Stratigraphic Framework for the Late Devonian Birdbear Formation North Dakota

By
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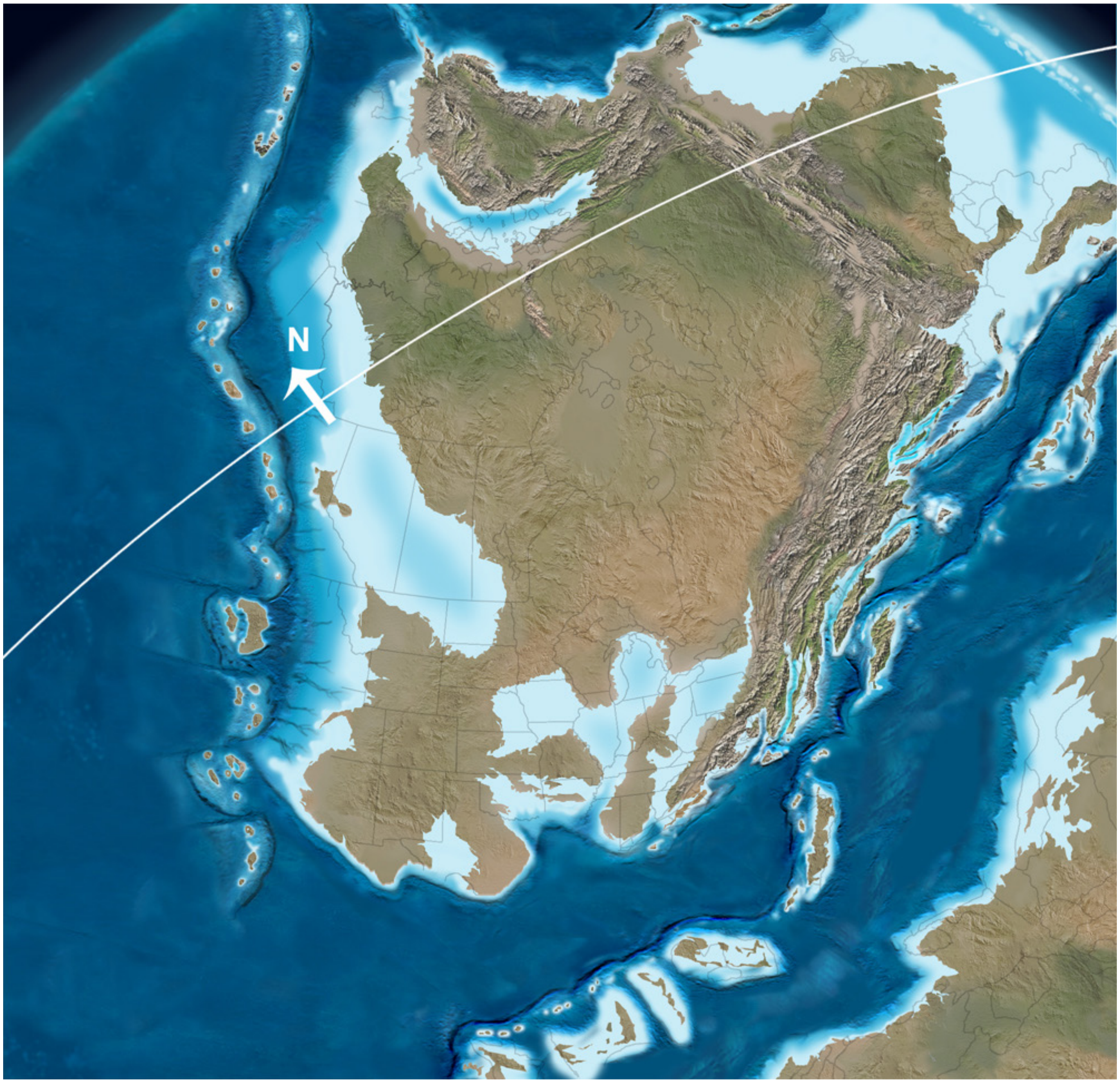

REPORT OF INVESTIGATION NO. 125
NORTH DAKOTA GEOLOGICAL SURVEY
Edward C. Murphy, State Geologist
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Cover Image: *Paleogeography of North America in the Middle Devonian just prior to Birdbear deposition (Blakey, 2013).*

ABSTRACT
This report presents a stratigraphic framework for the Birdbear Formation of North Dakota. Sixteen cores and associated well logs from across the state were studied in detail and compared with previous work performed in north-central North Dakota and Manitoba. Facies associations identified herein are consistent with previous works and include: 1) sabkha; 2) restricted marine; 3) bank; and 4) open marine environments. This study shows that the gamma-ray log signature for the Birdbear is very similar from well to well and is easily correlatable across the state. However, facies associations do not correlate with such ease and facies changes occur laterally.

