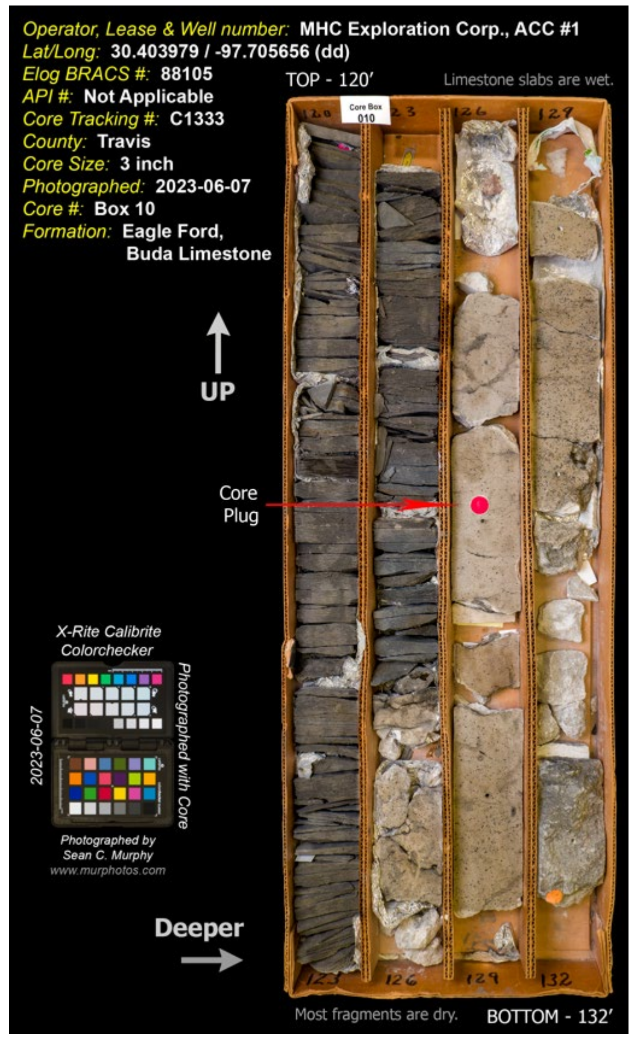
Final Report: Core Analyses for Various Aquifers

Texas Water Development Board Contract #2348302708



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August 9, 2024

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Geoscientist Seal

This report documents the work of the following Licensed Texas Geoscientists.

The Texas Water Development Board contracted with LRE Water, LLC, a licensed professional geoscientist firm (Texas License No. 50516) and licensed professional engineering firm (Texas License No. 14368).

This final report is released to the Texas Water Development Board by the following licensed professional geoscientist in the State of Texas:

Allan R. Standen, PG

Mr. Standen was the Project Manager for this work, with responsibility for all project tasks.

Signature 8/1/2024
Date

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Executive Summary

LRE Water was awarded the Texas Water Development Board (TWDB) Brackish Resources Aquifer Characterization System (BRACS) "Core Analyses for Various Aquifers" Contract Number: 2348302708 in early 2023. The purpose of this project is to provide directly measured rock parameters that are correlated with geophysical logs. This data will be used to facilitate the calculation of total dissolved solids (TDS) and the characterization of aquifer properties of downdip aquifers including the Maverick Basin (seven cores), Woodbine (four cores), Capitan Reef Complex (one core) and Edwards Balcones Fault Zone (one core). Measured rock parameters included bulk mineralogy, porosity, permeability, cementation or "m"-factor and nuclear magnetic resonance for each core plug interval. The project's fixed budget was $175,000 and a maximum of up to forty core plugs were to be analyzed for this contract. Work on this project commenced on May 11, 2023.

The Texas Water Development Board provided a curated list of thirteen cores for this study. After visual review of the cores, only twelve cores had intervals that could be used to extract core plugs. Maverick County core, C00540, did not have a usable core interval. Geophysical logs were located for twelve of the thirteen cores, a geophysical log was not found for the Travis County, Balcones Fault Zone (BFZ) core, C11333. Geophysical logs were used to identify stratigraphic intervals and formations of interest.

Detailed core lithologic descriptions were completed for twelve individual cores with a total length of over 400 feet of core analyzed. Maverick County core C00540 geophysical log was reviewed but this core was not described or photographed. A total of 144 high resolution core box photographs were completed. A total of 39 core plugs were successfully extracted and shipped to Core Labs in Houston, Texas for analysis. The Core Lab results are summarized in this report. The average cost for Core Lab analyses was $2,239.10 per core plug.

Section 1: INTRODUCTION

The Texas Water Development Board (TWDB) Brackish Resources Aquifer Characterization System (BRACS) program funded this project (Contract Number: 2348302708) to provide directly measured rock parameters integrated with geophysical logs. This data will be used to facilitate the calculation of total dissolved solids (TDS) and the characterization of aquifer properties of downdip aquifers including the Maverick Basin, Woodbine, Capitan Reef Complex and Edwards Balcones Fault Zone. The measured rock parameters included bulk mineralogy, porosity, permeability, cementation or “m”-factor and nuclear magnetic resonance (NMR) for each core plug interval.

The project fixed budget was $175,000 and included up to 40 core plug analyses. The project officially started on May 11, 2023.

1.1 TWDB Core Study Area

Figure 1-1 illustrates the TWDB provided core locations.

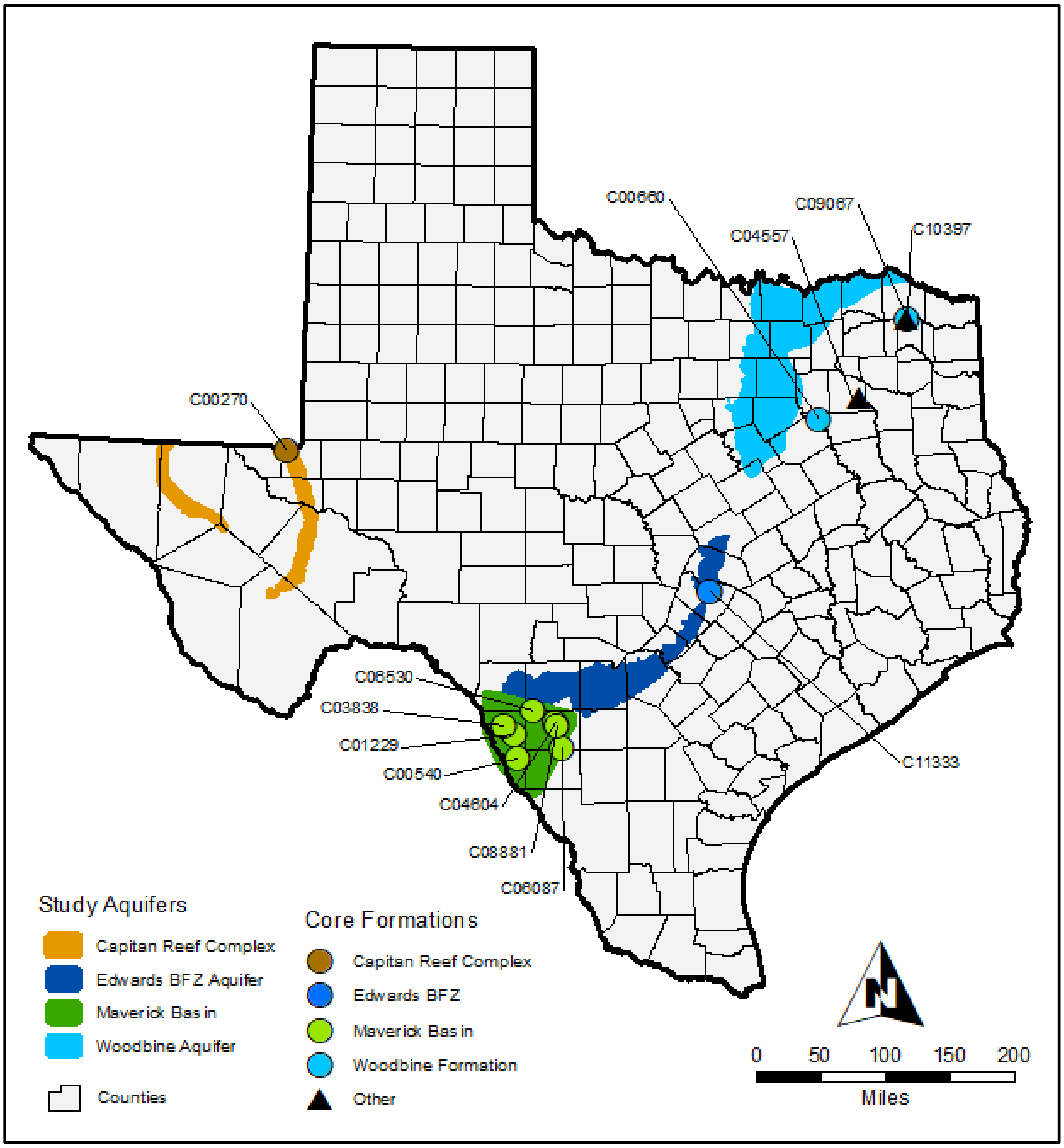

Figure 1-1. Study area and provided TWDB thirteen core locations.

1.2 FINAL CORE LIST

Table 1-1 provides information on each core analyzed during this project.

Table 1-1. Final core list.

Core ID[1]	County	Aquifer	API ID[2]	BRACS ID/SWN	TWDB Formation	Final Formation	Flat/Box Count	Top (Feet)	Bottom (Feet)	Log
C00270	Winkler	Capitan Reef Complex	49530886	--	Capitan Reef	Capitan Reef	34 flats	3,070	3,363	Yes
C00540	Maverick	Maverick Basin	32301126	20406	Pearsall / Sligo	Pearsall	1 flat, highly broken	6,020	8,978	Yes
C00660	Henderson	Woodbine	21300119	--	Woodbine	Woodbine	2 flats	3,016	3,126	Yes
C01229	Maverick	Maverick Basin	32300084	--	Pearsall	Upper /Lower Glen Rose	5 flats	4,770	6,038	Yes
C03838	Maverick	Maverick Basin	32332450	--	Glen Rose	Lower Glen Rose	9 flats	5,261	5,381	Yes
C04557	Van Zandt	Woodbine	46730737	--	Woodbine	Taylor Group	7 flats	2,780	2,836	Yes
C04604	Zavala	Maverick Basin	50700218	86710	Pearsall / Sligo	Lower Glen Rose / Pearsall	28 flats	7,500	7,968	Yes
C06807	Zavala	Edwards (BFZ) /Maverick Basin	50730444	--	Austin Chalk Edwards	Austin Chalk Edwards	9 flats	7,292	7,877	Yes
C06530	Zavala	Maverick Basin	50731296	--	Hosston	Hosston	2 flats	6,908	6,920	Yes
C08881	Zavala	Maverick Basin	50730132	86716	Glen Rose	Lower Glen Rose	5 flats	7,150	7,200	Yes
C09067	Titus	Woodbine	44930055	--	Woodbine	Woodbine	86 4” x 4’s boxes (13 flats)	3,437	3,764	Yes
C10397	Titus	Woodbine	449930212	--	Woodbine	Lower Glen Rose?	16 4” x 4’s boxes (6 flats)	4,858	4,906	Yes
C11333	Travis	Edwards (BFZ)	--	88105 / 5835701	Edwards (BFZ) / Equivalent	Edwards (BFZ) / Equivalent	18 flats	12	460	No

[1]Core ID = Bureau of Economic Geology, Core Research Center core tracking code
[2]API ID = American Petroleum Institute, hydrocarbon well tracking number

Section 2: SECTION 2: REVIEW OF TWDB CORE DATA

2.1 BACKGROUND ON CORE STUDY

When scoping this core project, the TWDB staff used the Bureau of Economic Geology's Core Research Center (CRC) database search engine ("CONTINUUM") to search for available cores by formation, county and well depth. This database provides well information including county, operator, lease, well number, and core attributes which includes the number and type of core boxes, whether the core has been slabbed and the top and base of the core interval. This database is sometimes incomplete and can be missing key core attributes such as the oil and/or gas well's unique identification number (API), core coordinates, missing core intervals, slabbed core diameter, and effort of curation. Core condition factors are also unknown until the core is pulled and physically reviewed.

Mr. Standen was the Austin CRC facility curator from 1986 to 1991 and is knowledgeable about CRC resources and protocols. Nearly all the cores at the CRC have been donated and were received with various levels of core curation and documentation. Core curation includes the experience level and professionalism of core handling at the drill site, use of different core box sizes, core orientation protocols, different core diameters and protocols for core box labeling of top and base (inside and outside of core box) and labeling missing core intervals. Because of these unknowns, core depth accuracy varies between cores and is dependent on the core curation at the time the core was extracted. Depth accuracy within half a foot or better was the goal for this project.

2.2 PHYSICAL REVIEW TWDB CORES

Thirteen TWDB cores from the project Request for Qualifications are listed in Table 1-1. Staged core viewing requests were submitted to the CRC staff to pull these cores to visually determine suitability for core plug analysis. The core curation and condition of these cores for this study were accepted as received from the CRC staff. Additional core curation was not performed through this study.

Cores were physically reviewed to determine actual slabbed core intervals, the level of core curation, core condition and thickness of the slabbed core (the slabbed core thickness needs to be at least one inch thick to extract a useable core plug for analyses). The following physical characteristics and curation status parameters were determined for each core:

1) Is the core slabbed? What is the core slabbed thickness? Is there a sample half of the core available for sampling?
2) Core curation status includes:

- The overall core condition, broken versus coherent core, bagged intervals, or if some core was dipped in wax or covered with aluminum foil?
- Are there core pieces greater than three inches long for core plugging?
- The accuracy and consistency of core box labeling, both inside and outside of each core box?

3) What are the core intervals, determine missing core intervals?
4) Do core intervals have the integrity to extract core plugs?

2.3 RESULTS OF PHYSICAL REVIEW OF CORE

Twelve of the thirteen cores had core intervals that could be used for core plugs (Table 1-1). The only core that did not have extractable core plug intervals was the Maverick County core, C00540. This core consisted of only one box of dark disintegrated shaley material (no core piece was larger than half an inch in length) with poorly documented core interval depths. A geophysical log was located and reviewed for C00540, but because of condition, lithology descriptions and photography were not completed for this core.

