Final Report – Seismic Procurement, Processing, and Interpretation – Edwards-Trinity (Plateau) Aquifer

Texas Water Development Board Report 2300012710-1

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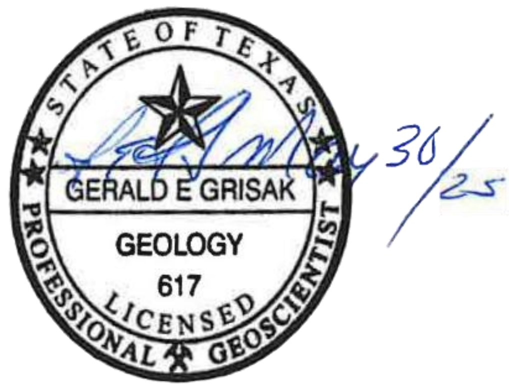
Mr. Grisak supervised INTERA geologists/hydrogeologists involved in the report development.



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Mr. Rochat was responsible for technical review of the report and for the generation of hydrogeologic and structural maps across the study area.

Preface

Reliable stratigraphic frameworks use an abundance of outcrop and/or core, geophysical, and seismic data (Kerans and Tinker, 1997). These data provide a rock-based framework to use for geologic interpretations. With this study, published outcrop studies are correlated with deeper portions of the Edwards Trinity (Plateau) Aquifer (ETPA) using 2D seismic lines. This report provides an example of how to leverage seismic data, geophysical well logs, and water well data to develop a groundwater resource evaluation. Data coverage from outcrop to relevant depths of an aquifer in combination with geophysical logs, water well logs, and water well performance advantages aquifer scientists.

Though the seismic lines and much of the geophysical log well data discussed in this report are available from vendors, the data are obtained at relatively high cost with oil & gas industry prices and confidentiality restrictions. Although the general location of seismic lines and well logs are indicated herein, the exact geographic locations and latitude/longitude references are for the most part confidential. INTERA/TWDB adhere in this document to confidentiality requirements with respect to their precise locations.

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Executive Summary

The Texas Water Development Board (TWDB) is exploring the potential use of seismic data for mapping and characterizing brackish aquifers in Texas. This study focuses on the use of seismic data for the Edwards-Trinity (Plateau) Aquifer (ETPA). INTERA Incorporated (INTERA) has partnered with the TWDB's Brackish Resource Aquifer Characterization System (BRACS) group to determine the feasibility of using existing seismic data, originally acquired for oil and gas exploration, to improve the understanding of aquifer structure and stratigraphy. The same methodologies detailed herein can also be used in other aquifers for assessing, reprocessing, depth-converting and integrating seismic data.

Texas is fortunate to have a wealth of historical seismic data throughout the oil- and gas-bearing areas of the state that can be used as demonstrated in this report. The same approach is applicable in non-oil and gas areas with seismic profiles developed specifically for the purpose of aquifer evaluation.

An additional strength of this project lies in its integrated approach to aquifer characterization. The incorporation of outcrop data into the seismic interpretation workflow has allowed for the development of a stratigraphic framework that extends from surface exposures to the deeper subsurface. This approach ties the subsurface model to the observed surface geology and provides a scientific basis for extrapolating aquifer properties and facies distribution throughout the study area.

The study began with a comprehensive evaluation of available seismic lines within the ETPA region. A total of 129 seismic lines were assessed based on various parameters, including acquisition characteristics, depth of the aquifer, presence of hydrocarbons, and availability of well log data. The seismic lines were then ranked using a weighted matrix approach to determine their feasibility for imaging the aquifer.

Southern Kinney County was identified as the most promising area for the study, with 14 seismic lines having feasibility scores above zero. INTERA and TWDB collaboratively selected a subset of these lines by considering factors such as line proximity, data quality, and cost. The selected lines were then leased from the seismic vendors.

After the seismic lines were acquired, INTERA contracted Tricon Geophysical (Tricon) to reprocess the 2D lines to enhance the resolution in near-surface portions of the seismic data that covered the aquifers. Tricon utilized a series of processing steps to achieve this goal, including initial reformatting and filtering, noise reduction and static corrections, stacking, and amplitude profiling. Each reprocessing step played a role in increasing data resolution by correcting various seismic traces that can distort the seismic signal and ultimately provided a more reliable representation of the subsurface geology.

Geophysical well logs were then utilized to correlate known depths to tops of

stratigraphic units to seismic horizons in nearby reprocessed seismic lines. Correlating these data allowed for a time-depth relationship to be established and for the well log data to be tied to the seismic data. Synthetic seismograms were then employed to refine the well ties and constrain the well log markers, ensuring the accuracy of the depth converted profiles.

This seismic interpretation workflow has successfully translated the reprocessed and depth-converted seismic data into a product that demonstrates a methodology suitable for developing a three-dimensional geological model of a specific target area of the ETPA, namely Kinney County, based on availability of suitable seismic data. The methodology outlined herein demonstrates that identification and interpretation of key seismic horizons, faults, and other geologic features can provide valuable insights into the aquifer's structural framework and stratigraphic architecture.

This study has demonstrated that high-resolution seismic data may be leveraged to better understand an aquifer's geometry, internal architecture, and potential higher yield groundwater production zones associated with faulted and fractured sections of the aquifer. This demonstration of seismic interpretation methodology illustrates the value of integrating seismic data with outcrop and well log information to develop a comprehensive and robust subsurface model of the aquifer. The integrated outcrop-log-seismic framework developed in this project serves as a template for future hydrogeologic investigations and underscores the importance of incorporating seismic data into groundwater resource assessments.

1 Introduction

The primary purpose of this report is to establish the feasibility of using two-dimensional (2D) seismic lines to help develop a reliable stratigraphic framework for the Edwards-Trinity (Plateau) Aquifer (ETPA). Though constrained by contractually-defined data confidentiality with respect to precise locations, the approach and methodology described herein are presented as a guide to researchers seeking to establish a scientific basis for the exploration and exploitation of the groundwater resources of the ETPA. The methodology of selecting, reprocessing, and depth-calibrating seismic data described herein may be applied to other aquifers, though differences in geologic assumptions exist. Sections 1 through 5 develop a stepwise approach to deriving a stratigraphic interpretation using seismic data and geophysical well log ties, while Section 6 presents an approach to data integration and interpretation within the general area of southern Kinney County. Section 7 presents the Conclusions of this report, and Section 8 lists the references used in this report. Section 9 addresses comments posed by the TWDB in response to an earlier draft of this report.

1.1 Seismic Line Descriptions

1.1.1 Goal and Purpose

The first piece of a seismic study is defining scope. For this study, seismic data will be used to provide definition on the structure and stratigraphy of the ETPA as part of the larger Brackish Resource Aquifer Characterization System (BRACS) Edwards-Trinity (Plateau) Aquifer study.

1.1.2 Data Collection

The first step in the data collection process is describing the available seismic lines. Characteristics of seismic data are available directly from the seismic vendors. This study describes 129 seismic lines taken from Draper and others (2021) that intersect the ETPA. This study did not gather the entire body of purchasable seismic data on a regional scale due to the high data costs. Rather, a few seismic lines were selectively chosen as representative and illustrative of ETPA structure and stratigraphy. Table 1-1 lists the seismic lines that were determined most likely to contribute to the objectives of this study.

Seitel and Seismic Exchange, Inc. (SEI) are two vendors in Texas controlling most of the seismic data, but Schlumberger, Viridien (formerly CGG), and the National Archive of Marine Seismic Surveys may also have usable data. Seitel and SEI both have websites that show the coverages of seismic lines and provide detailed information about each line. The vector data of these lines can be downloaded from their websites and then uploaded into a Geographic Information System program to determine whether they are spatially relevant to a given study area.

Draper and others (2021), in a BRACS-supported study to determine the availability and suitability of two-dimensional and three-dimensional (3D) subsurface seismic data for use in brackish groundwater studies within the State of Texas, established that 2D seismic data covered approximately 75 percent of the ETPA.

1.1.3 Describing Seismic Quality

The 129 seismic lines used in this study were downloaded along with their publicly available information. Seitel was asked to provide more details on each of their lines to supplement their online information. These 129 seismic lines are presented in Table 1-1, and Figure 1-1 shows the 129 seismic lines on the base of the ETPA (Draper and others, 2021). Table 1-1 provides the following details for each line: line name, line unique ID, cost per mile, survey, begin shot point, end shot point, group interval, source interval, length (miles), channel, fold, energy, shot by company, year shot, year the data were last processed, and dataset name. Some of these terms are self-explanatory; others are described below:

- Shot point – A location at which a seismic source is activated.
- Group interval – The distance between geophones or groups of geophones.

- Source interval – The distance between adjacent source points along a source line.
- Channel – A device to carry data from a geophone or geophones to a recorder. Simultaneous recording of 500 to 2,000 channels is common during 3D seismic acquisition, and 120 to 240 channels is common during onshore 2D seismic acquisition.
- Fold – A measure of the redundancy of seismic data, equal to the number of receivers that record a given data point or in each bin and are added during stacking to produce a single trace. Increasing fold correlates to increasing confidence in the data.
- Energy – Energy source used to create acoustic waves.

Considering the scope of this study, a seismic line can generally be categorized as *poor* or *good* based on its location and characteristics. An example of a comparatively *poor* line is 66-174-598 (Table 1-1). This line has a source interval spacing of 1,600 feet, a low fold value of 6, and was taken with dynamite in 1966. This line is likely only to resolve the coarsest features. However, it is relatively inexpensive at $2,075 per mile.

An example of a comparatively *good* line in Table 1-1 is E-SOH-SYM-1. Taken in 1982 with Vibroseis, it has a fold of 128 and source interval spacing of 80 feet. This is a very tight spacing and high fold for the data available in the area, which would provide significantly higher resolution data than 66-174-598. However, this line is somewhat more expensive at $3,075 per mile.

Table 1-1. Seismic line descriptions. Data from SEI, available online, and Seitel, provided on request.

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	544152	PR-KB-23	25.4	2,275	KERR BASIN TX #73757	10	416	330	330	24	12	VIBROSEIS	Ray Geophysical Co.	1968	2012	Western Geophysical	No	No	Dip	Yes
SEI	544165	PR-KB-22-PT3	14.5	2,275	KERR BASIN TX #73757	638	869	330	330	24	12	VIBROSEIS	Ray Geophysical Co.	1968	2011	Western Geophysical	Yes	No	Dip	Yes
SEI	544934	W017P-1	22.1	2,075	JURASSIC TREND/W017P	2	406	300	300	20	10	VIBROSEIS	Sun Oil Co.	1969	2011	Oryx-Sun	Yes	Yes	Outside Interpolation Extent	Yes
SEI	550187	LR-33	21.2	2,275	LAREDO RECON	202	540	330	660	48	12	VIBROSEIS	--	1981	1995	Laredo Recon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	550194	LR-36	30.6	2,275	LAREDO RECON	224	713	330	660	48	12	VIBROSEIS	SSC - Seismograph Service Corporation	1981	1995	Laredo Recon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	550200	LR-C	11.9	2,275	LAREDO RECON	102	291	330	660	48	12	VIBROSEIS	SSC - Seismograph Service Corporation	1981	1995	Laredo Recon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	557822	TG547-2	10.2	2,875	HALSELL RANCH/TG 547	101	589	110	220	192	60	DYNAMITE	Dawson Geophysical Company	1990	2011	Oryx-Sun	Yes	Yes	Outside Interpolation Extent	Yes
SEI	557823	TG547-4	11.1	2,875	HALSELL RANCH/TG 547	101	635	110	220	192	60	DYNAMITE	Dawson Geophysical Company	1990	2010	Oryx-Sun	Yes	Yes	Outside Interpolation Extent	Yes
SEI	557824	TG547-6	11.8	2,875	HALSELL RANCH/TG 547	101	664	110	220	192	60	DYNAMITE	Dawson Geophysical Company	1990	2010	Oryx-Sun	Yes	Yes	Outside Interpolation Extent	Yes
SEI	561769	TG547-1	25.6	2,875	HALSELL RANCH/TG 547	102	1330	110	220	192	60	DYNAMITE	Dawson Geophysical Company	1990	2010	Oryx-Sun	Yes	Yes	Outside Interpolation Extent	Yes
SEI	639248	PMF-9	14.4	2,875	BC1	1	231	330	330	121	60	VIBROSEIS	Petty Ray Geophysical	1985	2010	Amoco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	663666	63-11-595	26.7	2,275	CRETACEOUS	1155	1507	400	400	24	12	DYNAMITE	Shell Western E&P, Inc.	1963	2009	Shell	Yes	Yes	Dip	Yes
SEI	664218	65-253-1021	16.7	2,275	ONSHORE	239	451	400	400	24	12	DYNAMITE	Shell Western E&P, Inc.	1965	2010	Shell	Yes	Yes	Outside Interpolation Extent	Yes
SEI	664221	65-253-1022	11.6	2,275	MS1	411	563	400	400	24	12	DYNAMITE	Globe Exploration Service	1965	2010	Shell	Yes	Yes	Outside Interpolation Extent	Yes
SEI	664250	65-253-570	21.8	2,275	MS1	4006	4293	400	400	24	12	DYNAMITE	Globe Exploration Service	1965	2010	Shell	Yes	Yes	Outside Interpolation Extent	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	664811	70-111-1085A	28.9	2,275	MS1	1006	1386	400	800	48	12	DYNAMITE	Shell Western E&P, Inc.	1970	2010	Shell	Yes	Yes	Outside Interpolation Extent	Yes
SEI	684279	67-GL-243-0026	26.0	2,075	MS1	504	960	300	1200	48	6	DYNAMITE	Globe Exploration Service	1967	2009	Shell	No	No	Strike (oblique)	Yes
SEI	685153	69-120-1028	31.9	2,275	MS1	63	624	300	600	48	12	DYNAMITE	Shell Western E&P, Inc.	1969	2009	Shell	Yes	No	Strike	Yes
SEI	685158	68-120-591.5	16.2	2,075	MS1	710	1137	200	600	48	8	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	No	No	Dip	Yes
SEI	685159	69-120-592	13.9	2,275	MS1	666	909	300	600	48	12	DYNAMITE	Shell Western E&P, Inc.	1969	2009	Shell	Yes	No	Dip	Yes
SEI	685161	69-120-597	20.3	2,275	MS1	703	1060	300	600	48	12	DYNAMITE	Shell Western E&P, Inc.	1969	2009	Shell	Yes	No	Dip	Yes
SEI	685172	67-120-920	21.0	2,075	MS1	431	799	300	1800	48	8	DYNAMITE	Shell Western E&P, Inc.	1967	2009	Shell	Yes	No	Dip (oblique)	Yes
SEI	685175	68-120-924	15.1	2,075	MS1	271	668	200	600	48	8	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	No	No	Strike (oblique)	Yes
SEI	685180	68-120-930	37.4	2,275	MS1	122	943	300	600	32	12	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	Yes	No	Strike (oblique)	Yes
SEI	690222	69-120-594	39.9	2,275	MS1	280	1111	200	600	48	12	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	Yes	No	Dip	Yes
SEI	690225	67-120-918	33.6	2,075	MS1	460	903	400	2400	48	8	DYNAMITE	Shell Western E&P, Inc.	1967	2009	Shell	Yes	No	Dip	Yes
SEI	690236	66-174-598	13.8	2,075	MS1	817	998	400	1600	48	6	DYNAMITE	Shell Western E&P, Inc.	1966	2010	Shell	Yes	No	Dip	Yes
SEI	735253	63-11-1138	9.2	2,075	CRETACEOUS	1176	1297	400	800	24	6	DYNAMITE	Shell Western E&P, Inc.	1963	2009	Shell	Yes	Yes	Dip (oblique)	Yes
SEI	737091	69-120-573	14.1	2,275	MS1	364	612	300	600	48	12	DYNAMITE	Shell Western E&P, Inc.	1969	2009	Shell	No	No	Dip	Yes
SEI	737092	68-120-599	23.3	2,075	MS1	722	1,029	400	1200	48	8	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	Yes	No	Dip	Yes
SEI	737509	69-120-585.3	33.7	2,075	MS1	390	1,085	200	600	48	8	DYNAMITE	Shell Western E&P, Inc.	1968	2009	Shell	Yes	No	Dip	Yes
SEI	740981	GDI-ML-2	13.7	2,275	MCKNIGHT-LAGOON	103	321	330	660	48	12	VIBROSEIS	United Geophysical Co.	1982	1999	GDI	Yes	Yes	Outside Interpolation Extent	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	933963	BGS-5	14.7	2,475	BC1	4	779	100	200	96	24	VIBROSEIS	Seismic Resources, Inc.	1980	2011	Amoco	Yes	No	Dip	Yes
SEI	933964	BGS-6	15.7	2,475	BC1	4	834	100	200	96	24	VIBROSEIS	Seismic Resources, Inc.	1980	2011	Amoco	Yes	No	Dip	Yes
SEI	933965	BGS-8	13.5	2,475	OUACHITA THRUST	4	718	100	200	96	24	VIBROSEIS	Seismic Resources, Inc.	1980	2011	Amoco	Yes	No	Dip	Yes
SEI	933966	BGS-8A	8.7	2,475	BC1	724	1180	100	200	96	24	VIBROSEIS	Seismic Resources, Inc.	1980	2011	Amoco	Yes	No	Dip	Yes
SEI	975652	PMF-8	17.8	2,875	BC1	2	285	330	330	121	60	VIBROSEIS	Petty Ray Geophysical	1985	2010	Amoco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	1144308	E-SOH-SYM-1	23.3	3,075	CENTRAL MIDLAND BASIN	160	6320	20	80	1024	128	VIBROSEIS	Geophysical Service, Inc. (GSI)	1982	2016	Enserch/Sohio	No	No	Dip	Yes
SEI	2001103	42127-1271	30.1	2,275	DIMMIT	2012	2541	300	600	48	12	DYNAMITE	ExxonMobil Exploration Company	1971	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2001106	42127-12713	17.3	2,275	DIMMIT	2007	2422	220	220	96	48	VIBROSEIS	--	1985	2003	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2001115	42127-DI41	16.7	2,275	DIMMIT	565	785	400	400	24	12	DYNAMITE	ExxonMobil Exploration Company	1970	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2001116	42127-DI42	11.6	2,275	DIMMIT	793	945	400	400	24	12	DYNAMITE	--	1970	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2001122	42127-DI44A	29.1	2,275	DIMMIT	2398	2781	400	400	24	12	DYNAMITE	--	1964	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2001126	42127-DI46	10.9	2,275	DIMMIT	2793	2936	400	400	24	12	DYNAMITE	--	1965	2003	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2002486	42271-2713	16.8	2,675	KINNEY	2002	2404	220	220	96	48	VIBROSEIS	ExxonMobil Exploration Company	1984	2002	Exxon	Yes	No	Dip	Yes
SEI	2002487	42271-2714	20.3	2,675	KINNEY	1998	2483	220	220	96	48	VIBROSEIS	ExxonMobil Exploration Company	1984	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2002488	42271-2714A	9.5	2,675	KINNEY	2434	2660	220	220	96	48	VIBROSEIS	ExxonMobil Exploration Company	1985	2003	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2003063	42323-3231	11.6	2,275	MAVERICK	2014	2217	300	600	48	12	DYNAMITE	ExxonMobil Exploration Company	1972	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2003064	42323-32310	18.7	2,275	MAVERICK	1998	2985	100	300	92	15	DYNAMITE	Exxon Exploration Company	1978	2002	Exxon	Yes	Yes	Strike (oblique)	Yes

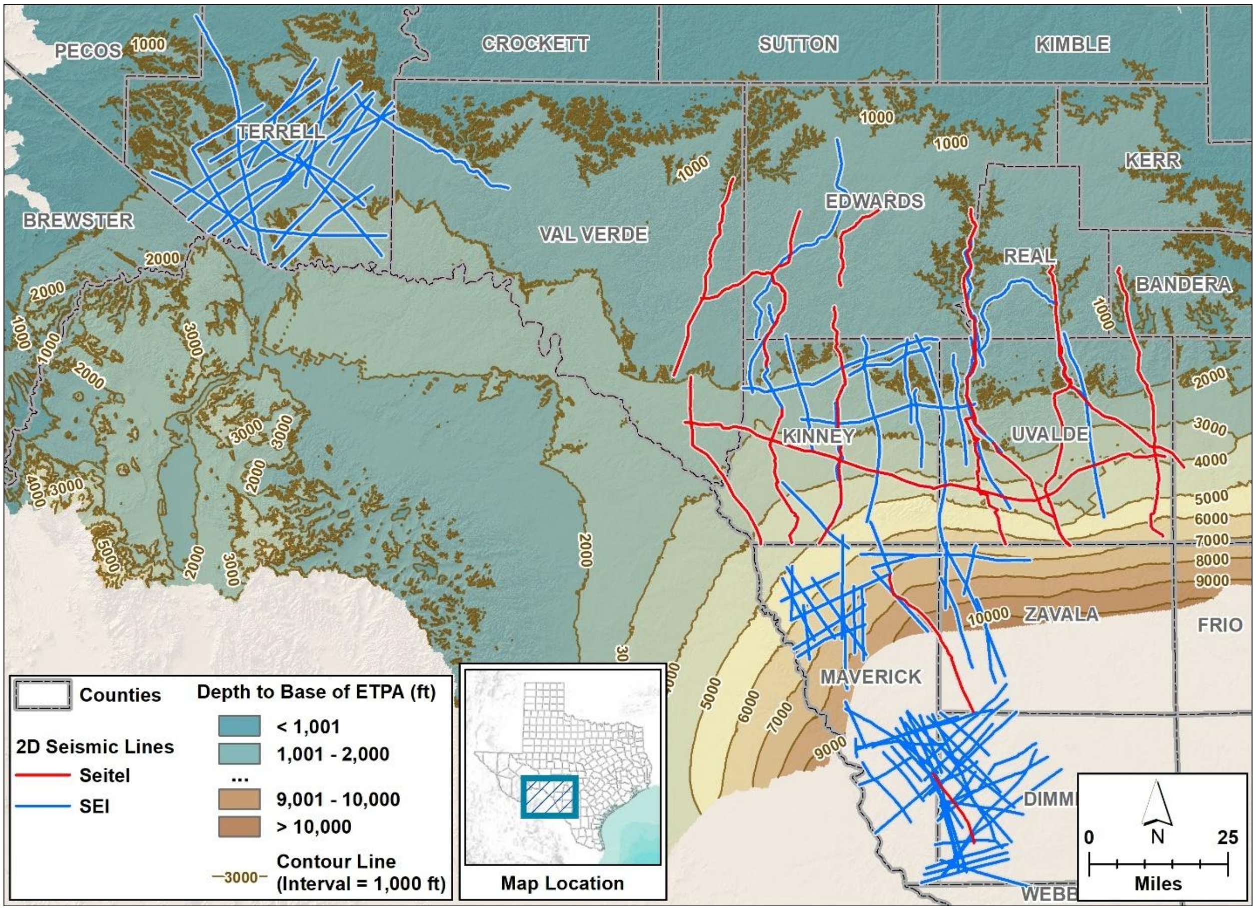
Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	2003065	42323-32311	16.4	2,275	MAVERICK	2026	2893	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2003066	42323-32312	14.9	2,275	MAVERICK	2031	2816	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2003067	42323-32313	11.6	2,275	MAVERICK	1987	2599	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2003068	42323-32314	9.3	2,275	MAVERICK	2037	2527	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2003069	42323-32315	11.7	2,275	MAVERICK	2045	2661	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1979	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2003070	42323-32316	13.1	2,275	MAVERICK	1716	2408	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1979	2002	Exxon	Yes	Yes	Strike (oblique)	Yes
SEI	2003072	42323-32318	14.2	2,275	MAVERICK	2016	2766	100	300	92	15	DYNAMITE	--	1979	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2003076	42323-32324	9.0	2,675	MAVERICK	2002	2216	220	220	96	48	VIBROSEIS	ExxonMobil Exploration Company	1984	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2003077	42323-32325	20.4	2,675	MAVERICK	2002	2491	220	220	96	48	VIBROSEIS	ExxonMobil Exploration Company	1984	2003	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2003078	42323-32326	20.7	2,675	MAVERICK	2002	2497	220	220	96	48	VIBROSEIS	--	1984	2002	Exxon	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2003079	42323-3236	10.9	2,275	MAVERICK	2075	2648	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Strike (oblique)	Yes
SEI	2003080	42323-3237	9.4	2,275	MAVERICK	2024	2519	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2003081	42323-3238	14.8	2,275	MAVERICK	2218	2996	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Strike (oblique)	Yes
SEI	2003082	42323-3239	8.9	2,275	MAVERICK	2070	2539	100	300	92	15	DYNAMITE	ExxonMobil Exploration Company	1978	2002	Exxon	Yes	Yes	Dip (oblique)	Yes
SEI	2004868	42507-5072	17.0	2,275	ZAVALA	2003	2302	300	600	48	12	DYNAMITE	Exxon Exploration Company	1971	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2004880	42507-5073	16.3	2,275	ZAVALA	2007	2292	300	600	48	12	DYNAMITE	ExxonMobil Exploration Company	1971	2002	Exxon	Yes	Yes	Dip	Yes
SEI	2016471	A74WGC-W-4-DMTT	10.7	2,275	MAVERICK BASIN	106	361	220	220	24	12	VIBROSEIS	Western Geophysical Company	1974	1975	Willisco	Yes	Yes	Outside Interpolation Extent	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	2066939	7268-10	20.9	2,475	MYSTIQUE	101	602	220	440	96	24	DYNAMITE	Texaco USA	1985	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066940	7268-11	21.4	2,475	MYSTIQUE	101	614	220	440	97	24	DYNAMITE	Texaco USA	1985	2010	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066950	7268-5	27.8	2,475	MYSTIQUE	101	767	220	440	97	24	DYNAMITE	Texaco E. & P.,Inc.	1984	2010	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066951	7268-6	18.7	2,475	MYSTIQUE	104	551	220	440	120	24	DYNAMITE	Texaco, Inc.	1985	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066952	7268-7	11.5	2,475	MYSTIQUE	101	377	220	440	96	24	DYNAMITE	Texaco USA	1984	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066953	7268-8	21.5	2,475	MYSTIQUE	102	616	220	440	97	24	DYNAMITE	Texaco E. & P.,Inc.	1984	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2066975	GTO1624-1	11.1	2,275	BRISCOE RANCH	126	656	110	220	48	12	DYNAMITE	Triangle Geophysical Co.	1982	2011	Texaco	Yes	Yes	Dip	Yes
SEI	2071725	7640-13	9.2	2,275	EL INDIO	1	110	440	440	24	12	DYNAMITE	--	1971	2013	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2071728	7640-4	14.6	2,275	EL INDIO	1	175	440	440	24	12	DYNAMITE	Texaco USA	1971	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2071729	7640-5	17.4	2,275	EL INDIO	1	210	440	440	24	12	DYNAMITE	Texaco USA	1971	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2071730	7640-6	11.0	2,275	EL INDIO	1	132	440	440	24	12	DYNAMITE	Texaco USA	1971	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2071731	7640-7	11.4	2,275	EL INDIO	1	137	440	440	24	12	DYNAMITE	Texaco E. & P.,Inc.	1971	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2072428	7264-3	16.3	2,475	CALAMARE	104	494	220	440	97	24	DYNAMITE	Southern Seismic Exploration, Inc.	1985	2010	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2072429	7264-4	15.6	2,875	CALAMARE	105	853	110	110	120	60	VIBROSEIS	Texaco USA	1985	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2072430	7264-5	14.3	2,475	CALAMARE	123	466	220	440	120	30	VIBROSEIS	Texaco E. & P.,Inc.	1984	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2072708	7640-3	11.5	2,275	EL INDIO	1	126	480	480	24	12	DYNAMITE	Texaco USA	1971	2011	Texaco	Yes	Yes	Outside Interpolation Extent	Yes
SEI	2564805	1368-14	9.8	2,275	UVALDE RECON	84	240	330	660	48	12	VIBROSEIS	Gulf Oil Company	1976	2013	Chevron	Yes	Yes	Dip	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	2564808	1368-17	15.3	2,275	UVALDE RECON	117	483	220	440	48	12	VIBROSEIS	Western Geophysical Company	1978	2011	Chevron	Yes	Yes	Strike	Yes
SEI	2564809	1368-17A	14.3	2,275	UVALDE RECON	507	848	220	440	48	12	VIBROSEIS	Western Geophysical Company	1978	2011	Chevron	Yes	Yes	Strike (oblique)	Yes
SEI	2565182	2184-3	8.8	2,275	DUNBAR RANCH	104	681	80	320	120	15	VIBROSEIS	SSC - Seismograph Service Corporation	1981	2013	Chevron	Yes	Yes	Strike	Yes
SEI	11183219	22230-2	23.1	2,675	BASSETT MOUNTAIN	1003	1557	220	220	96	48	VIBROSEIS	Teledyne Exploration Co.	1981	1982	ARCO-Vastar	No	No	Strike (oblique)	Yes
SEI	11183335	22230-4	14.0	2,675	BASSETT MOUNTAIN	1002	1336	220	220	96	48	--	--	1981	1981	ARCO-Vastar	No	No	Strike (oblique)	Yes
SEI	11183336	23327-176-04	33.7	2,675	PANDALE 80 SHEAR	1003	1810	220	220	96	48	VIBROSEIS	Teledyne Exploration Co.	1981	1982	ARCO-Vastar	No	No	Dip (oblique)	Yes
SEI	11183337	22234-249-1	12.3	3,075	PANDALE, W SHEAR ARRAY FORM	1005	2084	60	60	288	144	VIBROSEIS	--	1981	1982	ARCO-Vastar	No	No	Strike	Yes
SEI	11183410	22230-3	12.9	2,675	BASSETT MOUNTAIN	1002	1310	220	220	96	48	VIBROSEIS	Teledyne Exploration Co.	1981	1981	ARCO-Vastar	No	No	Strike	Yes
SEI	11183428	22230-7	26.2	2,675	BASSETT MOUNTAIN	1303	1930	220	220	96	48	VIBROSEIS	Teledyne Exploration Co.	1981	1981	ARCO-Vastar	No	No	Dip	Yes
SEI	11183489	22235-405-04	24.8	2,675	PLATFORM EDGE, S	2	298	440	440	96	48	DYNAMITE	Arco Exploration Co.	1983	2016	ARCO-Vastar	No	No	Strike	Yes
SEI	11183515	22235-405-06	21.7	2,675	PLATFORM EDGE, S	102	361	440	440	96	48	DYNAMITE	Arco Exploration Co.	1983	2014	ARCO-Vastar	No	No	Strike	Yes
SEI	11183516	22235-405-08	47.1	2,875	PLATFORM EDGE, S	2	566	440	440	120	60	DYNAMITE	Arco Exploration Co.	1983	2014	ARCO-Vastar	No	No	Dip	Yes
SEI	11183517	22235-405-25	45.3	2,875	PLATFORM EDGE, S	3	545	440	440	120	60	DYNAMITE	Arco Exploration Co.	1984	2016	ARCO-Vastar	No	No	Dip (oblique)	Yes
SEI	11183534	22237-802-1	33.8	2,875	BASSETT MOUNTAIN THRUST	1,003	1,812	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2016	ARCO-Vastar	No	No	Strike (oblique)	Yes
SEI	11183535	22237-802-2	22.2	2,875	BASSETT MOUNTAIN THRUST	1,005	1,536	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2016	ARCO-Vastar	No	No	Strike	Yes
SEI	11183536	22237-802-3	40.0	2,875	BASSETT MOUNTAIN THRUST	1,016	1,974	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2017	ARCO-Vastar	No	No	Strike	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
SEI	11183537	22237-802-4	14.0	2,875	BASSETT MOUNTAIN THRUST	1,005	1,340	220	440	240	60	DINOSEIS	Arco Exploration Co.	1985	2016	ARCO-Vastar	No	No	Strike	Yes
SEI	11183538	22237-802-5	24.7	2,875	BASSETT MOUNTAIN THRUST	1,004	1,595	220	440	240	60	VIBROSEIS	Petty Ray Geophysical	1985	2016	ARCO-Vastar	No	No	Strike	Yes
SEI	11183540	22237-802-7	22.0	2,875	BASSETT MOUNTAIN THRUST	1,004	1,532	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2016	ARCO-Vastar	Yes	No	Strike	Yes
SEI	11183541	22237-802-8	23.9	2,875	BASSETT MOUNTAIN THRUST	1,004	1,576	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2014	ARCO-Vastar	No	No	Dip	Yes
SEI	11183542	22238-8928-1	20.0	2,875	TWIN BUTTES 1985	1,005	1,483	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2016	ARCO-Vastar	No	No	Dip	Yes
SEI	11183543	22238-8928-2	19.3	2,875	TWIN BUTTES 1985	1,004	1,466	220	440	240	60	VIBROSEIS	Arco Exploration Co.	1985	2014	ARCO-Vastar	No	No	Strike	Yes
SEI	11183545	22235-405-07	14.9	2,875	PLATFORM EDGE, S	2	180	440	440	128	64	DYNAMITE	Arco Exploration Co.	1983	2014	ARCO-Vastar	No	No	Strike	Yes
SEI	11183546	22235-405-03	23.4	2,675	PLATFORM EDGE, S	3	283	440	440	96	48	DYNAMITE	Arco Exploration Co.	1983	1983	ARCO-Vastar	No	No	Strike (oblique)	Yes
SEI	11773382	D834-DB67-21	23.0	2,275	VAL VERDE BASIN GROUP 67	96	187	330	660	48	12	VIBROSEIS	Geophysical Service, Inc. (GSI)	1967	--	Oryx-Sun	No	No	Dip	Yes
Seitel	SDL-2142869	3A	40.9	--	Lower Ouachita Trend	1,343	1,996	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	Yes	No	Strike (oblique)	Yes
Seitel	SDL-2143153	5A	38.9	--	Lower Ouachita Trend	1,001	1,352	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	No	No	Dip (oblique)	Yes
Seitel	SDL-2143154	6A	31.3	--	Lower Ouachita Trend	1,101	1,600	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	No	No	Dip	Yes
Seitel	SDL-2143155	6B	4.6	--	Lower Ouachita Trend	1,153	1,175	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	Yes	No	Dip	Yes
Seitel	SDL-2143169	3B	39.6	--	Lower Ouachita Trend	1,949	2,581	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	Yes	No	Strike	Yes
Seitel	SDL-2179115	4	15.9	--	Lower Ouachita Trend	104	358	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	No	No	Dip (oblique)	Yes
Seitel	SDL-2180654	1	34.8	--	Lower Ouachita Trend	101	657	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	Yes	No	Dip	Yes
Seitel	SDL-2180655	1A	39.3	--	Lower Ouachita Trend	107	735	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	No	No	Dip	Yes

Vendor	Line identifier	Line name	Length (mile)	Cost per mile ($)	Survey	Begin shot point	End shot point	Group interval	Source interval	Channel	Fold	Energy	Shot By	Year	Last processed	Dataset	Necessary depth?	Hydrocarbons present?	Orientation	Geophysical log coverage
Seitel	SDL-2180656	2 PT 2	16.6	--	Lower Ouachita Trend	1,341	1,606	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	No	No	Dip	Yes
Seitel	SDL-2180657	2 PT 3,4	26.2	--	Lower Ouachita Trend	1,799	2,217	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	Yes	No	Dip	Yes
Seitel	SDL-2180658	2	24.4	--	Lower Ouachita Trend	101	470	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	No	No	Dip	Yes
Seitel	SDL-2180659	5	45.4	--	Lower Ouachita Trend	1,001	1,727	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	Yes	No	Dip	Yes
Seitel	SDL-2180660	6	23.3	--	Lower Ouachita Trend	1,101	1,472	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	Yes	No	Dip	Yes
Seitel	SDL-2180661	7	57.9	--	Lower Ouachita Trend	1,001	1,926	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	Yes	No	Dip	Yes
Seitel	SDL-2180664	9/P-REPROC	52.0	--	Lower Ouachita Trend	1,001	1,832	330	330	96	48	VIBROSEIS	Grant Geophysical	1982	1982	--	Yes	No	Dip	Yes
Seitel	SDL-2189969	TDY-19-O-P2	30.3	--	Texas	100	590	330	330	48	--	--	Teledyne	1982	1982	--	Yes	Yes	Dip	Yes
Seitel	SDL-2189985	TDY-17-O-P3	34.6	--	Texas	437	875	330	330	48	--	--	Teledyne	1982	1982	--	Yes	No	Dip (oblique)	Yes
Seitel	SDL-2189991	TDY-18-O-P2	24.0	--	Texas	505	895	330	330	48	--	--	Teledyne	1982	1982	--	Yes	No	Dip (oblique)	Yes
Seitel	SDL-2190587	TDY-18-O-P3	8.5	--	Texas	927	1,063	330	330	48	--	--	Teledyne	1982	1982	--	Yes	No	Dip	Yes
Seitel	SDL-2192224	TDY-20J-P4	14.7	--	Texas	695	739	1800	--	24	--	--	Teledyne	1971	1985	--	Yes	Yes	Outside Interpolation Extent	Yes
Seitel	SDL-2192449	3	18.3	--	Lower Ouachita Trend	1,101	1,392	330	330	96	48	VIBROSEIS	Grant Geophysical	1981	1981	--	Yes	No	Strike (oblique)	Yes



Note: ETPA = Edwards Trinity (Plateau) Aquifer), ft = feet, SEI = Seismic Exchange, Inc.

Figure 1-1. Seismic lines on the base of the Edwards-Trinity (Plateau) Aquifer. Many lines in Terrell, Edwards, Real and Bandera counties are too shallow to offer adequate resolution due to high seismic velocities. Depth to base of ETPA is constrained by BRACS database geophysical well logs and structure picks.

1.1.4 Describing Contextual Factors

In addition to factors that deal directly with the quality of seismic data, there are also contextual factors associated with the relevant strata. These contextual factors include necessary depth, presence of hydrocarbons, orientation, and borehole geophysical log presence.

Necessary depth is the most important factor in determining whether a seismic line is feasible for this study. The scope of this study includes the brackish or deeper portion of the ETPA where traditional oil and gas seismic data can be utilized.

In the Gulf Coast of Texas, traditional oil and gas seismic data can be shown to image strata at depths shallower than 1,000 feet (Draper and others, 2021). However, seismic velocities across the ETPA in Central Texas are much higher. These higher velocities exacerbate some of the negative surface effects and generally will mean a lower resolution than similar quality seismic data in the Gulf Coast Aquifer. The combination of high seismic velocity and insufficient depth means that much of the ETPA is not resolvable by traditional oil and gas seismic data and limits the scope of this study to the brackish, deeper parts of the ETPA. The basal depth of the ETPA is parameterized as "Necessary Depth" in Table 1-1. A seismic line is deemed not to have the necessary depth if fewer than three miles of the line is shallower than 2,000 feet. A Necessary Depth indication of "No" disqualifies the line from consideration for this study. In Figure 1-1, all lines in Edwards, Real, and Bandera counties, and most lines in Terrell County, are eliminated because the base of the ETPA is too shallow. Lines in Kinney, Uvalde, Zavala, Dimmit, and Maverick counties have sufficient depth to be retained for further consideration.

The presence of hydrocarbons is considered a disqualifier for feasibility in this study, as hydrocarbons can affect seismic velocities and formation density logs. The ETPA within Maverick, Zavala, and Dimmit counties is often charged with hydrocarbons (Clarke, 2009), which eliminates seismic lines from these counties from consideration. The presence of hydrocarbons is indicated by the "Hydrocarbons Present" column in Table 1-1.

Orientation of seismic lines to the structural trends of the base of the ETPA is important to consider. The column labeled "Orientation" in Table 1-1 contains the following terms: "dip," "strike," "oblique dip," "oblique strike," and "outside interpolation extent." Dip, strike, oblique dip, and oblique strike describe relative orientations of the seismic line to the local structural trend of the base of the ETPA. This stratigraphic study will require at least two dip and one strike line of adequate resolution that cover the base of the ETPA across the study area. The last term included in the "Orientation" column is "outside interpolation extent," meaning the base of the ETPA does not extend to these lines (Figure 1-1). These lines are all downdip and are further disqualified for the presence of hydrocarbons.

Lastly, borehole geophysical log coverage should be considered. The column "Geophysical Log Coverage" indicates whether there are sufficient well logs to characterize a seismic line. For this study, well-log coverage includes all free well-logs, SL&AL (Subsurface Library) and the University of Texas Bureau of Economic Geology logs that measure strata shallower than 5,000 feet, and any expensive log that has a sonic log, as those are typically the least common and most important for correlation of seismic data. This column is also a qualitative measure relative to a study area. A line with very poor coverage would have no well-logs within 50 miles, and a line with excellent coverage would have several well-logs within 100 feet of the line. A sliding scale exists between these two endmembers. For this study, all the seismic lines have sufficient well-log coverage. Seismic lines with poor well-log coverage should be procured and evaluated with caution, knowing that tying the seismic lines to equivalent depths without sufficient well-logs would be tenuous. Section 1.2 discusses well-log coverage.

The above methodology used to describe seismic lines is relatively straightforward. However, there is no substitute for viewing seismic data. After determining which seismic lines are the highest-ranked, it is deemed appropriate to examine them with the seismic vendors prior to purchase, if the vendor allows. This qualitative step nuances the evaluation and better informs the buyer.

1.2 Recruit Geophysical Logs

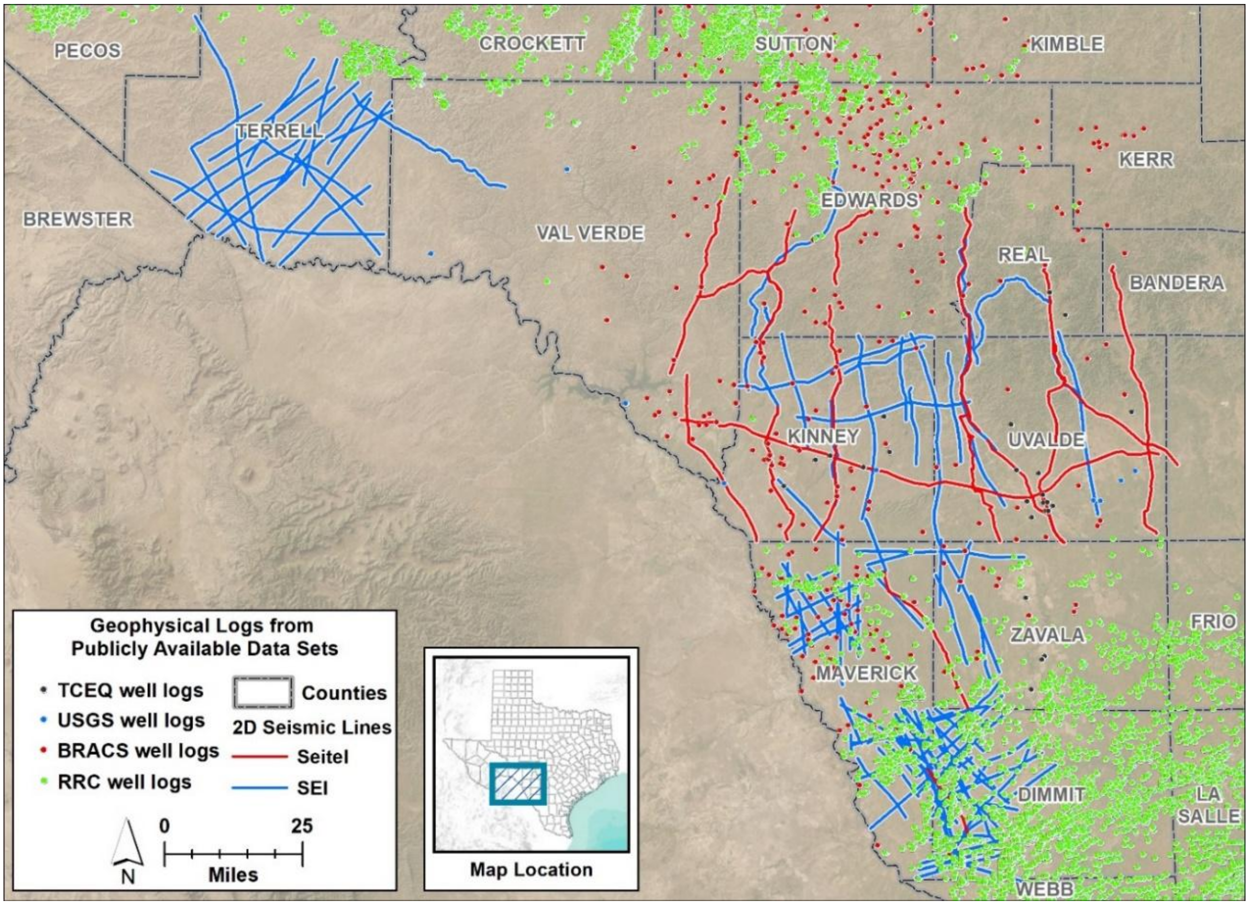
1.2.1 Goal and Purpose

Virtually all seismic studies use borehole geophysical well-logs. Well-logs provide excellent information that constrain seismic processing and interpretations, are cheap to acquire, and are abundant across the study area. Well-logs are also the best data source from which to build a velocity model to tie the seismic data from its native time format into equivalent depth. Seismic data depth conversion benefits greatly from having several key wells that have very complete log sets. For example, having 10 wells along a 10-mile, 2D line that all have gamma ray, porosity, resistivity, and sonic logs would provide excellent ties between seismic lines and equivalent depths. In some cases, three wells with the above suite of logs would be sufficient. Other areas, such as those with a large section, would need many wells to constrain seismic speeds.

