Sequence Stratigraphy of the Late Devonian Birdbear Formation, North Dakota

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INTRODUCTION

Sequence stratigraphy is used to analyze sedimentary rock packages in terms of base-level changes and depositional trends that arise as a result of the interplay between space that is available for sediments to be deposited (accommodation) and sedimentation itself. It is a powerful tool useful in analyzing local to global sea-level fluctuations in sedimentary basins, and thus is a fundamental change in how geologists conduct stratigraphic and facies analysis. Therefore, sequence stratigraphy is presently one of the most active areas of research in academia and industry alike, improving the predictive aspects of exploration and production of petroleum worldwide. This article summarizes the sequence stratigraphy of a potentially productive petroleum unit in North Dakota, the Birdbear Formation (Birdbear), based on examination of core and associated well logs from across the state.

GEOLOGIC SETTING

During the Middle to Late Devonian (Givetian Age), the Williston Basin in North Dakota was the southern extension of the Elk Point Basin (fig. 1; Martiniuk et al., 1995) where the Birdbear was deposited in a shallow epeiric sea that extended from Alberta to South Dakota (fig. 2; Burke and Sperr, 2006). The Birdbear is underlain by carbonate-evaporite deposits of the Duperow Formation and overlain by argillaceous carbonate-evaporite units of the Three Forks Formation (fig. 3). The formation represents a third-order depositional sequence within the overall second-order Devonian transgressive-regressive package (Burke and Sperr, 2006) and consists of 4–5 overall shallowing upwards cycles. The maximum transgression of the seaway into South Dakota occurred during deposition of the underlying Duperow Formation (Wilson and Pilatzke, 1987); therefore, Birdbear sediments were deposited during the subsequent regression, as the seaway retreated to the northwest.

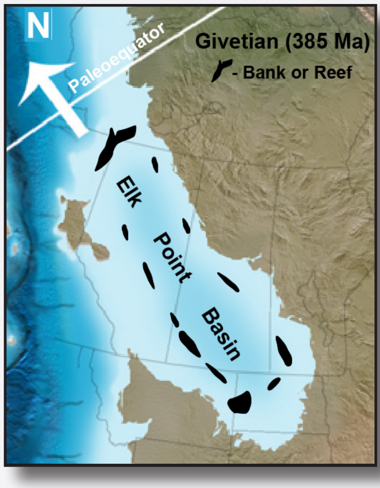

Figure 1. Paleogeographic map of the Elk Point Basin at 385 million years ago. Modified from Blakey, 2013.

SEQUENCE STRATIGRAPHY

Sequence stratigraphic principles presented by Catuneanu (2006) were utilized for this study. Reference to sea-level rise and fall are considered relative sea-level fluctuations, not absolute. The application of sequence stratigraphy to carbonate depositional systems has been a topic of debate since the 1980s (Sarg, 1988; Schlager, 2005; Catuneanu, 2006). Like clastic depositional systems, the principles of sequence stratigraphy can be applied similarly to carbonate systems even though there are fundamental differences for each. Shifting shorelines, base-level fluctuations as related to systems tracts, surfaces, and sequences may all be applied in the carbonate setting in the same manner as the clastic environment. The differences between the two, clastic versus carbonate, lie in the interplay between sedimentation rate, growth rate (GR) for carbonate organisms, and accommodation space (A)

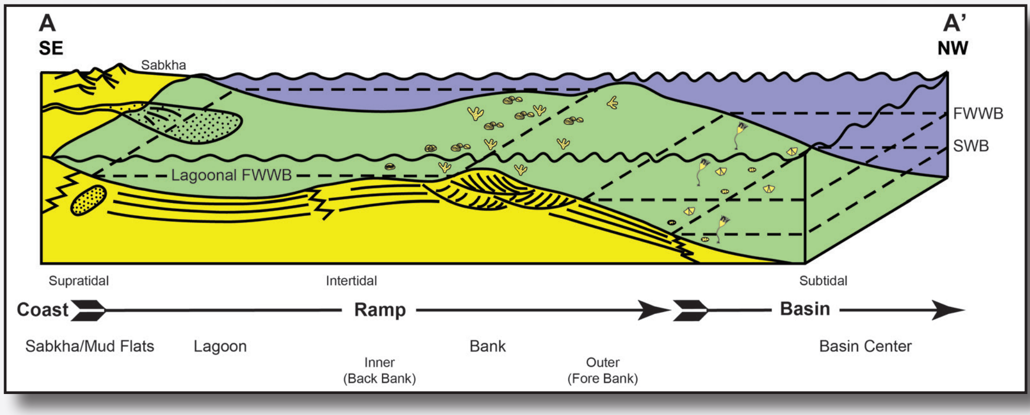

Figure 2. Epeiric platform schematic. Modified from Wilmsen et al. (2018). FWWB-fair-weather wave base, SWB-storm wave base.

