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Final: Core Testing for Hill Country Trinity Aquifer

Texas Water Development Board Contract #2000012440

Prepared for:

Texas Water Development Board

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September 24th, 2021

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1 Introduction

The TWDB has funded this core testing project to provide directly measured rock parameters to integrate with geophysical logs and more accurately calculate total dissolved solids (TDS) and aquifer properties for the downdip Trinity formations for the Texas Hill Country. The measured rock parameters include bulk mineralogy, porosity, permeability, and cementation or "m"-factor for each formation. The project was officially started at the December 1, 2020, kickoff meeting.

Access to the Bureau of Economic Geology's (BEG) Core Research Center (CRC) was not permitted until December 16th, 2020, because of the existing University of Texas Covid protocols. The CRC was shut down from December 18, 2020, to January 6, 2021, for the holidays.

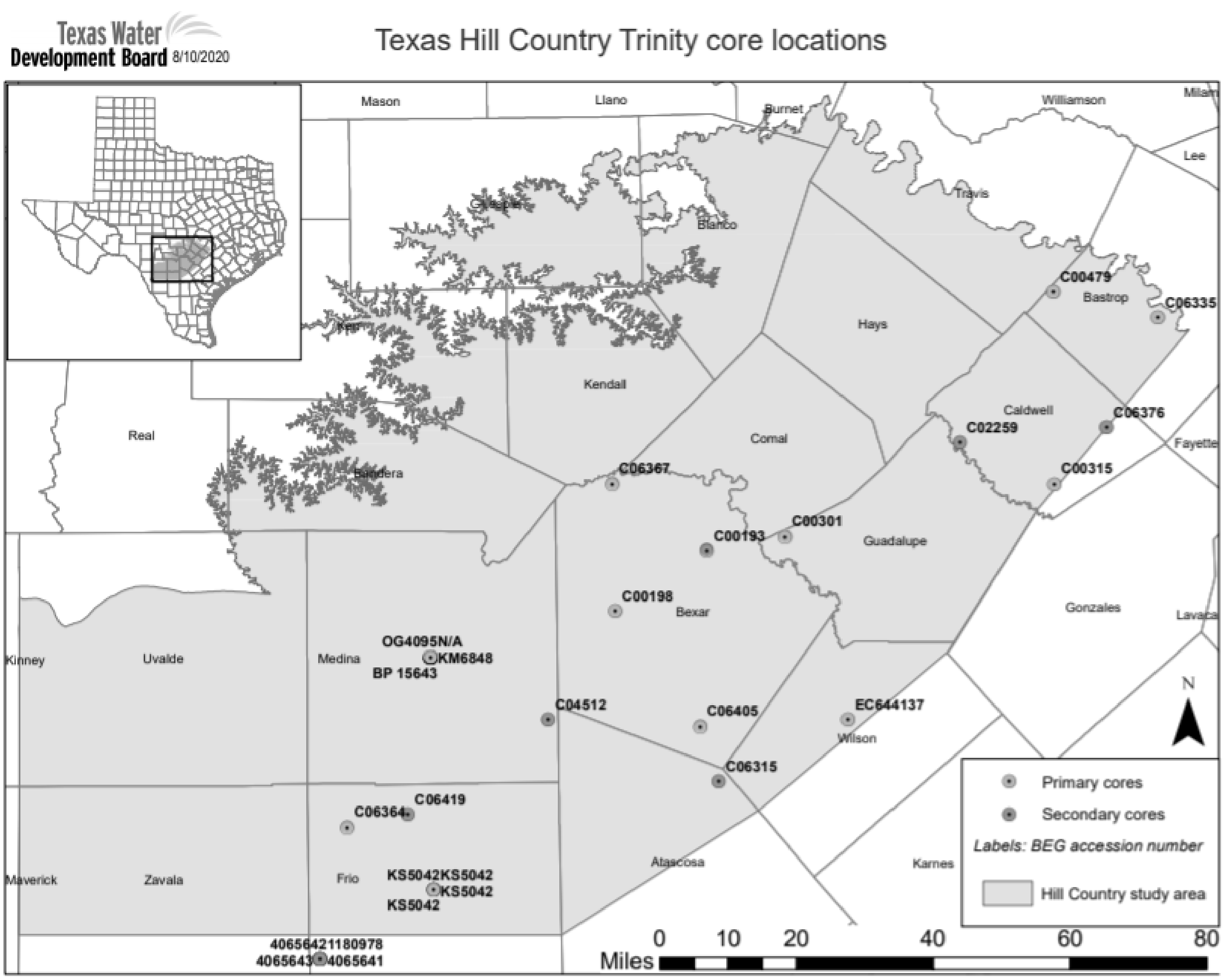

Figure 1-1. TWDB provided Primary and Secondary Core Locations.

The awarded Core Testing for Hill Country Trinity Aquifer contract includes five tasks,

- Task 1, Review provided core list,
- Task 2, Locate cores, compare core lithology to stratigraphic intervals and update core list as needed,
- Task 3 Core photographs and basic core description,
- Task 4a, Selecting core plugs,
- Task 4b, Core analyses and
- Task 5, Final report, and other deliverables.

The TWDB RFP provided Excel spreadsheets listing eleven primary and eight secondary cores and their locations. These core datasets included Trinity core tops and bases, BRACS well ID, length of core interval, the CRC core tracking number, and other attributes. The primary and secondary core locations are illustrated in Figure 1.1.

The TWDB primary core data was rearranged to create Table 1.1 which was used to estimate the possible maximum number of primary core boxes "Est. core interval (feet)" for this RFP. Table 1-1 was included in the RFP submittal.

Based on Mr. Standen's previous CRC experience, CRC Curator, 1986 to 1991, core boxes range from three to twelve feet of core per box, dependent on core's diameter. Flats with nine to ten feet of core are the most common. An average length of 10 feet of core per core box was assumed to estimate the possible maximum number of primary core boxes. Over 1,500 core boxes were initially estimated for this RFP.

There was no time to confirm assumptions prior to submitting the TWDB RFP because of the limited proposal time compounded by Covid restrictions and CRC staffing availability.

The CRC in Austin was contacted to determine core box pulling and viewing pricing. The Core Curator, Mr. Nathan Ivicic, 8/21/2020, provided the following pricing information for pulling and viewing core boxes.

The cost of pulling a core box from the warehouse for viewing is $10 per box. The CRC has three core viewing options using the existing core viewing rooms,

- Option 1 is $75 per day for 30-foot-long rolling table, limit of 300 feet of core.
- Option 2, rental of large viewing room, $1,000 per day, limit of 1,200 feet of core
- Option 3, rental of small viewing room, $400 per day, limit of 1,000 feet of core.

An arrangement was made to display the cores in the warehouse instead of using the core viewing rooms. The core warehouse has no air conditioning but did have sufficient lighting system for core viewing and logging but not for core photography.

Table 1-1. Summary of Primary Core, RFP Proposal Estimated Box Count.

