CRITICAL EVALUATION OF MIDDLE AND LATE PENNSYLVANIAN CYCLIC SEDIMENTATION AND STRATIGRAPHIC ARCHITECTURE IN THE SOUTHERN ANADARKO BASIN, OKLAHOMA

By

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Bachelor of Science in Geology

Oklahoma State University

Stillwater, OK

2014

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2016

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ACKNOWLEDGEMENTS

I owe a huge debt of gratitude to Dr. Pashin for his guidance and patience throughout the course of this thesis project. He put forth an extraordinary amount of time and effort in pointing me in the right direction, and I could not have arrived at this moment without his help. I am extremely grateful for my additional committee members, Dr. Puckette and Dr. Hileman, who were always eager and willing to go out of their way to better my understanding of geology. Collectively, the wealth of knowledge offered by my committee members is beyond words, and I consider myself truly privileged to have worked with each of them. I would like to thank the Boone Pickens School of Geology at Oklahoma State as well as the multitude of scholarship donors who made an advanced degree possible. I am grateful for every professor I have had along the way at OSU, who in one form or another helped shape my education. Each of them played a significant role in helping me reach my academic goals. I thank Tabitha Schneider, Sandy Earls and Tim Sickbert for their continuous support, which benefits so many students on a daily basis. I thank my student colleagues for their friendship and helping to maintain high spirits during trying times. I am thankful for Ed Gallegos at Territory Resources LLC, who generously allowed me to work on this thesis project after hours using his resources. I thank my parents and my wife for their unfailing emotional support. I thank God, for through Him all things are possible. Dr. Puckette, I thank you for the first time we ever met, when you gave my career a sense of hope and direction in the science of geology, which has completely transformed my life. To everyone mentioned above, and to anyone I may have forgotten, I am eternally grateful for your contributions and I wish you all the best in your future endeavors.

Name: MARK WILLIAM JENSEN

Date of Degree: JULY, 2016

Title of Study: CRITICAL EVALUATION OF MIDDLE AND LATE PENNSYLVANIAN
CYCLIC SEDIMENTATION AND STRATIGRAPHIC ARCHITECTURE IN
THE SOUTHERN ANADARKO BASIN, OKLAHOMA

Major Field: GEOLOGY

Abstract: Pennsylvanian cyclothems have been studied in detail in the eastern interior of the United States, but few researchers have applied quantitative stratigraphic analysis to test the concept. The Anadarko Basin contains a thick Pennsylvanian section and thus provides an ideal opportunity to qualitatively and quantitatively assess the vertical heterogeneity of the Pennsylvanian sedimentary record, and to determine the degree of stratal order and cyclicity in the lithologic succession. Two cross sections of the Middle and Late Pennsylvanian were constructed, and two wells were selected for Markov chain analysis and recurrence-frequency analysis. The study interval was evaluated at four observational and interpretive levels: rock type, lithofacies, depositional environment, and sequence stratigraphy. Rock types form mostly rhythmic associations, with highest transitional probability occurring in shale being succeeded by radioactive shale. The highest degree of order and cyclicity occurred at the sequence stratigraphic level, although recurrence interval of surfaces and systems tracts varies based on the degree of development of condensed sections. Glacial eustasy in the short eccentricity band controlled lithologic ordering and cyclicity, while accelerating basin subsidence was the dominant mechanism of sediment accommodation.

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CHAPTER 1

INTRODUCTION

Cyclothems are high-frequency depositional cycles thought to result from repeated transgressive-regressive events, and are typically associated with the Pennsylvanian-Permian section (Weller, 1930; Wanless, 1931). Cyclothems are thought to originate primarily from eustatic sea level change driven by Gondwanan glaciation, oscillating climatic conditions, and basin subsidence associated with Late Paleozoic orogeny (Wanless et al., 1963). Originally conceived from outcrops in the Illinois Basin, the concept was extended to the Cherokee and Forest City basins of Kansas, where a well-preserved stratigraphic section is thought to display a high degree of sensitivity to changes of relative sea level (Moore, 1948, 1964; Heckel, 1980). It is possible that many of the same processes driving depositional cycles in the cratonic Midcontinent can be traced into the extremely thick sedimentary succession of the Anadarko Basin. Stratigraphic patterns observed in geophysical well logs from the southern Anadarko Basin suggest that this region provides an exceptional high-resolution record of relative sea level changes during the Middle and Late Pennsylvanian.

The Anadarko Basin contains several of Oklahoma's most prolific oil and gas fields, many of which produce from Pennsylvanian strata (Figure 1). The complex facies patterns in the basin represent a mosaic of depositional environments that was related to the shifting climatic and tectonic conditions during Pennsylvanian time (Moore, 1979). Subsidence and sea level change are recorded by numerous transgressive-regressive depositional packages, which commonly contain one or more reservoir-quality sandstone and carbonate units. Understanding the heterogeneity associated with cyclic sedimentation is critical for effectively predicting and locating productive reservoir facies, sources, and seals (Posamentier and Weimer, 1993).

Heckel (1980) identified a need for more detailed work to be performed "in areas away from the fairly well known Midcontinent outcrop, in order to fully evaluate… variation in Pennsylvanian stratigraphy." The Anadarko Basin contains a Middle to Upper Pennsylvanian section that is in some areas more than 7,000 ft thick and contains a diverse assemblage of nonmarine and marine strata, but has surprisingly never been characterized qualitatively or quantitatively in terms of cyclothemic sedimentation. Yet the Anadarko section appears ideal for testing the concept of Pennsylvanian cyclicity and seems to lend itself to assessment of cycles, stratal ordering, and stochastic controls on stratigraphic architecture. Though the absence of exposures, cores and modern geophysical log suites has historically made this type of evaluation difficult (White et al., 1999), the drilling of many wells through the Devonian-Carboniferous section within the last 40 years has resulted in an abundance of modern geophysical logs. These data make it possible to analyze stratigraphic architecture in detail, which will help expand knowledge of Pennsylvanian sedimentation in the Midcontinent.

This study is designed to investigate stratigraphic architecture and cyclic sedimentation in the Middle and Upper Pennsylvanian strata of the southern Anadarko Basin (Figure 2). Primary questions to be addressed include:

1. Does stratal order exist at any level?
2. Are succession and thickness of stratigraphic units deterministic or probabilistic?
3. If cyclicity does exist, how can it be identified, and what controls it?

Using a critical approach to qualitatively and quantitatively describe the lithologic ordering and internal heterogeneity of depositional units will improve the understanding of the physical stratigraphy and sequence stratigraphy of the region and will extend the concept of cyclic sedimentation in the Pennsylvanian section to a commercially important area where such concepts have not been rigorously applied—this may, in turn, benefit petroleum exploration. Statistical analysis is a key approach that will be used to test whether cyclicity exists, is deterministic or probabilistic, and is periodic. Recent literature indicates that, although Pennsylvanian strata may record high-frequency, high-magnitude sea level variation, internal stratal ordering and cyclicity in Pennsylvanian strata may be much weaker than commonly thought (Wilkinson et al., 2003). Indeed, an important objective of this research is to determine at what levels human perception and geologic interpretation influence the recognition of cyclic stratigraphic successions. Is there a high level of stratigraphic ordering of raw rock types, or is interpretation of lithofacies and depositional environments required to characterize cyclic sedimentation? And since Pennsylvanian cycles are thought to be intimately related to glacial eustasy, does sequence stratigraphic interpretation reveal aspects of cyclicity that cannot be recognized through traditional lithologic, facies, and depositional analysis?

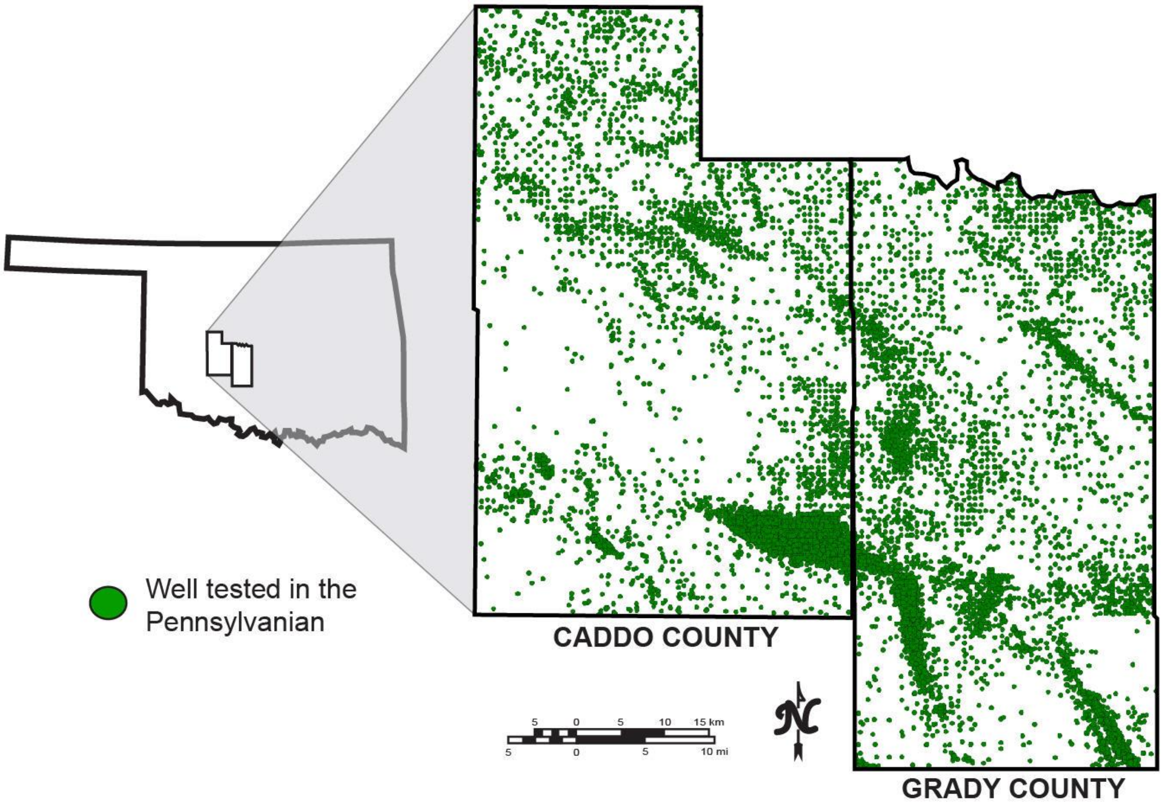


Figure 1. Map of Caddo and Grady counties showing the abundance of oil and gas wells drilled to Pennsylvanian strata in the Anadarko Basin.

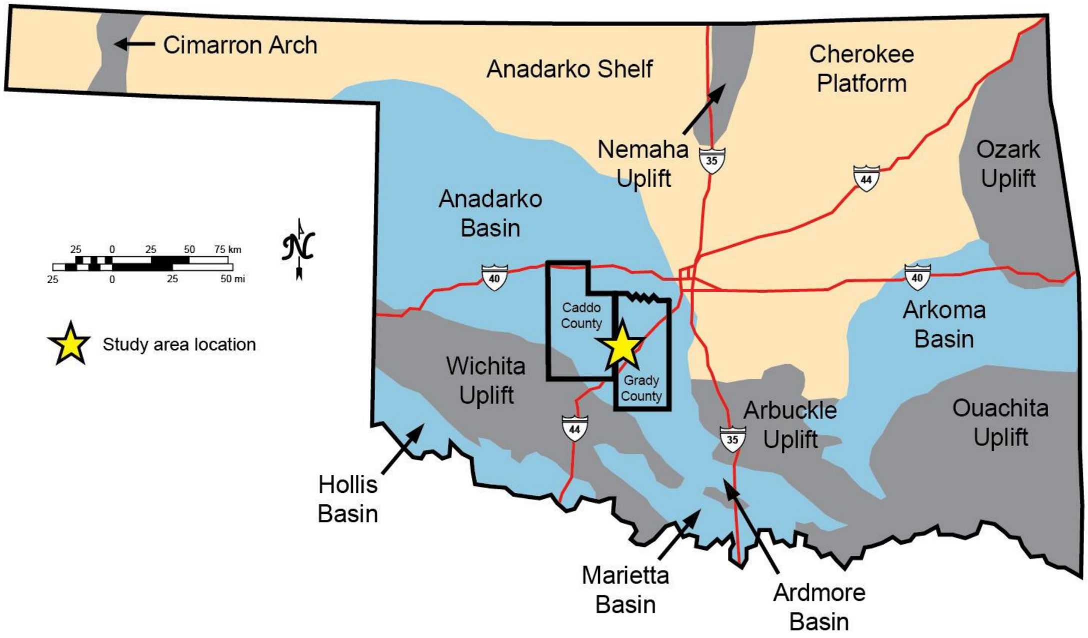


Figure 2. Map showing major geologic provinces of Oklahoma (modified from Northcutt and Campbell, 1996). The location of the study area, which is in Caddo and Grady Counties in the southern Anadarko Basin, is represented by the yellow star.

CHAPTER II

PREVIOUS WORK

Cyclothems

The Pennsylvanian cyclothem has been recognized for roughly a century (e.g., Udden, 1912; Weller, 1930). Alternation of marine and nonmarine strata in cyclothems has long been recognized to be indicative of rise and fall of relative sea level during deposition. Primary causes of relative sea level change during the Pennsylvanian were initially thought to be controlled by tectonic activity (Weller, 1930) or glacial eustasy driven by waxing and waning of a Gondwanan ice sheet (Wanless and Shephard, 1936). Today, the glacial eustatic hypothesis is largely accepted (Wanless et al., 1963; Heckel, 1986, 1994; Klein, 1994). Pennsylvanian cyclothems were first described in Illinois; however, the concept has been extended in various forms to many regions, including Kansas, parts of Oklahoma and north Texas, and the southern Appalachian foreland (e.g., Heckel, 1980; Boardman, 1984; Pashin, 2004). An ideal Illinois Basin cyclothem consists of up to 10 rock types occurring in an ordered succession, which reflects a transition from nonmarine to marine depositional environments (Weller, 1930; Wanless, 1957; Wilkinson et al., 2003) (Fig. 3). The Illinois Basin cyclothem, moreover, is bounded by the erosional surface at the base of a fluvial sandstone (Weller, 1930), and thus can be considered as an early recognition of an unconformity bounded depositional sequence, a concept that remains a centerpiece of modern sequence stratigraphy (Sloss, 1963; Mitchum et al., 1977; Vail et al., 1987; Posamentier et al;

1988).

Recent studies suggest that stratal ordering in Pennsylvanian cyclothems is significantly more complex than generally thought, because frequency of lithologic occurrence, thickness-frequency distributions of rock types, and extremely weak statistical ordering of rock types in the Illinois Basin point toward stochastic (i.e., probabilistic) rather than deterministic control of lithologic occurrence and succession (Wilkinson, et al. 2003). Autocyclic and allocyclic processes, moreover, must be considered among the multitude of dynamic processes contributing to depositional architecture of the Pennsylvanian System (Ferm and Weisenfluh, 1989; Cecil, 2003). Applying an idealized cyclothem to certain regions has been common practice by many previous workers (Figure 3). However, it is complicated by lateral depositional heterogeneity, even within a limited geographic area (Wilkinson et al., 2003). Basic lithologic components of cyclothems can in places be traced for hundreds of miles, but correlating a definitive succession of lithologic units is difficult (Watney, 1995). Though lithologic patterns observed in Pennsylvanian strata often appear to occur at regular intervals in ordered succession, the statistical analysis of Wilkinson et al. (2003) suggests that there is little statistical validation to support a distinct ordering of rock types and lithofacies. Nevertheless, results from some studies suggest that a higher degree of order may exist in the arrangement of lithofacies, depositional environments, parasequences, and depositional sequences that is not supported by rock type alone (Pashin, 2004).

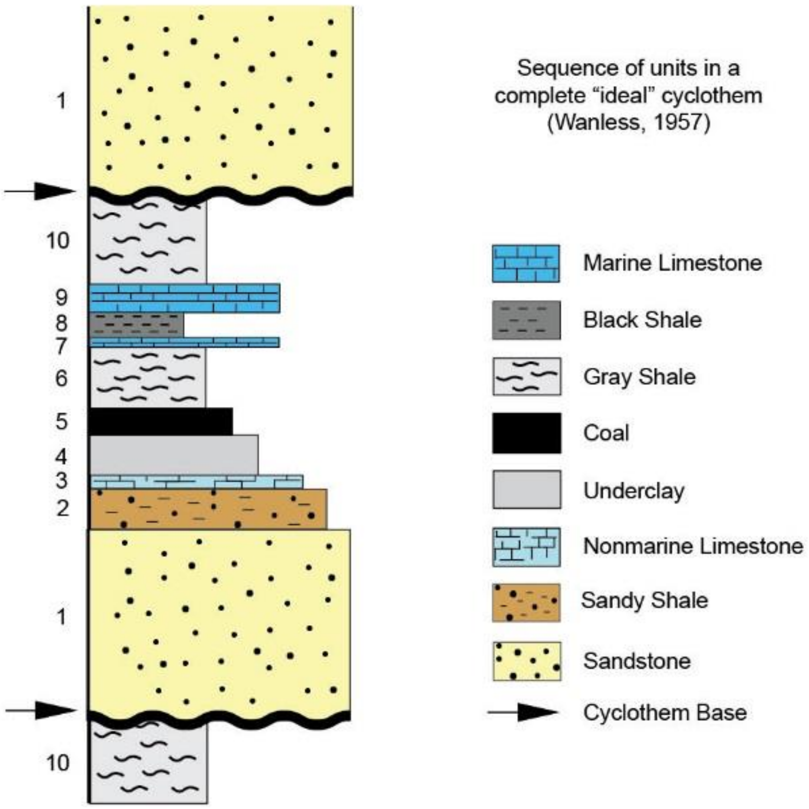


Figure 3. Illustration of 10-member "ideal cyclothem" based on Wanless (1957) in the Illinois Basin (modified from Wilkinson et al., 2003).

Sequence Stratigraphy

In Vail et al. (1987) and Van Wagoner et al. (1987), a depositional sequence is defined as genetically similar strata bounded by surfaces indicative of truncation or nondeposition (i.e., disconformities and their correlative conformities). The bounding disconformities of depositional sequences are likely linked to eustatic sea level changes that either abruptly inundate or expose sediment in such a way that the rate and type of deposition is interrupted or preexisting strata are eroded (Mitchum et al., 1977; Posamentier et al., 1988). Composing each sequence are parasequences, which consist of genetically related beds confined by marine flooding surfaces that represent a rapid increase in water level (Van Wagoner et al., 1987). In combination, parasequences form recognizable stacking patterns that often coincide with sequence and systems tract boundaries as shown in Figure 4 (Van Wagoner et al., 1988).

There is some discrepancy in the scale and recognition of depositional sequences, which in some cases can be identified best by facies successions, parasequence stacking patterns, and stratigraphic surface geometry (Olszewski and Patzkowsky, 2003). Whereas the early designation of a sequence is defined as a stratigraphic succession bound by unconformity surfaces (Sloss, 1963; Mitchum et al., 1977), Galloway (1989) described a genetic stratigraphic sequence as the interval from one transgressive erosional surface to the next. Watney (1995) described a wide range of thickness and lithologic characteristics in Midcontinent sequences and parasequences of the Pennsylvanian, which may represent timespans that vary by multiple orders of magnitude. With the extreme variability in the thickness and lithologic expression of stratigraphic sections in vastly different geographic locations, it is probable that the delineation of sequences and parasequences is not consistent, and must be selected by developing a hierarchical arrangement that best fits the area of interest (Embry, 1995).

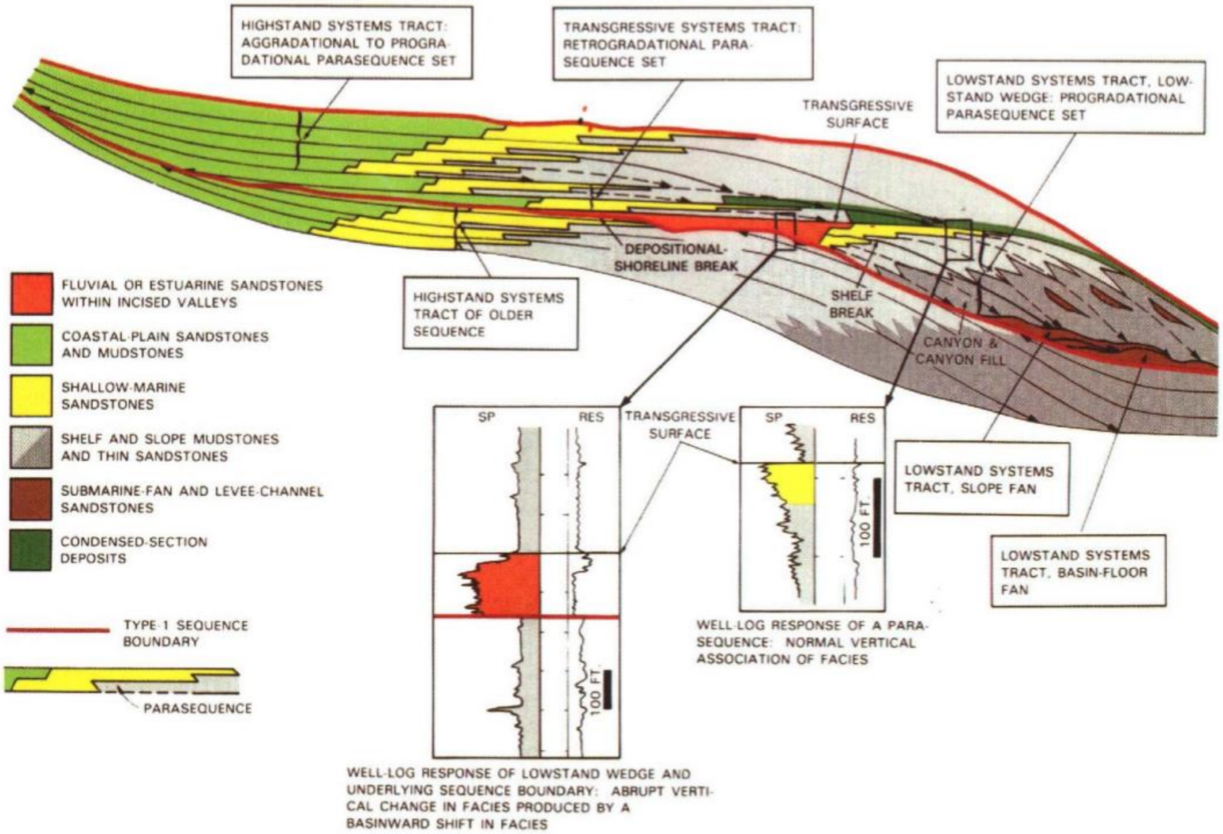


Figure 4. Illustration of depositional sequences, parasequences, and systems tracts across a shelf-to-basin transect (Van Wagoner et al., 1988). Notice the position of Type 1 sequence boundaries, which are characterized by major erosional surfaces.

Paleogeography

The paleogeography of the Pennsylvanian System was shaped by tectonic activity associated with the assembly of Pangea and variability in climatic conditions associated with Gondwanan glaciation, as well as uplift of orographic barriers to atmospheric and hydrospheric circulation, that resulted in continually changing depositional patterns and sedimentary facies (Wanless, 1963; Moore, 1979; Dewey and Pittman, 1998). Relative sea level during this time in the Midcontinent is thought by some to have fluctuated by up to 160 meters (Heckel, 1977; Klein, 1996). Much of the southern Midcontinent was submerged during the Carboniferous. Moore (1979) listed four primary events that help explain Pennsylvanian stratigraphic variation in the southern Midcontinent, which include: (1) orogenic uplift, which produced shifting sediment sources, (2) progressive closure of the Ouachita Embayment, which influenced the dispersal of sediment, (3) subsidence of the Anadarko Basin, which formed a significant sediment trap, and (4) inundation of the Midcontinent during Absaroka cratonic onlap. Superimposed on these events were oscillating climatic conditions that are interpreted to be modulated by Milankovitch orbital parameters. Heckel (1980) noted that, over the course of roughly 10 m.y., 25 regionally extensive cyclothems were deposited in the southern Midcontinent, which equates to an average of one cyclothem every 400 k.y. This suggests a correspondence with long eccentricity (Heckel 1986). In the Black Warrior Basin of Alabama, Pashin (2004) also found a relationship between cycle frequency and Milankovitch orbital parameters, and Greb et al. (2008) recognized a hierarchical stacking of short and long Milankovitch eccentricity cycles.

Climate changes during the Pennsylvanian are thought to be responsible for the waxing and waning of the Gondwanan ice sheet, which was the “longest period of continuous glaciation in the Phanerozoic” (Buatois and López-Gamundí, 2010); however, the continuity and extent of glaciation has been questioned (Isbell et al., 2008). The stratigraphic architecture of the Pennsylvanian often appears to reflect the slow buildup and rapid melting of continental ice sheets, which is driven by oscillating climate and is readily recognized in the isotopic record of the Pleistocene ice sheets (Petit et al., 1999). Climate change is also thought to have had a considerable impact on the magnitude and frequency of precipitation, which is a major factor affecting stream and sediment discharge (Cecil, 2003). Variation of sediment discharge can influence the alternation of nonmarine and marine strata observed within cyclothems. Regionally, orogenic events and the flexural downwarping associated with them provided accommodation space in the Midcontinent during the Pennsylvanian (Moore, 1979). The Ouachita Orogen and the Wichita-Amarillo Uplift served as major sediment sources that supplied siliciclastic material to the Anadarko Basin (Fig. 5). Tectonic activity is largely responsible for changing sediment dispersal patterns in the Appalachian-Ouachita Orogen, and is a reflection of the accelerating subsidence in related to advancing thrust and sediment loads in foreland basins (Pashin, 2004).

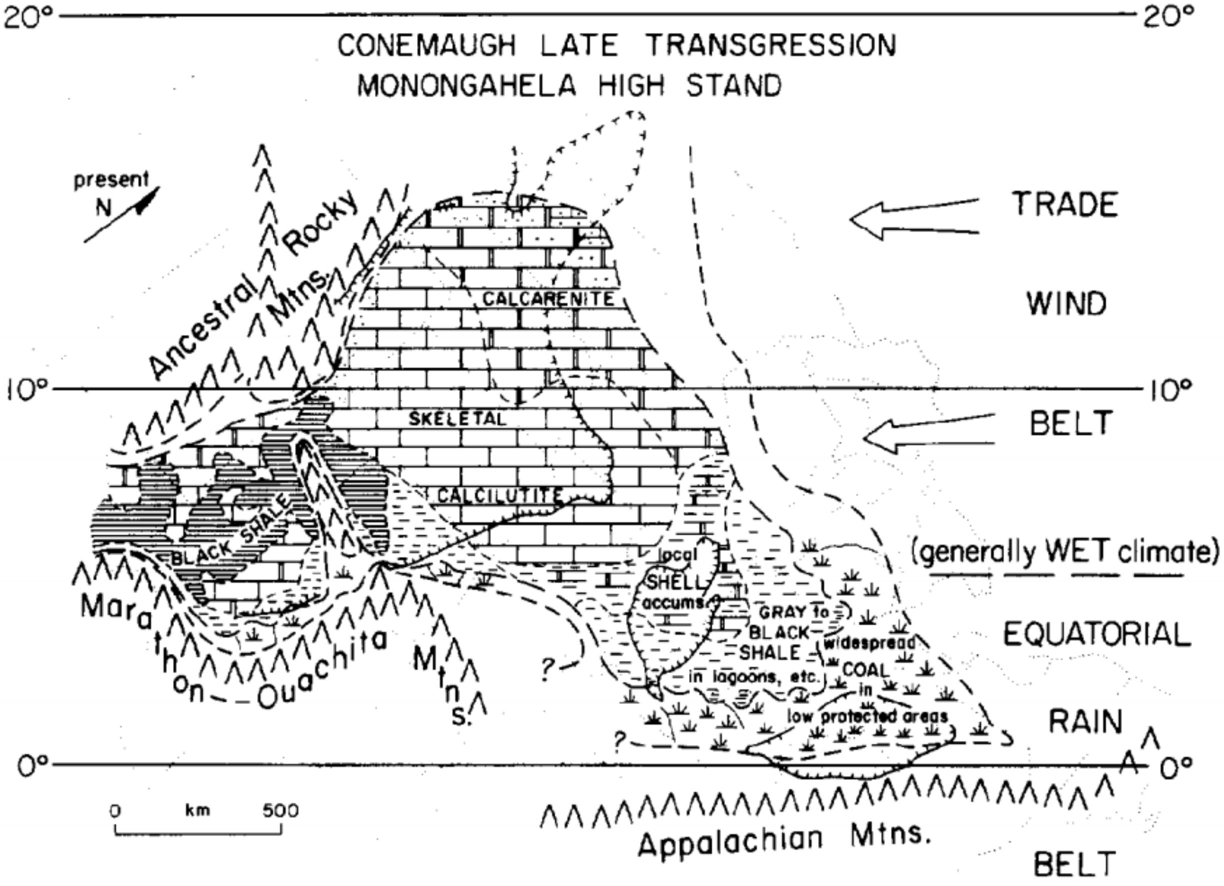


Figure 5. Paleogeographic map of central North America showing tectonic and depositional setting of the Late Pennsylvanian from Heckel (1995).

Geologic Setting

The Anadarko Basin formed as a result of intracratonic crustal flexure linked to thrusting and sinistral shear in the Wichita-Amarillo uplift during the Wichita Orogeny (Ball et al., 1991). Faulting and uplift are thought to have peaked in the Pennsylvanian, began to wane in the Early Permian, and the uplift was mostly buried by the end of the Permian (Ball et al., 1991). Flexural downwarping initiated the growth of the basin, after which subsidence resulting from sediment loading further contributed to its development. The basin was sourced at various times from nearly every direction; the Wichita and Amarillo uplifts to the southwest were proximal sources of coarse-grained sediment, the Ancestral Rockies to the west and the Ouachita Mountains to the east sourced fine siliciclastic sediments, while sedimentation various cratonic sources also contributed sediment (Johnson, 1989).

The Anadarko Basin is one of the deepest basins on the North American continent, with sediment thickness exceeding 40,000 ft in places (Gilbert, 1992; Henry and Hester, 1995). The basin also has great aerial extent, spanning approximately 50,000 square miles. The basin hosts a Pennsylvanian stratigraphic section that is more than 10,000 feet thick in southwestern Oklahoma near the Wichita structural front. The intercalation of marine and nonmarine rock types suggests that the basin was inundated periodically during the Middle and Late Pennsylvanian (Watney, 1995).

CHAPTER III

METHODS

The stratigraphic interval evaluated in this study includes the Desmoinesian, Missourian, and Virgilian Series between the base of the Red Fork Sandstone of the Cherokee Group and the top of the Oread Formation of the Shawnee Group (Figure 6). This interval was selected due to the vertical constraint of geophysical well logs in the area, as well as a high degree of difficulty correlating below the Red Fork Formation. The basic data used in the study include 34 geophysical well logs from Caddo and Grady Counties in southwestern Oklahoma, which were used to construct two stratigraphic cross sections (Figure 7). A dip cross section is oriented NE-SW (17 wells), and a strike cross section is oriented NW-SE (17 wells). Each cross section is approximately 34 miles long, and wells are spaced by 1-4 miles. Middle and Upper Pennsylvanian strata are not exposed in the basin, and no continuous cores are available from the study area. However, numerous geophysical logs are available that provide a continuous record of Middle and Upper Pennsylvanian stratigraphy. The log suite used to interpret rock types and depositional patterns includes a gamma ray, spontaneous potential, resistivity, neutron porosity, and density porosity curves. Additionally, photoelectric (PE) curves exist for many of the wells, as well as a total of 4 mud logs (three in the dip cross section and one in the strike cross section). The mud logs were used to validate the lithologic descriptions and provide additional information on rock color and composition. Rock types were identified in all 34 wells, and two wells near opposite ends of the dip-parallel cross section, the Campbell Trust 1-15, and the Burks 1-31, were selected for statistical analysis (Figure 7B).

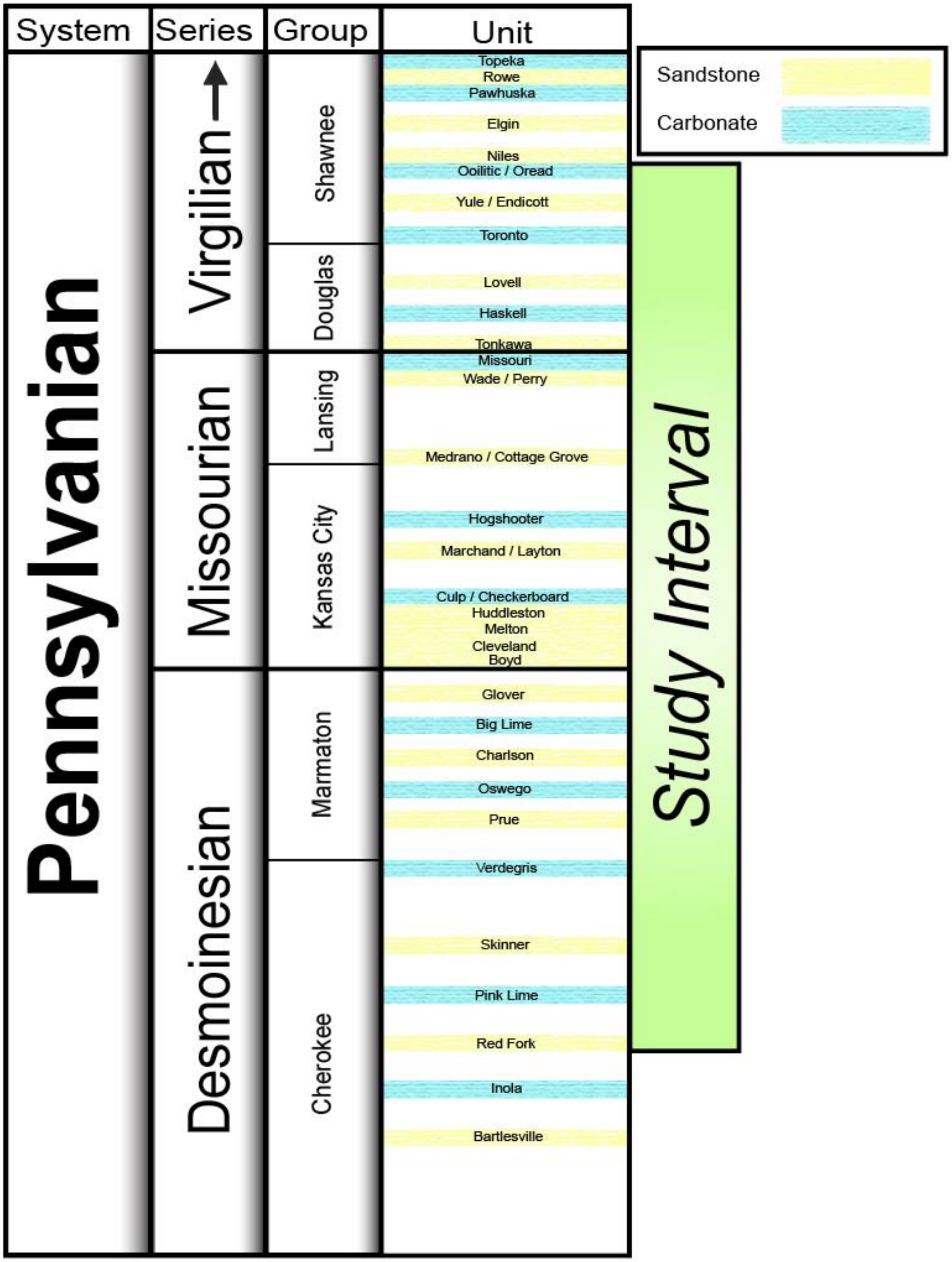


Figure 6. Pennsylvanian stratigraphy of the Anadarko Basin, indicating the extent of the study interval, as well as major reservoir units in sandstone and carbonate (modified from Boyd, 2008).

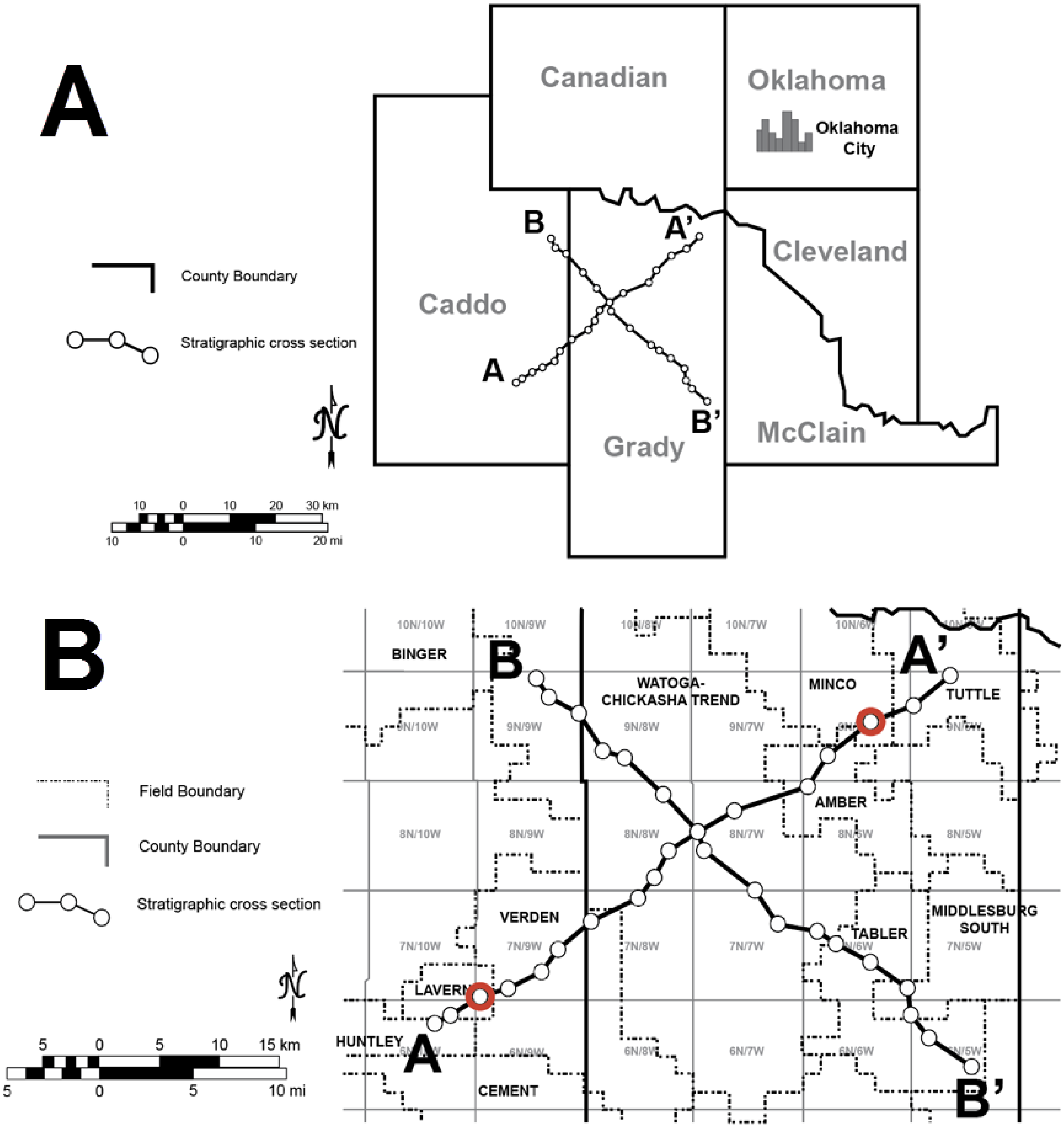


Figure 7. Map showing the location of the wells and stratigraphic cross sections used in this study (A) and a map of the major fields in the area of the cross sections (B). The locations of the two wells selected for statistical analysis, the Burks 1-31 (southwest) and the Campbell Trust 1-15 (northeast), are highlighted in red.

