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1 Executive Summary

House Bill 722 has established a legal framework for Groundwater Conservation Districts to permit the development of water supplies from designated brackish groundwater production zones. These water supplies can be local to regional in size, moderately to highly productive and slightly- to very-saline in water quality. Development of these zones requires reliable estimates of the extent and volume of the resources, as well as delineation of their locations and depths.

Seismic surveys are commonly used in the oil and gas industry to characterize subsurface reservoirs and evaluate fluid volumes; however, owing to the prohibitive costs, they are not as frequently used in evaluating fresh or brackish groundwater aquifers despite similarities between aquifers and producing oil and gas reservoirs. In support of ongoing efforts to quantifiably assess the brackish groundwater resources within the state, the Texas Water Development Board's Brackish Resources Aquifer Characterization System Group chose to explore and evaluate the potential for the application of seismic data to the mapping of brackish resources. The objectives of this study are to determine the availability and suitability of two-dimensional and three-dimensional subsurface seismic data for use in brackish groundwater studies within the State of Texas. This report was separated into five main tasks and documents the study of seismic applications in brackish groundwater exploration.

Task 1 included a thorough literature review that included a brief background on seismic data acquisition, identification of recent studies utilizing subsurface seismic data for aquifer characterization, an evaluation of methodologies used in these studies, and a summary of how existing work may be applied to a Brackish Resources Aquifer Characterization System aquifer study. Relevant studies were separated into one of five categories and a summary of each publication, and its specific relevance is addressed in Chapter 3. The literature review showed that the existing literature provides several case studies and examples from different aquifer lithologies, structural settings and varying data availability. These publications also illustrate a wide variety of methods that involve seismic data used to resolve geologic complexity over a wide variety of geological settings.

The literature review also showed that reprocessing of seismic data (two- and three-dimensional) originally acquired for hydrocarbon exploration has been highly useful in many areas, both to extend data to shallower depths (Woodward and Al-Jeelani, 1993) or to improve resolution and confidence in the shallow, lower-fold section (Al-Gain and others, 2020). Reprocessing is expected to be particularly useful in areas where the shallow section was not of interest to the original data processors and users. In each case where utilized, seismic reflection data have led to the ability to predict structural and stratigraphic data away from well control with a high degree of fidelity to the true nature of the subsurface. While there have traditionally been cost barriers to use in the groundwater industry, some forays have shown the utility of seismic aquifer exploration and characterization.

Task 2 involved a systematic review of seismic data availability in the state of Texas. As anticipated, most seismic reflection data (lines and volumes) in Texas were acquired for oil and gas exploration and development and, therefore, most of the existing seismic data that can be used for aquifer characterization exist in the productive oil and gas regions of Texas. These data have been acquired either by oil and gas companies ("proprietary data") or by seismic acquisition firms, with underwriting from oil and gas companies ("speculative data" or "multiclient data"). Much of the proprietary data have since been either sold or made available for licensing to seismic acquisition firms or seismic exchanges on similar terms to multiclient data. A small number of seismic exchanges control most of the multiclient seismic data available in Texas and the offshore shelf; the two largest are Seismic Exchange, Inc. and Seitel Data, followed by CGG and Fairfield Geotechnologies. In the Federal Outer Continental Shelf, the National Archive of Marine Seismic Surveys (operated by the United States Geological Survey) has many two-dimensional lines and three-dimensional volumes acquired from 1977 to 1995 available to use at no charge. INTERA accessed ESRI ArcGIS shapefiles of the aforementioned seismic vendor's catalogues and created maps showing seismic data availability by type (two- or three-dimensional) and vendor.

As we discovered, Texas contains a vast amount of seismic data, both two-dimensional profiles and three-dimensional volumes. Within the Gulf Coast and in most parts of West Texas, East Texas and the eastern Panhandle, one is likely to find data that are germane to groundwater/brackish water studies. Even areas with limited two-dimensional data, such as the Balcones-Dallas trend, may find some of the data useful in structural and stratigraphic correlation. The data coverage includes a wide variety of vintages. Multifold two-dimensional lines may be as old as the 1960s or early 1970s and were acquired in large amounts through to the 2000s. The three-dimensional surveys were experimental in the 1970s and began large-scale acquisition in the late 1980s and 1990s. Acquisition since 2008 has largely been in the active resource plays ("shale plays"), particularly in the Eagle Ford trend and the Midland and Delaware Basins.

Task 3 involved a review of data quality and limitations encountered when trying to incorporate a legacy seismic survey into an aquifer characterization. The review first addressed the goals of a common hydrogeologic investigation and included structural interpretation, stratigraphic interpretation, estimating aquifer extent in intervals and imaging aquifer and geobody properties and geometries. Following this, a review of the inherent limitations included an analysis of spatial coverage of the data, lack of salinity information, limits on resolution, limits on reflection strength and quality of the data at shallow depths. A review of the types of seismic reflection data was separated into two-dimensional, which are acquired along a line and produce a seismic profile, and three-dimensional data, which are acquired on a grid or patch and produce a volume of seismic data. High-resolution shallow seismic, specifically acquired for groundwater or geotechnical investigations, was reviewed and discussed.

This was followed by a discussion on shallow applications of seismic reflection data that included key questions to be answered when deciding when to license seismic data. These questions and subsequent discussions included: How to select seismic data that have the quality necessary for an investigation? What acquisition parameters are acceptable? Are there regional impacts on what can be expected from the data? Should one use the processed images of profiles or volumes that are given on licensing, or should one plan to reprocess the data to generate improved images?

Since most multifold seismic data require extensive processing to yield usable seismic images, Task 3 included an overview of regular processing and interpretation of seismic data. The processing is usually undertaken at a dedicated processing shop on dedicated workstations, due to the data volumes involved. A basic understanding of the processing steps as they are generally used is required to consider what enhancements are necessary for shallow reflectors and to develop a reprocessing workflow. The section was broken up into processing and interpretation sequences. Finally, pitfalls associated with processing and interpretation of shallow brackish aquifers were addressed and separated into issues in processing and issues in interpretation.

In summary, all issues associated with data quality and limitations can be examined in light of a few questions of resolution: the inherent resolution of our seismic data, what needs to be imaged in the depth range of brackish water aquifers, and what the sources of reflectors are.

Task 4 detailed a methodology for application of seismic data on brackish aquifers. Having considered the issues and limitations of conventional seismic reflection data as acquired for hydrocarbon exploration and subsequently applied to groundwater projects, the section first outlines a general workflow for integration of such data into groundwater projects. Following this, the possible workflow variations for different basins and aquifers in Texas are considered. A concluding section reviews the major aquifers of Texas for possible utility of conventional seismic data.

Task 5 allowed for the application of our workflow to a seismic dataset: the Stratton three-dimensional survey in South Texas. The dataset is located in southwestern Nueces and adjoining counties, to the southwest of Corpus Christi, Texas. This dataset was chosen as (1) it is free and can be published without proprietary restrictions, (2) it lies in the Gulf Coast aquifer system, which has excellent potential for brackish water and abundant seismic data, and (3) the dataset is high quality and has a three-dimensional seismic volume along with several well logs.

Our approach to evaluating the dataset was consistent with the methodology proposed in Task 4 and showed that legacy seismic data, three-dimensional in this case, can provide significant advantages and insights when attempting to characterize a groundwater system. The study is typical in that geophysical logs, mainly spontaneous potential and resistivity, are the primary means of developing the geologic model. This study is atypical in that it also incorporates legacy three-dimensional seismic data into the analysis in support of further refining our understanding of the local sequence stratigraphy, the local structure and the occurrence and distribution of permeable units and aquifers. Reprocessing of the Stratton three-dimensional shows that geologically useful, high resolution data can be derived for the shallow aquifer units below depths of about 900 feet (260 milliseconds). In many units, isolated channel systems can be imaged, and their trends can be determined and mapped in three dimensions. The more continuous sandy zones present in the Lagarto and Oakville units create more continuous and laterally distributed reflectors. Analysis of the inversion products provides a more complete understanding of the internal geometries within these sandy zones. Reprocessing the top 600 milliseconds of data (above 2,000 feet) was essential and also greatly improved imaging of the entire Miocene section. With a quality three-dimensional seismic dataset that has been taken through inversion, the interconnectivity of the aquifer rock undergoes minimal to no interpolation, and the resulting geobodies are actual (data-driven) as opposed to modeled.

This study highlights the ways seismic data can inform our understanding of brackish aquifers within the state of Texas. In particular, the use of conventionally acquired seismic reflection data that may be usable either as-is or with reprocessing to provide relatively shallow (1,000 to 5,000 feet depth) geologic information about stratigraphic and structural features of aquifers containing brackish groundwater. This work has determined that seismic data can assist in defining the distribution and continuity of aquifers and confining units, mapping freshwater and brackish aquifers, determining depth and thickness of aquifers, mapping faults and fractures that affect flow, understanding and mapping subsurface stratigraphy and, when combined with geophysical logs, lithology/water quality distribution and extent.

2 Introduction

House Bill 722 has established a legal framework for Groundwater Conservation Districts to permit the development of water supplies from designated brackish groundwater production zones. These water supplies can be local to regional in size, moderately to highly productive and slightly- to very-saline in water quality. Development of these zones requires reliable estimates of the extent and volume of the resources, as well as delineation of their locations and depths.

Seismic surveys are commonly used in the oil and gas industry to characterize subsurface reservoirs and evaluate fluid volumes; however, owing to the prohibitive costs, they are not as frequently used in evaluating fresh or brackish groundwater reservoirs despite similarities between aquifers and producing oil and gas reservoirs. In support of ongoing efforts to quantifiably assess the brackish groundwater resources within the state, the Brackish Resources Aquifer Characterization System Department at the Texas Water Development Board chose to explore and evaluate the potential for the application of seismic data for the mapping of brackish groundwater systems.

The objectives of this study are to determine the availability and suitability of two-dimensional and three-dimensional subsurface seismic data for use in brackish groundwater studies. The applicability of the seismic data is tried based on its ability to define aquifer and confining unit geometry, aquifer character, and subsurface aquifer structure and stratigraphy.

This study was divided into five main tasks. The first task was to conduct a literature review identifying recent studies utilizing subsurface seismic data for aquifer characterization. Commentary was to be given on the methodologies and to determine what could be gleaned for the Brackish Resources Aquifer Characterization System Department from these studies. The second task was to determine the availability and pricing of two-dimensional and three-dimensional seismic data in Texas, with some discussion of processing history. The third task was to perform an initial assessment of existing seismic data quality. This task included directions to evaluate spatial limitations of seismic data coverage, viability thresholds for vertical and horizontal resolution of seismic data, and limitations in data quality at shallow depth. The fourth task is to create a project methodology including an interpretation workflow diagram customized to meet the specific objectives for brackish groundwater studies with great level of detail. The task also discusses assumptions and limitations for conventional and unconventional seismic interpretation techniques and their benefits in an aquifer study. The methodology addresses data collection, stratigraphy, seismic-sequence stratigraphy, and geology as well as hydrogeology. The fifth and final task was to apply methodology to a completed Brackish Resources Aquifer Characterization System aquifer study that is best suited based on existing subsurface seismic data availability and data quality.

The Gulf Coast Aquifer was best suited for the Task 5 study since it has good data density and a publicly available three-dimensional seismic volume. The volume is over the Stratton field in Nueces and Kleberg counties. The seismic volume was made publicly available by the Texas Bureau of Economic Geology with the condition that “anyone who utilizes the Stratton seismic data in research, publishing or otherwise should acknowledge that the data were collected and made available for worldwide education and training by the Bureau of Economic Geology at the University of Texas at Austin”.

3 Literature Review (Task I)

The first step in this study on the application of seismic data for the mapping of brackish groundwater systems is a thorough literature review with the following criteria:

1. Identify recent studies utilizing subsurface seismic data for aquifer characterization.
2. Evaluate methodologies from the studies.
3. Summarize how existing work may be applied to a Brackish Resources Aquifer Characterization System aquifer study.

We will first provide a brief background on seismic data acquisition and the seminal publications that non-experts can reference in an attempt to better understand the fundamentals, acquisition methodologies, and applications of seismic data. While the seismic reflection method has been used in subsurface exploration for over 80 years, the majority of the applications are within the realm of petroleum exploration. Most applications of seismic data acquisition in support of groundwater characterization have been small scale and primarily related to resolving structural and sedimentological features, stratigraphic contacts, and depth to basement in a localized study area. There are a few studies that will be discussed in this review that use seismic data which was originally acquired for deep oil and gas targets, to better resolve the geology of overlying groundwater units. This can be difficult as the parameters set for the original seismic data acquisition were optimized for deeper hydrocarbon-bearing units at the expense of the data quality of the units above. Finally, there are groundwater characterization studies that try to resolve data quality issues by reprocessing of the originally acquired seismic data to better resolve the shallower groundwater units.

Relevant publications to this literature review have been placed into one of five categories which are as follows:

1. General background literature that the non-expert can use to better understand the history, science, acquisition, application, and processing of seismic data.
2. Newly acquired shallow-focused seismic data with the purpose of groundwater characterization.
3. Offshore studies that specifically use previously acquired seismic data (usually originally acquired for petroleum studies) but do not involve reprocessing the data.
4. Onshore studies that specifically use previously acquired seismic data (usually originally acquired for petroleum studies) but do not involve reprocessing the data.
5. Studies that involve the reprocessing of seismic data previously acquired (usually for characterizing oil and gas bearing units). The reprocessing would be in support of better resolving the seismic attributes of overlying groundwater bearing formations.

3.1 General Seismic Data Background Literature

The process of acquiring seismic reflection data is essentially like performing an ultrasound of the earth: acoustic waves are propagated from a source on the ground (sledgehammer, thumper, Vibroseis, dynamite, shotgun, etc.) into the earth. Portions of that acoustic signal bounce back (reflect) at various times and are received at a set of sensors, from which the signals are gathered, and the raw data are interpreted. The receiver records signal from these sensors from the moment the acoustic energy is initiated. During the time the receiver is recording, some portion of the seismic wave energy will reflect off a layer boundary with a difference in impedance (velocity times density), called a "reflector," and return to the surface. The rest of the energy will continue beyond the boundary, only to bounce off another, deeper reflector at a later time. At the surface, the wave energy is captured by a receiver at some distance from an artificial acoustic source. Following the capture of the reflected acoustic signals at the receivers, the returns may be plotted on a graph with two axes. The X axis is distance, and it measures distance from the source or along a surveyed line, and the Y axis measures two-way travel time. Two-way travel time is so named because the wave enters the subsurface and returns, so it is moving two ways. A two-dimensional seismic profile will result when numerous seismic wave propagations (shots) are received and integrated along a single surveyed line of profile. If enough shots and receivers are located over an area (usually as separate shot and receiver lines, commonly at right angles), a three-dimensional seismic survey can be generated. The resulting two- or three-dimensional datasets are then processed further using computer algorithms to create seismic profiles or other images of the subsurface that are interpreted by geologists or geophysicists.

The ability to acquire and interpret large amounts of seismic data represents one of the most significant technological advances in the application of geosciences to the oil and gas industry. The high costs incurred by these large-scale seismic efforts have limited their use almost exclusively to oil and gas exploration and development. Because of this, the oil and gas industry are responsible for most of the technological advances and scientific publications. This section will review a few of what is considered the more relevant publications to provide a primer for seismic data analysis. Broad overview publications include Morton-Thompson and Woods (1992), which provides a good overview on methods, and Alsadi (2017), which provides a concise summary of seismic interpretation. Also included is Vail (1987), a foundational paper in seismic stratigraphic interpretation. Fowler (2005) is an introductory geophysics textbook, and White and Simm (2003) is a tutorial on conducting a seismic well tie.

3.1.1 Fowler (2005)

Fowler (2005) is an introductory geophysics textbook which gives an overview of geophysical methods, especially general seismic wave theory.

Seismic Wave Propagation

A wave is a dilatational or rotational disturbance transmitted through a medium. In this case, rocks are the medium, and they are considered elastic for small disturbances over short time scales. The displacement is measured as amplitude as the wave travels at a velocity through a medium and when the displacement magnitude (amplitude) from seismic waves are plotted against time, they appear as a sine wave, and are described with the same terms. The wavelength (λ) is the distance between two crests (or peaks) or between two troughs. The frequency is the number of cycles that move through a given point in one second. The measure for frequency is called Hertz, and the formula is

$$T = 1/f, \qquad \text{(Equation 1)}$$

where T = time (in seconds) and f = frequency (in Hertz). The period is the duration of time required for one cycle (one wavelength) to pass any point. Velocity of a wave is described by

$$\mathrm{v} = \lambda f, \qquad \text{(Equation 2)}$$

where v = velocity. Figure 3-1 shows the anatomy of a seismic wave. The wave can be plotted as distance from the initial seismic disturbance, holding time constant, or as time from the initial seismic disturbance, holding distance constant.

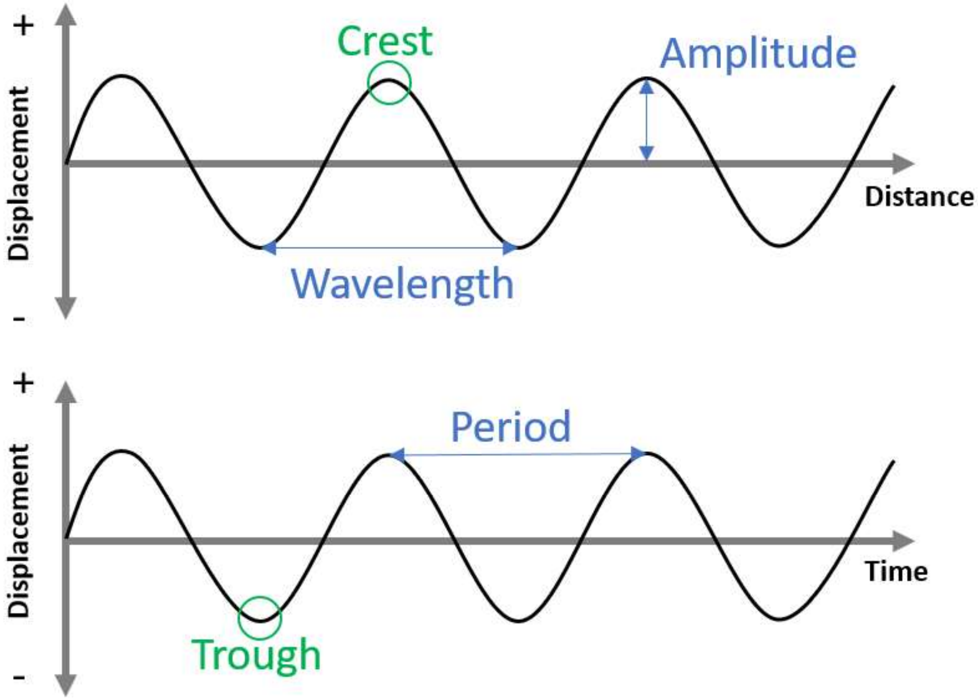


Figure 3-1. **Anatomy of a seismic wave. Displacement is plotted on the Y-axes, and distance or time is plotted on the X-axes. The sign, or positive and negative nature of the wave, is termed polarity.**

When a seismic wave that is initiated at the surface travels into the subsurface, it encounters an interface between two units with different seismic velocities. When a seismic wave hits the interface, some of the energy is reflected and some of the energy is refracted and transmitted. The angles the wave refracts and transmits from the boundary can be calculated using Snell's law, which has a generalized form of

$$\frac{\sin(i)}{\sin(r)} = \frac{\mathrm{v}_1}{\mathrm{v}_2}, \qquad \text{(Equation 3)}$$

where i = incident angle, r = refracted angle, v_1 = seismic velocity of medium 1 (the upper medium in this case), and v_2 = seismic velocity of medium 2 (the lower medium in this case). Snell's law states that the angle of refraction is governed by the seismic velocities on both sides of the interface, and the angle of the initial (incident) wave. In Figure 3-2, an incident wave encounters an interface, part of the energy is reflected, and part of the energy is refracted. The reflected wave returns at the same angle as the incident wave arrives. The refracted energy continues as a wave, now in a new medium with a new seismic velocity. This refracted energy will continue to a new reflector and reflect and refract again. Energy that is reflected once, and then returns to source, is called a primary reflection and is the signal that is the object the survey is designed to capture. Energy that reflects multiple times in the subsurface is called a multiple and is a source of distortion called noise. Any energy that is not a primary reflector can be grouped together as noise.

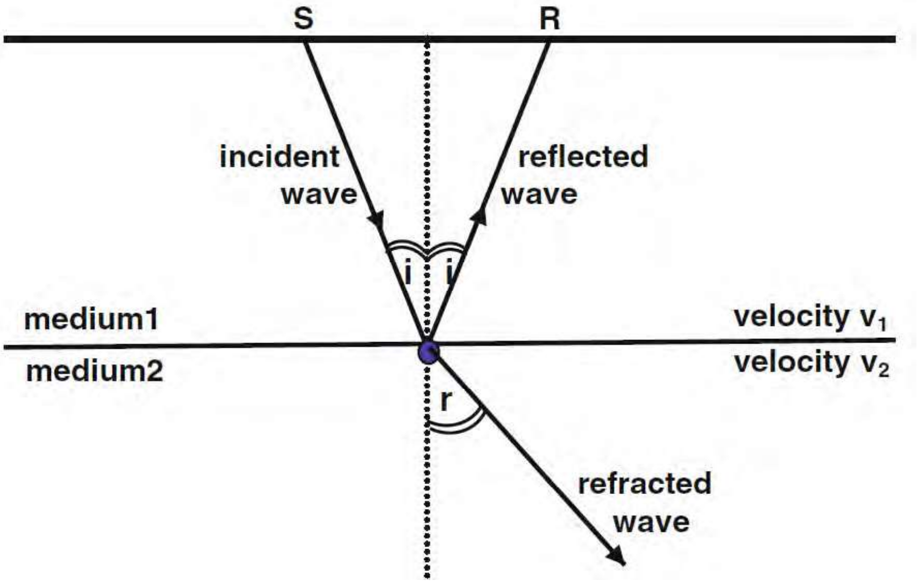


Figure 3-2. **From Alsadi (2017). Reflection and refraction of a seismic wave at an interface separating media (medium1 with velocity v_1) and (medium2 with velocity v_2) where $v_2 > v_1$.**

The general concepts behind wave reflection and refraction are critical to the understanding of the seismic reflection method. While the fundamental equations used to interpret seismic wave interactions are simple, they quickly become more complex as a function of subsurface heterogeneity.

The Nature of Seismic Reflections

The seismic reflection method assumes there is a stack of sedimentary bedding planes that each have a different acoustic properties. Acoustic properties of the rock are defined as its Acoustic Impedance (Z), which is the product of density (ρ) and velocity (v).

$$Z = \rho \mathrm{v}, \qquad \text{(Equation 4)}$$

Seismic velocity is an intrinsic value of the medium that determines the speed of the seismic wave through the medium in question. The acoustic impedance contrasts, called seismic reflectors, result from changes in lithology, pore fluid differences, diagenetic changes, and bedding contacts. The strength of the reflection generated at a boundary can be quantified in terms of the Reflection Coefficient (R), which at normal incidence is:

$$R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)}, \qquad \text{(Equation 5)}$$

where R is the Reflection Coefficient, z_1 is the acoustic impedence of medium 1 and z_2 is the acoustic impedence of medium 2.

3.1.2 Morton-Thompson and Woods (1992)

Morton-Thompson and Woods (1992) is a generally considered a reference manual with chapters covering various aspects of exploration and development. This review is a summary of relevant information in Part 7 of the manual: Geophysical Methods.

Seismic Acquisition

The authors describe a few main points of consideration when designing a seismic survey. They include the location, the source, the receiver, and the recorder (Figure 3-3). Sources commonly used in oil and gas exploration include explosives, vibrators, gas or air guns (especially offshore), or occasionally a weight drop instrument. High resolution shallow seismic data acquired for engineering or near-surface objectives may use shotguns, weight drops or sledgehammers. Source locations are often positioned on the ground in groups or arrays designed to eliminate surface-generated “noise,” which is ambient background seismic energy (such as air blast, ground roll and surface waves) that the receivers will detect in addition to the desired reflection signal. The receivers or geophones, frequently positioned as groups or arrays, will translate the seismic energy generated by the source into electrical voltage. Data carried from the geophone array moves along cables (or by wireless) and is recorded as a channel of data. The workflow for marine seismic acquisition is very similar, with adjustments for the water column. The surface source is usually an underwater air gun, and hydrophones are laid out in streamer(s) behind the seismic boat.

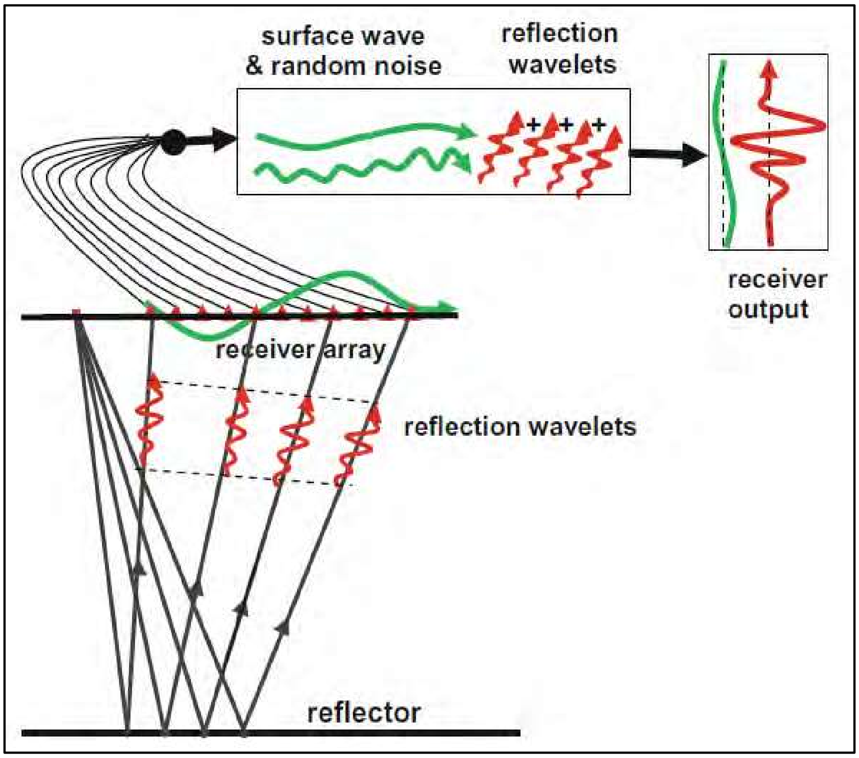


Figure 3-3. Modified from Alsadi (2017). The seismic experiment, showing the geometry of a seismic source, reflector, an array of receivers, and the output.

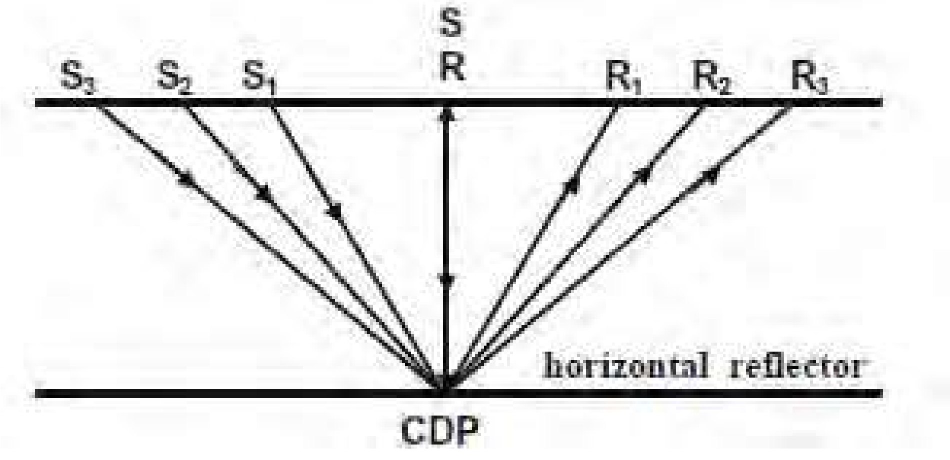
Seismic Processing

While the principles guiding seismic acquisition are relatively straightforward, seismic processing can quickly become complicated due to the myriad of techniques available to process the raw data. Seismic data processing is the science/art of removing unnecessary seismic noise, eliminating acquisition artifacts, and providing a valid image of the subsurface. The processing steps to go from raw to processed data can be binned into relatively broad categories: database building, editing and fundamental corrections, signal to noise enhancement, enhancement of resolution time, and enhancement of resolution in space.

Goals of seismic processing include increasing resolution and correcting for attenuation. Seismic resolution is the ability to distinguish between objects in the subsurface, whether horizontally or vertically. Horizontal resolution is regulated by trace spacing and uncertainties in the acquisition phase. Vertical resolution relates to how far apart two interfaces have to be in order to be distinguishable on seismic data. Two interfaces very close together will be harder to image than two interfaces far apart, because their reflections can overlap and be confused. Vertical resolution is affected by the depth of the interfaces because the signal becomes more attenuated with depth. Attenuation refers to the decrease in amplitude of seismic waves with increasing travel time (or depth).

Database building simply involves sorting the gathers (recorded information) into the right places spatially. Steps can include:

- Geometry - the association of recorded trace with shot and receiver, and assignment of the reflected energy to the midpoint between them (or common depth point) (Figure 3-4). Traces are a graph of amplitude (related to the difference in acoustic impedance and the wave character) as a function of travel time.



Note: CDP = common depth point. S= Source. R=Receiver.

Figure 3-4. Modified from Alsadi (2017). Definition of Common Depth Point.

Editing and fundamental corrections include fixing human and machine errors, fixing travel time changes due to elevation differences, and dealing with the weakening (attenuation) of the seismic signal with depth. Steps can include:

- Edit - Flagging traces, or partial traces, to be removed because of excessive noise or poor sampling of the seismic energy.
- Gain recovery - The weakening of the signal with depth is adjusted by multiplying the signal by a geometrical spreading factor.
- Statics – The removal of artifacts due to the variations in thickness and properties of the surface weathered layer and shallow alluvium.
- Demultiple – Seismic energy can bounce between strong reflectors or between the surface and a subsurface reflector, which causes misleading and distorted images. These secondary reflections are called multiples, which the demultiple process attempts to remove.
- Normal Moveout correction – A vertical time shift correction to the effect of different travel lengths from the source to the reflector to the receiver for various offsets (Figure 3-5). This correction should result in reflected energy within a gather (a group of traces representing the same common depth point) to be flat in time, allowing further processing and noise reduction.

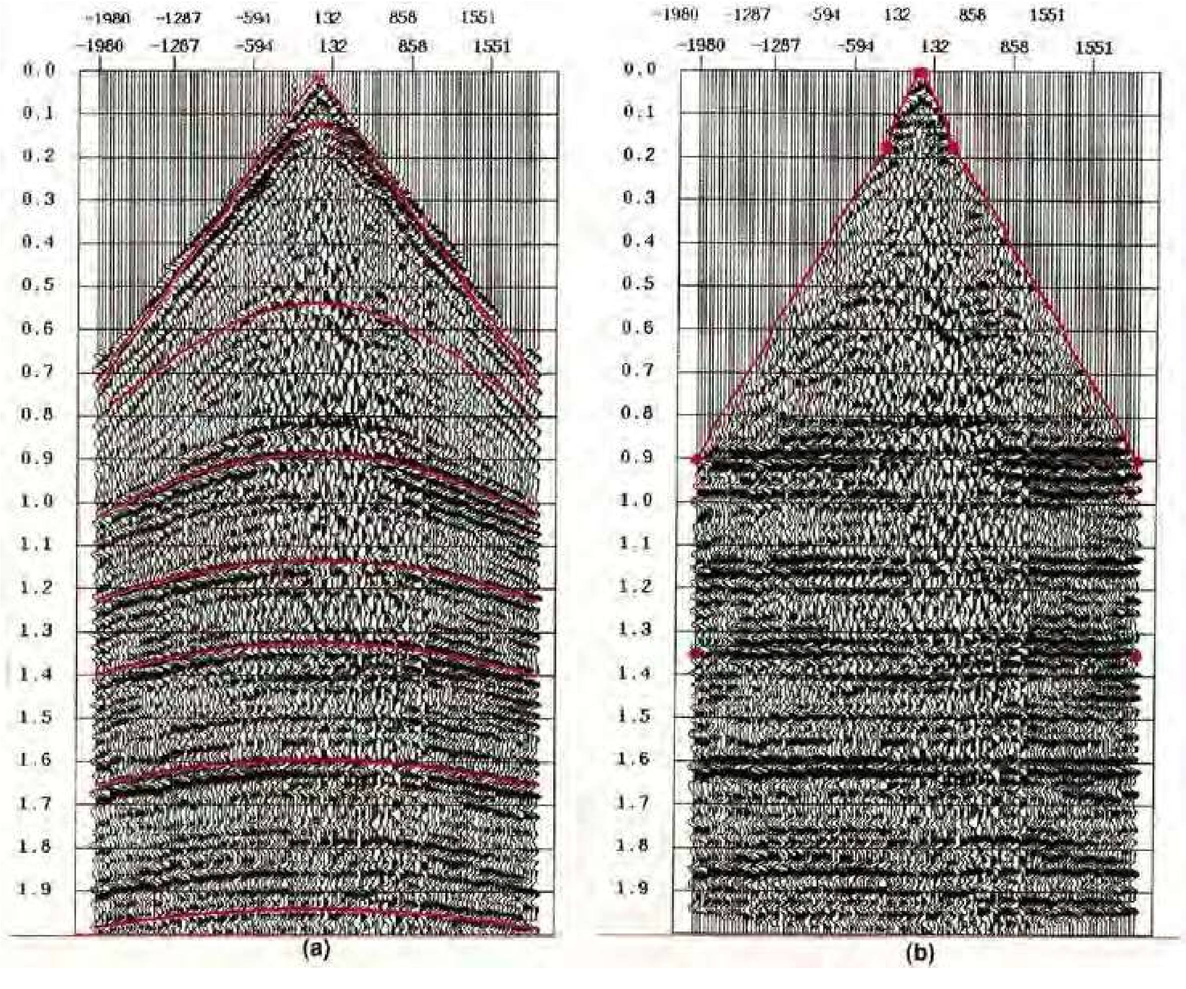


Figure 3-5. **From Morton-Thompson and Woods (1992). (a) A gather of traces with a common depth point location, processed to remove most ground roll and other surface noise. Shot-to-receiver offset is zero at the center of the gather and increases to about 2000 meters (6,562 feet) deep on either end. The offset related curvature of the reflections is due to normal moveout. (b) Normal moveout correction has been applied and the horizons are flat.**

- Dip Moveout correction – This correction is similar to the Normal Moveout correction but assumes dipping reflectors.

Signal to noise enhancement reduces noise by filtering the recording where it is apparent from visual estimation that there is significant noise. Steps can include:

- F-k or apparent velocity filter – Some signals recorded are not reflectors of subsurface layers. They commonly appear to have a constant velocity, commonly resulting from near-surface effects. A common approach is to eliminate energy resulting from that specific velocity range from the record.
- Stacking - Samples of the same subsurface location or common point depth are summed together or stacked to reduce random noise. Stacking is performed after a normal moveout correction.
- Poststack filter – This is commonly a band-pass filter to exclude certain frequencies that are too high (high-cut) or too low (low-cut), in an attempt to retain the part of the signal with the most signal and the least noise.

Enhancement of resolution in time begins to consider the effects of the length of the seismic wave and the response time of the geophone. The response time is the time it takes the geophone to react to a seismic pulse. A common technique is deconvolution. Convolution is a calculation of “smearing” of a seismic signal within the earth. Deconvolution is reversing the process and is a common seismic processing technique. There are various applications for deconvolution to increase the time resolution of an interval.

Enhancement of resolution in space involves understanding and correction of the increasing spread of a seismic pulse as it is propagating. The geophone does not record the origin or path of the pulse, only the travel time, so precise geometries are not possible without corrections to the data. The most common processing step here is migration. Migration is a transform for revealing the true subsurface structure. This process is called migrating because it involves moving, or migrating, the reflection events to their true position in depth. Migration can be performed before (prestack migration) or after stacking (post-stack migration), as the situation demands. Migration can occur in the time domain (two-way travel time), or in the depth domain with an appropriate velocity model, generally iterated to achieve the best result.

Seismic Interpretation

Once the dataset is assembled, a broad overview of the dataset is recommended to search for clues on the geologic setting, major structural features, and major stratigraphic surfaces like sequence boundaries. Following this, seismic mapping begins by interpolating surfaces and units outward from geological data, preferably wells tied to the seismic data. Correlations to all seismic profiles or to the entire three-dimensional volumes in the dataset will give a picture of the unit extents and thicknesses in the subsurface. After all seismic data have been interpreted, the interpretations can be presented as maps. Most common maps products include tops of units (in depth or time), isochrons (time difference), or isopachs (thickness). However, even the smallest facets and characteristics of the seismic data can be illustrated on a map quite easily in modern workstations.

3.1.3 White and Simm (2003)

White and Simm (2003) is a tutorial in tying seismic data to well logs. The authors explain that tying well data to logs provides a means of identifying stratigraphic surfaces to pick (identify and map) on seismic data and estimating the seismic character of the volume or profile. The procedure is outlined as: (1) edit and calibrate the sonic and density logs, (2) construct a synthetic seismogram from calibrated well-logs (referring to sonic and density) (choose the appropriate reflection series, construct the reflection series in two-way time) (3) Perform the match, compromising between best match to the log and a realistic representation of a wavelet.

Log calibration entails adjusting the logs into a timing agreement with vertical seismic profiles or checkshots in the area of interest. Vertical seismic profiles and checkshots are acoustic data showing the seismic velocities as a function of depth within boreholes. What the checkshots and vertical seismic profiles display about the timing of the geologic formations should agree with data from the acoustic logs. This process involves developing a model for how the seismic velocity of the strata varies with depth within a well bore. Next, a reflection series as a function of time is created. This is a series of seismic reflection coefficients for each geologic unit as a function of depth within the borehole and is created from acoustic logs, vertical seismic profiles, and checkshots. The reflectivity series will then be filtered into a synthetic seismic wavelet in order to account for the distortion and resolution of seismic waves in and through the earth.

A synthetic seismic wavelet is generated based on the seismic volume, with the aim of matching the properties of the other wavelets in the volume. The seismic volume can then be scanned or searched for the best location for this well tie, which may not be directly on the well location, due to migration or processing or any number of factors. Once a match has been found, the tie is checked for accuracy and goodness-of-fit. If deemed to be a quality tie, then the lithology boundaries can be interpolated into the seismic data.

3.1.4 Alsadi (2017)

Alsadi (2017) gives a broad overview of seismic acquisition, processing, and interpretation. It covers the geophysical methods and provides a useful overview of the seismic interpretation process. The author separates that process (an integration of geophysics and geology) into two categories: structural and stratigraphic. These processes are fundamentally related as an interpretation in one category affects the interpretation of the other.

Structural Seismic Interpretation

Structural seismic interpretation is the process of delineating folds, faults, fractures, karstic collapse, and other structural features within the dataset (Figure 3-6). The seismic image of faulting results from identifying offset reflectors, usually over a range of depths/times; also from coherency attribute discontinuities and fault-plane reflectors. The seismic image of folding is from folded reflectors. Fracturing is determined by coherency and curvature attributes, also seismic anisotropy. Karsting is seen by the apparent faults or fractures and infills of a subcircular depressions within reflectors. Fold, fault, and fracture patterns/trends can be used to infer broad structural trends and structural history of a specific area. Seismic structural interpretation is integrated with structural analysis of geophysical well log and geologic data including formation tops, fault cuts, local dips determined from dipmeter data, etc.

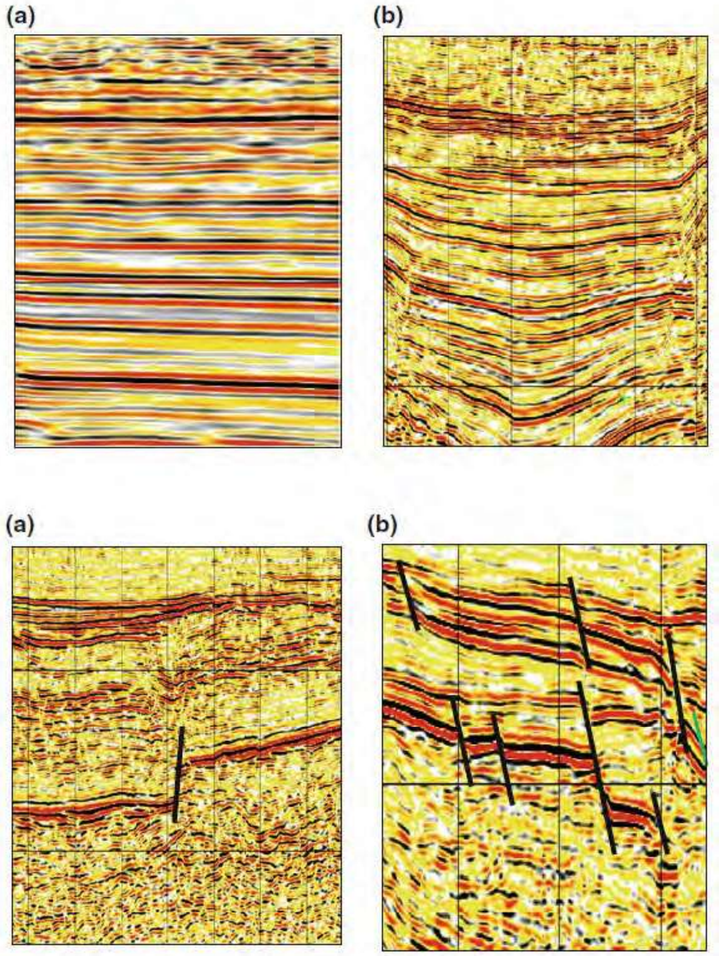


Figure 3-6. From Alsadi (2017). Top (a) – Seismic profile shows unfolded seismic reflectors. Top (b) – Seismic profile shows folded seismic reflectors. Bottom (a) – Reflector offset show a single fault. Bottom (b) – Reflector offset shows many faults.

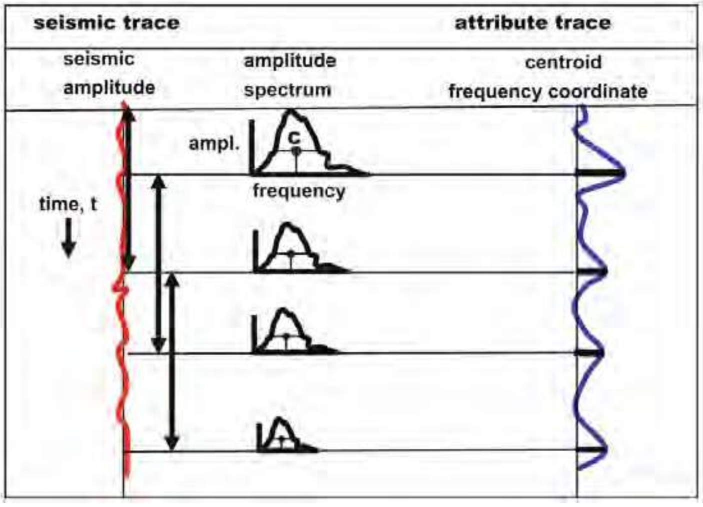
Stratigraphic Seismic Interpretation

Stratigraphic seismic interpretation, whether on two dimensional seismic profiles or three-dimensional seismic volumes, involves the delineation of stratigraphic packages or sequences and examination of seismic facies in these sequences. Seismic sequences are packages of reflectors that are bound above and below by unconformities or other surfaces, marked by reflector terminations. Once seismic sequences are identified, a variety of data can be used to delineate depositional trends and seismic facies. The integration of core and outcrop data allow researchers to tie lithofacies data to seismic character. Adding petrophysical data will give some quantitative estimate of character to the seismic data. Interpretations of these facies are governed by the current understanding of sedimentary systems. Some key facets of interpretation include analysis of shelf-margin trajectory, slope geometry, tectonic faulting, stacking patterns, identification of key stratigraphic surfaces, and facies distributions, to name a few. These interpretations will provide constraints on depositional processes and provide predictions away from direct lithofacies and well log control.

Seismic Attribute Interpretation

Fundamental to both stratigraphic and structural methods is the interpretation of seismic attributes. A seismic attribute is a "measured or computed value of a seismic parameter" of a wavelet (Alsadi, 2017). There are hundreds of attributes that have been defined with examples including time, amplitude, frequency, attenuation, coherency, curvature, and sameness. Attributes are divided by the author into instantaneous attributes, wavelet attributes, and spectral attributes and each is expanded upon in great detail. The underlying math behind resolving attributes is not simple and is usually performed using computing clusters and complex mathematical functions with the goal of identifying relevant geologic patterns that were not visible in the pre-processed seismic dataset.

An example attribute to consider is the spectrum centroid. The spectrum centroid is the center point of the frequency component of a selected wavelet. This is computed over a sliding window through the curve, as illustrated in Figure 3-7. When computed for a seismic stack section, a figure results as in Figure 3-8.



Notes: ampl. – amplitude. c – centroid. t – time.

Figure 3-7. **From Alsadi (2017). Sketch showing the definition of the attribute trace. Spectral attribute (spectrum centroid, C) is presented as function of reflection time.**

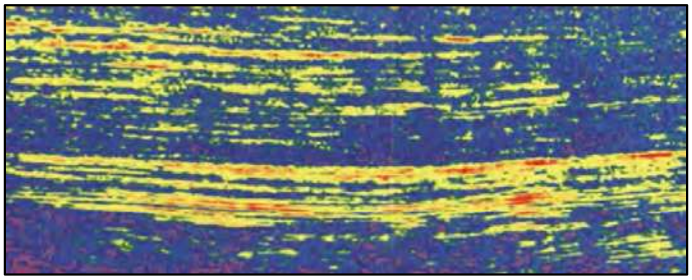


Figure 3-8. **From Alsadi (2017). Seismic-attribute color coded seismic profile: spectrum centroid section.**

3.1.5 Vail (1987); 'Exxon model' sequence stratigraphy

P.R. Vail and co-workers revolutionized seismic stratigraphy in the 1970s and 1980s. While there are many approaches that have shaped and reshaped the approach to seismic interpretation, the cited publication, which summarizes a decade of previously published work, is a foundational document that illustrates all the key concepts behind seismic interpretation.

The author records seven steps in seismic interpretation: (1) an analysis of the seismic dataset for sequence boundary information followed by (2) integration of well log information, and (3) creating well to seismic ties. This is followed by (4) seismic facies analysis, (5) interpretation of depositional environments, (6) forward seismic modelling, and (7) sequence stratigraphic interpretation. While seismic-well ties and well log stratigraphic signatures are discussed briefly in the introduction, little time is spent discussing them in the volume and the reader should consult additional literature for a more complete understanding of these concepts.

Seismic sequences as defined by Vail in siliciclastic environments (sands and shales) are groups of reflectors that are bounded by discontinuities (Figures 3-9, 3-10). Discontinuities are reflectors that other reflectors terminate against. Termination patterns include toplap, onlap, and downlap, with toplap and onlap defining the sequence boundaries (Figure 3-9). Toplapping reflectors terminate upward into an erosional surface. Downlap is when reflectors terminate downward onto a sequence boundary or flooding surface. Onlapping reflectors terminate landward onto another reflector. Vail interprets a single sequence to represent a single cycle of change in relative sea level, with the sequence boundaries representing sea level minima (lowstands). By definition, a Vail sequence begins with a sea level minimum (lowstand), passes through a maximum of sea level (highstand), and ends with another sea level minimum. Within the sequences, reflector geometries identify where on the sea level curve the internal reflector package belongs. These internal packages can belong to the lowstand systems tract (rocks deposited during sea-level lowstand), the transgressive systems tract (deposited during rising sea level), the highstand systems tract (deposited during sea-level highstand); or, alternatively, the shelf margin systems tract (a modified lowstand tract during lesser sea-level falls). The lowstand systems tract is deposited on the sequence boundary atop the highstand systems tract of the underlying sequence, and basinward of the previous shelf break due to the fall in relative sea level that migrates the zone of deposition basinward. The first flooding surface above the lowstand systems tract is the base of the transgressive systems tract. This surface marks a sea level rise or transgression; newly deposited strata are retrograding (stacking landward) from the position of the underlying lowstand systems tract. This tract thins basinward and generally fines upward. The transgressive systems tract is bounded on top by the maximum flooding surface, which is a horizon of slow sedimentation interpreted as the point of maximum sea level. It is also considered a downlap surface that is the base for the highstand systems tract. This tract is a prograding (basinward moving) sigmoid wedge that represents the forward movement of the shoreline/deltaic sediment system into the basin, downlapping onto the maximum flooding surface. The top boundary for the highstand systems tract is a sequence boundary, which is an unconformity on the shelf and a correlative conformity in the deep basin. Instead of being overlain by another lowstand systems tract, this sequence boundary can sometimes be overlain by a shelf margin systems tract. This tract onlaps and downlaps the sequence boundary without as clear a differentiation as the lowstand systems tract and represents a quick return to previous sea level after lesser sea-level lowstand.

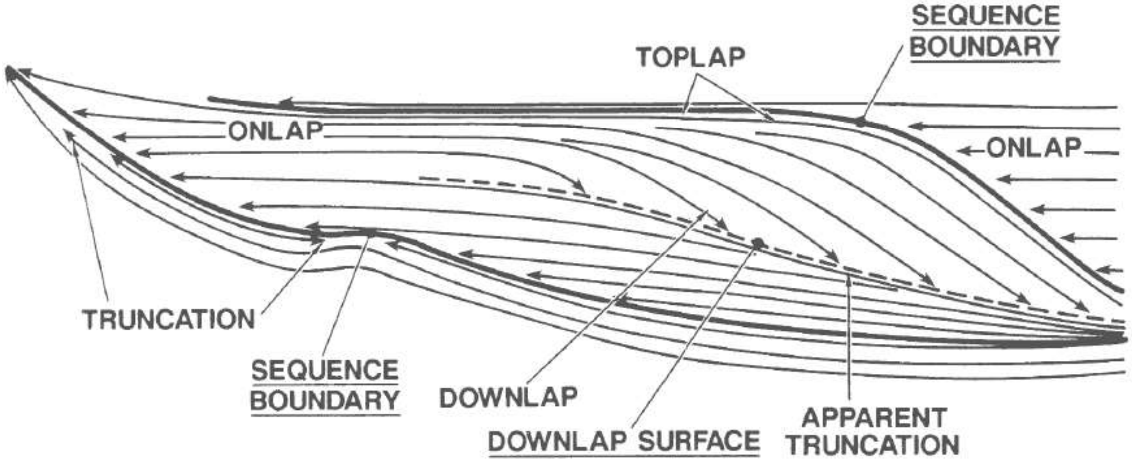


Figure 3-9. **From Vail (1987). Diagram showing reflection termination patterns and types of discontinuities. Discontinuity names are underlined.**

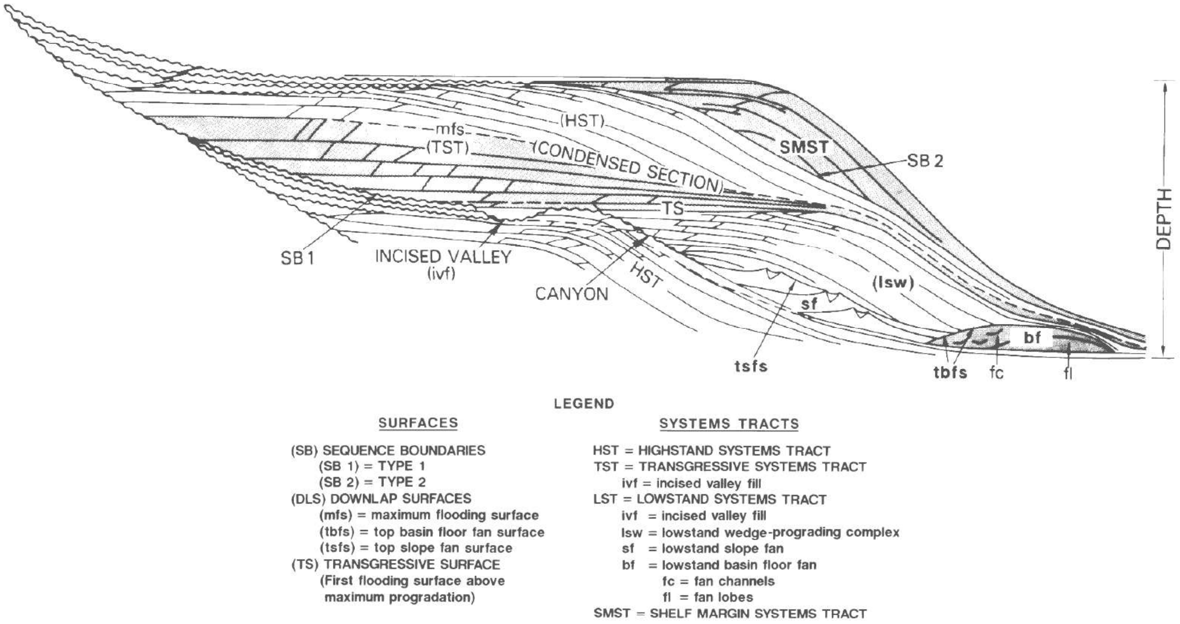


Figure 3-10. **From Vail (1987). Sequence stratigraphy diagrammatic section, showing sequences and systems tracts.**

Once the reflector packages are sorted into sequences, each reflector package within the dataset has a place on the sea level curve. Seismic facies analysis using two-dimensional seismic reflection data consists of looking at reflector patterns to identify slopes, mounds, channel/overbank complexes, lowstand wedges, and megabreccias. Following this, the lithofacies data can be integrated from available data, whether it be well logs, previous literature, core, cuttings, etc. Each of these systems tracts and their internal seismic and lithofacies data has significant impacts on the distribution of reservoir quality. The author shows that the seismic analysis is fundamental to oil and gas exploration and, the author provides a framework that can be used to predict reservoir quality trends and optimize hydrocarbon development.

The series of Vail publications is foundational to sequence stratigraphy. Vail (1987) presents the concepts clearly and concisely. However, there have been many authors that have built on and contest this work (Catuneanu and others, 2009). Vail (1987) focused on two-dimensional seismic in siliclastic systems, and not at all on three-dimensional seismic or carbonate systems.

3.2 Shallow-Focused Newly Acquired Seismic Data

3.2.1 United States Geologic Survey Carbonate Aquifer Characterization Lab

The United States Geological Survey's Carbonate Aquifer Characterization Lab has published a significant body of literature on seismic analysis related to the Florida Aquifer System. Publications include Cunningham (2013), Cunningham (2015), and Cunningham and others (2018a) and (2018b).

Cunningham (2013) addresses South Florida's needs to cultivate deeper water sources, specifically the Florida Aquifer System. Building upon a previous study (Cunningham and others, 2012), this study illustrates a set of seismic sections acquired by the United States Geological Survey and Broward County in 2010, and an integration with borehole data to define the structure of the Florida Aquifer System (Reese and Cunningham, 2013). The employed seismic and sequence stratigraphic methods provided a high-quality image of the subsurface in the Florida Aquifer System and identified tectonic faults and karst collapse.

The next study from Carbonate Aquifer Characterization Lab examined here is Cunningham (2015). This follow up study used seismic stratigraphy to examine the possibility of contamination in the Florida Aquifer System. Intermediate-depth seismic profiles were acquired both offshore and onshore. The depth of the contaminating zone is 2,750 to 3,300 feet, and the drinking water is at a depth of 825 to 1,580 feet. The seismic profiles were used to measure thickness, depth, structural features, and geometries of the Florida Aquifer System. The aquifer system was divided into seismic sequences, and the Biscayne aquifer and the various confining units were correlated along the seismic lines. A three-dimensional geomodel was created from the borehole and the two-dimensional seismic profile that illustrated the architecture and the structure of the Florida Aquifer System and shallow system. The result was a seismic stratigraphic model that identified four Florida Aquifer System sequences. Integration of well data helped identify karst collapse features. The study concluded that enough vertical permeability pathways had been imaged to suggest that upward directed flow of contaminated groundwater from the deep zone is plausible.

The next study from Carbonate Aquifer Characterization Lab is Cunningham and others (2018a). This is an expansion of Cunningham (2015), which sought to understand groundwater flow with respect to contamination pathways. Data studied include 80 miles of high-resolution two-dimensional seismic, biostratigraphy data, well logs, and cores from 44 wells. Data were compiled by starting with one-dimensional data (at individual wells) and then incorporating the two-dimensional seismic data to extend control away from the wells. Integration of available data led to the construction of a sequence seismic stratigraphic and hydrogeologic framework. Authors found that the seismic packages and units correlated well to the aquifers and confining layers. The delineation of the four permeable units led to an understanding of the porosity trends of the system. From the seismic interpretation, researchers discovered a reverse fault and some karst sag features that could be conduits of fluid flow upward. Figure 3-11 illustrates the karst sag and megabreccia that is common at the study area. The study concludes that the association of highly permeable units identified in well and core data with seismic horizons and packages was crucial to the production of a unified model incorporating sequence stratigraphy and hydrogeology.

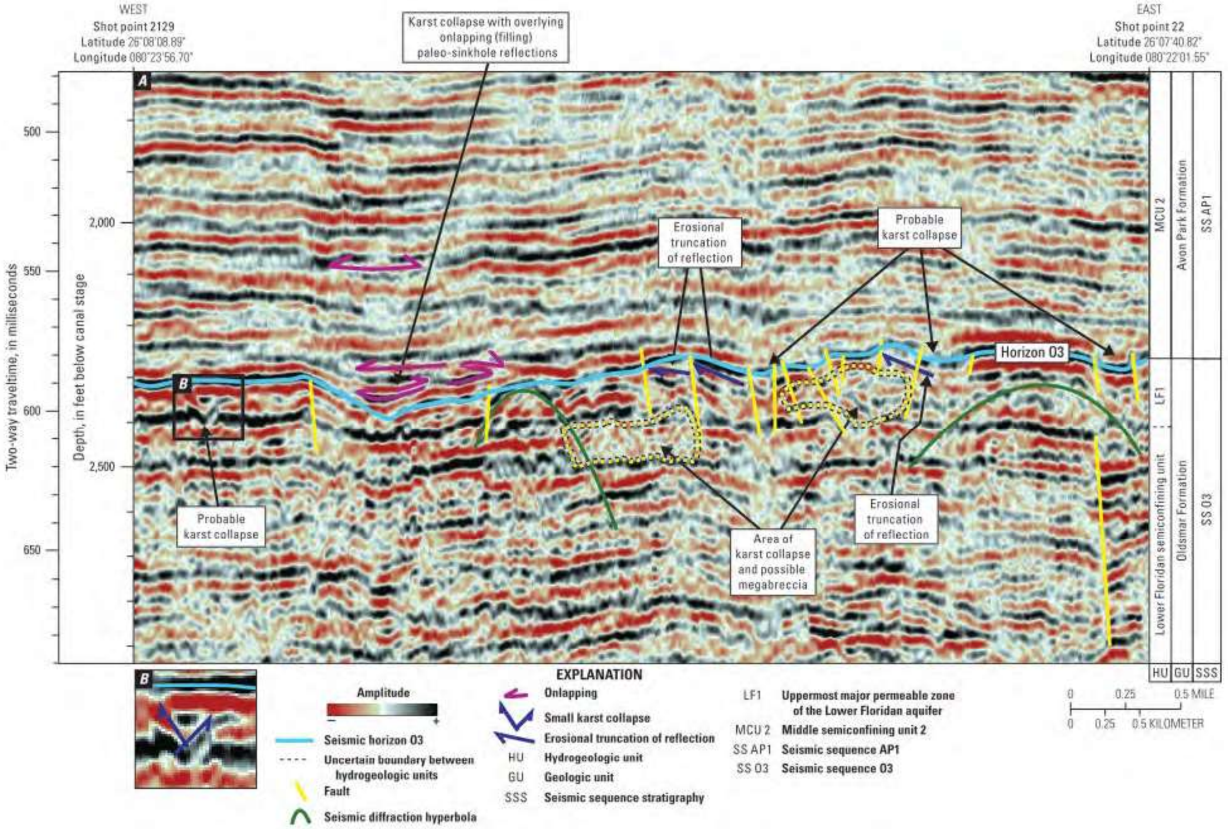


Figure 3-11. **From Cunningham and others (2018a). This figure shows a vertical seismic profile in time (annotations in depth) with annotations depicting karsting and faulting.**

The final study from Carbonate Aquifer Characterization Lab is Cunningham and others (2018b). This report was the first Carbonate Aquifer Characterization Lab study to incorporate high-resolution three-dimensional seismic. Two three-dimensional surveys totaling 3.4 square miles were acquired and interpreted. Five wells with geophysical logs and one cored well were also examined, there was also a sonic log available. In this study, the seismic surfaces from Cunningham and others (2018a) were correlated into the study area and structural features were identified. This analysis detected a greater proportion of faults in certain seismic horizons than others, indicating karst development below an unconformity. Twenty different seismic sag features were identified, as can be seen in the depressions on the seismic horizon in Figure 3-12.

The three-dimensional seismic was critical to the estimation of density of karsting and faulting within the study area.

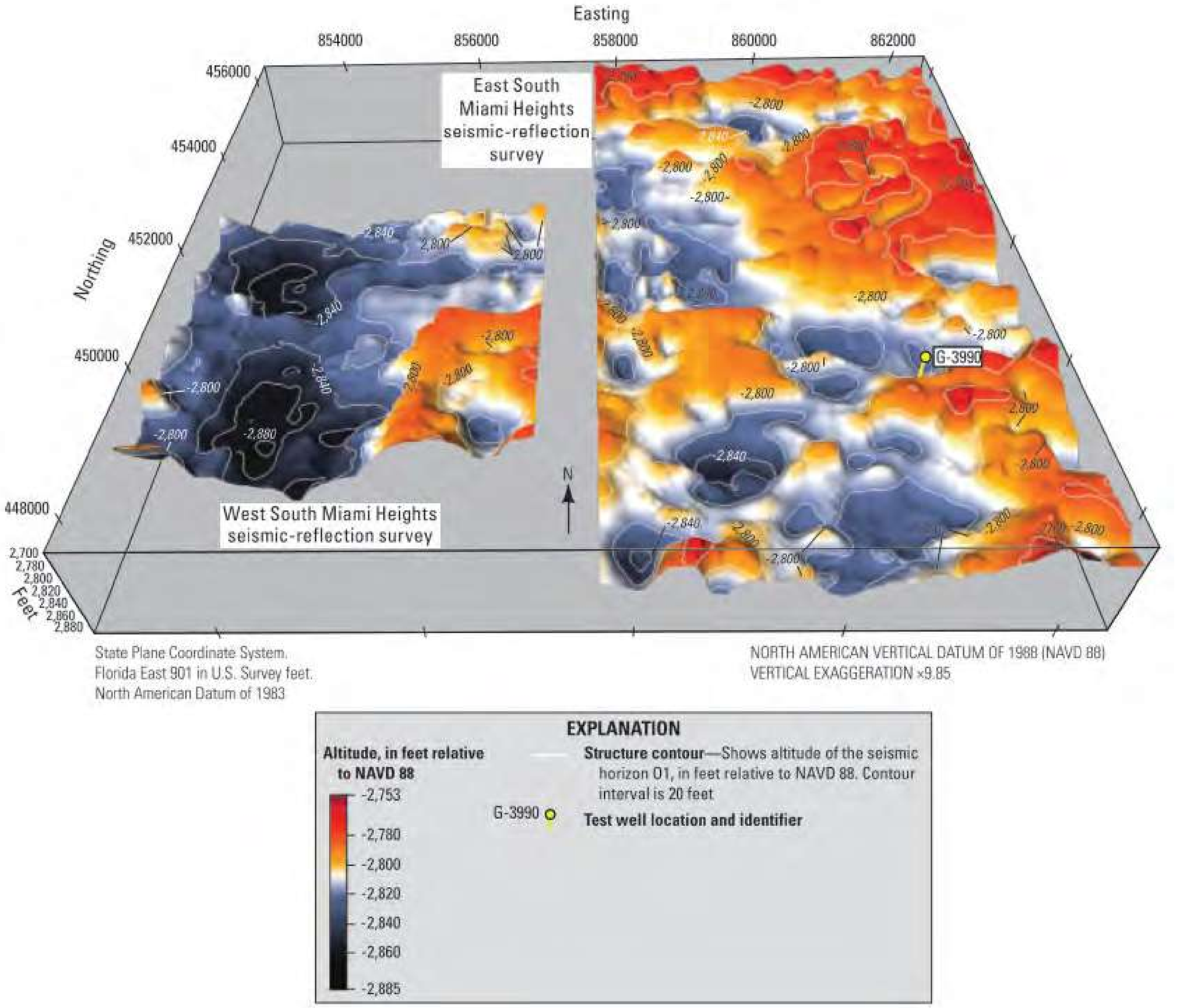


Figure 3-12. From Cunningham and others (2018b). A seismic surface pockmarked by karst features. Karsting results in irregular rounded depressions.

3.3 Offshore Studies Utilizing Previous Acquired Seismic Data without Reprocessing

3.3.1 Thomas and others (2019); Offshore New Jersey fresh-water reservoirs

Thomas and others (2019) is an overview of fresh groundwater reservoirs offshore on the New Jersey Shelf. The study utilized depth-migrated two-dimensional seismic data and well logs to image Oligocene and Miocene submarine sediments up to 2,000 meters (6,560 feet) in depth. Depth-migrated means the seismic was converted from the original acquisition (in two-way time) to depth. Analysis began by identifying seismic sequence boundaries and stratigraphic packages by delineating the geometries of reflector terminations. Depositional trends in the system were interpreted by identifying multiple reflectors that terminated against other reflectors in a consistent manner. Using the seismic stratigraphic model, the researchers were able to group the geometries into systems tracts and build a two-dimensional geological model in the software Petrel. The model was based upon the seismic line and core data in the area and provided facies proportions for the system. The lithology model was subsequently converted into a porosity model with the porosity and permeability data coming from core and well-log measurements that were calibrated to lithology. Once a porosity model was established, groundwater flow, solute and heat transport were simulated to match salinity profiles in three nearby wells. The authors found that the observed salinity distribution is strongly influenced by the stratigraphic architecture which controls permeability and porosity distribution across the shelf. Freshwater is preferentially preserved in low-permeability intervals. These low-permeability intervals act as barriers to the migration of salt water which is redirected laterally into adjacent permeable intervals.

3.3.2 Gustafson and others (2019); Electromagnetic techniques combined with seismic

Gustafson and others (2019) is a study on far offshore aquifer systems on the United States Atlantic Margin from New Jersey to Martha's Vineyard. Data included an electromagnetic and magnetotelluric survey over the study area (Figure 3-13). These data were processed to yield resistivity models. The focus of the study is the top 800 meters (2,624 feet). In these surveys, pore water salinity was joined with inferred or observed (previous literature) porosity data to yield a salinity value for the sediments. Resistive zones were interpreted as submarine aquifers, and available permeability data suggested that these zones would facilitate flow. Salinity data predicted in these aquifers were found to match the available salinity measurements from nearby wells. Seismic was then used to evaluate structural controls on groundwater distribution. Boundaries to the distribution of low salinity groundwater are all stratigraphic and were able to be imaged successfully using seismic techniques. The conductive zones do not seem to be aligned with stratigraphic boundaries, but the seismic resolution of faults in the study area suggest that saline waters could migrate up faults and interact with these zones. The study demonstrates that the coupling of electromagnetic surveys with seismic reflection data can be a powerful tool in imaging offshore aquifers, identifying boundaries, and finding controls on salinity distributions.

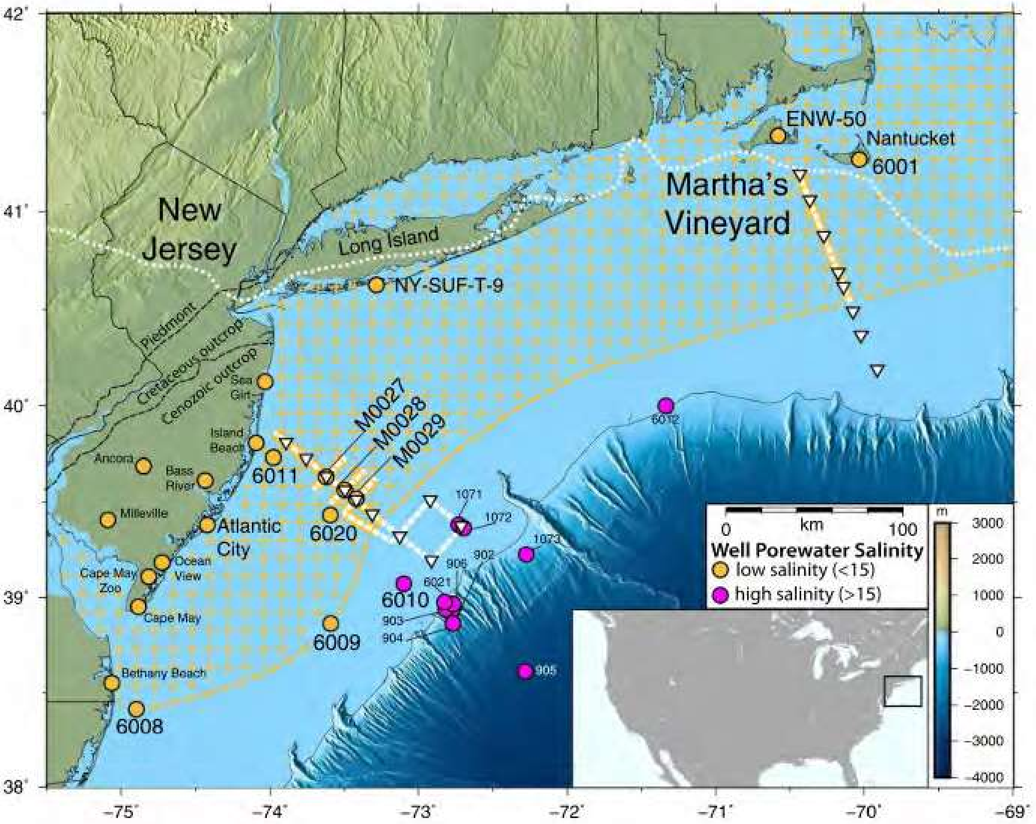


Figure 3-13. **From Gustafson and others (2019). EM survey of groundwater on the U.S. Atlantic continental shelf. Surface-towed CSEM profiles (white dashed lines) and seafloor MT stations (white triangles) were collected during surveys offshore New Jersey and Martha's Vineyard. Yellow solid lines show the portions of the survey profiles where the EM data support low-salinity pore water. Circles denoting onshore and offshore wells are colored where pore fluid salinities were observed offshore or where aquifers have been identified via geophysical data onshore. Wells featured in the text are labeled with a larger font size. Yellow crosses and the yellow dashed line show our inferred spatial extent of the low-salinity aquifer system. The white dotted line denotes the terminal moraine of the Laurentide ice-sheet at the Last Glacial Maximum.**

3.3.3 Bertoni and others (2020); Overview of offshore groundwater and seismic

Bertoni and others (2020) provides a broad overview of case studies from the United States and abroad where offshore groundwater systems are being explored with seismic reflection data (Figure 3-14). Two of the case studies were covered by the previously mentioned publications (Thomas and others, 2019 and Gustafson and others, 2019). Other notable case studies include

- Southern Florida, where seismic has been utilized to image karst collapse features on the surface and in the subsurface. These features highlight mixing zones that enhance limestone dissolution collapse.
- The Mediterranean region, where the author provides a brief comparison to New Jersey along with a summary of the extent of the aquifers that have been mapped with a mix of shallow and deep seismic data.
- The African country of Tanzania, where the author discusses an approach using repurposed oil and gas seismic data to image an offshore aquifer. The aquifer in question,

the Kimbiji, was discovered and studied using a combination of seismic and well log data. The data were used to define the scale and magnitude of the aquifer along with its possible connections to deeper strata.

- Canterbury Bight, New Zealand, where a multi-attribute facies classification was undertaken using seismic data. The construction of a stratigraphic framework allowed for understanding of spatial facies trends. Integration with resistivity survey data allowed the identification of low salinity groundwater bodies, their coincidence with various lithologies, and structural controls.
- The Gippsland Basin study in Australia is another example of repurposed petroleum seismic data. The integration of the available onshore data for the Latrobe aquifer, and then the marine seismic and well data for its offshore portion, allowed researchers to map and determine salinity distributions for the aquifer.

The publication concludes by stating that seismic reflection profiles have been used to great effect to image reservoir (aquifer) properties and architecture, aquitards, paleocoastlines, water conduits, and aquifer indicators (karst/sinkholes).

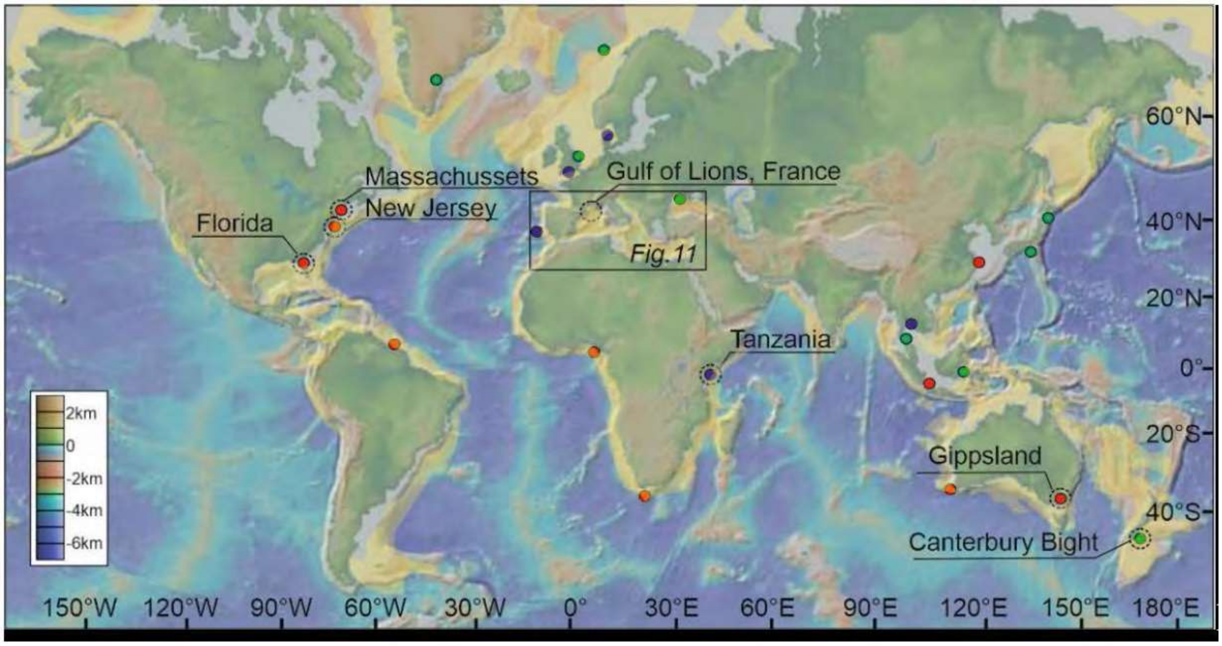


Figure 3-14. **From Bertoni and others (2020). Distribution of studies discussed. In red: groundwater systems proven by observational data, in green: reserves with brackish component highlighted by pore water analysis, in blue: significant meteoric offshore groundwater with indirect evidence based on onshore paleo-groundwater. In black dashed circles: case studies that use offshore geophysical data for groundwater analysis and are described in this paper. The yellow transparent overlay shows the highest density coverage of seismic reflection data, mostly from industry-funded and confidentiality protected sources.**

3.4 Onshore Studies Utilizing Previous Acquired Seismic Data without Reprocessing

3.4.1 Scharling and others (2009)

Scharling and others (2009) is a broad overview on shallow applications of seismic in the Miocene of Denmark, which contains an interval 400 meters (1,312 feet) thick and over 100 meters (328 feet) in depth. This regional study constructs a sequence stratigraphic framework for the Denmark Peninsula using a public dataset containing 55,000 boreholes, 42 palynology logs (a record of the occurrences of pollen in a core or cuttings.), 30 gamma-ray logs, and 1,500 kilometers (900 miles) of seismic data. The authors constructed a three-dimensional sequence stratigraphic framework based on traditional principles. Figure 3-15 shows the construction of the dataset, starting with one- and two-dimensional data and then constructing the three-dimensional stratigraphic model. Two-dimensional seismic profiles are used to constrain the sequence framework. The study concluded that the three-dimensional sequence stratigraphic framework improved the understanding of the hydrofacies and connectivity between aquifers.

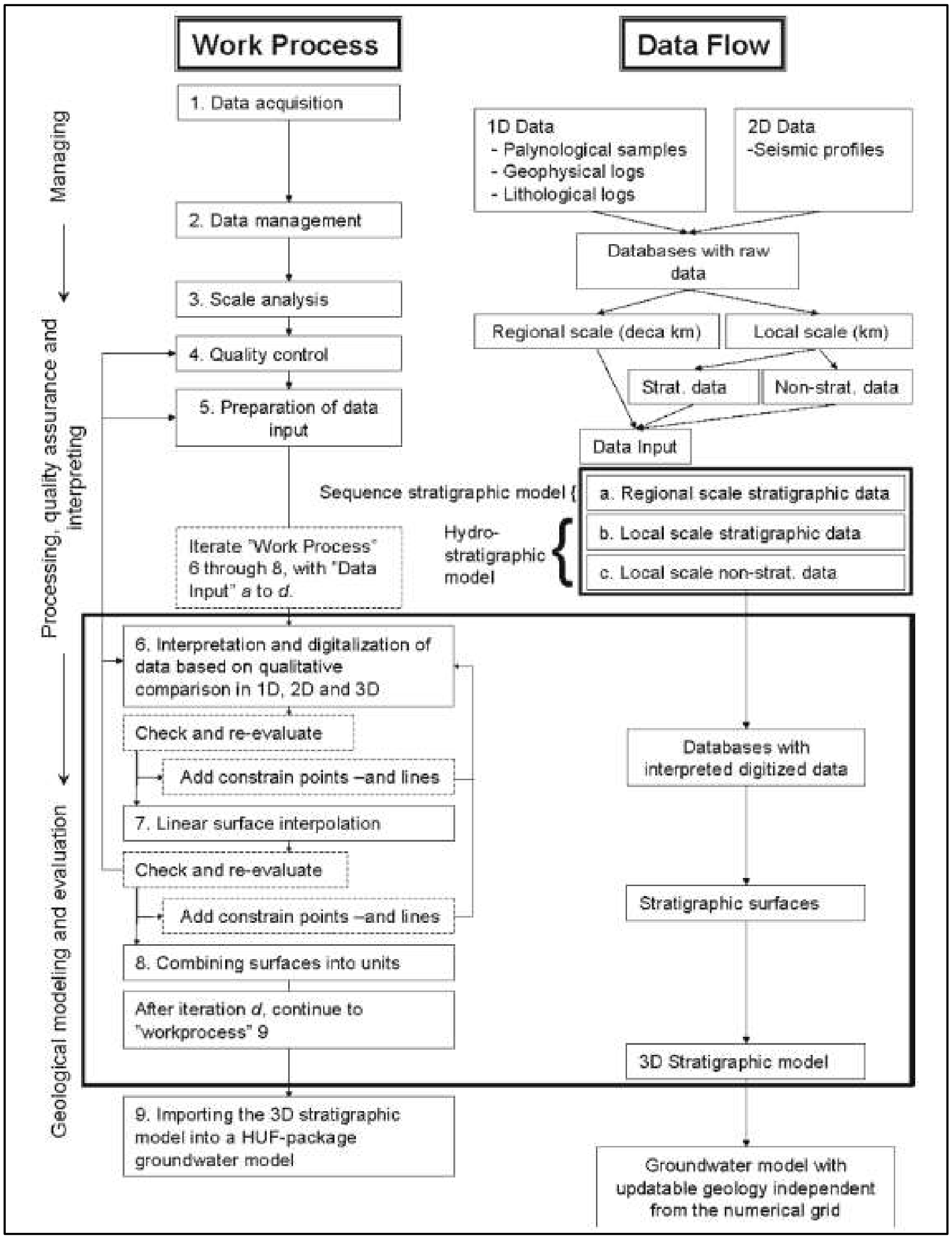


Figure 3-15. **From Scharling and others (2009). Flow chart displaying the work process and data flow for the conducted model work. The dark outline boxes represent the iterative process and data flow.**

3.4.2 Jansen (2015)

Jansen (2015) summarized insights from work conducted by groundwater consulting firms on the use of seismic data in groundwater projects. The study cited the high cost of drilling deep groundwater wells, the lack of other available methods below 500 feet, the complexities of electrically imaging brackish aquifers, and the availability of seismic as good reasons to use seismic data in groundwater. The study provides a good overview of seismic response to sediment lithology changes. Of particular interest is the attention paid to seismic attributes. These seismic-derived attributes include energy, homogeneity, cluster tendency, contrast, entropy, semblance, and curvature. The analyses of these attributes led the authors to identify three-dimensional geobodies of sand in the subsurface. The complete workflow entails licensing a three-dimensional seismic volume, correlating major water-bearing units, processing attributes along (or between) horizons, identifying channel geometries using the amplitude attribute and then sharpening the margins by using other attributes. Figure 3-16 shows how different seismic attributes can be used effectively to resolve channels. The publication outlines a study where such a workflow was employed. The Niobrara Energy Park case study was conducted in Weld County, Colorado in order to find a water supply by targeting channel sands in a shale-rich unit. In the first part of the study, the author was able to map channels with surface-based resistivity to over 400 feet depth. Next, the three-dimensional seismic volume was used to map sands up to 300 meters (1,000 feet) in depth. The resolution of the seismic dataset at shallow depths was fairly good. Following the delineation of these sands, a well was drilled that produced twice as much groundwater as expected. The study presents a general workflow and example of the capabilities of such a workflow.

