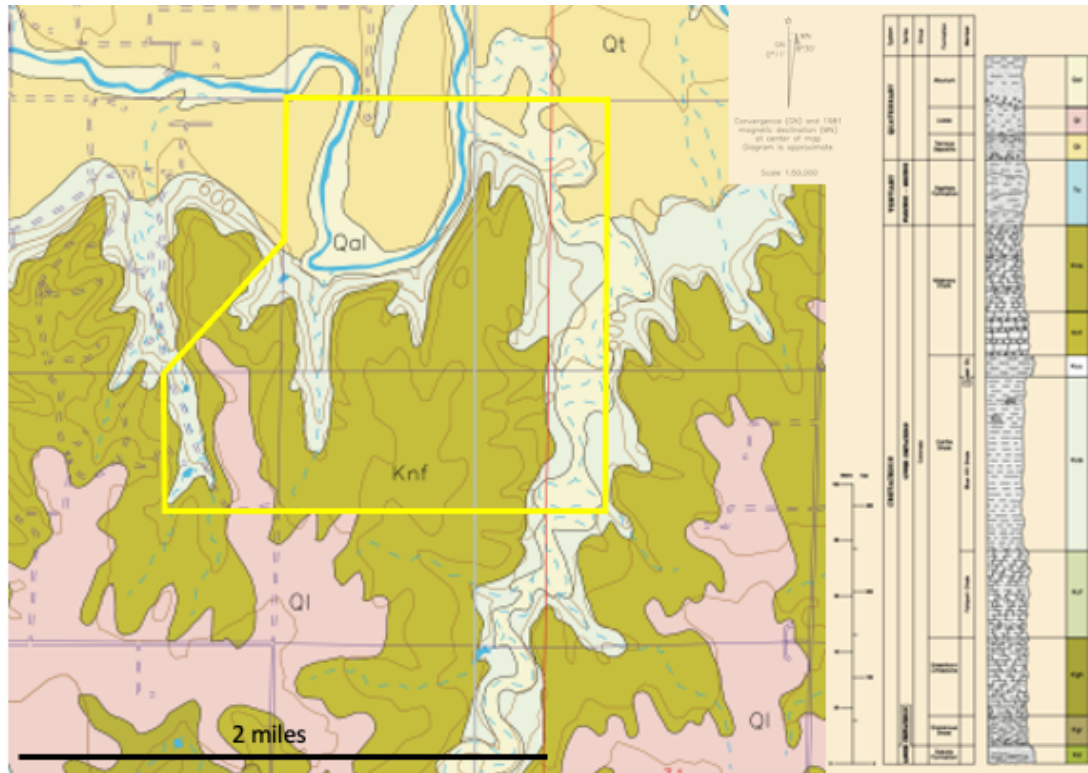


Figure 1.7 shows the surface geology of the study area (outlined in yellow). The geology shows clear resemblance to the topographic map in Figure 1.6, indicating that geology is a major control on topography in the area. In the central and southern portions of the study area, the Niobrara Chalk (Knf, denoted in green) is exposed at the surface, with the upper members of the Carlile Shale (Kc, denoted in light blue) exposed in the incised drainage channels. In the northern portion of the study area, the surface geology is primarily comprised of Quaternary alluvium (Qal, denoted in tan) and terrace (Qt, denoted in tan) deposits related to the Saline River. Due to the correlation between lithology and seismic behavior discussed earlier, it is likely that the differing geology across the study area has implications for refractor behavior.

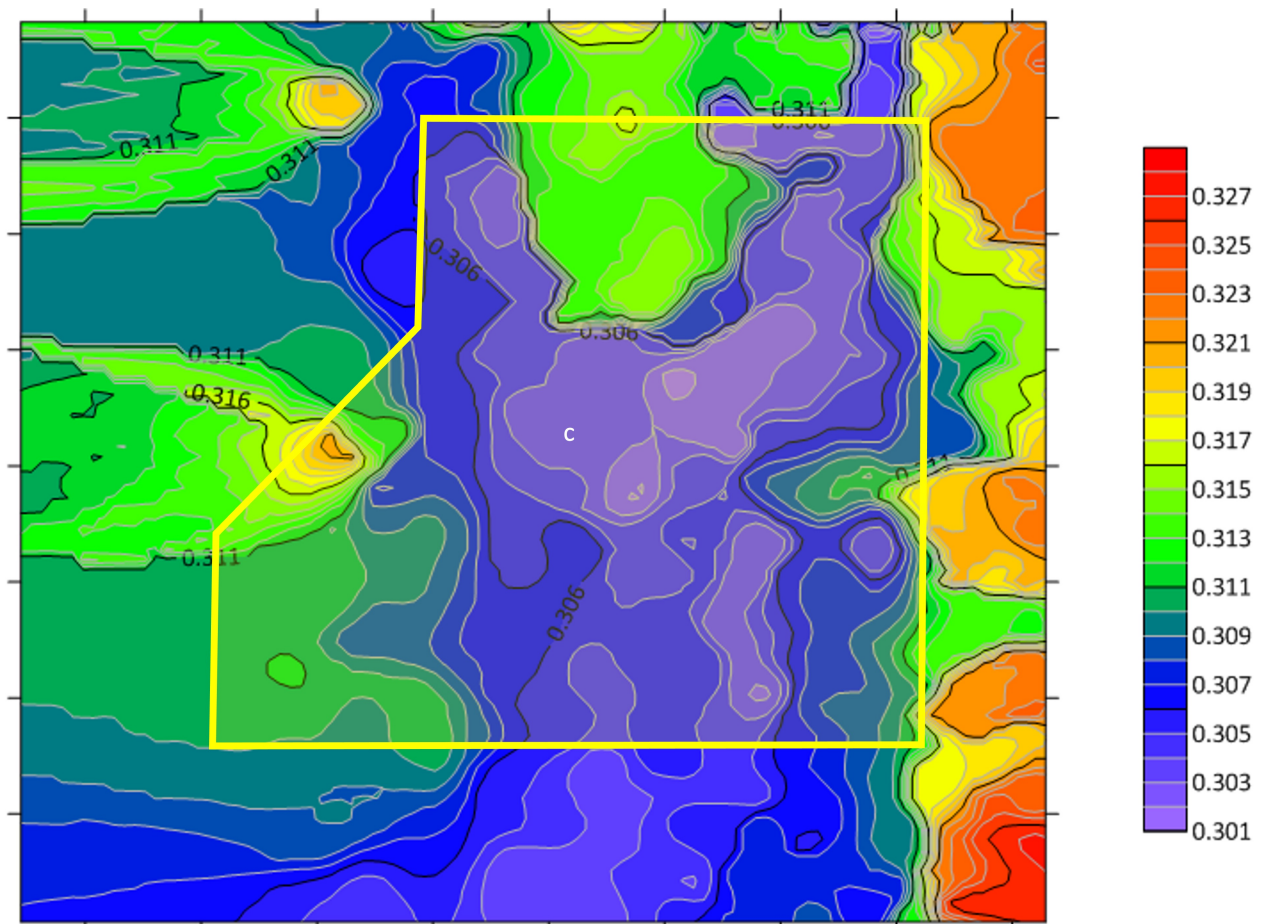


Figure 1.8 shows the time-structure map of the Stone Corral Evaporite surface. The study area is outlined in yellow; cool colors represent shorter two-way travel times, while warm colors represent longer two-way travel times. Travel times range from approximately 0.300 seconds to approximately 0.320 seconds. Note the feature in the center of the study area with shorter travel times (purple). This was interpreted by SOL to be a structural high. Figure modified from Tucci (2019).

A cross-sectional look at the original dataset displays these same apparent artifacts. In multiple shot gathers across the survey, there is a clear departure from the expected parabolic character of reflection events (Figure 1.9). The non-parabolic shape of reflectors is the result of a phase shift and is indicative of the short-wavelength static errors that need correcting. The original processing did not solve the issues, as is evident in both map and cross-sectional view. Figure 1.10 shows a cross sectional view of Crossline 102 and the Custer Valley #03-0217 well

that intersects it. This well was drilled in the area of the apparent structural high interpreted by SOL, which can also be seen in the cross section. It is important to note that in the near-surface directly above this high, there is a much degraded signal-to-noise ratio. There exists a lack of coherency between shallow reflectors that is not present in other areas of the survey. In the deeper reflectors, there is an upwards shift of reflectors relative to where the formations were encountered in the well. The formations tops, particularly the Stone Corral anhydrite and the Arbuckle Formation came in lower than predicted from the seismic data interpretation.

The original processing for this dataset used a replacement velocity of 9000 feet/second and a static datum of 2100 feet in order to resolve the near-surface statics. Given that there is an obvious imprint of the surface topography on subsequent subsurface reflections, it is clear that this is an inadequate statics solution. The drainage channels present in the study area are indicative of differential weathering of layers at the surface, and the large changes in elevation within short distances result in significant refraction of the incident seismic source waves. Such significant refraction obscures seismic reflection events from deeper within the subsurface, making it difficult to resolve offset and decreasing the signal-noise ratio. An in-depth study of the statics of the near-surface is required to resolve these issues, without which the seismic will be unusable. The first objective of this project is to investigate the near-surface statics solution of this dataset, in order to remove the effects of the weathered layer from the data. This is accomplished through detailed mapping of the first-arrival events from each source-receiver pair, as discussed in the Methods section.

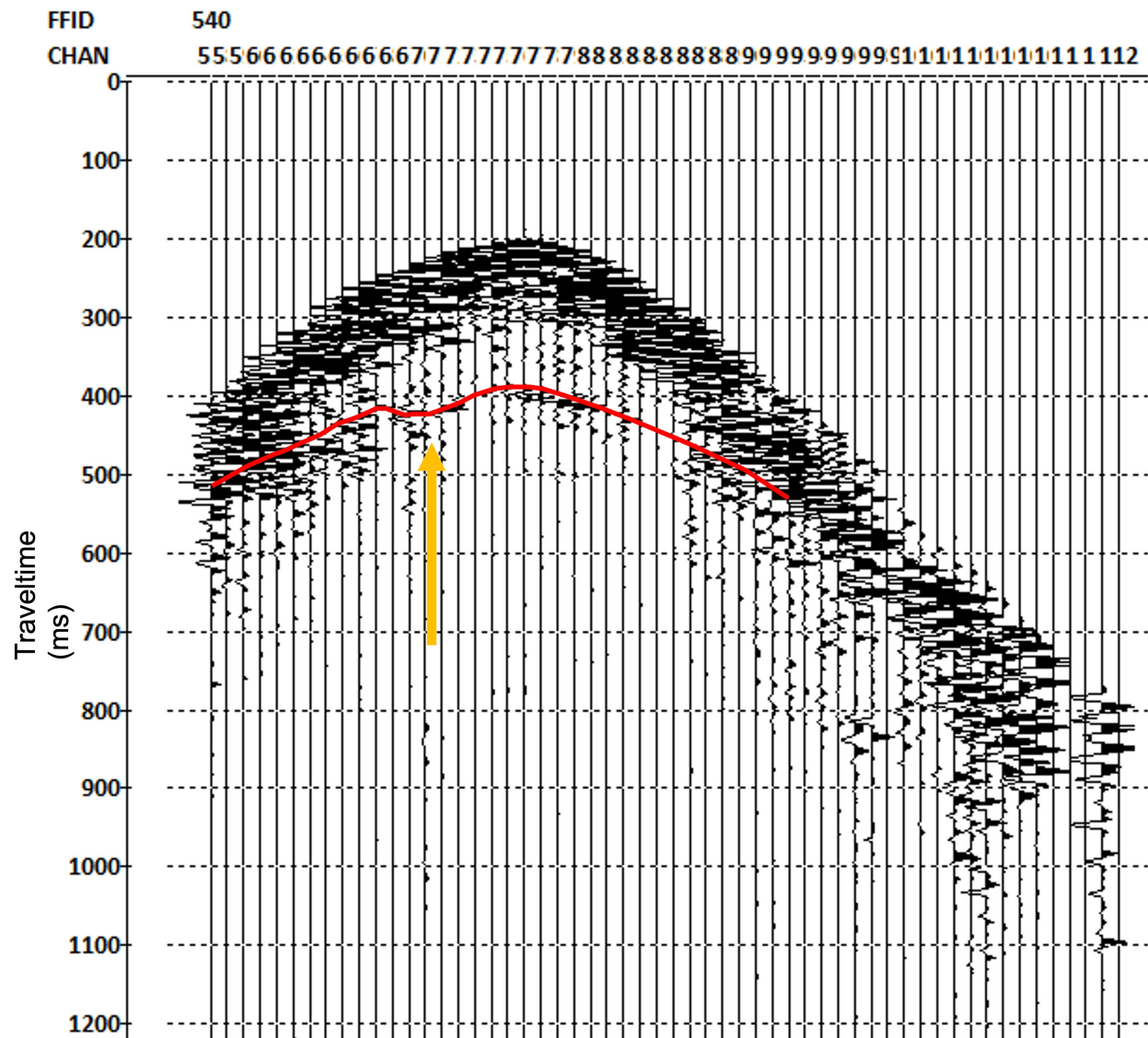


Figure 1.7 shows a preprocessed shot gather located in the southcentral portion of the survey, where the topographic gradient is greater in this area. The red line represents an interpreted seismic reflection event. Note that there is a clear departure from hyperbolic traveltime behavior, indicated by the yellow arrow.