The workflow was designed to critically evaluate depositional units at a variety of levels. Initially, rock types were identified in the Burks and Campbell wells. Lithofacies, were then defined using a combination of rock type and an interpretation of log pattern to identify progradational or aggradational intervals. Interpretations of depositional environment were then applied to the study interval based on the available literature (e.g., Heckel, 1977, 1980; Moore, 1979), treating genetically associated rock types and lithofacies as a single unit (e.g., prodelta, delta front, coastal plain, carbonate bank, etc.). In the final step, a sequence stratigraphic interpretation was developed using the procedures of Vail et al. (1987), Posamentier et al, (1988), and Galloway (1989), in which major stratigraphic surfaces, condensed sections, and systems tracts were identified. Comparisons could then be drawn between the four different levels of interpretation.

Evaluation of log data allowed for determining the depth of each lithologic transition and the thickness of every rock type at a resolution of 2 feet. Observations of bulk constituency and recurrence within the section could then be quantified in two forms; with distance treated as a function of (1) thickness and (2) number of beds or stratigraphic units. The latter is particularly important for determining transitional probabilities of the lithologic and interpretive elements that constitute a cyclothem, which is effectively characterized irrespective of bed thickness. Early statistical investigation sought to quantify gross parameters of the section, such as composition, thickness, percentage, and number of occurrences of each rock type. Markov chains were then constructed to determine the transitional probability of one rock type succeeding another. The results are indicative of stratal order in the section. The concept of a simple Markov chain is illustrated in Figure 8, which shows the difference between deterministic, non-random, and random associations of lithological units. Theoretical transitional probabilities for each stratal class were derived from qualitative observation of common Anadarko Basin lithologic successions. By comparing the observed transitional probabilities to those expected for deterministic and random systems, it is possible to discern stratal order and determine its relative strength. In a deterministic system, transition from one member of a depositional cycle to a successor is highly predictable. In contrast, a random system would have equal transitional probabilities among all lithologic members under consideration. The null hypothesis in a Markov chain is that all transitional probabilities are random, and that there is no memory in the system. In cases where the abundance of each member varies, a random system would have transitional probabilities that are dictated by the frequency of occurrence of a given member.

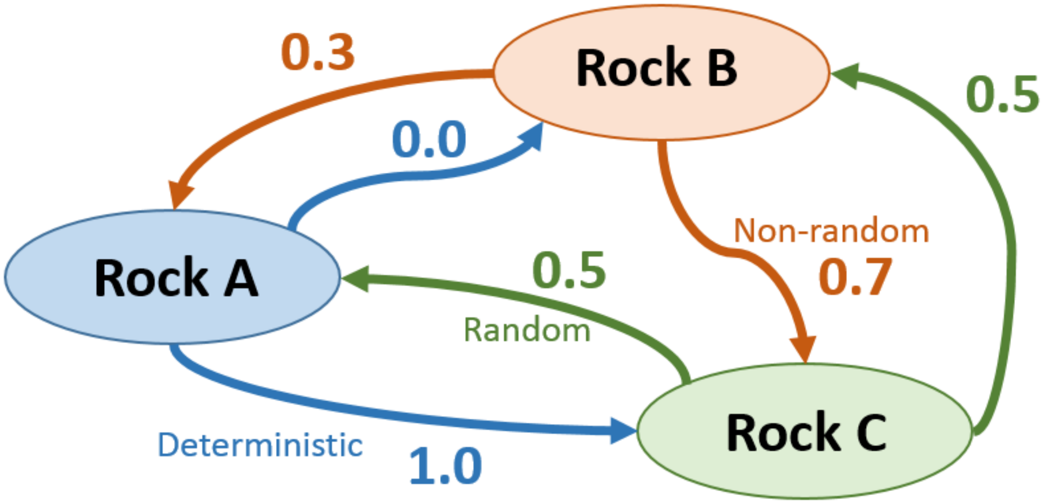


Figure 8. Diagram illustrating the basic concept of a Markov chain.

Recurrence frequency analysis was then conducted to determine the level of cyclicity that may exist in the system. In a theoretical 10-member cycle, composed of discrete lithologic units, a perfectly cyclic system would yield a modal recurrence interval of 10 for all units. By comparison, a random system would be composed of units with no consistent modal recurrence interval. Testing recurrence frequencies should distinguish cyclic and rhythmic associations of lithologic members, and can help to determine if a cyclic relationship exists among any or all units.

After first applying this progression of analysis to rock type, the procedure was repeated for lithofacies, interpretations of depositional environment, and interpretations of sequence stratigraphy. Once the statistical analysis was completed, the average duration of cyclic sedimentation in the system was determined by calculating the number of cycles identified in the section and dividing by duration of deposition represented by the section (e.g., Heckel, 1986). Periodicity was assessed by evaluating vertical trends and the consistency of cycle thickness and their relationship to basin subsidence history. According to the International Commission on Stratigraphy, the Desmoinesian-Virgilian boundary is placed at approximately 306 Ma and the Virgilian-Missourian boundary at 304 Ma (Cohen et al. 2013). Examination of the depth of paleovalleys can be used to estimate absolute sea level change, whereas the decompacted thickness of sediment between major marine flooding surfaces can be used to estimate the effect of effective subsidence on paleobathymetry and sediment accommodation (Pashin, 2004). Additionally, cycle thickness was plotted against depth to identify systematic changes of subsidence rate and their effects on sediment accommodation.

CHAPTER IV

RESULTS

IV.1 Overview of cross sections and wells

The dip cross section A-A’ extends from S. 10, T. 6 N, R. 10 W. in Caddo County northeast approximately 40 miles to S. 4, T. 9 N., R. 5 W. in Grady County (Plate 1). The study interval ranges in thickness from approximately 4,000-7,000 ft, and has a regional dip of 0.8° SW. Widespread shale beds are prominent throughout the sedimentary column. One shale bed at the top of the Missourian in the southwest portion of cross section A-A’ is more than 700 ft thick (e.g., Barrett Edwards 1-10, Terry 1D, Burks 1-31, Abbott 1-32). Shale units are commonly more than 100 ft thick, often separating heterogeneous bundles of sandstone, carbonate, and thinner shale units. Thin, radioactive shale beds occur sporadically in the vertical succession, and are laterally continuous. Sandstone beds are abundant throughout the study interval, and vary considerably in thickness from around 2-110 ft. The Medrano Sandstone in the upper Missourian, and the upper and lower Wade Sandstones of the Virgilian commonly approach 100 ft in thickness (e.g., K E West, Henricks 2-23). Though limestone beds are usually only 2-4 ft thick throughout the section, large, stacked limestone bodies (around 20-60 ft) occur in the upper part of the Missourian series and in the Virgilian series in the northeastern part of the cross section. Limestone beds are generally thicker in the upper part of the study interval. However, even the thickest beds are internally complex, and tend to be interbedded with shale or sandstone.

The strike cross section B-B’ extends from S. 3, T. 9 N., R. 9 W. in Grady County northwest to S. 22, T. 6 N., R. 5 W. in Caddo County (Plate 2). The study interval in this cross section is approximately 4,500 ft thick. Many shale beds in cross section B-B’ are 100-400 ft thick. The distribution of rock types is generally comparable to that observed in cross sections A-A’. Shale and sandstone are dominant, particularly in the west. The Haskell limestone beds observed in the upper Missourian series in the northeastern portion of cross section A-A’ are present in the southwest part of cross section B-B’, in wells southeast of the Otter Creek 1 well. Thick limestone beds in the Virgilian series are recorded in well logs southeast of the Walters 1-22H well. In both cross sections, many of the thickest beds of shale, sandstone, and limestone occur in the upper Missourian and Virgilian sections.

The Burks 1-31 well was drilled to the Springer Formation in S. 31, T. 7 N., R. 9 W. in the Lavern Field in Caddo County. The well lies near the southwest end of dip cross section A-A’ in a relatively deep portion of the Anadarko Basin (Plate 1). It contains a Pennsylvanian section that is thicker than 8,500 ft. The study interval in the Middle and Late Pennsylvanian in this well extends from 8,400 ft to 15,016 ft measured depth, covering 6,616 ft of section. The Burks 1-31 has a mud log, which helps support the identification and characterization of rock types. The stratigraphic section in the Burks 1-31 contains primarily shale and sandstone. Shale intervals range considerably in thickness, with the thickest shale interval measuring 692 ft. Shale units in the Burks are typically separated by thick sandstone or sandy shale coarsening to sandstone, which are sporadically capped by a thin layer of carbonate. Thick sandstone units are present, ranging from 50 ft to more than 100 ft thick. Radioactive shale beds are thin and highly irregular in distribution in this section. Coal was not recognized in the density log.

The Campbell Trust 1-15 well is in S. 15, T. 9 N., R. 6 W. in the Minco Field in Grady County and is near the northeast end of cross section A-A’ (Plate 1). The Campbell Trust well is approximately 26 miles northeast of the Burks 1-31 well. The well has a diverse geophysical log suite including a PE log, which proved extremely useful for differentiating limestone and sandstone. The study interval is only 3,644 ft thick, extending from 6,458 ft to 10,102 ft. The base of the study interval is similar to that in the Burks well. Shale is the dominant rock type by cumulative thickness. Radioactive shale beds are common in the Campbell Trust section, in marked contrast to the Burks section. The net thickness of carbonate in the Campbell Trust well is substantially greater than in the Burks well. A particularly thick section of Toronto Limestone (34 ft) and Haskell Limestone (58 ft) occurs at the top of the Missourian Series. Only one coal bed was observed in the Upper Desmoinesian series of the Campbell Trust well.

IV.2 Classification of rock types

Initially, the study interval was categorized by rock type. Rock types with distinctive log signatures include shale, sandy shale, sandstone, limestone, and coal. Shale tends to exhibit a gamma count between 90 and 150 API units. Mud logs show most shale in the Middle and Upper Pennsylvanian of the Anadarko Basin is light to medium gray and calcareous; some variegated reddish and greenish shale units occur in sandstone dominated parts of the section, particularly in the Missourian and Virgilian Series. The shale is typically silty, micaceous, and in places pyritic. Underclay, a classic component of the Pennsylvanian cyclothem, is recorded as shale in geophysical logs. Beyond 150 API units, shale registers on the repeat scale of most gamma ray logs and was classified as “radioactive”. Mud logs describe radioactive shale units as black and carbonaceous, and sometimes containing phosphatic inclusions. Weller (1930) described similar black fissile shale in the Illinois Basin, and Heckel (1977, 1986) mentioned that black phosphatic shale in the Midcontinent is rich in conodonts. The radioactive shale units in the cross sections are easily correlated, and even when an off-scale gamma reading is not observed, equivalent strata typically have at least slightly elevated radioactivity. Most radioactive shale beds can be correlated in all wells in both cross sections.

Sandy shale units have gamma counts between 75 and 90 API units with a minimum resistivity of 2 ohm-m (generally higher than adjacent shale). Mud logs refer to sandy shale as gray to light brown, containing silt or sand that ranges from calcareous to non-calcareous. Sandy shale is often described in the mud log as “becoming increasingly sandy,” and indeed, it is commonly an intermediate rock type that is part of a coarsening-upward shale-sandstone interval. In detail, strata classified herein as sandy shale include intervals ranging in composition from shaly siltstone to shaly sandstone and commonly includes thinly interbedded argillaceous and arenaceous strata.

Sandstone typically has a gamma count of less than 75 API units, and typically displays a strong negative SP deflection paired with separation in the deep and shallow resistivity logs, indicating elevated permeability. Though sandstone can in places closely resemble a limestone, it may be distinguished by a density of less than 2.68 g/cc and a PE value less than 4. Sandstone in both mud logs and the literature is described as ranging from white to gray to brown, and fine to medium grained, with subangular to subrounded grains; the sandstone is in places calcareous and can be friable (Sawyerr, 1972). Sandstone beds show a wide range of thickness throughout the study interval. Though several of the thick sandstone beds in the cross sections can be traced laterally for several miles, many are difficult to correlate with neighboring wells.

Limestone has an extremely low gamma count of less than 15 API units, high resistivity, a PE value of 4 to 5, and typically has a bulk density reading higher than 2.7 g/cc. Many of the limestone beds in the study interval contain skeletal particles that include bryozoans, echinoderms, brachiopods and foraminifera (Lange, 1984). Mud logs characterize carbonate beds as gray to brown, and ooilitic and dolomitic limestone are present in some locations. Limestone beds are thin and occur sporadically throughout the Desmoinesian and lower Missourian section (Plates 1, 2). Many of the thin Desmoinesian limestone beds are laterally continuous, but constitute lensoid bodies.

Coal typically has density of about 1.5 g/cc and thus appears as a high porosity spike in the density porosity logs, which are calculated on a limestone matrix. Coal is another traditional component of the Pennsylvanian cyclothem. In Wilkinson et al.'s (2003) critical evaluation of cyclothems, one of the few rock type relationships that showed a high degree of predictability was the transition from underclay to coal. However, very few coal beds were observed in the stratigraphic record of the Middle and Upper Pennsylvanian in the Anadarko Basin and many density spikes appear to be attributable to caving of weak mudstone rather than the occurrence of coal seams.

IV.3 Classification of lithofacies

Lithofacies define depositional units on the basis of rock type and log patterns. In particular, shale, sandstone, and limestone were distinguished as progradational (coarsening upwards), aggradational (blocky to fining upwards), or retrogradational (fining upwards) on the basis of gamma ray and resistivity patterns (Figure 9). Definition of lithofacies not only allows the sedimentary succession to be evaluated at a higher level of detail than can be achieved only by characterizing rock type, but was helpful for detecting lithologic patterns necessary to interpret depositional environment and establish a sequence stratigraphic framework. The lithofacies recognized in this study included radioactive shale, aggradational shale, progradational shale-sandstone, progradational sandstone, aggradational sandstone, progradational limestone, retrogradational limestone, and coal (Figure 10).

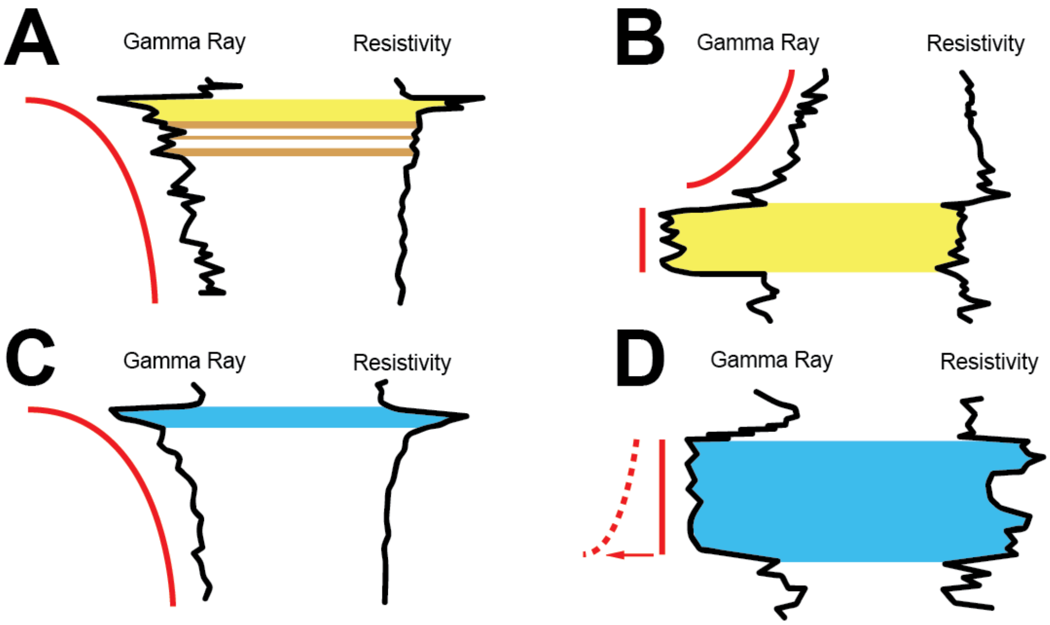


Figure 9. Identification of lithofacies based on log curve patterns. A) Coarsening-upward succession of progradational shale-sandstone to progradational sandstone. B) Aggradational (i.e., blocky to fining upward) sandstone succeeded by an aggradational shale. C) Progradational shale-sandstone overlain by progradational limestone. D) blocky, retrogradational limestone.

IV.4 Classification of depositional environments

Depositional environment was interpreted based on lithologic composition, depositional patterns, and previous interpretations of Pennsylvanian strata based on outcrop, core, and well logs (Figure 9). Radioactive black shales are considered to be the deepest-water facies (e.g., Heckel and Baesemann, 1975; Heckel, 1977, 1986), and thus were classified as having been deposited in an oxygen-deficient shelf environment. Radioactive particles and organic matter are preserved when water disturbance and siliciclastic input is minimal (Tourtelot, 1979). Oxygen deficient shelf deposits vary in levels of radioactivity, likely due to siliciclastic disturbances of deltaic origin, but none the less show elevated gamma counts that are detectable in geophysical logs. Progradational shale-sandstone successions represent major influxes of siliciclastic sediment, and are typical of prodelta and delta front successions in high accommodation depositional settings (e.g., Manos, 1967; Heckel, 1980; Chesnut, 1994; Greb et al., 2008). Distal prodelta deposits have long been known to be dominated by fine-grained sediment (Fisk et al., 1954). Prodelta deposits are generally characterized by a gradual transition of shale to siltstone and are identified in geophysical logs by smooth and gradual upward-coarsening gamma curve pattern.

The delta front is characterized by gradation from shale to siltstone or sandstone, and is identified by a coarsening upward log pattern that is steeper than the prodelta. Delta front progradational sandstone reflects the complex morphology of a marginal-marine setting and may be composed of terminal distributary channels, submerged levee deposits, or mouth bars (Olariu and Bhattacharya, 2006). Many deltaic deposits in the Anadarko Basin are tidally influenced (Baker, 1979; Rascoe, 1979). Distinctly aggradational sandstone units with an erosional base were interpreted as a variety of channel deposits, including fluvial and estuarine incised valley fills, distributary channel fills, and tidal channel fills (e.g., Kirschbaum and Hettinger, 2005). Clear examples of incised valley fills are observed in the Virgilian Series in the eastern portion of the cross sections, which in some cases cut over 100 ft into underlying shale (e.g., Wade Sandstone, Burks 1-31 well, Plates 1, 2). Tidal channel and distributary channel deposits are common throughout the study interval, but noteworthy examples occur in the lower Missourian and upper Desmoinesian (Plates 1, 2). Though some sandstone beds are thought to be fluvial, evidenced by conglomeratic facies seen in core (Lange Jr., 1984), many sandstone beds have a deltaic or tidally-influenced marine origin (Sawyerr, 1972; Baker, 1979; Northcutt and Johnson, 1996; White et al., 1999). Sedimentary structures such as herringbone cross-bedding and flaser bedding identified in the Marchand sandstone invariably points to a tidal origin at least in some locations (Baker, 1979).

Coastal plain deposits reflect highly variable depositional settings that range from shallow marine to terrestrial. The sedimentary assemblage is diverse, and demonstrates a significant degree of vertical and lateral heterogeneity. Deposits may include lagoonal aggradational shale, fining-upward distributary channel sands interbedded with mudstone, or red to green paleosols (Heckel, 1986; Watney, 1995). The fining upward succession associated with the coastal plain is important in determining the onset of transgression in the absence of an obvious lowstand channel fill sandstone. Coal, a common component of the coastal plain facies assemblage, represents extensive low lying swamp or marsh deposits that form\ on abandoned interdistributary lakes and bays, remnants of the deltaic system (Fielding, 1987; Ferm and Weisenfluh, 1989) or may be parts of the regionally extensive cratonic swamps that at times rivaled the size of the modern Boreal Swamp (Greb et al., 2006). Lowland coastal areas can contain abundant tidal or estuarine distributary channels. As such, thin aggradational or progradational sandstone irregularly occurs throughout the coastal plain environment in the cross sections (Plates 1, 2). Progradational limestone is considered a minor facies deposited as part of the prograding shoreline succession.

Aggradational and retrogradational limestone units represent a spectrum of ramp-type carbonate environments (Heckel, 1977, 1980; Watney et al., 2005), and were designated for the purposes of this study as carbonate bank deposits. Deposition of carbonate was primarily biogenic, and was heavily dependent on the depth of the photic zone and low turbidity (Yancey and Cleaves, 1990; Watney et al., 2005). Most carbonates developed in shallow and marginal marine settings, and facies changes reflect variable water depth (Watney et al., 1995). Facies of the Toronto Limestone in the early Virgilian (Plates 1, 2) range from lime mudstone, to skeletal wackestone, to ooilitic or peloidal grainstone (Troell, 1969).

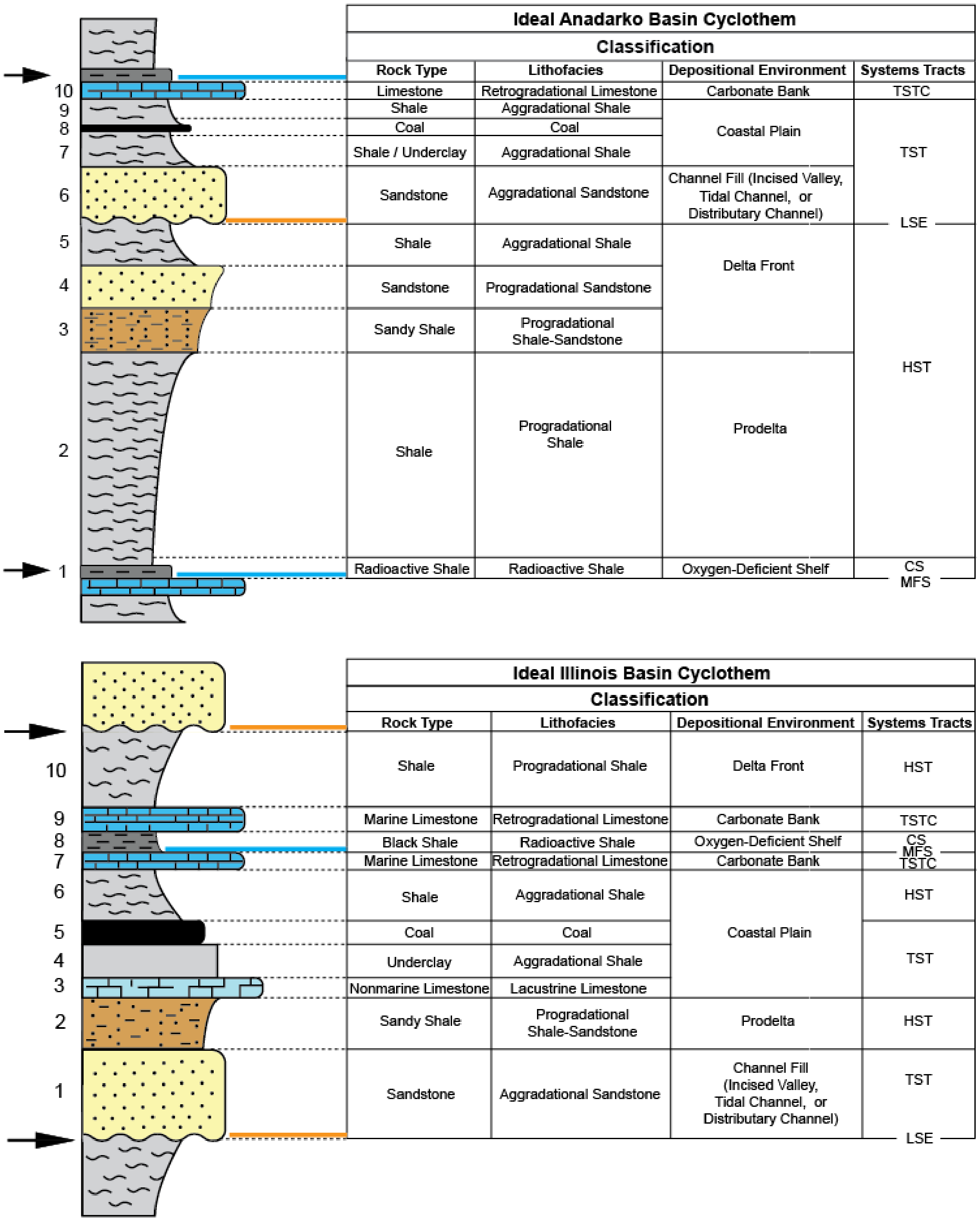
IV.5 Classification of sequence stratigraphic surfaces and tracts

Only after classifying rock types, lithofacies, and depositional environments was it possible to characterize the sequence stratigraphic framework (Figures 10, 11; Plates 3, 4). Identifying major stratigraphic surfaces based on key lithologic components and their geophysical well log signatures established a framework that is essential for the identification of systems tracts (Mitchum et al., 1977; Posamentier et al., 1988). The base of a radioactive shale is the transgressive surface of erosion or the maximum rate of sea level rise relative to successive units (Heckel, 1977, 1986). The transgressive surfaces of erosion (i.e., marine flooding surfaces) are indicated by thick pink lines in the cross sections (Plates 3, 4). The radioactive shale and correlative shale intervals with elevated gamma ray are representative of condensed sections.

The highstand systems tract is identified by the progradational signature of the gamma log, which incorporates the prodelta and delta front depositional environments. Sedimentary packages with an offlapping stratal geometry provide evidence for falling stage sedimentation (falling stage systems tract). An example of the falling stage systems tract may be observed at the top of the Cottage Grove Sandstone in the upper Missourian of cross section A-A’ (Plate 3). The lowstand surface of erosion is commonly identified as the unconformable surface at the base of an incised valley fill sandstone (Posamentier et al., 1988; Catuneanu, et al., 2011). However, identification of the lowstand surface in a typical succession in the Anadarko basin is not always obvious, and the presence of multiple stacked channel fills results in nonunique solutions. Indeed, the channel fills can be difficult to interpret, with some probably representing distributary channels that are a part of the constructive deltaic system and others representing tidal channels associated with the transgressive coastal plain.

Understanding the relative positions of the major marine flooding surfaces, the highstand systems tract, the simplest interpretation of the lowstand surface of erosion, and the distribution of limestone units, helped to identify the transgressive systems tract (i.e., the stratigraphic package between the lowstand surface of erosion and the succeeding marine flooding surface). Aggradational shale, sandstone, and retrogradational limestone beds helped to reaffirm the correct designation of the transgressive systems tract. Vail-type sequence boundaries marked by unconformities were difficult to distinguish in the Middle and Upper Pennsylvanian of the southern Anadarko Basin due to the extreme heterogeneity of sandstone beds throughout a given succession. In contrast, marine flooding surfaces, which are typically used for defining parasequence and genetic sequence boundaries (Van Wagoner et al., 1988; Galloway, 1989) were readily identified and represent the clearest, most consistent basis for subdivision of the study interval, as is the case in other Pennsylvanian-Permian successions (e.g., Liu and Gastaldo, 1992; Gastaldo et al., 1993; Miller and West, 1998; Pashin, 1994, 2004). These genetic sequence boundaries are marked with thick blue lines in the cross sections (Plates 1-4).

After classification of all levels of observation and interpretation was complete for the study interval, an “ideal” Anadarko Basin cyclothem was created from typical successions of rock types, lithofacies, depositional environments, and sequence stratigraphic components (Figure 10). Using the precedent set by Weller (1930) and other workers, when evaluating a frontier area, it is appropriate to build an ideal cyclothem model after sequence stratigraphic interpretation, to assure that the sequence boundaries and cycle components are properly recognized. It is important to note that the high degree of variability in the stratigraphic section cannot be adequately captured in a single model. Regardless, the idealized cycle can be used as a comparative benchmark for a reasonable stratigraphic section in testing for lithologic order and cyclicity in the Anadarko Basin.



Ideal Anadarko Basin Cyclothem

Classification

	Rock Type	Lithofacies	Depositional Environment	Systems Tracts
10	Limestone	Retrogradational Limestone	Carbonate Bank	TSTC
9	Shale	Aggradational Shale	Coastal Plain	TST
8	Coal	Coal		
7	Shale / Underclay	Aggradational Shale		
6	Sandstone	Aggradational Sandstone	Channel Fill (Incised Valley, Tidal Channel, or Distributary Channel)	LSE
5	Shale	Aggradational Shale	Delta Front	HST
4	Sandstone	Progradational Sandstone		
3	Sandy Shale	Progradational Shale-Sandstone		
2	Shale	Progradational Shale	Prodelta	
1	Radioactive Shale	Radioactive Shale	Oxygen-Deficient Shelf	CS MFS

Ideal Illinois Basin Cyclothem

Classification

	Rock Type	Lithofacies	Depositional Environment	Systems Tracts
10	Shale	Progradational Shale	Delta Front	HST
9	Marine Limestone	Retrogradational Limestone	Carbonate Bank	TSTC
8	Black Shale	Radioactive Shale	Oxygen-Deficient Shelf	CS MFS
7	Marine Limestone	Retrogradational Limestone	Carbonate Bank	TSTC
6	Shale	Aggradational Shale	Coastal Plain	HST
5	Coal	Coal		TST
4	Underclay	Aggradational Shale		
3	Nonmarine Limestone	Lacustrine Limestone		
2	Sandy Shale	Progradational Shale-Sandstone	Prodelta	HST
1	Sandstone	Aggradational Sandstone	Channel Fill (Incised Valley, Tidal Channel, or Distributary Channel)	TST LSE

Figure 10. Model Pennsylvanian cyclothem for the Anadarko Basin showing component rock types, lithofacies, depositional environments, and sequence stratigraphic interpretations. Blue lines represent marine flooding surfaces (genetic sequence boundaries) and orange lines represent disconformities (depositional sequence boundaries). Arrows mark boundaries used to define cycles.

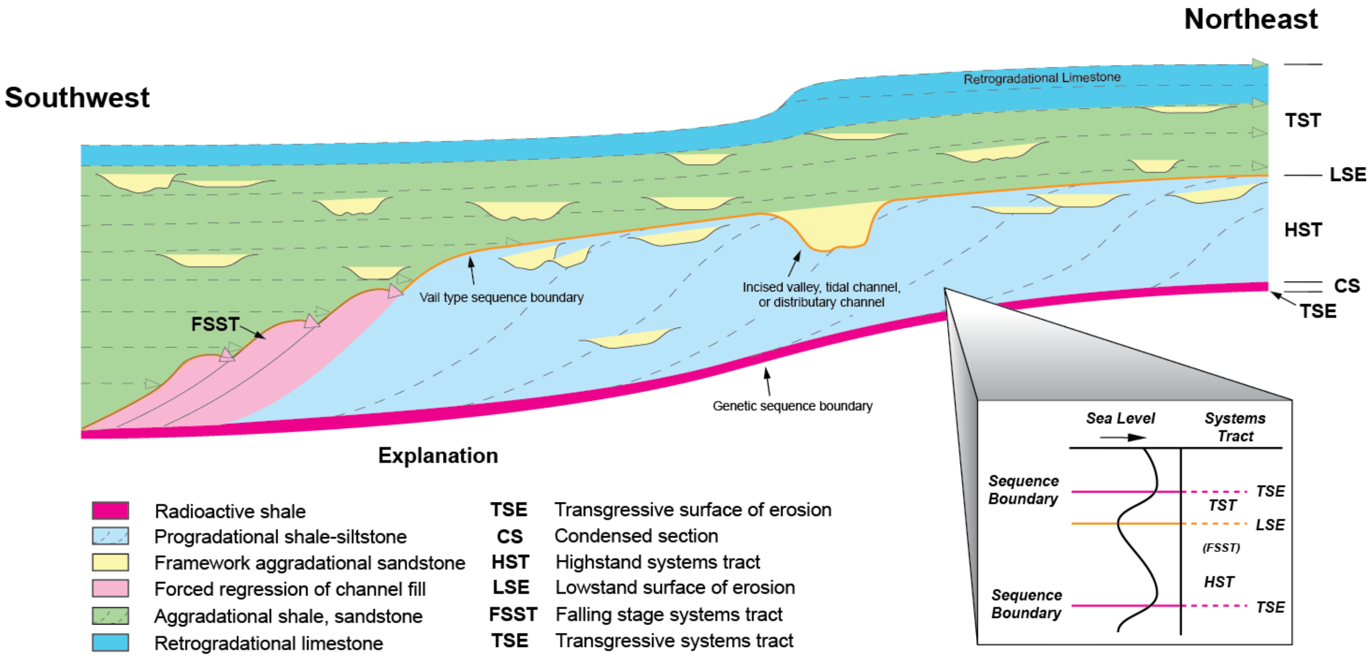


Figure 11. Sequence stratigraphic model shown with sequence boundaries coinciding with marine flooding surfaces.

IV.6 Statistical Analysis

Shale dominates the study interval, composing nearly 75% of the section by cumulative thickness in the Burks 1-31 well (Figure 12) and 67% of the section in the Campbell Trust 1-15 well (Figure 13). Sandstone is the second most abundant rock type by cumulative thickness in both wells, composing 17.5% of the section in the Burks well and 14.9% of the section in the Campbell Trust well. Both wells contain roughly 6% sandy shale by volume. However, limestone composes only 1.4% of the Burks well section and 10.5% of the Campbell Trust section. This difference is attributed to the thick carbonate units in the upper Missourian and Virgilian series in the Campbell Trust well. The ratio of sandstone to limestone in the Burks well is roughly 12:1, whereas the ratio in the Campbell well is approximately 3:2. Radioactive shale and coal represent only 1% or less of the section in both wells. Note that cumulative rock thickness decreases considerably from shale to coal (Figures 12 and 13).

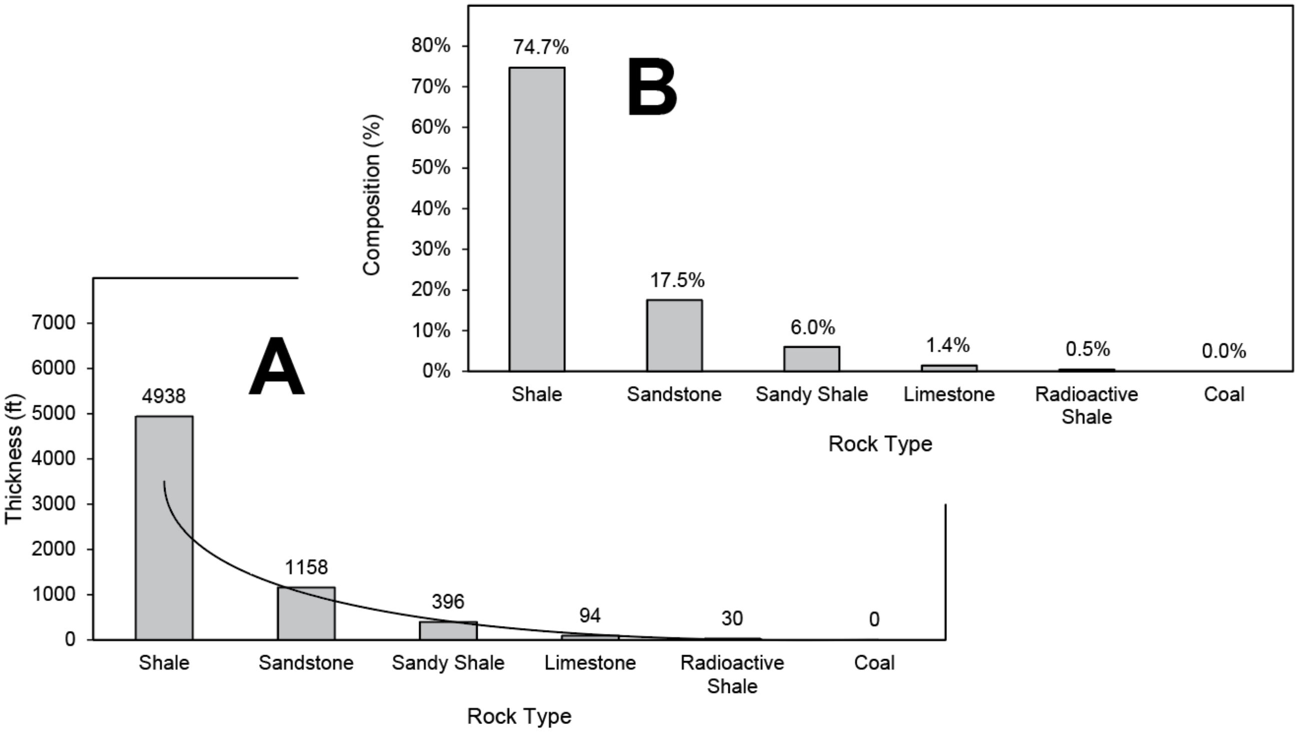


Figure 12. Cumulative thickness expressed in feet (A) and as a percentage (B) of each rock type in the Burks 1-31 section.