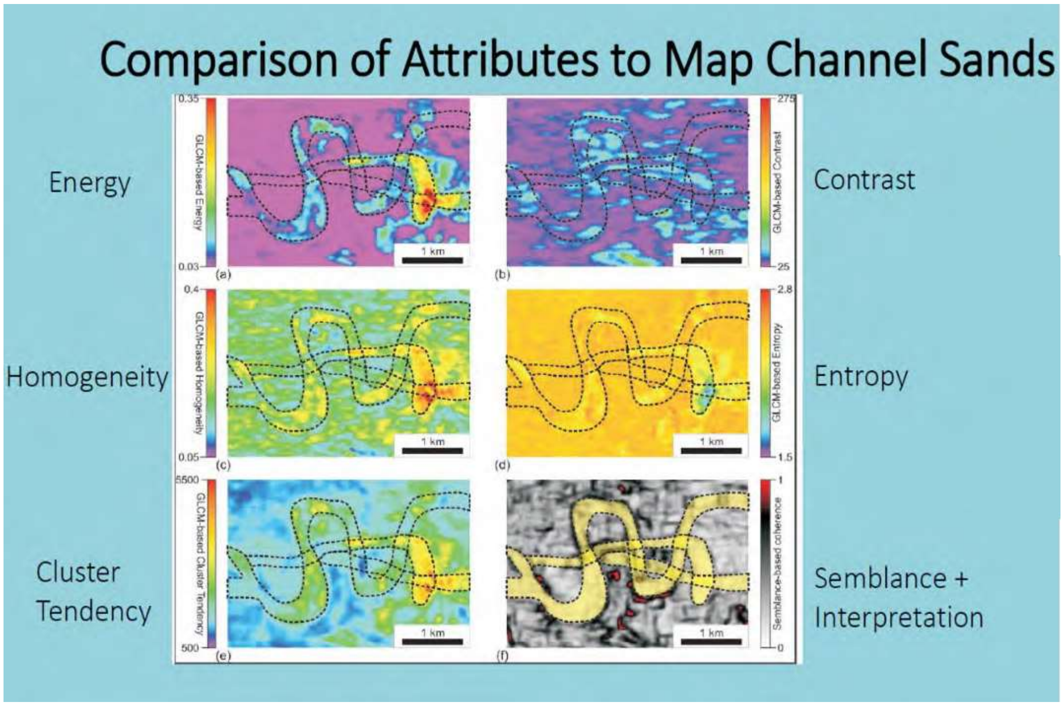


Figure 3-16. **From Jansen (2015). Six different horizontal slices are depicted through the seismic volume, each displaying a different seismic attribute. The outlines depict identified channel forms.**

3.4.3 Martin and others (2013)

Martin and others (2013) presents three case studies from the Western Australia Aquifer system, emphasizing the importance of defining the horizontal and vertical boundaries of an aquifer in estimating recoverable quantities of water. The first study is from the Canning Basin, and the next two are from the Perth Basin, at Gnangara Mound and at Allanooka. The first case study examined is in the Canning Basin. A seismic survey taken in the region was correlated with well data to show that the aquifer boundaries had been mislocated, and that the aquifer was significantly more extensive than previously thought. The second case study at the Gnangara Mound, Australia's largest water source. At this location, the major aquifer was intersected by a fault. The resolution of the seismic reflection survey allowed for a more precise characterization of the aquifer geometry and provided enough resolution to target the major fault for drilling and testing. The last study is a case at Allanooka, the authors show how interpretation of a seismic reflection profile can resolve vertical and horizontal aquifer boundaries on a seismic line. In this case, the boundaries were directly related to faulting (Figure 3-17). The survey also showed that subsidiary faulting to the regional faults is not seismically resolvable in the shallow section. The publication concludes that seismic has large value in resolving aquifer characteristics.

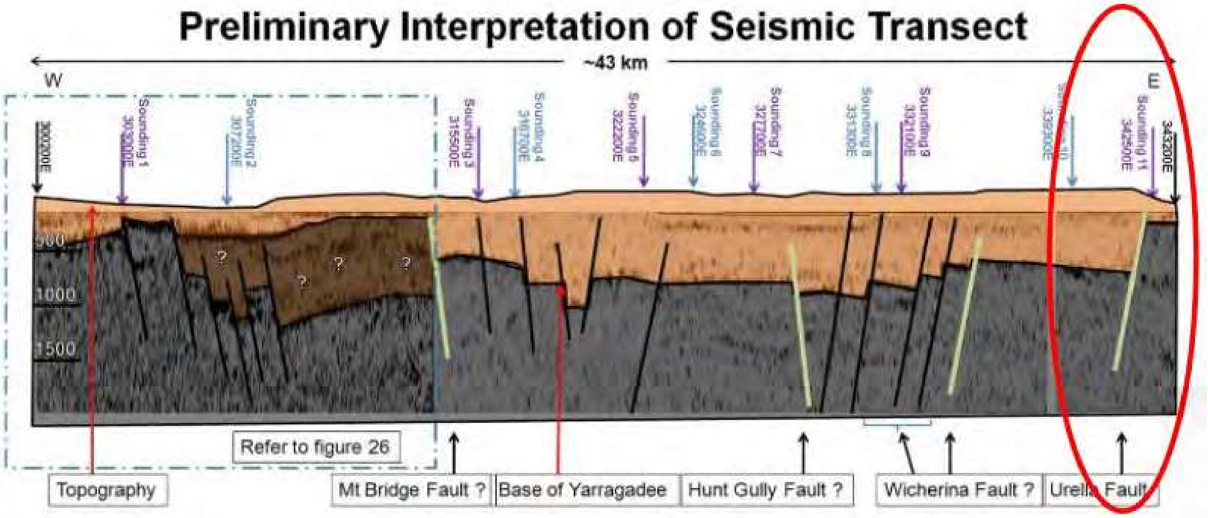
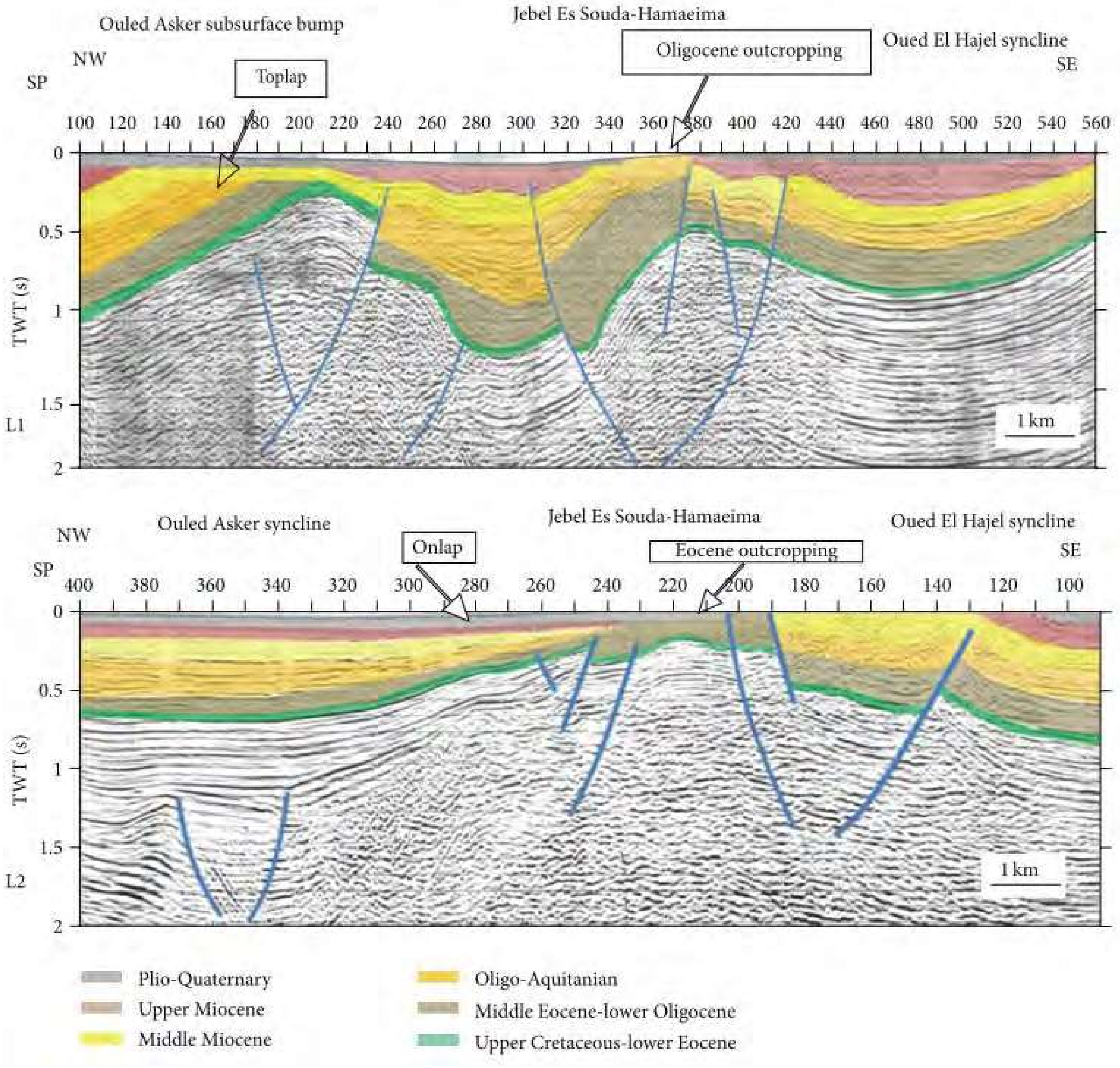


Figure 3-17. **From Martin and others (2013). Seismic reflection profile with schematic interpretation overlay spanning across the Allanooka region of the Perth Basin. Notice the large-scale structural fault illustrated by the red circle that acts as boundary extent for the basin (the image is taken from Gavin, 2010).**

3.4.4 Khazri and Gabtni (2015)

Khazri and Gabtni (2015) is a hydrogeophysical study on the semideep and deep aquifers (up to 1,300 meters, 4,265 feet depth) in Tunisia. The study was conducted using two-dimensional seismic profiles, combined with gravity data, outcrop and surface mapping data, and well data. The study began with regional analysis of gravity data to identify major structures and then integrated the seismic data to develop the stratigraphic and structural framework. Following this, the surface and well-based stratigraphic horizons were tied to the seismic and the structure and stratigraphy was delineated from reflector patterns. After individual seismic lines were interpreted, the top and base of the aquifers were mapped in three dimensions using the seismic and well control. The study delineated three aquifers and reservoirs via this method: a shallow siliciclastic reservoir (Langhian-Serravallian, Middle Miocene), an intermediate depth sandstone reservoir (Oligocene-Lower Miocene), and a deep carbonate aquifer (Campanian-Eocene). As well, the study delineated structural patterns, included faulted anticlines and synclines at large scale (Figure 3-18). The study concludes by affirming the use of seismic not only in horizon identification, but also in defining the structural style and trends of folding and faulting.

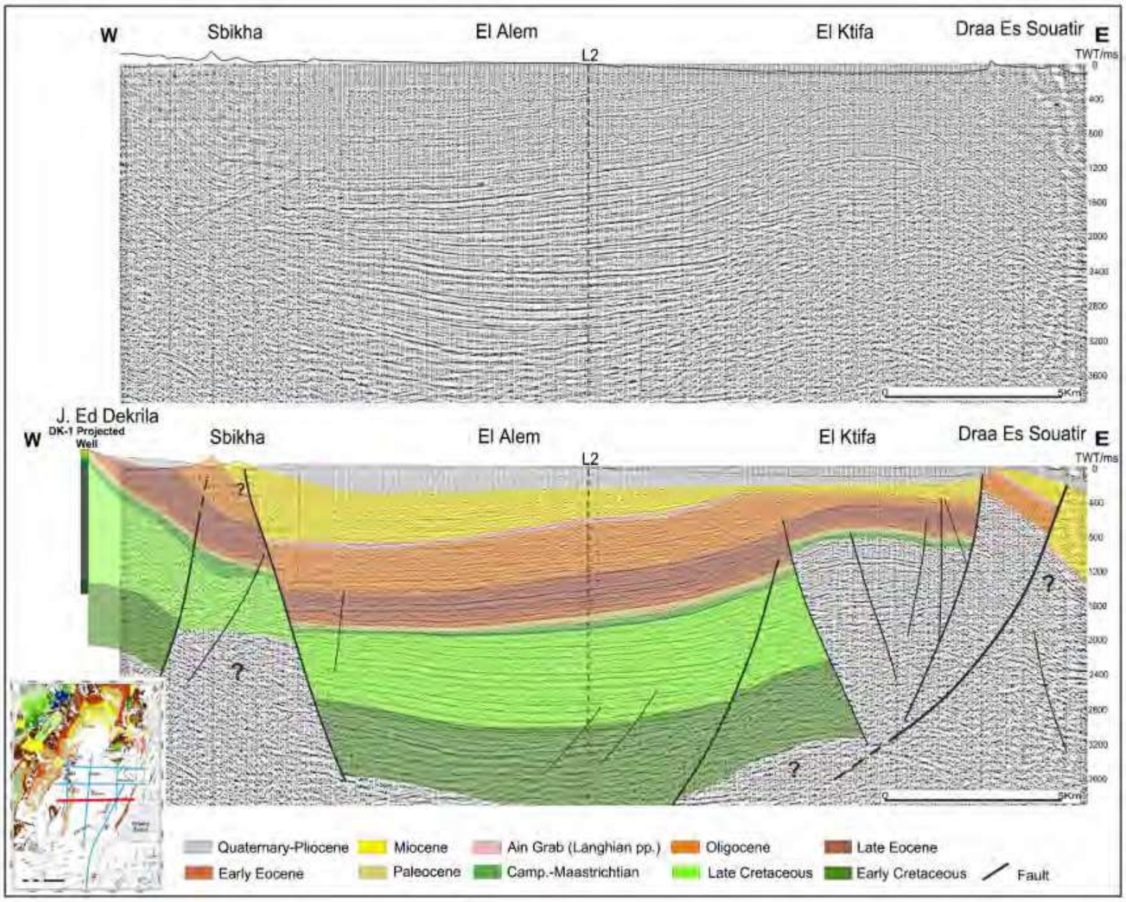


Notes: km = kilometer, L - (Line), s= (seconds), NW = northwest, P = (drilling wells), SE = southeast, TWT = (two-way time)

Figure 3-18. **From Khazri and Gabtni (2015). Upper and lower interpreted vertical seismic profiles show interpreted seismic lines with detailed units and faults.**

3.4.5 Souei and Zouaghi (2018)

Souei and Zouaghi (2018) is a case study that uses oil and gas seismic data to understand aquifers in the African country of Tunisia. The main aquifer of interest occurs within Oligocene and Neogene sandstones at depths between 60 to 300 meters (197 to 984 feet). Using data provided by local oil and gas companies, the work constructed a framework utilizing wells, two-dimensional seismic profiles, and outcrop data. Lithology, hydrology, cuttings, core, and seismic data were all analyzed. The researchers began by interpreting cutting and core data (constructing one-dimensional well-based models for the system). Then the seismic data was calibrated to key wells using acoustic logs in the area. Following the full integration of the seismic in depth (as opposed to time), the sediment packages identified from core and cutting analysis were extrapolated along the seismic sections to unify the data sets. Structure maps of seismic surfaces and interval thickness maps were made for the area, thereby extending identified aquifers away from well control. The work led to the detection of two families of major faults in the area, as well as halokinetic (salt) motion and other structural features (Figure 3-19). The study concludes by illustrating the utility of seismic to visualize geometry and structural implications for the area.

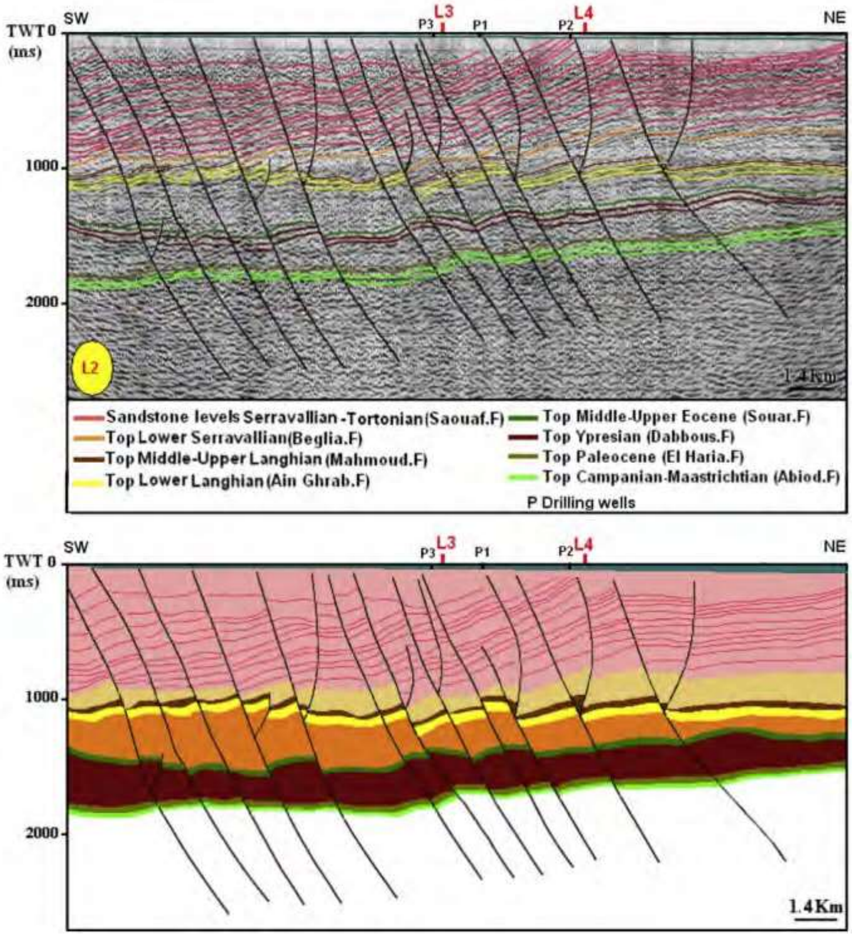


Notes: km = kilometers, L - (Line), ms= (milliseconds), E = east, P = (drilling wells), W = west, TWT = (two-way time)

Figure 3-19. From Souei and Zouaghi (2018). The upper figure illustrates an unannotated seismic line, with interpreted faults and seismic packages in the bottom of the image. Main aquifer intervals are Oligocene and shallower strata.

3.4.6 Bellali and others (2018)

Bellali and others (2018) characterized a deep aquifer system in the Dakhla syncline in northeastern Tunisia. The deep fluvial-deltaic Neogene composes the main aquifer, but there are a stack of aquifers that are also being considered. The base of the investigated section of aquifers has a depth of 3,000 meters (9,843 feet). The authors compiled petroleum wells, water wells, and eight seismic profiles. Some of the wells contained wireline logs and hydrology data. The intended goal of seismic analysis was to define the lithologic units, the geometry of the aquifer system, estimate aquifer thickness and extent, and map discontinuous zones like fractures and faults. The study begins by analyzing and correlating borehole data, thereby identifying five target aquifers ranging from the Late Cretaceous through the Quaternary. The two-dimensional seismic data are then integrated into the borehole framework. This led to direct identification of fault networks, geometry, and extent of the various aquifers (Figure 3-20). Following this, the hydrogeology data were integrated. However, the authors conclude that, while seismic reflection data highlighted thickness and depth trends as well as fault networks, more time is needed to establish a hydrogeologic model.



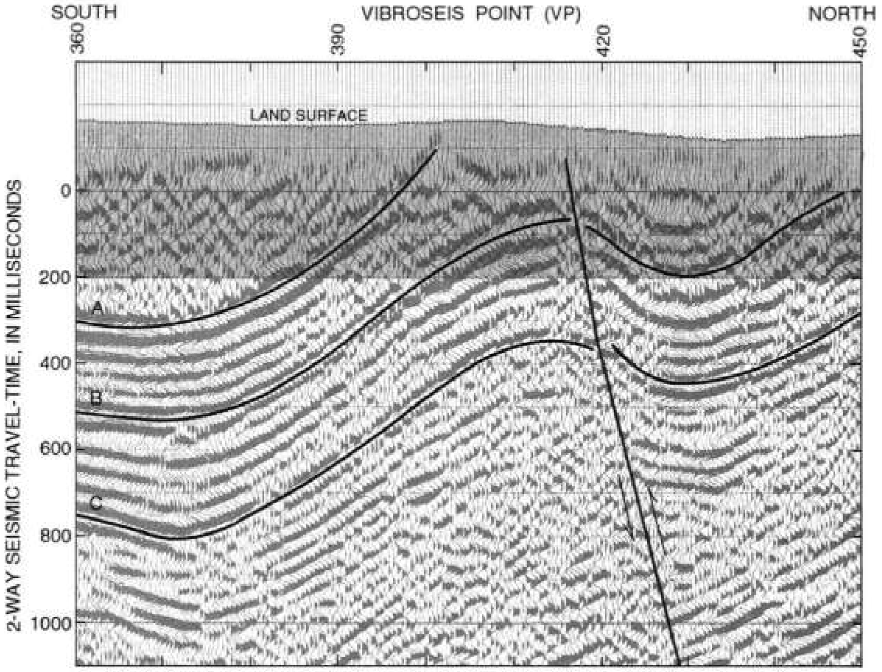
Notes: km = kilometers, L - (Line), ms= (milliseconds), NE = northeast, P = (drilling wells), SW = southwest, TWT = (two-way time)

Figure 3-20. From Bellali and others (2018). Top – Northeast-Southwest seismic profile in Dakhla syncline. Bottom – Interpretation of seismic line.

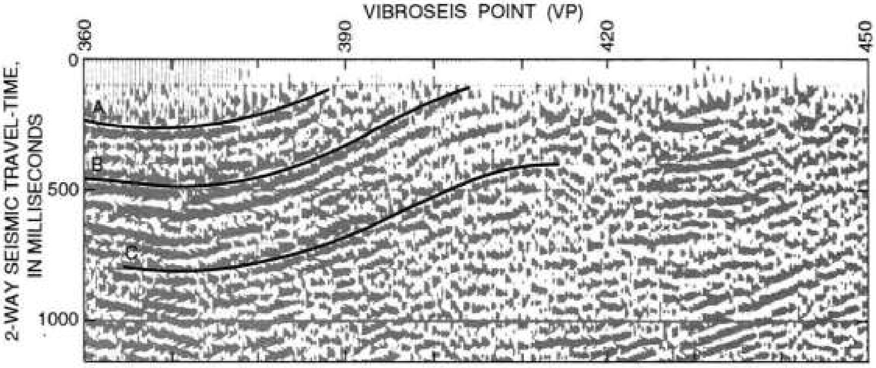
3.5 Using Previously Acquired Seismic with Reprocessing

3.5.1 Woodward and Al-Jeelani (1993)

Woodward and Al-Jeelani (1993) reported on reprocessing of seismic profiles, originally acquired to image petroleum reservoirs up to 6,000 meters (19,685 feet) in depth, in order to image aquifers less than 500 meters (1,640 feet) in depth in eastern Abu Dhabi. The work was necessary because all data relevant to the shallow section (less than150 meters [approximately 500 feet]) were muted on the original processed versions of the seismic lines. Such muting of the early returns is fairly common when imaging deep reservoirs as a cosmetic not to show noise from those returns in the seismic survey. The study detailed a workflow derived from many trial and error experiments in reprocessing. The main takeaway of the study is the processing workflow that was determined to be most useful in restoring the shallow seismic reflectors. Major enhancements resulted from a 20-hertz, low-cut filter, a static correction to a datum nearer to the land surface, intense velocity analysis, and careful application of near-trace muting. The low-cut filter eliminates frequencies lower than 20 hertz, as this is where the greatest amount of seismic noise was found in the study. Corrections to land surface are common and entail bulk shifts of times to accommodate the change in topography. Muting is a process whereby certain seismic traces are ignored. In this instance, some near traces were muted (the data from the geophones nearest to the source). The work resulted in 33 reprocessed sections that were able to restore seismic data in the top 500 meters (1,640 feet), as well as improving overall data quality (Figure 3-21). Woodward (1994) advanced this research with further hydrologic and lithologic analysis. The final seismic analysis of the area showed that tectonics of the region resulted in upthrusting of the evaporite units which has impacted groundwater flow and salinity.



a. Shaded part of section is shallow seismic data deleted from original section. Reflectors A, B, and C are delineated for comparison. Anticlinal crest at VP 413 and synclinal trough at VP 429 are well-defined by reflectors B and C.



b. Shallow seismic data above datum of 91.5 meters above sea level were deleted during original seismic processing. Reflectors A, B, and C are delineated for comparison. Continuity of reflector C becomes questionable near VP 415; the anticline and syncline noted in fig. 8a are not readily apparent in this section.

Figure 3-21. From Woodward and Al-Jeelani (1993). Top - the shaded section shows what was recovered from the original seismic volume. Bottom – the original seismic data, the interpretation lines along the reflectors are the same. The noise reduction between the bottom and top figures is striking.

3.5.2 Capetillo and others (2014)

Capetillo and others (2014) reported a seismic reprocessing study from Mexico City. The goal of the study was to identify drinking water reservoirs in depths of 800 to 2,000 meters (2,500 to 6,000 feet) for use in the Mexico City water supply. The study was conducted by acquiring 30 kilometers (18 miles) of new high resolution two-dimensional data and reprocessing 18 vintage seismic lines from 1986. Reprocessing of the old lines and processing of new lines were aimed mainly at improving seismic-horizon correlation and increasing spatial sampling for better noise attenuation. Special care was taken to preserve relative seismic amplitudes, so that attributes could be used alongside amplitude versus offset analysis to detect fluid targets. (Amplitude versus offset is the variation in seismic amplitude with change in source-geophone offset distance). Further information on the seismic reprocessing workflow was not provided. The authors also utilized gravity data and well log data. The well logs and seismic lines led to the identification of four different potential targets. The seismic information was also instrumental in the detection of shallow faults and other drilling hazards, which lowered drilling risks. The study resulted in 10 new drilling prospects for Mexico City, as well as a good understanding of potential aquifers, fault networks, and drilling hazards.

3.5.3 Hanot and others (2011)

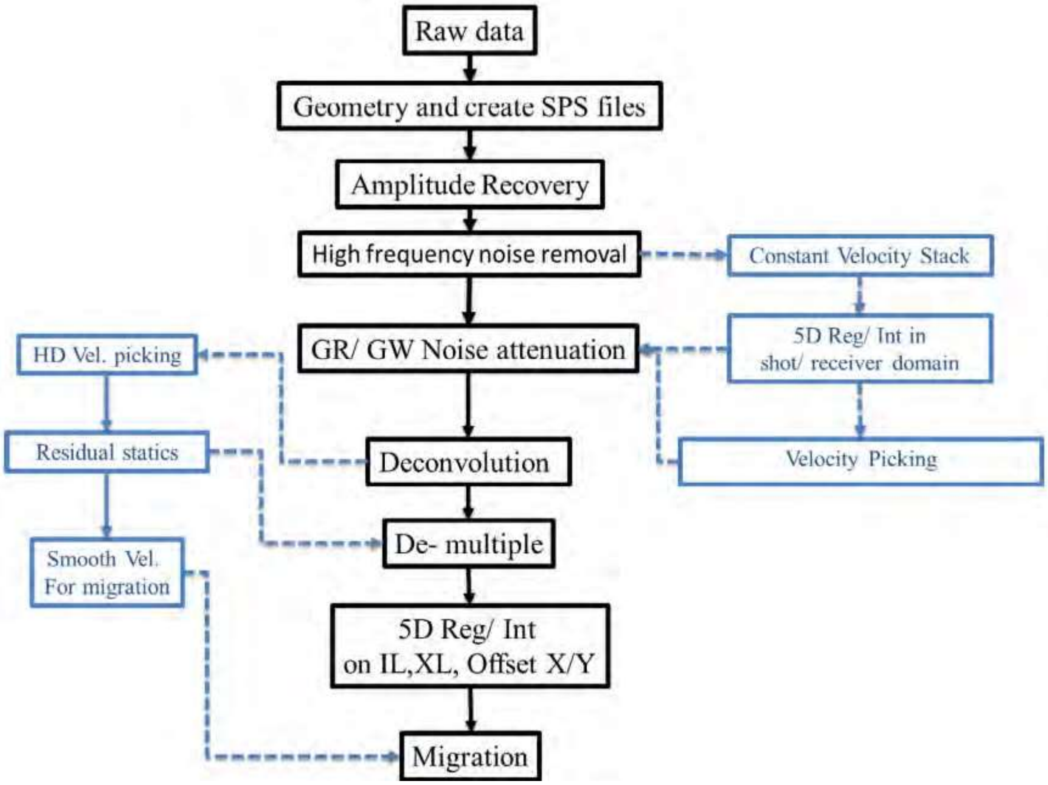
Hanot and others (2011) conducted a study in the Paris basin to define the geometry of possible carbon dioxide storage targets in deep saline aquifers. There are various aquifers down into the deep saline zone (below 3 kilometers [~10,000 feet]) and upward to the surface. The study mostly centers on the reprocessing of seismic and less on the actual geology and aquifers. The preliminary phase of the study included reprocessing 343 two-dimensional seismic lines originally acquired for oil and gas exploration. The authors deemed static corrections to be of great importance. The dataset was harmonized by a static multi-layer correction of the cover and by deconvolution. This work contains a detailed processing workflow for the two-dimensional lines. First, amplitude recovery was accomplished by using a correction to compensate for the energy decay due to spreading. Next, deconvolution was applied to increase resolution. Some traces were muted to reduce residual statics in the common depth point gathers. Following this, the authors improved the field statics, performed velocity analysis, estimated, and applied residual statics prior to low-cut/high-cut filtering and dip moveout. The stack was then created and the stacked traces were moved to the final datum. Post-stack processes included migration, another filter, and polarity harmonization. The researchers noticed that eight two-dimensional seismic lines denoted an increase in impedance as positive and other two-dimensional seismic lines denoted it negative, so a correction was applied. Synthetic seismograms were integrated at three wells and tied to the seismic data. Synthetic seismograms are created by processing well data into generating an estimation of what a seismic trace should look like at the well. This synthetic is used to get an estimate of what the seismic response should look like at each depth, and thus tie the seismic time to depth. The authors conclude by stating that the reprocessing was helpful in improving identification of structures, but the difference in quality of acquisition between the various surveys precluded comparison of lateral variation of facies.

3.5.4 Sowiżdżał and others (2020)

Sowiżdżał and others (2020) reported on the reprocessing of two-dimensional seismic data in Poland for the purposes of geothermal exploration. The main aquifer targeted for geothermal exploration is in the Lower Jurassic, which ranges from 100 meters to over 2,000 meters (300 to 6,100 feet) depth in the study area. The fairly typical seismic reprocessing workflow in this study involved amplitude spreading correction, elimination of amplitude distortions, noise reduction, and deconvolution. Apart from the seismic data, geophysical well logs were analyzed to determine lithofacies of the Jurassic, boundaries of those units, and quantitative porosity and clay content measurements. The seismic interpretation was then integrated with the geophysical well log data to construct a three-dimensional lithology and petrophysical model in the Petrel software. To better understand the role of frequency and rock porosity on amplitudes of the seismic reflectors and determine if seismic reflections could be used to predict the same, synthetic seismograms were created from acoustic logs in the area. The authors came up with some overall thickness information but did not examine units within the Lower Jurassic. The study concluded that seismic allowed for the interpretation of thickness and porosity trends across the area, and that further analysis was limited by the vertical resolution of 40 meters (131 feet).

3.5.5 Al-Gain and others (2020)

Al-Gain and others (2020) is about five-dimensional regularization and processing. The case study was performed on the Stratton dataset in south Texas and was effective at imaging shallow structures (above 600 milliseconds). This paper is a methods paper on regularization and interpolation of three-dimensional seismic workflow (Figure 3-22). Regularization is the art of transforming the number of traces per bin (a bin is the area between adjacent lines) to be more equal or better conditioned in the dataset. The irregular distribution of shot and receiver locations in the Stratton dataset have adverse effects on noise. The actual "five-dimensional" interpolation refers to the five elements of interpolation used to fill in gaps, (in this case, shot x, shot y, receiver x, receiver y, and frequency). These parameters can be used to interpolate what seismic traces should look like between other traces. Stacking with these interpolated traces will increase the signal-to-noise ratio and result in more coverage and higher resolution. Comparison between the five-dimensional interpolated data and the original shows that the five-dimensional processing did a much better job of reducing artifacts and noise. It especially did well to recover shallow structures and strata, as shallow as approximately 300 milliseconds (Figure 3-23).



Notes: 5D = five-dimensional, HD = high definition, IL = inline, SPS = Shell Processing Support (filetype), XL = crossline

Figure 3-22. **From Al-Gain and others (2020). Methodology workflow. Black boxes represent the main seismic data flow and blue boxes reflect preconditioning of the data, starting from reading the shot gathers and reformatting and extracting the missing files from data headers.**

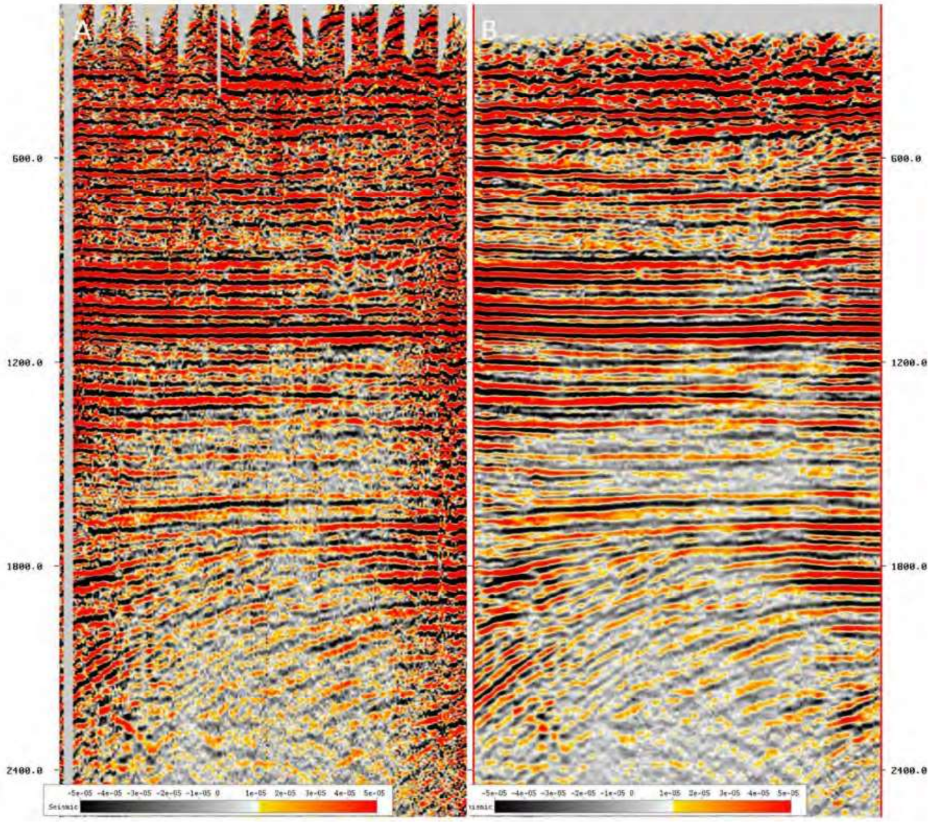


Figure 3-23. From Al-Gain and others (2020). (A) An example of the azimuth stack on in-line 240, where data are missing near the surface and the stack contains high-frequency, non-continuous geological layers. (B) An example of the azimuth stack on in-line 240, where full data are apparent at the near surface and with continuity in geological settings.

3.5.6 Young (2009)

Young (2009) is a short case study from the Oklahoma Water Resources Board presenting findings on using reprocessed seismic in a shallow karsted, structurally complex aquifer (Hunton Aquifer) in Oklahoma. The aquifer in this study ranges from 600 to 3,500 feet in depth. The shallowest information is supplemented by ground penetrating radar and resistivity imaging. Three seismic surveys were examined. While the reprocessing workflow is not described, the reprocessing was meant to give an opportunity for a "second opinion" on some basement disruption issues. Although being able to resolve the basement reflectors and much of the karsted character, the authors concluded that the near-surface geophysics (ground penetrating radar and resistivity) could map the faults efficiently at lower cost than seismic techniques.

3.6 Application to Brackish Resources Aquifer Characterization System Studies

The existing literature provides a number of case studies and examples from different aquifer lithologies, structural settings and data availability. These publications also illustrate a wide variety of methods that involve seismic data used to resolve geologic complexity over a wide variety of geological settings.

In general, many uses of seismic involve “classic” geophysical interpretation of faults, folds, and general stratigraphic packages. Generally, these have used two-dimensional profiles and helped to define the main basin aquifer elements (as in Tunisia and Australia). If the original data have sufficient resolution for the depths of interest, it is generally interpreted “as-is,” and the results are integrated with wells and surface information. Depending on the seismic resolution, this could apply to seismic in some plays in West Texas (base of the Dockum, reef and peri-reef trends of the Capitan Reef) and to look at faults that continue to shallow depths in the Gulf Coast. Offshore aquifers might be sought using the (less expensive) offshore data and electromagnetic surveys, as in New Jersey and elsewhere.

Reprocessing of seismic data (two- and three-dimensional) originally acquired for hydrocarbon exploration has been highly useful in many areas, both to extend data to shallower depths (Woodward and Al-Jeelani, 1993) or to improve resolution and confidence in the shallow, lower-fold section (Al-Gain and others, 2020). Reprocessing is expected to be particularly useful in areas where the shallow section was not of interest to the original data processors and users. This is particularly true in much of the Gulf Coast aquifer complex, where original targets lie below 8,000 feet depth in many areas.

Only a few published studies have worked with three-dimensional seismic surveys. These surveys offer an expanded and much more reliable image of aquifer patterns and connectivity, as noted by Jansen (2015). They also give a good image of the effects of karsting and fracturing in potential carbonate aquifer zones (Carbonate Aquifer Characterization Lab papers). Clearly, three-dimensional seismic surveys can bring tremendous advantages to the characterization of groundwater bearing units. Cost is the largest hurdle to the incorporation of three-dimensional seismic surveys to groundwater characterizations.

Beyond methods, the suite of publications presented covered a vast array of settings for aquifers. The Carbonate Aquifer Characterization Lab was focused on imaging karst in the Florida Aquifer System, Al-Gain and others (2020) was focused on onshore passive margin sediments, and Bellali and others (2018) focused on exploring deep aquifers of mixed lithologies in a structurally complex setting. The techniques employed in these various settings are insights on how to design a study and process data in different environments, especially as the differences in Texas aquifers comes into play. The Hickory, the Edwards, the Rustler, and the Gulf Coast represent a very diverse assemblage of settings that must be accounted for when attempting to apply seismic exploration methods. Even so, these are not so different from some of the aquifers covered here.

In each case where utilized, seismic reflection data has led to the ability to predict structural and stratigraphic data away from well control with a high degree of fidelity to the true nature of the subsurface. While there has traditionally been cost barriers to use in the groundwater industry, some forays have shown the utility of seismic aquifer exploration and characterization. As hydrogeologists seek better methods of evaluating and characterizing these aquifers, the value of seismic will increase; especially when considering the tremendous amount of two- and three-dimensional seismic data originally acquired for oil and gas exploration in Texas.

4 Seismic Data Availability (Task II)

Seismic reflection data, either two- or three-dimensional, have been acquired either by oil and gas companies ("proprietary data") or by seismic acquisition firms, with underwriting from oil and gas companies ("speculative data" or "multiclient data"). Much of the proprietary data have since been either sold or made available for licensing to seismic acquisition firms or seismic exchanges on similar terms to multiclient data. However, a significant amount of seismic data are still controlled by individual oil and gas companies or their successors, not all of which is available for licensing or even reported.

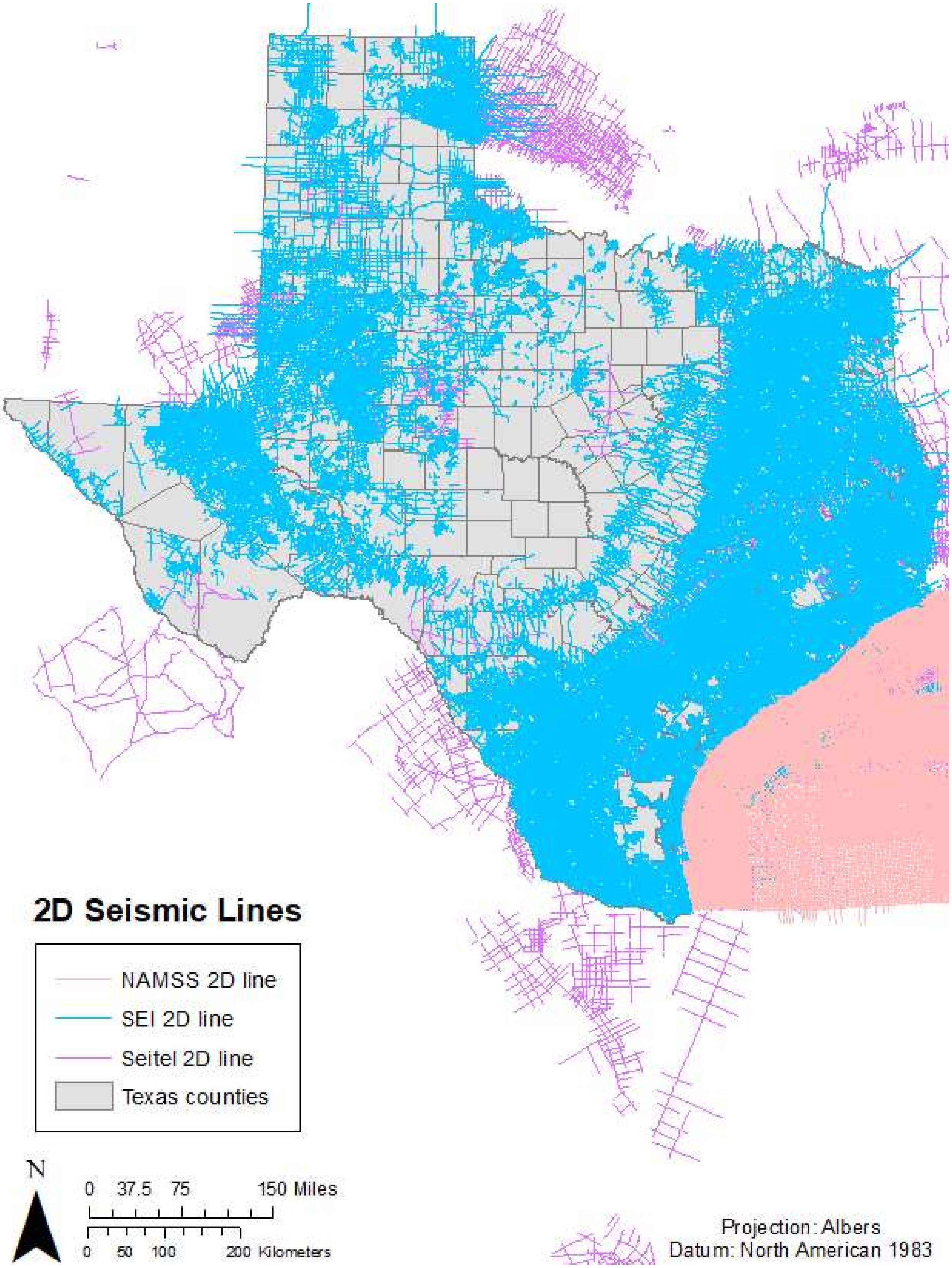
Multiclient data and much other seismic data are available for licensing but not for purchase. Licensing allows for data to be received, examined, and interpreted, and to be reprocessed if the appropriate data are available. Publication or other public display of data is restricted under most licensing agreements; such public use needs to be agreed to by the licensor, either in the licensing agreement or later.

A small number of seismic exchanges control most of the multiclient seismic data available in Texas and the offshore shelf; the two largest are Seismic Exchange, Inc. and Seitel Data, followed by CGG and Fairfield Geotechnologies. Other sources of data include smaller seismic acquisition companies and oil and gas companies. Land holders may also have data covering their properties that can be examined and possibly licensed as part of a project, depending on their agreement with the acquisition company.

In the Federal Outer Continental Shelf, the National Archive of Marine Seismic Surveys (operated by the United States Geological Survey) has many two-dimensional lines and three-dimensional volumes acquired from 1977 to 1995 available to use at no charge. More recent surveys are in their proprietary period and would have to be licensed from the data owner.

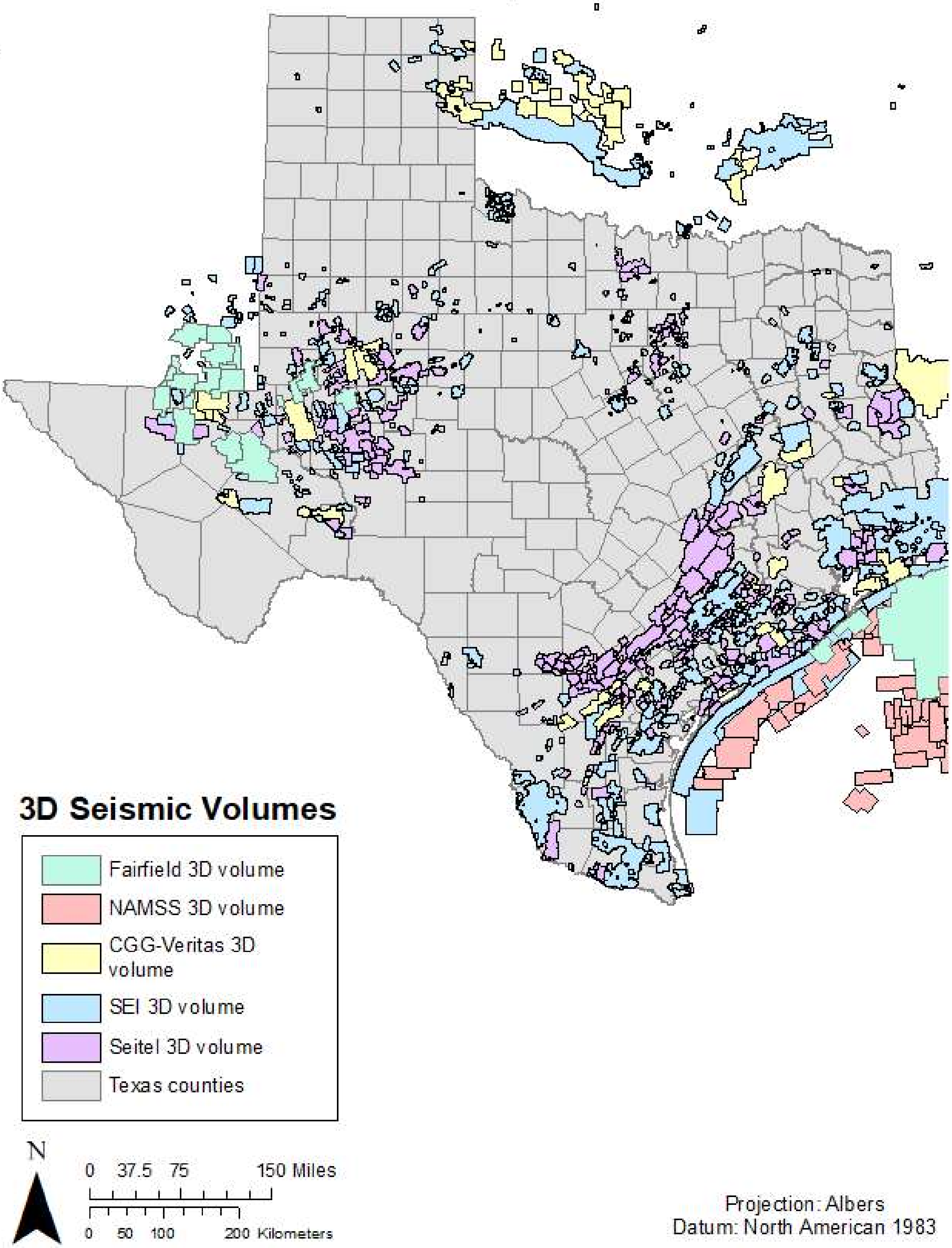
4.1 Available Texas Seismic Data Texas

Most seismic reflection data in Texas were acquired for oil and gas exploration and development. Therefore, most of the existing seismic that can be used for aquifer characterization exists in the productive oil and gas regions of Texas. Figure 4-1 shows the available two-dimensional data and Figure 4-2 shows the available three-dimensional data. Figure 4-3 shows the various oil and gas producing regions that are the subject of seismic imaging.



Note: 2D = two-dimensional, NAMSS = National Archive of Marine Seismic Surveys, SEI = Seismic Exchange, Inc

Figure 4-1. Distribution of two-dimensional datasets from the three main vendors in Texas.



Note: 3D = three-dimensional, NAMSS = National Archive of Marine Seismic Surveys, SEI = Seismic Exchange, Inc

Figure 4-2. Distribution of three-dimensional datasets from the five main vendors in Texas.

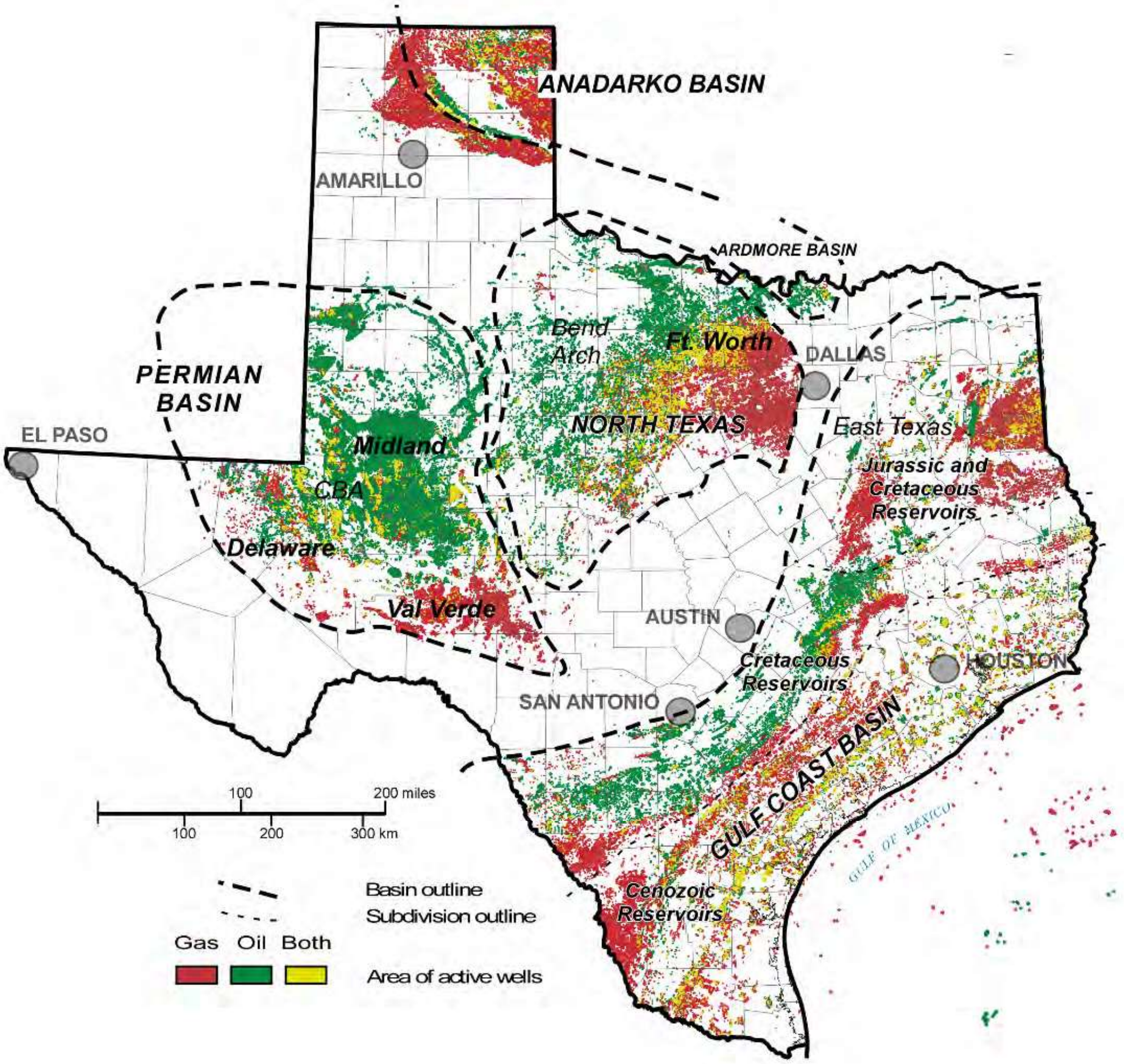
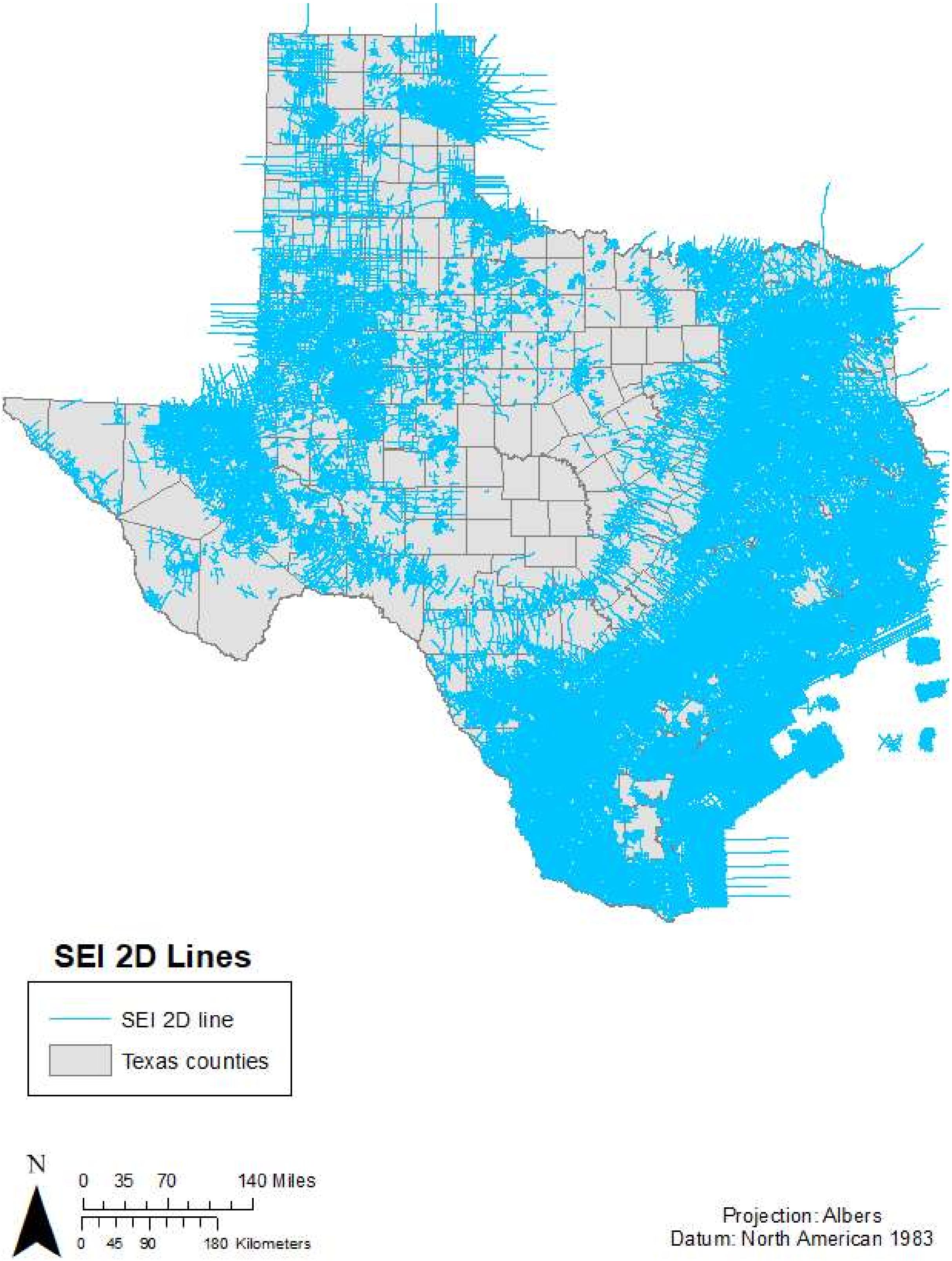


Figure 4-3. **From Ewing (2016). Distribution of oil and gas fields and provinces in Texas.**

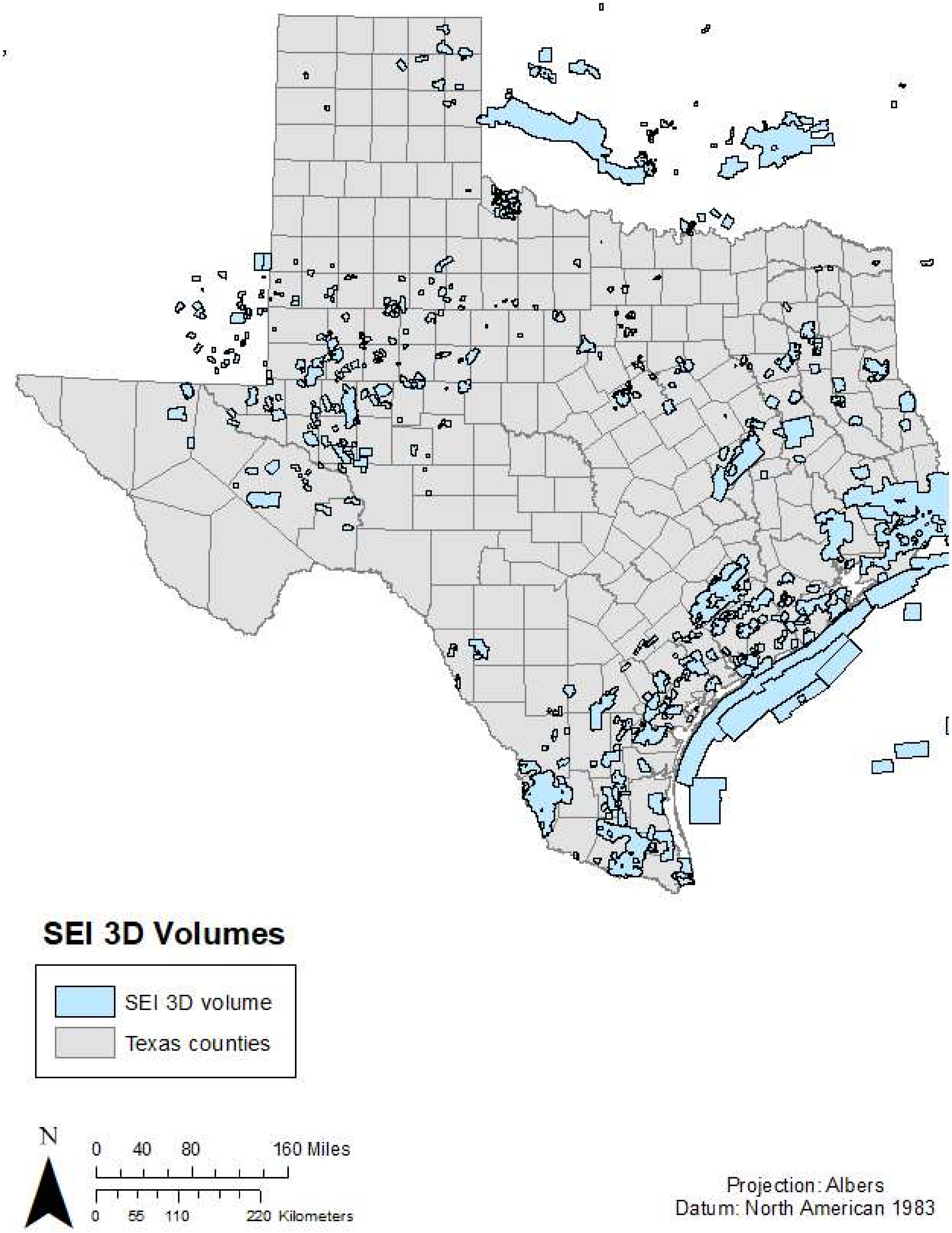
The availability and coverage of two-dimensional seismic lines offered by Seismic Exchange, Inc. is depicted in Figure 4-4. The two-dimensional coverage is the most extensive of any vendor and includes some offshore profiles. Areas that are not well covered include central Texas (including the Edwards and Trinity aquifers and the Llano region), the Fort Worth Basin (Northern Trinity aquifer), various portions of west Texas, far west Texas, and the Amarillo Uplift and associated areas in the Texas Panhandle. Cost for the two-dimensional datasets runs from $2,100 to $2,500 per mile depending on their fold (a measure of redundancy in the field data; higher fold yields higher quality sections), with a minimum purchase usually of 5 to 10 miles. Because the data coverage is so extensive, the acquisition and processing characteristics of these lines spans a range of dates and amount of processing. Some lines were scanned from paper and others still have the original tapes. All history and key data are available on the Seismic Exchange, Inc. website.



Note: 2D = two-dimensional, SEI = Seismic Exchange, Inc

Figure 4-4. **Distribution of Seismic Exchange, Inc. two-dimensional seismic lines in Texas.**

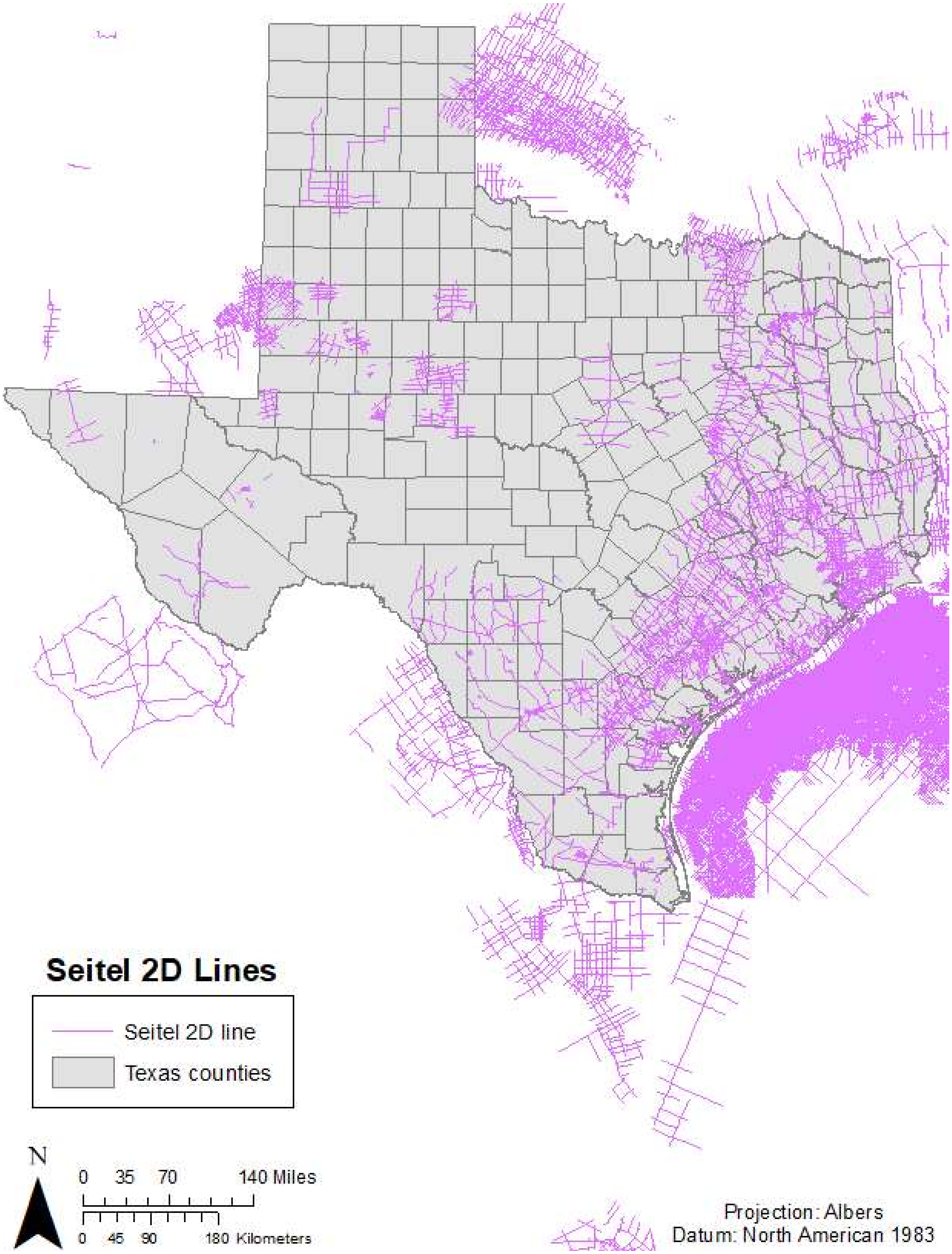
The availability and coverage of the Seismic Exchange, Inc. three-dimensional seismic volumes is depicted in Figure 4-5. There is coverage of large areas of the Gulf Coast, with scattered three-dimensional volumes in the Permian Basin and in the East Texas and Anadarko Basins. Some surveys are available along the coast in state waters and the adjacent Federal Outer Continental Shelf. Prices are quoted on request, but typically would run $10,000 to $30,000 per square mile (more in highly active trends); minimum purchases are probably 5 to 10 square miles. The state of processing, whether the volume was merged, and other acquisition and processing characteristics varies from volume to volume. However, the information is included on a convenient set of survey info sheets on the Seismic Exchange, Inc. website.



Note: 3D = three-dimensional, SEI = Seismic Exchange, Inc

Figure 4-5. **Distribution of Seismic Exchange, Inc. three-dimensional seismic volumes in Texas.**

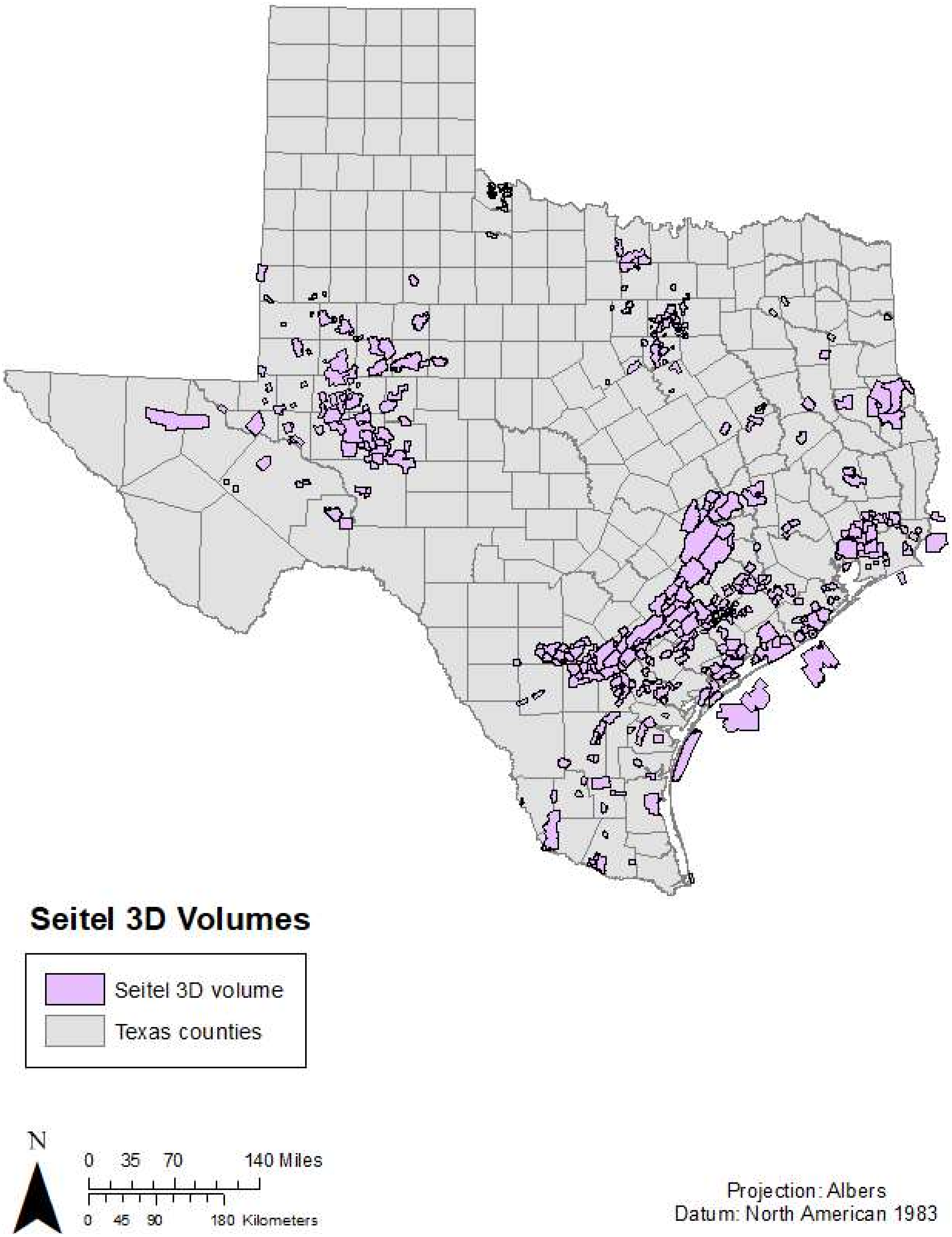
The availability and coverage of the Seitel two-dimensional seismic lines is depicted in Figure 4-6. Seitel's two-dimensional coverage is best on the Gulf Coast, and is sparse over the rest of the state, except for some few clusters of lines in the northern Midland Basin, the Panhandle, and the East Texas Basin. Some offshore two-dimensional lines are included. The Seitel two-dimensional lines are fairly numerous, and processing and acquisition parameters do vary.



Note: 2D = two-dimensional

Figure 4-6. **Distribution of Seitel two-dimensional seismic lines in Texas.**

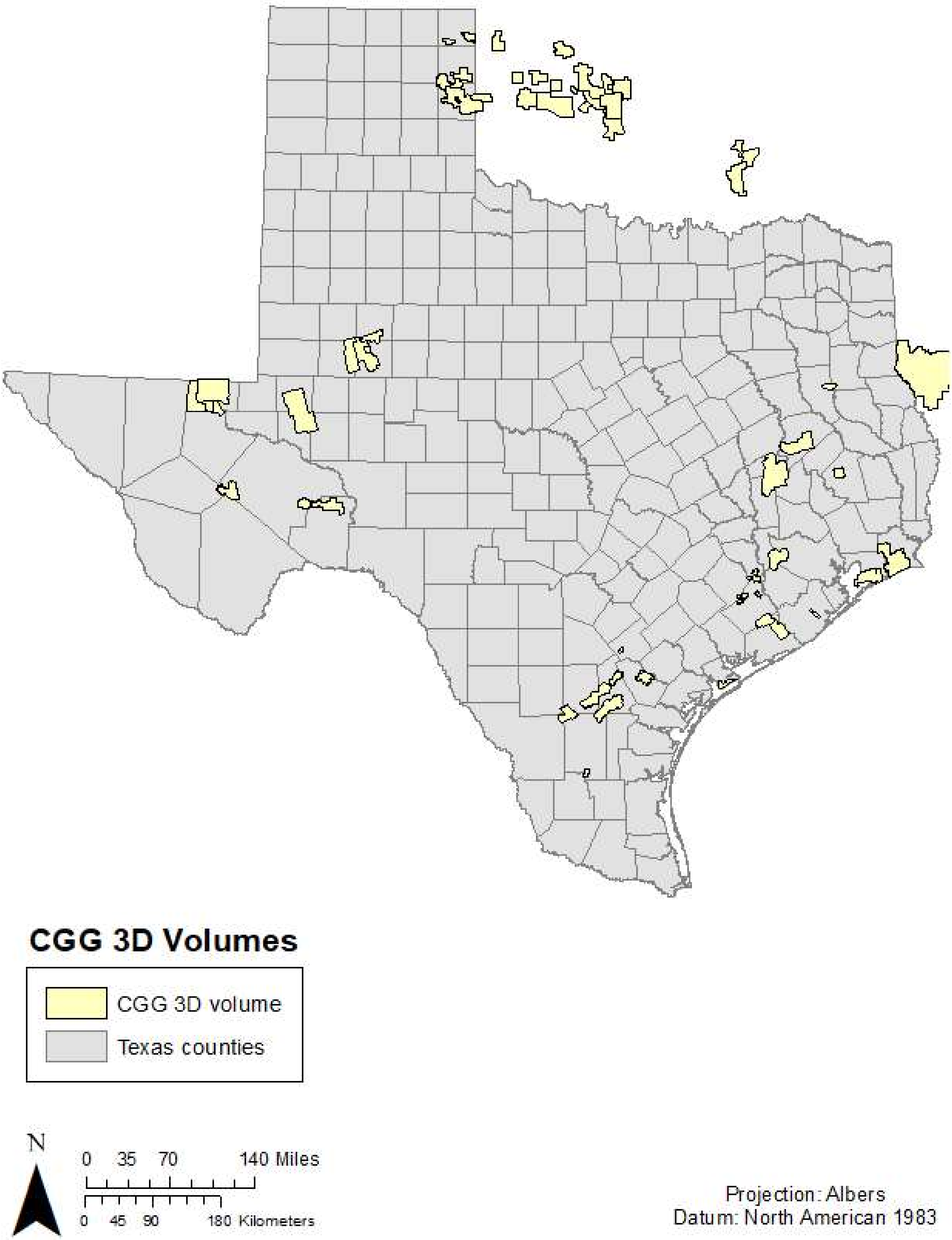
The availability and coverage of the Seitel Data three-dimensional seismic volumes is depicted in Figure 4-7. The best coverage comes from three-dimensional seismic in the area of interest for the Eagle Ford play, the Gulf Coast, and in the Midland Basin. Some small three-dimensional volumes exist in the Fort Worth Basin. The three-dimensional volumes that do exist for Seitel span a range of acquisition dates and processing extents and can be looked at individually on the Seitel website.



Note: 3D = three-dimensional

Figure 4-7. **Distribution of Seitel three-dimensional seismic volumes in Texas.**

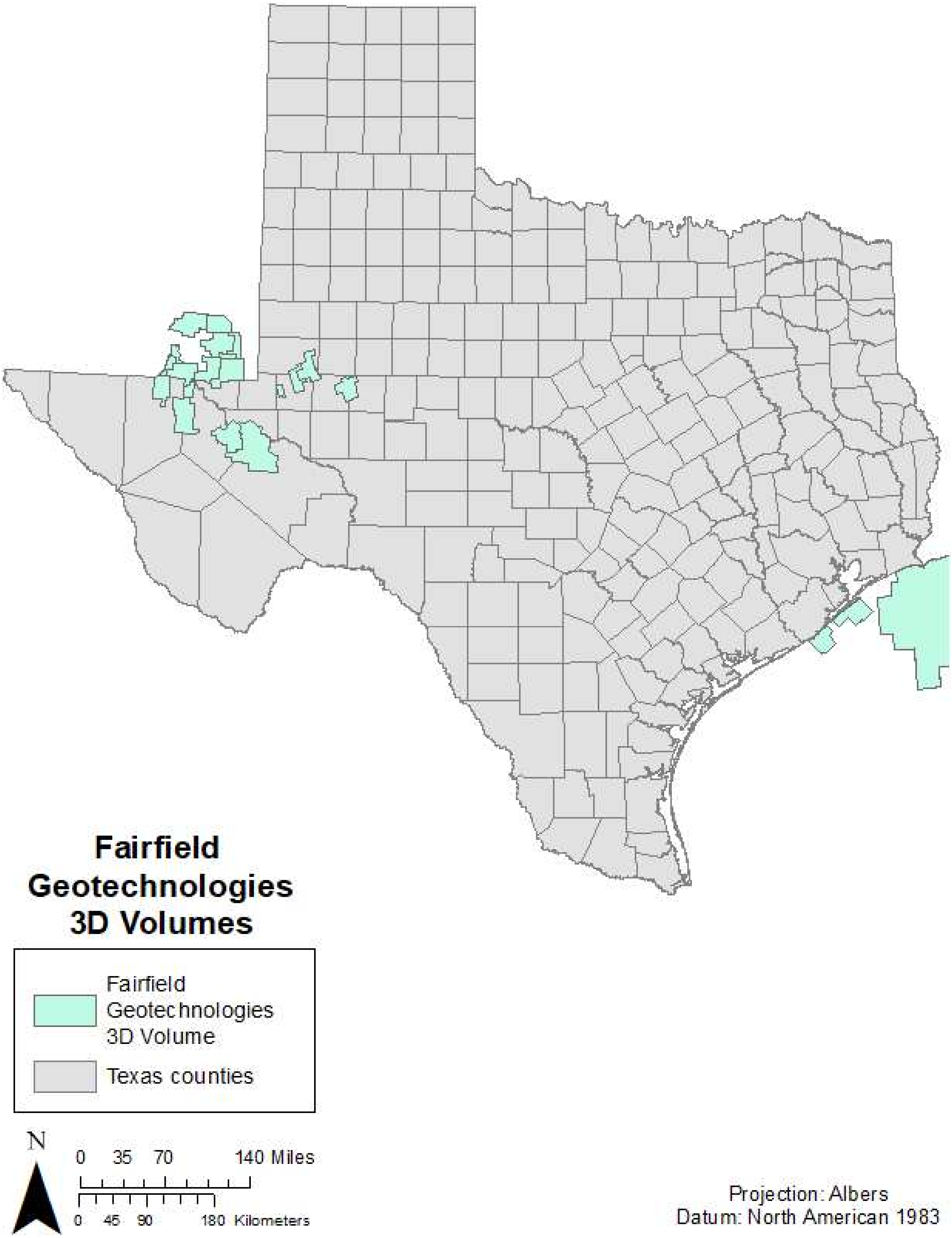
CGG offers a number of three-dimensional surveys scattered across Texas; six surveys in West Texas, seventeen in South and Southeast Texas (Gulf Coast), four in East Texas, five in the Texas Panhandle and five in the offshore shelf. The CGG coverage is depicted in Figure 4-8. CGG does not have two-dimensional lines available. Like most companies, the collection of volumes at CGG will not have uniform processing parameters or acquisition parameters. For a better estimate on a particular survey, the CGG website can be consulted.



Note: 3D = three-dimensional

Figure 4-8. Distribution of CGG three-dimensional seismic volumes in Texas.

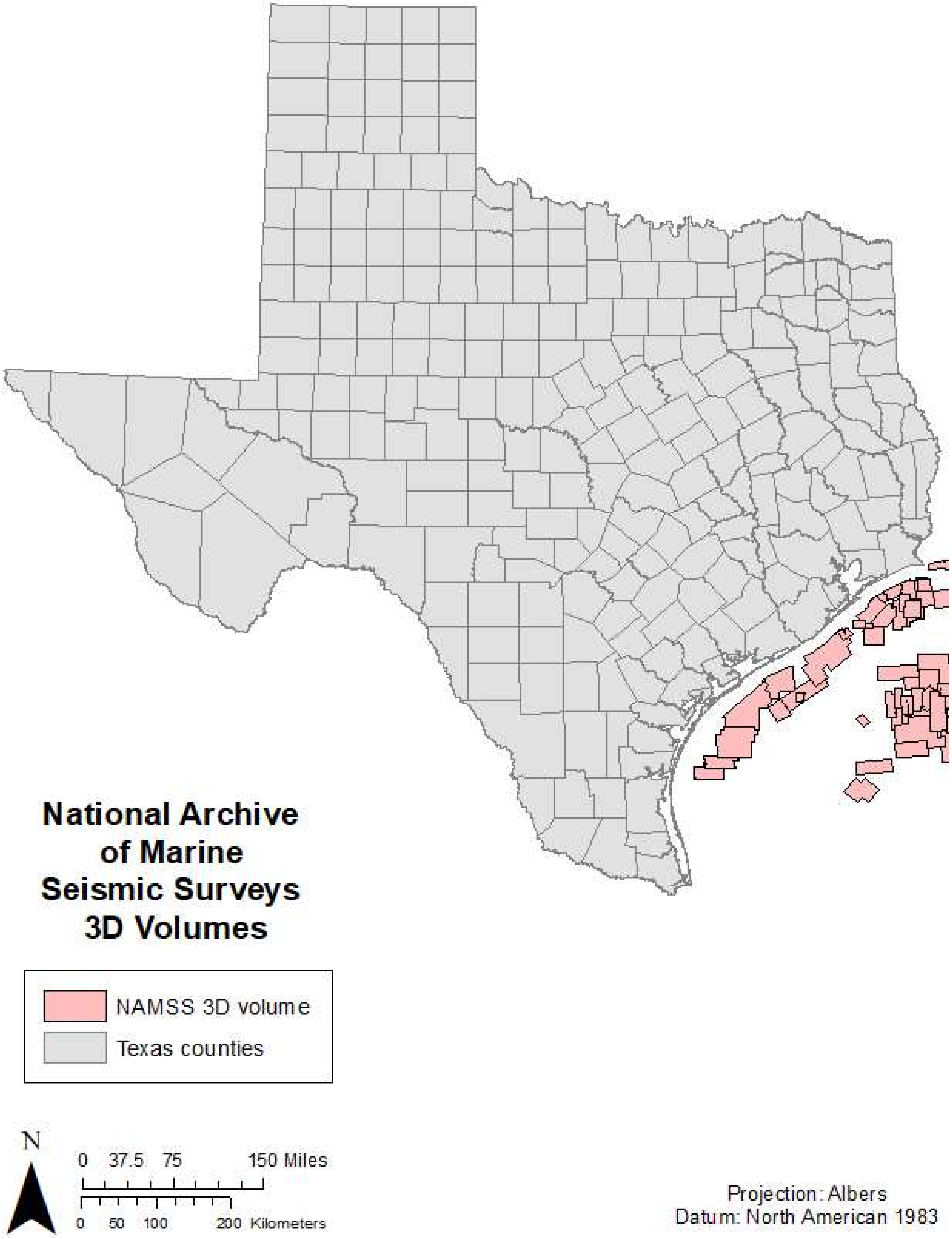
Fairfield Geotechnologies offers 10 three-dimensional surveys concentrated in the Delaware Basin section of the Permian Basin, also some offshore data southeast of Houston. The extent of the three-dimensional surveys is given in Figure 4-9. There are no available two-dimensional lines advertised by Fairfield Geotechnologies. The range of seismic surveys here are also non-uniform in acquisition parameters and processing traits.