1.2.2 Data Collection

A tool often used in the oil and gas industry that is not a borehole geophysical well-log, but may be useful in tying seismic data, is check-shot data. Check-shot data are a type of borehole seismic data taken when a geophone is lowered into a wellbore and a source is activated at the surface. This allows direct capture of acoustic data downhole and is often used to constrain velocity models. No check-shot data were found for this study.

When sourcing well logs, it is best to start with the publicly accessible databases and expand into costlier options as necessary. Publicly available datasets for well log information in Texas are the Railroad Commission of Texas (RRC), the BRACS Database, the Texas Commission on Environmental Quality (TCEQ) Database, and the United States Geological Survey (USGS) database. All no-cost well logs from these sources are shown on Figure 1-2.



Note: BRACS = Brackish Resource Aquifer Characterization System, RRC = Railroad Commission of Texas, SEI = Seismic Exchange, Inc., TCEQ = Texas Commission on Environmental Quality; USGS = United States Geological Survey

Figure 1-2. Seismic lines with no-cost publicly available geophysical well logs.

The next well log databases to examine are the lower-cost databases. Two examples that have data coverage across the area of interest of this study include the Subsurface Library and the Bureau of Economic Geology (BEG). The BEG well-logs cost $5 each, and Subsurface Library well-logs (images) are $19 each. These sources can fill in important missing spots in data coverage or can be used to source a particular well-log. For instance, sonic logs are very valuable in seismic studies because they are used to tie the seismic times to equivalent depths. BEG and the Subsurface Library can be queried to find these logs and recruit them. The locations of well-logs from these databases are shown in Figure 1-3.

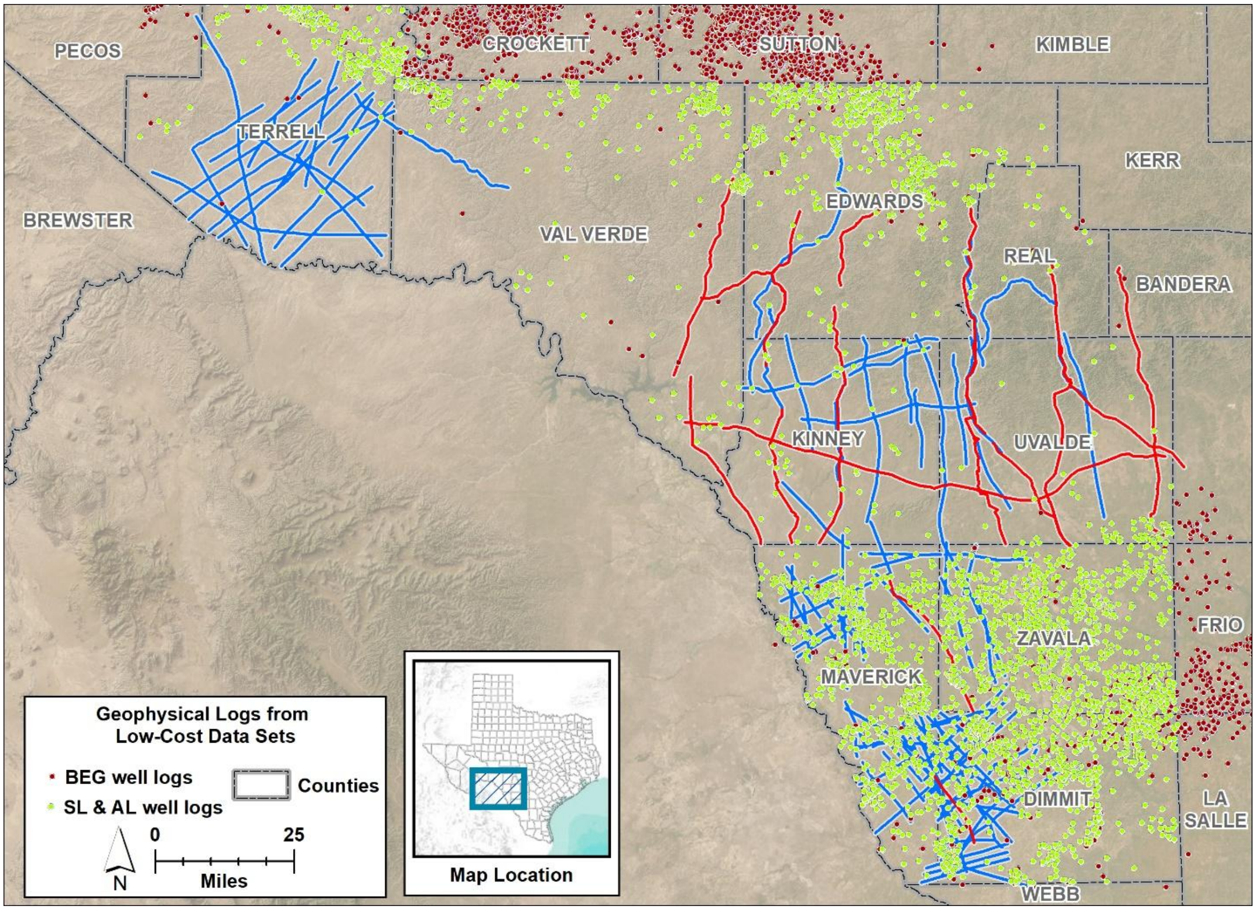


Figure 1-3. Seismic lines with low-cost geophysical well logs. SL & AL = Subsurface Library. BEG = Bureau of Economic Geology.

The final databases to examine are the high-cost databases. These include, but are not limited to, TGS Well Data Products and S&P Global. These databases come as subscription packages that range from a few thousand dollars per year to over a few hundred thousand dollars per year. These vendors often allow the purchase of individual well-logs. When the public and low-cost databases have been exhausted, the high-cost databases can be used to source hard-to-find logs or to fill in coverages in especially sparse areas. The locations of logs from these databases are shown in Figure 1-4.

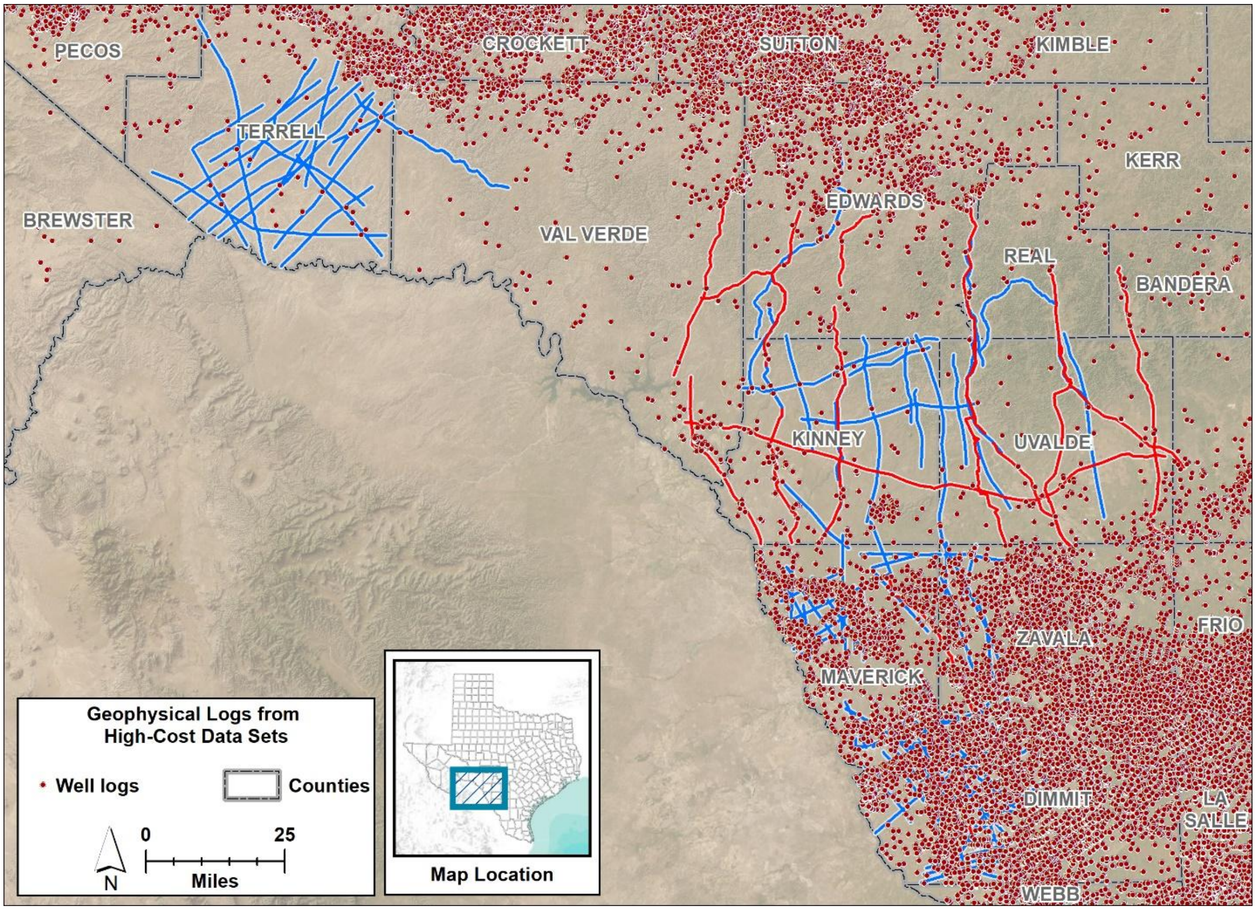


Figure 1-4. Seismic lines with high-cost geophysical well logs.

Once selections from the databases have been culled, all public well-logs could be used with a combination of well-logs from low and/or high-cost databases. With the project dataset assembled, the well-logs either need to be calibrated for use (depth-registered) or they need to be digitized. Digitization is the practice of tracing a well-log curve in a computer program to turn the curve into a text file that can be read by an interpretation software. INTERA Incorporated (INTERA) typically uses Well Green Tech to digitize logs because they offer affordable pricing.

Establishing a study area well-log database is an iterative process. During processing, the seismic processor may decide that more well-logs are needed for a good correlation, or that an area that was once insignificant is now very significant. An additional series of well-logs might be procured to address questions that come up during interpretation, or well-logs may be found to suffer from location or logging errors and removed from the database.

1.2.3 Well Log Dataset

The total coverage from all these datasets is shown in Figure 1-5, along with the seismic lines. This well-log data set is the basis for the last column in Table 1-1, "Geophysical Log Coverage." Figure 1-5 represents the total available data considered for this study. When a study has selected its seismic lines, the initial well-log dataset can be acquired. For this study, well-log coverage included all free well-logs, the SL&AL and BEG logs that measure strata shallower than 5,000 feet, and any expensive log that has a sonic log, as those are typically the least common and most important for correlation of seismic data.

From Figure 1-5, southern Terrell County, southern Val Verde County, southern Real County, northern Kinney County, and northern Uvalde County have less well-log coverage, with southern Terrell County having the worst coverage. Maverick, Dimmit, Zavala, southern Uvalde, and Kinney counties have better well-log coverage. Notably, there is no county with zero coverage.

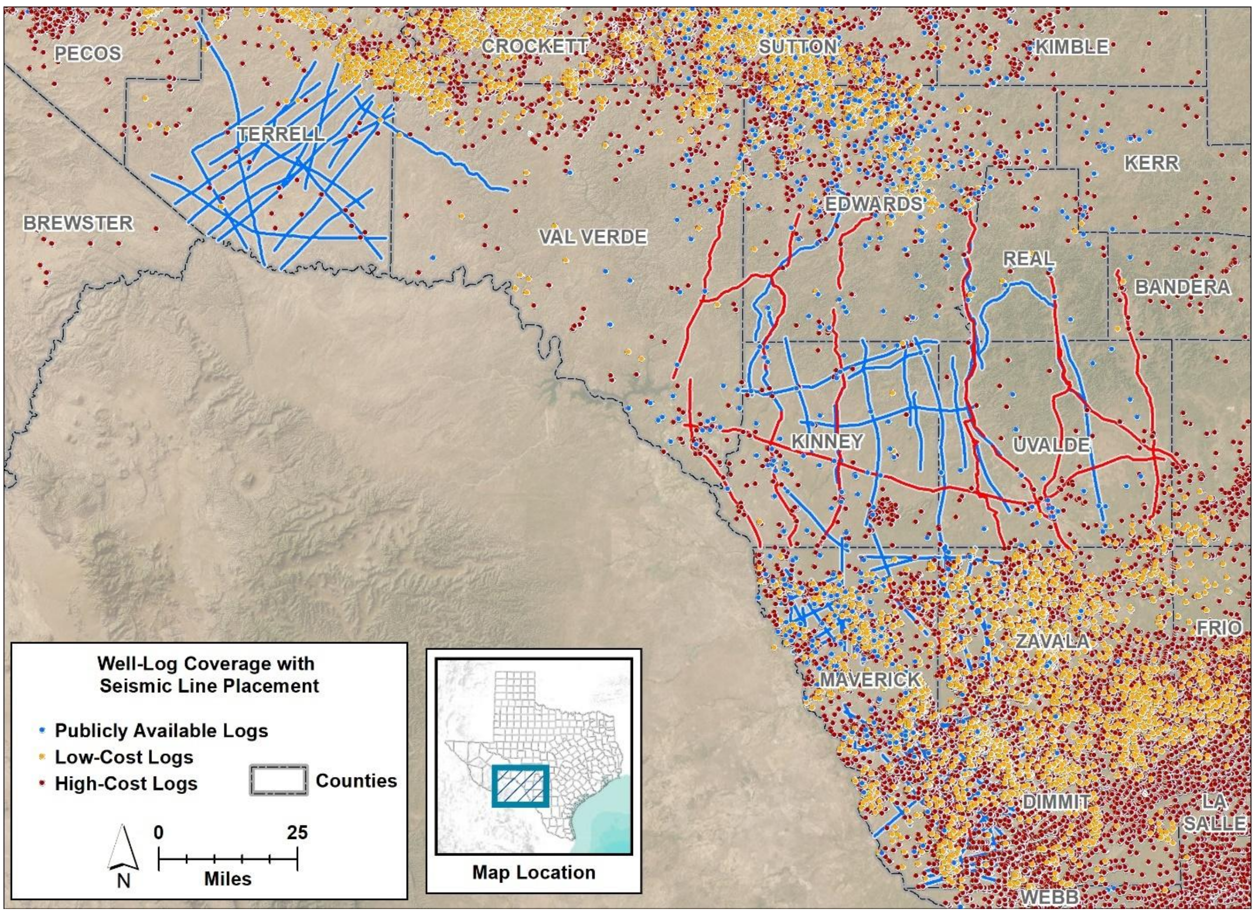


Figure 1-5. Seismic lines with all geophysical well logs.

1.3 Rank Seismic Lines

1.3.1 Method

A decision matrix can be made that ranks the seismic lines from most feasible to least feasible for imaging the ETPA Aquifer using information from the seismic line descriptions (Section 1.1) and the geophysical well-log dataset compilation (Section 1.2). Feasibility scores of zero are assigned to seismic lines with poor well-log coverage, insufficient depth, or hydrocarbon presence.

This study used a weighted matrix approach to provide scores for each seismic line. Quantification of exactly what weight each characteristic should have is somewhat subjective. Seismic line characteristics such as group spacing and source spacing can be weighted more or less than channel and fold, which can affect the feasibility of the seismic line in question. This matrix provides a rough guide that highlights characteristic differences in each line. This matrix weighting is also an iterative process. Upon reviewing the preliminary results, a geologist might want to tweak the matrix so that some line is ranked higher or lower, perhaps depending on the relative importance of a particular zone or area.

The seismic line characteristics that are assigned weights include group interval, source interval, channel, fold, energy, and year. These terms are defined in Section 1.1. Group and source interval are weighted relative to their highest values in the seismic line data set. Tighter spacing intervals should receive a higher score, so these have been measured relative to a standard "wide spacing" line. The benchmark for group interval at this study was set at 480 feet, which is at the wide end of the spectrum of represented lines. As an example, a line with group interval of 20 feet would be assigned a score of 460, and a line with 480 feet spacing would receive a score of zero. Source interval value assignment is the same as group interval, except the spacing benchmark for this study was 800 feet. However, this difference between standards means the effective weights have different ranges of values. Whether group or spacing interval should be weighted exactly at these values is subjective. It is important to understand these nuances and not treat these feasibility rankings and scores as absolute but rather as subjective indicators.

The channel value is added to the feasibility score directly with an implicit multiplier of 1. The fold value is multiplied by a factor of 6 and added to the seismic line ranking score. No points are assigned to the ranking score for an energy source of dynamite, and 250 points are assigned for an energy source of Vibroseis. Vibroseis has dominated seismic surveys in recent times because it can provide a full sweep of frequencies and provides more control over the survey. The last parameter to be considered for the feasibility ranking score is year. The year the survey was taken minus 1940 provides the score for year. Surveys taken more recently have taken advantage of new methods in seismic acquisition and are thus preferred to older surveys.

Rules and equations used to develop the seismic line ranking scores are given in Table 1-2. Seismic lines are sorted by calculated feasibility score in Table 1-3, along with calculated score components. Seismic line locations are shown colored by feasibility score in Figure 1-6. Table 1-3 and Figure 1-6 provide a detailed and spatial overview of the lines ranked relative to the objectives of this study.

Table 1-2. Rules and equations used to develop the seismic line ranking scores.

Feasibility score component	Calculation or rule
Necessary depth?	If "no": score = 0
Hydrocarbons present?	If "yes": score = 0
Group interval	480 – (group interval)
Source interval	800 (source interval)
Channel	Channel * 1
Fold	Fold * 6
Energy	If "VIBROSEIS": Add 250
Year	Year -1940

Table 1-3. Seismic lines with calculated feasibility scores.

Vendor	Line identifier	Length (mile)	Cost per mile ($)	Feasibility Score	Necessary depth disqualifier	Hydrocarbons present disqualifier	Feasibility score components					
							Group interval	Score interval	Channel	Fold	Energy	Year
SEI	2002486	16.792	$2,675	1518	OK	OK	260	580	96	288	250	44
SEI	11183540	22.042	$2,875	1515	OK	OK	260	360	240	360	250	45
SEI	933963	14.697	$2,475	1510	OK	OK	380	600	96	144	250	40
SEI	933964	15.739	$2,475	1510	OK	OK	380	600	96	144	250	40
SEI	933965	13.542	$2,475	1510	OK	OK	380	600	96	144	250	40
SEI	933966	8.655	$2,475	1510	OK	OK	380	600	96	144	250	40
Seitel	SDL-2143155	4.6		1296	OK	OK	150	470	96	288	250	42
Seitel	SDL-2143169	39.563		1296	OK	OK	150	470	96	288	250	42
Seitel	SDL-2180659	45.438		1296	OK	OK	150	470	96	288	250	42
Seitel	SDL-2180661	57.875		1296	OK	OK	150	470	96	288	250	42
Seitel	SDL-2180664	52		1296	OK	OK	150	470	96	288	250	42
Seitel	SDL-2142869	40.875		1295	OK	OK	150	470	96	288	250	41
Seitel	SDL-2180654	34.813		1295	OK	OK	150	470	96	288	250	41
Seitel	SDL-2180657	26.188		1295	OK	OK	150	470	96	288	250	41
Seitel	SDL-2180660	23.25		1295	OK	OK	150	470	96	288	250	41
Seitel	SDL-2192449	18.25		1295	OK	OK	150	470	96	288	250	41
SEI	544165	14.5	$2,275	994	OK	OK	150	470	24	72	250	28
Seitel	SDL-2189985	34.598		710	OK	OK	150	470	48	0	0	42
Seitel	SDL-2189991	24.046		710	OK	OK	150	470	48	0	0	42
Seitel	SDL-2190587	8.528		710	OK	OK	150	470	48	0	0	42
SEI	690222	39.887	$2,275	628	OK	OK	280	200	48	72	0	28
SEI	737509	33.674	$2,075	604	OK	OK	280	200	48	48	0	28
SEI	685153	31.932	$2,275	529	OK	OK	180	200	48	72	0	29
SEI	685159	13.864	$2,275	529	OK	OK	180	200	48	72	0	29
SEI	685161	20.341	$2,275	529	OK	OK	180	200	48	72	0	29
SEI	685180	37.425	$2,275	512	OK	OK	180	200	32	72	0	28
SEI	737092	23.333	$2,075	-196	OK	OK	80	-400	48	48	0	28
SEI	690236	13.788	$2,075	-610	OK	OK	80	-800	48	36	0	26
SEI	685172	20.966	$2,075	-697	OK	OK	180	-1000	48	48	0	27
SEI	690225	33.636	$2,075	-1397	OK	OK	80	-1600	48	48	0	27
SEI	1144308	23.337	$3,075	0	Disqualified	OK	460	720	1024	768	250	42
SEI	11183337	12.273	$3,075	0	Disqualified	OK	420	740	288	864	250	41
SEI	557822	10.188	$2,875	0	OK	Disqualified	370	580	192	360	0	50

Vendor	Line identifier	Length (mile)	Cost per mile ($)	Feasibility Score	Necessary depth disqualifier	Hydrocarbons present disqualifier	Feasibility score components					
							Group interval	Score interval	Channel	Fold	Energy	Year
SEI	557823	11.146	$2,875	0	OK	Disqualified	370	580	192	360	0	50
SEI	557824	11.75	$2,875	0	OK	Disqualified	370	580	192	360	0	50
SEI	561769	25.604	$2,875	0	OK	Disqualified	370	580	192	360	0	50
SEI	639248	14.438	$2,875	0	OK	Disqualified	150	470	121	360	250	45
SEI	975652	17.75	$2,875	0	OK	Disqualified	150	470	121	360	250	45
SEI	2072429	15.604	$2,875	0	OK	Disqualified	370	690	120	360	250	45
SEI	11183516	47.083	$2,875	0	Disqualified	OK	40	360	120	360	0	43
SEI	11183517	45.25	$2,875	0	Disqualified	OK	40	360	120	360	0	44
SEI	11183534	33.75	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183535	22.167	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183536	39.958	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183537	14	$2,875	0	Disqualified	OK	260	360	240	360	0	45
SEI	11183538	24.667	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183541	23.875	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183542	19.958	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183543	19.292	$2,875	0	Disqualified	OK	260	360	240	360	250	45
SEI	11183545	14.917	$2,875	0	Disqualified	OK	40	360	128	384	0	43
SEI	2002487	20.25	$2,675	0	OK	Disqualified	260	580	96	288	250	44
SEI	2002488	9.458	$2,675	0	OK	Disqualified	260	580	96	288	250	45
SEI	2003076	8.958	$2,675	0	OK	Disqualified	260	580	96	288	250	44
SEI	2003077	20.417	$2,675	0	OK	Disqualified	260	580	96	288	250	44
SEI	2003078	20.667	$2,675	0	OK	Disqualified	260	580	96	288	250	44
SEI	11183219	23.125	$2,675	0	Disqualified	OK	260	580	96	288	250	41
SEI	11183335	13.958	$2,675	0	Disqualified	OK	260	580	96	288	0	41
SEI	11183336	33.667	$2,675	0	Disqualified	OK	260	580	96	288	250	41
SEI	11183410	12.875	$2,675	0	Disqualified	OK	260	580	96	288	250	41
SEI	11183428	26.167	$2,675	0	Disqualified	OK	260	580	96	288	250	41
SEI	11183489	24.75	$2,675	0	Disqualified	OK	40	360	96	288	0	43
SEI	11183515	21.667	$2,675	0	Disqualified	OK	40	360	96	288	0	43
SEI	11183546	23.417	$2,675	0	Disqualified	OK	40	360	96	288	0	43
SEI	2066939	20.917	$2,475	0	OK	Disqualified	260	360	96	144	0	45
SEI	2066940	21.417	$2,475	0	OK	Disqualified	260	360	97	144	0	45
SEI	2066950	27.792	$2,475	0	OK	Disqualified	260	360	97	144	0	44
SEI	2066951	18.667	$2,475	0	OK	Disqualified	260	360	120	144	0	45

Vendor	Line identifier	Length (mile)	Cost per mile ($)	Feasibility Score	Necessary depth disqualifier	Hydrocarbons present disqualifier	Feasibility score components					
							Group interval	Score interval	Channel	Fold	Energy	Year
SEI	2066952	11.542	$2,475	0	OK	Disqualified	260	360	96	144	0	44
SEI	2066953	21.458	$2,475	0	OK	Disqualified	260	360	97	144	0	44
SEI	2072428	16.292	$2,475	0	OK	Disqualified	260	360	97	144	0	45
SEI	2072430	14.333	$2,475	0	OK	Disqualified	260	360	120	180	250	44
SEI	544152	25.438	$2,275	0	Disqualified	OK	150	470	24	72	250	28
SEI	550187	21.188	$2,275	0	OK	Disqualified	150	140	48	72	250	41
SEI	550194	30.625	$2,275	0	OK	Disqualified	150	140	48	72	250	41
SEI	550200	11.875	$2,275	0	OK	Disqualified	150	140	48	72	250	41
SEI	663666	26.742	$2,275	0	OK	Disqualified	80	400	24	72	0	23
SEI	664218	16.687	$2,275	0	OK	Disqualified	80	400	24	72	0	25
SEI	664221	11.591	$2,275	0	OK	Disqualified	80	400	24	72	0	25
SEI	664250	21.818	$2,275	0	OK	Disqualified	80	400	24	72	0	25
SEI	664811	28.864	$2,275	0	OK	Disqualified	80	0	48	72	0	30
SEI	737091	14.148	$2,275	0	Disqualified	OK	180	200	48	72	0	29
SEI	740981	13.688	$2,275	0	OK	Disqualified	150	140	48	72	250	42
SEI	2001103	30.114	$2,275	0	OK	Disqualified	180	200	48	72	0	31
SEI	2001106	17.333	$2,275	0	OK	Disqualified	260	580	96	288	250	45
SEI	2001115	16.742	$2,275	0	OK	Disqualified	80	400	24	72	0	30
SEI	2001116	11.591	$2,275	0	OK	Disqualified	80	400	24	72	0	30
SEI	2001122	29.091	$2,275	0	OK	Disqualified	80	400	24	72	0	24
SEI	2001126	10.909	$2,275	0	OK	Disqualified	80	400	24	72	0	25
SEI	2003063	11.591	$2,275	0	OK	Disqualified	180	200	48	72	0	32
SEI	2003064	18.712	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003065	16.439	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003066	14.886	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003067	11.61	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003068	9.299	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003069	11.686	$2,275	0	OK	Disqualified	380	500	92	90	0	39
SEI	2003070	13.125	$2,275	0	OK	Disqualified	380	500	92	90	0	39
SEI	2003072	14.223	$2,275	0	OK	Disqualified	380	500	92	90	0	39
SEI	2003079	10.871	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003080	9.394	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003081	14.754	$2,275	0	OK	Disqualified	380	500	92	90	0	38
SEI	2003082	8.902	$2,275	0	OK	Disqualified	380	500	92	90	0	38

Vendor	Line identifier	Length (mile)	Cost per mile ($)	Feasibility Score	Necessary depth disqualifier	Hydrocarbons present disqualifier	Feasibility score components					
							Group interval	Score interval	Channel	Fold	Energy	Year
SEI	2004868	17.045	$2,275	0	OK	Disqualified	180	200	48	72	0	31
SEI	2004880	16.25	$2,275	0	OK	Disqualified	180	200	48	72	0	31
SEI	2016471	10.667	$2,275	0	OK	Disqualified	260	580	24	72	250	34
SEI	2066975	11.063	$2,275	0	OK	Disqualified	370	580	48	72	0	42
SEI	2071725	9.167	$2,275	0	OK	Disqualified	40	360	24	72	0	31
SEI	2071728	14.583	$2,275	0	OK	Disqualified	40	360	24	72	0	31
SEI	2071729	17.417	$2,275	0	OK	Disqualified	40	360	24	72	0	31
SEI	2071730	11	$2,275	0	OK	Disqualified	40	360	24	72	0	31
SEI	2071731	11.417	$2,275	0	OK	Disqualified	40	360	24	72	0	31
SEI	2072708	11.455	$2,275	0	OK	Disqualified	0	320	24	72	0	31
SEI	2564805	9.813	$2,275	0	OK	Disqualified	150	140	48	72	250	36
SEI	2564808	15.292	$2,275	0	OK	Disqualified	260	360	48	72	250	38
SEI	2564809	14.25	$2,275	0	OK	Disqualified	260	360	48	72	250	38
SEI	2565182	8.758	$2,275	0	OK	Disqualified	400	480	120	90	250	41
SEI	11773382	23	$2,275	0	Disqualified	OK	150	140	48	72	250	27
SEI	544934	22.102	$2,075	0	OK	Disqualified	180	500	20	60	250	29
SEI	684279	25.966	$2,075	0	Disqualified	OK	180	-400	48	36	0	27
SEI	685158	16.212	$2,075	0	Disqualified	OK	280	200	48	48	0	28
SEI	685175	15.076	$2,075	0	Disqualified	OK	280	200	48	48	0	28
SEI	735253	9.242	$2,075	0	OK	Disqualified	80	0	24	36	0	23
Seitel	SDL-2143153	38.938		0	Disqualified	OK	150	470	96	288	250	42
Seitel	SDL-2143154	31.25		0	Disqualified	OK	150	470	96	288	250	41
Seitel	SDL-2179115	15.94		0	Disqualified	OK	150	470	96	288	250	41
Seitel	SDL-2180655	39.31		0	Disqualified	OK	150	470	96	288	250	41
Seitel	SDL-2180656	16.625		0	Disqualified	OK	150	470	96	288	250	41
Seitel	SDL-2180658	24.44		0	Disqualified	OK	150	470	96	288	250	41
Seitel	SDL-2189969	30.348		0	OK	Disqualified	150	470	48	0	0	42
Seitel	SDL-2192224	14.725		0	OK	Disqualified	-1320	800	24	0	0	31

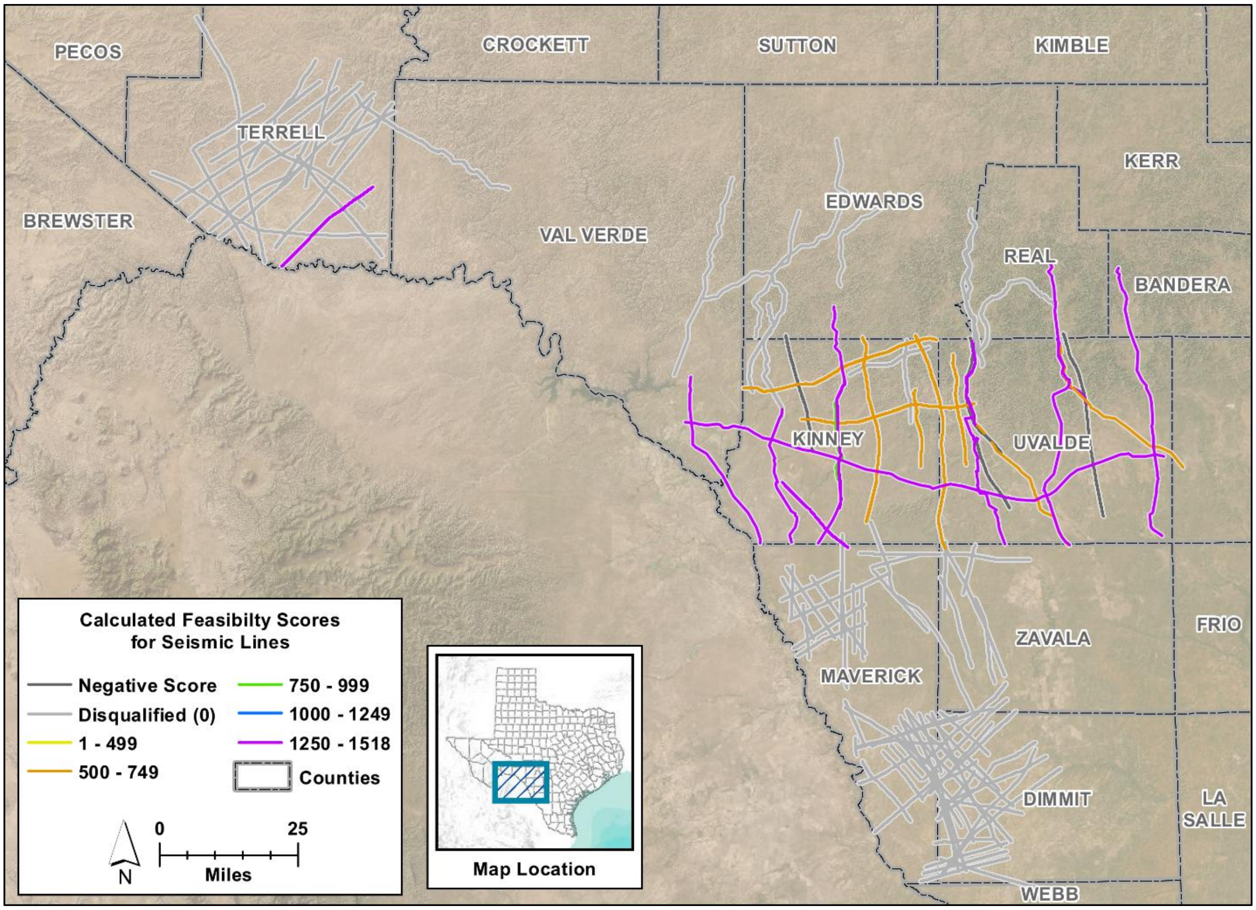


Figure 1-6. **Seismic lines colored by feasibility score.**

1.3.2 Discussion

It is important to recognize the shortcomings and subjectiveness of the ranking system. While uncertainty in the weighting system has already been discussed, there are other factors relating to the seismic lines not listed with the processed data that could disqualify a line's use. As an example, one such problem for aquifers is a seismic mute, which occurs when geophones do not record the first acoustic energy to be returned after the source. Seismic mute is measured in seconds. A half-second mute means the geophones do not record sound for a half-second post acoustic pulse. This is problematic because, often, the first half-second captures the acoustic energy relating to the aquifer. A viewing of the data and discussion with the vendor could identify and help avoid these issues before purchasing the data.

Another factor not considered in the feasibility ranking score is cost. If a groundwater developer has $20,000 for seismic data acquisition, and the vendor requires a 10-mile minimum, then most lines in this area are too costly. The importance of cost is highly dependent on the consumer of the seismic data.

1.3.3 Recommendation

It is apparent from Table 1-3 and Figures 1-5 and 1-6 that Kinney County, and in particular southern Kinney County, is reasonably well suited for this study. The main factors eliminating lines in other areas are insufficient depth and presence of hydrocarbons. Kinney County has somewhat fewer well-logs than many other counties but is by no means lacking in well-log coverage. There are 14 seismic lines in Kinney County with feasibility scores above zero. Most of these lines are dip lines, but there are a few oblique-strike and strike lines.

After the seismic lines have been described and evaluated, it is additionally important to understand how a seismic line individually contributes to the study. In some cases, two highly ranked seismic lines are very close to one another, so there is no reason to procure both. The best way to analyze the ETPA is by incorporating all available data sources, which includes local outcrop data, all previously established feasible well-log data, and seismic data. There is an outcrop area of the ETPA in northern Kinney County that can be utilized. However, the basal contact of the ETPA in northern Kinney is shallow, so well-logs will be heavily relied on to correlate outcrop data into the ETPA imaged on seismic data. In southern Kinney County, where the base of the ETPA is deeper, well-logs and seismic data can be used together to define the structure and stratigraphy of the aquifer. The ultimate purpose of this study is recruiting seismic lines that help achieve this goal. INTERA and the TWDB considered this goal with the available seismic data prices and agreed on seismic lines to procure in southern Kinney County.

2 Seismic Line Selection and Licensing

2.1 Approach

INTERA and BRACS reviewed the feasibility matrix developed above in Section 1.3. The matrix provided a comprehensive overview of the suitability of each seismic line for imaging the aquifer based on various parameters such as acquisition characteristics, depth of the aquifer, absence of hydrocarbons, and availability of well-log data.

INTERA and BRACS assessed feasibility scores, data quality, line proximity, and project objectives to select a subset of seismic lines in southern Kinney County for further evaluation and potential licensing. These chosen lines displayed the highest feasibility scores (recalling the scores consist of both objective and subjective criteria) and were expected to offer insights into the aquifer's structure and stratigraphy. The selection process involved extensive discussions between INTERA and BRACS to ensure agreement that the chosen lines aligned with the goals of the study and could effectively contribute to the understanding of the ETPA's brackish groundwater resources.

2.2 Seismic Data Licensing Process

Once the seismic lines were identified, INTERA initiated the licensing process, which involved several steps to ensure the quality of the data and secure terms for its use within the project.

2.2.1 Quality Check on Seismic Lines

Before finalizing the selection of seismic lines for licensing, INTERA conducted a thorough quality assurance process by visiting virtual data rooms provided by the seismic vendors. These data rooms allowed INTERA to visually inspect the seismic data and ensure that they met the project's primary objectives of understanding the structure and stratigraphy of the ETPA. This step was crucial in verifying that the seismic lines chosen based on the feasibility matrix were suitable for the study.

During the quality assurance process, INTERA paid close attention to factors such as signal-to-noise ratio, resolution, appearance in the shallow (<500 milliseconds [ms]) range, and overall data integrity. INTERA also assessed the compatibility of the data with the project's objectives and the proposed processing and interpretation workflows.

The quality assurance process provided an additional layer of confidence in the selected seismic lines, ensuring that the data were of sufficient quality to support the project's goals. This hands-on evaluation of the data in the virtual data rooms complemented the initial assessment based on the feasibility matrix, allowing for a more comprehensive understanding of the seismic lines' suitability for the study.

2.2.2 Obtaining Quotes

After confirming the quality and suitability of the selected seismic lines through the quality assurance process, INTERA requested quotes from the respective seismic vendors. The quotes included detailed information on the costs associated with licensing the data, restrictions on its use, and the deliverables to be provided.

INTERA worked closely with the seismic vendors to obtain transparent and comprehensive quotes, ensuring clear communication of all relevant information. This included details on the specific seismic lines to be licensed, the format and quality of the data, and any additional services or support to be provided by the vendors.

The quotes were carefully reviewed and compared to ensure they aligned with the project's budget and requirements. INTERA also engaged in discussions with the vendors to clarify any questions or concerns regarding the quotes and to explore potential opportunities for cost optimization without compromising data quality or project objectives.

2.2.3 Negotiating Terms and Data Publicity

INTERA engaged in negotiations with the seismic vendors to secure licensing terms that aligned with the project's budget and objectives. During these negotiations, particular attention was given to the extent to which the licensed seismic data and its derivatives could be published or shared publicly. Seismic data are often subject to strict confidentiality agreements, normal for leasing seismic data, and vendors may place limitations on the public dissemination of the data or interpretation. INTERA worked with the vendors to strike a balance between the project's need for transparency and the vendors' requirements for data protection. The negotiation process involved a series of discussions and exchanges with the seismic vendors, during which INTERA sought to secure the best terms possible for the use and publication of the seismic data. This included negotiating the scope of the license, the duration of the agreement, and any restrictions on the use or sharing of the data.

INTERA's and TWDB's experienced contracts teams played a crucial role in these negotiations, ensuring that the terms of the licensing agreements were clearly defined and legally sound. INTERA's and TWDB's contracts teams worked closely with the BRACS technical team to ensure that the negotiated terms aligned with the project's objectives and allowed for the necessary flexibility in data use and publication.

The outcome of these negotiations was a clear understanding of the terms under which the seismic data could be used, published, and shared with stakeholders. This information was documented and communicated to the TWDB to ensure compliance with the agreed-upon terms throughout the project's duration.

By following this systematic approach to seismic line selection and licensing, INTERA and BRACS secured the most promising seismic lines for the study, conducted thorough quality assurance, and negotiated licensing terms while navigating the complexities of data confidentiality and public dissemination. As discussed previously, the precise locations of the southern Kinney County seismic lines are confidential, though their general location and orientation as a single strike line and two dip lines are necessary context for demonstrating the approach and methodology in subsequent sections of this report. This process laid the foundation for the execution of the project, ultimately contributing to a better understanding of the ETPA's stratigraphic and structural framework in the context of brackish groundwater resources.

3 Seismic Line Reprocessing and Interpretation

3.1 Reprocessing Steps

A general workflow for reprocessing seismic data for utilization in aquifer characterization is described in Draper and others (2021) and shown in Figure 3-1. Specifically, tasks G through J of Draper and others (2021, p 91-92) correspond to steps G through J in the seismic workflow shown in Figure 3-1. These steps involve preprocessing and initial processing, noise reduction and statics, stacking, and the generation of final amplitude profiles and volumes.

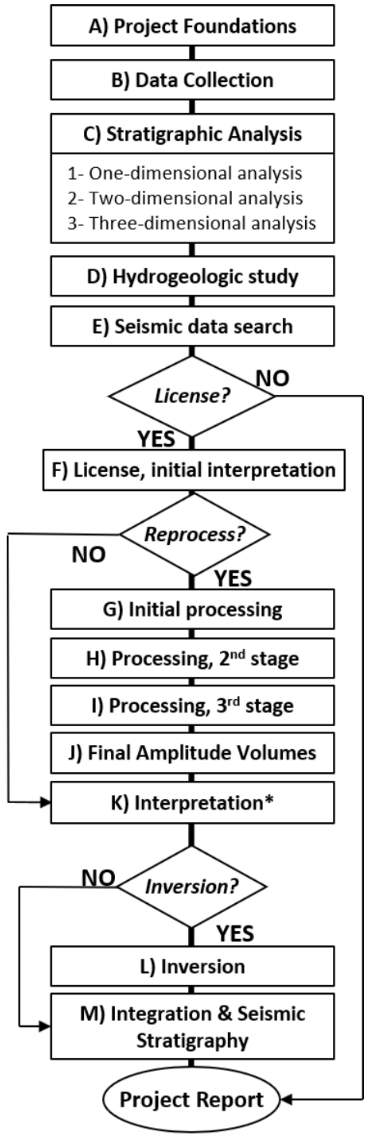
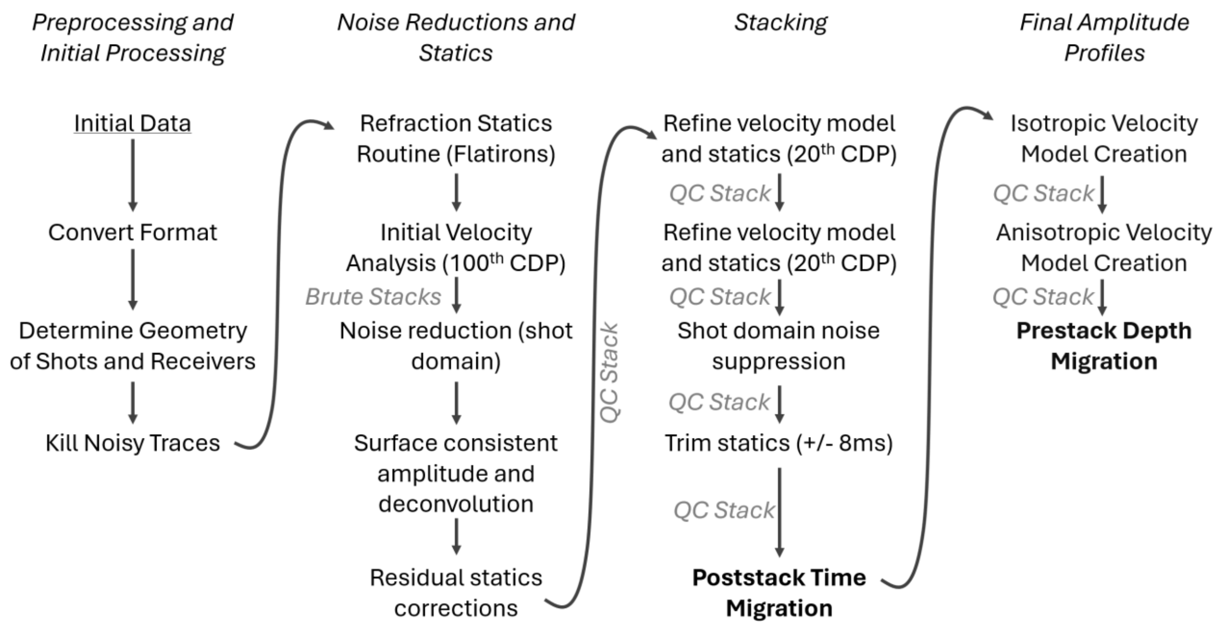


Figure 3-1. Seismic workflow diagram of steps A through M, from Draper and others (2021). This section describes steps G through J as applied to this study.