TWDB primary core number	Core access ID	BRA CS ID	County	Core top depth (feet)	Core base depth (feet)	Est. Core interval (feet)	Trinity formations	Est. box count	Est. # of core plugs
1	KS5042		Frio	7201	7228	27	<UG	3	3
2	KM6848		Medina	3464	3465	1	<HO	3	3
	OG4095			3933	3949	16	<HO		
3	C00479	14495	Bastrop	1734	2731	997	UG, <LG	100	6
4	C06405	16842	Bexar	3909	4841	932	<UG, LG, HE, CC, <SL	94	12
5	C06364	84839	Frio	5792	6947	1155	LG, HE, CC, <SL	116	9
6	C06335	14391	Bastrop	5430	6058	628	<LG, HE, CC, <SL	63	9
7	C00315	86591	Caldwell	2425	6490	4065	UG, LG, HE, CC, SL, HO	407	15
8	C00198	16843	Bexar	0	2658	2658	UG, LG, HE, CC, SL, HO	266	15
9	C00301	19297	Guadalupe	1072	2614	1542	<UG, LG, HE, CC, SL, HO	155	15
10	EC644137		Wilson	4656	7097	2441	UG, LG	245	6
11	C06367	48615	Bexar	340	890	550	HE, CC, SL, HO	55	9
				RFP estimated number of core boxes				**1,507**	
Est. = Estimate						**RFP estimated number of core plugs**			**102**

2 Task 1 Review Provided Primary Core List

The TWDB primary core list was reviewed, and a request was submitted to the CRC to determine core availability. What was not initially understood was that the CRC database, which was used to create the TWDB's primary core information, only listed the top and bottom of the core interval for a well. The CRC database does not list missing core intervals between the top and base of each core. The only way to determine what primary core that was available was to have the CRC staff physically pull the core and lay out the core boxes to physically examined.

2.1 Task 2 Locate Cores, Update Core List as Needed

A request was submitted for CRC staffs in Austin and Houston to pull the primary cores for viewing which occurred during January through April 2021. An accurate box count for each primary core was determined and is listed in Table 2-1. Primary cores were examined by the CRC staff (Houston) and/or Mr. Standen to determine if each core met the screening criteria to be useful for this study. The core screening criteria included.

1) Do the core depth ranges occur within the Trinity Aquifer based on TWDB provided depth interval information?
2) What is the type of core, core chips, core fragments, sidewall plugs, whole core, or slabbed core?
3) What is the thickness of the core; a slabbed core needs to be one inch or thicker to be acceptable for Core Labs core plug analyses.
4) Determine the core curation status of each core, which includes,

A) The overall core condition, broken versus coherent core, bagged intervals, etc.
B) Are there core pieces greater than three inches long for core plugging,
C) The accuracy and consistency of core box labeling, both inside and on the outside of each core box.

Only seven of the original eleven primary cores passed the screening criteria as shown in Table 2-1. Geophysical logs were located for all seven of the primary cores. The geophysical log for primary core #10, Southern, C64413, is of poor quality and was limited in use. Copies of the geophysical logs are in Appendix A.

Since four of the TWDB primary cores were eliminated during the core screening process, the TWDB provided list of secondary cores was reviewed to select supplementary cores. The seven primary cores are in, Bastrop, Bexar (2 cores), Caldwell, Frio, Guadalupe, and Wilson counties.

Improving the geographic coverage was a high priority, therefore, two TWDB secondary cores which passed the core screening criteria were selected to supplement the TWDB primary cores (Table 2-2). The supplemental cores are, secondary core #4, Suggs Everett #1, Tenneco Oil, C06315, Atascosa County, 16 boxes and secondary core #8, Carroll, John W. #1, Tenneco Oil, C04512, Medina County, 32 boxes. Geophysical logs were located for both secondary cores (the geophysical log for Suggs, C06315 is of poor quality) and are in Appendix A. Figure 2-1 illustrates the locations of the nine cores (seven primary and two secondary) studied for this project.

Table 2-1. Primary Core Actual Box Count and Final Status.

Primary #	Operator, lease, well #	Lat. and Long. (dd)	County	BRACS #	Core #	Box count	Status
1	Pan Am, T. A. Culpeper #1	28.86526, -99.11075	Frio		KS5042	4	Core fragments too small
2	Standard Oil, Wilson Devine Test Site, #1	29.35812, -99.11260	Medina		KM6848, OG4095	3	Core fragments too small
3	Ambassador Oil, Emma Anderson, #1	30.11194, -97.58194	Bastrop	14495	C00479	2	Core chips too small
4	Tenneco Oil, Virgilia Herrera, #1	29.20564, -98.46085	Bexar	16842	C06405	31	Completed
5	Tenneco Oil, W. A. Roberts, #1	28.99918, -99.31764	Frio	84839	C06364	17	Completed
6	Tenneco Oil, D. F. Kauffman, #1	30.05274, -97.32720	Bastrop	14391	C06335	31	Completed
7	Starr-Smith, C. Crowell, #1	29.70528, -97.58972	Caldwell	86591	C00315	5	Completed
8	General Crude, Rogers Ranch, #1	29.45187, -98.66298	Bexar	16843	C00198	1	Core interval is too deep
9	Stanolind Oil, T. E. Schmidt, #1	29.60531, -98.24808	Guadalupe	19297	C00301	108	Completed
10	Sohio Petroleum, Gayle U. Southern, #1	29.2150, -98.1028	Wilson		C64413	6	Completed
11	TWDB, AY-68-19-208	29.72167, -98.66722	Bexar	48615	C06367	21	Completed

Table 2-2. Secondary Core Actual Box Count and Status.

Secondary #	Operator, lease, well #	Lat. and Long. (dd)	County	BRACS #	Core #	Box Count	Status
4	Tenneco & Penzoil United, J. N. Suggs Everett et al., #1	29.08817, -98.41735	Atascosa		C06315	16	Completed
8	Tenneco Oil, Carroll, John W., #1	29.22338, -98.82908	Medina	84868	C04512	32	Completed