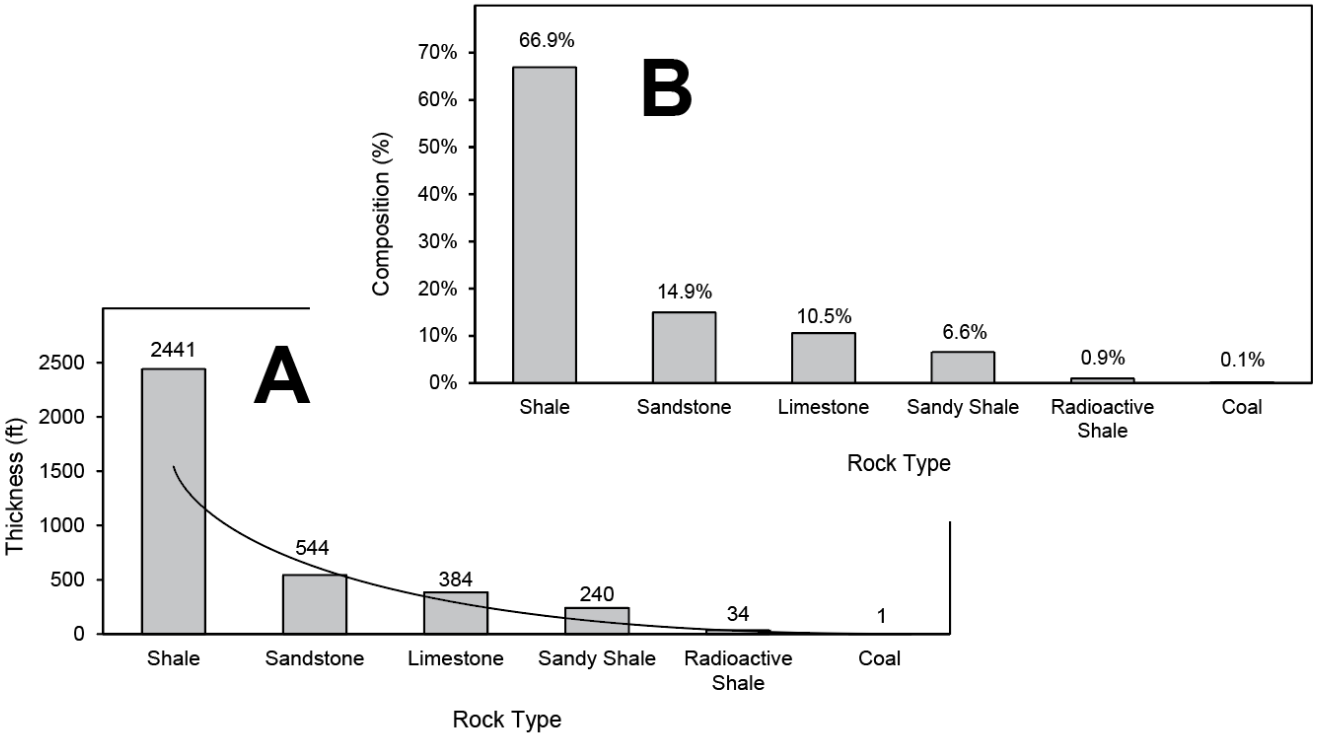


Figure 13. Cumulative thickness expressed in feet (A) and as a percentage (B) of each rock type in the Campbell Trust 1-15 section.

Geometric mean thickness of individual shale and sandstone beds are comparable in both wells. The geometric mean thickness of a shale bed in the Burks 1-31 well is 13 ft (Figure 14) and 11 ft in the Campbell Trust 1-15 well (Figure 15). Geometric mean thickness of sandstone beds approximates 7 ft in both wells. The relatively thin beds of shale and sandstone show that, even though many beds over 100 ft thick are present in the cross sections, the majority of beds are only a few feet thick. Geometric mean limestone thickness in the Campbell Trust well (6 ft) is twice that in the Burks well (3 ft). Mean thickness of radioactive shale and coal are 4 ft and 0.5 ft, respectively. Geometric mean thicknesses of rock types in both wells follows a logarithmic function.

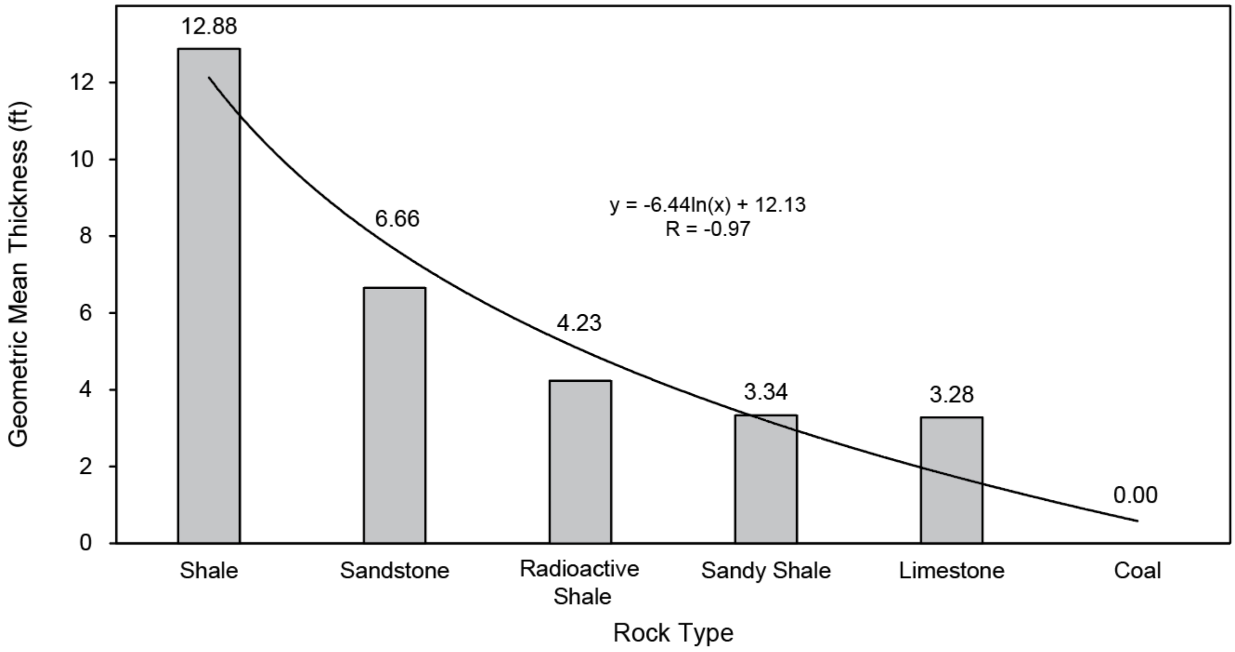


Figure 14. Geometric mean thickness of each rock type in the Burks 1-31 section.

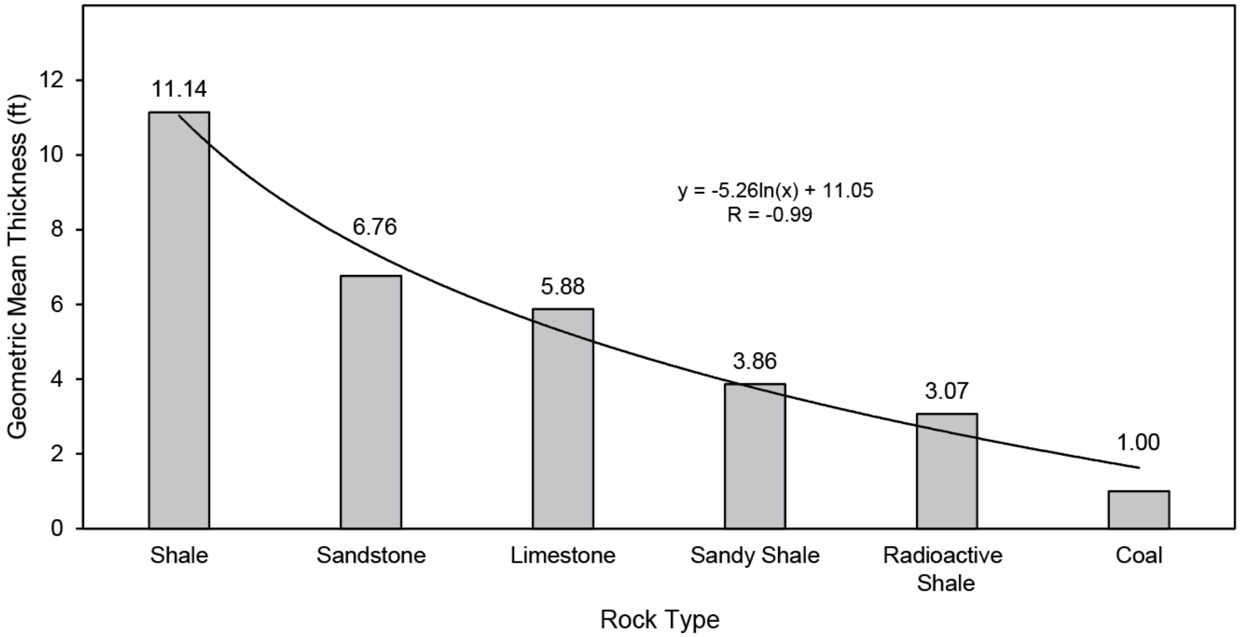


Figure 15. Geometric mean thickness of each rock type in the Campbell Trust 1-15 section.

The frequency distributions of bed thickness for each rock type in the Burks and Campbell Trust wells, are best characterized by power functions (Figures 16, 17). Hence, thickness frequency distributions of these rock types demonstrate stochastic control of bed thickness. Undersampling of radioactive shale is evident in both wells, and too few coal beds are logged in the section to define a frequency distribution.

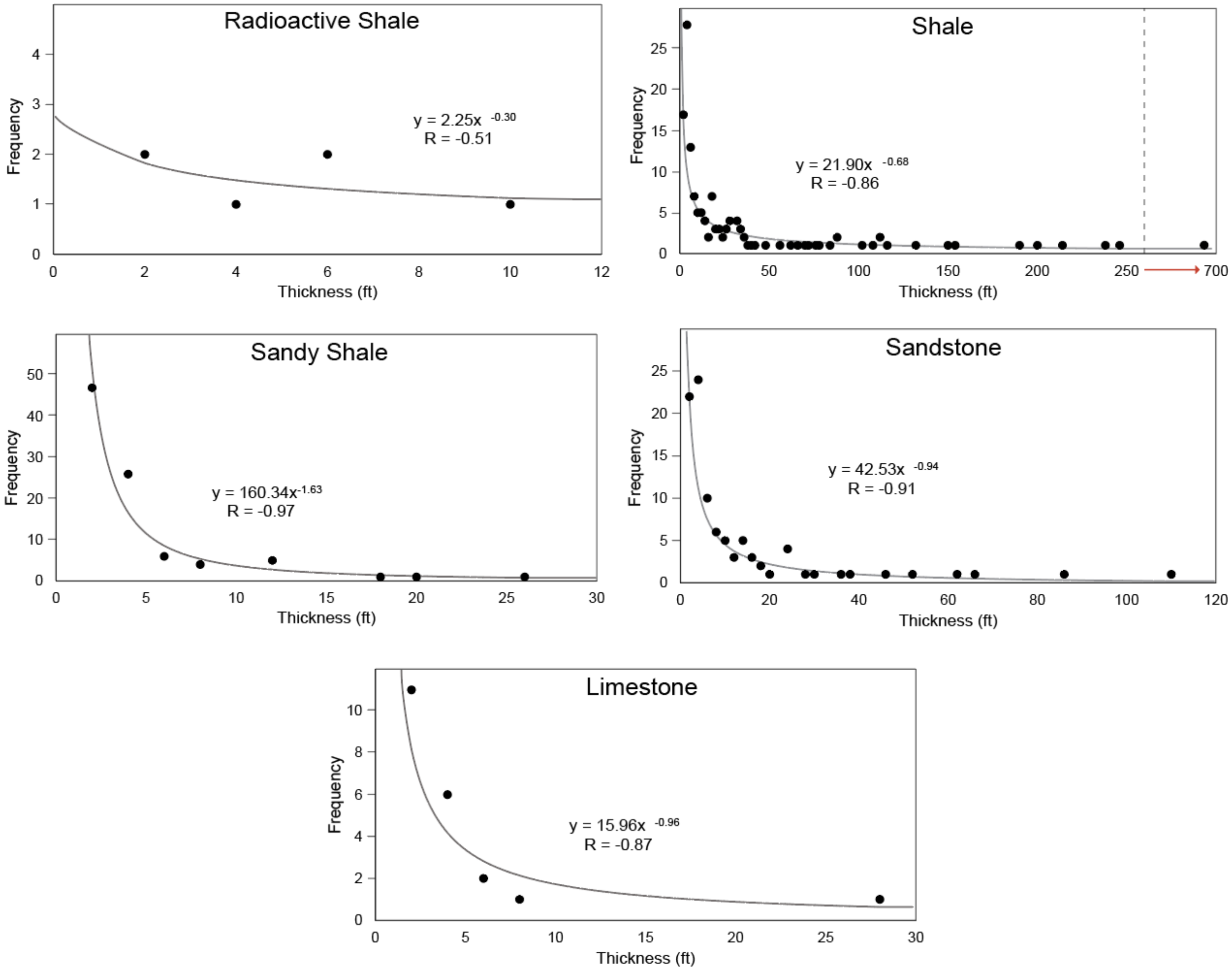


Figure 16. Thickness-frequency distributions for rock types in the Burks 1-31 well.

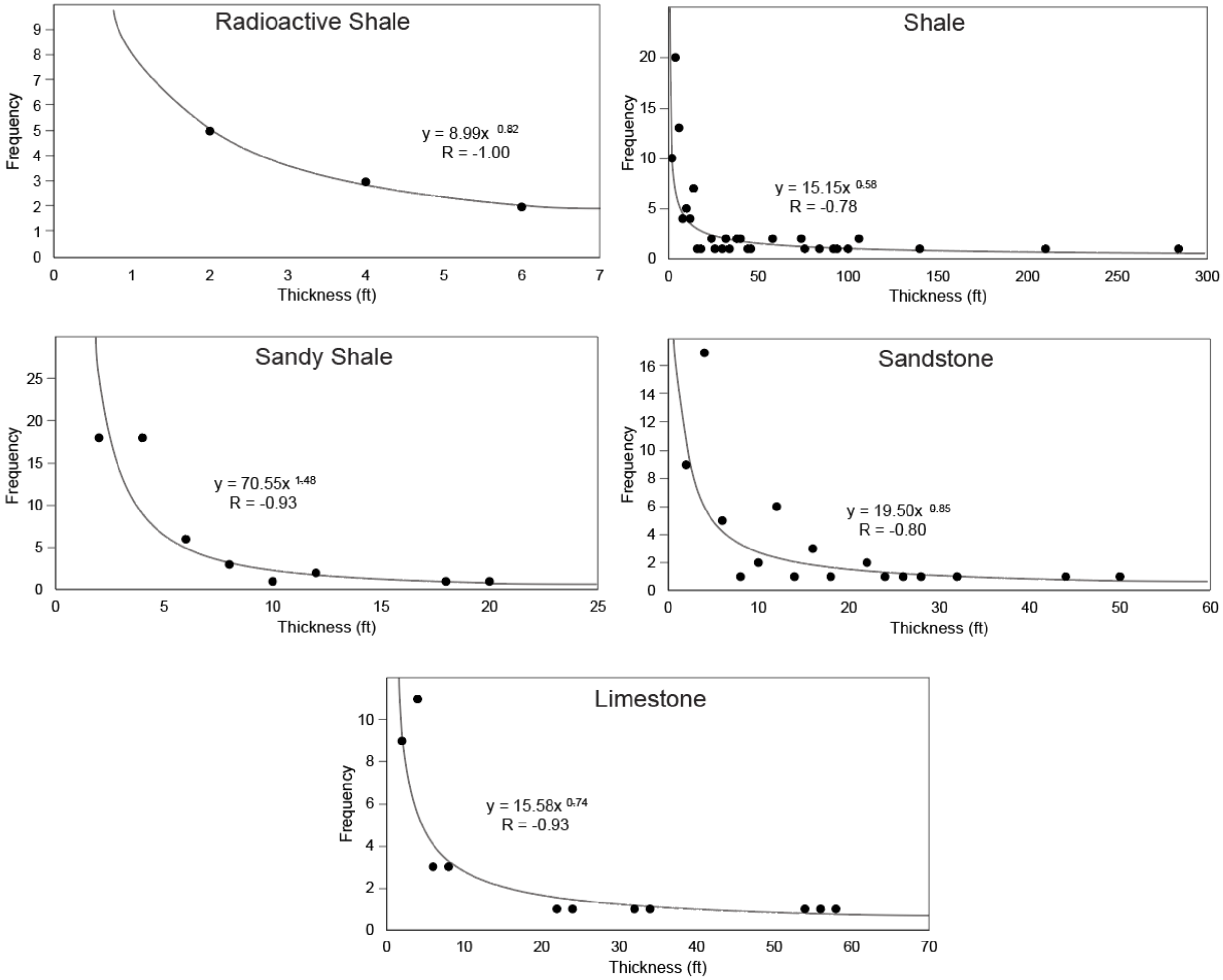


Figure 17. Thickness-frequency distributions for rock types in the Campbell Trust 1-15 well.

Beds thinner than 10 ft constitute about 75% of the rock types in the sample. Extraordinarily thick shale sections, nearly 700 ft in one sample, underscore the vertical stratigraphic variability and the lateral heterogeneity of the system. The geometric mean thickness for sandy shale in the Burks 1-31 well is in the 86th percentile, the highest for any rock type observed, and is lowest in radioactive shale in the 61st percentile (Figure 18). In the Campbell Trust 1-15 well, geometric mean thickness of sandy shale is also highest, in the 80th percentile (Figure 19). The mean thickness of shale and is lowest, falling at the 71st percentile. Percentile plots generally reflect a log-normal distribution of rock types, with undersampling particularly evident in radioactive shale.

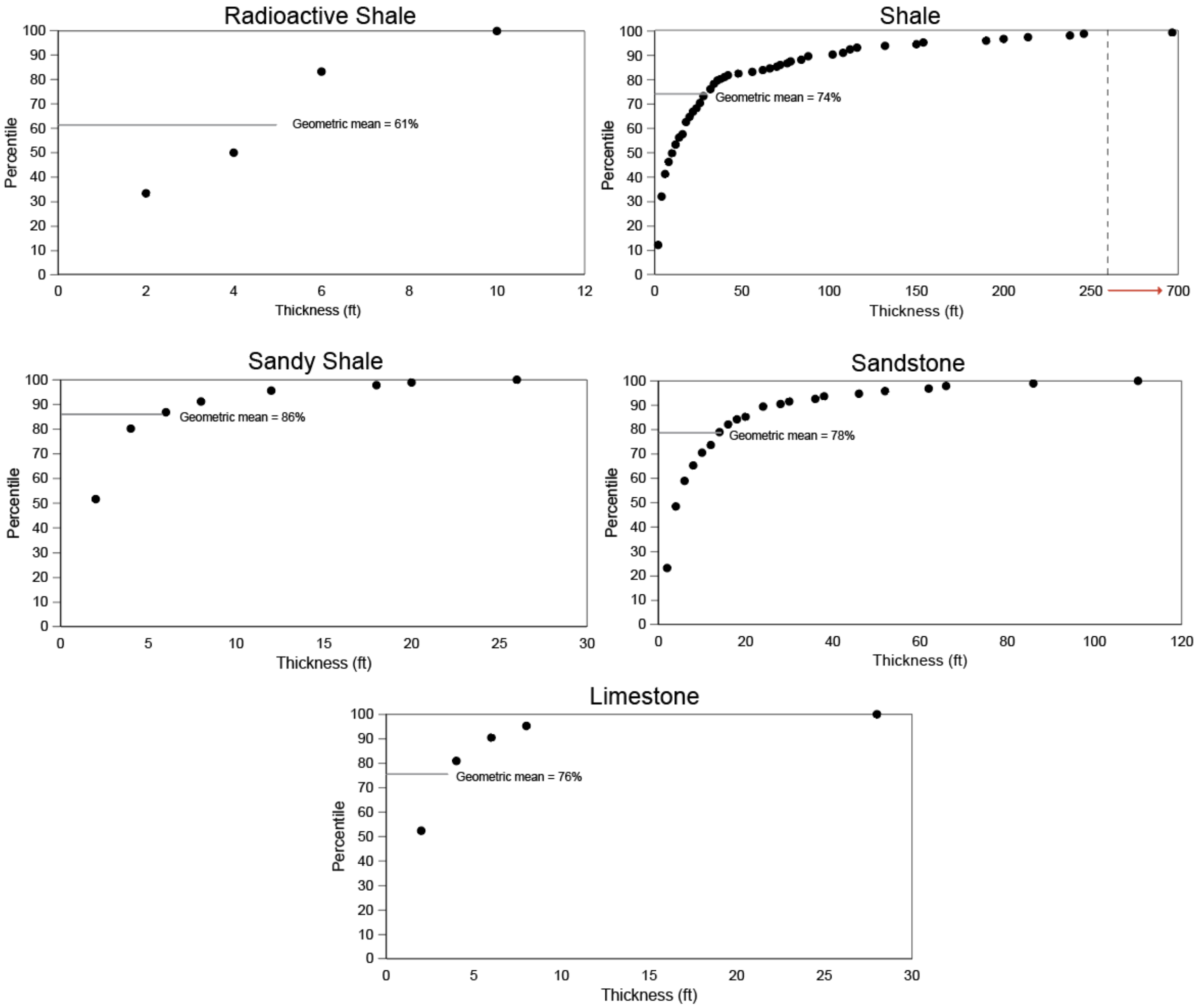


Figure 18. Percentile plot showing bed thickness distribution for each rock type in the Burks 1-31 well. Note the wide range in variability of shale thicknesses.

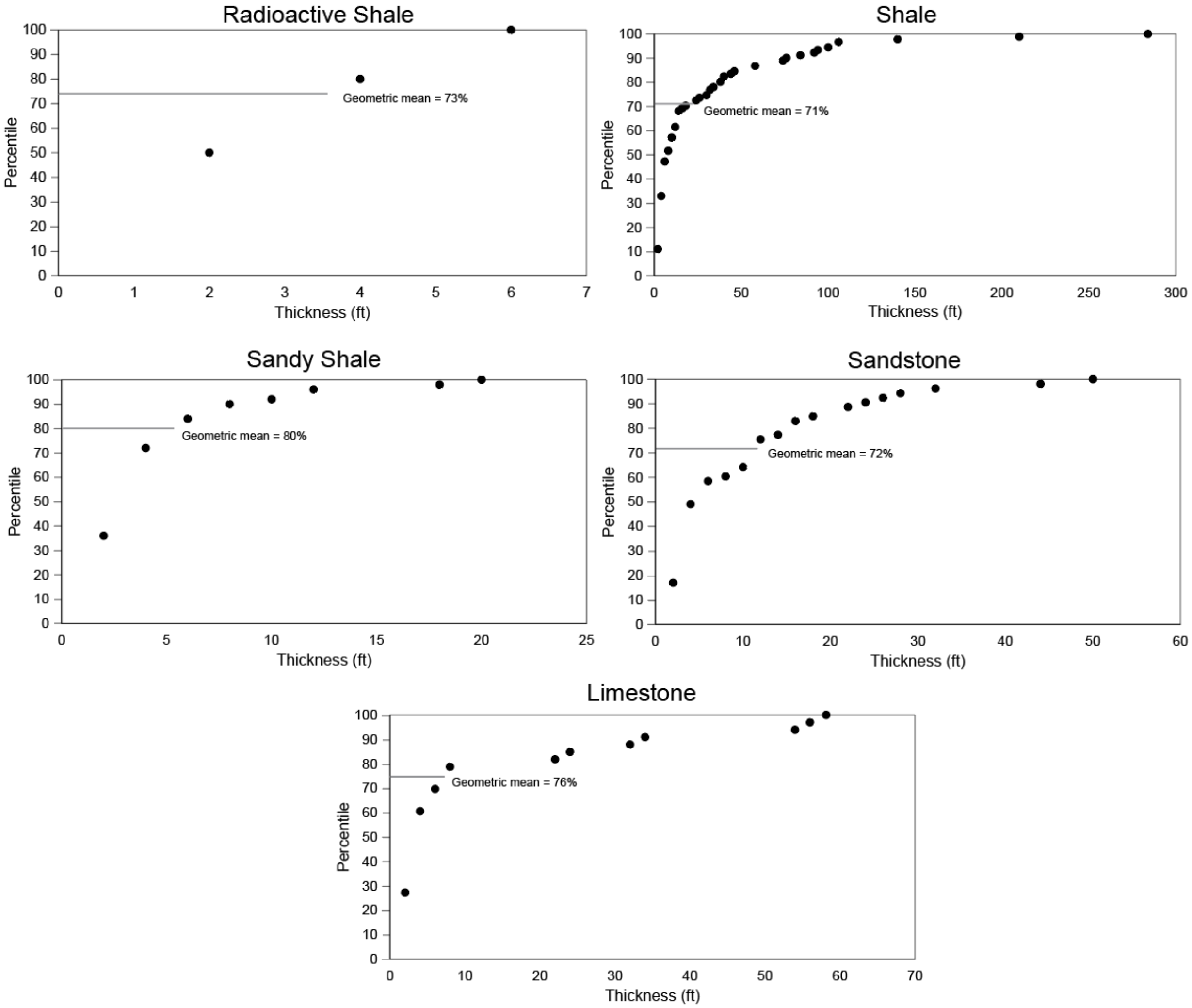


Figure 19. Percentile plot showing bed thickness distribution for each rock type in the Campbell Trust 1-15 well.

Occurrences of rock types rank similarly in the Burks 1-31 well (Figure 20) and in the Campbell Trust 1-15 well (Figure 21). Results show that rock occurrences decrease considerably with a decrease in rank, which is consistent with the findings of Wilkinson et al. (2003). Higher than expected occurrences of sandy shale in the Burks well account for much of the difference in slope observed between the two wells. In terms of thickness, sandy shale and limestone rank 3rd and 4th respectively, in the Burks well. In contrast, limestone ranks above sandy shale in the Campbell Trust well. Occurrence and thickness ranks of rock types follow a logarithmic function.

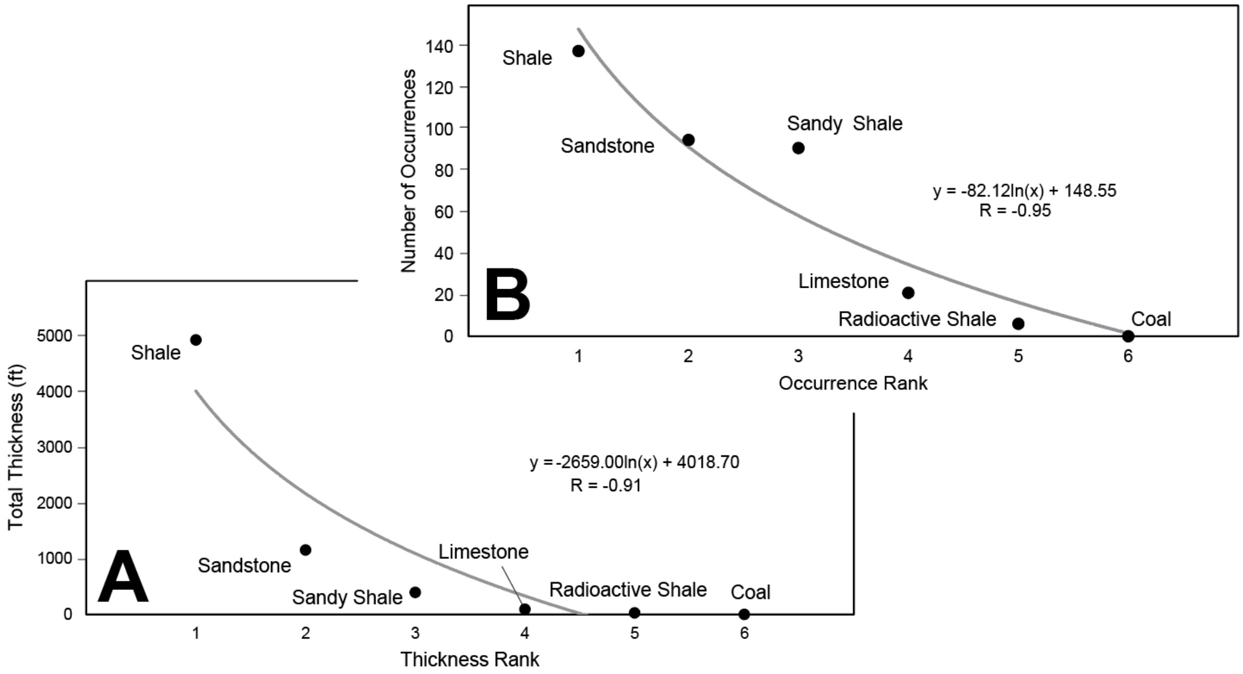


Figure 20. Thickness rank (A) and occurrence rank (B) in the Burks 1-31 well.

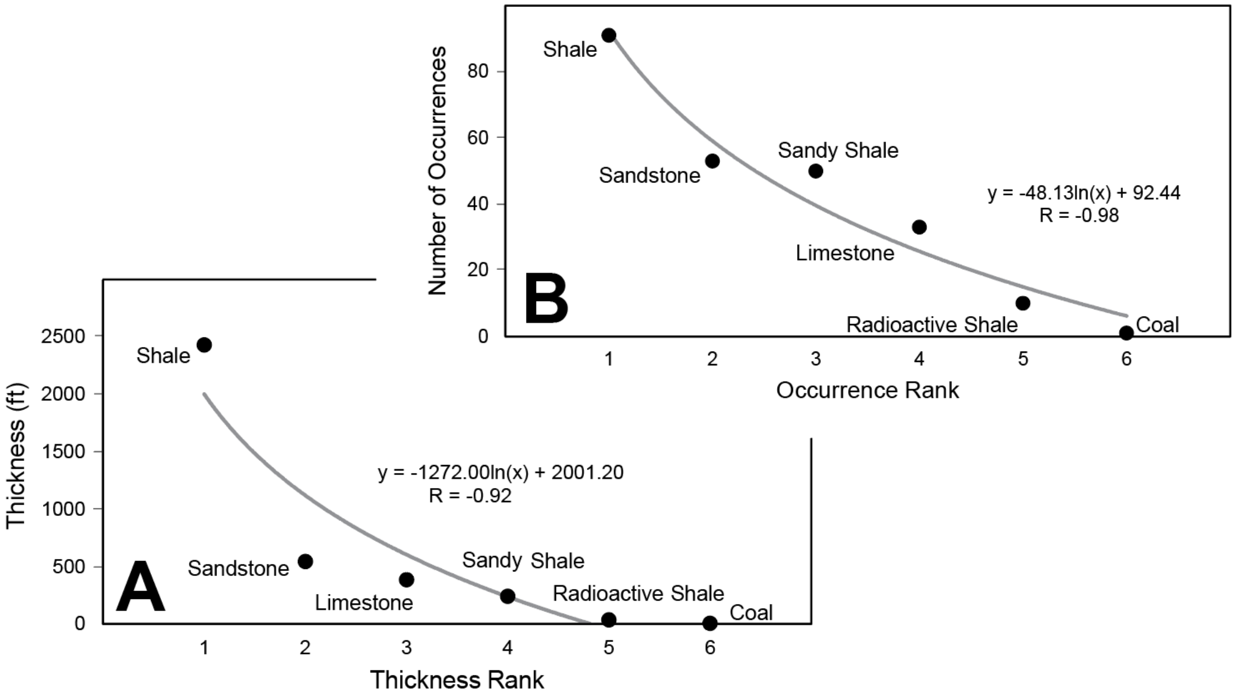


Figure 21. Occurrence rank (A) and thickness rank (B) in the Campbell Trust 1-15 well.

Occurrences of rock types in the study interval show markedly different spacing, both in terms of thickness and number of intervening beds (Figures 22, 23). In the Burks 1-31 well, the geometric mean separation between radioactive shale beds is 812 feet, composed on average of 37 intervening rock beds (Figure 22). The mean separation of radioactive shale is less in the Campbell 1-15 well at 164 ft and 11 intervening beds (Figure 23), reflecting the greater number of radioactive shale units preserved in the section. But it is still clear that radioactive shale is, on average, spaced much greater than other rock types. Spacing is also highly irregular. For example, 41 shale beds separate the radioactive shale beds at 12,878 ft and 10,784 ft, while only 5 shale beds separate the radioactive shale at beds at 10,784 ft and 10,300 ft. Though this alone does not refute cyclicity, it does demonstrate conclusively that an ordered succession in which rock types are repeated sequentially, and in which all potential lithologic members are present, does not exist. Mean separation of shale beds is low in regard to both thickness and number of intervening rock beds. Shale is commonly separated by only 2 to 3 units in 6 to 8 ft intervals, indicating that rock types tend to form thinly interbedded couplets with shale. Such rock types include sandstone, sandy shale, and to a lesser extent limestone, which also have relatively low separations of intervening beds (3 to 9).

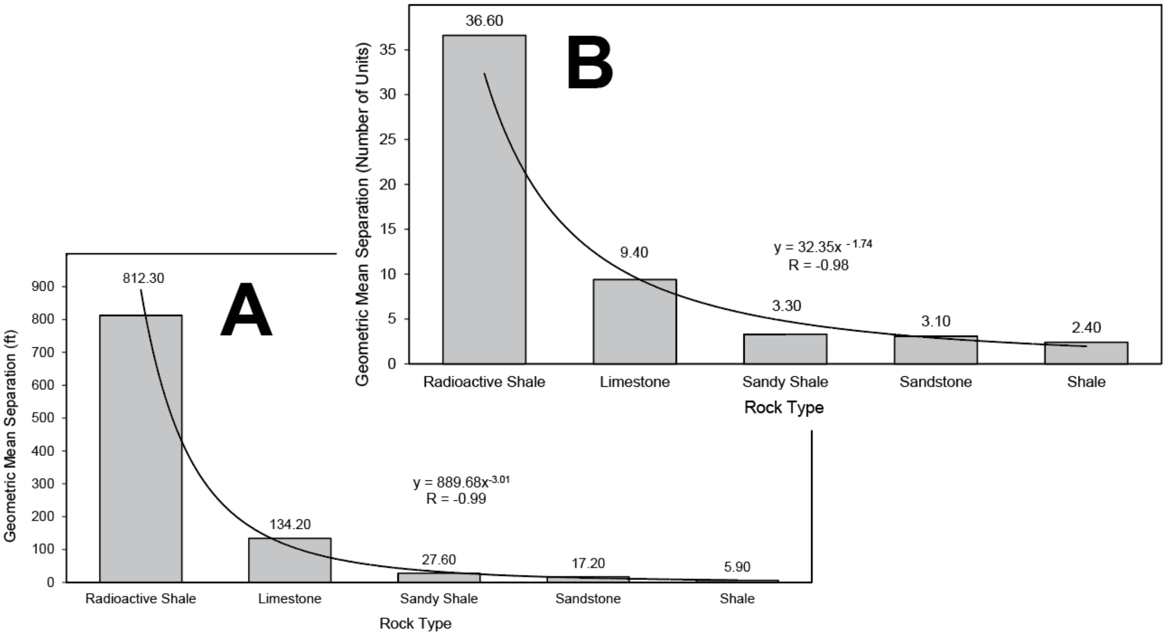


Figure 22. Geometric mean separation of rock types by thickness (A) and by intervening beds (B) in the Burks 1-31 well.

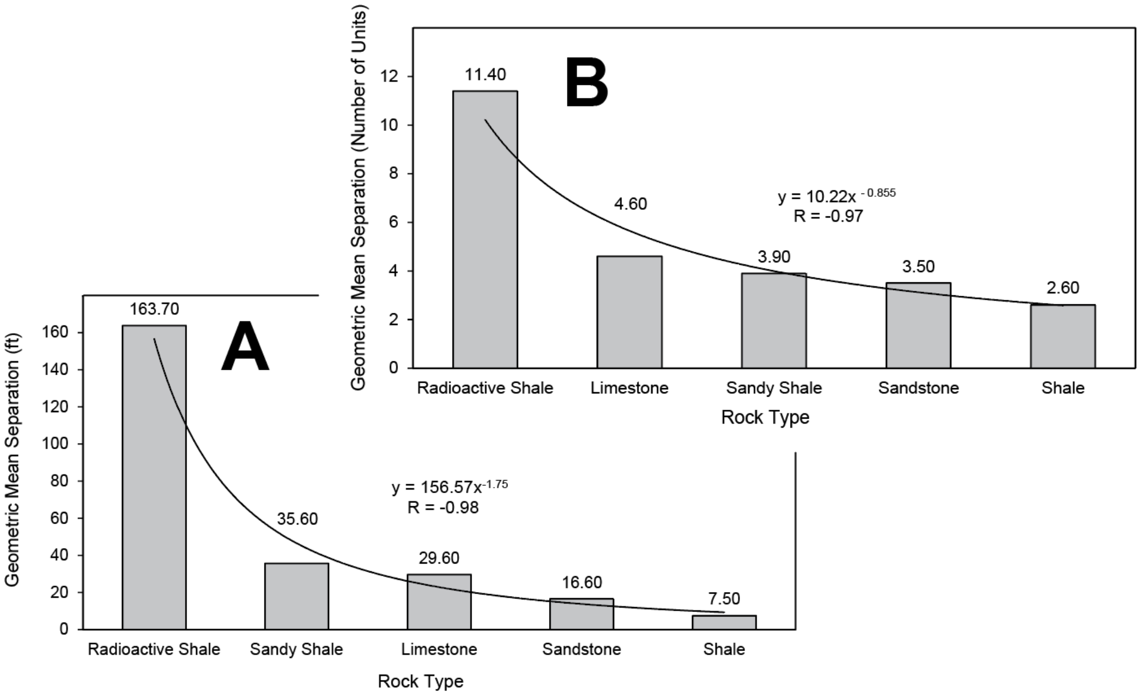
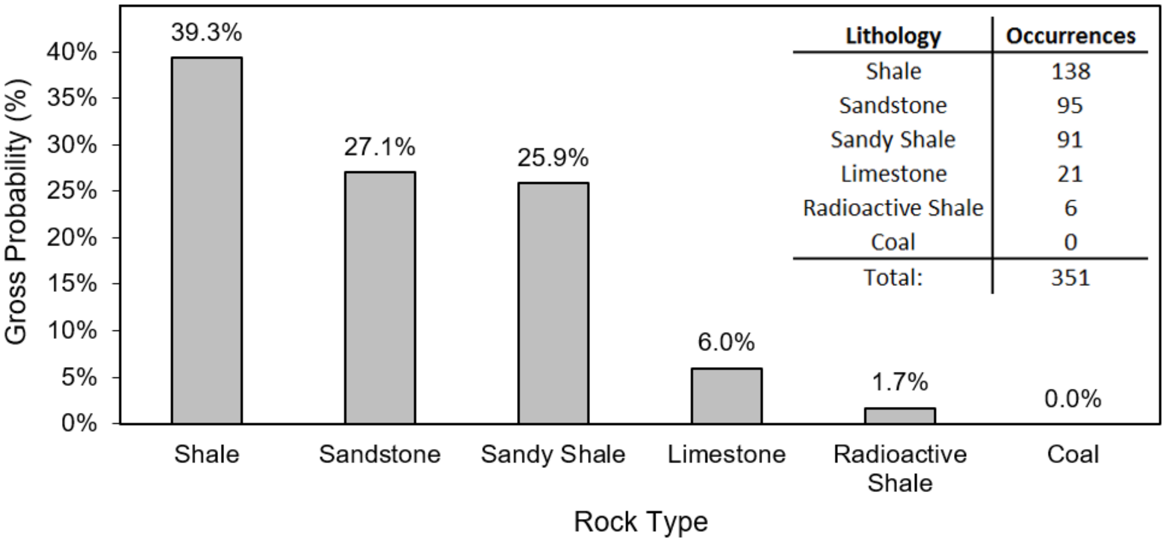


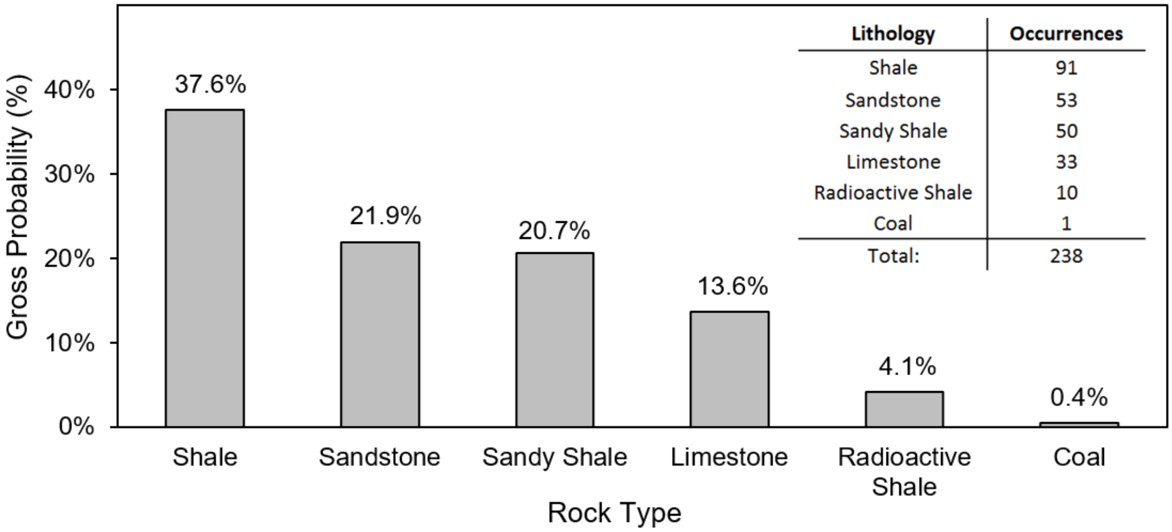
Figure 23. Geometric mean separation of rock types by thickness (A) and number of intervening beds (B) in the Campbell Trust 1-15 well.