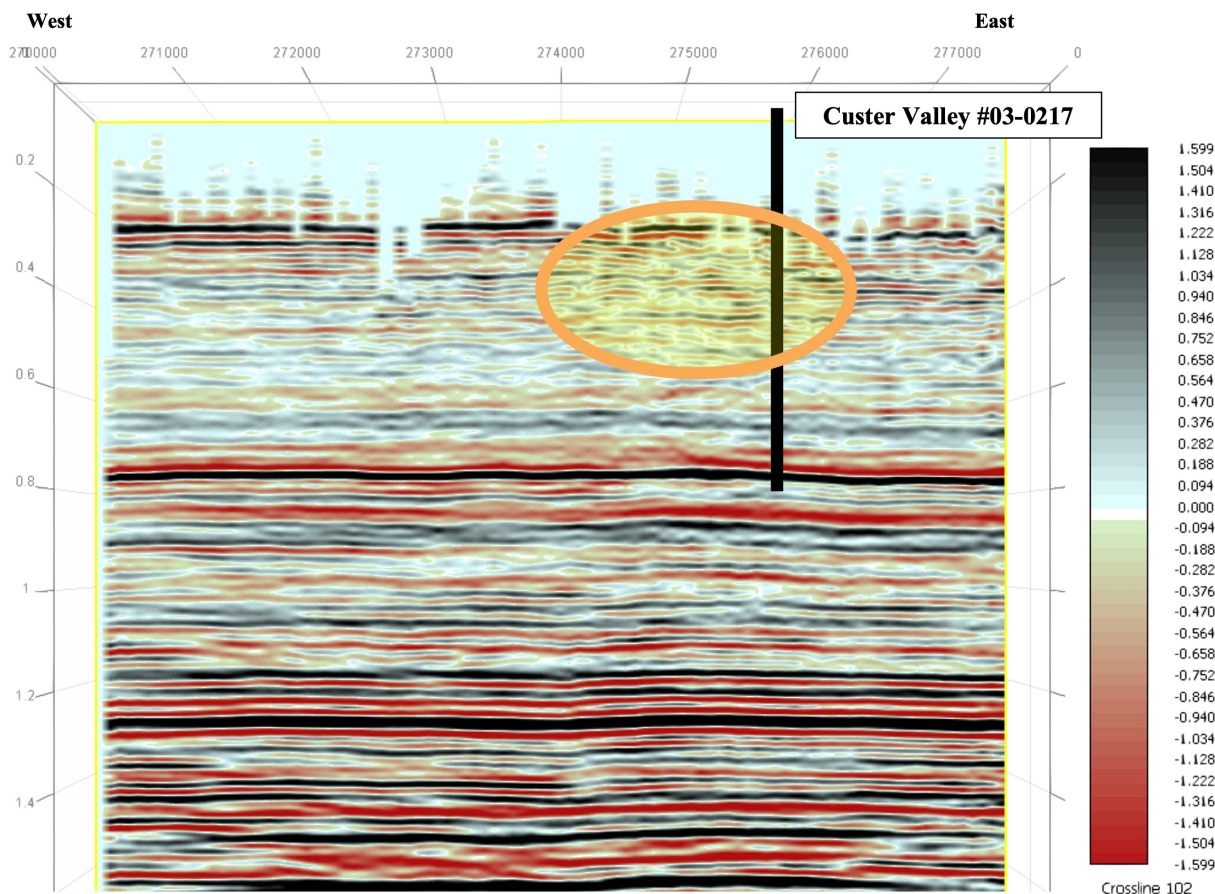


Figure 1.8 shows Crossline 102 of the original seismic dataset. This line crosses the northern portion of the survey area, intersecting the Custer Valley #03-0217 well. As can be seen, there is an apparent structural high in the west-central portion of the cross section. Directly above this apparent structure (highlighted in yellow), the signal-to-noise ratio is significantly degraded, and there is an obvious lack of coherent reflectors that is present in other portions of the cross section.

Previous Investigations into the Dataset

The Metz 3-D dataset was previously investigated in Tucci (2019). This thesis specifically details significant problems with the original geometry of the dataset and presents the geometric solution to these issues. Tucci (2019) reassigned the source and receiver locations based on geometric solutions that give coherent offset consistent with the distance between source and receiver. This is significant, as the physics of wave propagation demand that offset increases as the distance from the source increases. He also proposed an improved approach to

solving the static errors issues of the dataset, investigating the use of different seismic datums rather than the original 2100 ft used in the original processing. It is important to note that while Tucci (2019) resolved the problems with the dataset associated with the incorrect original geometries, his statics method did not entirely address issues related to the original static errors correction, velocity model, and signal-noise ratio. This thesis addresses the remaining issues.

Impact of Research

This study develops a processing workflow specifically tailored to the challenges that impact seismic datasets in Kansas. This work also distinguishes the steps in the processing workflow that are the most problematic in Kansas, prompting processors working with similar challenges to spend more time in these areas. Especially in areas where topography and surface lithology vary laterally, it is essential that static-errors corrections are specific to the study area. More tailored processing workflows generate higher quality datasets that are more useful, especially with regards to hydrocarbon exploration. Wells drilled based on quality seismic data are more likely to be productive, and so the techniques discussed in this project can contribute to higher success rates in the Kansas petroleum industry. On a larger scale, this project provides a preliminary model for generating static-errors corrections for data outside of Kansas, improving geophysical efficiency and increasing the usefulness of geophysical data elsewhere.

Background

Regional Geologic Setting

The regional geology of Kansas is comprised primarily of marine-derived sediments, with periodic influx of clastic material. Tectonically, the geology of the region is complicated by several large-scale compressional events, which caused uplift and basin formation (Merriam et al., 1961). The first of these events occurred in the Precambrian. During this time, Kansas was

located on a stable platform of the North American craton, which is an extension of the Canadian Shield (Merriam et al., 1961). These rocks make up the Precambrian granitic basement in the area (Merriam et al., 1961). Approximately 1100 million years ago, tectonic activity associated with the Central North American Rift system deformed the Kansas basement, leading to the development of local highs with up to 200 meters of relief (Cole, 1976; Yarger, 1983; Bunker et al., 1988; Berendsen and Weis, 2001). This deformation created a northwest to southeast trending high through central Kansas, called the Ancestral Central Kansas Arch (Merriam, 1963). In addition, tectonic activity produced a large- scale system of northeast trending faults and a conjugate set of northwest trending faults throughout Kansas (Baars, 1992; Baars et al., 1995). Reactivation of these faults largely controlled deformation in the overlying strata of the Arbuckle Group (Merriam et al., 1961).

The lowermost Cambrian strata consists of the Granite Wash – sediment from weathered Precambrian granitic basement (Merriam et al., 1961). The existence of the Granite Wash indicates exposure of the Precambrian basement for long periods of time prior to Late Cambrian deposition. The Late Cambrian represents the first transgression of the Sauk sequence, where a shallow epeiric sea covered much of the region. This resulted in deposition of the Reagan Sandstone, which is not present over local structural highs due to either nondeposition or subsequent erosion (Merriam, 1963). As transgression continued and the epeiric sea deepened, clastic sources (paleotopographic highs) were submerged, and the Bonneterre dolomite was deposited. A major regression occurred after the deposition of the Bonneterre dolomite, resulting in the erosion of this unit from structural highs (Bunker et al., 1988). Another major transgression occurred in the Upper Cambrian, and the Eminence Dolomite, recognized as the lowermost member of the Arbuckle Group, was deposited (Wilson, 1994). The end of the

Cambrian is characterized by a minor regression, causing subsequent members of the Arbuckle Group, deposited during a transgression in the middle-late Ordovician, to overlie the Eminence Dolomite unconformity (Franseen, 2004).

At the end of the Ordovician, a major fall in sea-level, coincident with the Sauk-Tippiecanoe cratonic sequence boundary, exposed the Arbuckle Group and equivalent strata to karst processes (Sloss, 1963; Kerans, 1988). This is known as the Ellenburger-Arbuckle-Knox-Prairie du Chien-Beekmantown-St. George karst plain (Kerans, 1988). The distribution of this karsting is likely one of the controls on reservoir quality in the Arbuckle throughout Kansas. The Middle and Upper Ordovician strata were deposited during the transgressive event through the beginning of the Tippiecanoe sequence. These, in order of deposition, are the Simpson Group, the Viola Limestone, and the Maquoketa Shale (Merriam, 1963). All are absent on the Central Kansas Uplift. Transgression continued through the Silurian and Devonian, resulting in the deposition of the limestones and dolomites of the Hunton Group (Merriam, 1963). These overlie the Ordovician strata and underlie Mississippian strata unconformably.

Throughout the Early and Middle Mississippian, large epeiric seas covered much of the region, and the lack of clastic input led to the deposition of limestones and calcareous shales (Moore, 1957). This changed in the Late Mississippian with the onset of deformation related to the Ouachita-Marathon orogeny (Kluth and Coney, 1981). The compressional stress that resulted from the collision of the North American and Gondwanan continents reactivated the Precambrian faults and caused significant uplift (Yarger, 1983; Kluth, 1996). This event uplifted the Central Kansas Uplift, a major structural feature in Kansas. Continued deformation and uplift through the Pennsylvanian caused significant erosion of Mississippian-Middle Ordovician strata, exposing the Arbuckle rocks once again to karsting processes (Newell et al., 1989). This results

in an unconformity above the Arbuckle, with missing section from the Middle Ordovician to the Middle Pennsylvanian. Very little deposition occurred during the first half of the Pennsylvanian, excepting eroded sediment in structurally low areas. This began to change in the Middle Pennsylvanian, as the Atokan-Middle Desmoinesian transgression inundated the region with seawater. During this time, the sands and limestones of the Cherokee Group were deposited, though these are not present over the Central Kansas Uplift (Merriam, 1963). Transgression continued through the end of the Pennsylvanian, resulting in the deposition of the Marmaton and Lansing-Kansas City Groups (Merriam, 1963).

Deposition in the early Permian comprised mostly of limestones and shales; however, as the epeiric sea shallowed towards the middle Permian, deposition favored evaporates and red terrigenous clastics (Merriam, 1963; Kluth, 1996). During this time, the Stone Corral Formation, an evaporate, was deposited. The Mesozoic strata in the region largely consist of limestones and shales. The Jurassic Dakota Formation overlies the Stone Corral Formation unconformably, followed by the Cretaceous Greenhorn Limestone, the late Cretaceous Niobrara Group, and the late Miocene-early Pliocene Ogallala Formation (Merriam, 1963).

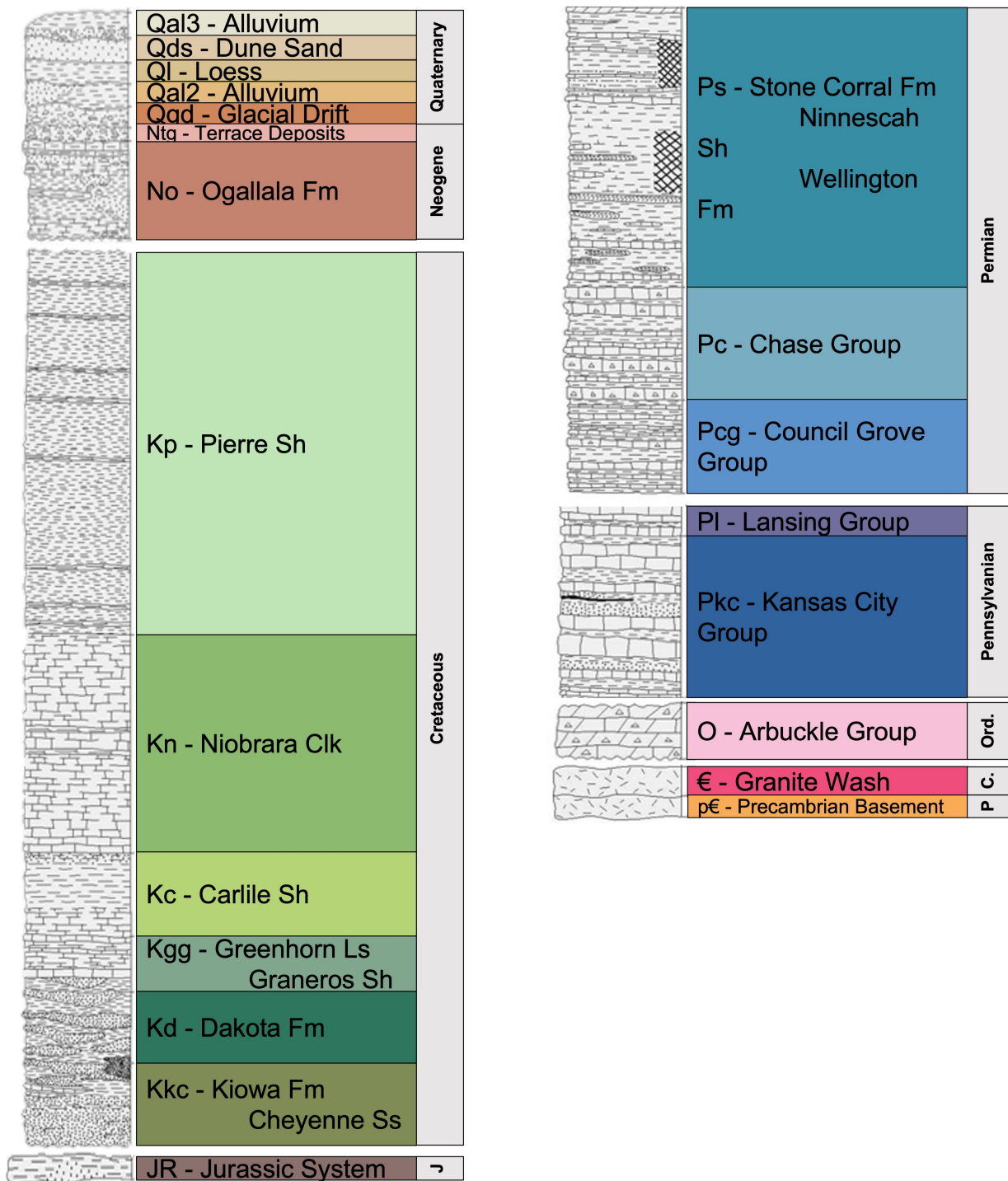


Figure 1.9 shows the stratigraphic column present in the study area. In comparison with the regional stratigraphic column (Figure 1.12), there are several formations not present, due to either nondeposition or uplift and subsequent exposure. Quaternary, Neogene, and Cretaceous sediments are exposed at the surface in the survey area. The surficial geology of the area is especially important, as it acts as a control on surficial weathering, and thus topography in the area. Figure modified from (Zeller, 1968).