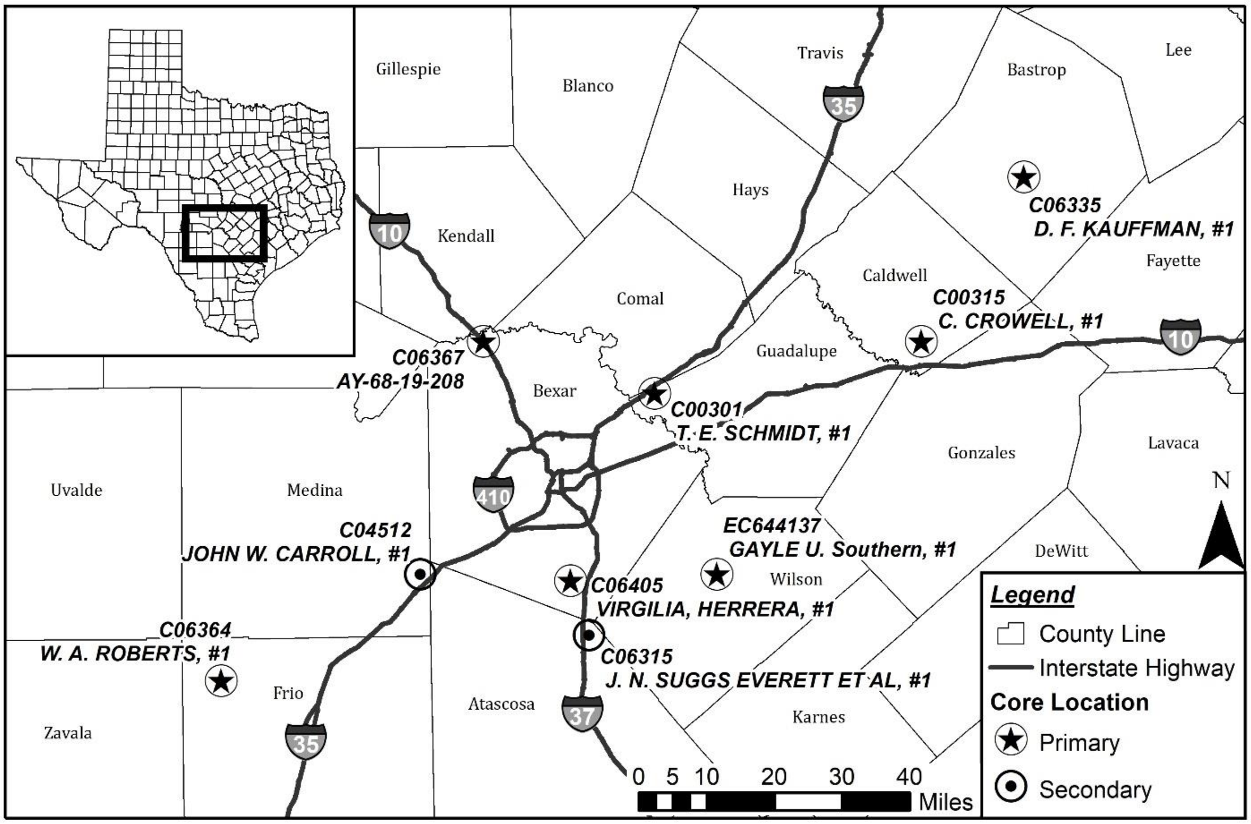

Figure 2-1. The locations of the nine cores evaluated for this study.

3 Task 2 Deeper Trinity Lithology and Stratigraphy

3.1 Published Resources

TWDB county publications within the study area were reviewed to obtain possible information about the deeper Trinity Aquifer. Reports reviewed include Texas Board of Water Engineer (TBWE) county reports, Austin (1954), Anders, 1957 and Alexander and others (1964) and TWDB numbered reports Alexander and White, (1966), Follett, (1966) and Follett, (1972).

Only TBWE Bulletin 5413 by Austin (1954) had any useful information, which provided one driller's report (well C-60) that provided a description of the lithology of the deeper Trinity in Bastrop County (Appendix B).

The Hill Country Trinity Aquifer was the focus of two recent TWDB Trinity studies, Stepchinski and others (2017) was a BRACS study and Toll, and others (2018) was a GAM study. Both studies provided generalized descriptions of the downdip lithology of the different Trinity formations. Table 3-1 summarizes these generalized lithologic descriptions.

Table 3-1. Generalized lithologic descriptions of the Trinity Formations.

Cretaceous, Trinity Formation	Summary of downdip generalized lithologic descriptions (Toll and others, 2018 and Stepchinski and others, 2017)	Downdip maximum thickness (feet)
Upper Glen Rose	Shallow limestones, dolomite, and claystone Boundary between upper and lower is a meter thick layer of small bivalve "Corbula"	>1,500
Lower Glen Rose		
Hensell (Bexar Shale)	Calcareous mudstone and shale	>200
Cow Creek	Coarse grained, calcarenitic (clastic) limestone, transitional boundary with underlying Hammett	>100
Hammett	Mudstone, siltstone, and carbonates (dolomite and limestone)	>100
Sligo	Shallow marine carbonate	>500
Hosston	Dolomitic carbonate	>1,000

Internet searches were conducted (1/24/2021) using different query language on the BEG website to identify references that could provide downdip lithologic descriptions of the Trinity formations. No useful BEG publications were identified.

Based only on the generalized lithologic descriptions provided by Stepchinski and others, 2017, and Toll and others, 2018, the Trinity appears to become increasingly more carbonate-rich and clastic-poor moving east, away from the Trinity formations outcrops.

Deep public water supply wells were also considered as a possible source for deeper Trinity lithology information. A website search of TWDB's submitted driller's reports (SDR) database for the deepest public water supply wells for the study area counties was conducted. Table 3-2 lists the deepest public water supply well for each county from the SDR website database. None of these public water supply wells penetrated the Trinity Formations. These SDR driller's reports are included in Appendix B.

Table 3-2. Texas Department of Licensing and Regulation Deep Public Water Supply Wells.

TDLR #	County	Well depth (feet)	Comment
457844	Atascosa	4,392	Too Shallow
400430	Bastrop	1,540	Too Shallow
129150	Bexar	1,964	Too shallow
546473	Bexar	1,987	Too shallow
565436	Caldwell	850	Too shallow
386817	Frio	2,104	Too shallow
433363	Guadalupe	1,575	Too shallow
485451	Medina	2,515	Too shallow
56985	Medina	2,045	Too shallow
574469	Wilson	3,140	Too shallow
448538	Wilson	3,220	Too shallow

The BEG's cable tool driller's report library was not accessible because of the University of Texas's Covid policy. Therefore, no BEG cable tool drillers reports were compiled for this study.

3.2 Review Each Core with Geophysical Log to Determine Formation Contacts

The TWDB provided stratigraphic picks for the different Trinity formation tops for the primary and secondary cores. Since the TWDB staff has Trinity expertise and has invested considerable time in selecting the provided Trinity stratigraphic formation tops based on regional information, ARS LLC used the provided TWDB formation tops for this study. If any TWDB geophysical log Trinity formation top picks were in question based on the lithology of the core, the TWDB staff was contacted to confirm formation picks which were used for this study.

The core lithologic logging on the nine cores confirmed that the Trinity becomes increasingly carbonate-rich moving downdip (Toll and others, 2018; Stepchinski and others, 2017). This transition to dominantly carbonate-rich environment included the typically more clastic up dip Trinity Hensell, Sligo, and Hosston Formations.

In addition, moving downdip to the east, the carbonate facies change as shown in Figure 3-1. These facies changes will impact the characteristics of geophysical log signatures. Further complicating any geophysical log interpretation are marine transgressions and regressions that probably occurred during the Cretaceous and potentially alternating the type of carbonate facies.