Note: 3D = three-dimensional

Figure 4-9. **Distribution of Fairfield three-dimensional seismic volumes in Texas.**

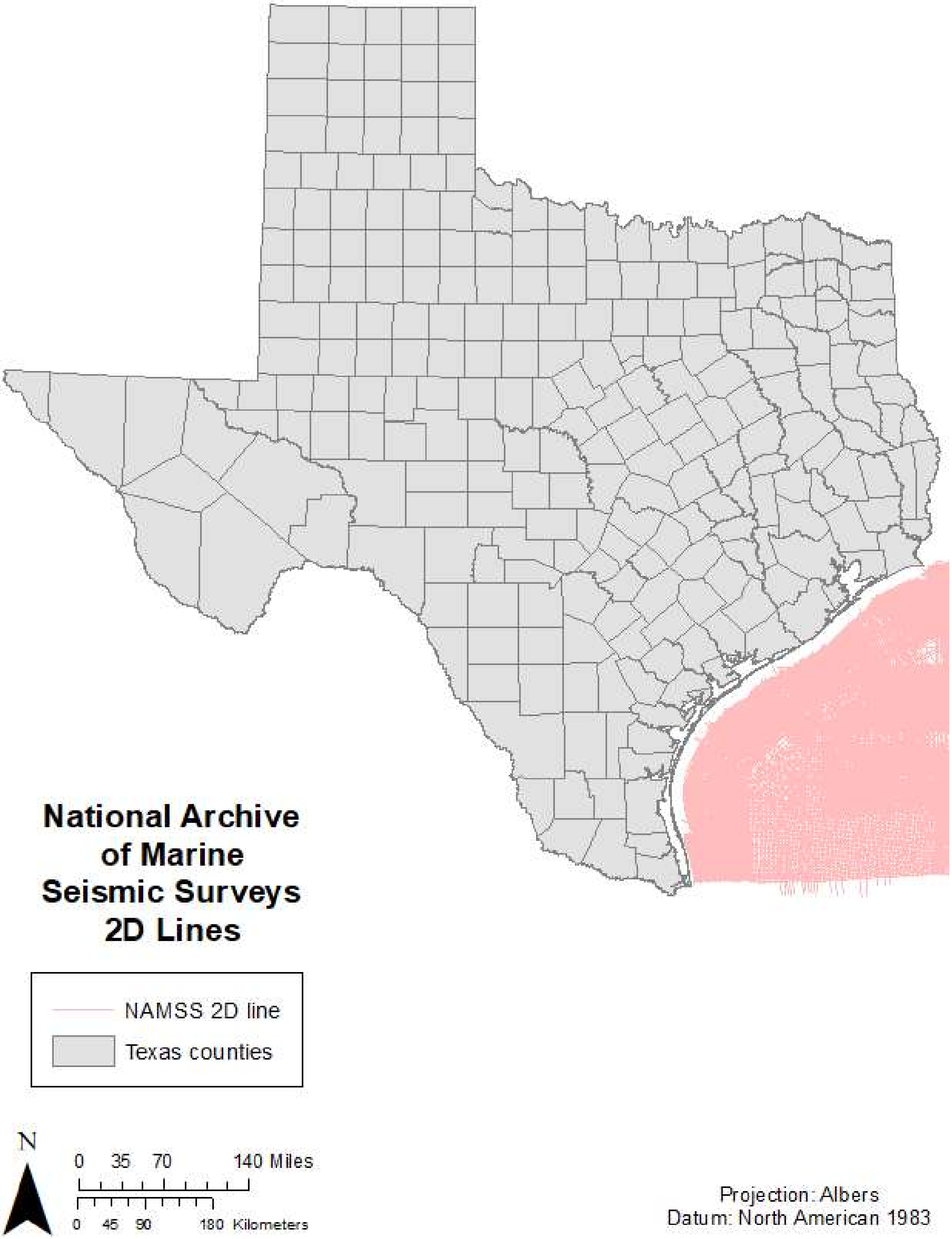
The availability and coverage of the National Archive of Marine Seismic Surveys three-dimensional seismic volumes at present is depicted in Figure 4-10. There are two main areas of coverage for these three-dimensional volumes. There are a number of nearshore volumes, which start from approximately 9 miles (3 leagues) offshore from Kleberg County northeast to Louisiana and extending in a belt to 100 miles offshore. The next covered interval is farther offshore in the Plio-Pleistocene and flexure trends, which begins perhaps 200 miles offshore and extends far into the Gulf. There is no cost for these publicly available lines, but all of the data are at least 25 years old. (Note that the original names, operators, and acquisition companies are stripped from the National Archive of Marine Seismic Surveys database, so survey history is hard to track.)



Note: 3D = three-dimensional, NAMSS = National Archive of Marine Seismic Surveys

Figure 4-10. **Distribution of National Archive of Marine Seismic Surveys three-dimensional seismic volumes in Texas.**

The availability and coverage of the National Archive of Marine Seismic Surveys two-dimensional seismic lines is depicted in Figure 4-11. The coverage beings approximately 20 miles offshore and continues into the gulf. Offshore coverage is very dense and extensive. There is no cost for these publicly available lines. All of the National Archive of Marine Seismic Surveys data are at least 25 years old. (Note that the original names, operators, and acquisition companies are stripped from the National Archive of Marine Seismic Surveys database, so survey history is hard to track.)



Note: 2D = two-dimensional, NAMSS = National Archive of Marine Seismic Surveys

Figure 4-11. **Distribution of National Archive of Marine Seismic Surveys two-dimensional seismic lines in Texas.**

If areas do not show seismic coverage within the major producing trends, they may be covered by proprietary surveys still held by oil and gas companies. There is no obligation in Texas to report or record when and where seismic surveys are acquired, so some data are "hidden." Using the services of a data broker is most helpful in locating these surveys and facilitating their quality checking and licensing. Such brokers are paid from the proceeds of licensing.

4.2 Discussion – Acquisition and Processing Histories

As can be seen, Texas contains a vast amount of seismic data, both two-dimensional profiles and three-dimensional volumes. Within the Gulf Coast and in most parts of West Texas, East Texas and the eastern Panhandle, one is likely to find data that is applicable to groundwater/brackish water studies. Even areas with limited two-dimensional data, such as the Balcones-Dallas trend, may find some of the data useful in structural and stratigraphic correlation.

The data coverage includes a wide variety of vintages. Multifold two-dimensional lines may be as old as the 1960s or early 1970s and were acquired in large amounts through to the 2000s. The three-dimensional surveys were experimental in the 1970s and began large-scale acquisition in the late 1980s and 1990s. Acquisition since 2008 has largely been in the active resource plays ("shale plays"), particularly in the Eagle Ford trend and the Midland and Delaware Basins.

Earlier data were acquired using older electronics and field designs, resulting in lower fold and limited offset distributions. In 1980, 24-channel two-dimensional recording was state of the art; more recent two-dimensional surveys can exceed 100 channels. The recording of three-dimensional surveys was even more striking; early surveys might have hundreds of live channels, modern surveys can have tens of thousands of channels. Extra channels allow denser sampling, higher fold, longer offsets, better azimuth distributions and other benefits. Not all of these benefits will necessarily apply to the shallower part of the seismic record (such as long offsets, which do not contribute to the stacking process at shallow depths).

After seismic data is acquired, it must be processed for use in geologic interpretation and geophysical analysis. Seismic processing has also advanced greatly from the early digital work of the 1960s to a range of sophisticated processing algorithms at present. Older data with appropriate acquisition parameters is commonly reprocessed using more advanced methods, often multiple times. Great improvements in imaging are achieved by this work. In general, two-dimensional reprocessing should cost about $200 per mile, and three-dimensional reprocessing can be in the vicinity of $1,000 to $1,500, depending on the products desired.

The strengths and weaknesses of existing seismic data acquisition and processing parameters for the zone of brackish water interest, the "top second" of seismic data, will be discussed at more length in Task 3.

4.3 Sources of Seismic Data Information

Attached here are names and uniform resource locators (web addresses) for major seismic vendors. There are smaller vendors not included and as mentioned, proprietary surveys will require the services of a data broker.

Seismic Exchange, Inc.	https://web.seismicexchange.com/1/
Seitel Data, Inc.:	https://www.seitel.com/index.php/seitel-map
CGG:	https://geostore.cgg.com
Fairfield Geotechnologies:	https://fairfieldgeo.com/map/all
National Archive of Marine Seismic Surveys:	https://walrus.wr.usgs.gov/namss/search/
Open Geophysical Data:	https://wiki.seg.org/wiki/Open_data

4.4 Open-Source Seismic Interpretation Software

Attached here are names and uniform resource locators (web addresses) for open-source seismic interpretation software. These links were taken from https://software.seg.org/.

Madagascar: www.ahay.org/wiki/Main_Page

- A public software package with a separated header data format. Madagascar includes an environment for creating and testing reproducible software experiments.

CWP/SU Seismic Un*x Home Page: www.cwp.mines.edu/cwpcodes/

- A free seismic processing system that uses an expanded SEGY-like data format.

OpendTect: opendtect.org/

- A free open-source seismic interpretation system. The core of the system is available under a public license. It is extendable with plugins, some of which require a commercial license.

qiWorkbench: qiworkbench.org/jsp/main.jsp

- A processing environment originally from BHP-Billiton that includes the bhpViewer as one component.

Stanford Exploration Project: sepwww.stanford.edu/software/

- SEPlib, a data-cube-based seismic processing system, along with other miscellaneous software.

The GeoCraft home page: www.geocraft.org/

- A ConocoPhillips-heritage processing system designed to be a lightweight framework for rapidly prototyping and deploying new geoscience algorithms.

The FreeUSP home page: www.freeusp.org/

- An Amoco/BP-heritage processing system that uses an expanded SEGY-like data format.

The Data Dictionary System: www.freeusp.org/DDS/index.html

- An Amoco/BP-heritage processing system supporting high-dimensional flexible-format data files.

ARCO heritage source code:	www.freeusp.org/Arco/Arco.html

- The Arco SPARC processing system, and some reflectivity modeling codes.

Computers and Geosciences:	www.iamg.org/CGEditor/index.htm

- Journal software archive

5 Data Quality and Limitations (Task III)

5.1 Utility of Seismic Reflection Data in Groundwater Studies

Any discussion on limitations of seismic data must first address the goals of seismic data acquisition and analysis. The following are common uses of seismic data that may be of use to a hydrogeologist.

- **Structural interpretation:** The most obvious use of seismic data is to evaluate the structural environment away from existing well control. These structural data include shallow faulting, changes in dip (folding), fracturing (extent and azimuth), and sinkholes/karst features.
- **Stratigraphic interpretation:** One use of seismic data is to confirm and extend correlations from well logs. Intervals between correlation horizons tied to well data can be studied by mapping their thickness and extent on seismic data.
- **Estimating aquifer extents in intervals:** If sufficiently precise velocity information from the seismic data is obtained, the percentage of sand and shale (or limestone and shale) in a stratigraphic interval might be estimated and allow general predictions of aquifer presence away from existing well control. Also, seismic sequence stratigraphy can help in predicting extent and character of geologic units within sequences.
- **Imaging aquifer and geobody properties and geometries:** In favorable situations, seismic data can directly image major geologic units. If aquifer units have different acoustic impedances from adjacent non-aquifer units, reflections can outline the geobody and allow its thickness to be estimated. This can be done by identifying the visual extent of reflectors, either on two-dimensional or (more powerfully) on three-dimensional data (a process known as "seismic geomorphology"), or by performing a quantitative inversion of reflection data to acoustic impedance, tied to well data to generate quantitative estimates of aquifer thickness and quality. This latter requires high-quality data and high-quality well ties (based on full log suites), which is discussed in more detail in the following section.

5.2 General Limitations of Seismic Reflection Data

Given the ways mentioned above to use seismic data, a discussion to reflect on its inherent limitations is warranted. They include limits in spatial coverage of data, lack of salinity information, limits on resolution, on reflection strength, and on data quality at shallow depths.

5.2.1 Spatial limitations

As mentioned in Task 2, typical pricing (before discounts) is \$2,000 to \$3,000 per line mile for two-dimensional data, and \$10,000 to \$20,000 per square mile and up for three-dimensional data. Reprocessing will add several thousand dollars to the cost. Because of this, it is unlikely that an operator would license enough data to image the entire aquifer system back to outcrop, particularly with three-dimensional imaging. To justify the expenses, seismic data are best used to solve specific, defined geologic problems and is probably best used at the localization phase of exploration. A reasonable area would be over a portion of a county located within a Brackish

Resources Aquifer Characterization System study area. An exception could be made if a brackish water resource can be defined in the Federal Outer Continental Shelf, where seismic data costs are minimal and total costs are those related to interpretation and possible reprocessing. That said, regional correlations where either three-dimensional seismic is not available or is too costly can still be substantially improved by the use of regional two-dimensional seismic data.

5.2.2 Salinity limitations

Seismic data will not differentiate aquifer water quality. The solute concentration makes no difference in velocity and causes only a very slight increase in density (about 0.01 grams per cubic centimeter for each 1,000 part per million increase in total dissolved solids). With other sources of variability due to noise, geologic thickness changes, and other factors, this difference is practically invisible. Geophysical studies to directly characterize aquifer water quality are usually conducted using resistivity or electromagnetic methods. In offshore environments, controlled-source electromagnetic techniques have been effective at determining zones of higher resistivity that, in combination with the seismic-generated interval stratigraphy, can used to better characterize brackish aquifers. An example of this approach applied offshore of New Jersey is presented in Gustafson and others (2019). Resistivity methods can also be applied onshore, but there are no vendors with libraries of such data. Further investigation of this topic falls outside of the present project. At present, direct sampling and well-based resistivity and porosity information is the best way to determine and map water salinity, especially when good log suites are available to delineate clean versus shaly sands. Numerous examples of these types of water quality classifications exist: Estepp (1998), Collier (1993), and Fogg and Blanchard (1986) among others.

5.2.3 Resolution limitations

Seismic data are limited in their power to resolve geologic features in vertical and lateral dimensions, largely because of its limited frequency content. Full vertical resolution (the ability to differentiate top and bottom surfaces of a geobody) is one-quarter of a wavelength; and wavelength depends on the frequency of the seismic wave and the velocity of the medium. As a geobody thins in a uniform medium, the top (positive) reflector and the base (negative) reflector overlap and create first a positive reinforcement of the waveform (called tuning) and then a negative destruction of the waveform until it vanishes (Figure 5-1). Geobodies are detectable by their amplitude response to a considerably thinner limit, estimated to be an eighth to sixteenth of a wavelength.

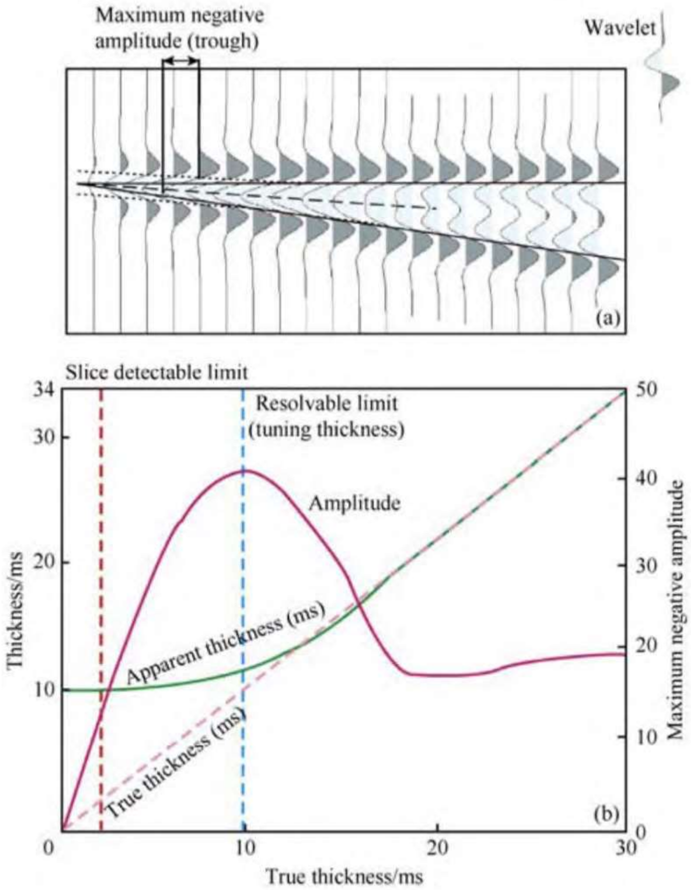


Figure 5-1. **Wedge model for a thinning geobody, calculated for a 50-Hertz wavelet. From Zeng and others (2012).**

Typical seismic frequencies for oil and gas data are 10 Hertz to 50 Hertz, sometimes up to 100 Hertz. At 10,000 feet per second, the wavelength of a 50 Hertz wavelet is 200 feet and the theoretical tuning thickness (one quarter of wavelength) would be 50 feet. At 5,000 feet per second, the wavelength would be 100 feet, and the tuning thickness reduced to 25 feet. The lower the velocity of the medium, the better the resolution; thus low-velocity areas such as the shallow Gulf Coast area have higher resolution than high-velocity areas like West Texas and North Texas (discussed further in the next section).

Horizontal resolution is more complicated, as it involves not only frequency and velocity but diffraction effects. The energy emitted by the source contacts not a single point on the reflector, yielding an exact image of that point, but a region of points on the reflector. The energy reflected from these points creates constructive interference, which impedes horizontal resolution (Sheriff, 1996). This zone, called the Fresnel zone, is dependent on the depth to the reflector and the length of the wavelength, and is given by Equation 6.

$$\left(z+\frac{\lambda}{4}\right)^2 = z^2 + r^2 \qquad \text{(Equation 6)}$$

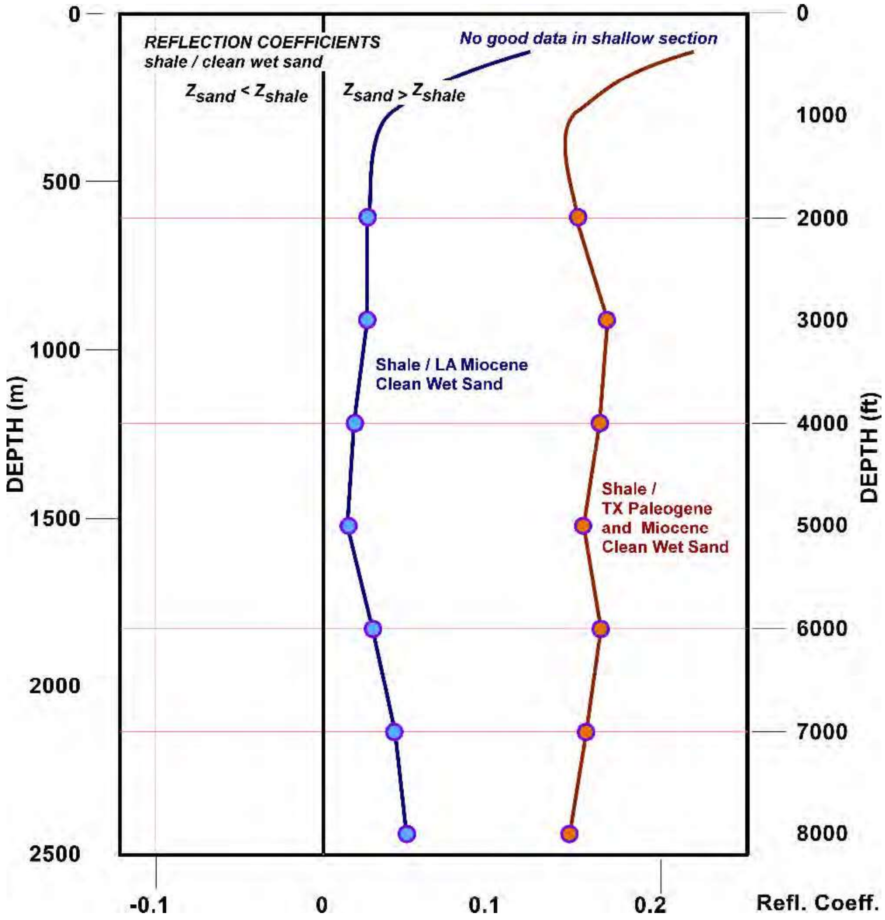
Where z is the depth (velocity multiplied by travel time) to the reflector, λ is the wavelength, and r is the radius of the Fresnel zone. As the radius of the Fresnel zone decreases, horizontal resolution increases (Sheriff, 1996). Therefore, horizontal resolution is improved by higher frequency and also by lower velocity.

5.2.4 Issues on reflection strength

The strength of a seismic reflection is primary governed by the impedance contrast between the materials overlying and underlying an interface. The reflection coefficient (R) is given in Equation 5, but can also be formulated as:

$$R = (\rho_2 V_2 - \rho_1 V_1) \,/\, (\rho_2 V_2 + \rho_1 V_1) \qquad \text{(Equation 7)}$$

with ρ being the bulk density and V the seismic velocity in media 1 (upper unit) and 2 (lower unit). This gives the percentage of down-going energy reflected at that interface. Several issues can arise. One simple issue is that in many cases an interface is not sharp but is gradational; this will tend to attenuate the reflection and must be modeled. In some rocks, mostly unconsolidated, young sands and shales, the impedance of the two lithologies may be nearly equal, leading to low acoustic impedance contrast (low reflection coefficients) and little or no useful reflection. In general, sands are both faster and denser than shales at depth but may be less dense at shallow depths. In fact, looking at typical Texas Gulf Coast data, this effect, if present at all, occurs only in very shallow horizons, where relevant data are very limited (Figure 5-2). In Louisiana and particularly offshore, it does affect sand-shale interfaces in Pliocene and Pleistocene reservoirs (Neidell and Berry, 1989). Texas Gulf Coast sandstones are generally more consolidated, hence have higher velocity and density (Loucks and others, 1979). It should be noted, however, that crossover of this sort does occur for gas-charged sandstones, which have lower velocity and density than shale at shallow to intermediate depths. Some very unconsolidated sand intervals may exhibit more "Louisiana" behavior and not generate strong reflections.



Note: ft = feet, m = meters

Figure 5-2. **Reflection coefficients with depth for clean, unconsolidated Louisiana Miocene sands (blue) and consolidated Texas Gulf Coast sandstones (red) encased in clean shale. No good data above 2000 feet and coefficients may increase or decrease. Base data from Neidell and Berry (1989), Avseth and others (2001), Loucks and others (1979).**

Two other effects on reflection strength occur. In some environments, the strongest reflectors are likely to be contrasts due to lime-cemented sand or limestone (such as oyster reefs), and not from sandstones. Sorting out these less abundant but seismically significant zones may be important in some areas. Also, the presence of natural gas in reservoirs, even at low percentages, creates significant amplitude anomalies, due to the effect of gas bubbles in lowering shear wave velocity and creating an increase or change in amplitude with offset of shot and receiver (or equivalently, angle of incidence; amplitude versus offset or amplitude versus angle). These effects are expected to be more local than regional but must be considered in interpretation.

5.2.5 Data quality issues at shallow depths

The shallower part of a seismic data volume (or line), the part most relevant for brackish water exploration, is subject to some special difficulties that may impede its usefulness. Close to the surface, the effects of the surface configuration of source points and receivers become more striking, essentially because the reflector is closer to them. This effect, known as “footprint” in three-dimensional surveys, skews the amplitude and offset distributions and disrupts the image.

Even below the footprint-influenced zone, the true fold at shallow depths is less than the quoted fold, as some of the shot-receiver combinations are not suitable for use in creating the processed trace. Also, for the same reasons, the distribution of offsets and azimuths in the gather (the group of field traces that are summed to create the final processed trace) becomes irregular and this creates poor imaging. These effects are discussed further in the report.

5.3 Types of Seismic Reflection Data

A basic division of seismic reflection data is into two-dimensional data, which are acquired along a line and produce a seismic profile, and three-dimensional data, which are acquired on a grid or patch and produce a volume of seismic data. Another primary division is into single-fold data, where one shot and receiver combination yields one trace on the resultant section, and multifold data, where records from various combinations of shots and receivers that reflect from a common depth point are summed to produce an output trace. Single-fold data was acquired before 1965 but was superseded by multifold data (two-dimensional and later three-dimensional) as the electronics became available. Multifold data acts to enhance signal-to-noise ratio and gives important information on velocity that is not obtainable from single-fold data.

5.3.1 Two-Dimensional Surveys

Acquisition of these surveys is designed to produce a profile or cross-section along a line. Source points ("shots") and receiver points (or groups of geophones) are ideally laid out in a straight line at regular spacing. A typical spacing might be 220 feet between receivers (“group interval”), and 440 feet between shots (“shot interval”), but others are possible. Receivers are laid out either on one side of a shot (“end on”) or on both sides (“split spread”). The nearest recorded trace is the “near trace” (generally equal to the receiver interval) and the most distant the “far trace.” The number of live channels (receiving data) increased with time due to advances in electronics, from one to six in the 1950s to 24 or 48 channels in the 1970s and 1980s to hundreds of channels in newer vintages. The seismic pulse received in the geophones (a trace) can be plotted on a “shot record,” but these traces are soon sorted into common depth-point gathers that group all shot-receiver combinations that reflect off a common point (assumed as the midpoint between shot and receiver) (see Figure 5-3).

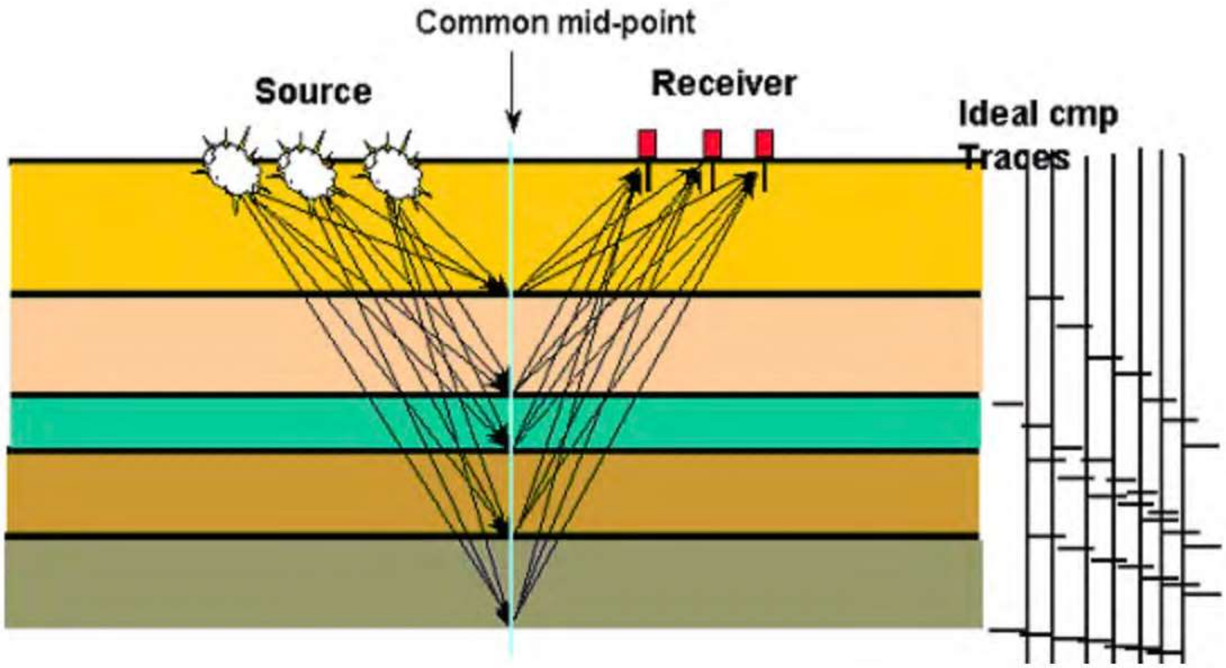


Figure 5-3. **Variety of traces in a common midpoint gather; and how reflectors should look on a gather (offset increasing to the right); from https://seabed.software.slb.com/seismic/webhelp.**

The earliest data acquired are single-fold data, for which the shot-receiver spreads were acquired sequentially without overlap. For this data, the shot records are merely displayed one against another and interpretations made. These single-fold records are abundant in all producing regions and can yield useful data. However, they contain little or no velocity information and do not have the information to resolve noise problems and multiple reflections. Because of this, the industry moved to multifold data in the 1960s.

Multifold two-dimensional data are useful for regional reconnaissance, as lines can be many tens of miles long. Lines oriented down regional dip or across structural grain (“dip lines”) are good at resolving faulting and can be used for sequence stratigraphy if the quality is adequate. Cross lines (“strike lines”) may image dip-oriented channels. Grids of two-dimensional lines can be interpreted to give structure maps in time or depth. However, such data have some limitations. Acquisition is rarely ideal; surface obstacles (buildings, no-permit zones, wellheads) require shots and receivers to be moved or skipped, which degrades the data. Lines may have to bend and wiggle, which has to be accounted for in processing. More fundamentally, the two-dimensional process (acquisition and processing) assumes that all reflection points are in the line of section. If the structure is three-dimensional (or the line not properly located), the observed reflectors may come from out of the plane of section and cannot be properly imaged. Thus, two-dimensional data are fundamentally inadequate in areas of three-dimensional structure, such as salt domes. Finally, two-dimensional data may not tie all of the available well control and projection of wells into the line can yield errors.

5.3.2 Three-Dimensional Surveys

Acquisition of these surveys is designed to produce a three-dimensional volume of data beneath a survey area. Several lines of receivers are laid out parallel to one another, with receivers (or groups) laid out along each line (thus there is a group interval and a receiver line interval). Seismic sources ("shots") are taken on separate lines; onshore, these lines are usually at a high angle to receiver lines. Shots are taken regularly along each parallel line (thus there is a shot interval and a shot line interval). Offshore, both sources and receivers are towed behind one or more ships, so a source line is parallel to a number of receiver lines. The number of live channels varies with time and effort but ranges from hundreds (in the 1980s and 1990s) to thousands or even tens of thousands in modern data. The traces are sorted into "bins" (equivalent to common depth point gathers) based on the reflection point of various shot-receiver combinations. Various combinations have different offsets as in two-dimensional data (yielding velocity information), but also come from different angles or azimuths (which can yield information on anisotropy, including fracture trends and spacing).

Three-dimensional data are expensive to acquire, as it involves considerable field effort (particularly onshore). Because of this, many surveys are focused on specific producing fields or prospective trends, with some surveys at little as five square miles in extent, but others of several hundred square miles. Despite this, three-dimensional surveys have a lot of advantages over two-dimensional data. Three dimensional surveys yield an interpretable volume of data, which gives a clearer picture of faults, fractures, and stratigraphy than can be resolved with a two dimensional line.

5.3.3 High-Resolution Shallow Seismic

Seismic reflection technology has been applied to problems of engineering or hydrogeologic interest that involve the near subsurface, typically the top 200 milliseconds of record (less than 1,000 feet depth). Seismic (two- or three-dimensional) in this shallow environment has distinct features and problems. High frequencies are desired in shots and geophones to achieve maximal resolution (such high frequencies are filtered out with depth and cannot be used in conventional surveys). To achieve this, seismic sources include shotguns, weight drops, and hammers. Receivers are special geophones optimized for frequencies of 100-5,000 Hertz. Acquisition geometries are an order of magnitude tighter (tens of feet vs hundreds of feet in source and receiver intervals) than for conventional oil and gas data, which increases cost per mile or per square mile. For this reason, most high-resolution seismic surveys have been very local and designed to answer specific questions about faulting, stratigraphy, water table, among other things. There is no library or exchange for high-resolution shallow seismic data known to the authors. Further discussion of this sort of data falls outside the scope of this project. It should be noted, though, that some efforts have been made in integrating high-resolution seismic and conventional data.

5.4 Discussion on Shallow Applications of Seismic Reflection Data

This section addresses three important themes that influence choices and workflows for interpreting seismic data in support of brackish water resource characterization. Key questions to be answered throughout this section include: How to select seismic data that have the quality necessary for an investigation? What acquisition parameters are acceptable? Are there regional impacts on what can be expected from the data? Should one use the processed images of profiles or volumes that are given on licensing, or should one plan to reprocess the data to generate improved images?

5.4.1 Acquisition Parameters and Quality Checking

The discussion above has introduced the basic concepts of source, receiver, geometry, and fold. Here one needs to look at these parameters in more detail as they affect shallow reflectors.

Almost all conventional seismic data acquired for onshore oil and gas exploration uses two classes of seismic sources: dynamite and Vibroseis. Dynamite use involves drilling a shallow hole, loading, and sealing a charge (usually 5 to 20 pounds) and then exploding it at a precise time. Dynamite explosions yield a wide range of frequencies; small charges of high-velocity explosives tend to yield more of the higher frequency range (50 to 100 Hertz). By contrast, Vibroseis techniques (the word is a trademark, but commonly used for all vibrator trucks and devices) use powerful motors mounted on several heavy trucks, each over a metal plate, to put a controlled sweep (linear or nonlinear) of frequencies into the ground. A typical sweep might take 6 seconds to run from 8 to 80 Hertz. The field traces are very complex but can be converted by correlating to the known input into a shot record very similar to dynamite data. Offshore seismic data use airguns as a seismic source, which create and implode a bubble of steam generated by an electric charge. Airguns have a complex signature but yields comparable seismic data.

For shallow seismic data, a geoscientist wants the highest frequencies that can be obtained for maximum resolution. At depth, the earth filters out high frequencies. However, energy reflecting from shallow reflectors passes through less earth, more high frequency energy is recoverable in the shallow subsurface. Regardless, since most data is acquired for deeper targets, many Vibroseis sweeps may stop at 50 or 55 Hertz. There is little use in looking for higher frequencies than were put into the ground. Therefore, for shallow targets, a geoscientist looks for higher Vibroseis sweeps, preferably 80 to 90 Hertz. The Stratton dataset from Nueces County (see Chapter 7) has sweeps up to 120 Hertz, which is unusually high.

Receivers (geophones) are rugged, compact portable seismographs with an induction device that senses ground motion through a spike. These devices have a definite frequency response. However, these limits do not seem to be critical in the high-frequency end of the spectrum. Geophones traditionally were employed in arrays to reduce the shot noise that is carried in the air and in surface layers (ground roll and air blast). These arrays can also attenuate high frequency and short-time signals, hence more recent recording has minimized the use of long arrays.

The shot and receiver geometry has important effects on shallow targets, on both two- and three-dimensional data. Depth points that are distant from shots or receivers (in the three-dimensional case, between lines as much as 1,700 feet apart) only receive traces that are more offset, whereas depth points on lines receive near-offset and far-offset traces. The different offset distances create differences in amplitude, fold, and in the quality of stacking (summation of traces) that results in a marked “footprint” of the surface geometry (Figure 5-4). At shallow depths, there are no data in the inter-line points; deeper, the data shows a waffle pattern (on three-dimensional, similar results on two-dimensional data but less dramatic) that can continue down to 1 second travel time. Any irregularities or skips in the shot-receiver pattern only strengthen the effect and increase its depth of penetration. To minimize this, short inter-line spacings (as well as group and shot intervals) are preferred for shallow data (reaching their short limits in high-resolution seismic data), but the increased ground effort make such data more expensive than is desired for oil and gas targets.

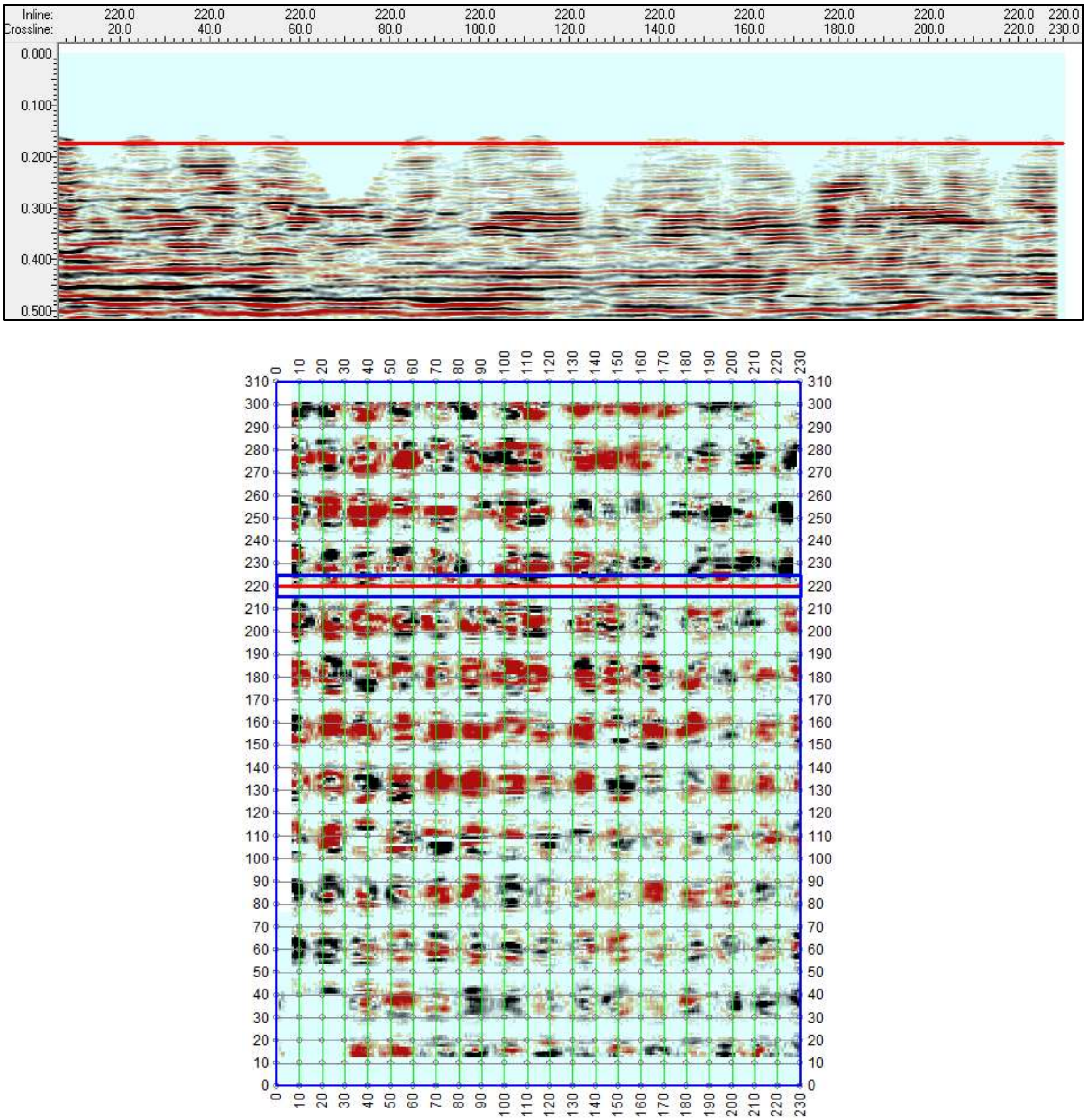


Figure 5-4. **Footprint effects from the Stratton Three-Dimensional Survey. At top is the upper part of Inline 220; a red line depicts the time slice illustrated in the base map. At base is the time slice of the seismic data set, with Inline 220 highlighted. At shallow depths, the survey has large data gaps, where there is no data on inter-line points, forming a waffle pattern. This waffle pattern is detectable up to 500 milliseconds.**

Phase and polarity of the seismic data must also be assessed. Phase is a shift in time with respect to other seismic waves (Alsadi, 2017). Polarity is a sign that shows whether there is an increase or decrease in impedance at a specific reflector (Alsadi 2017). There is first the issue of nomenclature. The American convention is that an increase in impedance is portrayed as blue, and the European convention portrays it as red (Figure 5-5) (Brown, 2008). This leads to a need to discuss polarity when acquiring seismic data. The phase of seismic data has a large impact on the apparent position of the reflectors in the subsurface. Figure 5-6 shows a difference between zero phase and minimum phase (90-degree) wavelets. If the phase of the seismic data was unknown, then it would not be possible to determine what part of the wavelet actually depicted the reflector. Given ambiguity about a phase shift, the lithologic and acoustic impedance boundary could be at the peak or trough of the wave, or the zero crossing before or after. The combination of phase and polarity factors can lead to total confusion on what the seismic wavelet is illustrating. Figure 5-7 shows that a simple impedance increase at a reflector can be illustrated as peak or trough or as a zero-crossing preceding a peak or a trough, depending on polarity convention and phase. Therefore, it is critical to have and understanding of these factors before working with seismic data. Some assistance can be provided by "unique" reflectors where the impedance contrast between the units is known (Simm and White, 2002). This can be the bottom of the seafloor, or igneous basement, or a large unconformity. This will give an indication of the polarity at that boundary.

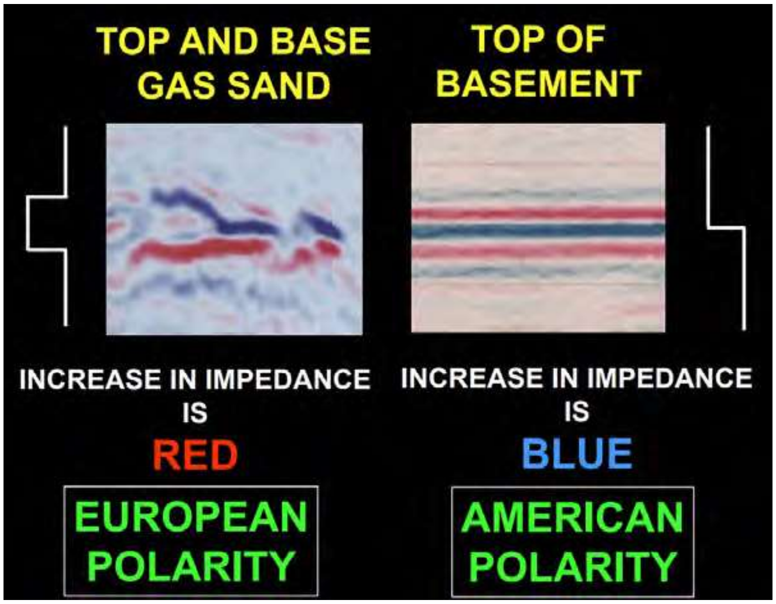
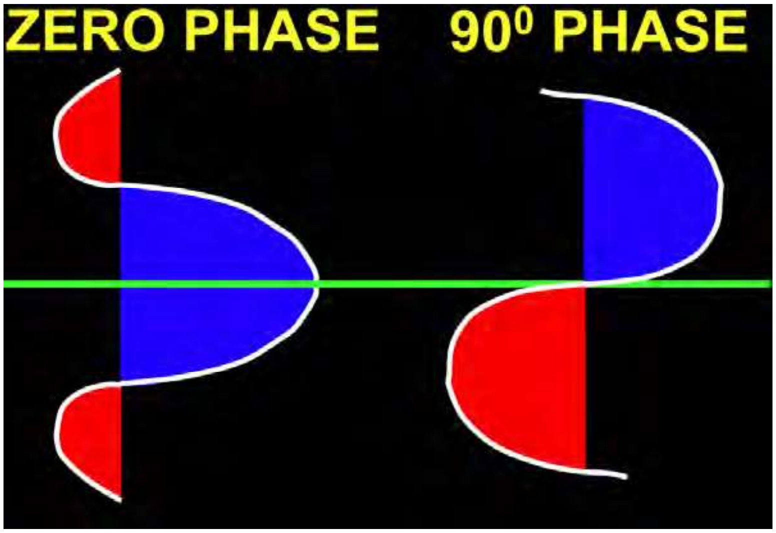
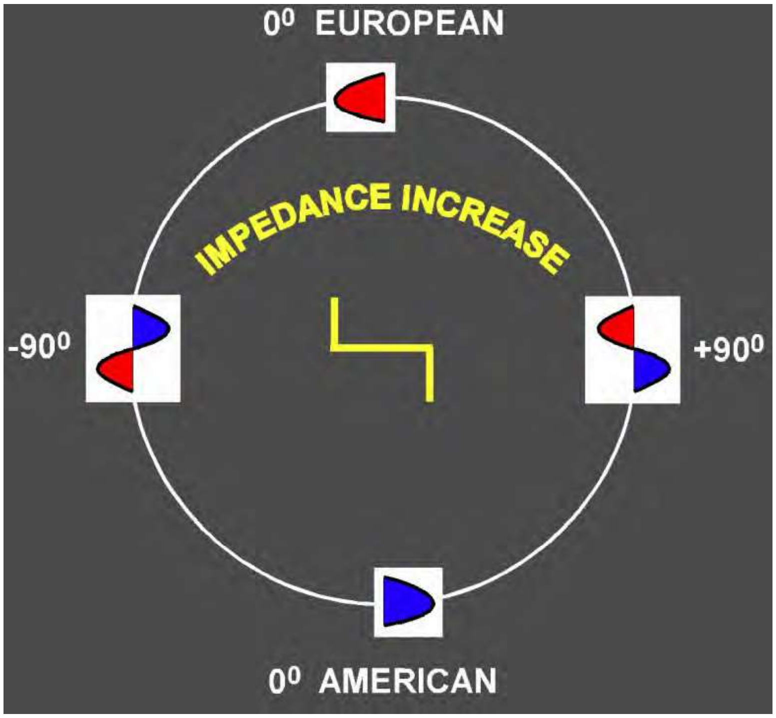


Figure 5-5. Difference between European and American polarity conventions. From Brown (2008).



Note: ° = degrees

Figure 5-6. **Difference between zero phase and minimum phase (90-degree phase) wavelets. From Brown (2008).**



Note: ° = degrees

Figure 5-7. **The effects of phase shift from normal to reverse polarity and polarity convention on the appearance of seismic data. From Brown (2008).**

Finally, one should realize that the stated fold of a survey (that is, the number of traces summed together in a stack or on a common depth point gather) is valid only for deep data. At shallow depths, the angle of incidence on a reflector of a shot-receiver combination quickly becomes too high to yield valid reflection data since energy is siphoned into refracted waves and other complexities. Therefore, the high-angle traces are muted and not used in processing the shallow data. This may mean that data claiming to be 96-fold on the data description may be less than 20-fold at the shallow levels of interest. This, combined with muting to reduce ground noise, limits the quality of the stack and the resulting images.

5.4.2 Regional Differences in Seismic Data affecting Shallow Targets

The quality, resolution, and usefulness of seismic data may vary widely depending on the geologic character of different regions.

In Texas, the Gulf Coast region consists of Cenozoic poorly consolidated formations (mostly sand and shale) in the shallow subsurface. Because of this, seismic velocities are low (Figure 5-8) and resolution in the shallow intervals is high. Surface conditions are generally conducive to data acquisition, with belts of sandy soils absorbing more seismic energy and shallow gravel channels creating the major geologic difficulties. Noise levels due to culture are frequently high. Offshore data is generally high quality, as conditions tend to be uniform and low-noise. However, data in the shallow bays and nearshore areas is more difficult and requires special acquisition techniques.

In the Permian Basin and North Texas, the rocks at the surface are Paleozoic and Mesozoic sandstone, shale, limestone, and evaporite that are hard (highly cemented) and have high seismic velocities. This leads to lower resolution of aquifers, resolution in the Permian Basin and North Texas is less than half as good in quality compared to the Gulf Coast area. Major difficulties exist in the surface conditions of various parts of the West and North Texas regions, including surface carbonates and evaporites with karsting and salt dissolution that scatters and traps seismic energy, sand dunes and sand sheets that attenuate energy, and variable surface conditions (including topography) that create irregular offsets in seismic traces and seriously degrade the stack. In these areas, careful attention to static corrections (which account for the near-surface variability of geology and velocity) is necessary to obtain satisfactory images.

Conditions in East Texas and along the Balcones trend are intermediate in character between the onshore Gulf Coast and West and North Texas regions. Surface conditions east of the Lower Cretaceous outcrop are comparable the Gulf Coast region, although with areas of deep sand and hillier topography. Near-surface rocks are more consolidated than in the Gulf Coast, but still slower than rocks to the west.

Figure 5-8. **Map of time corresponding to 5,000 feet below well datum for Texas, with data averaged by counties. Data from files of Frontera Exploration Consultants.**

5.4.3 Using Original or Reprocessed Data

All recorded seismic data must be processed to yield usable seismic profiles. Licensing data provides the worker with one or more seismic profiles of the post-processing data, typically a seismic profile after stack and one after a migration routine (which images dipping reflectors and reflector terminations more accurately). One may also receive displays using only near-offset traces, far-offset traces, and other specialty products.

Depending on the age of the processing, the seismic profiles may be of sufficient quality to use directly in brackish water aquifer evaluation. However, processing routines have improved greatly over time, thus reprocessing of older data is generally useful in improving quality and reliability. In addition, reprocessing allows one to optimize the seismic profiles for the depths of interest and to acquire more information from the data. Reprocessing costs are typically around 10 percent of original licensing costs. Much of the older data in the SEI and other exchange libraries have been reprocessed in recent years, so it is unusual to see truly old processing there, whereas data from proprietary surveys may need reprocessing to be useful.

Reprocessing may be most valuable in Gulf Coast situations. In that trend, most of the data were acquired for deeper oil and gas targets, typically 4,000 to 15,000 feet, and to understand deep structure. The quality of the shallow reflectors was not of primary interest, and processing was optimized for deep structure and stratigraphy. Similar questions occur in West Texas; however, the quality of the complex statics calculations (refraction statics) required is often measured by the quality and stability of the shallow reflectors. This, combined with the inherently lower resolution, may favor the use of existing images, if they were created in recent years with industry-current algorithms.

The use of reprocessing vs existing images must be determined for each project, depending on the aims of the interpretation project and the quality of the existing images to achieve those aims.

5.5 Overview of Regular Processing and Interpretation

All multifold seismic data requires extensive processing to yield usable seismic images; this is usually undertaken at a dedicated processing shop on large computers, due to the data volumes involved. A basic understanding of the processing steps as they are generally used is required to consider what enhancements are necessary for shallow reflectors and to develop a reprocessing workflow. For a fuller discussion of the process, see Yilmaz (2001). Data that has been stacked or migrated is generally interpreted on PC-based workstations.

5.5.1 Processing Sequences

Field data (traces recorded for each channel at each shotpoint or correlated vibration record) are examined and edited, with bad traces discarded. Some noise can be removed directly. Traces are sorted to common depth point gathers and a correction for geometric spreading (attenuation with depth due to wavefront expansions) is applied. Additional noise removal steps can be taken such as preliminary statics adjustments, topography correction, and selective muting of high-angle traces. These steps improve the signal-to-noise ratio and increases interpretability. Additionally, statics corrections and a deconvolution filter (which mathematically compresses the seismic pulse and improves resolution) may be applied. Velocity is then estimated from the parabolic curvature of the common depth point gather, yielding an estimate of an average (root-mean-square) velocity with time. This velocity is used to flatten the common depth point gather and iterated with statics to produce a high-quality gather. Prestack migration routines may be applied, or “dip moveout” filters applied, to account for structure. Finally, the data is stacked or summed using the final velocity determination. Stacked data may then be migrated to give a structurally correct image. If a depth velocity model is made, the stacking and migration may be done in depth domain rather than travel time, yielding a (prestack) depth migration. This will be further discussed and diagramed in the next chapter.

5.5.2 Interpretation Sequences

After stacking, the file size for the seismic data is reduced to the point where it can be handled on a PC workstation and interpreted using commercial software. Some attributes and the creation of seismic inversion products may, however, be taken at the processing shop; this must be done if the product requires prestack data. A great variety of interpretation techniques are possible; the one presented would be typical for onshore data with good well control.

Initial interpretation of the volume focuses on identifying key reflectors that are continuous across the survey and structural elements such as faults. In order to identify reflectors, a tie with existing acoustic well data (which generally have a correlation or other interpretation already) is sought. Tying wells to seismic is a major subject that is frequently essential to the success of a project. In an overall sense, what is needed is a time-depth chart (unless a depth migration volume is available). This is traditionally derived from a “check shot” survey, which is performed on a few key wells by lowering a geophone down the hole and firing a surface source (usually Vibroseis or airgun) and measuring the time taken to reach the geophone (Figure 5-9). The modern vertical seismic profile is a multi-geophone modification of this process, with a string of geophones downhole. Vertical seismic profiles supply much more information on individual reflector correlations to lithologic units. Time-depth information can also use sonic logs recorded in some wells; in this case, corrections for the time to top of the log and for washouts need to be made. Once time-depth calibration is achieved, significant lithologic tops can be interpreted across the data (yielding structure or time-structure maps) and thickness information on intervals can be obtained and plotted on isopach maps.

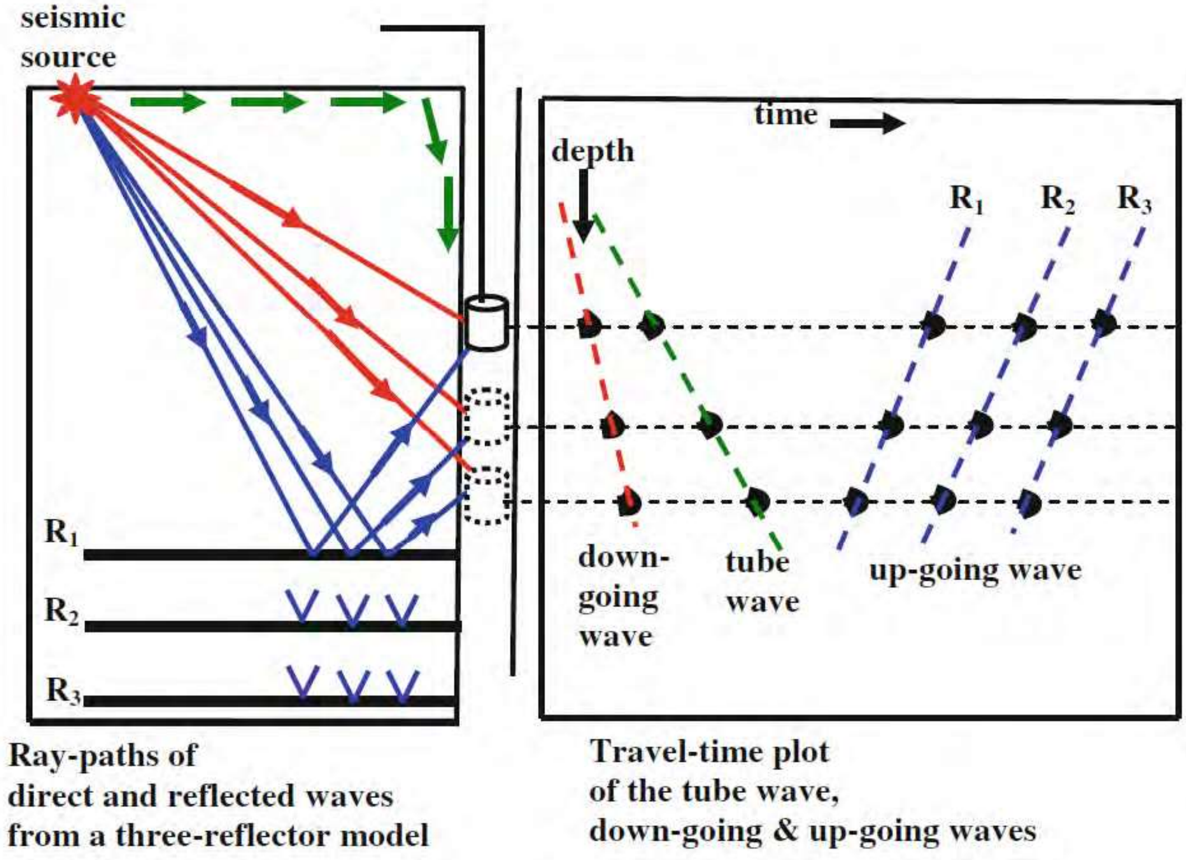


Figure 5-9. **Ray-path diagram and the corresponding travel time plot of a Vertical Seismic Profile survey of a geological model made up of three reflections. From Alsadi (2017). A tube wave is a wave that travels along the borehole. It is a type of coherent noise common to Vertical Seismic Profiles, easily removed during processing.**

At this point, more exact ties may be obtained with individual reservoir units: in particular, sand bodies, channels, and channel complexes. For this purpose, a vertical seismic profile can be used if available. For wells with sonic and density logs, a synthetic seismogram may be computed by calculating the reflection coefficients of each interface. This process requires good quality log data, including corrections for washouts. The well data can be used to generate models of what a thicker unit would look like, or a thinner one; these can be compared to the seismic data.

One technique that is most helpful in shallow sections is to apply a high-pass frequency filter to the seismic data. A high-pass filter eliminates frequencies below a cutoff frequency. This enhances the high-frequency content of the seismic data and allows more exact ties to lithologic units. However, if the seismic sources are limited in high frequency, this process will mostly amplify noise and distort the signal.

For three-dimensional data, the volume can be examined in a map section, either at constant time (or depth) or in a time or depth offset to a regional reflection (called a flattened time slice), which may vary with thickness variation across an area (then called stratal slicing). In this view, a distinct reflector attribute (amplitude or other attributes) is visible across the data volume, and edges (such as channel edges and karstic features) can be clearly seen. This visual method in many situations would be called “seismic stratigraphy.” Basically, the process looks for the geomorphology associated with particular geobodies, such as meandering streams, valley systems, reefs, and other depositional environments.

More advanced interpretation can include generation of various attributes of the seismic data. Many of these are post-stack and can be generated within the workstation; others may come from the processor. Attributes can outline structural features such as small faults and fracture trends (particularly coherency, variance, and curvature); other attributes can give lithologic information. Finally, a seismic inversion may use all existing well control and seismic data to estimate quantitatively the distribution of petrophysical variables (impedance and stiffness parameters). Such inversions are limited by the frequency content of the seismic data, particularly the lack of low frequencies, and require good quality well information to generate valid results. Most recently, artificial intelligence/machine learning techniques have been applied to seismic data to generate likelihood maps of reservoir parameters. To our knowledge, this has not yet been applied to hydrogeologic issues.

5.6 Pitfalls in Seismic Processing and Interpretation of Shallow Brackish Aquifers

In many ways, interpreting seismic data for shallow reflectors follows the standard processing sequence. This is understandable since seismic analysis began with oil and gas exploration at shallow depths and have moved steadily to longer offsets and deeper resolution. However, there are several items that need to be carefully examined in order to get the best product from the effort spent on seismic data acquisition, processing, and interpretation.

5.6.1 Issues in Processing

The goal of seismic processing for shallow reflectors must be to minimize the effects of “footprint,” irregular gathers and low fold on the amplitude and frequency of shallow reflectors. Careful examination of shot and common depth point gathers through the early processing sequence is required. Noise needs to be identified and eliminated with minimal interference to traces with valid reflection data (the signal). Interpolation routines can decrease the irregular and limited character of shallow gathers and allow better velocity estimation and noise reduction, and reduction of footprint effects. Careful velocity estimate is important, particularly if interval velocities derived from the processing algorithm are to be used in interpreting lithology in aquifer intervals. Gathers need to be examined to identify problems with noise, irregular offsets, and gas saturation.

5.6.2 Issues in Interpretation

The most important interpretation issues involve well data and tying wells to seismic. Many wells are not logged in the shallow zone, especially above the surface casing (assumed to be set at the approximate base of fresh water). Many logged wells do not have sonic or density data, yet both are needed to generate high-quality synthetic seismograms. Even if well data exist, there may be problems with them. Washouts are frequent in the shallow section, either in unconsolidated sands or in muddy intervals. In the Gulf Coast, many wells drilled with "natural mud" (mud derived from washing out the formation), and only control the composition and weight of mud when the objective horizons are drawing near. Sonic and density logs are sensitive to hole diameter. Logs need to be edited to counter the washout effects. In areas of poor control, it may be necessary to use regional estimates of sand and shale impedance at various depths, but this will be inexact as it does not account for the shale content of individual sand bodies. Also, as mentioned previously, the strongest seismic reflectors may represent anomalous zones, such as lime-rich oyster reefs and cemented horizons in the Gulf Coast sand-shale sequence. Interpretation needs to work around these strong horizons; high frequency content helps in this process.

5.7 Summary

In summary, all of the above can be examined in light of a few questions of resolution: the inherent resolution of our seismic data, what needs to be imaged in the depth range of brackish aquifers, and what the sources of reflectors are.

The resolution of seismic data is primarily dependent on frequency, and secondarily on quality of reflection data. As mentioned, in the Gulf Coast, seismic data can likely resolve reflections vertically in the 25 to 40 feet range, the scale of typical sand or channel bodies. In West Texas, resolution may be limited to 80 to 100 feet, which may resolve more general trends of aquifer units. Resolution in the horizontal sense depends on the quality of acquisition and processing, but should be adequate to define channel trends and overall aquifer geometry.

For imaging in the depth range of brackish aquifers (about 1,000 to 5,000 feet), most data will be of sufficient quality. However, data with closer group and shot intervals (in two-dimensions) and closer line intervals (in three-dimensions) is preferable in order to minimize data footprint. The data should have some high-frequency content, either dynamite source or a Vibroseis sweep to at least 60 Hertz, but preferably higher. All data should be subject to quality control before licensing, to make sure there are no problems with skips or gaps in the record or other problems that would make the data less useful. If possible, reprocess data to interpolate the gathers at shallow depth and optimize velocity information and gather quality.

In interpreting the shallow data, it is important to keep in mind the lithologic source of the reflectors. As indicated, in pre-Pliocene reservoirs the sand-shale contrast in acoustic impedance is always positive, indicating that reflectors should be present. Strong reflectors, however, may be due either to gas effect (gas bubbles or gas reservoirs generating amplitude anomalies in far traces, also some crossover effects) or to lime-cemented zones. In West Texas, strongest reflectors will be due to lime or evaporite zones and may contain limited lithologic information on the aquifer units.

6 Methodology for Application of Seismic Data on Brackish Aquifers (Task IV)

Having considered the issues and limitations of conventional seismic reflection data as acquired for hydrocarbon exploration and subsequently applied to groundwater projects, this section first outlines a general workflow for integration of such data into groundwater projects. Following this, the possible workflow variations for different basins and aquifers in Texas are considered. A concluding section reviews the major aquifers of Texas for possible utility of conventional seismic data. Figure 6-1 shows the diagram for a potential workflow. Figure 6-2 shows the diagram for a potential workflow for seismic interpretation.

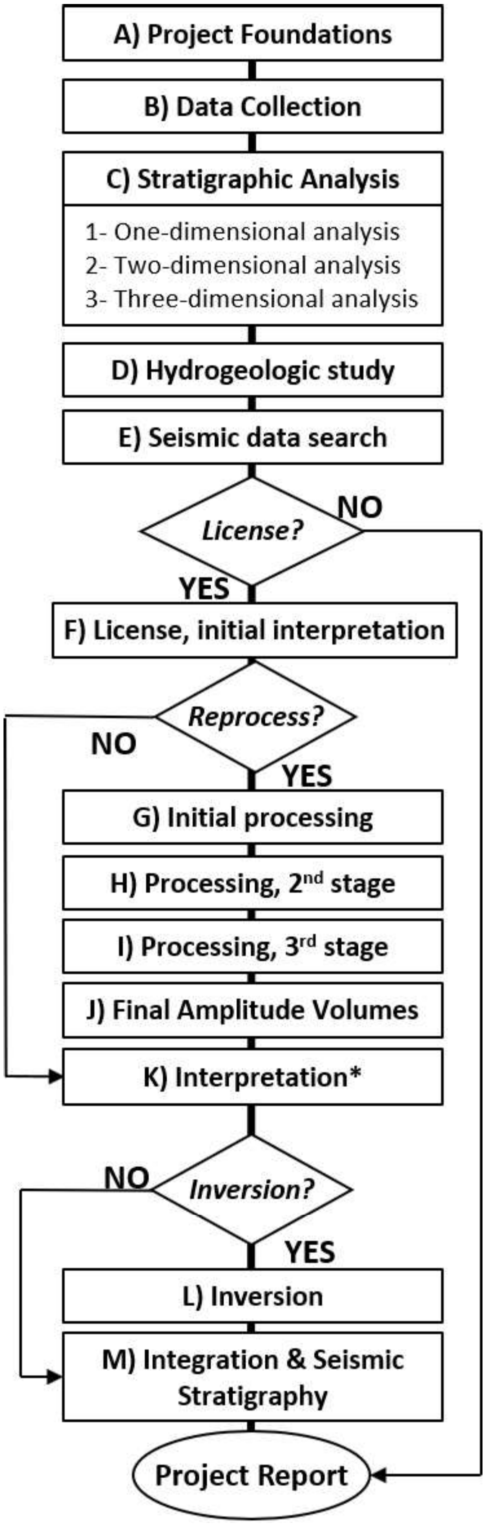


Figure 6-1. Workflow diagram.

Figure 6-2. Interpretation Workflow Diagram.

6.1 General Workflow Template

6.1.1 Project Foundations (Task A)

A clear understanding of the scope of the study is necessary to establish priorities in data collection and efficiently allocate resources. For instance, if the goal of the study is very broad, as to cover the entire Gulf Coast Aquifer, then sub-foot resolution in wells probably will not be prioritized above regional cross section lines, either well or seismic based. However, at the field scale, well-based data such as core analyses rise in priority above a regional 2D seismic line.

Usually, external factors will determine the location of the study, the size of the area of interest, and an interval of interest, as well as the funding that can be made available for licensing of well and seismic data. Once the location is constrained, and the interval of study selected, work may begin.

A geographic information system is a required tool for the display and analysis of spatial datasets. Such programs include, but are not limited to ArcGIS, QGIS, IHS Petra, IHS Kingdom, and OpendTect. These programs allow for quick referencing and map making, and IHS Petra/ Kingdom and OpendTect support cross section construction and interpretation. A geographic information system allows the user to investigate geospatial data and begin to develop hypotheses about what the data is showing. It is at this point that the user can determine if their hypothesis could be further supported/validated by incorporating legacy seismic data. At that point they could bring in the geospatial files representing the distribution of two-dimensional and three-dimensional seismic data and determine whether data exists for their area of study.

6.1.2 Data Collection (Task B)

Once the decisions regarding scope and location of the proposed study have been made, data collection can proceed. The review should begin with a thorough review of the literature, followed by a search for relevant groundwater databases, well logs, core data, seismic data (Task E), and paleontological data.

Literature

A thorough literature review is intended to provide an understanding of the existing state of knowledge of an area or aquifer. Literature can provide useful stratigraphic models, facies information, hydrologic data and more. Common databases to search include Google Scholar, university libraries, Web of Science, the American Association of Petroleum Geologists (Datapages), Texas Water Development Board, Texas Bureau of Economic Geology, and the Society for Exploration Geophysics. Maps and cross sections can be digitized and subsequently incorporated into the project dataset. Overlaying this information atop the designated area of interest will help guide the more detailed interpretations made during the study.

Groundwater Databases

Within the state of Texas, groundwater data is available from a number of different entities including, but not limited to the Texas Water Development Board, The Texas Commission on Environmental Quality, the United States Geological Survey, groundwater conservation districts, subsidence districts, amongst many other sources of groundwater data. This information is publicly available online and represents a tremendous source of groundwater information.

Core and Outcrop Data

In Texas, cores and cuttings from wells are available to the public at the Bureau of Economic Geology Core Research Center, the United States Geological Survey Core Research Center, and the International Ocean Drilling Project's Gulf Coast Repository at Texas A&M. These centers have websites with searchable core databases and members of the public can order the core pulled out for display and then go to the facility to examine it. However, cores covering aquifer sections are not generally acquired.

Outcrop data on aquifer units can be gleaned from literature or acquired in the field. The Bureau of Economic Geology provides the most comprehensive dataset on Texas outcrop data. These datasets are also available in geographic information system format and can be readily incorporated into a study. If further resolution is needed a trip to the field site with a competent field geologist will be required.

Biostratigraphic Data

Biostratigraphy and paleontological data are used to constrain stratigraphic intervals to specific periods of geologic time as well as to correlate units between sampled locations. Public paleontological data is available at the Bureau of Ocean Energy Management website. While these data are limited to the Gulf of Mexico, they can be used to anchor offshore biostratigraphic picks with well log and lithologic picks that can then be brought onshore using only well log and lithologic picks. Other (onshore) biostratigraphic data can be gleaned from existing literature, specifically master's theses and dissertations.

Well Log and Velocity Data

Due to the abundance of hydrocarbon resources, well-log data is fairly plentiful in Texas. A geologist may search the catalogs of IHS Markit, TGS, The Subsurface Library, the Texas Water Development Board Brackish Resources Aquifer Characterization System database, and the United States Geological Survey database, as well as local log libraries. Common logs used in stratigraphic framework construction are gamma ray, resistivity, spontaneous potential, porosity, density and photoelectric logs. Sonic logs are especially useful for calibrating seismic data. A well with both sonic and density over the interval of interest can be extremely useful to create high-quality synthetic seismograms.

A search of relevant proprietary or government databases for velocity survey information (velocity surveys or "check shot surveys," also vertical seismic profiles although these are not generally made public) also needs to be performed in support of seismic interpretation, specifically tying well data to seismic reflections.

Seismic Data

Seismic data availability and vendors have been discussed in Chapter 3 of this study.

6.1.3 Stratigraphic Analysis (Task C)

Once the data have been assembled and visualized, decisions must be made on how to begin the stratigraphic analysis. A review of any existing stratigraphic frameworks documented in relevant literature will provide a foundation for interpretations. The literature review will provide the user with a first order understanding of data availability in the area and can help direct the approach taken to acquire additional supporting data. Ideally, the aim is to start with the rock data and then extend the interpretations to other data types. Practically, this means to start with core and outcrop data and integrate well-log and biostratigraphic data: the one-dimensional analyses. Combining one-dimensional data types across space in a cross-section moves the interpretation to a two-dimensional analysis. Following this, well-logs without core data are incorporated. The addition of well-logs and, if possible, seismic data escalates the analysis to a three-dimensional interpretation. Ideally, such an analysis should start in the most data-rich area(s) and proceed to the data-poor areas.

Despite best efforts, data gaps may persist due to lack of available data and the economic burden of acquiring new data. In these cases, the methodology for completing a study is amended and abbreviated to reflect data availability and reconsidered project goals. Coarse (low resolution) stratigraphic models can be constructed using only well-log data. For example, a coarse investigation for sand presence and interconnectivity can be conducted by examining well log information and inferring sands based on various log signatures and mud logs. These inferred sands can be correlated by examining similar depths on nearby well logs, using geologic insights to find the correlative sand on neighboring well logs, and assuming connection. While this may represent the best analysis available, these types of analyses are highly subjective and allow for non-experts to infer connectivity: an assumption that is often poorly based. Additionally, geologic structures such as faults are difficult to interpret when only using well log data to characterize stratigraphic models.

However, three-dimensional seismic attribute analysis imposed on cores and well logs provide a quantitative basis for a higher resolution correlation of sands within an interval as well as high resolution stratigraphic framework. An expert would still be required to provide the characterization and justification for the sand interconnectivity but, they would be working with a much larger and higher resolution dataset and would gain a large advantage over a non-seismic exploration effort. It must be stated plainly that the incorporation of the seismic data (process or unprocessed) usually comes at a high cost to the project budget. Despite the additional costs, it is becoming abundantly clear that incorporating seismic data to support the development of a high-resolution sequence stratigraphic framework will vastly improve our understanding of groundwater systems.

Most sequence stratigraphic analysis methodologies were developed in support of hydrocarbon development. Relevant examples include Kerans and Tinker (1997) and Van Wagoner and others (1990). The concepts developed in these studies support geologic characterizations and, if the data availability are similar, methodologies are directly applicable in characterizing the geology of a groundwater flow system. While this study will discuss how to build a sequence stratigraphic framework, the reader is referred to the aforementioned texts for a greater level of detail on rock and well log analysis. A typical sequence stratigraphic analysis in the oil and gas industry is supported with significant data availability. Few groundwater studies can afford the type of data acquisition programs that are standard in the oil and gas industry. This being the case, while much of the data acquired for a typical oil and gas study is for intervals far below the target groundwater intervals, byproducts of the data acquisition process will include well logs and seismic data acquired in the shallow subsurface. These datasets, especially the well logs, usually make up the bulk of the supporting data in a geologic characterization of a groundwater system.

One-Dimensional Analysis

A good sequence stratigraphic approach should begin with data closest to the rocks. For most applications, this means beginning with core data or outcrop data supplemented with well log data. While it is preferable to begin with rock or core data, this is often not feasible for groundwater applications. While core data are limited, most aquifers in Texas have some sort of exposure at outcrop, which can be utilized to the same effect. When neither core nor outcrop are available, the study should begin with well-log information.

Outcrop and core description is a complicated process with many moving pieces. The goal with this type of an analysis is to record qualitative observation on a log versus depth. Figure 6-3 shows a log which specifically has a column for depth or elevation (the one dimension that varies in this analysis) and then a graphic and textual description of the core or outcrop. Observations must include rock fabric, texture, grain type, grain size, sedimentary structures, pore types, fossils present, and lithology. Common and useful frameworks to guide interpretations include the Dunham classification for carbonate rocks and the Wentworth grain size analysis supplemented with a lithology analysis for clastic rocks.

Biostratigraphy data, well-log data, and core test data will be incorporated with the lithologic data. Biostratigraphy data will instruct the geologist on time boundaries. Key surfaces that have been identified in the core should have a predictable petrophysical response, which allows a relationship between the core depth and the well log depth to be established. Core test results including thin section analyses can provide quantitative measurements that can be used to constrain interpretations during the logging process and provide petrophysical analogues. Lithology logs and other associated supplemental data can often be found in literature and should be used to increase data density.

The resulting logs will record a series of beds, which are the basic building block of a stratigraphic succession (Campbell, 1967). A bed is a laterally traceable, three-dimensional rock body of relatively uniform physical, mineralogical, and biological composition, distinguishable from the rock above and below (McKee and Weir, 1953). Beds are grouped into bedsets based on their relative conformity. In clastic rocks, beds or bedsets can then be grouped into a parasequence. A parasequence is bound by marine flooding surfaces (or their correlative surfaces) (Van Wagoner and others, 1988). In carbonate rocks, beds or bedsets are grouped into a high-frequency cycle (Kerans and Tinker, 1997). These parasequences and high-frequency cycles are the building blocks of higher orders of cyclicity. Figure 6-4 shows the orders and relative magnitude of the orders of cyclicity. For groundwater applications, it can be assumed that the analysis will involve the basic 5th and 4th order cycles (low order), 3rd order cycles will be common, but not ubiquitous, and 2nd order cycles (high order) will be rare. For an estimation of scale, the Capitan Reef deposition is 14 high-frequency sequences in just under 2 composite sequences (Kerans and others, 2014).

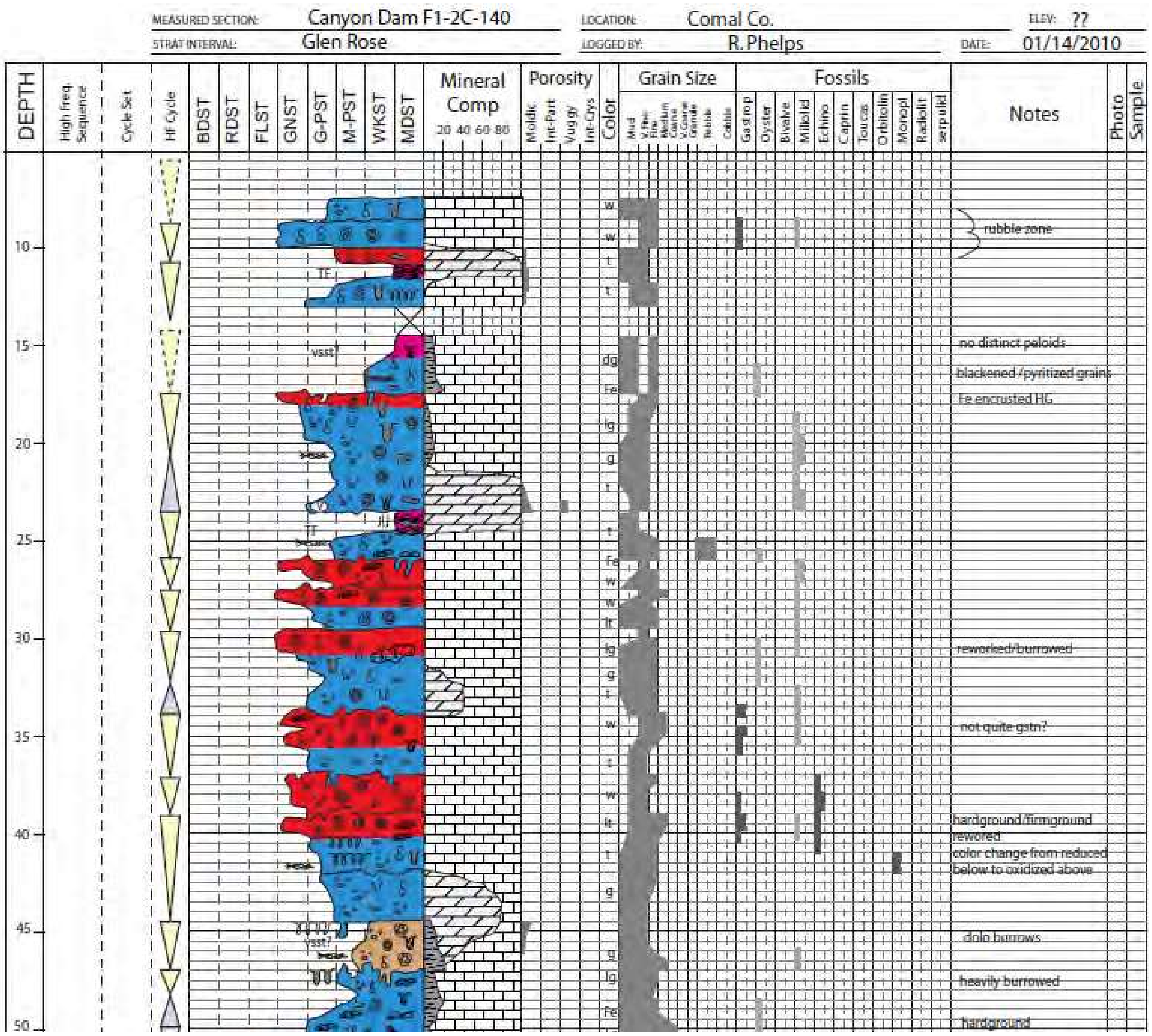


Figure 6-3. Core log from Phelps (2011).

Tectono-Eustatic/ Eustatic Cycle Order	Sequence Stratigraphic Unit	Duration (my)	Relative Sea Level Amplitude (m)	Relative Sea Level Rise/Fall Rate (cm/1,000 yr)
First		>100		<1
Second	Supersequence	10-100	50-100	1-3
Third	Depositional Sequence Composite Sequence	1-10	50-100	1-10
Fourth	High Frequency Sequence, Parasequence and Cylce Set	0.1-1	1-150	40-500
Fifth	Parasequence, High-Frequency Cycle	0.01-0.1	1-150	60-700

Figure 6-4. Orders of cyclicity. From Kerans and Tinker (1997).

The geologist must interpret the logs (integrated with other data) and delineate the cycles, their components, stacking patterns, and overall system progression. This step is facilitated by the discretization of the of rocks present into a series of facies. These facies will represent bins of rocks with consistent fabric and texture, each representative of a unique depositional environment. Once the facies are assigned to the log, interpretation of cycles and bounding surfaces becomes easier. It also becomes easier to delineate whether a cycle and cycles are progradational, retrogradational, or aggradational, which helps the interpreter determine where in the cycle hierarchy each bed belongs. Facies descriptions are commonly found in literature, and these should be considered when understanding the core data. An example would be the Capitan Reef aquifer/formation. Given over a century of publications, theses and dissertations on the Capitan Reef, facies classifications abound for this formation.

The ideal situation is to have a series of core and outcrop evaluations that form a dip-oriented line across the study area. The lithologic data comprising the dip-oriented line will serve to document the facies changes across the study area and will provide the basis for understanding cyclicity across the study area. This will serve as the basis for the two-dimensional analysis.

Two-Dimensional Analysis: Cross Section Construction

Once cyclicity has been determined in core or outcrop and integrated into well-logs and biostratigraphy, the process of carrying correlations across the study area can begin. The best way to accomplish this is to make a series of well-log cross sections integrated with core data, when available, first along structural or stratigraphic dip, and then connected by strike cross sections. This will provide a grid of two-dimensional sections that can be used as control when delineating patterns between the grid lines. Regional correlations and markers are commonly found in existing literature.

In each cross section, there should be a series of observations from the one-dimensional analysis (core or outcrop data integrated with well logs) and new data from well logs with no core data integrated. The interpretations from the one-dimensional data should be transferred to the new well-logs on the cross section. The correlation is a mix of geologic interpretation and pattern recognition, with the patterns assumed to represent known lithologies or a justification for changes in lithology within a unit over space. Surfaces identified in the one-dimensional analysis that have expressions in well-logs are the prime candidates for correlation. Most often it will not be feasible to correlate each high-frequency cycle or parasequence, the more significant surfaces for correlation usually are on higher orders and represent more geologically significant events than low order cycle or parasequence tops.

Following the cross section development, two-dimensional (or two-dimensional slices of three-dimensional) seismic can be incorporated in an attempt to transfer geologic information into the seismic data space. Seismic acquisition and processing will be discussed in the next section, and seismic analysis will be discussed from section 6.1.6 to 6.1.13.

Three-Dimensional Analysis

Once the cross sections have been created, they can be used as a guide to correlate the surfaces to wells outside the cross sections. This should continue until a reasonable number of wells in the dataset are included to constrain an interpretation. Grids should be interpreted from the well data to highlight problematic areas where there may be a missed correlation. Isopach mapping, or thickness mapping, is especially useful for this purpose since large and sudden thickness changes at one or two well locations are usually caused by a missed correlation. Isopach mapping and structure mapping are also the first three-dimensional products produced from the study and will be crucial in sorting hydrologic data into the correct formation.

From this step, any three-dimensional seismic data also feeds into three-dimensional analysis, and will be discussed from section 6.1.6 to section 6.1.13.

6.1.4 Hydrogeologic Study (Task D)

Once the geologic framework has been established using the aforementioned techniques and associated data, the next step is to acquire relevant groundwater data and to determine lateral and vertical distribution of the groundwater well data. Some areas have wells that are mainly completed within one interval (the Ogallala aquifer for example) while other areas have wells that are completed over multiple intervals (the Northern Trinity aquifer for example). Using geographic information system software and the geologic surfaces created during the three-dimensional analysis the completion information at individual wells can be examined to determine what stratigraphic unit the groundwater well is completed. Once the groundwater wells are understood in terms of the unit(s) they are completed in, hydraulic data can be incorporated and subsequently evaluated in the context of specific geologic units within the study area. Water chemistry data from sampled groundwater wells can be used to better understand the hydrogeochemical system and to constrain water quality calculations made using electric (resistivity/induction/spontaneous potential) logs. In the end, incorporation of the available groundwater data with the geologic data and associated interpretations should result in a comprehensive understanding of area hydrogeology. If the geologic interpretation requires additional resolution, then incorporation of a seismic dataset is the next step.