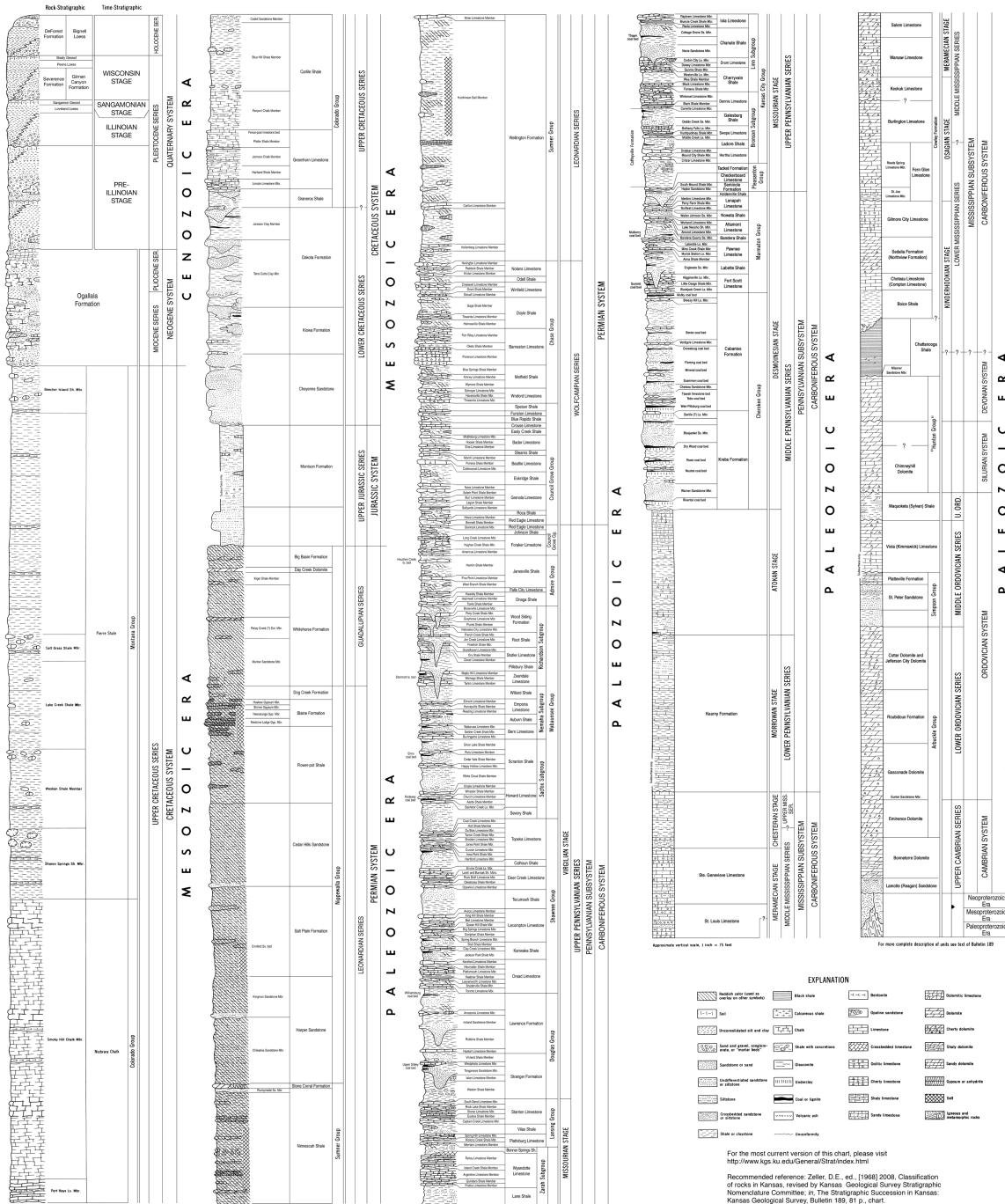


Figure 1.10 shows the typical stratigraphic succession in Kansas. This represents a complete stratigraphic column, however not all units are present in the study area. As discussed, the units from the middle Ordovician to the late Missourian have been removed through erosion, so that the Lansing and Kansas City Groups directly overlie the Arbuckle Group. Figure from Zeller (1968).

Chapter 2 - Methods

Seismic Amplitude Modeling

Seismic amplitude modeling was completed in order to assess the impact of frequency corrections on seismic amplitude response. It is especially important to have correct amplitude response, as this is the basis for first arrivals picking and static errors corrections. This was completed using Ricker continuous wavelets, described by the equation below:

$$\psi(t) = \frac{2}{\sqrt{3}\sigma\pi^{1/4}} \left(1 - \left(\frac{t}{\sigma} \right)^2 \right) e^{-\frac{t^2}{2\sigma^2}}$$

Where $\psi(t)$ represents seismic amplitude, σ represents wave frequency in Hertz, and t represents wave travel times in milliseconds. The Ricker wavelet represents a zero-phase, continuous wavelet, which is the negative normalized second derivative of a Gaussian function (Yilmaz, 2001). This function is often used to model seismic data, and as such was used in this project. Travel times (t) were modeled for values between 0.05 and -0.05 milliseconds (ms), for frequencies ranging from 15 to 60 Hertz (Hz). This demonstrates the affect of slight time shifts on seismic wavelets and their correspondent amplitude expressions.

First Arrivals Picking

There are multiple methods with which a near-surface statics solution can be reached, however this project used first arrival picking to characterize seismic energy refraction across the survey. The first arrival, also called a first break, in this dataset was defined as the first positive reflection above a certain amplitude threshold, as is standard within the American Polarity convention. The first breaks were interpreted along collinear source-receiver lines in the Deco Geophysical RadExPro® 2020.4 seismic processing software based on this definition.

Velocity Modeling

The time picks of the first arrivals were then loaded into a refraction-based travel-time tomography inversion. This window displays the x-location of the receiver along the horizontal axis, against the travel-time of each pick along the vertical axis. Each shot-gather appears as an individual curve in the window, with the picks represented by points along the curve. A linear best-fit curve was generated for each segment and the slope of these curves was used to determine velocities of the refracted seismic waves; greater slope corresponds to lower velocity. Velocity curves were modeled for segments with constant slope using the Generalized Reciprocal Method (GRM) (Yilmaz, 2001). This method uses the following equation as the velocity analysis function, the slope of which is the inverse of velocity:

$$t_v = \frac{1}{2}(t_{s1} - t_{s2} + t_{s1s2})$$

Where t_v represents modeled travel time at a given velocity, t_{s1} represents segment 1 travel time, t_{s2} represents segment 2 travel time, and t_{s1s2} represents the summed segment 1 and segment 2 travel time. The slope of the linear equation generated by the velocity analysis function is equal to the ray parameter, the inverse of which is the modeled velocity of the refractor. This particular velocity analysis function is used in cases of a shallow interface with strong velocity contrast, as is expected in a weathered layer. The velocities were generated according to the above equation by the RadExPro® 2020.4 software.

Depth Conversion

Depth conversion was completed using the Generalized Reciprocal Method, using the velocities generated in the velocity modeling. The modeled velocities were input into the following equation, which represents a combination of the time-depth and the depth functions of the GRM:

$$Z = \frac{(t * V_2 * V_1) - (XY * V_1)}{2\sqrt{V_2^2 - V_1^2}}$$

where Z = depth (feet), t = two-way travel time (seconds), V₁ = first segment velocity (feet/second), V₂ = second segment velocity (feet/second), and XY = offset (feet). Statistical analysis of the resulting modeled depth values was completed for quality assurance of results. In addition, using the IHS Kingdom® 2022 software, individual modeled depth values were plotted in three-dimensional space in order to create structure contour maps of the first refractor boundary. Several extrapolation techniques were used in between points, including kriging and least-squares regression modeling. The individual modeled depths were also plotted against XY location in order to create cross-sectional views across individual receiver lines.

Seismic Datum Adjustments

The seismic survey was adjusted to the new seismic datum in both time and depth dimensions. The datum generated in the depth conversion was subtracted from originally interpreted surfaces provided by SOL, in order to remove the low-velocity layer (LVL) and its subsequent static errors effects. This subtraction was completed using a simple surface arithmetic calculation, performed in the IHS Kingdom® 2022 software. The newly generated surfaces were then compared to the original surfaces to evaluate the effectiveness of the static errors solution.

Chapter 3 - Results

Seismic Amplitude Modeling

Seismic amplitudes were modeled using Ricker wavelets, as described in Chapter 2. Frequencies of 15 Hz, 25 Hz, 35 Hz, 45 Hz, 55 Hz, and 60 Hz were used, with the resulting wavelets shown in Figure 3.1. It is clear that while the general character of the wavelet does not change with frequency – i.e. the wavelet remains a zero-phase wavelet comprised of a positive peak centered on $t=0$ with two mirrored, smaller side lobes – the breadth of the wavelet does change as frequencies change. At lower frequencies, such as 15 Hz, the wavelet is wider, with the peak spanning across a larger range of time. At higher frequencies, however, the peak becomes increasingly narrow, with greater slopes and narrower lobes. Thus, at higher frequencies, amplitudes for seismic events will be more constrained in time than at lower frequencies. The summation of these amplitudes will also look quite different, which has implications for static errors corrections.

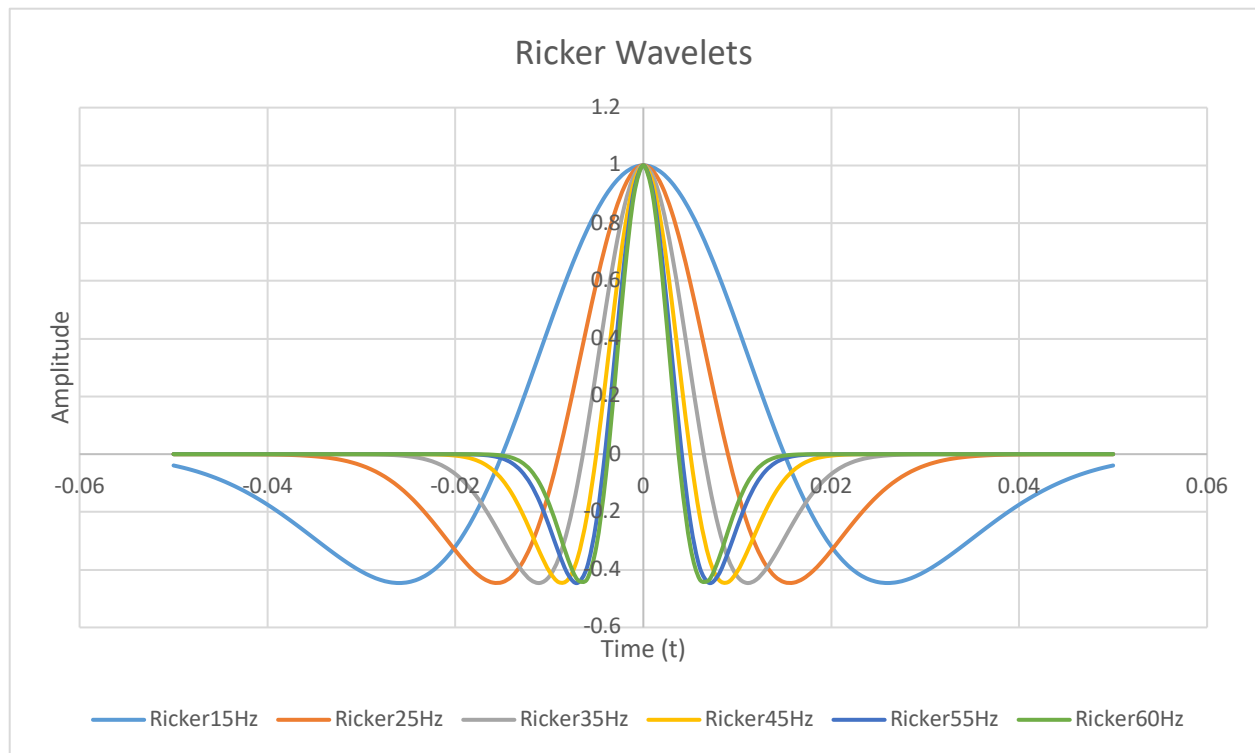


Figure 3.1 shows the modeled Ricker wavelets at six different frequencies. It is clear that while the overall shape of the wavelet remains constant, at higher frequencies (i.e. 60 Hz) the central peak spans a narrower time range, while at lower frequencies (i.e. 15 Hz) the central peak is broader. This relationship between frequency and wavelet width is also seen in the wavelet lobes.

First Arrivals Picking

To deal with the near-surface static errors, first arrivals were interpreted along shot-gathers at co-linear sources receivers-line throughout the survey. Overall, a total of 157 pairs were interpreted (Figure 3.2). Gathers with hyperbolic first arrival character were not used, as these are likely impacted by side-scatter and will not yield accurate first arrival travel times (Yilmaz, 2001). The interpretation was made in a window display with parameters consistent with standard processing methodology. This constrains the threshold of the first arrival event and gives confidence that the interpreted horizon is associated with the first refraction event. In the majority of the shot-gathers, there were two distinct arrival events. These appear as different

slopes in the shot-gather. A selection of shot gathers from across the study area are presented in Figures 3.3, 3.4, and 3.5.