Occurrence of rock types in the Middle and Upper Pennsylvanian strata of the Anadarko Basin is skewed heavily toward shale, sandstone, and sandy shale, which together form 92.32% of all rock occurrences in the Burks 1-31 well (Figure 24), and 80.16% of all occurrences in the Campbell Trust 1-15 well (Figure 25). Occurrence of limestone beds is highly variable. Limestone is more than twice as likely to occur in the Campbell section than in the Burks section. This is readily apparent in the cross sections, which show that limestone is most common in the eastern part of the area (Plates 1, 2). Radioactive shale occurrence probability is low in both the Burks well (1.71%) and the Campbell Trust well (4.20%). Coal thick enough to resolve in well logs is rare or absent in the two wells. Total number of rock beds is 32% lower in the Campbell Trust well than in the Burks well, corresponding with a difference in cumulative rock thickness of 2,972 ft.



Lithology	Occurrences
Shale	138
Sandstone	95
Sandy Shale	91
Limestone	21
Radioactive Shale	6
Coal	0
Total:	351

Figure 24. Gross probability of occurrence of major rock types in the Burks 1-31 well.

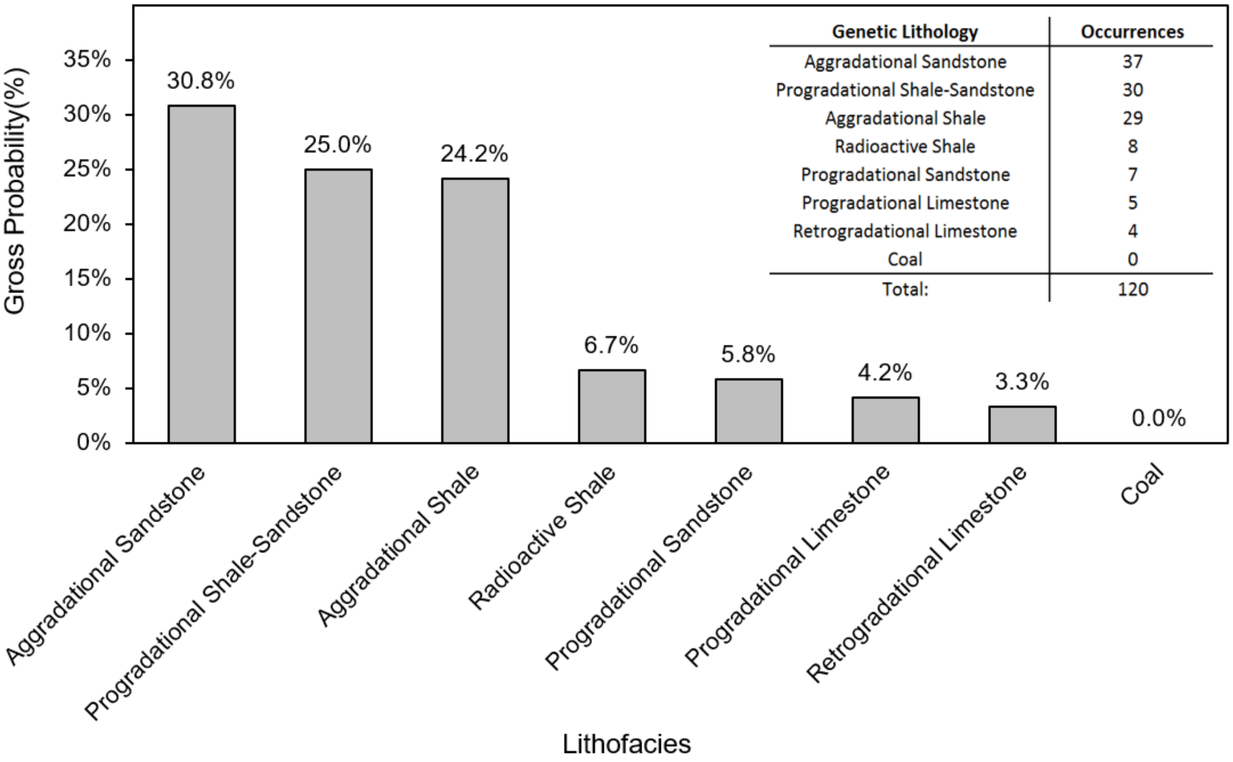


Lithology	Occurrences
Shale	91
Sandstone	53
Sandy Shale	50
Limestone	33
Radioactive Shale	10
Coal	1
Total:	238

Figure 25. Gross probability of occurrence of rock types in the Campbell Trust 1-15 well.

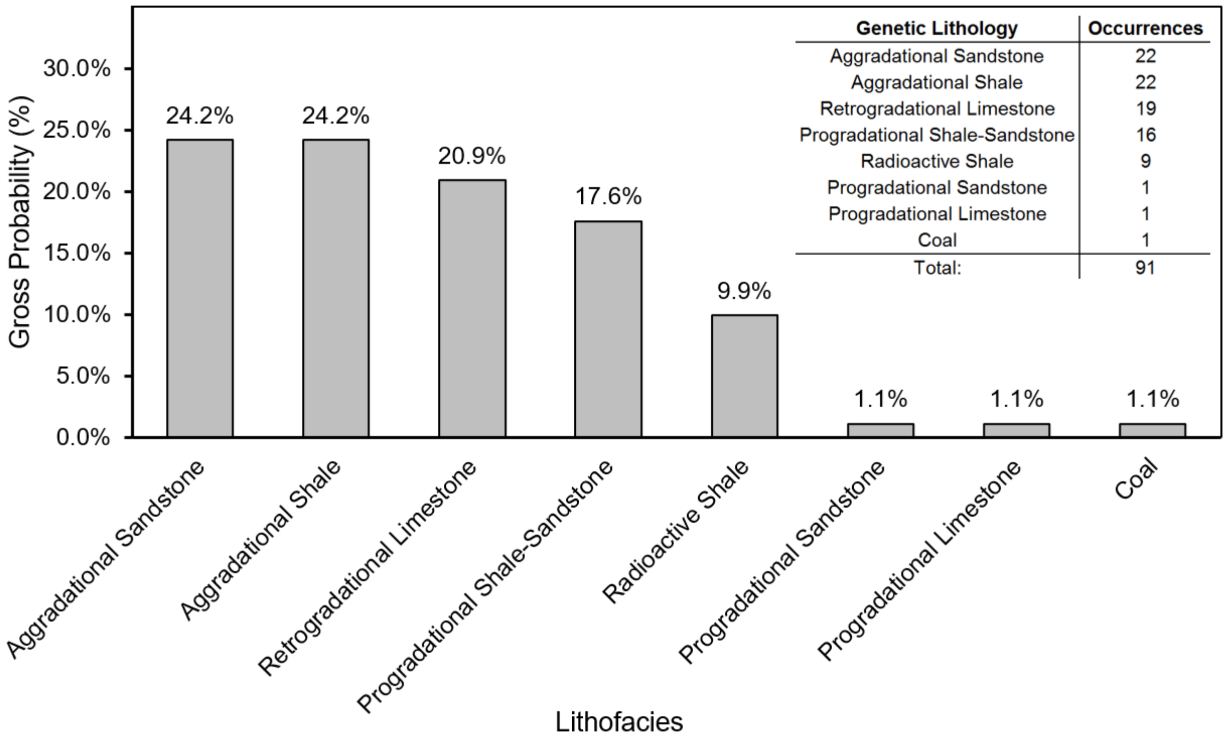
Occurrence of lithofacies in the Burks 1-31 well is bimodal (Figure 26). Aggradational sandstone, progradational shale-sandstone, and aggradational shale are abundant, with a combined 80% chance of occurrence, while radioactive shale, progradational sandstone, progradational limestone, and retrogradational limestone have a combined 20% chance of occurrence. For example, an aggradational sandstone is 10 times more likely to occur in the section than a retrogradational limestone. Such a skewed ratio is compatible with stochastic control of facies occurrence.

Lithofacies occurrence in the Campbell Trust well is also nonuniform, but less distinctly bimodal than in the Burks well (Figure 27). The occurrence probability of retrogradational limestone is 17.55% higher in the Campbell Trust well than in the Burks well. Aggradational sandstone, aggradational shale, retrogradational limestone and progradational shale-sandstone represent 87.82% of all lithofacies occurrences in the Campbell Trust well. In stark contrast, progradational sandstone, progradational limestone, and coal make up only 3.30% of occurrences in this well. This disproportionality at the lithofacies level implies that a perfect succession of lithofacies is unlikely to exist. The significant discrepancies in lithofacies occurrences in each well, and the contrast observed between the two wells points toward a high degree of stochasticity at the facies level of classification.



Genetic Lithology	Occurrences
Aggradational Sandstone	37
Progradational Shale-Sandstone	30
Aggradational Shale	29
Radioactive Shale	8
Progradational Sandstone	7
Progradational Limestone	5
Retrogradational Limestone	4
Coal	0
Total:	120

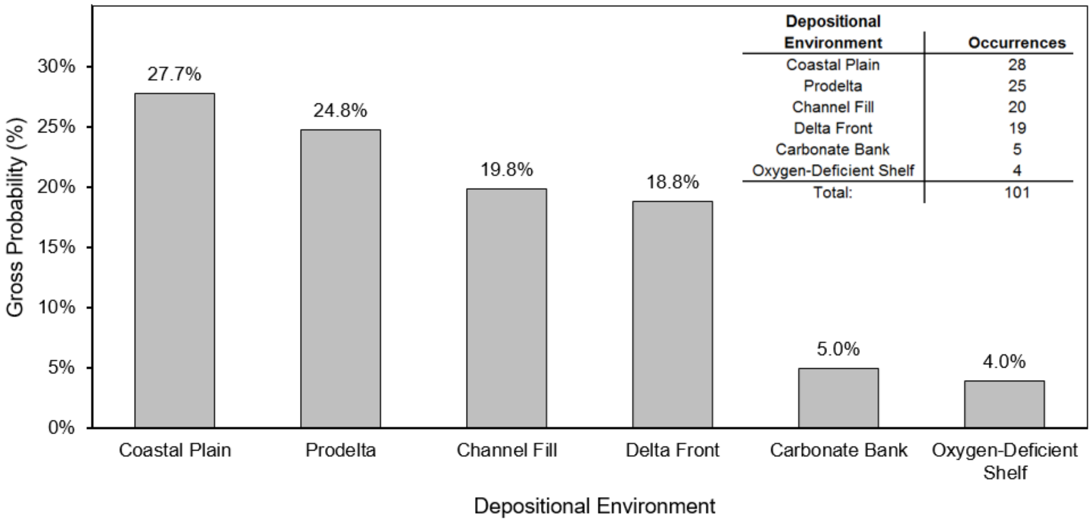
Figure 26. Gross probability of occurrence of lithofacies in the Burks 1-31 well.



Genetic Lithology	Occurrences
Aggradational Sandstone	22
Aggradational Shale	22
Retrogradational Limestone	19
Progradational Shale-Sandstone	16
Radioactive Shale	9
Progradational Sandstone	1
Progradational Limestone	1
Coal	1
Total:	91

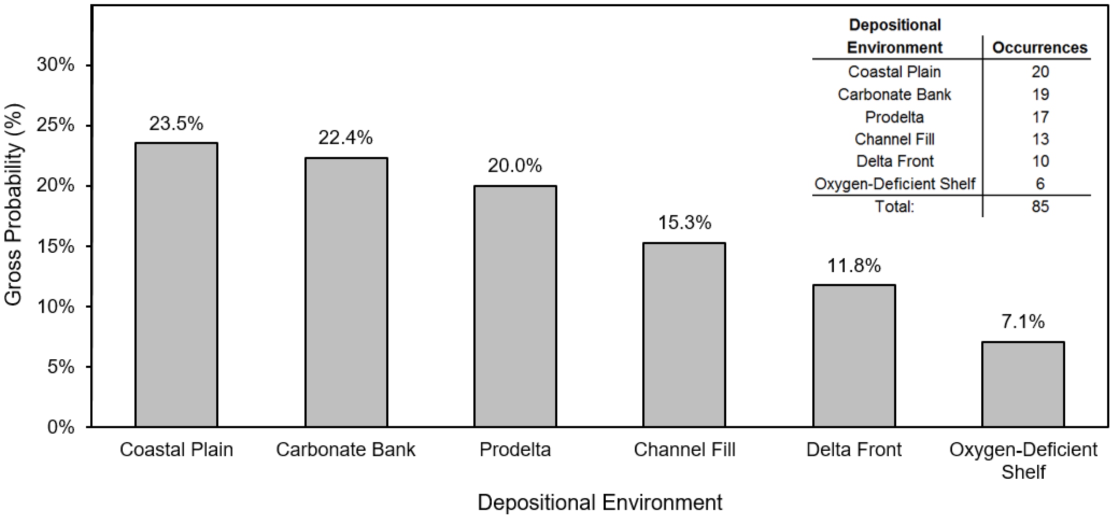
Figure 27. Gross probability of occurrence of major lithofacies in the Campbell Trust 1-15 well.

Occurrence probabilities of depositional environments in the Burks 1-31 well are bimodal (Figure 28). The coastal plain, prodelta, channel fill and delta front environments each have more than 18% chance of occurrence, while occurrence probabilities of the oxygen-deficient shelf and carbonate bank environments have only a 4 to 5% or chance of occurring. The paucity of limestone and radioactive shale in the Burks well again results in a heavily skewed distribution at multiple levels of classification. Distribution of occurrence probabilities of depositional environments in the Campbell 1-15 well is considerably more even (Figure 29). Coastal plain, carbonate bank, and prodelta are the most common depositional environments in the Campbell Trust 1-15 well. The coastal plain is the most common depositional environment, and oxygen-deficient shelf is the least common in both wells. However, whereas the total range of occurrence probabilities in the Burks well is 23.76%, it is only 16.47% in the Campbell Trust well. The carbonate bank environment is observed 17.4% more commonly in the Campbell Trust well than in the Burks well. Still, with an average range of occurrence probabilities of 20%, a perfect repretition of all six depositional environments does not exist, and the variability from well to well emphasizes a stochastic element in the occurrence of environments of deposition.



Depositional Environment	Occurrences
Coastal Plain	28
Prodelta	25
Channel Fill	20
Delta Front	19
Carbonate Bank	5
Oxygen-Deficient Shelf	4
Total:	101

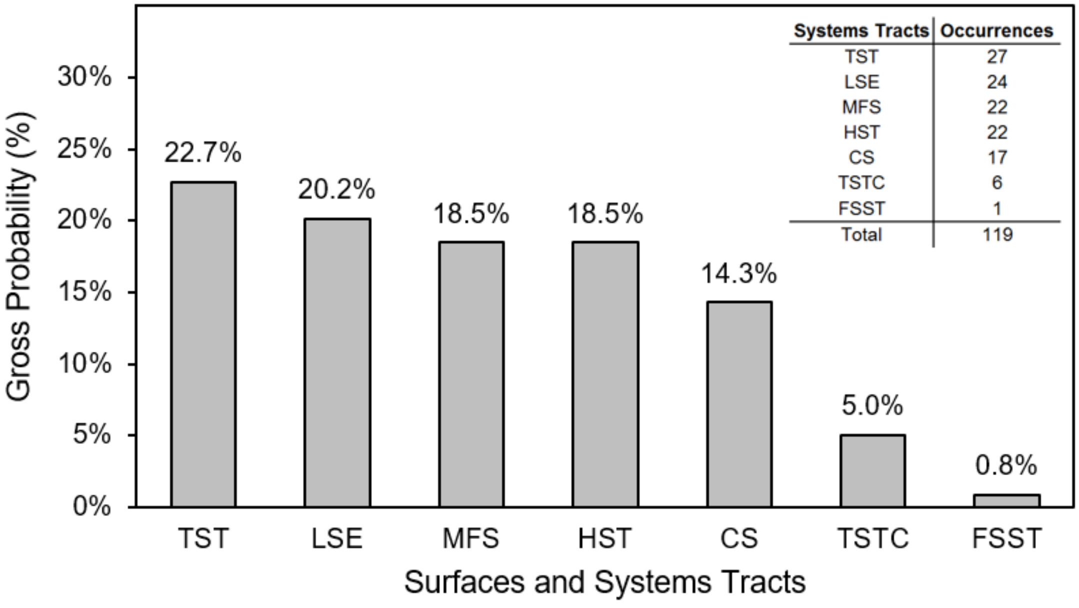
Figure 28. Gross probability of occurrence of depositional environment in the Burks 1-31 well.



Depositional Environment	Occurrences
Coastal Plain	20
Carbonate Bank	19
Prodelta	17
Channel Fill	13
Delta Front	10
Oxygen-Deficient Shelf	6
Total:	85

Figure 29. Gross probability of occurrence of depositional environments in the Campbell 1-15 well. The distribution of percentages is less pronounced than when the section is classified by rock type or lithofacies, but a range of 16.4% in occurrences still infers stochasticity.

Sequence stratigraphic components in the Burks 1-31 well display a more even distribution of occurrence probabilities than do rock types, lithofacies, or depositional environments, but stochasticity is still evident (Figure 30). Results show 5 of 7 units have a probability of occurrence within a range of 8.4%, but the carbonate transgressive systems tract and the falling stage systems tract are underrepresented. Notice that at the interpretive level, marine flooding surfaces are common, but they are not always overlain by a condensed section. In fact, the marine flooding surface has the highest occurrence probability (25%) of all sequence stratigraphic components in the Campbell Trust 1-15 well (Figure 31). Condensed sections and falling stage systems tracts are underrepresented in the Campbell Trust, indicating that they are not essential components of a sequence. Regardless, a range of 10.5% exists in the 5 most common stratigraphic units, showing that stochasticity is still a factor at the sequence stratigraphic level.



Systems Tracts	Occurrences
TST	27
LSE	24
MFS	22
HST	22
CS	17
TSTC	6
FSST	1
Total	119

Figure 30. Gross probability of occurrence of stratigraphic surfaces and systems tracts in the Burks 1-31 well

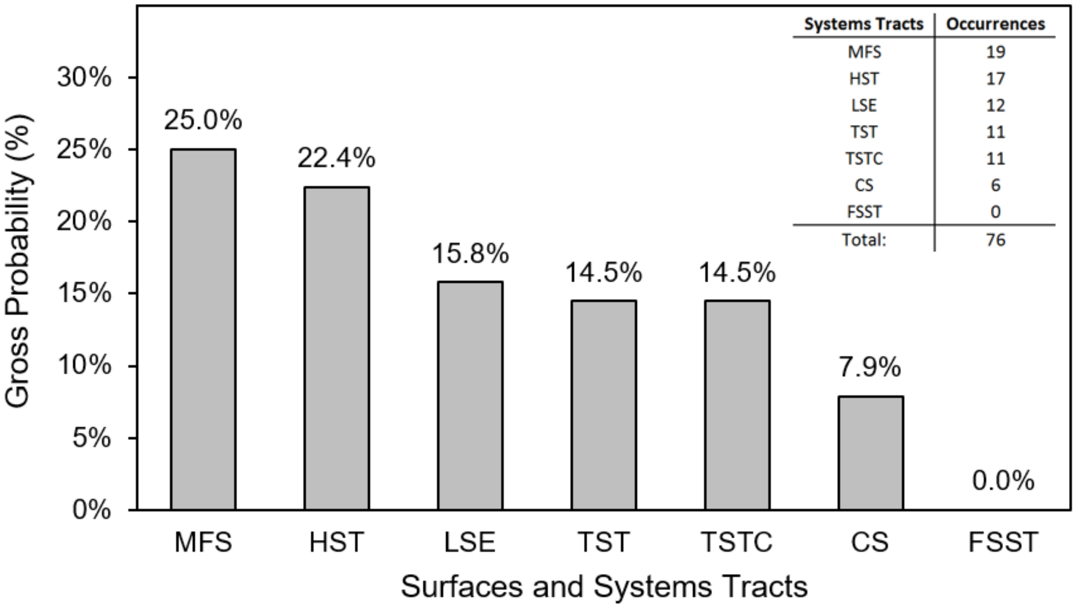
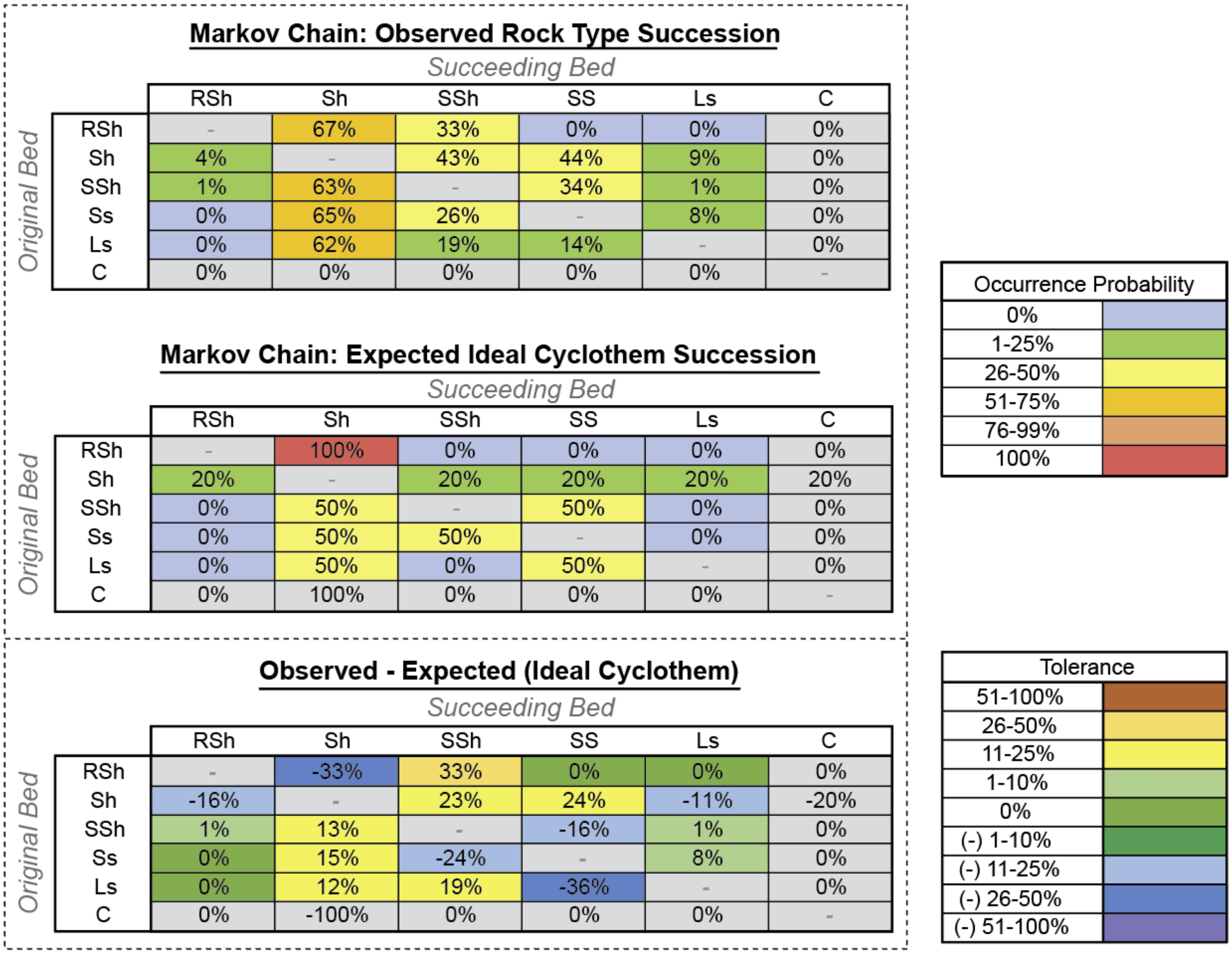


Figure 31. Gross probability of occurrence of stratigraphic surfaces and systems tracts in the Campbell Trust 1-15 well.

The highest observed transitional probability in the Burks well occurs in succession of radioactive shale by shale, occurring 67% of the time (Figure 32). In fact, radioactive shale. sandy shale, limestone, and sandstone, all show more than 62% probability of transitioning to shale. In the Campbell Trust well, radioactive shale transitions to shale 90% of the time (succession of coal by shale at 100% is a result of undersampling) (Figure 33). Succession of limestone by shale is also high in the Campbell Trust well at 73%. In both wells, transition from all rock types to shale was common, followed by transition to sandstone. In contrast, succession of limestone by sandstone occurred roughly 35% less than expected in both wells. In the Burks 1-31 well, transitions of rock types to sandy shale, and sandstone were difficult to predict. In the Campbell Trust 1-15 well, transitions of rock types to sandstone deviated from expectation. The unpredictability of these relationships in rock type point to probabilistic patterns of occurrence, and also shows that the natural variability of the system cannot be captured in a single model.



Markov Chain: Observed Rock Type Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	67%	33%	0%	0%	0%
Sh	4%	-	43%	44%	9%	0%
SSh	1%	63%	-	34%	1%	0%
Ss	0%	65%	26%	-	8%	0%
Ls	0%	62%	19%	14%	-	0%
C	0%	0%	0%	0%	0%	-

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	100%	0%	0%	0%	0%
Sh	20%	-	20%	20%	20%	20%
SSh	0%	50%	-	50%	0%	0%
Ss	0%	50%	50%	-	0%	0%
Ls	0%	50%	0%	50%	-	0%
C	0%	100%	0%	0%	0%	-

Observed - Expected (Ideal Cyclothem)

Succeeding Bed

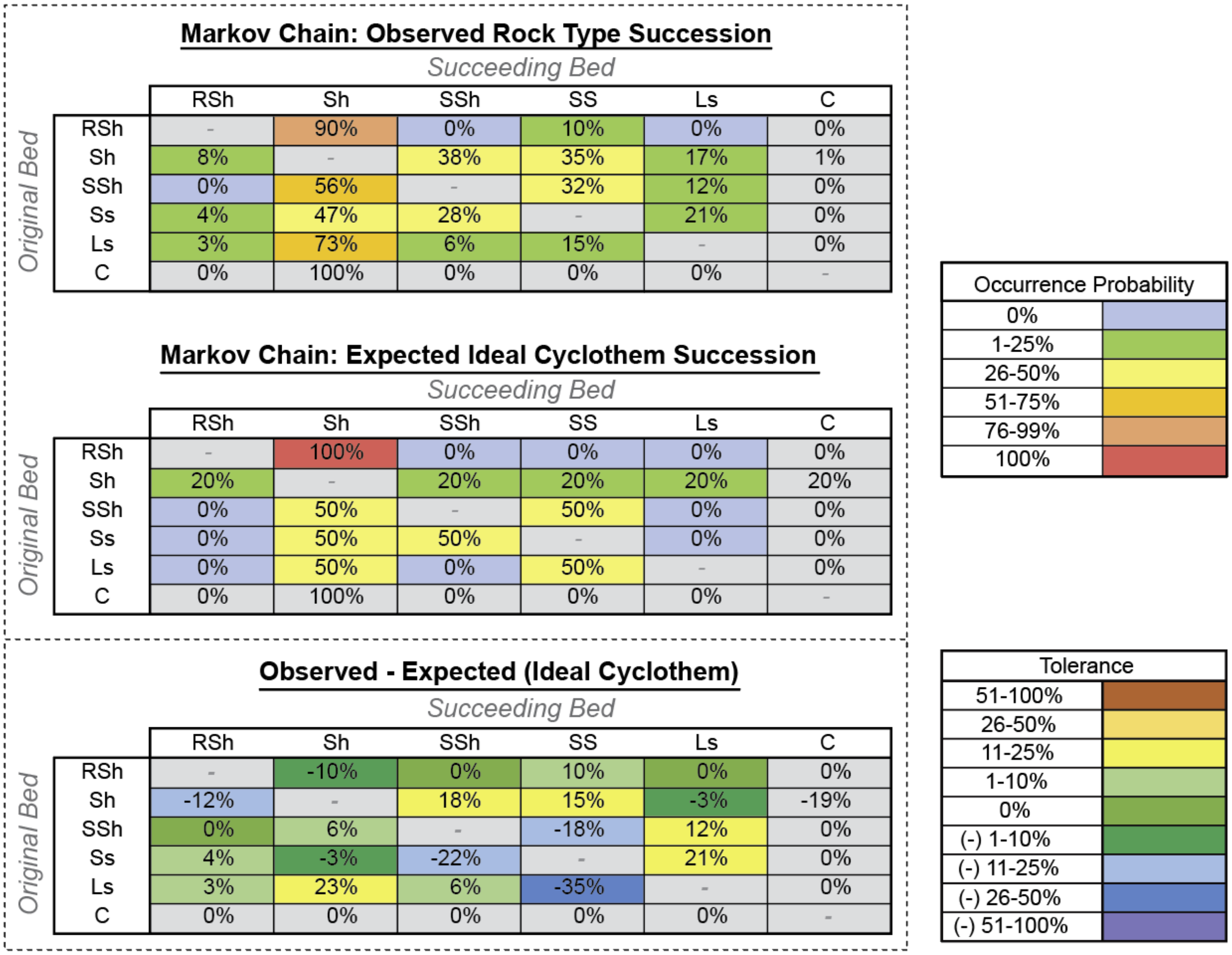
Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	-33%	33%	0%	0%	0%
Sh	-16%	-	23%	24%	-11%	-20%
SSh	1%	13%	-	-16%	1%	0%
Ss	0%	15%	-24%	-	8%	0%
Ls	0%	12%	19%	-36%	-	0%
C	0%	-100%	0%	0%	0%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟫
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 32. Markov chain probability matrices showing observed transitional probabilities of rock types in the Burks 1-31 well in comparison to probabilities expected for the ideal Anadarko Basin cyclothem (RSh = radioactive Shale, Sh = shale, SSh = sandy shale, Ss = sandstone, Ls = limestone, C = coal). Successions of severely underrepresented units are shown in gray. Note that the bottom table represents the difference between the observed and expected transitional probabilities.



Markov Chain: Observed Rock Type Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	90%	0%	10%	0%	0%
Sh	8%	-	38%	35%	17%	1%
SSh	0%	56%	-	32%	12%	0%
Ss	4%	47%	28%	-	21%	0%
Ls	3%	73%	6%	15%	-	0%
C	0%	100%	0%	0%	0%	-

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	100%	0%	0%	0%	0%
Sh	20%	-	20%	20%	20%	20%
SSh	0%	50%	-	50%	0%	0%
Ss	0%	50%	50%	-	0%	0%
Ls	0%	50%	0%	50%	-	0%
C	0%	100%	0%	0%	0%	-

Observed - Expected (Ideal Cyclothem)

Succeeding Bed

Original Bed

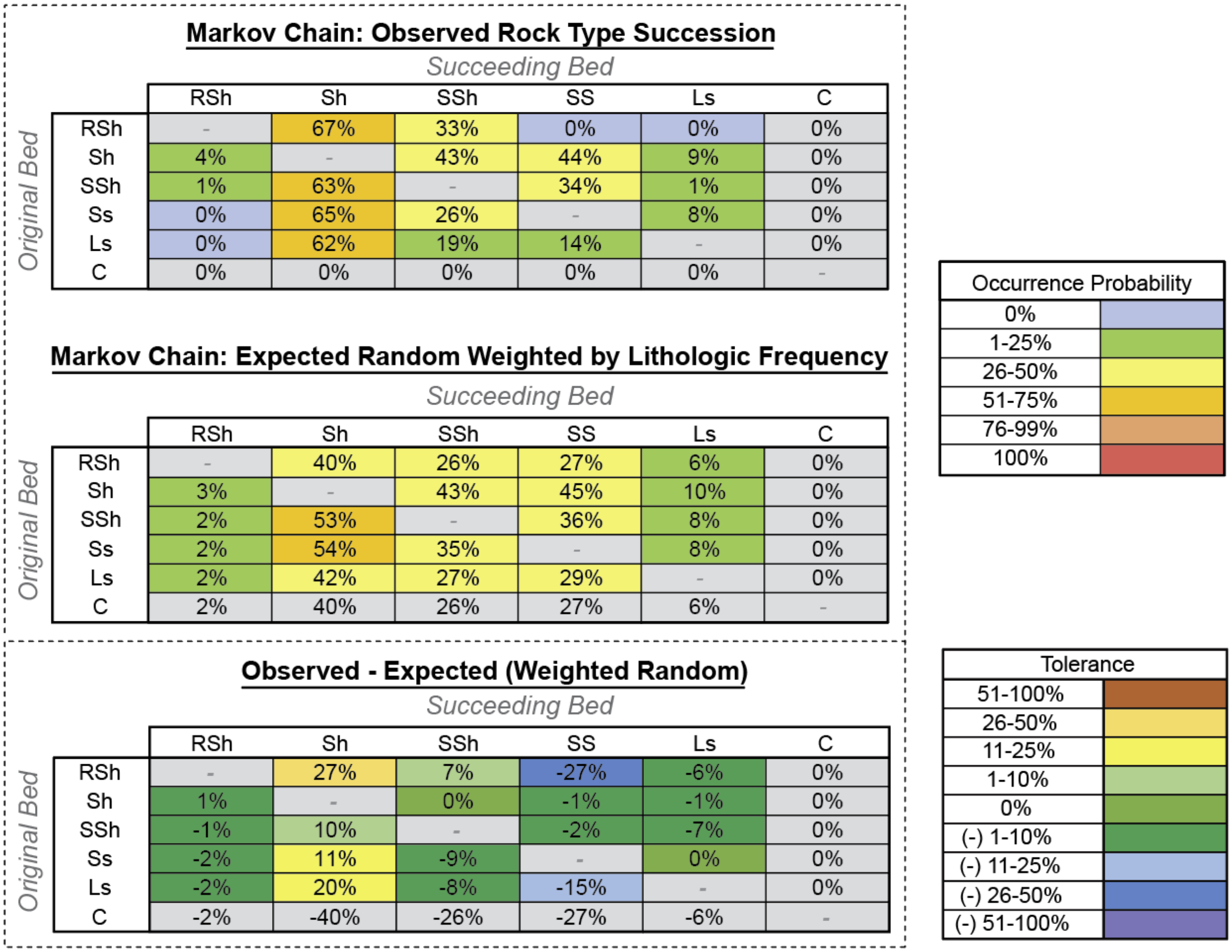
	RSh	Sh	SSh	SS	Ls	C
RSh	-	-10%	0%	10%	0%	0%
Sh	-12%	-	18%	15%	-3%	-19%
SSh	0%	6%	-	-18%	12%	0%
Ss	4%	-3%	-22%	-	21%	0%
Ls	3%	23%	6%	-35%	-	0%
C	0%	0%	0%	0%	0%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 33. Markov chain probability matrices showing observed transitional probabilities of rock types in the Campbell Trust 1-15 well compared to probabilities expected for the ideal Anadarko Basin cyclothem. Successions of severely underrepresented units are shown in gray.

Comparison of transitional probabilities for the Burks 1-31 well against a random model weighted by frequency of rock type occurrence demonstrates that some rock type transitions are nonrandom (Figure 34). Transitions from most rock types to shale occur more often than expected (e.g., more than 27% expected succession of radioactive shale by shale), and transition to sandstone occurs less than expected (less than 27% expected succession of radioactive shale by sandstone). In the Campbell Trust 1-15 well, transition of all rock types to radioactive shale and limestone occurs less commonly than expected, and transitions of all rock types to shale occurs considerably more often than expected (Figure 35). This reiterates the tendency of rocks in the study interval to form couplets with shale. In particular, radioactive shale is succeeded by shale 83% more often than expected, and limestone is succeeded by shale 51% more than expected. Though these results provide compelling evidence for nonrandomness in rock type succession, compatibility of many rock transitions with the random model also suggests for a high degree of stochasticity.



