The Pennsylvanian Claytonville Canyon Lime Unit of West Texas

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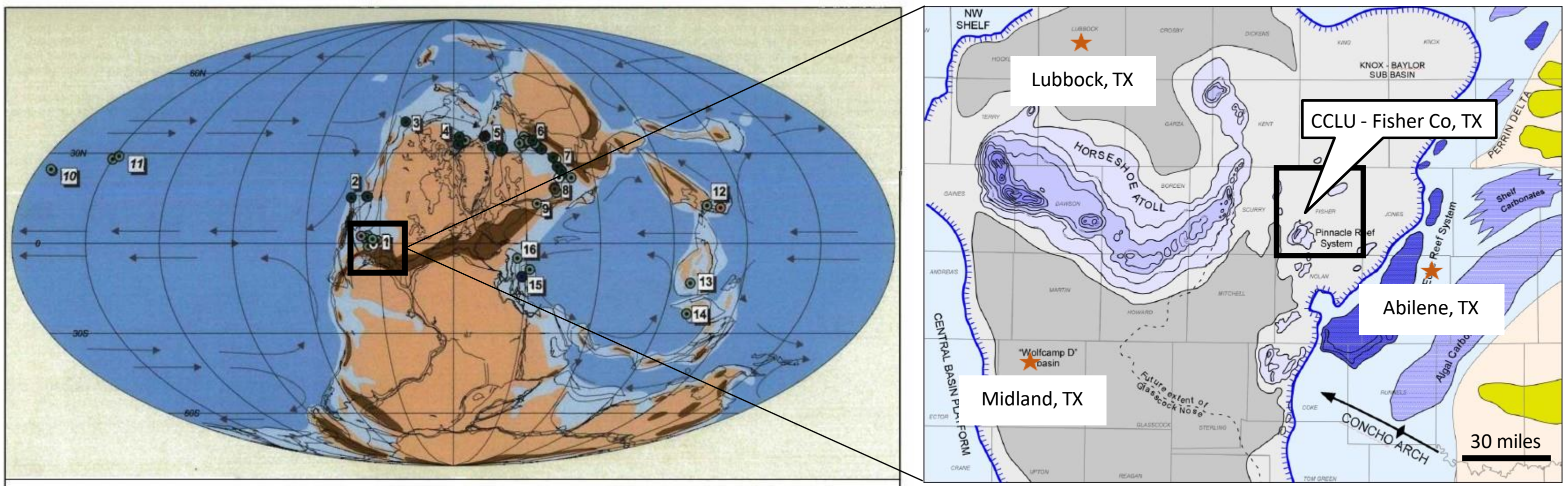
Introduction

Pennsylvanian and Early Permian paleoclimates were very conducive to the formation of carbonate buildups in many shallow marine regions, including portions of the Permian Basin in west Texas. Unlike modern reefs that are primarily composed of corals, such as the Great Barrier Reef, Carboniferous-Permian reefs were largely composed of phylloid algae, sponges, and bryozoans. Favorable seawater temperature, nutrient supply, and light availability in shallow clear water that led to the growth of these reefs occurred in many near equatorial shelf environments (Wahlman 2002 Figure 1A). After being buried for hundreds of millions of years, hydrocarbons that were sourced



A B

Figure 1. A: Late Carboniferous and Early Permian paleogeographic map with dots showing locations of reefs (from Wahlman, 2002). B: A close up of box 1 shows the location of the Horseshoe Atoll and Claytonville Canyon Lime Unit (CCLU) reefs of the Midland Basin. Fisher County, TX is outlined in blac (modified from Sinclair et al., 2017).

from time-equivalent deep-water, organic rich shale source rocks migrated into these buried reefs. Figure 1-B highlights a cluster of carbonate reefs in west Texas that includes the Horseshoe Atoll and the Claytonville Canyon Lime Unit (CCLU) carbonate complexes of the Midland Basin in the eastern Permian Basin. These two time-equivalent complexes serve as excellent examples of how important these reefs are as hydrocarbon reservoirs. The Horseshoe Atoll is a massive chain of reef-shoals discovered in 1938 that spans an area of approximately 8,100 mi^2 and hosts more than seventy oil fields that have produced over 2.6 billion barrels of oil (BBO) to date (Dutton et al, 2005; Waite, 2021). This amount of production makes this complex one of the largest oil accumulations in the Permian Basin. Though much smaller than the Horseshoe Atoll, the CCLU field is the next largest oil accumulation in the northern Midland Basin region. The CCLU field covers approximately 3,840 acres (6 mi^2 / 15.5 km^2) and is the focus of this study.

The Claytonville Canyon Lime Unit (CCLU) is a subsurface Pennsylvanian pinnacle reef complex located in Fisher County, Texas. This complex is composed of several mounds whose carbonate facies included grainstones, packstones, and wackestones ranging from 100% limestone to zones that are 100% dolomite. The field is composed of multiple cycles of shallow marine carbonates that are stacked on top of each other, juxtaposed against deep open marine shales. The CCLU complex has produced approximately 66 million barrels of oil (MMBO), 86.7 billion cubic feet of gas (BCFG), and 133.4 million barrels of water (MMBW) since its discovery in 1952 and has an estimated 147 MMBO oil in place (Texas BEG, 1991). Initial production from this field was driven by a natural solution gas drive that was aided by waterflooding beginning in 1960. The average depth from surface to the top of the reef, which will henceforth be referenced to as the Top of the Penn Lime, is -5700 ft measured depth. CCLU has an average porosity of 6.5% and is primarily composed of limestone with occasional dolomitized sections and shale stringers. A stratigraphic column showing the general vertical distribution of these formations is shown in Figure 2.