2.4 RESEARCHING AND IDENTIFYING GEOPHYSICAL LOG FOR EACH CORE

An API number and the corresponding geophysical log was acquired from either the TWDB BRACS database, the Bureau of Economic Geology (BEG), the Texas Railroad Commission (RRC) or The Subsurface Library to match the CRC's core county, operator, lease and well depth on the labeled boxes. Twelve of the thirteen cores have an API number and associated geophysical (electric) log which are listed in Table 1-1. Core hole C11333, from Travis County, did not have a geophysical log. Research shows that this core was previously drilled for the TWDB through an interval that included the Edwards Aquifer and overlying formations and/or equivalent formations.

2.5 USING THE CORE GEOPHYSICAL LOG TO IDENTIFY FORMATION TOPS

Most of the TWDB BEG cores for this project are in areas with minimal to no well control, especially for the Maverick Basin (new aquifer with minimally published formation information) and Woodbine Aquifer cores (cores were beyond downdip limits of prior groundwater studies). This created a challenge when using geophysical logs to identify a formation's top depth as there were little to no nearby "type" logs. Additionally, some of the geophysical logs were of inferior quality and/or had poor curve resolution (Appendix A).

During 2023, the TWDB made available, a GIS shapefile of formation stratigraphic picks from the BRACS database. This information improved the interpretations of formation top picks for the Maverick Basin (seven cores) and Woodbine Aquifer (four cores). Table 2-1 summarizes the estimated formation top picks interpreted from each core's geophysical log (Appendix A).

Table 2-1. Geophysical log formation picks.

Core ID[1]	API ID[2]	Operator, Lease, Well Number	County	Aquifer	Geophysical Log Top Pick, Depth from land surface (feet)
C00270	49530886	Gifford, Mitchell & Weisenbaker, Lone Wolf #2	Winkler	Capitan Reef Complex	Top of Capitan at 2,750'
C00540	32301126	Union Producing, Halsell, #29-1	Maverick	Maverick Basin	Poor quality log. Unable to make a formation pick. No core plugs.
C00660	21300119	DeArmand, Hunt & McMillion, Pearsons #1	Henderso n	Woodbine	Poor quality log. Unable to make a formation pick.
C01229	32300084	Continental Oil, Chittim, #155-1	Maverick	Maverick Basin	Upper Glen Rose at 4,700'. Pearsall at 5,670'.
C03838	32332450	Prime Operating, La Paloma #1-84	Maverick	Maverick Basin	Lower Glen Rose at 5,250'.
C04557	46730737	Richard Griffin, Howell #2	Van Zandt	Woodbine	Too shallow for Woodbine, possibly Taylor Group
C04604	50700218	Tenneco Oil, Chester Kiefer, #2	Maverick	Maverick Basin	Poor quality log. Lower Glen Rose at 5,650'? Pearsall Unknown.
C06087	50730444	Getty Oil, Weaver #2 "A"	Zavala	Maverick Basin	Austin Chalk 7,320'. Edwards Group at 7,810'.
C06530	50732296	Eason Oil, Flowers Ward #1	Zavala	Maverick Basin	Hosston at 6,885'.
C08881	50730132	Richard Hass, Elizabeth Barlett, #1A	Zavala	Maverick Basin	Poor quality log. Lower Glen Rose at 7,160'.
C09067	44930055	Sun Oil, Bankhead, Hoffman Unit #1	Titus	Woodbine	Poor quality log. Unable to make a formation pick.
C10397	44930212	Sun Oil, Bankhead #20	Titus	Woodbine	Log starts at 3,900', too deep for Woodbine. Lower Glen Rose at 4,865'.
C11333	N/A	TWDB Well	Travis	Edwards	Eagle Ford at 89'. Buda Limestone at 125'. Edwards Group at 132'.

[1]Core ID = Bureau of Economic Geology, Core Research Center core tracking code
[2]API ID = American Petroleum Institute, hydrocarbon well tracking number

Section 3: STRUCTURE AND/OR GENERAL GEOLOGY OF CORE AQUIFERS

The TWDB core list included thirteen cores (Figure 1-1), seven for the Maverick Basin (C00540, C01229, C03838, C04604, C06087, C06530 and C08881), four from the Woodbine Aquifer (C04557, C00660, C09067 and C10397), one from the Capitan Reef Complex Aquifer (C00270) and one from the Edwards BFZ Aquifer (C11333), (Table 1-1). The following sections include brief summaries of the TWDB core's aquifer structure and/or general geology.

3.1 MAVERICK BASIN STRUCTURE AND GENERAL GEOLOGY

The Maverick Basin is a small sedimentary basin that has been infilled with a thick sequence of dominantly Cretaceous limestones and mudstones. The basin is in south Texas along the Rio Grande River where it forms the southern edge of the Eagle Ford Basin (Sasser, 2016). The Maverick Basin is located within counties, Dimmit, Kinney, Maverick, Uvalde, Webb and Zavala (Figure 3-1).

Fresh groundwater was discovered within the deep Cretaceous Glen Rose formation at depths ranging from 5,000 to 8,000 feet during hydrocarbon exploration and the conversion of an oil well to a water well (Texas Railroad Commission RRC, Form P-13). The TWDB is presently conducting research to be published in the future to determine if this is a viable new aquifer.

Figure 3-2 illustrates the complex structural and geological features of the Maverick Basin. Major structural features include the Edwards Arch and the Chittim Anticline. The Maverick Basin has been subdivided into subbasins (Sasser, 2016, Alexander, 2015).

The northern Maverick Basin consists of two deep and narrow Jurassic subbasins, the Moody and Paloma Basin (Figure 3-2). Both subbasins trend southeast-northwest (Alexander, 2015). The northern subbasin is separated from the central Maverick subbasin by the southwestern trending Edwards Arch (Figure 3-2) consisting of a series of interpreted basement highs (Alexander, 2015).

The central Maverick Basin consists of the Chittim subbasin which is a Jurassic-aged rift basin. Within the central portion of the Maverick Basin is a Cretaceous-aged thrust structure, the Chittim Anticline (Figure 3.2), which overlies Jurassic-aged carbonates and clastic sediments. (Alexander, 2015).

There has been minor hydrocarbon production from the Austin Limestone, Eagle Ford, Glen Rose and Pearsall Group (directly below the Glen Rose Formation) (Sasser, 2016, Tucker and Ruppel, 2011).

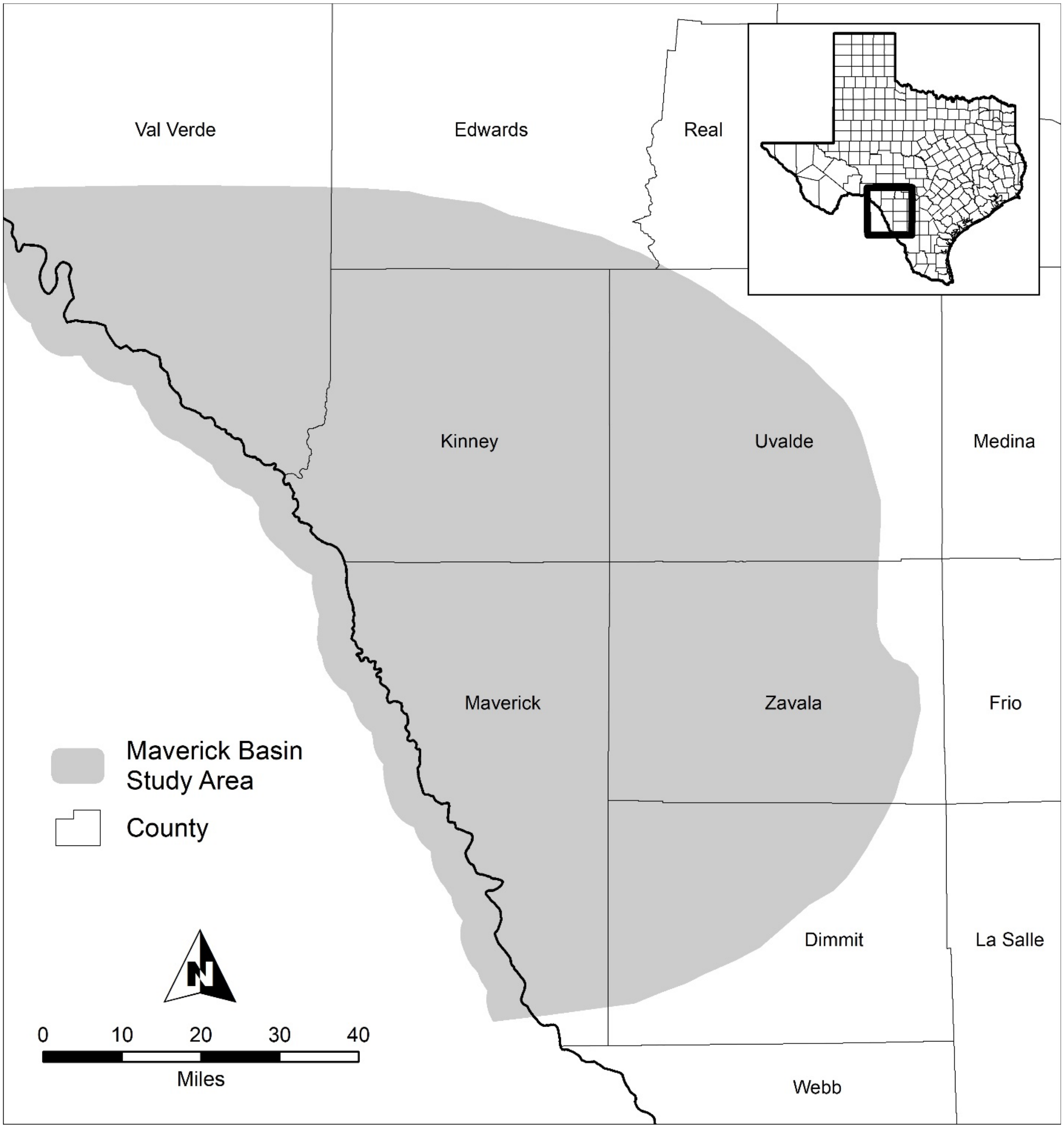

Figure 3-1. Extent of the Maverick Basin study area.

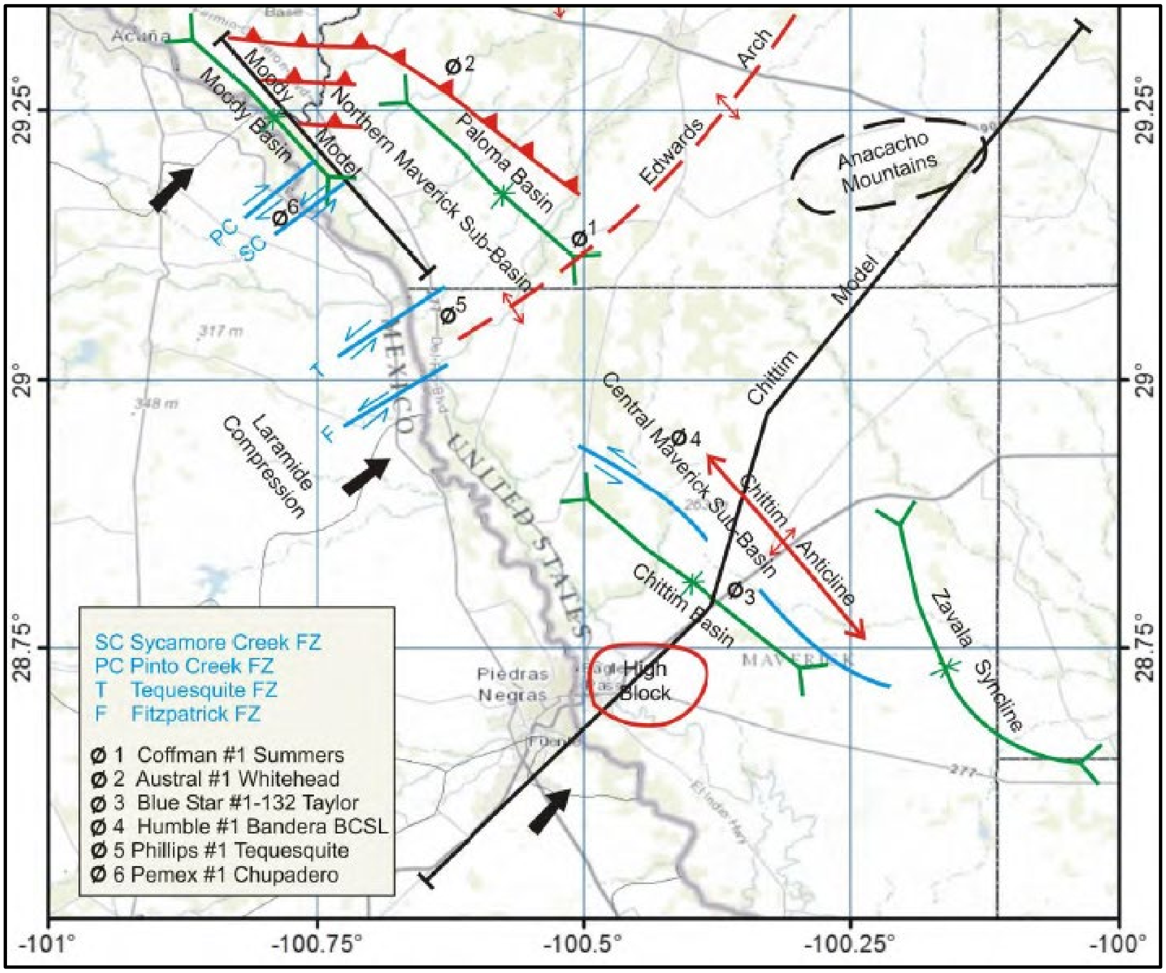

Figure 3-2. Maverick Basin structure and geological features (Alexander, 2015).

The Maverick Basin aquifer, Glen Rose Formation, is highlighted in blue in Figure 3-3. The following general stratigraphy and lithologic descriptions are from Clark (2003) describing the Uvalde County portion of the Maverick Basin. Figure 3-3 geologic descriptions begin (bold black outlined area) with the Del Rio Clay ranging from a bluish green to yellowish brown clay and has a thickness ranging from 50 to 110 feet thick.

Underlying the Del Rio Clay is the Edwards Group equivalent formation called the Salmon Peak with consists of mudstones and fossiliferous and locally karstified limestones. The Salmon Peak Formation ranges from 380 to 400 feet thick in Uvalde County (Figure 3-3). Underlying the Salmon Peak is the Edwards Group equivalent McKnight Formation which grades from brownish mudstone and limestone in the upper portion to laminated petroliferous fissile mudstone and mudstone and limestones at the base. The thickness of the McKnight Formation is approximately 280 feet (Clark, 2003).