Reprocessing the seismic data is a crucial step in imaging the ETPA. By applying modern processing techniques and algorithms, the quality of the seismic data is enhanced, especially in the shallower regions that are most relevant to the aquifer characterization.

The reprocessing of the 2D seismic data for this study was performed by Tricon Geophysical. Three lines (Line A, Line B, and Line C) were submitted to Tricon. The specific steps and parameters used in reprocessing are determined based on the characteristics of the acquired seismic lines and the objectives defined in this study.

A summary diagram of processing steps employed for this study is shown in Figure 3-2.



Note: CDP = Common Depth Point

Figure 3-2. Summary diagram of seismic processing steps employed in this study. Brute stack refers to unrefined seismic traces added together with minimal corrections. QC stack refers to seismic data that have undergone quality control review, including spectral (frequency) analysis and amplitude corrections to reduce noise and improve signal-to-noise ratio.

3.1.1 Preprocessing and Initial Processing

Once BRACS approved the acquisition of the selected seismic data, INTERA recommended Tricon Geophysical (Tricon) as the seismic data processor. INTERA had Seitel deliver all field data and records to Tricon via a mailed hard drive. INTERA delivered the relevant well-logs via email to Tricon. Tricon loaded the data and began the preprocessing and initial processing.

Tricon reformatted the data from SEG-Y (Society for Exploration Geophysicists data formatting designation) into a format compatible with their processing software. This allowed for easier manipulation and analysis of the data. Tricon determined the geometry of the shots and receivers and quality checked the determined geometry. This step was important as it determined the locations of the common depth points for the gathers. Bad or noisy traces were then identified and removed from the dataset. These traces can arise from equipment malfunctions, environmental noise, or other factors and can negatively impact the quality of the final seismic image if not addressed.

3.1.2 Noise Reduction and Statics

After the initial steps, Tricon applied a refraction statics routine. Refraction statics corrections were applied to compensate for variations in the near-surface velocities. These variations can cause time delays in the seismic data, leading to misalignment of reflectors. The Flatirons™ refraction tomography method was used to estimate the near-surface velocity model and calculate the necessary time shifts to correct for these delays. The result was reduced noise, improved frequency and information content, and reduced near-surface variations.

An initial velocity analysis was performed on a subset of the common depth points (every 100th common depth point) to estimate the velocity structure of the subsurface. This coarse analysis provided a starting point to create the simple stacks (also called "brute stacks") and refine the velocities. A stack is a collection of wavelets sorted, ordered, and overlain in order to form a seismic profile. Brute stacks were created using the elevation statics, and the cursory velocity analyses for initial quality checks, and then were updated using the refraction statics. Brute stacks for the three lines occur in Figures 3-3 through 3-5. These initial brute stacks were examined for reasonableness of the processing steps thus far at reducing noise and showing the distribution of offsets and the number of effective traces in the shallow section.

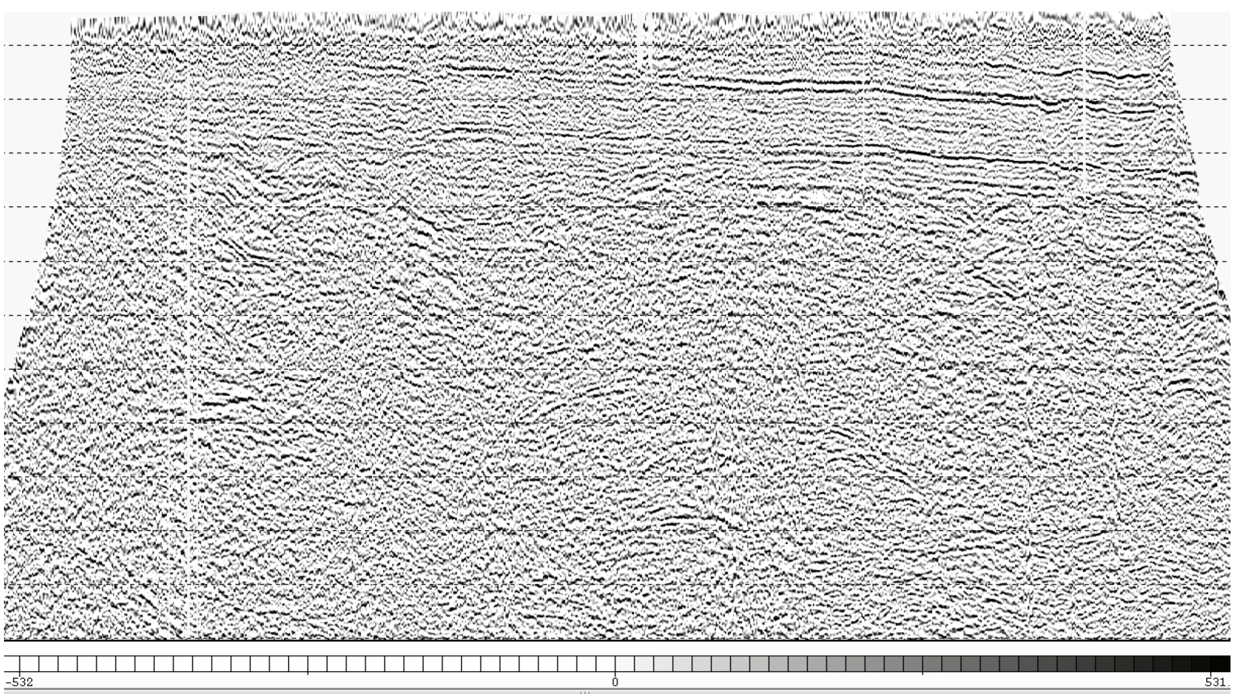


Figure 3-3. Brute stack of Line A. All seismic profiles have had filter and amplitude scaling applied to enhance the visibility of weak signals and improve the overall appearance of the seismic section for display purposes.

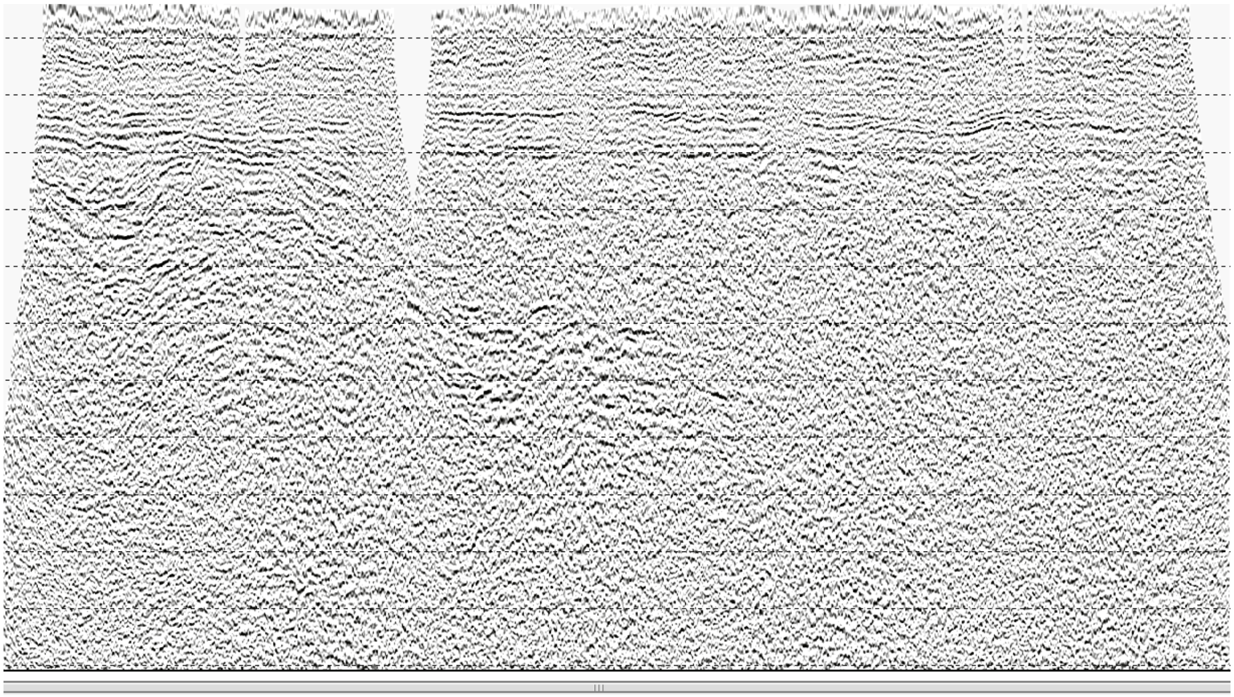


Figure 3-4. Brute stack of Line B.

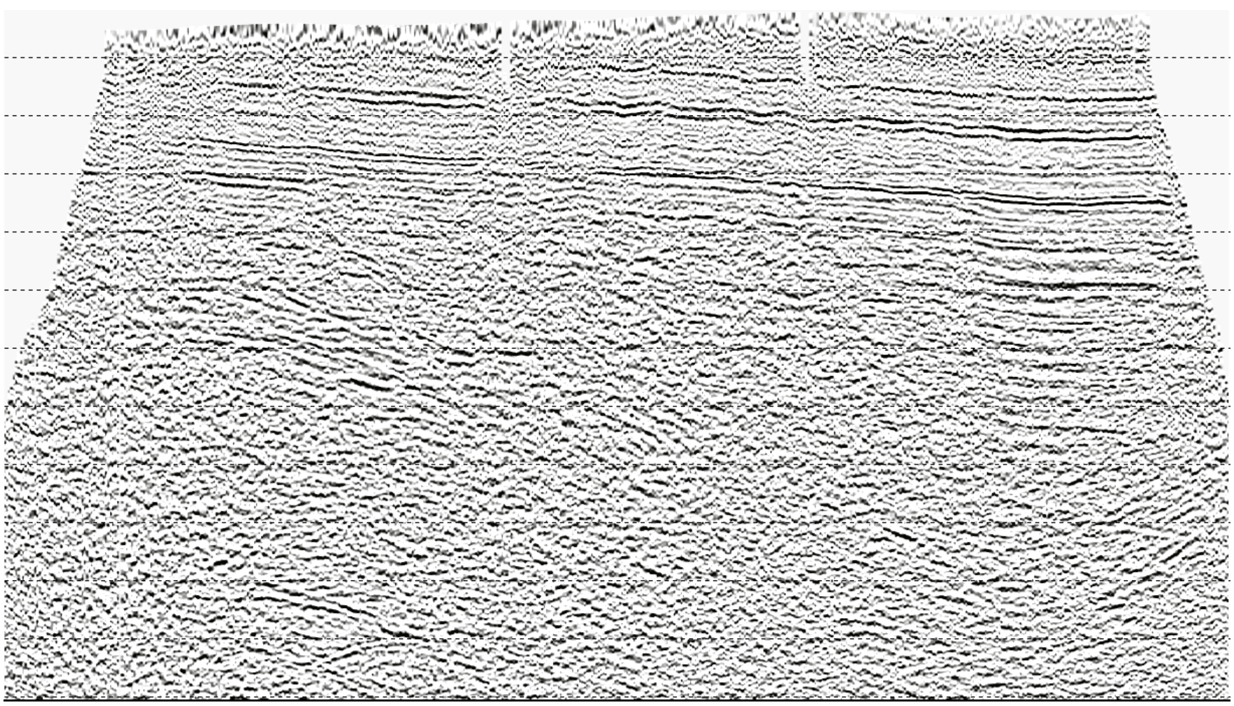


Figure 3-5. Brute stack of Line C.

The next processing step was noise reduction from the shot domain. Shot domain refers to all traces with a common shot point. Various noise reduction techniques were applied to the data. These techniques include frequency filtering, amplitude balancing, and coherent noise removal. The goal was to enhance the signal-to-noise ratio and improve the overall quality of the data.

Following this step, surface consistent amplitude and surface consistent deconvolution corrections were applied. Surface-consistent amplitude corrections address amplitude variations caused by near-surface conditions, such as changes in soil type or weathering. A two-pass method was employed, first correcting for shot-related amplitude variations, then for receiver-related variations. Deconvolution mathematically estimates, then compresses, the input seismic wave to its most compact form, which is then applied to remove reverberations and multiples of the acoustic waves. This improves frequency content, removes ringing and ghosting reflectors, and enhances information content. Following these steps, a preliminary pass of residual statics corrections was applied to fine-tune the alignment of seismic traces. These corrections accounted for any remaining time shifts caused by near-surface irregularities or errors in the refraction statics solution.

3.1.3 Stacking

Tricon iterated stacking with various processing steps to prepare for pre-stack depth migration. A quality control stack was first generated to assess the effectiveness of the noise reduction, amplitude corrections, and initial residual statics from tasks G and H, where the velocity model was refined on a finer grid than the previous model, which took every 100th common depth point into consideration. For stacking, every 20th common depth point was taken into consideration. Another correction was performed on the residual statics, which used the refined velocities from the velocity analysis. Then another quality control stack was generated to evaluate the impacts of the velocity and statics updates. Another pass was then performed on the velocity model and the statics adjustments to create finer adjustments. This allowed for another quality control stack to assess the final results of the velocity refinements and statics corrections.

Tricon opted to perform some additional shot-domain noise suppression to raise the signal-to-noise ratio. Further noise suppression and signal enhancement techniques were applied in the shot domain to improve the overall quality of the data. Filtering removed remaining coherent noise or enhanced specific signal characteristics. Another quality control stack was generated to assess the effects of the noise suppression. Trim statics corrections were then applied to fine-tune the alignment of traces within each common depth point gather. These corrections were small, with a maximum shift of approximately 8 milliseconds, and helped improve the coherency of the final stacked section. A final quality control stack was generated to assess the impact of the trim statics corrections. These final quality control stacks are shown in Figures 3-6 through 3-8.

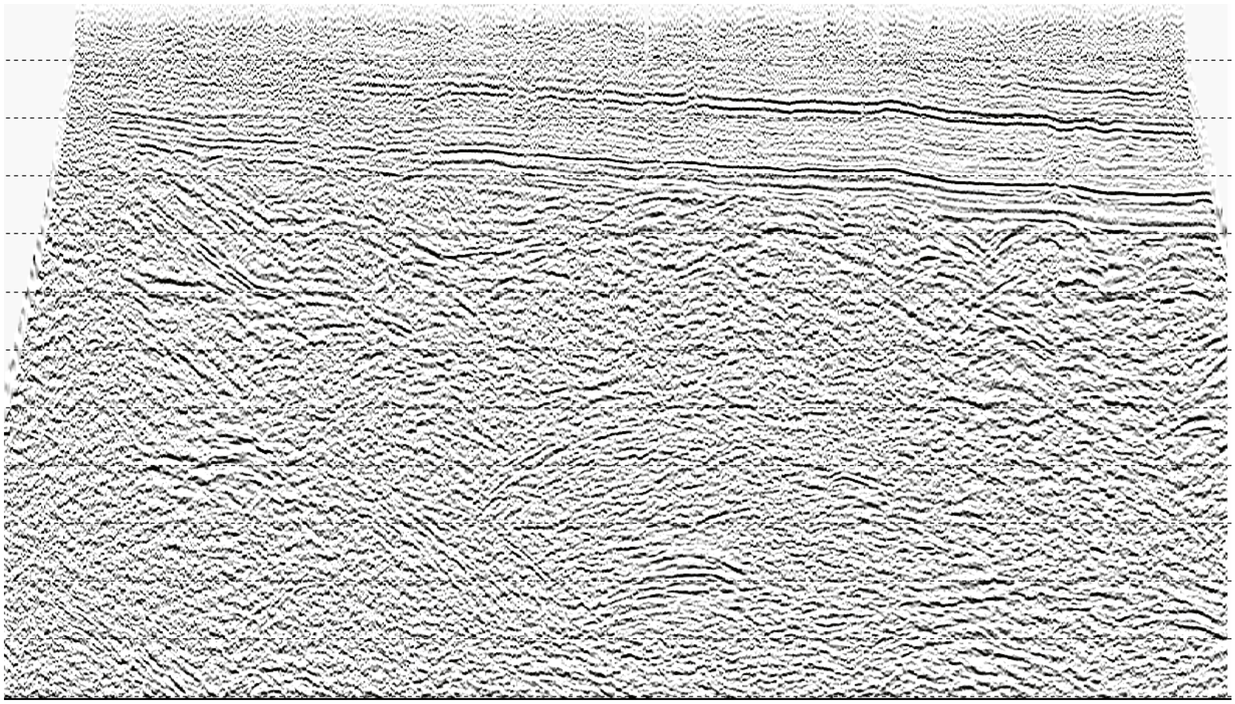


Figure 3-6. Processed stack of Line A. Result of all processing steps prior to post-stack time migration.

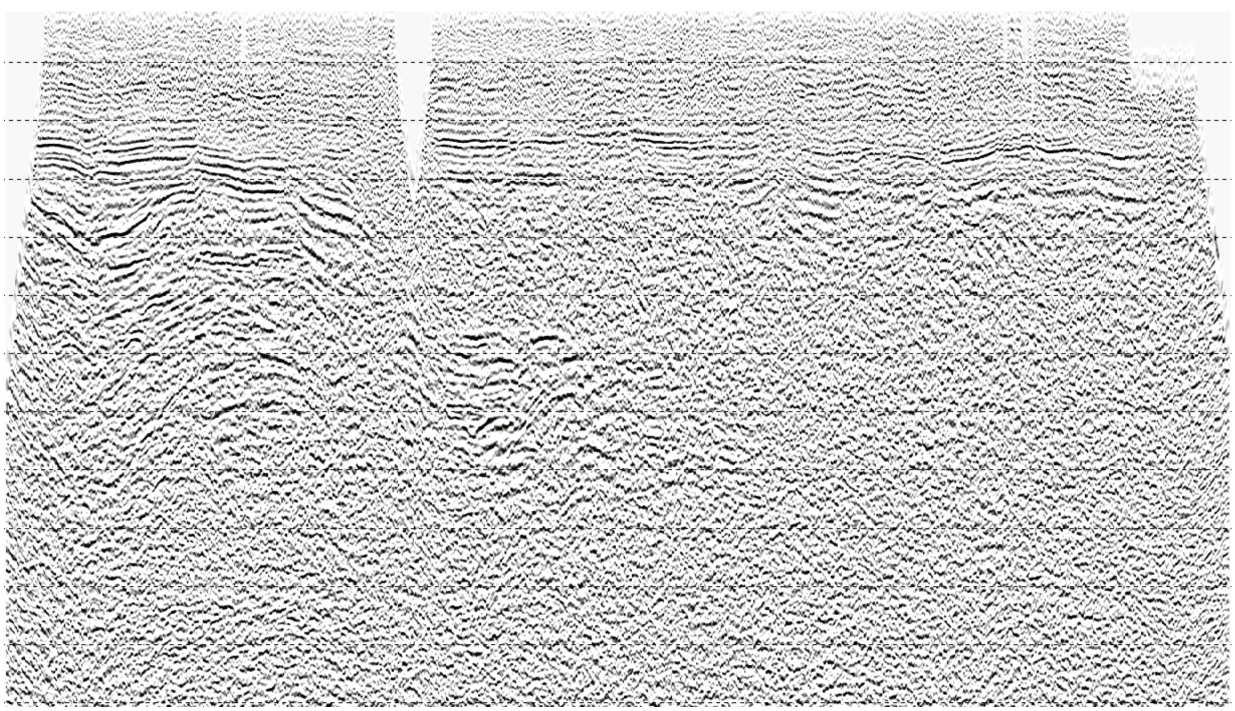


Figure 3-7. Processed stack of Line B. Result of all processing steps prior to post-stack time migration.

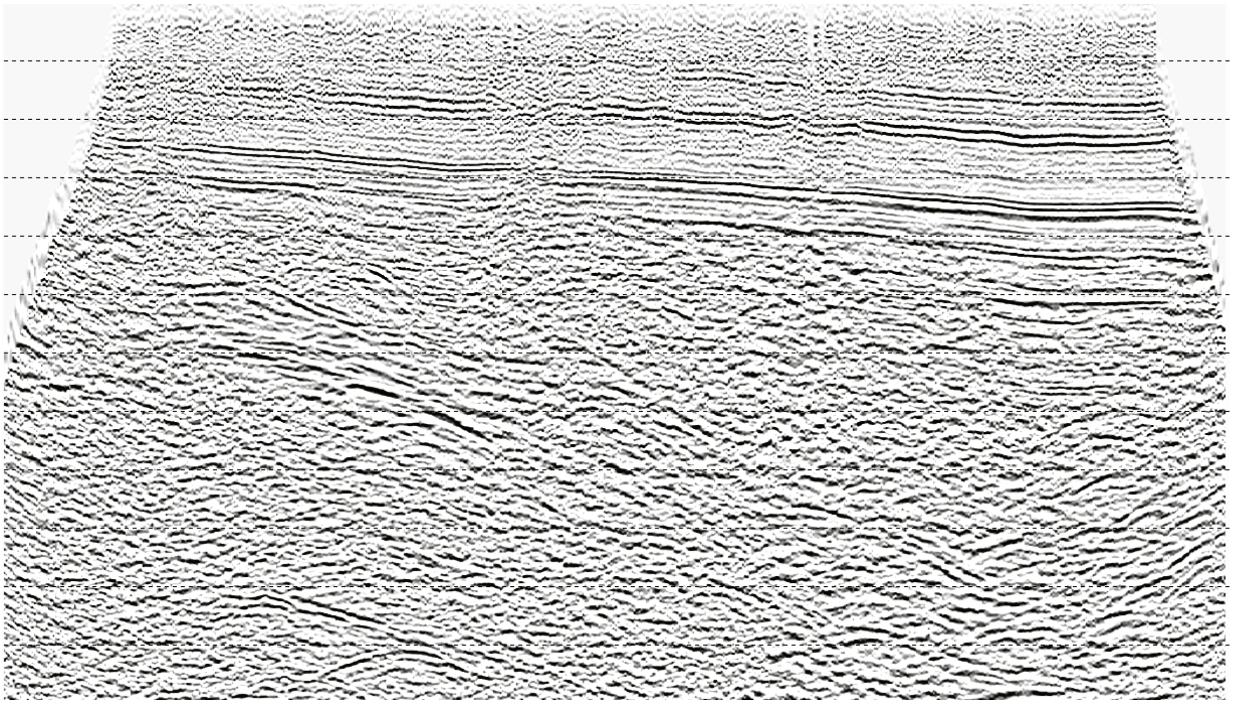


Figure 3-8. Processed stack of Line C. Result of all processing steps prior to post-stack time migration.

A post-stack time migration was applied to generate an initial time-migrated profile of each seismic line. The MIGFX program, which is based on a finite-difference approximation to the monochromatic wave equation, was used to perform post-stack time migration. This process moves dipping reflectors to their true subsurface positions. The migration is performed using smoothed versions of the final velocity fields obtained from the velocity analyses. Figures 3-9 through 3-11 show the seismic profiles following this post-stack time migration.

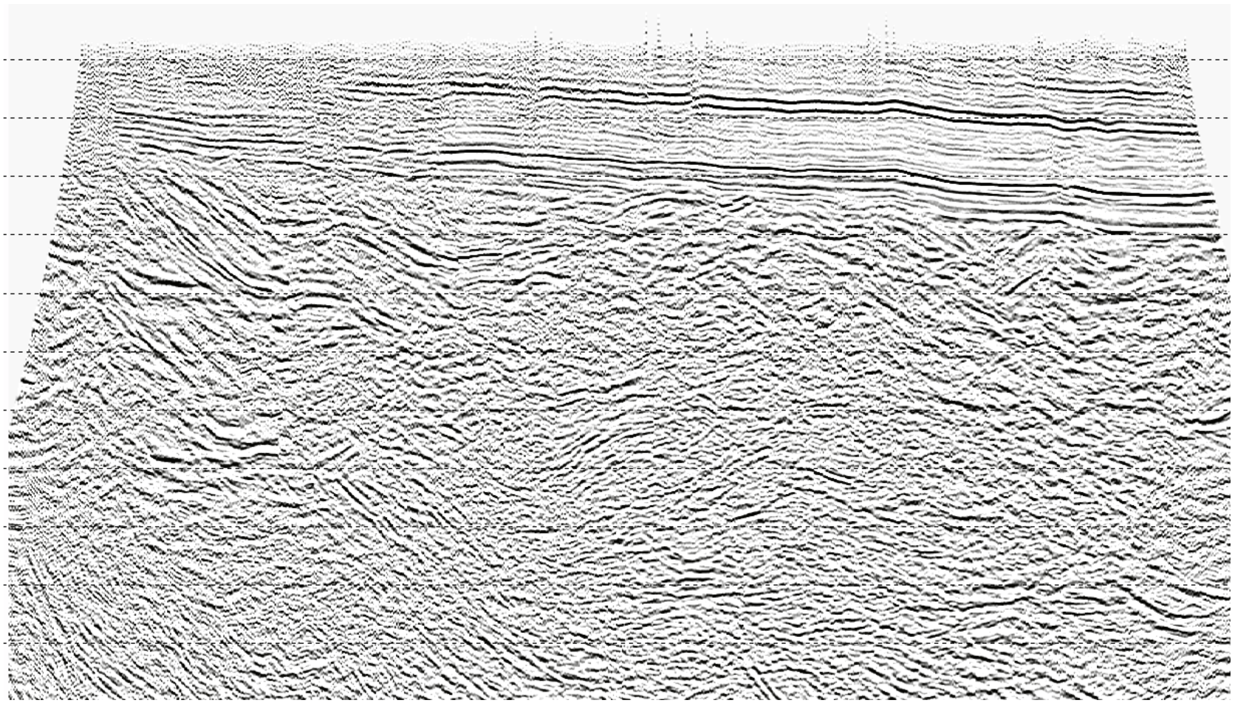


Figure 3-9. Post-stack time migration of Line A.

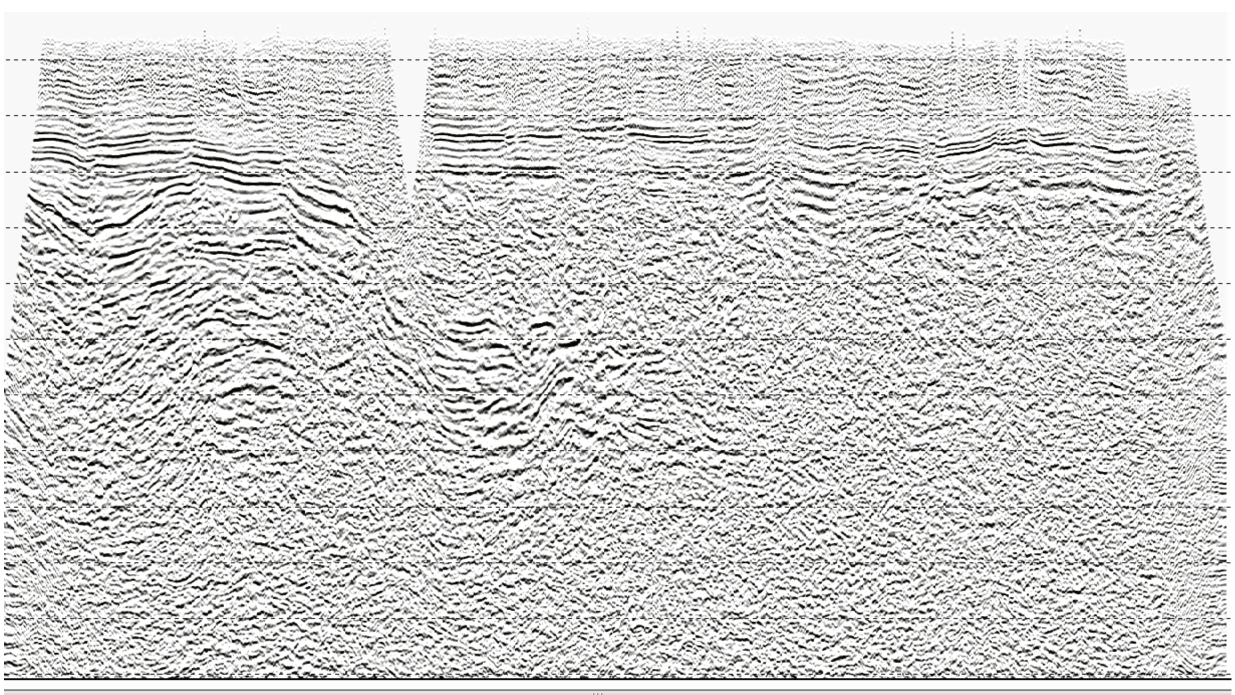


Figure 3-10. Post-stack time migration of Line B.

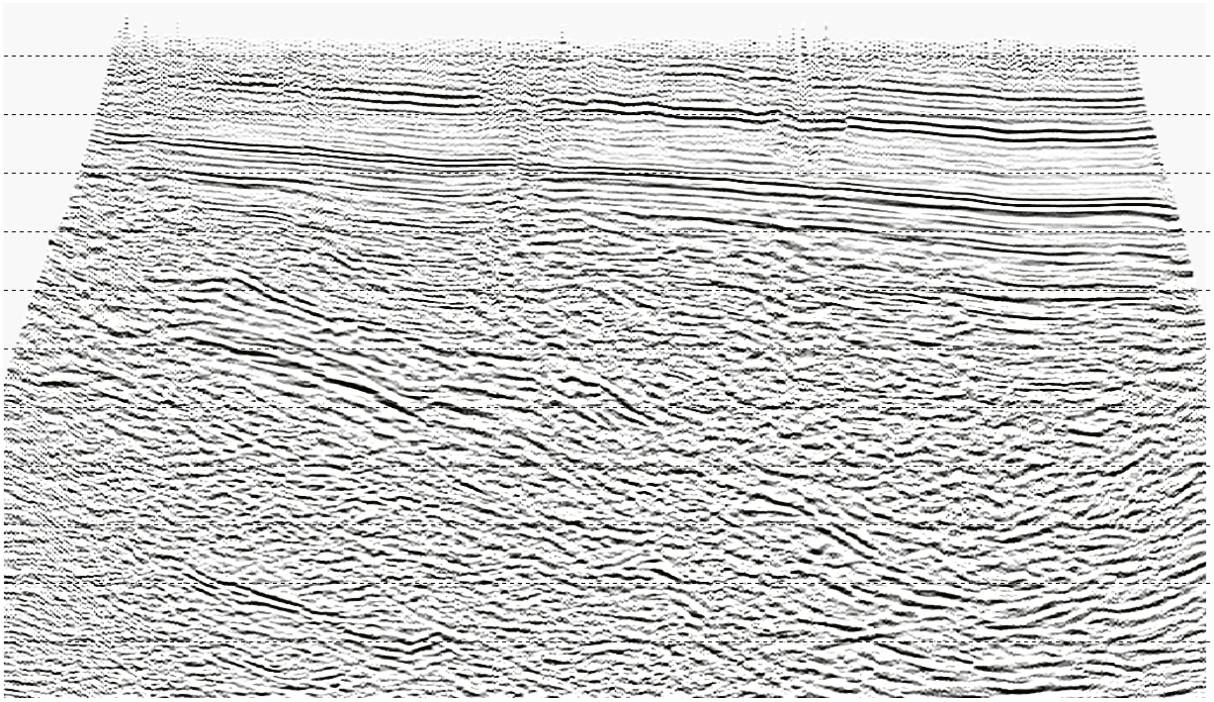


Figure 3-11. Post-stack time migration of Line C.

3.1.4 Final Amplitude Profiles

A pre-stack depth migration algorithm was utilized to convert the seismic profiles back into depth. The first step of pre-stack depth migration was to build a P-wave interval velocity model for each line. A diagram for velocity model creation is shown in Figure 3-12.

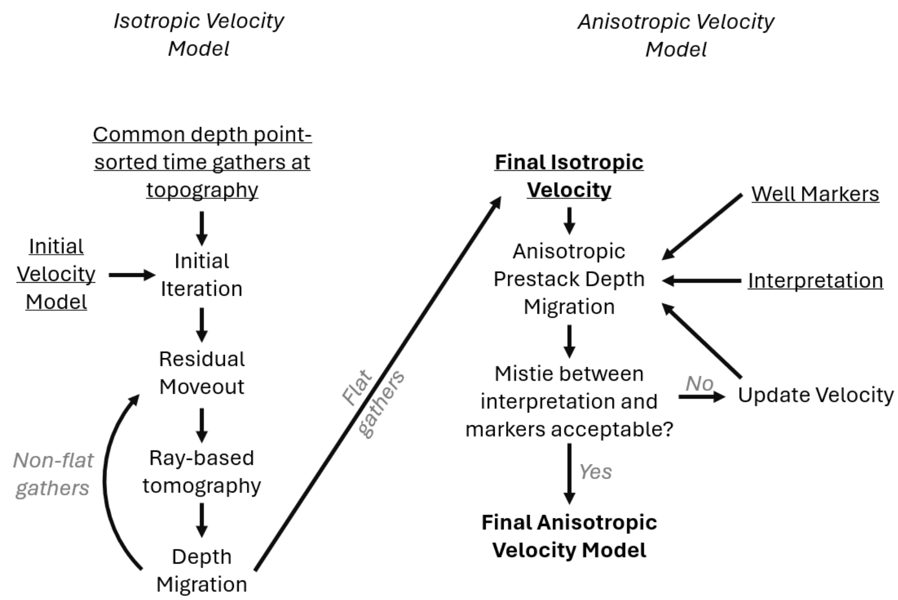
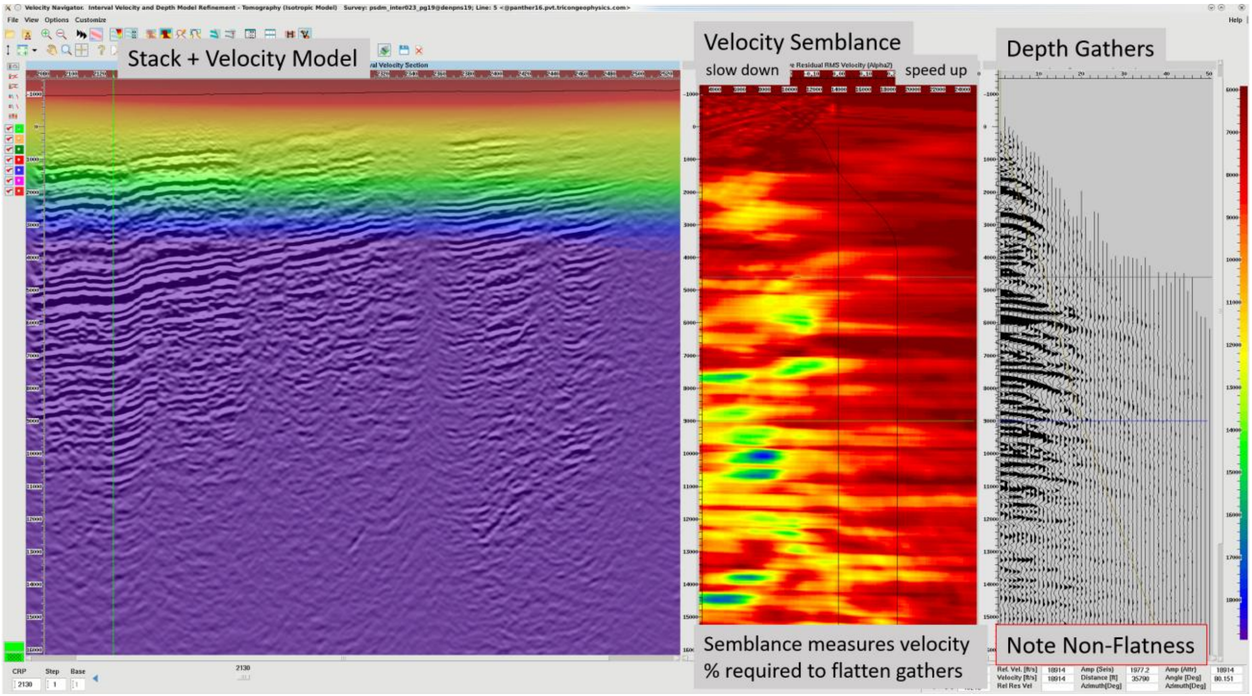


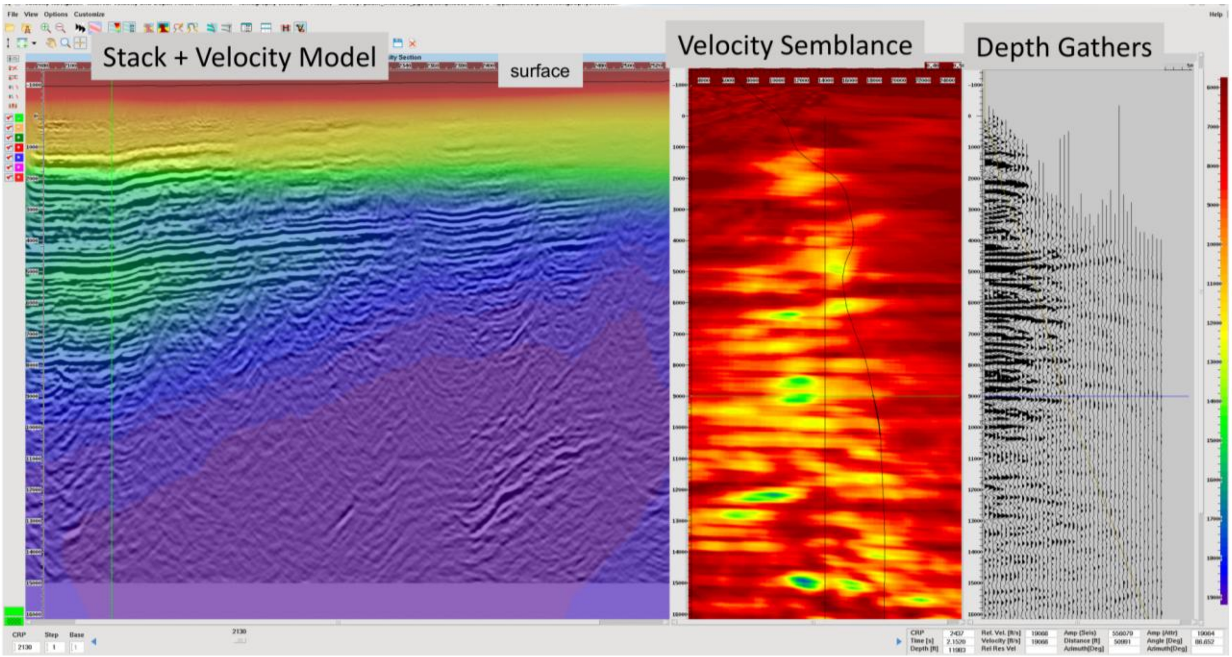
Figure 3-12. Isotropic (left side) and anisotropic (right side) velocity model creation. Inputs are underlined, outputs are bolded, divergence conditions are in gray with italics.

This first velocity model was isotropic and was used to flatten the gathers across seismic events, where non-flatness of the gathers indicated velocity errors in the model. The inputs to Line C's model were the initial velocity models based on the refraction velocities and the gathers. Following the initial iteration of the models, the models were then updated through two iterations of a three-step process consisting of residual moveout correction, ray-based tomography, and depth migration. Non-flat gathers were recycled to a subsequent three-step process, and flat gathers were moved to the final isotropic velocity model. With the approach used to develop the velocity model of Line C, vertical functions were developed for Line B and Line A to build the initial velocity sections for these lines. The velocity models for Line B and Line A were then updated through two iterations of the three-step process each. The stack with the initial velocity model applied for Line C is shown in Figure 3-13. The stack with the final isotropic velocity model applied for Line C is shown in Figure 3-14.



Note: Notice the color overlay (representing velocity) is totally flat. The velocity semblance is a measure of the velocity change required to flatten the gathers. When the color anomalies are centered, there is no need to alter velocities. The depth gathers on the right display the flatness (or lack thereof) of the gathers, which is a measure of how much anisotropy is present in the imaged strata. In this case, the depth gathers are curved and dipping to the right (not flat).

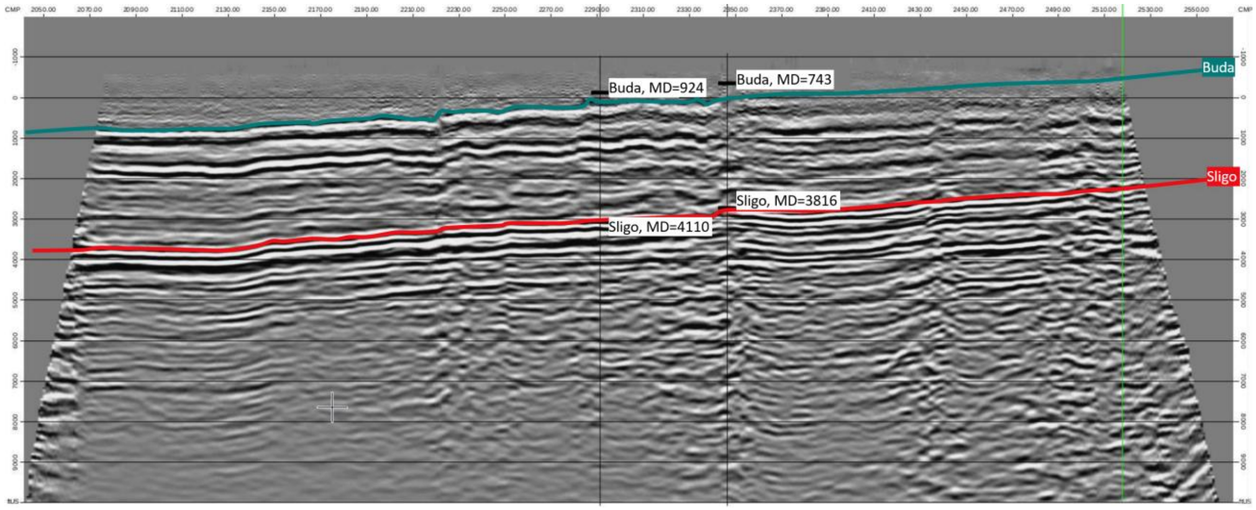
Figure 3-13. The stack with the initial velocity model applied for Line C, using a simple isotropic velocity model.



Note: Notice the color overlay (representing velocity) is not flat, unlike in Figure 3-13, but is instead dipping with the reflectors. The velocity semblance graph has color anomalies much more centered than Figure 3-13, and the depth gathers show flat reflectors, indicating the anisotropy has now been accounted for.

Figure 3-14. The stack with the final isotropic velocity model applied for Line C.

In the second stage of pre-stack depth migration, an anisotropic velocity model was created. Anisotropy was assumed to account for the differences between seismic depths and well marker depths. A diagram for this step is shown in Figure 3-15.



Note: MD = Measured depth (feet)

Figure 3-15. Post-stack depth migration stack model 4 anisotropic. Nearest wells show markers relative to horizons, Buda interpretation is ~277 feet deeper than well marker. Sligo interpretation ties to markers.

In this stage, wells were brought in to provide a standard to correlate the seismic data with depth. These well markers were tied to an interpreted surface on the seismic: in this case, the top of the Buda and Sligo Formations. A model was built with corresponding delta and epsilon sections. Delta was calculated from the depth differences, while epsilon was assumed to be a scalar of delta. The new model was related to the isotropic model and delta, where delta was a scalar that reduced the interval velocities. When the interval velocity decreased, the depths of seismic events decreased to be more consistent with well marker depths. The development of a proper delta and epsilon section also kept the gathers flat and generated the best stack image. The seismic profiles in this case had smooth lateral velocity changes, a Kirchhoff ray-based velocity modeling and migration algorithm was used, which does not preserve azimuth. It is important to note that the well locations do not lie directly on any of the seismic lines. For Line A and Line C, one well was used for each line, with an offset of approximately 900 feet from the lines. This offset made it difficult to achieve accurate depth reflectors on the pre-stack depth migration stack. However, this still represents the best possible solution apart from drilling and logging a new borehole on each of the seismic lines. The pre-stack depth migration for Line C and the two nearest well ties is shown on Figure 3-16.

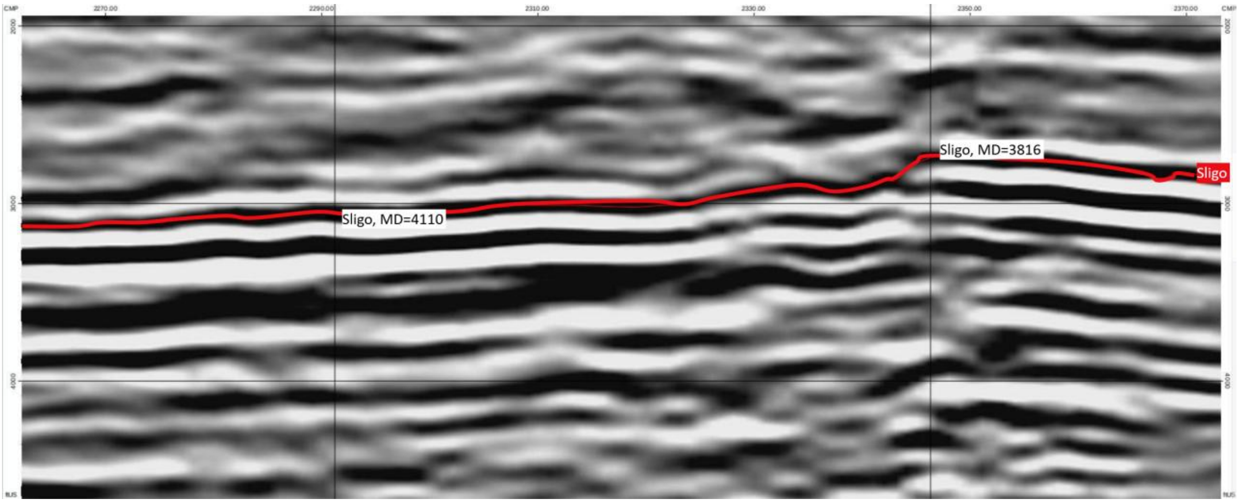


Figure 3-16. Line C: Post-stack depth migration stack model. Sligo Formation interpretations tie to well markers at two well locations closest to Line C.