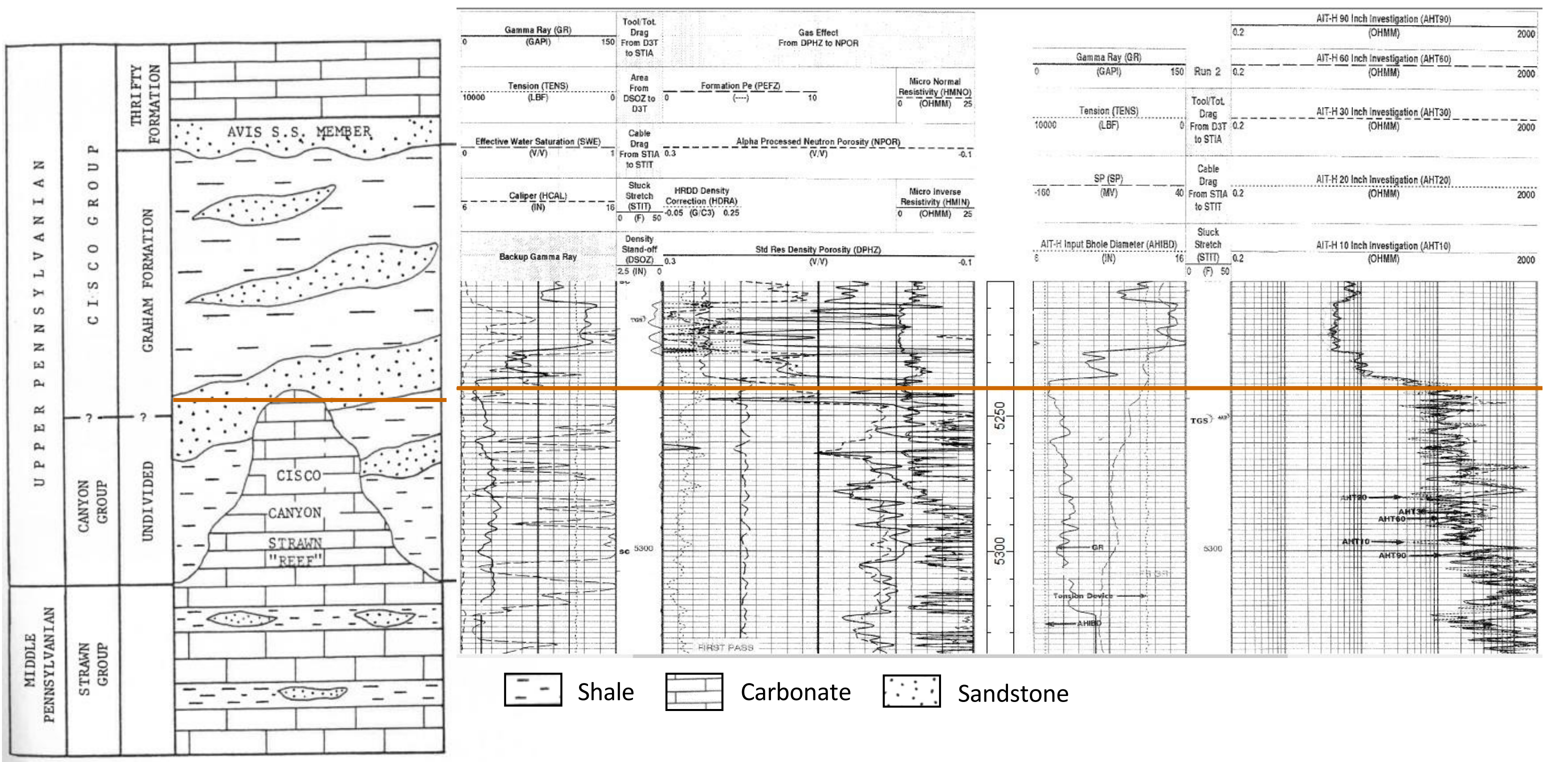


Figure 2. Stratigraphic column of the CLLU field tied to log signature identifying the top of Canyon formation (reddish-brown line). The top of the Pennsylvanian Canyon Lime formation is identified on well logs by a sharp drop in gamma signature, sharp drop in neutron porosity, and a rapid increase in resistivity. (Modified from Snyder, 1977).

Methods

Cross-sections and structure maps shown in this paper were done using IHS Markit's Petra geologic interpretation software. Formation tops were picked on either scanned or digitized logs from each of the ninety-two wells with relevant logs to evaluate. Once the stratigraphic tops were defined, structure maps were generated using Petra's grid function. All grids were made using the minimum curvature gridding algorithm and estimating grid size from Z data using the "Smaller" option. Grid limits were restricted to the "Limits of Well Data". All other gridding options were left at their default settings.

Core analysis discussed in this paper was conducted on whole core samples of the CCLU 7-9 and CCLU 29-3 wells by a third-party company that specializes in analysis of core samples. This analysis was conducted by a prior operator of this field who did not provide details on the analysis parameters. Only the analysis results were available for this study.

Reef Morphology and Structure

The stratigraphic column (Fig. 2) illustrates the prominent pinnacle-like structure of the CCLU reef and shows that it is composed primarily of carbonates, with flanking shale and sandstones. As discussed below, the reef is composed of four primary carbonate cycles. These cycles include two different limestone facies and a dolomite section, discussed in greater detail below. The overall structure of the reef complex is shown in Figure 3. This reveals that the CCLU reef consists of three primary lobes which trend northeast-southwest and span an approximate horizontal distance of 22,000 ft. The reef structure has steep slopes on all sides, attesting to the ridge-like nature of the complex. The top of the Pennsylvanian Canyon Lime formation is identified on well logs by a sharp drop in gamma signature and neutron porosity and a rapid increase in resistivity. An example of these log characteristics is shown in Figure 2. Identifying these log signatures on wells in the CCLU field yielded the structure map in Figure 3. The base of the CCLU reef is defined by the top of the underlying Strawn shale and sandstone formation (Fig. 2).