Directly underneath the McKnight Formation is the West Nueces Formation, the basal formation of the Edwards Group (Figure 3-3). This formation consists of thick bedded, fossiliferous limestones and has a basal unit of nodular mudstone to limestone. This formation has variable thickness ranging from 140 to 320 feet (Clark, 2003).

Conformably underlying the base of the West Nueces Formation is the Upper Glen Rose Formation consisting of yellowish to tan thinly bedded limestones and marl and some interbedded evaporite beds (Figure 3-3). The thickness ranges from 350 to 500 feet (Clark, 2003). Figure 3-4 presents elevation contours of the top of the upper Glen Rose formation as mapped and by the Texas Railroad Commission of Texas (RRC, 2021).

The Lower Glen Rose limestone consists of a shallow carbonate platform characterized by middle shelf localized patch reef facies of rudistids, algae, and stromatolites. The original porosity of the Lower Glen Rose Limestone has been modified and increased by diagenesis (Anocha, 2008; Muncey and Drimal, 1993). The thickness of the lower Glen Rose is estimated to vary between 500 to 1,000 feet thick.

At the base of the Lower Glen Rose is the Pearsall Shale (Figure 3-3) is comprised of dark organic shale, marine marlstone and thick limestone shoals (Ewing, 2016).

Figure 3-5 illustrates the locations of the seven TWDB proposed Maverick Basin cores including C01229, C03838, C04604, C06087, C06530, C08881, and C00540. Core plugs were not obtainable from C00540. The Maverick Basin Cretaceous cores studied for this report were in either Maverick or Zavala counties, and included core plugs from the Austin Chalk, Glen Rose Limestone (upper and lower), Pearsall Shale and the basal Hosston formations.

<table>
<tr><th>System</th><th>Series</th><th colspan="2">Group</th><th>Formation</th><th>Thickness</th><th>Lithology</th></tr>
<tr><td rowspan="4">Upper Cretaceous</td><td rowspan="2">Gulfian</td><td rowspan="7">Fredericksburg</td><td rowspan="4"></td><td>Austin Chalk</td><td>300</td><td>Limestone</td></tr>
<tr><td>Eagle Ford</td><td>130 -150</td><td>Shale, Limestone</td></tr>
<tr><td rowspan="8">Comanchean</td><td>Buda Limestone</td><td>70 - 90</td><td>Limestone</td></tr>
<tr><td>Del Rio Clay</td><td>50 - 110</td><td>Clay</td></tr>
<tr><td rowspan="6">Lower Cretaceous</td><td rowspan="3">Edwards</td><td>Salmon Peak</td><td>380 - 400</td><td>Mudstone, Limestone</td></tr>
<tr><td>McKnight</td><td>200 - 280</td><td>Mudstone</td></tr>
<tr><td>West Nueces</td><td>140 - 320</td><td>Limestone, Mudstone</td></tr>
<tr><td rowspan="3">Trinity</td><td rowspan="3"></td><td>Upper Glen Rose</td><td>350 - 500</td><td>Limestone, evaporites</td></tr>
<tr><td>Lower Glen Rose</td><td>500 – 1,000</td><td>Limestone and patch reefs</td></tr>
<tr><td>Pearsall Shale</td><td>500 - 600</td><td>Shale, Limestone</td></tr>
</table>

Figure 3-3. Maverick Basin stratigraphic column (Uvalde County, modified after Clark, 2003).

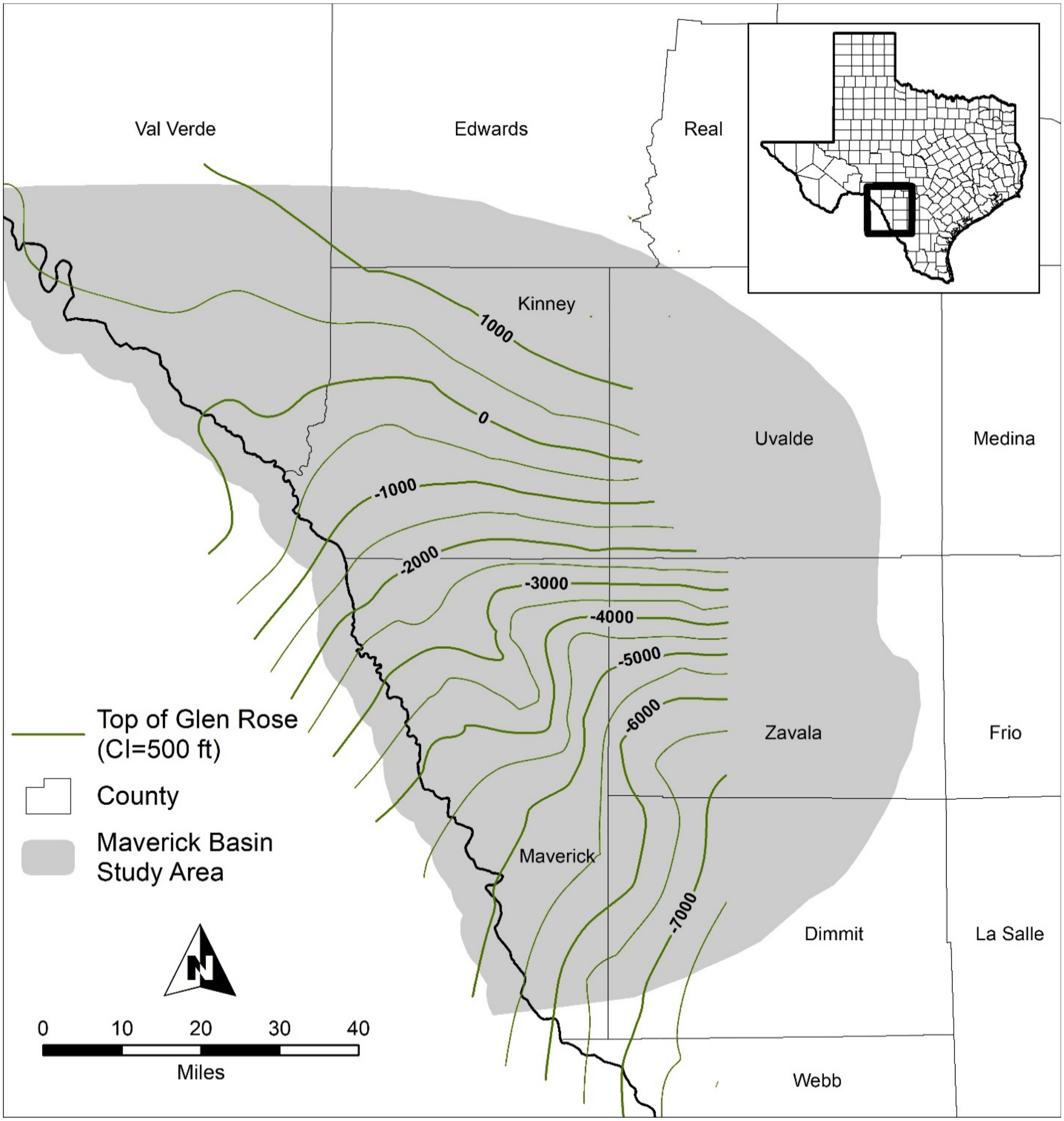

Figure 3-4. Structural top contours of Glen Rose (TWDB BRACS department, 2023)

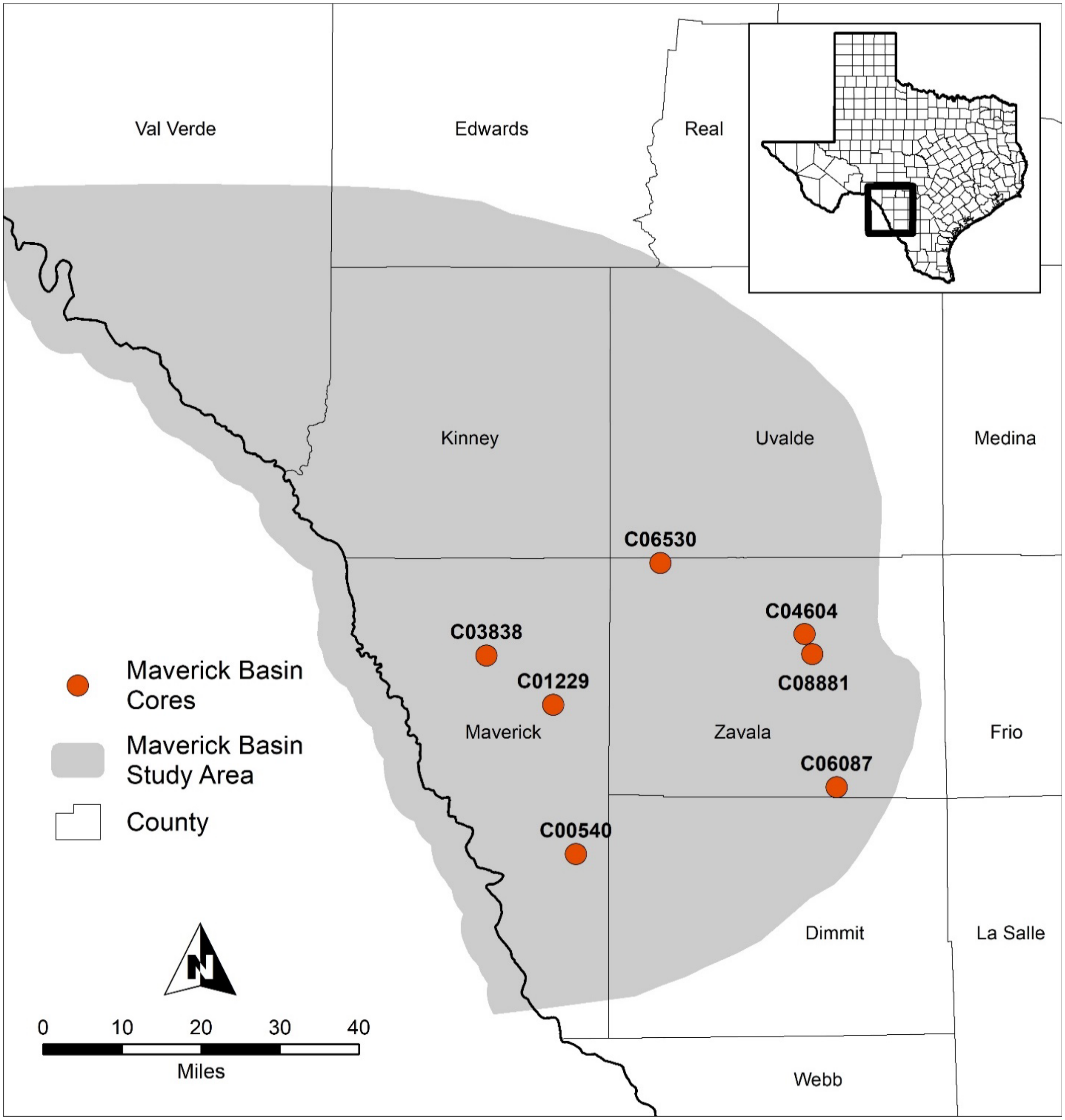

Figure 3-5. Maverick Basin study area core locations.

3.2 WOODBINE GROUP STRUCTURE AND GEOLOGY

The TWDB GAM modeled area of the Cretaceous Woodbine Group spans all or part of numerous counties in north central Texas (Figure 3-6). The TWDB BRACS portion of the Woodbine Aquifer extends approximately fifteen miles east of the Mexia-Talco Fault Zone as also illustrated in Figure 3.6.

The Woodbine Group consists of late Cretaceous basin-scale fluvial-deltaic siliciclastic deposition which reaches a maximum thickness of over 1,000 feet at locations along the basin's North-South axis (Kelly and others, 2014), The formations within the Woodbine Group include the Lewisville, Dexter and the Pepper Shale to the south and are comprised of conglomerate, sandstone with interbedded shale and clay (Hentz and others, 2014).

The conglomerate and sandstone intervals within the Lewisville and Dexter formations form the Woodbine Aquifer (Figure 3.7).

The NE trending Mexia-Talco Fault Zone paralleling the Gulf Coast displaces the Woodbine Aquifer sandstones (Figure 3-6). This down the coast faulting offset impacts the connectivity of Woodbine Aquifer sandstones resulting locally in reduced groundwater flow and quality (Harden, 2004). Figure 3-6 illustrates the outcrop fresh water (<1,000 mg/l, (TDS)) and downdip extent to brackish water to 3,000 mg/l total dissolved solids (TDS) within the Woodbine Aquifer. The TDS in the Woodbine Aquifer increases to the east moving downdip towards the East.

Figure 3-7 is a simplified stratigraphic column of the Cretaceous formations directly above and below the Woodbine Group**.** The Woodbine Group is unconformably overlain locally by Eagle Ford Shale with a thickness up to 500 feet (Kelly, et al. 2014 and Harden, 2004). Underlying the Woodbine Group is the Maness Shale which is interbedded with the Buda Limestone with a thickness ranging from 90 to 210 feet (Hentz and others, 2014).

Figure 3-8 is a west to east downdip cross-section that illustrates the Woodbine Aquifer and underlying Cretaceous formations moving towards the Gulf Coast.

Figure 3-9 illustrates the locations of the four initially proposed Woodbine cores. Research determined that two cores C00660 (Henderson County) and C09067 (Titus County) were located within the brackish extent of the Woodbine Formation. Cores C04557 (Van Zandt County, potentially Taylor Group) and C10397 (Titus County, potentially Glen Rose, or Pearsall) were identified as core intervals representing other Cretaceous formations.