6.1.5 Seismic Data Search (Task E)

A search for relevant seismic data is conducted first using major vendors, but also considering proprietary surveys using a seismic data broker. Once potential data is identified, the acquisition parameters must be carefully examined, and a visual examination of the data made by a qualified professional to evaluate its suitability for the intended project. As part of this examination, the professional should determine if data requires reprocessing for use or if reprocessing would significantly enhance interpretation. This task concludes with a decision to license data.

6.1.6 License and Initial Interpretation (Task F)

Once the licensing agreement is completed, the digital data will be received in SEG-Y format from the vendor. It is important to make sure to have access to field data (for reprocessing) and to receive survey and observer notes (also for reprocessing) and to follow any loading instructions for the data. Next step is to load data into the interpretation software of choice, along with the well locations and other data. Following this, the scientist should perform an initial interpretation the data supplied (two-dimensional profiles or three-dimensional volumes), carrying key marker horizons identified by applying one or more time-depth conversion tables to the log interpretations. Seismic should be used here to identify major structures (fault and folds) and other major features affecting the target interval. Based on this initial interpretation and close examination of the data as interpreted, final decision is made on whether or not to reprocess the data. If no reprocessing is to be performed, skip to interpretation.

6.1.7 Preprocessing and Initial Processing (Task G)

Having decided on reprocessing, one should select a reliable seismic data processor, making sure they have experience with the processes desired. The scientist should obtain the survey and observers records and field information from the vendor and deliver them to the processor. The processor then applies standard preliminary processing (preprocessing) steps. Of particular importance are determining the geometry of shots and receivers (which determines the location of common depth points and sorting into bins) and the application of spherical divergence to equalize amplitudes between low-angle and high-angle paths. Traces are examined and problem traces (high-noise, low coupling, etc.) may be muted or edited. A “brute stack” may be generated for quality control, using an initial estimate of velocities. (Examples of these products, and other results of processing, will be presented in Chapter 7). Note: following discussion assumes three-dimensional seismic data, hence the use of the terms “volumes” and “bin gathers” instead of “profiles” and “Common Depth Point gathers”.

6.1.8 Processing: Second Stage (Noise Reduction and Statics) (Task H)

After the initial steps, the processor applies additional routines to reduce noise and improve frequency and information content and reduce near-surface variations (static corrections). A most important step is deconvolution, which mathematically estimates then compresses the input seismic wave to its most compact form. This improves frequency content, removes ringing and ghosting reflectors due to near-surface conditions, and enhances information content. A series of statics routines are applied, which adjust traces for near-surface velocity variations that cause "bumpiness" in the gathers and degrade the stacked signal. The recommended standard consists of refraction statics, which creates a near-surface model of velocities derived from the part of the signal that follows near-surface boundaries, then applies that model to adjust the traces. The interpreter should examine the refraction statics model for reasonableness and for possible integration with the deeper reflection models generated later. At this point, the contents of gathers or bins should be examined for effective statics and noise reduction, for frequency content in the shallow section, and for distribution of offsets and number of effective traces in the shallow section. The muting of high-offset (high-angle) traces at shallow depths is necessary to create a stackable gather. This is also a good time to examine the effects of azimuth (direction of source-receiver pairs) in three-dimensional data, and to look for significant effects of anisotropy (varying velocities with azimuth).

6.1.9 Processing: Third Stage (Stacking) (Task I)

Refined velocity estimates are made from the conditioned gathers to create intermediate stacks. In many cases in the shallow section (less than full fold), the number and distribution of traces is not sufficient to achieve a reliable stack. In that case, the processor may perform interpolation of traces in multiple dimensions to "fill in" the gather with reliable estimated traces; this allows much better determination of stacking velocity and is a chief means of reducing "footprint" of the shot/receiver geometry. The interpreter receives quality control plots of the interpolation results.

6.1.10 Final Amplitude Profiles/Volumes (Task J)

Final velocities are determined from the interpolated data and applied to the gathers to achieve a final stack. Prestack routines to migrate data (correcting for structure and diffraction) are commonly applied and together with poststack migration led to a final migrated data volume and associated velocity volumes. The interpreter then can compare the reprocessed volumes (or profiles) to the original data, noting improvements or raising questions. The interpreter can also look at frequency filters on the stacked or migrated data to maximize resolution, or the processor may apply routines to achieve a similar result.

6.1.11 Interpretation of Data (Task K)

With the loaded amplitude and velocity data from above in hand, the interpreter first ties wells and well horizons (from Task C) to the data using well-based time-depth functions. Well ties involve editing and calibrating the velocity and acoustic data, then constructing a synthetic seismogram from calibrated well-logs, and then performing the match. For a tutorial on performing a well tie, a suggested publication is White and Simm (2003). These may be supplemented by seismic velocity analyses and the velocity volume supplied by the processor; however, seismic-generated stacking velocities must be corrected to be used for time-depth conversion.

A case may arise where there is no sonic log to tie. In this case, estimates can be generated from available data. Stacking velocities, resistivity or porosity logs, or data from literature can be used to generate a one-dimensional depth profile of estimated sonic or other properties, called a pseudo-sonic log or a pseudo well. This estimate profile can be used to generate a synthetic seismogram in lieu of a real sonic log. This synthetic seismogram can be tied to the seismic data just the same as one from calibrated sonic logs.

The interpreter then uses the well tie (or relies on some other time-depth relationship) to identify seismic reflectors that correspond to significant aquifer units. The interpreter then carries key horizons or interval boundaries, as approximated by key continuous reflectors, through the data set to yield seismic structure and isopach maps. Not all geologic-defined boundaries are associated with high-quality reflectors. Evidence of significant sequence boundaries or other unconformities should also be sought and evaluated. These can also be imported from work in Task C or literature. Correlation of seismic horizons also assists in seismic structural analysis. As the horizons are interpreted, faults, folds, and deformation should be noted and interpreted.

The velocity information should be examined to see if bulk rock percentages can be determined. In areas where well control is sparse interval velocity can be examined to determine relative percentages of lithologic end members. In a sand-shale environment, sands are generally higher velocity, so an overall sand percentage may be estimated. Carbonates would yield a stronger effect. These estimates will be rough and not high-resolution but might be useful in areas with little knowledge and significant lithologic change.

To enhance the interpretation, the seismic interpreter can generate poststack attributes (calculated from the amplitude data) that can be used to identify structural and stratigraphic elements of interest more clearly. These attributes can include coherency (the similarity or dissimilarity of one trace to another), dip and curvature (systematic vertical changes in reflectors between traces), and frequency variations (effective frequencies returned from a limited interval on the trace). A useful modern version of frequency attributes is known as spectral decomposition, in which the strength of a range of frequencies is calculated and then superimposed in a colorful display to emphasize lithologic contrasts. These attributes can be used to map structural features and geobodies that were previously unobserved.

The processor can supply a depth-domain seismic volume/profile, using stacking velocities as corrected by well information. However, this is probably not worth the extra cost, at least in subregional areas with gentle or no structures and limited variation in velocity.

After the bulk of interpretation is completed and evaluated, the project team can decide on advanced processing, such as inversion.

6.1.12 Inversion (Task L)

If warranted, the processor can proceed to produce an inversion of seismic data, working back from the seismic amplitudes to generate a display of estimated inverted acoustic impedances of the various aquifer and inter-aquifer units that were responsible for the seismic response. Because of the limitations of seismic data, this process needs to be constrained using one or more suites of high-quality log data, including sonic and density logs over the target intervals. Petrophysical analysis of this data is a necessary part of the process. If a constrained model of impedance is derived, the interpreter can use this to generate a quantitative estimate of aquifer thickness and/or quality, and the connectivity of aquifer units.

6.1.13 Integration and Seismic Stratigraphy (Task M)

The results of seismic interpretation (and inversion, if performed) then need to be integrated into the hydrogeologic model of Tasks C and D. Hopefully, the enhanced data can resolve aquifer geobodies (elements) with their dimensions, azimuths, and connectivity, which can inform more realistic models of aquifer properties and yield in the project area.

Section 6.1.11 discussed the utility of seismic analysis in lithology and structural determinations. This final step is particularly directed at the seismic stratigraphic three-dimensional analysis, utilizing all data. This is not possible at all locations where seismic has utility. The seismic analysis may feel free to conclude with Task K and be satisfied that the seismic study has been completed. The last step of seismic stratigraphy is less about small scale efforts and more about broad trends. For instance, it may not be helpful in identifying flow units at the field scale, such as sand-shale patterns or facies differentiation, depending on the scale of the field. However, hopefully it will assist in picking large scale progradation and retrogradation. This can be useful when identifying broad trends.

Following Kerans and Tinker (1997), the core-well log cross sections with their interpretations should be overlain with seismic data. This allows for the interpreter to see the seismic response of the data previously interpreted into low order cycles.

Seismic allows for the imaging of three-dimensional geometries and architectures of individual units. Vail (1987) suggests first picking candidate seismic sequence boundaries. These boundaries are reflectors that other reflectors terminate against. For a discussion on reflector geometries and types, the reader is referred to section 3.1.1. The interpreter will choose the sequence boundaries and marry them to the low order sequence boundaries he or she has picked. Once completed, there is some cohesion and unity in interpretations between data types. Further delineation of surfaces and packages in core, well-logs, and seismic will place the rest of the volume in sequence stratigraphic context.

One technique common to seismic stratigraphy is the delineation of seismic facies. Similar to lithologic facies, this is a discretization of a spectrum of reflector configurations, continuities, and amplitudes. Bachtel (2004) is a good reference on developing a set of seismic facies. Essentially the interpreter develops a set of seismic facies that sort reflectors into groups of like geometries and continuities. Further interpreting these seismic facies as unique depositional environments places constraints on the geologic system.

Following the integration of all data into a three-dimensional sequence stratigraphic framework, development of a mathematical model to represent fluid flow in the subsurface would be the next step. In oil and gas, this would be a reservoir model constructed by a reservoir engineer. In groundwater, this would be a groundwater model constructed by a groundwater modeler.

6.2 Regional Considerations

The workflow presented above is generally applicable to all groundwater basins with available seismic data; however, the relative significance of different tasks and procedures will vary.

In the Gulf Coast and East Texas regions, relatively slow velocities in the target depth range will yield better resolution of aquifer elements. Reprocessing should improve imaging at shallow horizons, as most of the oil and gas targets for which seismic was acquired occur deeper than the aquifers. Anisotropy in these regions is not thought to be significant, except around shallow salt diapirs and perhaps in the Balcones fault zone (due to fracturing).

In the West Texas and North Texas regions, faster seismic velocities in the target depth range will reduce resolution; however, this may be compensated somewhat by higher input frequencies. Statics assume major importance, and integration of static correction techniques and shallow velocity functions should be considered. Modern processing on received data may be good enough to obviate reprocessing. Anisotropy may be significant in some basins and should be evaluated during reprocessing.

The decision on reprocessing will depend on the nature of the information sought. In some aquifers, identification of faulting may be primary (as in Balcones fault zone aquifers), and original processing might suffice. Also, the received processing may vary widely from 1970s to 2010s technology; older lines that have not been reprocessed before licensing may require reprocessing to interpret. In this case, the vendor may work with the operator to get the reprocessing done at little or no cost, as they can add the improved data to their library.

6.2.1 Aquifer Specific Considerations

Table 6-1 summarizes the available two- and three-dimensional seismic coverage of the groundwater systems in Texas that are recognized by the Texas Water Development Board as major and minor aquifers. The three-dimensional coverage was determined by first calculating the area of each aquifer footprint using Arc GIS shapefiles available on the Texas Water Development Board's webpage. Then, using the "Merge" Tool within Arc GIS, the coincident area covered by both the three-dimensional seismic data and the aquifer in question was calculated. Given that the two-dimensional seismic data coverage was represented by a line, the data were converted into a polygon by using the buffer tool to create a 0.5-mile buffer around the line. The resulting 0.5-mile buffer was then used to calculate the coincident area using the "Merge" Tool in Arc GIS. Again, it should be stressed that the seismic coverage is that of the major vendors described in Chapter 4; other data does exist and might be accessed.

Table 6-1. 2D and 3D seismic coverage for Texas aquifers.

Aquifer	Total Area (sq. mi)	Three Dimensional Seismic Coverage Area (sq. mi)	Percent Covered	Two Dimensional Seismic Coverage Area (sq. mi)	Percent Covered	Seismic Speed
Blaine	5676	414	7.30%	2785	49.10%	Fast-Medium
Blossom	277	0	0.00%	82	29.70%	Medium
Bone Spring – Victorio Peak	713	0	0.00%	41	5.70%	Fast
Brazos River Alluvium	1057	316	29.90%	788	74.50%	Medium
Capitan Reef Complex	1850	553	29.90%	968	52.30%	Fast
Carrizo	53004	14140	26.70%	40905	77.20%	Medium
Cross Timbers	17790	479	2.70%	1914	10.80%	Fast
Dockum	42347	9220	21.80%	23220	54.80%	Fast
Edwards	4052	0	0.00%	1080	26.70%	Medium
Edwards-Trinity	35425	6407	18.10%	11952	33.70%	Fast
Edwards-Trinity (High Plains)	7912	536	6.80%	5989	75.70%	Fast
Ellenburger-San Saba	5307	0	0.00%	107	2.00%	Fast
Gulf Coast	52836	27668	52.40%	45749	86.60%	Slow
Hickory	8519	0	0.00%	405	4.70%	Fast
Hueco-Mesilla Bolson	1376	0	0.00%	336	24.40%	Fast
Igneous	6075	18	0.30%	848	14.00%	Volcanic-Fast
Lipan	1995	93	4.70%	564	28.30%	Fast
Marathon	391	0	0.00%	4	1.00%	Fast
Marble Falls	215	0	0.00%	2	1.00%	Fast
Nacatoch	1830	2	0.10%	1518	82.90%	Medium
Ogallala	36327	3685	10.10%	19266	53.00%	Fast
Pecos Valley	6829	3239	47.40%	4858	71.10%	Fast
Queen City	33265	10429	31.40%	28775	86.50%	Medium
Rita Blanca	918	0	0.00%	344	37.40%	Fast
Rustler	5191	2748	52.90%	4284	82.50%	Fast
Seymour	3391	250	7.40%	1700	50.10%	Fast

Aquifer	Total Area (sq. mi)	Three Dimensional Seismic Coverage Area (sq. mi)	Percent Covered	Two Dimensional Seismic Coverage Area (sq. mi)	Percent Covered	Seismic Speed
Sparta	7870	3947	50.20%	7119	90.50%	Medium
Trinity	32092	1538	4.80%	9024	28.10%	Medium
West Texas Bolsons	1898	0	0.00%	381	20.10%	Fast
Woodbine	7346	435	5.90%	3429	46.70%	Medium
Yegua-Jackson	31239	13258	42.40%	29270	93.70%	Medium

Note: % = percent, 3D = three-dimensional, 2D = two-dimensional, sq mi = square miles

6.2.2 Aquifer Specific Considerations

This section introduces each aquifer and then discusses potential pitfalls and benefits of utilizing seismic data. Aquifer summaries are from George and others (2011).

Blaine

The Blaine Aquifer is a minor aquifer situated in sixteen counties in north Texas (Figure 6-5). It is composed of red silty shale, gypsum, anhydrite, salt, and dolomite. Solution pores in the anhydrite and gypsum are the primary porosity, which contributes to the poor water quality. Thickness reaches 300 feet. Bottom depths range up to 2000 feet, but little of the aquifer extends to depths conducive to seismic imaging. Most water exceeds 3,000 milligrams per liter total dissolved solids. Water use is mainly agricultural.

Seismic data coverage is moderate: 7.3 percent for three-dimensional data and 49.1 percent for two-dimensional data. The central portion of the aquifer lacks significant seismic data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, presence of salt and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, tight velocity modelling, and statics adjustments. The benefits of seismic data for the Blaine if it could be done include identification of cavernous porosity, tight control where there is little well data, rock composition analysis, constraints of aquifer extent and thickness. High resolution seismic data would be especially helpful in the detection of extensive solution pores, and in imaging the boundaries between salt and siliciclastic material.

Blossom

The Blossom Aquifer is a minor aquifer in three counties of northeast Texas (Figure 6-6). It is composed of sandstone and intervening claystone. Despite the thickness ranging up to 400 feet, sandstone makes no more than a third of that thickness. Bottom depths range up to 2,500 feet, but little of the aquifer extends to depths conducive to seismic imaging. The aquifer has a wide range of water quality. A large percentage of water use goes to municipal pumping.

Seismic data coverage is absent to sparse: 0.0 percent for three-dimensional data and 29.7 percent for two-dimensional data. The seismic velocities in this part of the state are somewhat fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, lack of log data, and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data and conducting new surveys. The benefits of seismic data, if useable data at these depths could be acquired, would include imaging channels and geobodies, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness.

Bone Spring-Victorio Peak

The Bone Spring-Victorio Peak Aquifer is a minor aquifer in Hudspeth County in west Texas (Figure 6-7). It is predominantly composed of limestone. Solution cavities along joints and fractures contain most of the water. The aquifer is generally slightly saline. Water use is mainly agricultural.

Seismic data coverage is absent to sparse: 0.0 percent for three-dimensional data and 5.7 percent for two-dimensional data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of data, expected fast seismic velocities, lack of log data, and near surface effects. Recommendations to combat these issues include investigations for more data and conducting new surveys. The benefits of seismic data in this aquifer include identification of karst and faulting, tight control where there is little well data, rock composition analysis and constraints of aquifer extent and thickness.

Brazos River Alluvium

The Brazos River Alluvium Aquifer is a minor aquifer in 13 counties of east-central Texas (Figures 6-8 and 6-9). It is composed of alluvial floodplain and terrace deposits. The floodplain alluvium deposits are complicated, with lenses of sand and gravel that pinch out laterally or grade to finer sediment. Thickness and therefore depth ranges up to 168 feet. The aquifer is generally fresh and water use is mainly irrigation.

Seismic data coverage is abundant: 29.9 percent for three-dimensional data and 74.5 percent for two-dimensional data. Lack of seismic data occurs only in the northwestern part of the aquifer. The seismic velocities in this part of the state are slow to medium. Barriers to effective seismic imaging on conventional surveys are the shallow depth of the aquifer. Unless targeted high-resolution seismic data is acquired, this aquifer will not be well imaged.

Capitan Reef Complex

The Capital Reef Complex Aquifer is a minor aquifer in eight counties of west Texas (Figure 6-10 and 6-11). It is composed of limestone, dolomite, and siliciclastic material. The aquifer has significant primary and secondary porosity. Thickness ranges up to 2360 feet. Bottom depths range from shallow to in excess of 5,000 feet. Down-dip the aquifer is generally slightly saline to saline in quality and fresh in and immediately down-dip from outcrop. Water use is mainly industrial.

Seismic data coverage is fairly abundant: 29.9 percent for three-dimensional data and 52.3 percent for two-dimensional data. The western portion of the aquifer lacks available seismic data, but the eastern portion well represented. The seismic velocities in this part of the state are very fast. Barriers to effective seismic imaging include fast seismic velocities, difficult near-surface effects, presence of salt, and lateral changes in geology. Recommendations to combat these issues include careful statics adjustments and tight velocity modelling. The benefits of seismic data in this aquifer include imaging geobodies, identification of cavernous porosity, identification of faulting, tight control in between well data, rock composition analysis, and constraints on aquifer extent and thickness. The Capitan Reef Complex is a favored candidate for seismic exploration and characterization. The lateral variability in facies, porosity, and presence of the aquifer are all problems that can be informed by use of seismic data.

Carrizo-Wilcox

The Carrizo-Wilcox Aquifer is a major aquifer in 66 counties of south, central and east Texas (Figures 6-12 and 6-13). It is composed of sand, shale, clay, and lignite. Thickness ranges up to 3,000 feet, including both the upper Carrizo and lower Wilcox portions of the aquifer. Bottom depths range from shallow to in excess of 6,000 feet. The aquifer is generally fresh. Water use is mainly irrigation and municipal supply.

Seismic data coverage from vendor maps is abundant: 26.7 percent for three-dimensional data and 77.2 percent for two-dimensional data. The seismic velocities in this part of the state are slow to medium. Barriers to effective seismic imaging include limited near surface effects that can be treated using trace interpolation and statics adjustments. The benefits of seismic data in this aquifer include imaging channels and submarine canyons, identification of faulting, tight control in between well data, and good constraints of aquifer extent and thickness. The Carrizo-Wilcox aquifer represents an excellent candidate for seismic interpretation.

Cross Timbers

The Cross Timbers Aquifer is a minor aquifer present in 31 counties of north Texas (Figure 6-14). It is composed of limestones, shales, and sandstones of Pennsylvanian age. Thickness ranges up to 4,000 feet. Bottom depths range from shallow to 6,000 feet, increasing westward. Water quality is highly variable wells are mainly domestic and stock wells.

Seismic data coverage from vendors is nearly absent to sparse: 2.7 percent for three-dimensional data and 10.76 percent for two-dimensional data. Most of the aquifer lacks seismic data, though some are present locally. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of data, fast seismic velocities, and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, and statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of cavernous porosity, tight control in areas with little well data, rock composition analysis, and constraints on aquifer extent and thickness.

Dockum

The Dockum Aquifer is a minor aquifer in 46 counties in west and northwest Texas (Figures 6-15 and 6-16). It is composed of siliciclastic materials including gravels, sands, silts and clays. Most water comes from the sands and gravels in the middle and at the bottom of the unit (Santa Rosa Sandstone). Thickness ranges up to 1,400 feet. Bottom depths range from shallow to in excess of 2,250 feet. The water is typically of poor quality, but fresher water does exist towards outcrop in the far western (New Mexico) and far eastern portions of the aquifer.

Water use is mainly for irrigation, municipal water supply and some oilfield waterflooding operations.

Seismic data coverage from vendors is fairly abundant: 21.8 percent for three-dimensional data and 54.8 percent for two-dimensional data. The seismic velocities in this part of the state are very fast. Barriers to effective seismic imaging include lack of depth in some areas, fast seismic velocities, lack of log data in the northern part of the aquifer, severe near surface effects, and lateral changes in geology. Recommendations to combat these issues include interpolation, statics adjustments, and tight velocity modelling. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, tight control where there is little well data, rock composition analysis, and constraints on aquifer extent and thickness. The rapidly changing geology across the large extent of the aquifer could be a potential area to use regional seismic data and velocity-based rock composition analysis.

Edwards (Balcones Fault Zone)

The Edwards (Balcones Fault Zone) Aquifer is a major aquifer in 13 counties of southwestern Texas (Figure 6-17). It is mainly composed of limestone. Faulting/fracturing and subsequent dissolution of the limestone has created cavernous porosity that typifies the fluid flow regimes in the aquifer. Thickness ranges up to 600 feet. Bottom depths range from shallow to in excess of 3,000 feet. The aquifer is generally fresh where used, but slightly saline to brackish downdip. Water use is mainly for municipal, irrigation, and recreation.

Within the Texas Water Development Board defined footprint, seismic data coverage is absent to sparse: 0 percent for three-dimensional data and 26.7 percent for two-dimensional data. The Edwards extends down dip of the Texas Water Development Board boundary and is commonly used for oilfield wastewater injection. Available seismic data is lacking for the freshwater portion of the aquifer except for Medina and Uvalde counties. Down-dip of the aquifer boundary, two-dimensional seismic coverage is abundant and could help resolve aquifer structure. The seismic velocities in this part of the state are medium to fast. Barriers to effective seismic imaging include lack of depth near outcrop, lack of data in areas, fast seismic speeds, lack of log data in outcrop, and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, and statics adjustments. The benefits of seismic data in this aquifer include identification of cavernous porosity, identification of karst, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. The Edwards is a good candidate for seismic exploration, especially for using regional two-dimensional lines to identify Balcones and Luling fault patterns.

Edwards-Trinity (Plateau)

The Edwards-Trinity (Plateau) Aquifer is a major aquifer in 40 counties in west-central Texas (Figures 6-18 and 6-19). It is composed of limestone, dolomite, and sands. Total thickness of the combined Edwards and Trinity can exceed 1,000 feet. Bottom depths range from shallow to (rarely) in excess of 800 feet. The aquifer is generally fresh to slightly saline. Water use is mainly irrigation with some municipal and livestock.

Seismic data coverage is sparse to moderate: 18.1 percent for three-dimensional data and 33.7 percent for two-dimensional data. The eastern part of the aquifer lacks significant seismic data. The seismic velocities in this part of the state are very fast. Barriers to effective seismic imaging include lack of depth, lack of data in the east, fast seismic speeds, and near surface effects. It will be difficult to manage the shallow depths coupled with the high speeds for this aquifer. If it could be done, it would be shooting high-resolution seismic at shallow depths. Recommendations to combat these issues include interpolation, and statics adjustments, tight velocity modelling. The benefits of seismic data in this aquifer include imaging geobodies, identification of cavernous porosity, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness.

Edwards-Trinity (High Plains)

The Edwards-Trinity (High Plains) Aquifer is a minor aquifer in 14 counties of west Texas (Figure 6-20). It is composed of sandstone and limestone. Regional flow is directed toward the southeast; however, the local geology influences flow counter to that direction. Thickness ranges up to a few hundreds of feet. Bottom depths range from shallow to in excess of 600 feet. The aquifer is generally slightly saline. Water use is mainly for irrigation.

Seismic data coverage is fairly abundant: 6.8 percent for three-dimensional data and 75.7 percent for two-dimensional data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, fast seismic speeds, and near surface effects. If high resolution could be shot, there would be some assistance from the data, but it may not be economical versus using another geophysical imaging method. Potential benefits would include a more detailed characterization of the occurrence and extent of the aquifer as it exists between the Ogallala aquifer and Dockum aquifer. Current characterization efforts rely on a combination of water well driller’s logs and gamma logs run through multiple casing strings.

Ellenburger-San Saba

The Ellenburger-San Saba Aquifer is a minor aquifer in 16 counties of central Texas (Figure 6-21). It is composed of limestone and dolomite. The aquifer outcrops surrounding the Llano uplift and dips away from outcrop. Thickness ranges up to 2,700 feet. Bottom depths from Shi and others (2016) range from shallow to 9,000 feet in Williamson County. The aquifer is generally fresh to slightly saline. Water use is mainly municipal, domestic, irrigation and livestock.

Seismic data coverage is nearly absent: 0 percent for three-dimensional data and 2 percent for two-dimensional data. The seismic velocities in this part of the state are fast to very fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, lack of log data, and near surface effects. Investigations in this area may consider conducting new high-resolution surveys. The benefits of seismic data in this aquifer include identification of cavernous porosity, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. If available, seismic data would be an ideal control for this aquifer. Given the complex structure and limited available well logs, two-dimensional seismic data could provide valuable insights into the occurrence and distribution of structural contact, significant faulting and karst features. Therefore, while this aquifer is currently extremely data poor with respect to seismic, it still represents a prime candidate for future seismic studies.

Gulf Coast

The Gulf Coast Aquifer is a major aquifer complex in 54 counties of south and southeast Texas and may extend into the offshore shelf (Figures 6-22 and 6-23). It is composed of sands and clays of Oligocene through Pleistocene age. Net sand thickness ranges from 700 to 1,300 feet. Bottom depths range from shallow to over 5000 feet. The aquifer has generally good water quality in the central and northern portions in zones near the outcrop and becomes more saline to the south and with depth. Water use is mainly municipal, industrial, and irrigation. Subsidence may be an issue for extensive development of this aquifer. One solution could be the development of brackish groundwater resources in offshore Texas State Waters and the Federal Outer Continental Shelf, where subsidence would be less likely to impact surface and near-surface infrastructure.

Seismic data coverage (derived from vendor maps) is abundant: 52.4 percent for three-dimensional data and 86.6 percent for two-dimensional data. The only areas that lack seismic data are certain ranches in south Texas (but data certainly exists there also) and in a few major metropolitan areas. The seismic velocities in this part of the state are slow to very slow. Barriers to effective seismic imaging are limited to accessing the data. Recommendations to combat these issues include extensive reprocessing using interpolation, and careful refraction statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. The Gulf Coast represents the highest potential with respect to use of seismic in aquifer characterization. The slow seismic speeds coupled with the proven ability to image channels in the subsurface makes seismic characterization of the Gulf Coast Aquifer favorable. Offshore, no-cost seismic data can be found in the southernmost Texas State Waters and in the Federal Outer Continental Shelf. This region is essentially unexplored with respect to available water resources. Furthermore, existing characterizations of the Gulf Coast aquifer could be highly refined through the incorporation of seismic data into existing studies.

Hickory

The Hickory Aquifer is a minor aquifer in 19 counties of central Texas (Figure 6-24). The water bearing units within the aquifer are composed of permeable sandstones that are separated by thin shale units and impermeable sandstones. The aquifer exists below the Ellenburger-San Saba Aquifer and has a similar structural trend of outcropping around the Llano uplift and dipping away from the outcrop ring. Thickness ranges up to 480 feet. Bottom depths from Shi and others (2016) range from shallow to 10,000 feet in Burnet County. The aquifer is generally fresh but does not meet the Texas standard for drinking water due to iron content and radionuclides. Water use is mainly irrigation and municipal.

Seismic data coverage is absent to sparse: 0 percent for three-dimensional data and 4.7 percent for two-dimensional data. Only the southeast fringe of the aquifer area is crossed by any data. The seismic velocities in this part of the state are probably fast to very fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, lack of log data, near surface effects, and lateral changes in geology. Recommendations to combat these issues include conducting new surveys. The benefits of seismic data in this aquifer would include imaging channels and geobodies, identification of faulting, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness. As with the other units within the Llano Uplift aquifer, complex structural trends could be much better understood with the acquisition of new seismic data.

Hueco-Mesilla Bolsons

The Hueco-Mesilla Aquifer is a major aquifer in El Paso and Hudspeth counties in far west Texas (Figure 6-25). It is composed of gravel, sand, and clay. The aquifer consists of two basins (or "bolsons") that reach 9,000 feet in thickness in the Hueco bolson and 2,000 feet in thickness in the Mesilla bolson. Bottom depths range from shallow to 9,000 feet. The aquifer water quality ranges from fresh to moderately saline. Water use is mainly for public water supply.

Seismic data coverage is absent to sparse: 0 percent for three-dimensional data and 24.4 percent for two-dimensional data. No seismic data is located in the northern Hueco bolson and the Mesilla bolson, and only sparse two-dimensional data in the southern Hueco bolson. The seismic velocities in this part of the state are moderate to fast. Barriers to effective seismic imaging include lack of data, fast seismic velocities, lack of log data, and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, and statics adjustments. The benefits of seismic data in this aquifer would include identification of faulting, rock composition analysis, and constraints on aquifer extent and thickness. The Bolsons are a good candidate for seismic exploration, especially new high-resolution surveys. Typically, on a structurally closed basin, the edges of the basin are subject to loose constraints based on the density of wells in the area that either intersect or do not intersect the basin. Seismic data, properly located, can better image the basin geometry. In addition to basin edges, properly located seismic data could also provide better imaging of down-thrown blocks that could provide areas of increased aquifer thickness.

Igneous

The Igneous Aquifer is a complex minor aquifer in five counties in trans-Pecos Texas (Figure 6-26). It is composed of igneous rock with minor sandstone, conglomerates, and breccia. The aquifer contains over 40 named units. Thickness may range up to 6,000 feet. Bottom depths range from very shallow to perhaps 6,000 feet. The aquifer is generally fresh but does have high fluoride and silica content. Water use is mainly municipal.

Seismic data coverage is nearly absent to sparse: 0.3 percent for three-dimensional data and 14.0 percent for two-dimensional data. Seismic coverage is focused in northern Presidio County (Marfa basin) and the northeastern fringe, and is very limited elsewhere. The seismic velocities in this part of the state are fast to very fast. Barriers to effective seismic imaging include lack of data, fast seismic velocities, lack of log data, and strong near-surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, statics adjustments, and tight velocity modelling. The benefits of seismic data in this aquifer could include identification of faulting, rock composition analysis, tight control where there is little well data, and some constraints on aquifer extent and thickness. The igneous aquifer represents a good candidate for seismic analysis. It is a common but unsupported assumption that seismic data in an igneous substrate may not yield usable information. There is abundant literature to show that seismic surveys can delineate faults, layering and other geobodies in igneous rock, especially when the data are carefully processed for elevation and varying velocities. The complex geometries and structure of the igneous aquifer are good candidates to leverage seismic imaging. Furthermore, drilling in igneous rock can be expensive and the utilization of new or existing seismic data to guide drilling would likely increase success rates.

Lipan

The Lipan Aquifer is a minor aquifer in 8 counties near San Angelo in west-central Texas (Figure 6-27). It is composed of alluvium with some contribution underlying strata of Permian age. Thickness ranges up to in excess of 1,000 feet where the entire stratigraphic section is present and considered. Bottom depths range from shallow to 1,000 feet. The aquifer is generally fresh to slightly saline. Water use is mainly irrigation.

Seismic data coverage is sparse: 4.7 percent for three-dimensional data and 28.3 percent for two-dimensional data. Lack of seismic data is nearly total for the western sectors and the eastern extent of the aquifer. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, and near surface effects. Recommendations to combat these issues include interpolation, investigations for more data, conducting new surveys, and statics adjustments. The benefits of seismic data in this aquifer could be significant and would include imaging channels, imaging geobodies, constraints of aquifer extent and thickness including better resolution of the contact between the Lipan alluvium and underlying Paleozoics. The Lipan is fairly shallow, and most of the aquifer extent could be imaged in other ways. Seismic could be acquired and used in the deeper portion of the aquifer but its quality may be affected by the San Angelo metropolitan area. Like the bolson deposits, the Lipan aquifer could benefit from a more detailed characterization of basin thicknesses and extents that would serve to bolster the existing characterizations that are largely based on driller’s reports and well logs. Understanding of the occurrence, distribution and structure of the underlying Paleozoics could be greatly enhanced through acquisition of new seismic data.

Marathon

The Marathon Aquifer is a minor aquifer in Brewster County in trans-Pecos Texas (Figure 6-28). It is composed of a wide variety of lithologies and geologic units. The aquifer is tightly folded and faulted. Thickness ranges up to 900 feet. Depth ranges are unknown at this time. The aquifer is generally fresh and water use is mainly municipal.

Seismic data coverage is nearly absent: 0.0 percent for three-dimensional data and 1.0 percent for two-dimensional data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, lack of log data, near surface effects, and lateral changes in geology. The benefits of seismic data in this aquifer could include imaging geobodies, identification of cavernous porosity, identification of karst, identification of faulting and folding, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness. The Marathon Aquifer would be a great candidate for new seismic exploration because of its structural complexity and lack of well control. Lack of well-based data is a large barrier and interpretation would need to tie multiple sonic logs together because the complex folding and faulting will cause sharp lateral changes in the velocity structure of the aquifer. That said, while seismic data would provide insights into aquifer occurrence and distribution, the need for closely spaced sonic logs to combat extreme/abrupt geologic changes would make it uneconomic.

Marble Falls

The Marble Falls Aquifer is a minor aquifer in eight counties in central Texas (Figure 6-29). It is primarily composed of limestone. The aquifer consists of several outcrops separated and spread out across central Texas. Thickness ranges up to 600 feet. Bottom depths range from shallow to 4,000 feet; however, the official outline of the aquifer does not include a subsurface extent. The aquifer generally produces good quality water. Water use is mainly municipal, industrial, and agricultural.

Seismic data coverage is nearly absent: 0.0 percent for three-dimensional data and 1.0 percent for two-dimensional data. The seismic velocities in this part of the state are probably fast to very fast. Barriers to effective seismic imaging include lack of data, shallow aquifer in the known segments, fast seismic speeds, lack of log data, and near surface effects. Recommendations to combat these issues include conducting new surveys, and processing to modern standards. The benefits of seismic data in this aquifer could include imaging geobodies, identification of cavernous porosity, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. Like other member of the Llano Uplift system, the Marble Falls aquifer would be a good candidate for seismic characterization, except for lack of data. The subsurface extent is mostly unknown (therefore not represented on Figure 6-28), and there are few well data. Seismically imaging the Llano Uplift system could result in the differentiation of the Marble Falls aquifer from the Ellenburger-San Saba, Hickory and other associated aquifers.

Nacatoch

The Nacatoch Aquifer is a minor aquifer in 15 counties in northeast Texas (Figure 6-30). It is composed of sandstone and intervening clay. Thickness of individual sand units ranges up to 100 feet. Bottom depths range from shallow to in excess of 1,500 feet. The aquifer is generally fresh to slightly saline. Water use is mainly for domestic and livestock.

Seismic data coverage is limited to two-dimensional: 0.1 percent for three-dimensional data and 82.9 percent for two-dimensional data. The seismic velocities in this part of the state are moderate to fast. Barriers to effective seismic imaging include moderate seismic velocities, and near surface effects. Recommendations to combat these issues include interpolation, and statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of faulting, rock composition analysis, and constraints of aquifer extent and thickness. The Nacatoch aquifer is a fair candidate for seismic characterization. Provided the shallow image can be determined from new three-dimensional data, seismic geomorphology would allow for the interpretation of channels, geobodies and fault determinations.

Ogallala

The Ogallala Aquifer is a major aquifer in 48 counties of northwest Texas (Figures 6-31 and 6-32). It is composed of siliciclastic sediments. Thickness ranges up to 800 feet. Bottom depths range from shallow to 800 feet. The aquifer is generally fresh to slightly saline. Water use is mainly irrigation.

Seismic data coverage is fairly abundant: 10.1 percent for three-dimensional data and 82.9 percent for two-dimensional data. Seismic coverage is present mainly to the south and the northeast (Midland and Anadarko basins). The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, fairly fast seismic velocities, and near surface effects. Recommendations to combat these issues include interpolation, shooting new high-resolution data, and statics adjustments. The existing data is unlikely to image the very shallow Ogallala. However, if it could be managed, the benefits of seismic data in this aquifer, especially newly-acquired high-resolution data, would include imaging channels, imaging geobodies, and constraints of aquifer extent and thickness. There is abundant well control for the Ogallala, so seismic data can be well constrained. Seismic data may be most prospective relative to other geophysical methods to the north, where the aquifer is the deepest.

Pecos Valley

The Pecos Valley Aquifer is a major aquifer in 12 counties of west Texas (Figures 6-33 and 6-34). It is composed of alluvial deposits and windblown sands. The aquifer occurs in two roughly northwest-southeast oriented basins. Thickness ranges up to 1,500 feet in areas. Bottom depths range from (shallow) to (deep) feet. The aquifer is generally fresh to slightly saline, but often does not meet standards for drinking water due to sulfate and chloride content, some naturally occurring and some resulting from old oilfield wastewater disposal practices. Water use is mainly for municipal and irrigation.

Seismic data coverage from vendors is abundant: 47.4 percent for three-dimensional data and 71.1 percent for two-dimensional data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth in many areas, fast seismic velocities, and severe near surface effects. Recommendations to combat these issues include interpolation, careful refraction statics adjustments, and tight velocity modelling. The benefits of seismic data in this aquifer include imaging geobodies, identification of faulting, rock composition analysis, and constraints of aquifer extent and thickness. The Pecos Valley Aquifer is a great candidate for seismic exploration. Typically, on a structurally closed basin (of which there are two here), the structure of the basin is subject to loose constraints based on the density of well logs in the area that either intersect or do not intersect the basin. Seismic data will help to better define basin structure. Assuming the seismic is of adequate resolution, vertical and lateral facies changes resulting from alluvial type deposition in a rapidly subsiding basin could be much better understood. Conceptualizations for the depositional facies model governing the sediment distribution within the Pecos Valley Alluvium are non-existent. Either processing existing or acquiring new three-dimensional seismic data could provide significant insights into the facies geometries and would assist in the creation of a depositional facies model or models to characterize the system. A better understanding of the facies geometries would directly benefit the sighting of high-capacity water wells and water well fields.

Queen City

The Queen City Aquifer is a minor aquifer in 42 counties of central and east Texas (Figures 6-35 and 6-36). It is composed of sand and intervening clay. Thickness ranges up to 2,000 feet. Bottom depths range from shallow to over 6,000 feet. The aquifer is generally fresh but decreases in quality downdip. Water use is mainly livestock and domestic.

Seismic data coverage is abundant: 31.4 percent for three-dimensional data and 86.5 percent for two-dimensional data. The seismic velocities in this part of the state are medium to slow. Barriers to effective seismic imaging are limited to lack of depth, and near surface effects. Recommendations to combat these issues include interpolation and careful statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. The Queen City is a good to excellent candidate for seismic characterization, given the simple geology, abundance of well control, and ability to image geobodies.

Rita Blanca

The Rita Blanca Aquifer is a minor aquifer in Dallam and Hartley counties in northwest Texas (Figure 6-37). It is composed of coarse sand and gravel. The aquifer underlies the Ogallala. Thickness ranges up to 250 feet. Bottom depths range from shallow to 500 feet. The aquifer is generally fresh. Water use is mainly agricultural.

Seismic data coverage is absent to sparse: 0 percent for three-dimensional data and 37.4 percent for two-dimensional data. Seismic data are evenly distributed but sparsely populated across the aquifer. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic velocities, lack of log data, and near surface effects. Recommendations to combat these issues include investigations for more data, conducting new surveys, and statics adjustments. The benefits of seismic data in this aquifer include imaging geobodies, tight control where there is little well data and constraints of aquifer extent and thickness. Seismic data would be most economical in the deepest parts of the aquifer, where other geophysical imaging methods may be too shallow, however, 500 feet is too shallow for conventional seismic, and would require high-resolution surveys.

Rustler

The Rustler Aquifer is a minor aquifer in 7 counties in west Texas (Figures 6-38 and 6-39). It is composed of carbonates, clastics and evaporites. Most water is found in solution pores or fractures in the carbonates and evaporites. Thickness ranges up to 670 feet. Bottom depths range from shallow to over 2,250 feet. The aquifer is generally slightly to moderately saline. Water use is mainly for irrigation, livestock, and waterflood operations.

Seismic data coverage is abundant: 52.9 percent for three-dimensional data and 82.5 percent for two-dimensional data. The seismic velocities in this part of the state are very fast. Barriers to effective seismic imaging include lack of depth near the outcrop, fast seismic velocities, near surface effects, presence of salt, and lateral changes in geology. Recommendations to combat these issues include interpolation, and careful refraction statics adjustments. The benefits of seismic data in this aquifer include identification of cavernous porosity, identification of faulting, tight control where there is little well data, rock composition analysis, constraints of aquifer extent and thickness. The contrast between the various lithologies of the Rustler, in combination with significant structure, makes this aquifer ideal for seismic analysis in its deeper areas. Seismic characterization could help reveal lateral changes in geology and further image the structure of the aquifer.

Seymour

The Seymour Aquifer is a major aquifer in 25 counties in north Texas (Figures 6-40 and 6-41). It is composed of isolated and scattered patches of alluvium. Thickness ranges up to 360 feet. Bottom depths below the land surface range from shallow to 360 feet. The aquifer is generally fresh to slightly saline, however more saline water is known to be found locally in the aquifer due to dissolution of Permian evaporites. Water use is mainly for irrigation.

Seismic data coverage is moderate: 7.4 percent for three-dimensional data and 50.1 percent for two-dimensional data. Many isolated segments lack seismic data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of depth, lack of data, fast seismic speeds, lack of log data, near surface effects, and lateral changes in geology. The benefits of new high-resolution seismic data in this aquifer include tight control where there is little well data and constraints of aquifer extent and thickness. The Seymour aquifer is a poor candidate for conventional seismic imaging given its low thickness, lack of depth, and limited utility of utilizing seismic data over other geophysical imaging methods.

Sparta

The Sparta Aquifer is a minor aquifer in 25 counties of central and east Texas (Figures 6-42 and 6-43). It is composed of sand, silt, and clay. Thickness ranges up to 700 feet. Bottom depths range from shallow to excesses of 6,000 feet. The aquifer is generally fresh to slightly saline. Water use is mainly domestic and livestock.

Seismic data coverage is abundant: 50.2 percent for three-dimensional data and 90.5 percent for two-dimensional data. The seismic velocities in this part of the state are medium to slow. Barriers to effective seismic imaging include lack of depth in parts of the area, and near surface effects. Recommendations to combat these issues include interpolation and statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. The Sparta is a good candidate for seismic characterization in its deeper areas, given the simple geology, abundance of well control, and necessity to image geobodies.

Trinity

The Trinity Aquifer is a major aquifer in 61 counties of central and north Texas (Figures 6-44 and 6-45). It is composed of limestones, sandstones, clays, and conglomerates. Thickness ranges up to 1,900 feet. Bottom depths range from shallow to over 7,500 feet. The aquifer is generally fresh to brackish, and quality worsens with increasing depth and easterly extent. Water use is mainly municipal.

Seismic data coverage is limited: 4.8 percent for three-dimensional data and 28.1 percent for two-dimensional data. The seismic velocities in this part of the state are medium to fast. Barriers to effective seismic imaging include lack of depth and data at outcrop, fast seismic velocities, lack of log data, and some near surface effects. Recommendations to combat these issues include interpolation, and statics adjustments. The benefits of seismic data in this aquifer include imaging aquifer units and geobodies, identification of cavernous porosity, identification of karst, identification of faulting, rock composition analysis, and constraints of aquifer extent and thickness. The Trinity is a good candidate for seismic imaging due to the utility that rock composition analysis, structural imaging, and geobody analysis will provide; but the lack of three-dimensional data will likely constrain its utility to faulting and interval studies.

West Texas Bolsons

The West Texas Bolsons Aquifer is a minor aquifer in four counties of trans-Pecos Texas (Figure 6-46). It is composed of sands and gravels, limestones, volcanics, silts, and clays. The aquifer is separated into several basins (or “bolsons”). Thickness ranges up to 3,000 feet. Bottom depths range from shallow to 3,000 feet. The aquifer’s water quality ranges from fresh to moderately saline depending on depth and basin. Water use is mainly irrigation, livestock, and municipal.

Seismic data coverage is absent to sparse: 0.0 percent for three-dimensional data and 20.1 percent for two-dimensional data. Most parts of the bolsons lack seismic data. The seismic velocities in this part of the state are fast. Barriers to effective seismic imaging include lack of data, fast seismic velocities, lack of log data, near surface effects, and lateral changes in geology. Recommendations to combat these issues include investigations for more data, conducting new surveys, interpolation, and statics adjustments. The benefits of seismic data in this aquifer would include identification of faulting, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness. Typically, on a structurally closed basin (of which there are several here), the edges of the basin are subject to loose constraints based on the density of wells in the area that either intersect or do not intersect the basin. Seismic data can help to better image the basin and its internal structure, although the basin edges are probably too shallow to image directly. In addition, the varying lithologies of the basins could be characterized by high-quality seismic data.

Woodbine

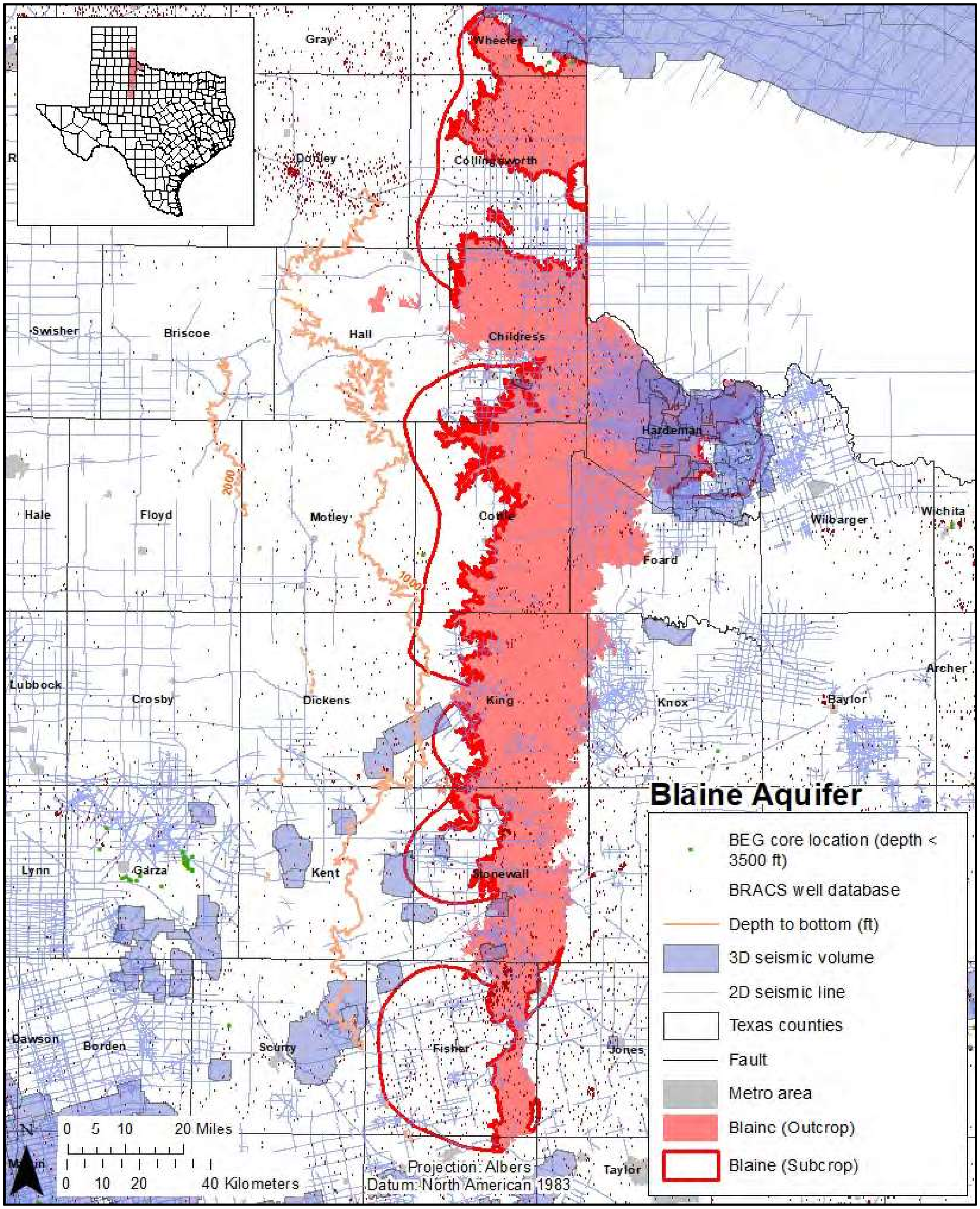
The Woodbine Aquifer is a minor aquifer in 17 counties in north and northeast Texas (Figure 6-47). It is composed of interbedded sandstones, and clays. Thickness ranges up to 600 feet. Bottom depths range from shallow to over 4,000 feet. The aquifer generally ranges from fresh to moderately saline with depth. Water use is mainly for municipal, industrial, domestic, livestock, and small irrigation supplies.

Seismic data coverage is limited: 5.9 percent for three-dimensional data and 46.7 percent for two-dimensional data; most three-dimensional data is at the shallow western edge of Woodbine outcrop. The presence of the Dallas-Fort Worth metro area creates a major lack of seismic data. The seismic velocities in this part of the state are moderate to fast. Barriers to effective seismic imaging include lack of depth at outcrop, fast seismic speeds, and near surface effects. Recommendations to combat these issues include interpolation and statics adjustments. The benefits of seismic data in this aquifer include identification of faulting, tight control where there is little well data, rock composition analysis, and constraints of aquifer extent and thickness; three-dimensional data would also allow imaging of geobodies. The Woodbine would be a good candidate for seismic geomorphological analysis to identify geobodies and channels that are zones of interconnected permeability, if three-dimensional data were acquired.

Yegua-Jackson

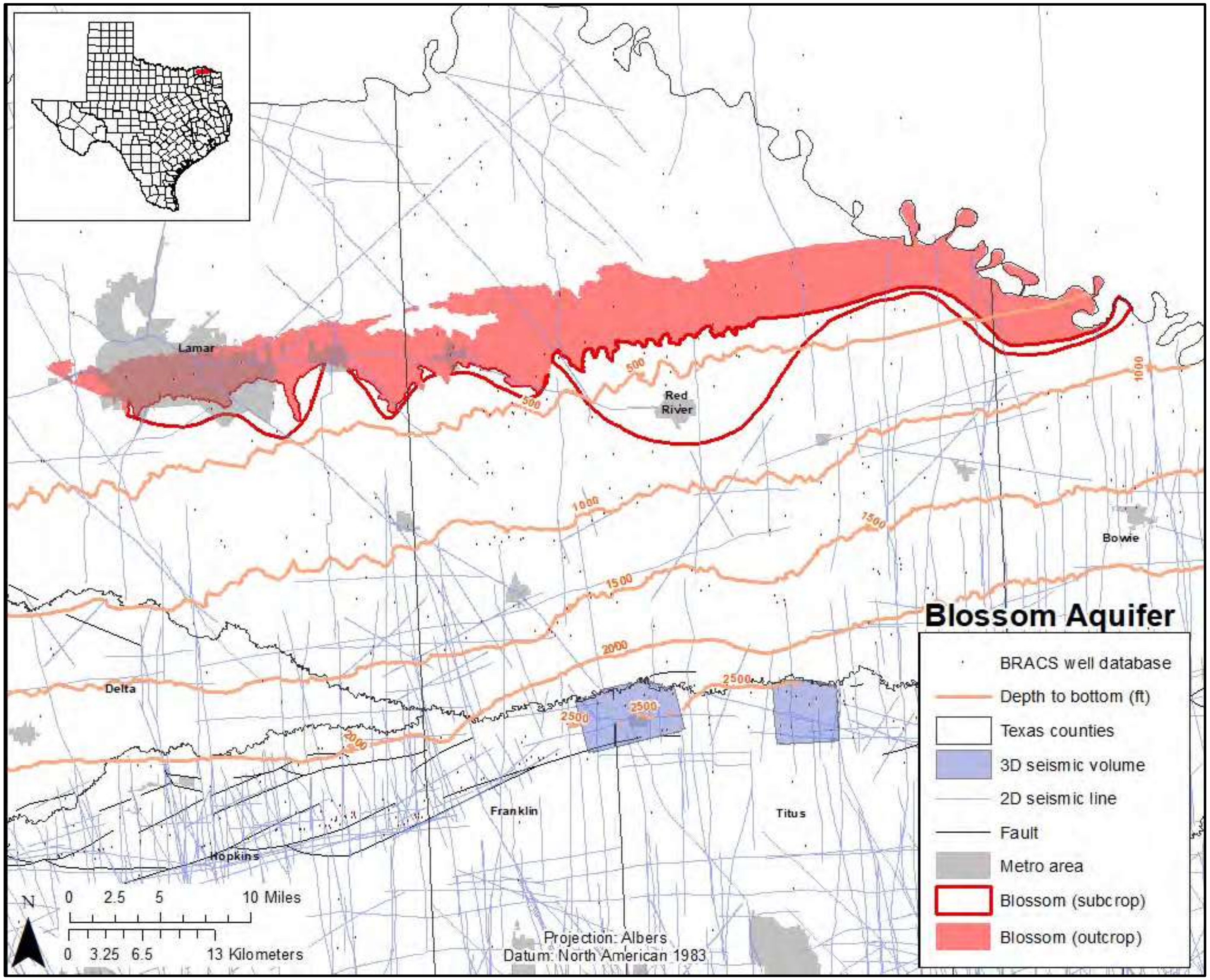
The Yegua-Jackson Aquifer is a minor aquifer in 34 counties of south and southeast Texas (Figures 6-48 and 6-49). It is composed of interbedded sand, silt, and clay. Thickness ranges greatly but freshwater thickness averages 170 feet. Bottom depths range from shallow to over 5,000 feet. The aquifer is generally fresh to slightly saline. Water use is mainly domestic and livestock, but also for municipal, industrial, and irrigation.

Seismic data coverage is abundant: 42.4 percent for three-dimensional data from vendors and 93.7 percent for two-dimensional data. The seismic velocities in this part of the state are medium to low. Barriers to effective seismic imaging include lack of depth in outcrop, and near surface effects. Recommendations to combat these issues include interpolation and statics adjustments. The benefits of seismic data in this aquifer include imaging channels, imaging geobodies, identification of faulting, tight control where there is little well data, and constraints of aquifer extent and thickness. The Yegua-Jackson is a very good candidate for seismic characterization, given the simple geology, abundance of well control, and necessity to image geobodies.



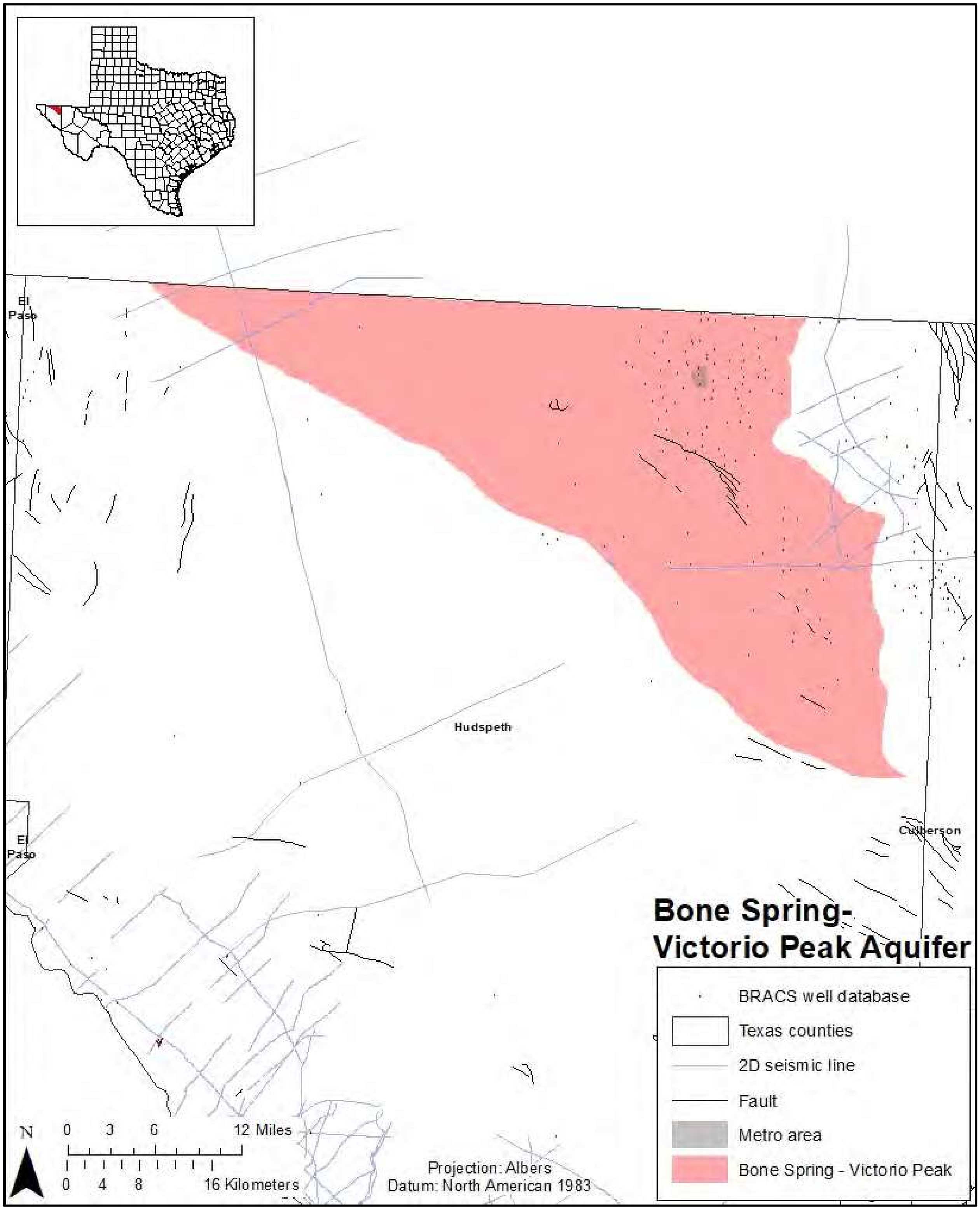
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-5. Seismic coverage for the Blaine Aquifer. Depth contours from Finch and others (2016). Contour interval is 1,000 feet.



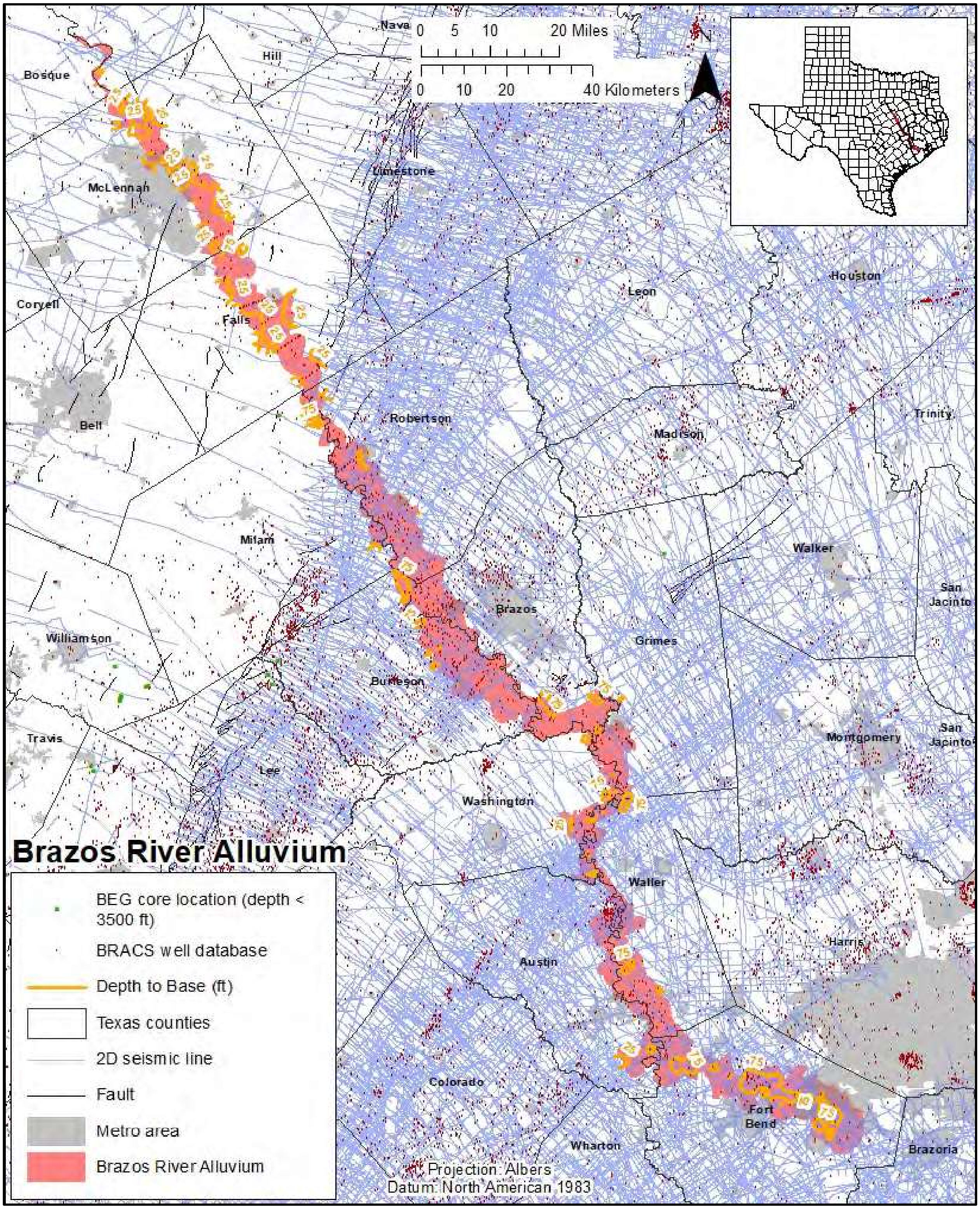
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, ft = feet

Figure 6-6. **Seismic coverage for the Blossom Aquifer. Depth contours from Beach and Laughlin (2017). Contour interval is 500 feet.**



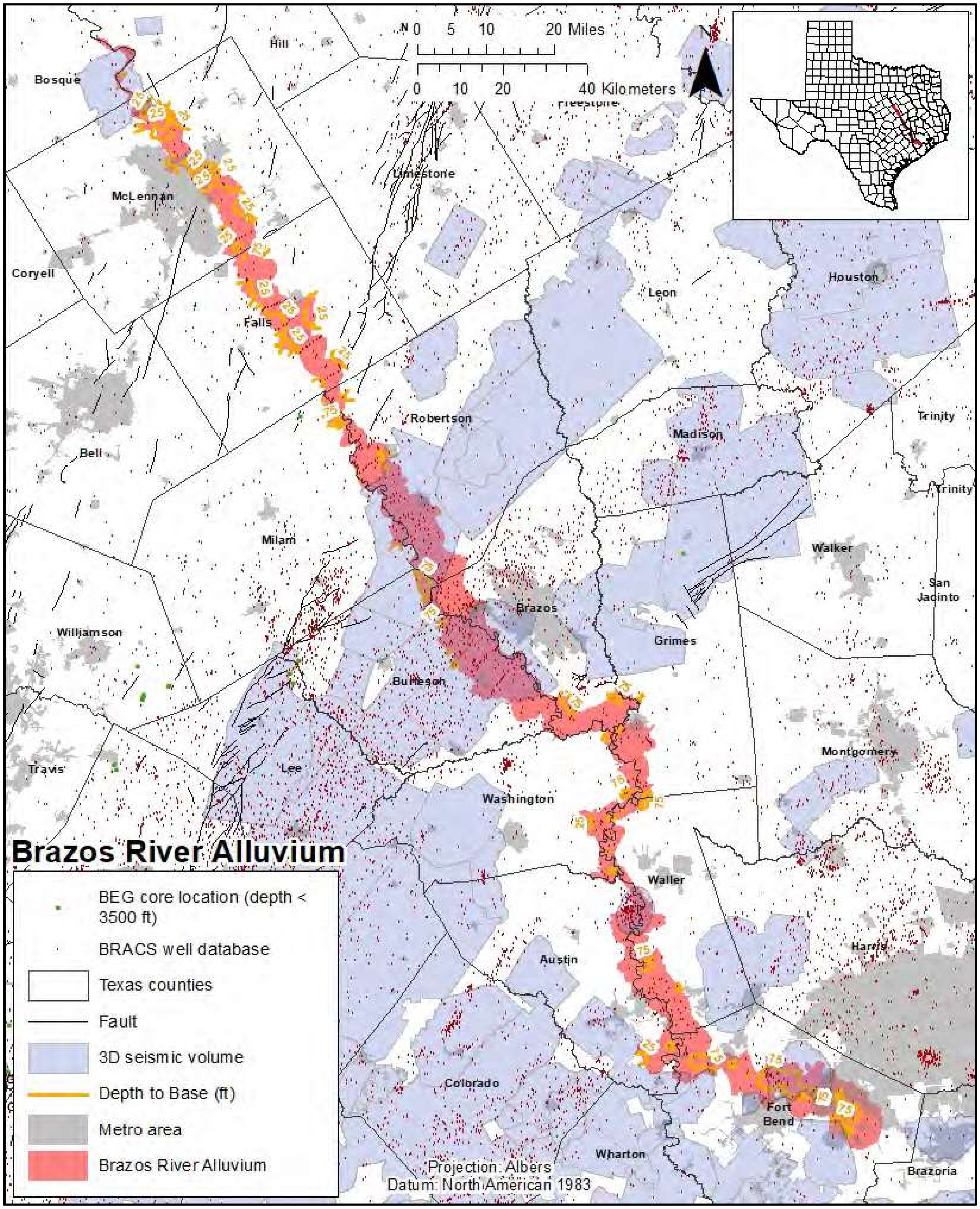
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System

Figure 6-7. **Seismic coverage for the Bone Spring-Victorio Peak Aquifer.**



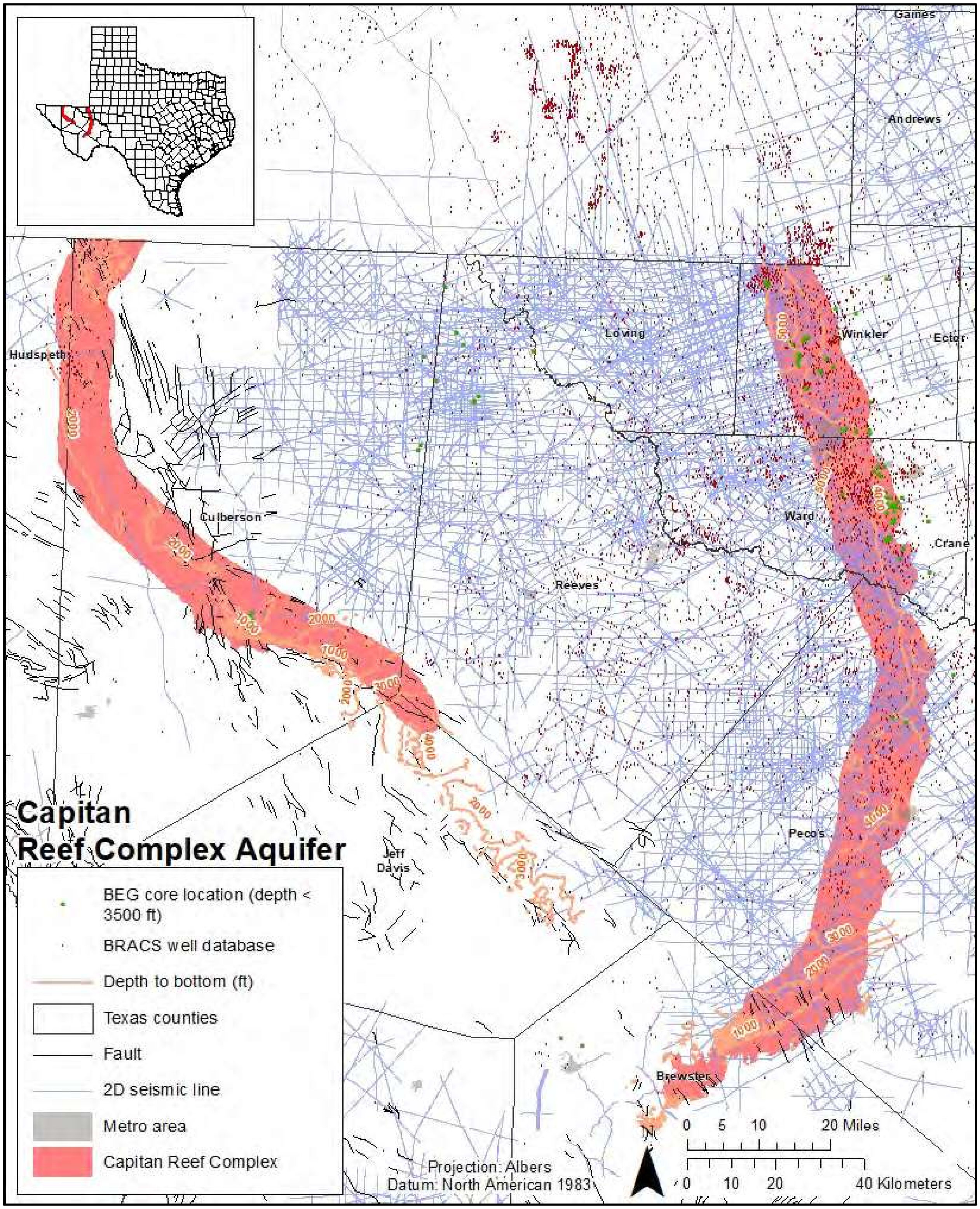
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-8. **Seismic two-dimensional coverage for the Brazos River Alluvium Aquifer. Depth contours from Ewing and Jigmond (2016). Contour interval is 50 feet.**



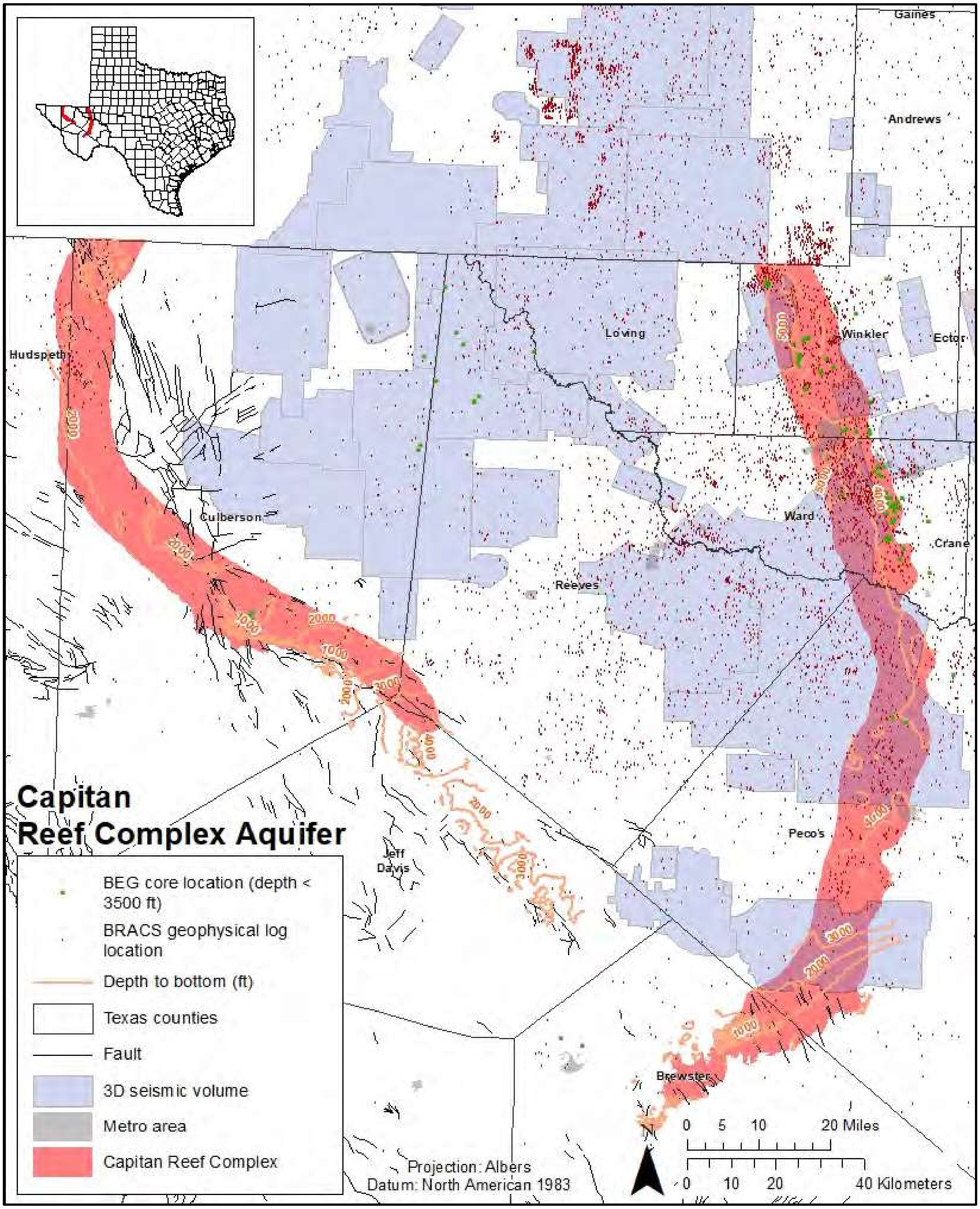
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-9. **Seismic three-dimensional coverage for the Brazos River Alluvium Aquifer. Depth contours from Ewing and Jigmond (2016). Contour interval is 50 feet.**



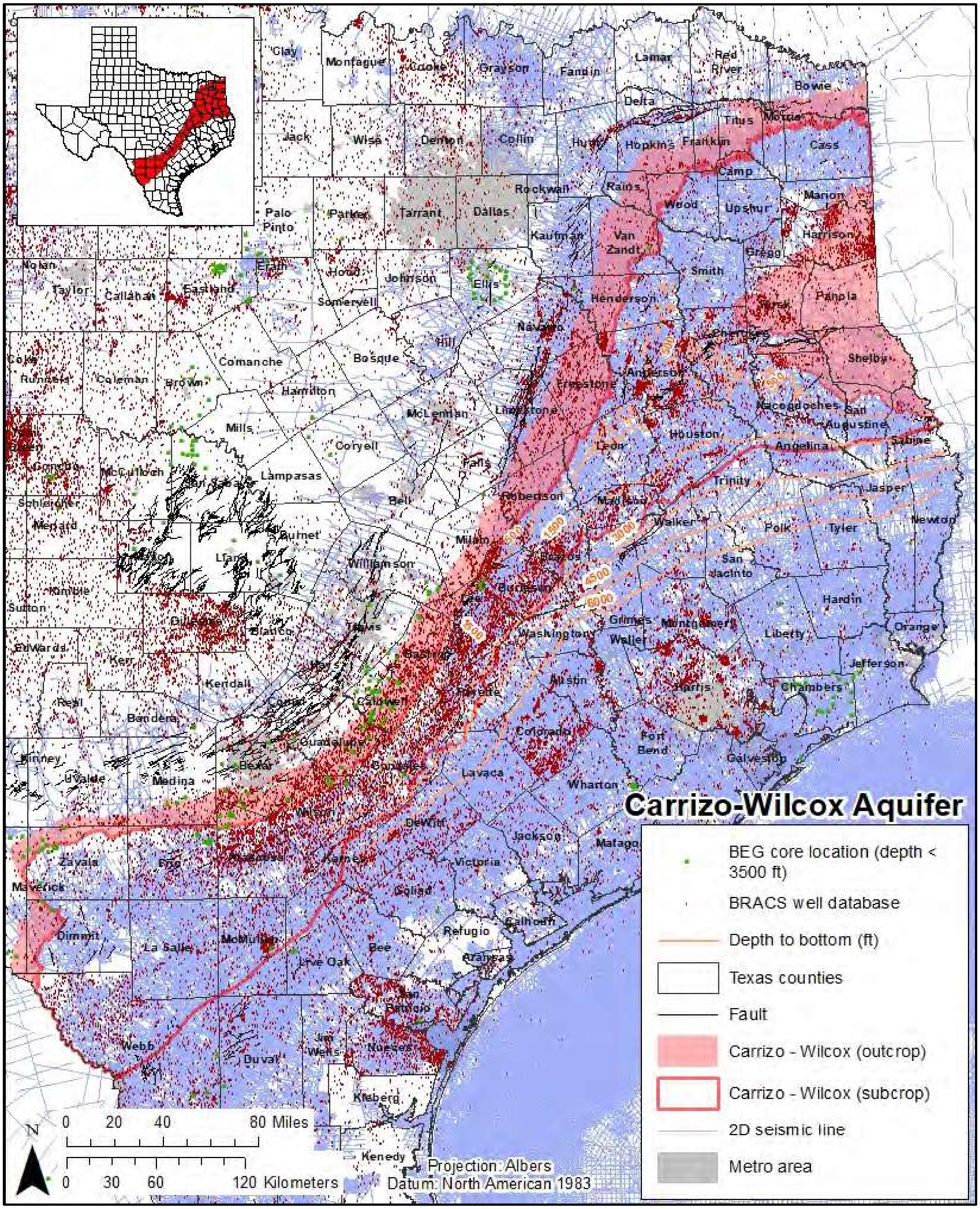
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-10. Seismic two-dimensional coverage for the Capitan Reef Complex Aquifer. Depth contours from Jones (2016). Contour interval is 1,000 feet.