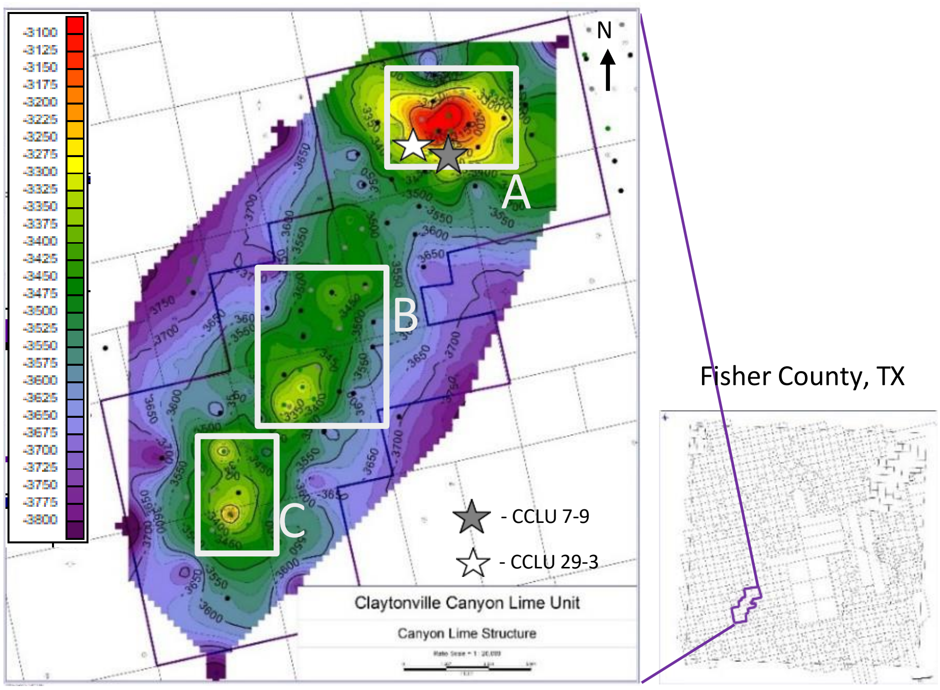


Figure 3. Structure map of the Pennsylvanian Canyon Lime formation top in CCLU highlighting the three primary reef accumulations, labeled A, B, and C. Contour depths measured in subsea feet. Wells with core data are starred. This structure map was generated by picking tops and creating a grid from the tops via the methods described in the "Methods" section of this paper

The three lobes in this field are labeled A, B, and C in Figure 3, with A being the northeastern-most lobe, B representing the central lobe, and C being the southwestern-most lobe. NW-SE cross-sections across each of these lobes are shown in Fig. 4, 5, and 6. A cross-section, oriented NE-SW, describing the subsurface structure of the entire CCLU field is shown in Figure 7. This cross-section highlights the vertical relief of the overall structure while also showing the variation in height between the different lobes. Lobe A is approximately 3000 ft E-W and 2000 ft N-S and is the widest of the three lobes, containing the greatest accumulation of reef growth within the field. Using a -3850 ft. subsea depth structural contour to represent the approximate base of the reef, Lobe A reaches a maximum height of -4980 ft subsea depth, a total of 1,130 ft., which is over 600 ft higher than the next tallest lobe, Lobe C. The cycles of reef growth are discussed in greater detail below but it is important to note that the prominence of lobe A is a result of an additional cycle of reef growth that is seen almost exclusively on this lobe. A cross-section of the subsurface structure of Lobe A is shown in Figure 4. Lobe B is separated from Lobe A by a low that is, approximately 4700’ wide E-W direction, and approximately 8700’ wide N-S. The structural high of this lobe is located in the south and has a maximum height of 3350 ft subsea depth, projecting a total of 500 ft above the base of the reef. A smaller accumulation is located in the north on a broader and flatter section of this reef with a maximum height of 3425 ft subsea depth. A cross-section describing the structure of this lobe can be seen in Figure 5. Lobe C is similarly separated from Lobe B by another low. This lobe is approximately 3300 feet wide E-W and 6100 feet wide N-S. Lobe C has 2 distinct pinnacle accumulations, separated by a small structural low, with heights of -3400 and -3375 ft subsea depth in the northern and southern portions of this lobe, respectively. The tallest portion of Lobe 2 projects a total of 475 ft above the base of the reef. A cross-section illustrating the structure of this lobe is shown in Figure 6.