Markov Chain: Observed Rock Type Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	67%	33%	0%	0%	0%
Sh	4%	-	43%	44%	9%	0%
SSh	1%	63%	-	34%	1%	0%
Ss	0%	65%	26%	-	8%	0%
Ls	0%	62%	19%	14%	-	0%
C	0%	0%	0%	0%	0%	-

Markov Chain: Expected Random Weighted by Lithologic Frequency

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	40%	26%	27%	6%	0%
Sh	3%	-	43%	45%	10%	0%
SSh	2%	53%	-	36%	8%	0%
Ss	2%	54%	35%	-	8%	0%
Ls	2%	42%	27%	29%	-	0%
C	2%	40%	26%	27%	6%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Observed - Expected (Weighted Random)

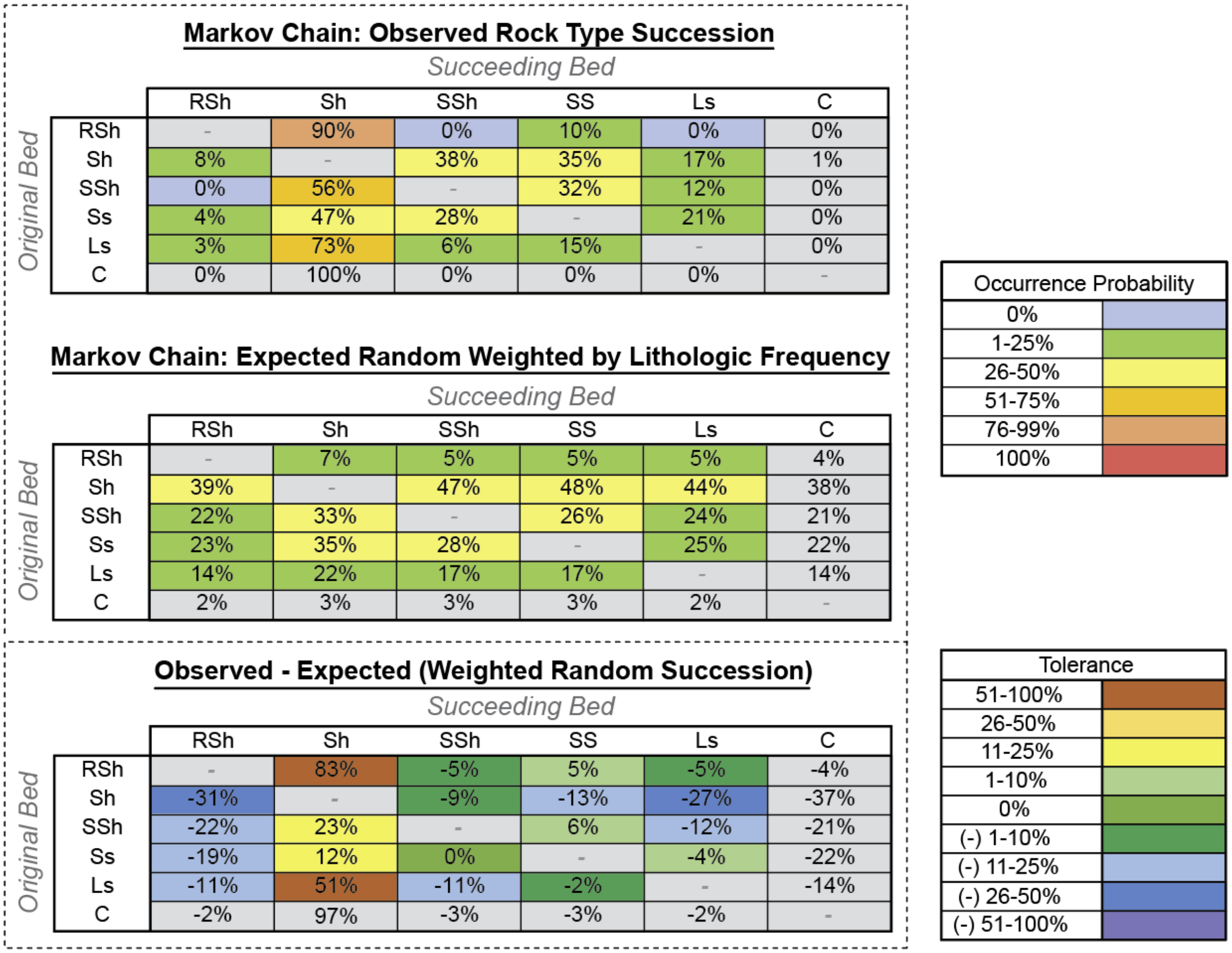
Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	27%	7%	-27%	-6%	0%
Sh	1%	-	0%	-1%	-1%	0%
SSh	-1%	10%	-	-2%	-7%	0%
Ss	-2%	11%	-9%	-	0%	0%
Ls	-2%	20%	-8%	-15%	-	0%
C	-2%	-40%	-26%	-27%	-6%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 34. Markov chain probability matrices showing observed transitional probabilities of rock types in comparison to probabilities expected for a random system weighted by occurrence frequency in the Burks 1-31 well. Successions of severely underrepresented units are shown in gray.



Markov Chain: Observed Rock Type Succession

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	90%	0%	10%	0%	0%
Sh	8%	-	38%	35%	17%	1%
SSh	0%	56%	-	32%	12%	0%
Ss	4%	47%	28%	-	21%	0%
Ls	3%	73%	6%	15%	-	0%
C	0%	100%	0%	0%	0%	-

Markov Chain: Expected Random Weighted by Lithologic Frequency

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	7%	5%	5%	5%	4%
Sh	39%	-	47%	48%	44%	38%
SSh	22%	33%	-	26%	24%	21%
Ss	23%	35%	28%	-	25%	22%
Ls	14%	22%	17%	17%	-	14%
C	2%	3%	3%	3%	2%	-

Observed - Expected (Weighted Random Succession)

Succeeding Bed

Original Bed

	RSh	Sh	SSh	SS	Ls	C
RSh	-	83%	-5%	5%	-5%	-4%
Sh	-31%	-	-9%	-13%	-27%	-37%
SSh	-22%	23%	-	6%	-12%	-21%
Ss	-19%	12%	0%	-	-4%	-22%
Ls	-11%	51%	-11%	-2%	-	-14%
C	-2%	97%	-3%	-3%	-2%	-

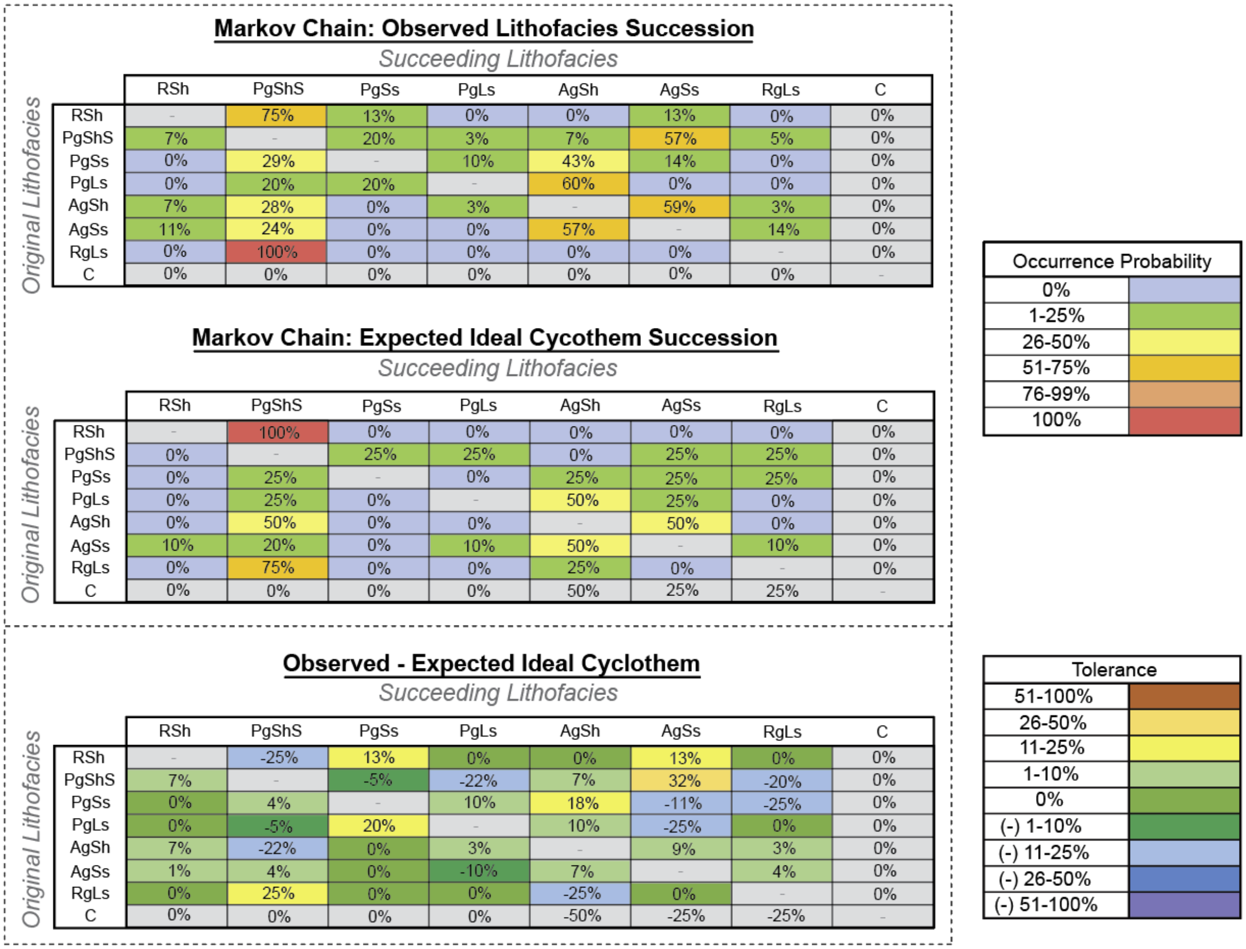
Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 35. Markov chain probability matrices displaying observed transitional probabilities of rock types relative to probabilities expected for a random system weighted by occurrence frequency Campbell Trust 1-15 well. Successions of severely underrepresented units are shown in gray.

Lithofacies analysis in the Burks 1-31 well shows that the highest observed transitional probability is succession of radioactive shale by progradational shale-sandstone at 75% and retrogradational limestone by progradational shale-sandstone at 100% (though there are only 3 occurrences of retrogradational limestone) (Figure 36). Progradational limestone, aggradational sandstone, and progradational sandstone show a tendency to transition to aggradational shale (43 to 60% transitional probability). Retrogradational limestone was not predicted to be succeeded by progradational sandstone, but instances of this in the section are rare and undersampling is evident. progradational shale-sandstone was succeeded by aggradational sandstone 32% more often than expected, while retrogradational limestone was succeeded by progradational shale-sandstone 75% less than expected.

In the Campbell Trust 1-15 well, the highest meaningful associations of lithofacies were observed in radioactive shale succession by progradational shale-sandstone at a rate of 67%, aggradational sandstone succession by aggradational shale (55%), and aggradational shale by sandstone (50%) (Figure 37). Succession of progradational sandstone, progradational limestone, and coal, are severely underrepresented in the Campbell Trust section. Transition to retrogradational limestone and progradational shale-sandstone shows little predictability. Aggradational shale was succeeded by retrogradational limestone 40% more often than expected. In contrast, most transitional probabilities of lithofacies being succeeded by progradational shale-sandstone were much less than expected. Aggradational shale was succeeded by progradational shale-sandstone 53% less than expected. Results from both wells indicate that transitional probabilities of lithofacies exhibit a relatively low degree of predictability.



Markov Chain: Observed Lithofacies Succession

Succeeding Lithofacies

Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	75%	13%	0%	0%	13%	0%	0%
PgShS	7%	-	20%	3%	7%	57%	5%	0%
PgSs	0%	29%	-	10%	43%	14%	0%	0%
PgLs	0%	20%	20%	-	60%	0%	0%	0%
AgSh	7%	28%	0%	3%	-	59%	3%	0%
AgSs	11%	24%	0%	0%	57%	-	14%	0%
RgLs	0%	100%	0%	0%	0%	0%	-	0%
C	0%	0%	0%	0%	0%	0%	0%	-

Markov Chain: Expected Ideal Cycothem Succession

Succeeding Lithofacies

Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	100%	0%	0%	0%	0%	0%	0%
PgShS	0%	-	25%	25%	0%	25%	25%	0%
PgSs	0%	25%	-	0%	25%	25%	25%	0%
PgLs	0%	25%	0%	-	50%	25%	0%	0%
AgSh	0%	50%	0%	0%	-	50%	0%	0%
AgSs	10%	20%	0%	10%	50%	-	10%	0%
RgLs	0%	75%	0%	0%	25%	0%	-	0%
C	0%	0%	0%	0%	50%	25%	25%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟧
100%	🟥

Observed - Expected Ideal Cyclothem

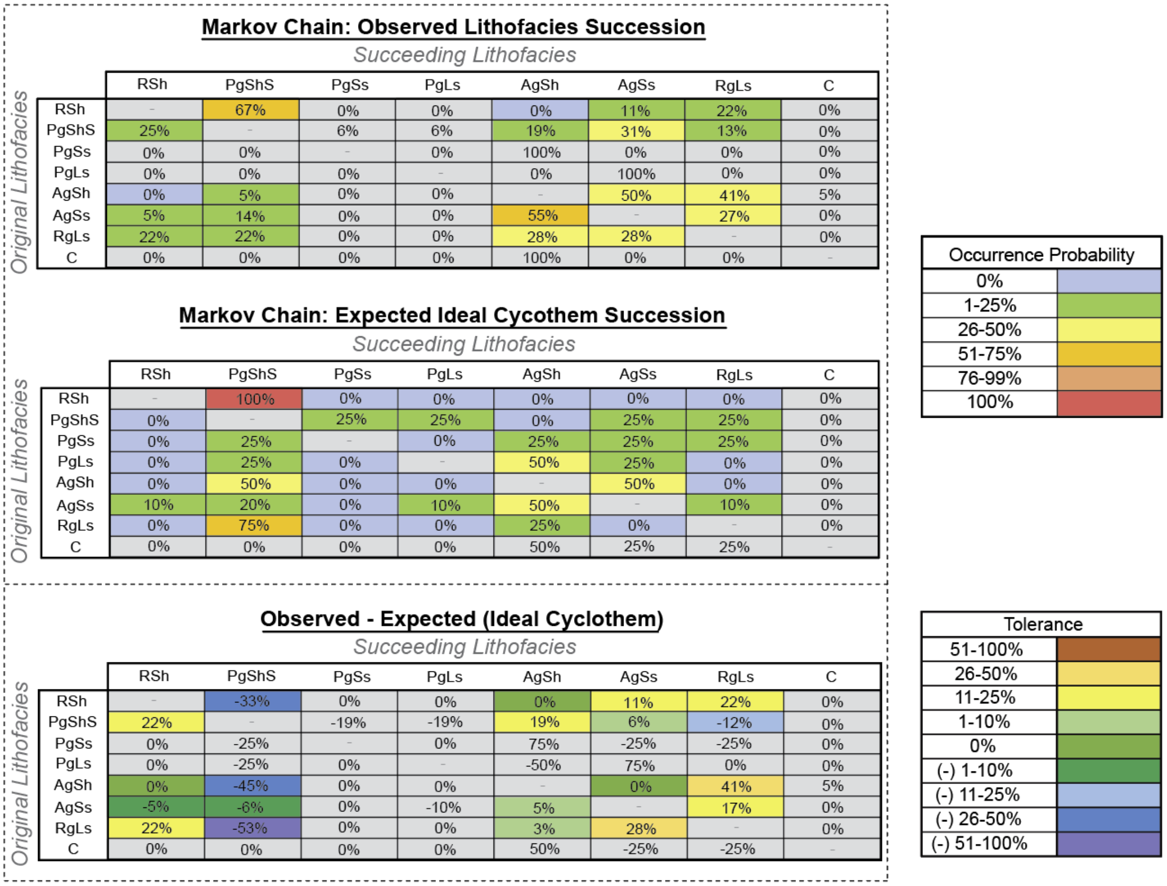
Succeeding Lithofacies

Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	-25%	13%	0%	0%	13%	0%	0%
PgShS	7%	-	-5%	-22%	7%	32%	-20%	0%
PgSs	0%	4%	-	10%	18%	-11%	-25%	0%
PgLs	0%	-5%	20%	-	10%	-25%	0%	0%
AgSh	7%	-22%	0%	3%	-	9%	3%	0%
AgSs	1%	4%	0%	-10%	7%	-	4%	0%
RgLs	0%	25%	0%	0%	-25%	0%	-	0%
C	0%	0%	0%	0%	-50%	-25%	-25%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 36. Markov chain probability matrices for the Burks 1-31 well showing observed transitional probabilities of lithofacies in comparison to probabilities expected for an ideal Anadarko Basin cyclothem (RSh = radioactive Shale, PgShS = progradational shale-sandstone, PgSs = progradational sandstone, PgLs = progradational limestone, AgSh = aggradational shale, AgSs = aggradational sandstone, RgLs = retrogradational limestone, C = coal). Successions of severely underrepresented units are shown in gray.



Markov Chain: Observed Lithofacies Succession

Succeeding Lithofacies

Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	67%	0%	0%	0%	11%	22%	0%
PgShS	25%	-	6%	6%	19%	31%	13%	0%
PgSs	0%	0%	-	0%	100%	0%	0%	0%
PgLs	0%	0%	0%	-	0%	100%	0%	0%
AgSh	0%	5%	0%	0%	-	50%	41%	5%
AgSs	5%	14%	0%	0%	55%	-	27%	0%
RgLs	22%	22%	0%	0%	28%	28%	-	0%
C	0%	0%	0%	0%	100%	0%	0%	-

Markov Chain: Expected Ideal Cycothem Succession

Succeeding Lithofacies

Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	100%	0%	0%	0%	0%	0%	0%
PgShS	0%	-	25%	25%	0%	25%	25%	0%
PgSs	0%	25%	-	0%	25%	25%	25%	0%
PgLs	0%	25%	0%	-	50%	25%	0%	0%
AgSh	0%	50%	0%	0%	-	50%	0%	0%
AgSs	10%	20%	0%	10%	50%	-	10%	0%
RgLs	0%	75%	0%	0%	25%	0%	-	0%
C	0%	0%	0%	0%	50%	25%	25%	-

Occurrence Probability
0%
1-25%
26-50%
51-75%
76-99%
100%

Observed - Expected (Ideal Cyclothem)

Succeeding Lithofacies

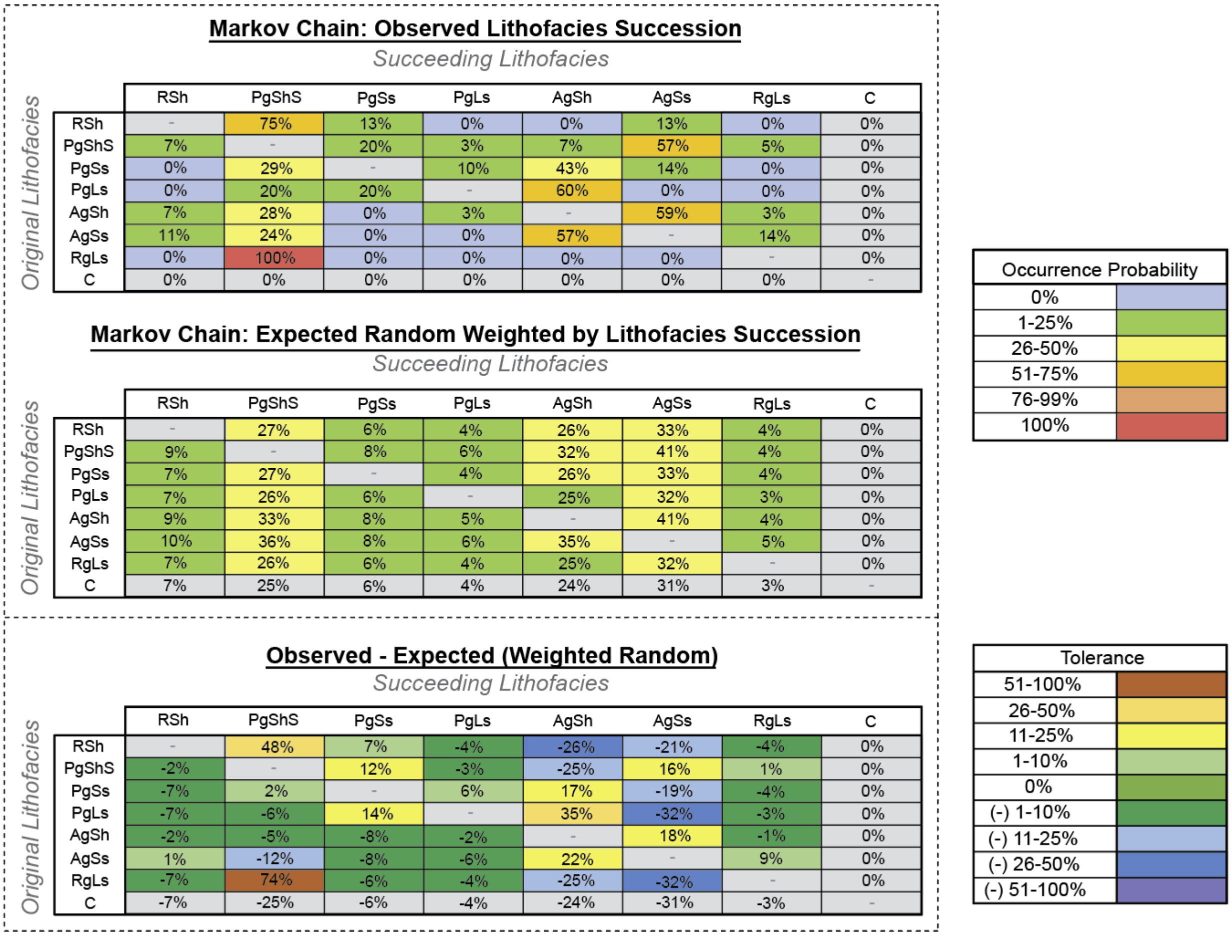
Original Lithofacies

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	-33%	0%	0%	0%	11%	22%	0%
PgShS	22%	-	-19%	-19%	19%	6%	-12%	0%
PgSs	0%	-25%	-	0%	75%	-25%	-25%	0%
PgLs	0%	-25%	0%	-	-50%	75%	0%	0%
AgSh	0%	-45%	0%	0%	-	0%	41%	5%
AgSs	-5%	-6%	0%	-10%	5%	-	17%	0%
RgLs	22%	-53%	0%	0%	3%	28%	-	0%
C	0%	0%	0%	0%	50%	-25%	-25%	-

Tolerance
51-100%
26-50%
11-25%
1-10%
0%
(-) 1-10%
(-) 11-25%
(-) 26-50%
(-) 51-100%

Figure 37. Markov chain probability matrices for the Campbell Trust 1-15 well of observed transitional probabilities of lithofacies compared to probabilities expected for an ideal Anadarko Basin cyclothem. Successions of severely underrepresented units are shown in gray.

In the Burks 1-31 well, succession of lithofacies by progradational shale-sandstone, aggradational shale, and aggradational sandstone appear nonrandom (Figure 38). Numerous successions occur more often than expected for a random system, including radioactive shale succession by progradational shale-sandstone (48%) and retrogradational limestone succession by progradational shale-sandstone (74%). Meanwhile, succession by aggradational facies tends to occur less often than expected at random, such as succession of limestone facies by aggradational sandstone (-32%). In the Campbell Trust 1-15 well, the transition of radioactive shale to progradational shale-sandstone is 47% more common than expected in a random system, while the succession of radioactive shale by aggradational shale occurs 27% less often (Figure 39).



Markov Chain: Observed Lithofacies Succession

Succeeding Lithofacies

Original Lithofacies	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	75%	13%	0%	0%	13%	0%	0%
PgShS	7%	-	20%	3%	7%	57%	5%	0%
PgSs	0%	29%	-	10%	43%	14%	0%	0%
PgLs	0%	20%	20%	-	60%	0%	0%	0%
AgSh	7%	28%	0%	3%	-	59%	3%	0%
AgSs	11%	24%	0%	0%	57%	-	14%	0%
RgLs	0%	100%	0%	0%	0%	0%	-	0%
C	0%	0%	0%	0%	0%	0%	0%	-

Markov Chain: Expected Random Weighted by Lithofacies Succession

Succeeding Lithofacies

Original Lithofacies	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	27%	6%	4%	26%	33%	4%	0%
PgShS	9%	-	8%	6%	32%	41%	4%	0%
PgSs	7%	27%	-	4%	26%	33%	4%	0%
PgLs	7%	26%	6%	-	25%	32%	3%	0%
AgSh	9%	33%	8%	5%	-	41%	4%	0%
AgSs	10%	36%	8%	6%	35%	-	5%	0%
RgLs	7%	26%	6%	4%	25%	32%	-	0%
C	7%	25%	6%	4%	24%	31%	3%	-

Occurrence Probability	
0%	🟪
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

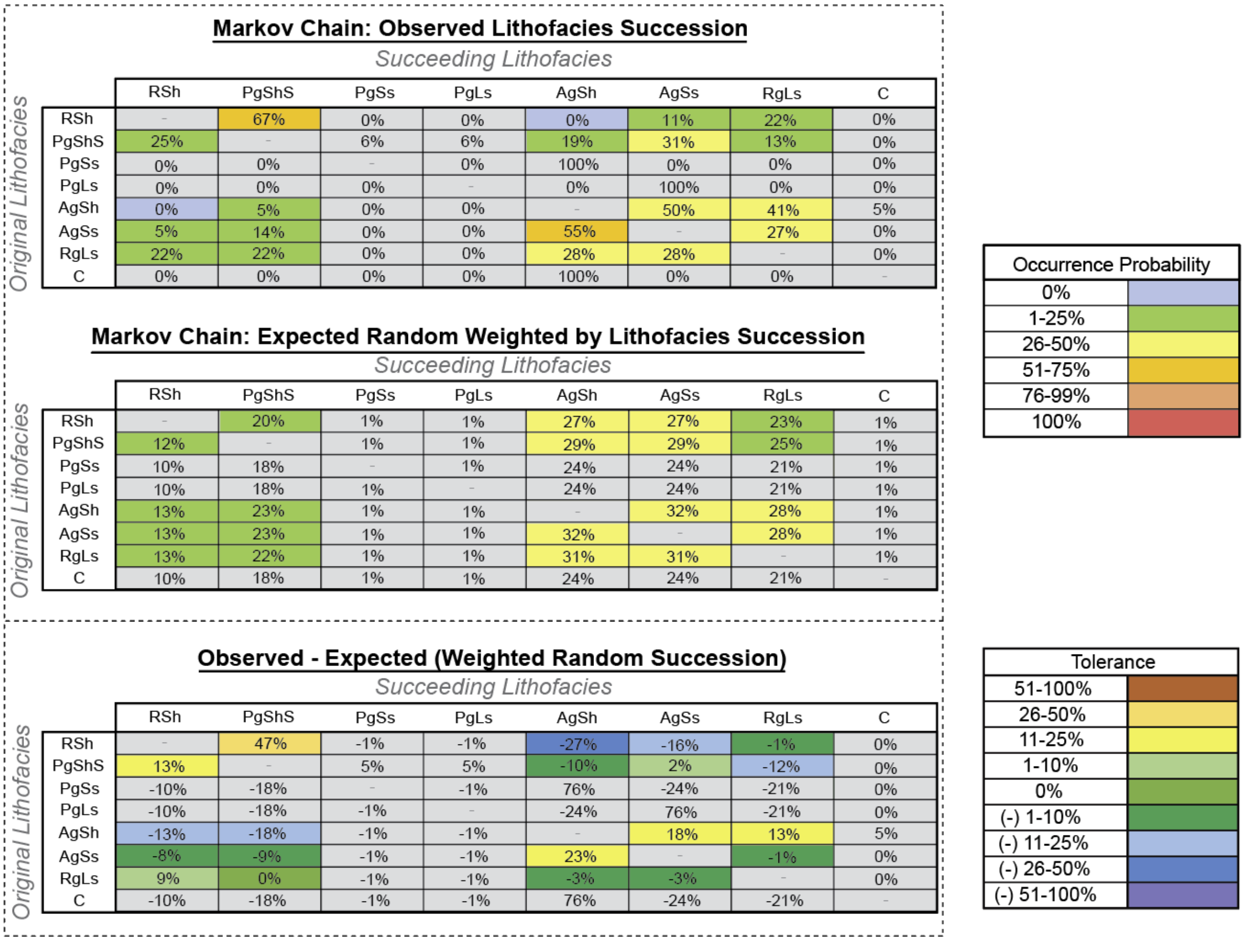
Observed - Expected (Weighted Random)

Succeeding Lithofacies

Original Lithofacies	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	48%	7%	-4%	-26%	-21%	-4%	0%
PgShS	-2%	-	12%	-3%	-25%	16%	1%	0%
PgSs	-7%	2%	-	6%	17%	-19%	-4%	0%
PgLs	-7%	-6%	14%	-	35%	-32%	-3%	0%
AgSh	-2%	-5%	-8%	-2%	-	18%	-1%	0%
AgSs	1%	-12%	-8%	-6%	22%	-	9%	0%
RgLs	-7%	74%	-6%	-4%	-25%	-32%	-	0%
C	-7%	-25%	-6%	-4%	-24%	-31%	-3%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 38. Markov chain probability matrices for the Burks 1-31 well showing observed transitional probabilities of lithofacies types in comparison to probabilities expected for a random system weighted by frequency occurrence of lithofacies. Successions of severely underrepresented units are shown in gray.



Markov Chain: Observed Lithofacies Succession

Succeeding Lithofacies / *Original Lithofacies*

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	67%	0%	0%	0%	11%	22%	0%
PgShS	25%	-	6%	6%	19%	31%	13%	0%
PgSs	0%	0%	-	0%	100%	0%	0%	0%
PgLs	0%	0%	0%	-	0%	100%	0%	0%
AgSh	0%	5%	0%	0%	-	50%	41%	5%
AgSs	5%	14%	0%	0%	55%	-	27%	0%
RgLs	22%	22%	0%	0%	28%	28%	-	0%
C	0%	0%	0%	0%	100%	0%	0%	-

Markov Chain: Expected Random Weighted by Lithofacies Succession

Succeeding Lithofacies / *Original Lithofacies*

	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	20%	1%	1%	27%	27%	23%	1%
PgShS	12%	-	1%	1%	29%	29%	25%	1%
PgSs	10%	18%	-	1%	24%	24%	21%	1%
PgLs	10%	18%	1%	-	24%	24%	21%	1%
AgSh	13%	23%	1%	1%	-	32%	28%	1%
AgSs	13%	23%	1%	1%	32%	-	28%	1%
RgLs	13%	22%	1%	1%	31%	31%	-	1%
C	10%	18%	1%	1%	24%	24%	21%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Observed - Expected (Weighted Random Succession)

Succeeding Lithofacies / *Original Lithofacies*

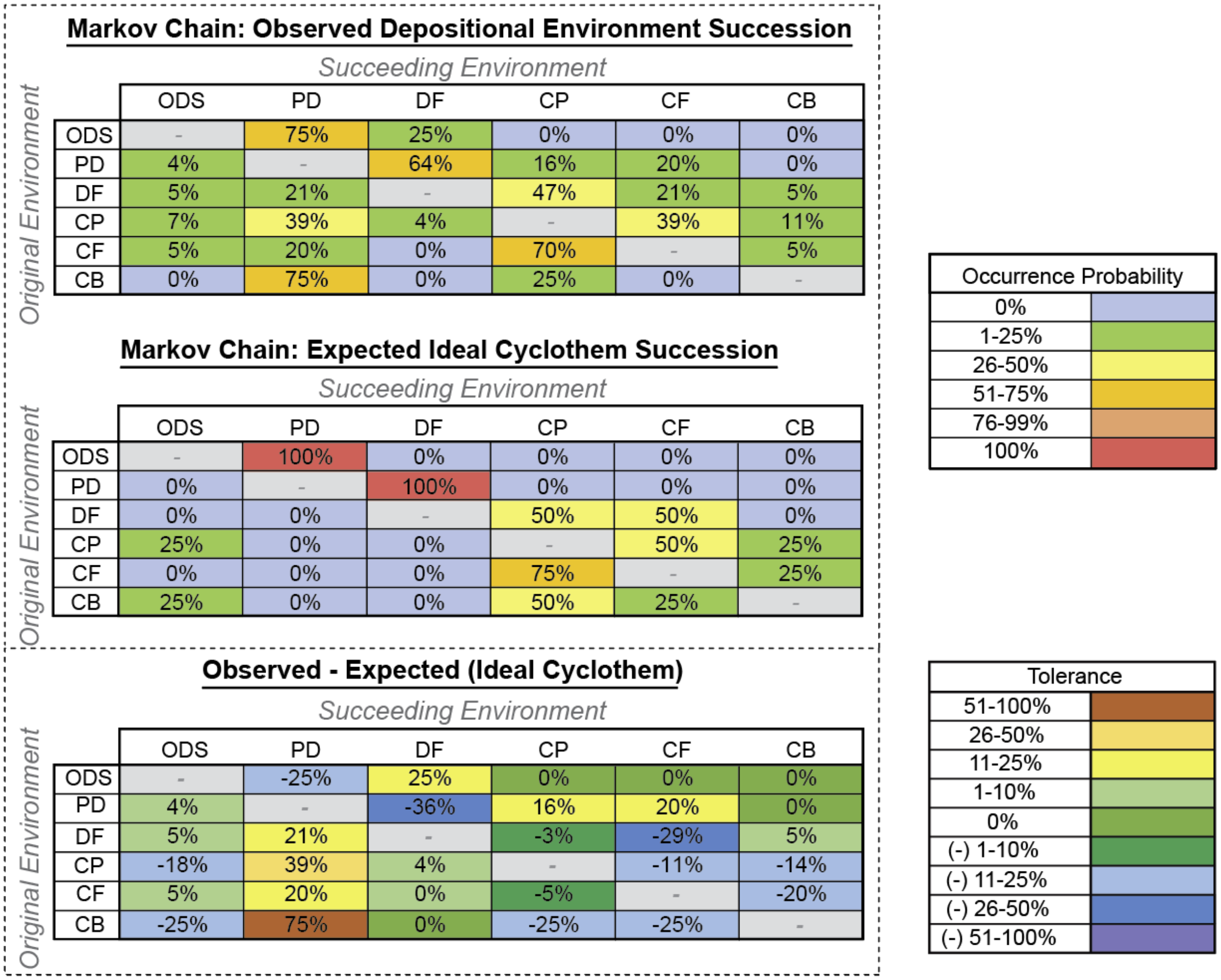
	RSh	PgShS	PgSs	PgLs	AgSh	AgSs	RgLs	C
RSh	-	47%	-1%	-1%	-27%	-16%	-1%	0%
PgShS	13%	-	5%	5%	-10%	2%	-12%	0%
PgSs	-10%	-18%	-	-1%	76%	-24%	-21%	0%
PgLs	-10%	-18%	-1%	-	-24%	76%	-21%	0%
AgSh	-13%	-18%	-1%	-1%	-	18%	13%	5%
AgSs	-8%	-9%	-1%	-1%	23%	-	-1%	0%
RgLs	9%	0%	-1%	-1%	-3%	-3%	-	0%
C	-10%	-18%	-1%	-1%	76%	-24%	-21%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 39. Markov chain probability matrices for the Campbell Trust 1-15 well comparing observed transitional probabilities of lithofacies types with probabilities expected for a random system weighted by lithofacies occurrence frequency. Successions of severely underrepresented units are shown in gray.

Markov chain analysis of depositional environments in the Burks 1-31 well show several predictable associations, which include: oxygen-deficient shelf deposits and carbonate bank deposits succeeded by prodelta deposits (75% probability), succession of prodelta deposits by delta front deposits (64% probability), and succession of channel fill deposits by coastal plain deposits (70% probability) (Figure 40). Other notable transitions include succession of delta font deposits by coastal plain deposits and coastal plain succession by prodelta or channel fill deposits (39 to 47% probability of occurrence). Succession by prodelta deposits occurred more often than expected. Whereas prodelta deposits were only expected to succeed oxygen-deficient shelf deposits, results show they were equally likely to succeed a carbonate bank, and they succeeded delta front, coastal plain, and channel fill deposits in 20-39% of occurrences. Many successions also occurred less than expected in the Burks 1-31 well. Delta front deposits succeeded prodelta deposits 36% less than anticipated, and channel fill deposits succeeded delta front deposits 29% less.

The Campbell Trust 1-15 well also shows high successive probabilities between certain depositional environments: oxygen-deficient shelf deposits are always succeeded by prodelta deposits, whereas succession of prodelta deposits by delta front deposits and succession of delta front and channel fill deposits by coastal plain deposits occur at relatively high probabilities of 50-54% (Figure 41). The succession of coastal plain deposits by carbonate bank deposits is substantially higher in the Campbell Trust well (60% probability) than in the Burks 1-31 well (11% probability). Major differences from the ideal cyclothem include a lack of succession of prodelta deposits by delta front deposits (47% less than expected), and higher than expected succession of carbonate bank deposits by prodelta deposits and coastal plain deposits by carbonate bank deposits (33-35% more probable than expected). Although depositional environments in the Burks and Campbell Trust wells show more intimate relationships than most of those observed in rock types or lithofacies, predictability is still limited by lateral variation of facies, as well as local juxtaposition of what may appear to be disparate depositional environments.