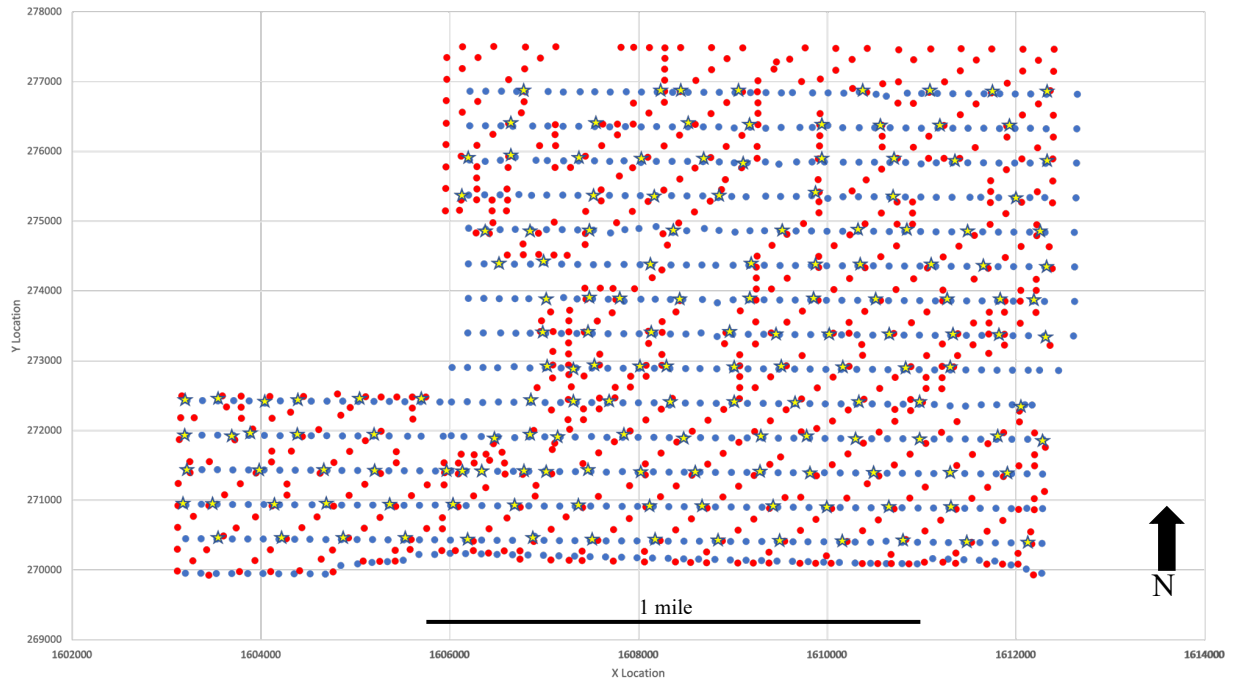


Figure 3.2 displays a map of the source (red) and receiver (blue) locations of the seismic survey, as well as the co-linear pairs (yellow) that were used to interpret the first arrivals across the survey. As can be seen, first arrivals were picked across the survey, with a regular occurrence. This ensures that there is a representative sample of first arrivals interpreted, and thus the velocity modeling is representative of the entirety of the seismic survey area. A total of 157 source-receiver pairs were interpreted using an iterative approach.

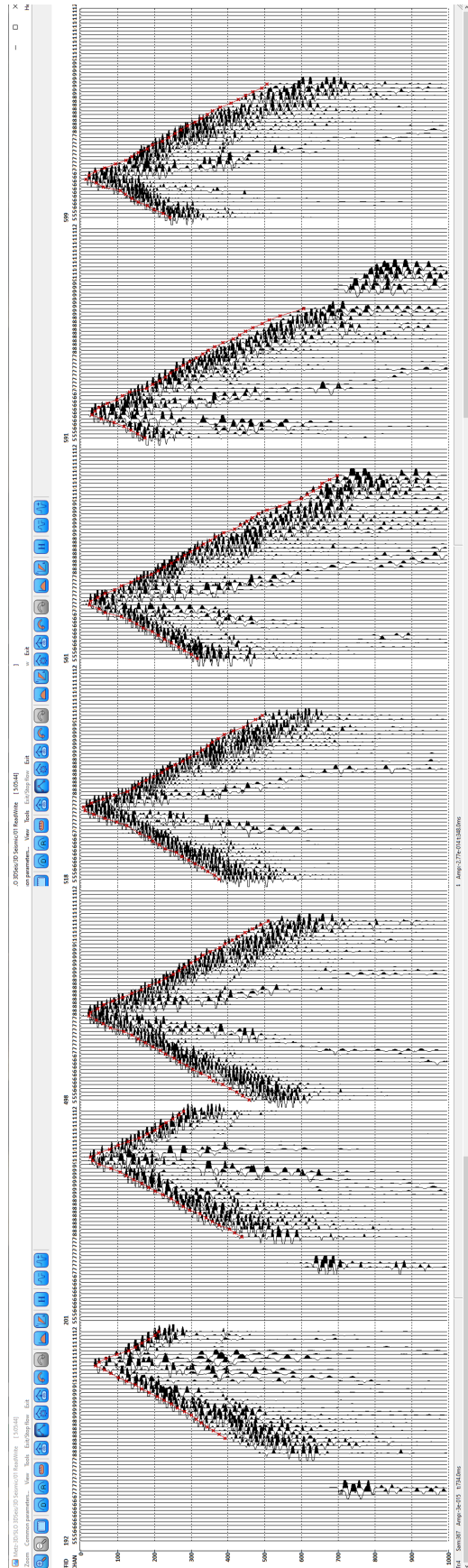


Figure 3.3 shows the shot gathers with first-arrivals (red) interpreted along source line 104 of the seismic survey. The gathers, from left to right, display the southernmost portion of the dataset from west to east. Note the gathers show two distinct characters, with differing slopes from the earliest first arrivals to the later first arrivals.

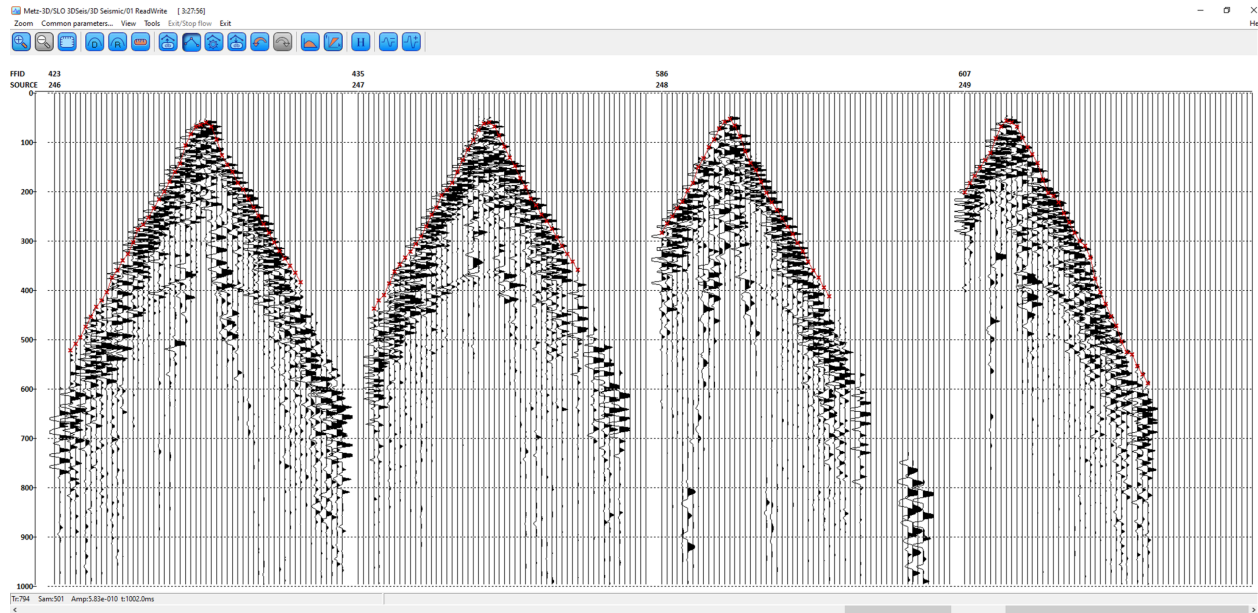


Figure 3.4 shows shot gathers from the eastern portion of receiver line 113 of the survey. The location of these gathers, especially gather FFID 435, are in the same area as well #02-116 and give a good idea of the character of the first arrivals (interpreted in red) in the area near this well.

Refraction Velocity Model Building

The time picks were loaded into a refraction-based travel-time tomography module of the RadExPro® 2020.4 software (Figure 3.6). This module displays the x-location of the receiver along the horizontal axis, against the travel-time of each pick along the vertical axis. Each shot-gather appears as an individual curve in the window, with the picks represented by points along the curve. The slope of these curves was used to determine velocities of the refracted waves; greater slope corresponds to lesser velocity. Velocity curves were modeled for segments with constant slope. As in the shot-gathers, there are two distinct segments visible for most of the curves. The first segment (pink) has a steeper slope than the second (yellow), indicating that the pink segment represents a slower propagating wave. Additionally, there is some evidence of a third segment (white), however this was inconsistent and not visible across the entire study area, so is not discussed in this thesis.

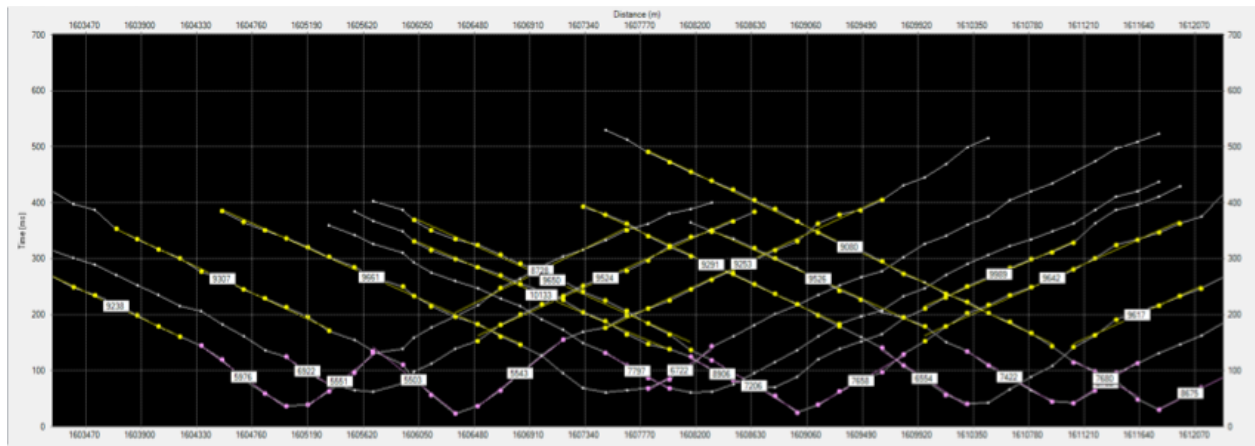


Figure 3.6 The window for velocity modeling in the RadEx Professional software. Each curve represents the first arrivals picks of a shot gather, plotted with time (ms) on the vertical axis and X position on the horizontal axis. The curves plotted above represent the velocities modeled across source line 113, through the central portion of the study area. They are divided into segments based upon the slope of the curve. As can be seen, there are two segments for each curve: one with a steeper slope (pink) and one with a lesser slope (yellow).

It is also important to note the variability in the modeled first refractor velocities throughout the study area. For the first segment, velocities vary between 5488 ft/s and 9910 ft/s. The distribution of velocities is shown in Figure 3.7. As can be seen in the histogram, the velocity models are skewed towards lower velocities, with an average mean velocity of 7550 ft/s, and a standard deviation of 934 ft/s.

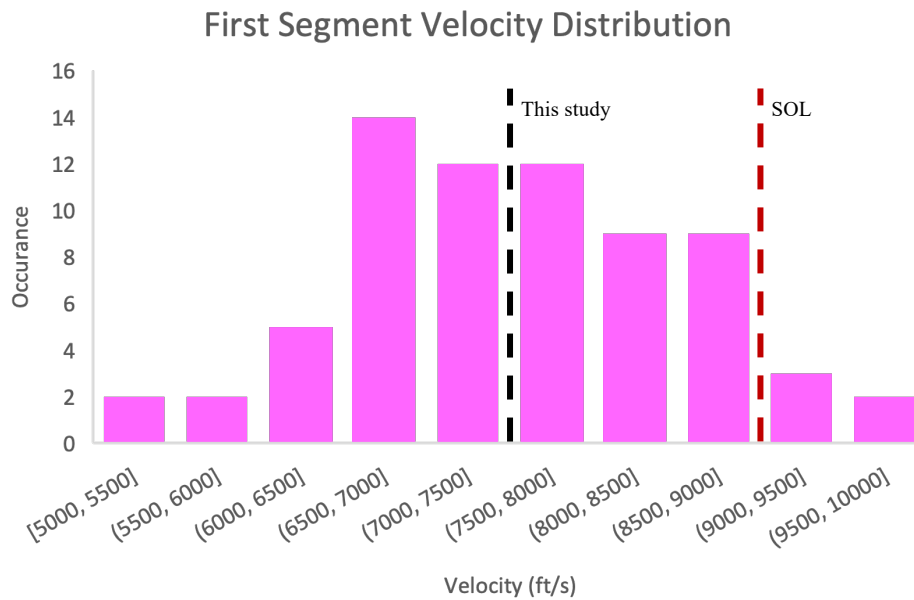


Figure 3.7 shows a histogram of the velocities modeled across the study area based upon the first arrivals segment 1, with occurrence on the y-axis and velocity in feet per second (ft/s) on the x-axis. The velocities have a range of nearly 5000 ft/s and show a slight skew towards lower velocities. It is important to note that the modeled velocities of this segment center on a velocity of 7000-7500 ft/s (mean average denoted by black dashed line), and not 9000 ft/s (SOL replacement velocity denoted by red dashed line) as assumed in the original processing.

In the second segment, velocities vary from 8266 ft/s to 10778 ft/s, with a mean average of 9436 ft/s. As with the first segment, a histogram of the velocities displays a skew towards lower velocities, although this skew is less pronounced (Figure 3.8). The standard deviation of segment two is 453.5 ft/s. When we compare the distributions of the two segments, we can see that there is a greater variability in modeled velocities in the first segment than in the second

(Figure 3.9). It is also important to note that the modeled velocities are consistently higher in the second segment than the first.