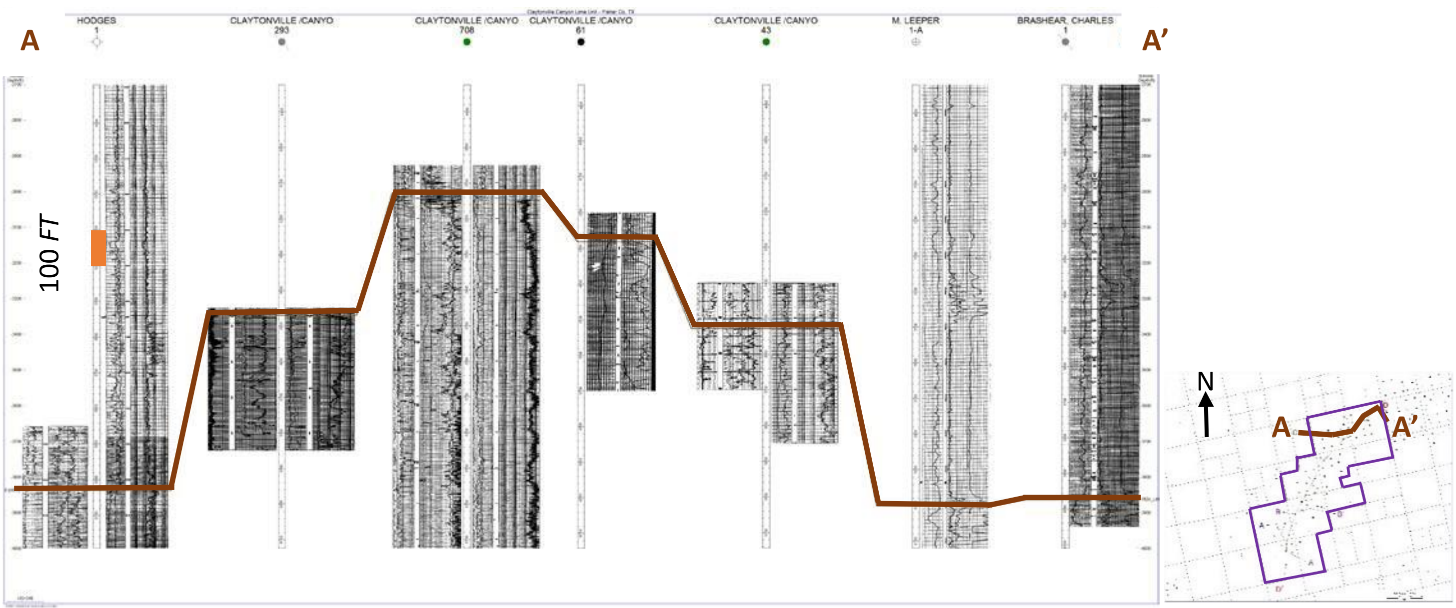


Figure 4. West-east cross-section showing Lobe A of the CCLU field. Datum is sea-level.

Reef Facies

Full core samples were taken in two wells in the NE lobe: CCLU 7-9 (API# 42151326140000), and CCLU 29-3 (API# 42151327930000). The location of these wells is highlighted in Figure 3. Analysis of the core data and the associated well logs reveals cycles of massive, crystalline carbonates and granular sections within the reef that indicate changing ocean depths at the time of deposition. The crystalline carbonates indicate pure reef accumulation while grainstones indicate carbonate accumulation near the reef. The limestone sections of the core samples are either light gray or tan in color. The gray limestone sections have a variety of characteristics that range from unfractured to highly fractured with a massive, crystalline matrix. The more fractured this limestone is, the more porous it is, with pore sizes ranging from 0.5 mm to 2 mm wide. More porous zones contain some fluorescent minerals. Fractures can be filled with calcite cement and do not have a specific orientation. Stylolites also appear in the more fractured zones. All lab analysis from core data discussed in this study are from the Claytonville CCLU 29-3 and Claytonville CCLU 7-9 unpublished core reports. This lab analysis reveals that permeability ranges from 0.0001 to 2.03 mD, porosity ranges from 0.65 to 7.11 %, density ranges from 2.67 to 2.72 g/cc, water saturation (Sw) ranges from 30.1 to 52.6 %, and oil saturation (So) ranges from 0 to 16.7 %. Fluorescence, which indicates the presence of hydrocarbons, is not often present in this lithology but can be almost 100% when it does exist.

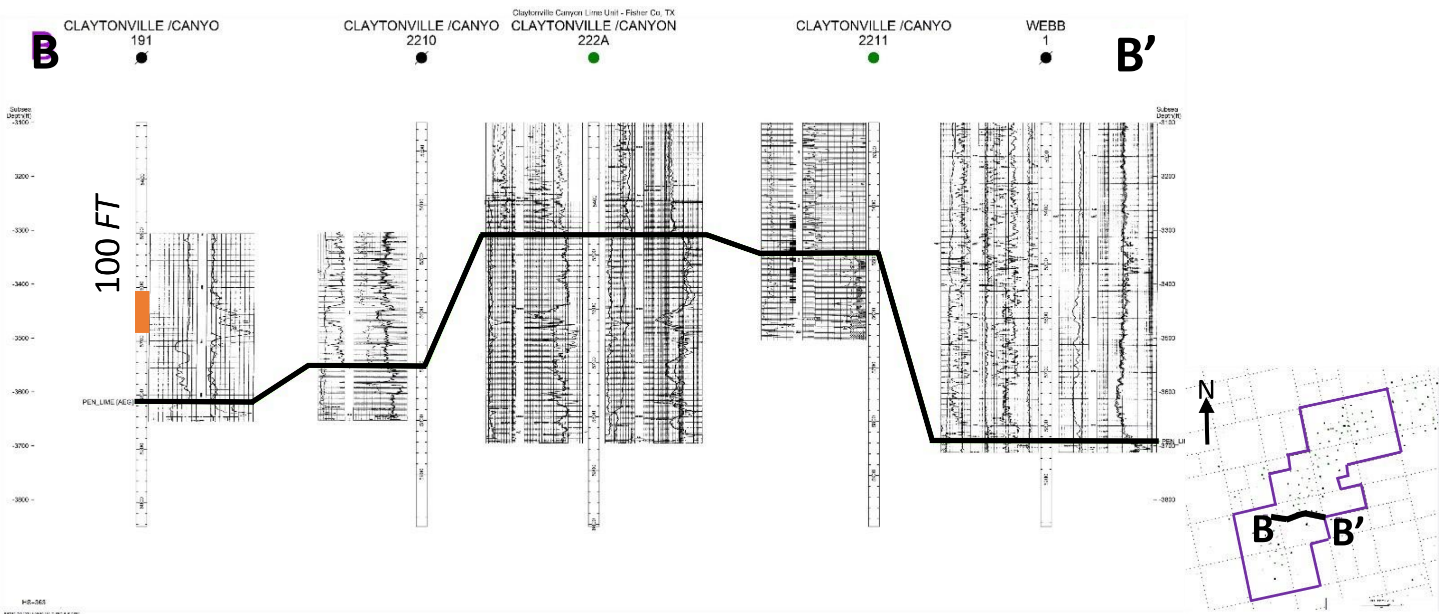


Figure 5. West-East cross-section across Lobe B of the CCLU field. Datum is sea-level.