Markov Chain: Observed Depositional Environment Succession

Succeeding Environment (columns); *Original Environment* (rows)

	ODS	PD	DF	CP	CF	CB
ODS	-	75%	25%	0%	0%	0%
PD	4%	-	64%	16%	20%	0%
DF	5%	21%	-	47%	21%	5%
CP	7%	39%	4%	-	39%	11%
CF	5%	20%	0%	70%	-	5%
CB	0%	75%	0%	25%	0%	-

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Environment (columns); *Original Environment* (rows)

	ODS	PD	DF	CP	CF	CB
ODS	-	100%	0%	0%	0%	0%
PD	0%	-	100%	0%	0%	0%
DF	0%	0%	-	50%	50%	0%
CP	25%	0%	0%	-	50%	25%
CF	0%	0%	0%	75%	-	25%
CB	25%	0%	0%	50%	25%	-

Observed - Expected (Ideal Cyclothem)

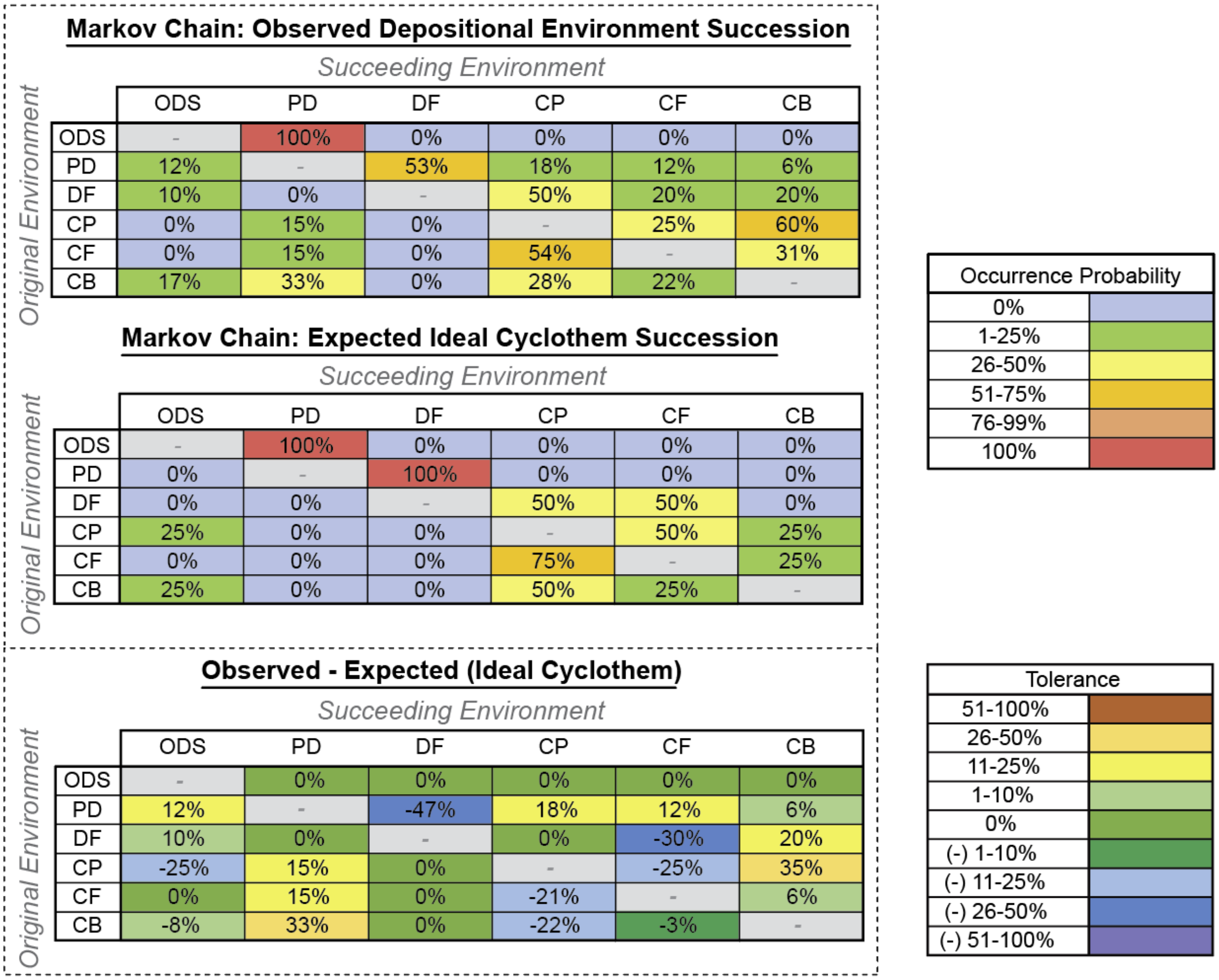
Succeeding Environment (columns); *Original Environment* (rows)

	ODS	PD	DF	CP	CF	CB
ODS	-	-25%	25%	0%	0%	0%
PD	4%	-	-36%	16%	20%	0%
DF	5%	21%	-	-3%	-29%	5%
CP	-18%	39%	4%	-	-11%	-14%
CF	5%	20%	0%	-5%	-	-20%
CB	-25%	75%	0%	-25%	-25%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟧
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 40. Markov chain probability matrices for the Burks 1-31 well showing observed transitional probabilities of depositional environment relative to probabilities expected for an ideal Anadarko Basin cyclothem. (ODS = oxygen-deficient shelf, PD = prodelta, DF = delta front, CP = coastal plain, CF = channel fill CB = carbonate bank).



Markov Chain: Observed Depositional Environment Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	100%	0%	0%	0%	0%
PD	12%	-	53%	18%	12%	6%
DF	10%	0%	-	50%	20%	20%
CP	0%	15%	0%	-	25%	60%
CF	0%	15%	0%	54%	-	31%
CB	17%	33%	0%	28%	22%	-

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	100%	0%	0%	0%	0%
PD	0%	-	100%	0%	0%	0%
DF	0%	0%	-	50%	50%	0%
CP	25%	0%	0%	-	50%	25%
CF	0%	0%	0%	75%	-	25%
CB	25%	0%	0%	50%	25%	-

Observed - Expected (Ideal Cyclothem)

Succeeding Environment

Original Environment

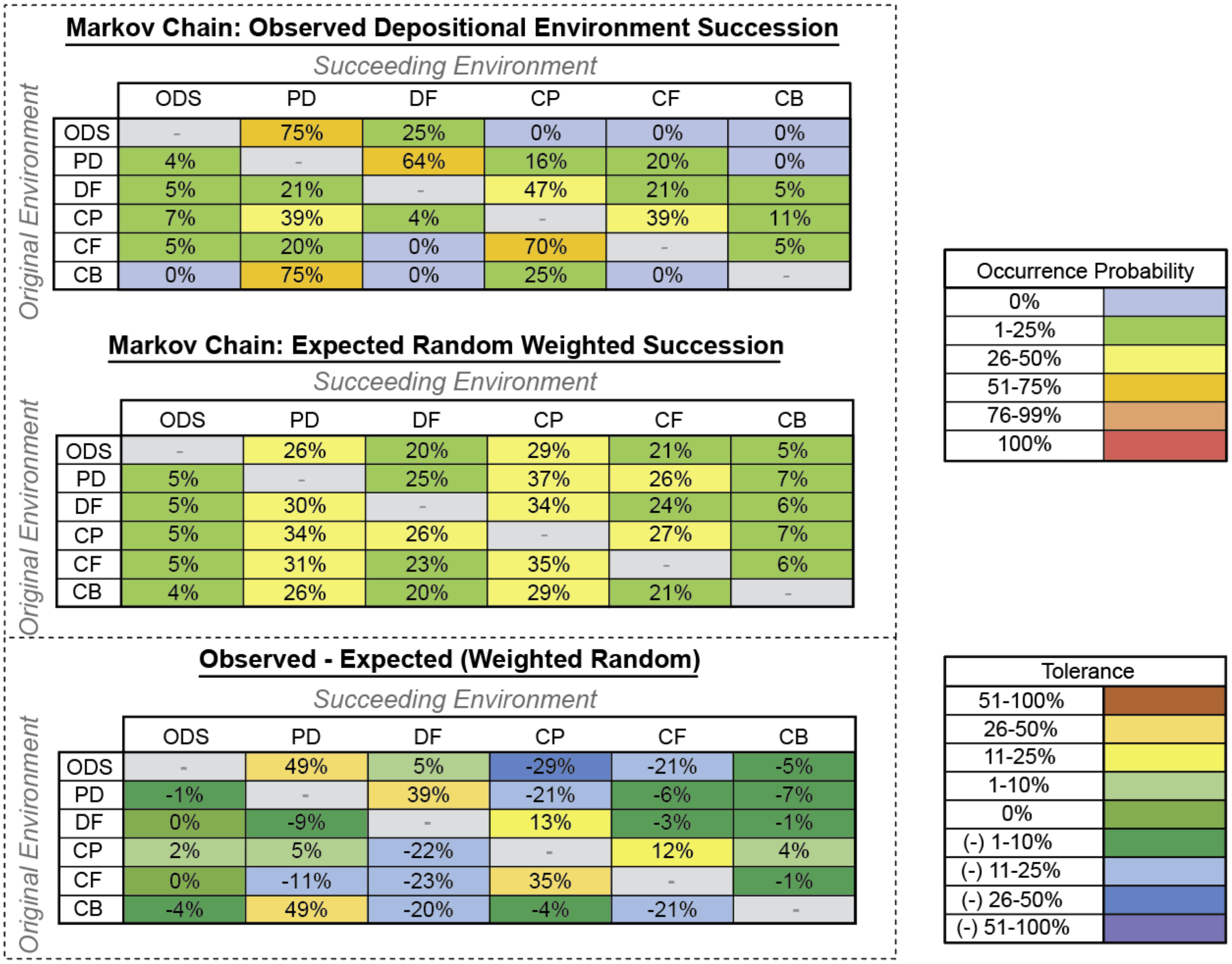
	ODS	PD	DF	CP	CF	CB
ODS	-	0%	0%	0%	0%	0%
PD	12%	-	-47%	18%	12%	6%
DF	10%	0%	-	0%	-30%	20%
CP	-25%	15%	0%	-	-25%	35%
CF	0%	15%	0%	-21%	-	6%
CB	-8%	33%	0%	-22%	-3%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 41. Markov chain probability matrices for the Campbell 1-15 well displaying observed transitional probabilities of depositional environment in comparison with probabilities expected for an ideal Anadarko Basin cyclothem.

Comparison of the Burks 1-31 and Campbell Trust 1-15 wells with a random model weighted by lithologic occurrence shows that many transitional probabilities of depositional environment are nonrandom. In the Burks 1-31, transitional probabilities that involve succession by prodelta, delta front, coastal plain, and channel fill deposits deviate considerably from those expected for a random system (Figure 42). The strongest non-random transitions are in the succession of oxygen-deficient shelf and carbonate bank deposits by prodelta deposits, occurring 49% of the time. Most successions of depositional environment are nonrandom in the Campbell Trust well (Figure 43). In particular, succession of oxygen-deficient shelf deposits by prodelta deposits occurs at 74% greater probability than expected in a random system. Succession of coastal plain by carbonate bank is also higher than expected at random (53%).



Markov Chain: Observed Depositional Environment Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	75%	25%	0%	0%	0%
PD	4%	-	64%	16%	20%	0%
DF	5%	21%	-	47%	21%	5%
CP	7%	39%	4%	-	39%	11%
CF	5%	20%	0%	70%	-	5%
CB	0%	75%	0%	25%	0%	-

Markov Chain: Expected Random Weighted Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	26%	20%	29%	21%	5%
PD	5%	-	25%	37%	26%	7%
DF	5%	30%	-	34%	24%	6%
CP	5%	34%	26%	-	27%	7%
CF	5%	31%	23%	35%	-	6%
CB	4%	26%	20%	29%	21%	-

Observed - Expected (Weighted Random)

Succeeding Environment

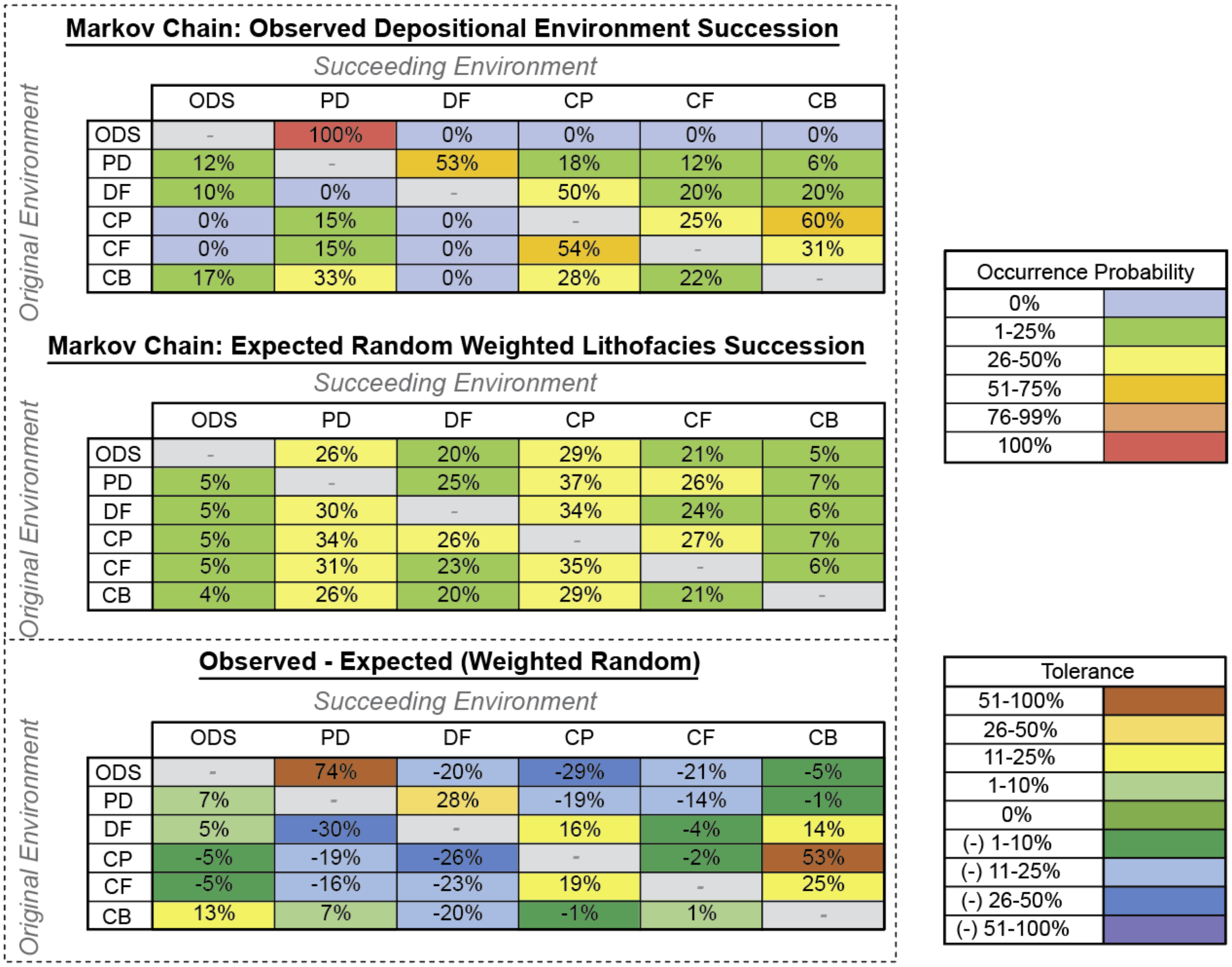
Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	49%	5%	-29%	-21%	-5%
PD	-1%	-	39%	-21%	-6%	-7%
DF	0%	-9%	-	13%	-3%	-1%
CP	2%	5%	-22%	-	12%	4%
CF	0%	-11%	-23%	35%	-	-1%
CB	-4%	49%	-20%	-4%	-21%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 42. Markov chain probability matrices for the Burks 1-31 well showing observed transitional probabilities of depositional environments in comparison to probabilities expected for a random system weighted by frequency occurrence of units.



Markov Chain: Observed Depositional Environment Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	100%	0%	0%	0%	0%
PD	12%	-	53%	18%	12%	6%
DF	10%	0%	-	50%	20%	20%
CP	0%	15%	0%	-	25%	60%
CF	0%	15%	0%	54%	-	31%
CB	17%	33%	0%	28%	22%	-

Markov Chain: Expected Random Weighted Lithofacies Succession

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	26%	20%	29%	21%	5%
PD	5%	-	25%	37%	26%	7%
DF	5%	30%	-	34%	24%	6%
CP	5%	34%	26%	-	27%	7%
CF	5%	31%	23%	35%	-	6%
CB	4%	26%	20%	29%	21%	-

Observed - Expected (Weighted Random)

Succeeding Environment

Original Environment

	ODS	PD	DF	CP	CF	CB
ODS	-	74%	-20%	-29%	-21%	-5%
PD	7%	-	28%	-19%	-14%	-1%
DF	5%	-30%	-	16%	-4%	14%
CP	-5%	-19%	-26%	-	-2%	53%
CF	-5%	-16%	-23%	19%	-	25%
CB	13%	7%	-20%	-1%	1%	-

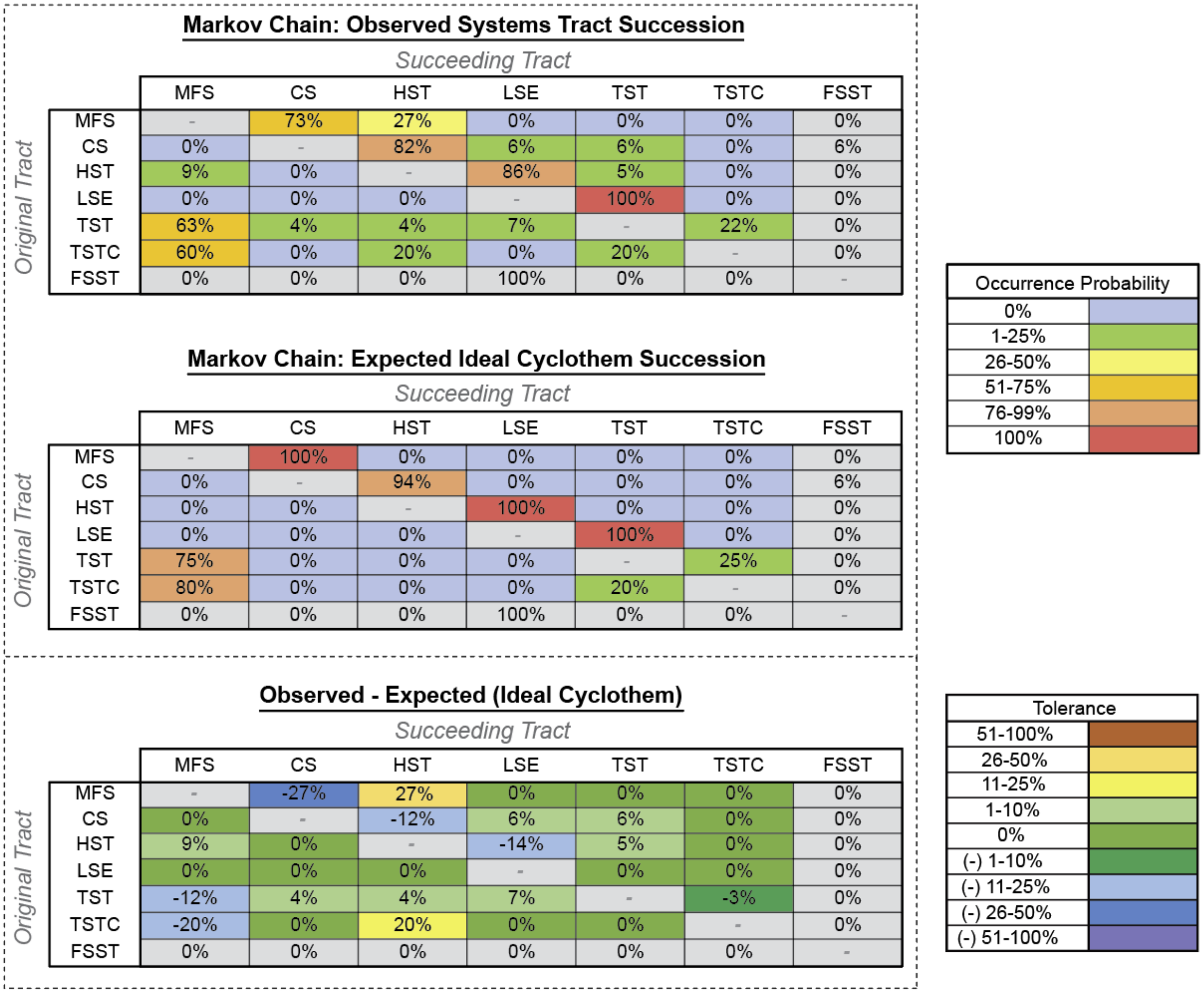
Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 43. Markov chain probability matrices for the Campbell 1-15 well showing observed transitional probabilities of depositional environment types in comparison to probabilities expected for a random system weighted by frequency occurrence of units.

Analysis of the Burks 1-31 and Campbell 1-15 wells shows a high degree of association between key sequence stratigraphic surfaces and systems tracts. In the Burks well, condensed sections transition to a highstand systems with a probability of 82%, and every occurrence of a lowstand surface of erosion is succeeded by a transgressive systems tract (Figure 44). In the Campbell Trust well, condensed sections and marine flooding surfaces are succeeded by the highstand systems tract in 67% of occurrences (Figure 45). Transgressive systems tracts succeed a lowstand surfaces of erosion with a transitional probability of 83%. Moreover, the carbonate transgressive systems tract in the Campbell Trust well is always succeeded by a marine flooding surface.

These probabilities indicate that successive sequence stratigraphic elements have a high degree of predictability, as would be expected considering the inherent interdependence among stratigraphic surfaces, systems tracts, and relative sea level change. The strongest relationship in the sequence stratigraphic framework is the transition of the highstand systems tract to the lowstand surface of erosion, the lowstand surface of erosion to the transgressive systems tracts, and the transgressive systems tracts to the marine flooding surface. This recurring succession can be seen in detail in the cross sections (Plates 3, 4). However, a stochastic component continues to be present, even at the highest level of interpretation. The salient stochastic elements include variable development of condensed sections and development of the falling stage systems tract, in which forced regressions most commonly succeed highstand sedimentation and less commonly succeed the transgressive systems tract (e.g., Cottage Grove sandstone in cross-section A-A'; Plate 3).



Markov Chain: Observed Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	73%	27%	0%	0%	0%	0%
CS	0%	-	82%	6%	6%	0%	6%
HST	9%	0%	-	86%	5%	0%	0%
LSE	0%	0%	0%	-	100%	0%	0%
TST	63%	4%	4%	7%	-	22%	0%
TSTC	60%	0%	20%	0%	20%	-	0%
FSST	0%	0%	0%	100%	0%	0%	-

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	100%	0%	0%	0%	0%	0%
CS	0%	-	94%	0%	0%	0%	6%
HST	0%	0%	-	100%	0%	0%	0%
LSE	0%	0%	0%	-	100%	0%	0%
TST	75%	0%	0%	0%	-	25%	0%
TSTC	80%	0%	0%	0%	20%	-	0%
FSST	0%	0%	0%	100%	0%	0%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Observed - Expected (Ideal Cyclothem)

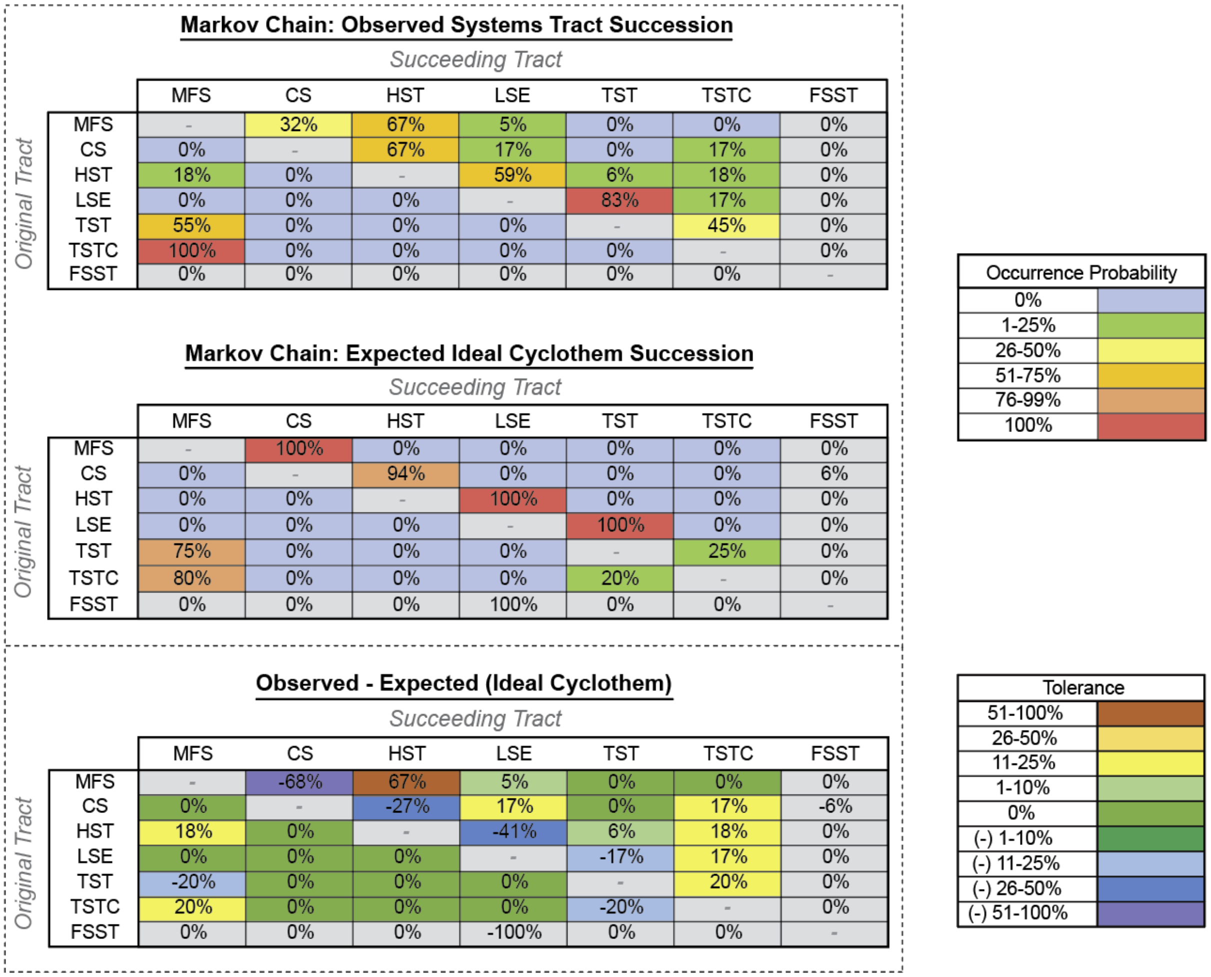
Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	-27%	27%	0%	0%	0%	0%
CS	0%	-	-12%	6%	6%	0%	0%
HST	9%	0%	-	-14%	5%	0%	0%
LSE	0%	0%	0%	-	0%	0%	0%
TST	-12%	4%	4%	7%	-	-3%	0%
TSTC	-20%	0%	20%	0%	0%	-	0%
FSST	0%	0%	0%	0%	0%	0%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 44. Markov chain probability matrices for the Burks 1-31 well exhibiting observed transitional probabilities of stratigraphic surfaces and systems tracts relative to probabilities expected for an ideal Anadarko Basin cyclothem (MFS = marine flooding surface, CS = condensed section, HST = highstand systems tract, LSE = lowstand surface of erosion, TST = transgressive systems tract, TSTC = carbonate transgressive systems tract, FSST = falling stage systems tract). Successions of severely underrepresented units are shown in gray.



Markov Chain: Observed Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	32%	67%	5%	0%	0%	0%
CS	0%	-	67%	17%	0%	17%	0%
HST	18%	0%	-	59%	6%	18%	0%
LSE	0%	0%	0%	-	83%	17%	0%
TST	55%	0%	0%	0%	-	45%	0%
TSTC	100%	0%	0%	0%	0%	-	0%
FSST	0%	0%	0%	0%	0%	0%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Markov Chain: Expected Ideal Cyclothem Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	100%	0%	0%	0%	0%	0%
CS	0%	-	94%	0%	0%	0%	6%
HST	0%	0%	-	100%	0%	0%	0%
LSE	0%	0%	0%	-	100%	0%	0%
TST	75%	0%	0%	0%	-	25%	0%
TSTC	80%	0%	0%	0%	20%	-	0%
FSST	0%	0%	0%	100%	0%	0%	-

Observed - Expected (Ideal Cyclothem)

Succeeding Tract

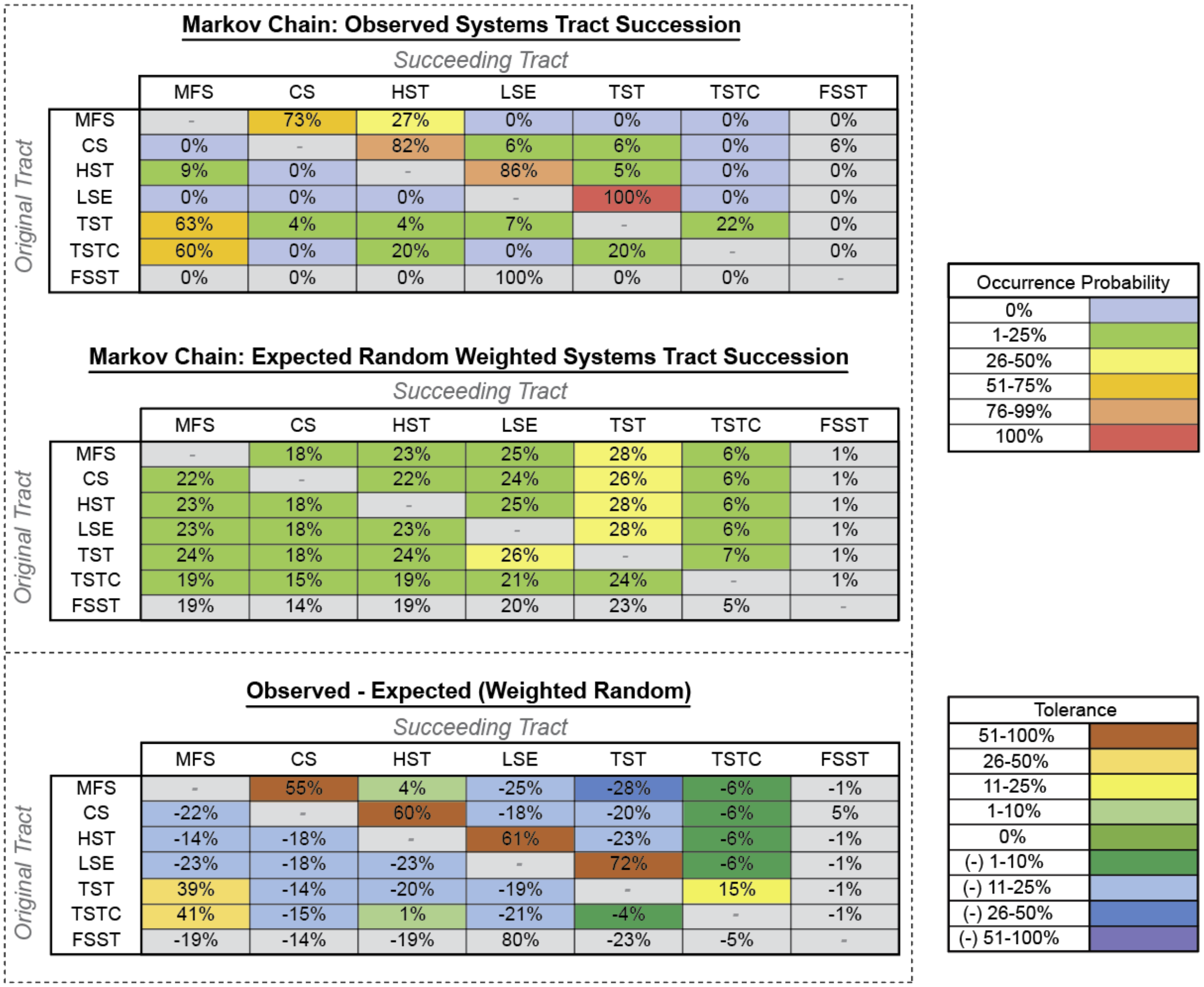
Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	-68%	67%	5%	0%	0%	0%
CS	0%	-	-27%	17%	0%	17%	-6%
HST	18%	0%	-	-41%	6%	18%	0%
LSE	0%	0%	0%	-	-17%	17%	0%
TST	-20%	0%	0%	0%	-	20%	0%
TSTC	20%	0%	0%	0%	-20%	-	0%
FSST	0%	0%	0%	-100%	0%	0%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 45. Markov chain probability matrices in the Campbell 1-15 well showing observed transitional probabilities of systems tracts compared to probabilities expected for an ideal Anadarko Basin cyclothem. The falling stage systems tract is absent from the Campbell Trust section. Successions of severely underrepresented units are shown in gray.

Sequence stratigraphic successions in the Burks 1-31 and Campbell Trust 1-15 wells are strongly nonrandom. Transitional probabilities of five sequence stratigraphic components in the Burks 1-31 well are 55% to 80% higher than expected for a random system weighted by frequency of occurrence (Figure 46). Seven transitions in the Campbell Trust 1-15 well are more than 25% more probable than expected in a weighted random system (Figure 47).



Markov Chain: Observed Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	73%	27%	0%	0%	0%	0%
CS	0%	-	82%	6%	6%	0%	6%
HST	9%	0%	-	86%	5%	0%	0%
LSE	0%	0%	0%	-	100%	0%	0%
TST	63%	4%	4%	7%	-	22%	0%
TSTC	60%	0%	20%	0%	20%	-	0%
FSST	0%	0%	0%	100%	0%	0%	-

Markov Chain: Expected Random Weighted Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	18%	23%	25%	28%	6%	1%
CS	22%	-	22%	24%	26%	6%	1%
HST	23%	18%	-	25%	28%	6%	1%
LSE	23%	18%	23%	-	28%	6%	1%
TST	24%	18%	24%	26%	-	7%	1%
TSTC	19%	15%	19%	21%	24%	-	1%
FSST	19%	14%	19%	20%	23%	5%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟧
76-99%	🟫
100%	🟥

Observed - Expected (Weighted Random)

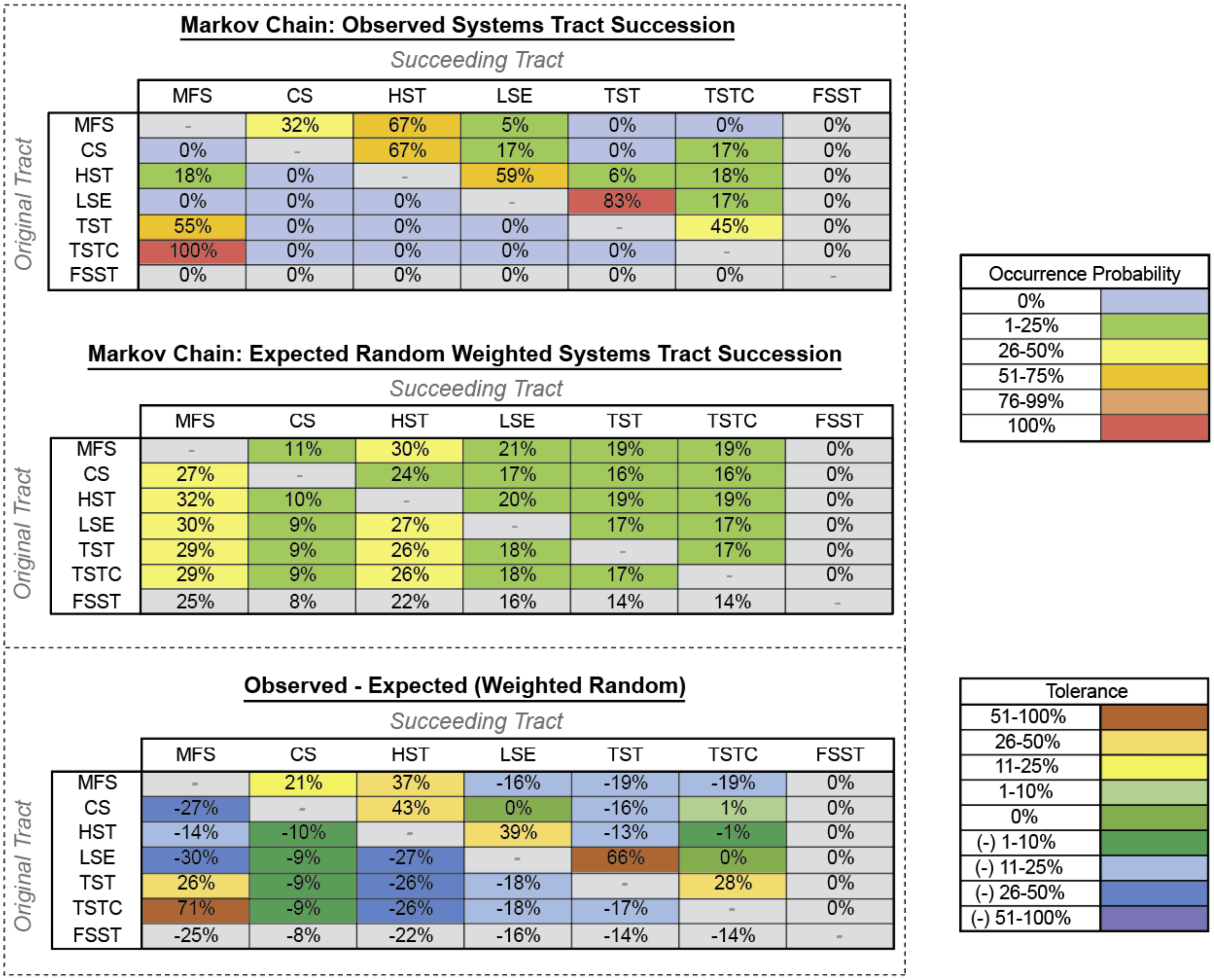
Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	55%	4%	-25%	-28%	-6%	-1%
CS	-22%	-	60%	-18%	-20%	-6%	5%
HST	-14%	-18%	-	61%	-23%	-6%	-1%
LSE	-23%	-18%	-23%	-	72%	-6%	-1%
TST	39%	-14%	-20%	-19%	-	15%	-1%
TSTC	41%	-15%	1%	-21%	-4%	-	-1%
FSST	-19%	-14%	-19%	80%	-23%	-5%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 46. Markov chain probability matrices for the Burks 1-31 well of observed transitional probabilities of systems tracts relative to probabilities expected for a random system weighted by frequency of occurrence of stratigraphic surfaces and systems tracts. Successions of severely underrepresented units are shown in gray.