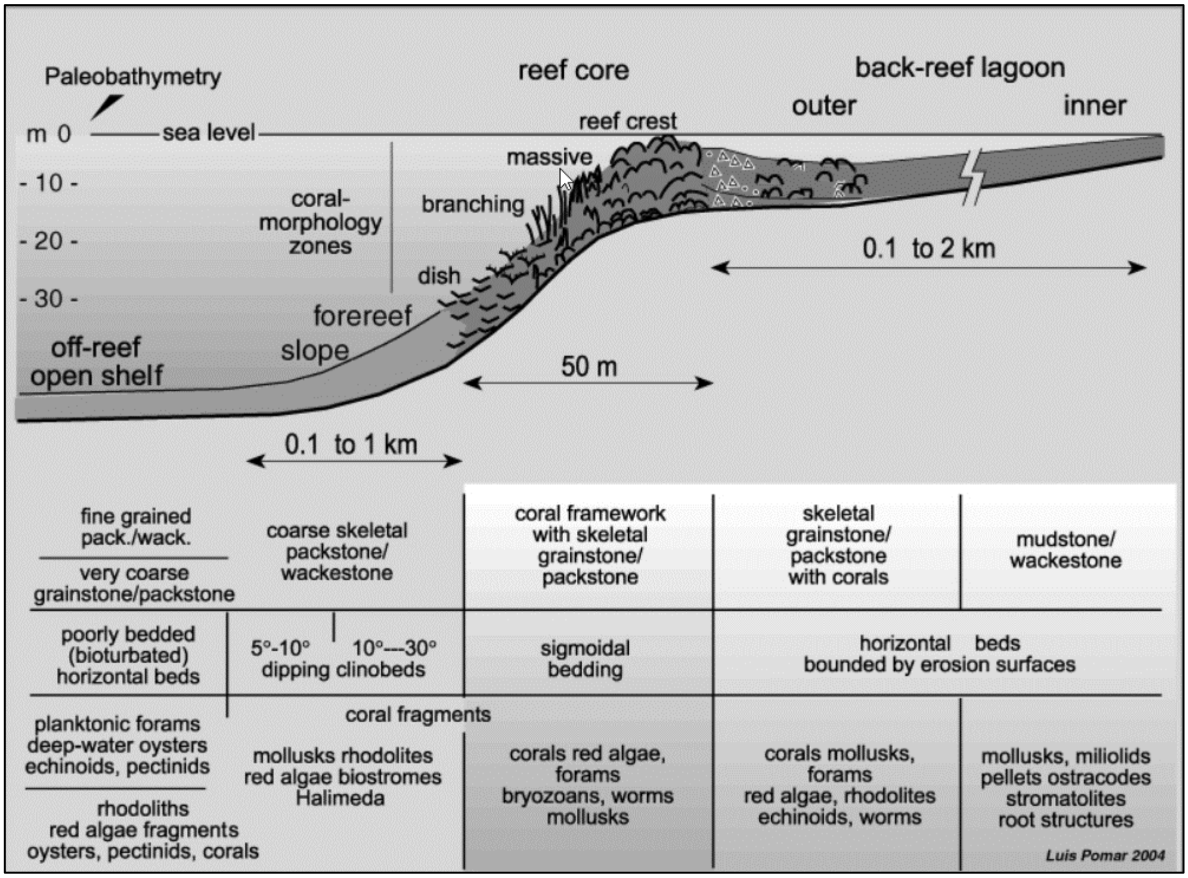

Figure 3-1. Facies Model of Relative Stratal Geometries (Rock Textures) (Pomar, 2004)

4 Task 3 Core Logging and Photography

4.1 General Information about the CRC Cores

Mr. Standen was core curator at the CRC from 1986 to 1991. Based on his experience, many of the historical donated cores curated by the CRC were accepted as received (often with limited core curation documentation). These donated cores have different levels of core curation, which includes,

- the experience level and professionalism of core handling at the drill site,
- different core box sizes,
- core orientation protocols,
- different core diameters,
- protocols for core box labeling of top and base,
- protocols for handling of missing core (<100% recovery)

Some core donations just include a slabbed portion (1/3 or 2/3) of the whole core and there may be selected intervals within a continuous core interval withheld by the donator. Core curation and condition of the cores for this study were accepted as received from the CRC staff, no additional core curation was conducted.

The CRC staff repackaged two cores during this study, Kauffman, C06335, (after original logging of core) and Herrera, C06405, (before logging of core).

4.2 Carbonate Rock Descriptions

The downdip lithology of the Trinity is dominantly carbonates including limestone and/or dolomite. Description of carbonate environments in core is a very specialized expertise. Mr. Standen had no previous experience describing carbonate environments, his core logging experience included mineral exploration and overseeing core curation at the CRC.

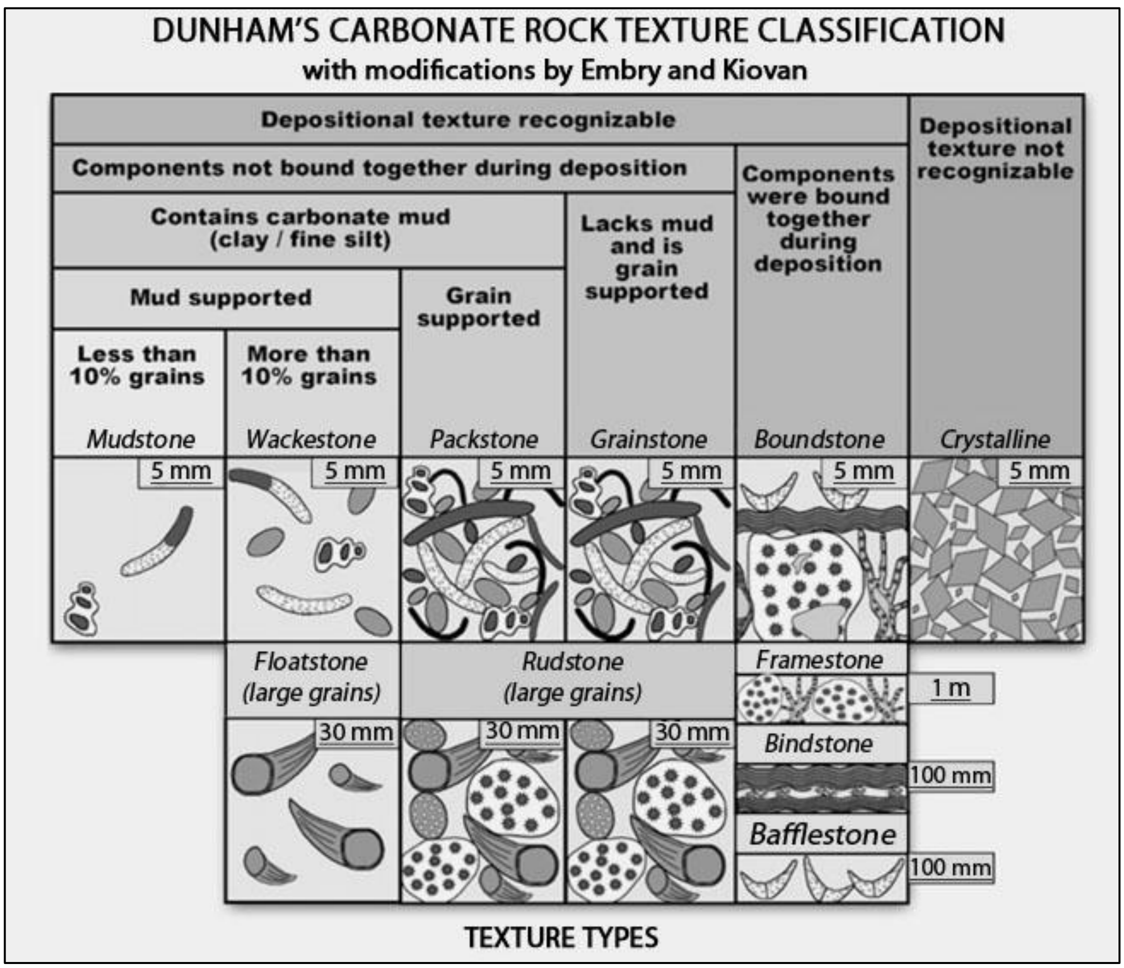

Figure 4-1. Dunham Carbonate Classification (Loucks and others, 2001)