which controls the type of shoreline trajectory that ultimately develops. In turn, these shoreline shifts control sediment budget across the basin and the geometry of systems tracts. Figure 4 shows evolution of the Birdbear carbonate shelf through time (T1–T4) and the lower Three Forks Formation (T5–T6) and figure 5 is the corresponding sea-level curve.

Sediment supply in the carbonate environment is very important because sediment is almost entirely intra-basinal, formed in the shallow water "carbonate factory," mostly on the top of the platform (fig. 4; Catuneanu, 2006). Because of this, sediment supply (as related to base-level change) is key to understanding carbonate sequence stratigraphy. Changes in

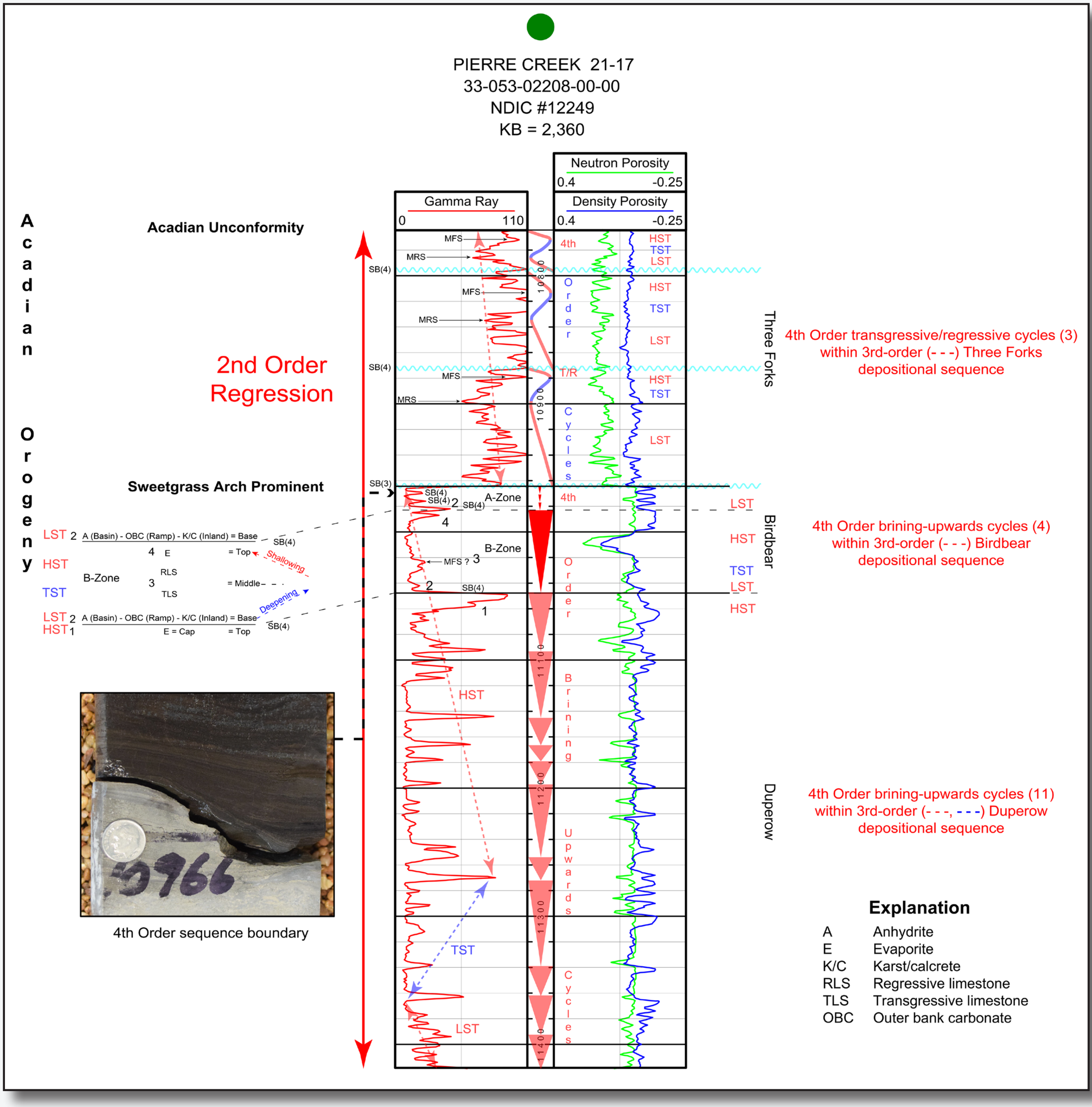

Figure 3. Type log Devonian sequence stratigraphy. See figure 4 for other abbreviations.