Markov Chain: Observed Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	32%	67%	5%	0%	0%	0%
CS	0%	-	67%	17%	0%	17%	0%
HST	18%	0%	-	59%	6%	18%	0%
LSE	0%	0%	0%	-	83%	17%	0%
TST	55%	0%	0%	0%	-	45%	0%
TSTC	100%	0%	0%	0%	0%	-	0%
FSST	0%	0%	0%	0%	0%	0%	-

Markov Chain: Expected Random Weighted Systems Tract Succession

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	11%	30%	21%	19%	19%	0%
CS	27%	-	24%	17%	16%	16%	0%
HST	32%	10%	-	20%	19%	19%	0%
LSE	30%	9%	27%	-	17%	17%	0%
TST	29%	9%	26%	18%	-	17%	0%
TSTC	29%	9%	26%	18%	17%	-	0%
FSST	25%	8%	22%	16%	14%	14%	-

Occurrence Probability	
0%	🟦
1-25%	🟩
26-50%	🟨
51-75%	🟨
76-99%	🟧
100%	🟥

Observed - Expected (Weighted Random)

Succeeding Tract

Original Tract

	MFS	CS	HST	LSE	TST	TSTC	FSST
MFS	-	21%	37%	-16%	-19%	-19%	0%
CS	-27%	-	43%	0%	-16%	1%	0%
HST	-14%	-10%	-	39%	-13%	-1%	0%
LSE	-30%	-9%	-27%	-	66%	0%	0%
TST	26%	-9%	-26%	-18%	-	28%	0%
TSTC	71%	-9%	-26%	-18%	-17%	-	0%
FSST	-25%	-8%	-22%	-16%	-14%	-14%	-

Tolerance	
51-100%	🟫
26-50%	🟨
11-25%	🟨
1-10%	🟩
0%	🟩
(-) 1-10%	🟩
(-) 11-25%	🟦
(-) 26-50%	🟦
(-) 51-100%	🟪

Figure 47. Markov chain probability matrices for the Campbell 1-15 well of observed transitional probabilities of systems tracts relative to probabilities expected for a random system weighted by occurrence frequency of stratigraphic components. Successions of severely underrepresented units are shown in gray.

Markov chain analysis of the Burks 1-31 and Campbell Trust 1-15 wells yielded varied results, although all relationships appear to be nonrandom and probabilistic. The strongest transitional association among rock types is a tendency for each rock type to be succeeded by shale. Lithofacies show a similar level of organization, and the clearest associations are succession radioactive shale by progradational shale-sandstone and intercalation of aggradational shale with aggradational sandstone and retrogradational limestone. Depositional environments have a higher degree of organization, with the strongest relationships being succession of oxygen-deficient shelf deposits by prodelta and the delta front deposits. Above the deltaic section, channel fill, coastal plain, and carbonate bank deposits have weak transitional associations, although carbonate bank deposits tend to be overlain by either oxygen-deficient shelf or prodelta deposits. By far, the highest degree of predictability exists at the sequence stratigraphic level, where successive stratigraphic surfaces and systems tracts commonly have transitional probabilities greater than 80%.

Recurrence frequencies of units in each level of observation and interpretation were investigated for modal recurrence interval amplitudes to test for cyclicity. In a simple theoretical model of an ideal cyclothem, unit recurrence intervals would be the same, or bimodal, depending on the model’s framework. In reality, some degree of noise is expected to be present; a dominant recurrence value of 2 is indicative of couplets, whereas a dominant unique value greater than two indicates cyclicity. Prominence of a given value is indicative of signal strength, and a broad range of values may represent a significant stochastic component. If units are not repeated in a prototypical cyclothem, then the modal recurrence will equal the number of units in the cycle.

Analysis of recurrence intervals of rock types in the Burks 1-31 well show shale, sandy shale, and sandstone have a modal recurrence interval of 2, demonstrating a strong tendency to form couplets (i.e., sedimentary rhythms) (Figure 48). Radioactive shale and limestone have no clear peak recurrence frequency, reflecting the sporadic occurrence of these rock types in this section. In the Campbell Trust 1-15 well, shale, sandy shale, sandstone, and limestone have a modal recurrence interval of 2, and radioactive shale again has no clear recurrence interval (Figure 49). In both wells, signal strength is highest in shale by a significant margin, with a frequency of 100 in the Burks well and a frequency of 57 in the Campbell Trust. This shows that the most common relationship is rock types forming couplets with shale. The exponential decline of recurrence interval for most rock types is a clear indication of stochastic control of sedimentation. Based on this result, there is no indication of cyclic control of rock type distribution in the study interval.

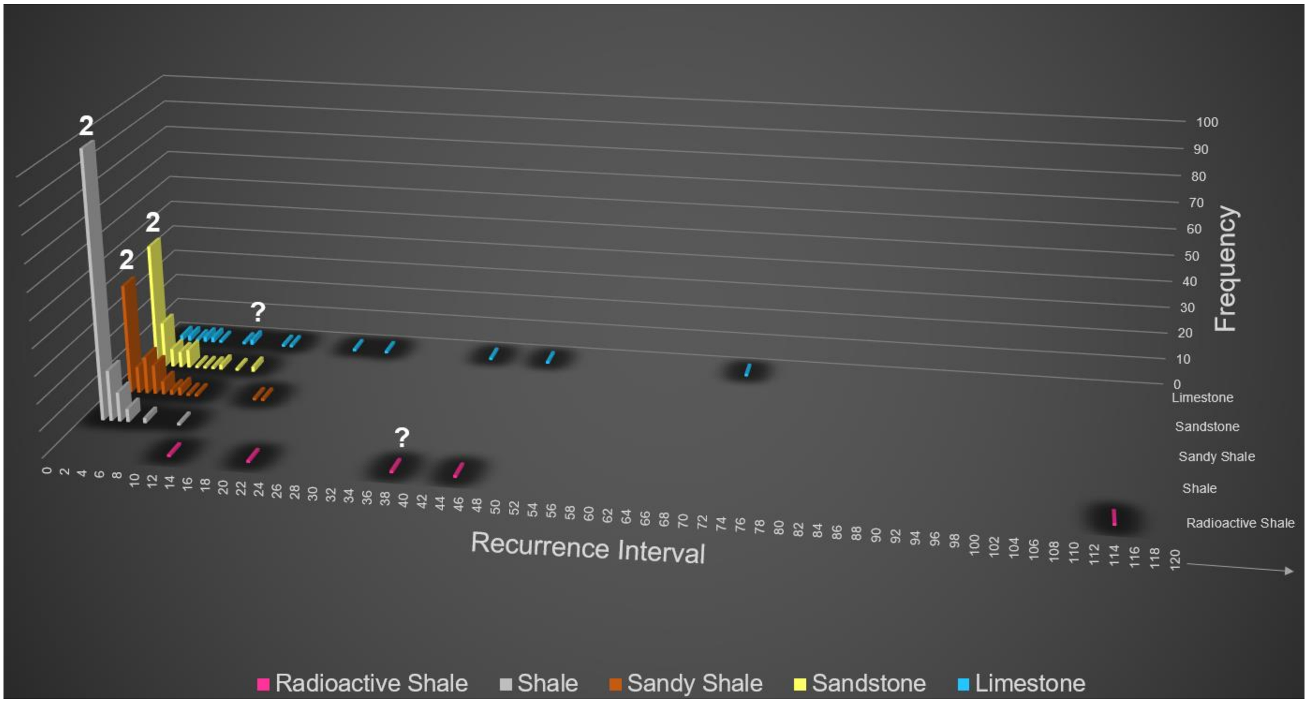


Figure 48. Recurrence interval frequencies for rock types in the Burks 1-31 well. Dominant modal recurrence intervals are given in white above the respective column.

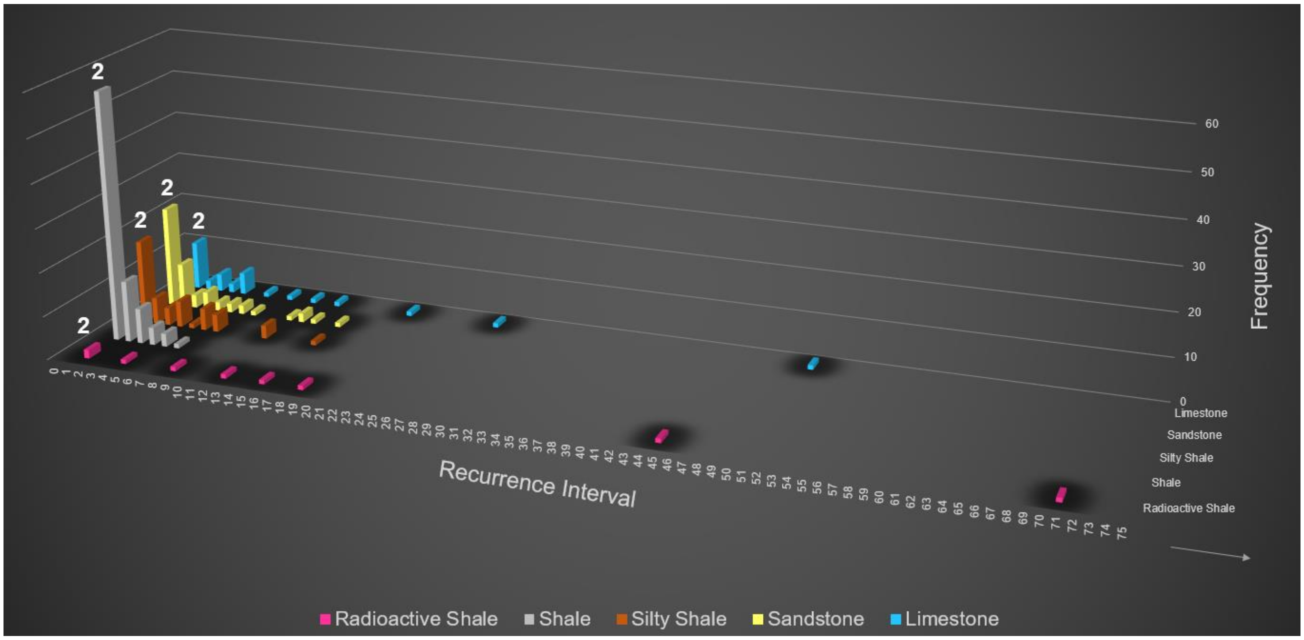


Figure 49. Recurrence interval frequencies for rock types in the Campbell Trust 1-15. Modal recurrence intervals, if distinct, are listed in white above the respective column.

In the Burks 1-31 well, variation exists in modal recurrence intervals for most lithofacies, ranging from a weakly dominant signal of 2 in aggradational units, to a weak signal of 5 in radioactive shale (Figure 50). Progradational sandstone and progradational shale-sandstone exhibit a weak signal of 4, while modal recurrence intervals for limestone are indistinguishable. All lithofacies in the Campbell Trust 1-15 well display a dominant modal recurrence interval of 2, although peaks of 2 and 4 exist for retrogradational limestone (Figure 51). Though the tendency of lithofacies members to form couplets is prevalent in both wells, recurrence intervals of 3 and 4 are more common for lithofacies than for rock types. Sampling of lithofacies is highly uneven, and it appears that several of the recurrence interval distributions are undersampled. Where a significant population was sampled, however, recurrence interval frequency tends to decrease progressively above a value of 2, indicating stochastic, rather than cyclic, control of lithofacies recurrence interval resembling that observed for the major rock types.

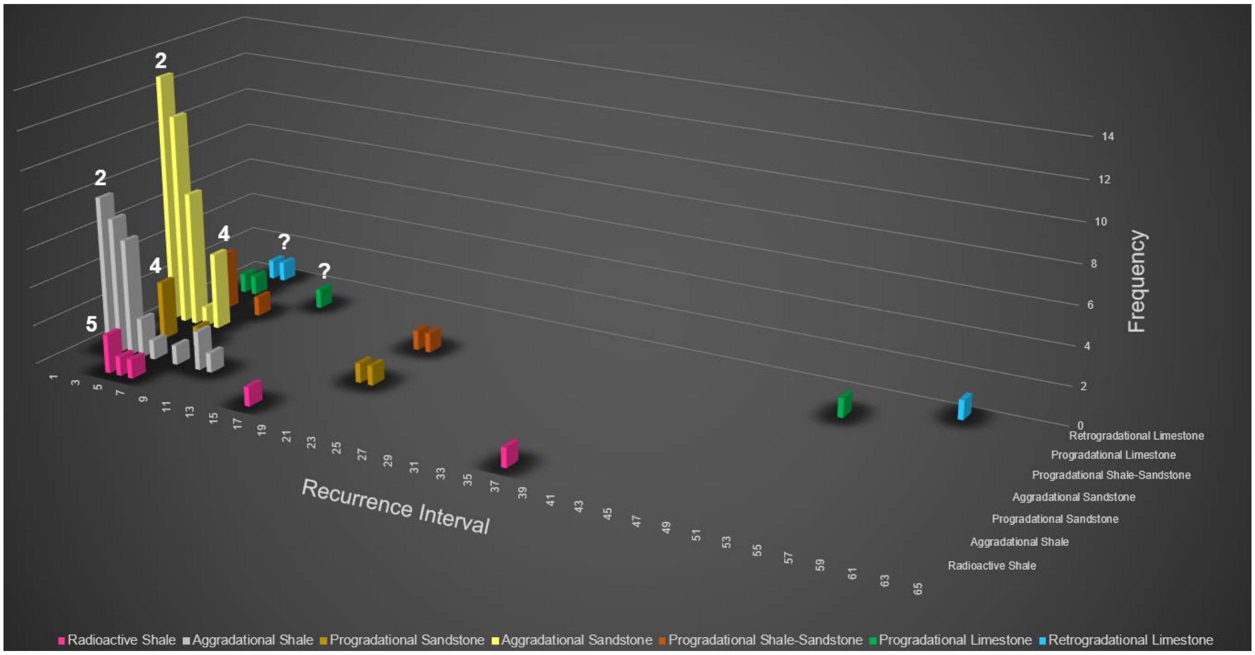


Figure 50. Recurrence interval frequencies for lithofacies in the Burks 1-31 well.

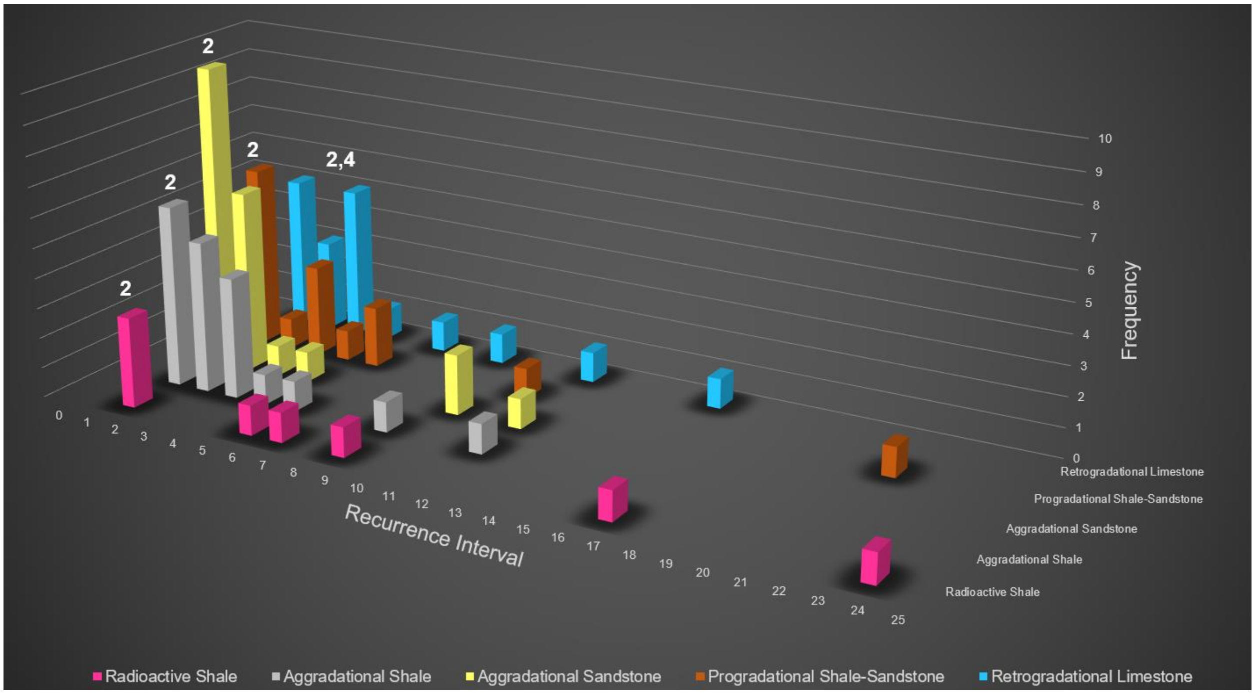


Figure 51. Recurrence interval frequencies for lithofacies in the Campbell Trust 1-15 well.

At the interpretive level of depositional environment, a general increase in modal recurrence intervals is observed, and recurrence intervals are highly variable. Environments in the Burks 1-31 well display a range of peak recurrence frequencies, with prodelta deposits showing a recurrence tendency of 3-4, delta front from 2-6, and coastal plain from 2-3 (Figure 52). Channel fill sandstone shows a weak modal recurrence interval of 4 with a well-developed, positively skewed tail. Oxygen-deficient shelf and carbonate bank environments lack a distinct peak recurrence interval, likely due to undersampling. Modal recurrence intervals also vary in the Campbell Trust 1-15 well (Figure 53). A dominant recurrence interval of 3 is observed in prodelta and carbonate bank environments, which also have the highest signal strength. Coastal plain and channel fill deposits exhibit a weak modal recurrence interval of 4. Peak recurrence intervals are indistinguishable for oxygen-deficient shelf and delta front environments. Though a single modal recurrence interval is not shared between all environments, a noticeable cluster in the frequency distribution is centered around recurrence intervals of 2 to 6 in both the Burks and Campbell Trust wells. Yet, skewed tails in the distribution of most environments show that cyclicity is not apparent.

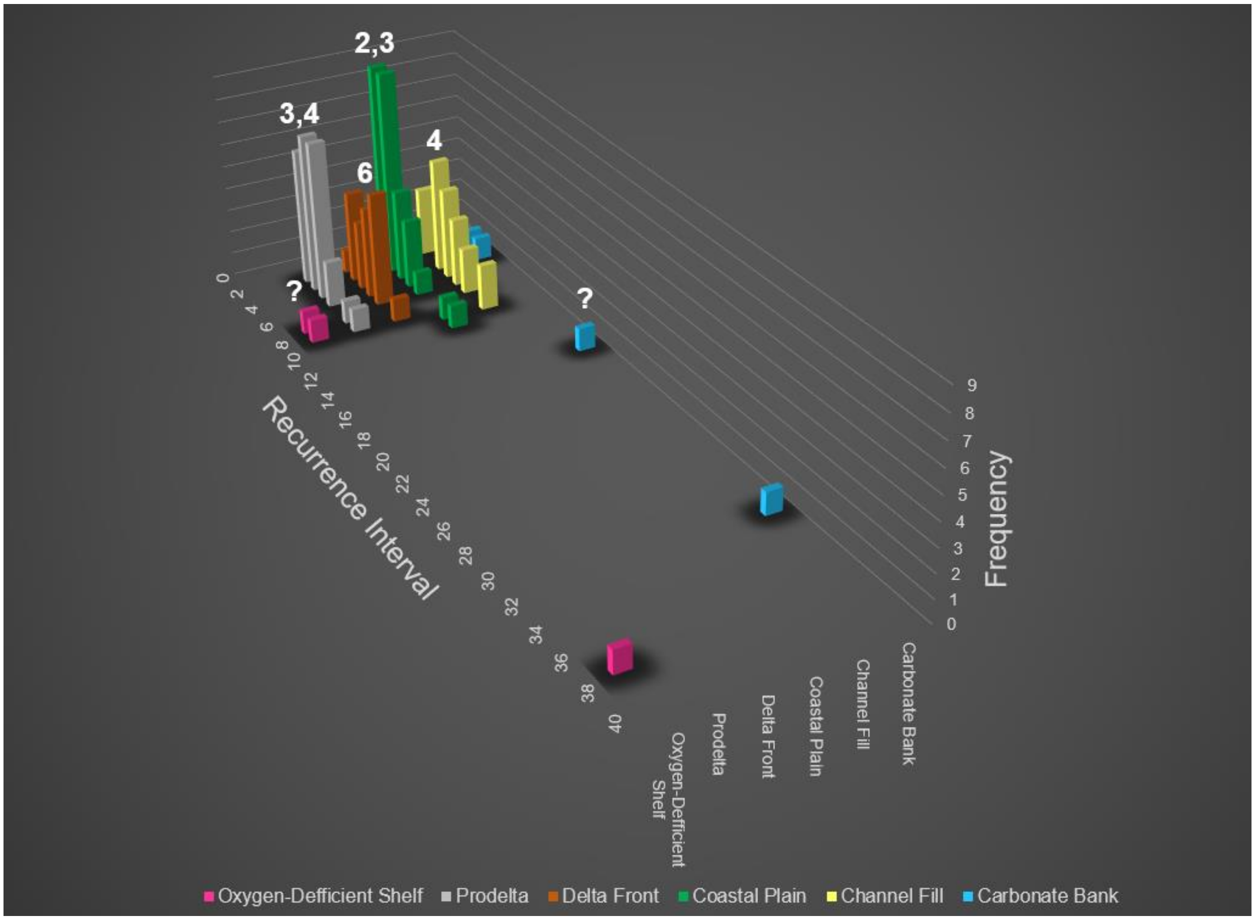


Figure 52. Recurrence interval frequencies for depositional environment in the Burks 1-31 well.

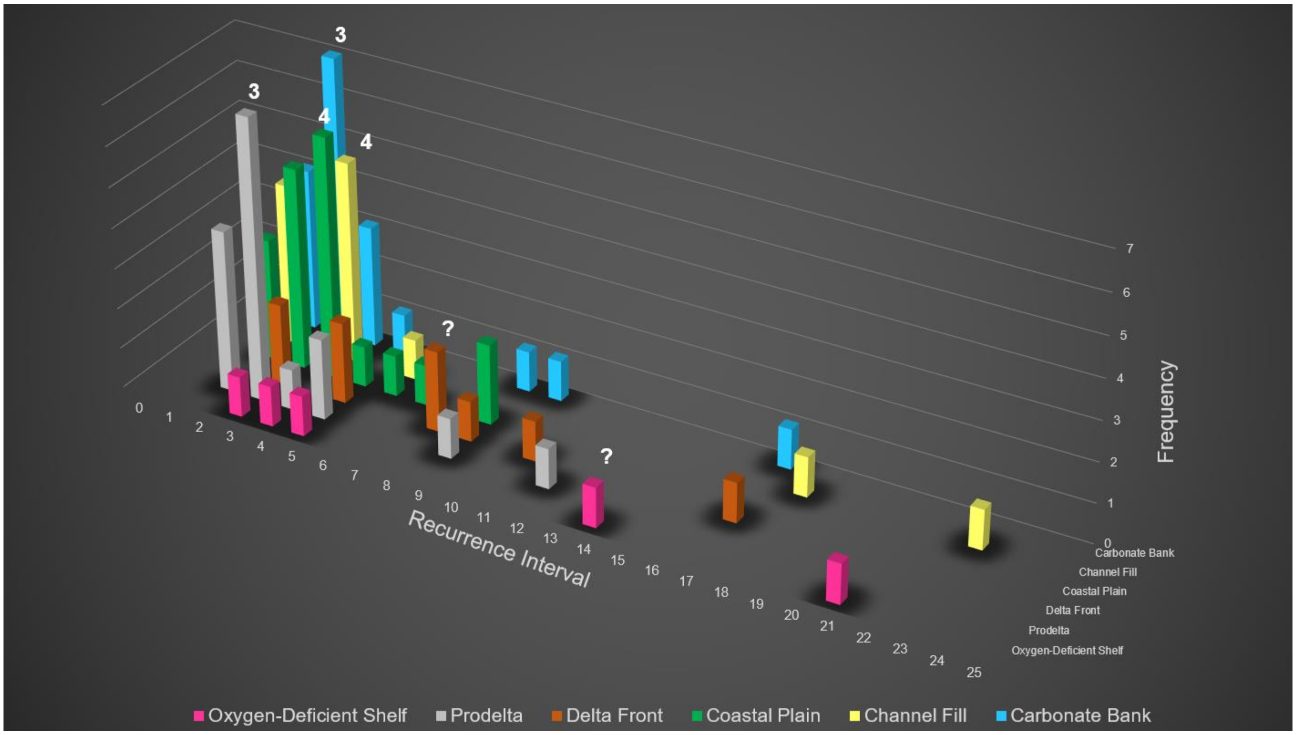


Figure 53. Recurrence interval frequencies for depositional environments in the Campbell Trust 1-15 well.

At the sequence stratigraphic level, a strong signal in a modal recurrence interval of 5 is manifested in the Burks 1-31 well (Figure 54). The carbonate transgressive systems tract is an exception, displaying no clear pattern of recurrence in this well. Most stratigraphic tracts and surfaces in the Campbell 1-15 well show a modal recurrence interval of 4 (i.e., the marine flooding surface, highstand systems tract, lowstand surface of erosion, and the transgressive systems tract) (Figure 55). Exceptions are the carbonate transgressive systems tract, with no obvious peak recurrence interval, and the marine flooding surface with a peak recurrence interval of 9. For both the Burks and Campbell Trust wells, highest signal strength is observed in the highstand systems tracts (12 and 7, respectively). The falling stage systems tract is not included due to no recurrences in the wells analyzed. In general, prevalent modal recurrence interval of 5 is observed for sequence stratigraphic surfaces and systems tracts in the Burks 1-31 well, and 4 in the Campbell Trust 1-31 well. The difference in modal recurrence value between the two wells relates to a comparative lack of condensed section deposits in the Campbell Trust well. Although consistency and signal strength in modal recurrence intervals of sequence stratigraphic components reflect a high degree of stratal order and cyclicity, the long tails present in each distribution clearly indicate stochastic control. Moreover, the wide range of recurrence intervals in both wells suggests most unit occurrences are still probabilistic, and the pattern in the Burks well defines a log normal population distribution.

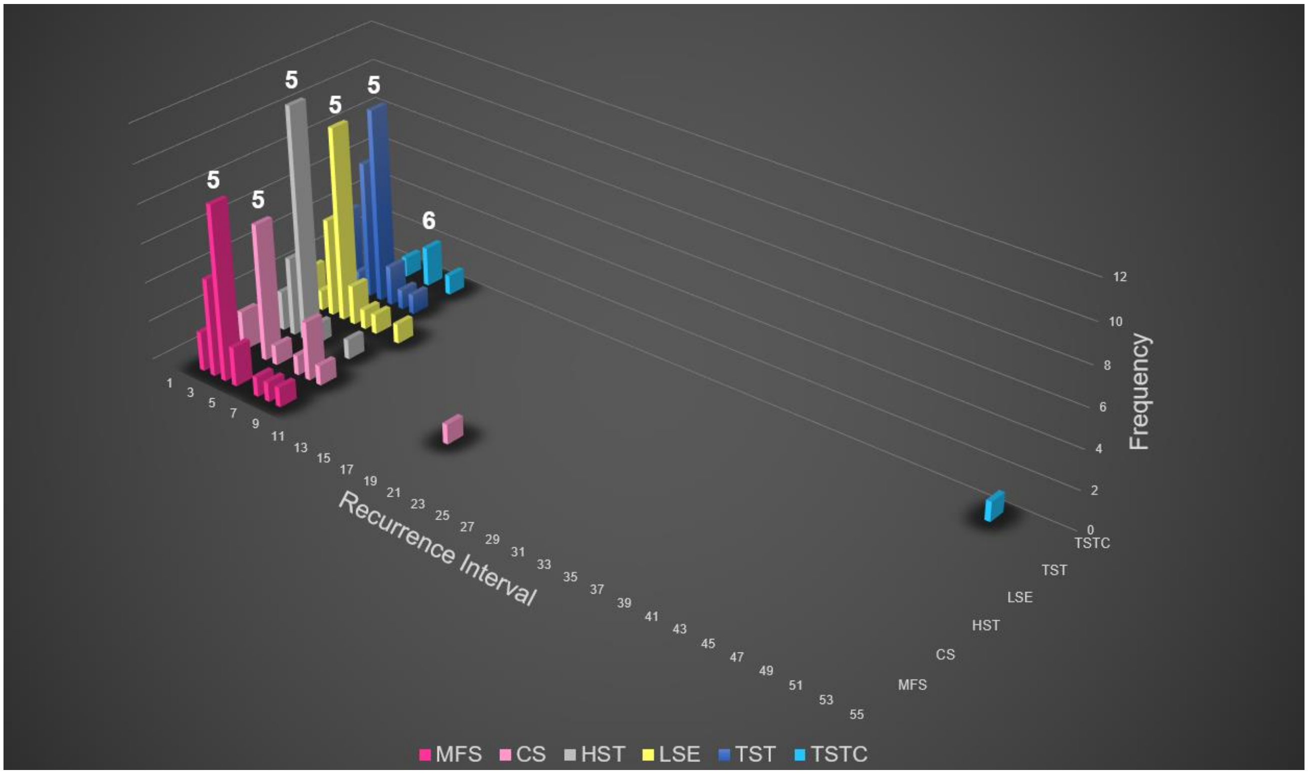


Figure 54. Recurrence interval frequencies for stratigraphic surfaces and systems tracts for the Burks 1-31 well.

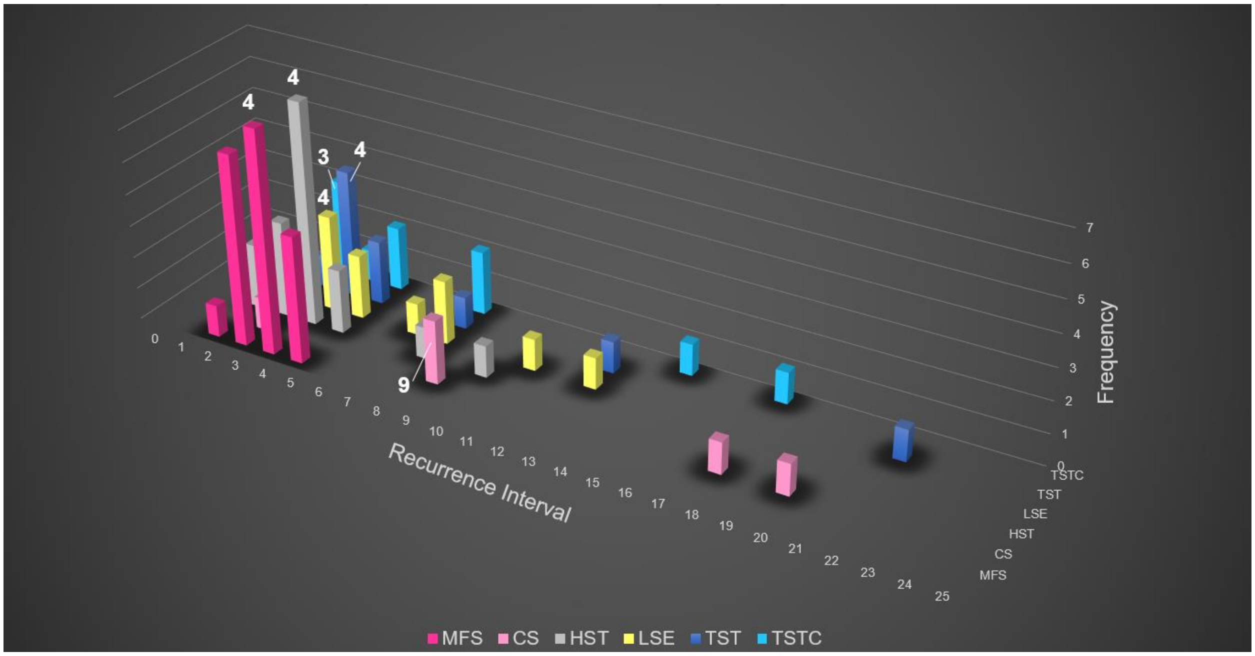


Figure 55. Recurrence interval frequencies for systems tracts in the Campbell Trust 1-15.

In the Burks 1-31 well, the modal recurrence interval is 5 for all stratigraphic components shown when the carbonate transgressive systems tract is unified with other transgressive deposits (Figure 56). The unified transgressive system tract in the Burks yields a high signal strength of 12, matching that of the highstand systems tract. In the Campbell Trust 1-31 well, modal recurrence interval remains 4 for all but the condensed section when the carbonate and clastic transgressive systems tracts are treated as a single unit (Figure 57). Collectively, sequence stratigraphic interpretation yields the highest level of stratigraphic order observed in this study. A cyclicity of 5 in the Burks well and 4 in the Campbell Trust well are apparent. However, even at the highest interpretive level, log-normal distributions of sequence stratigraphic components show positively skewed tails, demonstrating that the controls on surface and systems tract recurrences are fundamentally stochastic.

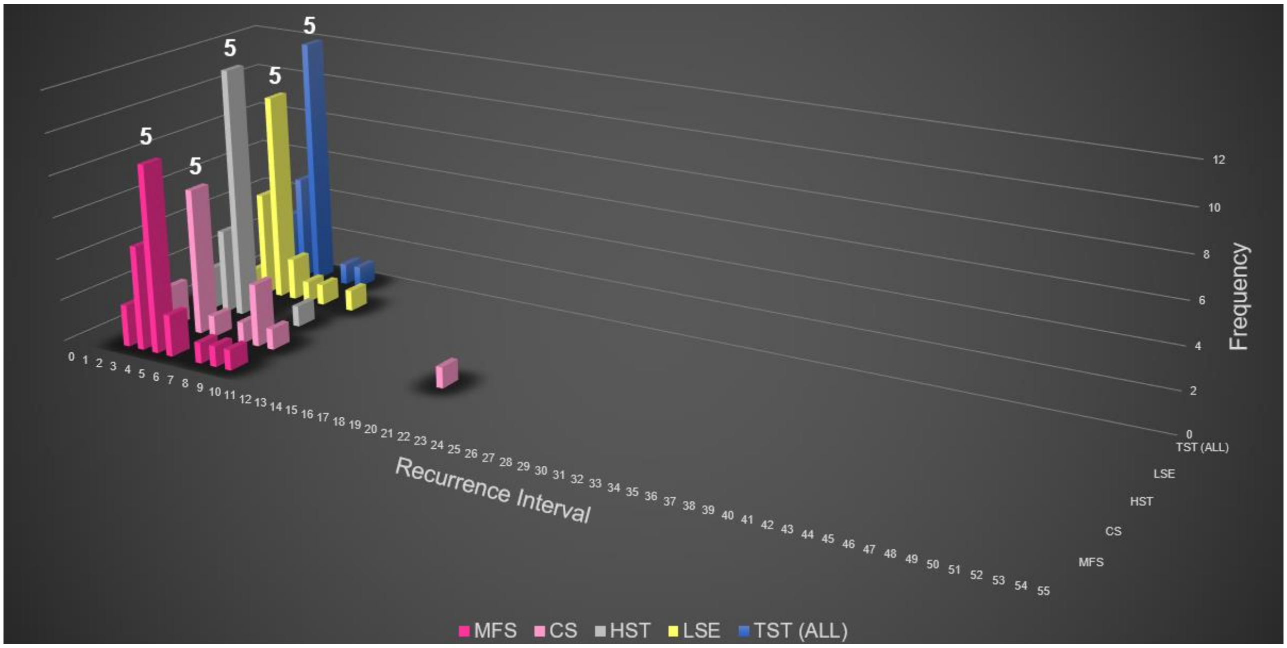


Figure 56. Recurrence interval frequencies for systems tracts and stratigraphic surfaces in the Burks 1-31 well. The falling stage systems tract is not included due to no recurrences observed in the stratigraphic succession.

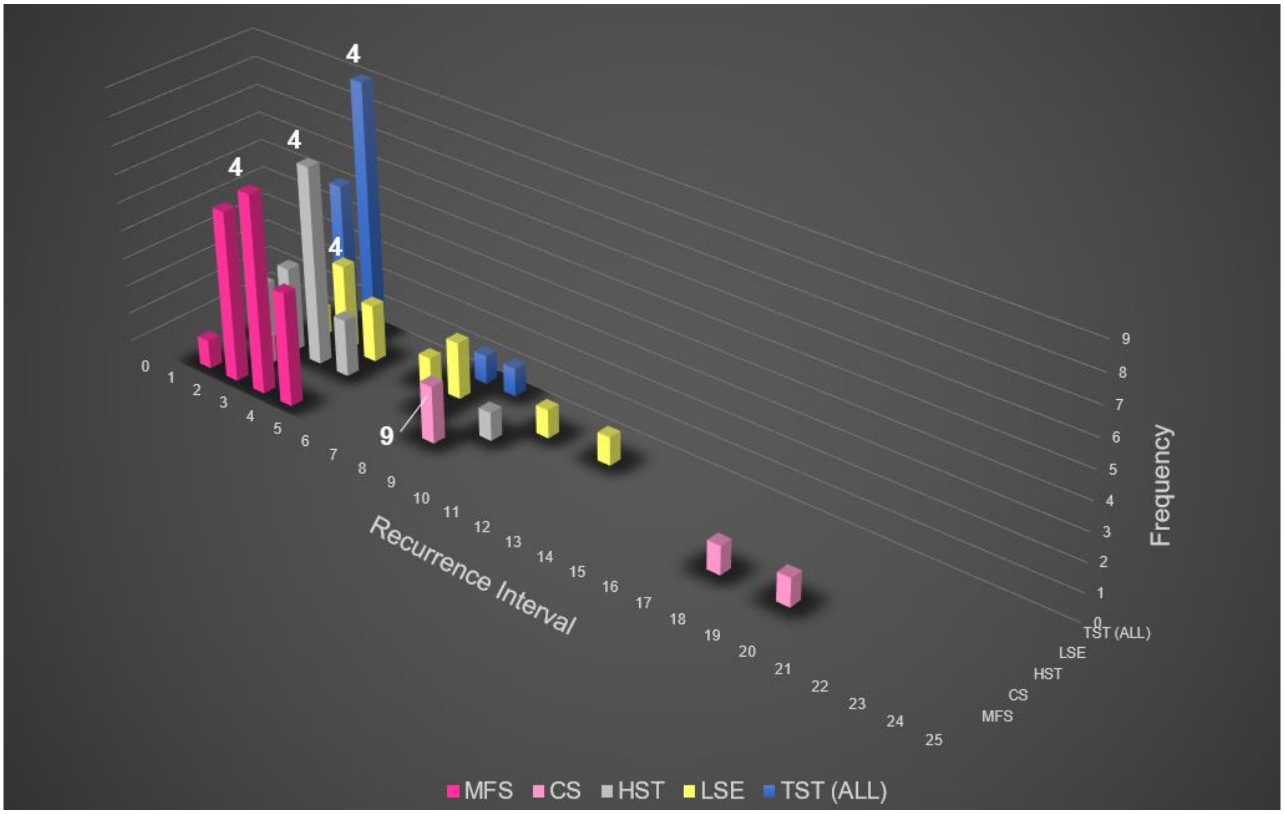


Figure 57. Recurrence interval frequencies for systems tracts in the Campbell Trust 1-15.