The final anisotropic velocity model obtained from the second stage of pre-stack depth migration was applied to the seismic data to generate the final pre-stack depth migration section. These profiles were used through the remainder of this study. Several sources of uncertainty can affect the accuracy of the reflection events on the depth sections, including:

- The accuracy of the interpretations both in seismic data and well logs
- Well marker depths offset from the seismic lines, ranging from 800-2,000 feet
- Low signal-to-noise ratios in the shallow areas and along Line B

These uncertainties should be recognized when making geological or geophysical inferences based on the data.

3.2 Reprocessing Conclusions and Uncertainty Mitigation

The seismic data processing workflow described in tasks G through J (Figure 3-1) were designed to enhance the quality of the seismic data and improve the accuracy of the final seismic sections. Each step played a role in reducing noise, correcting for various factors that can distort the seismic signal, and ultimately providing a more reliable representation of the subsurface geology. However, it is essential to recognize the limitations and uncertainties associated with the data and processing techniques, particularly when making interpretations based on the final seismic sections. Section 4 describes approaches to uncertainty mitigation, including velocity analysis using multiple borehole ties, inversion, geologic modeling, and pre-stack depth migration (PSDM) routines. In this study, the pre-stack depth migration and anisotropic velocity modeling routine performed by Tricon is far more effective at providing a depth-converted profile than single well ties. However, the seismic well tie process is still effective in constraining the seismic character of the well log markers and providing a quality check on the depth converted profiles.

4 Synthetic Seismogram and Well Ties

4.1 Introduction

The primary purpose of a seismic well tie is to establish a correlation between seismic data and well-log data, which allows for more accurate interpretations of subsurface geology. This process helps interpreters determine which horizons to pick and supplements the seismic data with detailed well-log data. Additionally, it provides a time-depth relationship, which is valuable for converting seismic data, natively in two-way travel time, to recorded depth.

White and Simm (2003), in combination with tutorials on the OpendTect website and YouTube channel, provide the groundwork for well ties performed in this study.

The inputs for a seismic well tie include:

1. A seismic volume or profile
2. Seismic horizons on the seismic data
3. Well-log stratigraphic markers (typically geologic formation tops or bottoms)
4. A well-log suite (typically, but not limited to, sonic and density logs)

The outputs from a seismic well tie include:

1. The seismic reflection characteristics of the well log markers
2. A time-depth relationship between the depth of the well log and the seismic profile at the location of the seismic well tie

Most seismic studies will have all the input data. The importance of the outputs varies from study to study. In this study, it was crucial to accurately interpret the seismic expression of the well log stratigraphic markers. Additionally, the relationship between time and depth obtained were used to verify the velocity modelling completed by Tricon.

4.2 Methods

4.2.1 General Methodology

There are two main approaches to performing a seismic well tie:

1. Well Marker Tie:

   This method involves directly correlating well markers, such as formation tops or other geologic boundaries, to seismic horizons. Well markers are identified in the well data such as well logs, core data, or geologic interpretation, and then tied to corresponding reflectors in the seismic data. This method relies on the interpretation of seismic horizons and the identification of well markers, which can be subjective and may require additional geologic context. Well marker ties are valuable for establishing a general framework for seismic interpretation and can help constrain the seismic horizons.

2. Synthetic Seismogram Tie:

   This technique involves creating a synthetic seismogram using well log data such as sonic and density logs and comparing them to the actual seismic data at the well site. The synthetic seismogram is produced by convolving the reflectivity series derived from the well logs with a selected wavelet. Convolution takes two functions and "slides" one of them over the other, multiplying the function values at each point where they overlap, and adding up the products to create a new function. The synthetic seismogram is then adjusted to match the seismic data by stretching, squeezing, or shifting it. This allows for the calibration of the seismic data with the well data. This method enables a detailed comparison between the well and seismic data, facilitating the identification of key reflectors and the refinement of the time-depth relationship (Figure 4-1).

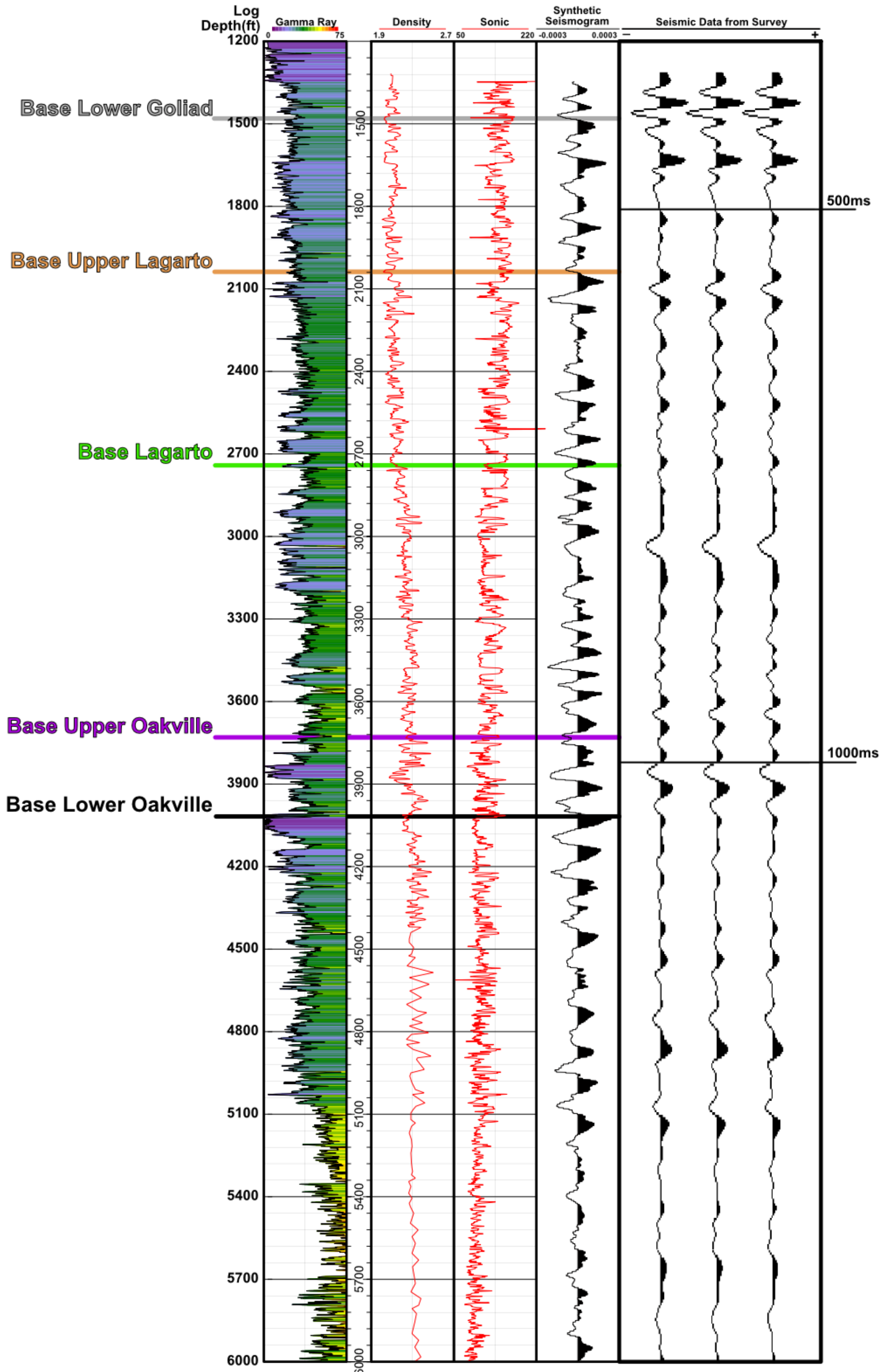


Figure 4-1. Example Synthetic Seismogram Well Tie. Petrophysical curves, synthetic seismogram, and seismic data from survey for Wardner #268. The Z axis is in depth with reference points for time in the volume listed to the right. From Draper and others (2021).

In practical applications, a combination of both methods is often used to achieve a robust seismic well-tie. The synthetic seismogram tie provides a detailed comparison between the well and seismic data, while the well marker tie helps establish a geologic framework and constrain the seismic interpretation.

4.2.2 Well Tie with a Synthetic Seismogram

A synthetic seismogram is a simulated seismic response generated typically from velocity and density well-log curves. Its purpose is to compare the seismic data at the well site and establish a connection between the well and seismic data. This workflow is shown in Figure 4-2.

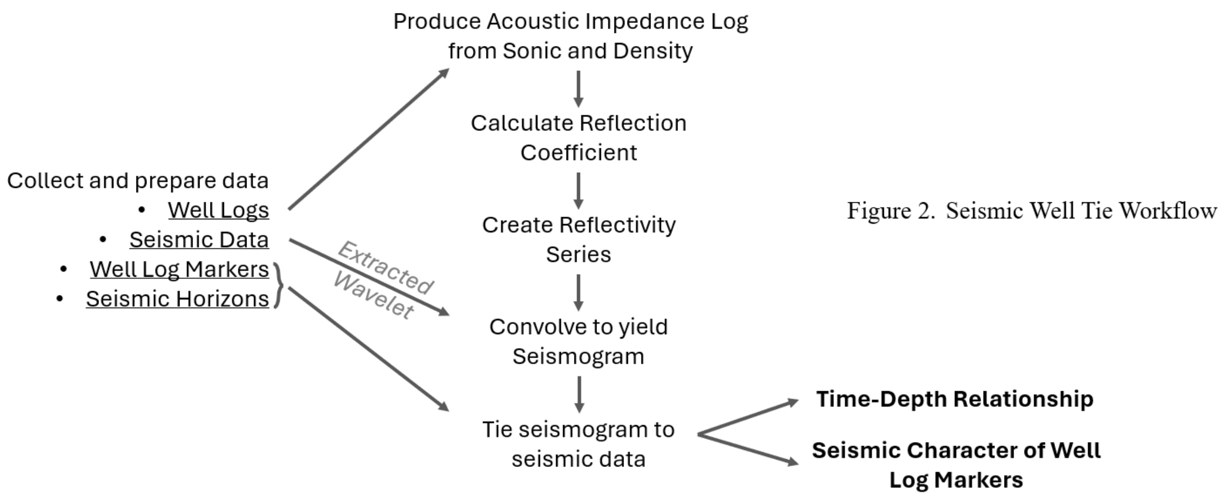


Figure 4-2. Seismic well tie workflow.

First, necessary well-log data are collected and prepared. The velocity and density logs should be calibrated and edited to remove any inaccurate measurements. If the sonic and density logs have different sampling intervals, the logs should be resampled to a common depth increment. Interpolating between points could also resolve different sampling intervals.

Second, a calculation is performed to generate an acoustic impedance series from the logs (Figure 4-3). Acoustic impedance (AI) is the product of the velocity (V) and density (ρ) at each depth point, as shown in Equation 4-1.

Equation 4-1

$$\mathrm{AI} = \rho * \mathrm{V}$$

Third, reflection coefficients (RC) are calculated, representing the contrast in acoustic impedance between adjacent layers. The reflection coefficients at each interface are calculated using Equation 4-2.

Equation 4-2

$$RC = \frac{AI_2 - AI_1}{AI_2 + AI_1}$$

where AI_1 and AI_2 are the acoustic impedances of the upper and lower layers, respectively.

Fourth, the reflectivity series is created by compiling the reflection coefficients at each depth or time sample along the well profile. These depth-based reflection coefficients can be converted to a time-based reflectivity series using the velocity log (Figure 4-3). The result is a series of spikes that represent the reflection coefficients at each time sample.

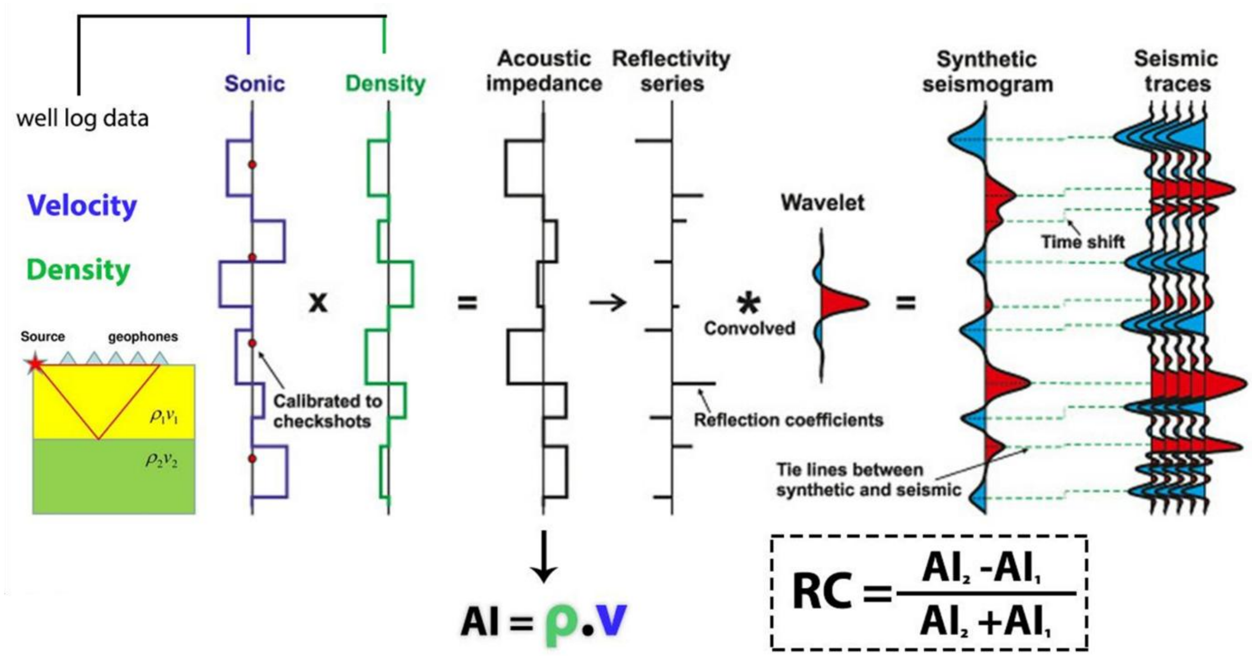


Figure 4-3. Seismic well tie workflow (after El-Gnady [2023]).

Fifth, a wavelet that represents the seismic data at the location of the seismic well tie is selected (Figures 4-3 and 4-4). It is important that a seismic wavelet is chosen that accurately reflects the characteristics of the seismic data, including its frequency content and phase. The wavelet can be extracted from the seismic data near the well site or by modelling it based on the anticipated seismic source and earth properties using seismic interpretation software.

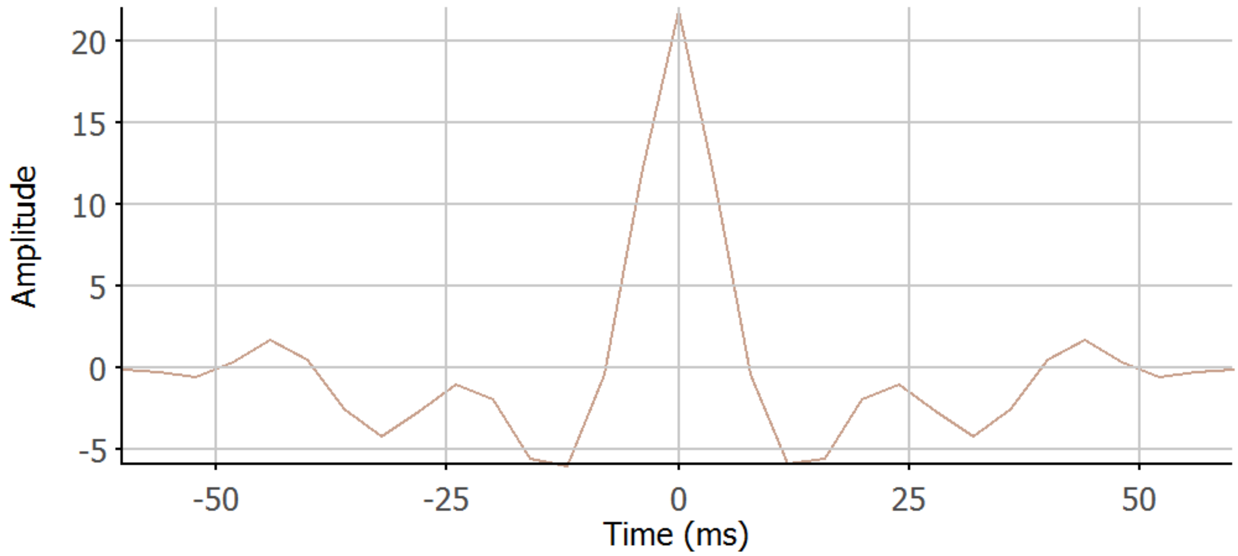


Figure 4-4. Example wavelet produced with OpendTect.

Sixth, the reflectivity series is convolved with the chosen wavelet to generate the synthetic seismogram. As noted above, convolution is a mathematical operation that combines the reflectivity series and the wavelet to simulate the seismic response.

Seventh, a quality check on the synthetic seismogram is performed. A display is created with the resulting synthetic seismogram alongside the actual seismic data at the well site, and the two are compared. This comparison serves as a check to ensure that the previous steps have accomplished their goal.

Finally, the well tie is adjusted by stretching, shifting, and squeezing the synthetic seismograms. The seismic horizons are first displayed on the seismic data, and the well-log markers are displayed on the synthetic seismogram (Figure 4-3). Overlaying these data allows the processor to compare the two-way time of the seismic horizons and the well log markers. It is important to note the fit between the two curve sets may not be perfect. To improve the quality of the tie, processors often adjust the seismogram by additionally stretching, shifting, and squeezing it.

The synthetic seismogram generation process involved simulating the propagation of seismic waves through the earth and the interaction with the subsurface layers, using the well-log data as a reference. By comparing the synthetic seismograms with the seismic data, a connection is developed between the selected wells and seismic domains.

4.3 Implementation

This study utilized a reprocessed iteration of the lines discussed in Section 3. Specifically, the pre-stack time migration profiles were used to determine which seismic line to tie. The chosen seismic line is the one with the highest number of easily identifiable reflectors. Line C was selected because the Sligo and Hosston formations were thicker along Line C compared to Line A, allowing for better resolution based on the reflector size (Figure 4-5). Since there were no wells with density data near Lines A and C, the nearest sonic log was used to calculate a pseudo-density log using Gardner's equation, Equation 4-3 (Gardner and others, 1974). In such cases, interpreters can borrow a log from a well farther away from the seismic profile or calculate a pseudo-density log. Because there were no density logs reasonably close, and the geology has a considerable dip with thinning and thickening seismic packages, it is reasonable to calculate a density log. While used for illustration purposes in this discussion, Tricon employed a much more sophisticated approach to develop a pseudo-density log.

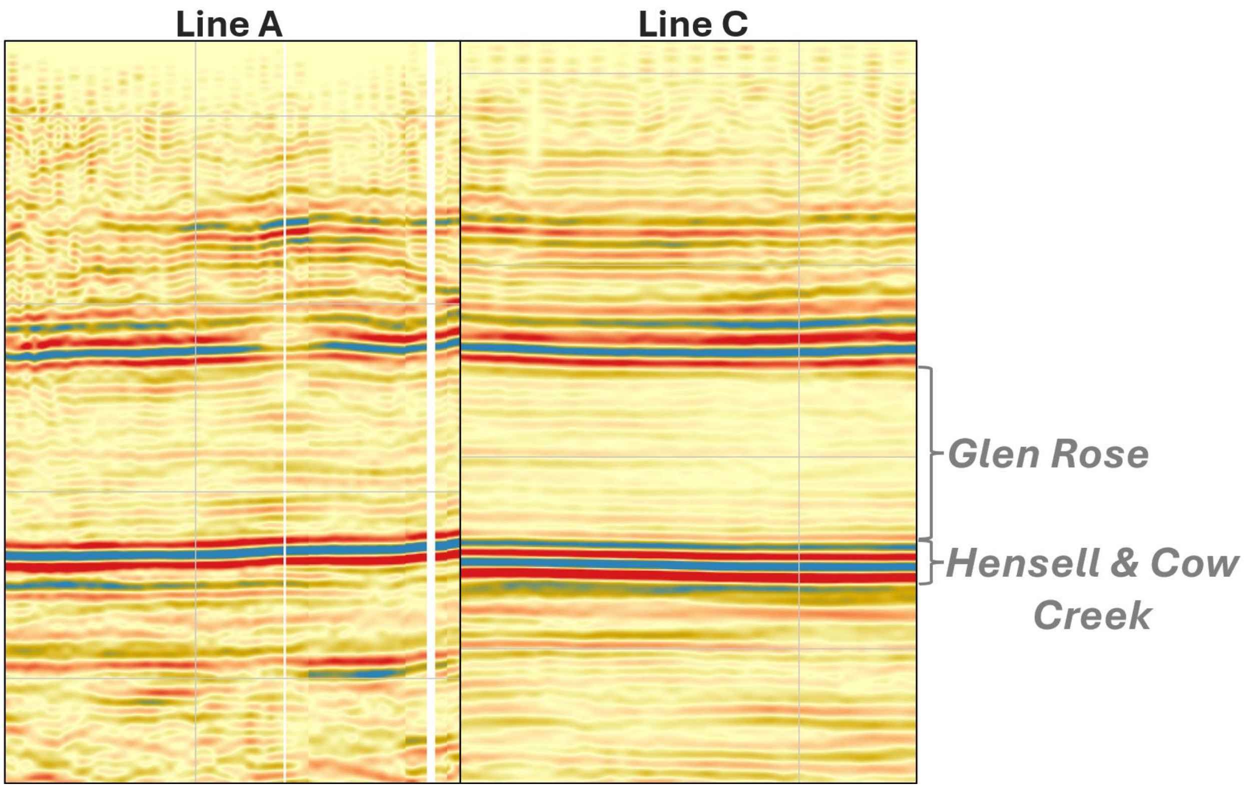


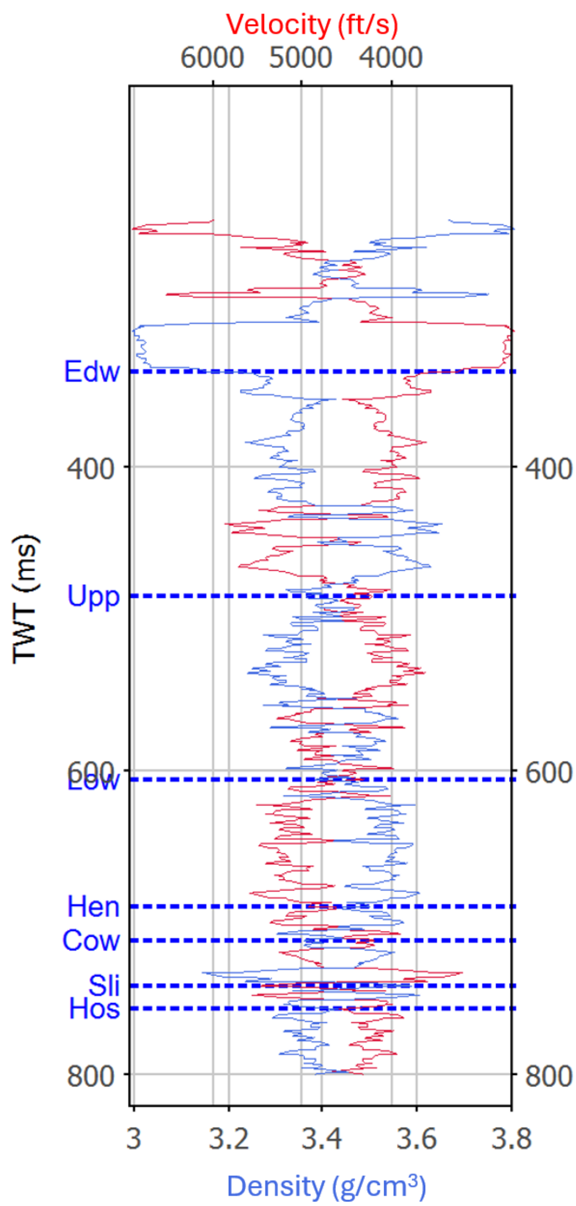
Figure 4-5. Seismic Line A vs Line C and reflection expression.

Gardner's equation (Equation 4-3) is an empirically derived equation that relates seismic P-wave velocity to the bulk density of the lithology in which the wave travels (Gardner and others, 1974).

Equation 4-3

$$\rho = \alpha {V_p}^{\beta}$$

Where ρ is bulk density given in grams per cubic centimeter (g/cm^3), V_p is p-wave velocity given in feet per second (ft/s), and α and β are empirically derived constants that depend on the local geology. For this study, α and β were determined to be 0.23 and 0.25, respectively. A complete set of empirically derived constants can be found in Gardner and others (1974). The sonic log employed was converted to p-wave velocity and the accompanying density log is shown in Figure 4-6.



Note: ft/s = feet per second, g/cm³ = grams per cubic centimeter, TWT = Two Way Travel Time (ms = milliseconds)

Figure 4-6. P-wave velocity and calculated density log with well tops noted on the left. Edw – Top Edwards Group, Upp – Top Upper Glen Rose Formation, Low – Top Lower Glen Rose Formation, Hen – Top Hensell Formation, Cow – Top Cow Creek Formation, Sli – Top Sligo Formation, Hos – Top Hosston Formation.

To tie the well data to the seismic data, this study utilized both synthetic seismograms and well markers. The available seismic data in the area provided a sufficient understanding of the reflectors for the formations examined, especially the Glen Rose, Sligo, and Hosston Formations (Figure 4-7, Figure 4-8). Formation tops, depicted as measured depths, for these units across the study area were acquired through the BRACS Database, which allowed this study to correlate the elapsed time to the reflectors on the seismic data and the measured depth of the corresponding well markers (Figure 4-9). This information established an initial time-depth relationship that was further refined using a synthetic seismogram well tie.

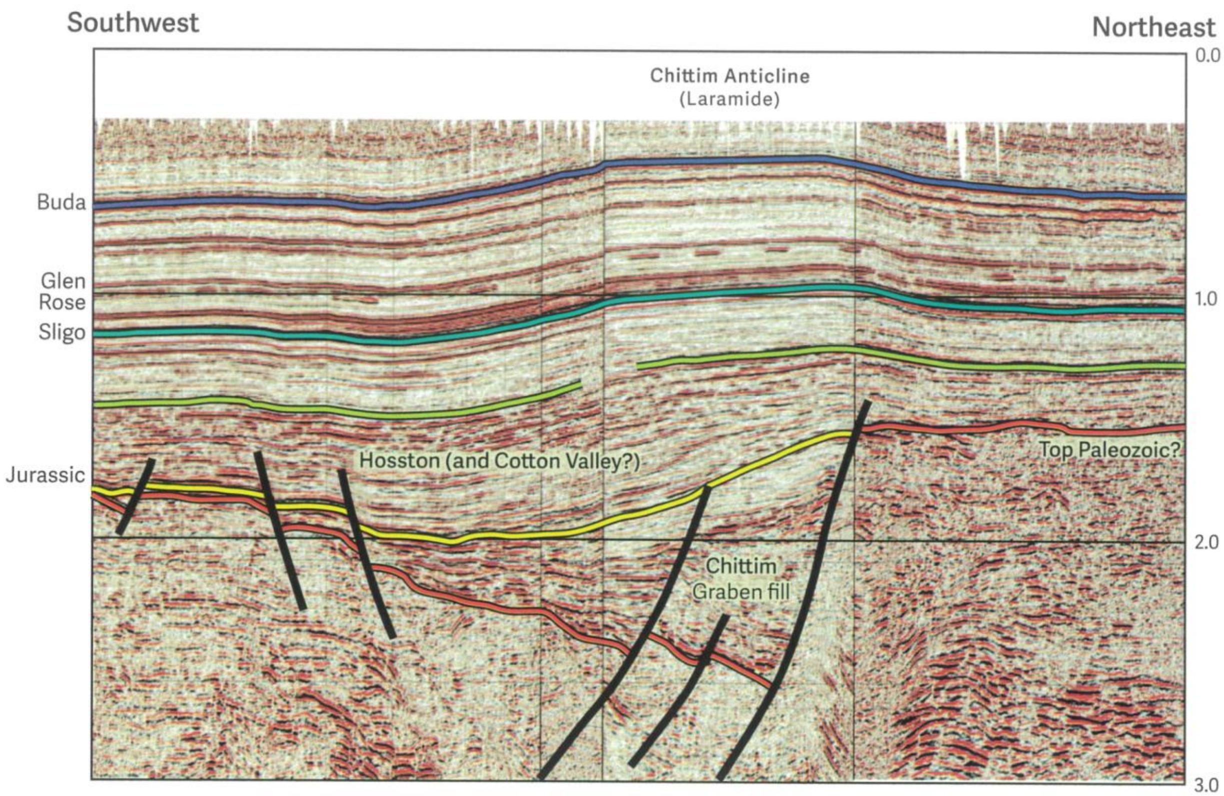
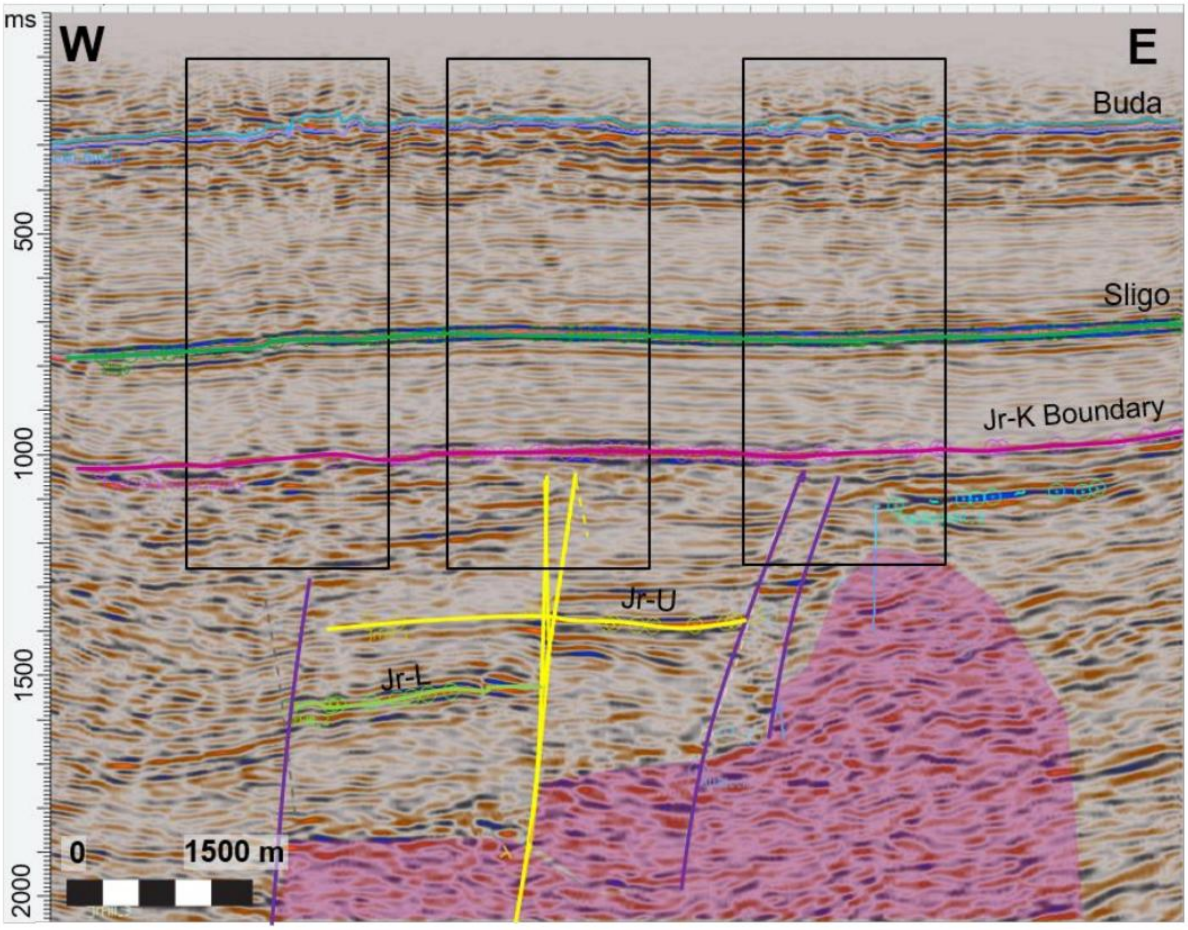


Figure 4-7. Seismic reflection image of the Chittim half-graben northeast of Eagle Pass, showing Buda and Sligo interpreted horizons with Glen Rose annotated (Ewing, 2016).



Note: JR-K, the Jurassic-Cretaceous boundary layer, marks a change in the character of the seismic reflectors above and below ~1,000 milliseconds. JR-U marks upper Jurassic layers. Jr-L marks lower Jurassic layers. Subvertical discontinuities mark breaks in the Jr-U and Jr-L and surrounding reflectors. Cretaceous layers in the black boxes show some zones more discontinuous than others. Pink polygon is interpreted as Ouachita thrust Paleozoic metamorphic rocks.

Figure 4-8. 2D profile extraction of 3D data from Sasser (2016) showing Buda and Sligo tops in Maverick County.

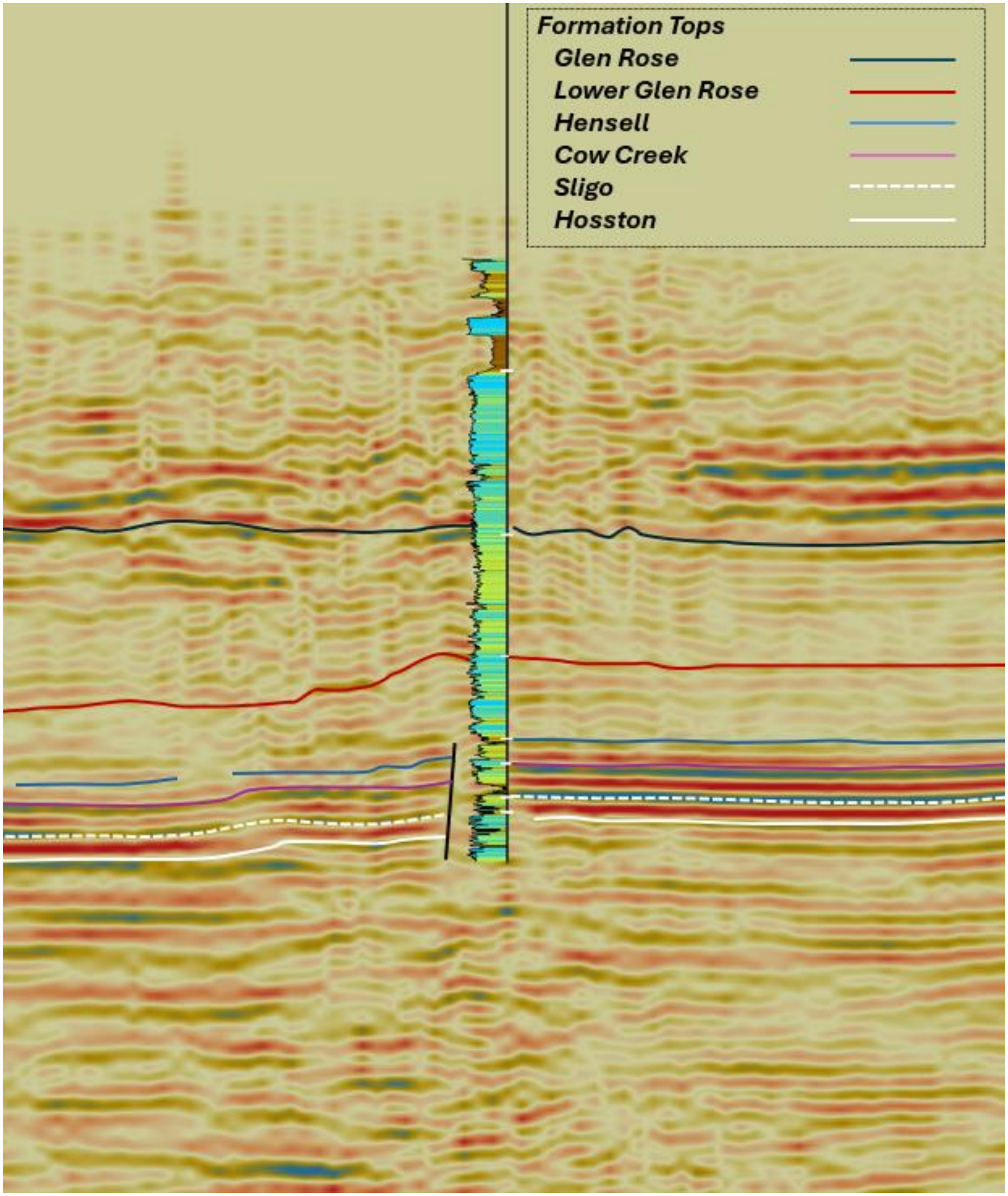
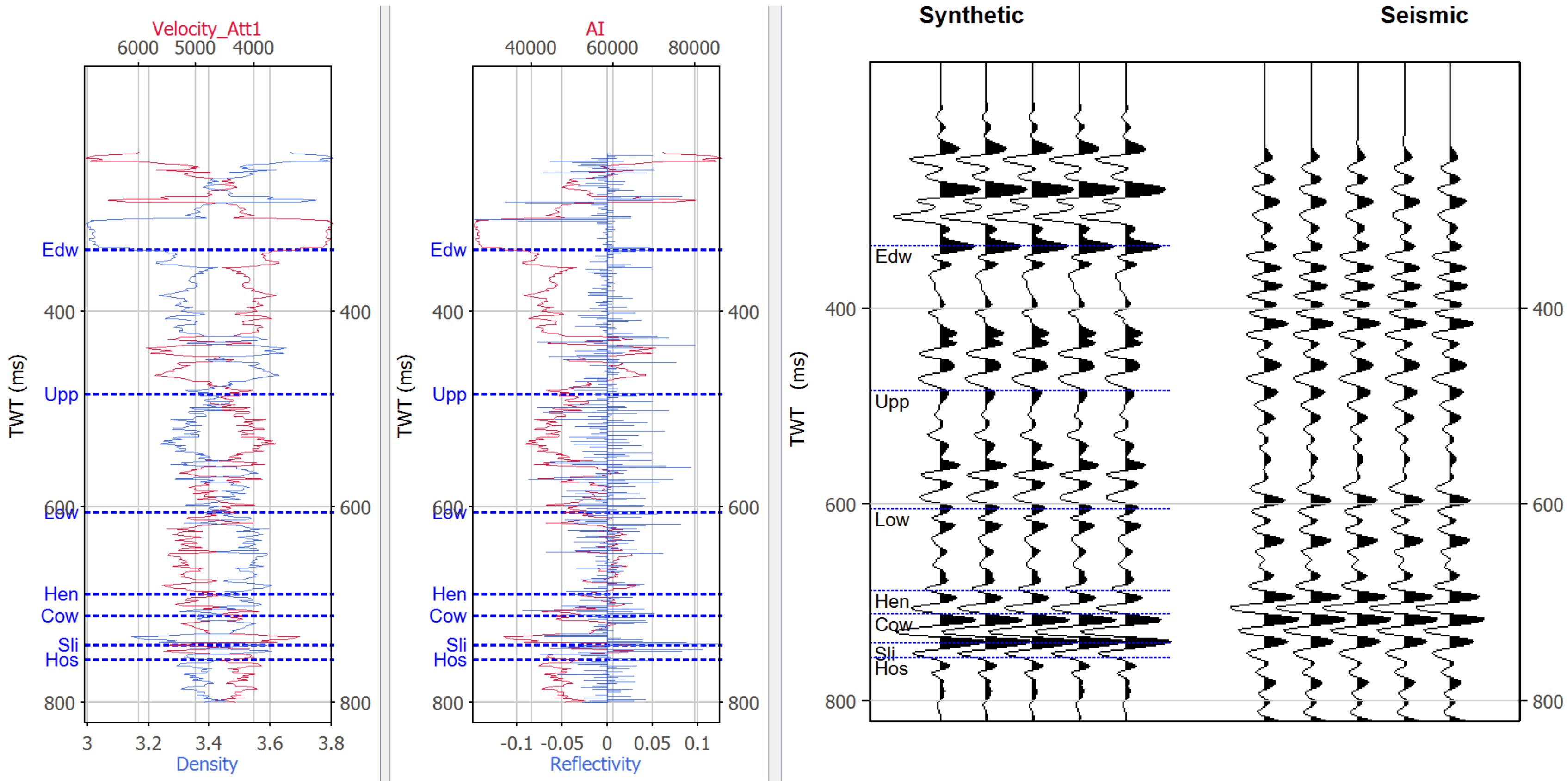


Figure 4-9. Seismic section with tied well log. Well log shown is a gamma ray log, scale is 0-60 API.

The synthetic seismogram was generated by converting the sonic log to a time-based reflectivity series then convolving it with a representative wavelet extracted from seismic data near the well site. The resulting synthetic seismogram was then compared with the seismic data at the well site to assess the quality of the tie (Figure 4-10). Adjustments, such as stretching, shifting, and squeezing the seismogram, were made to improve the alignment between the synthetic seismogram and the seismic data. The seismic character of the markers is expressed in Table 4-1.



Note: The synthetic seismogram is constructed from the acoustic travel time (Att), and density logs are used to calculate the acoustic impedance (AI), which is mathematically convolved with a representative wavelet extracted from actual seismic data near the well site to develop a synthetic seismogram. The synthetic seismogram is then adjusted (stretched, shifted, squeezed) to improve the alignment between the synthetic seismogram and the actual seismic data.

Figure 4-10. Synthetic seismogram and adjacent seismic data.

Table 4-1. Formation tops and accompanying seismic character.

Formation Top	Seismic Character
Edwards	Deeper peak of a twin peak
Upper Glen Rose	Zero crossing from trough to peak
Lower Glen Rose	Peak
Hensell	Zero crossing from trough to peak
Cow Creek	Zero crossing from trough to bright peak
Sligo	Bright Peak
Hosston	Zero crossing from trough to peak

By combining the well marker tie and the synthetic seismogram tie, the authors established a strong connection between the well data and the seismic data. This allowed for the calibration of the seismic interpretation with the well data, leading to a more accurate understanding of the subsurface geology and the identification of key horizons in the seismic data, such as the Glen Rose, Sligo, and Hosston Formations.

4.4 Discussion

Using a well tie as the only source of a time-depth relationship in a region with significant structural dip can lead to several inaccuracies when interpreting the data. The main issue arises from the varying thicknesses and depths to the relevant geologic units. In regions with significant dip, like southwest Texas, lateral velocity variations of seismic data are common due to changes in lithology, porosity, and fluid content along the dipping layers. A single well tie will not account for these lateral variations, and so inaccurate time-depth conversions result farther away from the well location.

Whether the geology is dipping or not, a single well tie provides information only at one location, which may not represent the entire region, especially in areas with complex geology and significant dip. Relying solely on a single well tie could lead to errors in the interpretation of the subsurface geology away from the well location.

Another important factor concerning single well ties is the difference between the character of the rocks found by sonic logs and the character found in seismic data. A potential drawback that may affect the time-depth relationship of seismic well ties is, in some cases, the seismic velocities derived from well-logs (used in the well tie) may not match the seismic velocities observed in the seismic data due to geologic reflector factors such as frequency dispersion, attenuation, or the presence of thin layers below the seismic resolution. These discrepancies can lead to errors in the time-depth relationship.

To mitigate these issues, it is common to use multiple well ties. Having more data points helps to better constrain the region versus relying on a single well tie. Other available options include velocity analysis and inversion, geologic modeling, and pre-stack depth migration (PSDM) routines.

In this study, the pre-stack depth migration and anisotropic velocity modeling routine performed by Tricon were far more effective at providing a depth converted profile than single well ties. However, the seismic well tie process as demonstrated herein is still effective in constraining the seismic character of the well log markers and providing a quality check on the depth converted profiles.