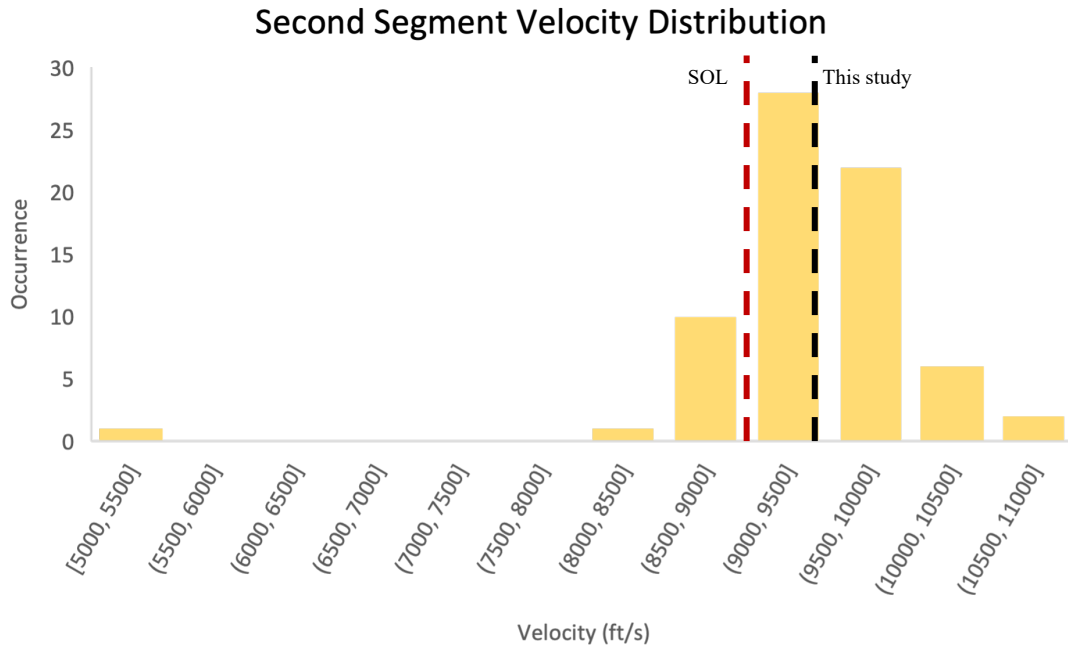


Figure 3.8 shows a histogram of the velocities modeled across the study area based upon the first arrivals segment two, with occurrence on the y-axis and velocity in feet per second (ft/s) on the x-axis. The velocities have a range of nearly 3000 ft/s, and the distribution approaches normal, but with a slight skew towards lower velocities. The velocities tend to center on 9500 ft/s (mean average denoted by black dashed line), which deviates from the 9000 ft/s replacement velocity used in the original processing (denoted by red dashed line).

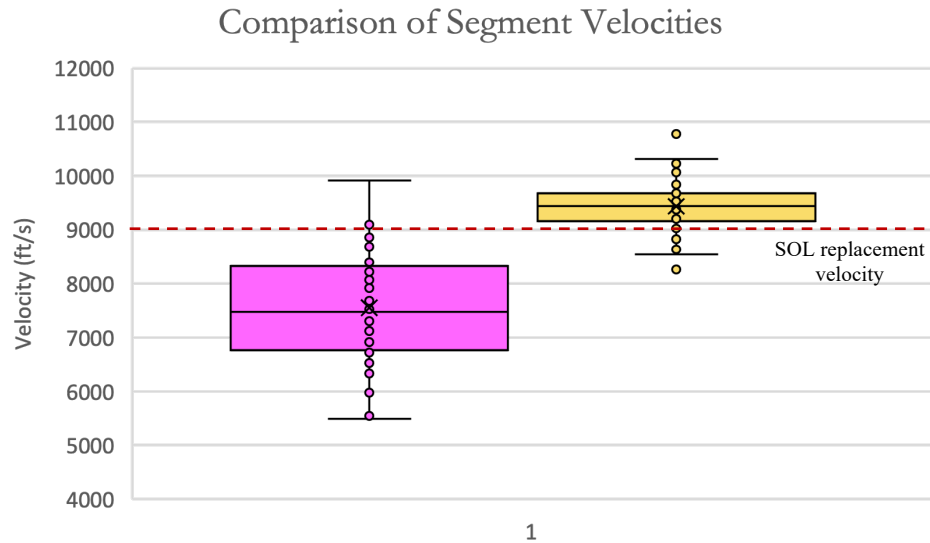


Figure 3.9 shows a box and whisker plot in order to visualize the variation in the modeled velocities of the two segments. Segment one (pink) has a much large range and standard deviation but is centered on lower velocities than segment two (yellow), which has a smaller range and is centered on higher velocities. There is better agreement between the mean (represented by the X) and median (represented by the solid central line of the box plot) averages in the segment two velocities, indicating a closer to normal distribution than the slightly skewed distribution of segment one. Neither segment agrees well with the 9000 ft/s replacement velocity used in the original processing (denoted by the red dashed line).

Figure 3.10 shows a sample of gather picks across a single receiver line; there is nearly a 3000 ft/s difference between the minimum and maximum velocities shown.

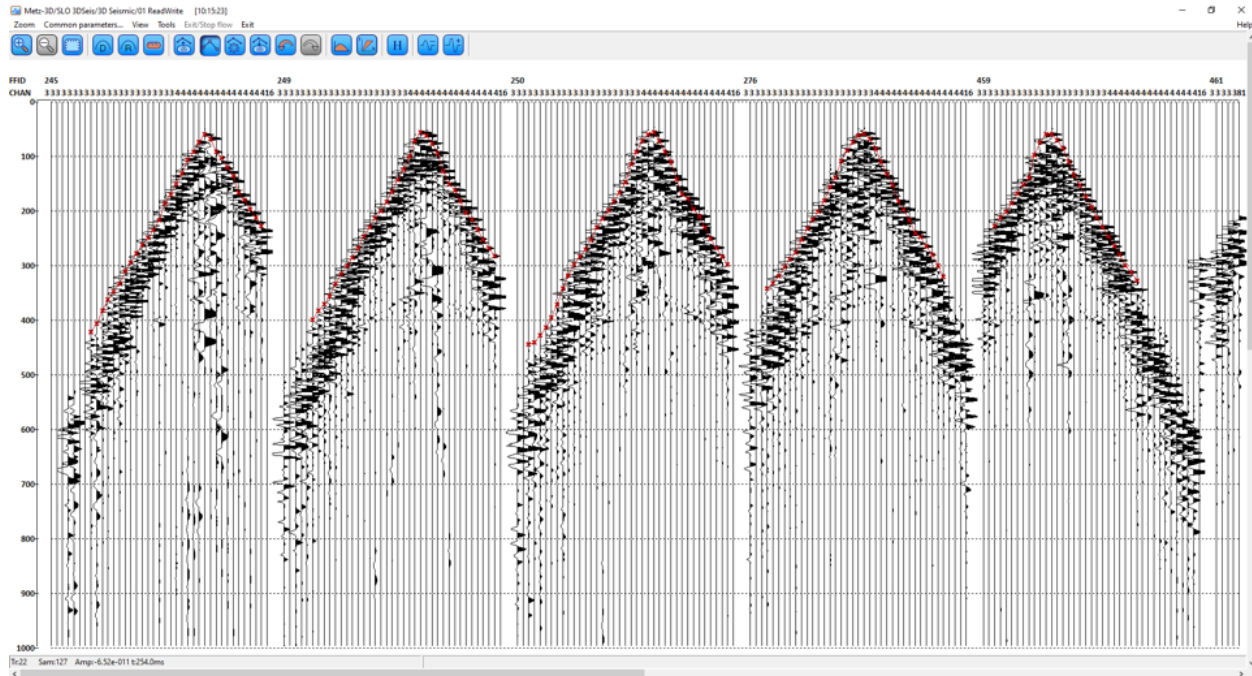
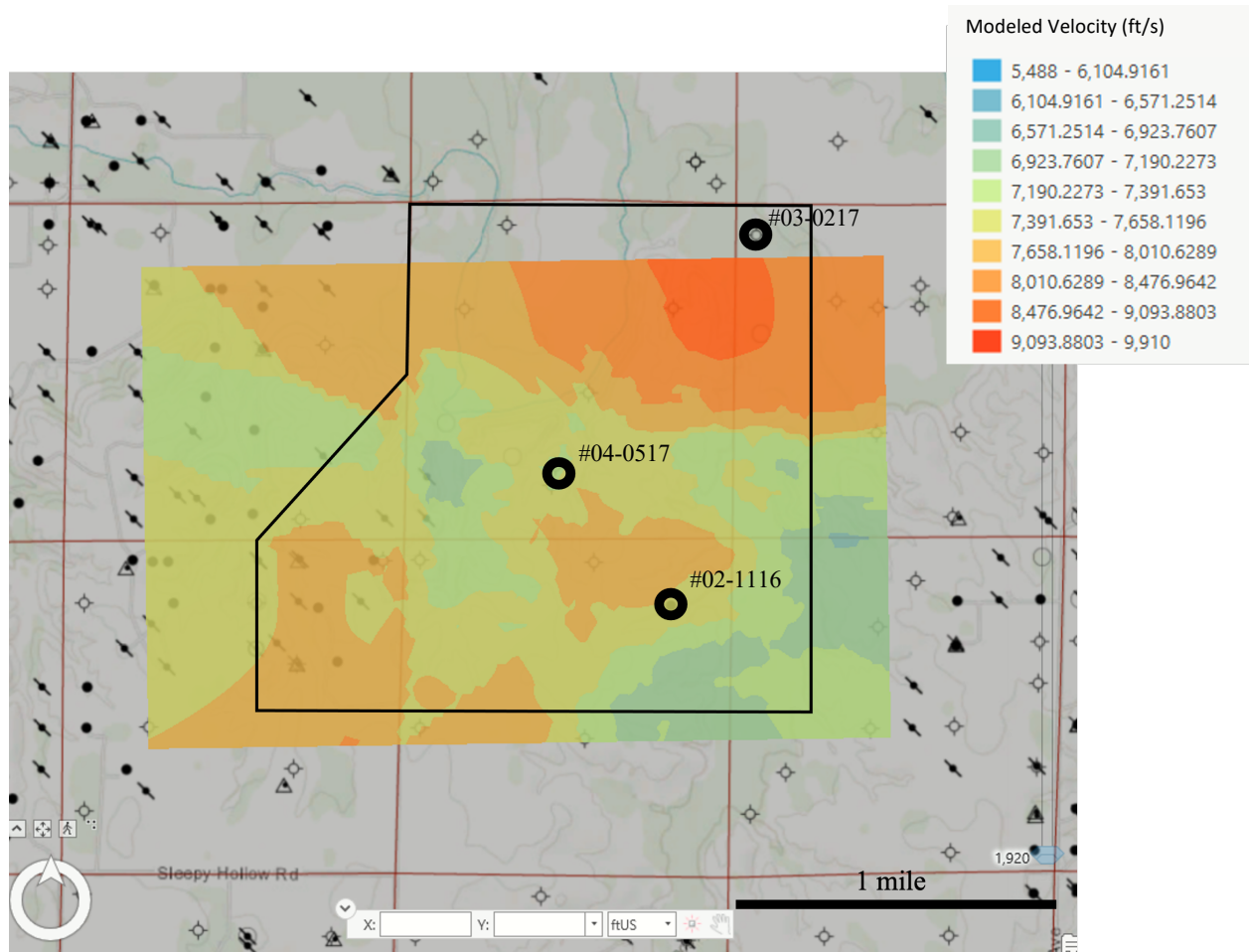


Figure 3.10 shows gathers from a portion of source line 122 from the seismic survey. As can be seen, the first arrivals have been interpreted (shown in red). Note that the character of the first arrivals is consistent across the line, with a steeper slope representing the earlier arrivals, and a gentler slope representing the first refractor.

This heterogeneity in velocity can also be shown on modeled velocity maps of the study area (Figure 3.11, Figure 3.12). Spatially, we can see that the greatest deviations of modeled velocities from the 9000 ft/s original replacement velocity occur in the same area as the apparent structural high in the original seismic interpretation from SOL (Figure 1.3, Figure 1.8). There is a strong correlation between changes in modeled velocity and changes in topography in both the first segment velocity map and the first refractor velocity map. In addition, there is a significant difference in modeled velocities between the areas of limestone bluffs versus the alluvial deposits corresponding to the Saline River.