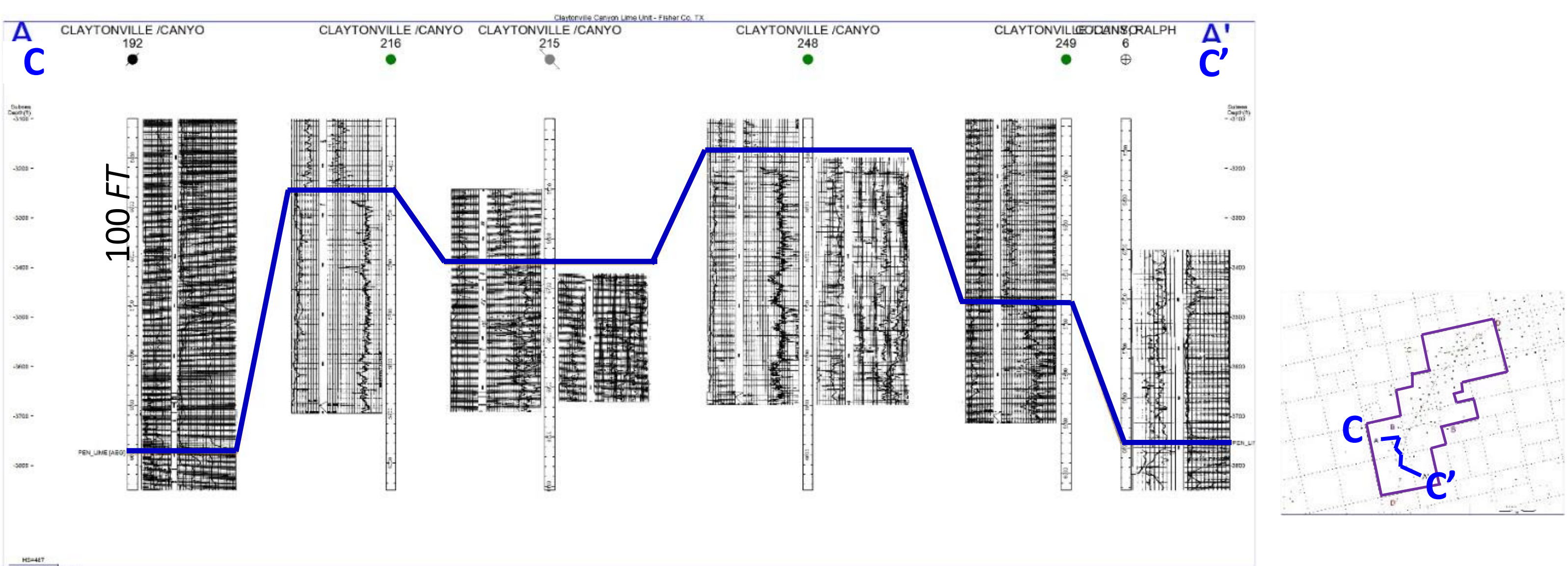


Figure 6. NW-SE cross-section through Lobe C of the CCLU field. Datum is sea-level.

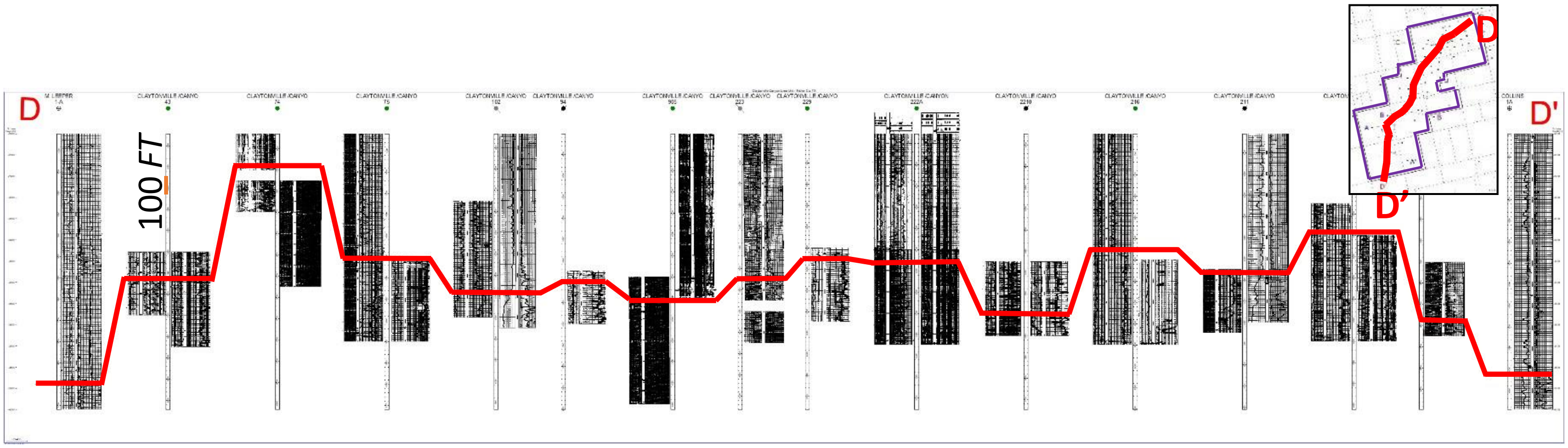


Figure 7. NE-SW cross-section through the entire CCLU field. Datum is sea-level.

The tan limestone primarily consists of grainstones, unlike the crystalline matrix of the gray limestone. The grainstone matrix consists primarily of sand-sized carbonate grains, with some very fine-grained particles, which are well-sorted and rounded. Grain size ranges from 2 mm to 1.5 cm. Stylolites are common within this facies. Laboratory analysis of the grainstones reveal permeabilities ranging from 0.0033 to 405 mD, porosity ranging from 1.11 to 15.03 %, density ranging from 2.67 to 2.8 g/cc, water saturations ranging from 24.2 to 50.3 %, oil saturations ranging from 0 to 19.9 %, and up to 100% fluorescence. There is also a dolomitized section that is the most productive hydrocarbon zone and has several unique characteristics. It consists primarily of a crystalline dolomite matrix with vuggy porosity but can also contain crystalline dolomite matrix with very little porosity. Vugs are occasionally encased in calcite crystals. When porosity is present, the vugs range from 1 mm to 1 cm wide. Fossil fragments can also be found in this facies; these appear to be crinoids when large enough to be identified. Lab analysis of this dolomitized section reveals permeability from 0.0011 to 3042 mD, porosity from 1.51 to 23.43 %, density from 2.86 to 2.89 g/cc, Sw from 25.2 to 48.2 %, So from 0 to 19.6 % and fluorescence from 0 to 100%.