5 Depth Conversion

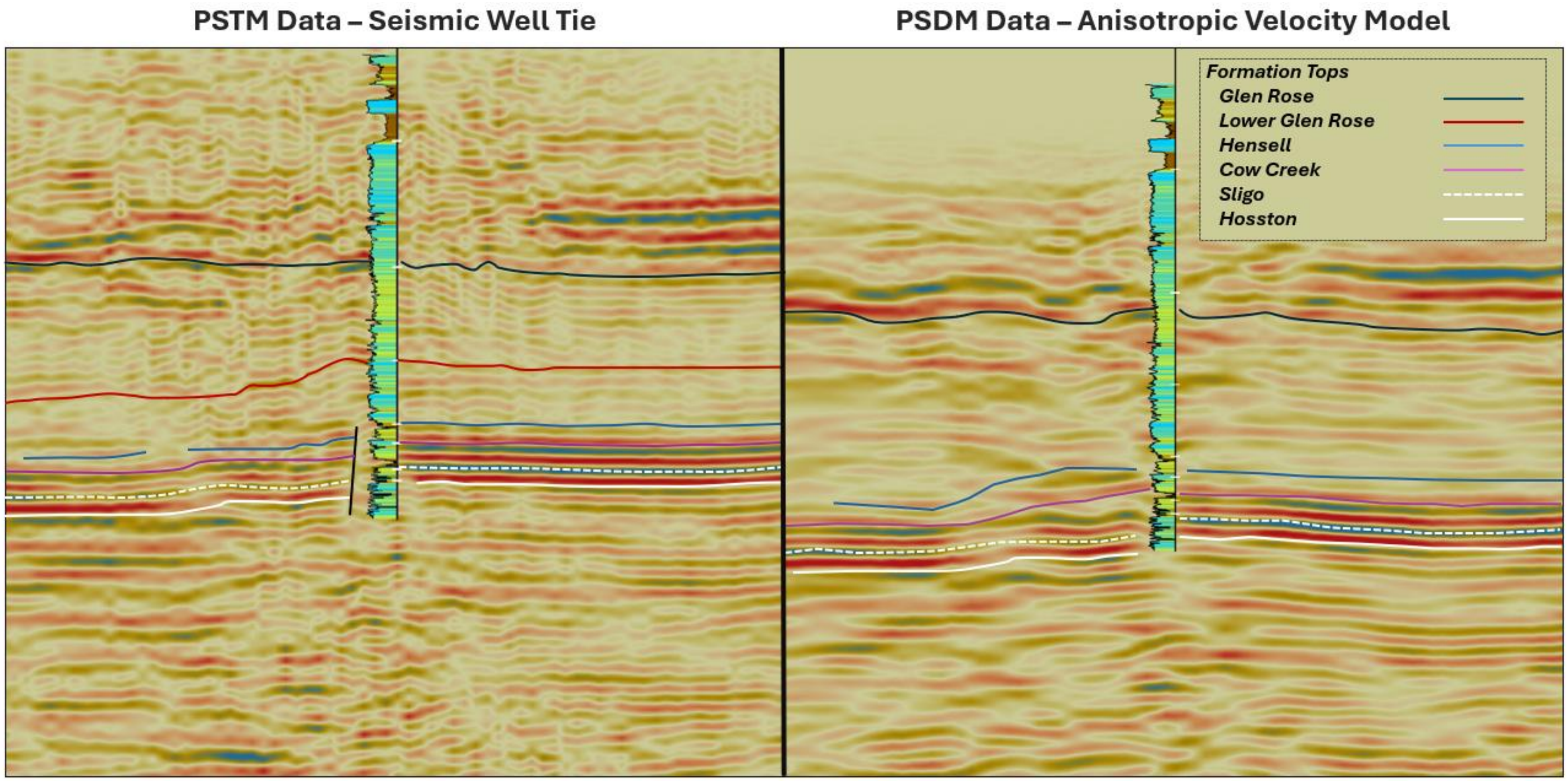
5.1 Introduction

Depth conversion is a critical step in seismic data interpretation; it ensures that the subsurface features identified in time-domain data are accurately represented in their true spatial positions. The primary objective of depth conversion is to translate seismic reflection data, recorded in elapsed time, into a depth model that can be used for accurate geological and reservoir characterization.

The time-depth relationship is used to depth-convert the seismic data. It establishes a correlation between the travel time of seismic waves and the corresponding depth of the subsurface reflectors. This relationship is generally derived from well data, seismic velocity information, and other geological insights. In Section 4.2.2, this relationship was solved for via a seismic well tie.

There are several drawbacks to the method employed in Section 4.2.2. Because subsurface geology is not typically uniform across large study areas, there are variations in seismic wave velocities along any seismic profile. These variations can introduce significant errors when a generalized time-depth conversion is applied. In regions with sparse well control, the time-depth relationship may be inadequately constrained, resulting in less reliable depth conversion farther away from well ties. Even when there is sufficient well control, a common assumption of each layer having a constant seismic velocity is often not true in heterogeneous subsurface environments.

To mitigate the drawbacks associated with time-depth relationships, advanced velocity modeling techniques are employed. Velocity modeling involves constructing a detailed velocity model that represents the subsurface velocity variations. This model is then used to convert seismic time data to depth. Advanced velocity modeling was performed by Tricon and documented in Section 3. The key figure for comparing these two methods is Figure 5-1.



Note: PSTM – Post-Stack Time Migration. PSDM – Pre-stack Depth Migration. Formation tops in the PSDM model on the right are somewhat less well defined: for instance, the top of the Lower Glen Rose is indistinguishable, while the Hensell is very poorly defined. The deeper units (the Cow Creek, Sligo, and Hosston) are relatively well defined.

Figure 5-1. Comparison between seismic depth-converted via seismic well tie (left) and those converted via anisotropic velocity model (right).

5.2 Comparison of Two Methods

The seismic well tie (PSTM Data) and anisotropic velocity model (PSDM Data) methods were compared to assess their accuracy in depth conversion. The comparison revealed that the seismic well tie method provided a better fit to the reflectors at the well's location. Specifically, the seismic well tie method displayed more accurate alignment with lithologic variances indicated by the well-log data. In contrast, the anisotropic velocity model, despite its detailed approach, did not align the reflectors with the well-log data as accurately at this well.

In this example, the less expensive seismic well tie method outperformed the more advanced anisotropic velocity model in terms of fitting reflectors at the well location, despite the additional resources and model inputs the anisotropic velocity model utilizes.

This result is likely to due to increased accuracy of seismic well ties at individual locations and the proximity of those wells to the seismic line. Despite the general advantages of the anisotropic velocity model in handling complex geological variations, the model did not fit the reflectors to the same accuracy at this well. This indicates that the effectiveness of velocity models can be highly dependent on the specific geological context.

Since the seismic well tie method is less expensive and requires fewer resources, it is an effective option. For regions with similar geological characteristics and well control, the seismic well tie method can be a reliable and cost-effective choice for depth conversion. However, it is essential to consider that this may not be universally applicable, and each case should be evaluated individually.

In conclusion, the comparison underscores that, while advanced techniques like anisotropic velocity modeling can be beneficial for detailed subsurface analysis, simpler methods like the seismic well tie can in some cases provide better results. This highlights the importance of selecting the appropriate method based on the specific requirements and conditions of a project.

6 Seismic Interpretation and Integration

6.1 Introduction

6.1.1 Motivation

The best subsurface stratigraphic frameworks use an abundance of outcrop and/or core, geophysical, and seismic data (Kerans and Tinker, 1997). These data provide a solid rock-based framework to use for geologic interpretations and resource exploration. With this study, an opportunity is available to correlate published outcrop studies to the deeper portions of the Edwards Trinity (Plateau) Aquifer (ETPA) using 2D seismic lines. Having continuous data coverage from outcrop to relevant depths of an aquifer in combination with water well performance advantages aquifer scientists. This Section provides an example of how to leverage seismic data with water well analyses and well log interpretation in order to produce a groundwater resource evaluation.

Southern Kinney County was identified in the preceding Sections as the most promising area for the focused study, with 14 seismic lines having feasibility scores above zero. INTERA and TWDB collaboratively selected a subset of these lines (referred to as Lines A, B, and C) by considering factors such as line proximity, data quality, and cost. The selected lines were then leased from the seismic vendors.

This Section covers the geologic setting of the focused study area in southern Kinney County, details the methods employed and the data available, and presents results. The ensuing discussion centers around the utility of the seismic lines as an addition to the non-seismic informed groundwater resource analysis. Conclusions on the utility of seismic and the recommendations for resource evaluation in the study area follow.

6.2 Geologic Setting

6.2.1 Introduction

The focused study area in southern Kinney County is on the northern flank of the Maverick Basin. The Maverick Basin is a Cretaceous intra-shelf basin overlying an earlier Mesozoic rift feature (Figure 6-1). It is bounded by the San Marcos Arch to the northeast and structural uplifts in Mexico to the southwest (Ewing, 2016). The basin was formed by differential subsidence beginning in the mid-Albian. Middle and Upper-Cretaceous units are relatively thin and are nearer ground surface over the San Marcos Arch and thicken and deepen into the Maverick Basin to the southwest (Figure 6-2). The basin is dominated by clastic sediment deposition in the Jurassic and early Cretaceous, then transitions to carbonate deposits until the Late Cretaceous, when it was again dominated by clastic deposition (Scott, 2004).

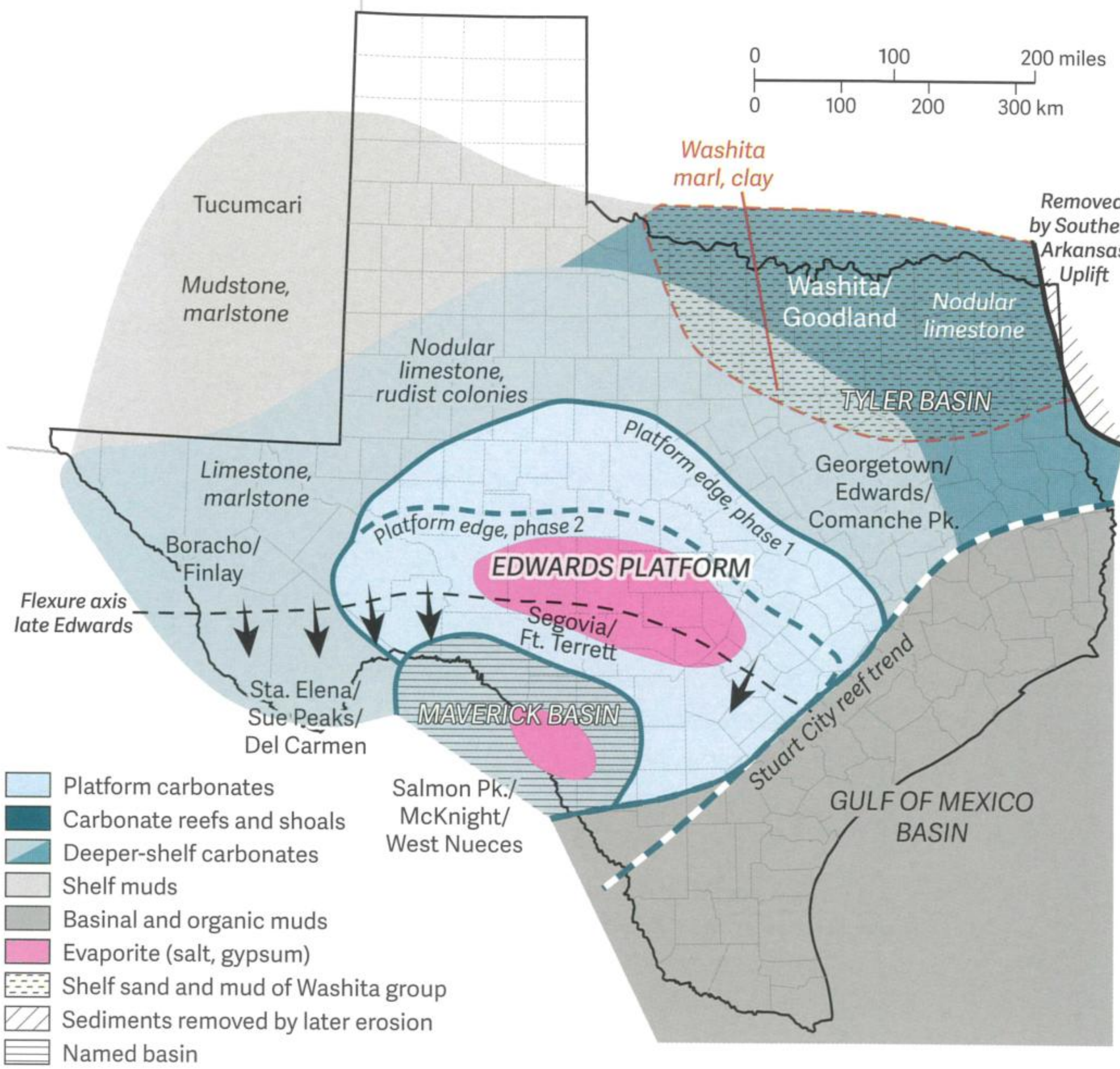


Figure 6-1. Overview of the Maverick Basin and Edwards Platform during the Middle Albian. From Ewing (2016). Kinney County, where the example seismic sections in Section 6 are located, is located immediately north of the magenta evaporite polygon in the Maverick Basin.

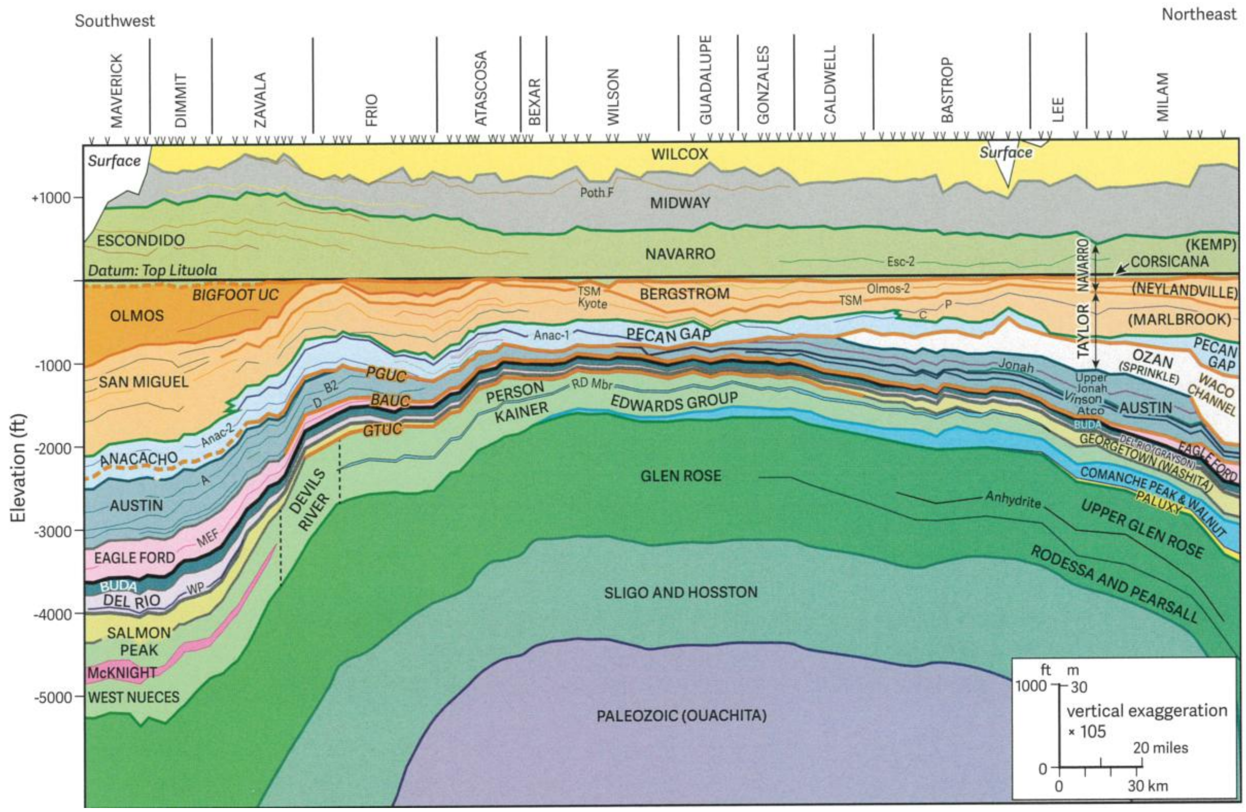


Figure 6-2 **Cross section of the San Marcos Arch; vertical datum on base of Escondido or middle Navarro. This stratigraphic section highlights the thickening of units in the Maverick Basin, and the timing of the thickening from West Nueces (mid-Cretaceous Fort Terrett equivalent) to Olmos (upper Cretaceous) deposition. From Ewing (2016).**

6.2.2 Paleozoic

The orientation of dominant structures in south Texas was influenced by Paleozoic and early Mesozoic events. The Ouachita Orogen (Ouachita front depicted in Figure 6-3) marks the closure, in late Paleozoic time, of a deep, possibly oceanic basin that once rimmed the southern margin of the Precambrian craton of North America. The Ouachita Orogen is now exposed in the Ouachita Mountains in Oklahoma and the Marathon Uplift and Solitario domes in the Trans-Pecos region of Texas. The Paleozoic basinal strata were thrust northwestward over the Precambrian craton and its cover, forming a "frontal thrust belt." This thrust belt covers most of the southern United States. Under the Maverick Basin, little is known about the Paleozoic rocks that were emplaced over the North American Craton (Ewing, 2016).

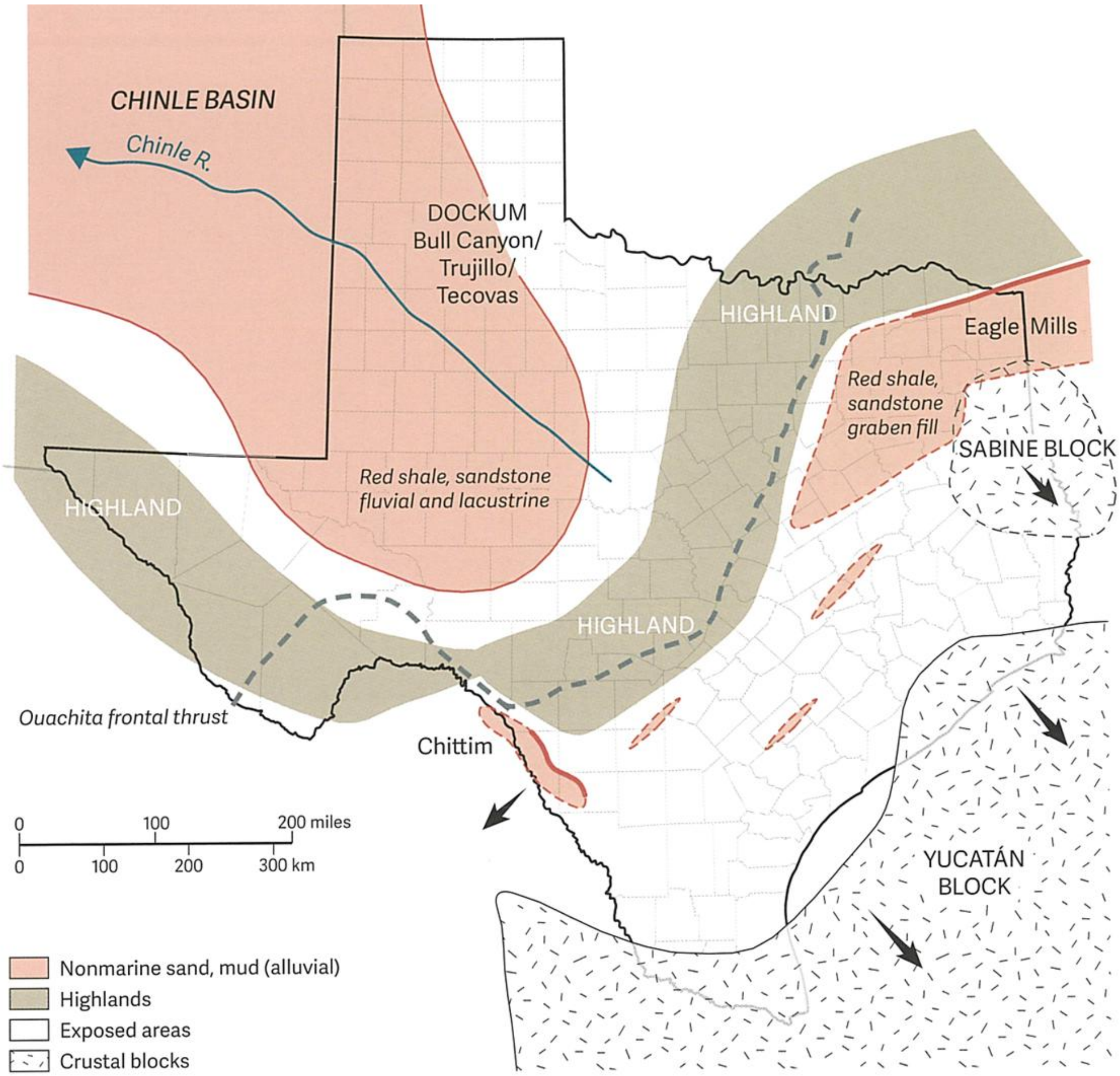


Figure 6-3. Texas in the Late Triassic, showing the Chittim Rift and directions of extension. The Ouachita frontal thrust is labeled to the west of the Texas-Mexico border and is approximated by the Highland area. From Ewing (2016).

6.2.3 Mesozoic

Regionally, across the Maverick Basin, the timing of deposition is categorized into Chittim Rift, Pre-Maverick Basin, Syn-Maverick Basin, and Post-Maverick Basin. These time blocks guide the dominant accommodation creation mechanism behind each sediment package.

Chittim Rift

Coarse clastic "redbed" strata are known or inferred to overlie deformed Ouachita rocks over a large area of south Texas. A specific section of these redbed strata were deposited within the "Chittim rift" (Figure 6-3). In Maverick County, seismic data reveal an extensive northwest-trending half-graben complex that lies beneath a thick Mesozoic section (Scott, 2004). This graben complex formed during Triassic-Jurassic rifting and is known as the Chittim Rift. Faults of the Chittim Rift were later reactivated by Paleogene (Laramide) compression to form the broad Chittim Anticline (Figure 6-4). On the seismic line presented in Figure 6-4, the fill of the half-graben exceeds 500 milliseconds, approximately 3,500 feet, in thickness. The Chittim Rift was filled by the beginning of the Cretaceous, and there was no expression of the Maverick Basin by the thickening of stratigraphic units until partway through the Albian, when Maverick Basin subsidence increases (Ewing, 2016).

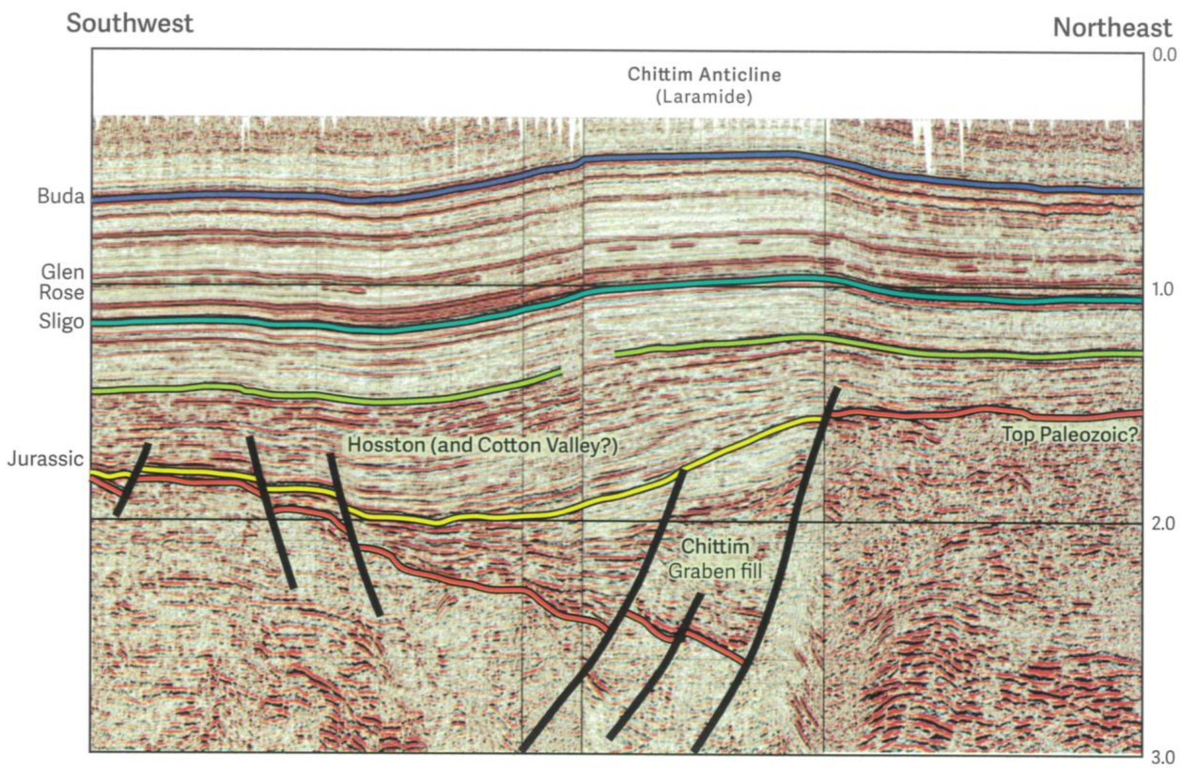


Figure 6-4. Seismic line from within the Marathon Basin showing the Chittim Rift, a feature that predates the development of the basin. From Ewing (2016).

Pre-Maverick Basin

Pre-Maverick Basin grouping includes Cotton Valley through lower Edwards Group strata (Figure 6-5). The upper part of this set of strata comprises the Trinity Group and lower Edwards Group of the Edwards-Trinity (Plateau) Aquifer (ETPA) (George and others, 2011).

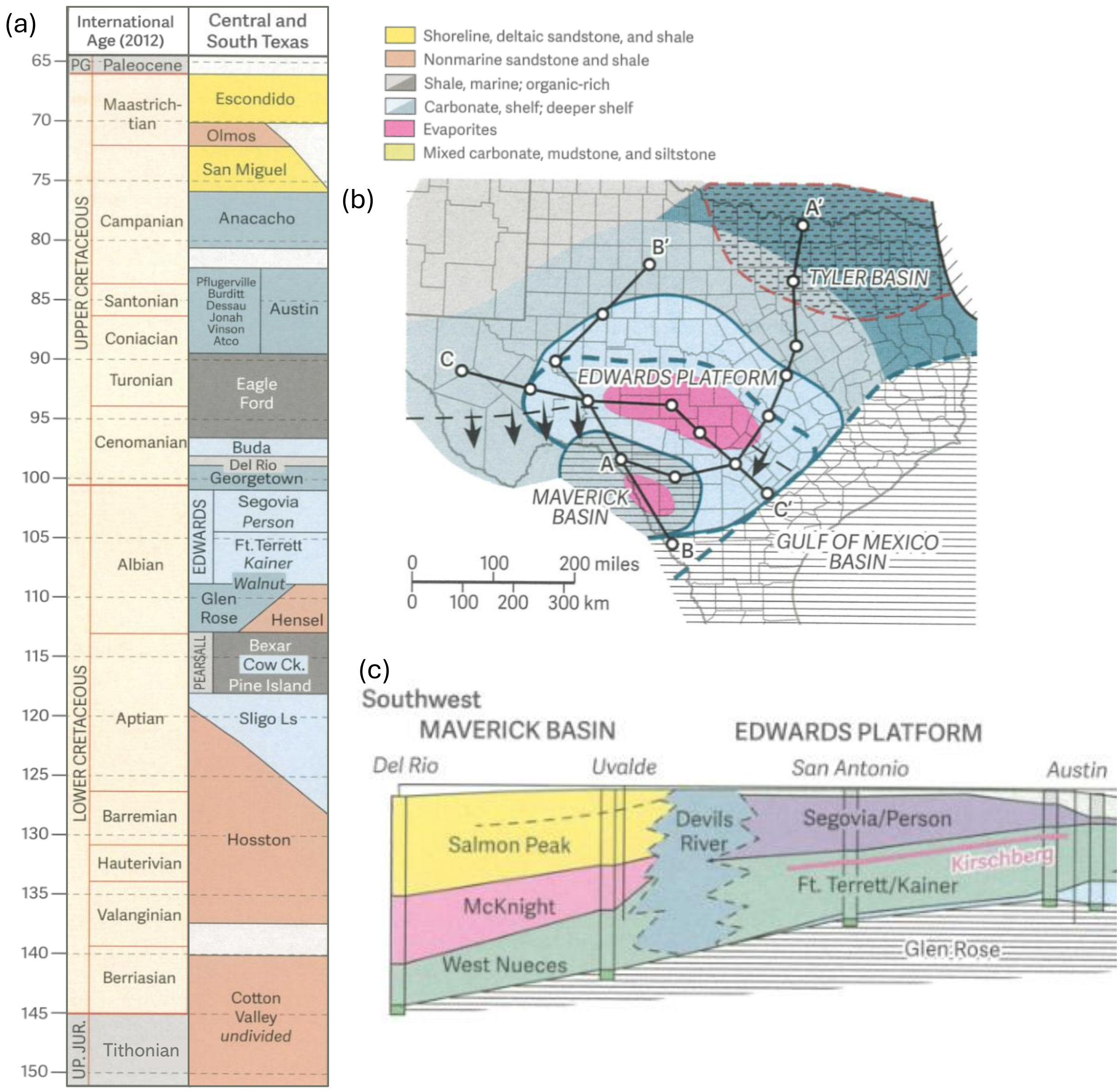


Figure 6-5. **Stratigraphic column for the Cretaceous in central Texas (a), basemap for cross section A-A' (b), and stratigraphic section depicting Edwards Group stratigraphy in the Maverick Basin versus the rest of the Edwards Platform. From Ewing (2016).**

The Cotton Valley is an Upper Jurassic-Lower Cretaceous sandstone that was deposited over the filled Chittim Rift. The overlying Hosston is the lowest unit in the ETPA, which was deposited in the study area as non-marine sands (Figure 6-6). Following the Hosston, the rest of the Cretaceous in the Maverick Basin area is predominantly carbonate units (Ewing, 2016). Clastic sedimentation into the Gulf of Mexico basin waned into Aptian time, and carbonates that developed downdip of the Hosston in the Early Cretaceous spread across the entire Gulf of Mexico Shelf (Ewing, 2016). The development of carbonate environments in the middle and late Cretaceous was enabled by global rise in sea levels that covered some of the continent. The first carbonate unit in the Cretaceous is the Sligo Formation, which expands in depositional area as the Hosston contracts updip (Figure 6-5, Figure 6-7).

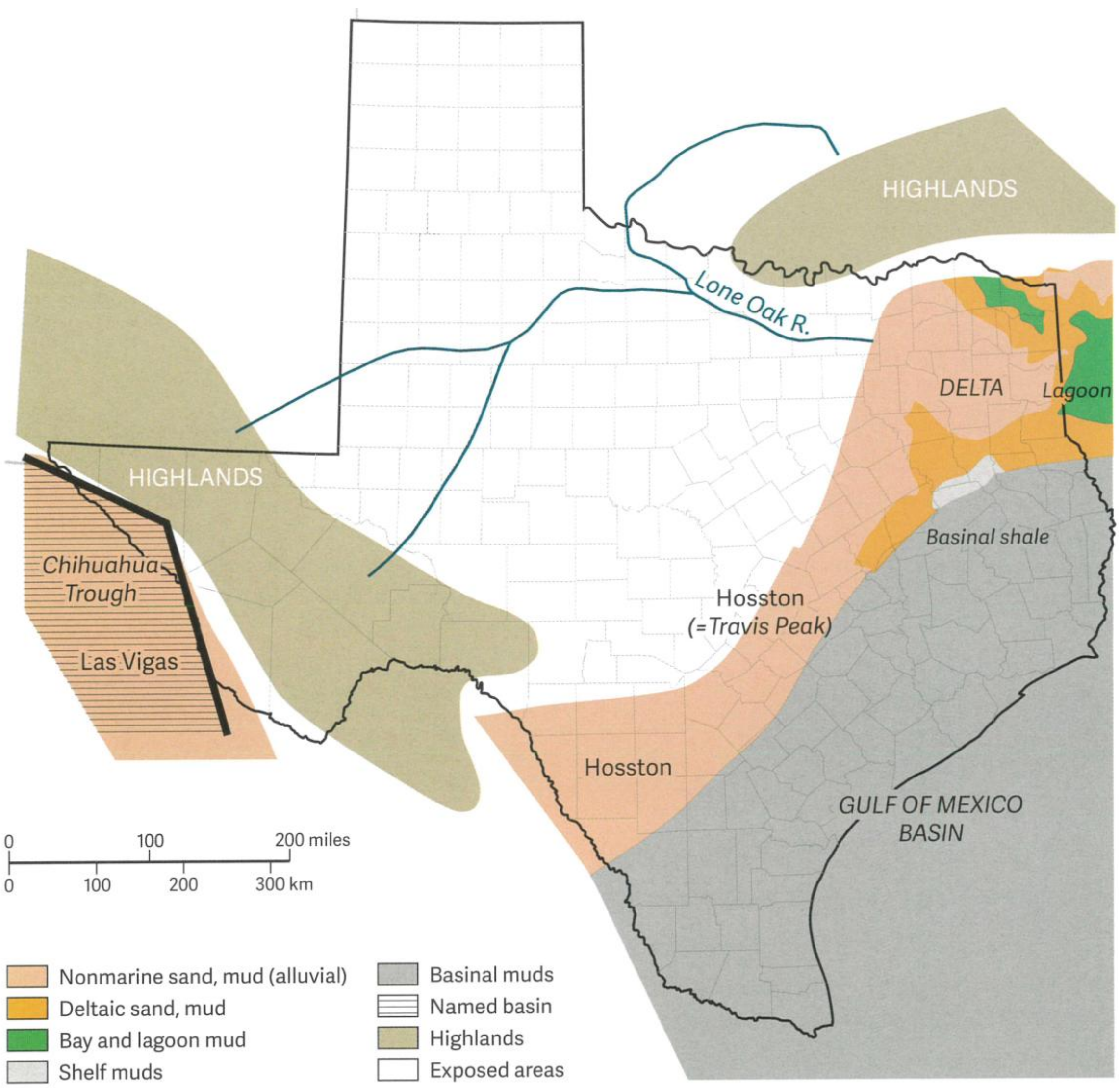


Figure 6-6. **Barremian (Early Cretaceous-Coahuilan) environments and rocks; Hosston and equivalents. From Ewing (2016).**

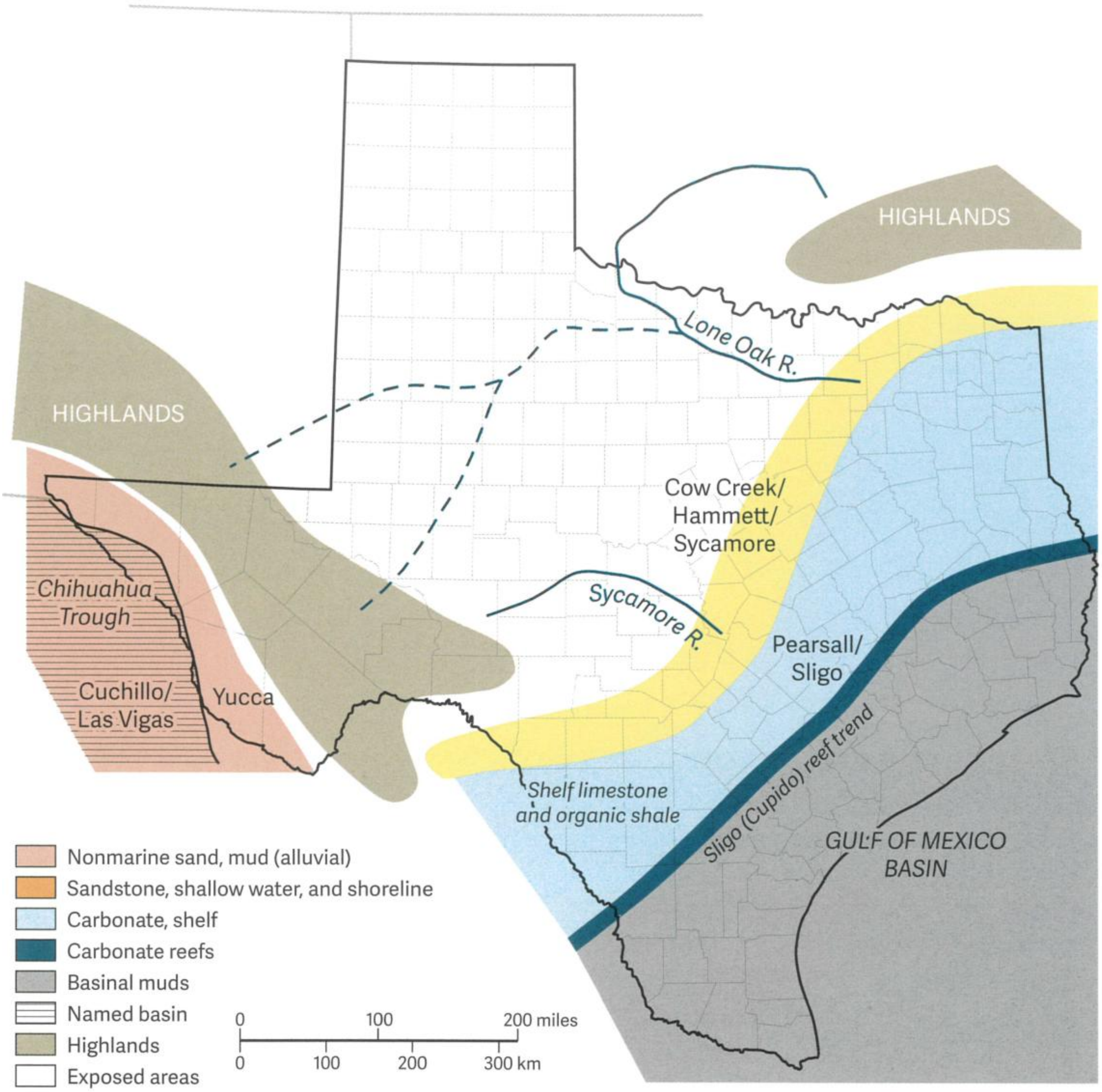


Figure 6-7. Aptian environments and rocks. From Ewing (2016).

Sligo deposition is recorded to precede a fall in global sea-levels across the region. A rise in sea-levels accompanied by an ocean anoxic event then allowed for the deposition of the organic-rich Pearsall Group. The Pearsall Group is comprised of three organic shale-dominated members; the Pearsall Shale, the Cow Creek Limestone, and the Bexar Shale. Environmental factors allowed carbonate sedimentation to restart in the earliest Glen Rose until ultimately there was a full reef margin in the Edwards Group in the latest Albian (Phelps, 2013).

The Glen Rose holds local significance as an aquifer with fresh to slightly saline water in Maverick County (Railroad Commission of Texas, 2021). In the study area, the Glen Rose consists of shelf carbonates with occurrences of patch reefs from Maverick County into central Texas (Scott, 2004). At the time of Glen Rose deposition, there was little relief to the Maverick Basin (Figure 6-8) (Scott, 2004).

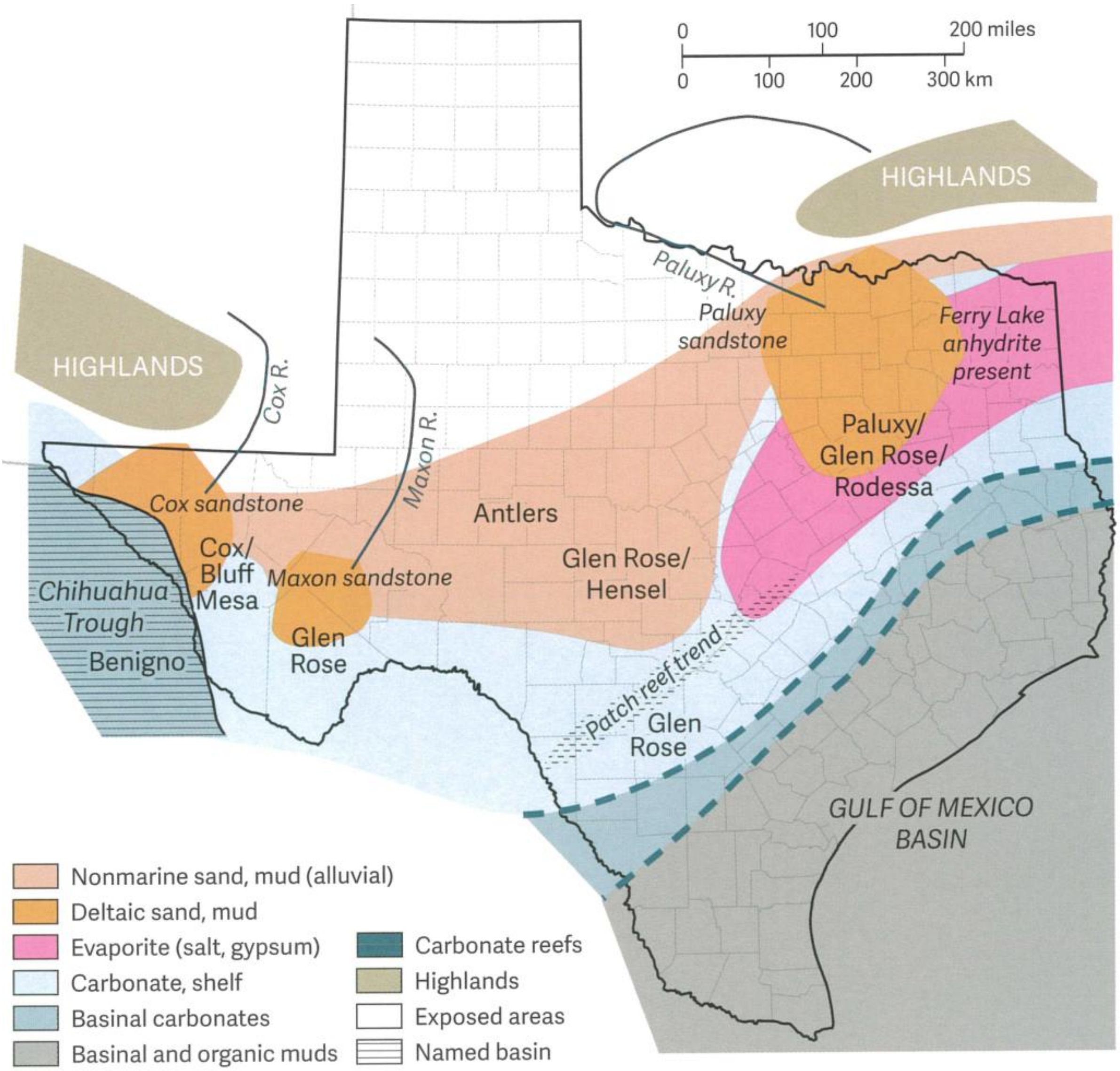


Figure 6-8. Early Albian environments and rocks. From Ewing, (2016).

Syn-Maverick Basin

Syn-Maverick Basin grouping includes Edwards Group to the Escondido Formation of the latest Upper Cretaceous. The Edwards Group comprises the upper ETPA (Figure 6-9) (George and others, 2011).

Following Glen Rose deposition, the lower Edwards Group was widely deposited throughout Texas. In the Maverick Basin, the West Nueces Formation and the McKnight Evaporite are equivalent to the Edwards (Figure 6-5) (Ewing, 2016). The McKnight Evaporite is a distinct evaporite unit found only in the Maverick Basin. These two are the first units overlying the Glen Rose Formation, but neither have been discovered to hold fresh or even slightly saline water.

As the McKnight Evaporite continued being deposited, there was greater subsidence in the basin, causing stratigraphic units to thicken. Simultaneously, the San Marcos Arch uplifted as a forebulge in response to the rapid subsidence of the basin (Ewing, 2016; Phelps, 2013).