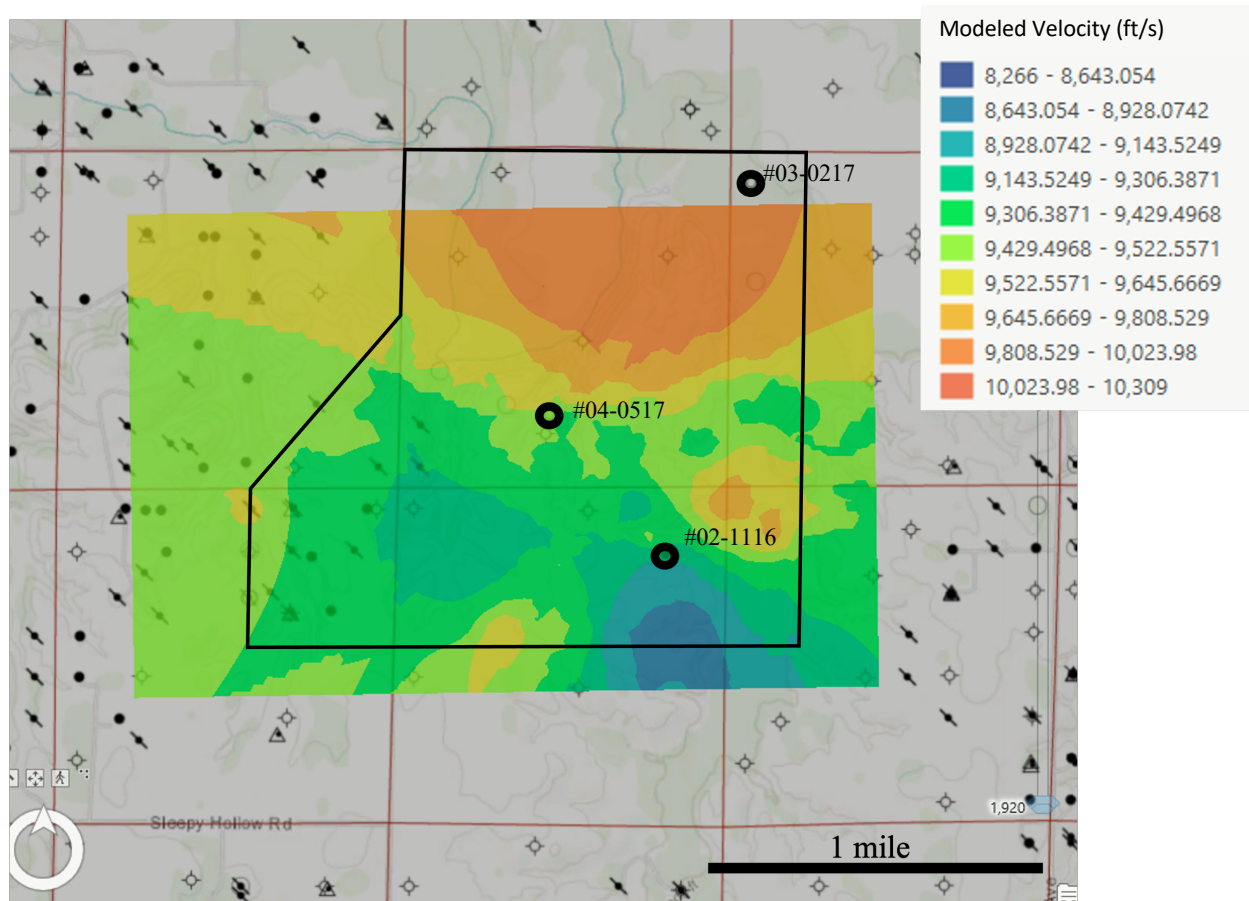


Figure 3.12 shows a map of the modeled velocities corresponding to the first refractor. The survey boundary is shown in black, with the three SOL wells highlighted with black circles. Other symbols on this map represent other oil wells not relevant to this study. The same grid as the map in Figure 3.10 is used. The map was generated using empirical Bayesian kriging in IHS Kingdom® 2022 to extrapolate between the modeled velocities locations. As with the first segment modeled velocity map, there is a strong correlation between changes in the first refractor velocities and topography throughout the area. The velocities most closely resemble the replacement velocity used in the area of well #02-1116 and deviate more in the areas of wells #04-0517 and #03-0217. There is significant heterogeneity throughout, especially through the central portion of the study area.

Depth Conversion

The interpreted velocities are used as the input for tomographic inversion. The result is a model of the depth of the first refraction event at each input point. This model shows significant variations across the survey area, with depths ranging from 429 feet to 2449 feet, a mean depth of 913 feet, and a standard deviation of 420 feet. The distribution of modeled depth points is

shown in Figure 3.13. This distribution displays a large skew towards shallower depths, with the primary peak centered in the 500-700 feet range. There is also a weak bimodal character, with a secondary peak centered in the 1030-1130 feet range. The mean of the data, 913 feet, is in the middle of these two peaks. A structure-contour map corresponding to the base of the low velocity layer (LVL) (Figure 3.14) displays the spatial heterogeneity in the thickness of the LVL across the study area. This map is created using empirical Bayesian kriging in IHS Kingdom® 2022 to extrapolate between modeled depths to the base of the LVL, with the same grid discussed above. Overall there is an apparent correlation between topography and changes in depth to the base of the LVL. In the areas dominated by limestone bluffs (Figure 1.7), the LVL thickness is noticeably thinner than in areas dominated by alluvial lowlands and steep drainage channels. There is also an area of increased thickness in the LVL in the central portion of the study area, trending north-south. This feature is in the same location as the apparent structural high seen in the originally processed seismic from SOL. Well #04-0517 is also located in this area; there is a 14 foot discrepancy between the expected depth of the top of the Arbuckle surface as interpreted from the original seismic data, and the actual depth of the top of the Arbuckle surface noted in the well logs.

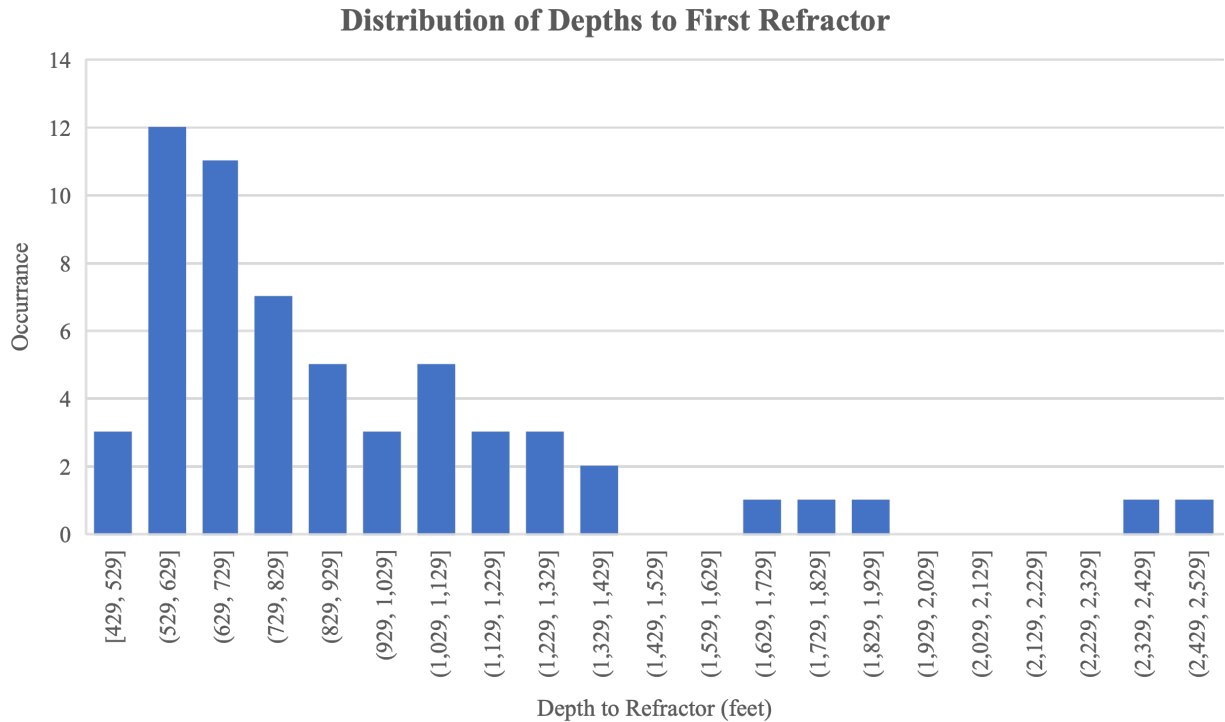


Figure 3.13 presents the distribution of depths to the first refractor in histogram form. There is a large spread of depths, ranging from 429 feet to 2449 feet. Each bar of the histogram represents the occurrence for depths in intervals of 100 feet. The mean of this dataset is 913 feet; however, there are more data points clustered around the intervals representing 529-729 feet. The distribution displays a large skew towards the shallower depths, and a long tail towards greater depths. There is an almost bimodal character of the distribution as well, with the secondary peak centered on the 1029-1129 feet interval.

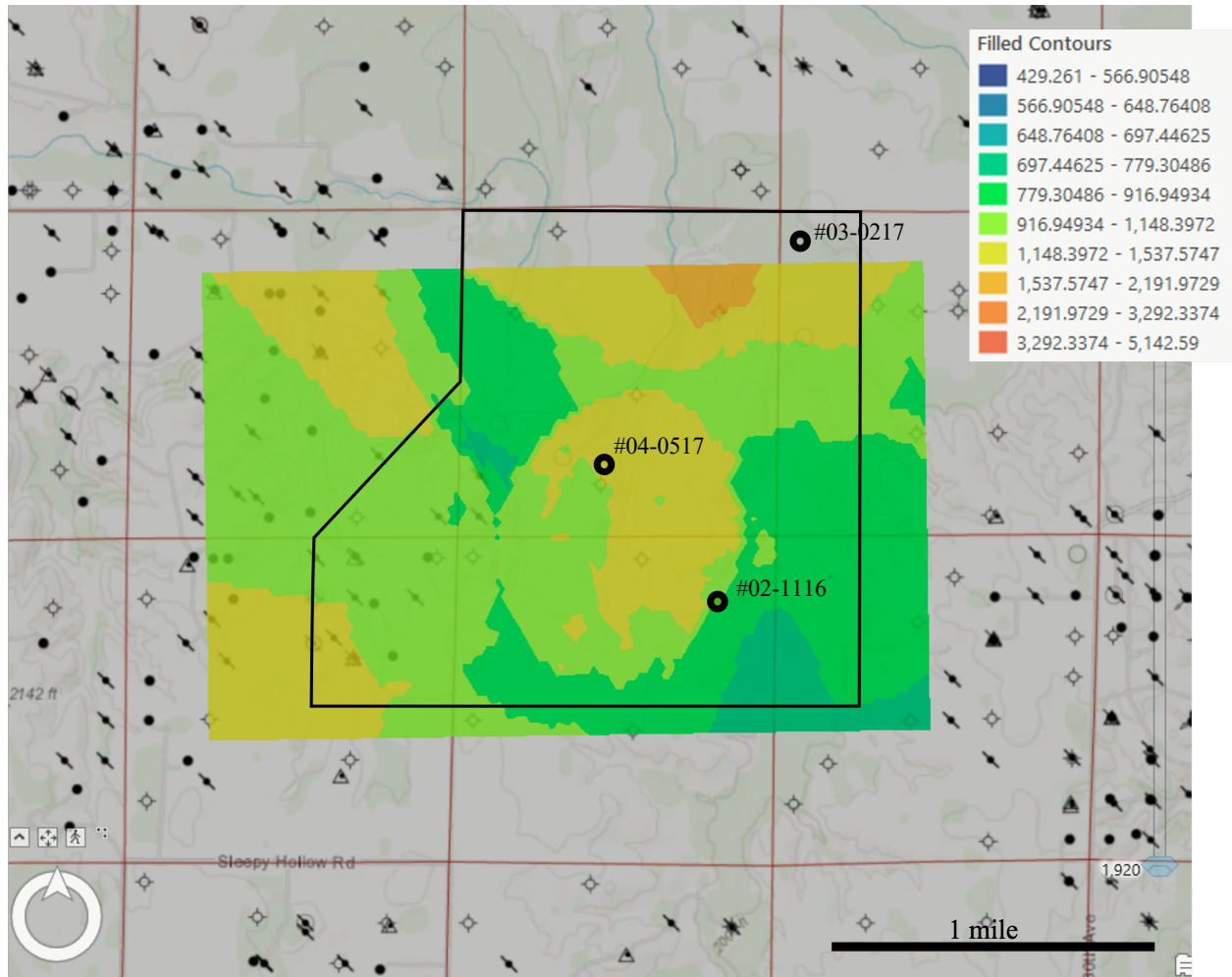


Figure 3.14 shows a structure-contour map of depth to the base of the low velocity layer based on the modeled velocities. The seismic survey area is outlined in black, with the three SOL wells highlighted. The map was generated using empirical Bayesian kriging in IHS Kingdom® 2022 with the same grid as the velocity maps shown above. Warmer colors correspond to greater depths to the base of the LVL, while cooler colors represent shallower depths to the base of the LVL. As with the other maps, there is a strong correlation between topographic changes and depth changes (compare with Figure 1.6 and Figure 1.7). It is also important to note that through the central portion of the study area, in the same area as the apparent structural high in the original interpretation by SOL, there is a notable increase in depth to the LVL.

The variation is also evident in a cross-sectional view (Figure 3.15, 3.16, 3.17). It is clear there is lateral variation in the depth to the first refractor boundary both along source-receiver lines and across source-receiver lines. This spatial heterogeneity often coincides with changes in topography and varies by 500 feet, on average, across each receiver line.

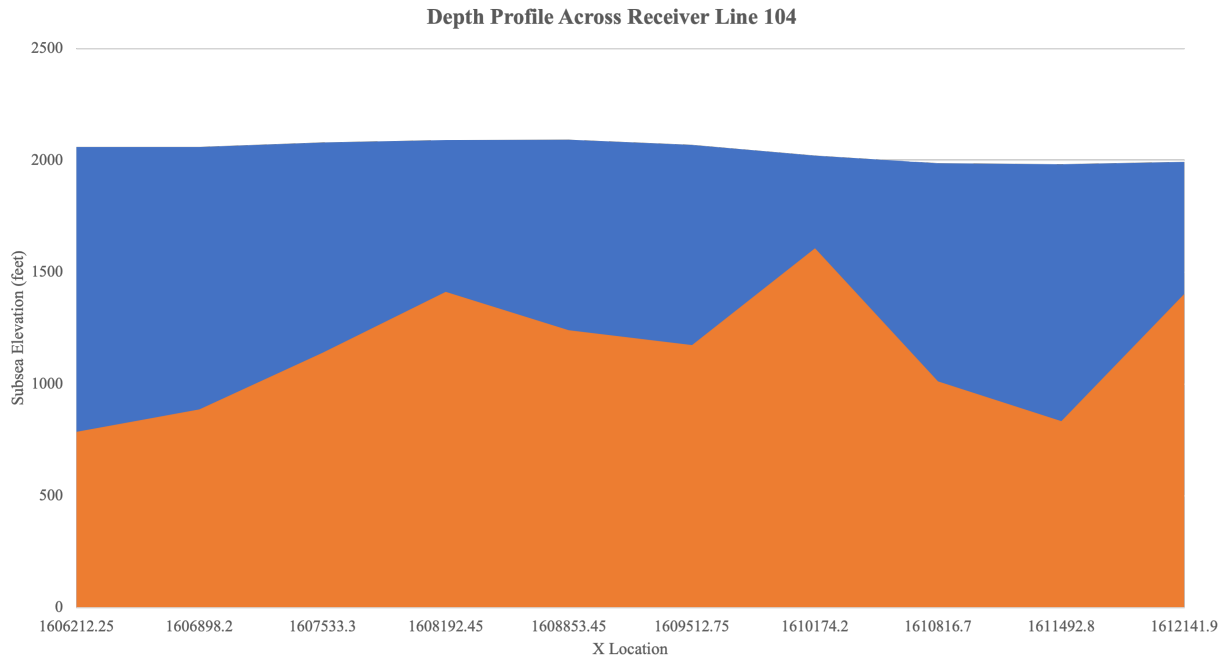


Figure 3.15 shows the modeled depth profile of the first refractor boundary across receiver line 104, in the southernmost portion of the study area. The shot gathers and interpreted first arrivals from this line are shown in Figure 3.3. It is clear the base of the refraction boundary (shown as the boundary between blue and orange) varies in depth laterally across the line. It is also important to note that the portions of the cross section with deeper refractor boundary depth correspond to areas with drainage features in the study area.