The grey limestone consists of interbedded limestone and shale. The carbonates of this facies are wackestones that consist of a gray matrix with gray crinoid and gastropod fragments. The wackestone is interbedded with an brittle dark gray shale that does not contain any fossils. The contact between these two lithologies varies from sharp to gradational to a mixture of limestone clasts suspended in shale. These clasts are angular and range from 1 to 2 cm wide. Lab analysis determined that this lithology contains permeability ranging from 0.0012 to 0.0876 mD, porosity from 1.06 to 1.56 %, density from 2.69 to 2.73 g/cc, and Sw ranging from 46.4 to 48.2%. There is no So or fluorescence present in this lithology type. A type log that correlates these different lithology categories to their corresponding log signatures is shown in Figure 8.

Depositional Environments and Sea-level History

Analysis of core data and e-log signatures indicate a number of repetitive grainstone-wackestone cycles, interpreted to reflect sea level changes. These sea-level cycles are designated, from oldest to youngest, M1, M2, M3, and M4 (Figures 9,10). Each of these cycles is interpreted to represent a long-term (2nd-order) transgressive-regressive change in sea-level over hundreds of thousands of years. However, within each of these larger M cycles are a great number of shorter cycles of transgression and regression on the order of tens of thousands of years. These short-term cycles, also called cyclothems, are interpreted to represent glacial eustatic controlled changes in sea-level resulting in the deposition of numerous cyclothems. Considering the previously defined lithologies identified in core samples, the muddy, gray limestone with a crystalline matrix may indicate deposition in calmer, deeper ocean waters associated with a sea-level transgression. The tan limestone that lacks mud and has a grain-supported matrix may indicate deposition in shallower, more energetic marine environments associated with a sea level regression. Comparing these carbonate lithologies, their inferred depositional environments, and the global eustatic curves shown in Figure 9 confirms the existence of smaller transgressive-regressive cycles within larger cycles. An example of this is seen in the M3 cycle, shown in the type-log shown in Figure 9, that contains three to four smaller-scale depositional cycles. The dolomite section in M3 and M4 cycles may reflect diagenesis associated with a regression and reef exposure, but a complete understanding of the nature of the dolomite is beyond the scope of this study.

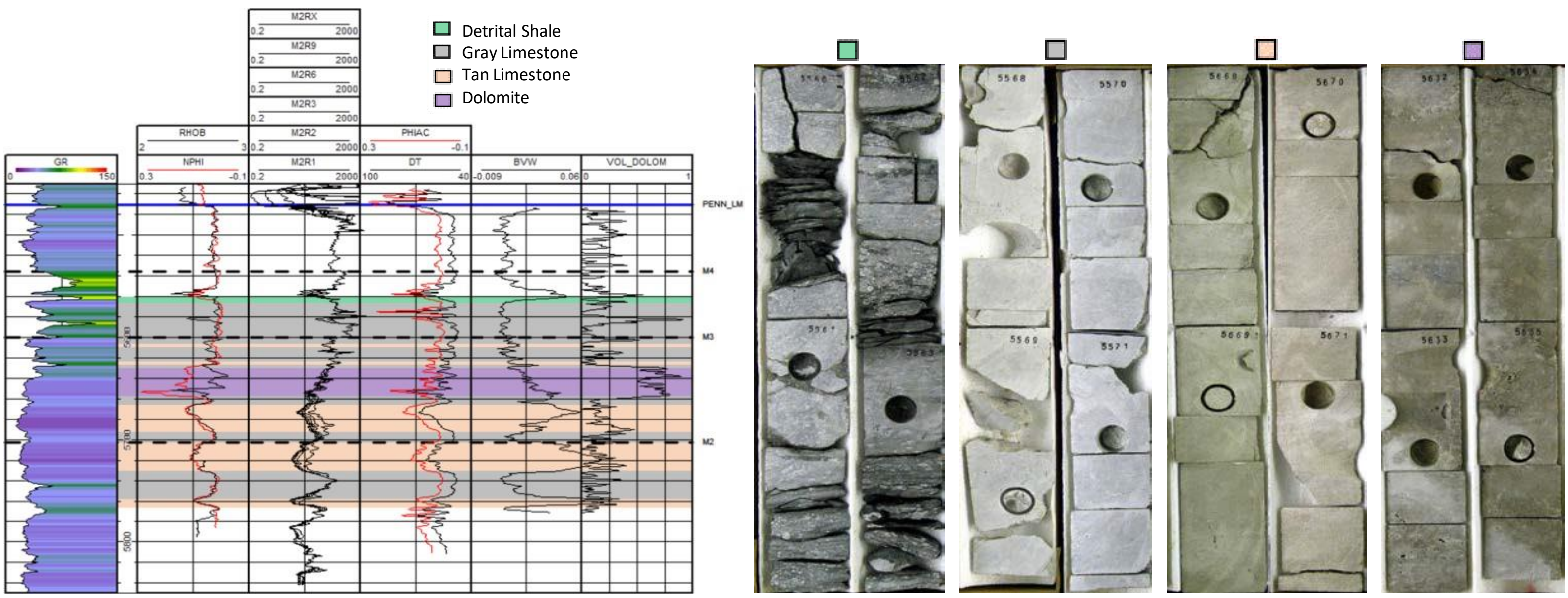


Figure 8. Left: Type log of the CCLU 29-3 showing the log characteristics of the Claytonville Canyon Lime and its depositional sub-sections M2, M3, and M4. Each sub-section has been correlated to whole core samples taken from the CCLU 29-3 well (Right).