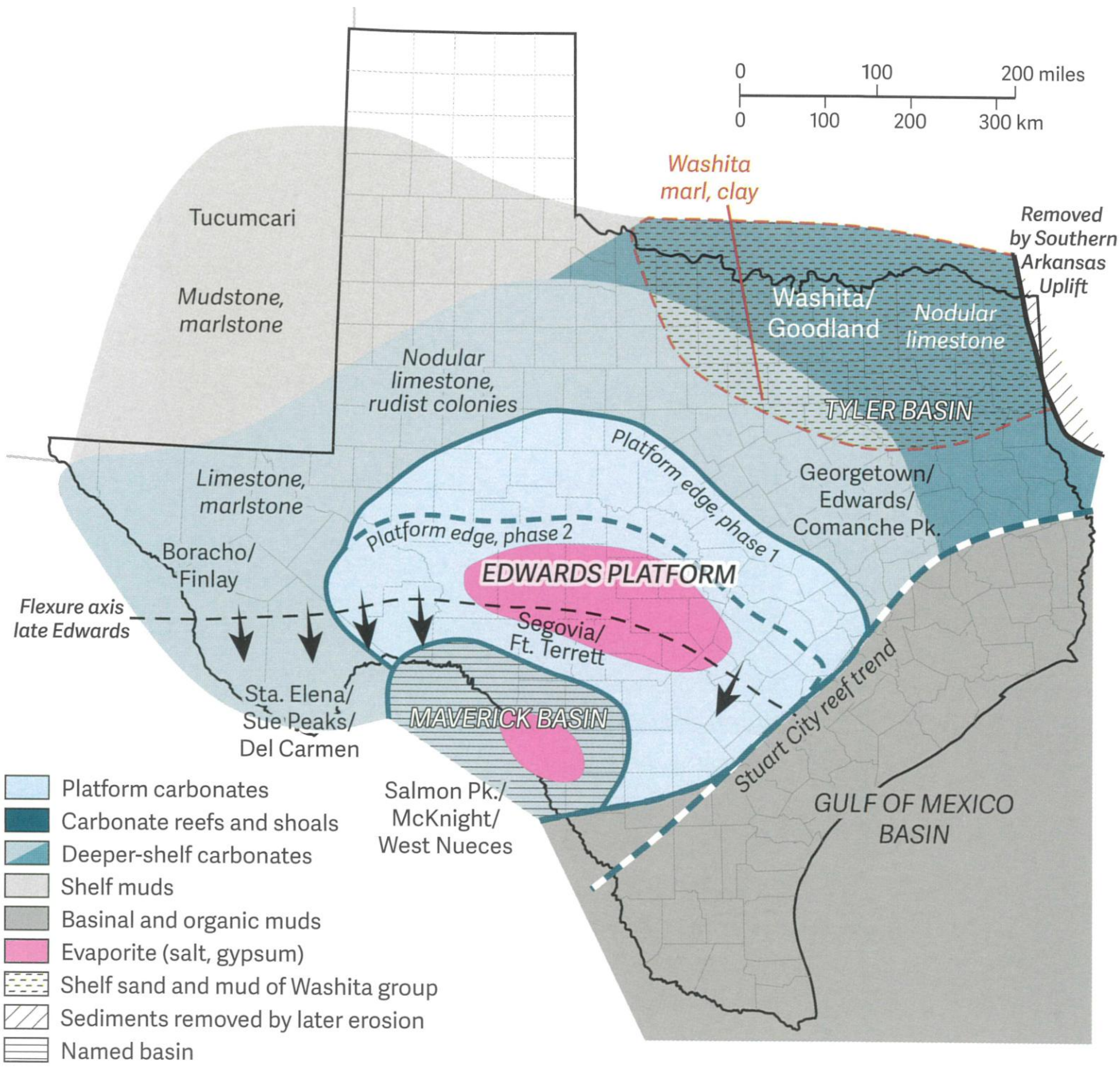


Figure 6-9. Middle Albian (Early Cretaceous Comanchean) environments and rocks; Edwards Group and equivalents. From Ewing (2016).

6.2.4 Late Cretaceous - Cenozoic

Post-Maverick Basin

Post-Maverick Basin grouping includes the Paleogene Midway Formation through the most recent Eocene sedimentary units in the Maverick Basin. Active in the Late Cretaceous, the Laramide Orogeny was a mountain building event that created northwest trending basement-cored, fault-bound features from northeastward compressional stresses originating from the southwestern margin of Laurasia (Ewing, 2016). Across the study area, structural features related to Laramide deformation are present, such as the Chittim Anticline and Zavala Syncline.

6.3 Methods

Integrating correlated geophysical well logs and seismic data can add insight for a subsurface geologic study. This approach is thoroughly examined in Kerans and Tinker (1997), as detailed in SEPM Short Course Notes 40. The methodology outlined in Kerans and Tinker (1997) provided a comprehensive framework for interpreting carbonate reservoir systems and emphasized the importance of integrating various data types to achieve a more accurate geologic model. By following the principles outlined in Kerans and Tinker (1997), this study enhances our understanding of the subsurface geology of the ETPA in Kinney County and adjacent areas.

Kerans and Tinker (1997) advocate for a detailed, step-by-step process that begins with the identification and correlation of well logs, followed by the integration of seismic data to establish a coherent and comprehensive geological model. Kerans and Tinker (1997) underscore the significance of understanding depositional environments, diagenetic alterations, and structural features to accurately interpret subsurface geology. This framework was instrumental in guiding seismic interpretation in this study in Kinney County.

The initial phase of this study involved the examination and correlation of existing structural surfaces with a comprehensive well log dataset. Subsequently, we tied specific well logs to the seismic data to determine the seismic signatures of various geologic contacts and formations. This step was crucial in identifying and mapping the subsurface features accurately in the seismic sections. By correlating well log data with seismic reflections, this study delineated key geological units and established spatial distributions within the study area.

Overall, this study's approach leveraged the methodologies outlined by Kerans and Tinker (1997) and tailored them to the specific geologic context of Kinney County. The integration of correlated well logs and seismic data provided a framework for understanding the subsurface geology and aided in a more accurate interpretation of groundwater resources in the region.

6.4 Data

6.4.1 Outcrop Data

This study utilized outcrop data from the Geologic Atlas of Texas (Waechter and others, 1977) to provide a detailed analysis of the surface geology in Kinney, western Uvalde, and eastern Val Verde counties. Waechter and others (1977) offer comprehensive geological mapping at a regional scale, helping to identify the distribution and characteristics of the Edwards and Trinity groups. The use of the geologic mapping done by Waechter and others (1977) ensures that this study is grounded in accurate and well-documented geologic information.

Lozo and Smith (1964) provide a series of stratigraphic sections through the Edwards Group in Kinney and Uvalde counties. The goal of Lozo and Smith (1964) was to provide a regional stratigraphic synthesis to clarify stratigraphic nomenclature. The composite sections presented in Lozo and Smith (1964) detail over 700 feet of Edwards Group strata and is some of the most comprehensive work done on Edwards Group outcrop.

6.4.2 Subsurface Structure Data

Alexander (2014) describes the basement architecture and structural style of the northern Maverick Basin, included in the study area. Alexander (2014) is primarily based on seismic data and literature in southwest Kinney County and northern Maverick County. The analysis of regional Paleozoic structural trends outlined in Alexander (2014) was very helpful in understanding the seismic lines chosen for this study.

6.4.3 Previous Groundwater Investigations

Green and others (2006) conducted a comprehensive evaluation of groundwater resources in Kinney and Uvalde counties, focusing on the dynamics of recharge, discharge, and aquifer storage within the Edwards Aquifer (study area in Figure 6-10). Bennett and Sayre (1962) and Green and others (2006) highlight the importance of understanding regional hydrology with respect to water management and the growing demand for groundwater in the area. These reports, and the subsequent initiation of the BRACS program in 2009, indicate the expanding focus by the State of Texas on the evaluation of groundwater resources and the integration of technical information necessary for the continued development and utilization of groundwater throughout the state.

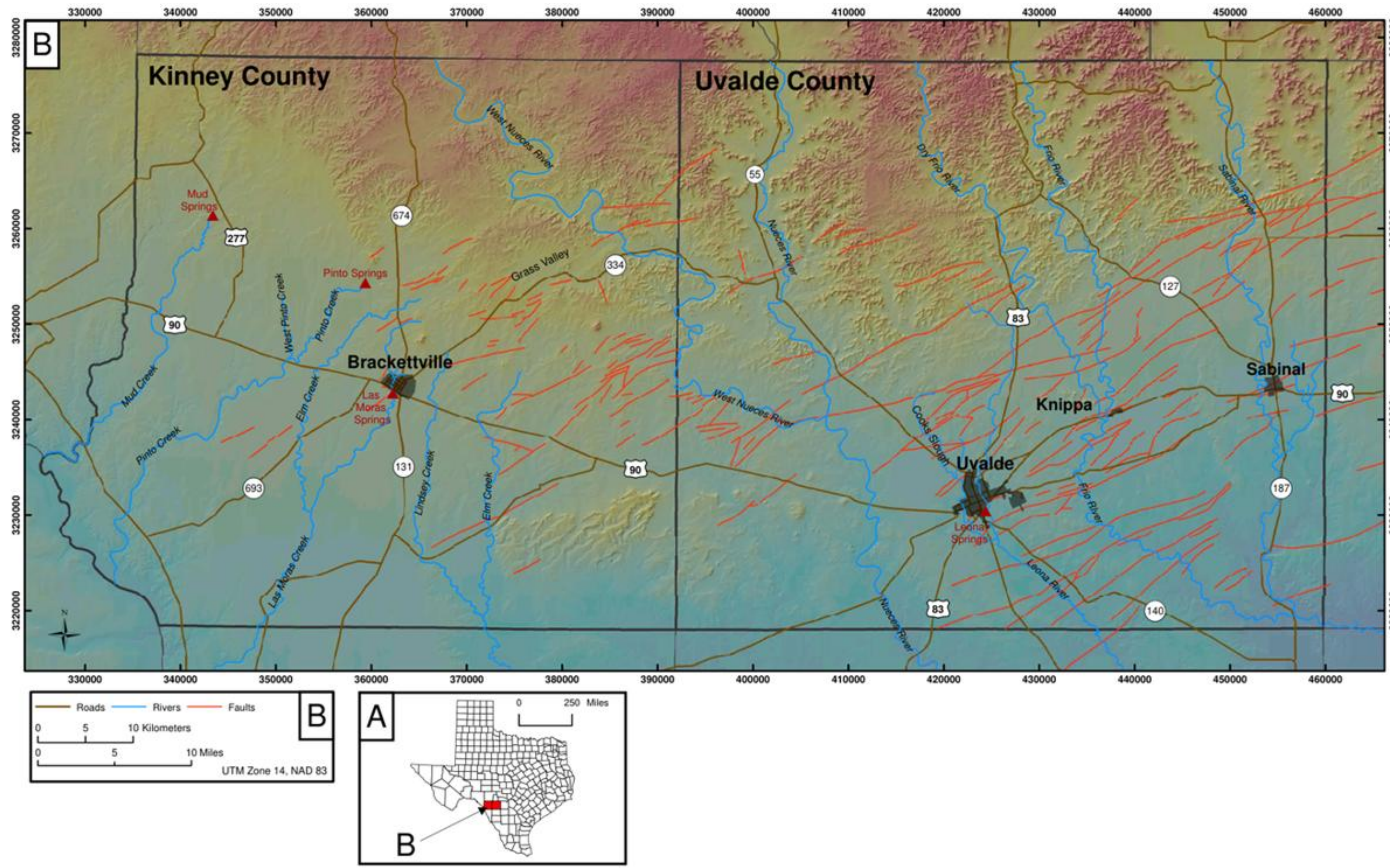


Figure 6-10. Map of Green and others (2006) study area.

6.4.4 Well Log Data

Well logs and formation tops used in this study were gathered as noted in Section 1.2, with the stratigraphic tops provided by BRACS. These logs and detailed stratigraphic information from wells throughout the study area were instrumental in identifying key subsurface formations, such as the Edwards and Trinity groups. The stratigraphic tops derived from these logs allowed for geologic correlations and a better understanding of the regional aquifer system.

6.4.5 Seismic Data

The seismic data utilized in this study were procured and subsequently reprocessed following the methods outlined in the preceding Sections. The data acquisition process involved obtaining three high-resolution seismic profiles within the study area, which were then subjected to advanced reprocessing techniques to enhance signal clarity and improve subsurface imaging. These techniques included noise attenuation, velocity modeling, and depth conversion, all designed to refine the interpretation of key geologic structures and stratigraphic features. This reprocessed seismic data provided insights into the subsurface framework and helped to correlate well log data with seismic reflections across the study area.

6.4.6 Water Well Data

This study utilized data from the Groundwater Database and the Submitted Driller's Report database, that, in combination with geologic surfaces provided by the BRACS program, allowed for the integration of well information, water levels, and formation tops, enabling an analysis of the regional aquifer system.

6.4.7 Groundwater Resource Evaluation

The Edwards-Trinity (Plateau) Aquifer (ETPA) is a major aquifer extending across most of the southwestern part of the State. The primary water bearing units are the carbonates of the Edwards Group and the underlying sands and carbonates of the Trinity Group and Cow Creek Formation. The ETPA as a whole has been extensively studied due to its significance in Kinney and Uvalde counties. The carbonate units in the upper part of the ETPA (the Glen Rose and overlying Edwards Formations) are better understood than the lower part of the aquifer.

Basemap

The basemap of the study area in Kinney County (Figure 6-11) provides a geographic reference for understanding the region's geology and groundwater resources provided in subsequent figures. It includes key features such as the boundaries of Kinney County, major roads, and water bodies, offering a clear spatial context for the analysis.

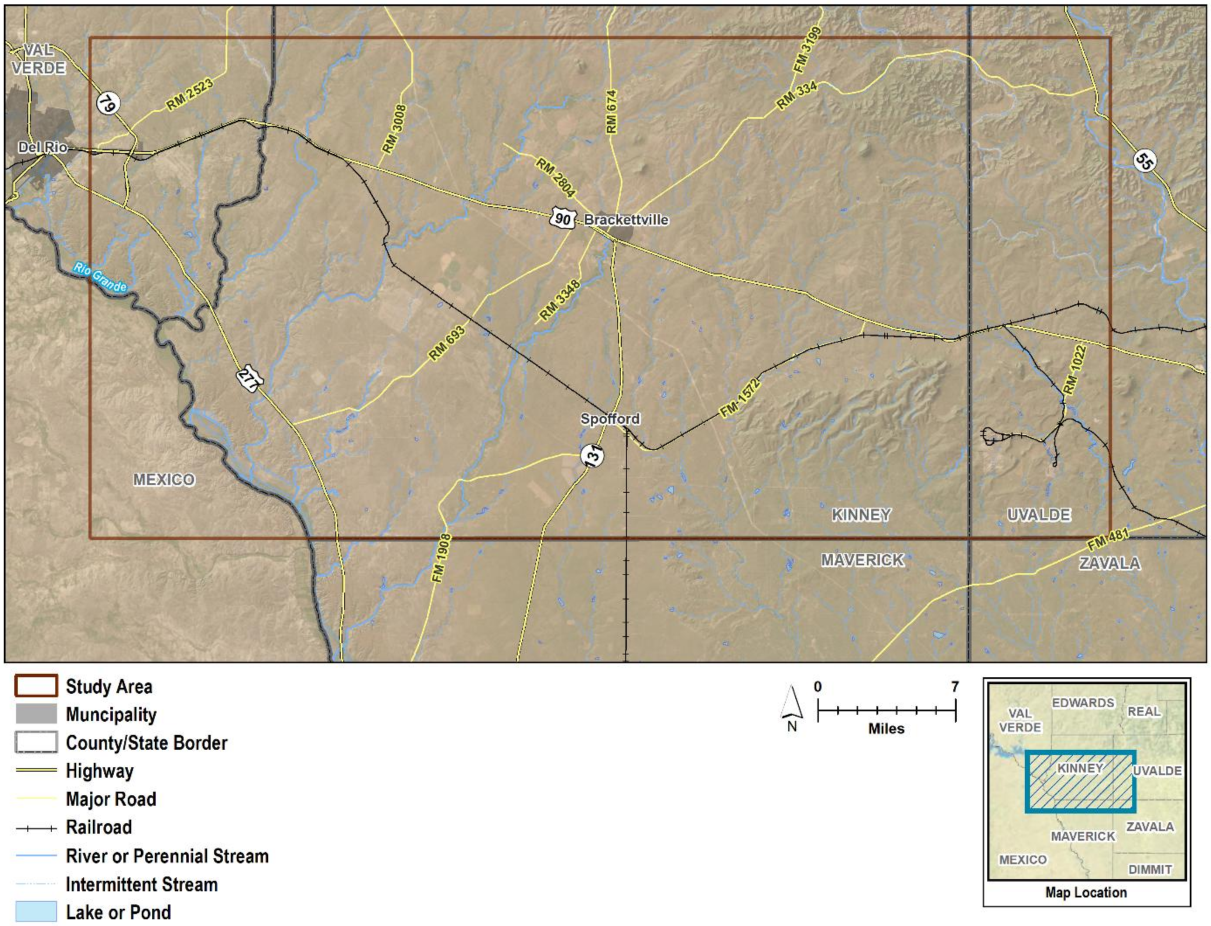


Figure 6-11. Basemap of study area.

Aquifer Map

The aquifer map of the study area in Kinney County illustrates the spatial extent and boundaries of two key aquifers: the Edwards (Balcones Fault Zone) Aquifer and the ETPA (Figure 6-12). The Edwards (Balcones Fault Zone) Aquifer is characterized by its faulted, karstic nature, with flow heavily influenced by fractures and faults, especially within the Balcones Fault Zone. This aquifer is highlighted in the eastern portion of the map. The ETPA, located to the west and northwest, provides groundwater over a broader region with less faulting in outcrop.

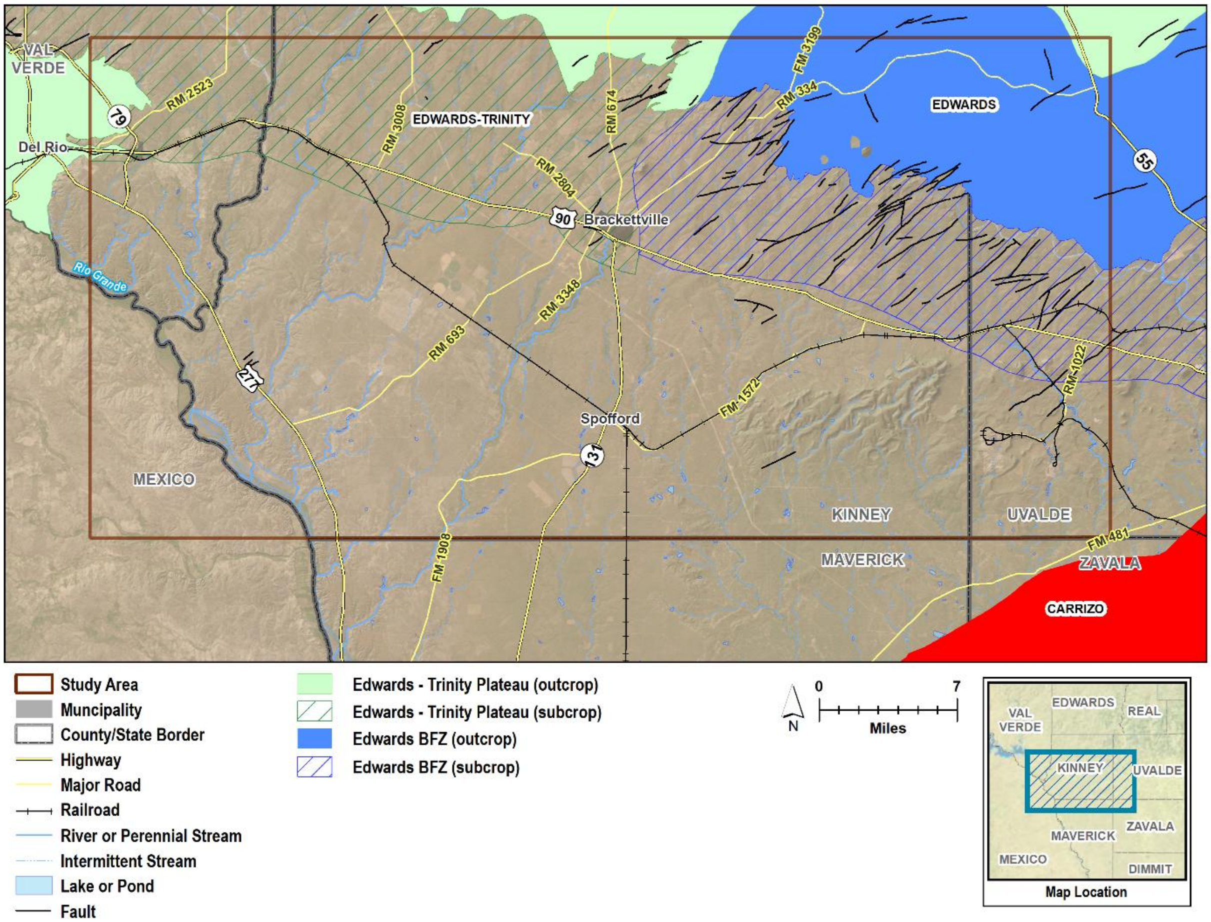


Figure 6-12. Major aquifers in the study area. Faults are part of the Balcones Fault Zone (BFZ).

Geologic Map with Springs

The geologic map of the study area in Kinney County integrates key geological formations with the locations of springs (Figure 6-13).

Overlaying the springs data on the geologic map allows for an understanding of how geological features influence spring locations. Many springs are found along fault lines or at the contact between different rock formations, especially where the Edwards (Balcones Fault Zone) Aquifer outcrops.

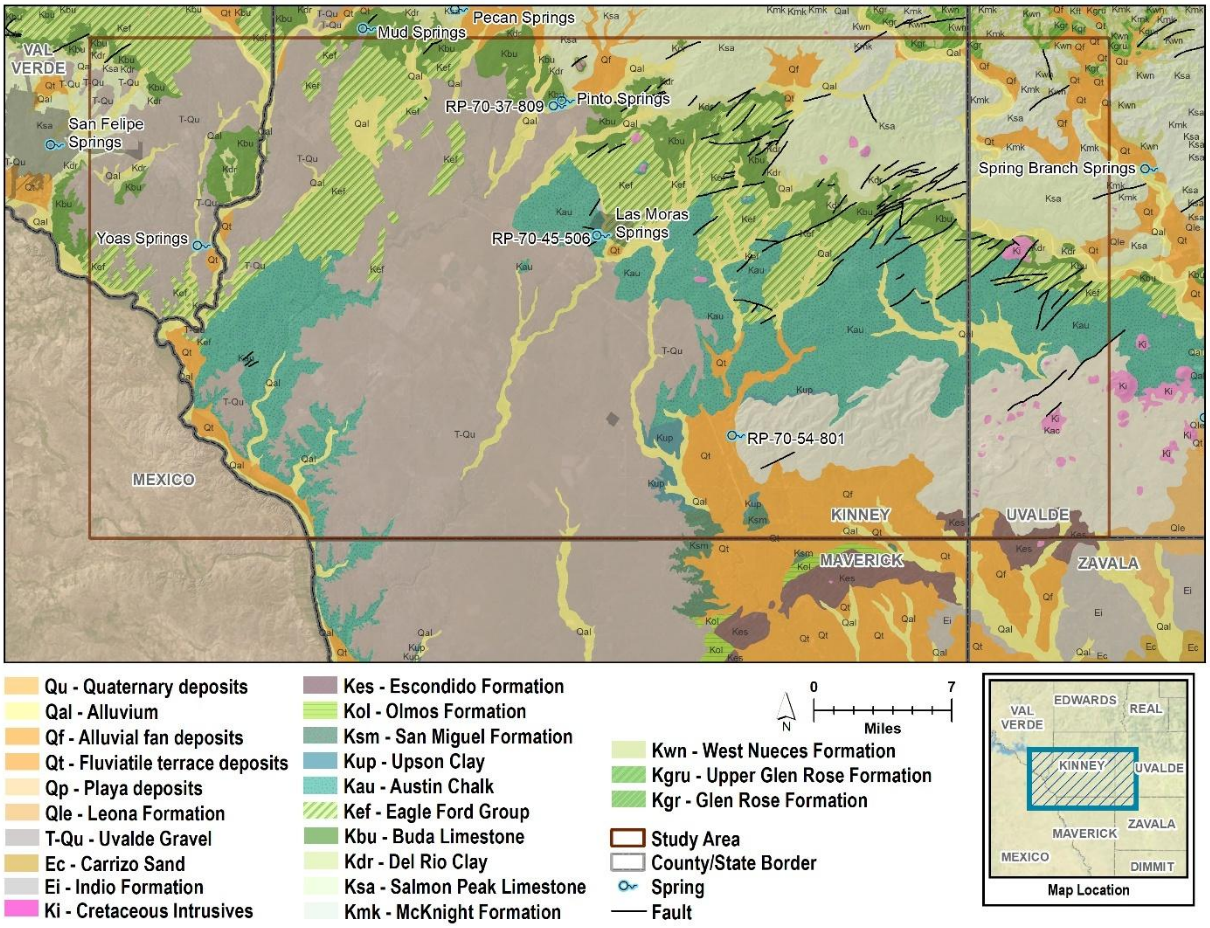


Figure 6-13. Geologic map of the study area with springs denoted and labeled. Faults are part of the Balcones Fault Zone. See Figure 6-12 for location of highways, roads, railroad, rivers, etc.

Edwards Group Well Depths

The majority of the wells queried as a part of this study within the Edwards Trinity (Plateau) Aquifer were Edwards (Balcones Fault Zone) Aquifer wells. This is unsurprising as the Edwards (Balcones Fault Zone) Aquifer is the shallowest unit of the Edwards Trinity (Plateau) Aquifer. However, the Edwards (Balcones Fault Zone) and the ETPA are considered separate major aquifers by the TWDB. Most water well records in the area simply refer to the aquifer intersected and screened as the Edwards.

Figure 6-14 is a map of the depth to the top of the Edwards Group with water wells symbolized by total depth. Water wells were sorted via bottom depth. Ideally, water wells are sorted into formation via screened intervals, but many wells did not record screen intervals in an accessible format. For wells that did have bottom depth and screen intervals, the wells were usually screened near the bottom depth, so bottom depth was used as a proxy for aquifer grouping. Additionally, the trend in total depths of wells shallower than the depth to the top of the Edwards Group is very similar to the structural trend of the top of the Edwards Group.

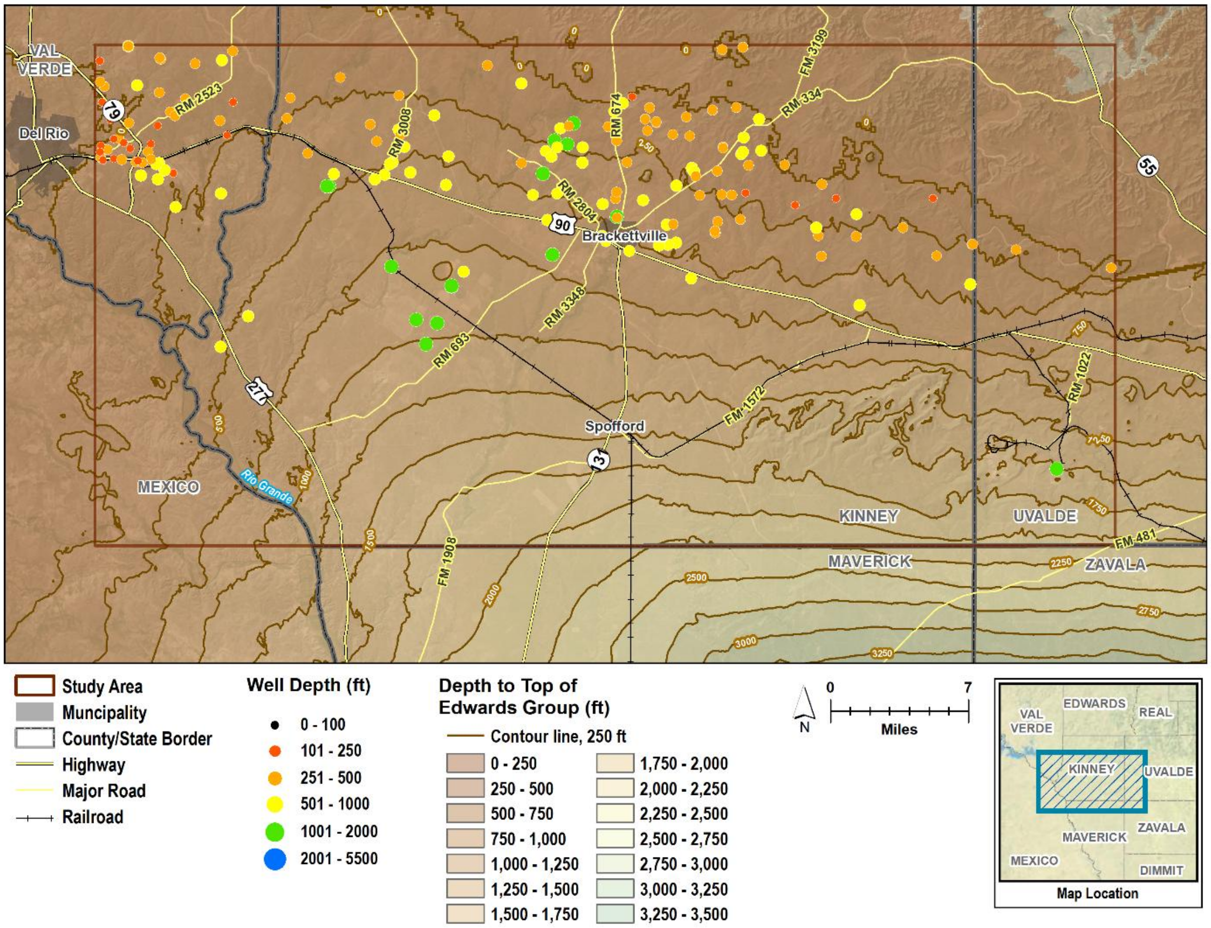


Figure 6-14. **Map of the top of the Edwards Group plotted with Edwards Group water wells symbolized by depth.**

Edwards Group Well Types

Figure 6-15 shows the top of the Edwards Group with water wells symbolized by well type. Most wells in the Edwards Group are domestic, irrigation, or stock wells. There are two public supply wells: one near Del Rio, TX, in the western part of the study area, and one near Brackettville, TX, in the central part of the study area.

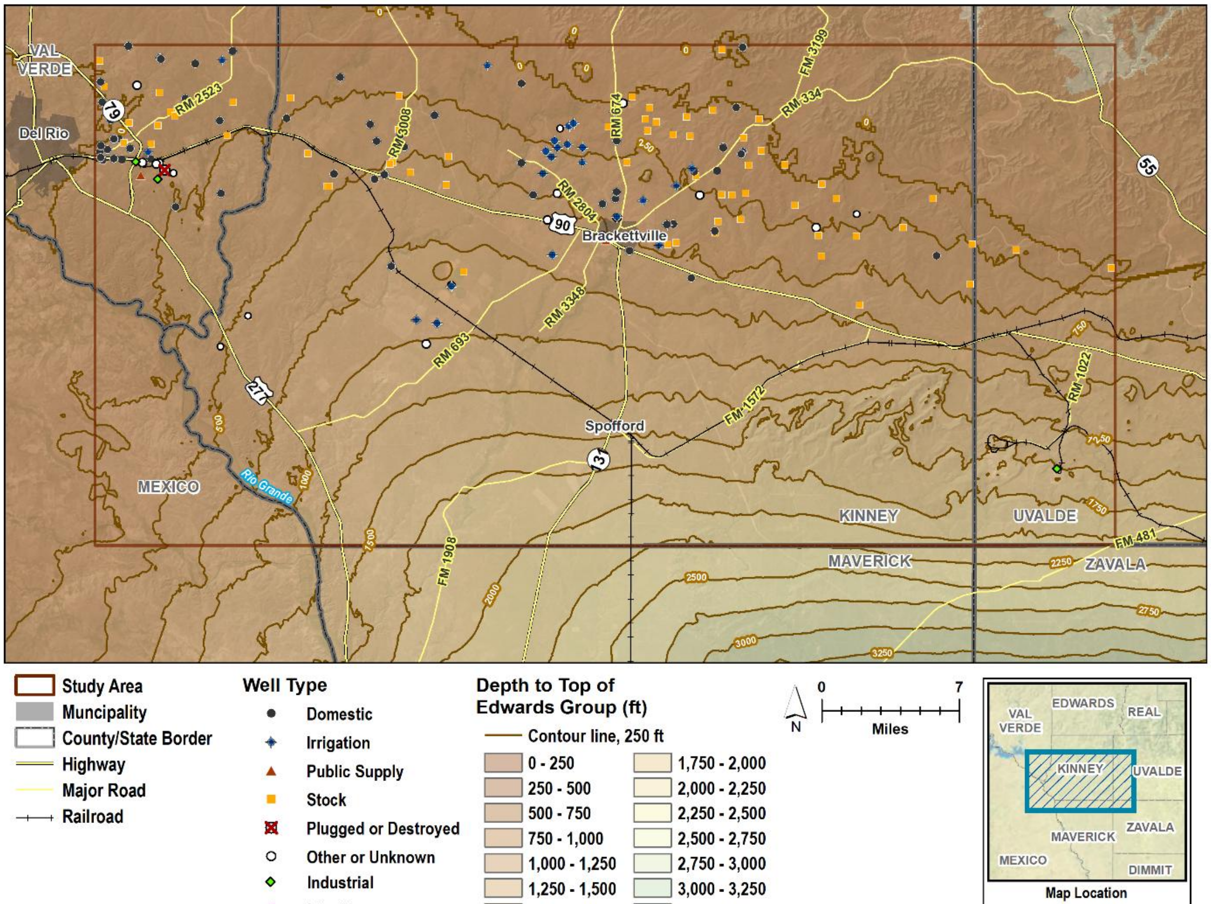


Figure 6-15. Map of the top of the Edwards Group plotted with Edwards Group water wells symbolized by type. Public water supply wells are located in Brackettville and Del Rio.

Edwards Group Water Levels

A contour map of groundwater elevations from the January-February of 2006 synoptic survey is illustrated in Figure 6-16 (Green and others, 2006). Groundwater elevations are decreasing to the south and east. Elevation contours also reflect the structural grain of the region and have the same trend as the Balcones faults. Groundwater elevations decrease from approximately 1,400 feet above mean sea level down to 800 feet above mean sea level near Sabinal, TX.

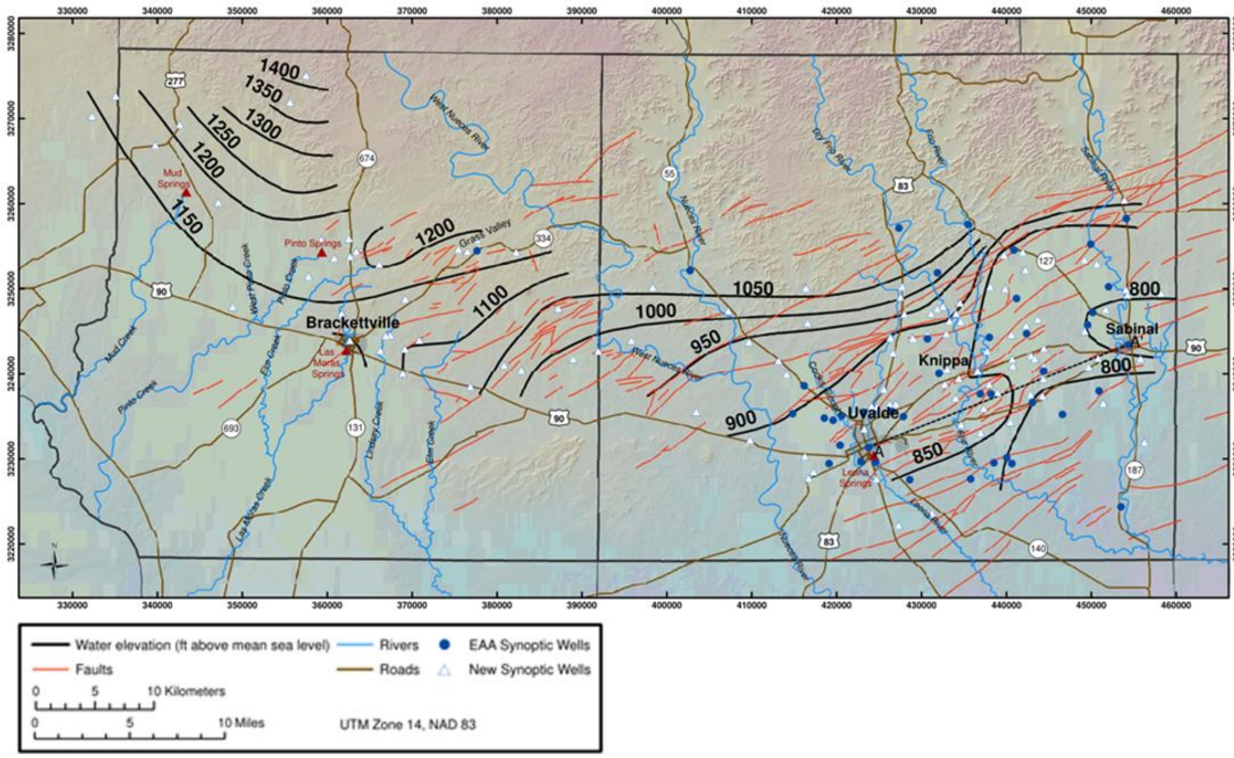


Figure 6-16. Map of Kinney and Uvalde Counties with groundwater elevation contours of the Edwards Aquifer from Green and others (2006).

Edwards Group Well Yields

Most Edwards Aquifer wells have reported yields less than 50 gallons per minute (Figure 6-17). There are several notable wells that produce several hundred gallons per minute. Wells with higher yields seem to cluster where there are high total number of wells, but there does not seem to be a location constraint on these higher yield wells.

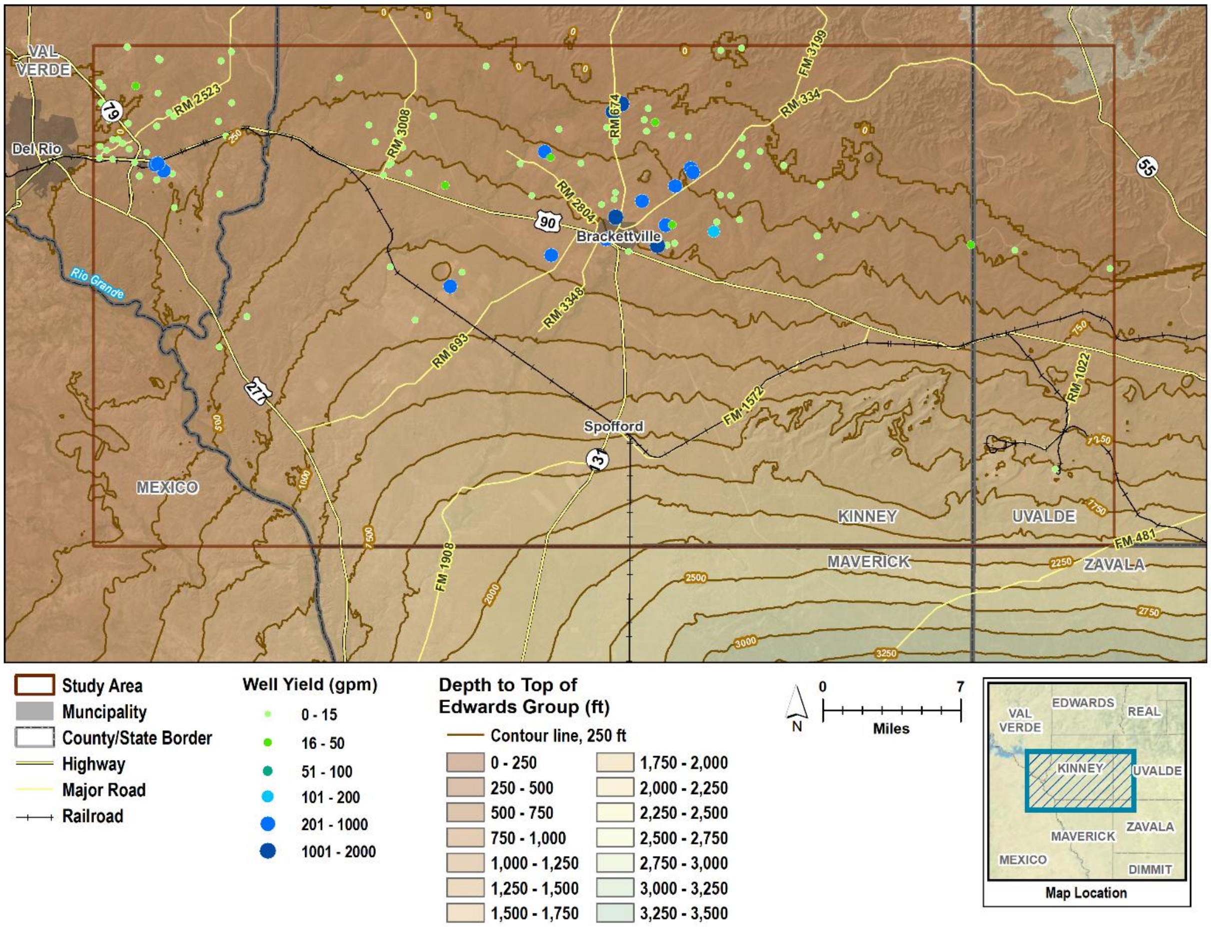


Figure 6-17. Map of the top of the Edwards Group plotted with Edwards Group water wells symbolized by yield. gpm = gallons per minute.

Edwards Group Water Quality

Figure 6-18 is a map from Green and others (2006) that shows water quality for Edwards Aquifer Wells from Kinney County to Medina County. This map from Green and others (2006) shows water quality becoming more brackish south of Highway 90.

From Green and Others (2006):

"Inspection of the hydrochemical data for Edwards Aquifer wells reveals and corroborates spatial trends observed in several previous investigations. Bennett and Sayre (1962) and Welder and Reeves (1962) noted the general decrease in water quality of Edwards wells to the south and southwest within Kinney County and to the south in Uvalde County. The occurrence of degraded water quality, as indicated by increased TDS values to the south of U.S. Highway 90 in Kinney County and south of the City of Uvalde in Uvalde County, is apparent from the data (Figure 5.3.1) and coincides well with the historical placement of the saline-water line in this region.

Wells to the south of this boundary are high in TDS (>1000 ppm) and sulfate and, as a result, most water wells south of U.S. Highway 90 in Kinney County are completed in the Austin Chalk (Figure 5.3.1). From the data in the Bennett and Sayre (1962) report, the Austin Chalk fresh waters have a slightly higher average TDS content and significantly higher chloride content than Edwards Aquifer fresh waters in Kinney County; the data shown in Figure 5.3.1 are consistent with this observation. Also notable in Figure 5.3.1 are wells (YP-69-36-301 and TD-69-31-801) in northern Uvalde and Medina counties that are identified (by the Texas Water Development Board groundwater database) as completed in Edwards Aquifer rocks but that have high TDS relative to other Edwards Aquifer wells nearby. When combined with data for the concentration of sulfate (Figure 5.3.2) in these wells, they (along with well TD-69-30-601) appear to be drawing water from the Trinity Aquifer and not the Edwards Aquifer. The characteristically higher sulfate and chloride content of Trinity Aquifer water is observed in these wells."

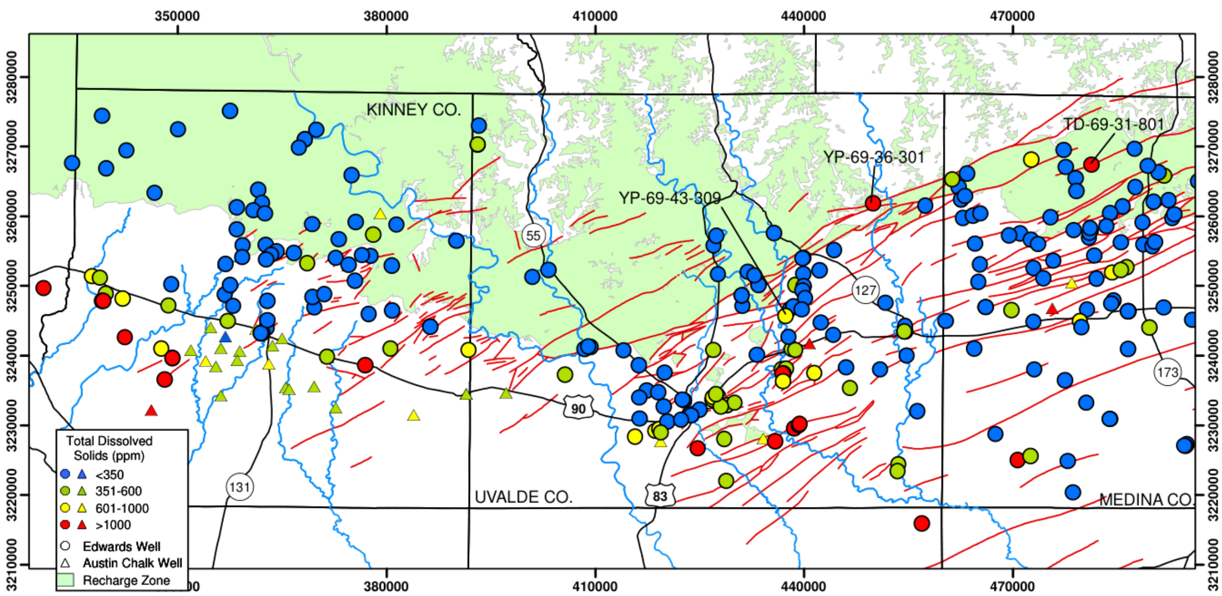


Figure 6-18. Map of the Kinney and Uvalde Counties with water quality of the Edwards Aquifer from Green and others (2006); ppm = parts per million.