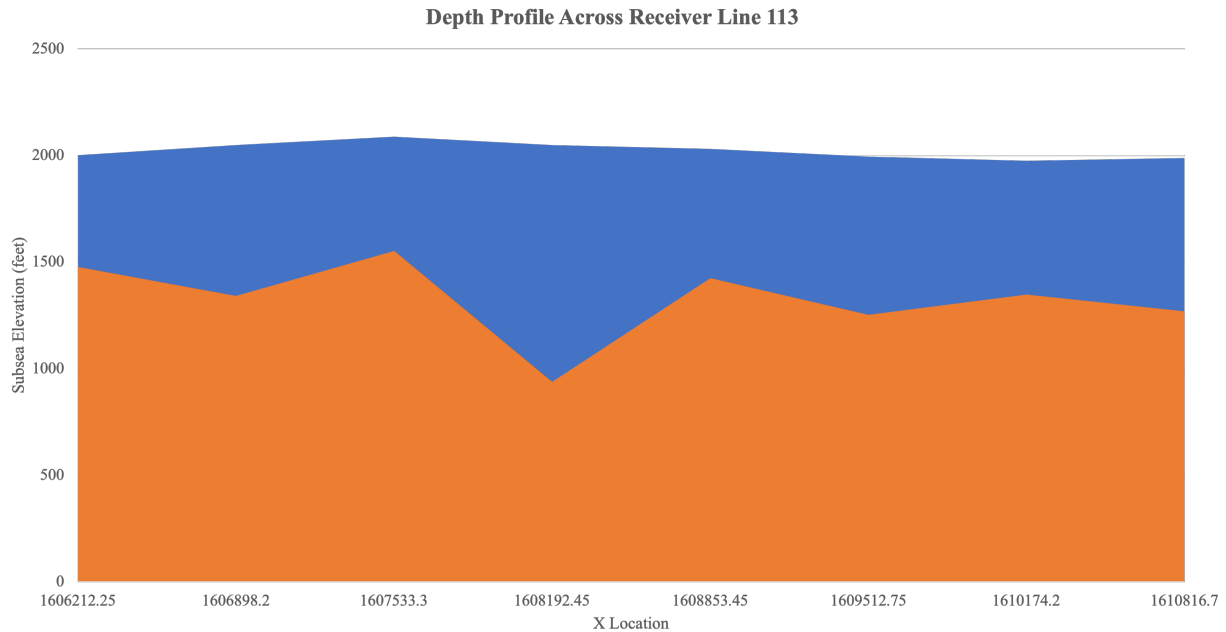


Figure 3.16 shows the modeled depth profile of the first refractor boundary across receiver line 113 also in the southern portion of the study area. The shot gathers and interpreted first arrivals for this line are shown in Figure 3.4. There is significant lateral variation in the depth of the first refraction boundary, with a variation of nearly 500 feet in places. The central portion of this profile, where the depth to refraction boundary is greatest, coincides with a drainage channel in this part of the study area.

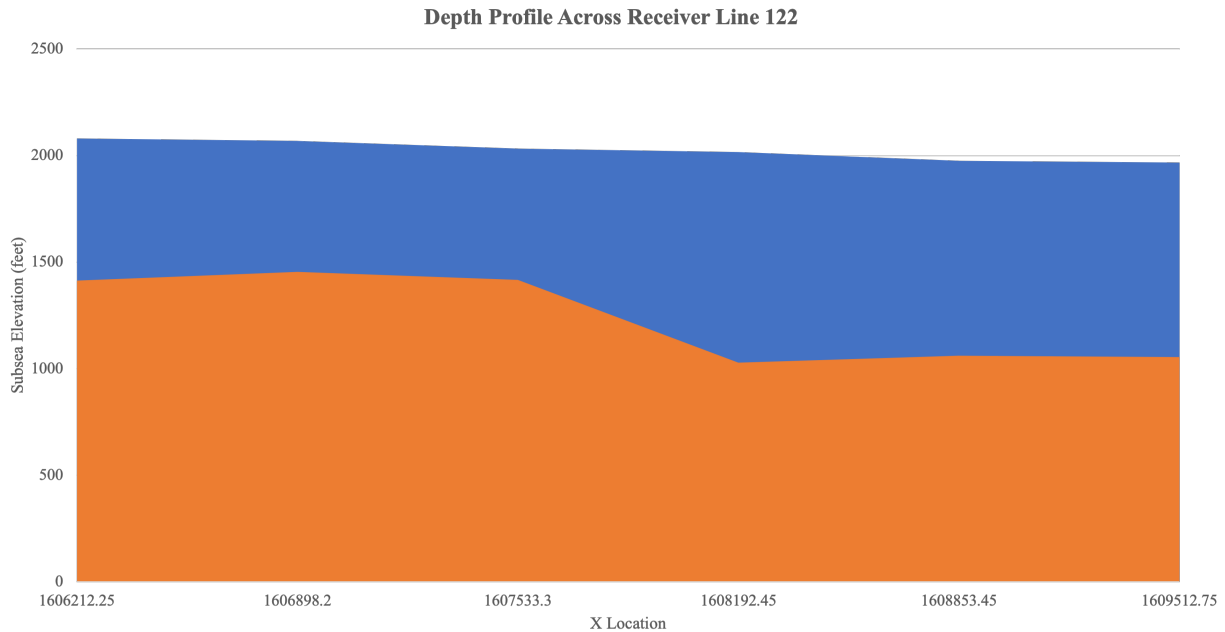


Figure 3.17 shows a depth profile of the first refractor boundary across receiver line 122 in the central portion of the survey area. The shot gathers and interpreted first arrivals for this line are displayed in Figure 3.5. There is some lateral variation across the profile, notably a monoclinial dip towards the east in the central portion of the profile.

Seismic Datum Adjustments

The shallow refraction model was subtracted from surfaces of interest in order to create datum-corrected surfaces. Modeled bulk time shifts across the study area show significant departure from flat, uniform time shift (Figure 3.18). There is heterogeneity in static shifts, with upward shifts along the topographically high limestone bluffs in the western portion of the study area, and downward shifts in topographically low areas dominated by alluvium (compare Figure 3.18 with Figure 1.18). There is a significant downward time shift (upwards of 100 ms) through the central portion of the study area, in the same general area as the apparent structural high noted by SOL. The Custer Valley #04-0517 well is located on the flank of this feature. Between these features, bulk shifts are smaller, generally between 30 ms and 80 ms.

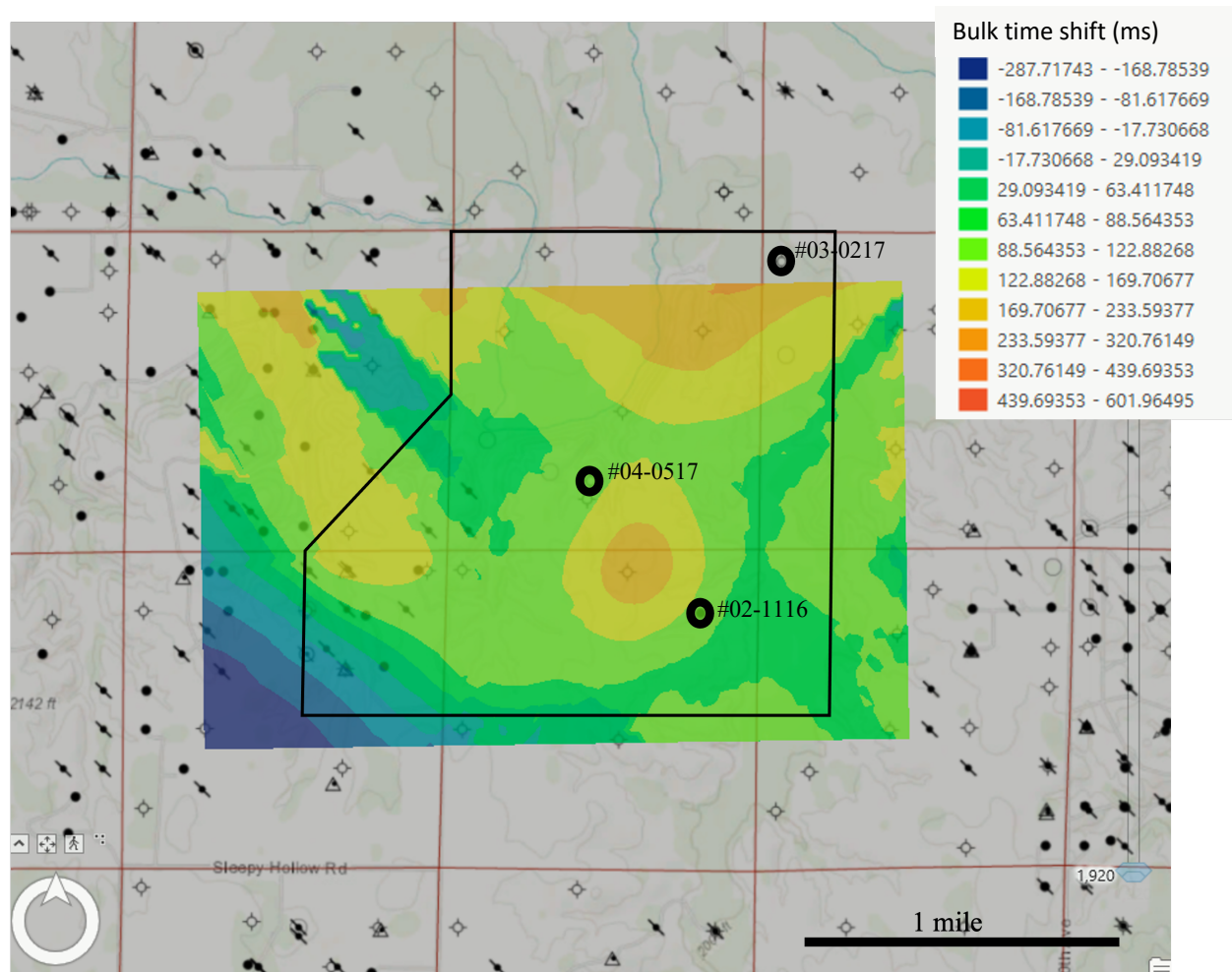


Figure 3.18 displays a map of the bulk time shifts executed across the study area. Upwards time shifts are represented by cooler colors (blue) while downward time shifts are represented by warmer colors (green to red). Most of the study area shows a downward shift, but there are several features of note. The most obvious of these is the significant downward shifts in the center of the study area, with shifts of 100 ms and greater. There are two wells on the flanks of this feature, Custer Valley #04-0517 to the northwest and Custer Valley #02-1116 to the southeast. There is also notably a dry hole in the center of the feature. There are upwards time shifts in the southwestern portion of the study area dominated by topographically high limestone bluffs, and downwards time shifts in the northern portion of the study area dominated by alluvial lowlands.

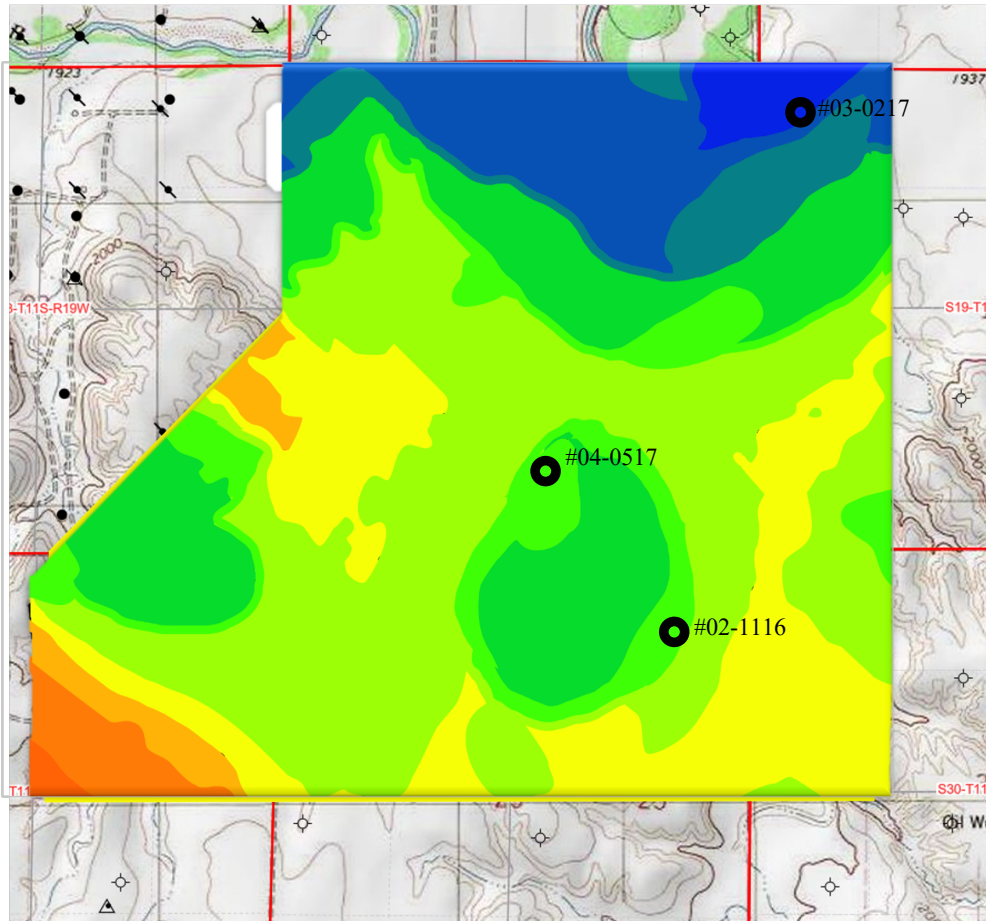


Figure 3.19 shows the datum-corrected Stone Corral anhydrite time-contour map, which shows no apparent structural high in the central portion of the map. Rather, the apparent structure appears to be generally flat with minor differences through the center of the study area. There also seems to be a gentle dip towards the east-northeast, consistent with the eastern limb of an anticlinal structure. In addition, there is better agreement between this Stone Corral anhydrite surface and well log data across the area.