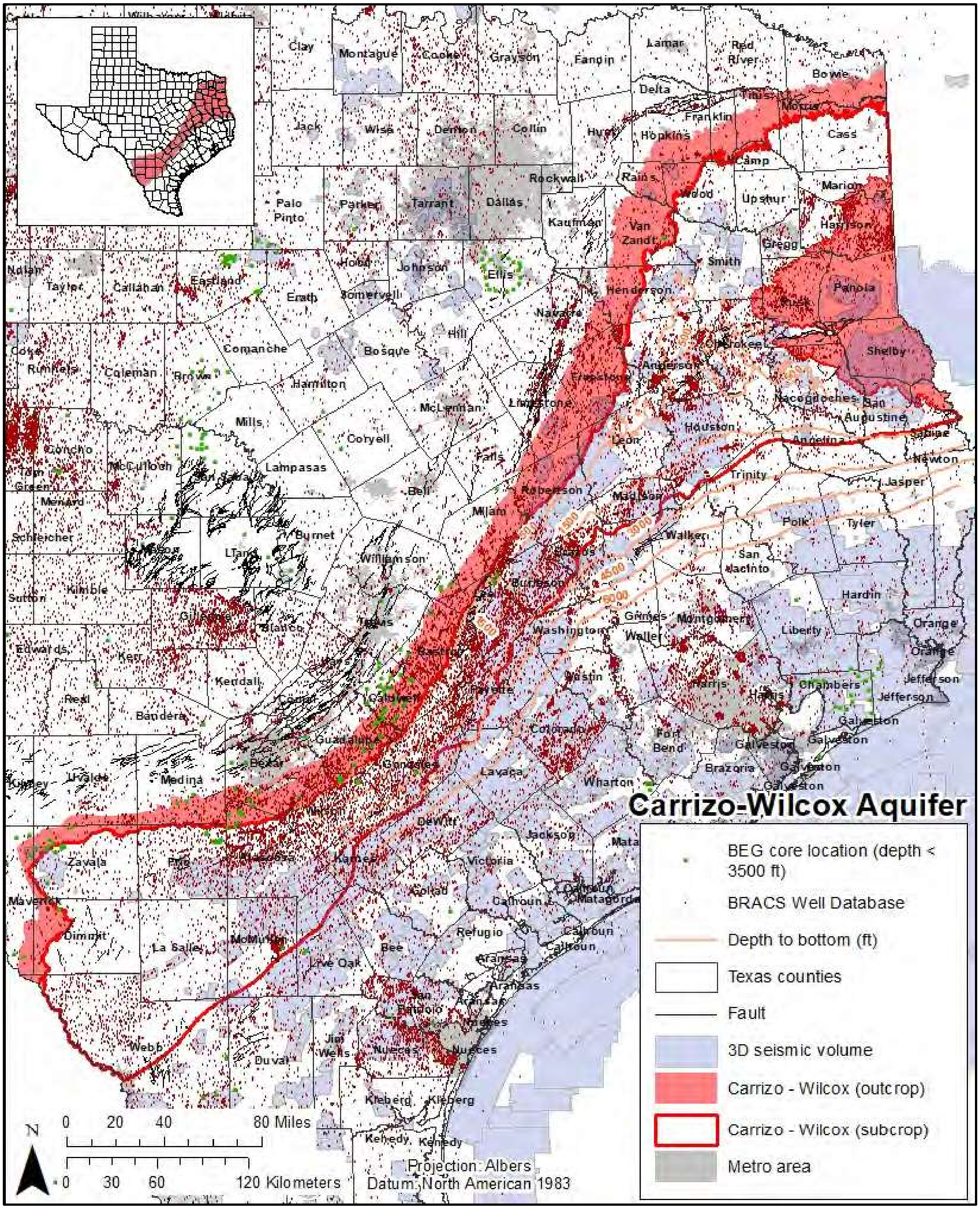
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-11. **Seismic three-dimensional coverage for the Capitan Reef Complex Aquifer. Depth contours from Jones (2016). Contour interval is 1,000 feet.**



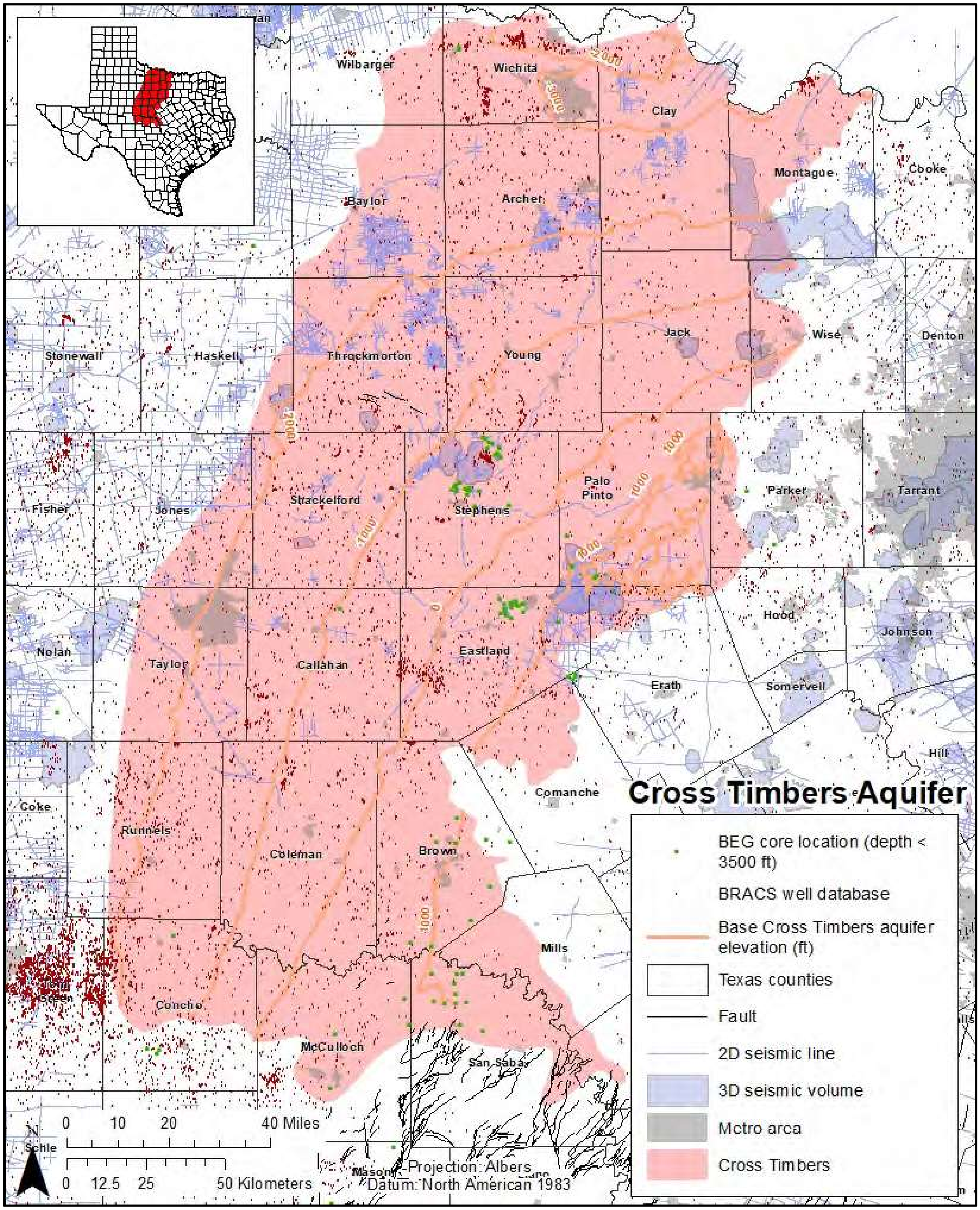
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-12. **Seismic two-dimensional coverage for the Carrizo-Wilcox Aquifer. Contours from Young and others (2018). Contour interval is 1,500 feet with an additional 500 foot contour.**



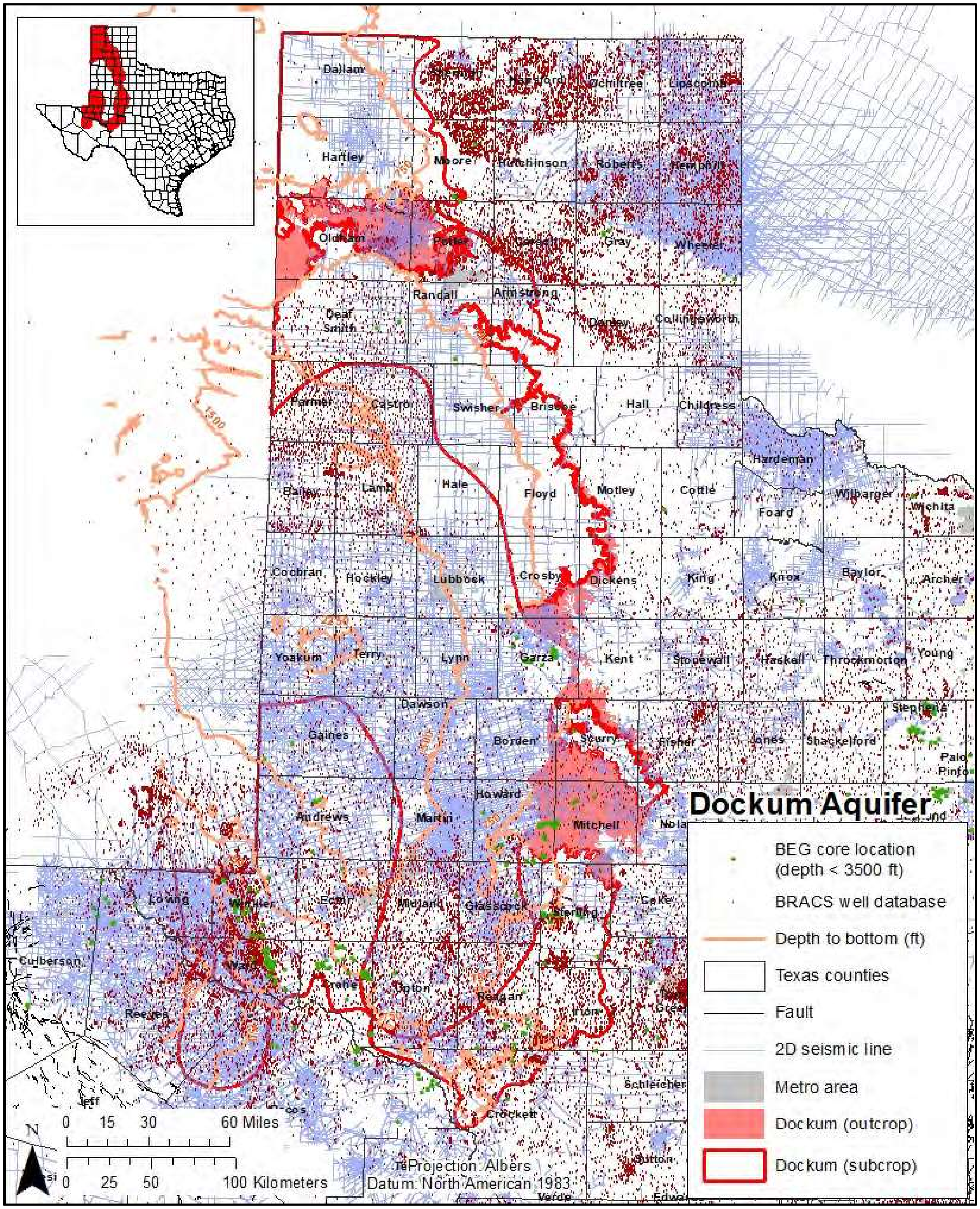
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-13. **Seismic three-dimensional coverage for the Carrizo-Wilcox Aquifer. Contours from Young and others (2018). Contour interval is 1,500 feet with an additional 500 foot contour.**



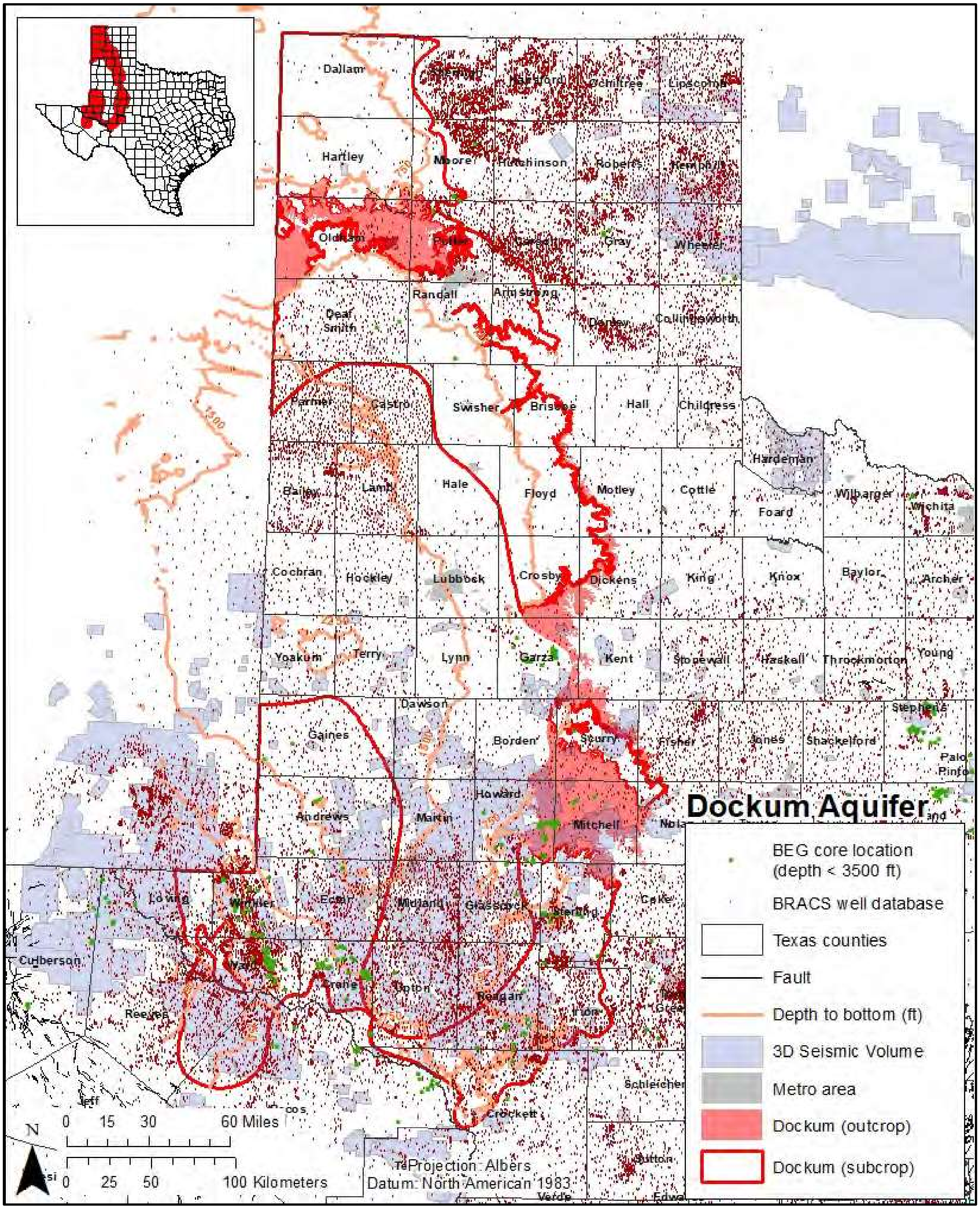
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-14. **Seismic coverage for the Cross Timbers Aquifer. Contour interval is 1,000 feet.**



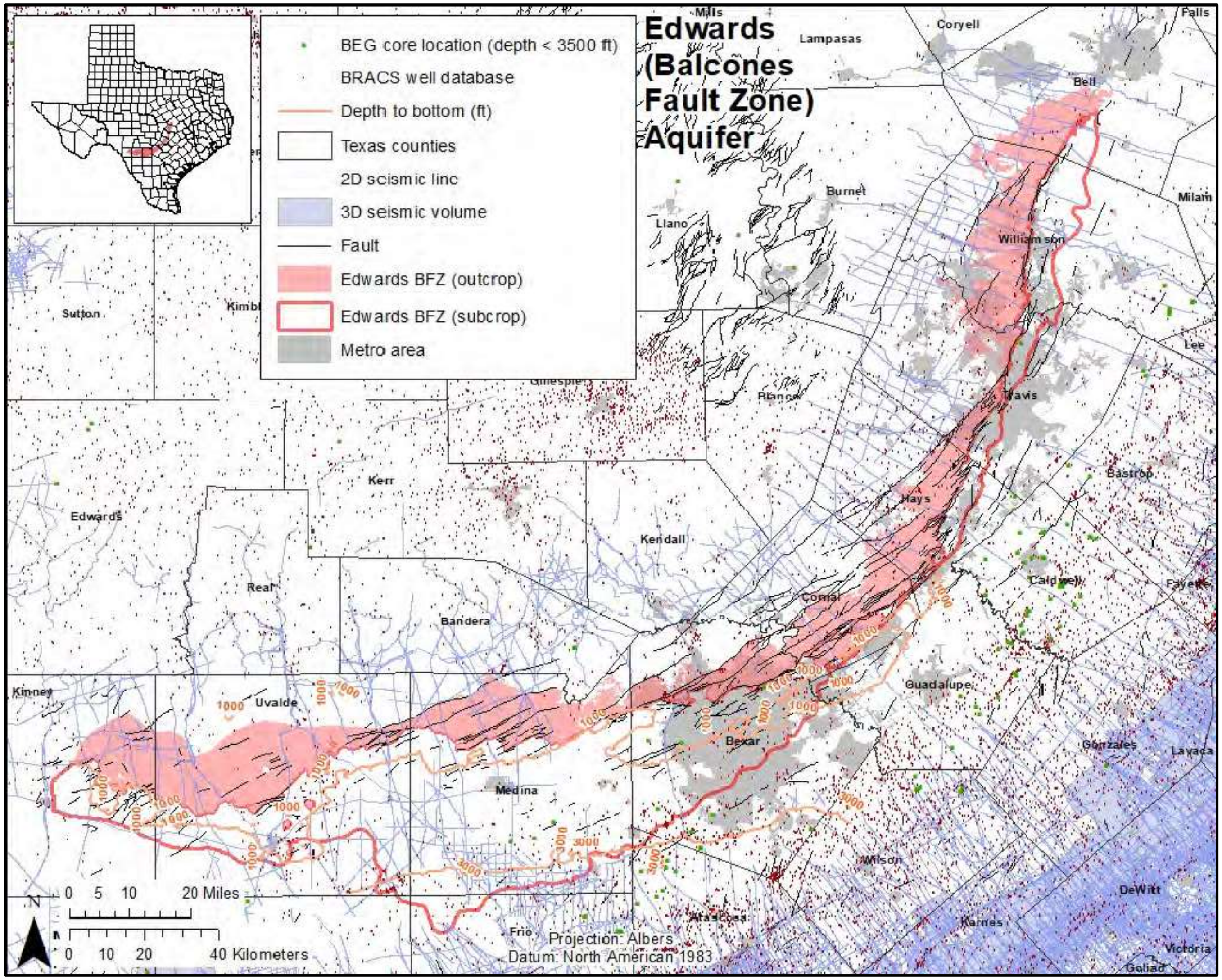
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-15. **Seismic two-dimensional coverage for the Dockum Aquifer. Depth contours from Deeds and others (2015). Contour interval is 750 feet.**



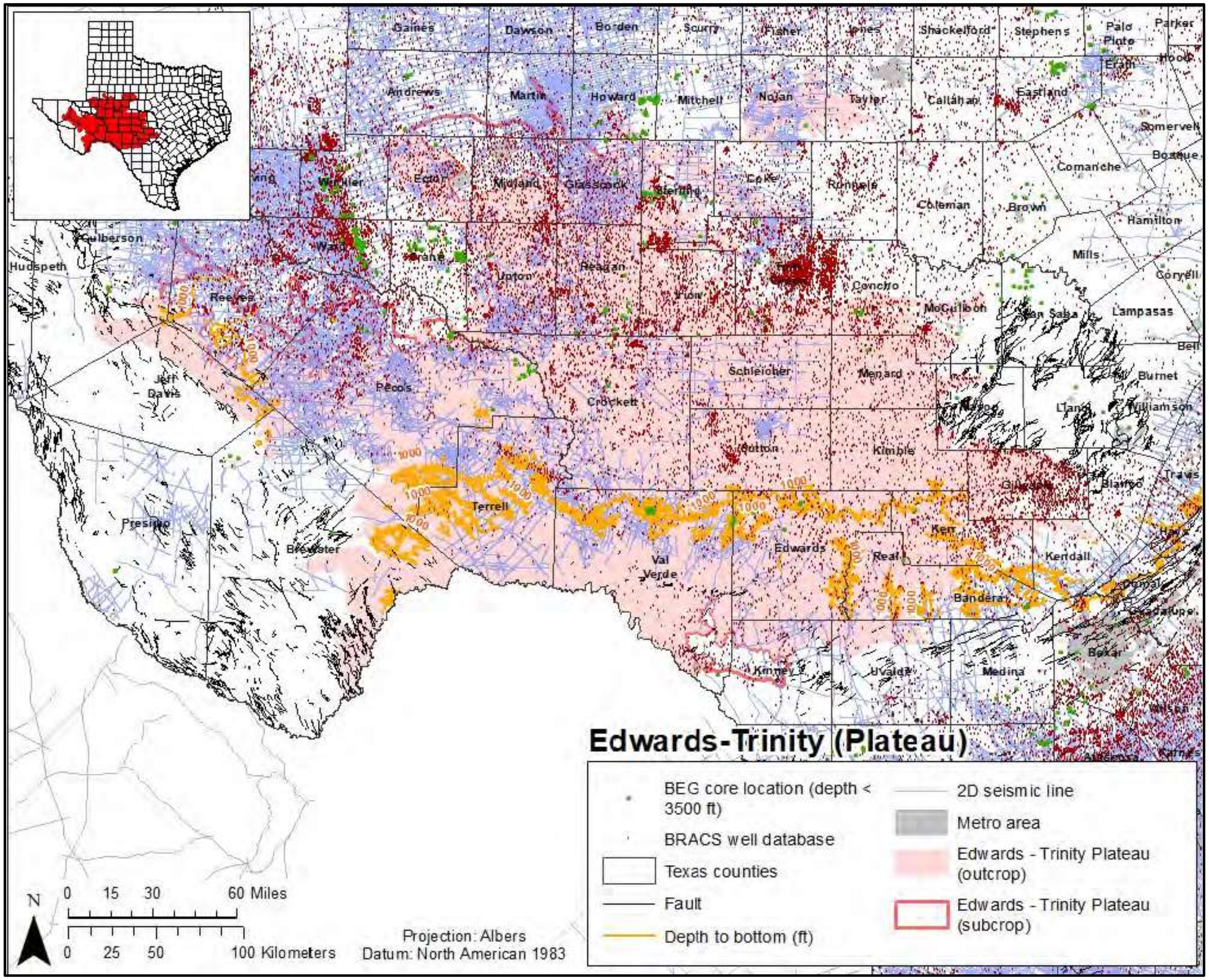
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-16. **Seismic three-dimensional coverage for the Dockum Aquifer. Depth contours from Deeds and others (2015). Contour interval is 750 feet.**



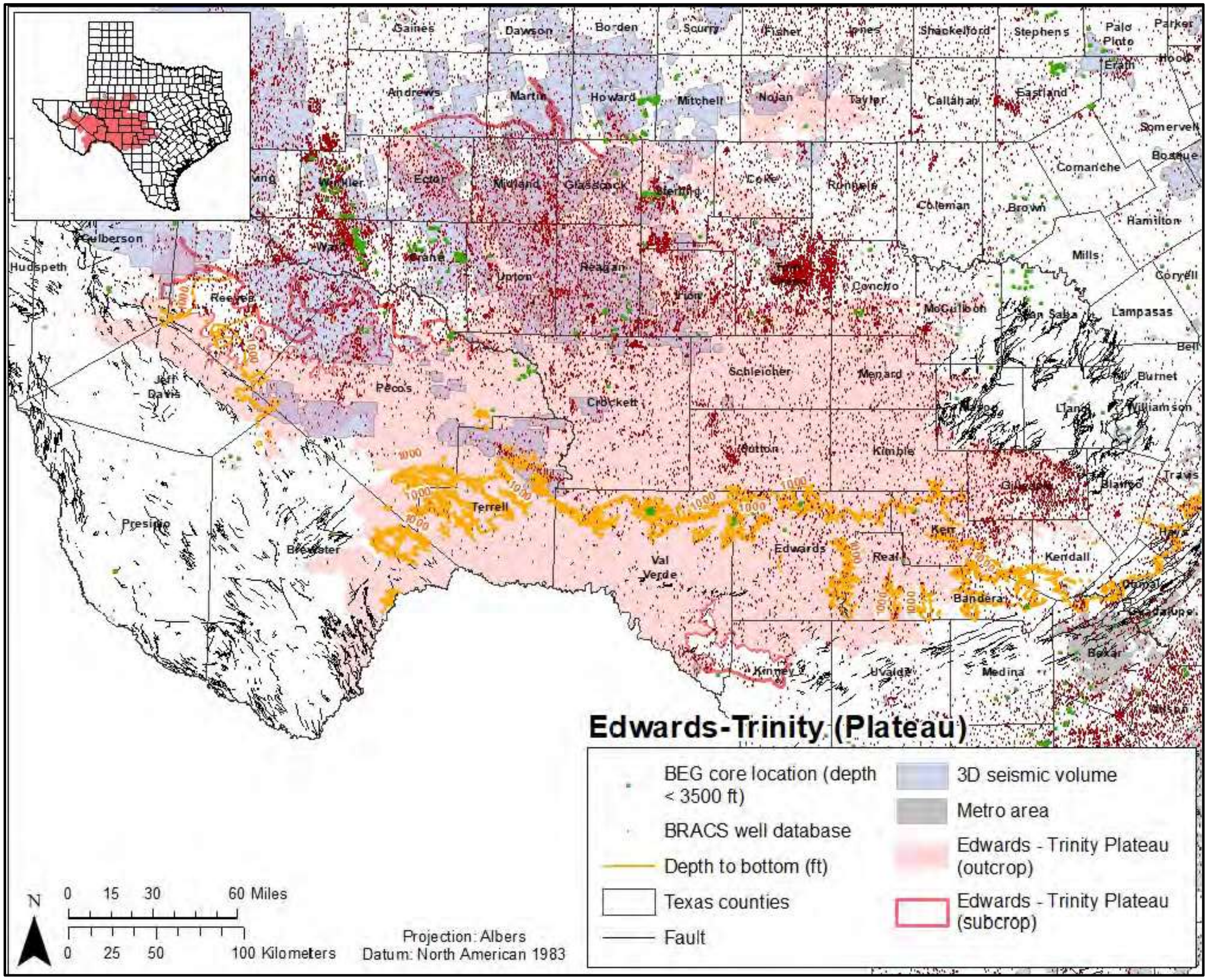
Note: 2D = two-dimensional, 3D = three-dimensional, BFZ = Balcones Fault Zone, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-17. Seismic coverage for the Edwards (Balcones Fault Zone) Aquifer. Depth contours from Lindgren and others (2004). Contour interval is 2000 feet.



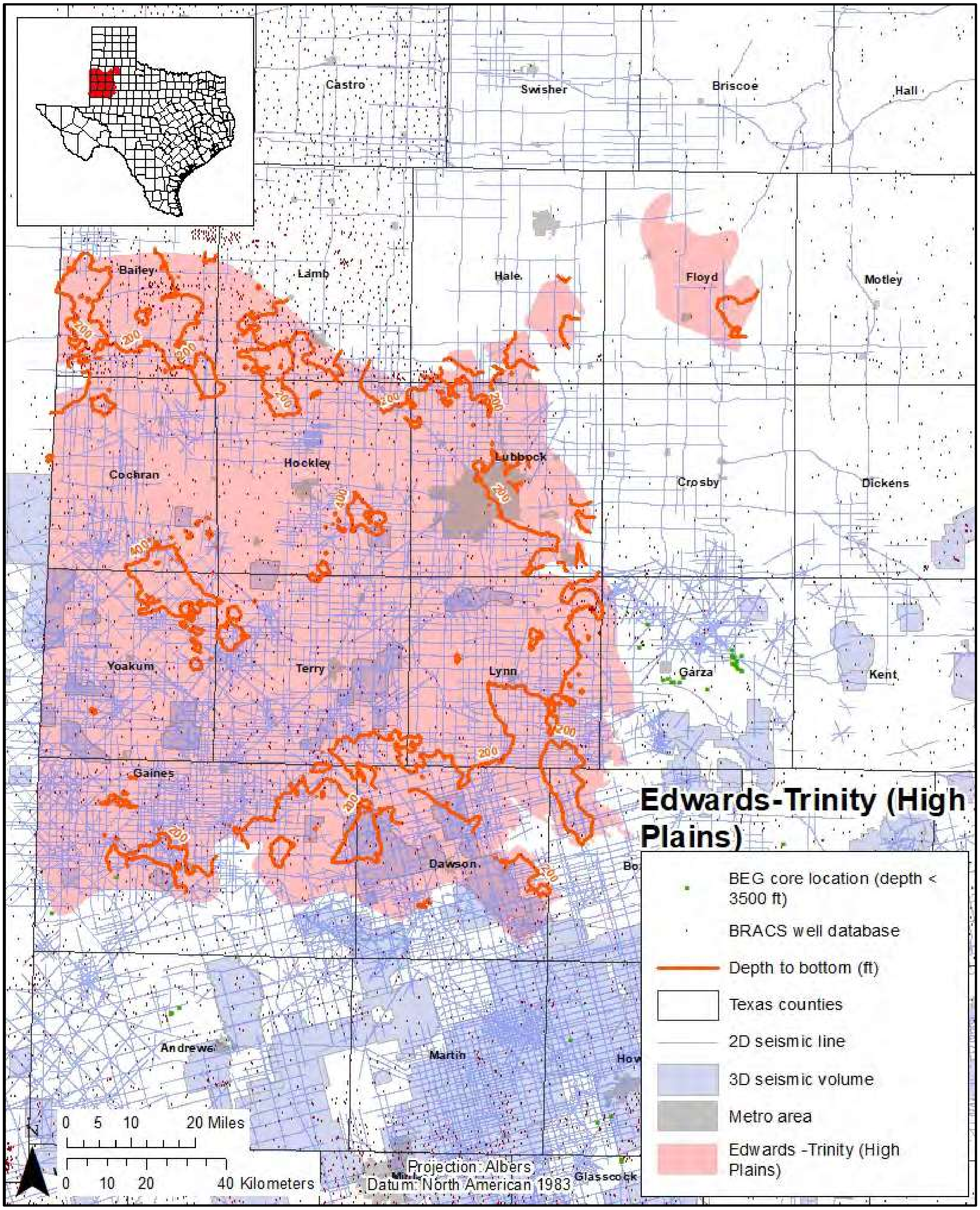
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-18. **Seismic two-dimensions coverage for the Edwards-Trinity (Plateau). Depth contours from Texas Water Development Board (2021). Contour labeled is 1,000 feet. Structure deepens to the South and is shallower to the North.**



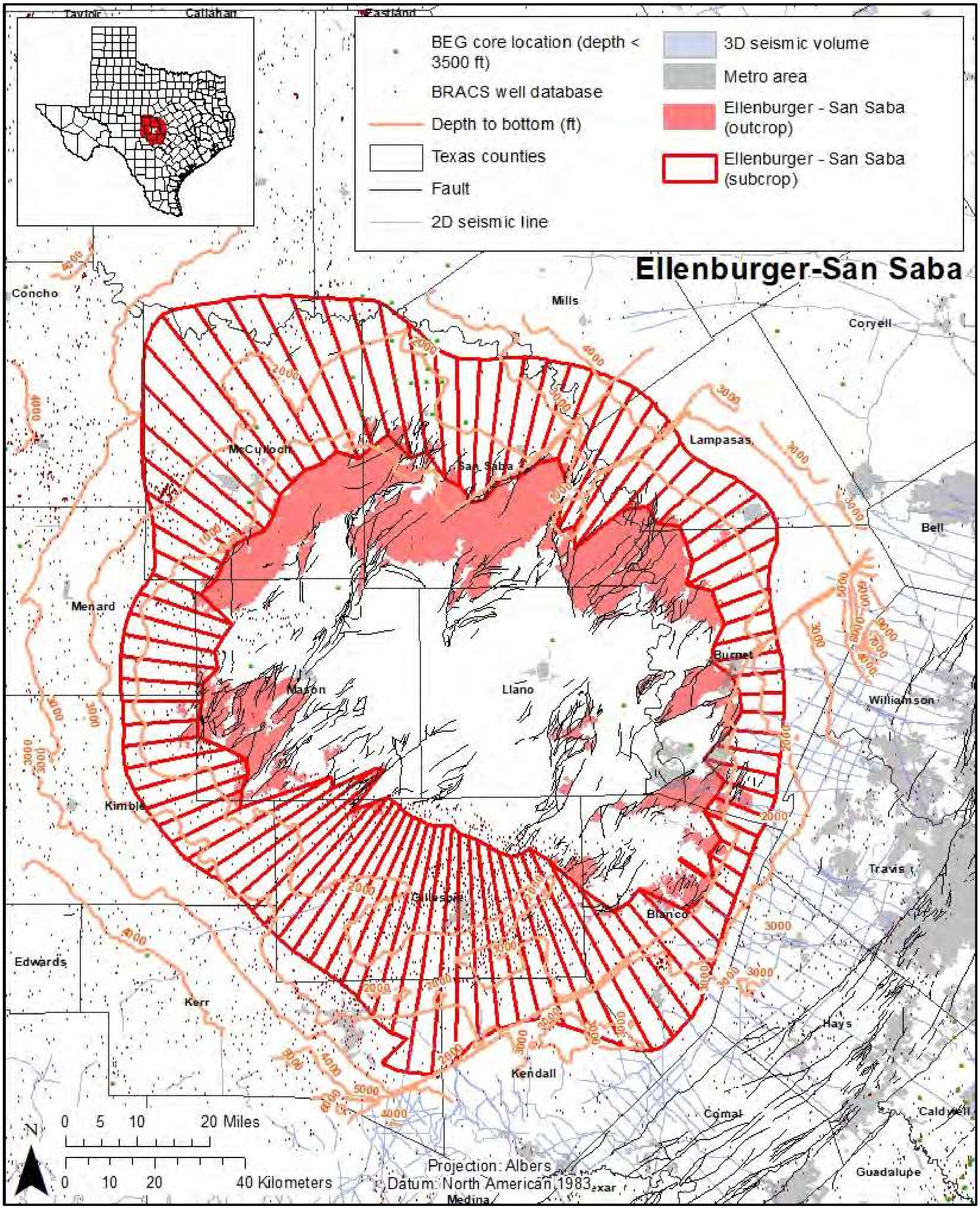
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-19. **Seismic three-dimensions coverage for the Edwards-Trinity (Plateau). Depth contours from TWDB (2021). Contour labeled is 1000 feet. Structure deepens to the South and is shallower to the North.**



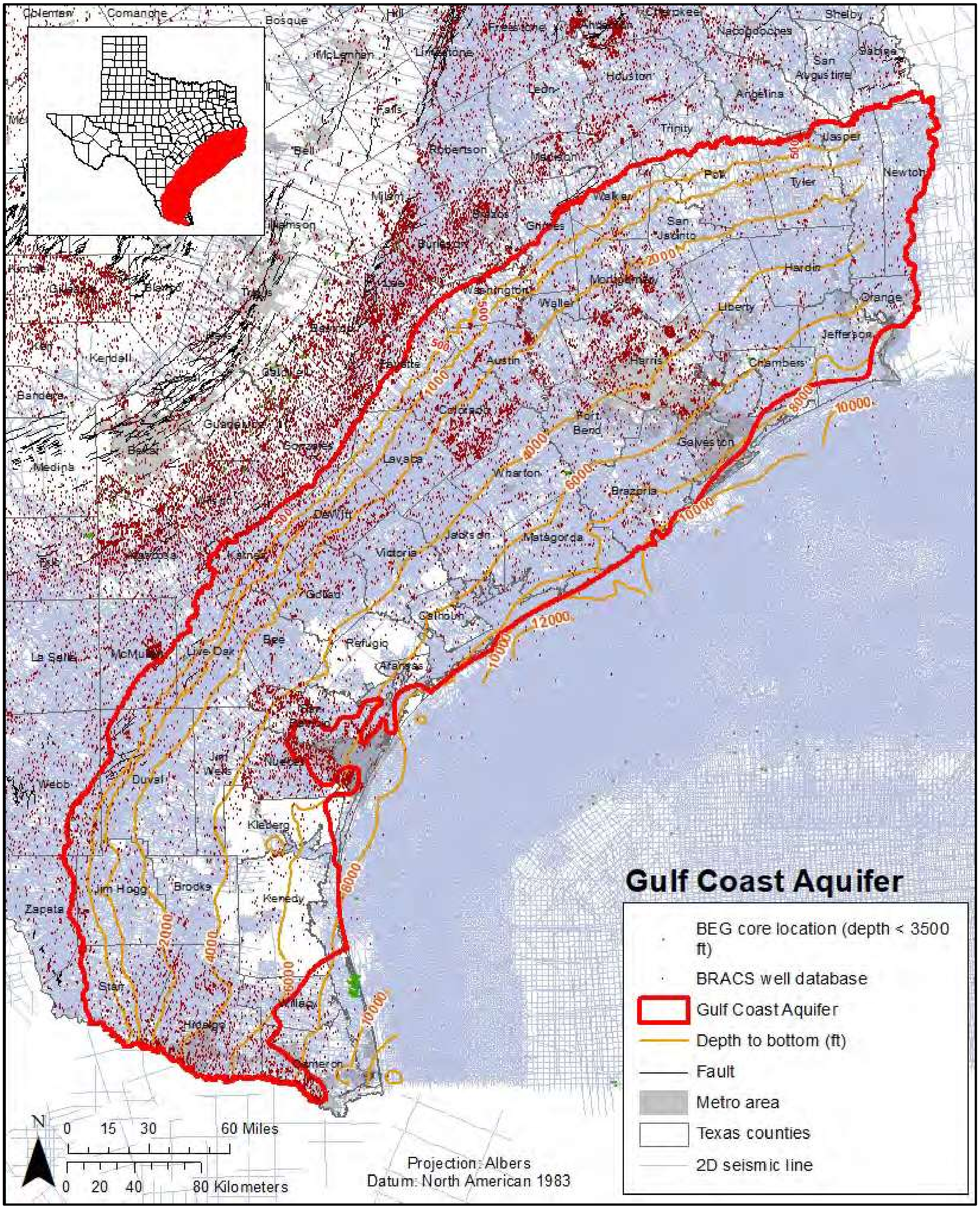
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-20. **Seismic coverage for the Edwards-Trinity (High Plains) Aquifer. Depth contours from Deeds and others (2015). Contour interval is 200 feet.**



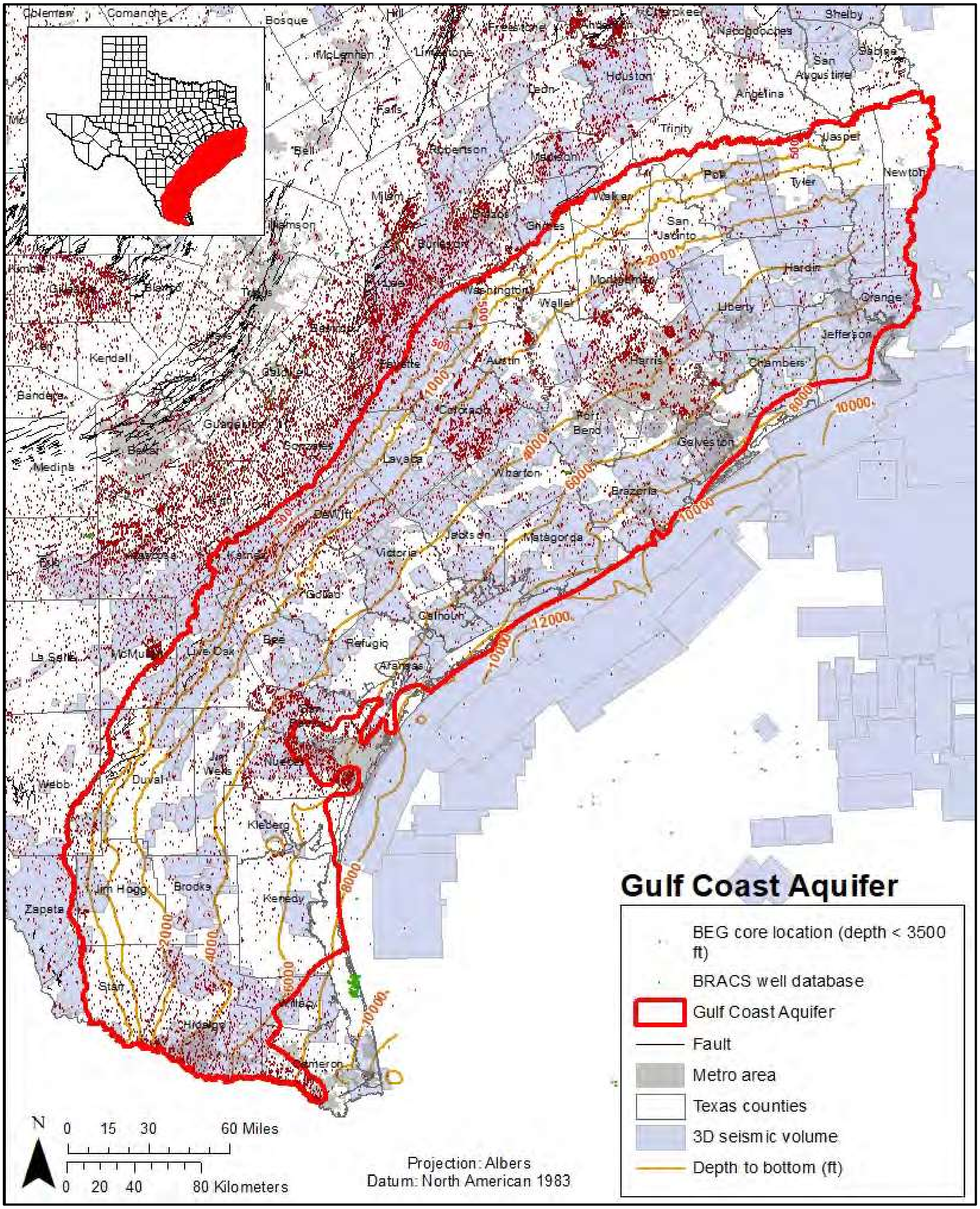
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-21. **Seismic coverage for the Ellenburger-San Saba Aquifer. Depth contours from Shi and others (2016). Contour interval is 1,000 feet.**



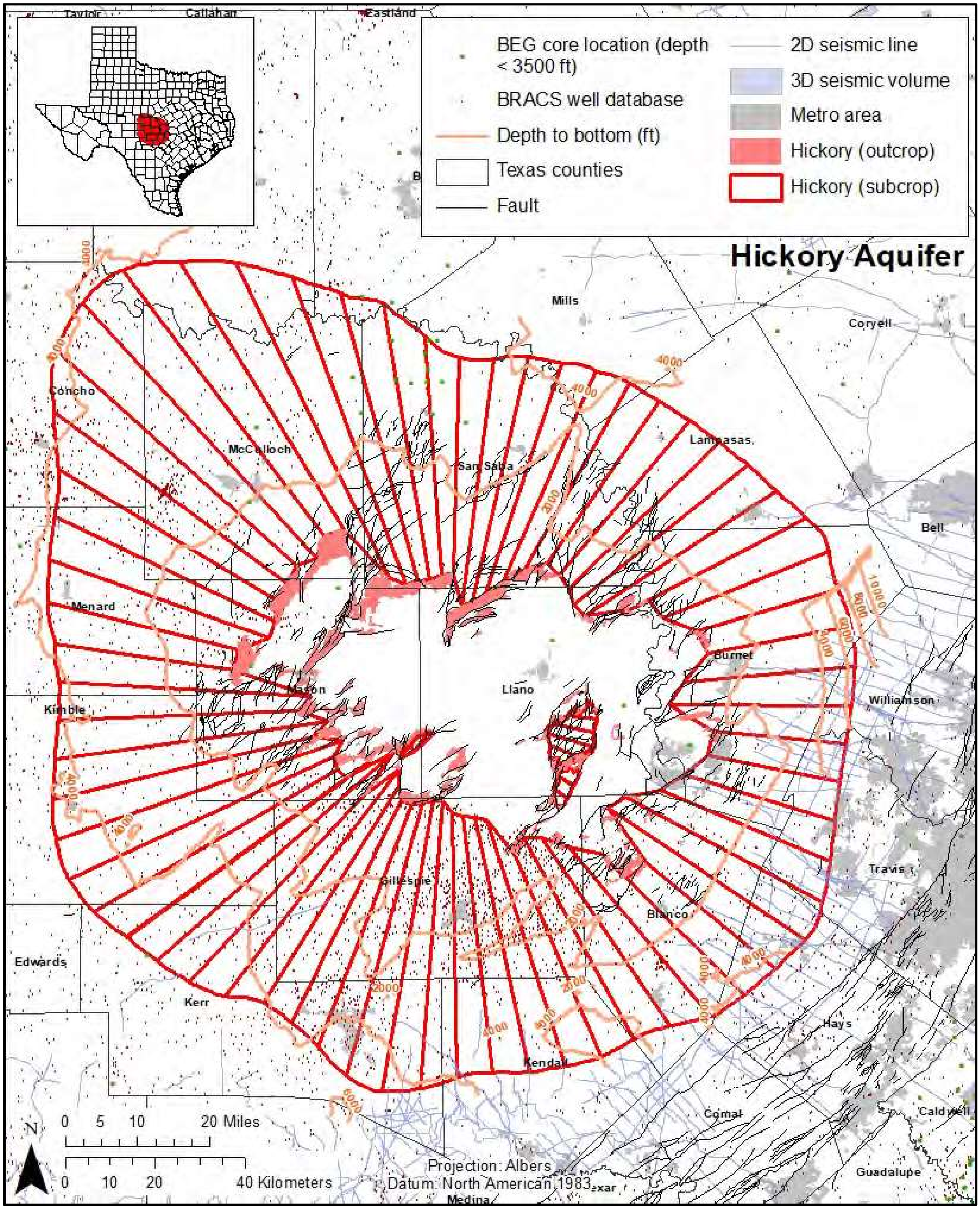
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-22. **Seismic two-dimensional coverage for the Gulf Coast Aquifer. Contours from Young and others (2016). Contour interval is 2,000 feet with an additional 500 foot contour.**



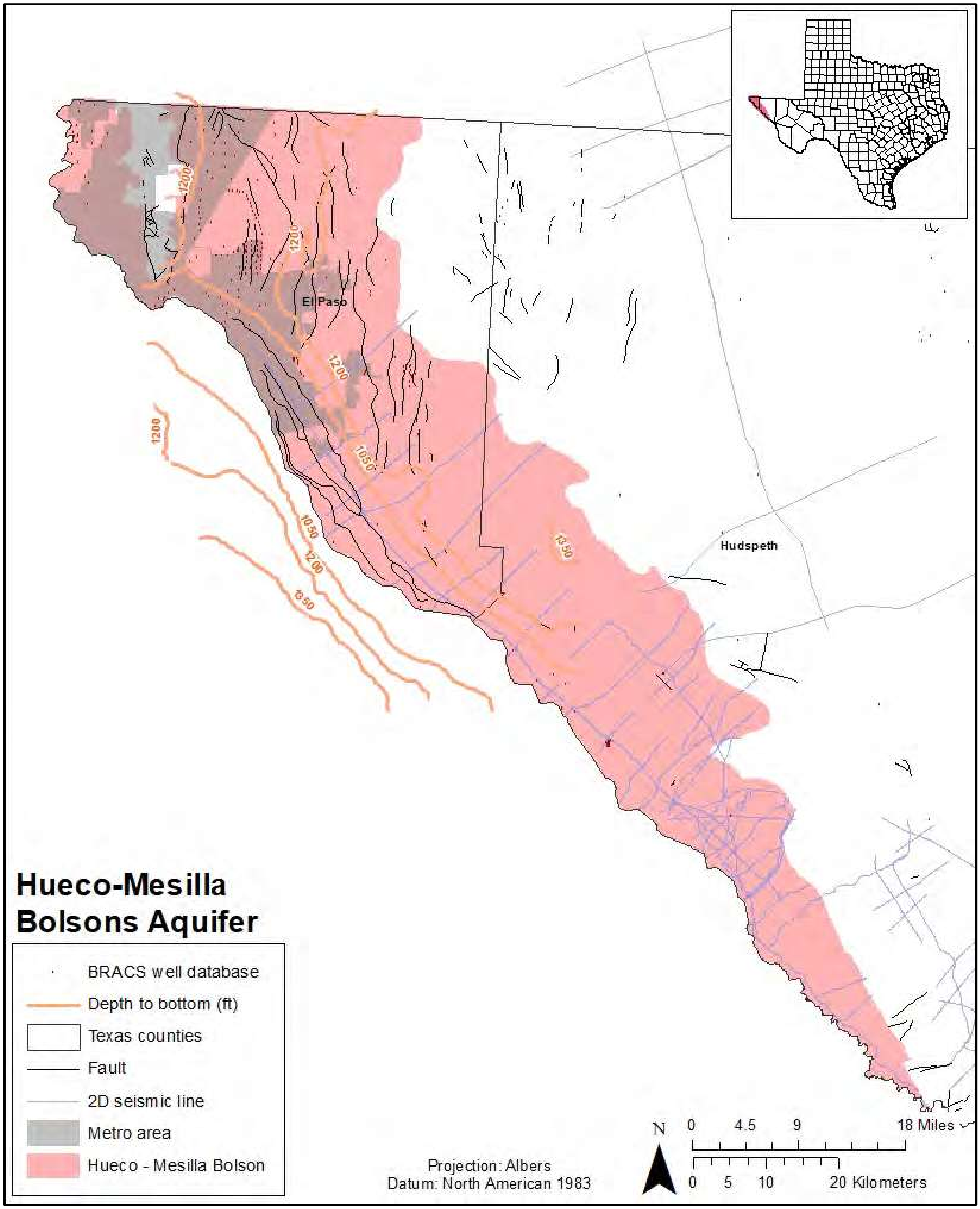
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-23. **Seismic three-dimensional coverage for the Gulf Coast Aquifer. Contours from Young and others (2016). Contour interval is 2,000 feet with an additional 500 foot contour.**



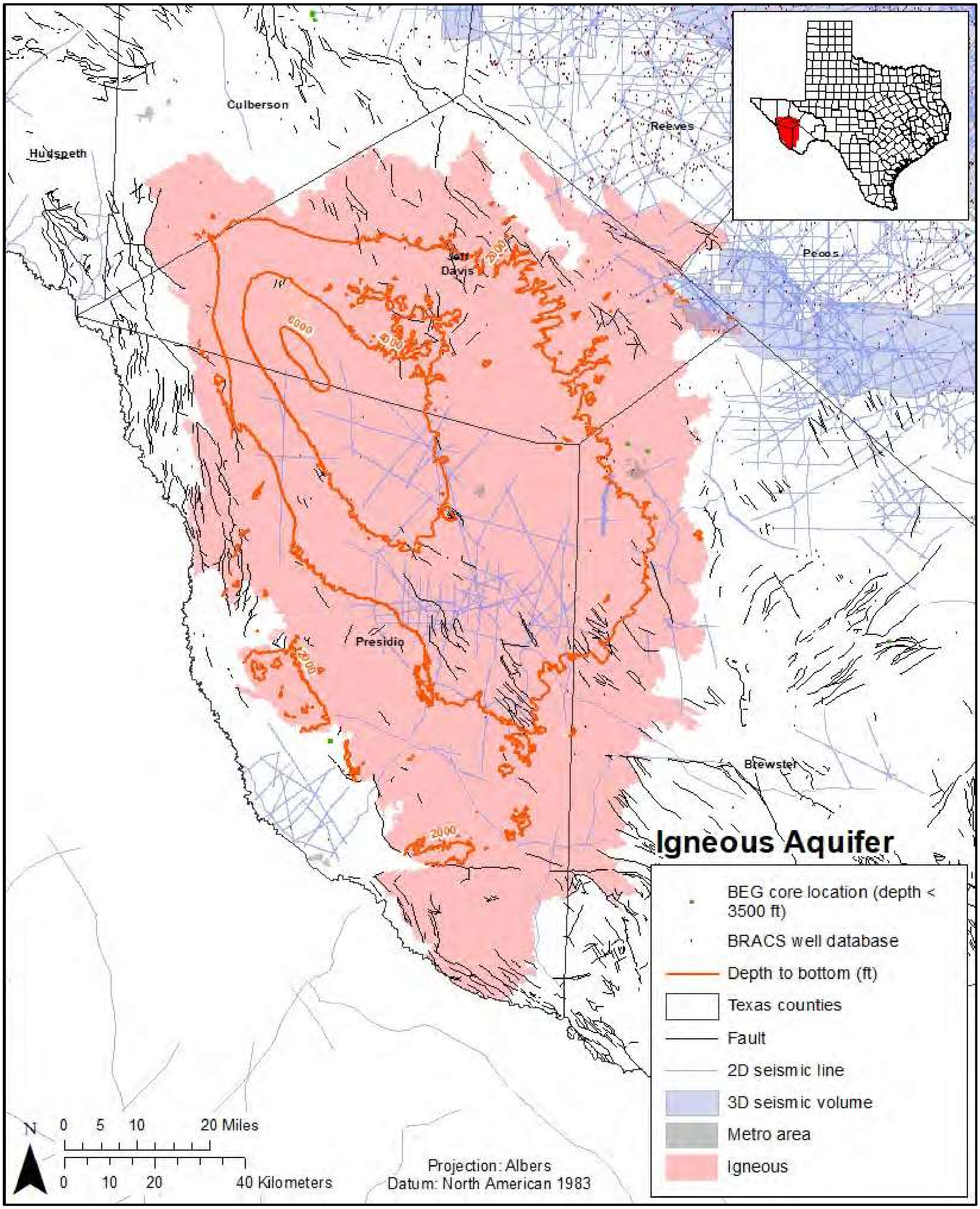
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-24. Seismic coverage for the Hickory Aquifer. Depth contours from Shi and others (2016). Contour interval is 2,000 feet.



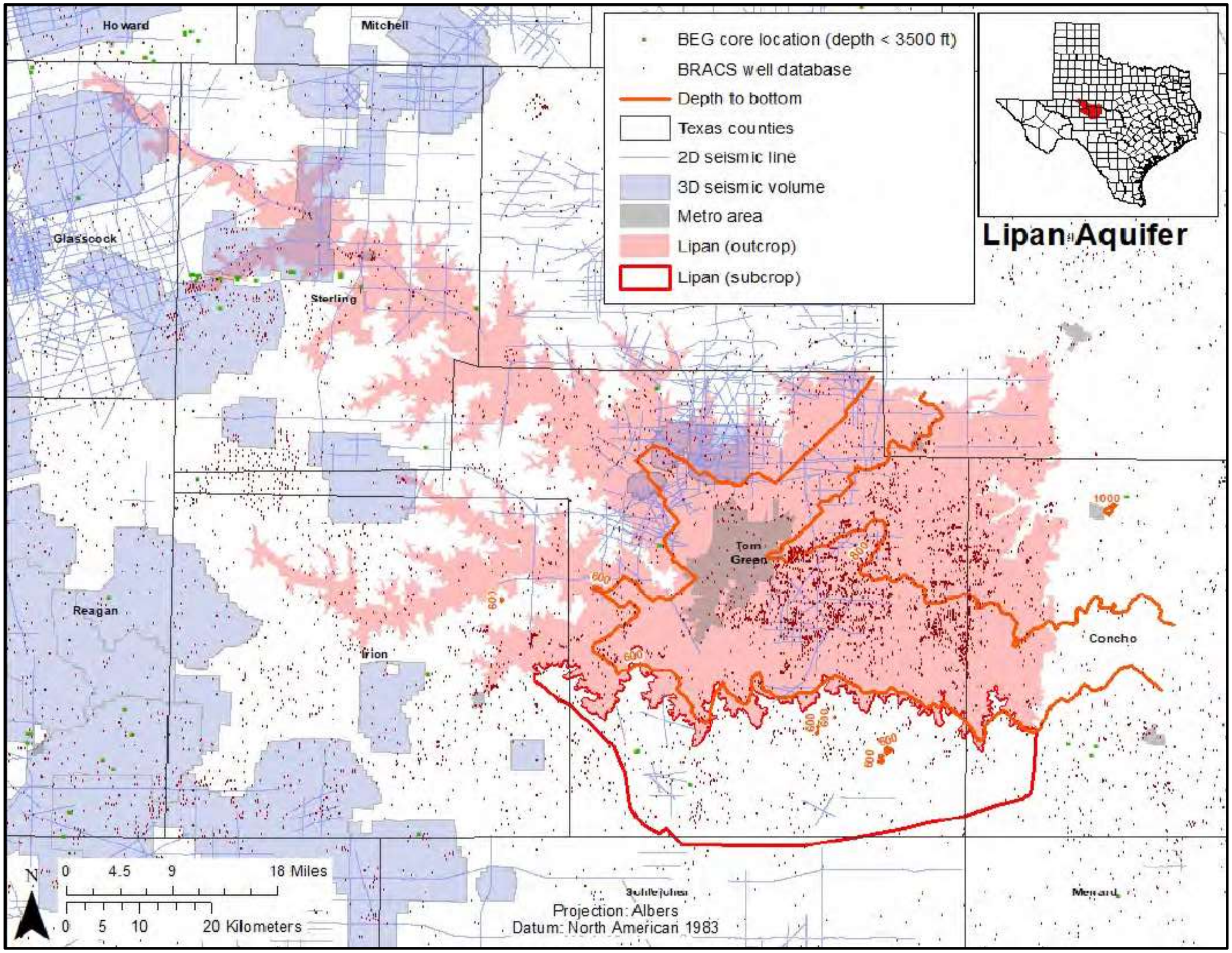
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, ft = feet

Figure 6-25. **Seismic coverage for the Hueco-Mesilla Bolsons Aquifer. Depth contours from Heywood and Yager (2003). Contour interval is 150 feet.**



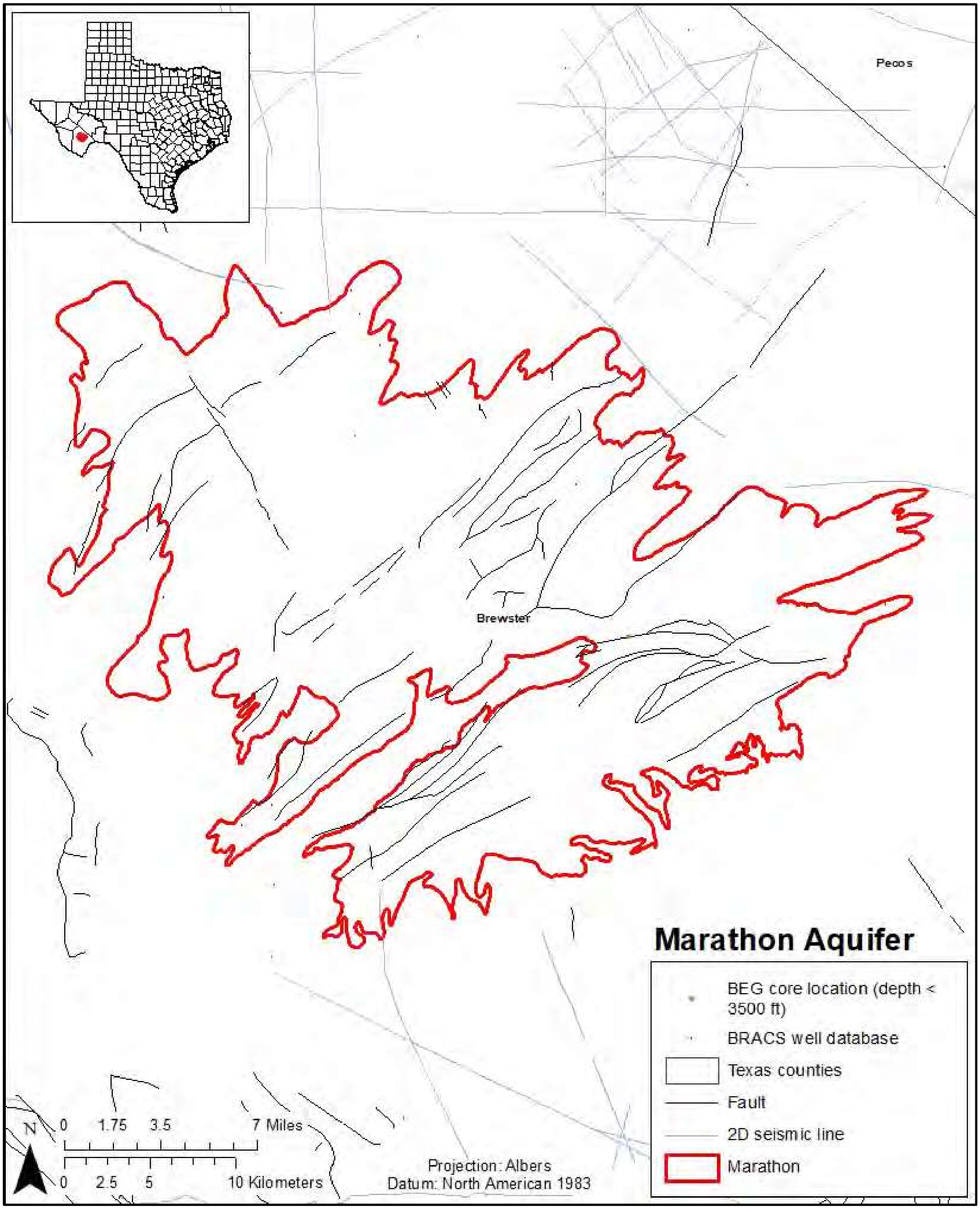
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-26. **Seismic coverage for the Igneous Aquifer. Depth contours from Beach and others (2004). Contour interval is 2,000 feet.**



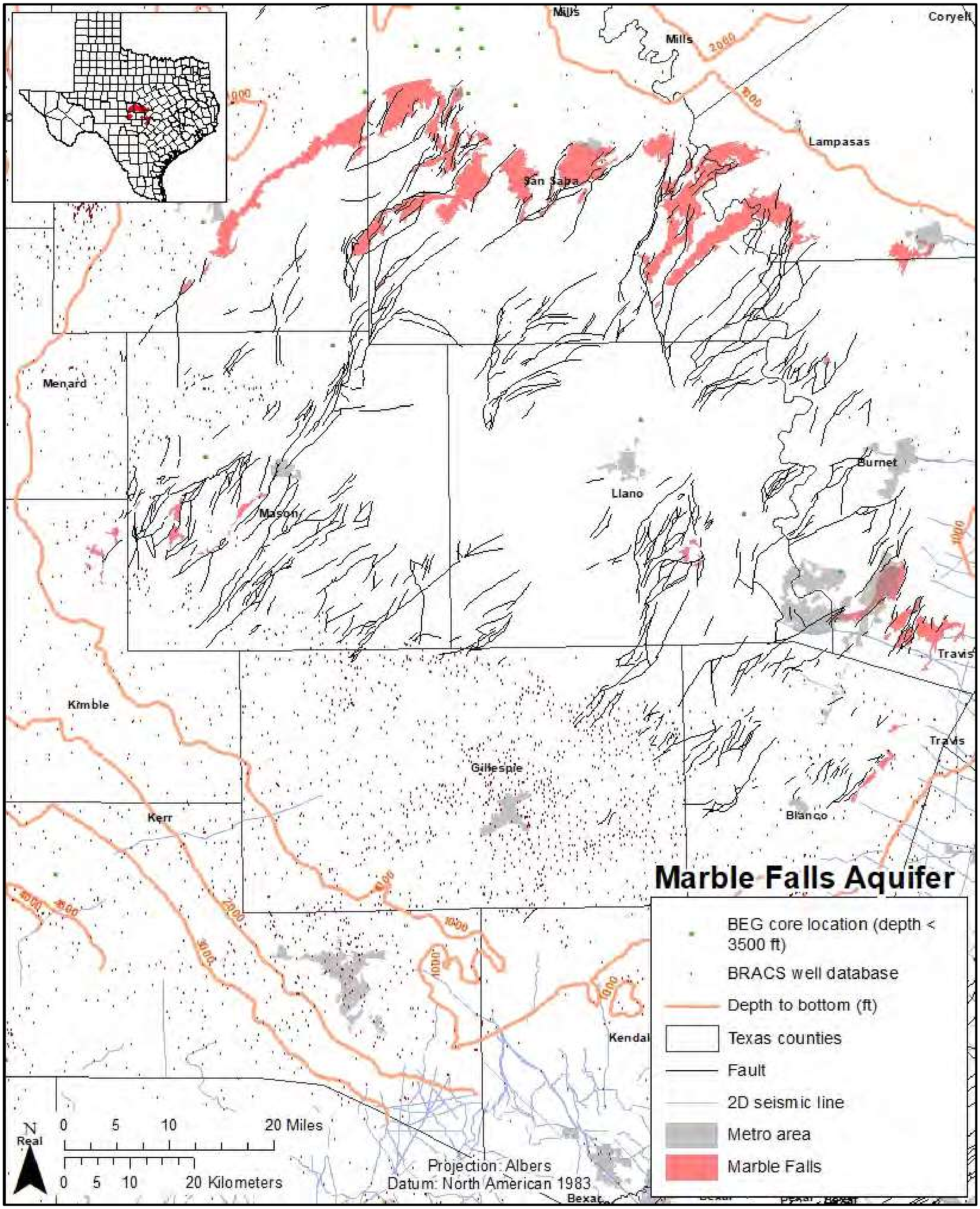
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-27. **Seismic coverage for the Lipan Aquifer. Depth contours from Beach and others (2004). Contour interval is 600 feet and all depths are shallower outside of that contour.**



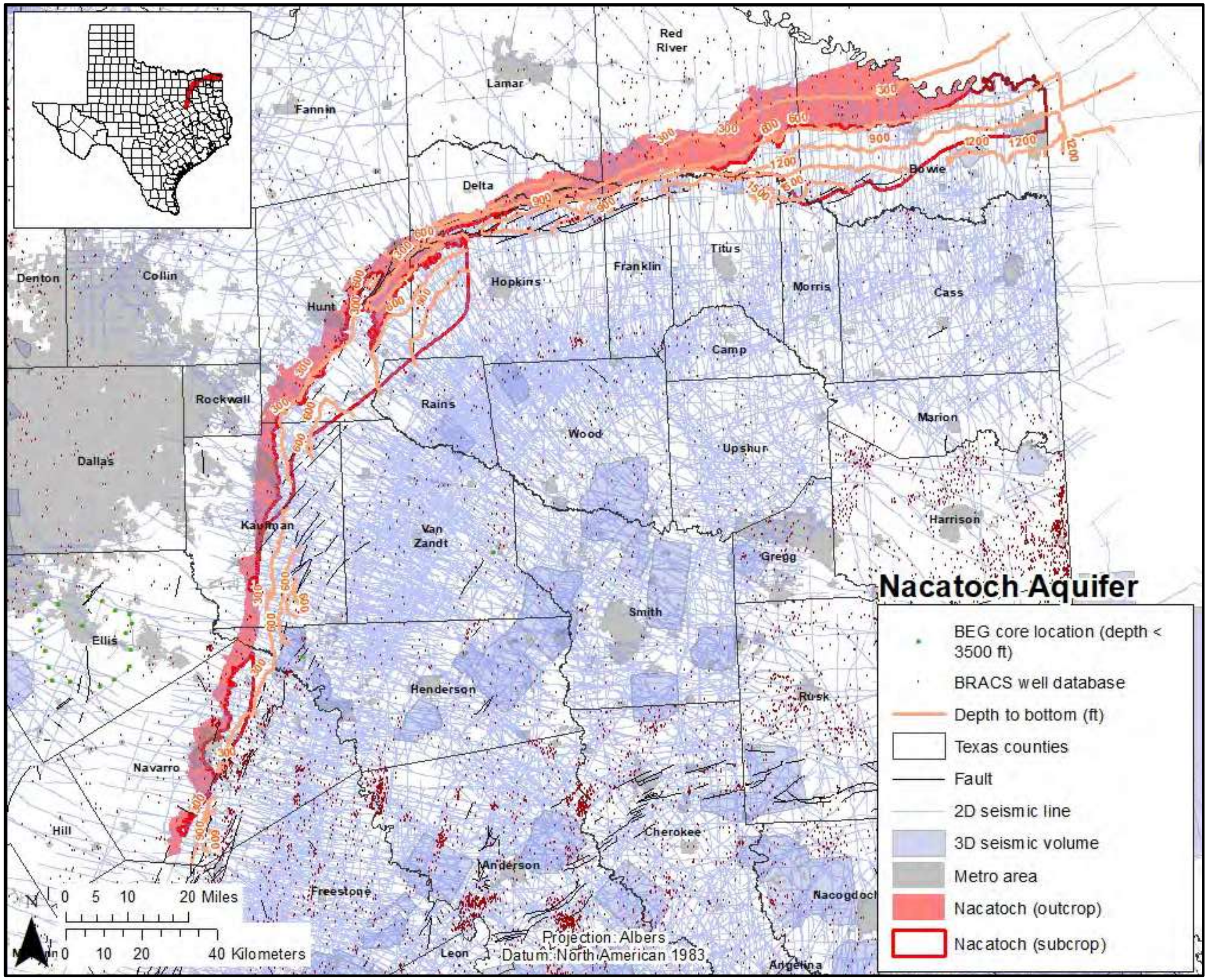
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-28. **Seismic coverage for the Marathon Aquifer.**



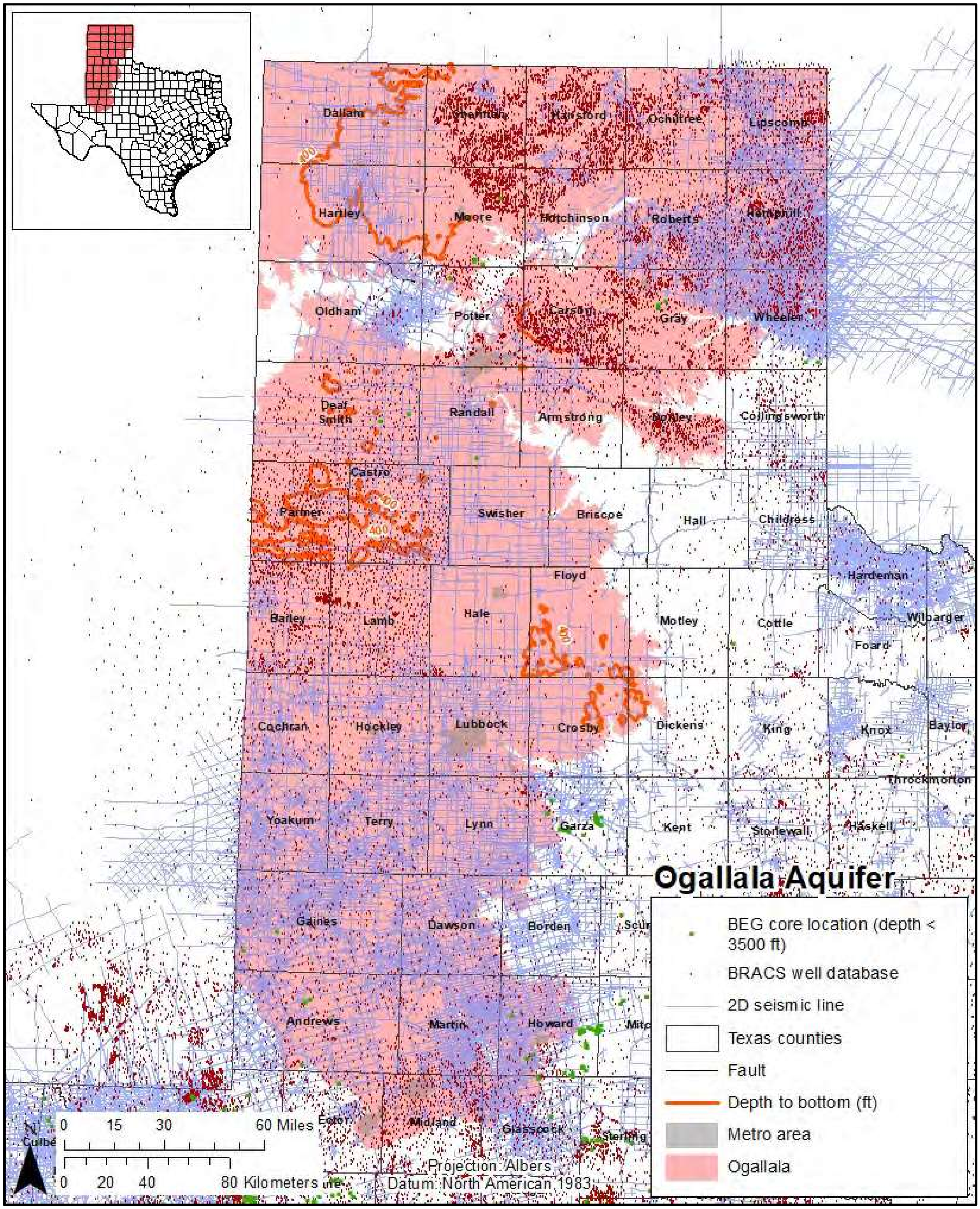
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-29. Seismic coverage for the Marble Falls Aquifer. Depth contours from Shi and others (2016). Contour interval is 1,000 feet.



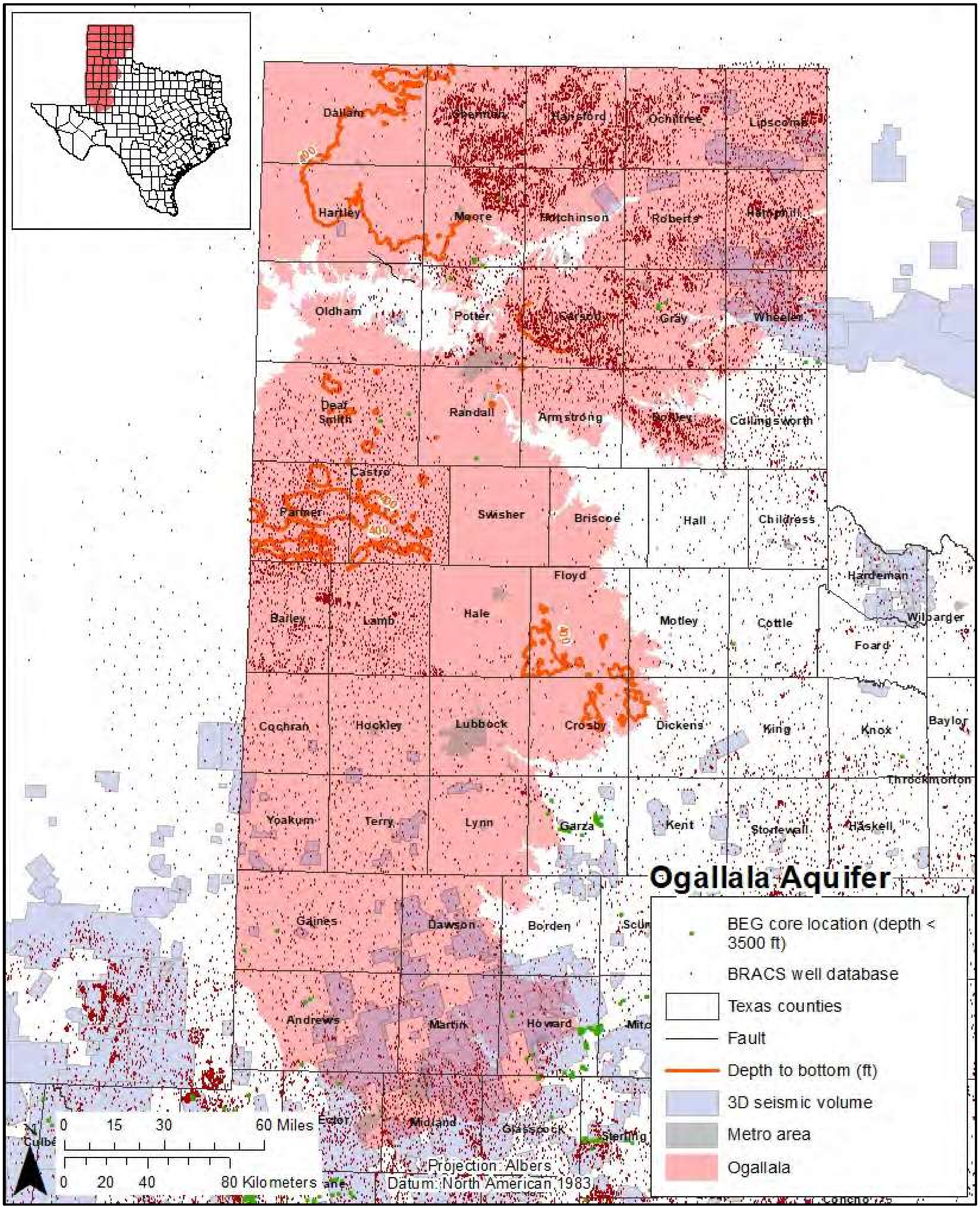
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-30. **Seismic coverage for the Nacatoch Aquifer. Depth contours from Beach and others (2009). Contour interval is 300 feet.**



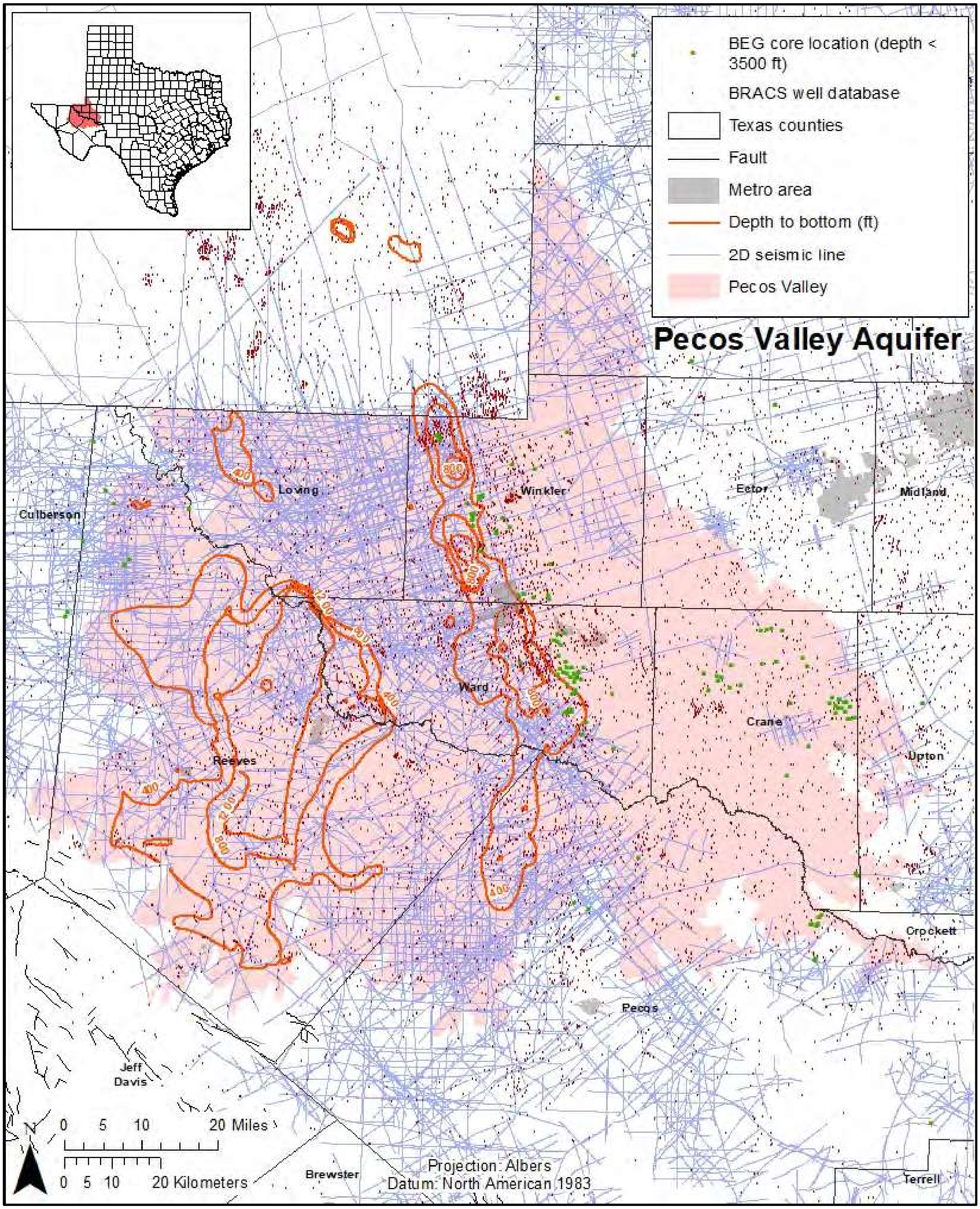
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-31. **Seismic two-dimensional coverage for the Ogallala Aquifer. Depth contours from Deeds and others (2015). Contour posted is 400 feet. All other areas are less than 400 feet.**



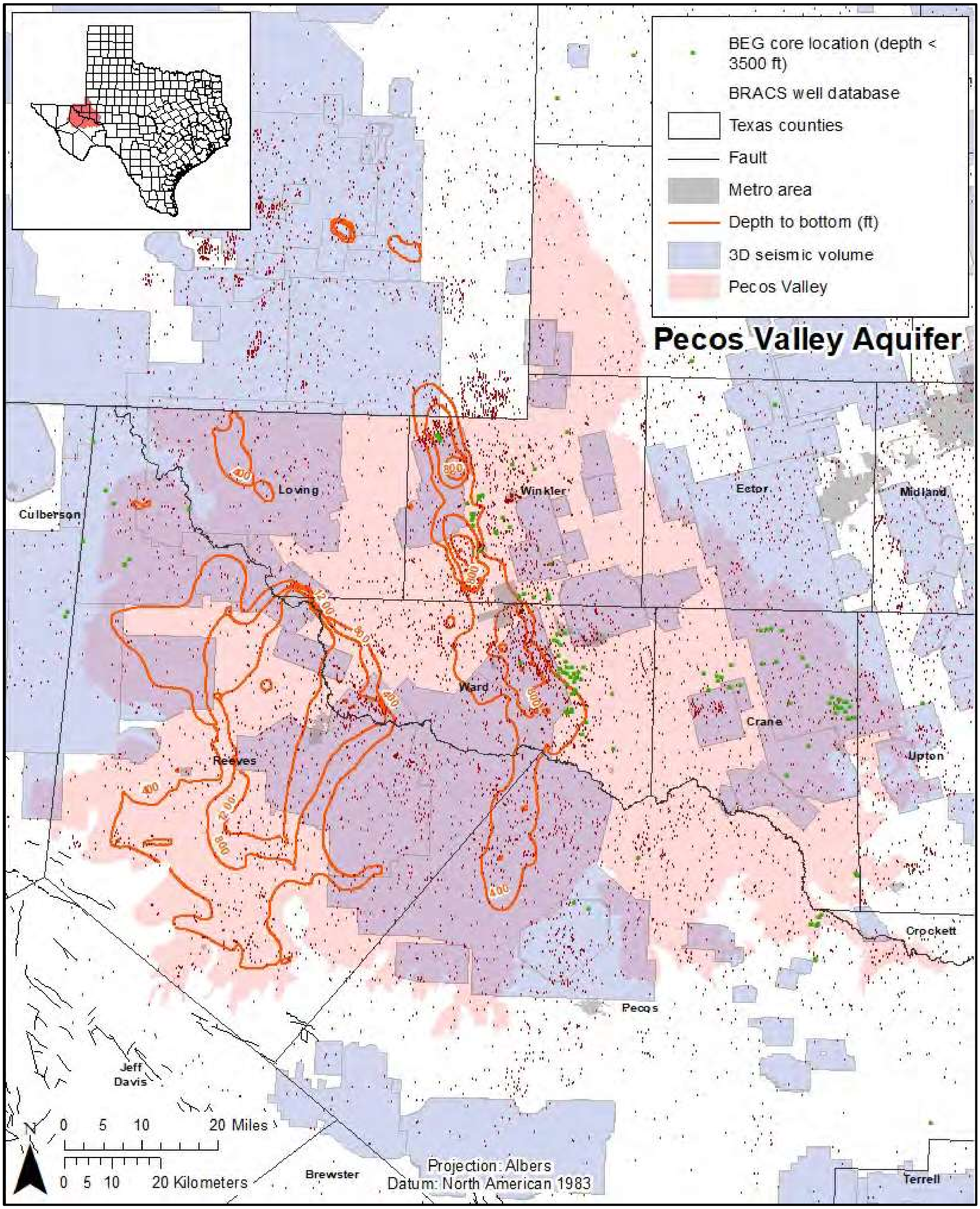
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-32. **Seismic three-dimensional coverage for the Ogallala Aquifer. Depth contours from Deeds and others (2015). Contour posted is 400 feet. All other areas are less than 400 feet.**



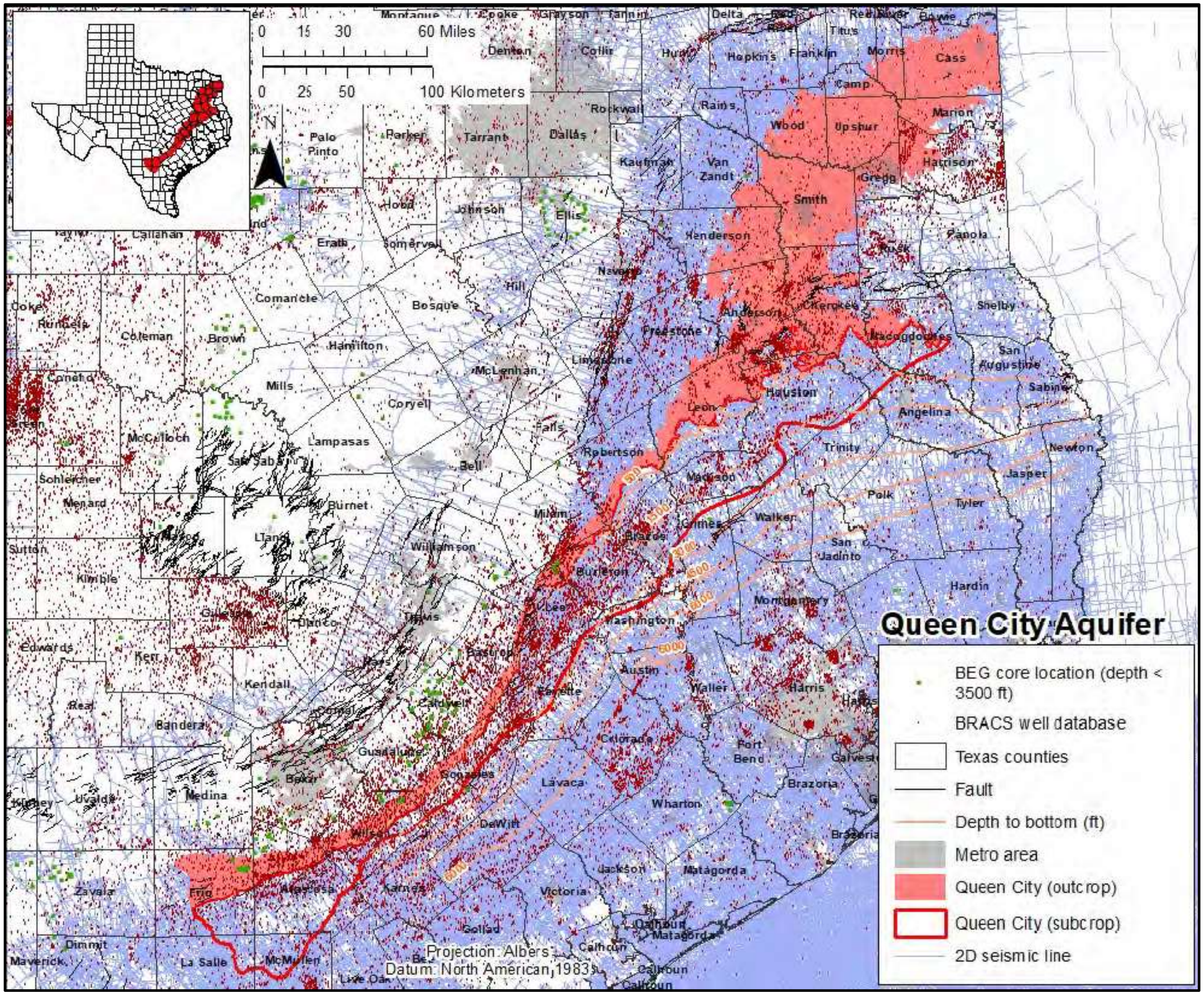
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-33. Seismic two-dimensional coverage for the Pecos Valley Aquifer. Depth contours from Meyer and others (2012). Contour interval is 400 feet.