Genetic sequences (i.e., flooding surface-bounded depositional units) in both wells were plotted to detect a changes in sequence thickness through time. Results for the Burks 1-31 and the Campbell Trust 1-15 wells (Figure 58) show that sequence thickness can vary by location. However, three primary trends are observed in the data. Sequences 1-8 and 15-26 represent two thrusting episodes. They are interrupted by a period of relaxation, or isostatic rebound. This shows that tectonic influence in the basin was variable, as was sediment supply. In the Burks and Campbell Trust wells, 14 sequences are developed in the Missourian Series (upper Kasimovian), which represents a timespan of about 2.0 m.y. (Gradstein et al., 2012). The Kasimovian Stage spans 3.3 ±0.2 m.y., and the top of the Missourian section corresponds with the top of the Kasimovian. However, it is important to note that the age of the base of the Missourian is not as well constrained as the base of the Kasimovian. Estimating geochronologic uncertainty at the base of the Missourian at ±0.5 m.y. suggests that the 14 genetic sequences in the Missourian Series were deposited in 1.4-2.6 m.y. This indicates that genetic sequences in the Middle to Upper Pennsylvanian in the Anadarko Basin represent an average duration of 100 to 190 k.y. Hence, the average duration of genetic sequences in the study area corresponds with changes of relative sea level in the Milankovitch eccentricity band (95-410 k.y.) and appear most compatible with short eccentricity (95-125 k.y.).

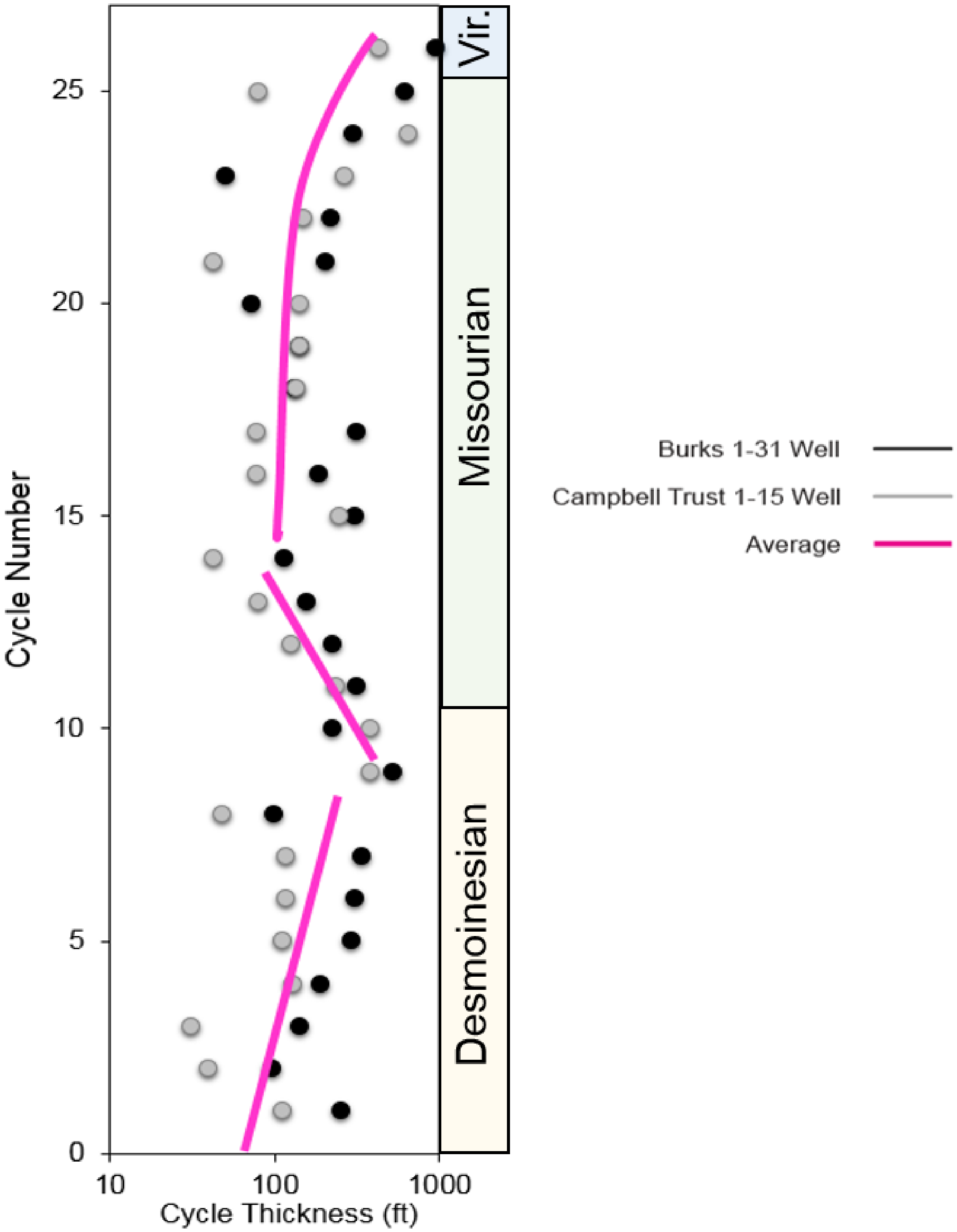


Figure 58. Sequence thickness plotted against order of occurrence in the Burks 1-31 and Campbell Trust 1-15 wells.

CHAPTER V

DISCUSSION

The concept of Pennsylvanian cyclicity has only been recognized in southwestern Oklahoma on a qualitative level by previous workers (Rascoe, 1979; Heckel, 1980). Wilkinson et al.'s (2003) work on Illinois basin cyclothems casts doubt on the concept of determinism in sedimentary succession, and questions the very concept of the Pennsylvanian cyclothem by making a case that Pennsylvanian cycles in the Illinois Basin are poorly ordered at best. They demonstrated that the typical Illinois basin cyclothem contains only 2 to 4 of the 10 lithologic units in the classic ideal succession of Weller (1930). Moreover, only 2 units, underclay and coal, show a high degree of transitional dependency, and the only other significant transitional dependency is succession of sandstone by shale (Wilkinson et al. 2003). This inspired the current study of Pennsylvanian architecture in the southern Anadarko Basin to see if what appeared to be a cyclic succession based on casual observation could be substantiated by numerical analysis.

Results are variable and depend strongly on the level of observation and interpretation. In the final analysis, it is clear that frequency of occurrence, thickness-frequency distribution, and recurrence intervals are nonrandom variables that can be characterized by stochastic functions. Analysis shows that shale is the most abundant rock type in the Middle and Upper Pennsylvanian of the southern Anadarko Basin, followed by sandstone and sandy shale. Together, shale, sandstone and sandy shale constitute 86% of all rock type occurrences. Radioactive shale is limited in occurrence throughout the study interval. Each well contains an average of only 8, irregularly spaced, radioactive shale units. The lack of radioactive shale at anticipated intervals suggests that marine flooding events were not always accompanied by anoxic to dysoxic, deep marine conditions (e.g., Heckel, 1977; Piper and Calvert, 2009). Watney (1995) noted that in some cases, inconspicuous condensed sections are marked by only a “thin phosphatic and skeletal lag deposit,” which would be difficult to detect in geophysical logs. Coal is the rarest rock type observed in the section, which points to a lack of preservation or inadequate thickness to detect in well logs.

Limestone distribution is variable among wells. The cumulative carbonate thickness of 384 ft in the Campbell Trust well is more than 4 times that observed in the Burks well. The differences in location of the two wells in the basin reflects asymmetry of subsidence rate relative to absolute sea level variation, which would affect the timing and magnitude of relative sea level change, as well as sediment accommodation and the distribution of facies and depositional environments (Jervey, 1992). Over a distance of 26 miles between the wells, it is possible that carbonate growth in the Burks could not keep up with the relatively higher subsidence rate, or its position resulted in increased disturbance from clastic influx which would inhibit carbonate development. The appearance of the large carbonate bank on the eastern ends of both cross sections (west edge of range 6, Plates 1, 2), suggests a north-south orientation of the paleo-shelf of the basin and infers that the study area straddled the eastern edge of the basin towards the end of the Missourian.

The greatest transitional probability for any rock type was succession of radioactive shale by shale (79%). In fact, each of the five highest transitional probabilities involved various rock types (radioactive shale, sandy shale, sandstone, limestone and coal) being succeeded by shale. The average probability of any rock type transitioning to shale is 62%. This is significantly higher than the sixth highest transitional probability, which was exhibited by shale to sandy shale at a probability of only 41%. The data highlight a primary recurring theme for the fundamental building blocks of the system – the rock types that can be diagnosed in geophysical well logs tend to form couplets with shale. The highest transitional probability between two non-shale lithologies was succession of sandy shale to sandstone at only 33%. The statistical analysis of rock occurrence, frequency, thickness, and succession negates any possibility of deterministic order in sedimentary cycles at the lithologic level. Lithologic order does exist as nonrandom associations of succeeding rock types, and all of these relationships can be characterized by stochastic criteria.

This study tested for order at three additional levels of observation and interpretation not considered by Wilkinson et al. (2003) in their evaluation of the Illinois Basin: lithofacies, depositional environments, and sequence stratigraphy. Lithofacies were defined to identify key genetic elements of the Anadarko succession, specifically progradational (coarsening-upward) facies associated with deltaic sedimentation and aggradational-retrogradational facies (blocky to fining-upward) associated with coastal and carbonate bank facies. Aggradational sandstone, aggradational shale, and progradational shale-sandstone are the most abundant lithofacies with a combined probability of occurrence of 73%. Retrogradational limestone is relatively rare in the Burks 1-31 well (3.3%) and is much more common in the Campbell Trust 1-15 (21%). Carbonates show a tendency to succeed aggradational units and progradational shale-sandstone The most meaningful associations of lithofacies included succession of aggradational shale by aggradational sandstone (55%), succession of aggradational sandstone by aggradational shale (54%), and succession of progradational shale-sandstone by aggradational sandstone (44%). The high probabilities of succession between shale and sandstone lithofacies again show that shale couplets dominate at a fundamental level of observation. As was displayed by rock types, many lithofacies relationships are certainly nonrandom, but results still indicate a high degree of stochasticity in lithofacies transitions.

Depositional environments showed a much more even distribution of occurrence than either rock type or lithofacies. Though the oxygen-deficient shelf environment was underrepresented (6% of occurrences), the coastal plain, carbonate bank, prodelta, channel fill, and delta front deposits exhibited a range in occurrence probability of only 12%. The coastal plain was the most common depositional environment with a 26% occurrence probability, followed by prodelta (22%) and channel fill deposits (18%). Whereas the carbonate bank was second least common in the Burks 1-31 well, it was second most common in the Campbell Trust 1-15, showing that paleogeographic conditions along the basin slope were highly variable by location. Many associations between depositional environments had high transitional probabilities; oxygen deficient shelf succeeded by prodelta (88%), channel fill succeeded by coastal plain (62%), prodelta succeeded by delta front (59%) and carbonate bank succeeded by prodelta (54%). Relationships exhibiting over 50% probability are compelling evidence for non-randomness, and the strongest associations represent basic depositional transitions among nearest-neighbor depositional environments, which would be expected in any sedimentary succession in which sedimentation was continuous or interrupted by relatively small magnitude erosional and sea-level forcing events.

At the sequence stratigraphic level, major stratigraphic surfaces and systems tracts exhibited the most even distribution of occurrences. The exception to this was the falling stage systems tract, which was underrepresented because it is not a common component of the genetic or depositional sequences in the study interval. Markov chain analysis shows that among all levels of classification, sequence stratigraphic components share some of the strongest relationships. The lowstand surface of erosion has a 92% likelihood of succession by the transgressive systems tract. Other high successions include the succession of the carbonate transgressive systems tract by a marine flooding surface (80%), succession of the condensed section by the highstand systems tract (74%) and succession of the highstand systems tract by the lowstand surface of erosion (73%). It is notable that the carbonate transgressive systems tract commonly succeeds the clastic transgressive systems tract in a given sequence. The frequent transition of the carbonate transgressive systems tract to the marine flooding surface is important, because it helps identify critical sequence boundaries that may lack a distinct radioactive shale.

The greatest predictability of any class considered in the study occurs at the sequence stratigraphic level of geologic interpretation, which also is the level most directly related to sea level change. Although many relationships have high transitional probabilities, a distinct stochastic component is still evident at the sequence stratigraphic level. One reason for an imperfect succession of sequence stratigraphic components is that disparate surfaces and systems tracts can locally be juxtaposed due to discontinuity of condensed sections, deep channel incision at lowstand, and forced regression during falling stage. By examining the cross sections (Plates 1-4), it is clear that all of these factors were active. Apparent discontinuity of some cycles on a spatial scale may be a result of channel incision and loss of stratigraphic resolution with decreasing sediment accommodation. And the high degree of sequence thickness that is apparent in the cross sections reflects a combination of variations in regional sediment accommodation, variations in sediment supply, which is thought to have originated from multiple remote sources (Rascoe, 1979), forced sea level change, episodic buildup of carbonate during transgression.

The ideal Anadarko Basin cyclothem (constructed prior to quantitative analysis in this study) fared much better than the ideal Illinois Basin cyclothem, with 74% of transitional probabilities observed falling within 10% of expectation. However, the strong stochastic control of sediment occurrence, thickness, and distribution limits the utility of this type of model for predicting relationships among rock types, lithofacies, or depositional environment. Without the aid of statistical analysis or a detailed characterization of lateral and vertical stratigraphic relationships, it is impossible to capture the range of lithologic, facies, depositional, and sequence stratigraphic variation in an idealized vertical column. Indeed, this study is a simple demonstration that the cyclic characteristic commonly attributed to the Pennsylvanian section from a qualitative standpoint is readily undermined by any application of statistical rigor.

Frequency of recurrence intervals plotted for units in each classification scheme aided in determination of cyclicity at different levels. Analysis shows that rock types have a strong tendency to form couplets. This implies rhythmic, rather than cyclic, association of units. As determined by the Markov chains, the highest degree of association is a couplet formed with shale. Thinly interbedded sand and shale, or sandy shale and shale, may hint at a high frequency of sea level change tied to obliquity and precession cycles (Soreghan, 1997). Position of the study location in the basin may also explain the common transition to and from shale. Whereas a low-relief, shoal-water shelf or peneplain are particularly sensitive to small changes of sea level, deep channels and offshore areas are less sensitive, but may also provide a higher resolution of subtle paleoclimatic and paleogeographic changes. Lithofacies demonstrate modal recurrence intervals that range from 2 to 5, showing a subtle preference for couplets. For depositional environments, modal recurrences intervals ranged considerably, which is indicative of the combined autocyclic and high-frequency allocyclic processes which would result in a heterogeneous sedimentary succession. Although there are distinctive successional associations at all levels of observation and interpretation, a dominant modal recurrence interval greater than 2 only emerged after sequence stratigraphic interpretation. Hence, it is difficult to call the succession of rock types, lithofacies, or depositional environments cyclic. Only after sequence stratigraphic interpretation did modal recurrence frequency indicate cyclicity. However, the modal recurrence frequency was 5 in the Burks well, whereas the frequency was 4 in the Campbell Trust well, demonstrating that cyclicity can be expressed differently in a pair of stratigraphic sections from the same region. In this case, the difference was related to a paucity of condensed sections in one of the wells.

Sea level is most likely responsible for much of the lateral and vertical heterogeneity in the Middle and Late Pennsylvanian strata in the Anadarko Basin. Klein (1974, 1996) suggested that paleobathymetry can be estimated by the thickness from the top of a maximum transgressive surface to the top of regressive facies. If so, water depth in the Anadarko Basin commonly varied by 100 to 200 ft, and possibly by as much as 800 ft in the Upper Missourian, which is compatible with some of the depth indicators identified in phosphatic radioactive shale units by Heckel (1977). But the vast majority of the bathymetry can be attributed to basin subsidence rather than sea level change. The depth of valley incision provides a proxy for eustatic sea level variation because incision requires a lowering of sea level that opposes basin subsidence (Pashin, 2004). Accordingly, eustatic sea level is estimated to have fluctuated by 20 to 100 ft, and in extreme cases by up to 200 ft in the Virgilian, as evidenced by the deepest channel fills. These values are comparable to Pleistocene sea level change. This is remarkable, considering that only a southern ice cap formed during the Carboniferous and Permian, and the geographic extent of that ice cap is a subject of debate (Isbell et al., 2003). Certainly tectonic activity such as flexural downwarping and associated subsidence of the basin had a strong influence on the accommodation space available, and change in relative sea level. Pashin (2004) discussed a variety of ways that Pennsylvanian cycles offer eustatic records of foreland basin subsidence. Sequences show two distinct trends of thrusting separated by a period of relaxation or isostatic rebound. This could suggest variable subsidence rate and indicated that the basin was experiencing tectonic forcing through the early Virgilian.

A typical genetic sequence in the Anadarko Basin consists of a marine flooding surface succeeded by a thick highstand tract, a lowstand surface of erosion, and a transgressive systems tract. The transgressive systems tract, which can consist of clastic or carbonate facies, are then abruptly terminated by the next major flooding surface. It is probable that this coincides with glacial eustatic sea level changes tied to the rapid thawing of Gondwanan glaciers followed by slow build-up as suggested by Heckel (1986). Figure 59, illustrating the behavior of sea level from late Pleistocene to Recent, represents a modern analog for the way sea-level likely behaved in the short eccentricity band during the Pennsylvanian. The figure shows that cyclicity of sea level occurs more than one frequency, reflecting interaction of short eccentricity cycles and higher frequency insolation events (i.e., incident solar radiation) associated with orbital obliquity and precession. In the Pleistocene, large, prominent rises of sea level mark each short eccentricity cycle. However, multiple smaller events of contrasting size occur between maxima and would be expected to result in a highly complex depositional history, particularly in a high accommodation setting like the Anadarko Basin.

In Figure 60, a sequence stratigraphic interpretation of Pleistocene sea level is offered in a way that relates to the Pennsylvanian sedimentary succession of the Anadarko Basin. Eustatic fall is expressed as subtle sea level rise, potentially resulting in multiple highstands and falling stages in a given cycle. This helps explain the heterogeneous nature of the Anadarko section. It also shows how the distinction between highstands and transgressions can be unclear after a large sea level peak. Each short eccentricity cycle has a peak followed by a shoulder, which is then followed by a long period of low sea level. In a high accommodation setting, that shoulder has a transgressive element. What appears as a eustatic lowstand approaching or following a maximum ice sheet advance becomes transgressive. There is little distinction between late highstand and transgression in the most recent short eccentricity cycle. It is also apparent that falling stage events can occur sporadically. Similar behavior can reasonably be expected of Pennsylvanian sea level cycles.

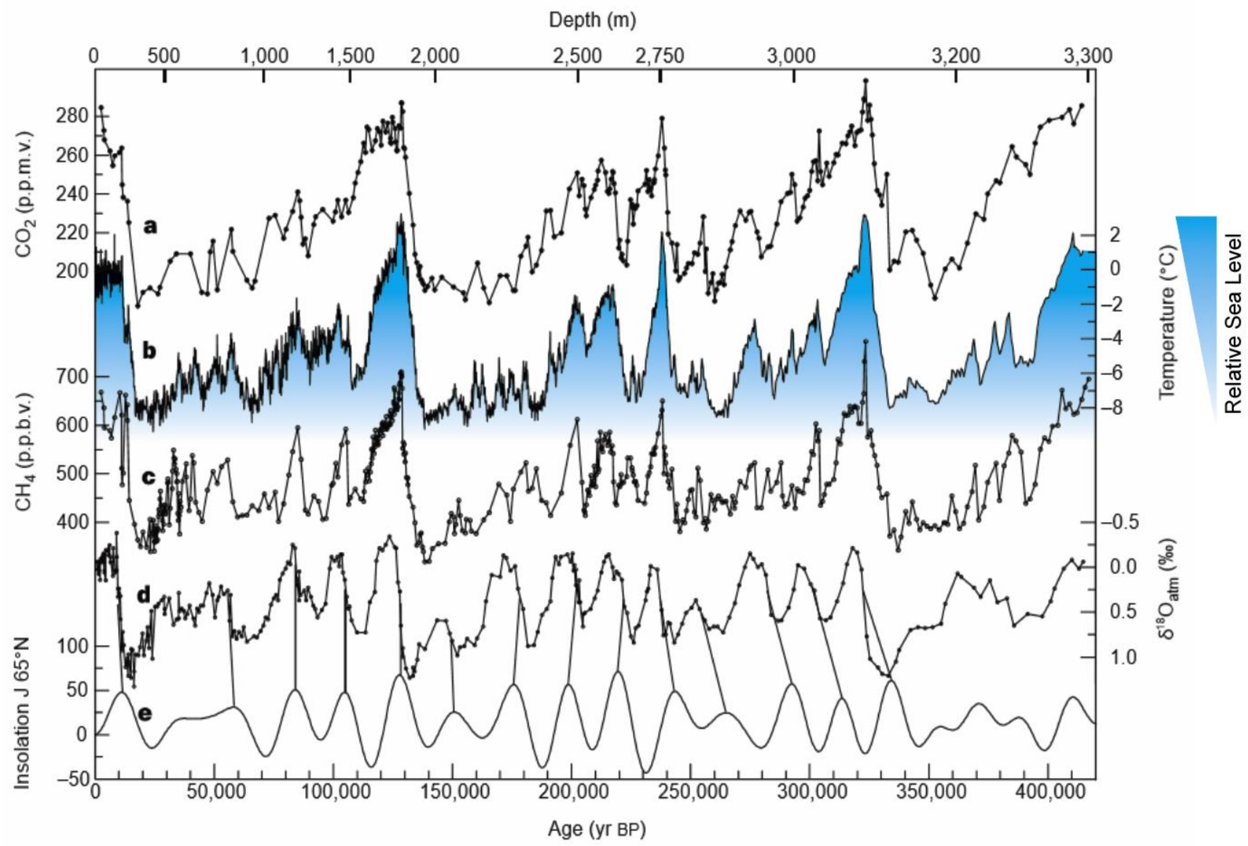


Figure 59. Trends in Pleistocene glaciation shown in data from the Vostok core (modified from Petit et al., 1999).

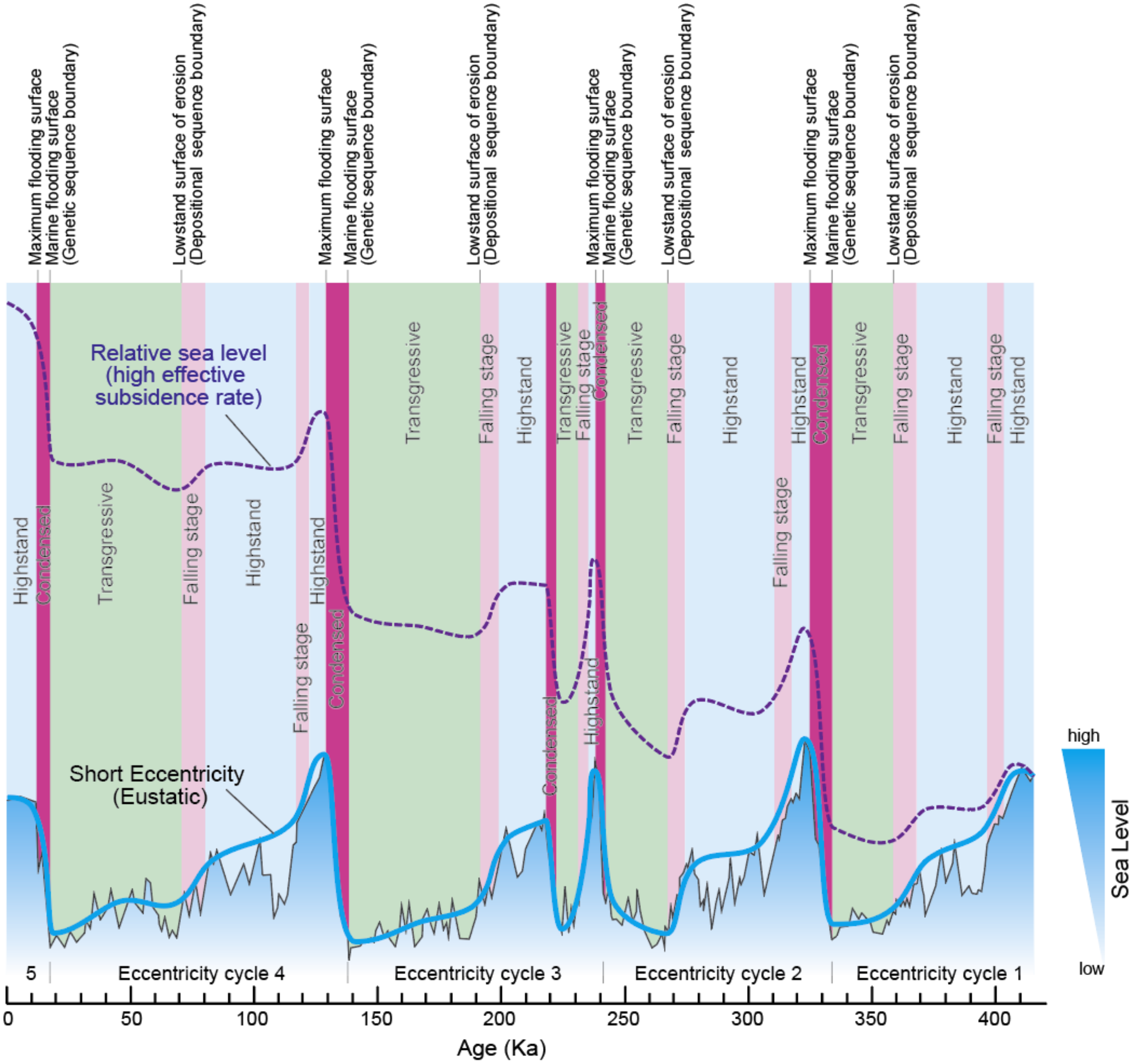


Figure 60. Sequence stratigraphic interpretation of sea level variation in the Pleistocene.

Cyclic sea level changes during the Pennsylvanian are thought to correspond with Milankovitch orbital parameters that drive oscillating climatic conditions (e.g., Heckel, 1980; Pashin, 2004). The duration of time represented by the number of sequences composing the geologic section can be used to estimate the periodicity of the system. A total of 14 cycles are identified in the study interval in the Missourian series of the Anadarko Basin, which represent a depositional timespan of 2 million years. This would implicate the deposition of approximately one cycle every 100 to 190 k.y., given the geochronologic uncertainty of the base of Missourian point of reference in the cross sections, suggesting a correlation with the short eccentricity Milankovitch band. Cycles occurring on the scale of 0.1-0.2 m.y. are common for parasequences or high frequency depositional sequences (Mitchum and Van Wagoner, 1991). The strong stochastic of sedimentation likely be associated with high frequency events such as obliquity (41 k.y.) and precession (23 k.y.). Though precession and obliquity are cyclic, they occur at such high frequency that they are extremely difficult to distinguish, especially at when Milankovitch orbital parameters are out of phase. Accordingly, high-frequency climate events combined with autocyclic processes are a significant source of noise in the sedimentary succession. That noise is probably reflected in the long positively skewed tails in recurrence frequency distribution in rock types and lithofacies of the Middle and Upper Pennsylvanian in the southern Anadarko Basin and help explain the stochastic nature of lithologic and stratigraphic ordering.

Only at the most advanced level of geologic interpretation are the data filtered to an extent that a high degree of stratal order and cyclicity are observed, but the stochastic component is never eliminated. And the reason that cyclicity only emerges at the level of sequence stratigraphic interpretation is because sea level is the cycle that resulted in nonrandom successions of rock types, lithofacies, depositional environments, and sequence stratigraphic elements. And it is this recognition of high-frequency, high-magnitude sea level change that influenced Weller (1930) and Wanless and Shepard (1936) to envision lithologic cyclicity where none exists—and this vision still influences innumerable geologists to this day. Indeed, the recognition of cyclicity in Pennsylvanian strata goes to the core of human perception and the desire to recognize order in physical systems where probabilistic processes prevail. And in the case of the Pennsylvanian cyclothem, substantiation of cyclicity requires the development and systematic analysis of an observational and interpretive framework that captures the stochastic nature of the system, revealing cyclicity only at the interpretive level that directly addresses the basic process of sea level change.

CHAPTER VI

CONCLUSIONS

The southern Anadarko Basin in Oklahoma contains a thick and diverse Pennsylvanian section, which reflects a multitude of dynamic processes. Evaluating depositional architecture not only improves the general stratigraphic knowledge of an extremely important oil and gas province in the southern Midcontinent, it also contributes to the understanding of cyclicity on Pennsylvanian strata. Furthermore, this analytical approach may promote additional research on the characterization and statistical testing of stratal order and cyclicity in sedimentary rocks.

In the study interval, the highest degree of stratal order was found to exist at the sequence stratigraphic level of classification, whereby many key associations of systems tracts and major stratigraphic surfaces showed high transitional probabilities, and modal recurrence intervals were mostly consistent. In contrast, rock types showed the highest tendency to form probabilistic successions, and were rhythmic, rather than cyclic, in occurrence. The importance of these findings is that order does not necessarily need to exist at the most fundamental levels to be present in some form in a system. Of the four classification schemes assessed in the study, a prominent cyclicity was observed in only one of them.

The Late Carboniferous was a time of constant change in the southern Midcontinent, in which fluctuating sea level had a profound effect on the sedimentary record. A primary catalyst of sea level change is thought to be the climatic variable, which demonstrates cyclic motion with oscillating magnitude. Additional factors responsible for sea level changes include tectonic activity and subsidence. Through application of various techniques, these mechanisms can generally be accounted for in the stratigraphic succession. However, the strength of the stochastic variable is quite evident in the Anadarko Basin, where the composition and thickness of cycles is highly variable. Each cycle analyzed contains a unique succession of rock types.

Sequences in the Middle and Late Pennsylvanian in the Anadarko Basin were calculated to have a periodicity of about 100 to 190 k.y., which appears to coincide with short eccentricity. High-frequency cycles are thought to correspond with periods of continental glaciation and pronounced climatic shifts. All available evidence seems to suggest that sea level drives the cycles. Pleistocene glaciation is an appropriate analog for sea level behavior, which shows that cycles can be predictable, but still contain significant internal heterogeneity. This same variability is on display in the Anadarko Basin Pennsylvanian sedimentary record reflecting Gondwanan glaciation. Large sea level cycles corroborate with the major surfaces and systems tracts that quantitatively uphold the stratigraphic framework. However, the internal complexity of a given sequence is extremely difficult to characterize or quantify, likely due to noise introduced by precession and obliquity cycles. Ultimately, both order and disorder appear throughout the Pennsylvanian section of the Anadarko Basin, but are highly dependent on the level of geologic interpretation used to classify the stratigraphic succession.

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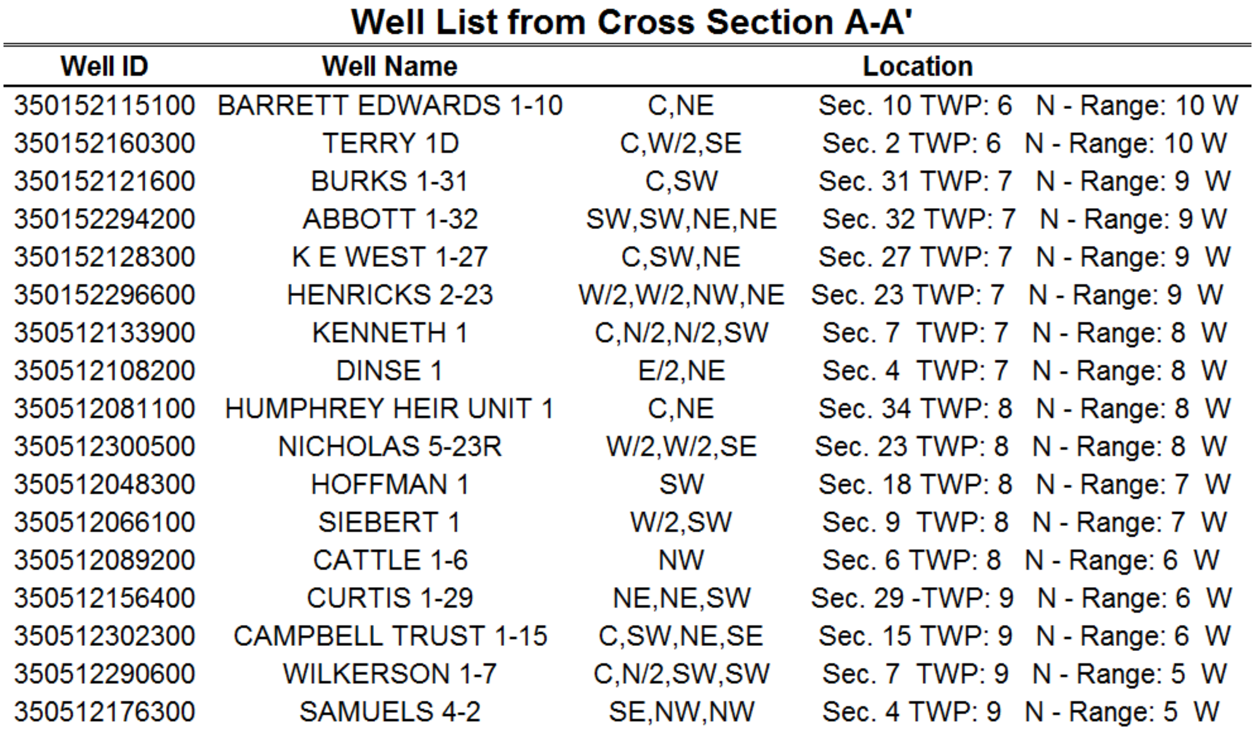
APPENDICES



Well List from Cross Section A-A'

Well ID	Well Name	Location	
350152115100	BARRETT EDWARDS 1-10	C,NE	Sec. 10 TWP: 6 N - Range: 10 W
350152160300	TERRY 1D	C,W/2,SE	Sec. 2 TWP: 6 N - Range: 10 W
350152121600	BURKS 1-31	C,SW	Sec. 31 TWP: 7 N - Range: 9 W
350152294200	ABBOTT 1-32	SW,SW,NE,NE	Sec. 32 TWP: 7 N - Range: 9 W
350152128300	K E WEST 1-27	C,SW,NE	Sec. 27 TWP: 7 N - Range: 9 W
350152296600	HENRICKS 2-23	W/2,W/2,NW,NE	Sec. 23 TWP: 7 N - Range: 9 W
350512133900	KENNETH 1	C,N/2,N/2,SW	Sec. 7 TWP: 7 N - Range: 8 W
350512108200	DINSE 1	E/2,NE	Sec. 4 TWP: 7 N - Range: 8 W
350512081100	HUMPHREY HEIR UNIT 1	C,NE	Sec. 34 TWP: 8 N - Range: 8 W
350512300500	NICHOLAS 5-23R	W/2,W/2,SE	Sec. 23 TWP: 8 N - Range: 8 W
350512048300	HOFFMAN 1	SW	Sec. 18 TWP: 8 N - Range: 7 W
350512066100	SIEBERT 1	W/2,SW	Sec. 9 TWP: 8 N - Range: 7 W
350512089200	CATTLE 1-6	NW	Sec. 6 TWP: 8 N - Range: 6 W
350512156400	CURTIS 1-29	NE,NE,SW	Sec. 29 -TWP: 9 N - Range: 6 W
350512302300	CAMPBELL TRUST 1-15	C,SW,NE,SE	Sec. 15 TWP: 9 N - Range: 6 W
350512290600	WILKERSON 1-7	C,N/2,SW,SW	Sec. 7 TWP: 9 N - Range: 5 W
350512176300	SAMUELS 4-2	SE,NW,NW	Sec. 4 TWP: 9 N - Range: 5 W

Well List from Cross Section B-B'

Well ID	Well Name	Location	
350152220900	PARTON 2-3	E/2, NW	Sec. 3 TWP: 9 N - Range: 9 W
350152230500	HOLLIS 2-11	C,SW,NW	Sec. 11 TWP: 9 N - Range: 9 W
350152176600	MURROW 2-13	C,NE	Sec. 13 TWP: 9 N - Range: 9 W
350512138400	HANDKE 2-29	C,NW	Sec. 29 TWP: 9 N - Range: 8 W
350512169800	CRIST 1-28	SW,NE,SW	Sec. 28 TWP: 9 N - Range: 8 W
350512168800	MYERS 2-2	W/2,E/2,SW	Sec. 2 TWP: 8 N - Range: 8 W
350512048300	HOFFMAN 1	SW	Sec. 18 TWP: 8 N - Range: 7 W
350512186200	GILES FARMS 1-19	W/2,NW,SW,SE	Sec. 19 TWP: 8 N - Range: 7 W
350512375600	STEWART RANCH 1-24-27XH	SW,SE,SE,SW	Sec. 34 TWP: 8 N - Range: 7 W
350512167700	OTTER CREEK 1	C,W/2,SE	Sec. 11 TWP: 7 N - Range: 7 W
350512119000	SHIPLEY 18-1	NE	Sec. 18 TWP: 7 N - Range: 6 W
350512351900	BALLARD 1-17H	SE,SW,SE,SE	Sec. 17 TWP: 7 N - Range: 6 W
350512359600	WALTERS 1-22H	S/2,SE,SW,SE	Sec. 22 TWP: 7 N - Range: 6 W
350512357300	PYLE 1-36	SE,NE,SW,NE	Sec. 36 TWP: 7 N - Range: 6 W
350512356000	WHEELER 1-1	S/2,NE,SE,SE	Sec. 1 TWP: 6 N - Range: 6 W
350512353600	CHITWOOD 1-18	C,NE,NE,NE	Sec. 18 TWP: 6 N - Range: 5 W
350512357900	GRIBI 1-22	N/2,S/2,N/2,SW	Sec. 22 TWP: 6 N - Range: 5 W

VITA

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Master of Science

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