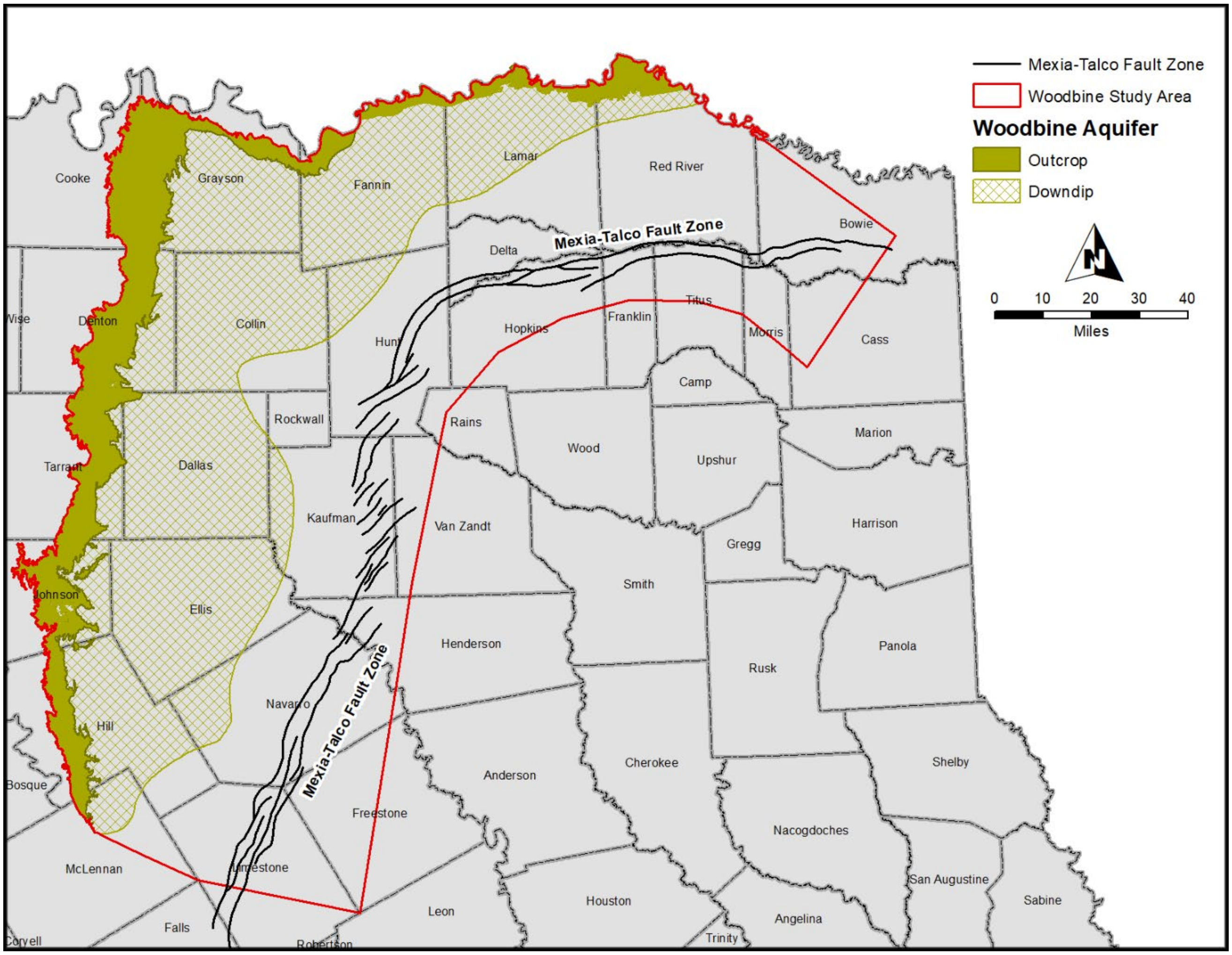

Figure 3-6. TWDB Woodbine Aquifer Extent & Structure within the BRACS Woodbine Aquifer study area.

System	Group	Formation		Thickness (feet)	Lithology
Upper Cretaceous	Eagle Ford	Eagle Ford		200 to 500	Shale, thin Limestone
	Woodbine	Woodbine Aquifer	Lewisville Dexter	Up to 1,090	Conglomerate, Sandstone Clay and Shales
		Pepper Shale (south)			Shale
Lower Cretaceous	Washita	Maness Shale or Buda		Interbedded shale and/or limestone 90 to 210	Shale and Limestone

Figure 3-7. Woodbine Aquifer stratigraphic column (Harden, 2004, Hentz, and others, 2014).

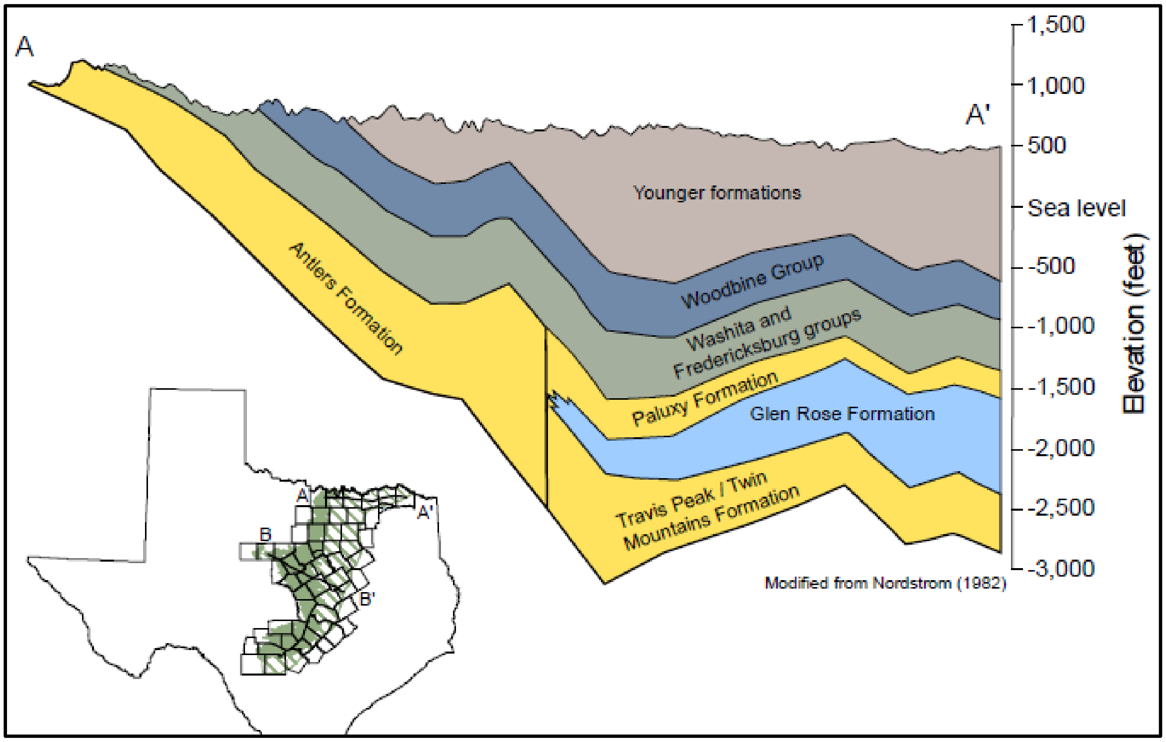

Figure 3-8. Woodbine Aquifer cross-section downdip to Gulf Coast (Kelley and others, 2014).

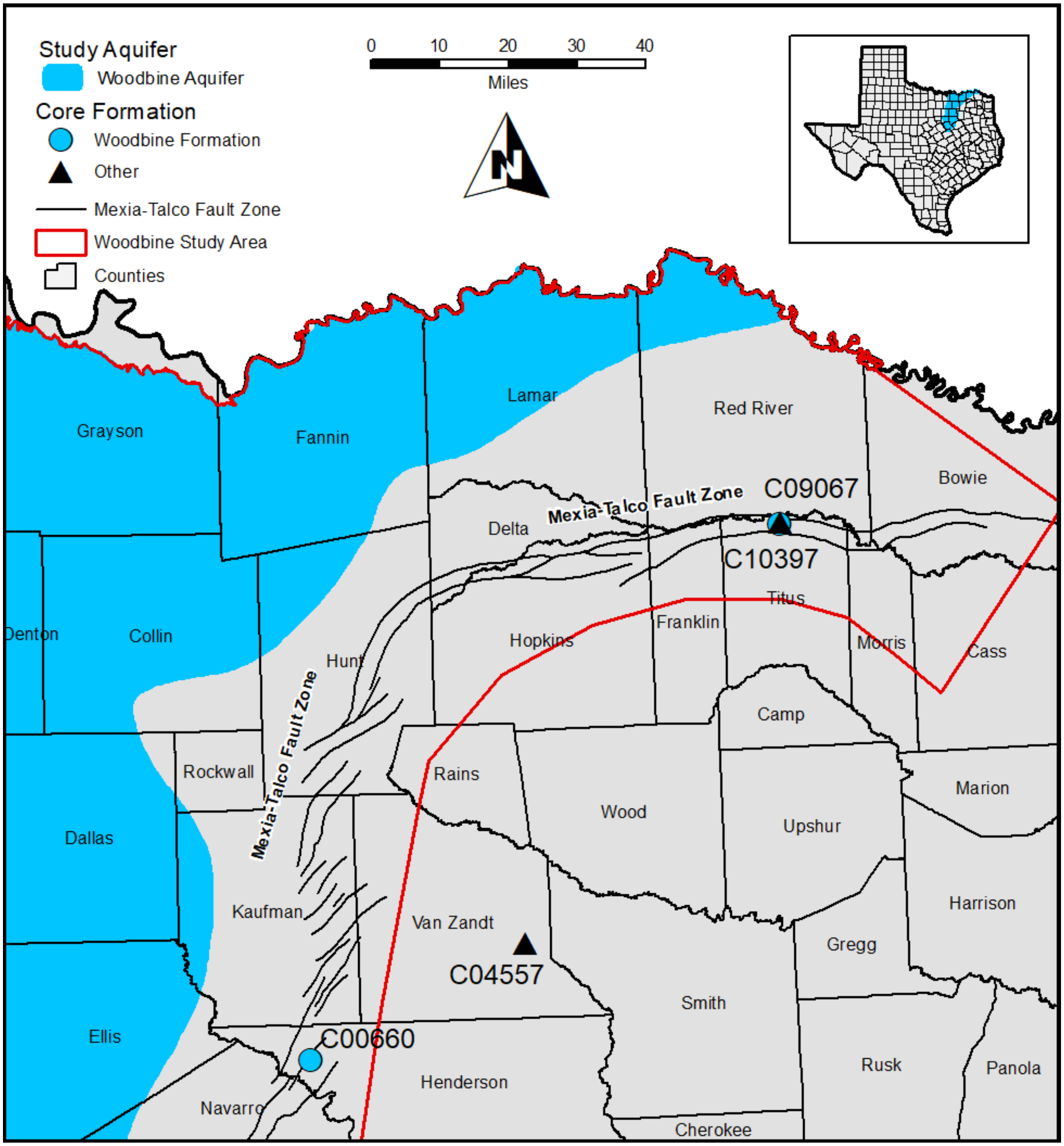

Figure 3-9. **Woodbine Aquifer core locations.**

3.3 Capitan Reef Complex Aquifer Structure and General Geology

The Capitan Reef Complex is a horseshoe shaped carbonate feature in the Permian-aged Delaware Basin in West Texas and consists of massive, fossiliferous limestone primarily composed of calcareous sponges and encrusting algae (stromatolites) (Figure 3-10). The Capitan Reef Complex includes the Tessey, Goat Seep, Capitan and Carlsbad limestones and has both forereef and backreef facies (Standen, 2009).

Figure 3-11 illustrates the back reef (Northwest Shelf) and fore reef (Delaware Basin) complex stratigraphic sequence of the Capitan Reef Complex Aquifer. Back reef facies are massive limestone and gypsiferous limestone and includes the Artesia Group (Yates, Queen, Seven Rivers, and Grayburg Formations). Fore reef facies consist of evaporites and thin bedded limestone, shale, and sandstone (Standen, 2009).

Subsequent tectonic activity, related faulting and localized karstification forms a series of disconnected and highly permeable segments of the Capitan Reef Aquifer (Standen, 2009).

Figure 3-12 illustrates the location of the Capitan Reef Complex core in Winkler County, C00270.

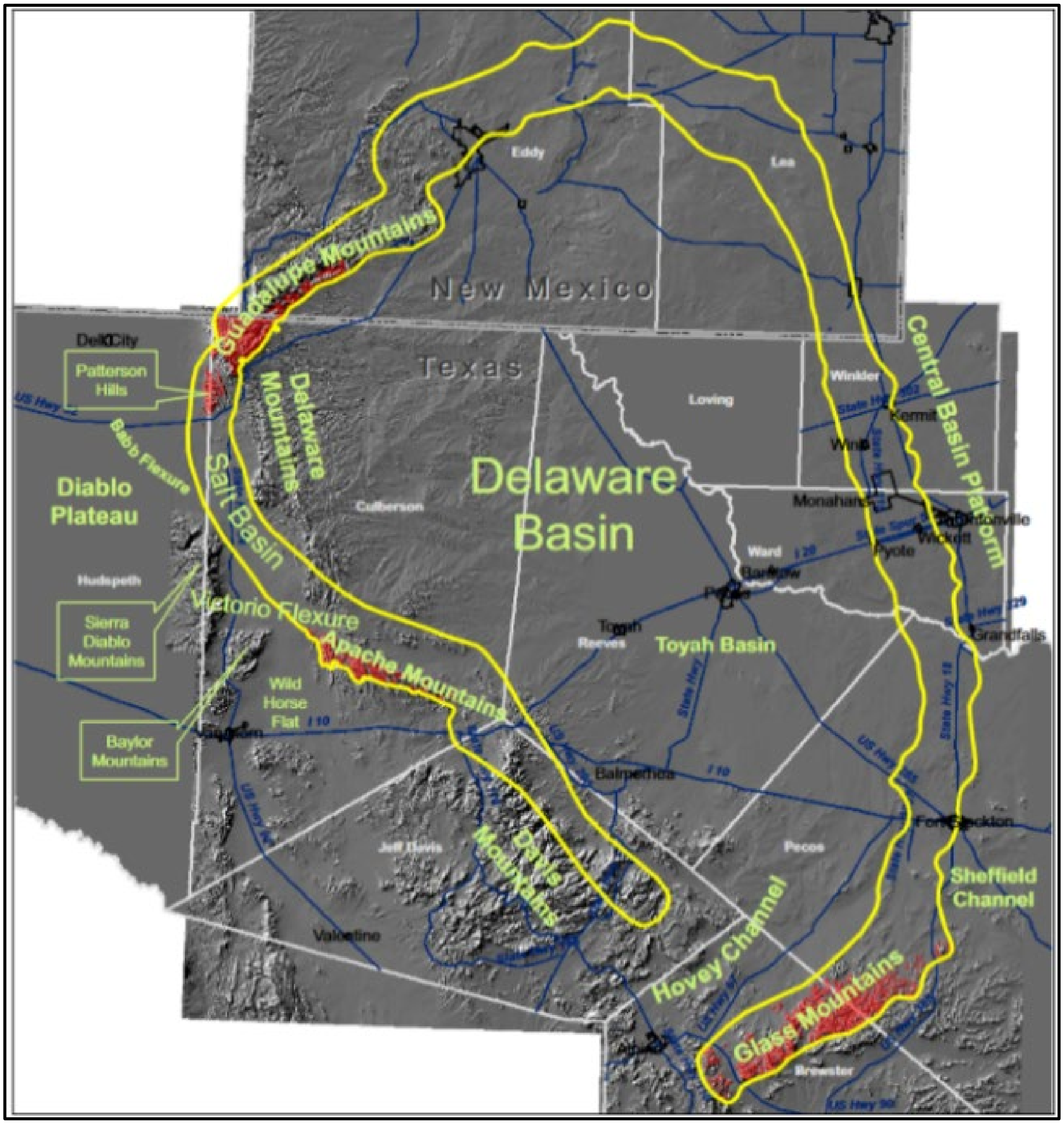

Figure 3-10. Capitan Reef Complex extent (Standen, 2009).