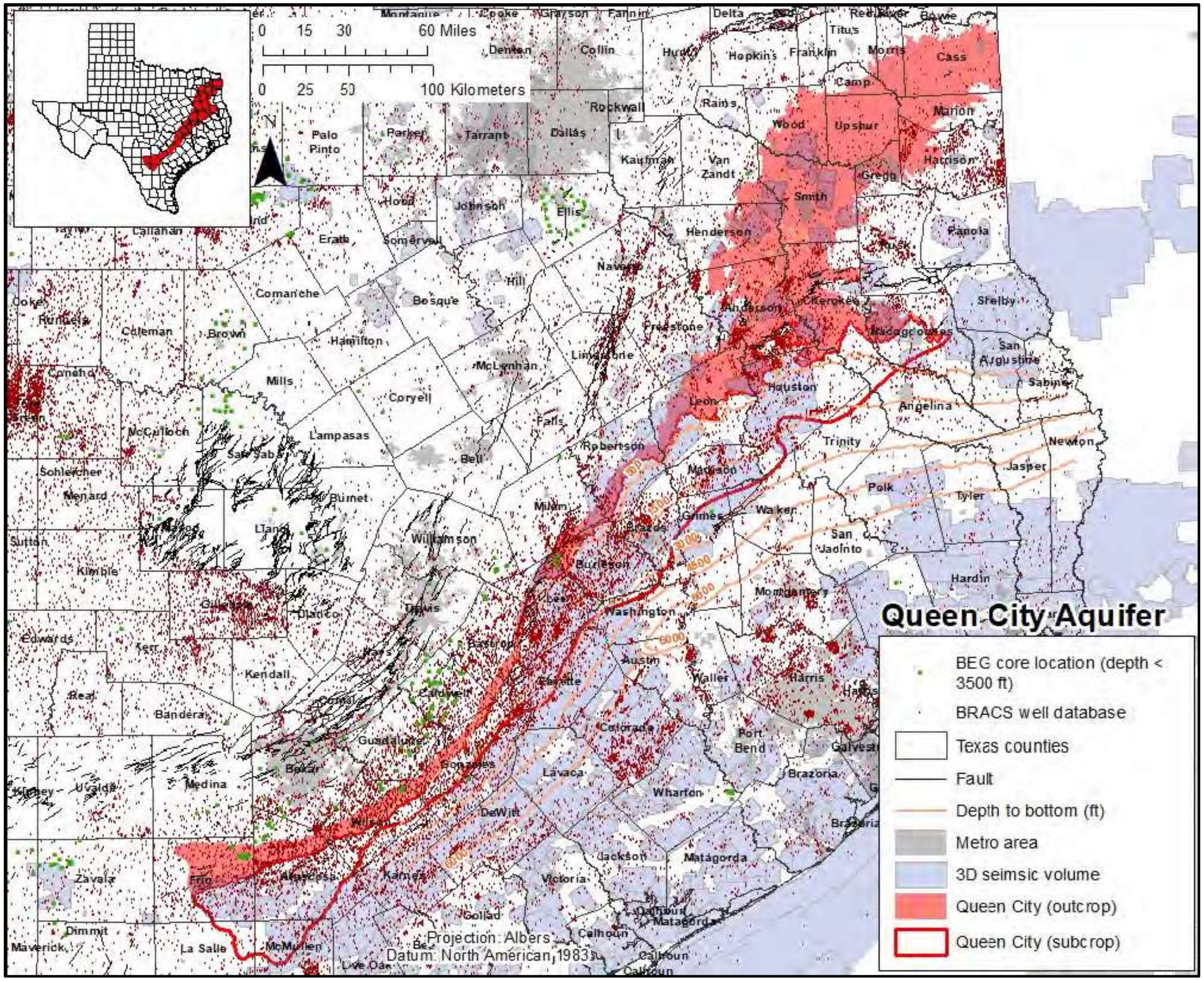
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-34. Seismic three-dimensional coverage for the Pecos Valley Aquifer. Depth contours from Meyer and others 2012. Contour interval is 400 feet.



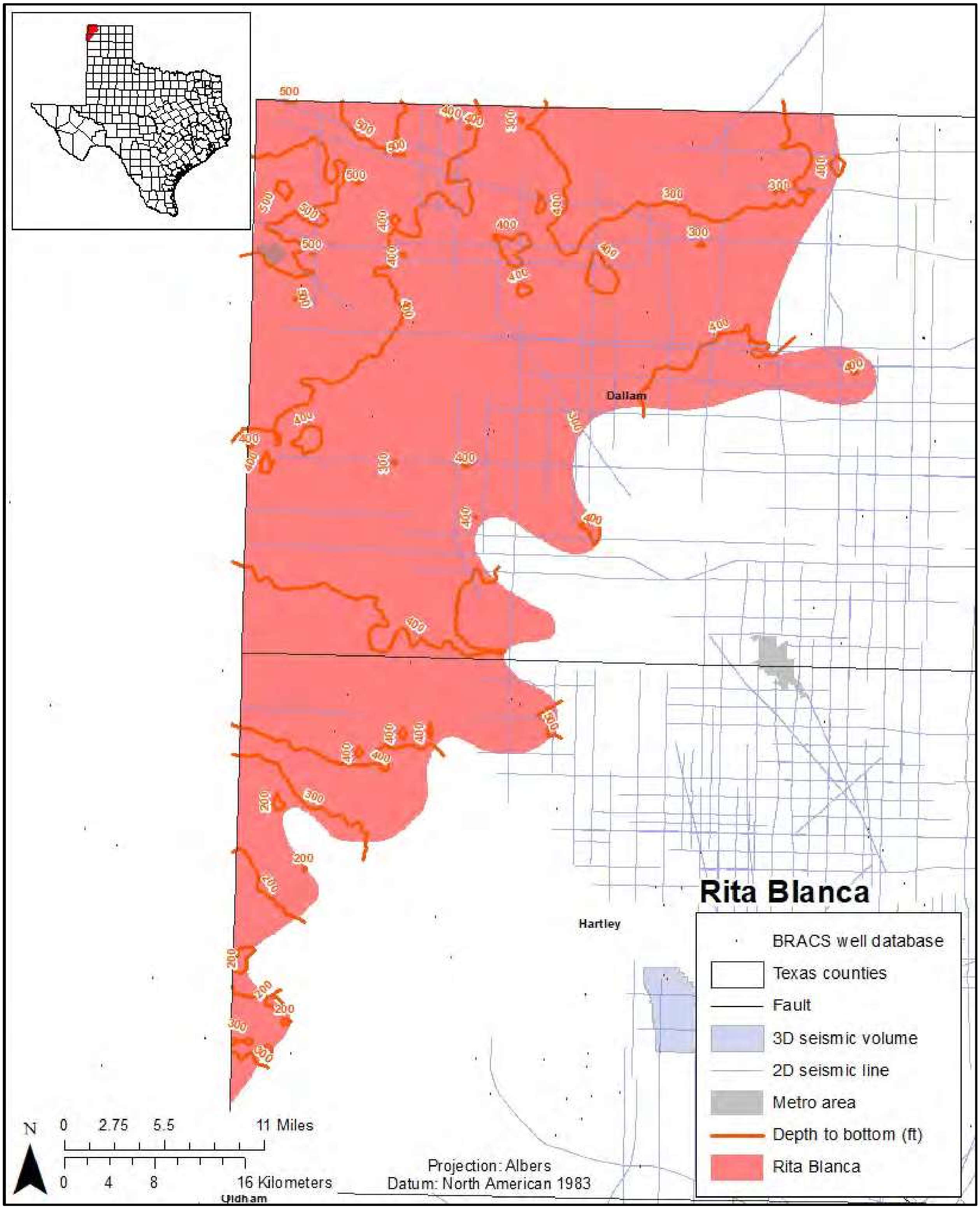
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-35. **Seismic two-dimensional coverage for the Queen City Aquifer. Contours from Young and others (2018). Contour interval is 1,500 feet with an additional 500 foot contour.**



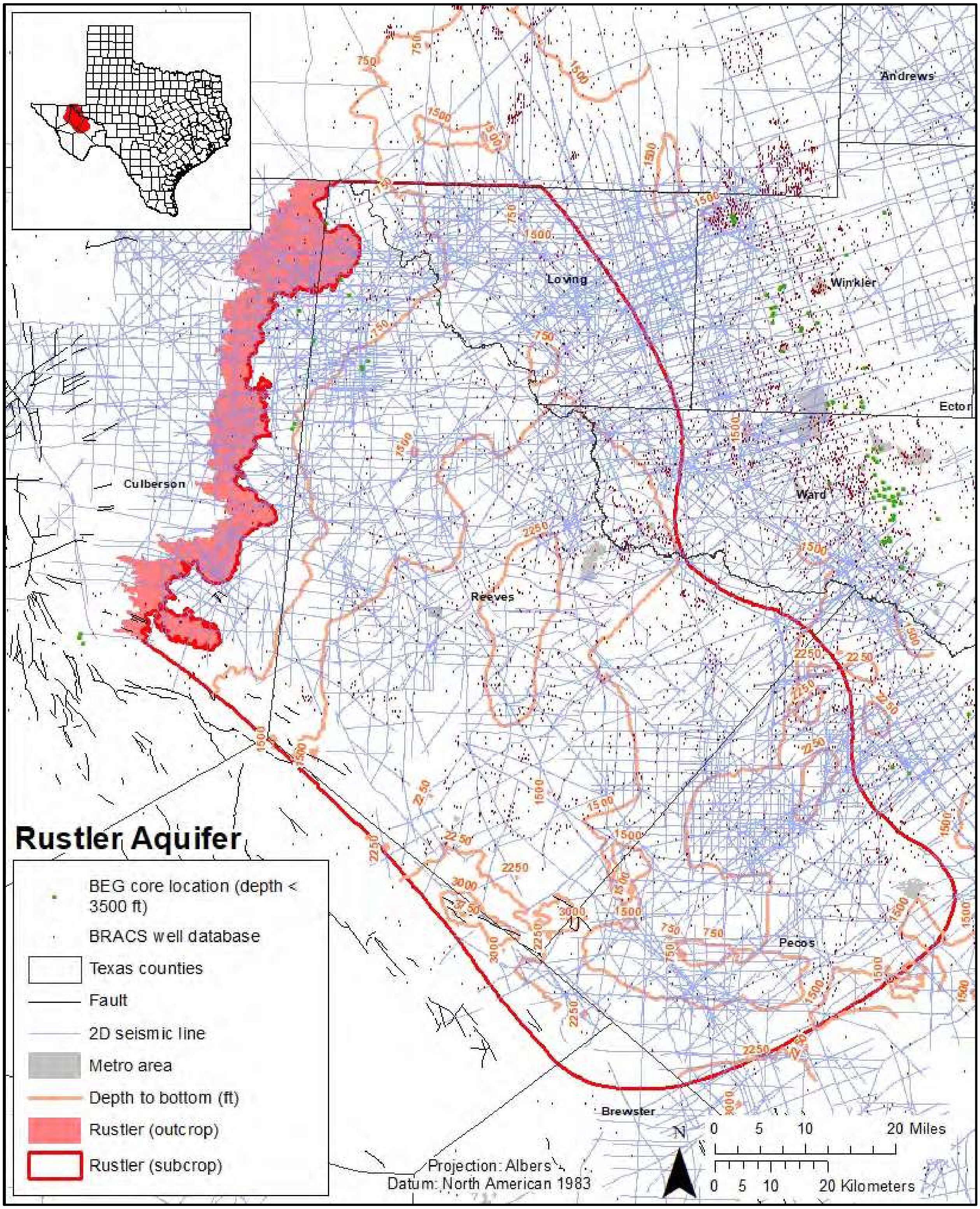
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-36. **Seismic three-dimensional coverage for the Queen City Aquifer. Contours from Young and others (2018). Contour interval is 1,500 feet with an additional 500 foot contour.**



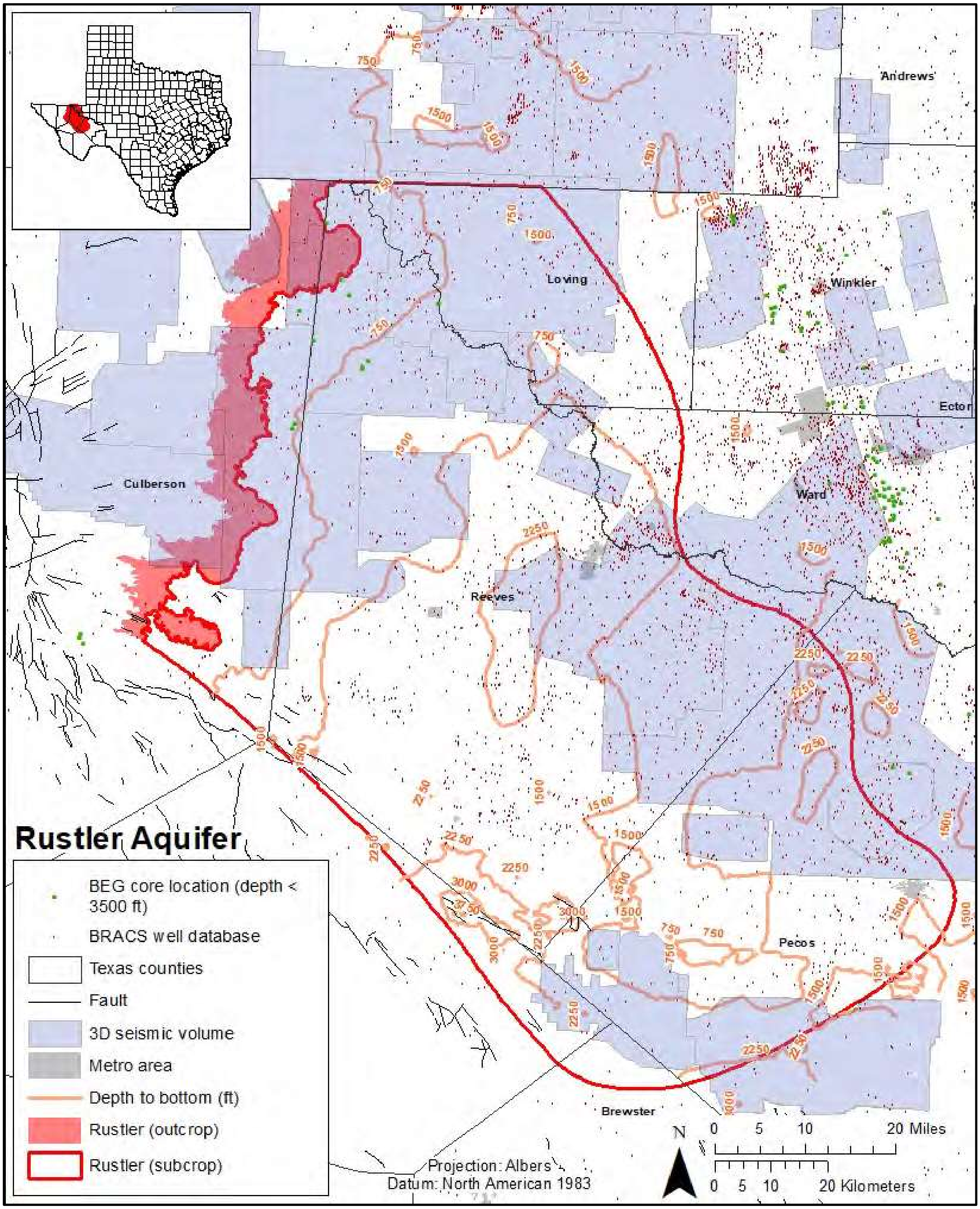
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System,

Figure 6-37. **Seismic coverage for the Rita Blanca Aquifer. Depth contours from Deeds and others (2015). Contour interval is 100 feet.**



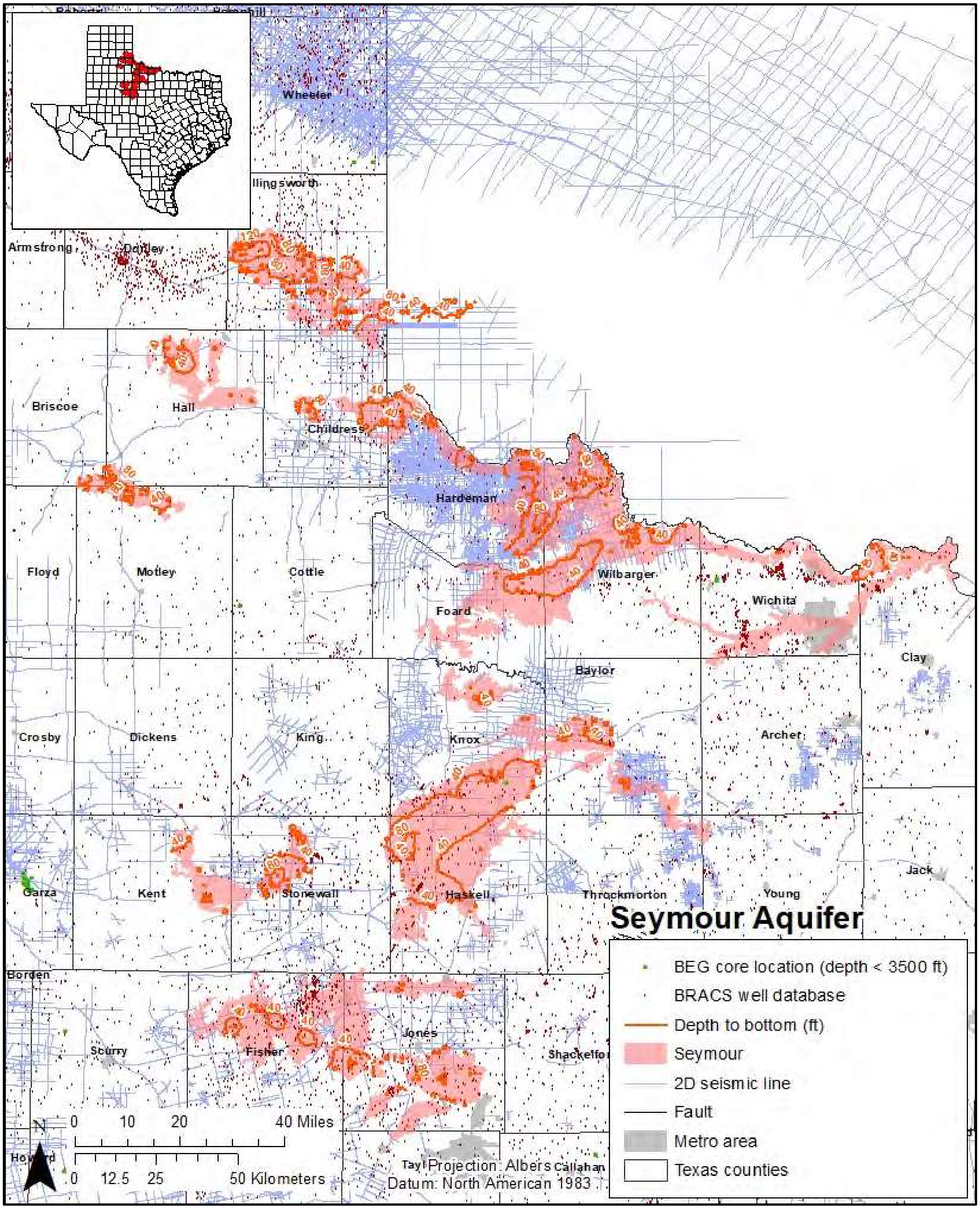
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, ft = feet

Figure 6-38. **Seismic two-dimensional coverage for the Rustler Aquifer. Depth contours from Ewing and others (2012). Contour interval is 750 feet.**



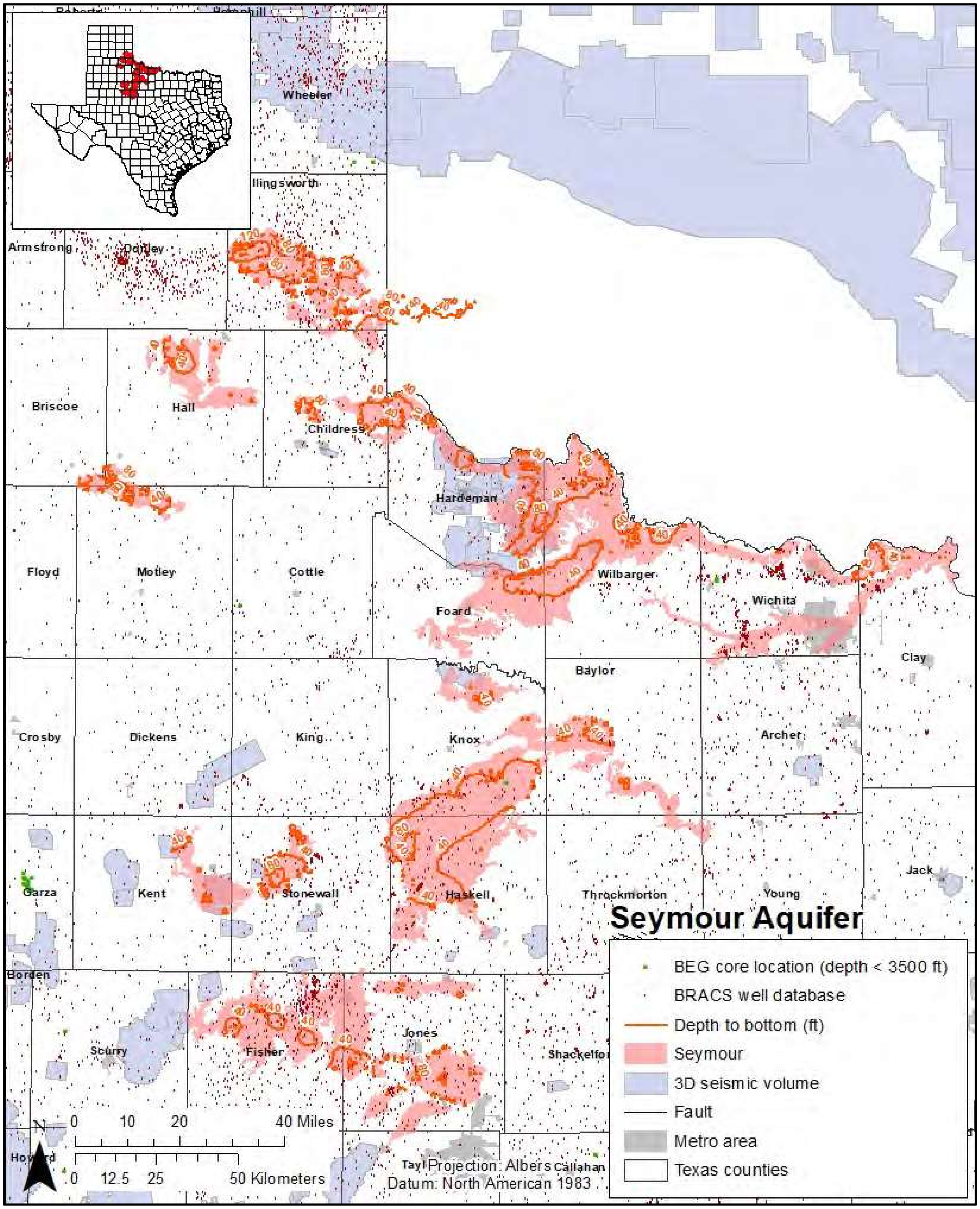
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-39. **Seismic three-dimensional coverage for the Rustler Aquifer. Depth contours from Ewing and others (2012). Contour interval is 750 feet.**



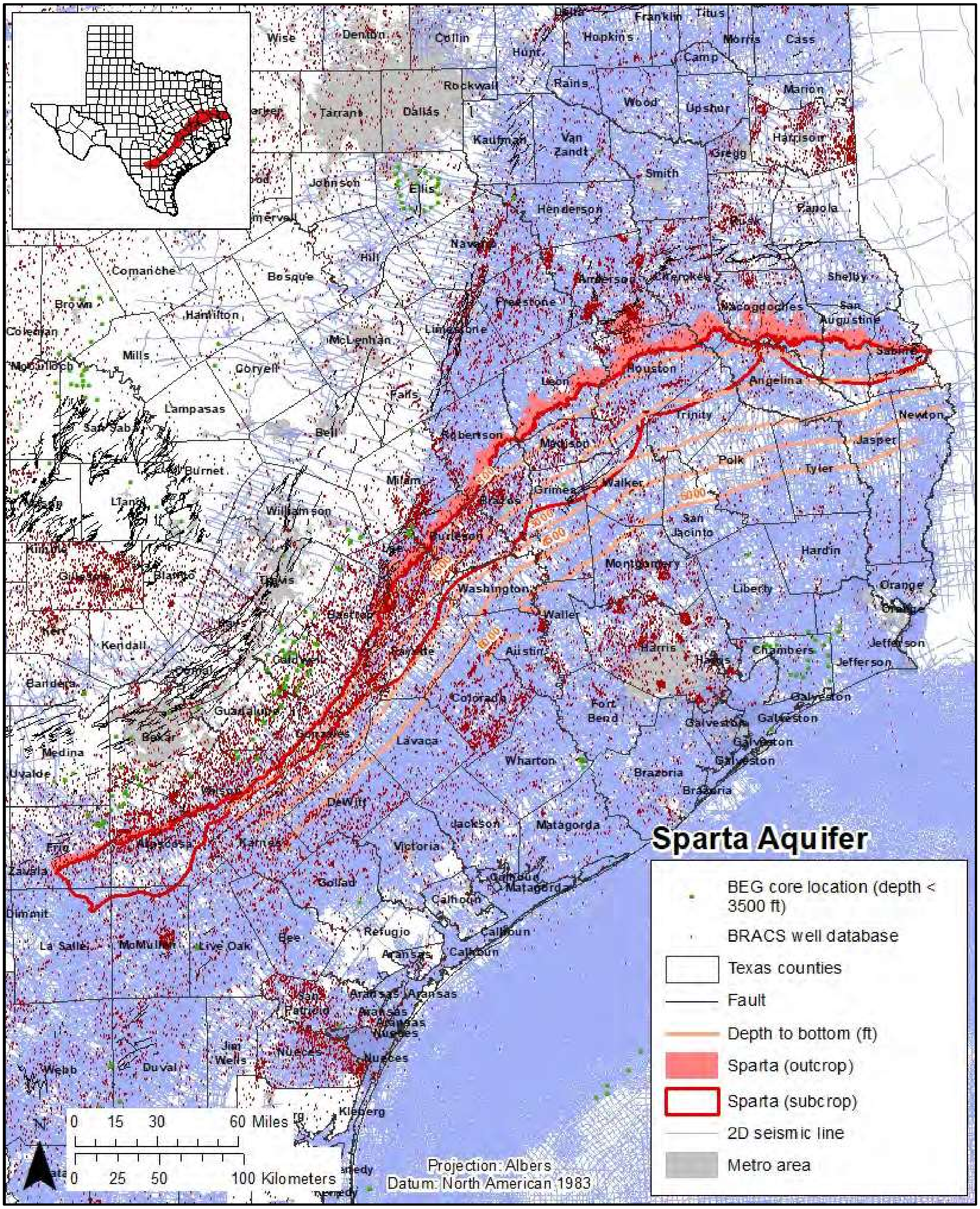
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-40. **Seismic two-dimensional coverage for the Seymour Aquifer. Depth contours from Jones and others (2012). Contour interval is 40 feet.**



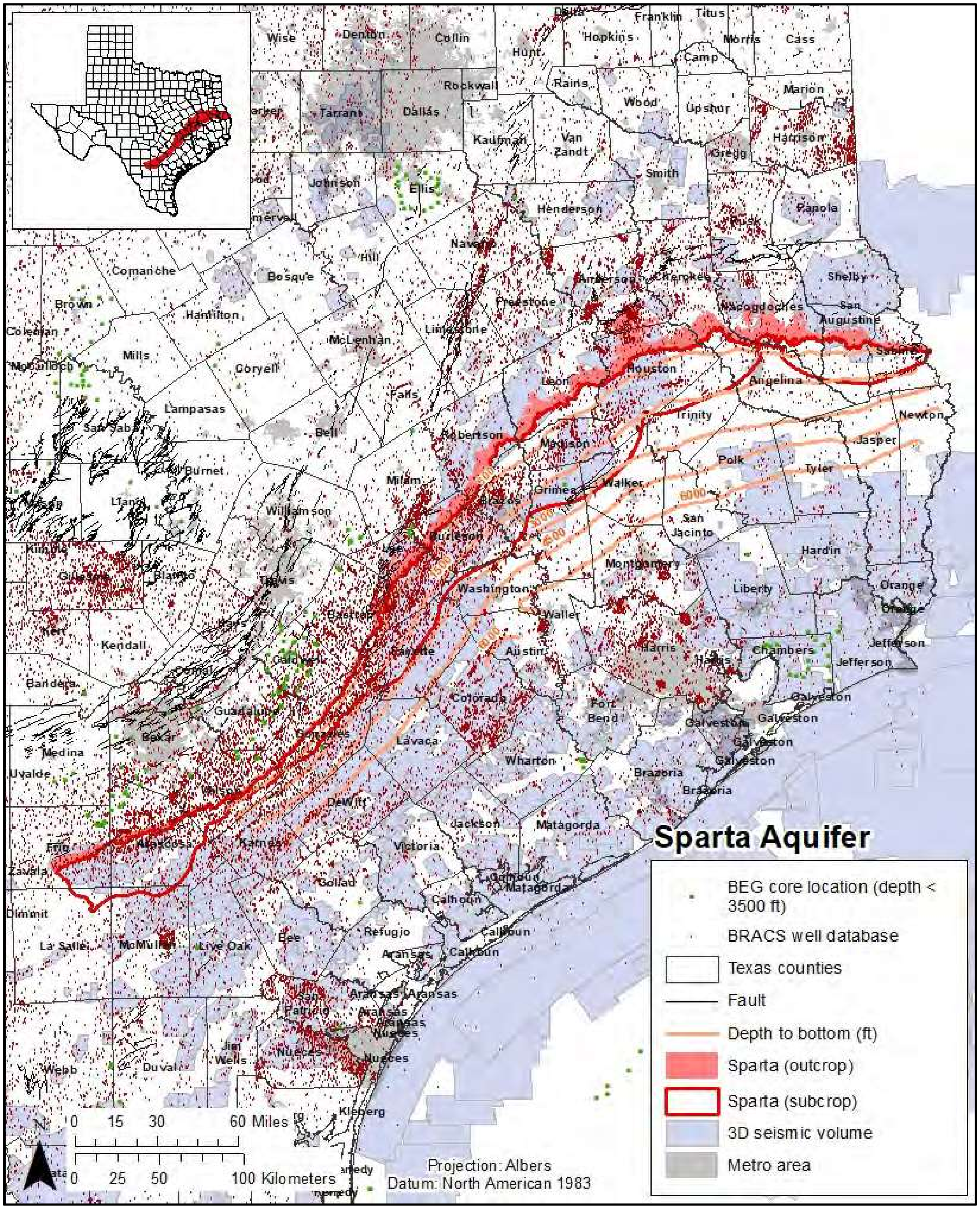
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-41. **Seismic three-dimensional coverage for the Seymour Aquifer. Depth contours from Jones and others (2012). Contour interval is 40 feet.**



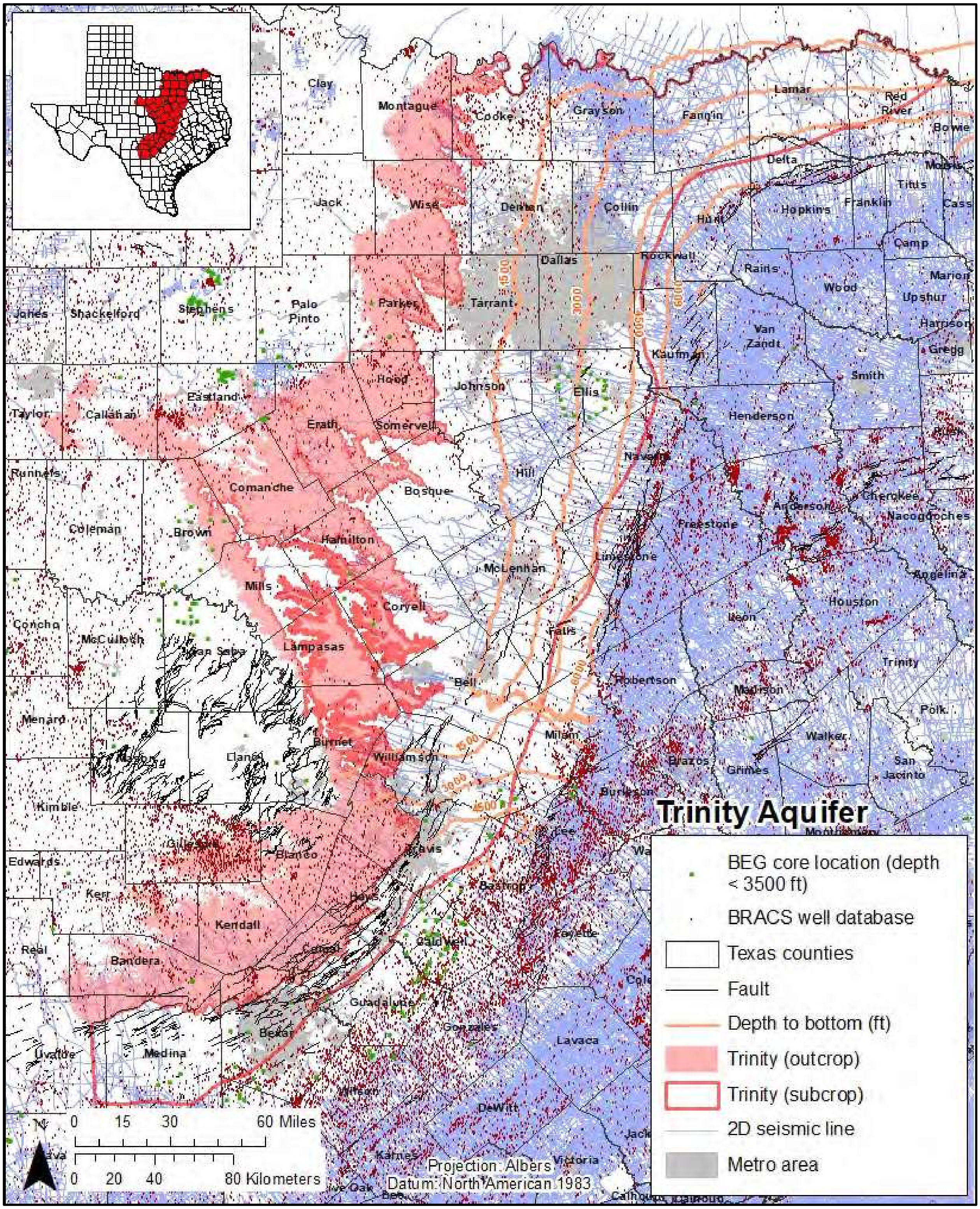
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-42. **Seismic two-dimensional coverage for the Sparta Aquifer. Contours from Young and others (2018). Contour interval is 1,000 feet with an additional 500-foot contour.**



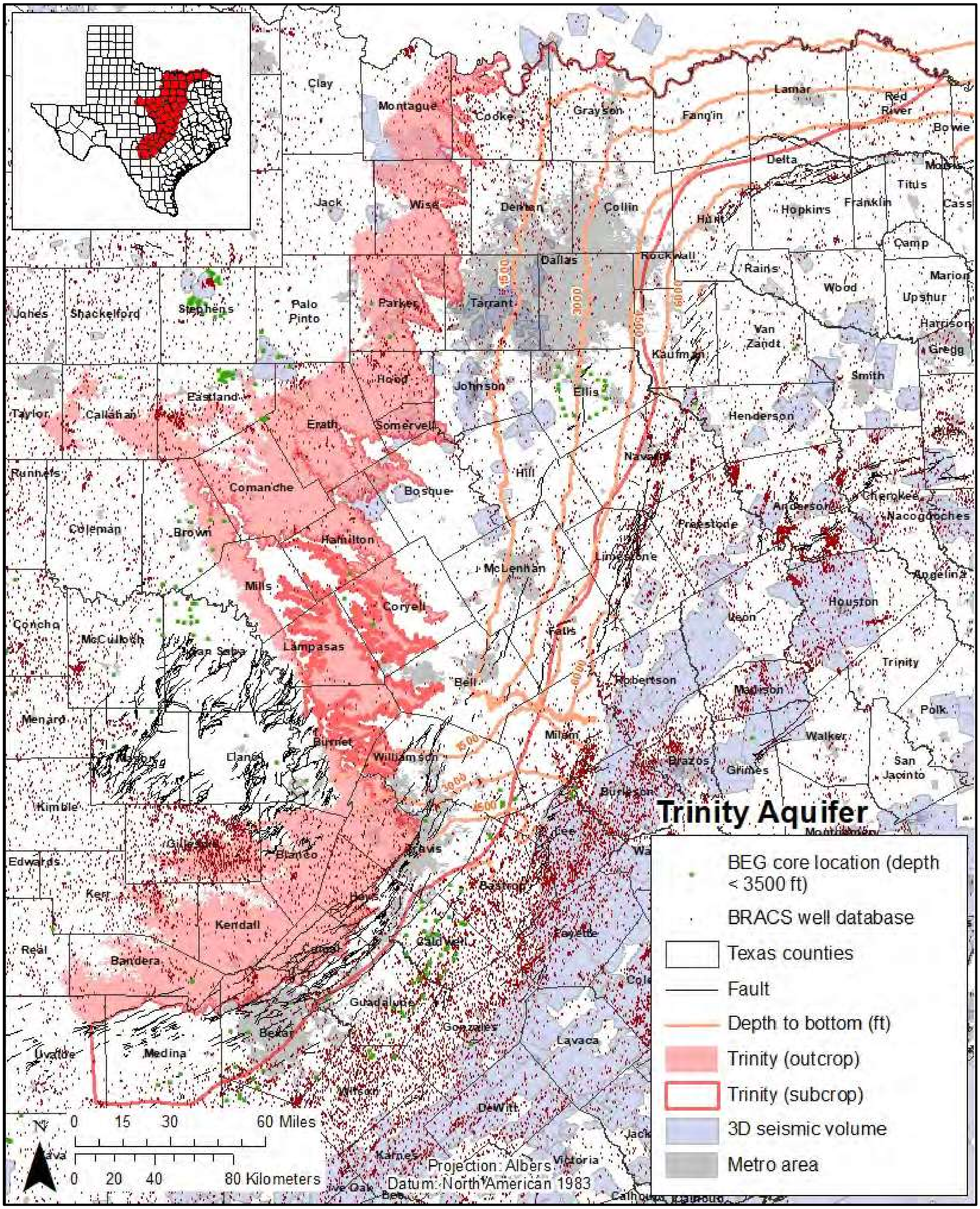
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-43. **Seismic three-dimensional coverage for the Sparta Aquifer. Contours from Young and others (2018). Contour interval is 1,000 feet with an additional 500-foot contour.**



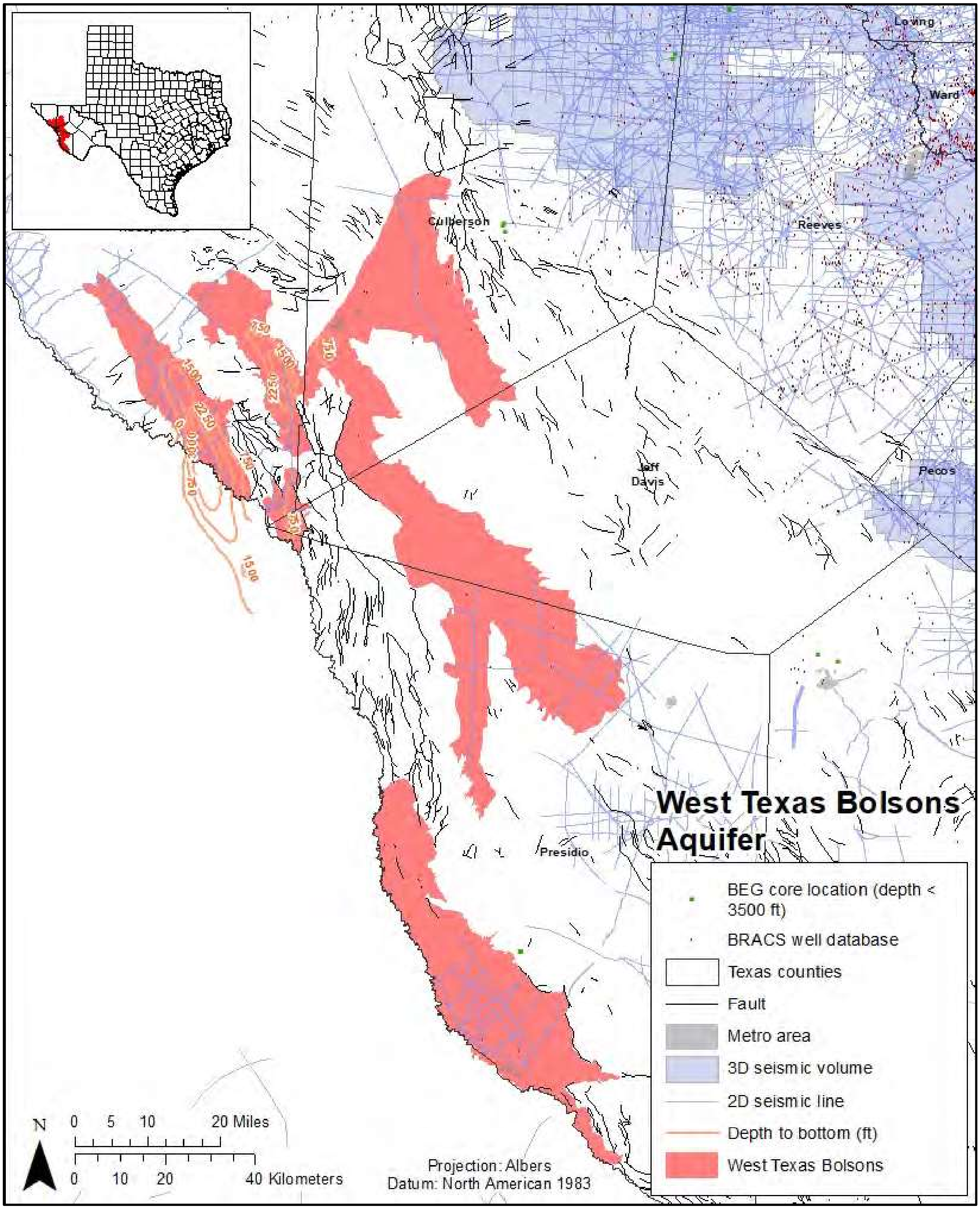
Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-44. **Seismic two-dimensional coverage for the Trinity Aquifer. Depth contours from Kelley and others (2014). Contour interval is 1,500 feet.**



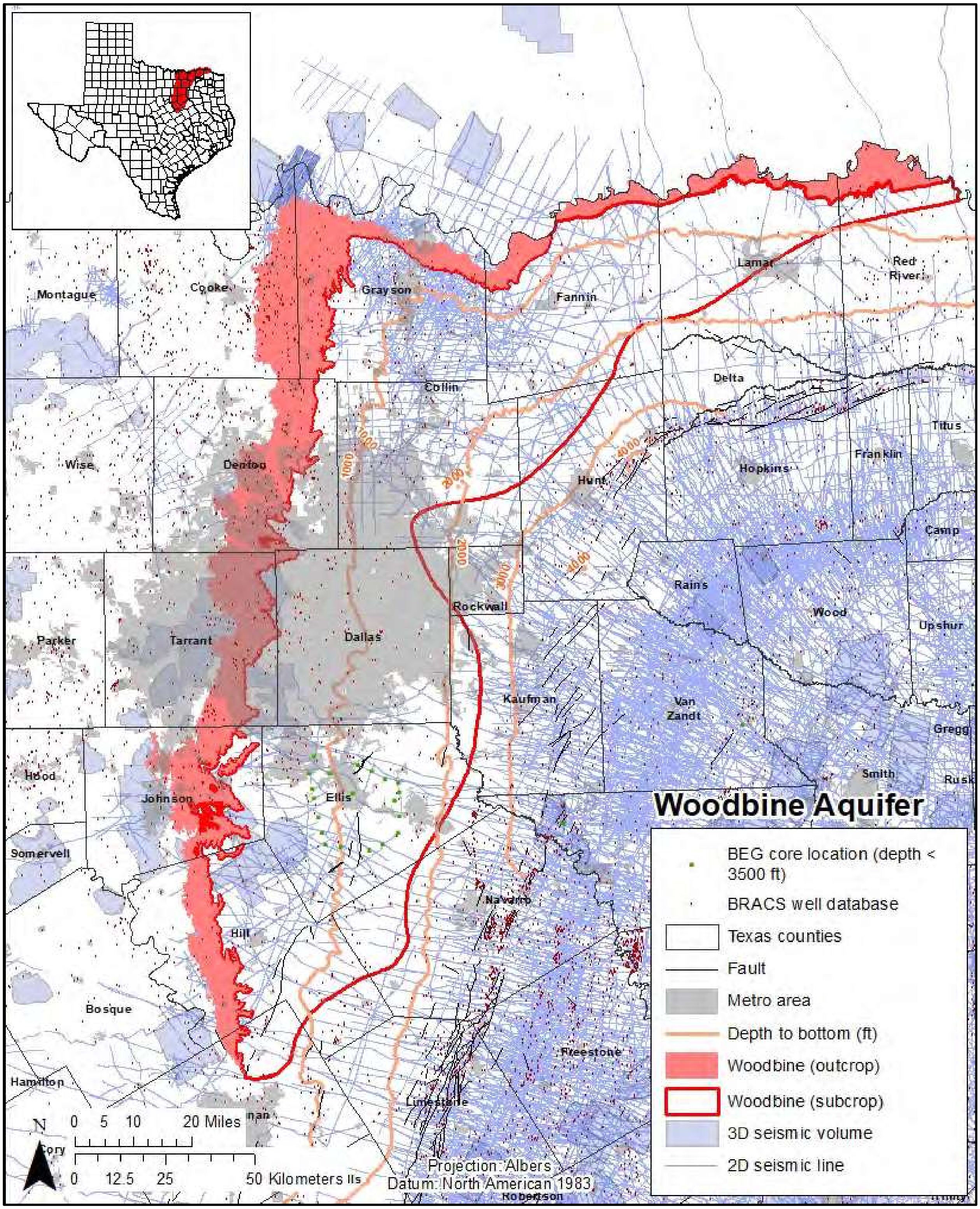
Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-45. **Seismic three-dimensional coverage for the Trinity Aquifer. Depth contours from Kelley and others (2014). Contour interval is 1,500 feet.**



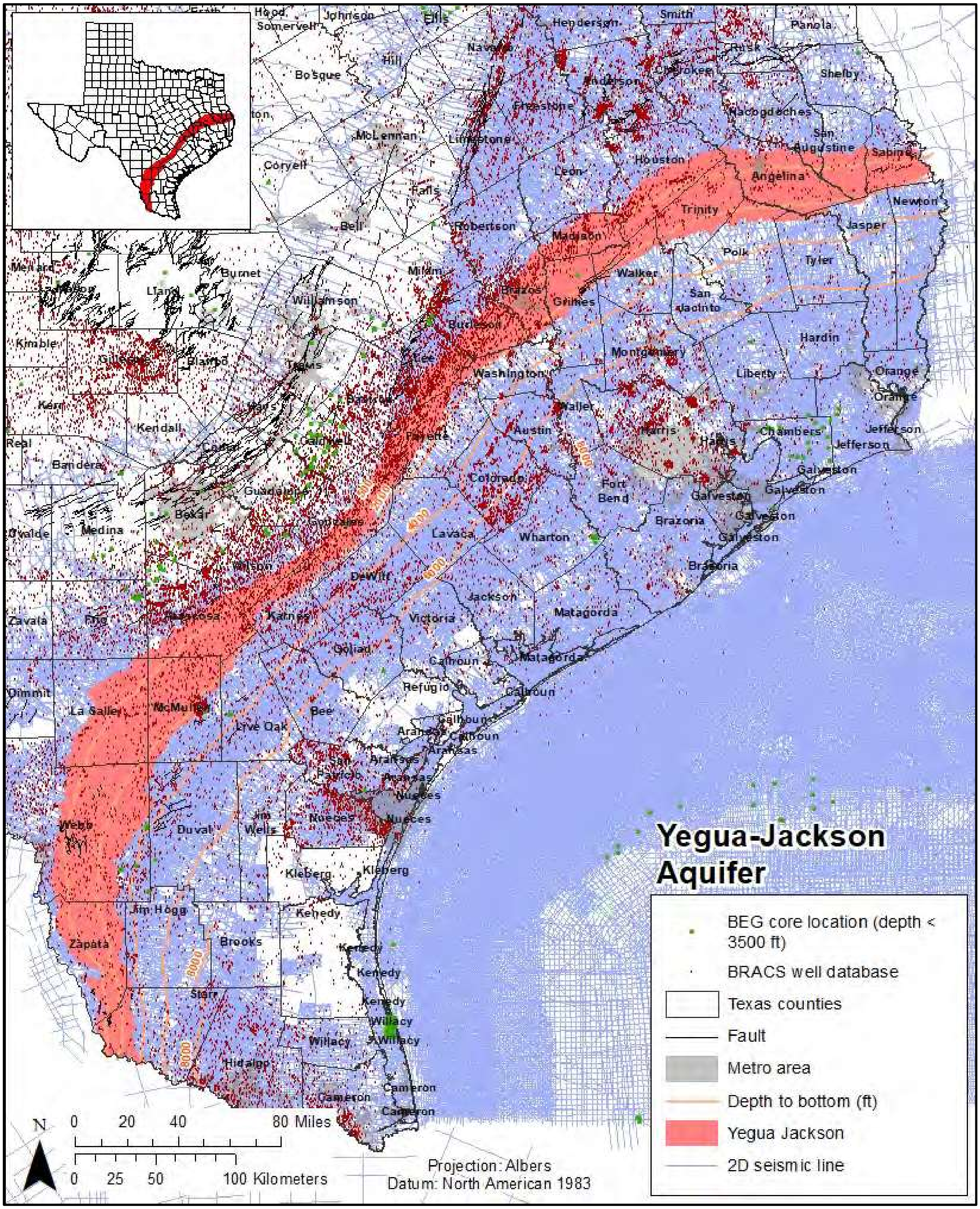
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-46. Seismic coverage for the West Texas Bolsons Aquifer. Depth contours from Beach and others (2008). Contour interval is 750 feet.



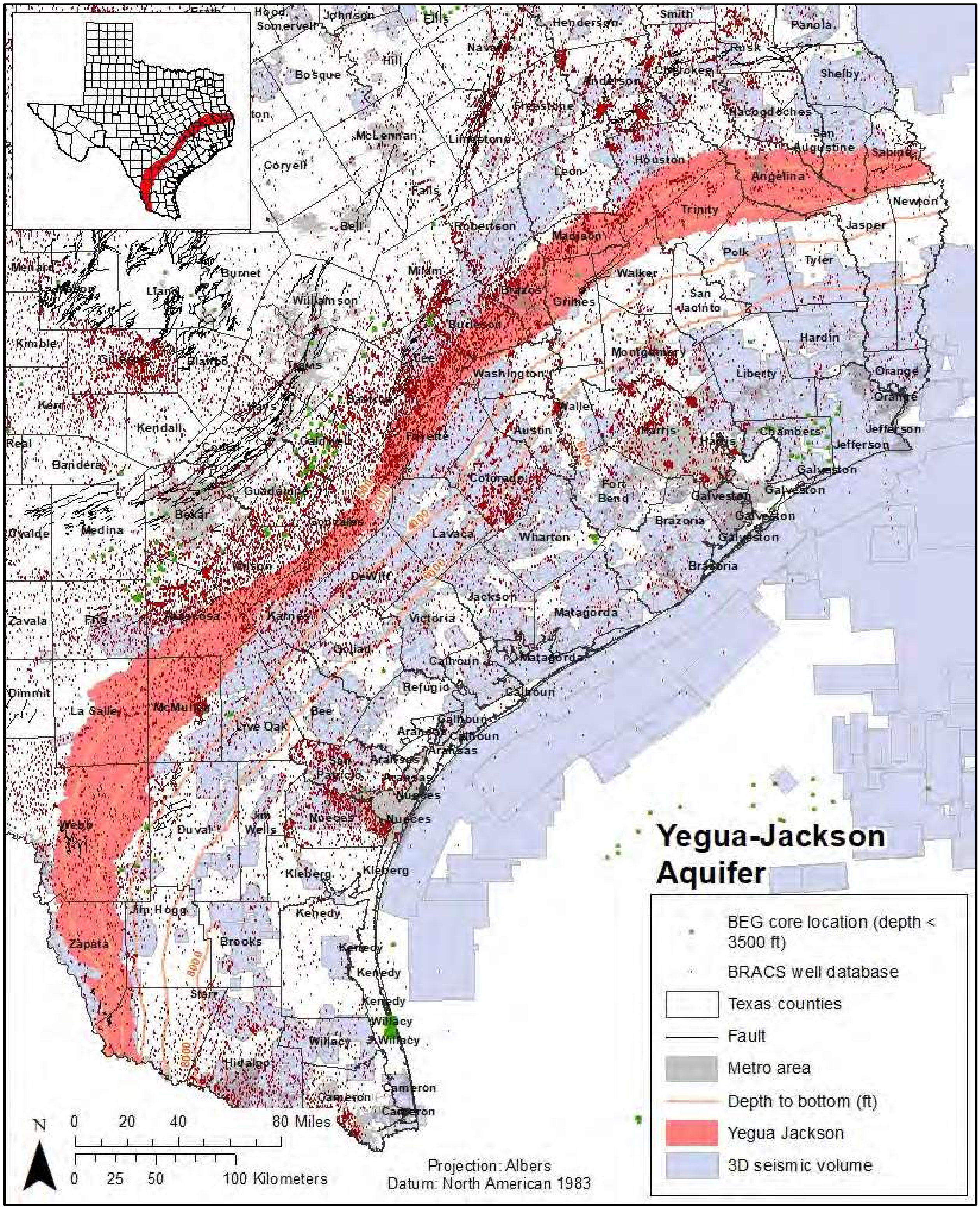
Note: 2D = two-dimensional, 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-47. Seismic coverage for the Woodbine Aquifer. Depth contours from Kelley and others (2014). Contour interval is 1,000 feet.



Note: 2D = two-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-48. **Seismic two-dimensional coverage for the Yegua-Jackson Aquifer. Contours from Young and others (2018). Contour interval is 1,000 feet with an additional 500 foot contour.**



Note: 3D = three-dimensional, BRACS = Brackish Resources Aquifer Characterization System, BEG = Bureau of Economic Geology, ft = feet

Figure 6-49. **Seismic three-dimensional coverage for the Yegua-Jackson Aquifer. Contours from Young and others (2018). Contour interval is 1,000 feet with an additional 500 foot contour.**

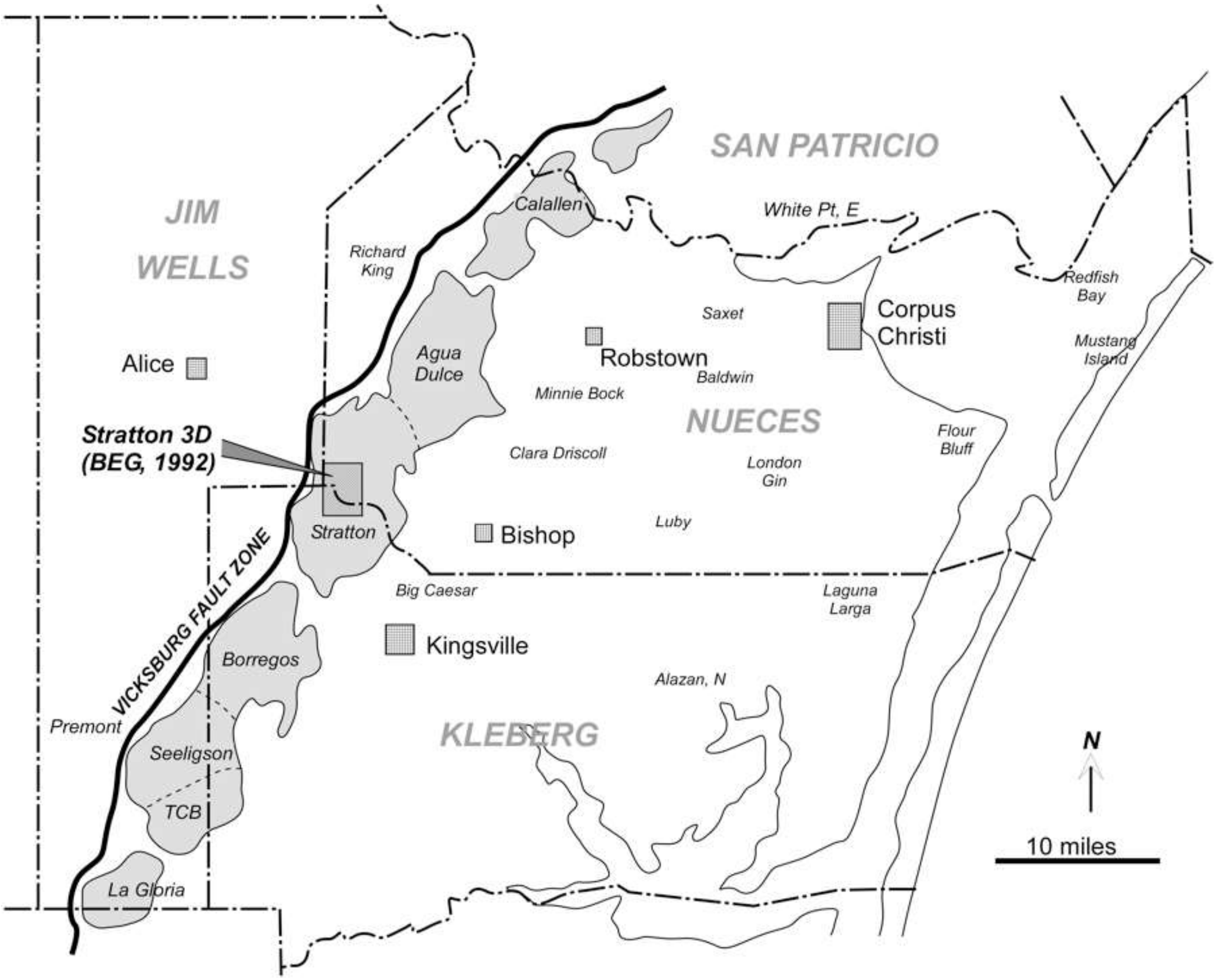
7 Application of Workflow to a Seismic Dataset: Stratton Three-Dimensional Survey, Nueces County (Task V)

The Stratton three-dimensional dataset was chosen to evaluate the proposed workflow for processing and interpreting conventional three-dimensional seismic data in support of brackish groundwater characterization. The dataset is located in southwestern Nueces and adjoining counties, to the southwest of Corpus Christi, Texas. These data were chosen as (1) they are free and can be published without proprietary restrictions, (2) they lie in the Gulf Coast aquifer system, which has excellent potential for brackish water and abundant seismic data, and (3) the dataset is high quality and has a three-dimensional seismic volume along with several well logs.

Stratton field, in southwestern Nueces and adjoining Jim Wells and Kleberg counties, is a major gas and oil field within the Vicksburg Flexure producing trend of south Texas (Figure 7-1). It extends north-northeast into Agua Dulce field in western Nueces County and is separated by a shallow sag from Seeligson field in Kleberg and Jim Wells counties. All of these fields (and more to the south), are located in the FR-4 gas fairway of Kosters and others (1989), which consists of hundreds of individual reservoirs within the Frio and Vicksburg formations, draped across a broad anticlinal closure extending north-northeast for over 60 miles. Individual reservoirs are typically dip-oriented fluvial channels, although deeper Vicksburg units represent deltaic deposits. The reservoirs are largely gas-bearing but have oil rims. Oil wells form a halo around the central gas producing area.

Stratton was the second field discovered on the trend (after Agua Dulce, which produced hydrocarbons at 1,900 feet in 1928). The discovery well was drilled in December 1931 (Stanolind #1 Stratton). East flank oil was discovered in 1940 (Southern Minerals #1 Stratton Community). Reservoirs range from 4,100 to over 7,160 feet, mainly in the Middle Frio and some from deeper Lower Frio and Vicksburg sands. Over 408 billion cubic feet of gas was produced by the end of 1946, with 14.8 million barrels of oil. Over 2400 billion cubic feet of gas has been produced to 1990 (Sippel and Levey, 1991).

The Wardner lease, 11 square miles in extent in the center of the field, is the site of the three-dimensional survey. This lease was drilled by J.F. Camp in the late 1930s, then Corpus Christi O&G and Chicago Corp (who drilled 60 wells) in the 1940s. It passed to Champlin about 1957, who drilled some 90 wells. Champlin became a subsidiary of Union Pacific in 1970 and became part of Union Pacific Resources in 1987, with 87 wells drilled under that name. The property was sold in 1997 to Collins and Ware (about 11 wells) and then Apache (55 wells to 2004) in 1999 and 2000. Offsetting leases were developed by Humble/Exxon as part of the King Ranch. The discontinuous reservoirs, with a history of interwell barriers and surprises, led to intensive study of depositional systems and experimentation with technologies to identify additional reserves to be tapped by "in-field wildcatting" or "secondary gas recovery" (see Libson, 1985; Kerr, 1990; Sippel and Levey, 1991; Levey and others, 1994b).



Note: 3D = three-dimensional, BEG = Bureau of Economic Geology

Figure 7-1. **Location of Stratton Field in Nueces and Kleberg counties and the Vicksburg Flexure producing trend. Area of three-dimensional survey shown.**

In 1992, the Bureau of Economic Geology, under a contract with Gas Research Institute, acquired a 7.65 square mile three-dimensional seismic survey on the Wardner lease (then held by Union Pacific Resources). In conjunction with this, a vertical seismic profile was acquired in the Wardner #175. This dataset was interpreted for Frio channels and secondary gas targets (Hardage et al, 1994, 1996). Shortly thereafter, in 1993, Union Pacific Resources acquired a 90-square-mile three-dimensional survey, which extended north into Agua Dulce field. This field was interpreted for Frio channels and published by El-Mowafy and Marfurt (2016) but does not form a part of the present work. The Bureau of Economic Geology released a 2.14-square-mile subset of this data along with digitized logs for 21 wells, and the time-depth chart from the vertical seismic profile well, in 1994 (Levey and others, 1994a).

In 2014, the Bureau of Economic Geology released the entire survey, including shot gathers and vertical seismic profile data, on the Society of Exploration Geophysicists Wiki, “for worldwide education and training” (SEG Wiki 2020).

7.1 Background Geology

Geologic units on the Gulf Coast Aquifer system dip east or southeast toward the coast at a direction roughly perpendicular to the local shoreline. Older units dip more steeply because of the accumulated subsidence and tilting since their deposition. Growth faults (faults that greatly expand the thickness of one or more geologic units) occur frequently in the Gulf Coast and are most pronounced near the paleoshelf margin of a geologic unit (the geomorphic shelf edge as the unit was being deposited). The shelf margin has grown southeastward toward the center of the Gulf of Mexico over time, so that growth faults affecting older units are well inland, and growth faults in units deposited today are several tens of miles offshore. Some older growth faults have continued to move slightly, and units within the Gulf Coast Aquifer may be impacted by localized changes in dip angle. Salt and shale movement (diapirism) can significantly modify local area structures, lithologies and in turn hydrogeology (Hamlin, 2006).

The Gulf Coast Aquifer comprises sediments ranging in age from Miocene to Holocene (Figure 7-2). The Oligocene Frio (or Catahoula) Formation underlies the Gulf Coast Aquifer and contains the shallowest gas targets at Stratton. Overlying the Frio are the oldest formations in the Gulf Coast Aquifer: the Oakville and overlying Lagarto Formations. These formations compose two significant depositional episodes, with the Oakville representing progradation in the Lower Miocene *(Anahuac* to *Marginulina* ascensionensis) and the Lagarto representing the Middle Miocene (*Marginulina* A to *Anomalina* B). The Oakville Formation ranges at outcrop from 300 to 700 feet to 1,000 to 2,000 feet thick near the modern shoreline, whereas the Lagarto Formation ranges at outcrop from 700 to 1,400 feet thick to 2,000 to 3,000 feet thick near the coast (Baker, 1979; Galloway and others, 1982, 1986). The Oakville and Lagarto here are comprised of the Santa Cruz fluvial sandstones that feed into the North Padre delta system. The Oakville and Lagarto in mid-dip areas, such as Stratton, are characterized by broad, dip-oriented, sand-rich belts composed of superposed and laterally amalgamated channel-fill and channel-margin splay facies, encased in mud-dominated floodplain facies. Regionally, the Oakville unit is sandier than the Lagarto; however, the basal Lagarto also contains significant sandstone at Stratton.

The Goliad formation overlies the Lagarto and represents late middle to late Miocene deposition (*Anomalina* B to *Bigenerina* A). The Goliad Formation ranges in thickness from 200 feet at outcrop to about 1,400 feet near the modern shoreline. Net sandstone thicknesses range from 100 to 800 feet, and sandstone content decreases regionally to the southwest (Morton and others, 1988). The Goliad at the Stratton area was deposited from Realitos fluvial system. Typical Goliad included both bedload and mixed load channel-fill facies in outcrop. Gravelly coarse sand, sandy gravel, and pebble-to-cobble-sized gravel dominate bed-load channel-fill facies, while coarse sand and sandy gravel are overlain by medium-to-fine sand, and very fine sand and silt in the mixed-load channel-fill succession. The Realitos fluvial system includes spectacular pebble- and cobble-sized gravels in outcrop (Plummer, 1932; Hoel, 1982), but in mid-dip positions such as Stratton, Realitos channel belts are narrow and include relatively less aggregate net sand than the other Goliad fluvial systems.

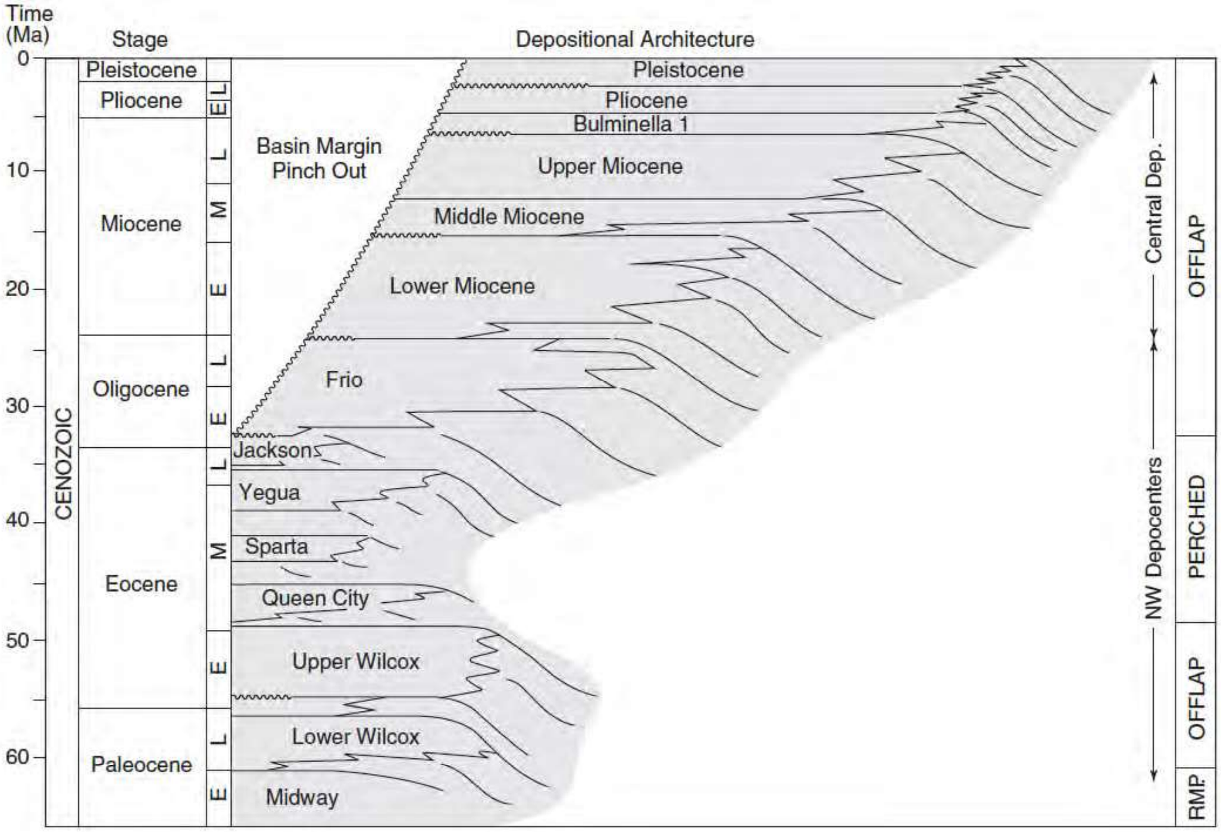


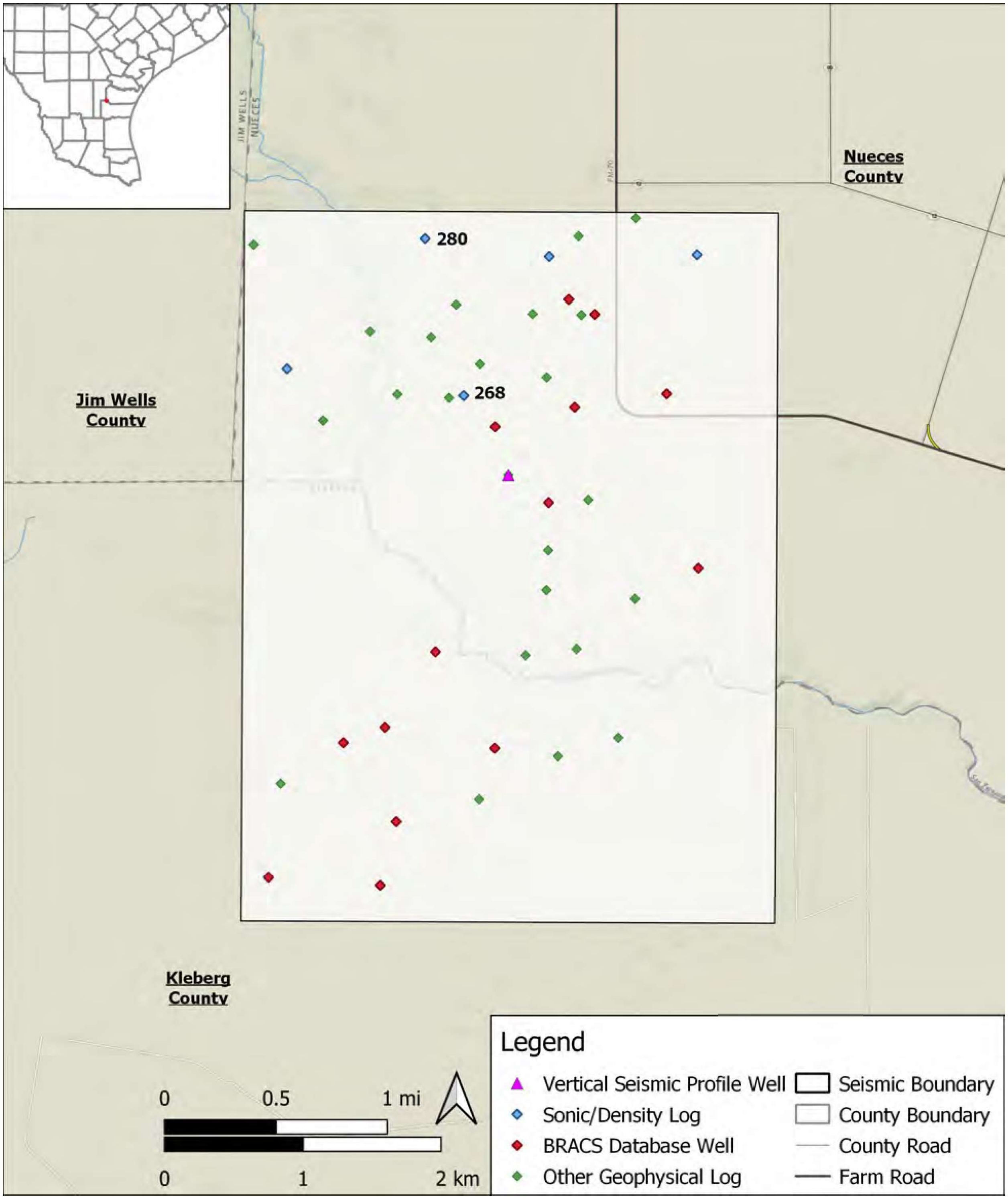
Figure 7-2. **Generalized Cenozoic stratigraphic succession and architecture of the Northern Gulf of Mexico basin. From Galloway (2008).**

The Willis is the shallowest unit that might be resolved by the seismic dataset. It represents Pliocene deposition and, similar to the Goliad, the Willis was dominated by nonmarine, fluvial depositional systems in the onshore part of the Texas Coastal Plain (Guevara-Sanchez, 1974; Solis, 1981; Galloway and others, 2000). At outcrop, the Willis is composed of gravelly coarse sand in several upward-fining successions that are interpreted as incised valley fills overlain by transgressive deposits (Morton and Galloway, 1991).

7.2 Methodology Evaluation

7.2.1 Project Foundations (Task A)

The scope of this portion of the project is to apply our methodology, as developed in Task 4 (Chapter 6), to a completed Brackish Resources Aquifer Characterization System aquifer study. Our completed Brackish Resources Aquifer Characterization System study is the Identification of Potential Brackish Groundwater Production Areas – Gulf Coast Aquifer system (Young and others, 2016). Our study area is the Stratton seismic area (as defined by the 7.5-square-mile extent of the seismic volume), and the interval of study is the Miocene to Holocene (Figures 7-2 and 7-3).



Note: BRACS = Brackish Resources Aquifer Characterization System

Figure 7-3. **Basemap of the Stratton Dataset.**

7.2.2 Data Collection (Task B)

The Bureau of Economic Geology dataset has been used in several research papers, focused on seismic geomorphology of the fluvial-deltaic Frio reservoirs (El-Mowafy and Marfurt, 2016). Of particular interest, Al-Gain and others (2020) applied five-dimensional interpolation processing to improve imaging of Frio sandstone reservoirs. Al-Gain and others (2020) was previously discussed in Task 1 (Chapter 3). No previous work, however, has focused on the water-bearing Miocene sandstones above the hydrocarbon reservoirs.

The Bureau of Economic Geology survey was acquired using 4 vibrators running 8 linear sweeps from 10-120 Hertz at each source point (Hardage and others, 1994). Receiver groups were spaced 110 feet apart on east-west lines. The east-west lines were spaced 1,320 feet apart. Source points were 220 feet apart on north-south lines. The north-south lines were spaced 880 feet apart. This created bins of 110 feet north-south by 55 feet east-west with nominal 20-fold data at depth (Figure 7-4). Acquisition used four four-receiver-line swaths. This means that the shots were recorded by receiver lines first in swath 1, and then in swaths 2, then 3 and 4. This results in azimuths that are sharply limited to the dip (east-west) direction.

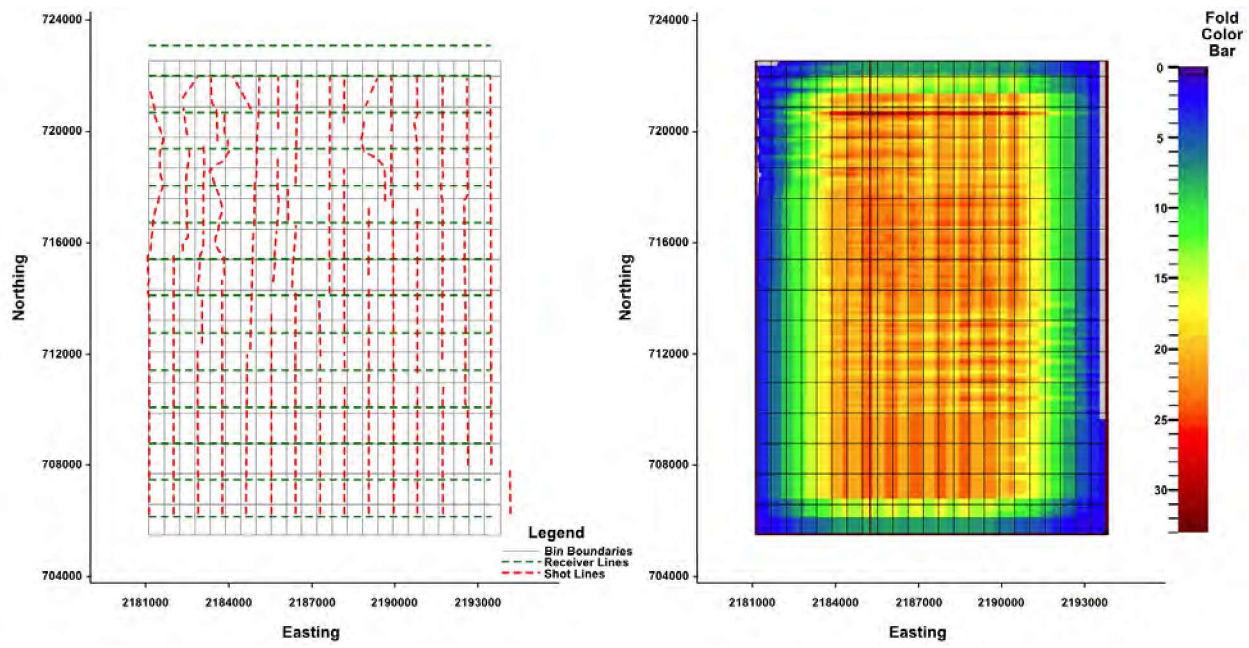


Figure 7-4. (Left) Shot and Receiver line map of the Stratton survey. Shot lines were roughly oriented North-South and receiver lines were oriented East-West. Easting and Northing are in Texas State Plane coordinates, South Zone, the coordinate reference system used for documenting geometry of Stratton. (Right) Map of fold derived from source and receiver geometry. The color of the map indicates the fold of the seismic data. Folds range from 0-5 on the fringes of the survey to near 30 in the center.

To conduct the present study, a search for logs was conducted throughout the 7.5-square-mile survey and a limited area around it. Most of the open-hole logs start around 1,500 feet (the casing point to protect fresh water), with some old logs going shallower and some shallow cased-hole logs included. Four wells had sonic logs below 1,500 feet and one had a density log in the same interval. These have been digitized and were critical to the reprocessing effort described below. In general, the lack of logs over the shallow section (especially density and sonic) is a major issue with reprocessing the Stratton dataset. This problem is in no way limited to the Stratton dataset and represents one of the main obstacles to incorporating legacy seismic when evaluating (shallow) brackish groundwater systems. However, since there are adequate brackish targets at Stratton below 1,500 feet, this can be mitigated. The section above 1,500 feet simply has less information in the time-depth relationship compared with further down the section.