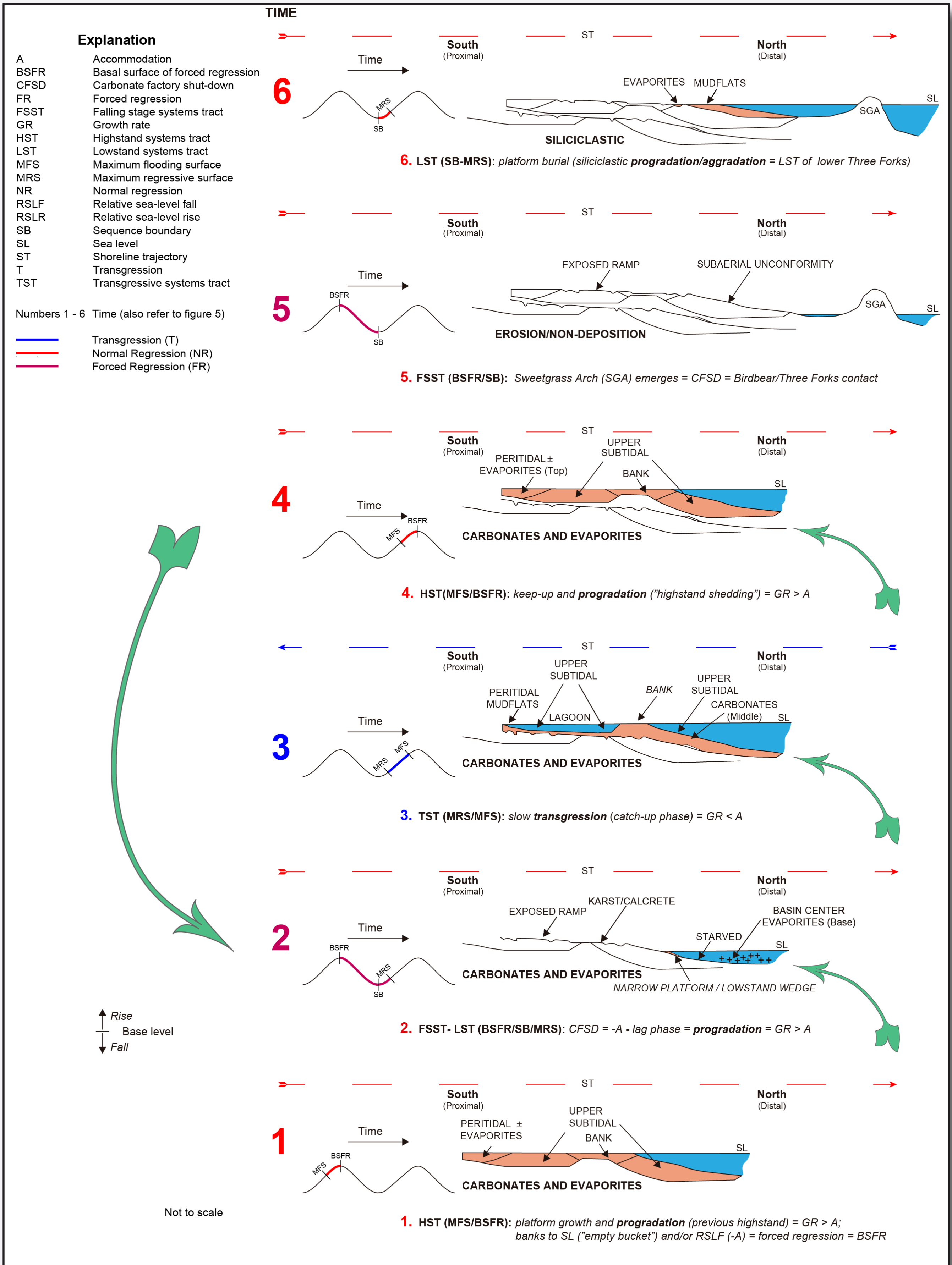

Figure 4. Sequence stratigraphic model for an epeiric platform. Modified from Catuneanu (2006).

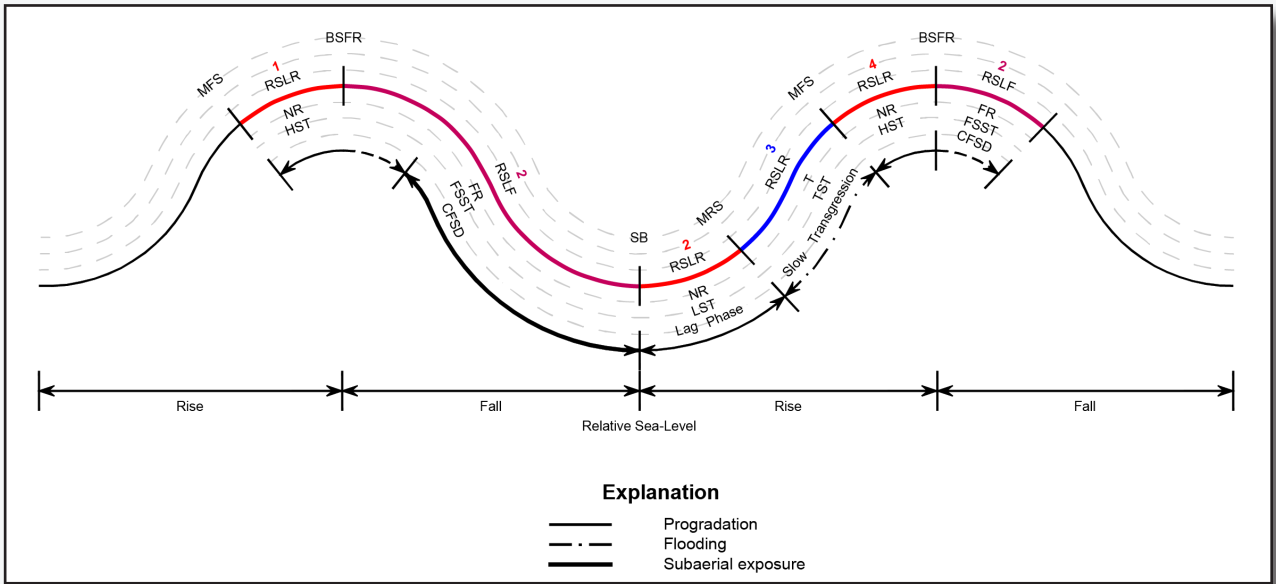

Figure 5. Sea-level curve. See figure 4 for abbreviations.

base level in carbonate environments have a reciprocal effect as compared to clastic basins. For instance, deeper water carbonate accumulations occur during highstand when the carbonate factory is at its optimum production, as compared to clastic basins where deep water accumulations occur during lowstand. Again, this reciprocal effect will lead to differing geometries for systems tract packages and is directly related to the intra-basinal source of sediment versus an extra-basinal source (clastics). Response of the carbonate platform to base-level fluctuations is also dependent on the geometry of the basin and relationship of the platform to the basin margins. This is particularly so for a shallow epeiric platform where minimal fluctuations in sea level can have broad and regional implications as shown on figures 4 and 5. Unlike the clastic environment, where sediment may accumulate to sea level at any water depth, presuming there is a sediment source, carbonate sediment generation is proportional to the productivity of the shallow carbonate factory at the top of the platform. Therefore, because base-level changes in the carbonate environment are directly related to production, such production is very sensitive to sea-level fluctuations in an epeiric seaway. Lowering of base-level leads to subaerial exposure of the platform top and a shutdown of the carbonate factory; whereas base-level rise creates accommodation space allowing for development of the platform, but only at a rate that is sufficient for the top of the platform to stay in the photic zone. Base-level rise at rates that are too high for carbonate growth to keep up will drown the platform below the photic zone, again shutting down the carbonate factory.