There are clear deviations from the original interpreted Stone Corral anhydrite surface; instead of an apparent high in the center of the study area (original), the surface is generally flat with minor deviations through the center of the study area. Additionally, there is a gentle apparent dip towards the east-northeast portion of the area. This is consistent with the geometry of an eastern limb of an anticlinal structure. It is notable that the area dominated by the Saline River alluvium displays a distinctly different character to the rest of the study area. It is possible

that this is associated with the different sonic properties of the clastic alluvium overlying the Stone Corral anhydrite rather than the carbonate-dominated depositional facies of the southern portion of the study area.

Chapter 4 - Discussion

One of the primary aims of this thesis is to characterize the effects of changes in velocity on a collection of wavelets, which manifest as time shifts on the seismic traces. We can see the effects of changes in velocity on the shape of wavelets through forward modeling of Ricker wavelets. At higher frequencies, the breadth of the wavelets increases, meaning the amplitude peaks associated with each wavelet occur at different travel times. When the wavelets are then summed, the overall effect on amplitude is compounded.

From an investigation of the pre-stack dataset provided by SOL, it is clear that even small time shifts can affect deeper portions of the seismic trace (Figure 1.10). This is true of velocities both faster and slower than the original processing replacement velocity. In areas where the velocities are overestimated by the original replacement velocity, there is a vertical shift upwards on the seismic traces (compare Figure 3.8, 3.12, and 3.18). Horizons come in higher than their actual ground truth (Table 1.1). Where velocities are overestimated by the original processing replacement velocity, there is a downwards time shift in the traces (compare Figure 3.8, 3.12, and 3.18). Horizons come in lower than their actual ground truth (Table 1.1). It is clear that accurate static errors corrections are essential to a processing workflow. A time shift can be used to correct the results of erroneous velocity values and shallow velocity estimations without completely distorting the character of the seismic data at deeper intervals.

One of the effects generally associated with high relief features in a survey study area is side scatter (Yilmaz, 2001). It is obvious that there is an impact from this phenomenon on the dataset. Side scatter adds artifacts to the traces not associated with the base of the LVL and, thus, presents an issue to accurate interpretation of that surface. It is important to choose first arrivals

on the gathers least affected by side scatter. Therefore, the interpreted first arrivals and the subsequent modeled velocities in this study were screened for quality in this regard.

It is commonly accepted that the first segment distinguished during the first arrivals interpretation represents the direct arrivals, the wave energy that travels along the ground surface to receivers, while the second segment represents the first refraction event (Lawton, 1989). It is clear from the velocity modeling that there is significant variation in the velocities of both the direct waves and first refractors across the study area (Figure 3.11, 3.12). In some respect this is unsurprising, as unconsolidated alluvium has different geophysical properties than weathered limestone. The heterogeneity in the geological makeup of the study area also is a control on topography, and we see a correlation between areas that have significant topographic changes and areas with significant variation in modeled velocities (compare Figure 1.6 with Figure 3.11 and 3.12). This level of correlation further shows the inadequacy of a singular replacement velocity across a seismic dataset as this. The areas that show the greatest disparity between the velocity used in the original processing and the newly modeled velocities correspond to those areas with the greatest disparity between the interpretation by SOL and the actual geology as interpreted from well information (Compare Figures 3.11 and 3.12 with Table 1.1). The modeled velocities of the direct arrivals show a greater variation than the first refractors (see Figure 3.9), which is likely due to greater heterogeneity at the surface. For example, the direct arrivals distribution is skewed towards slower velocities (Figure 3.7); surface material is more likely to be unconsolidated, especially where there is alluvium, favoring slower velocities. A similar skew towards slower velocities can be seen in the first refractor arrivals (Figure 3.8); however, the modeled velocities of the first refractors are centered on much higher velocities. This reflects the

greater variation in geophysical character at the ground surface and the increased velocity with depth.

Modeled velocities, in both the direct arrivals and the first refractors, are significantly greater than those expected in the LVL by at least an order of magnitude. These velocities are more akin to those of consolidated rock. This implies that the material in this interval is not unconsolidated, aerated sediment. It also indicates that the first refractor occurs at some erosional surface within the stratigraphic column not generally noted on the seismic. The geology of the study area is made up of a series of cyclothems, with various incidents of exposure of bedrock at the surface throughout its history (Merriam, 1961). It is thus reasonable to assume that weathering has variably affected the stratigraphic column, which would contribute to heterogeneity of acoustic properties across the study area. This has important implications for static errors corrections across Kansas and other areas where the shallow stratigraphy is primarily comprised of series of cyclothems. From this point forward, the low velocity layer will refer to the erosional surface at which the first refraction event occurs.

A closer look at the modeled depths to the LVL further indicates a relationship between geology, topography, and first refractor behavior. As with modeled velocities, modeled depths vary across the study area (Figure 3.14). It is clear that the base of the LVL is not flat, nor horizontal, as is assumed in the original processing. This can be seen in the cross-sectional profiles across the study area (Figures 3.15, 3.16, 3.17). These figures show that depths to the LVL base are greater where there are drainage features, as would be expected, and in the areas dominated by alluvium surficial geology. One would expect a thicker weathered zone within a river floodplain and along drainage channels where more intense weathering has occurred, and the depth model reflects this. This has deep implications for any static errors solution, especially

in areas similar to this study area, where there is such extreme differential weathering. A blanket static errors solution would not adequately address the heterogeneity present, but a close investigation of first arrivals can help to diagnose or mitigate issues in a simple and time-efficient manner, as shown in this study.

As expected based on the modeled velocities, the depths to the LVL base are much greater than one would expect of a traditional LVL comprised of unconsolidated, aerated sediment. This supports the idea that significant impacts from weathering, associated with the cyclothem stratigraphy in the study area, are observed. It is possible that there are multiple erosional surfaces and a gradational velocity change in the subsurface in lieu of a significant refractor surface. This poses numerous challenges when determining a velocity model, especially at depth (Yilmaz, 2001). It is likely that, as with the static errors correction, a deep velocity correction will need to encompass significant spatial variation in both the lateral and vertical directions. A bulk shift statics correction is insufficient to resolve the level of heterogeneity seen in this dataset and others like it.

As with velocity and depth, modeled bulk shift statics display spatial heterogeneity across the study area, likely related to a topographic control (compare Figure 1.6 and 3.18). Generally, there are upward time shifts along the topographic highs and downward time shifts in the topographic lows. There also seems to be a strong lithologic control on datum corrections (compare Figure 1.7 and 3.18). There is a marked difference between areas where there are cliff-forming limestone bluffs versus those dominated by the alluvium associated with the Saline River. The footprint of the Saline River as it moves through the study area is very clearly distinguished by increased downward bulk time shifts (Figure 3.18). It is also noteworthy that there is a larger downward shift in the central portion of the study area, in the same location as

the apparent structural high in the original interpretation by SOL. This confirms that the apparent structural high was an artifact of an inadequate statics solution, and not related to an actual anticlinal structure. In general, we see larger bulk shifts in areas where there are greater deviations from both the original seismic datum of 2100 ft above sea level and the original replacement velocity of 9000 ft/s. It is clear from Figure 3.19 that the method used here is capable of accommodating these deviations to create a static errors correction tailored to specific datasets.

The greatest differences between the original surface of the Stone Corral formation occur where the velocities show the most deviation from the 9000 ft/s replacement velocity of the original processing. There is a clear difference in the apparent structure in these areas; the static corrections done here have removed the topographic imprint from the deeper surfaces (compare Figure 1.8 and 3.19). Where there is an apparent structural high through the center of the study area with the original processing, after static corrections there is no such feature, and the study area broadly dips to the east. This broadly dipping apparent structure fits with known geology of the surrounding areas. There is a highly productive field directly adjacent to the study area to the west, determined to be an anticlinal trap, and it is likely that the study area is located along the eastern dipping limb of that anticlinal structure.

It is important to note that the method employed in this study successfully removed topographic imprint without the need for additional data. This indicates that the method is well suited to characterizing the near surface in areas with previously shot seismic data, especially in areas where well data and seismic interpretations lack agreement.

There are certainly some limitations with the methodology presented here. Firstly, it is imperative that the datasets possess well-resolved geometries. This is true of any tomographic

methodology but is especially important when dealing with the near surface. Correct geometry was an issue with the Metz 3D dataset, but this was mostly resolved through the work of Tucci (2019).

We have inferred that the base of the LVL does not represent a singular geologic unit, but rather a series of erosional surfaces. If correct, additional velocity analysis is necessary to fully characterize the stratigraphic column. The methodology developed here is effective in determining where static errors issues may be most severe, and in resolving some of the near surface statics disparities relating to refraction processes. It is not, however, an effective replacement for characterizing velocities at depth, and significant velocity modeling is still needed to adequately perform well-to-seismic ties and time-depth conversions. In addition, this method represents a secondary analysis, and does not actively measure velocity at depth. A borehole geophysical survey is recommended in order to accurately measure velocities downhole, which could then be used to constrain velocity modeling as part of the seismic data processing for a survey. Such an analysis was not included in this project due to well access restrictions, but future work would greatly benefit from including such information.

Chapter 5 - Conclusions

Static errors corrections are an essential portion of the seismic data processing workflow, and inadequate or incorrect solutions have profound negative impacts on seismic datasets and subsequent interpretation. This seems to be especially true in areas like the Ellis Co. study area – areas with steep topography, rapid changes in relief, and variable impacts from weathering. Large-scale differential weathering, especially when compounded over long periods of geologic time, causes significant variation of geophysical properties such as porosity and other related responses (such as acoustic impedance and travel time). This project has shown that in areas affected by differential weathering, a simple, constant replacement velocity is unable to adequately capture the variability in seismic velocities. Using such an average generates unwanted artifacts within the dataset, especially those associated with lithological changes. As lithology is often a control on topography, there can be a topographical “imprint” on the data even at depth. This can cause significant problems when attempting to accurately characterize areas based on seismic data.

First-arrivals picking was used to interpret the arrivals of both the direct wave and the first refractor, and the slopes of these were used to model velocities of these segments. Significant variation of velocity exists, both within segment populations and between them. The segment associated with the direct waves showed larger variations in velocity, with velocities ranging between 5488 ft/s and 9910 ft/s, while the segment associated with the first refractor displayed slightly less variation, ranging from 8266 ft/s to 10,778 ft/s. As expected, velocities associated with the first refractor are greater than those associated with the direct wave. It is notable that the modeled refractor velocities center on 9500 ft/s, a departure from the 9000 ft/s replacement velocity used in the original processing. In a map of the Stone Corral anhydrite, the

greatest deviations from the 9000 ft/s replacement velocity are seen in the area of the apparent structural high interpreted by Stroke of Luck Energy and Exploration LLC. Given the results of the first refractor velocity modeling, it is clear that a blanket replacement velocity is inadequate for static errors corrections in this dataset.

The velocities modeled are significantly higher than those expected in a traditional low-velocity layer. There are several potential reasons for this, but it is likely that the differential weathering of the cyclothem stratigraphy through time is a control. There are likely many erosional surfaces through the stratigraphic column that cause refraction, and it is possible that a gradational velocity model would be better suited to capture this than the traditional low-velocity layer concept.

A bulk time shift computed from the modeled velocities across the study area shows the variable time shifts necessary to resolve some of the near-surface static errors. A map of the bulk shifts shows that the largest shifts are in the locations of the largest deviations from the 9000 ft/s replacement velocities of the original processing, and in the central portion of the study area. After completing the bulk time shift for the Stone Corral anhydrite time-contour map, one can see that there is a significant difference in the apparent structure. Instead of an apparent high in the central portion of the study area, the study area is generally flat, with an east-northeast apparent dip. This is more consistent with other interpretations of geology in the area, which place the study area on the eastern limb of an anticlinal structure. Given this, it is likely that the methodology, at least in part, was able to adequately resolve some of the issues in the near-surface statics of the original dataset.

The methodology used in this project, while imperfect, is adequate for determining a more correct static errors solution. Picking first arrivals and determining first refractors is a cost

effective method for reevaluating existing datasets without the need for collecting additional data, and it lends itself well to accurately modeling direct wave and refractor velocities in a study area. Travel time tomographic inversion is an established method that is well equipped to deal with velocity variations across a study area that worked well in this case. Through these methods, it was possible to apply a bulk time shift, and the topographic artifact was removed in both the time and depth dimensions. This is significant, as it implies that this method could be applied with some success to other datasets that exhibit similar issues.

There are several limitations to this method. Namely, there are more sophisticated inversion methodologies that may be better equipped to deal with variations across short distances. In addition, this is an indirect method to modeling velocities. A downhole geophysical study of vertical velocity profiles would help to constrain velocity modeling and provide more directly measurable data. Both of these would improve the accuracy and resolution of the static errors corrections and would be useful case studies to complete in the future. Overall, however, this methodology could be an important diagnostic tool to help determine the cause of issues with seismic datasets in Kansas, as well as a baseline improvement upon poorly resolved static errors issues in those same datasets.

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