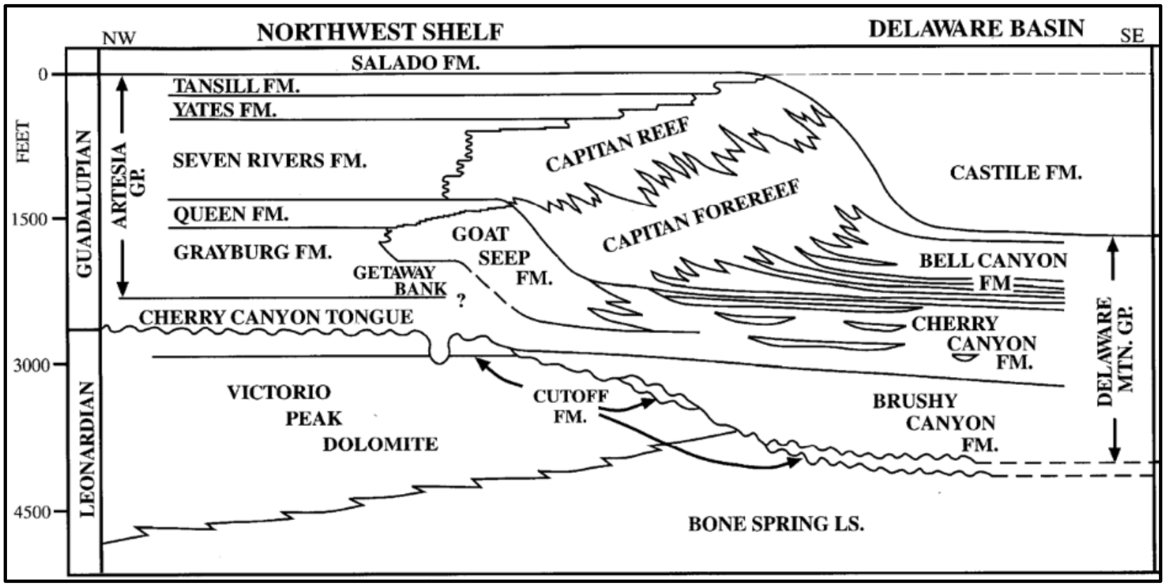

Figure 3-11. **Capitan Reef Complex stratigraphy schematic (Standen, 2009).**

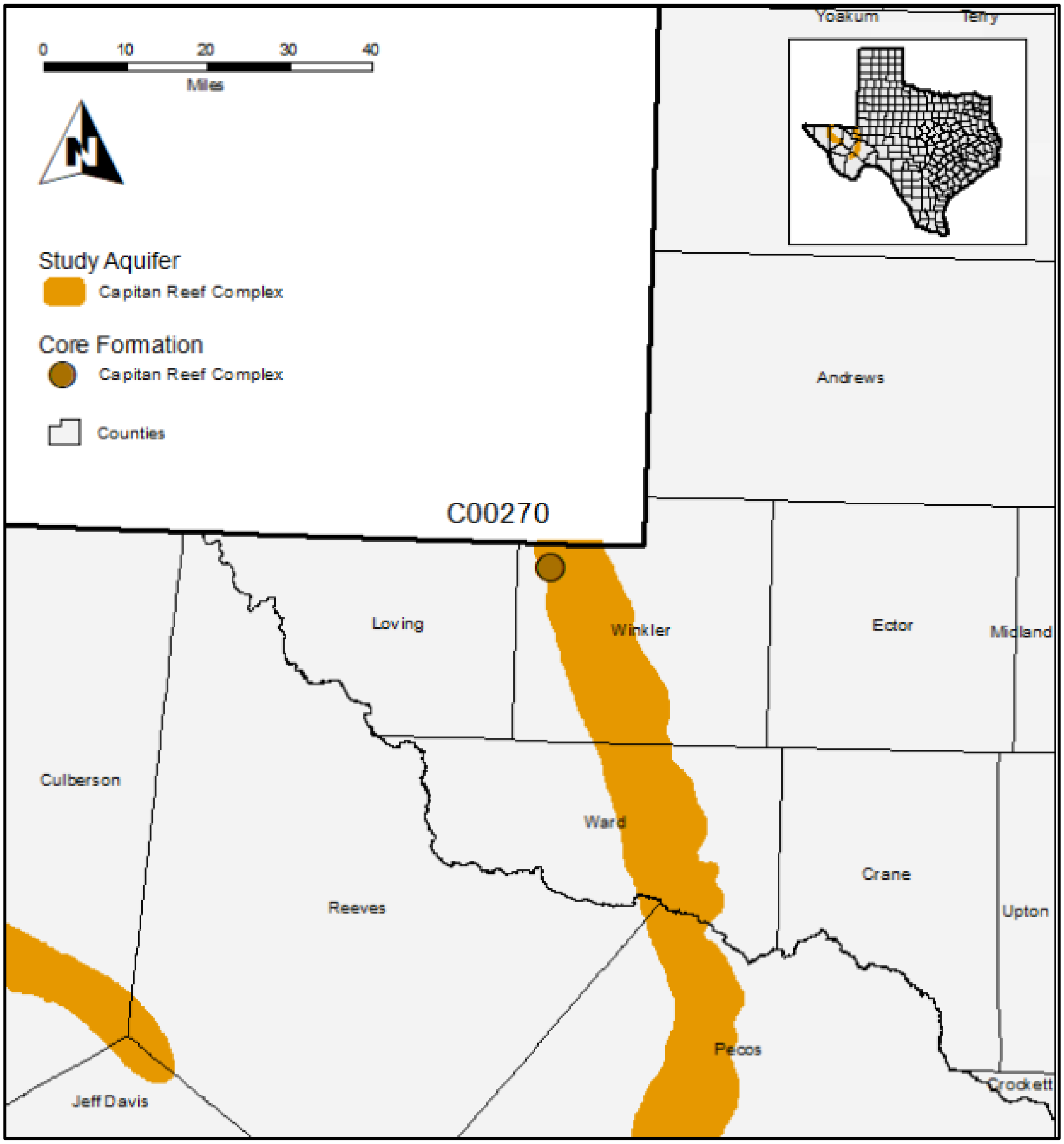

Figure 3-12. Capitan Reef Complex core location.

3.4 NORTHERN EDWARDS BFZ GENERAL GEOLOGY

Figure 3-13 illustrates the northern segment of the Balcones Fault Zone (BFZ) consisting of the Comanche Peak Limestone, Edwards Limestone, and Georgetown Formation. The Lower Washita and the Upper Fredericksburg are collectively referred to as the Edwards. The aquifer overlies older Cretaceous formations including the Walnut Formation and is overlain by younger units that consist of the Del Rio Clay, Buda Limestone, and Austin Chalk (Jones, 2003).

Figure 3-14 is a stratigraphic column from land surface in the core plug vicinity. The top of the core interval includes the Austin Chalk, a chalky, grayish white, microgranular calcite with pyrite nodules commonly weathering to limonite and the thickness of 350 feet. (Rodda and others, 1970).

Underlying the Austin Chalk is the Eagle Ford Shale consisting mostly of dark gray, massive, calcareous clay, with about nine feet of thin interbeds of silty and sandy, flaggy limestone, clay with a thickness of about forty feet (Rodda and others, 1970).

Below the Eagle Ford Shale is the Buda Limestone comprised of a hard, fine grained, light gray to pale orange bioclastic limestone with marly interbeds, commonly glauconitic, pyrite, hard, and locally massive. The thickness is 35 feet or less (Rodda and others, 1970).

Underlying the Buda Limestone is the Del Rio Clay, a dark olive or bluish gray to yellow-brown, pyritic, gypsiferous clay and marl which contains iron nodules and abundant clams and oysters. The Del Rio is about 75 feet thick and is the upper confining unit of the Edwards Aquifer (Rodda and others, 1970).

The top of the Edwards Group is the Georgetown Formation consists mostly of thin interbeds of gray to tan, richly fossiliferous, nodular, fine-grained limestone, marly limestone, and marl. Fossil oysters are varied and abundant; many beds are composed of oyster shells. Thickness ranges from 40 to 60 feet (Rodda and others, 1970).

Underlying the Georgetown Formation is the Edwards Formation which is generally characterized by tan to light gray rudist limestones, dolomite, nodular chert, and solution-collapse features. The Edwards Limestone has been subdivided into members including the Kainer, Person, Kiamichi, and Duck Creek formations. The Edwards Limestone is vuggy in places because of the occurrence of solution-collapse zones which are parallel bedding planes and are the result of dissolution of gypsum beds (Rodda and others, 1970).

Figure 3-15 illustrates the location of the BFZ core C11333 in northern Travis County.

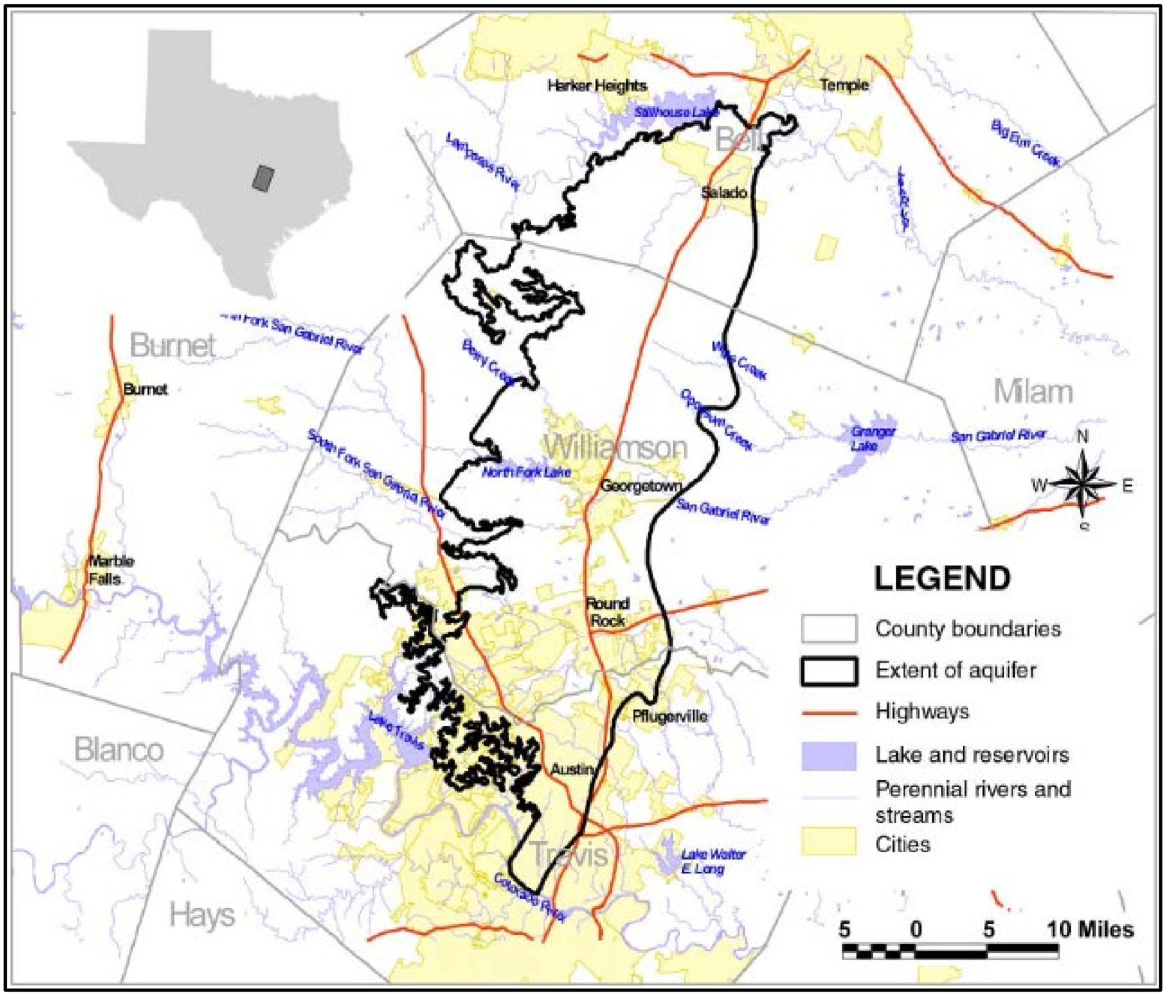

Figure 3-13. **Northern extent of the Edwards Balcones Fault Zone (BFZ) Aquifer (Jones, 2003).**

Group	Formation	Hydrologic Unit	Maximum Thickness (Feet)
Navarro		Navarro and Taylor Group	850
Taylor			
Austin		Austin Chalk	450
Eagle Ford	Eagle Ford		50
Washita	Buda Limestone		50
	Del Rio Clay		60
	Georgetown Formation	Edwards Aquifer	100
Fredericksburg	Edwards Limestone		200
	Comanche Peak Limestone		50
	Walnut Formation		150

Figure 3-14. Northern Edwards (BFZ) Aquifer stratigraphic column (Jones, 2003)