An internet search was conducted to find guidance documents and definitions to assist in the description of the carbonates and other lithologic textures. The Durham (1962) carbonate classification chart which was modified by Loucks, and others (2001) was selected for core lithologic descriptions because it is the classification system used by existing BEG researchers and it presented a more simplified visual approach to carbonate textural descriptions (Figure 4-1).

There was a concerted effort to standardize carbonate core lithologic descriptions between the different core holes.

4.3 Core Preparation and Lithologic Logging

A core box survey was conducted on each core to determine the actual core interval or intervals within each core box. Table 4-1 lists the actual core intervals of each core hole. The Trinity Formation abbreviations used are, Top of Upper Glen Rose = UG, Top of Lower Glen Rose = LG, Top of Hensell = HE, Top of Cow Creek = CC, Top of Hammett = HM, Top of Sligo = SL and Top of Hosston = HO.

The first step of core preparation was to place a laminated, white core box number at the upper left-hand corner of each core box to synchronize and track progress of core lithologic logging and photography.

Core logging and core photograph (Excel) documents were created and were approved by the Project Manager, Mr. Mark Robinson, by the end of January 2021. Upon completion of the core box survey, an Excel core lithologic and photography tracking document was created for each core. Header information included CRC number, operator, lease and well number, BRACS number, API number, TWDB number, number of core boxes for the core, and the document listed core interval(s) for each core box.

The submitted TWDB RFP stated that the core box lithologic descriptions include core box sequence, number, major color (using a Munsell rock color chart), major lithology (shale, sandstone, limestone, evaporite), type of cement (spot HCl testing), bedding thickness and grain size range (using grain size chart).

Core lithologic logging preparation involved rotating the core slabbed surface up, wiping dust off the slabbed surface with a wet towel and spraying the core slabbed surface with a water.

Upon the initial logging of the core, it was determined that assigning Munsell Rock color chart codes and range of colors for each core box was time consuming, especially if there was a large range of colors within the core box. The solution was to provide a general description of the color range and to provide a color bar with each core box photograph.

Core box description of the lithology included major and minor lithologies within the core interval which may have different aquifer properties.

While reviewing each core box, thin lines of 10% HCL were applied to core pieces within each core box to determine carbonate core intervals. A scraping instrument was used to create a powder to test with 10% HCL to identify suspected dolomitic intervals. The HCL residue was then removed with a water spray bottle.

The determination of bed thickness was attempted while logging the core. Because of the numerous, thin, and interbedded sequences with different carbonate textures, bedding tops and bases could not be identified. A better approach would be using a combination of log signatures from the core hole's geophysical log to determine bedding thicknesses.

While logging core, a large 4X magnifying glass and a transparent plastic grain size chart was available to determine grain size. Pervasive carbonate cementation often made it difficult to see individual sand grains in the core. The preliminary screening of core for grain size involved using the fingertips to feel for relative roughness changes along the slabbed core surface. Grainy areas were then confirmed with the magnifying glass and a grain size range was estimated using a plastic grain size chart.

Loucks and others (2001) carbonate classification chart Figure 4-1 was subjectively used to describe one or more carbonate textures in a core box. Additional carbonate descriptive features were also included.

Mr. Standen has limited understanding of fossil identification, therefore, the term "fossil fragments" (Appendix C) was used in core interval descriptions which would include all partial and/or complete marine fossils, ooids and/or pellets.

Another term used to simplify core interval descriptions was "intraclasts" (Appendix C) which would include any eroded or spatially offset carbonate rock and/or other rock fragments (chert, anhydrite, dolomite, etc.).

The description "worm burrow" includes burrows and/or traces which may be created by crustaceans (Appendix C).

Wavy bedding (Appendix C) is defined by the author as "Original horizontal bedding becoming broken up, distorted and within a spatially disturbed matrix which includes, fossil fragments, formation fragments and other intraclasts. Wavy bedding may be result of bioturbation, soft sediment deformation and/or a depositional event."

Table 4-1. Core box intervals and Texas Water Development Board Trinity Formation Tops

Lease	CRC	County	Core intervals	UG	LG	HE	CC	HM	SL	HO
Herrera	C06405	Bexar	3909 - 3984.5, 4290 - 4375, 4625 – 4676, 4785 - 4831	3326	3942	4543	4674	4720	4767	5089
Roberts	C06364	Frio	5792 – 5806, 5842 – 5918, 6497 – 6549.5, 6694 – 6697, 6899 - 6949	4936	5803	6377	6683	6837	6889	7371
Kauffman	C06335	Bastrop	5430 – 5607.5, 5995 - 6058	4584	5361	5739	5846	5914	5943	6243
Crowell	C00315	Caldwell	2425 – 2546, 3061 – 3118, 3241 – 3243, ?– 4639, 5340 – 5430, 5829 – 5842, 6370 - 6415	3793	4468	4982	5164	5203	5236	5685
Schmidt	C00301	Guadalupe	1072 – 2614 (many small gaps)	917	1439	1751	1893	1940	1975	2099
Southern	C64413	Wilson	4656 – 4697, 7087 - 7097	5781	6378	6967	7089	7142	7174	7659
AY-68-19-209	C06367	Bexar	340 – 360, 390 – 491, 658 – 668, 750 – 755, 820 - 893	1	92	345	406	488	526	606
Suggs Everett	C06315	Atascosa	6812 – 6825, 7073 - 7266	5634	6269	6857	7081	7165	7197	7601
Carroll	C04512	Medina	3484 – 3538, 3883 – 4001, 4190 – 4231, 4300 - 4360	2834	3444	3970	4128	4220	4264	4468

Top of Upper Glen Rose = UG, Top of Lower Glen Rose = LG, Top of Hensell = HE, Top of Cow Creek = CC, Top of Hammett = HM, Top of Sligo = SL and Top of Hosston = HO.

A focus of the Hill Country Trinity Core project was to identify potential pathways or areas with enhanced porosity and/or permeability for groundwater flow. Potential permeable features may include stylolites and/or vertical fractures (partially healed and not healed). Other permeable intervals may include, fault zones, dark shaley laminated intervals with bedding plane fractures, intervals with increased secondary carbonate porosity and areas with larger sand grain sizes.