The Birdbear may be categorized as a third-order depositional sequence consisting of several shallowing upwards carbonate and carbonate evaporite cycles. These cycles are ideal for petroleum hydrocarbon generation and entrapment, as organic-rich source rock, dolomitized reservoir rock, and evaporite seal are present in both the A- and B-zones. Sequence stratigraphy further enhances our understanding of these relationships and will help in identifying future plays in the Birdbear-Duperow Petroleum System of North Dakota. This study also indicates that Antler orogenesis may have begun in late Birdbear time, thus changing the depositional setting into the Late Devonian as the overlying Three Forks Formation was deposited.

INTRODUCTION
The Birdbear Formation (Birdbear) of North Dakota is a unit that may contain significant hydrocarbon reserves based on previous investigations (Martiniuk et al., 1995; Burke and Sperr, 2006; LeFever, 2009), having produced over 21.5 billion barrels of oil to date. This report presents a general review of Birdbear stratigraphy and provides preliminary sequence stratigraphic models. It includes: 1) lithologic descriptions of core (Appendix A); 2) identification of facies associations and correlation of such; and 3) depositional setting interpretation, based on core and wireline log analysis.

GEOLOGIC SETTING AND PREVIOUS WORK
During the Middle to Late Devonian (Givetian), the Williston Basin in North Dakota was the southern extension of the Elk Point Basin (Figs. 1A and1B; Martiniuk et al., 1995) where the Birdbear was deposited in a shallow epeiric sea that extended from Alberta to South Dakota (Burke and Sperr, 2006). 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 (Bader, 2019; Appendix A). 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. 2). The maximum transgression of the seaway into South Dakota occurred during deposition of the underlying Duperow (Wilson and Pilatzke, 1987); therefore, Birdbear sediments were deposited during the subsequent regression, as the seaway retreated to the northwest.

Birdbear stratigraphy has been previously defined in two ways. Sandberg and Hammond (1958) formally defined the unit based on core from the Mobil Oil Producing Company No. 1 Bird Bear well located in Dunn County, North Dakota.

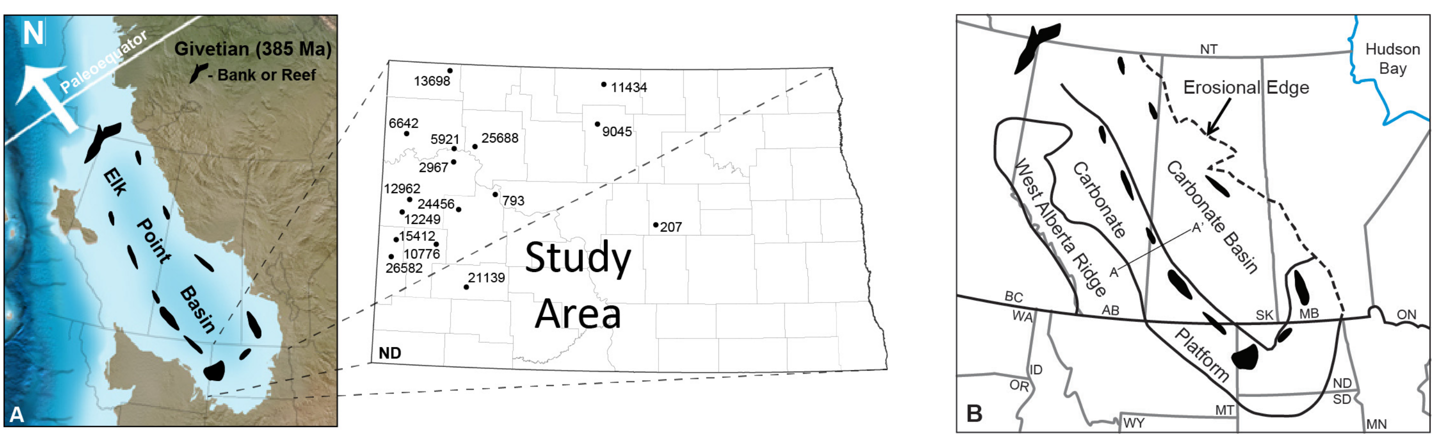

Figure 1. (A)–Paleogeographic map of the Elk Point Basin at 385 million years ago with index map of North Dakota showing study area and well locations with NDIC # and cores utilized for the study. Modified from Blakey, 2013. (B)–Geologic setting for the Birdbear Formation at 385 million years ago. Modified from Martiniuk et al., (1995).