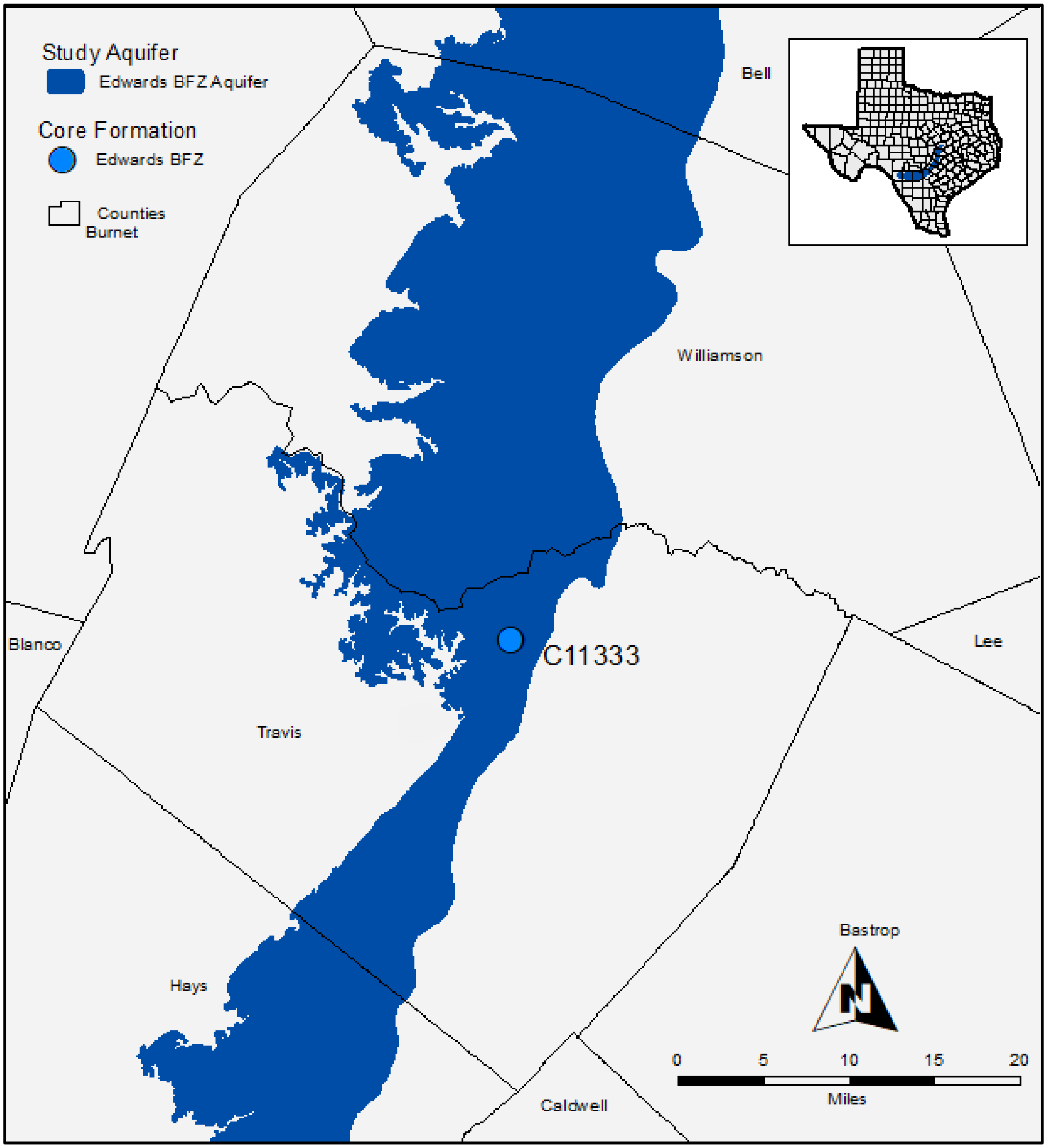

Figure 3-15. Northern Edwards (BFZ) core location.

Section 4: SECTION 4: CORE LITHOLOGY SUMMARIES

The following brief summaries of the lithology and bulk minerology analysis results for each core were prepared by Ms. Lauren Swientek of LRE Water.

4.1 C00270, GILFORD & MITCHELL, LITTLE WOLF 2 - CAPITAN REEF FORMATION

The C00270 Little Wolf #2 core consists of an interval from 3,070 feet to 3,362 feet within the Capitan Reef Formation in Winkler County. The interval consists of dolomite, algal and peloid packstones, floatstones, and wackestones. Bindstones and terrigenous mud laminations are common. Skeletal material consists primarily of gastropods, sponges, and fusulinids. Although the core is vuggy in areas, anhydrite has filled many of the cavities. Scours and dissolution features are common. Styolites, some large, are abundant throughout the core. A detailed lithologic description is available in Appendix B. Four core plugs were extracted from C00270 at 3,124.5 feet, 3,198.5 feet, 3,254.5 feet, and 3,328.5 feet.

4.2 C00660, DEARMAND PEARSONS, ESTATE 1 – WOODBINE FORMATION

The C00660 DeArmand Pearsons Estate #1 core consists of intervals 3,016 feet to 3,018 feet and 3,104 feet to 3,126 feet within the Woodbine Formation in Henderson County. Two distinct lithologies within the reviewed core intervals are the gray, laminated, argillaceous lime mudstone from 3,014 feet to 3,018 feet and the parallel and cross-bedded, red and tan, fine sandstone from 3,105 feet to 3,126 feet. Skeletal material are concentrated within event beds. Weakly laminated clay beds are located within the massive sandstone beds from 3,105 feet to approximately 3,018 feet (with low core recovery in this area). The detailed lithologic description is available in Appendix B. Two core plugs were extracted from C00660 at 3,104 feet and 3,125 feet.

4.3 C01229, CONOCO, CHITTIM 155-1 – UPPER AND LOWER GLEN ROSE FORMATION

The C01229 Cono-Chittim #155-1 core consists of interval 4,770 feet to 5,696 feet within the Glen Rose Formation in Maverick County. The examined core interval ranges from a dolomitized skeletal peloidal grainstone from 4,770 feet to 4,781 feet to a bioturbated skeletal lime mudstone from 5,691 feet to 5,696 feet and a lithoclast-rich highly fossiliferous, dolomitized lime rudstone from 5,988 feet to 6,038 feet. Large skeletal material found throughout most of the core primarily consists of calcite-replaced rudists (some less than one inch), oysters, mollusks, and chondrodonts. The detailed lithologic description is available in Appendix B. Four core plugs were extracted for C01229 at depths: 4,771.5 feet, 5,693 feet, 6,003 feet, and 6,037 feet.

4.4 C03838, Prime Operating, La Paloma 1-84 – Lower Glen Rose

The C03838 Prime Operating, La Paloma #1-84 core consists of the interval from 5,261 feet to 5,381 feet within the lower Glen Rose Formation in Maverick County. The Glen Rose Formation occurs between 5,261 feet and approximately 5,355 feet of the core interval. It consists primarily of a partially dolomitized, grain-rich lime rudstone with many styolites and healed scours. Skeletal material primarily consists of recrystallized corals and oysters. Stromatoperoids and anhydrite nodules are also abundant through the section. The Pearsall Formation, overlain by the Glen Rose Formation, occurs from approximately 5,355 feet to 5,381 feet in the observed core interval. It is composed of a burrowed lime mudstone intermixed with terrigenous mud. Pressure solution seams and healed vertical and horizontal fractures are common. The transition between the two formations consists of abundant stained dissolution features and pathways for approximately six feet (5,349 feet to 5,355 feet). The detailed lithologic description is available in Appendix B. Three core plugs were extracted at depths 5,328.5 feet, 5,338.5 feet, and 5,362.5 feet.

4.5 C04557, Richard Griffin, Howell 2 – Cretaceous, Taylor Group

The C04557 Richard Griffin, Howell #2 core interval reviewed for this study was from 2,780 feet to 2,836 feet within the Woodbine Formation in Van Zandt County. The examine core interval was composed of bioturbated, massive to wavy, laminated, argillaceous lime wackestones and mudstones with skeletal material consisting primarily of inoceramids and mollusks. Massive to thinly laminated terrigenous siltstones with framboidal pyrite and anhydrite interbed the argillaceous lime wackestones. Here, rip-up clasts and packstone event beds are common. The detailed lithologic description is available in Appendix B.

Early in the project, these three core plugs (2,782 feet, 2,811 feet and 2,830.5) were extracted from this core but were determined not to be representative of the Woodbine Aquifer but probably the Cretaceous Taylor Group using the geophysical log. These plugs were not submitted to Core Labs for analysis but are included in the report submittal to the TWDB.

4.6 C04604, Tenneco Oil Co., Chester Kiefer 2 – Lower Glen Rose and Pearsall

The C04604 Tenneco Oil Co., Chester Kiefer #2 core reviewed for this study consisted of Lower Glen Rose from 7,500 feet to around 7,880 feet and Pearsall Formation 7,880 feet to 7,968 feet in Zavala County. Gaps in the observed core interval occur between 7,594 feet to 7,700 feet and 7,749 feet to 7,880 feet.

The intervals 7,500 feet to 7,749 feet within the Lower Glen Rose Formation consists of skeletal, oncolytic lime wackestones to mud dominated packstones. Terrigenous mud laminae containing dolomite silt interbeds the lime wackestone. The abundance of oncolids and other skeletal fragments varies, and calcite filled scours and vugs are common. Framboidal pyrite is also common throughout the interval. Terrigenous (often oxidized) mud laminae may provide a system of connected pathways for fluid transport. Three core plugs extracted from the Lower Glen Rose Formation at depths 7,502.2 feet, 7,585.5 feet and 7,742.5 feet.

The core transitions into the Pearsall Formation at 7,880 feet, where the interval from 7,880 feet to 7,915 feet consists of fissile, interbedded lime and terrigenous mudstones that lack skeletal material but are abundant in oxidized grains. Below 7,915 feet to 7,968 feet the Pearsall consists of partially dolomitized and bioturbated lime wackestones to mudstones. Terrigenous laminae and skeletal fragments are common but not as abundant as in the Pearsall Formation. The detailed lithologic description is available in Appendix B. Two core plugs were extracted from the Pearsall Formation at depths of 7,920 and 7,948 feet.

4.7 C06087, Getty Oil 2 Weaver A – Austin and Edwards Formations

The C06087 Getty Oil #2 Weaver A core reviewed for this study consisted of intervals 7,292 feet to 7,348 feet of the Austin Chalk Formation and 7,840 feet to 7,874 feet of the Edwards Group in Zavala County. A gap within the observed core interval occurs from 7,351 feet to 7,840 feet.

The Austin Chalk Formation consisted of white, tan, and light gray, heavily bioturbated lime mudstone. Large styolites and other dissolution features are common, as well as floatstone event beds that can are adjacent to the dissolution features. Terrigenous mud drapes also occur within this interval. The Edwards Group consists of partially dolomitized skeletal lime wackestones to floatstones and laminated lime mudstones with pyrite. Scour surfaces and healed vertical and horizontal fractures are common within the dolomitic lime wackestones and floatstones. The detailed lithologic description is available in Appendix B.

Three core plugs were extracted from this core, one plug was taken from the Austin Chalk Formation at 7,322 feet and two plugs were taken from the Edwards Group at 7,846.5 feet and 7,867.5 feet.

4.8 C06530, Eason Oil, Flowers Ward 1 – Hosston Formation

The C06530 Eason Oil, Flowers Ward #1 core observed for this study consisted of interval 6,908 feet to 6,920 feet of the partially dolomitized, red, medium to coarse sandstones and conglomerates of the Hosston Formation in Zavala County. Sandstones consist of red, moderately to poorly sorted, subrounded, medium to coarse grains with parallel and cross bedding. The conglomerates contain red sand with white, yellow, red, black, and brown sub rounded pebbles. The detailed lithologic description is available in Appendix B. Two core plugs were extracted from C06530 at 6,910.5 feet; the second core plug was at 6,911.5 feet.

4.9 C08881, Richard Haas, Elizabeth Bartlett 1A – Lower Glen Rose Formation

The C08881 Richard Hass Bartlett #1A core observed for this study consisted of interval 7,150 feet to 7,199.5 feet within the Lower Glen Rose Formation in Zavala County. Interval 7,150 feet to 7,172 feet consisted of a skeletal lime floatstone to wackestone with terrigenous mud drapes. Burrowed in places. Skeletal material, primarily mollusks, has been replaced by calcite. Many large styolites healed fractures. Interval 7,172 feet to 7,186 feet consisted of a lithoclast-rich lime floatstone to wackestone. Many styolites and healed fractures were observed. Anhydrite nodules were common and skeletal material, primarily mollusks, has been replaced by calcite. Interval 7,186 feet to 7,199.5 feet consisted of a lime wackestone to mudstone that is dolomitized and argillaceous in areas. Terrigenous mud drapes and scour surfaces are common. Some pyrite nodules were observed throughout the interval. The detailed lithologic description is available in Appendix B. Three core plugs were extracted from depths of 7,163 feet, 7,169 feet, and 7,189.5 feet analyses of bulk mineralogy.

4.10 C09067, Sun Oil, Bankhead Hoffman Unit 1 – Woodbine Formation

The C09067 Sun Oil, Bankhead Hoffman Unit #1 core reviewed for this study consisted of interval 3,437 feet to 3,746 feet of the Woodbine Formation in Titus County. Gaps in core occur within this section at 3,482 feet to 3,561 feet, 3,568 feet to 3,631 feet, 3,646 feet to 3,710 feet and 3,722 feet to 3,737 feet.

The 3,437 feet to 3,562 feet core interval consisted of parallel to cross-bedded argillaceous fine sandstones, interbedded with burrowed lime wackestones to mudstones and shale. Some events beds contain skeletal fragments and lithoclasts. Intervals of organic-rich mudstones have expanded, and yellow and white sulfate minerals have precipitated out since being slabbed for this project. The 3,562 feet to 3,722 feet interval consisted of green, yellow, orange, red, and brown bioturbated siltstone paleosols. The stratification was not preserved. Burrows, root traces, and hematite grains were observed within the section. The 3,737 feet to 3,746 feet interval consisted of a gray to green, glauconitic, argillaceous fine sandstone with parallel bedding and pebble event beds. Cementation of the paleosol is weak within this interval. 3,746 feet to 3,764 feet consists of tan, red, and greenish gray, weakly laminated to massive argillaceous siltstone. Bioturbation, scour surfaces, and soft sediment deformation structures are common within this interval. The detailed lithologic description is available in Appendix B. Five core plugs were extracted from C09067 at 3,475 feet, 3,635 feet, 3,719 feet, 3,738 feet, and 3,748 feet.

4.11 C10397, Sun Oil, Bankhead 20 –Lower Glen Rose

The C10397 Sun Oil, Bankhead 20 core reviewed for this study consisted of interval 4,866 feet to 4,906 feet within the Lower Glen Rose Formation in Titus County. Gaps within the observed core interval exist between 3,482 feet to 3,561 feet, 3,568 feet to 3,631 feet, 3,646 feet to 3,710 feet, and 3,722 feet to 3,737 feet.