It is very important to understand the eustatic cycles occurring at the time of CCLU reef deposition and how these affected especially water depth conditions needed to generate carbonates in the photic zone. Understanding these relationships helps to better understand preserved reef morphology. The three prominent pinnacles or lobes of the CCLU reef are interpreted here as reflecting two main types of carbonate accumulation called “Catch Up” and “Keep Up” (Kendall and Schlager, 1981). “Catch Up” carbonate accumulation is defined by a rapid rise in sea level that moves carbonate accumulation conditions outside of their optimal zone only enough to slow reef growth, not stop it. The rise in sea level then slows to the point where carbonate accumulation concentrates and results in vertical reef growth. “Keep Up” accumulation describes a situation where sea level rises at a steady rate that results in vertical carbonate accumulation. The primary difference between “Catch Up” and “Keep Up” accumulation environments is that “Keep Up” sees more uniform deposition of carbonates in the vertical and lateral direction while “Catch Up” accumulation sees primarily rapid, vertical growth that tends to focus in a conical growth pattern due the rapid rise of the optimal carbonate accumulation zone (Kendall and Schlager, 1981).

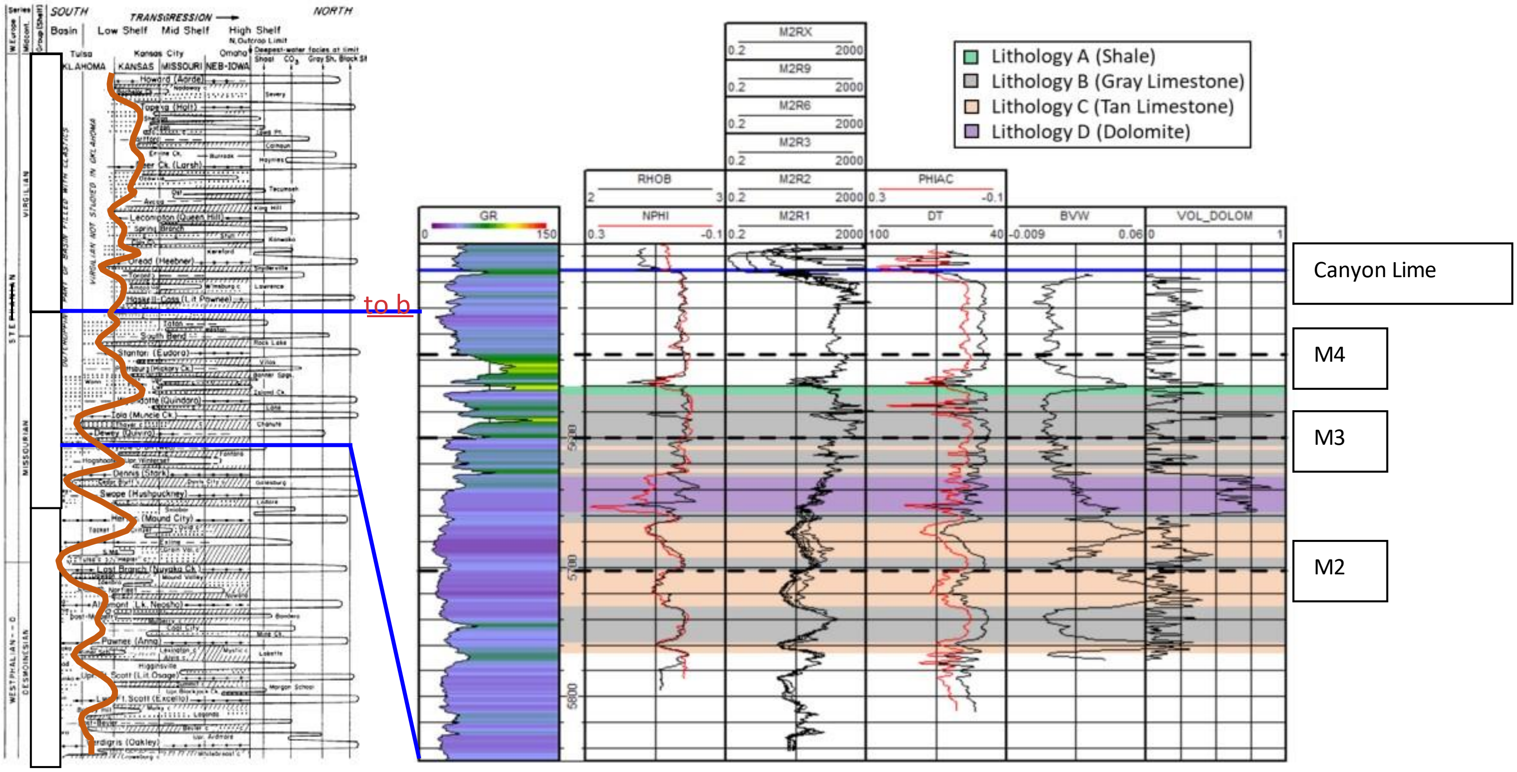


Figure 9. Pennsylvanian eustatic marine transgressive-regressive cycles tied to the type log of the Canyon Formation. The orange curve on the left indicates larger scale cycles while the black curves to the right of the orange curve indicate smaller scale cycles. Blue lines tie the type-log to the timescale associated with the eustasy curves (modified from Heckel, 1986). Each "M" marker indicates the beginning of a section of the CCLU reef that is interpreted to encompass a transgressive-regressive cycle. The entire CCLU reef contains four of these "M" cycles, with M1 being the oldest. No wells drilled in the reef go deep enough to penetrate and log the M1 section. The presence of a postulated M1 section is confirmed via seismic reflection data in Fig 10.

"Keep up" accumulation is the scenario that best explains the growth of lobes "C" and "B" shown in Figure 3. This is indicated by the greater lateral propagation of these lobes in the SW-NE direction, especially in lobe "B". The low between these two lobes is also less pronounced than the low that separates lobe "B" and "A" which makes "B" and "C" more likely to be a part of the same growth event. The pinnacles seen in lobes "C" and "B" are likely the result of the previously described steady rise in sea levels that focus carbonate accumulation vertically. The variations between lateral and vertical growth seen in these lobes also gives additional evidence to the previously described changes in sea level rise. "Catch Up" accumulation likely describes the growth of lobe "A". This is because this lobe is isolated from the other two lobes, indicating that it grew rapidly as one, uniform accumulation. The higher vertical accumulation of this lobe also indicates the focus of growth in this direction that is associated with "Catch Up" accumulation.