Figure 4 also presents a sequence stratigraphic model for the lifecycle of the Birdbear carbonate shelf with corresponding sea-level curve and associated sequence stratigraphic surfaces and systems tracts for one-full sequence (fig. 5). At Time 1, the previous “highstand” deposits, or an underlying sequence/formation (e.g., Duperow Formation), are shown. Deposits of the highstand (HST) normal regression are favorable for carbonate production due to flooding of the platform during transgression and creation of accommodation during slowing base-level rise (GR > A). These include “deeper” water as well as platform deposits. As base-level rise rate continues to decline, carbonate production increases to the point of exceeding accommodation space (i.e., reaches base level) and some material may be transferred (highstand shedding) to the slope and/or shallow basin floor during storm surges. As base-level rise continues to slow, carbonate production may reach sea level, also leading to shut down of the carbonate factory (empty bucket stage) and eventual sea-level fall (-A) during the falling stage (FSST) forced regression (FR). Biohermal banks develop during the highstand normal regression and may include both inner and outer bank facies, formed laterally to the core bank environment.

Time 2 represents the falling stage (FSST) and lowstand (LST) combined, thus defining both the lower sequence boundary (SB) and the maximum regressive surface (MRS), as they may be considered here as one in the same (figs. 4 and 5). After the previous highstand, water depths are extremely shallow because most accommodation has been consumed during the highstand normal regression (NR). Even with minimal base-level fall (-A) this leads to a rapid forced regression and subaerial exposure of the platform top, which continues through the lowstand (lag phase), where deposition on the platform is limited to a thin and relatively narrow band of progradational (GR > A) open marine sediments at the edge of the platform (platform wedge). Therefore, basinward sedimentation is minimal, but sediment starvation and shallow saline water within the basin may promote precipitation of basin-centered evaporites. Landward, the forced regression also leads to shut down of the carbonate factory thus subjecting the exposed platform to karstification, or calcrete deposits in more arid settings. The basal, deepening upwards platform package is inferred in core from north-central North Dakota (Martiniuk et al., 1995) and is present in core from this study.

Slow transgression (TST) characterizes Time 3. At this time, the carbonate factory will continue to grow as accommodation space is created, eventually catching-up with rising base-level during the subsequent highstand. Initially, this corresponds to a "deepening" package (including previously deposited LST platform sediments) of lower Birdbear deposits as the accommodation is created across the entire carbonate shelf. This leads to formation of shallow subtidal depocenters (lagoons) between the bank and the shoreline with deposition of transgressive open marine carbonates in the basin, and restricted marine carbonates in the lagoons. Regressive open-marine carbonates of the HST subsequently overlie the TST deposits separated by a maximum flooding surface (MFS) that may be difficult to detect visually in core (fig. 5). The regressive open-marine deposits are subsequently overlain by bank deposits of the HST, where water depth and environment allow for bank development.

Time T4 represents the highstand phase of the current cycle, as described for Time 1 and for the previous cycle highstand. Cycle repetition is likely due to carbonate factory shutdown as bank growth reaches sea level and sea-level drops. At some point, cyclicity is terminated, likely related to a significant basin event such as a rapid transgression which drowns the carbonate factory and leads to filling of created accommodation space by siliciclastic progradation (Catuneanu, 2006), and/or tectonism that significantly disturbs the basin geometry and depositional setting. It is postulated that such an event occurred near the end of Birdbear time, as the Acadian orogeny began (Time T5). Uplift of the Sweetgrass arch across the Elk Point Basin may have shut off the proto Williston Basin from the open ocean, leading to a significant change in climate, depositional setting, and sediment input (clastic) from the newly formed Antler orogen to the west (Time T6; figs. 4 and 5).