Interval 4,866 feet to 4,881.5 feet consists of massive to laminated lime mudstone. Argillaceous, bioclast-rich, and organic-rich in areas. Skeletal material is primarily mollusks and gastropods. Fissile in areas. Some scour surfaces and many storm deposits, some are peloidal. From 4,881.5 feet to 4,906 feet the core is a massive lime mudstone wackestone with few bioclasts. Organic-rich mud laminae are present at 4,889 feet and from 4,897 feet to 4,902 feet. Burrows, lithoclasts, and argillaceous sediment are common. Large, healed scour surfaces and styolites are present throughout the section and are abundant from 4,902 feet to 4,906 feet. The detailed lithologic description is available in Appendix B. Three core plugs were taken from the C10397 core at 4,870.5 feet, 4,883.5 feet, and 4,897.5 feet.

4.12 C11333, MHC Exploration Corp, ACC #1 – Austin Chalk, Eagle Ford, Buda, and Edwards Group

The C11333 MHC Exploration Corp., ACC #1 core reviewed for this study consisted of 12 feet to 460 feet within the Austin Chalk, Eagle Ford, Buda Limestone, and the Edwards Group in Travis County. A core gap occurs from 125 feet to 357 feet, where the core size changes from three inches to 1.75 inches from 357 feet to 460 feet.

Interval from twelve feet to 80 feet within the Austin Chalk consists of argillaceous lime wackestones to mudstones. Bioturbation and lithoclasts are common, as well as pyrite nodules. Terrigenous mud laminae are intermittent and contain dolomitized silt. There are short intervals (< 1feet) of parallel to wavy, laminated terrigenous muds interbedding the lime wackestones to mudstones. Styolites and healed scours are common.

Interval 80 feet to 125 feet within the Eagle Ford Formation consists of a laminated lime mudstone. Pyrite nodules are common and few event beds are present. Skeletal fragments are uncommon and absent from most of the interval. Few scour surfaces and no styolites are present. Small sections (< 0.5 feet) of orange, yellow, and green clays are located within the mudstone from 97 feet to 109 feet. Storm deposits are also more abundant within this interval and skeletal material is found within these beds.

Interval 125 feet to 132 feet is the Buda Limestone consisting of a massive lime wackestone with red oxidized grains and limited skeletal material. Healed scours and terrigenous mud drapes are common.

The interval from 357 feet to 460 feet is the Edwards Group consists of a massive lime to dolomitic wackestone to packstone. Sponge borings and burrows are common. Vuggy in areas, indicating internal, primary porosity. Scours and dissolution seams are common. The interval is locally dolomitized and increasingly recrystallized after 438 feet. Organic-rich from 417.5 feet to 419 feet with stained fractures present to 425 feet indicating possible fluid pathways. Healed fractures are common throughout interval and large slickenside is present at 428.5 feet. Burrows and scours common after 450.5 feet. The detailed lithologic description is available in Appendix B. Five core plugs were extracted from the C11333 core at 61.5 feet in the Austin Chalk, 100.5 feet in the Eagle Ford, 127.5 feet in the Buda Limestone and 433.5 feet and 457.5 feet in the Edwards Group.

Section 5: SECTION 5: CORE PLUG SELECTION, SAMPLING, PACKAGING AND SHIPPING

5.1 SELECTION CRITERIA FOR CORE PLUGS

The TWDB project manager allowed Mr. Standen to select core plug intervals after the core was initially reviewed. Plugging intervals are representative of different lithologies or geological textures within the core interval(s).

Upon selecting core intervals for each core hole, Mr. Standen placed a red sticker on each core plug location to be further reviewed by CRC staff (Mr. Brandon Williamson) and the CRC manager (Mr. Nathan Ivicic) for correct depth, core piece interval length and a core integrity determination. Mr. Standen then labeled core plug sample envelopes with the core hole identification information and confirmed core interval information. Table 5-1 summarizes the core plugs extracted for this study.

5.2 CORE PLUG EXTRACTION AND PACKAGING

Upon approval from the CRC staff and manager, CRC staff moved the selected core intervals (at least three inches in length) to the CRC saw room for extraction (Table 5-1). After each core plug was extracted, the core plug was rinsed off with distilled water, dried and then placed into the prepared sample envelope. Mr. Standen then reviewed each extracted core plug to verify plug integrity and core plug length (one inch long or greater) and returned the plug to the prepared sample envelope.

Table 5-1. Core plug extraction summary table.

Core ID[1]	County	Operator, Lease, Well Number	API ID[2]	BRACS ID[3]	Aquifer	Core Top/Bottom	Core Plugs
C00270	Winkler	Gifford, Mitchell & Weisenbaker, Lone Wolf #2	49530886	--	Capitan Reef Complex	3070/3362	3124.5’ 3198.5’ 3254.5’ 3328.5’
C00660	Henderson	DeArmand, Hunt & McMillion, Pearsons #1	21300119	--	Woodbine	3016/3026	3104’, 3125’
C01229	Maverick	Continental Oil, Chittim #155-1	32300084	--	Maverick Basin	4770/6038	4771.5’, 5693’, 6003’, 6037’
C03838	Maverick	Prime Operating, La Paloma #1-84	32332450	--	Maverick Basin	5261/5381	5328.5’, 5338.5’, 5362.5’
C04604	Maverick	Tenneco Oil, Chester Kiefer #2	50700218	86710	Maverick Basin	7500/7968	7502.2’, 7585.5’, 7742.5’, 7920’, 7948’
C06087	Zavala	Getty Oil, Weaver #2, “A”, Zavala County	50730444	--	Maverick Basin	7292/7877	7322’, 7846.5’, 7867.5’
C06530	Zavala	Eason Oil, Flowers Ward #1	50732296	--	Maverick Basin	6908/6918	6910.5’, 6911.5’
C08881	Zavala	Richard Hass, Elizabeth Barlett #1A	50730132	86716	Maverick Basin	7150/7200	7163’, 7169’, 7189.5’
C09067	Titus	Sun Oil, Bankhead Hoffman Unit #1	44930055	--	Woodbine	3410/3764	3475’, 3635’, 3719’, 3738’, 3748’
C10397	Titus	Sun Oil, Bankhead #20	44930212	--	Woodbine	4858/4906	4870.5, 4883.5, 4897.5
C11333	Travis	N. A. TWDB Well	N/A	--	Edwards	12/460	100.5, 127.5, 433.5, 457.5
C00540[4]	Maverick	Union Producing, Halsell #29-1	32301126	--	Maverick Basin	6020/8978	Highly broken, plugs not taken.
C04557[4]	Van Zandt	Richard Griffin, Howell #2	46730737	--	Woodbine	2780/2836	Too shallow, plugs not submitted. (2785, 2811, 2830.5)

[1]Core ID = Bureau of Economic Geology, Core Research Center core tracking code
[2]API ID = American Petroleum Institute, hydrocarbon well tracking number
[3]BRACS ID = Geophysical log BRACS database tracking number
[4]No core plug analysis

5.3 Core Plug Shipping

The required Core Labs forms for shipping and core analyses were completed, including each core identification, core plug interval and type of analyses requested. The Core Labs forms were both emailed and included within the FedEx box. The FedEx box was shipped priority overnight with morning delivery.

The required formation pressure and estimated total dissolved solids (TDS) information for each core plug was provided by Mr. Mark Robinson at the TWDB and was usually included or was later provided with shipments to Core Labs.

All shipments were confirmed as received with the Core Lab's Project Manager, Stephanie Livesay, the next business day. There were four core plug batch shipments to Core Labs, the shipping dates, batch number and description of source of the core plugs shipped are listed below.

- Shipment #1, April 29, 2023, (nine plugs total), C00270, (4 plugs) Little Wolf #2, Winkler County and C04604 (5 plugs) Chester Kiefer #2, Zavala County
- Shipment #2, May 16, 2023, (nine plugs total), C06530, (2 plugs) Flowers Ward #1, Zavala County, C01229, (4 plugs), Chittim #155-1, Maverick County, and C08881, (3 plugs) Hass Bartlett 1A, Zavala County.
- Shipment #3, June 8, 2023, (eleven plugs total), C03838, (3 plugs) La Paloma #1-84, Maverick County, C10397 (3 plugs), Bankhead #20, Titus County, C00660, (2 plugs) DeArmand Pearson #1, Henderson County and C06087 (3 plugs), Weaver #2 "A", Zavala County
- Shipment #4, June 29, 2023, (ten plugs total) C09067, (5 plugs) Bankhead Hoffman Unit 1, Titus County and C11333, (5 plugs), ACC#1, Travis County

Section 6: SECTION 6: CORE PHOTOGRAPHY

Core photography, photo processing and Section 6 of this report were completed by Sean C. Murphy. A search of the available BEG references indicated that there were no existing core photographs for any of the thirteen wells for this study.

Core lithologic logging and core photography often occurred weeks apart. There was a concern that core box photography may not match the core box lithologic descriptions. During the initial core box screening, a white laminated label with a sequential number was placed in the upper left-hand corner of the core box which stayed with the core box during lithologic logging and core box photography. Core box number and box depth intervals for each core box was entered into the TWDB approved lithologic logging and photography documents (Appendix B (lithologic descriptions) and Appendix C (Core Photography).

The core box number provided the ability to track and guarantee that the core box lithologic logging depth interval would match and core box photograph depth interval. The intent of the core photography document was only to provide a reference to confirm the core lithologic description intervals matched core box photography intervals for each core box.

6.1 CORE PHOTOGRAPHY INTRODUCTION

This task resulted in the completion of 144 core box photos documenting thirteen wells and more than 400 feet of core. These core box photographs (Appendix C) supplement the other compiled datasets (Appendix A, Core Geophysical Logs, Appendix B, Core Lithologic Descriptions and Appendix D, Core Plug Analyses) and should provide hydrogeologists with a better comprehensive lithologic characterization of these BRACS aquifers. The intent is to deliver photographs that convey enough detail and resolution that geoscientists can readily identify lithologies, color, bedding features, fossils, textures, and formation boundaries. Professional quality photographs should minimize or eliminate the need to re-examine the rocks in the core facility.

Specimen photography for scientific research and for archiving and sharing natural history and museum collections is well established, and some protocols have been codified that inform the techniques and procedures adopted for this project. These include gauging the size of the specimen for the viewer by including a reference scale within the picture frame.

Controlling color accuracy can be difficult, but photographers use a continuous source lamp of known wavelength and place a readily available standard color card in each photograph; this ensures that computer monitors can be calibrated and/or prints can be adjusted to reproduce the color of the specimen accurately. A greyscale card references the exposure, as dark specimens may require over-exposure and light specimens may require under-exposure to be able to discern surface textures and details.

A professional grade, mirrorless digital camera with a wide-angle lens capable of producing very sharp images was used for this project. Photographs were taken using the smallest possible exposure index (historically referred to as "film speed" or ISO) to minimize the signal-to-noise ratio on individual pixels to achieve image sharpness. The highest resolution that the camera could produce (3888 x 5184) was selected, which was cropped in the final image down to the size of the box. "Raw" digital format images were captured to maximize software processing flexibility.

Every effort was made to maintain consistency from the first box of core to the last. All the core was imaged using the same camera (same settings and focal length) in the same location with the same treatments (oiling) and processed using consistent post-digital settings (Adobe Lightroom and Photoshop). The lighting setup was improved after the first well (C04604_Tenneco, Chester Kiefer #2) with the addition of a polarization filter over the light source (described below, in Core photography lighting**).**

6.2 Core Photography Preparation and Orientation

The wells selected for this project had been slabbed by a rock saw to present a flat surface. Most of the cuts were clean, presenting an almost "polished" flat surface, but some were rough, clearly presenting radial cut marks. Both surfaces created unique challenges to eliminate reflections that would obscure photographic and lithographic detail.

Attempts on a previous TWDB core project, (Standen and Murphy, 2021), to wet the core slabs with a water spray and wipe to enhance visibility proved inadequate. Even if the three to twelve feet of core in a box was sprayed quickly, most of the surface water had evaporated or had been absorbed by the porous surface before the photographic image could be captured.

After a literature search and testing, it was determined that pharmaceutical grade mineral oil provided the most practical and photogenic wetting agent. It did not evaporate, nor was it completely absorbed before the box could be photographed; but being relatively inert, the oil was absorbed or evaporated from the rocks within days. In the short term, it enhanced the appearance of most of the rock types in the core, intensifying the color and revealing subtle features and textures. The temporary effect of the oil replicates the permanent effect achieved by sealing a slabbed rock surface with epoxy or plastic and polishing, a technique commonly used for thin sections and other petrographic analysis. Photographing the core without coating slabs with mineral oil would yield quite different color results and make it difficult to see many subtle textures and features.

Before a core box was photographed, the rock core was oriented by hand so that the slab surfaces were parallel with the camera lens and sensor. At this point most of the rocks were cleaned with a water spray bottle and cloth to remove any residual rock dust and grit. As described above, the slabs were wiped down with pharmaceutical grade mineral oil just prior to photographic exposure.

During the previous project, reflections from the oil could be a problem, especially with some of the finer-grained limestones; most of these reflections could be eliminated by slightly angling the slabbed core. A new technique, "Cross-polarized light source photography," (described below) was used for this project and eliminated the reflections from the oiled slabs. Oiling did not enhance all rock types; it often does not enhance high porosity intervals and is not practical for friable shales and fragments. The wetted status of core intervals within a box are noted in each core photograph.

The boxes were adjusted on the viewing table to be centered within the frame of the full-size sensor/photograph frame (to minimize distortions), and oriented to minimize the crop for the final portrait image. Most of the cores were in flats, holding 9 to 12 feet of core and photographed one box at a time.

6.3 CORE PHOTOGRAPHY LIGHTING

Improved lighting, more reproducible color calibration, and the elimination of reflections from the oiled core were achieved for this project based on the experience from the last project, better equipment, and a new technique (described below).

Ensuring consistent lighting from day-to-day has proven to be problematic in the CRC. The artificial lighting in the warehouse is provided by traditional fluorescent bulbs mounted on the ceiling, and even though it is 25 to 35 feet above, it is noticeable on the camera screen. Unfortunately, this artificial lighting was inconsistent because of flickering bulbs, and intermittent as individual bulbs lit and extinguished with age, but also proved strong enough to induce shadows on the core. There was also a contribution of natural lighting provided by the large, high windows in the warehouse; the color temperature from natural lighting can vary from daily weather conditions (sunny ~ 5500Kelvin (K); overcast ~10,000K), and hourly changes (sunrise and sunset ~3-4000K; mid-day sun-up to 6500K).