Keeping in mind the previously described accumulation models and the specific conditions required to generate carbonates, reef morphology implies an environment affected by differential subsidence at the time of accumulation. Subsidence seems to have likely occurred faster in the southwest resulting in that part of the reef drowning before the northeastern portion. Additionally, the northeast portion of the reef is the paleowindward side. This likely allowed for greater nutrient supply and carbonate growth and accumulation on this lobe.

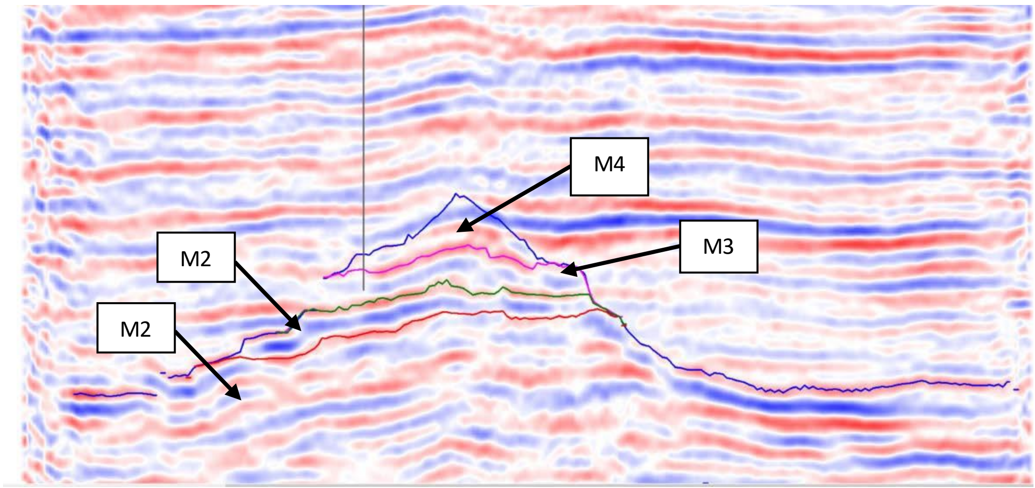


Figure 10. Seismic data covering the CCLU Reef showing all four M cycles. The red line denotes the top of the M1 cycle, green the top of the M2 cycle, pink the top of the M3 cycle, and blue shows the overall top of the reef. The M4 cycle is only present In the portion of the reef that contains carbonate accumulation above the pink M3 marker. The top of the M4 cycle in this area is also the top of the reef, which is why the blue marker was used to denote the end of the M4 cycle.

Deposition of the Claytonville reef likely started with a "Keep Up" accumulation scenario that started with the slower, broader generation of a basal carbonate extending beneath the entire reef complex. During the overall rise in Late Pennsylvanian sea-level, differential vertical accumulation of the reef ensued. Due to the presence of a slightly higher accumulation on the southern pinnacle of lobe C, it is likely that local subsidence associated with sea-level rise concentrated carbonate accumulation on the C pinnacle. Following a slight drop in sea-level a second sea-level rise resulted in more accumulation at the top of lobe C. It is likely that lobes A and B became isolated at this time. As sea level continued to rise, vertical accumulation occurred on both of these pinnacles until the sea-level rose beyond photic zone and accumulation slowed at lobe B. Due to the broader nature of lobe B, it appears that the period of slower carbonate accumulation for this part of the reef occurred longer than for the other two lobes. This slower aggregation was then followed by another period of rapid sea-level rise, with some falls and rises that resulted in vertical accumulation and the multiple pinnacles seen on this lobe. Finally, there was a sharp enough rise in sea-level to produce a prominent low between lobes A and B. It is likely at this point that sea level started rising much faster resulting in a "Catch Up" type of accumulation to produce the more vertical structure of lobe A. When the combination of subsidence and long-term sea-level rise resulted in the region of lobe A falling below the photic zone, carbonate deposition ceased at Claytonville, with a lack of any other reef buildups in the surrounding region. Increased clastic flux could also have contributed to slow reef growth.

Summary and Recommended Future Work

The paleoclimates of the Pennsylvanian and Early Permian allowed deposition of abundant carbonate rocks that would eventually become important hydrocarbon reservoirs within the Eastern Shelf region of West Texas. The pinnacle reef complex that contains the Claytonville Canyon Lime Unit field of Fisher County, Texas is one of these fields. Well log analysis shows the reef trends SW-NE for ~4 miles and is composed of three primary accumulations or lobes, each 3,000-5,000 feet wide and 475 and to 1,130 feet tall. The largest and tallest of these lobes is located in the northeastern portion of the reef. There were many small-scale shifts in sea level while the reef accumulated. Core analysis reveals three main types of carbonates: gray limestone, tan limestone, and dolomite. The gray limestone is muddier and has a crystalline matrix, indicating deposition in deeper, calmer ocean water. The tan limestone has a mud-free, granular matrix indicating deposition in shallower, more energetic oceanic environments. The shift between these two types indicates short-term changes in sea-level at the time of deposition.

There is much more additional work that can be done to describe and understand the history of the Claytonville reef. More in-depth core analysis would be one of the most important tasks for further describing the lithologic and petrophysical characteristics of this reef. More detailed core analysis would also aid in more detailed descriptions of the various facies contained of the reef. Thin-section analysis of representative facies types would provide additional valuable insights into the biota, carbonate texture, and diagenetic history of the reef, including the nature of the dolomite. There has also been a number of seismic surveys conducted on this reef, and should any of these surveys be made available, analysis of this data would help to better describe the morphology of the reef than log data can offer. This could be especially useful for understanding the lower M1 cycle of reef accumulation that is not covered by log data due to a lack of well penetrations. Though quite a bit of work has been done on understanding this field, the Claytonville Canyon Lime Unit still has many fascinating, unanswered questions. The answers to these questions could be very important to understanding many other Pennsylvanian carbonate accumulations around the world.

Acknowledgements

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