Devonian Sequence Stratigraphy

Late Devonian (Duperow, Birdbear, and Three Forks Formations) sequence stratigraphic relations are shown on figure 3 utilizing logs from the Pierre Creek 21-17 well. The entire section represents the regressive phase of the overall second-order Devonian transgressive-regressive sequence. The Birdbear and upper Duperow are third-order regressive depositional packages. Maximum transgression of the Elk Point seaway is identified at approximately 11,270 feet at the transition from third-order transgressive to highstand systems tracts. Fourth-order transgressive-regressive cycles for the Three Forks are also shown in contrast to fourth-order brining upwards cycles for the Birdbear and Duperow. Fourth-order packages have been further subdivided into lowstand, transgressive, and highstand systems tracts for the Three Forks and Birdbear.

The Birdbear represents four, fourth-order shallowing-upwards cycles within the third-order Birdbear depositional sequence (fig. 3). Systems tracts and sequence boundaries can be identified within each of these cycles, just like in the siliciclastic environment. Here a fourth-order sequence boundary at the base represents retreat from the area of the sea after Duperow deposition. Subsequent sea-level rise initiated Birdbear deposition on the platform margin where outer bank carbonates begin to prograde into the basin during the lowstand. Eventually, sea-level rise exceeded carbonate growth rates as a slow transgression resulted in transgressive and regressive open marine deposits during the deepening and early shallowing phase. As shallowing continued, biohermal banks formed during the highstand and were eventually capped by shallow-water lagoonal and sabkha deposits forming the B-zone (fig. 3). Sea level then dropped again and the cycle repeated itself three more times during deposition of the A-zone. This repetitive pattern is represented by the "Systems Tracts/ Times 1, 2, 3, 4, 2-pattern" shown on the inset blow-up in figure 3 and depicted on figure 4. A representative fourth order sequence boundary is shown from 10,966 feet on fig. 3.

A significant change occurs between deposition of the A-zone and the overlying Three Forks Formation, which is defined by a third order sequence boundary. This transition is marked by a change from carbonate deposition of the A-zone to siliciclastic deposits of the lower Three Forks. This transition is likely due to the Acadian orogeny which likely began during A-zone deposition and culminated at the end of Three Forks time, as represented by the Acadian unconformity. This tectonism effectively shut-down the Birdbear carbonate factory (figs. 3 and 4) leading to a more restricted basin with hypersaline conditions in an arid environment during deposition of the Three Forks.

SUMMARY

This article presents a sequence stratigraphic model for the Birdbear Formation of North Dakota based on the study of cores and associated well logs from across the state. The Birdbear may be categorized as a third-order depositional sequence consisting of several shallowing upwards carbonate and carbonate evaporite cycles. Sequence stratigraphic relationships further enhance our understanding of these relationships and will help in identifying future plays in the Birdbear-Duperow Petroleum System of North Dakota.

References

Blakey, 2013, North America key time-slices: Colorado Plateau Geosystems.

Burke, R.B., and Sperr, T.J., 2006, Birdbear Formation lithofacies in west-central North Dakota – some characteristics and insight: North Dakota Department of Mineral Resources Geo News, v. 33, no. 1, p. 1–5.

Catuneanu, O., 2006, Principles of sequence stratigraphy: Elsevier, Amsterdam, 375 p.

Martiniuk, C.D., Young, H.R., and LeFever, J.A., 1995, Lithofacies and petroleum potential of the Birdbear Formation (Upper Devonian), southwestern Manitoba and north-central North Dakota, in Vern Hunter, L.D., and Schalla, R.A., eds., 7th International Williston Basin Symposium 1995 Guidebook: Billings, Mont., Montana Geological Society, p. 89–102.

Sarg, J.F., 1988, Carbonate sequence stratigraphy, in Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea Level Changes-An Integrated Approach: SEPM Special Publication 42, p. 155–182.

Schlager, W., 2005, Carbonate sedimentology and sequence stratigraphy: SEPM Concepts in sedimentology and Paleontology no. 8, 200 p.

Wilmsen, M., Berensmeier, M., Fürsich, F.T., Majidifard, M.R., and Schlagintweit, F., 2018, A Late Cretaceous epeiric carbonate platform – the Haftoman Formation of Central Iran: Facies, v. 64, no. 2, article 11.

Wilson, J.L., and Pilatzke, R.H., 1987, Carbonate-evaporite cycles in Lower Duperow Formation of the Williston Basin, in Longman, M.W., ed., Williston Basin – Anatomy of a Cratonic Oil Province – 1987 Guidebook: Denver, Colo., Rocky Mountain Association of Geologists, p. 119–146.