While logging core, dark shaley laminated intervals often seem to be associated with bedding plane fractures. These core fractures appear to mimic shaley, laminated surfaces and may be planes of weakness and/or possibly potential preferred flow pathways. While describing these dark shaley laminated intervals, the statement "bedding plane fractures" (Appendix C) was often included to bring attention to these intervals. These observed bedding plane fractures may be the result of clay or shale desiccation within the core boxes and may not represent downhole fracturing.

Depths in the core lithologic descriptions are based on the depths provided on the core boxes or in some cases depth provided on the back of the core piece. The depth accuracy for each core is dependent on the core's original curation (See Section 4.4).

The core descriptions do not follow any grammatical protocols, the intent of the lithologic description is to describe the core within a limited text space.

The RFP requested more detailed lithologic descriptions for the selected core plug intervals. Detailed, lithologic core descriptions were provided for all core boxes which includes the core plug intervals.

Lithologic core box descriptions fore nine cores are located within Appendix D.

4.4 Core Logging Observations, Core Accuracy and Problems Encountered

Kauffman, C06335, this was the first core studied and logged that initially had 93, 4 inches by 4 inches by 3-foot core boxes. This core had three core intervals that were duplicated, Boxes 14 and 15, or 5,466.5 to 5,469.5 feet and Boxes 22 and 23, 5,485 to 5,487 feet and Boxes 86 and 87, 6,037.5 to 6,040.5 feet. This duplication raises concern that the depth accuracy of this core is questionable near these duplicated intervals. Core plugs length was no issue in this core. Core accuracy is at best one foot and is probably three or more feet after Box 14. This core was reboxed by the CRC staff from 93 three-foot long boxes to 19 flats with three rows and up to 9 feet of core per flat (Appendix D, #1)

Roberts, C06364, this was a small diameter core, the whole core was 2.5 inches thick. The slabbed core was slightly greater than one inch thick and finding a slabbed sample half of the core thick enough for core plugging was challenging. Decent job of core curation, lots of Styrofoam spacers and empty core box rows, minor labeling errors. Missing core intervals with no spacers. Core accuracy is at best one foot (Appendix D, #2).

Crowell, C00315, this core has a high level of core curation. Most core piece backs were labeled with a depth. There were many depth gaps between the core pieces in Boxes 2, 3, 4, and 5. The top of the second core interval within Box 2 was not discernable, the base is 4369. All core plug depths were extracted from a depth labeled core piece. Core accuracy is probably half a foot in this core (Appendix D, #3).

AY-68-19-208, C06367, this core has a high level of core curation by the TWDB. Mr. John Ashworth was the site geologist and provided a detailed lithologic description of the core. This core sequence is the shallowest for this study. The core was the most interesting core to log. Core box interval tops were not labeled from core box 15 to core box 21, making core plug depths estimates less accurate. Core plug depth accuracy is probably one foot for this core. Last two core box intervals are probably in a fault zone (Appendix D, #4).

Herrera, C06405, this core has a high level of core curation. Finding a coherent core piece from the highly broken up core in core boxes 18 thru box 24 was challenging, because of the highly laminated and/or fissile core. The core had minor missing core gaps and labeling issues. Core plug depth accuracy is probably one foot for this core (Appendix D, #5).

Southern, C64413, this core has a high level of core curation. Very poor-quality geophysical log. This core is only six boxes, and the first four boxes are above the top of the Glen Rose. Minor core labeling issues. Core accuracy is probably half a foot in this core (Appendix D, #6).

Schmidt, C00301, this core has a high level of core curation. Core box interval tops were not labeled for each core box row in some core boxes. Core box small white background labeled numbers starting at box 42 to box 75 represent locations of BEG XRD analyses. Minor issues with small gaps of missing core. Core accuracy is probably half a foot in this core. Last two core box intervals probably include fault zone and underlying Paleozoic (Appendix D, #7).

Suggs, C06315, this core has a high level of core curation. Poor quality geophysical log. Minor core labeling issues. Last core box, number 16 has a confusing arrangement of core. Core accuracy is probably half a foot in this core (Appendix D, #8).

Carroll, C04512, this core has a high level of core curation. Minor core labeling issues. Core accuracy is probably half a foot in this core (Appendix D, #9).

4.5 Scheduled Meetings with the TWDB Staff

There were four scheduled meetings with the TWDB staff to resolve core depth accuracy, lithological logging, and photography issues. In addition, there were numerous phone calls and email exchanges between Mr. Robinson and Mr. Standen and Mr. Sean Murphy during this project. The scheduled meetings were held on these dates.

December 1, 2020, Zoom project kickoff meeting

December 18, 2020, Physical meeting at CRC with Mr. Evan Strickland, Main topics, core logging and interval issues

April 12, 2021, Zoom meeting with TWDB, Main topics, core logging and core photography

May 27, 2021, Zoom meeting with TWDB, Main topic, core photography

4.6 Core Photography

Core photography, photo processing and report writeup 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 nine cores 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 (Section 4.3).

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.

4.6.1 Core Photography – Introduction

This task (281 photos documenting nine wells and more than 2,500 feet of core), combined with the detailed core box descriptions (Appendix D) and plug analyses (Appendix F) will provide hydrologists with a new and comprehensive lithologic data set to further characterize the Trinity Aquifer. 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.

Figure 4-2. CRC warehouse core photography camera mount, with lights and camera mounted.

A professional grade mirrorless digital camera was used and a wide-angle lens with the capability of producing very sharp images was purchased specifically 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 maximize 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, which was difficult because there was an inevitable learning curve. All the core was imaged using the same camera (same settings and focal length) in the same location with the same lighting and treatments (oiling) and processed using consistent post-digital settings (Adobe Lightroom and Photoshop).

4.6.2 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 detail.

Early in the project, before the first well was photographed, it was obvious that simple water spray and wipe was 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 very different color results and make it difficult to see many of the subtle textures and features.

Before boxes were photographed, 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. Reflections from the oil could be a problem, especially with some of the finer-grained limestones; most of these reflections were eliminated by slightly angling the slabbed core.

Some of the core intervals were not with mineral oil for various reasons, 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.

The Kauffman, R.D. #1, C06335 core, which was slabbed four-inch diameter core stored in a single box three-feet long, was photographed in groups of five and clipped in Photoshop to three. After photography of this core was completed, this core was reboxed into flats (nine feet per flat) by the CRC staff.

4.6.3 Core photography lighting

Ensuring consistent lighting from day-to-day proved to be somewhat problematic in the core facility warehouse at the BEG. The CRC warehouse artificial lighting is provided by traditional fluorescent bulbs mounted on the ceiling, and even though it was 25 to 35 feet above, was 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).

The primary lighting was provided by two 42-Watt, 5500K, 120 Volt white fluorescent studio lights enclosed in small reflectors, covered with gauze fabric, and suspended approximately four feet above the core. The changing color temperature was adjusted automatically by the white balance sensor in the camera, and a representative color standard card was photographed each day to provide a reference.

4.6.4 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 20 mega-pixel resolution, its 5-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 O.I. 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 was also the remote trigger for the camera which reduced physical vibrations during long exposures. The camera was mounted to a specialized frame (provided by the CRC) that rigidly suspended the camera (and lamps) 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.