One way to reduce the variability is to place a stronger light source directly over the core boxes. This year the primary lighting was provided by a five-socket fixture filled with 25-Watt, 5500K, 120 Volt white LED studio lights mounted inside a Softbox on an adjustable stand. The Softbox mutes the light from the bare bulbs with gauze fabric and for this project covered a custom mounted neutralizing linear polarizing film (*Rosco Polarizing #7300*). The bright LED lights minimized the confounding effects of the other light sources in the warehouse (natural and fluorescent). The addition of the Rosco polarizing film resulted in a source emitting a single plane of polarized light waves, which, when combined with a circular polarizing filter on the camera lens, enables a photographer to remove the specular component of the reflections off the subject (in this case, oiled core) by rotating the circular filter to produce a very clean looking image. This technique has matured and is now more common because of the demand for high quality 3-D object and specimen photography (for online shopping and photo-realistic gaming).

Accurate color reproduction was achieved by photographing a color/grey scale target, specifically the "Calibrite ColorChecker Passport," every day, and using Calibrite's custom software plugin in Adobe Lightroom to create a unique color profile for each well. If an extensive well with many core boxes was photographed over multiple days, additional profiles were created and applied. The unique color targets are included in each core box photograph, so that color monitors and printers can be adjusted to reproduce the colors of the rock core accurately (the Calibrite target is considered universal, is inexpensive, and can be purchased online or at photography stores).

6.4 Core Photography Settings and Exposure

The digital camera used for this project is a professional grade, mirrorless Olympus model OM-D E-M1 Mark 2. The specifications important for this project include its twenty mega-pixel resolution, its five-axis stabilization which minimizes vibration degradation during long exposures, and the quality of the Olympus lenses. The camera can be paired to an external mobile device using built-in Wi-Fi and device software ("Olympus Image Share," or OI-Share); for this project, the camera was paired with and controlled remotely by an Apple iPad. The external touch screen tablet provides a larger screen than the camera viewfinder and makes it easier to optimize the position of the box and the orientation of the slabs to reduce reflections. The tablet is also the remote trigger for the camera which reduces physical vibrations during long exposures. The camera was mounted to a specialized frame (provided by the CRC) that rigidly suspended the camera directly over the core.

The ISO (equivalent to film speed) was set to the lowest setting possible to reduce sensor-generated noise, which necessitated relatively long exposures (up to two seconds). The aperture f-stop (opening size) of the lens was set for optimum lens sharpness and a depth-of-focus large enough to encompass the distance from the center of the image to the edge of the boxes.

- Camera: Olympus OM-D EM-1 Mk II
- Lenses: Olympus M. ZUIKO 12MM F2.0 for Micro Four Thirds
- ISO speed rating: ISO 64
- Aperture: f/6.3
- Single exposure: 0.5 seconds (typical)
- Multiple exposures: 1/3 to 2.0 seconds (for HDR, see below)
- Focus: Automatic (in camera) using phase detection technology
- White Balance: Automatic
- Photo Format: Olympus Camera Raw (unprocessed, uncorrected)
- Photo Dimensions: 3888 x 5184 pixels, cropped to ~ 1550 x 4000 pixels.

6.5 Photography Software Processing

The raw photos were automatically converted to Adobe's archival Digital Negative (DNG) format when transferred into the computer. Digital Negative (DNG) is a patented, open, lossless raw image format developed by Adobe with a license that allows use without cost. Developed in 2004, and submitted for ISO certification, it is intended to be a universal, archival image format that simplifies the proliferation of manufacturer-specific raw formats.

The images are stored and processed using Adobe's Lightroom software application. Lightroom includes an automatic feature that merges multiple (identical) images with different exposures to create a single photograph with a higher-than-normal dynamic range (revealing the deepest shadows and the brightest highlights). There is no penalty for utilizing this feature, and it only required exposing a series of photos for a box of core automatically, rather than just one. The most obvious effect was that very dark features could be lightened without overexposing the brighter features. After merging and creating a single High Dynamic Range (HDR) photo, it was corrected for slight perspective distortions (squared) and then cropped to the box exterior size. Minimal exposure, contrast, and tone corrections were applied consistently throughout a given well. Color was uniformly corrected for all the boxes photographed on a given day, using the profile generated using the Calibrite software plugin. An adjustment brush called "Dehaze" removed slight haze and reflections and noticeably improved the clarity of the core. It was applied selectively to all the wells.

The core photographs were transferred to Adobe's Photoshop software application to create a consistent format. Completed wells were exported to both JPEG (Joint Photographic Experts Group) and TIFF (Tagged Image File Format) digital formats. There are advantages and disadvantages to each. JPEGs are smaller files, are more popular, and are better suited for online access as they are compressed for faster online transmission. Unfortunately, JPEG is a lower quality format, which means that each time photographs are modified and saved, resolution could be degraded. TIFFs are uncompressed, do not lose detail when saved, are more widely used for archival purposes but are typically much larger files and less suited for online sharing.

6.6 DETERMINATION OF FINAL CORE BOX PHOTO FORMAT

Oil and gas companies, the United States Geological Survey (USGS,) and state geological divisions have been photographing rock core for years and a standard set of information has emerged as critical for the viewer. These include a Metric and English scale, a color and greyscale card or reference, notation of the top and bottom of the well, and depth of the core. Often these items are physically placed and photographed with every core box on a standard platform. The problem with this approach is that these paper-based physical references fade or degrade over time and can be difficult to see. Since the final format for this project was rendered in Photoshop, it was possible to standardize the references. A physical scale was initially photographed with each well and then was reproduced graphically in Photoshop. In a comparable manner, the Calibrite color and greyscale target was photographed with each well and "dropped" into a set location in each photograph. Any software modifications made to the core photographs were also applied to the color target.

Wells are named and/or referenced by several different systems, including name, latitude and longitude, American Petroleum Institute (API) well number, and others, as listed below:

- Operator, Lease & Well number
- Lat/Long (latitude and longitude decimal degree location)
- The well ID number from the Texas Water Development Board Brackish Aquifer Characterization System (BRACS) database
- API # (American Petroleum Institute well number)
- Core Tracking # (Bureau of Economic Geology, CRC, core reference #)
- County
- Core Size (diameter)
- Date Photographed
- Core # (Box number)
- Core box top and bottom elevation
- Formation

6.7 Core Photographic Observations

The following are brief summaries of the photograph**y** observations for each core, listed by core number.

6.7.1 Core ID C00270, Gifford & Mitchell, Lone Wolf 2, Winkler County

This thick sequence of massive dolomite from the Capitan Reef Formation was oiled and had a wide variety of features and colors, but they are often hard to see because of the huge yellow and orange permanent footage markings that were written directly on the core.

6.7.2 Core ID C00660, DeArmand Pearsons 1, Henderson County

There were only two boxes of core from this well, covering 100 feet with a lot of missing intervals. The first box contains fragments; the second box contains light grey massive limestone that was not slabbed, and therefore not oiled.

6.7.3 Core ID C01229, Conoco-Chittim 155-1, Maverick County

There were five boxes of core from this well, covering over a thousand feet, with a large gap in Box 1, marked with a slip of paper. The oiled core was light tan to brown, with lots of fossil fragments contrasting white against the background limestone.

6.7.4 Core ID C03838, Prime Op Co, La Paloma 1-84, Maverick County

The four-inch diameter core (thin) slabs for this well were packed on styrofoam backs in a different size box than the rest of the wells in this study (24 inches x 19 inches). This well was obviously used for a previous study, as there were labels throughout identifying fossil species and trace fossils (burrows) in the lime mud. Boxes 1 through 5 consisted of consistent fossiliferous limey mud, which took the oil and revealed the fossils and structures with clarity.

The core changed color in Box 6 at 5,349 feet, with features (scours and styolites) that were not very visible, until the slabs (and polarizing filter) were oriented to accentuate the reflections. As a result, the limestone appears almost golden, rather than the dark greenish brown that is an accurate color.

6.7.5 Core ID C04557, Richard Griffin, Howell 2, Van Zandt County

The core in this section ranges from massive to very crumbly and fissile limestone. The massive limestone was oiled and ranged from light tan to dark brown. The broken fragments were not oiled and are mostly light grey.

6.7.6 Core ID C04604, Tenneco, Chester Kiefer 2, Zavala County

This was the first core photographed, and I had not received the linear polarization filter which enabled cross-polarized light source photography. This is evident from the top to the bottom of the cored interval, as nearly every box displays some reflections from the non-absorbent limestone (mud). There were 28 boxes of core from this well, and the rock was relatively uniform from a photographic perspective. The un-oiled rock is medium grey to brown, the oiled rock took on a much darker tan-to-brown color. All the rock that was slabbed was oiled. The carbonate features were enhanced with oiling. Intervals containing only fragments of limestone between boxes 12 through 28 were not oiled. Boxes 18 through 21 contained only small fragments, which were not oiled.

6.7.7 Core ID C06087, Getty Oil, 2, Weaver "A", Zavala County

Most of the nine boxes of core contained massive, but fragmented limestone with lots of gaps (marked by styrofoam blocks, so most of this well was oiled for increased visibility. The core was marked with permanent marker for depth, either by the drillers or subsequently. The styrofoam blocks added extreme contrast, so High Dynamic Range processing was used to handle the contrast.

6.7.8 Core ID C06530, Eason Oil, Flowers Ward 1, Zavala County

There were only two boxes of core from this well, covering a short interval of twelve feet. The core was a distinctive red color throughout, and despite being a mix of sandstones and conglomerates, the core did not absorb the oil and it enhanced the clastic features dramatically. Box two contained several feet of fragments which were not oiled and those reveal the paler color of the natural sandstone in the Hosston Formation.

6.7.9 Core ID C08881, Richard Haas, Elizabeth Barlett 1A, Zavala County

There were five boxes of core from this well, and gaps in the core were marked with styrofoam. The un-oiled rock is dark grey, tan, or brown, the oiled rock took on a much darker tan-to-brown color. All the rock that was slabbed was oiled. There are some fragments throughout that were not oiled. The carbonate features (styolites, etc.) and fossils were enhanced with oiling.

6.7.10 Core ID C09067, Sun Oil, Bankhead Hoffman Unit 1, Titus County

The clastic sandstones, siltstones, shales and paleosols in this Woodbine sequence of thirteen boxes and 300 feet of core was the most colorful and variable of the wells in this study. The colors ranged from black to brown to tan to green to red to yellow to blue to white. Given the porosity of most of the sequences, applying oil was problematic, so the boxes are selectively oiled, as noted. This core was slabbed specifically for this project, so the fragile core was carefully laid out on a styrofoam base, and the interval depths labeled on individual pieces of cardboard by BEG staff. The dramatic color and shade differences clearly benefitted from the High Dynamic Range (HDR) processing in Adobe Lightroom, and for this well five different exposure values were merged into the final photo.

6.7.11 Core ID C10397, Sun Oil, Bankhead 20, Titus County

The first three boxes of this well contain fissile, laminated lime mudstone which was so highly fragmented that it was difficult to oil, but the oiled sections are obvious in the photographs and are marked. The natural fragments are light to dark grey, but oiled the rock takes on a medium to dark greenish brown color. The remaining boxes are primarily a more massive tan-colored limestone.

6.7.12 Core ID C11333, MHC Exploration Corporation, ACC 1, Travis County

This local Austin well was notable for being extremely shallow (starting at twelve feet), for changing core diameter from three inches to less than two inches, and for cutting through four different formations (Austin Chalk, Eagle Ford, Buda, and Edwards Group). Given the number of formations, the rock type is extremely variable and demanding photographically. The HDR software processing managed the extreme color variation (from light to dark), and the cross polarization eliminated the glare, so the lithologic features, fossils and trace fossils and mineralogy are revealed in the photographs.

Section 7: SECTION 7: CORE LAB ANALYSES SCOPE AND ANALYSES RESULTS

7.1 CORE LAB ANALYSES SCOPE

Core Laboratories (Houston) was the subcontractor for core plug analyses. The following analyses were requested: bulk mineralogy, porosity (using X-Ray Diffraction "XRD" analysis), permeability, and cementation exponent (m-factor) and Nuclear Magnetic Resonance (NMR) spectroscopy. Available price discounts for the State of Texas were requested. A total of 39 core plugs were analyzed.

The core information requested by Core Labs, including salinity and reservoir pressure estimates for each core hole was provided by Mr. Mark Robinson via email exchange. The average final cost for the Core Labs analyses was $2,239.10 per core plug.

7.2 CORE LAB ANALYSES RESULTS

Core Lab results of the 39 core plugs are summarized in Appendix D, Table 4. Five constituents (quartz, anhydrite, calcite, dolomite, and total clay) from the XRD analyses are included in the Appendix D summary. These five constituents represent 90% or more of each core plug's total mineralogy with two exceptions.

The first exception is C08881 (Zavala County, Maverick Basin, Lower Glen Rose) at 7,169 feet with 9.2% fluorite. The second exception is C09067 (Titus County, Woodbine) at 3,475 feet with 28.5% siderite.

Appendix D, Table 4 also includes NMR analyses for porosity, Klinkenberg permeability, effective porosity, T2 log mean and the Formation Resistivity Factor batch of analyses which includes, grain density, Klinkenberg permeability, porosity fraction, formation factor and cementation exponent.

Section 8: SECTION 8: ACKNOWLEDGEMENTS, CONCLUSIONS AND RECOMMENDATIONS

8.1 ACKNOWLEDGMENTS

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8.2 CONCLUSIONS

This TWDB core project was more efficient than the previous completed TWDB core project (Standen and Murphy, 2021) because of the better understanding of task sequence (initial review of core, select, extract and ship core plugs, photograph core boxes and complete lithologic descriptions). Core Labs analyses results usually require about two months. Two of the cores were whole cores (C03838 and C09067, Table 1) and required the CRC staff to slab and re-box these core intervals into flats.

8.1 RECOMMENDATIONS

After all the core viewing, plugging, lithologic logging and core photography had been completed, Mr. Standen (with guidance from Nathan Ivicic, CRC Core Curator) was researching CRC's CONTINUUM core database to confirm data for this report. Once all the cores were mapped, we selected the most up dip core locations. It is recommended that in the future the CRC staff assist in researching core-related projects.

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