Upper Glen Rose Well Depths

The remainder of the wells that are not completed in the Edwards Group or shallower formations are completed in the Upper Glen Rose Formation. The Upper Glen Rose Formation is the uppermost unit of the Trinity Group.

Figure 6-19 is a map of the depth to the top of the Glen Rose Formation with water wells symbolized by total depth. Consistent with symbology presented in Figure 6-14, water wells were sorted via bottom depth and the structural trend of the Upper Glen Rose is consistent with the total depth of the wells.

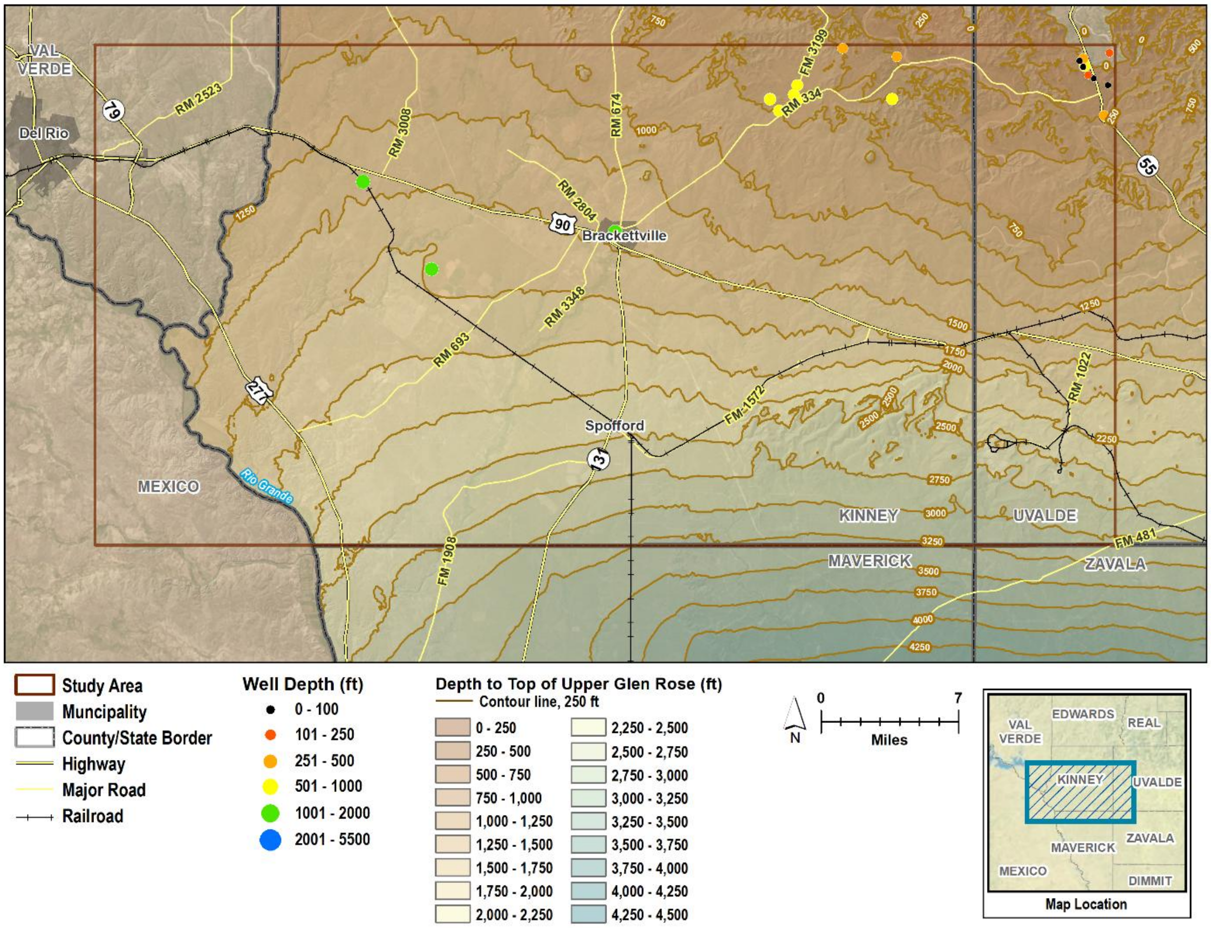


Figure 6-19. **Map of the top of the Upper Glen Rose plotted with Upper Glen Rose water wells symbolized by depth.**

Upper Glen Rose Well Types

Figure 6-20 shows the top of the Upper Glen Rose Formation with wells symbolized by well type. Most wells in the Upper Glen Rose Formation are domestic wells or classified as other. There is one public supply well in Brackettville, TX.

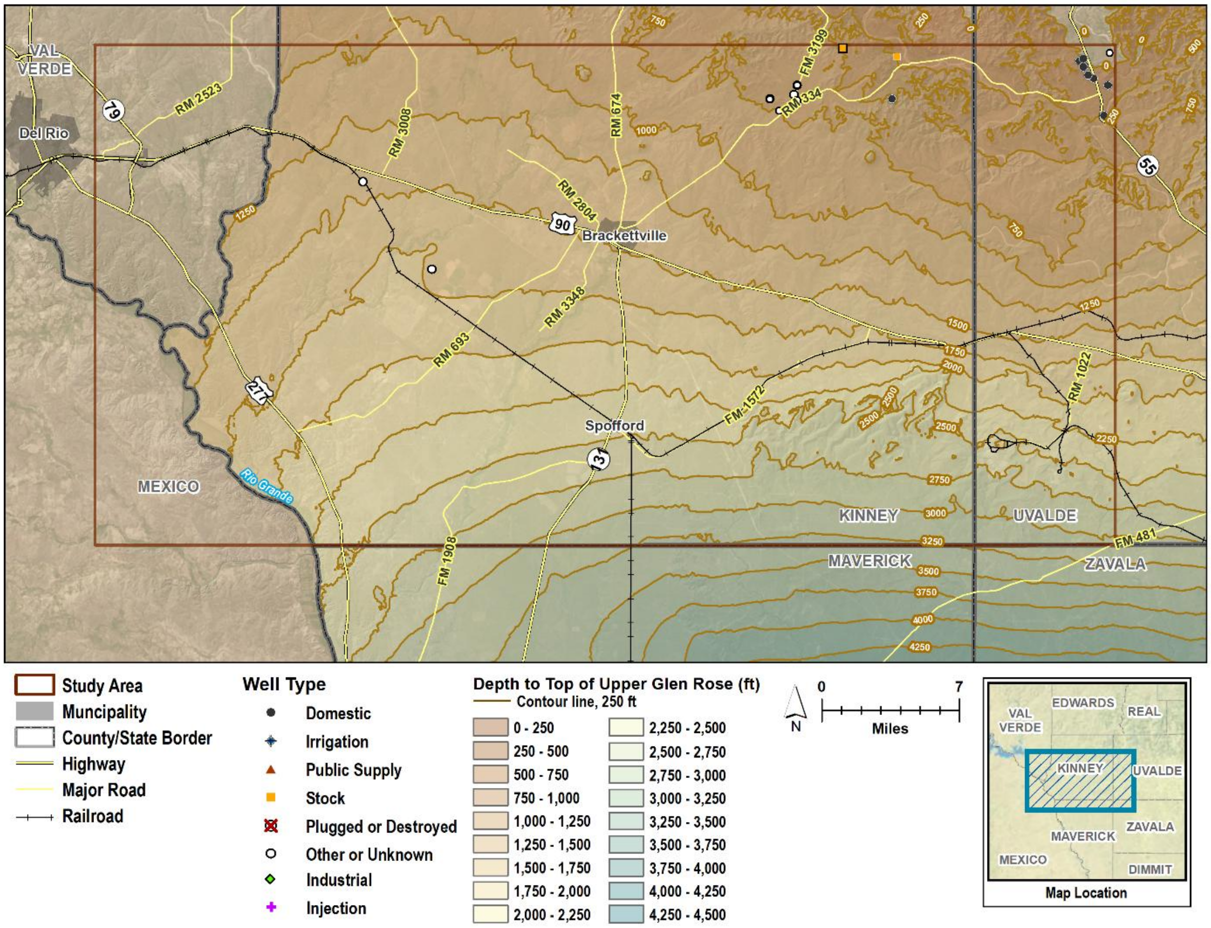


Figure 6-20. **Map of the top of the Upper Glen Rose plotted with Upper Glen Rose water wells symbolized by type. There is one public water supply well in Brackettville.**

Upper Glen Rose Water Levels

Figure 6-21 shows the top of the Upper Glen Rose Formation with wells symbolized by water level.

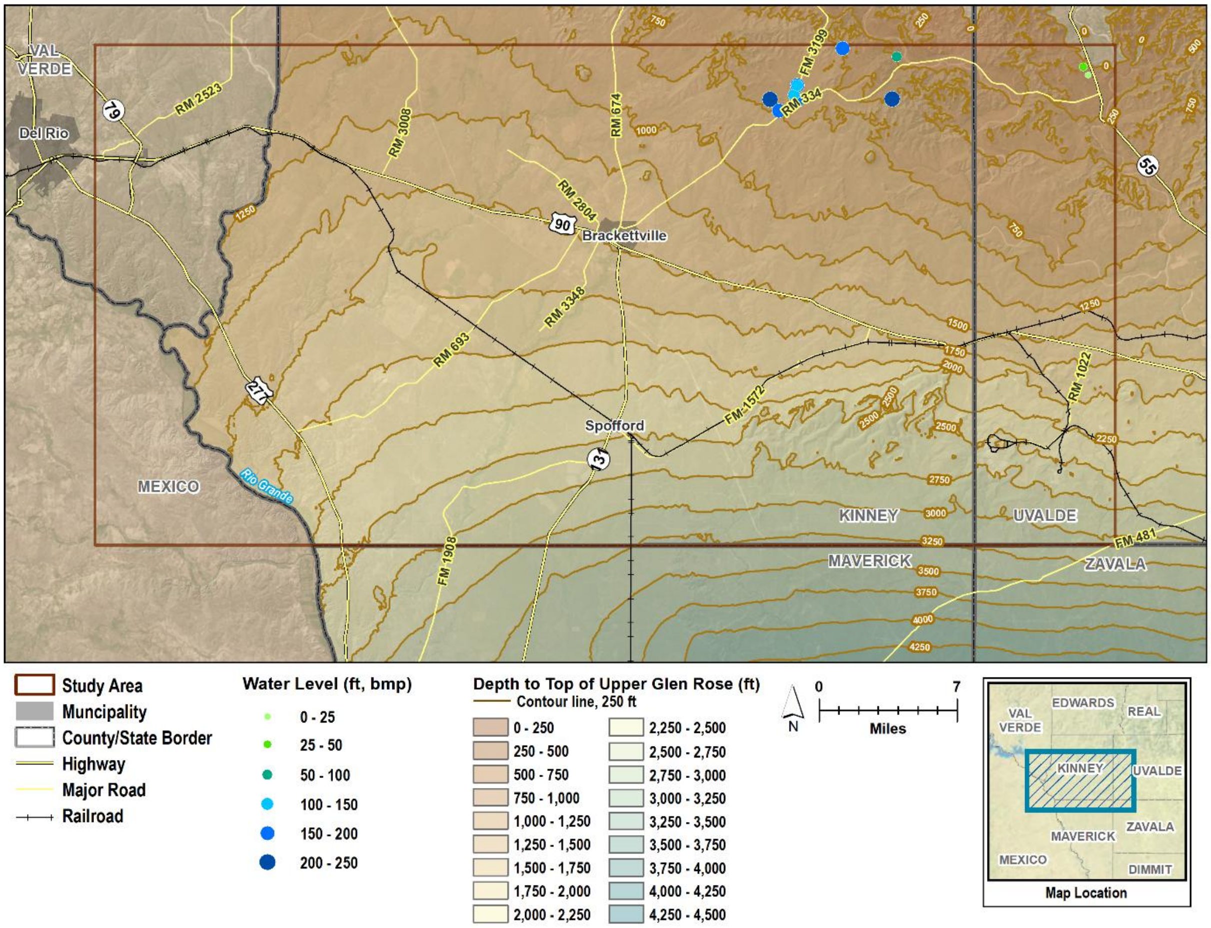


Figure 6-21. Map of the top of the Upper Glen Rose plotted with Upper Glen Rose water wells symbolized by water level; bmp = below measuring point.

Upper Glen Rose Well Yields

Most Glen Rose Formation wells have reported yields of less than 50 gallons per minute (Figure 6-22). There is one well that does several hundred gallons per minute. This well is located in Brackettville, TX and is a public supply well. Thus, the higher yield may be a result of the pump size and delivery requirements rather than location or geology.

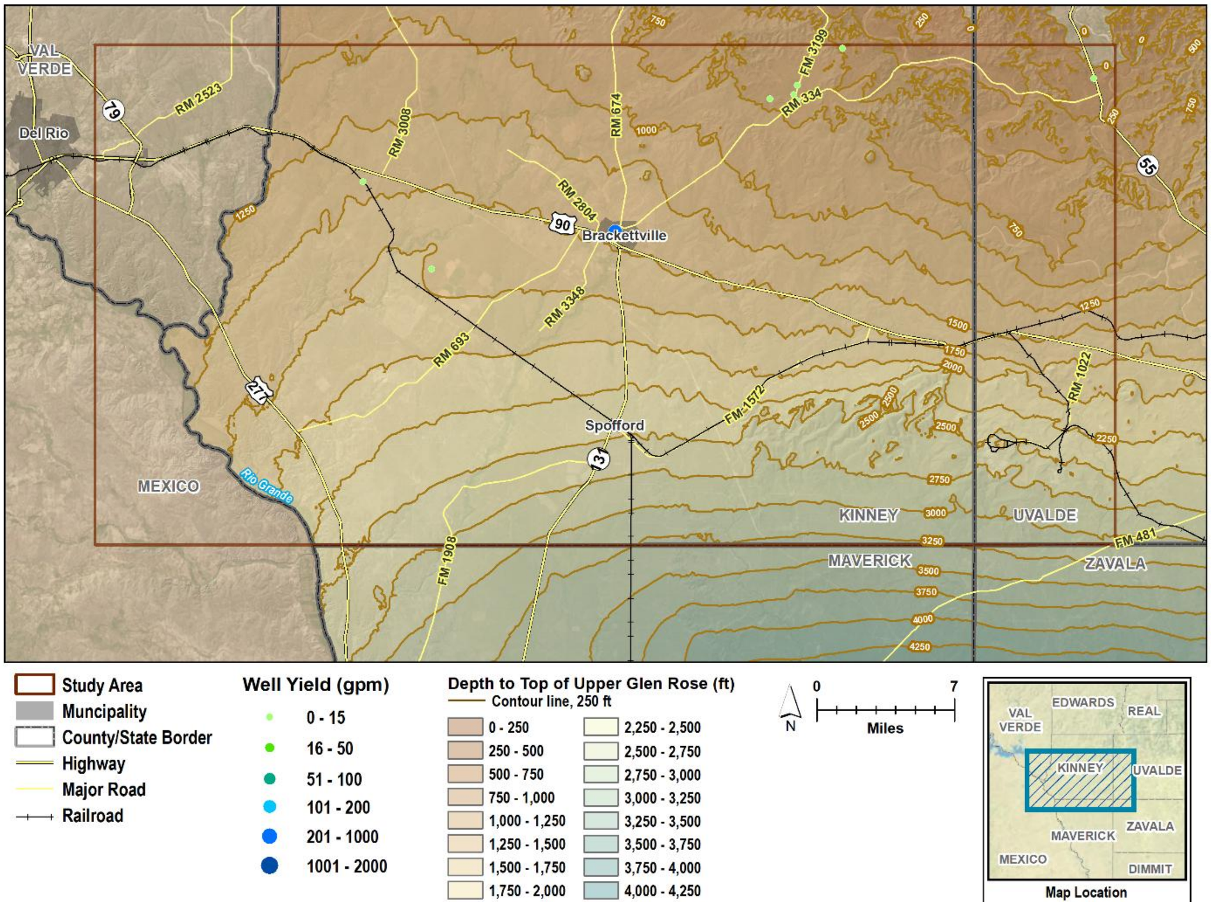


Figure 6-22. **Map of the top of the Upper Glen Rose plotted with Upper Glen Rose water wells symbolized by yield; gpm = gallons per minute.**

Upper Glen Rose Water Quality

A single well in the Upper Glen Rose near the eastern side of Uvalde County reports a Total Dissolved Solids (TDS) content of 2,777 milligrams per liter (mg/L) (Robinson and others, 2022). General Edwards water quality, shown in Figure 6-18, shows a decrease in water quality to the south and southeast, trending toward TDS in excess of 1,000 mg/L toward southern Kinney County.

6.4.8 Outcrop-Well Log-Seismic Data Analysis

Outcrop Data

The most comprehensive outcrop source is a section through the formations of the Edwards Group described by Lozo and Smith (1964). Since the Edwards (Balcones Fault Zone) Aquifer contains the most water wells in this study, it is fitting to discuss the section here. Lozo and Smith (1964) provide type sections for the West Nueces, McKnight, and Salmon Peak formations of the Edwards Group. Together, the West Nueces, McKnight, and Salmon Peak formations comprise the Edwards Aquifer. The map of the locations of the type sections are presented in Figure 6-23, with the type sections presented in Figures 6-24, 6-25, 6-26, and 6-27. All of these formations have been referenced in Figure 6-1.

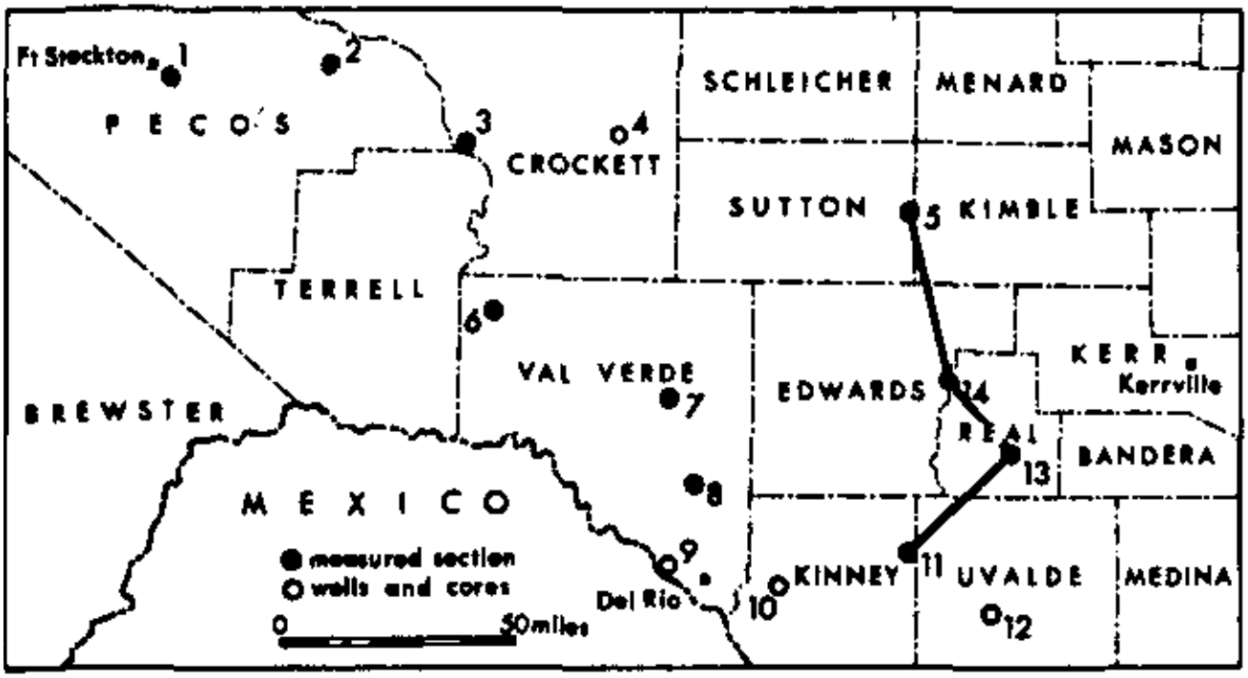


Figure 6-23. Map of the Edwards Group type sections. Section 11 is the West Nueces River Composite from Lozo and Smith (1964).

The West Nueces Formation is the lowermost formation of the Edwards Group. The type section, as described by Lozo and Smith (1964), is presented in Figure 6-24.

From Lozo and Smith (1964):

"The type section is about 145 feet thick and is in sharp concordant contact with the underlying Glen Rose. The lower 60 feet is the regional basal transgressive unit nodular, shell fragment wackestone with common oysters and other molluscan fossils — generally called Comanche Peak (cf. Bennett and Sayre, 1962). The overlying 80-85 feet of massive bedded, miliolid, pellet, shell fragment wackestones to mudstones with some grainstones is the so-called Edwards where the overlying flaggy unit is referred to as the Kiamichi (Welder and Reeves, 1962) Others have referred informally to the upper West Nueces unit as the "first zone of the Edwards," to the flaggy unit as the "second zone," etc. (Bennett and Sayre, 1962). Southerly from the type area, the West Nueces can be defined objectively over most of southern Uvalde and Kinney Counties by recognition of the basal nodular wackestone beds... Beyond this limit in the subsurface the basal contact is indefinite within a transitional interval, and the projected position of the West Nueces-Glen Rose contact over most of the Maverick basin is conjectural. In practice, the area of application is coincident with the limits of

the overlying McKnight Formation."

Based on the type section and accompanying data from Lozo and Smith (1964), the West Nueces formation is generally mud-dominated, with not many ideal facies to target. Outcrop data reduce the desire to target.

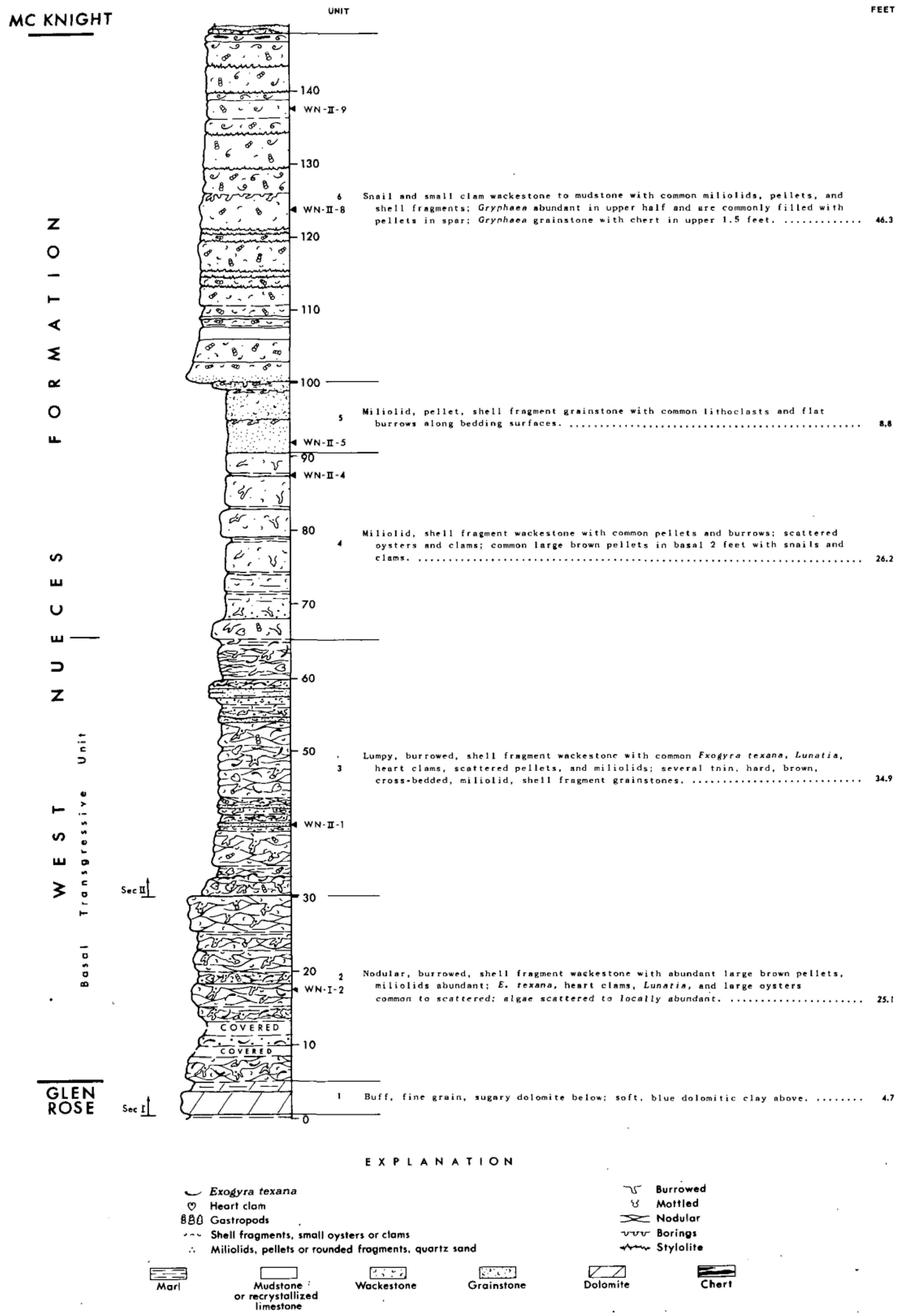


Figure 6-24. West Nueces Formation type section from Lozo and Smith (1964). Location indicated by measured section 11 in Figure 6-23.

The McKnight Formation is the middle formation of the Edwards Group. The type section, as described by Lozo and Smith (1964), is presented in Figure 6-25.

From Lozo and Smith (1964):

"The maximum outcrop thickness of the McKnight is about 145 feet, and the section is divisible into lower and upper thin-bedded limestone units separated by a 25-foot section of black, laminated, fissile, clayey lime mudstone beds. The 70-foot lower section of brown shell fragment and pellet grainstones with thin chert layers is overlain by lighter mudstones with solutioned zones and collapse breccia. The 55-foot upper unit, as exposed at Chalk Bluff, is mostly thin-bedded mudstone; it also contains thin chert layers, solution zones, and another collapse breccia bed near the middle. The solution zones and breccia beds represent evaporite beds in the subsurface."

Based on the type section and accompanying data from Lozo and Smith (1964), the McKnight formation is generally mudstone and evaporites, with not many ideal facies to target. Outcrop data reduces the desire to target.

The Salmon Peak Formation is the uppermost formation of the Edwards Group. The type section, as described by Lozo and Smith (1964), is presented in Figures 6-26 and 6-27.

From Lozo and Smith (1964):

"The type section is about 380 feet thick and in the type area of Uvalde and Kinney counties is divisible into two distinct parts: a lower, 305-foot unit of thick-bedded, white, globigerinid lime mudstone with large, irregular masses of chert in the upper half, and an upper, 75-foot unit of worn shell fragment grainstone cross-bedded near the top and with scattered caprinid fragments throughout (Figure 12). The upper grainstone unit, a tongue of Devils River lithofacies, is replaced southward by the mudstone. At the outcrop, the Salmon Peak disconformably overlies the McKnight, and the basal bed is conglomeratic with pholad-bored pieces of the thin-bedded, fecal pellet McKnight grainstone in a lime mudstone matrix. The upper contact is likewise an emersion surface underlying the lower Del Rio (West Prong beds of Greenwood, 1956)… The Salmon Peak Formation is coextensive with the McKnight on both sides of the Rio Grande and is present in similar facies over the entire Maverick basin."

Based on the type section and accompanying data from Lozo and Smith (1964), the Salmon Peak Formation, Lower Unit is mostly mudstone, with not many ideal facies to target. The Upper Unit of the Salmon Peak Formation, however, has an upper interval of about 75 feet of grainstones, which can even be cross-bedded. These facies are ideal for targeting a water well. Outcrop data increases the desire to target.

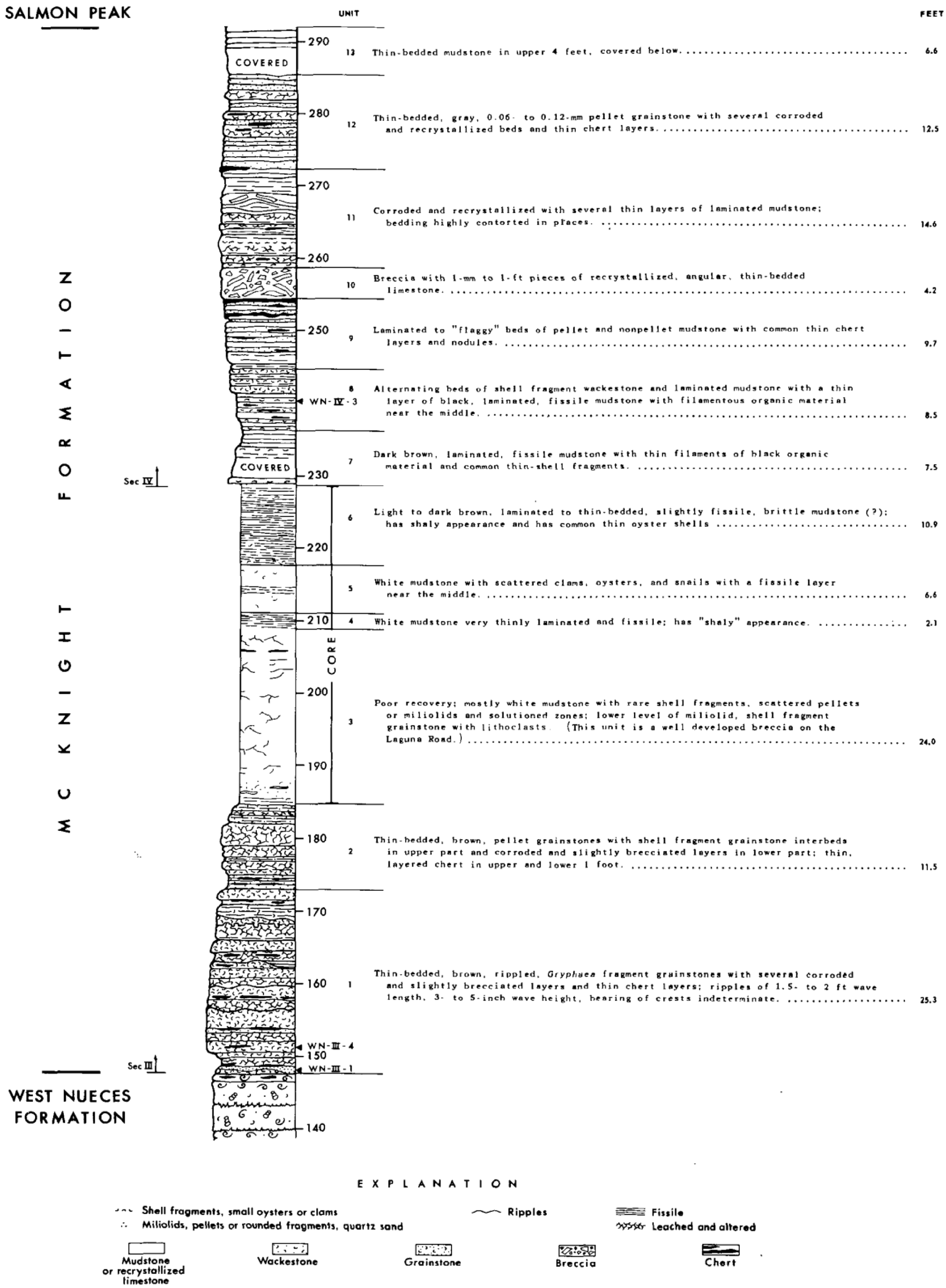


Figure 6-25. McKnight Formation type section from Lozo and Smith (1964). Location indicated by measured section 11 in Figure 6-23.

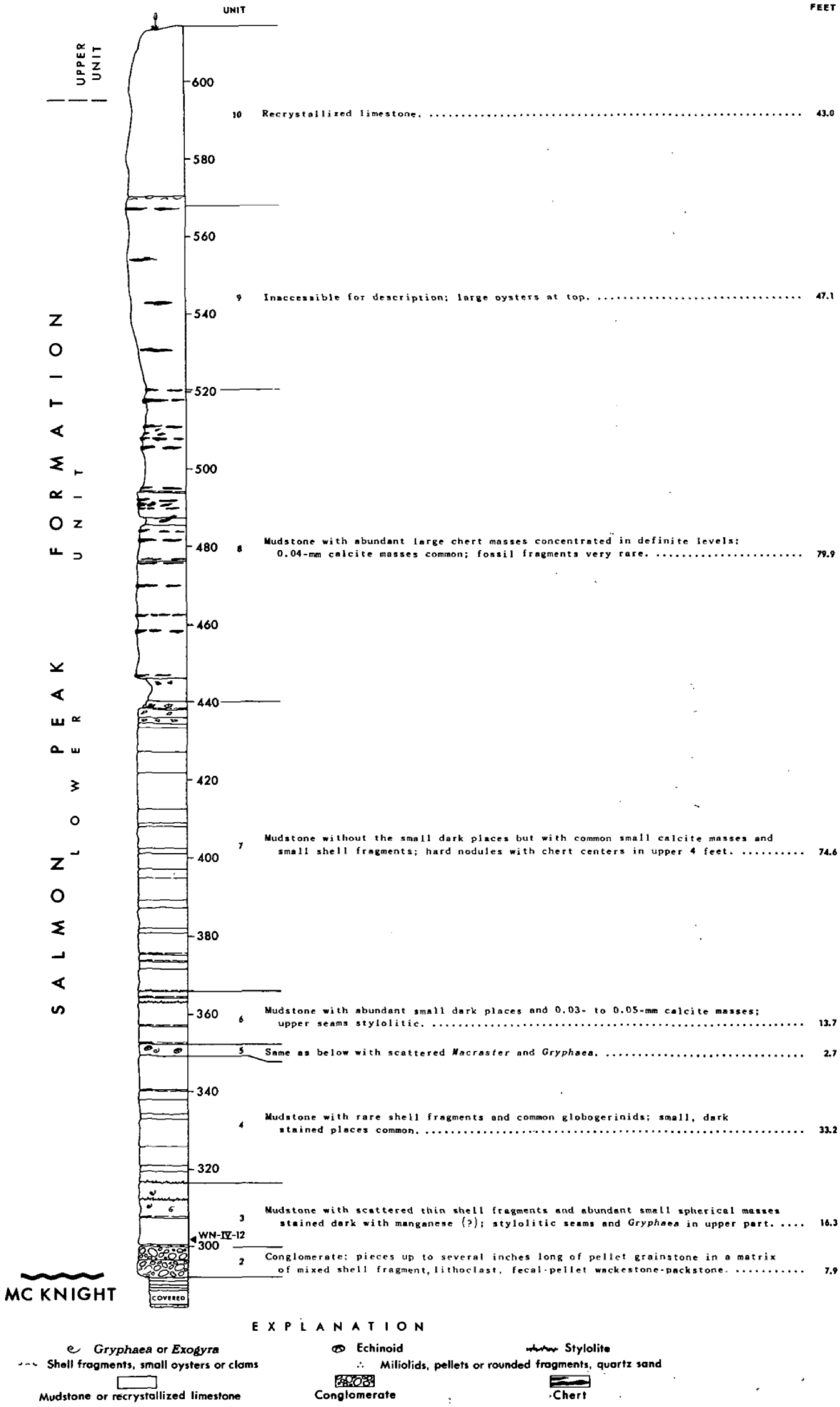


Figure 6-26. **Salmon Peak Formation, lower unit type section from Lozo and Smith (1964). Location indicated by measured section 11 in Figure 6-23.**

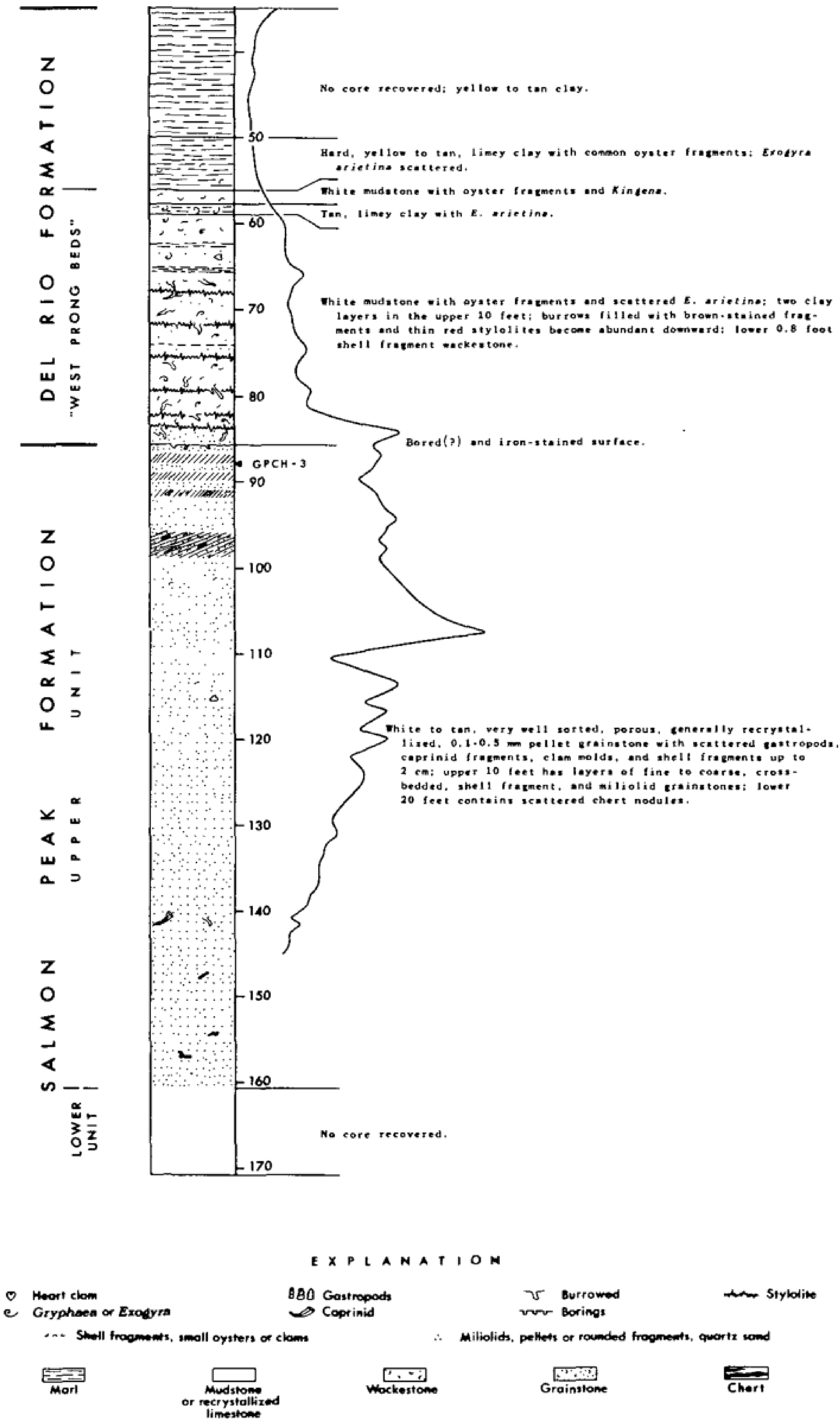


Figure 6-27. Salmon Peak Formation, upper unit type section from Lozo and Smith (1964). Location indicated by cored section 9 in Figure 6-23.

Based on the outcrop data, the best targets are the top 75-feet of the Salmon Peak Formation, which is comprised of sorted and porous grainstones. Facies within formations vary laterally, and Lozo and Smith (1964) present some evidence for aerial extents of different facies belts within the Edwards Group. Even so, some caution must be taken in extrapolating correlations from outcrop into the subsurface, as facies changed should be expected. Additional core data closer to the target well is always preferable.

Well Log Data

Two main sources of data for well logs were utilized for this study. The first well log dataset was comprised of well logs from a variety of publicly available and paid subscription-based sources and is discussed in Section 1. The other well log dataset utilized by this study is from Lozo and Smith (1964) described previously. Next to composite type sections, Lozo and Smith (1964) present a resistivity log to illustrate the resistivity profile of each facies change. Sections are presented for each data source and discussed in this subsection.

Three well logs compiled in the Section 1 dataset are presented in Figure 6-28. Stratigraphic tops are shown for each formation of the Edwards Group. The Edwards Group, in Figure 6-28, is locally approximately 900 feet thick compared to approximately 700 feet thick in measured section 11 from Lozo and Smith (1964), presented in Figure 6-29.

From outcrop and literature, it is known that the McKnight is not a very desirable groundwater target. This leaves the Salmon Peak and the West Nueces as targets. Because the two units have basically the same gamma ray and resistivity curves, the target should be the thicker unit—in this case the Salmon Peak Formation—since the effective thickness would be greater. The other option is to screen both units.

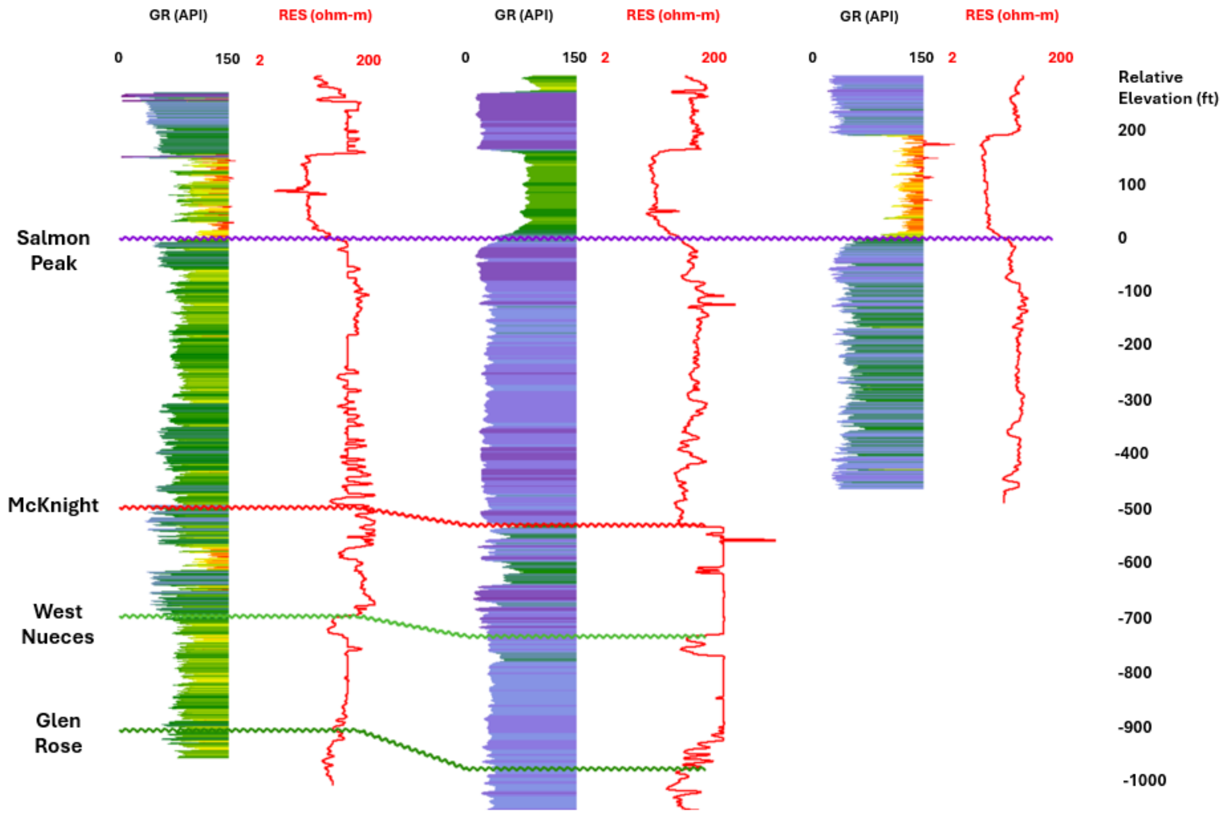


Figure 6-28. Cross section of geophysical logs nearby seismic lines, through the Edwards Group.

Lozo and Smith (1964) present their own resistivity log, one which corresponds to their facies much better. Figure 6-29 shows a cross section of the West Nueces composite section, along with a nearby core log in Val Verde County. The right side of the figure has a complete resistivity log. On this log, the most resistive part of the section is the top of the Salmon Peak, which fits nicely with their facies model.