<u>Camera</u>: Olympus OM-D EM-1 Mk II

<u>Lenses</u>: 1) M. ZUIKO ED 12-40MM F2.8 PRO zoom lens, and 2) M. ZUIKO 12MM F2.0

<u>Camera Settings</u>:

ISO speed rating: ISO 64

Aperture: f/6.3

Focal Length: 12 mm on both lenses

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

4.6.5 Post - Core photography software processing

The raw photos were automatically converted to Adobe's archival Digital Negative (DNG) format when loaded 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. The photos were initially 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. It was discovered midway through the project that an adjustment brush called "Dehaze" removed slight haze and noticeably improved the clarity of the core. It was applied selectively to all the wells except for 1) Crowell, C.C. Starr Smith, and 2) Kauffman, R.D. #1.

The core photographs were transferred to Adobe's Photoshop software application to format to a consistent style. 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, 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.

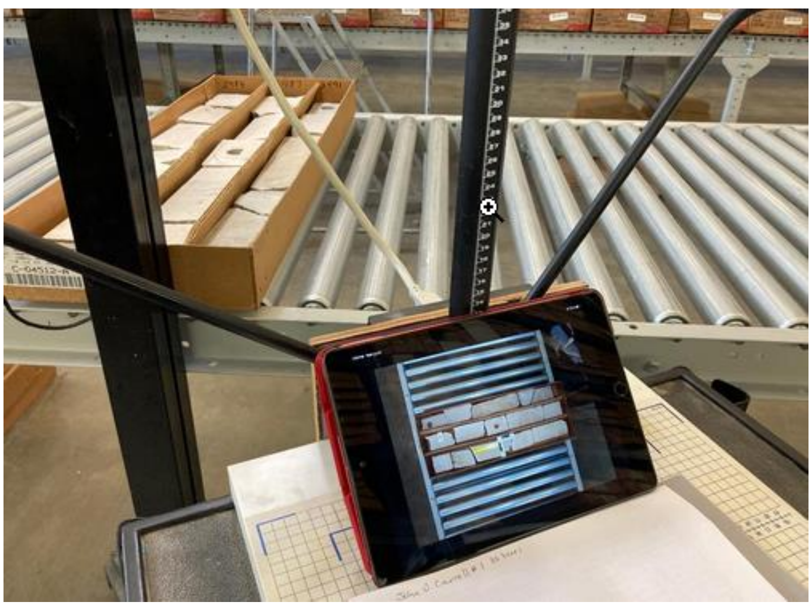

Figure 4-3. Remote view of rock core using Olympus camera Wi-Fi and Olympus O.I. Share software application on Apple iPad. Useful for hands-free viewing of core and orienting slabs to reduce glare.

4.6.6 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 on the references. A physical scale was initially photographed with each well and then was reproduced graphically in Photoshop. In a similar manner, the color and greyscale reference were photographed with each well and "dropped" into Photoshop. Any software modifications made to the core photographs were applied to the color and greyscale.

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

1) Operator, Lease & Well number
2) Lat/Long (latitude and longitude decimal degree location)
3) The well ID number from the Texas Water Development Board Brackish Aquifer Characterization System (BRACS) database
4) API # (American Petroleum Institute well number)
5) Core Tracking # (Bureau of Economic Geology, CRC, core reference #)
6) County
7) Core Size (diameter)
8) Date Photographed
9) Core # (Box number)
10) Formation (Trinity formation(s) represented within each box)

5 Task 4a, Core Plug Selection, Sampling, Packaging and Delivery to Core Labs

The TWDB Core Testing for Hill Country Trinity Aquifer RFP suggested that there should be several samples and types of lithologies to be analyzed for each stratigraphic formation as listed below.

• Three (3) samples each for the Upper and Lower Glen Rose formation: Massive dolomite, marly limestone, and anhydrite.

• Two (2) samples each for the Cow Creek and Sligo formations: Massive limestone and marly limestone

• Two (2) samples for the Hensell Formation: Clean sandstone and silty sandstone

• Three (3) samples for the Hosston Formation: Clean sandstone, silty sandstone, and sandy siltstone.

Core plug selection considered this guideline but also had to consider what Trinity formations core intervals were available, the core interval thickness, and was the core coherent enough to extract a core plug without breakage.

5.1 Selection Criteria for Core Plugs

A meeting was arranged with TWDB Project Manager, Mr. Robinson to discuss core plug selection criteria and logistics. Because of the Covid epidemic, the BEG was limiting visitors to the CRC facilities. If the TWDB staff were physically involved with the selection and approval of the core plug intervals, then coordinating meeting logistics for the core plug selection would be complicated and time consuming. After a detailed discussion of core plug selection criteria, Mr. Robinson approved that Mr. Standen could select the core plug intervals without prior review by the TWDB.

After completing a thorough review of the total core hole, Mr. Standen would place a red sticker on each selected core plug location to be reviewed by the CRC staff, Mr. Brandon Williamson before actual plug extraction.

5.2 Core Plugging

The CRC required that core plugging be completed by the CRC staff, no core intervals were extracted by the Core Labs as was proposed in the RFP. A completed CRC “Sampling Contract” was submitted to the CRC manager, Brandon Williamson for plugging intervals of each core. A labeled envelope for each core plug interval was created by Mr. Standen. Upon Mr. Williamson’s confirming the depth of each core plug for each labeled envelope and the determination if the core plug interval had plugging integrity, an approval was given to proceed with the core plug extraction.

Once the core plugs were extracted by CRC staff, the core plug intervals were returned to the appropriate core box by Mr. Williamson and the labeled envelopes with the extracted core plugs were given to Mr. Standen.

Table 5-1 lists each core with the available core intervals, the selected core plug intervals, and Trinity formation tops. The shaded Trinity formations indicate formation intervals with core plugs.

Table 5-1. Core Intervals, Core Plug Depths, Trinity Formation Tops, Shaded Areas Have Trinity Formation Core Plugs