7.2.3 Stratigraphic Analysis (Task C)

Stratigraphic research, specifically on the water bearing units above the hydrocarbon producing intervals at the Stratton field has not been published, neither is there any core data from the Bureau of Economic Geology. Therefore, this study begins with well log integration into the established regional cross sections (Young and others, 2010; Young and others, 2012; and Young and others, 2016). The regional cross sections and their supporting documentation were acquired, examined, and brought into the interpretation software. The markers and formation boundaries were then transferred from the regional cross sections into the logs referenced in this project. INTERA has carried base Oakville, base lower Lagarto, base middle Lagarto, base upper Lagarto, base lower Goliad and base upper Goliad from the regional studies, as well as an estimate of base Willis (based on regional outcrop); Beaumont is at the surface (Young and others, 2016). These surfaces are based on biostratigraphy and a sequence stratigraphic approach to the characterization of the Gulf Coast aquifer system.

7.2.4 Hydrogeologic Study (Task D)

The Texas Water Development Board databases have limited water well data specifically for the brackish sections overlying the Stratton field, and no water chemistry samples (Figure 7-3). Instead, water salinity has been estimated using earlier regional work (Young and others, 2016). From that work, the base of the very saline zone (35,000 milligrams per liter total dissolved solids) is roughly at the Base of Oakville. Interestingly, salinities of 15,000 milligrams per liter chlorine are reported from Frio reservoirs (though other anions may be contributing; Libson and others, 1985). The top of the very saline zone (10,000 milligrams per liter total dissolved solids) is within the Lower Lagarto, and the top of the moderately saline zone (3,000 milligrams per liter total dissolved solids) is within the Lower Goliad. Fresh water is confined to the Willis and younger units. These water quality surfaces are regional in extent and should be considered an approximation of formation water quality. No direct estimates of salinity have been made at Stratton Field for this study.

7.2.5 Seismic Data Search and License, Initial Interpretation (Tasks E and F)

In a typical seismic data evaluation, the analyst would have an area of study in mind and then would consult the various seismic databases for relevant data. However, given the unique nature of this particular study, the seismic dataset was located first, and then the study was built around the seismic dataset. The raw data was downloaded from the Society for Exploration Geophysicists Wiki and loaded into OpendTect and into IHS Kingdom, the data quality was reviewed and subsequently approved by INTERA and the decision to invest in reprocessing the data prior to further interpretation was made.

7.2.6 Processing Workflow and Introduction

The flow of processing for the Stratton dataset was similar to the general workflow presented in Task 4 (Chapter 6), proceeding from preprocessing and deconvolution to refraction statics, rebinning and five dimensional interpolations, to final velocities and prestack migration. Additional steps were run to obtain higher-resolution velocity fields, to look at maximum high-frequency resolution, and to clean the gathers for further interpretation.

Enhanced processing of the Stratton three-dimensional survey was carried out by Tricon Geophysical: David Williams, vice president; Jim Sobczak, processor; Vladimir Rabinovich, petrophysicist; and Francisco Bolivar, responsible for seismic inversion.

7.2.7 Preprocessing and Initial Processing (Task G)

The steps taken for Task G in Task 4 are initial steps to correct for some basic sources of error prior to a more involved interpretation. Steps included interpreting geometry of sources and receivers (which will provide instruction on how to sort the seismic information) and performing a spherical divergence correction (which is a correction for geometric spreading within the earth). These steps were executed for Stratton. Pre-processing proceeded as normal processing, with special attention to making sure sources of error were eliminated in the first 1.5 seconds of data (Miocene and upper Frio).

7.2.8 Processing: Second Stage (Noise Reduction and Statics) (Task H)

The second stage of processing consists of steps to reduce non-signal influence on the seismic data, and to correct for near surface effects that often disrupt a clear seismic signal. Reverberations and a type of noise called multiples can be mitigated by a process called deconvolution. Near surface effects by can be mitigated by statics corrections.

For the Stratton dataset, deconvolution proceeded as normal, with attention paid to the first 1.5 seconds of data, roughly equal to the top 6,000 feet. Refraction statics were calculated across the data set in source and receiver domains. Both sets of statics corrections are small. The combination of deconvolution and the minor statics adjustments resulted in noticeably cleaner data with reduced noise.

7.2.9 Processing: Third Stage (Stacking) (Task I)

Originally, the bins from the acquisition geometry were rectangular (110 by 55 feet). In order to present an unbiased interpretation, the data were rebinned to 55 by 55 feet square bins. The rebinning process involves defining a new geometry for the bins (55 by 55 feet here) and then sorting traces by their midpoint into their respective 55-foot square. The trace representing the bin in the volume is the compilation, or stack, of the traces in the bin. Interpolation using a five-dimensional interpretation algorithm was undertaken to increase the trace density and allow for more confident velocities and increased signal-to-noise ratio in the final data. The actual five-dimensional interpolation refers to the five elements of interpolation used to increase trace density where there is no trace, (in this case, shot x, shot y, receiver x, receiver y, and frequency). These parameters can be used as terms in an algorithm to interpolate what seismic traces should look like between other traces, thus increasing trace density.

The interpolated bins were then analyzed for stacking velocities, first at selected bins then for each bin. Tricon named this process Fastvel. This careful examination of velocities yields low-frequency, laterally varying information that may reflect lithology variations, and is used in determining the initial model for inversion. Task 4 (Chapter 6) listed this velocity analysis as a possible way to estimate bulk rock percentages. At this area, an attempt to estimate the bulk rock percentages would be a very rough estimate. However, using the Fastvel analysis technique during the inversion process can generate high confidence estimates of facies allocations.

Following sorting and Fastvel, the data were run through a prestack time migration algorithm, stacked and final volumes were produced. Seismic migration is a process where reflectors are re-located to the location where the event occurred in the subsurface rather than the location that the event was recorded at the surface, increasing accuracy. Not only is this necessary due to counter diffraction, but it also increases spatial resolution. Stacking is the compilation of traces to amplify signal and dampen noise. Substantial improvement was achieved over the original reprocessing (Figure 7-5). This volume contains a wide range of frequencies to about 80 Hertz, with smaller amounts of higher frequency signal (Figure 7-6). Although reprocessing allows for higher resolution given modern seismic processing techniques, reprocessing was not focused on improving vertical resolution. The frequency spectrum was largely unchanged through reprocessing. The raw seismic data remained the same, and any increase in vertical resolution was due to modern imaging techniques, and not due to any new data.

A final volume is made available to the interpreter both as vertical sections parallel and normal to the direction of the receiver cables, called inlines and crosslines, respectively. The volume can also be imaged by drawing off-axis lines or timeslices through the inlines and crosslines. This survey has 310 inlines and 230 crosslines.

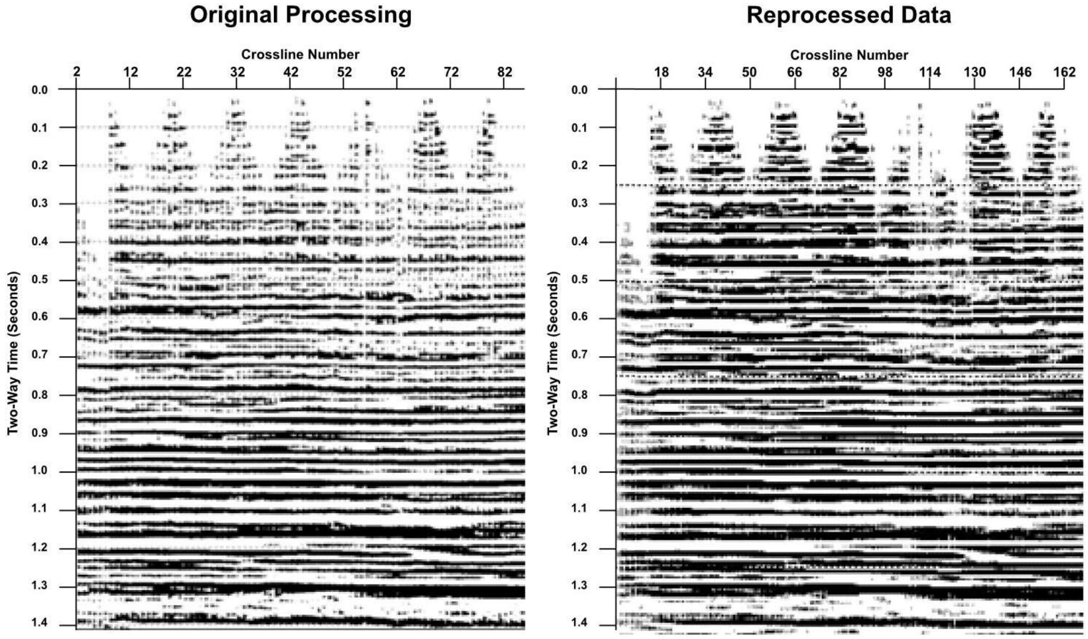
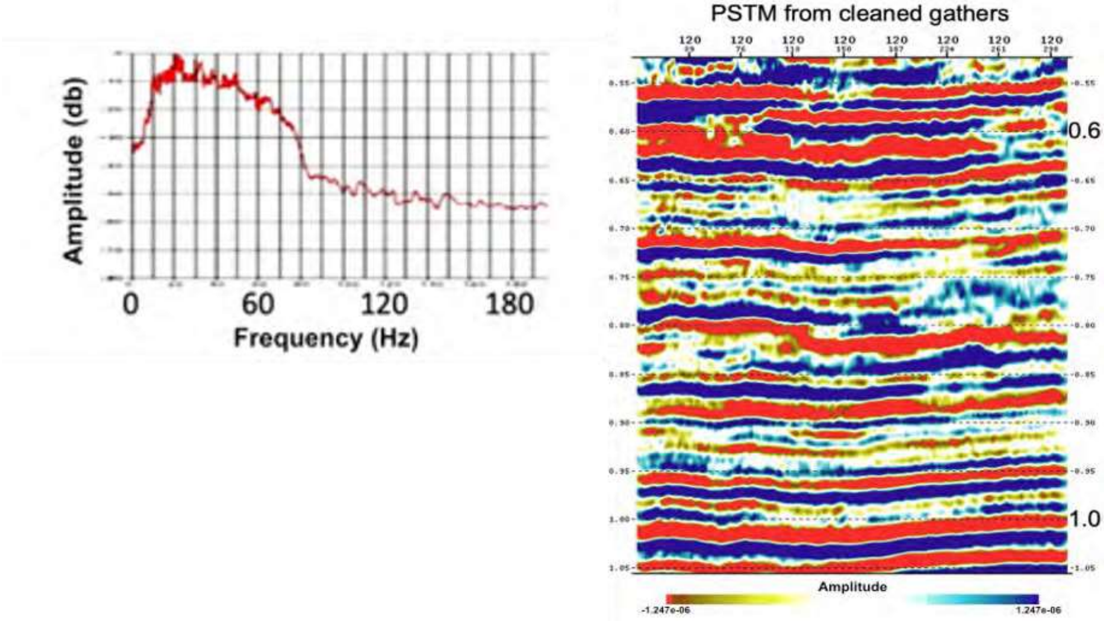


Figure 7-5. Inline 120, top 1.4 seconds shown. (Left) Original seismic line. (Right) Seismic line after reprocessing and five-dimensional interpolation. This seismic line depicts amplitude at depth. The shallow sawtooth structure in the images is caused by spacing between shot point lines. Note the increase in quality from the original. Quality here can be estimated by focusing on the continuity of the reflectors in the image, particularly in the shallow section.



Note: db = decibels, Hz = hertz

Figure 7-6. (Right) Final PSTM (prestack time migration volume), inline 120. This is a seismic line showing amplitude, but instead of black and white, the color blue indicates positive amplitude, and red indicates negative, with other colors indicating values between the endmembers. See color bar. (Left) Frequency spectrum of data. Frequency is a large control on vertical resolution of seismic data and is one of the mechanical attributes of the data useful to understand when processing and interpreting the data.

7.2.10 Final Amplitude Profiles/Volumes (Task J)

A set of typical final common midpoint gathers (seismic traces that get stacked together from a single bin), after interpolation, velocity analysis, final cleaning and flattening, is shown on Figure 7-7, along with an overlay of angle of incidence (angle of the reflected wave from normal off of the reflector in the subsurface, near traces are low, and far traces are high). The color overlays on Figure 7-7 allows for direct identification of low-angle (vertical) versus higher angle (oblique) traces are present at each depth. Due to excessive noise, the gathers have been muted from 50 degrees angle of incidence on up (yellow-red boundary). With this muting, the gathers show a good signal-to-noise ratio throughout. Note that a full fold is achieved below about 1.0 second, but adequate traces occur up to shallow times. Full fold means that each potential receiver is recording the reflectors from that depth. For instance, at the scale of Stratton, acoustic waves cannot travel from one end of the field to a reflector and return to the other end of the field in 500 milliseconds. This means some receivers will not record any information after a shot for up to a second before the acoustic energy is able to reach them. At one second, signal is recorded in all receivers, so there is full fold at one second. It is also worth noting that the zone above 600 milliseconds has essentially no low-angle traces (blue and purple in Figure 7-7); all traces are moderate to far offset. Thus, the sections as presented are dominated by far-offset (high-angle) information, which is more affected by shear velocities.

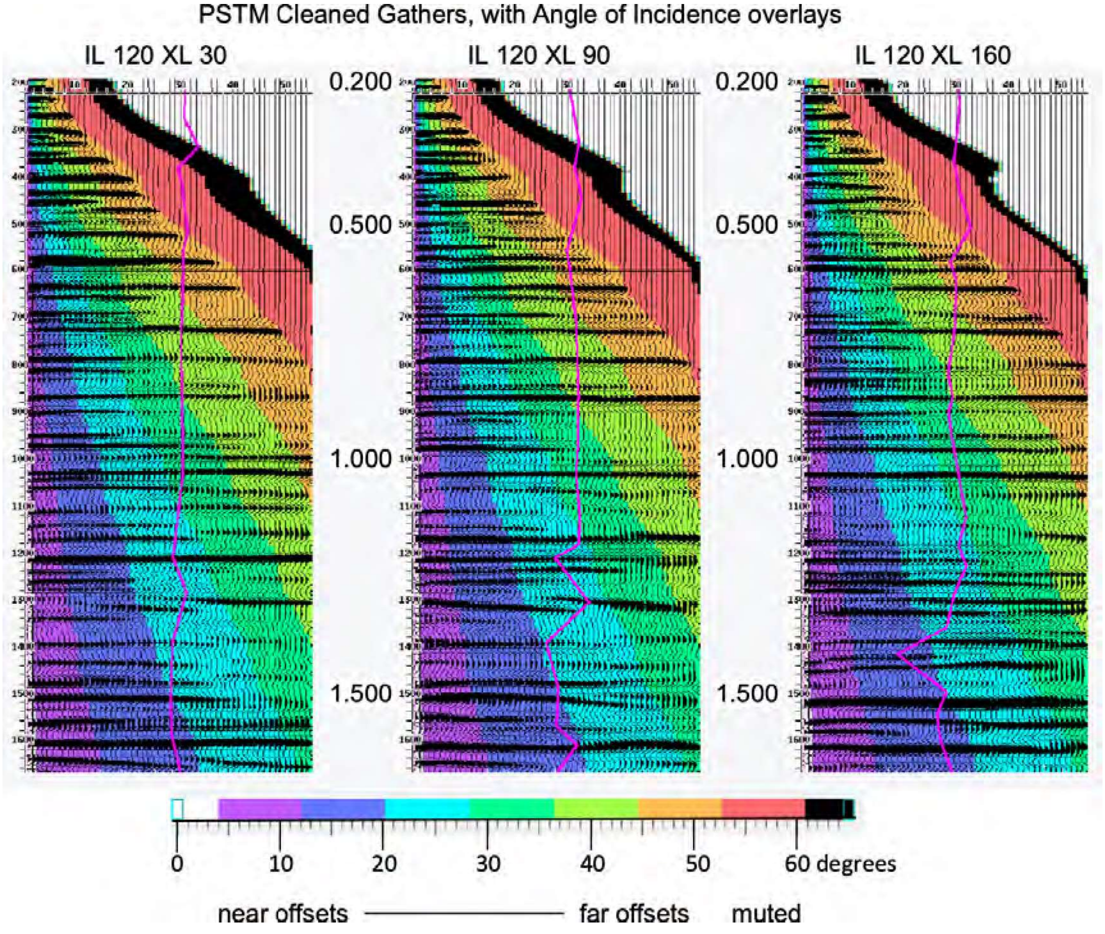


Figure 7-7. **Final gathers after all processes applied, overlaid with angle of incidence. The gathers are a collection of traces grouped by a common midpoint. Here we see unique wavelets for each trace. These wavelets indicate amplitude, but instead of the color bitmap as in previous figures, these are a collection of wavelets that indicate positive and negative anomalies by deflecting to the right (positive) or left (negative). Right, positive deflections are black filled. Note the lack of vertical (low angle) gathers above 600 milliseconds (purple and blue), and mute at about 50 degrees (no wavelets in red or black).**

7.2.11 Final Amplitude Volumes (Task J)

The reprocessing resulted in a great improvement over the previous processing as provided on Society of Exploration Geophysicists Wiki (Figure 7-8). In part this is due to increased attention to the shallow reflectors at all stages of processing. Much of the increase, though, can be ascribed to the five-dimensional interpolation routine. A statics problem in the earlier processing that led to a mistie between wells and reflectors in parts of the survey has been corrected in the new data, a large benefit of this reprocessing.

In the new processing, geologically reasonable and interpretable reflectors can be mapped throughout the Miocene section; even a shallow reflector roughly at the Base of Willis (Pliocene) can be interpreted at 150 milliseconds (about 250 feet), albeit with very high levels of noise. Greater continuity of reflectors was achieved at all depths. The effects of acquisition footprint can be seen throughout the section, increasing upward; but geologically reasonable reflection images are obtained into the shallow parts of the Upper Miocene.

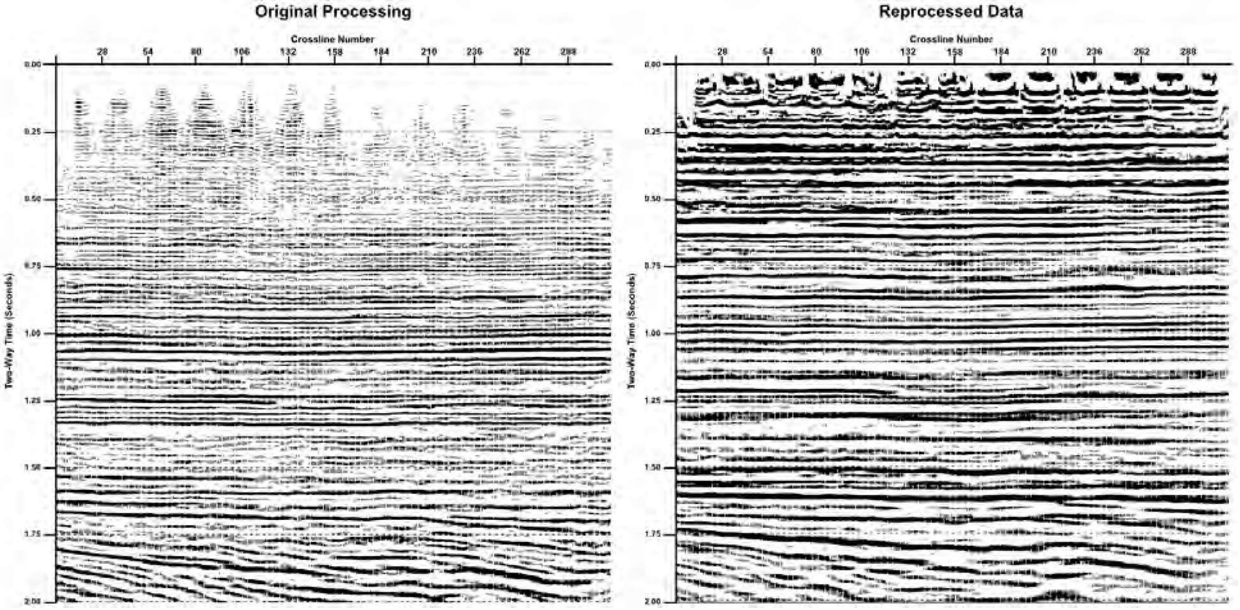


Figure 7-8. **Original processing vs pre-stack time migration interpolated reprocessing, inline 120. Amplitude peaks are white and amplitude troughs are black.**

7.2.12 Interpretation of (Seismic) Data (Task K)

Seismic Well Tie

Four wells had sonic logs below 1500 feet, and one had a density log in the same interval. The sonic logs were taken on Wardner wells 280, 146, 152, and 154. Above 1500 feet, the sonic information is not recorded. These have been digitized and were used to generate a synthetic log to tie the seismic dataset. Wells have been correlated into the seismic data, using synthetics generated from five sonic logs in the survey as well as the vertical seismic profile. An example of synthetic and input logs are given in Figure 7-9. During the seismic-well tie process, two types of transformations can be applied to the synthetic seismic log, stretching and bulk shifting. A bulk shift shifts the entire log in time and stretching is changing the time-depth relationship of the synthetic log in an interval to better match the seismic data. A bulk shift of the data of +40 milliseconds was found to give optimal ties to the sonic information, along with some minor stretching. Reflectors corresponding to various well log tops were carried across the data set. The synthetic seismogram and seismic data from the survey are given in Figure 7-10.

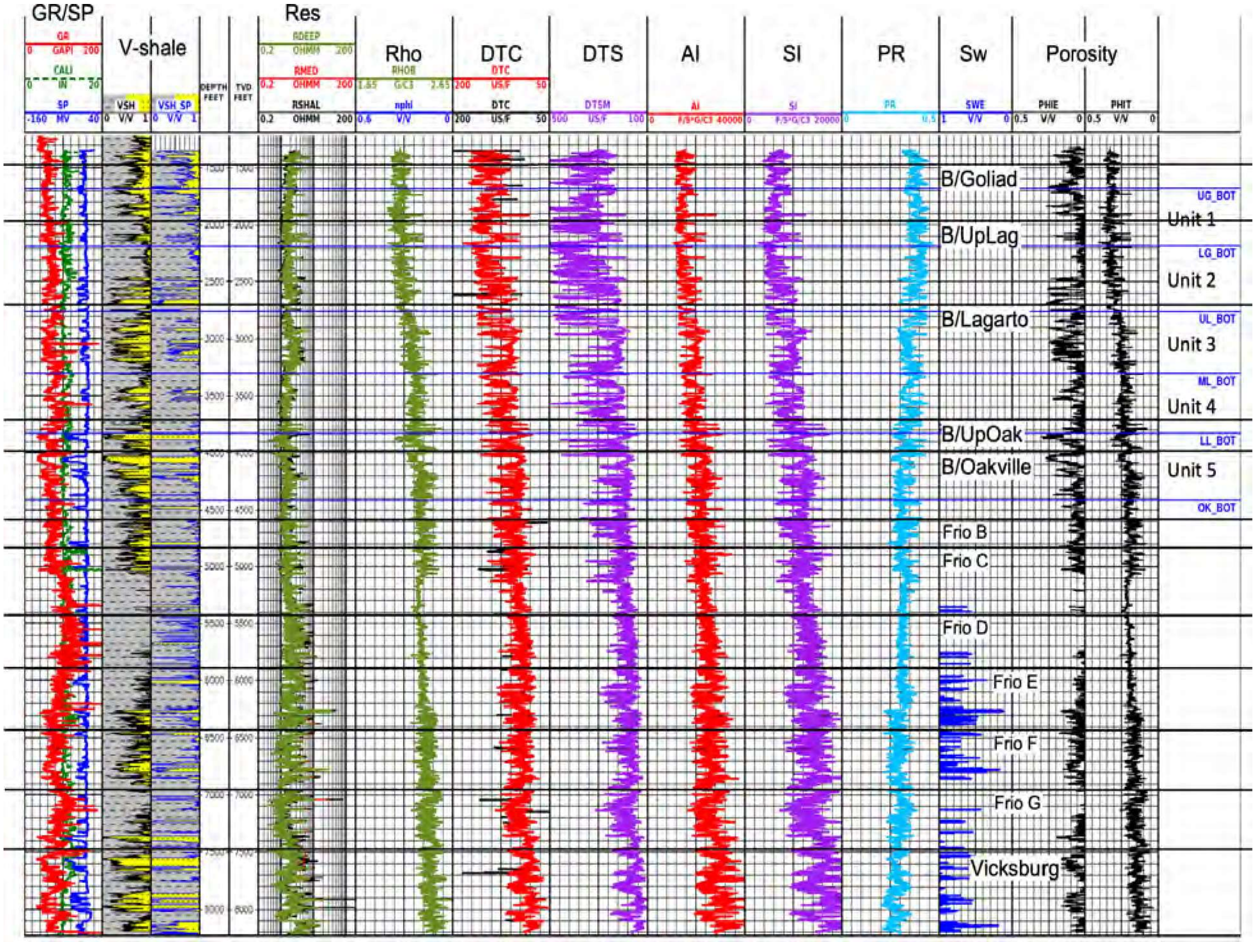


Figure 7-9. **Input and output petrophysical curves for Wardner #268. Curves left of depth track show lithology (gamma ray, spontaneous potential, shale volumes); four tracks right of depth are input curves (density from Wardner 280); next three tracks are acoustic impedance (red), shear impedance (purple) and Poisson's ratio (light blue); then water saturation (pay flags in Frio), and porosity (effective and total).**

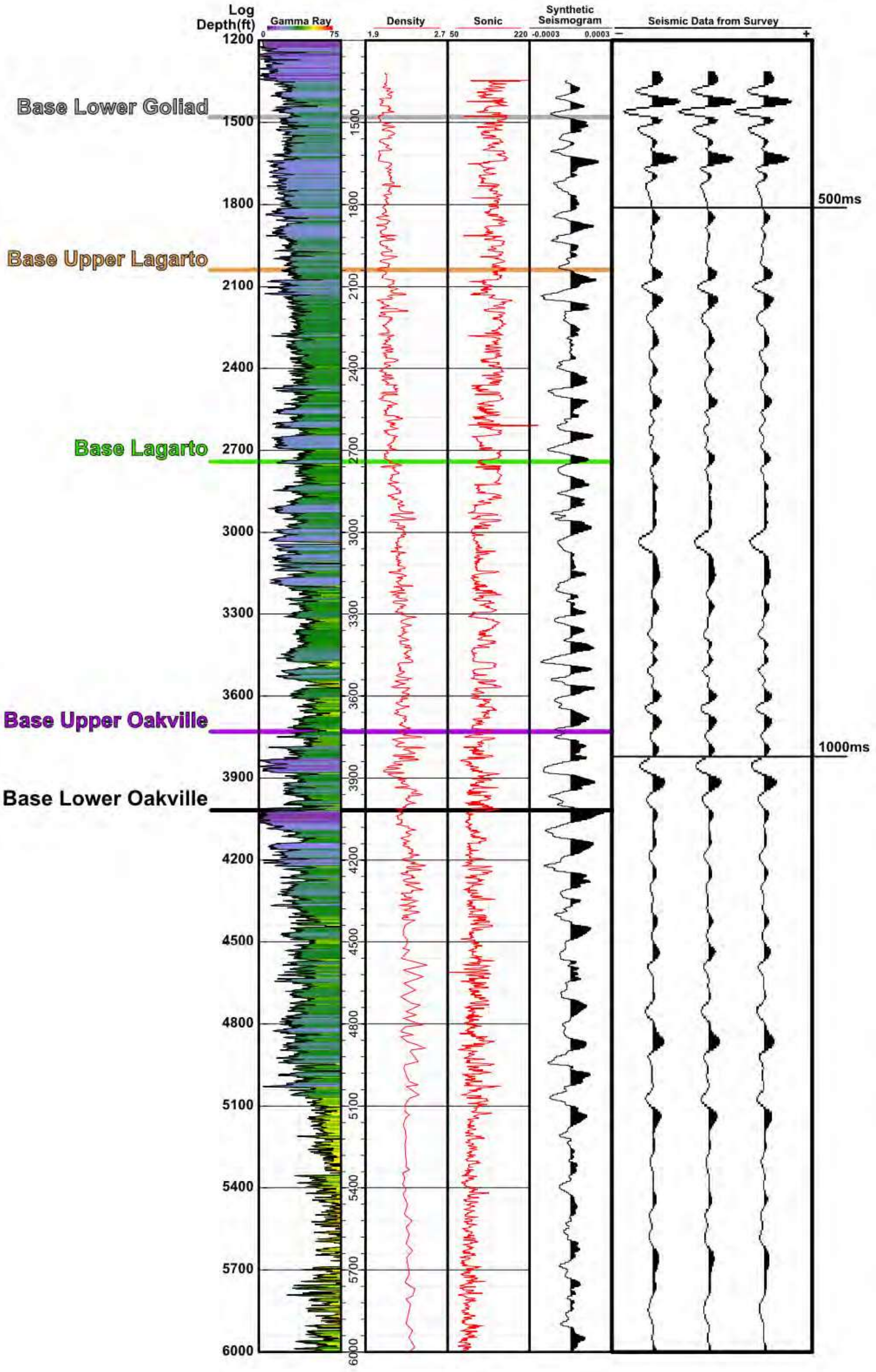


Figure 7-10. Petrophysical curves, synthetic seismogram, and seismic data from survey for Wardner #268. Curves show gamma ray, density, and sonic. The seismograms include the synthetic generated for the well as well as seismic data from the survey surrounding Warnder 268. The synthetic seismogram and the seismic from the survey have been tied. Z axis is in depth with reference points for time in the volume listed to the right.

Tie Well Horizons

Integrating the well logs with the seismic data, it is worthwhile to examine the seismic character in the different parts of the Miocene, from Oakville and uppermost Frio (lowest) through Lagarto to Goliad (highest) (Figure 7-11, Table 7-1). All units are interpreted according to correlations based on interpolation between downdip marine shales and surface stratigraphy (Young and others, 2016).

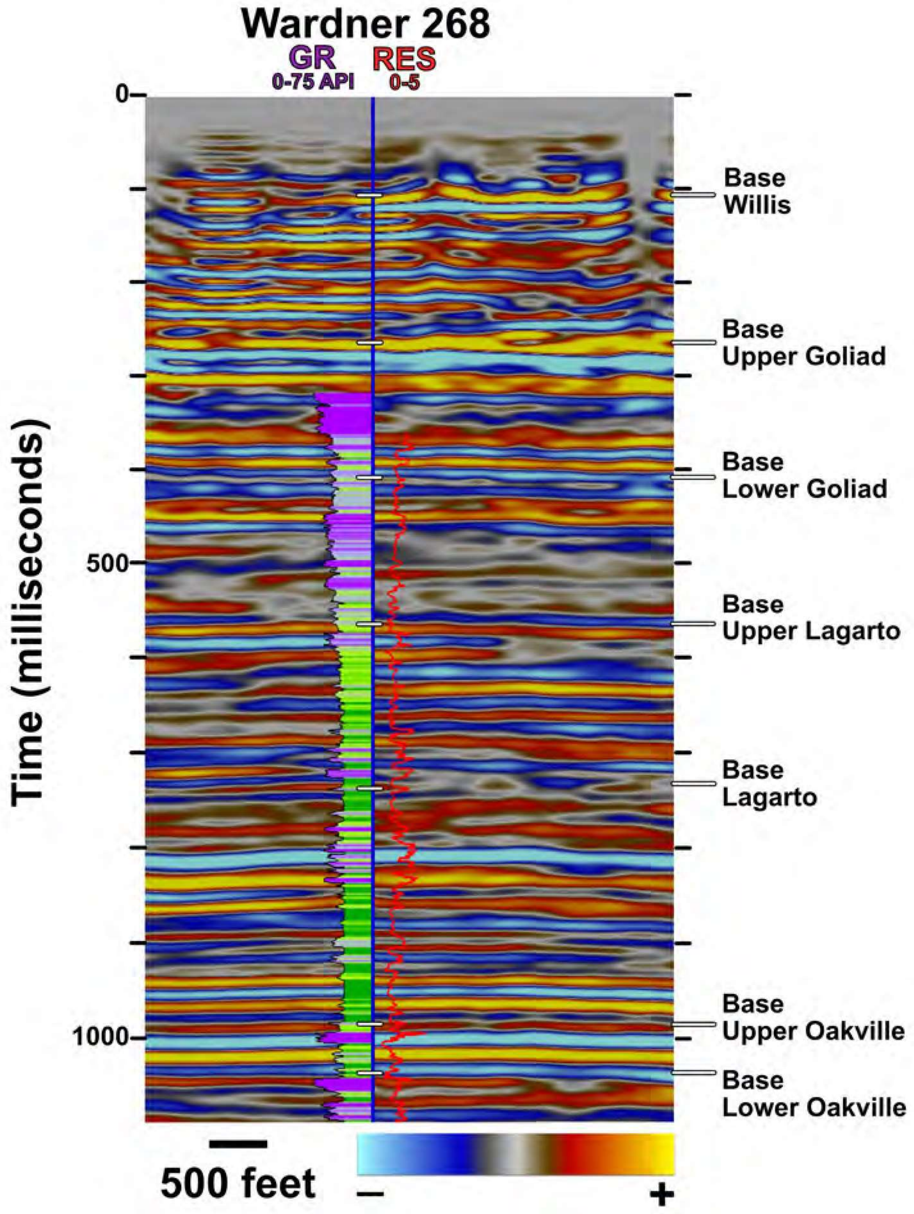


Figure 7-11. **Portion of inline 230, showing the 268 well logs versus seismic amplitude information for the Oakville to the surface. Color bar refers to seismic amplitude. Depth marks in milliseconds are given in black and the formation boundaries are given in white lines on the well track and on the right margin.**

Table 7-1. **Table of formations penetrated by Wardner 268, and corresponding depth in milliseconds and depth in feet.**

Base Depth (milliseconds)	Base Depth (feet)	Average Interval Velocity (feet per second)	Geologic Unit	Hydrogeologic Unit
110	~222	~2018	Willis	Chicot
264	~1064	~4030	Upper Goliad	Evangeline
403	1485	3685	Lower Goliad	
539	1967	3649	Upper Lagarto	
711	2751	3869	Middle and Lower Lagarto	(Burkeville &) Jasper
970	4018	3856	Oakville	

Overall Interpretation of Section

The following paragraphs will discuss the features of each formation (Figure 7-11). The formations were examined on various seismic sections with tied logs, and also on selected time slices. Tops were carried from the logs onto the seismic and then were correlated in the seismic dataset.

The Oakville interval from 2,750 to 4,200 feet (780 milliseconds to 1.090 seconds) is comprised of strong, parallel, continuous reflectors that carry through the study area. The lower Oakville interval (1.05-1.09 seconds) generally contains two sandy horizons, each about 50 feet thick, which yield moderate to strong seismic reflections. The uppermost of the sandstone levels occurs immediately below the Siphonina davisi marker (mid-Oakville) correlation, which is associated with a pronounced trough over peak. The upper Oakville is a thicker interval, which includes two continuous sand-bearing intervals with multiple individual sandstones included. These intervals show up as strong, continuous reflectors on the seismic data.

The Lagarto interval from 1,500 to 2,750 feet (430 to 780 milliseconds) includes a continuous, thick sandy interval at the base, overlain by a mudstone-rich zone with more isolated sand bodies. The unit is relatively transparent on seismic data, with some reflection strength reflecting the basal sands and some towards the top of the interval.

The Goliad interval from 250 to 1,500 feet (150 to 430 milliseconds) is comprised of strong, parallel, relatively continuous reflectors of variable strength that carry through the study area. The Goliad interval has increased sandstone content, mainly (at least where logs are available) as thin-bedded sandstones in thin but complex sand zones. Seismic reflections are stronger and more numerous in this zone. Most well log information terminates at the base of the Goliad, except for cased-hole logs and a very few older logs.

Seismic Interpretation by Time slice Analysis

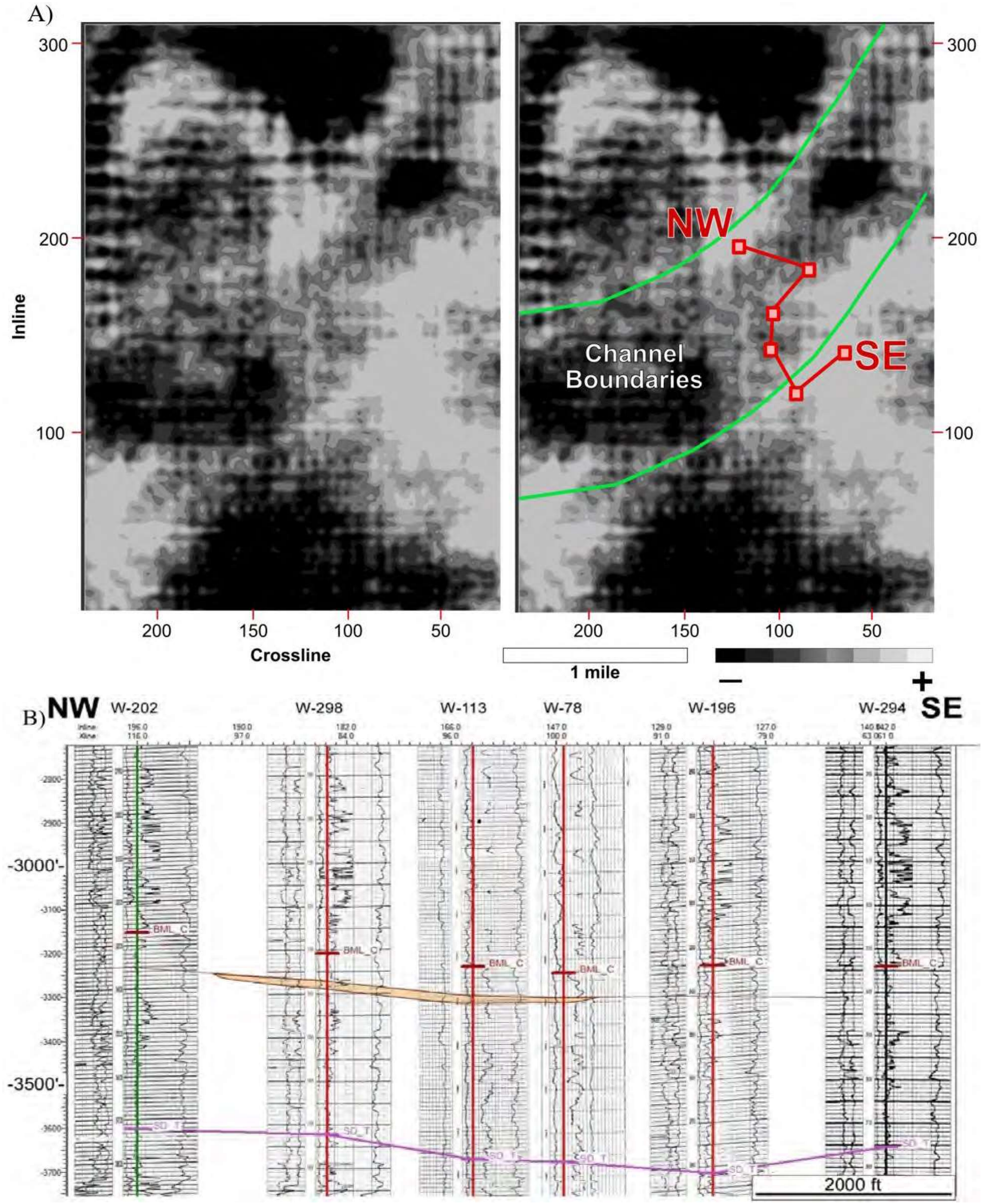
Channels in this volume were identified by stepping through the volume in time slices until a channel feature appeared. Time slice analysis allows for the investigation of amplitude trends along the X and Y plane, beneficial for channel hunting. When a channel is found, it is investigated on a vertical seismic line and in the logs to see if the candidate channel morphology and petrophysical character is consistent with the characteristics of typical channels. Other sand intervals that are found in this dataset are sheetlike, with a high width to height ratio, spanning large portions or all of the seismic survey area. These sands are hard to image from amplitude data alone, and the need to image these sands would be a case for inversion or rock property analysis in the volume. The preliminary amplitude volume time slice analysis in combination with seismic attribute analysis reveals at least three channels in the study area (Figures 7-12 through 7-16).

Channels have been identified in the upper Oakville, and the lower Lagarto. Some channels have a width of some 2,000 to 3,000 feet and can be mapped across the survey in several cases (at least 2.5 miles). There is another case that has a much narrower expression in the Upper Oakville. The channel thickness is not determinable from the amplitude data but are generally thin. Well data indicate a thickness of 20 to 50 feet thicknesses.

In the Upper Oakville, a discrete channel, named Upper Oakville Channel 1, is imaged in the shale-rich zone above the lower sand interval (938 milliseconds; Figure 7-12). The channel basemap is depicted on Figure 7-12A, and well-log-seismic cross section on Figure 7-12B. The channel trends northeast to east and ranges from gently curving to nearly straight.

A use of this three-dimensional imaging is the calculation of volume. Advanced volumetric analysis are possible with an advanced interpretation suite, but a simple one is provided here. Direct measurement of the upper Oakville channel gives an area of about 1384 acres. Multiplying this by an anticipated average channel thickness of 20 feet would yield about 1.2 billion cubic feet of sand. If porosity is assumed to be 25 percent, pore volumes would equal about 302 million cubic feet or about 7,000 acre-feet. Even though this is a coarse calculation, this is far more accurate than a desktop analysis of well-log data can approximate. So, estimates of the volumes of groundwater are far more accurate with three-dimensional seismic data.

The Upper Oakville Channel 1 can also be imaged via seismic attributes (Figure 7-13). Discussed in Chapter 6, seismic attributes are aspects of the seismic signal that can be parsed to determine various geological features. Attributes analyzed include instantaneous envelope weighted phase, instantaneous envelope weighted frequency, instantaneous frequency, instantaneous amplitude, semblance, similarity, and energy. Figure 7-13 shows the different attributes at 938 milliseconds and how they resolve the channel. The attributes found to be useful in resolving this channel were instantaneous envelope weighted phase, instantaneous envelope weighted frequency, and instantaneous frequency. Instantaneous returns the attribute at a single location (instead of over a range). Instantaneous frequency then is a measure of the frequency at a given location. Envelope refers to a line that connect the peaks of a seismic trace and a line that connects the troughs of a seismic trace to form an "envelope" that the amplitudes of the trace all fall within. Weighting improves interpretability of instantaneous attributes by removing spikes and reducing noisy variations. So, the attribute instantaneous envelope weighted frequency refers to the examination of frequency at a given location using a weighting function that considers the seismic trace envelope.



Notes: BML_C – Base Uppermost Oakville. SD_T – Siph. Davisi Top (Biostratigraphic Marker).

Figure 7-12. **Upper Oakville Channel 1 imaged on seismic data. A) Annotated and unannotated amplitude volume time slice of channel at 938 milliseconds. B) Well-log section along zigzag line on A, showing imaged channel. Logs to left of depth track are spontaneous potential and caliper, to the right are resistivity and often conductivity.**

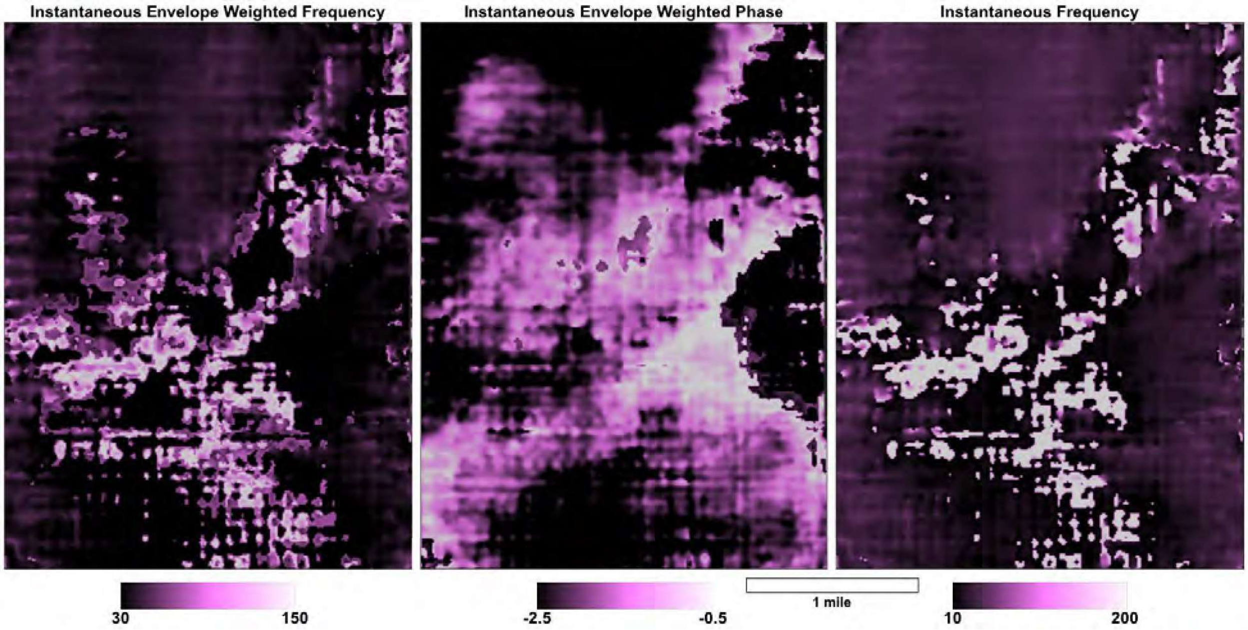


Figure 7-13. **Upper Oakville Channel 1 imaged using seismic attribute data. Left- Instantaneous Envelope Weighted Frequency. Middle- Instantaneous Envelope Weighted Phase. Right- Instantaneous Frequency.**

Another channel, named Upper Oakville Channel 2, occurs in the upper Oakville at 842 milliseconds (Figure 7-14). The channel is unlike the others mentioned here in that it does not have a broad expression, instead it is fairly narrow. This channel was identified in Pennington and others (2002), and also here. The channel trends east-southeast. The dimensions of this channel are not conducive to cross section construction with all but the tightest well spacing, so this channel is difficult to explore via cross section analysis. This provides a further point of evidence to support seismic imaging.

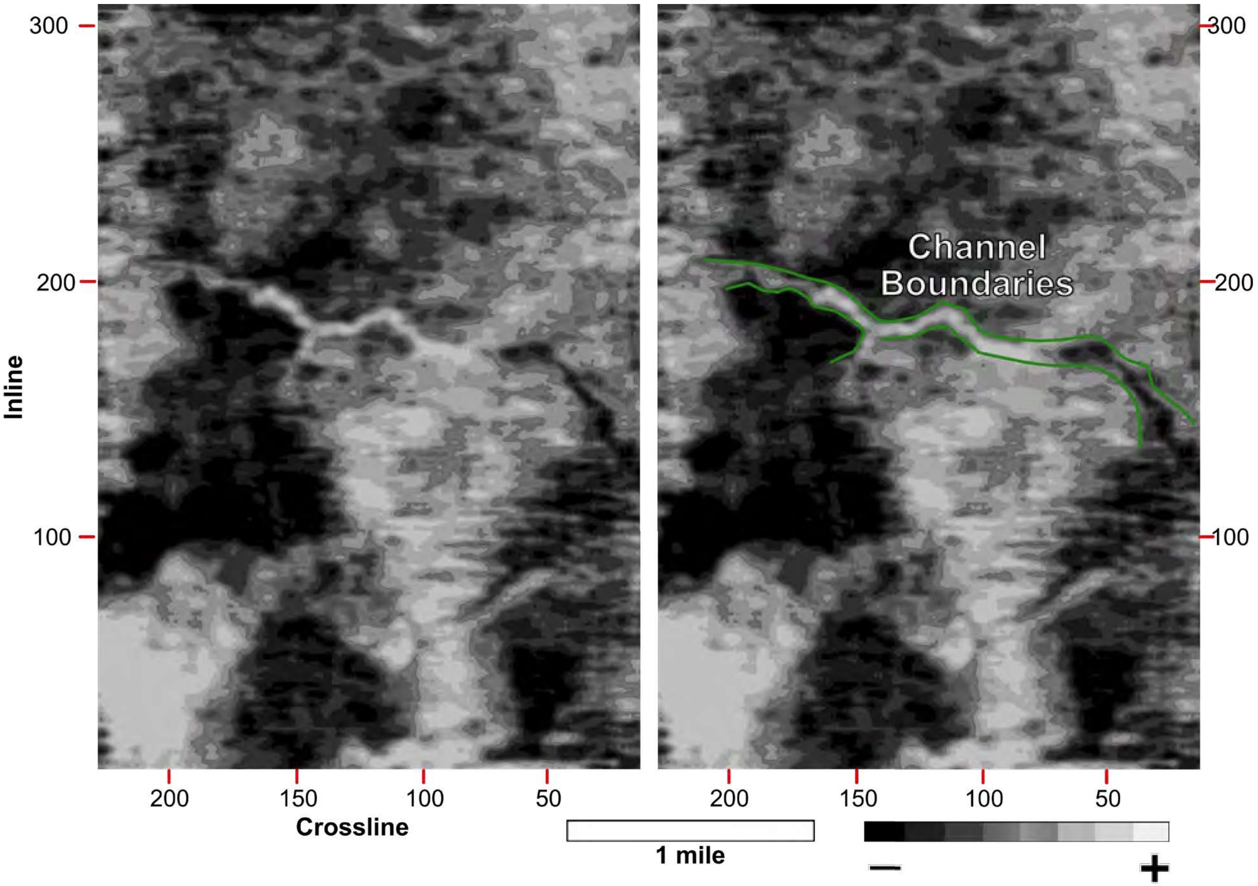


Figure 7-14. **Annotated and unannotated Upper Oakville Channel 2 imaged on amplitude volume time slice at 842 milliseconds depth. Color bar depicts amplitude. The channel is narrow as compared to the other imaged channels and shows what is perhaps a fork to the central western portion of the dataset.**

In the Lagarto, a discrete channel, named Lagarto Channel, is imaged on the seismic data at 600 milliseconds, below the lower sand interval (Figure 7-15). The channel basemap is depicted on Figure 7-15A and associated cross section in Figure 7-15B. The channel trends roughly south, is gently curving, and may feed into a more regional sand interval to the southwest.

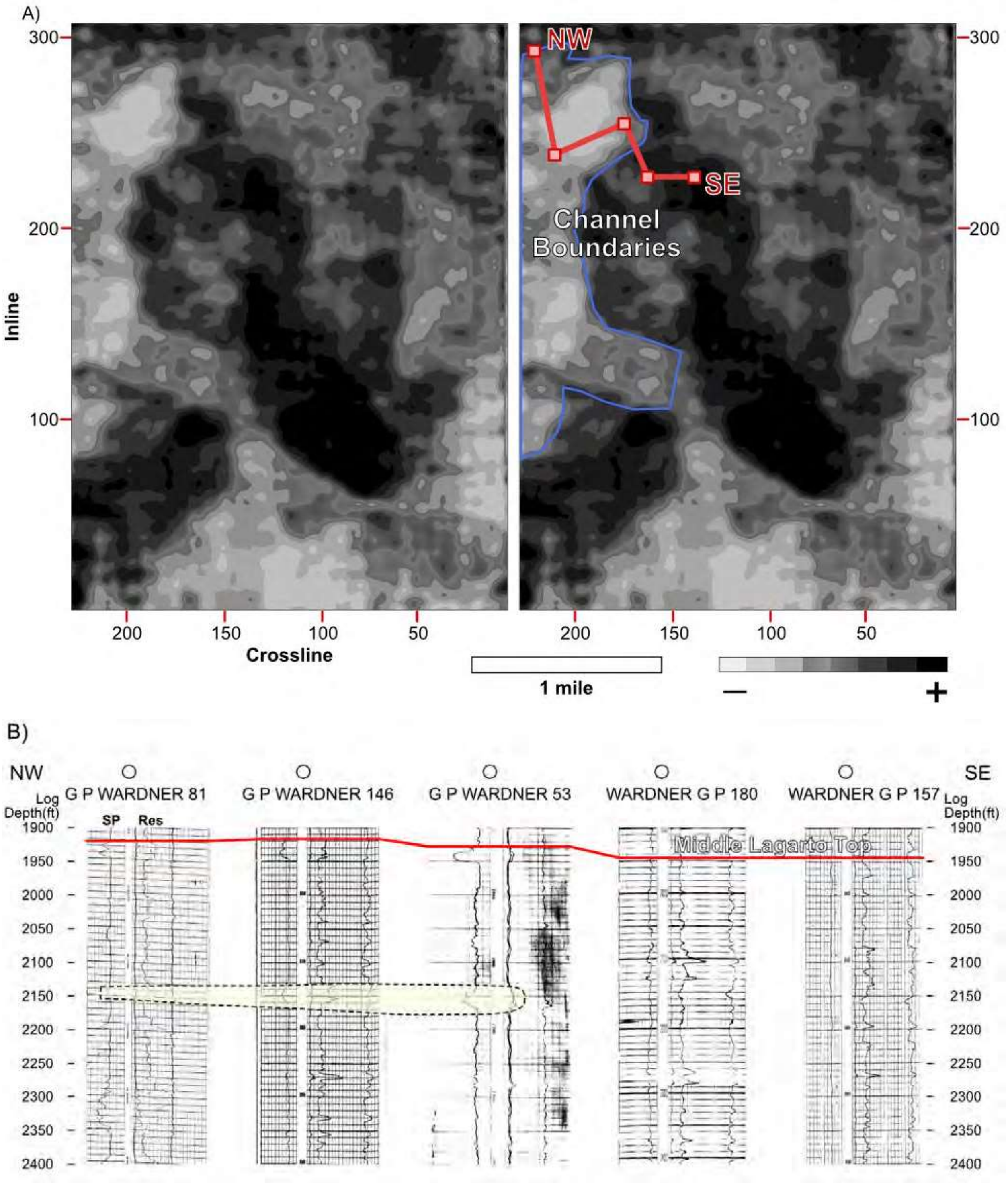


Figure 7-15. **Lagarto Channel imaged on seismic data at 600 milliseconds and in cross section. (A) Amplitude volume time slice with and without channel annotation and cross section line. (B) A cross section depicting the channel in depth. The sand outlined at roughly 2,150 feet is the channel imaged in the time slice.**

A map of the channel footprints is located in Figure 7-16. This figure shows the utility in developing many targets for development. At the overlap locations indicated, at multiple channels exist. Assuming that all of the sands were productive, a well screened to multiple channels would increase production potential relative to a well that was only intersecting one.

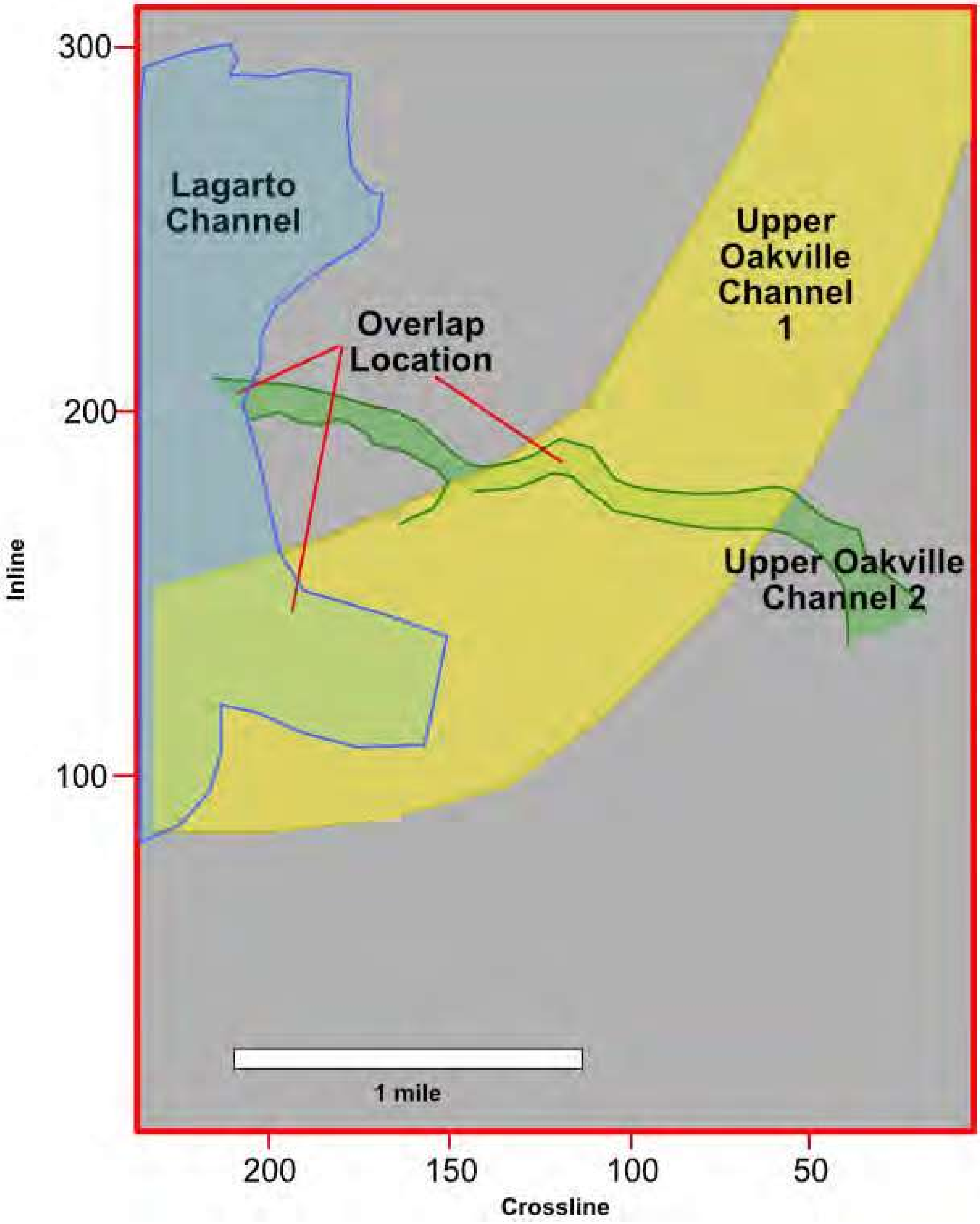


Figure 7-16. **Schematic diagram illustrates the positions of the channels relative to the survey within 600 milliseconds to 940 milliseconds interval corresponding to Oakville and Lagarto Formations.**

7.2.13 Inversion (Task L)

Purpose of Inversion

Inversion gets the interpreter one step closer to the strata than amplitude volumes alone. Amplitude volumes record properties at interfaces (amplitude of the seismic wave returning from the reflectors). Inversion takes those interface properties and converts them (along with well-log data) into a rock property called acoustic impedance, which is the product of acoustic velocity and density. Two varieties of impedance can be calculated, one from near-offset traces (P-wave impedance) and one from far-offset traces (yielding shear impedance) These properties can be used to solve for a variety of rock properties, such as:

- Poisson's ratio (ν): a measurement of the magnitude of deformation of a substance normal to the direction of applied force.
- shear modulus (μ): a measurement of the ratio of shear stress to shear strain.
- bulk modulus (λ): The ability of a substance to withstand changes in volume per changes in pressure.
- density (ρ): the mass of a substance divided by its volume.
- P-wave velocity to S-wave velocity ratio (Vp/Vs): Speed of a P-wave through a substance over the speed of an S-wave through a substance.

These properties are useful only in so far as they can be combined to get the interpreter closer to facies determinations. Different properties are sensitive to different features in the subsurface. P-wave impedance and λρ inform the interpreter about pore space effects such as porosity. S-wave impedance and μρ inform about lithology with effects of pore space and fluid removed. Comparisons between properties can illustrate whether an effect is from pore spaces or from lithology (Francis, 2013).

Utility of Inversion for Stratton

At Stratton, inversion was undertaken (contracted to Tricon) for a three main reasons: (1) the aquifer strata (permeable sand) has rock properties and characteristics that differ from non-aquifer strata (impermeable clay and shale), (2) the geometry of many of the potential aquifers are not sufficiently delineated from an amplitude volume alone, and (3) this study contains the necessary log suite to perform the inversion.

Taking the seismic data through inversion represents additional project costs and effort that may not be necessary. Examples of when inversion might not be necessary would include: (1) a fractured aquifer, or some aquifer where the aquifer strata are similar to the non-aquifer strata; (2) when project scope is limited to searching for easily discerned geobodies; (3) when attempting to determine fault locations since the faults will be clear on the normal seismic amplitude volume. Also, inversion usually requires well data on sonic and density through the target interval, possibly supplemented with detailed seismic velocity analysis. Without sufficient log data, an inversion would provide questionable results at best.

Necessary Data

To reliably invert the seismic dataset, the low frequency variation must be recovered. This can be done to an extent using the detailed stacking velocity profiles or volume generated for this study by the Fastvel process. Further corrections are made by generating a detailed petrophysical model of one or more wells in the survey area using sonic and density logs. This model is then used to calculate the true acoustic impedance at the well or wells, and other rock parameters necessary for the inversion.

In the Stratton area, the study has four wells with sonic data below 1,500 feet measured depth. The Wardner #268 well was chosen for modeling since it is the most central within the three-dimensional survey (Figure 7-3). One drawback of the Wardner #268 well was that no density log data was available over the Miocene section. Fortunately, Wardner #280, roughly 3,500 feet northwest of #268 had density data over the Miocene section. The density log from Wardner #280 was used to create a pseudolog for #268 by projecting the #280 well data into the #268 well. This was done with the aid of the stratigraphic correlations and resistivity log signatures. This process could be an issue with anomalies that occur at the #280 location that do not appear at the #268 location. For instance, a random oyster bed intersecting the top Goliad at #280 might not be present at #268. This risk is small, and usually low consequence, over the short distances and flat geology involved.

Pseudolog

Following the creation of the density pseudolog, the pseudolog and the sonic logs are edited, density is checked against resistivity information, and the volume of shale is estimated from gamma-ray and spontaneous potential logs. Porosity and water saturation are calculated from density and resistivity information. The result of these actions is a reliable breakout of sands, shaly sands and silts, and shales from the dataset.

The results of this work for the entire well Wardner #268 are shown on Figure 7-9. The left-hand tracks show sand/shale characterization from gamma-ray and spontaneous potential. The high gamma-ray below 5,000 feet is due to abundant volcanic ash in the Frio (Catahoula) section, as described by Kerr and Grigsby (1991). All curves related to acoustic impedance and rock properties show a strong compaction trend, with density, velocity, acoustic impedance, and shear impedance increasing with depth, and Poisson's ratio and porosity decreasing with depth. Acoustic impedance and shear impedance are higher in sands than in shales, as expected from regional work. However, the difference is not large, and is overwhelmed by the compaction trend unless the log is analyzed zone-by-zone (here using tops from the Brackish Resources Aquifer Characterization System database). Details of the log curves are shown in a series of figures in Appendix 1.

Pseudolog Cross-plots

The resulting data from Wardner #268 set can be viewed with color-coding of sand versus shale (Figure 7-17). The shale (red) yields a smooth compaction trend, porosity decreasing with increasing depth. The sands (green and blue) are mainly lower porosity and higher grain density. Thus, the acoustic impedance of sands is generally higher than shale). This is important because as the ability arises to identify differences in facies on crossplots, there becomes an expectation of what the seismic volume will show. Variability with depth is shown in rock mechanical properties, as shown on a series of plots of $\mu\rho$ versus $\lambda\rho$ (Figure 7-18) for units from shallow (base of Goliad) to deep (top of Frio). These are important because the interpreter should be able to recognize the influence of signals apart from a depth trend. The compaction trend effect allows a broad first order check on the rock properties.

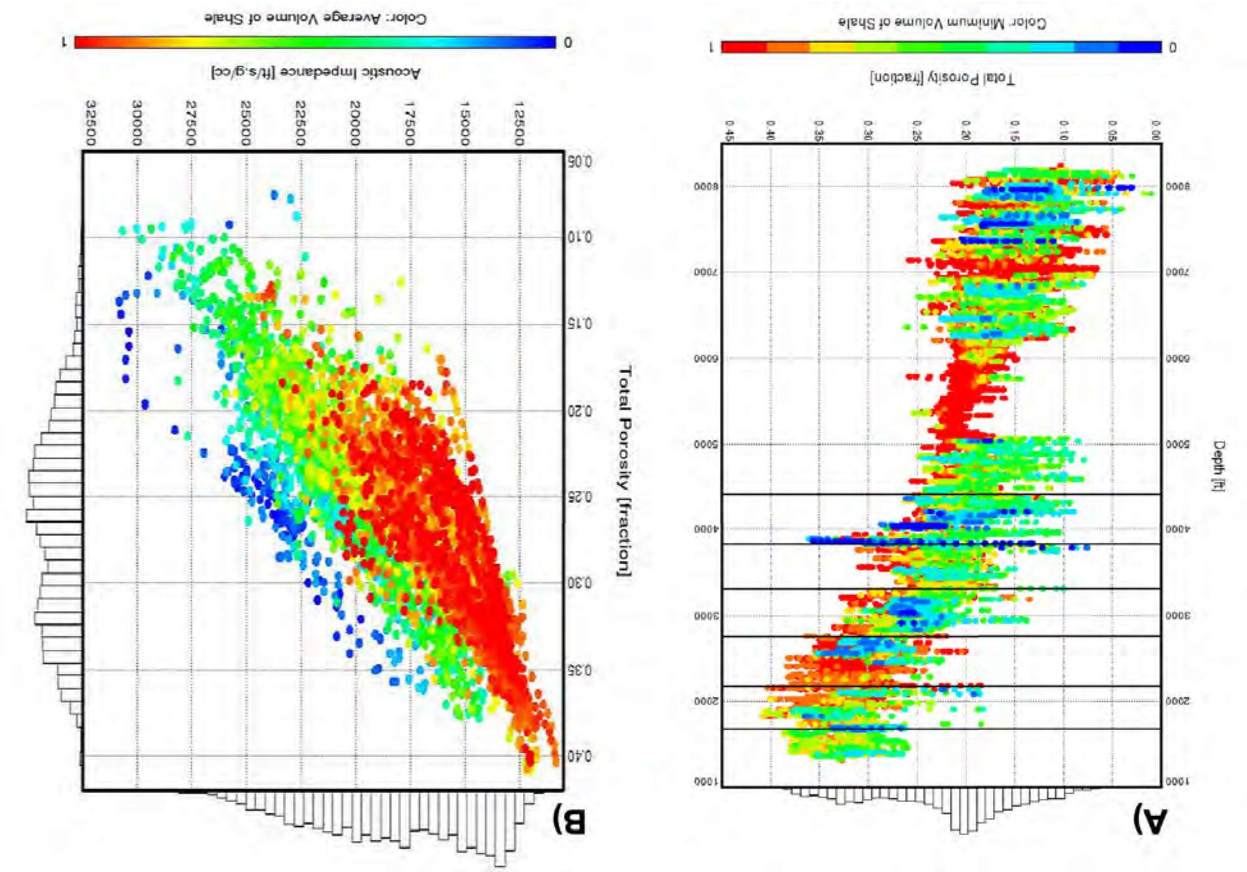


Figure 7-17. **Compaction trends of sands and shales in Wardner #268. (A) porosity versus depth; shales (in red) show a smooth curve, sands (in green and blue) are mainly lower porosity at any depth. (B) Acoustic impedance versus porosity; sands are higher in acoustic impedance at any porosity, but the fields overlap.**

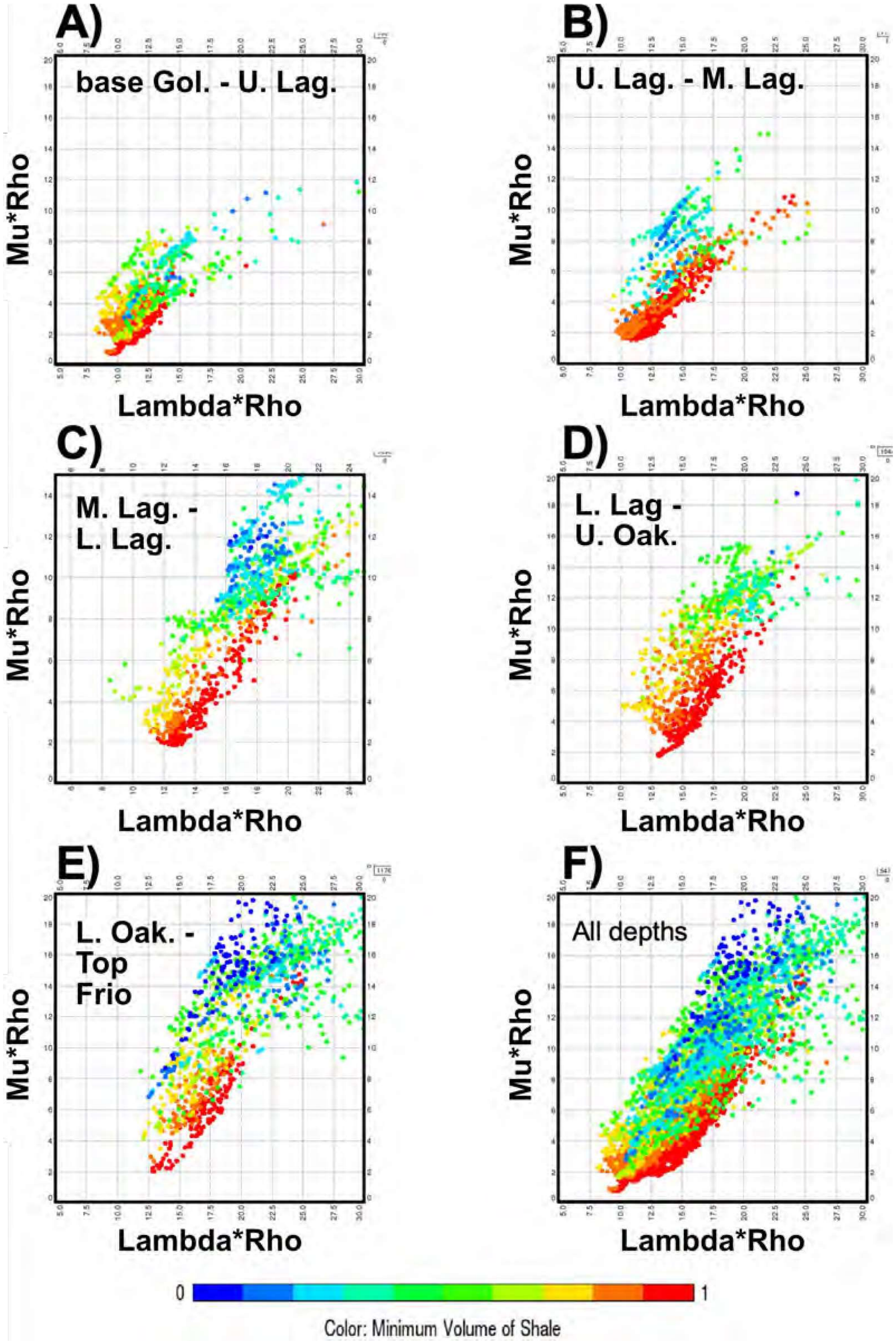


Figure 7-18. Rock property plots (μρ vs λρ) for sands and shales in Wardner #268, zoned from shallowest (base Goliad to upper Lagarto) to deepest (lower Oakville and top Frio); and for all depths. Sands tend to show lower λ and higher μ than shales, as normalized by density; but both values are required for a clean separation, and the fields vary strongly with depth.

Integration of Fastvel Data

Now that the impedance model at the #268 well is set, it is upscaled to match the resolution of the seismic dataset, and then the model can be supplemented with the Fastvel data. The Fastvel data was obtained during reprocessing (Section 7.2.9). It represents carefully determined, low-frequency stacking velocities at each seismic bin that can be used to extrapolate and modify the well model in areas away from the well. However, the Fastvel velocities need to be corrected for an anisotropic effect caused by the layering of strata, so the best approach is to use the well and the Fastvel data together to generate the initial impedance model so the inversion can proceed (Figure 7-19).

Generation of Acoustic Impedance and Rock Property Volumes

To invert the seismic volume once the initial impedance model is complete, the model is operated on to allow the typical wavelength of the seismic data to modify the shape of the impedance volume. This is called "convolving" the model with the seismic wavelet. This is done so that the impedance model shape and the amplitude data shape match, so the amplitude data can be inverted. Then the model is iterated to minimize the difference between the model and the real seismic amplitude data. The initial model is especially important, as it provides the low-frequency information that is required for a realistic inversion and is the basis for refinement using the seismic data.

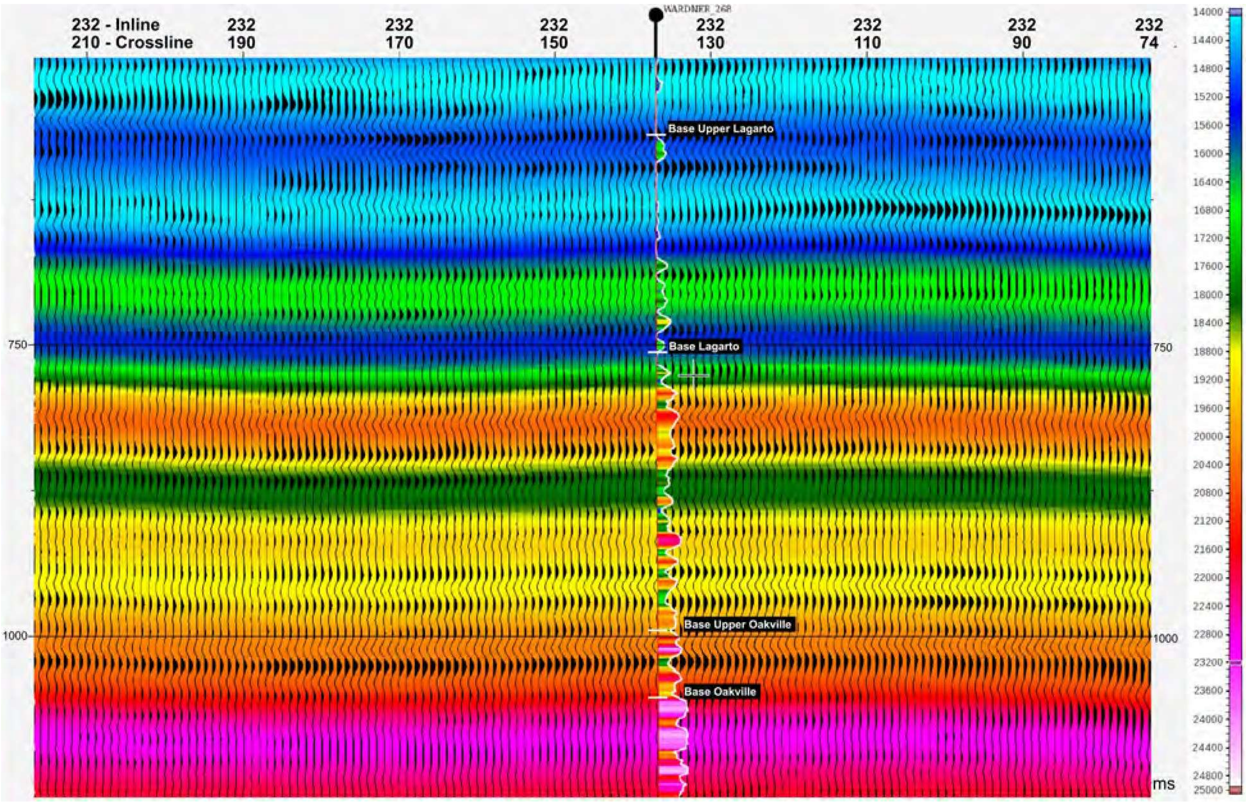


Figure 7-19. **Initial impedance model, inline 232; mainly based on Wardner #268 log calculations, with some lateral variability from Fastvel results. Color bar depicts absolute impedance.**

Once the initial model is in hand, the inversion of seismic reflectors to acoustic impedance proceeds to output impedance volumes. For the P-wave inversion, the seismic data used is the near-trace stack, with angles from the normal of 15 degrees or less (traces with sources and receivers close to the bin). These traces have little effect from shear waves. A typical resulting section tying Wardner #268 is shown on Figure 7-20. The strong compaction trend is obvious in the blue (low) to red (high) gradient.

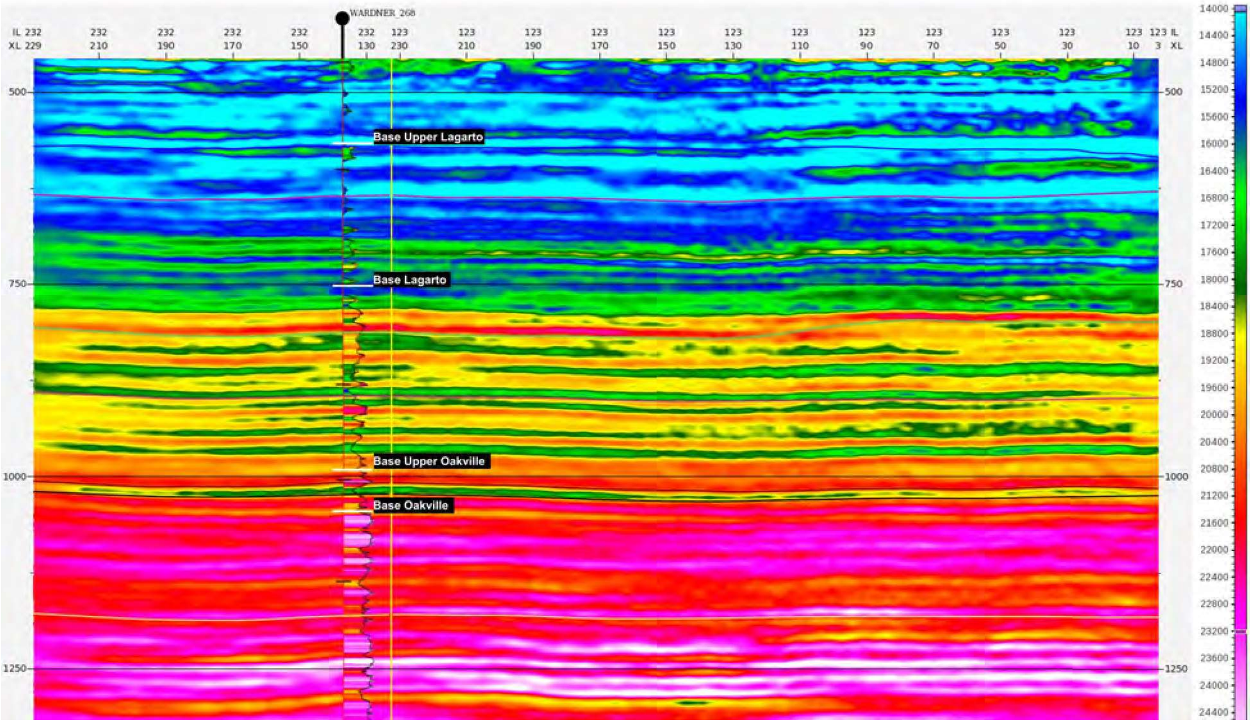


Figure 7-20. **Final acoustic impedance from P-wave inversion; composite of inline 232 and inline 123. Vertical yellow line indicates boundary between inline 232 and inline 123. Color bar is absolute impedance.**

The inversion process is repeated, to generate a volume of shear impedance. Data used will be the far-offset (high-angle) seismic data, which are strongly affected by shear waves.

Subsequent volumes are calculated from the above; they include Poisson's ratio (ν), shear modulus (μ), bulk modulus (λ), and density (ρ), and the ratio of P-wave velocity (V_P) and S-wave velocity (V_S). The λρ and μρ volumes, with information about porosity and matrix properties, can then be used with the zonal analysis to identify sands and shales within each zone. From these volumes, an advanced interpretation can flag sands on the volume and image them as geobodies (Figure 7-21). Use of these rock property volumes can be leveraged with great effect for aquifer characterization. Strong compaction trends somewhat obscure the pattern of sand deposition and require constant shifting of scales. To remove the compaction trend, a "relative acoustic impedance" volume was created that removes the initial model from the inversion product. This gives a fairer representation of aquifer distribution through the Miocene interval (Figure 7-22).

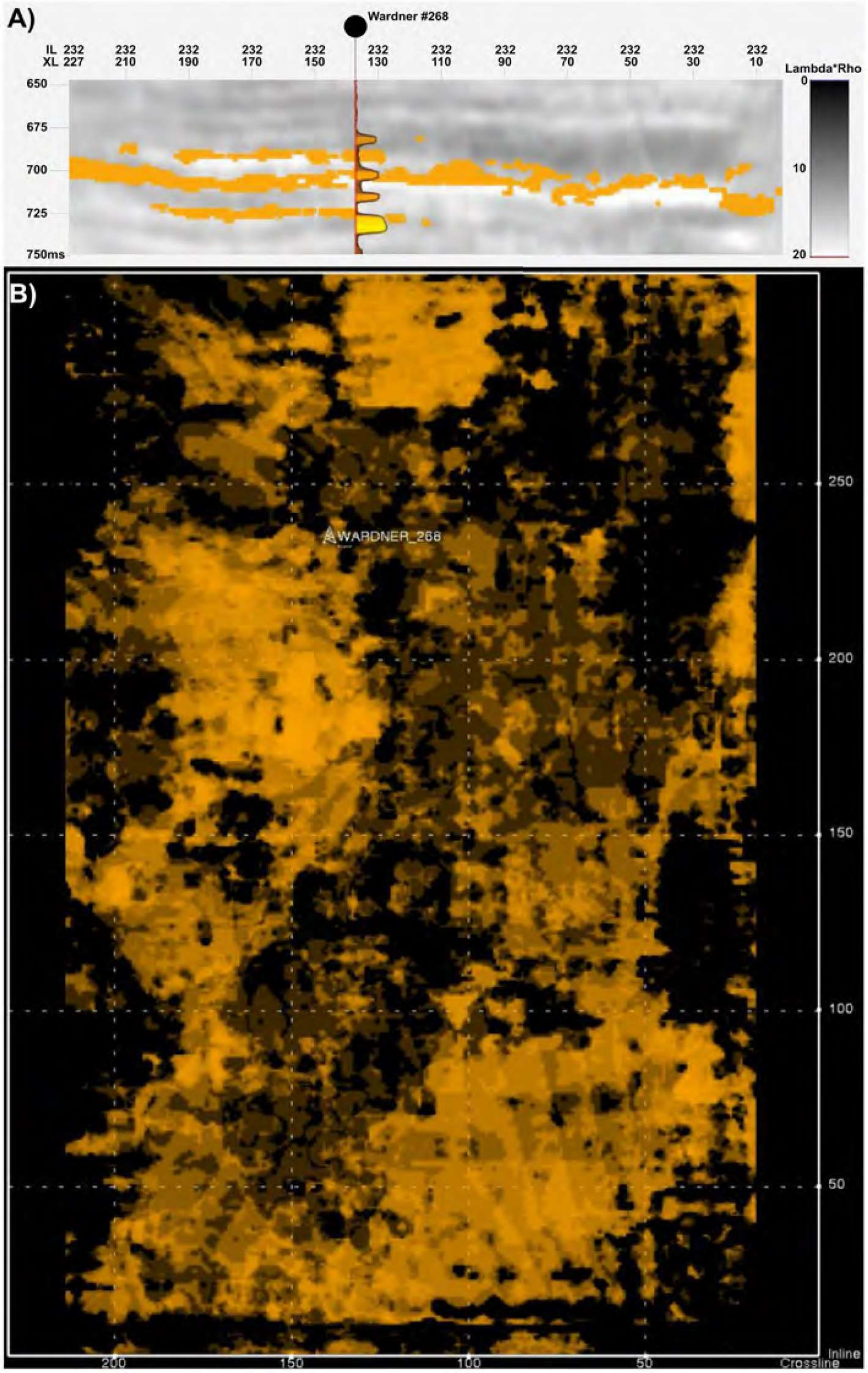


Figure 7-21. Flagging sands: A) Cross section through the Lagarto showing orange flags on a λρ volume overlain with the calculated percent shale log for Wardner #268. These flags identify areas where impendence volumes show high likelihood of sand. B) Map view of the geobody created from the flags for 650 to 750 milliseconds (lower Lagarto) over the Stratton dataset with the location of the Wardner #268. The geobody is a single color (same as the polygon) with the same opacity for all samples. However, because the viewing angle is down the z axis, some areas with thicker sands or multiples stacked thin sand bodies look more "solid" because the superposition of highlighted samples.