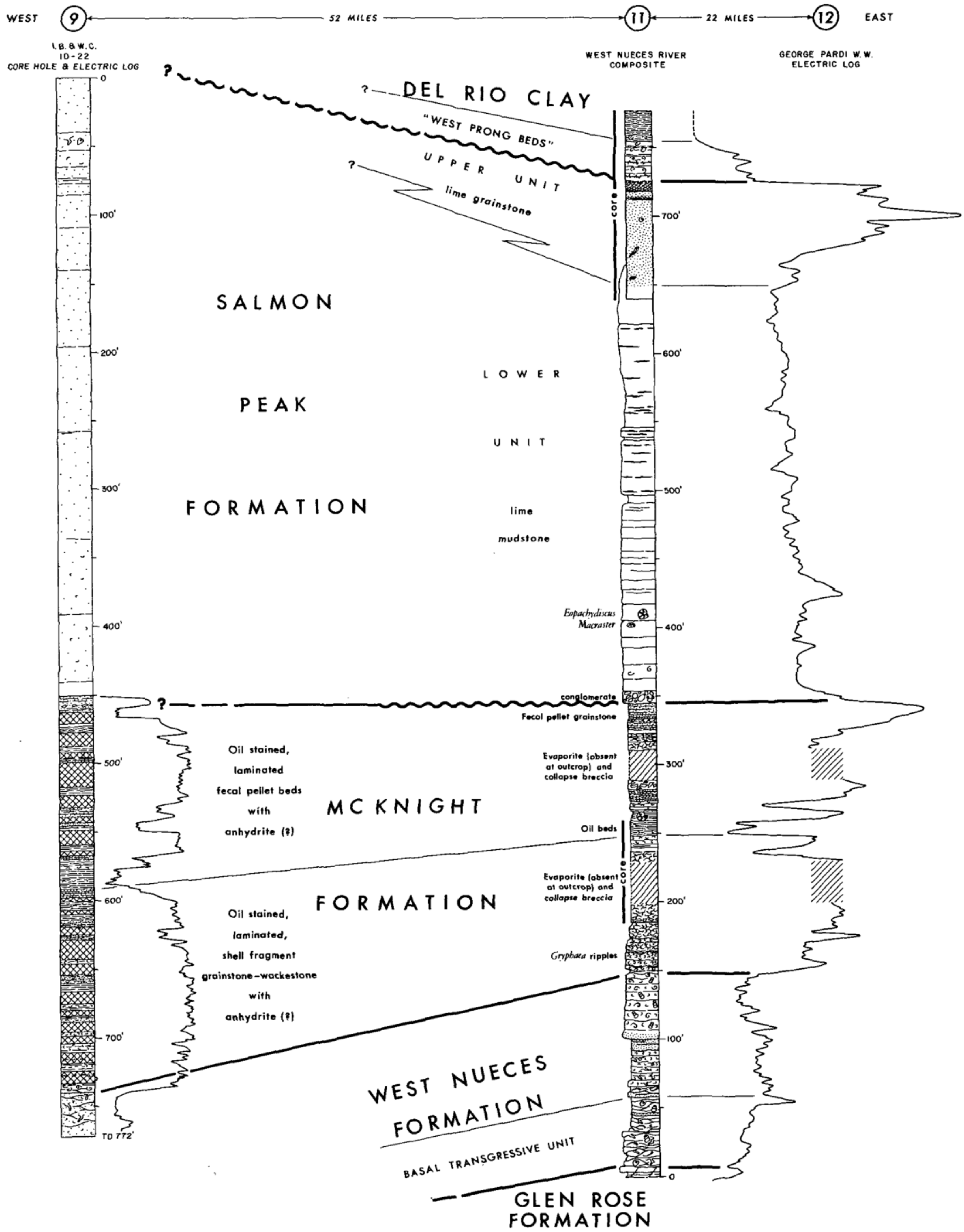


Figure 6-29. Correlation of Lozo and Smith (1964) type logs; well and core from measured section 9, measured section 11, and electric well log from measured section 12, across the Edwards Group. From Lozo and Smith (1964).

Seismic Data

Line A is one of three lines analyzed, selected, reprocessed, and utilized in this study[1].

Line A is an oblique-dip oriented line relative to the local east-west structural trend of the ETPA. Line A hosts a complete section of the Edwards and Trinity aquifers. Figure 6-30 presents Line A with interpreted tops of aquifer groups without well log overlays (A), and Line A interpreted with nearby well logs projected into the section (B).

The reflector representing the lower Trinity is moderately bright, but is the least continuous boundary reflector of Line A. Two normal faults are present in the Lower Trinity: one in the down-dip direction and one in the up-dip direction.

The base of the middle Trinity is a bright, continuous reflector easily tracked across Line A. A graben is present in the north-central part of Line A and marked by the bounding faults shown in Figure 6-30. The upper portion of the middle Trinity and the entirety of the upper Trinity are a series of mostly transparent reflectors, indicative of homogenous stratigraphy.

The lower Edwards is marked by a pair of bright, continuous reflectors across Line A. Faults penetrating the lower Edwards continue into the upper Trinity. The upper Edwards has poor resolution in the up-dip section, but resolution increases in the downdip section, marked by a series of moderately bright, continuous reflectors.

Generally, the reflectors increase and decrease in brightness and lateral continuity proportionately. These reflect the contrasts between formations of the ETPA.

Analysis of the outcrop from Lozo and Smith (1964) shows the upper portion of the Edwards is likely to be a target. Additionally, faulting is a major driver for production within the Edwards Aquifer. Ideally, one would be able to target a faulted upper Edwards section. However, the upper Edwards is the least resolved, and no apparent faulting can be interpreted there, but there is less certainty than in the lower Edwards. A prospective developer would need to use best judgement to determine whether to try to target a lower-confidence fault in the upper Edwards or whether to target a clearly resolved fault within the lower Edwards. The value judgment comes down to whether to focus on developing primary porosity, which the upper Edwards has, or secondary porosity, which is the dominant porosity type in higher-producing Edwards wells. Ideally, both would be targeted, but additional information is needed to decide whether that is possible.

[1]Higher resolution plates of seismic lines A, B, and C are available and can be obtained from the TWDB BRACS group.

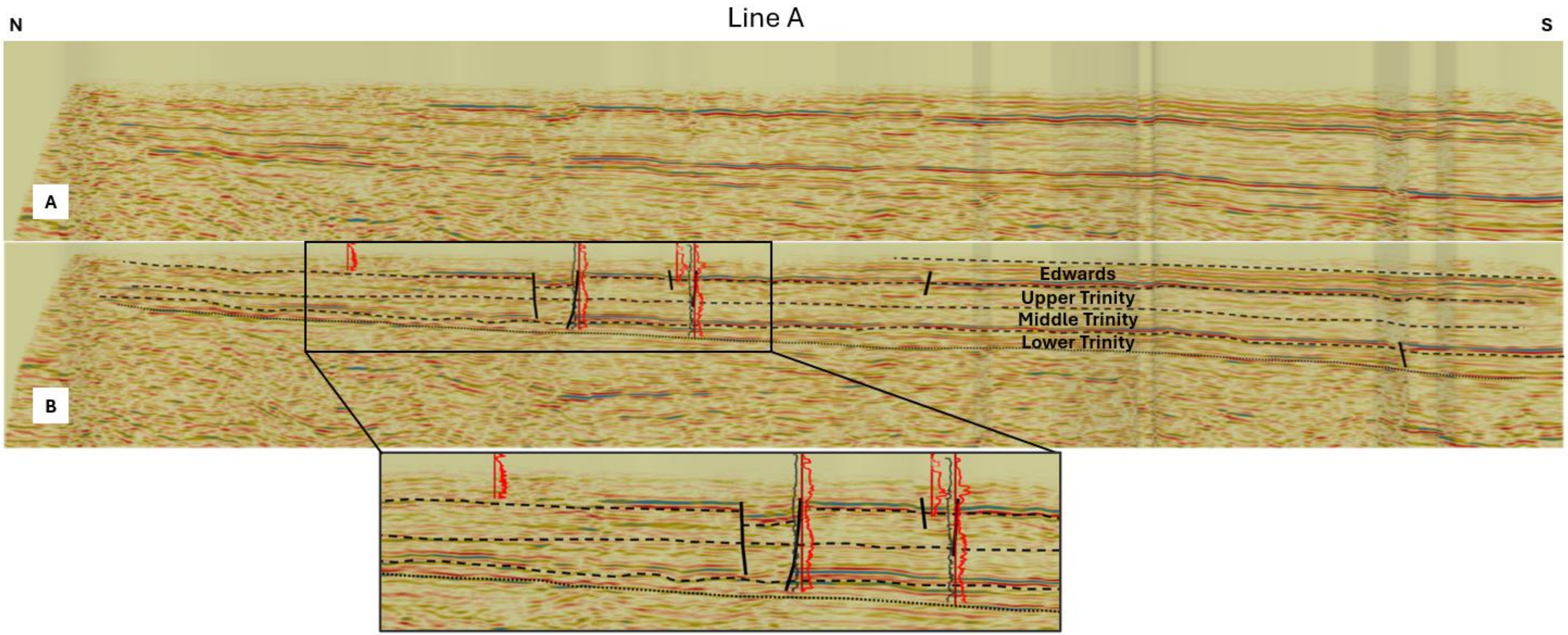


Figure 6-30. (A) Reprocessed seismic line A, and (B) reprocessed seismic line A with interpreted formation surfaces from nearby geophysical well log ties.

Line B is the second of three lines analyzed, selected, reprocessed, and utilized in this study.

Line B is an oblique-strike oriented line relative to the local east-west structural trend of the ETPA. Figure 6-31 presents Line B after being reprocessed (A), and Line B interpreted with aquifer group tops and nearby well logs projected into the section (B).

Reflector quality varies widely across the profile of Line B. Compared to Line A, seismic reflectors that pertain to the individual formations of the ETPA are not easily identified in Line B. Generally, the only distinction that can be made is the boundary between the Edwards and the Trinity groups. The lack of available geophysical well log ties throughout the section, and discontinuous reflectors restrict the ability to better define the formations of the ETPA.

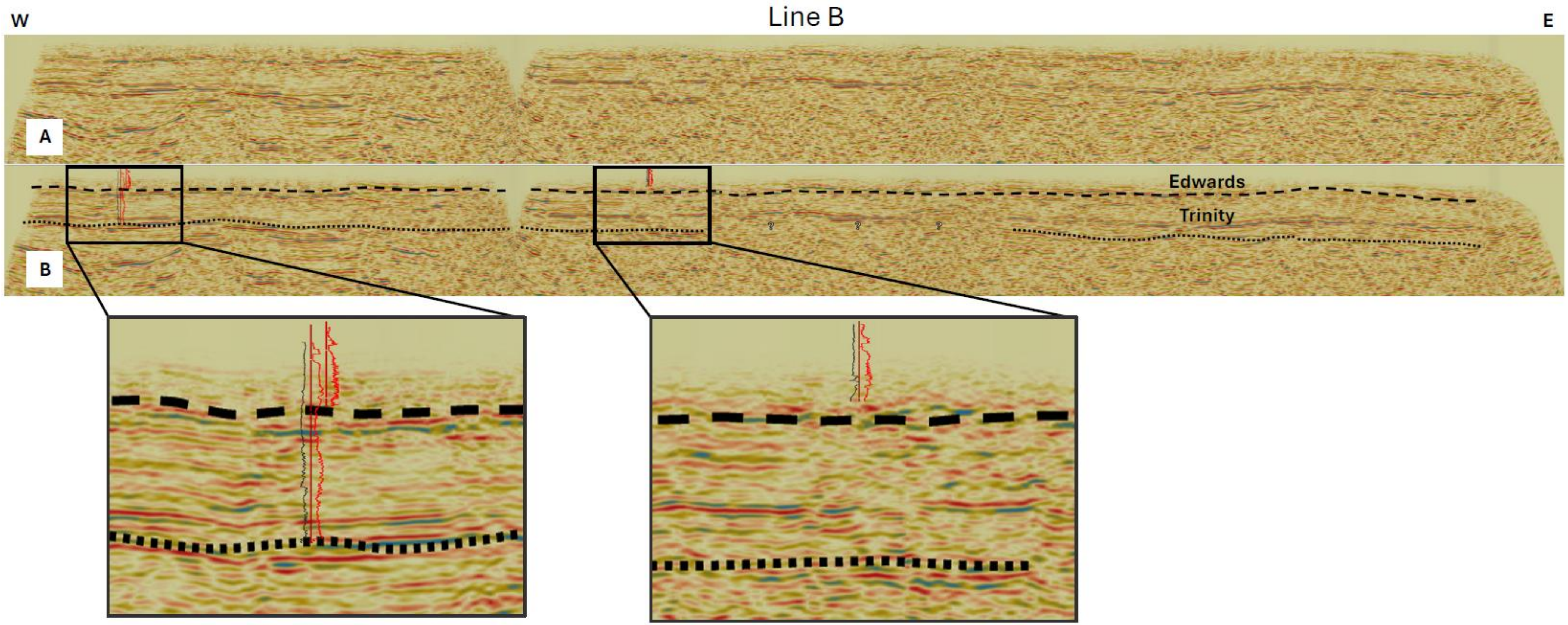


Figure 6-31. (A) Reprocessed seismic line B, and (B) reprocessed seismic line B with interpreted formation surfaces and nearby geophysical well log ties.

Line C is the third of three lines analyzed, selected, reprocessed, and utilized in this study.

Line C is an oblique-dip oriented line relative to the local east-west structural trend of the ETPA. Line C hosts a complete section of the Edwards and Trinity aquifers. Figure 6-32 presents Line C with interpreted tops of aquifer groups without log overlays (A), and Line C interpreted with nearby well logs projected into this section (B). The basal reflector of the lower Trinity is moderately bright and the least continuous of Line C. Two faults are present in the lower Trinity and extend into the overlying middle Trinity, in the northern half of Line C.

The basal reflector of the middle Trinity is bright and continuous. The upper portion of the middle Trinity (the lower Glen Rose Formation), and the upper Trinity, present a series of mostly transparent reflectors.

The base of the Edwards Group is marked by two to three bright, continuous reflectors through Line C. There is one fault bounded block in the Edwards Group. The upper Edwards has poor resolution in the up-dip direction, and high resolution in the down-dip direction.

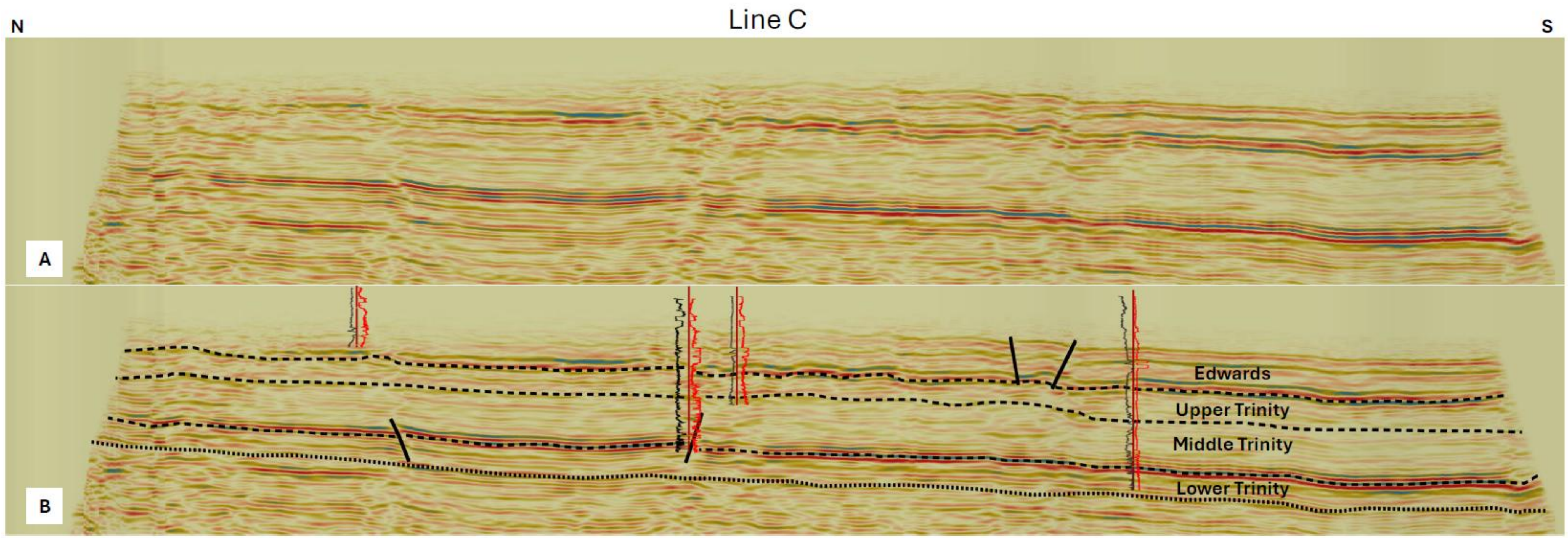


Figure 6-32. (A) Reprocessed seismic line C, and (B) reprocessed seismic line C with interpreted formation surfaces and nearby geophysical well log ties.

6.5 Discussion

6.5.1 Limitations of this Method

Extrapolation of Outcrop Data

As discussed in Section 6.4, using outcrop type sections can help synthesize the stratigraphic interpretation of the ETPA. However, extrapolating localized outcrop data across an entire region is inherently limited because type sections provide localized observations that may not capture lateral or vertical heterogeneity of rock units across an entire region. Physical characteristics of a formation can vary significantly over short distances due to changes in depositional environments and diagenetic processes, and structural influences like faulting and folding can influence the homogeneity of a formation across a region. To limit the primary and secondary influences, this study tied geophysical well logs to nearby seismic lines and compared them to type sections described by Lozo and Smith (1964). This methodology helped determine lateral and vertical continuity of targeted formations, as well as characterizing reservoir continuity, in particular faulting and fault zones.

Depth Constraints

When attempting to image a geologic formation using 2D seismic data, it is difficult to achieve high resolution data in the shallow subsurface. Limiting principles are discussed in detail in Draper and others (2021) and presented in detail in Sections 1 through 5 of this report. While aquifers are generally developed in the shallowest viable areas, seismic data generally increase in resolution at depth. This relationship between targeted development depths of aquifers and fair seismic resolution is inversely related. This study shows, however, that in some cases where groundwater may be developed at deeper depths, seismic data tied to well logs can help characterize a regional hydrogeologic system.

6.5.2 Interplay Between Seismic Data, Water Wells, Well-Logs, and Outcrop Data

In groundwater exploration, the combination of seismic data, well-log data, and outcrop data can offer a comprehensive analysis of an aquifer. These data can help hydrogeologists make informed decisions about aquifer locations, physical properties, and resource potential. In this study, outcrop sections, published literature, 2D seismic lines, and publicly available water well data helped characterize potentially productive formations and structural discontinuities within the ETPA. To further understand the relationship of outcrop and well log data, this study highlighted that the Salmon Peak Formation had the best reservoir quality based on outcrop. However, well logs across the study area showed the Salmon Peak Formation and the West Nueces Formation were characteristically similar. Seismic data presented in lines A, B, and C show that faulting and folding is present throughout the study area. Faults and fractures present in the ETPA Aquifer can act as pathways for groundwater flow, and, when intersected in a water well, can lead to greater production potentials.

6.5.3 Seismic Exploration for Groundwater Resources

This study highlights the use of 2D seismic data in the shallow subsurface. Stratigraphic and structural continuity/discontinuity can be interpreted using the seismic data and well logs. Clearly one of the most applicable uses for seismic in groundwater exploration is identifying faults in the aquifers, where faults and fault zones have the highest potential for groundwater flow, well development and groundwater yields. The findings in this report direct the use of 2D seismic towards more groundwater development in faulted and fractured zones. In aquifer systems with faulted and fractured zones, such as the deeper formations of the ETPA, seismic data can provide valuable insights into the location and orientation of faults and fractures that may significantly influence groundwater flow. With seismic data, the complex structure of these faulted aquifers is explicitly shown on seismic sections, informing exploratory water well drilling and increasing the likelihood of higher yield water wells in structurally deformed/fractured/faulted areas.

6.5.4 Cost-Effectiveness of Seismic Data

Seismic data are expensive to acquire, and while seismic data can identify faults at depth, it is not cost-effective in shallow aquifers or in aquifers not influenced by faults at depth. For example, imaging the Gulf Coast Aquifer of Texas (consisting of basinal fill comprised of discontinuous sands, silts, clays, and gravel beds), seismic data would not provide additional value in pursuit of groundwater development because the Gulf Coast Aquifer, although influenced by faulting, is relatively shallow. In most cases, a dataset comprised of proper well log coverage, combined with published stratigraphic and hydrogeologic data, is often sufficient to accurately define an aquifer's extent and productive zones. Well logs are also more cost-effective and have better resolution across shallower formations than seismic data and are more widely available.

7 Conclusions

This ETPA seismic interpretation project has demonstrated the value of integrating seismic data with outcrop and well-log data to develop a comprehensive subsurface stratigraphic and structural model of the aquifer. High-resolution insights provided by seismic data advance our understanding of the aquifer's geometry, internal architecture, and potentially higher yield groundwater production zones associated with faulted and fractured sections of the aquifer. The study documents the steps and approach needed to lease, process/reprocess, and depth-convert the seismic data in sufficient detail to provide an example of the application in a specific study area, Kinney County. The Kinney County area is an example of the quality of seismic data that can be obtained for relatively shallow depths and compared to the deeper oil and gas-bearing formations that were the original primary target of the seismic lines.

One of the strengths of this project lies in its integrated approach to aquifer characterization. The incorporation of outcrop data into the seismic interpretation workflow has allowed for the development of a stratigraphic framework that extends from surface exposures to the deeper subsurface. This approach ties the subsurface model to the observed surface geology and provides a scientific basis for extrapolating aquifer properties and facies distribution throughout the Kinney County study area.

Integration of the TWDB's previous ETPA studies and the geophysical log framework developed in this project enhance the reliability and accuracy of the seismic interpretation approach and methodology. By incorporating the existing hydrogeologic understanding and well log correlations into the seismic interpretation workflow, this study has produced a subsurface model that is well-grounded in the geologic and hydrogeologic data available for the Kinney County study area.

The reprocessing of the seismic data, as outlined in Sections 1 through 5, has played an important role in optimizing and imaging the ETPA. The application of modern processing techniques and the development of robust velocity models have enabled accurate depth conversion of seismic data, providing a realistic representation of the aquifer's geometry and structure. The seismic interpretation workflow presented herein has translated the reprocessed and depth-converted seismic data into a local geological model of the ETPA, constrained by the location and depth confidentiality of the seismic data. The identification and interpretation of key seismic horizons, faults, and other geologic features have provided insights into the aquifer's structural framework and stratigraphic architecture in the Kinney County study area.

A well tie provides information at a specific location, which may not represent the entire region, especially in areas with complex geology and significant dip. However, the single well tie process as demonstrated herein was effective in constraining the seismic character of the well-log markers and providing a quality check on the depth converted profiles as determined by the pre-stack depth migration and anisotropic velocity modeling performed by subcontractor Tricon.

The development of an integrated outcrop, borehole-log seismic framework for a portion of the ETPA represents a significant advancement in the characterization of the aquifer's groundwater resource potential. This framework, conceptually extended to the larger aquifer footprint, provides a promising basis for delineating the aquifer's boundaries, understanding its internal architecture and facies distribution, and assessing its hydraulic connectivity and compartmentalization. These insights are essential for the effective management and development of the aquifer's groundwater resources; informing decisions related to well placement such as proximity to faults, fault intersections and seismic discontinuities; pumping strategies; and the potential for aquifer storage and recovery. Moreover, the workflow and methodologies demonstrated in this project can be readily adapted and applied to other parts of the aquifer and to other aquifer systems, promoting a more comprehensive and integrated approach to aquifer characterization and groundwater resource assessment.

Note that seismic velocities can be a constraint and be quite different between different rock types. Velocities in limestones and dolomites, which comprise much of the central Texas ETPA, are commonly significantly higher than sediments in the Gulf Coast Aquifer. Using traditional oil and gas seismic data, Texas Gulf Coast Aquifer strata can be imaged at depths shallower than 1,000 feet (Draper and others, 2021), while the higher velocities in the ETPA in central Texas generally mean a lower resolution at shallower depths than similar quality seismic data in the Gulf Coast Aquifer. The combination of high seismic velocity and insufficient depth means that much of the ETPA is not resolvable by traditional oil and gas seismic data and limits the scope of this study to the brackish, deeper parts of the ETPA.

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9 Attachment 1: INTERA's Response to TWDB Comments to Draft Report

9.1 General comments

Where possible in the Executive Summary, Introduction, and Conclusions, please add verbiage of how this study may be applicable to other aquifers (not just the ETPA). For example, the same methodologies in assessing, reprocessing, depth-converting, and integrating seismic data can be used.

Per the TWDB Report Guidelines, please limit the use of acronyms, for example, the Bureau of Economic Geology. Consider whether the acronym ETPA is necessary or could rather spell out Edwards-Trinity (Plateau) Aquifer.

9.2 Response to General Comments

As requested, verbiage has been added to the Executive Summary, Introduction, and Conclusions regarding the applicability of the approach presented in this report to other aquifers.

The use of acronyms has been reduced as appropriate, but for specific instances where the acronym may be part of a formal name or designation.

The first paragraphs of the Executive summary are restated as follows:

> *The Texas Water Development Board (TWDB) is exploring the potential use of seismic data for mapping and characterizing brackish aquifers in Texas. This study focuses on the use of seismic data for the Edwards-Trinity (Plateau) Aquifer (ETPA). INTERA Incorporated (INTERA) has partnered with the TWDB's Brackish Resource Aquifer Characterization System (BRACS) group to determine the feasibility of using existing seismic data, originally acquired for oil and gas exploration, to improve the understanding of aquifer structure and stratigraphy. The same methodologies detailed herein can also be used in other aquifers for assessing, reprocessing, depth-converting and integrating seismic data.*
>
> *Texas is fortunate to have a wealth of historical seismic data throughout the oil and gas bearing areas of the state that can be used as demonstrated in this report. The same approach can also be applied in non-oil and gas areas with seismic profiles developed specifically for the purpose of aquifer evaluation.*
>
> *An additional strength of this project lies in its integrated approach to aquifer characterization. The incorporation of outcrop data into the seismic interpretation workflow has allowed for the development of a stratigraphic framework that extends from surface exposures to the deeper subsurface. This approach ties the subsurface model to the observed surface geology and provides a scientific basis for extrapolating aquifer properties and facies distribution throughout the study area.*

Minor changes for clarity were made in wording in subsequent paragraphs.

9.2.1 List of Figures

List of Figures starts at Figure 3-1. Please add Figures 1-1, 1-2, 1-3, 1-4, 1-5, and 1-6 to the List of Figures.

Response done. Additional Figures 4-6 through 4-10 added to List of Figures.

Figure 4-6 is also missing from the List of Figures. Please check that all Figures are in the List of Figures.

Response done.

Figure 3-14. Shorten this caption to give some space between the end of the caption and the page number (40).

Response done. Document spacing will be reconfigured once revisions are completed.

Figure 3-15. In second sentence remove comma and put a semi colon after "horizons".

Response done.

Figure 4-1. In the second sentence, place "The" before the "Z" to avoid starting a sentence with a single consonant letter.

Response done.

9.2.2 Executive Summary

First paragraph, first line. Please change to something like: "The Texas Water Development Board (TWDB) is exploring the potential use of seismic data for mapping and characterizing brackish aquifers in Texas. This study focuses on the use of seismic data for the Edwards-Trinity (Plateau) Aquifer (ETPA).

Response done.

Sixth paragraph, first sentence, change "methodology" to "product".

Response revised wording to "product demonstrating a methodology".

Last paragraph. Should "outcrop data" have been mentioned earlier in the Executive Summary?

Response Following verbiage from the Conclusions Section is added to the Executive Summary to emphasize the use of outcrop data.

"An additional strength of this project lies in its integrated approach to aquifer characterization. The incorporation of outcrop data into the seismic interpretation workflow has allowed for the development of a stratigraphic framework that extends from surface exposures to the deeper subsurface. This approach ties the subsurface model to the observed surface geology and provides a scientific basis for extrapolating aquifer properties and facies distribution throughout the study area."

Last paragraph, first line. Recommend rewording as "This study has demonstrated that high-resolution seismic data may be leveraged to better understand an aquifer's geometry…"

Response done.

9.2.3 Main Text

1 Introduction. First paragraph. Please add sentence after second sentence (after "ETPA) something to the effect of: "The methodology of selecting, reprocessing, and depth calibrating seismic data described herein may be applied to other aquifers, though differences in geologic assumptions exist."

Response done.

1 Introduction. First paragraph, change third sentence to "Sections 1 through 5 develop…".

Response done.

Section 1.1.1 Remove "and most important". In the second sentence, remove "constraints" and consider a term such as "definition".

Response done.

Section 1.1.2. First paragraph, third sentence: change to "Draper and others (2021) that intersect the ETPA." Fourth sentence: change "This study will not" to "This study did not". The last paragraph is one sentence; consider breaking into multiple sentences or combining with above paragraphs.

Response Third sentence - done.

Fourth sentence – done.

Last paragraph – retained as is.

Table 1-1. Please add to the caption details of where the data came from, such as "Data from SEI, available online, and Seitel, provided on request". At the end of the table, either delete the words "Source: Seitel", or update to include SEI.

Response done.

Figure 1-1. For the caption, perhaps add the source of the "Depth to Base of ETPA (ft)" data. Also, consider commenting that many of the seismic lines on this map were excluded from the study as they were too shallow (described lower in Section 1.1.4). Include an inset map of Texas with the study area highlighted, as this is the first figure in the report.

Response Caption now includes ETPA raster source. Following sentence added to caption…" Depth to base of ETPA is constrained by BRACS database geophysical well logs and structure picks."

Text revision re shallow lines – done.

Inset map of Texas added.

Section 1.1.4. First paragraph, first sentence: change to "contextual factors associated with the relevant strata."

Response *done.*

Section 1.1.4. Third paragraph, last sentence. Please change to "In Figure 1-1, all lines in Edwards, Real, and Bandera counties, and most lines in Terrell County, are eliminated because the base of the ETPA is too shallow. Lines in Kinney, Uvalde, Zavala, Dimmit, and maverick counties have sufficient depth to be retained for further consideration."

Response *done.*

Section 1.1.4. Paragraph 6: The paragraph discusses well log coverage, well-to-seismic tie, and refers to Table 1-1, Geophysical Log Coverage column. It is unclear whether you considered logs of all suites, or only those usable for well-to-seismic tie to enter 'Yes' in the Geophysical Log Coverage column. The explanation is given much late in Section 1.2.3, where it is stated that "This well log data set (referring to total coverage from all datasets) is the basis for the last column in Table 1-1, 'Geophysical Log Coverage'."

Response *Following verbiage added to paragraph 6 of Section1.1.4.*

"For this study, well-log coverage includes all free well-logs, SL&AL (Subsurface Library) and the University of Texas Bureau of Economic Geology logs that measure strata shallower than 5,000 feet, and any expensive log that has a sonic log, as those are typically the least common and most important for correlation of seismic data.".

Section 1.2.2. Third paragraph, "databases" instead of data bases.

Response *done.*

Table 1-2. Consider adding additional space between the report title header and the table.

Response *done.*

Section 1.3.3, Paragraph 2: the abbreviation for the Texas Water Development Board was already provided earlier in the Executive Summary.

Response *revised.*

Figure 3-2: This figure might benefit from what is meant by QC stack in this context.

Response *Caption revised to the following:*

Figure 3-2. Brute stack refers to unrefined seismic traces added together with minimal corrections. QC stack refers to seismic data that has undergone quality control review, including spectral (frequency) analysis and amplitude corrections to reduce noise and improve signal-to-noise ratio.

Section 4.1, paragraph 2: I would suggest reformatting the website references. “White and Simm (2003), in combination with tutorials on the OpendTect website and YouTube channel, provide the groundwork for well ties performed in this study.” Then, include the full reference in a foot note or reference list.

Response *Text revised as suggested and full reference listed in References.*

Figure 4-1. Add “The” before Z axis in the caption text.

Response *done.*

Figure 4-5: The font appears to be too large, which prevents the figure from being centered on the page.

Response *Retained as is. Cut/paste limitation.*

Figure 4-6. Please un-highlight “grams per cubic centimeter”.

Response *done.*

Figure 4-8. Since abbreviations are used, might be necessary to add abbreviation explanations to the caption.

Response *Caption revised and broken up to place explanation above the caption.*

> ***2D profile extraction of 3D data from Sasser (2016) showing Buda and Sligo tops in Maverick County. JR-K, the Jurassic-Cretaceous boundary layer, marks a change in the character of the seismic reflectors above and below ~1,000 ms. JR-U marks upper Jurassic layers. Jr-L marks lower Jurassic layers. Subvertical discontinuities mark breaks in the Jr-U and Jr-L and surrounding reflectors. Cretaceous layers in the black boxes show some zones more discontinuous than others. Pink polygon is interpreted as Ouachita thrust Paleozoic metamorphic rocks.***

Figure 4-8. Label on Figure or state in caption what the magenta polygon is. Also, it is unclear what the boxes outline-please clarify in caption.

Response *Caption clarified per immediately previous response.*

Figure 4-9. The formation top fonts are too large, which detracts from the seismic data underneath.

Response *Formation tops legend added.*

Figure 4-10. In the caption, please briefly explain the significance of the two figures on the left labeled Velocity_Att1 and AI on top, and Density and Reflectivity on bottom, and/or how they relate to the synthetic seismogram on the right.

Response *Caption is revised and broken up to place explanation above the caption.*

> ***Synthetic seismogram and adjacent seismic data. The synthetic seismogram is constructed from the acoustic travel time (Att) and density logs used to calculate the acoustic impedance (AI), which is mathematically convolved with a representative wavelet extracted from actual seismic data near the well site to develop a synthetic seismogram. The synthetic seismogram is then adjusted (stretched, shifted, squeezed) to improve the alignment between the synthetic seismogram and the actual seismic data.***

Figure 5-1: Please label the formation tops in the right-hand figure or list the formation tops that are interpreted in the caption.

Response *Formation tops legend added, and caption revised to place explanation above the caption .*

Comparison between seismic depth-converted via seismic well tie (left) and those converted via anisotropic velocity model (right). PSTM – Post-Stack Time Migration. PSDM – Pre-stack Depth Migration. Formation tops in the PSDM model on the right are somewhat less well defined: for instance, the top of the Lower Glen Rose is indistinguishable, while the Hensell is very poorly defined. The deeper units (the Cow Creek, Sligo, and Hosston) are relatively well defined.

Section 6.1.1. Please remove this subsection header (6.1.1) and move the paragraphs under 6.1 Section 6.1 could remain as "Introduction" or renamed to "Motivation".

Response *Retained subsection header 6.1.1 Motivation as is to reduce heading reorganization and referencing.*

Figure 6-1. Please indicate the location of Kinney County on the map. It could be a star that is noted in the caption.

Response *Caption revised as follows.*

Overview of the Maverick Basin and Edwards Platform during the Middle Albian. From Ewing (2016). Kinney County, where the example seismic sections in Section 6 are located, is located immediately north of the magenta evaporite polygon in the Maverick Basin.

Section 6.3. First paragraph, last sentence. Says "this study enhances our understanding of the subsurface geology of the ETPA." Please change to "this study enhances our understanding of the subsurface geology of the ETPA in Kinney County and adjacent areas." Or something to that effect.

Response *done.*

Figure 6-10. The legend font and symbols are too small. Need to remove the reference to the original figure: 'Figure 1.1: Location of the study area.'

Response *Figure resized, and 'Figure 1.1: Location of the study area.' removed.*

Section 6.4.6. Please remove the parts about geologic surfaces and formation tops provided by BRACS, which was already mentioned in Section 6.4.4 Well Log Data.

Response *partially retained BRACS geologic surfaces reference for completeness purposes.*

Section 6.4.7. Edwards Group Water Levels. Last sentence. Typo in "feet above meal sea level" (mean sea level).

Response *corrected.*

Figure 6-10. Is this Figure necessary in the context of the report? Consider providing more detail in the text body on the usefulness of the figure. If keeping this figure, consider eliminating the holdover "Figure1…" text on the figure itself, as it may cause confusion with the actual figure caption.

Response *Figure retained and revised per previous comment on Figure 6-10. Text discussion in Section 6.4.3 expanded as follows to elucidate continuing technical evaluation of groundwater resources in the state.*

Section 6.4.3 Previous Groundwater Investigations

Green and others (2006) conducted a comprehensive evaluation of groundwater resources in Kinney and Uvalde counties, focusing on the dynamics of recharge, discharge, and aquifer storage within the Edwards Aquifer (study area in Figure 6-10). Bennett and Sayre (1962) and Green and others (2006) highlight the importance of understanding regional hydrology with respect to water management and the growing demand for groundwater in the area. *These reports, and the subsequent initiation of the BRACS program in 2009, indicate the expanding focus by the State of Texas on the evaluation of groundwater resources and the integration of technical information necessary for the continued development and utilization of groundwater throughout the state.*

Figures 6-11 through 6-17, and 6-19 through 6-22. The legends and labels on the maps are in general too small and hard to read. Please consider putting each figure on its own landscape oriented page, or increasing the font size in the figures.

Response *Font size in legend and map labels increased in each figure.*

Figures 6-11 and 6-12. Major Road labels and municipality labels on the map are very hard to read. Rivers and streams are missing from the map (e.g., West Nueces River and Nueces River).

Response *Maps revised.*

Figure 6-12 and 6-13. Consider labeling the geographic name, if one exists, for the large number of faults in the northeast corner of the primary map.

Response *The fault zone in Figures 6-12 and 6-13 consists of primarily normal faults with throw ranging from a few feet to about 75 feet, with the downthrown side to the southeast (Bennett, R. R., and A. N. Sayre, 1962. Geology and Ground-Water Resources of Kinney County, Texas. U.S. Geological Survey Bulletin 6216, 113 p.). The fault zone does not appear to be related to the Carta Valley fault zone, an east-west zone of wrench faults across the Val Verde/Edwards north-south county line. The fault zone appears to be toward the eastern end and part of the Balcones fault zone.*

Caption has been revised to indicate the faults are part of the Balcones Fault Zone.

Figure 6-13. The legend (first column) has items that are not present on the map (e.g. major roads, railroad, rivers, etc).

Response *Caption has been revised as follows to refer reader to Figure 6-12 for location of these features.*

Figure 6-13. Geologic map of the study area with springs denoted and labeled. Faults are part of the Balcones Fault Zone. See Figure 6-12 for location of highways, roads, railroad, rivers, etc.

Figures 6-14 and 6-15. Rivers and streams are missing from the map.

Response *Features removed from map legend.*

Figure 6-16. Need to remove the reference to the original figure: 'Figure 4.2 …'.

Response *done.*

Figures 6-17 to 6-22. Rivers and streams are missing from the map (e.g. West Nueces River and Nueces River).

Response *Figure 6-17. Rivers and streams are not necessarily required on the map of the top of the Edwards Group and the location of water wells.*

Figure 6-18. Rivers and streams are not necessarily required on the map of water quality of the Edwards aquifer. Caption is incorrect. See caption revision below in Figure 6-18 response.

Figure 6-19. Rivers and streams are not necessarily required on the map of the top of the Upper Glen Rose and the location of Glen Rose water wells symbolized by depth.

Figure 6-20. Rivers and streams are not necessarily required on the map of the top of the Upper Glen Rose and the location of Glen Rose water wells symbolized by type.

Figure 6-21. Rivers and streams are not necessarily required on the map of the top of the Upper Glen Rose water wells symbolized by water level.

Figure 6-22. Rivers and streams are not necessarily required on the map of the top of the Upper Glen Rose water wells symbolized by water yield.

Figure 6-18. Please mention in the caption that the map includes the wells discussed in the excerpt from Green and others (2006).

Response *Caption already indicates the source as Green and others (2006).*

Figure 6-18. This Figure does not appear to contain groundwater elevation contours, as is stated in the caption text. Please update the caption text accordingly.

Response *done.*

Figure 6-26. Please resize so that the caption fits on the same page.

Response *done*.

Section 6.4.8. Well Log Data. Second paragraph. Need space between "approximately and "700 feet".

Response *done.*

Figure 6-29, caption. Please change “Section 9” to “measured section 9”, and “Section 12” to “measured section 12”.

Response *done.*

Figure 6-31. Would it be possible to split Line B onto two different pages? The resolution makes it hard to see detail.

Response *Reprocessed seismic lines A, B, and C provided as separate pdfs and noted in footnote as available from TWDB.*

Section 6.5.1. Extrapolation of Outcrop Data. Need a space between “Section” and “6.4”.

Response *done.*

Conclusions. Please expand upon the value of the project, as it has identified potentially useful seismic lines for studying the ETPA aquifer in the feasibility analysis; documents the steps needed to lease, process, and depth convert the data; and has produced an example of the quality of seismic that can be obtained for relatively shallow depths in the area.

Please minimize the parts discussing the creation of a 3D geologic model, as this isn’t a deliverable. Instead focus on any insights that the 2D lines bring to the area, such as potential faulting, continuity of the units from outcrop to the subsurface, and any other features of interest.

Emphasis is put on the entire ETPA in discussing the seismic. Please narrow the emphasis to the ETPA in the area of Kinney County.

Please include the conclusion that a well tie provided a more accurate depth conversion at a local area than the depth conversion process by Tricon.

The last paragraph seems an unnecessary restatement of aspects written earlier in the conclusions. Consider removing or editing.

Response *Conclusions have been restated as suggested, de-emphasizing 3D interpretation, retaining emphasis on extrapolation of outcrop data to the subsurface, identification of discontinuities in the seismic data and faults/fault intersections as potential groundwater development targets, and the significance of a well tie in constraining the depth converted profiles by pre-stack depth migration and anisotropic velocity modeling.*

Conclusions section is restated as follows:

This ETPA seismic interpretation project has demonstrated the value of Integrating seismic data with outcrop and well-log data to develop a comprehensive subsurface stratigraphic and structural model of the target aquifer. High-resolution insights provided by seismic data advance our understanding of the aquifer's geometry, internal architecture, and *potentially higher yield groundwater production zones associated with faulted and fractured sections of the aquifer. The study documents the steps and approach needed to lease, process/reprocess, and depth convert the seismic data in sufficient detail to provide an example of the application in a specific study area, Kinney County. The Kinney County area is an example of the quality of seismic data that can be obtained for relatively shallow depths, compared to the deeper oil and gas-bearing formations that were the primary target of the seismic lines.*

One of the strengths of this project lies in its integrated approach to aquifer characterization. The incorporation of outcrop data into the seismic interpretation workflow has allowed for the development of a stratigraphic framework that extends from surface exposures to the deeper subsurface. This approach ties the subsurface model to the observed surface geology and provides a scientific basis for extrapolating aquifer properties and facies distribution throughout the Kinney County study area.

Integration of the TWDB's previous ETPA studies and the geophysical log framework developed in this project enhance the reliability and accuracy of the seismic interpretation approach and methodology. By incorporating the existing hydrogeologic understanding and well log correlations into the seismic interpretation workflow, this study has produced a subsurface model that is well- grounded in the geologic and hydrogeologic data available for the Kinney County study area.

The reprocessing of the seismic data, as outlined in Sections 1 through 5, has played an important role in optimizing and imaging the ETPA. The application of modern processing techniques and the development of robust velocity models have enabled accurate depth conversion of seismic data, providing a realistic representation of the aquifer's geometry and structure. The seismic interpretation workflow presented herein has translated the reprocessed and depth-converted seismic data into a local geological model of the ETPA, constrained by the location and depth confidentiality of the seismic data. The identification and interpretation of key seismic horizons, faults, and other geologic features have provided insights into the aquifer's structural framework and stratigraphic architecture in the Kinney County study area.

A well tie provides information at a specific location, which may not represent the entire region, especially in areas with complex geology and significant dip. However, the single well tie process as demonstrated herein is still effective in constraining the seismic character of the well log markers and providing a quality check on the depth converted profiles as determined by the pre-stack depth migration and anisotropic velocity modeling performed by subcontractor Tricon.

The development of an integrated outcrop-borehole log-seismic framework for the ETPA represents a significant advancement in the characterization of the aquifer's groundwater resource potential. This framework, conceptually extended to the larger aquifer footprint, provides a promising basis for delineating the aquifer's boundaries, understanding its internal architecture and facies distribution, and assessing its hydraulic connectivity and compartmentalization. These insights are essential for the effective management and development of the aquifer's groundwater resources, informing decisions related to well placement such as proximity to faults, fault intersections and seismic discontinuities, pumping strategies, and the potential for aquifer storage and recovery. Moreover, the workflow and methodologies demonstrated in this project can be readily adapted and applied to other parts of the aquifer and to other aquifer systems, promoting a more comprehensive and integrated approach to aquifer characterization and groundwater resource assessment.

Note that seismic velocities can be a constraint and be quite different between different rock types. Velocities in limestones and dolomites, which comprise much of the central Texas ETPA, are commonly significantly higher than sediments in the Gulf Coast Aquifer. Using traditional oil and gas seismic data, Texas Gulf Coast Aquifer strata can be imaged at depths shallower than 1,000 feet (Draper and others, 2021), while the higher velocities in the ETPA in central Texas generally mean a lower resolution at shallower depths than similar quality seismic data in the Gulf Coast Aquifer. The combination of high seismic velocity and insufficient depth means that much of the ETPA is not resolvable by traditional oil and gas seismic data and limits the scope of this study to the brackish, deeper parts of the ETPA.