Lease, CRC #, county	Core intervals	Core plug depths	UG	LG	HE	CC	HM	SL	HO
			Trinity formation number of core plugs ( )						
Herrera, C6405, Bexar	3909 - 3984.5, 4290 - 4375, 4625 – 4676, 4785 - 4831	3933.0, 3951.5, 3968, 3982, 4355, 4629.5, 4668, 4799, 4823.5, 4830 (10)	3326 (1)	3942 (4)	4543 (2)	4674	4720	4767 (3)	5089
Roberts, C06364, Frio	5792 – 5806, 5842 – 5918, 6497 – 6549.5, 6694 – 6697, 6899 - 6949	5793, 5804, 5851.5, 5887.5, 6512.5, 6524.5, 6538, 6544, 6695.5, 6908, 6921, 6940 (12)	4936 (1)	5803 (3)	6377 (5)	6683 (1)	6837	6889 (3)	7371
Kauffman, C06335, Bastrop	5430 – 5607.5, 5995 - 6058	5435, 5450, 5506.5, 5513.5, 5996.5, 6021, 6039, 6054 (8)	4584	5361 (4)	5739	5846	5914	5943 (4)	6243
Crowell, C00315, Caldwell	2425 – 2546, 3061 – 3118, 3241 – 3243, ? – 4639, 5340 – 5430, 5829 –5842, 6370 - 6415	5358, 5404, 5430, 5830, 5836, 5842, 6405 (7)	3793	4468	4982	5164	5203	5236 (3)	5685 (4)
Schmidt, C00301, Guadalupe	1072 – 2614 (many small gaps)	1371, 1434, 1479.5, 1618.5, 1718.5, 1754.5, 1791, 1815, 1887.5, 1929, 1966, 1998.5, 204(5), 2092.5, 2116, 2292.5, 2541, 2585, 2606.5 (19)	917 (1)	1439 (4)	1751 (4)	1893 (1)	1940 (1)	1975 (3)	2099 (5)
Southern, C64413, Wilson	4656 – 4697, 7087 - 7097	7090.5, 7095.5 (2)	5781	6378	6967	7089 (2)	7142	7174	7659
AY-68-19-209, C06367, Bexar	340 – 360, 390 – 491, 658 – 668, 750 – 755, 820 - 893	344, 354.5, 396, 405.5, 435, 447, 480.5, 663, 827.5, 860, 879, 883 (12)	1	92 (1)	345 (3)	406 (3)	488	526	606 (5)
Suggs Everett, C06315, Atascosa	6812 – 6825, 7073 - 7266	6814, 7110, 7225, 7261 (4)	5634	6269 (1)	6857	7081 (1)	7165	7197 (2)	7601
Carroll, C04512, Medina	3484 – 3538, 3883 – 4001, 4190 – 4231, 4300 - 4360	3523, 3929.5, 3994.5, 4217, 4230.5, 4330.5, 4353 (7)	2834	3444 (2)	3970 (1)	4128 (2)	4220 (1)	4264 (2)	4468

5.3 Core Plug Preparation and Shipping

Upon receiving the core plugs from the CRC staff, the well depth was confirmed, and each core plug was inspected for length and integrity. Unfortunately, some of the core plugs were a little short in length and would require Core Labs to modify their core plug analyses sequence. After confirming the integrity of each core plug, the core plug was returned to the correctly labeled envelope.

A standard FedEx box was used to ship the core plugs. Package cushioning was used to protect the core plugs from shipping damage. The required Core Labs forms for shipping and core analyses were completed which required the listing of each core plug and core name and type analyses requested. The Core Labs forms were emailed and included within the FedEx box. The FedEx box was shipped priority overnight with morning delivery. There was a total of 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. All shipments were confirmed as received with Core Labs (Jasmine Langston, 713–328-2429) the next business day.

Feb 3, 2021, Batch 1, (18 total plugs), Kauffman (8 plugs) and Roberts (10 plugs)

April 2, 2021, Batch 2, (31 total plugs), 12 AY-68-19-209 (12 plugs), Crowell (7 plugs), Roberts (2 additional plugs), Herrera (10, plugs)

May 18, 2021, Batch 3, (21 total plugs), Southern (2 plugs) and Schmidt (19, plugs)

May 28, 2021, Batch 4, (11 total plugs), Suggs (4 plugs) and Carroll (7, plugs)

6 Task 4b, Core Lab Analyses Scope and Analyses Results

Core Laboratories (Houston) was the subcontractor for core plug analyses.

The following analyses were requested in this RFP, bulk mineralogy (XRD), porosity, permeability, and cementation exponent (m-factor). The RFP also requested NMR (Nuclear Magnetic Resonance) but after talking with Steve Alexander (Core Labs salesperson), he thought that the NMR analyses would not be useful for reservoir analyses when considering the core sample interval represented such a small formation interval of a much larger, highly heterogeneous depositional system. Mr. Alexander stated that NMR was expensive, at $705 per plug, and the information gained for such small subsurface intervals has limited application. ARS LLC recommended that NMR analysis not be considered in the submitted RFP.

Available price discounts for the State of Texas were requested.

Requested information by Core Labs included guidance on salinity and reservoir pressure for each core hole which was provided to Mr. Standen by email as received by the TWDB project manager, Mr. Robinson. The average final cost for the Core Labs analyses of the 81 total core plugs was $1,515.68 per plug.

6.1 Core Lab Documents and Core Lab Results

Core Lab results of the 81 core plugs are summarized in an Excel spreadsheet in Appendix F. Five constituents from the Core Lab's XRD analyses are included in the Appendix F summary. These five constituents include quartz, anhydrite, calcite, dolomite, and total clay and were selected because these constituents represent 95% or more of each core plug's total mineralogy, except for the Schmidt, 2605.5 core plug analysis.

Schmidt, 2,606.5, had high plagioclase at 40.2%, total clay at 36.9% and marcasite content at 10.5%. This interval is thought to be representative of the underlying Paleozoic rocks.

The core plug from AY-68-19-209, at 883 feet of depth, only has XRD analyses. The core plug crumbled during Core Labs pre-treatment and no other analyses could be conducted. This core interval was intact, but poorly cemented when submitted and is described as a multicolored, silty shale, within a highly broken, probable fault zone.

Included within Appendix F is a folder with summary reports of each type of Core Lab analyses and a second folder containing the individual received Core Lab reports.

7 TWDB Draft Report Comments

Appendix G are the responses to the "TWDB Comments on Draft Report".

8 Acknowledgements

ARS LLC would like to acknowledge the CRC staff who were always available, helpful, and dedicated to the success of this study. The CRC staff includes, Mr. Nathan Ivicic, the curator, Mr. Brandon Williamson, the CRC Manager and Mr. Rudy Lucero the CRC Warehouse Supervisor. I am deeply grateful for their help, guidance, and participation.

ARS LLC would like to acknowledge the professionalism and perseverance of Sean C. Murphy and his dedication to create high quality and detailed core photographs for this project. He conducted numerous experiments and photograph iterations to generate a final outstanding photography product.

ARS LLC would like to acknowledge, the TWDB project manager, Mr. Mark Robinson, who was always available for discussion, provided valuable guidance and/or was very patient and helpful in resolving problems.

9 Conclusions and Recommendations

This project presented numerous logistical and technical problems, all of which were resolved. The task sequence including the core box survey, core lithologic logging, photography and plugging activities was more important than first realized resulting in time delays. The final task sequence is the core box survey, the selection and extraction of core plugs, core photography followed by core lithologic logging. A total of nine cores, representing approximately 2,500 feet of core within 267 core boxes were studied.

The submitted RFP estimate for core box lithological logging was up to 50 boxes per day. Based on experience from this project, a good day (6 hour plus) resulted in a maximum of 25 core boxes (depending on feet of core in box) which is more realistic. Core preparation for photography and lithologic logging was also more time consuming than initially estimated. The professional time and effort required for the core photography, the subsequent photo processing and final photo format creation was significantly underestimated when submitting this RFP.

Future core logging TWDB projects of this scale should consider a full year for completion. The TWDB may also want to consider a core depth limitation for future brackish studies. An additional potential source of information which could be used to supplement the deeper Trinity core lithologic description are the cable tool drillers reports stored at the Bureau of Economic Geology Library.

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