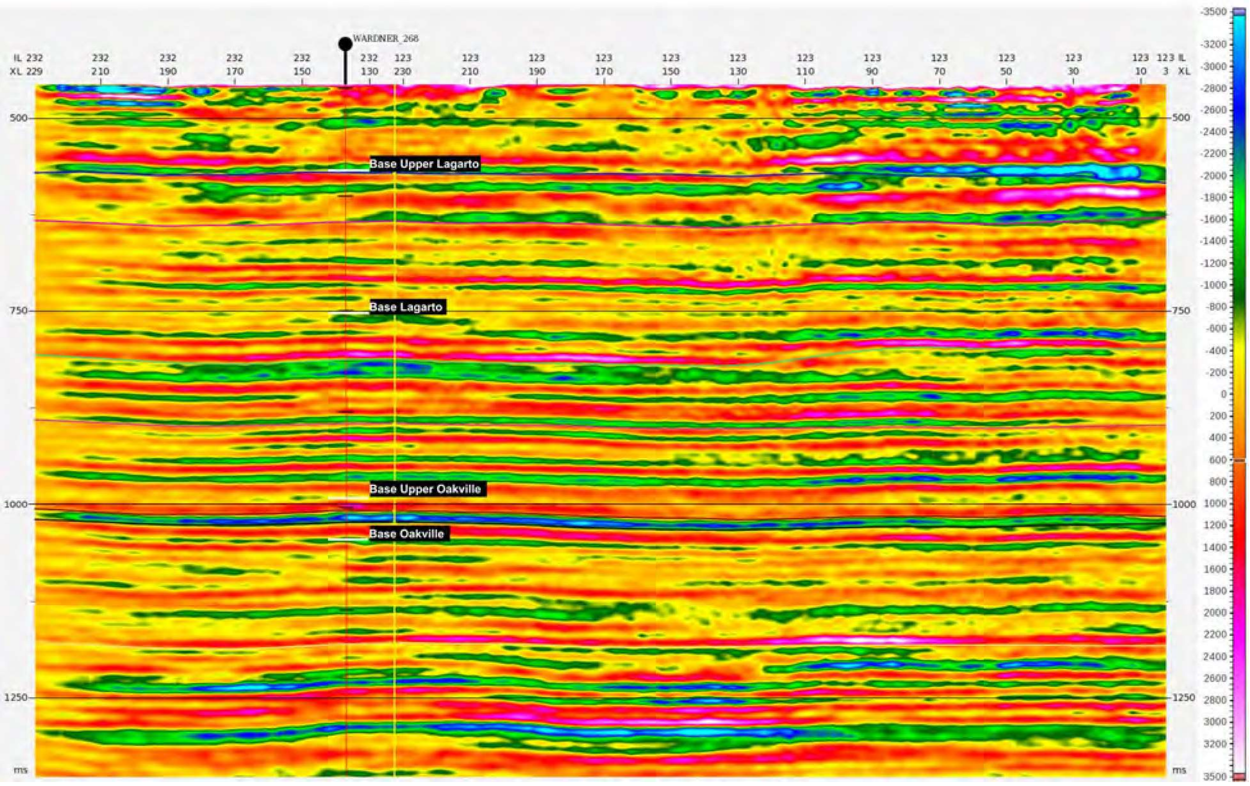


Figure 7-22. **Relative acoustic impedance on a composite of inline 232 and inline 123. The strong compaction is removed by subtracting the initial model from the acoustic impedance volume. Vertical yellow line indicates boundary between inline 232 and inline 123. Color bar indicates relative acoustic impedance.**

Examination of Acoustic Impedance and Relative Acoustic Impedance Volumes

Both the acoustic impedance and the relative acoustic impedance provide detailed estimates that can be compared to the 50 to 100 feet thick sandstone intervals in the Stratton wells. Both volumes were examined. For the figures shown (Figure 7-23 to Figure 7-28), the relative acoustic impedance was used, as it presents a more uniform appearance and does not require changing of color bars for each zone.

For this discussion, a cross section will be utilized along with three wells. Figure 7-23 provides a basemap of the location of these wells as well as the cross-section line Z-Z'. Figure 7-24 is the cross section.

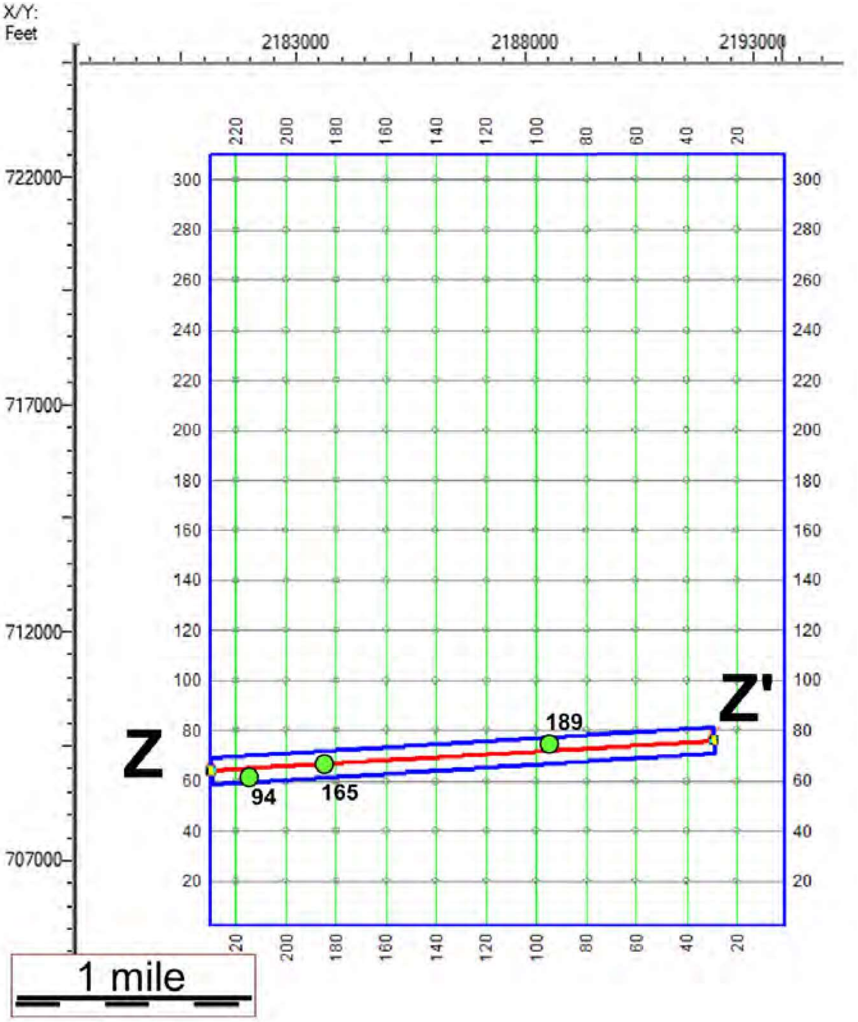


Figure 7-23. **Basemap showing location of cross section Z-Z' with Wardner wells 94, 165, and 189.**

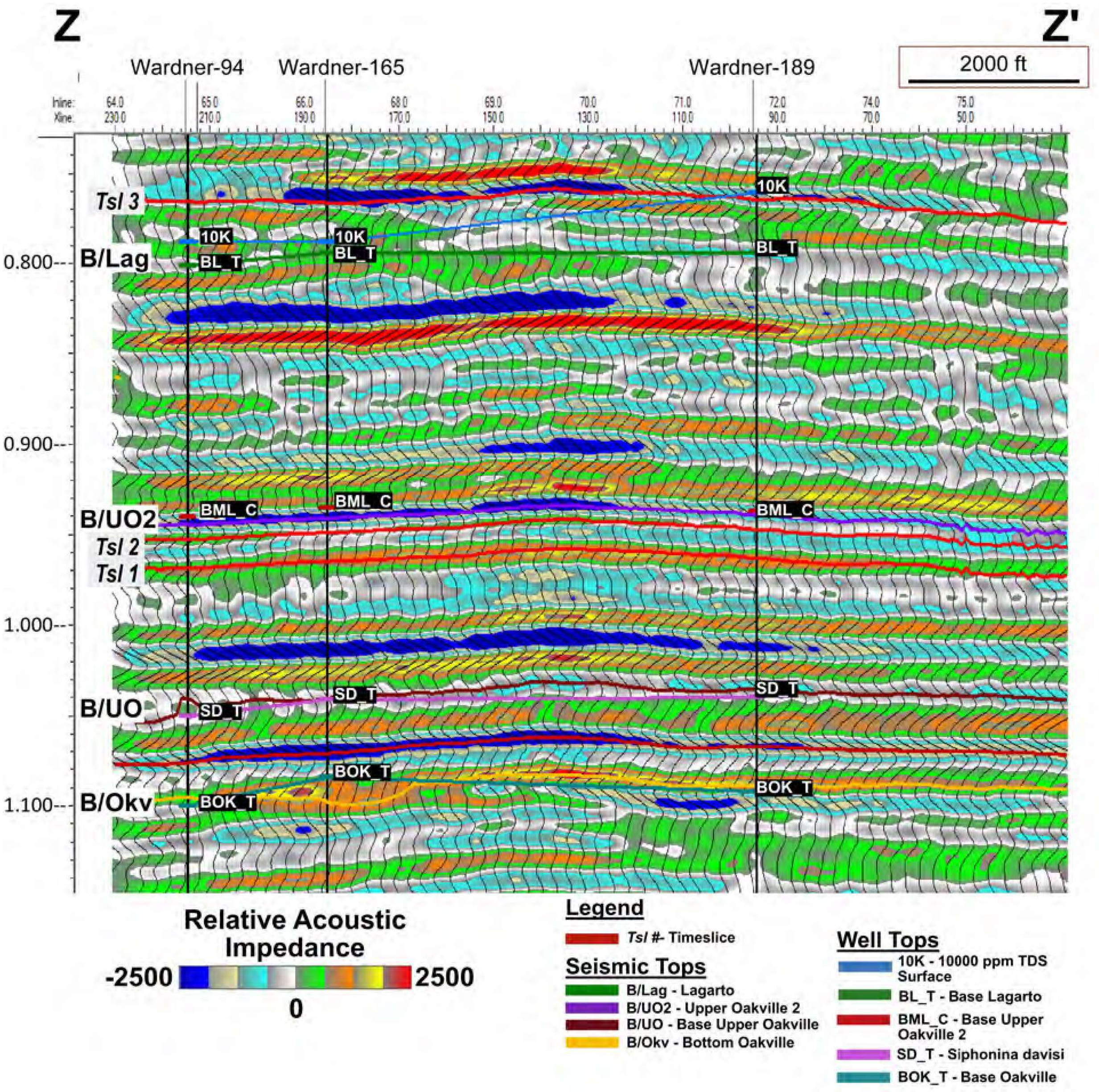


Figure 7-24. **Relative acoustic impedance cross section Z-Z'. Time slices are indicated as Tsl 1, 2, and 3 (Figures 7-25 to 7-27). Time slices here refers to horizons picked to show stratigraphic features on a map view and does not necessarily refer to slices of uniform time across the dataset.**

The utility of the inversion and resulting impedance volumes can be ascertained by examining the lower Lagarto through the Oakville. This will give examples of channel and "blanket" sands. As known from well logs, the Oakville interval contains several zones of bedded sandstone and shale that are continuous across the area ("blanket" sands). The relative acoustic impedance volume shows strong (high RAI) continuous trends across the survey (Figure 7-25).

Time slice 1 within the lower upper Oakville blanket zone around 965 milliseconds shows this continuity, but also contains some hints of variability in quality and thickness, and faint northeast-trending lineation (Figure 7-25).

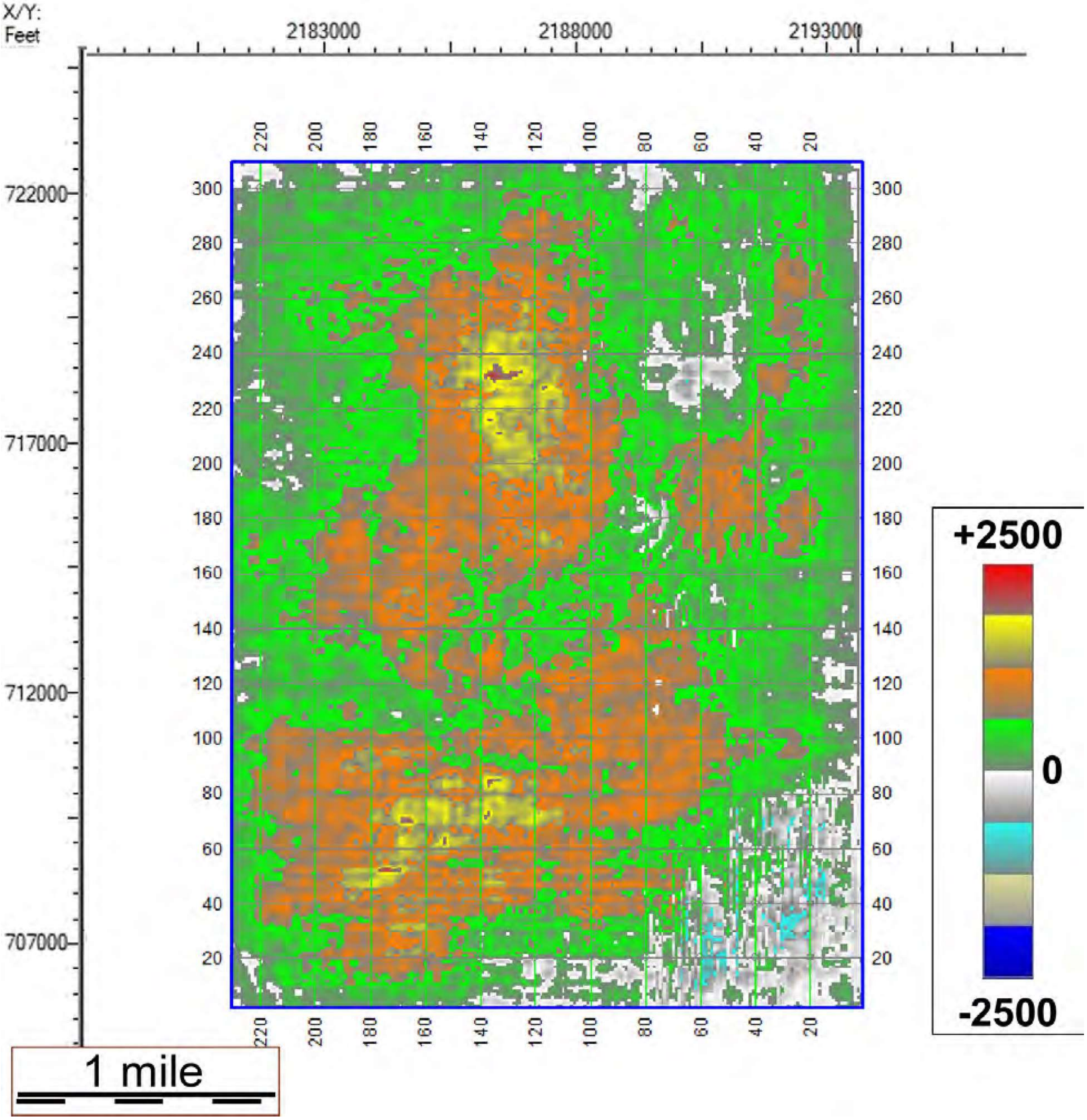


Figure 7-25. **Time slice 1 from Figure 7-24. Upper Oakville time slice in a 'blanket' sand unit (~965 milliseconds).**

Just above the B/UO2 seismic horizon on Figure 7-24 is Upper Oakville 938 millisecond channel sand described on seismic amplitude volume as Upper Oakville Channel 1; the relative acoustic impedance time-slice defines the channel orientation much more clearly than amplitude volume timeslice and identifies the zone of thickest sand (Figure 7-26).

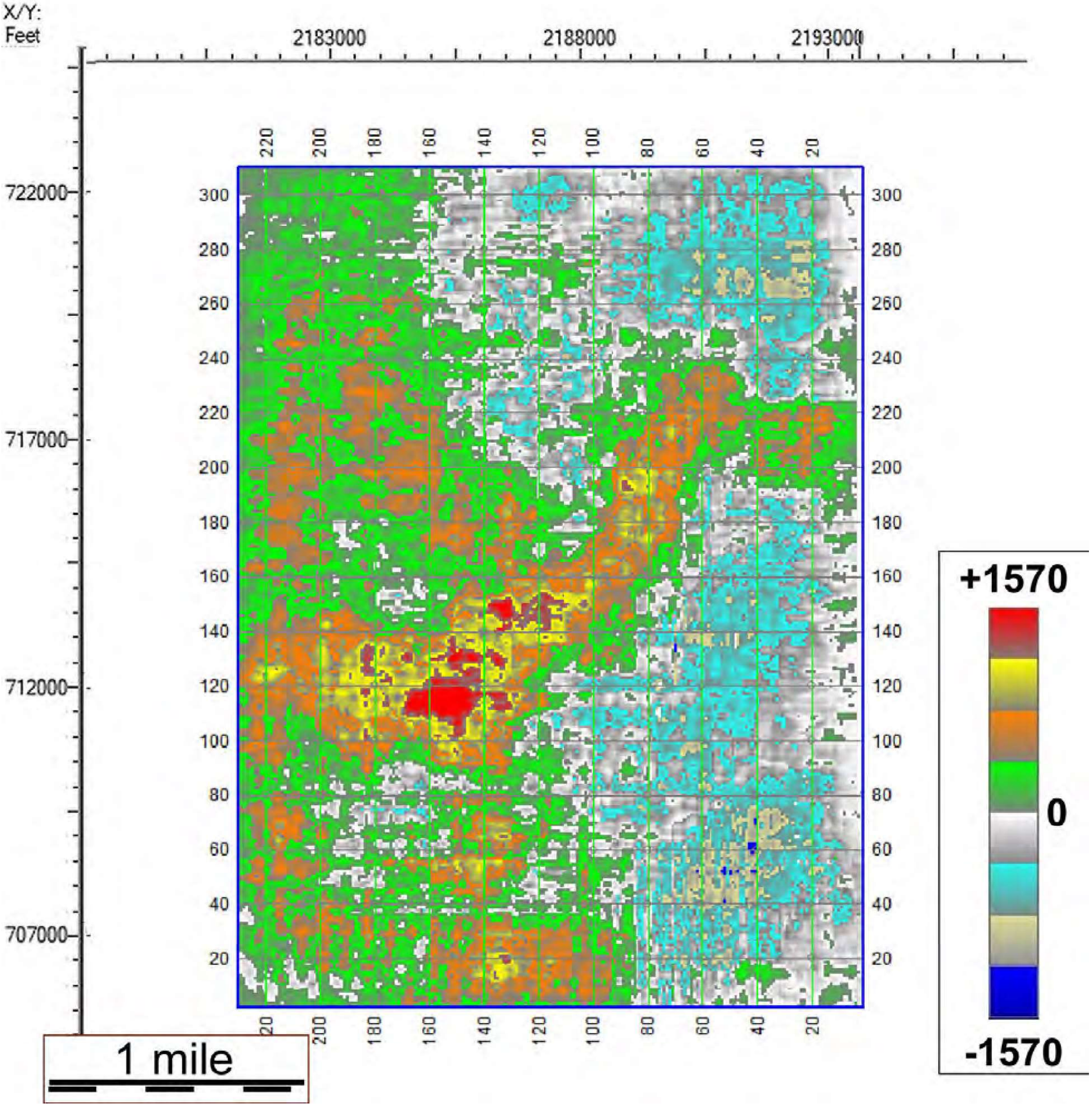


Figure 7-26. **Time slice 2 from Figure 7-24. Acoustic impedance time-slice of the ~940 millisecond channel (compare to Upper Oakville Channel 1 on Figure 7-12).**

As shown in the same cross section (Figure 7-24), the basal Lagarto is another blanket sandy interval. A time slice within this zone shows pronounced variations in impedance probably related to sand distribution within this zone (Figure 7-27).

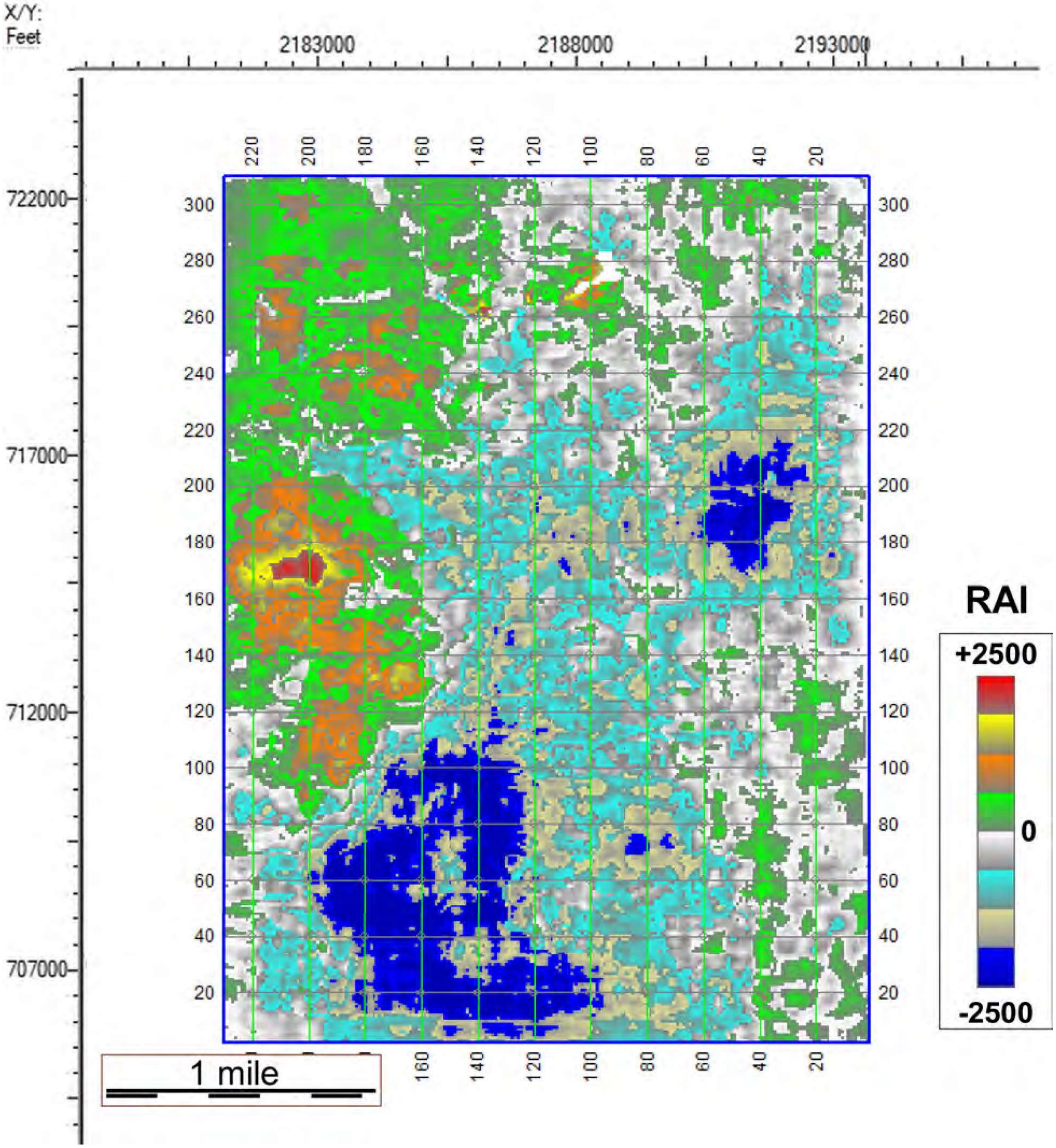


Figure 7-27. **Time slice 3 from Figure 7-24. Relative acoustic impedance time slice of basal Lagarto horizon (~760 milliseconds).**

The upper Lagarto is mainly mudstone with fewer, isolated sand bodies. At the base Lower Goliad, the relative acoustic impedance display indicates stronger variations (Figure 7-28). This interval is above the constraint of the Wardner #268 data and is harder to evaluate. The zone is, however, richer in sandstone, and mapping of geobodies using the impedance data could be a beneficial source of information in the shallow zones. To effectively interpret this section, additional study of the compaction trend and scaling of section should be undertaken.

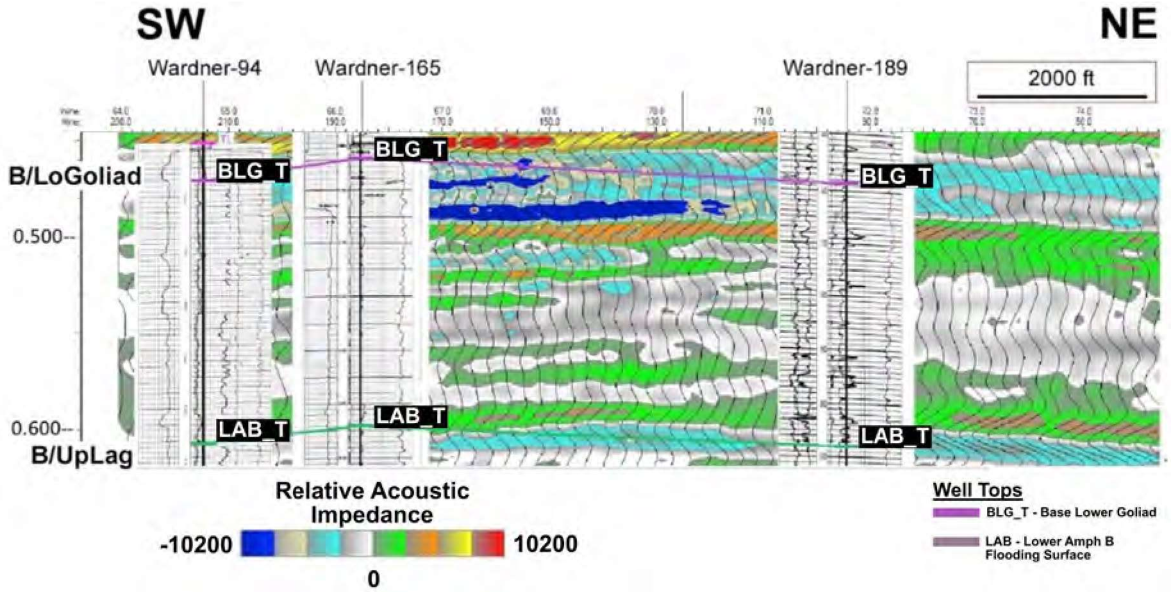


Figure 7-28. **Southwest-northeast section of the relative acoustic impedance volume, showing upper Lagarto to basal Goliad section.**

7.2.14 Integration and Seismic Stratigraphy (Task M)

Attempts at seismic stratigraphy in the Miocene to Holocene section at Stratton are hindered by its position landward of the shelf edge, and the small areal extent of the data. As such, the effects of sediment supply and accommodation are not obvious in the strata. However, the presence and continuity of sandy intervals in the Oakville and basal Lagarto are probably driven by sequence stratigraphic concepts on a regional scale. The close examination of the Stratton three-dimensional data should be combined with a more regional (at least county-scale) study to determine the stratigraphic linkages.

The integration of this dataset with the Young and others (2016) salinity depth rasters was covered in section 7.2.4 and is simple given the small quantities of data. In pursuing this area, additional salinity analyses would be undertaken.

7.3 Brackish Groundwater Resources Assessment of the Stratton Three-Dimensional Area

The Brackish Resources Aquifer Characterization System Group at the Texas Water Development Board is interested in the potential utility of legacy seismic data for the characterization of brackish groundwater resources. This project is the result of that interest and represents an opportunity to evaluate the costs and benefit of incorporating a three-dimensional seismic dataset into a typical groundwater study. This study is typical in that geophysical logs, mainly spontaneous potential and resistivity, are the primary means of developing the geologic model. This study is atypical in that it also incorporates legacy three-dimensional seismic data into the analysis in support of further refining our understanding of the local sequence stratigraphy, the local structure and the occurrence and distribution of permeable units and aquifers. The legacy seismic data was freely available, and the Brackish Resources Aquifer Characterization System Group was able to forgo the tens to hundreds-of-thousands of dollars usually required to purchase legacy seismic data or, the millions of dollars required to undergo a new seismic acquisition program. Unless the study area is in United States boundary waters, costs of legacy seismic data acquisition may preclude its incorporation into a typical groundwater resource assessment project. However, it could well be within the scope of a major brackish-water development project.

The Stratton three-dimensional survey area and its immediate surroundings contains hundreds of oil and gas wells with well log data but, very little groundwater data is present. Ideally, groundwater data would be available to confirm actual aquifer productivity and water quality (total dissolved solids in milligrams per liter). Given the adequate quality and quantity of the fresh groundwater in the overlying shallow section, there has historically been no reason to investigate deeper brackish water resources. However, as complex channel trends can be identified and rock properties can be mapped away from wellbores, this makes the case for incorporation of seismic into a brackish resource evaluation. In a survey area with fewer total wells or large undrilled portions of a study area, the value of seismic information increases.

Reprocessing of the Stratton three-dimensional shows that geologically useful, high resolution data can be derived for the shallow aquifer units below depths of about 900 feet (260 milliseconds). In many units, isolated channel systems can be imaged, and their trends can be determined and mapped in three dimensions. The more continuous sandy zones present in the Lagarto and Oakville units create more continuous and laterally distributed reflectors. Analysis of the inversion products provides a more complete understanding of the internal geometries within these sandy zones. Reprocessing the top 600 milliseconds of data (above 2,000 feet) was essential and also greatly improved imaging of the entire Miocene section.

Following re-processing of the data to better resolve the shallow intervals, structural and stratigraphic analysis is facilitated and validated using the seismic volumes. Even in heavily drilled and geophysically logged areas like Stratton, the interconnectivity of the aquifer is always suspect if the analysis is log-based. The interconnectivity estimations can be improved using two-dimensional or three-dimensional interpolation algorithms informed by approximations of depositional patterns and post depositional impacts but, these remain interpolations as compared to remotely sensed measurements of subsurface phenomena. With a quality three-dimensional seismic dataset that has been taken through inversion, the interconnectivity of the aquifer rock undergoes minimal to no interpolation and the resulting geobodies are actual (data-driven) as opposed to modeled.

As previously mentioned, to determine acoustic impedance, it is essential to have at least one well with sonic and density information through the target interval(s). Fortunately, this study has sonic and density logs (in separate wells) that could be carefully merged to provide an initial model. However, this data extended upwards only to 1,400 feet depth; above that point, the inversion is constrained only with the Fastvel data. That lack of data, combined with the dominance of high-angle reflections at shallow depths, leads to an uncertainty in acoustic impedance calculations in most of the Goliad section. In design of a major project using seismic data, the need for good log suites must be kept in mind; if possible, a well drilled through the target interval should acquire sonic and density information to bolster the existing wealth of seismic information.

As follows is the hydrogeologic assessment of the study area as based on the combination of well logs and processed three-dimensional seismic data.

7.3.1 Seismic Structural Interpretation

Structural complications explored for in the amplitude seismic data included evidence of salt tectonism, folding or faulting. The stratigraphic findings of this study (summarized in Section 7.2.12) showed little evidence of a structural control on sedimentation patterns, no evidence of faulting in the interval of interest, salt tectonism or any substantial folding. However, a growth fault does influence stratigraphy in the Vicksburg which is substantially below the brackish zone.

7.3.2 Geobody Delineation

As a result of detailing the process, three channels were found within the Miocene (examples were provided in Figures 7-11, 7-12, 7-13, 7-14). These channel bodies are inferred to be continuous geobodies of interconnected sands although, it is not known how far they extend beyond the Stratton field. While these features lack the size to be looked at as high-capacity brackish water fields, they could be useful in locating individual wells for other, less intensive, purposes. While locating one well may not justify the cost for seismic acquisition, it can be of use to an operator that already has access to seismic data (example in Jansen, 2015). At Stratton, three channels were identified as part of a proof of concept for the process. This investigation was by no means exhaustive, and it is likely that other, less noticeable, sand channels exists. Further, some of these channels are vertically stacked and could possibly be exploited by a single well with a multi-screen completion; assuming that it would not cause commingling (Figure 7-13). The seismic data would be adequate to use when determining well construction, drilling times, anticipated lithologies, and other factors. Further, given the understanding of the channel geometry along with approximations of hydraulic properties, primarily hydraulic conductivity and storage coefficient, from the literature (example: Young and others, 2016), estimations can be made for total recoverable water in place along with potential drawdown associated with a or multiple production wells. These estimations can be made in individual or stacked aquifer systems. Results from these calculations can be used to understand the potential of a brackish system more completely.

7.3.3 Rock Property Determinations

The worth of the seismic inversion process is in the final determinations of facies allocations. Attempts via other means at discerning spatial allocations of high- and low-quality aquifers are usually efforts to correlate one-dimensional data through a study volume. However, a carefully calibrated seismic inversion process can give real data at all locations within the volume resulting in a three-dimensional distribution of hydrogeologic facies. This not only has implications for the targeting of large, interconnected sand bodies for water supply but also groundwater model parameterization.

At Stratton, the inversion was calibrated using limited well log information, and velocity analysis acquired during reprocessing. The first products were the P-wave and S-wave acoustic impedances, which were used in turn to solve for many rock properties. With the properties solved for, the industry standard bulk modulus-density and shear modulus-density volumes were used to locate sand distributions and illustrated to show proof of concept. These volumes can be tied to well log calculations of sands and clays and result in three-dimensional geobodies representing sand occurrence. This represents a massive leap over extrapolating from a sand in a well away from well control.

7.3.4 Sand Interconnectivity

This study documents multiple ways that sand interconnectivity might be probed: through geobody analysis and through direct imaging of sand bodies. The reprocessed data allows sand interconnectivity to be assessed through time slice images and reflectors. With a constrained inversion, better inferences and estimations can be made on the locations of sand and shale, which can yield a series of targets for brackish water development. For instance, in the hypothetical surface location for a well to develop resources on the channels from Figure 7-13, rock property determinations also show that there is a sand sheet under those channels with tens of feet of thickness that spans the entire study area. Assuming that they are closely enough spaced vertically, these additional targets derisk each well installed. The best way to minimize costs is to expand the number of targets per well. Seismic data allows for the precise targeting in areas where there is potential to intersect multiple stacked aquifers. Where aquifer geometries are not sheet-like and more channelized, it is nearly impossible to accurately characterize these. Point data from well logs would need to be interpolated using an algorithm trained to the assumed depositional environment. Such a process increases project risk substantially.

7.3.5 Risk Assessment

Risks associated with drilling high-capacity municipal groundwater wells include shallow seismic hazards, thief zones, uncertainty of formation thickness, and faulting, among other risks. The incorporation of a high-quality three-dimensional seismic dataset is a standard practice in the oil and gas industry and, if the data and budget were available, could be incorporated into the groundwater industry. There is no doubt that oil and gas companies operating in the Stratton area used the seismic data to show that shallow seismic hazards were not an issue at the Stratton field. Thief zones, which refer to zones of high porosity that end up “stealing” mud from circulation during the drilling process, were likely identified by the geologists and relayed to the drilling coordinator. These zones are usually permeable intervals that are drilled through on the way to the target formation. Once identified, mud programs can be designed to either try and seal off the zone or, drill through the zone rapidly and set casing.

Consistency of formation thickness is important, especially when considering that the only potential water resource targets within the Stratton field are small, non-anastomosing fluvial channels and sheet sands. Under normal circumstances, these targets would not exist if one were to design drilling targets only from the existing well log data. However, the extent to which these permeable units are interconnected is a risk to a groundwater development project that can be mitigated with three-dimensional seismic data that has undergone processing. Once the proper color scheme has been set and the time slices containing the drill target have been identified, the degree of interconnectivity of the sands can be determined and the ideal location for drilling can be identified.

For obvious reasons, faults remain one of the largest risks to both the immediate drilling program and the long-term operation of the wellfield. Faults can be imaged in three dimensions using seismic surveying and the impacts to the drilling program can be assessed. This can include presence or absence of the target formation, downthrow/upthrow of the target formation, and juxtaposition of lower permeability units that could impact the shape of a wells cone of influence. Significant faults were not observed in the Stratton field and therefore would not pose a threat to the development of a wellfield.

7.3.6 Implications for Modelling

Traditional approaches to the parameterization of a groundwater model involve the determination of sand fraction by unit or layer from a geophysical log, mainly spontaneous potential and resistivity. That point value for a particular unit or layer would be interpolated along with other data points and the resulting sand percent surface would be used to inform the hydraulic conductivity field that would go into the groundwater model. Ideally, the interpolation algorithm is constrained by a facies model that attempts to represent the theoretical distribution of sands and clays as well as measurements of hydraulic conductivity directly from pumping tests. At that point, model layering could be readjusted to lump trends in hydraulic conductivity (sand distribution).

Seismic surveying can enhance the traditional method of parameterizing groundwater models based on analysis of geophysical logs in at least two ways. First, seismic surveying can assist in the measurement of aquifer geometry and extent, providing a good compliment to sparse borehole data (Martin and others, 2013). Second, a three-dimensional seismic survey with inversion can provide a much clearer picture of the distribution of both hydrostratigraphic layering and sand interconnectivity within a groundwater flow system. Imaging the distribution of sand bodies can provide valuable information because often sandstone aquifers consists of discontinuous sand bodies distributed in a low-permeability matrix. The arrangement and interconnectedness of these lithofacies strongly influences spatial patterns of hydraulic conductivity (Fogg, 1990).

A clear example of how seismic data can provide insight in the layer and interconnectivity of sand bodies is shown on Figure 7-20, which identified a sheet sand within the Stratton dataset in the upper Oakville. This sand geobody and its surrounding low permeability units are resolved in three-dimensional space and a direct picture of sand interconnectivity is imaged. While it would normally not be necessary to try and model high resolution facies distribution for a regional groundwater flow model, it could be useful for a local scale model that would benefit from that level of resolution. An example would be a contaminated groundwater site where a high-resolution environmental sequence stratigraphic approach to aquifer characterization would inform groundwater model discretization and ultimately would help guide remediation efforts. Environmental sequence stratigraphy is based on scale-specific sequence stratigraphic concepts and is used to evaluate the detailed site information in the context of the site's geologic, depositional, and erosional history (Schultz and others, 2017).

At this point, there is no reason for creating a groundwater flow model out of the data in the Stratton field. A coarse resolution regional model of the Gulf Coast aquifer system currently exists and is used by groundwater conservation districts and regional planning groups that overlie the Gulf Coast aquifer system to better understand how they want to manage the aquifer. Scaling data with the level of resolution found in the Stratton dataset to a regional groundwater availability model would be impractical. However, small scale trends observed in the Stratton dataset could be used to inform simplified representations of the depositional systems on a more regional scale. As shown in Figure 6-23, three dimensional seismic datasets are available throughout the Gulf Coast aquifer area. As with the Stratton dataset, some number of these datasets could be acquired, processed, interpreted, and ultimately used to inform the parameterization of portions of a regional groundwater availability model.

8 Conclusions

This study highlights the ways seismic data can inform our understanding of brackish aquifers within the state of Texas. In particular, the use of conventionally acquired seismic reflection data that may be usable either as-is or with reprocessing to provide relatively shallow (1,000 to 5,000 feet depth) geologic information about stratigraphic and structural features of aquifers containing brackish groundwater. This work has determined that seismic data can assist in defining the distribution and continuity of aquifers and confining units, mapping freshwater and brackish aquifers, determining depth and thickness of aquifers, mapping faults and fractures that affect flow, understanding and mapping subsurface stratigraphy and, when combined with geophysical logs, lithology/water quality distribution and extent.

This study is an initial foray into the utility of conventional seismic data for brackish groundwater exploration. More work certainly remains to be done to improve our understanding, notably studies in other aquifer systems and in areas with less well control. However, the following conclusions can be drawn from this study:

- The existing literature for seismic characterization of aquifers shows substantial potential for delineation of aquifer geometries. Seismic surveys have probed groundwater reserves in onshore and offshore settings in a variety of geological environments and structural settings.
- Texas has large areas of the state with very good seismic coverage. Four main vendors (SEI, Seitel, Fairfield Geo, and CGG-Veritas) own most of the seismic data in Texas and in Texas state waters. On the Federal Outer Continental Shelf, the National Archive of Marine Seismic Surveys has made many lines and volumes free to access.
- The resolution of seismic data is primarily dependent on frequency, and secondarily on quality of reflection data. Large variances in seismic resolution can occur due to the seismic velocity of various geologic settings in Texas. For imaging in the deeper depth range of brackish aquifers (about 1,000 to 5,000 feet), much data will be of sufficient quality. In some instances, it may be necessary to reprocess data to interpolate the gathers at shallow depth and optimize velocity information and the quality of imaging.
- A modular methodology was constructed to delineate stratigraphy, structure, and hydrostratigraphic features in Texas aquifers using seismic data. Following a preliminary stratigraphic analysis, hydrogeologic study, and a seismic data search, the decision whether or not to license will be made. If the data are licensed, the next decision will be whether or not to reprocess the data. If the data is reprocessed, whether or not to perform inversion is the last key decision.
- A table was provided summarizing the coverage and relative seismic velocity of each of the aquifers in Texas. For each aquifer, a figure was provided showing the aerial coverage of seismic data as well as some recommendations and concerns for seismic exploration efforts.
- The seismic study at the Stratton field showed processing the seismic volume was able to resolve meaningful reflectors and geologic data as shallow as 900 feet.
- The Stratton study showed that modern seismic processing resulting in amplitude is sufficient in determining structure and is helpful in identifying channel morphology but is less helpful in identifying sheet-like sands.

- The inversion process, to generate acoustic impedance and other volumes, requires sufficient well-log data to be geologically reasonable and useful. Specifically sonic and density logs. This could be considered a limitation when trying to incorporate legacy seismic data into a groundwater study since sonic and density logs are not always available; especially in the Gulf Coast province where electric logs dominate. This study also utilized detailed seismic velocity analysis to constrain the inversion.
- Seismic inversion may be worth the additional cost for parties interested in de-risking estimations of (sand) aquifer volume or water in place. It is also useful in identifying aquifers with different properties than adjacent non-aquifers, or with geometries not conducive to detection via amplitude. There are limits in imaging thin, complex sand intervals which should be studied further.
- Seismic data, whether legacy or newly acquired, can provide substantial gains when attempting to characterize a groundwater system in anticipation of either groundwater flow modeling or water resource development. That said, incorporation of seismic data usually comes at a substantial cost to the project budget and the dataset should be scrutinized by a trained expert prior to purchase and processing.
- Seismic data can be used to de-risk a groundwater development project. This could be in the form of fault imaging, sand thickness delineation, seismic hazard identification or presence of thief zones. This is a common use for seismic data in the oil and gas industry and there are direct parallels to a standard groundwater development program.
- In addition to groundwater development projects, Aquifer Storage and Recovery projects could substantially gain from the incorporation of seismic data, whether two- or three-dimensional. Being able to reliably image faults and determine aquifer thickness, lateral extent and depth would all serve to inform and derisk a typical Aquifer Storage and Recovery program.
- While legacy seismic datasets in Texas are not generally ideal for the shallow subsurface, a newly acquired three-dimensional seismic dataset, with accompanying hydrogeologic and well log (acoustic and density) data, would be ideal for the characterization and subsequent parameterization of an environmental sequence stratigraphic model. These models are commonly constructed for groundwater remediation programs with complex injection and extraction well arrays where an accurate representation of the interconnection of the flow units is required to optimize remediation efforts.

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10 Appendix

10.1 Appendix 1. Log analysis for Wardner #268 (using density information from #280), by zone from shallow to deep.

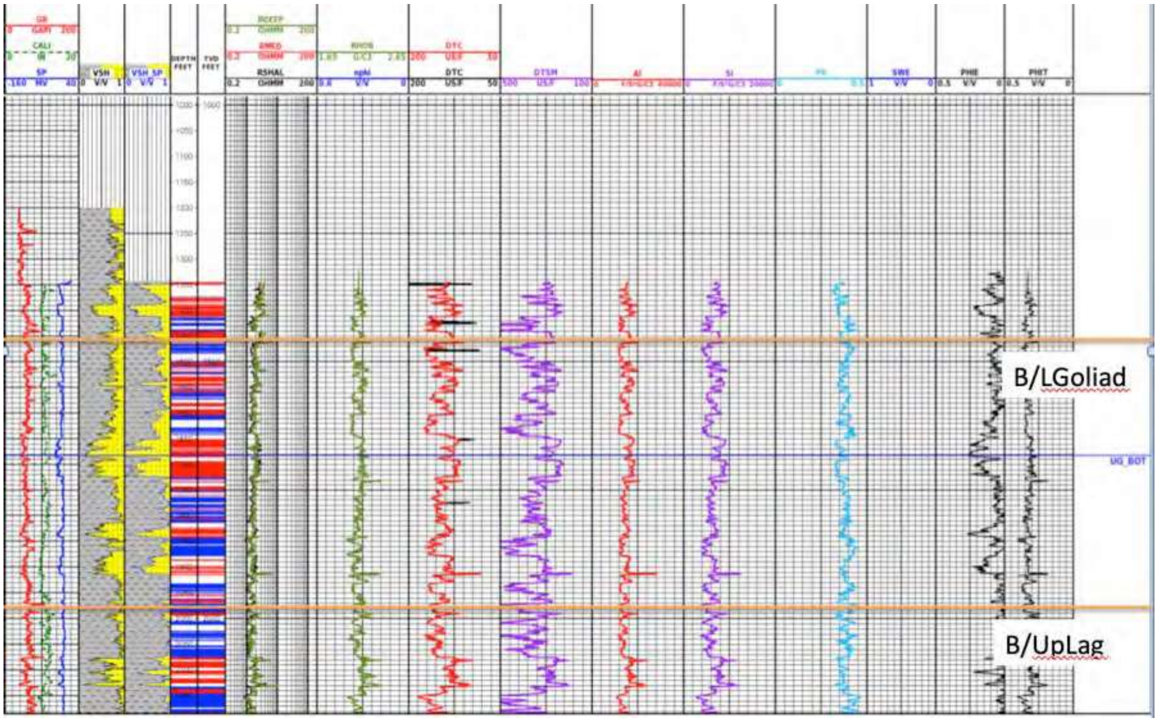

Figure 10-1. **Logs for Wardner #268: Unit 1 (Base Goliad and upper Lagarto). Note that depth track is colored with flags for sand (red) and shale (blue); uncolored segments are silty or impure.**

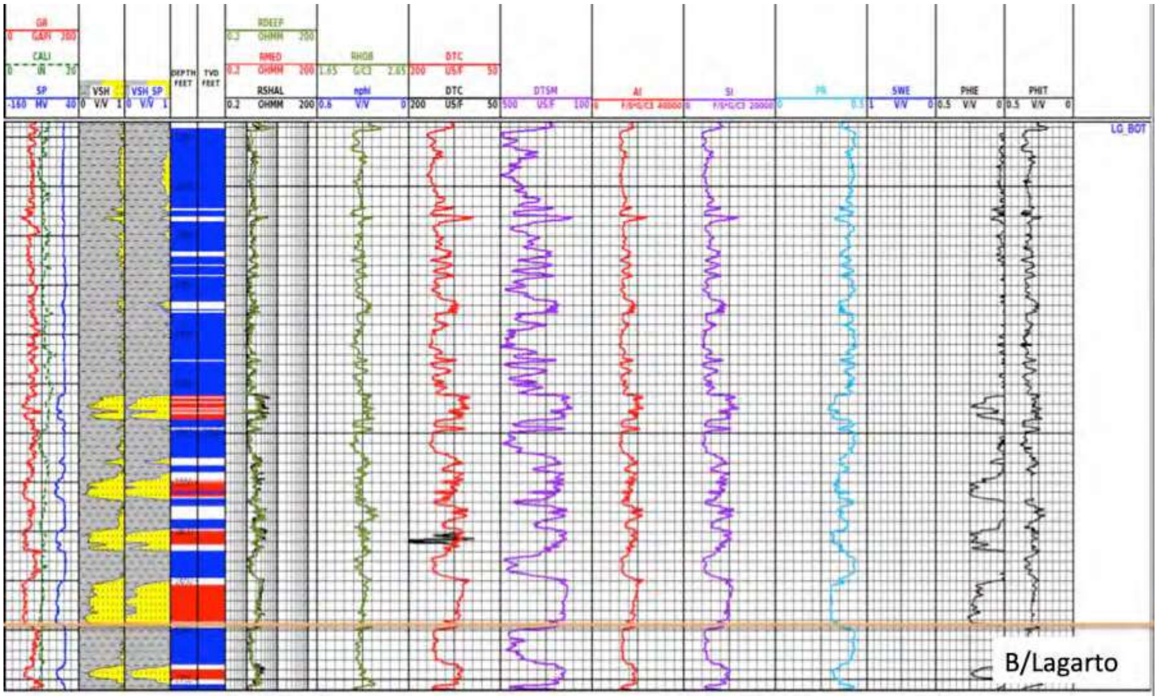

Figure 10-2. **Logs for Wardner #268: Unit 2 (Lagarto)**

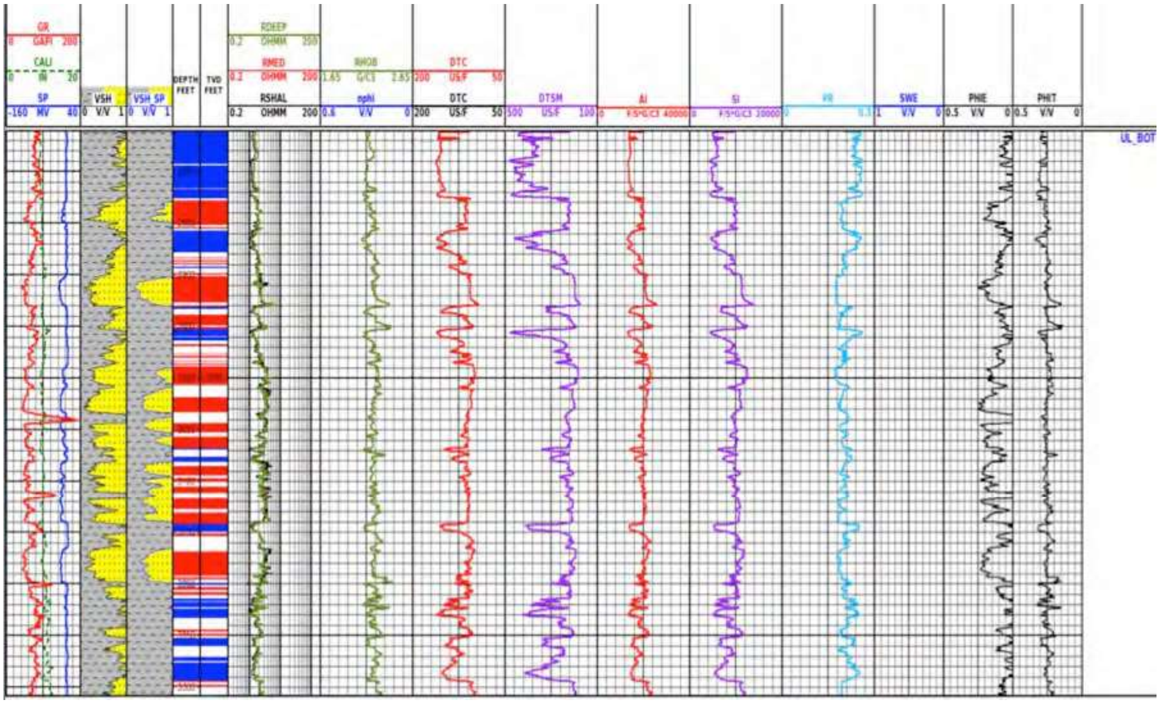

Figure 10-3. **Logs for Wardner-268: Unit 3 (Upper Oakville 1)**

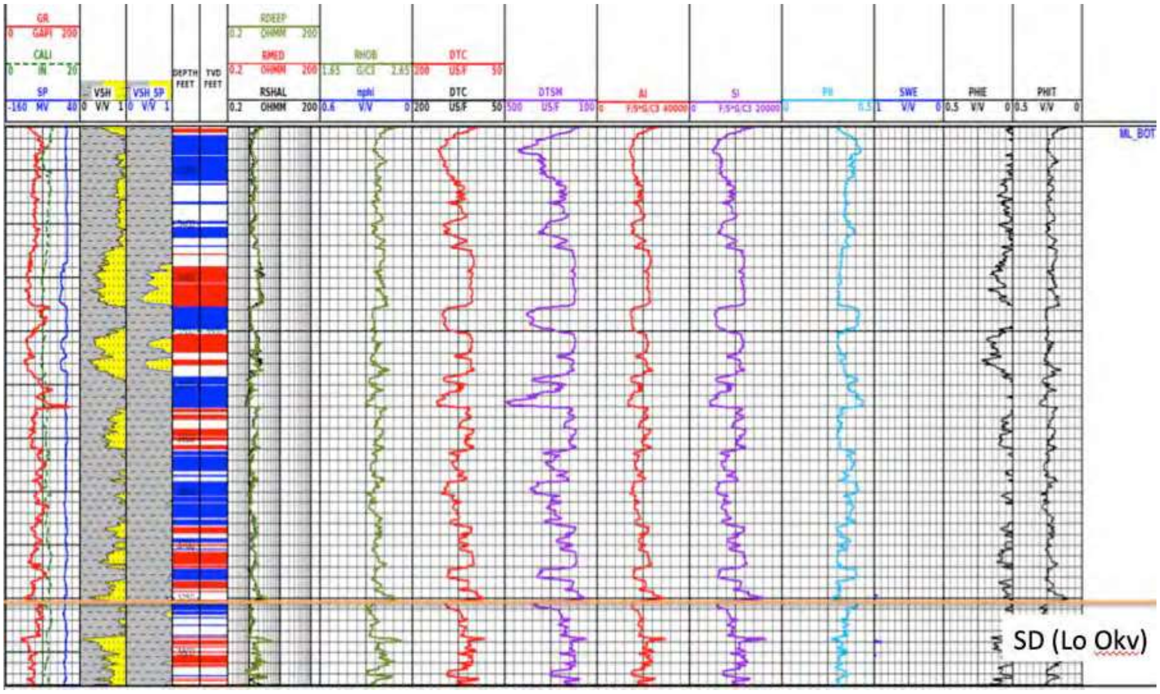

Figure 10-4. **Logs for Wardner-268: Unit 4 (Upper Oakville 2)**

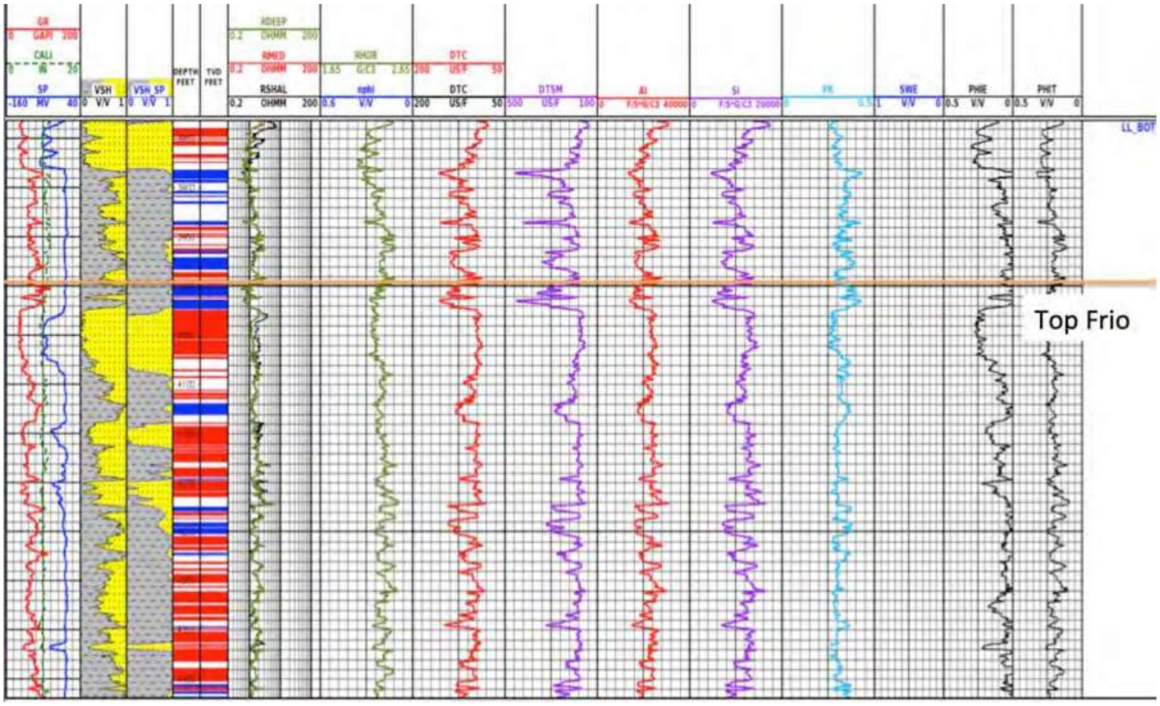

Figure 10-5. **Logs for Wardner-268: Unit 5 (Lower Oakville and upper Frio)**

10.2 Appendix 2. Geographic Information System Datasets

10.2.1 GIS_Final (main folder)

The geographic information system (GIS) datasets used in the current study are located in the GIS_Final" folder included in the electronics deliverables. The structure of this folder is as follows:

All .mxd files corresponding to map figures in the report

The main folder contains all mxds used in the report.

.gdb File

Table 10-1. Folder structure: SeismicInterpretation.gdb/

SeismicInterpretation.gdb	
Name	**Type**
AquiferBottoms	Feature Dataset
SeismicVolumesandLines	Feature Dataset
BEG_core	Point Feature Class
BRACS_GIS	Point Feature Class
Texas_counties_pg	Polygon Feature Class
Texas_fault_pl	Polyline Feature Class
Texas_major_aquifer_extent_pg	Polygon Feature Class
Texas_metro_areas_pg	Polygon Feature Class
Texas_minor_aquifer_extent_pg	Polygon Feature Class

Table 10-2. Folder structure: SeismicInterpretation.gdb/AquiferBottoms

AquiferBottoms Feature Class	
Name	**Type**
BL_bd_c1000_pl	Polyline Feature Class
BR_bd_c25_pl	Polyline Feature Class
CR_bd_c500_pl	Polyline Feature Class
CT_be_c1000_pl	Polyline Feature Class
CZ_bd_c1500_pl	Polyline Feature Class
DO_bd_c750_pl	Polyline Feature Class
EBFZ_bd_c1000_pl	Polyline Feature Class
ES_bd_c1000_pl	Polyline Feature Class
ETHP_bd_c100_pl	Polyline Feature Class
ETPL_bd_c100_pl	Polyline Feature Class
GC_bd_c500_pl	Polyline Feature Class
HCMS_bd_c150_pl	Polyline Feature Class
HY_bd_c1000_pl	Polyline Feature Class

IG_bd_c100_pl	Polyline Feature Class
Kb_bd_c500_pl	Polyline Feature Class
Kn_bd_c300_pl	Polyline Feature Class
LN_bd_c200_pl	Polyline Feature Class
MF_bd_c1000_pl	Polyline Feature Class
O_bd_c200_pl	Polyline Feature Class
PV_bd_c400_pl	Polyline Feature Class
QC_bd_c1500_pl	Polyline Feature Class
RB_bd_c100_pl	Polyline Feature Class
RU_bd_c750_pl	Polyline Feature Class
SP_bd_c1500_pl	Polyline Feature Class
SY_bd_c40_pl	Polyline Feature Class
TR_bd_c1500_pl	Polyline Feature Class
WB_bd_c1000_pl	Polyline Feature Class
WTBL_bd_c750_pl	Polyline Feature Class
YJ_bd_c2000_pl	Polyline Feature Class

Table 10-3. Folder structure: SeismicInterpretation.gdb/SeismicVolumesandLines.

SeismicVolumesandLines	
Name	**Type**
All_2D	Polyline Feature Class
All_3D	Polygon Feature Class
CGG_3D	Polygon Feature Class
FG_3D	Polygon Feature Class
NAMSS_2D	Polyline Feature Class
NAMSS_3D	Polygon Feature Class
SEI_2D	Polyline Feature Class
SEI_3D	Polygon Feature Class
Seitel_2D	Polyline Feature Class
Seitel_3D	Polygon Feature Class

10.2.2 GIS File Name Codes

.mxd Files

The .mxds are labelled with the corresponding figure number and a short description of the figure. As an example, “4-4 SEI 2D” is the .mxd corresponding to Figure 4-4.

Feature Classes

Table 10-4. GIS File naming codes applied for feature classes containing seismic data.

Seismic Volumes and Lines Naming Convention		
Position of Code	**Code Type**	**CODE**
1	Company	CGG
1	Company	FG
1	Company	SEI
1	Company	Seitel
1	Company	NAMSS
1	Company	All
2	Type	2D
2	Type	3D

Table 10-5. GIS File naming codes applied for feature classes containing aquifer structure contour data.

Bottom Contour Naming Convention				
Position of Code	**Code Type**	**Code**	**Description**	**Example**
1	Aquifer	BL	Blaine	BL_bd_c1000_pl
1	Aquifer	BR	Brazos River Alluvium Aquifer	BR_bd_c25_pl
1	Aquifer	CR	Capitan Reef Complex Aquifer	CR_bd_c500_pl
1	Aquifer	CT	Cross Timbers Aquifer	CT_be_c1000_pl
1	Aquifer	CZ	Carrizo-Wilcox Aquifer	CZ_bd_c1500_pl
1	Aquifer	DO	Dockum Aquifer	DO_bd_c750_pl
1	Aquifer	EBFZ	Edwards Balcones Fault Zone Aquifer	EBFZ_bd_c1000_pl
1	Aquifer	ES	Ellenburger-San Saba Aquifer	ES_bd_c1000_pl
1	Aquifer	ETHP	Edwards-Trinity High Plains Aquifer	ETHP_bd_c100_pl
1	Aquifer	ETPL	Edwards-Trinity Plateau Aquifer	ETPL_bd_c100_pl
1	Aquifer	GC	Gulf Coast Aquifer	GC_bd_c500_pl
1	Aquifer	HCMS	Hueco Mesilla Bolsons Aquifer	HCMS_bd_c150_pl
1	Aquifer	HY	Hickory Aquifer	HY_bd_c1000_pl
1	Aquifer	IG	Igneous Aquifer	IG_bd_c100_pl
1	Aquifer	Kb	Blossom Aquifer	Kb_bd_c500_pl
1	Aquifer	Kn	Nacatoch Aquifer	Kn_bd_c300_pl
1	Aquifer	LN	Lipan Aquifer	LN_bd_c200_pl
1	Aquifer	MF	Marble Falls Aquifer	MF_bd_c1000_pl

1	Aquifer	O	Ogallala Aquifer	O_bd_c200_pl
1	Aquifer	PV	Pecos Valley Alluvium Aquifer	PV_bd_c400_pl
1	Aquifer	QC	Queen City Aquifer	QC_bd_c1500_pl
1	Aquifer	RB	Rita Blanca Aquifer	RB_bd_c100_pl
1	Aquifer	RU	Rustler Aquifer	RU_bd_c750_pl
1	Aquifer	SP	Sparta Aquifer	SP_bd_c1500_pl
1	Aquifer	SY	Seymour Aquifer	SY_bd_c40_pl
1	Aquifer	TR	Trinity Aquifer	TR_bd_c1500_pl
1	Aquifer	WB	Woodbine Aquifer	WB_bd_c1000_pl
1	Aquifer	WTBL	West Texas Bolsons Aquifer	WTBL_bd_c750_pl
1	Aquifer	YJ	Yegua-Jackson Aquifer	YJ_bd_c2000_pl
2	Depth or elevation	bd	Bottom Depth	DO_bd_c750_pl
2	Depth or elevation	be	Bottom Elevation	CT_be_c1000_pl
3	contours or single contours	c	contours	DO_bd_c750_pl
3	contours or single contours	scl	single contour line	SP_bd_scl500_pl
4	Number	ex. 500	contour interval	DO_bd_c750_pl
5	Type	pl	polyline	DO_bd_c750_pl

10.3 Appendix 3. Naming Convention for Seismic Datasets

Seismic Data Naming Convention

Name	**Unabbreviated Name**	**Description**
FVCDPangleGthrs.sgy	Fastvel common depth point angle gathers	Tricon Fastvel interval velocity analysis volume gathered by angle
FVCDPoffsetGthrs.sgy	Fastvel common depth point offset gathers	Tricon Fastvel interval velocity analysis volume gathered by offset
FVFullStack5-45.sgy	Fastvel full stack 5-45	Fastvel interval velocity analysis volume from 5-45 degrees
int_vels_042021.sgy	Interval velocities 042021	Interval velocities
pstmstk_rap_042021.sgy	Prestack time migration relative amplitude 042021	
pstmstk_raw_042021.sgy	Prestack time migration raw 042021	
pstmstk_str_042021.sgy	Prestack time migration structural 042021	

rms_vels_042021.sgy	Root mean square velocity 042021	Root mean square velocity 042021
UpdtdINTvel.sgy	Updated interval velocity	Updated interval velocity
UpdtdRMSvel.sgy	Updated root mean square velocity	Updated rms velocity
xfreq_042021.sgy	Cross frequency high frequency enhancement	Volume which enhances high frequencies
AcousticImpedance.sgy	Acoustic Impedance	Attribute volume for acoustic impedance
ERho.sgy	Young's Modulus*Rho	Attribute volume for Young's Modulus*Rho
LambdaRho.sgy	Lambda*Rho	Attribute volume for Lambda*Rho
MuRho.sgy	Mu*Rho	Attribute volume for Mu*Rho
Poissonratio.sgy	Poisson's Ratio	Attribute volume for Poisson's Ratio
RAI.sgy	Relative Acoustic Impedance	Attribute volume for relative acoustic impedance
ShearImpedance.sgy	Shear Impedance	Attribute volume for shear impedance
Stack5-17.sgy	Partial Angle Stack 5-17 degrees	Partial stack only using incidence angles of 5-17
Stack5-47.sgy	Partial Angle Stack 5-47 degrees	Partial stack only using incidence angles of 5-47
Stack15-27.sgy	Partial Angle Stack 15-27 degrees	Partial stack only using incidence angles of 15-27
Stack25-37.sgy	Partial Angle Stack 25-37 degrees	Partial stack only using incidence angles of 25-37
Stack35-47.sgy	Partial Angle Stack 35-47 degrees	Partial stack only using incidence angles of 35-47
VpVsratio.sgy	P-wave velocity to S-wave velocity ratio	Volume of ratio between P-wave velocity and S-wave velocity
LoadingSheetStratton3d.xls	Loading Sheet Stratton Three-Dimensional Dataset	Loading sheet for interpretation program

10.4 Appendix 4. Responses to TWDB Comments on Draft Report

10.4.1 General comments:

1. TWDB has provided tracked changes in MS Word document for ease of use, please address comments and edits in the Word document and the comments included in the list below.

   Response. Thank you for that.
2. A header with the name of the report and TWDB contract number should appear at the top of each page, beginning with page ii.

Response. Concur, change made.

3. Please keep captions on the same page with the figure.
4. Please make sure abbreviature BRACS is expanded correctly: Brackish Resources Aquifer Characterization System.

   Response. Concur, change made.
5. Please add Executive summary.

   Response. Added.
6. Please use “aquifer” instead of “reservoir” throughout the report.

   Response. Done where appropriate (ex. Oil and gas reservoirs).
7. Please update the List of Figures and List of Tables.

   Response. Done.
8. Please make sure all references are in the reference list.

   Response. Done.

10.4.2 Specific comments:

1. Blank page, page ii: This project is funded by TWDB solely, that’s why no funding source is needed. This page would instead say: This page is intentionally blank. This page must have number ii (since the Title page is page i, but no page number will appear). This page also must have a header section.

   Response. Change made.
2. Geoscientist and Engineering Seal page: This page must have number iii.
3. Table of Contents: Please add Table of Contents, List of Figures and List of Tables.
4. Introduction, page 2, paragraph 2 and paragraph 4: please correct to Brackish Resources Aquifer Characterization System Department.

   Response. Done.
5. Chapter 3 Literature review, page 4, paragraph 1: First sentence belongs to Introduction.

   Response. Change made.
6. Chapter 3, page 4, paragraph 2: not clear what “secondary enhancement features” is referring to? Please rephrase.

   Response. Rephrased.
7. Chapter 3, page 4: Please delete the following sentence: “As follows is a summary of relevant publications”.

   Response. Deleted.
8. Chapter 3, section 3.1 Relevant Publications: There is an orphaned header (section 3.1), please delete section 3.1 Relevant Publications, which will help move up headings a level.

   Response. Done, with headings moved.
9. Chapter 3, section 3.1 General Seismic Data Background Literature, page 5, paragraph 2: Reference Morton-Thompson (1992) in the text vs Reference Morton-Thompson (1993) in the reference list, please correct.

   Response. 1992, change made in references.

10. Chapter 3, section 3.1 General Seismic Data Background Literature, page 5, paragraph 2: Please add Fowler (2005) and White & Simm (2003) in the broad overview publications description.

    Response. Change made.
11. Chapter 3, subsection 3.1.1 Fowler (2005), Seismic Wave Propagation, paragraph 1: Please delete the following sentence: "The positive portions of a wave are noted as having a normal polarity…".

    Response. Deleted.
12. Chapter 3, subsection 3.1.1 Fowler (2005), Seismic Wave Propagation, last paragraph: Please delete the very last sentence.

    Response. Deleted.
13. Chapter 3, subsection 3.1.1 Fowler (2005), Equation 5: Please define Z1 and Z2 since P1, P2, V1, V2 are not in the equation.

    Response. Change Made.
14. Chapter 3, subsection 3.1.2 Morton-Thompson (1992): Morton-Thompson (1992) in the header and Figure 3-5 captions vs Reference Morton-Thompson (1993) in the reference list, please correct.

    Response. Reference changed to 1992.
15. Chapter 3, subsection 3.1.4 Alsadi (2017), Structural Interpretation, page 13, paragraph 1: not clear what "borehole breakout directions" is refering to? Please rephrase.

    Response. Rephrased.
16. Chapter 3, section 3.2 Shallow-Focused Newly Acquired Seismic Data, please add USGS abbreviation in the header, example USGS Carbonate Aquifer Characterization Lab.

    Response. Added "United States Geological Survey" to header.
17. Chapter 3, section 3.2 Shallow-Focused Newly Acquired Seismic Data, pages 17, 18, 19: Cunningham and others (2018a) and (2018b). There is no reference for 2018b in the reference list.

    Response. B added to reference list. There is also a comment on Cunningham and others (2012) not being in the list. It is now added.
18. Chapter 3, subsection 3.3.2 Gustafson and others (2019); (EM) techniques combined with seismic: Please don't use abbreviation in the header.

    Response. Replaced with 'electromagnetic'.
19. Chapter 3, subsection 3.3.2 Gustafson and others (2019), figure 3-13: Please expand the figure to 5.5 inches graphic width. Please use abbreviations in the captions.

    Response. Done.
20. Chapter 3, subsection 3.4.1 Scharling and others (2009), page 23, paragraph 1, first sentence: not clear "succession" of what? Please rephrase.

    Response. Replaced with 'interval'.
21. Chapter 3, subsection 3.4.2, Figure 3-16: Expand this figure to 5.5 inches graphic width.

    Response. Done.
22. Chapter 3, subsection 3.4.3 Martin and others (2013), page 27, paragraph 1, last sentence: the exact page (or pages) must be given to a quoted reference.

    Response. Quote removed.

23. Chapter 3, subsection Tunisia, paragraph 1: Please delete this subsection followed by a short paragraph. Next subsection will be 3.4.4 Khazri and Gabtni (2015).
    Response. Done.
24. Chapter 3, subsection 3.4.5 Souei and Zouaghi (2018), paragraph 1: please use “aquifers” instead of “reservoirs”.
    Response. Change made.
25. Chapter 3, subsection 3.4.5 Souei and Zouaghi (2018), paragraph 1: Please use “acoustic logs” instead of “well log velocity curves”, and “aquifers” instead of “reservoirs”.
    Response. Done.
26. Chapter 3, subsection 3.5.5 Al-Gain and others (2020), paragraph 1, sentences 1 and 3: Please correct parentheses.
    Response. Parentheses corrected.
27. Chapter 3, subsection 3.5.5 Al-Gain and others (2020), figure 3-22: Please expand this figure to 5.5 inches graphic width.
    Response. Resized.
28. Chapter 3, 4.2 Discussion – Acquisition and Processing Histories, paragraph 4: Please use dollar sign ($) for the cost estimate (example $2,000).
    Response. Done.
29. Chapter 3, 4.3 Sources of Seismic Data Information: Please provide link in the following format (example: https://web.seismicexchange.com/1/).
    Response. Formatted.
30. Chapter 5 Data Quality and Limitations, subsection 5.2.1 Spatial limitations, paragraph 1: please use dollar sign ($) for the cost estimate of a seismic data.
    Response. Used.
31. Chapter 5, subsection 5.2.4 Issues on reflection strength, equation 7: Reflection coefficient has been previously defined as R (Chapter 3).
    Response. Conflict mitigated.
32. Chapter 5, subsection 5.2.4 Issues on reflection strength, paragraph 2: Reference to Figure 3-2 is supposed to be to Figure 5-2.
    Response. Change made.
33. Chapter 5, subsection 5.2.4 Issues on reflection strength, figure 5-3: Please provide link in the following format (example: https://web.seismicexchange.com/1/).
    Response. Change made.
34. Chapter 5, subsection 5.3.2 Three-Dimensional Surveys, paragraph 2: Please rephrase.
    Response. Rephrased.
35. Chapter 5, subsection 5.4.1 Acquisition Parameters and Quality Checking, figures 5-5, 5-6, 5-7: Please make these figures same in graphic width (3.5 – 4 inches).
    Response. Corrected to 4” graphic width.
36. Chapter 5, subsection 5.4.1 Acquisition Parameters and Quality Checking, figure 5-5 captions: Please correct to: “Difference between European and American polarity conventions”.
    Response. Corrected.

37. Chapter 5, subsection 5.5.2 Interpretation Sequences, paragraph 4: Does high-pass frequency filter also mute lower frequencies throughout the dataset? If yes, please add.
    Response. Added explanation.
38. Chapter 6 Methodology for Application of Seismic Data on Brackish Aquifers, subsection 6.1.3 Stratigraphic Analysis (Task C), paragraph 2: Please add following sentence: "Additionally, geologic structures such as faults are difficult to interpret when only using well log data to characterize stratigraphic models".
    Response. Added sentence.
39. Chapter 6, subsection 6.1.3 Stratigraphic Analysis (Task C), paragraph 3: Please correct to: "However, three-dimensional seismic attribute analysis imposed on cores and well logs provide a quantitative basis for a higher resolution correlation of sands within an interval as well as high resolution stratigraphic framework".
    Response. Corrected.
40. Chapter 6, subsection 6.2.1 Aquifer Specific Consideration, Table 6-1: Please don't use all caps in the first column. Adjust the width of the columns to avoid splitting units in the header. In the Notes below, please add 3D = three-dimensional.
    Response. Table, caption, and notes adjusted.
41. Chapter 6, Figures:
    Response. Figure 6-6, Blossom: Please correct to "2D seismic line" in legend.
        i. **Corrected.**
    Response. Figure 6-7, Bone Spring-Victorio Peak: Please add Contour interval in the captions. Please remove "3D seismic volume" from the legend.
        i. **There are no contours on this image.**
    Response. Figure 6-14 Cross Timbers: Please add Contour interval in the captions. Please correct to "3D seismic volume" in legend.
        i. **Added and corrected.**
    Response. Figure 6-16 Dockum: Please correct to "3D seismic volume" in legend.
        i. **Corrected.**
    Response. Figure 6-18, 6-19, ETP: Please correct to "2D seismic line" in legend. Please correct contour interval in the captions.
        i. **Done.**
    Response. Figure 6-28, Marathon: Please add contour interval.
        i. **No contours on this figure.**
    Response. Figure 6-30, Nacatoch: 3D seismic volume is very hard to see. Please correct to "3D seismic volume" in the legend.
        i. **Fixed visibility issue, corrected to 3D seismic volume in legend.**
    Response. Figure 6-32, Ogallala: Please correct to "3D seismic volume" in the legend.
        i. **Done.**
    Response. Figure 6-40, 6-41, Seymour: Depth to bottom contour lines are barely distinguishable.
        i. **Colors adjusted.**
    Response. Figure 6-44, 6-45, 6-46, 6-47: Please add Contour interval in the captions.

   i. **Added.**

   Response. Figure 6-5 – 6-49: Please add picture borders of 1pt in Word.

   i. **Borders added.**

42. Chapter 7, subsection 7.2.2 Data Collection (Task B), paragraph 1: Please correct to "Al-Gain and others (2020) was previously discussed in Task 1 (Chapter 3)".
    Response. Concur. Made change.
43. Chapter 7, subsection 7.2.4 Hydrogeologic Study (Task D): Please use milligrams per liter TDS.
    Response. Made change.
44. Chapter 7, Table 7-1: Table captions precede the table. Caption 10 pt. bold, hanging indent 1"; 18 pt. space before; 12 pt. space after; tabs 1". Table column heads: Times New Roman 10 pt. bold; single spacing; centered. Table text: Times New Roman 10 pt.; single spacing.
    Response. Made change.
45. Figure 7-1: Please expand the figure to 6.5 inches graphic width.
    Response. Made change.
46. Figure 7-9: Please move to subsection 7.2.13. Provide another figure on synthetics generated.
    Response. I think the placement is better here because the synthetic logs were used for the seismogram. Added figure with synthetic seismogram.
47. Figure 7-10: Please mention what color scale defines.
    Response. Made change.
48. Figure 7-11: Please add stratigraphy abbreviation description under Notes below.
    Response. Added.
49. Figure 7-13: Please mention what color scale defines.
    Response. Mentioned.
50. Figure 7-14: Please add stratigraphic tops/bottoms.
    Response. Added Middle Lagarto Top.
51. Figure 7-16: Please expand the figure to 6.5 inches graphic width.
    Response. Made change.
52. Figure 7-18, 7-19, 7-21: Please expand the figure to 6.5 inches graphic width; indicate what color scale defines (in captions); add stratigraphic tops/bottoms along Wardner 268 and stratigraphy abbreviation description under Notes.
    Response. Changes made.
53. Figure 7-20: A - Please add stratigraphic tops/bottoms along Wardner 268. Captions: B - Please add interval in ms, within which geobogy is located. Please add what geologic formation this interval corresponds to.
    Response. Addressed.
54. Figure 7-22: Please collapse the figure to 4.5 inches graphic width.
    Response. Made change.
55. Figure 7-23: Cross section: Tsl 3 is at 765ms, but it must be at 720ms according to fig. 7-26; Tsl 2 is at 955ms, but it has to be at 938ms just above B/UO2 according to Fig. 7-25; There is no B/Lag seismic horizon, just label; Formation top labels are very difficult to

read. Legend: please use 10.000 TDS; There is no B/Lag in the abbreviation description of seismic tops. Please consider placing the Color bar and Legend under the cross section – this will help expanding the cross section. Legend can be divided into two columns.

Response. Comments addressed. Time slice references adjusted. Time slices may vary some over the study area, since Tom was slicing these based on a reflector at a certain time.

56. Figure 7-25: Please add “compare to Upper Oakville Channel 1” to captions, and please correct the figure cross reference used.

    Response. Added, fixed.

57. Figure 7-27: Formation top labels are difficult to read. Please consider placing the Color bar and Legend under the cross section – this will help expanding the cross section. Legend can be divided into several columns. Tls label and line should be removed from the cross section since no time slice provided.

    Response. Adjusted.

58. Chapter 7, subsection 7.2.13 Inversion, Pseudolog Cross-plots, paragraph 1: Please check figure cross references in the text.

    Response. Changed.

59. Chapter 7, subsection 7.2.13 Inversion, Examination of Acoustic Impedance and Relative Acoustic Impedance Volumes, paragraph 1: Please provide a range of figures where RAI was used for interpretation.

    Response. Provided.

60. Chapter 7, subsection 7.2.13 Inversion, Examination of Acoustic Impedance and Relative Acoustic Impedance Volumes, page 187: Please correct to: “At the top of this lower zone (just above the B/UO2 mark) is Upper Oakville 938 millisecond channel sand described on seismic amplitude volume as Upper Oakville Channel 1…”. Please specify what “lower zone” stands for.

    Response. Just referring to lower portion of the seismic, removed for clarity.

61. Chapter 7, subsection 7.3.2 Geobody Delineation, paragraph 1: Please correct figure cross references.

    Response. Figure references corrected.

62. References: Not all references are in the reference list, and some reference in the text don’t match those provided in the reference list (see examples above, please note that only Chapter 3 references have been checked against reference list). Some references are not in alphabetical order

    Response. Done, references fixed.

63. Appendix, tables: Caption 10 pt. bold, hanging indent 1"; 18 pt. space before; 12 pt. space after; tabs 1". Table column heads: Times New Roman 10 pt. bold; single spacing; centered. Table text: Times New Roman 10 pt.; single spacing.

    Response. Formatted.