Martiniuk et al. (1995) divided the Birdbear into two distinct lithologic packages for north-central North Dakota, informally defined as upper (carbonate-evaporite) and lower (carbonate) units (Fig. 2). The Birdbear has also been sub-divided into A- and B-zones in western and north-central North Dakota based on gamma-ray log signature and sequence stratigraphy (Fig. 2; Burke and Sperr, 2006; LeFever, 2009; Bader, 2018, 2019; this report) as described below. However, these zones do not correspond to the upper and lower member designations of Martiniuk et al. (1995). Therefore, the A- and B-zone designations, and particularly the following facies associations, although partially based on lithology, are not pertinent to stratigraphic nomenclature for the Birdbear and should not be misconstrued as such.

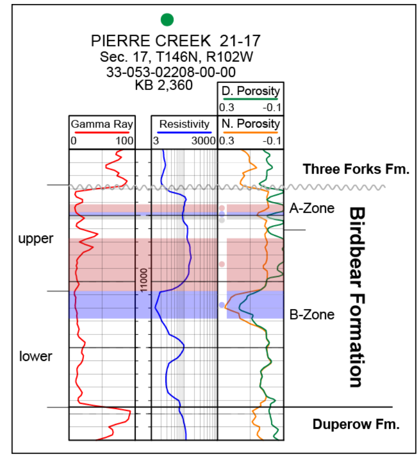

Figure 2. Type log Birdbear Formation. KB–Kelly bushing elevation in feet.

METHODS

Sixteen representative Birdbear cores from across North Dakota were examined and described at the Wilson M. Laird Core and Sample Library in Grand Forks, ND (Appendix A). Corresponding wireline logs were also evaluated with respect to the core to prepare a stratigraphic framework for the Birdbear. Four (4) main facies associations (FA) were identified, correlated, and compared to pertinent previous studies (Fig. 3; Table 1; Plate 1; Martiniuk et al., 1995). Isopach maps were also constructed for the A- and B-zones (Figs. 4 and 5).

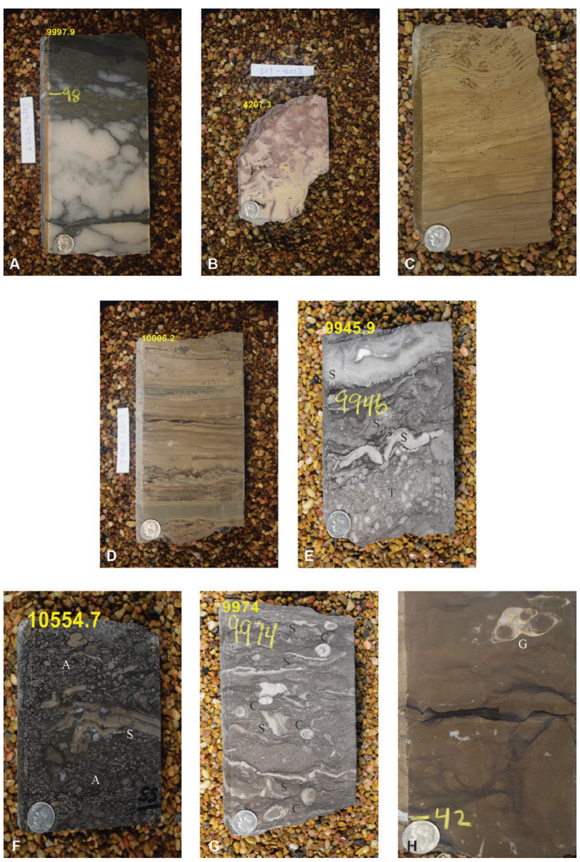

Figure 3. (A)–Nodular anhydrite (FA-1A) from well #21139, (B)–Calcrete (FA-2A) with vuggy porosity from well #207, (C)–Dolostone (FA-2B) from well #13698, (D)–Interbedded mudstone/shale and dolostone from well #21139, (E)–Bank facies (FA-3A) with stromatoporoids (S) and thamnopora (T) from well #5921, (F)–Backbank facies with amphipora (A) and stromatoporoids (S) from well #2967, (G)–Forebank facies with coral (C) and stromatoporoids (S) from well #5921, (H)–Open marine facies (FA-4A) with gastropods (G) from well #21139.

RESULTS/INTERPRETATIONS

Facies Associations (FA)

The four main lithofacies associations identified in cores from this study include: 1) sabkha; 2) restricted marine; 3) bank, and 4) open marine. Each is further subdivided based on lithology and tidal zone, and each is described below and summarized on Table 1. These facies were found to be consistent with those identified by Martiniuk et al. (1995) for north-central North Dakota and southern Manitoba, Canada.

Sabkha/Mud Flats (FA-1A, FA-1B)

The sabkha facies consist dominantly of nodular anhydrite **(FA-1A)**. The nodular anhydrite (Fig. 3A) is interpreted to be deposited subaerially in the upper supratidal environment; however, these may occur both proximally, as nearshore evaporites (A and B-zones), or distally, as basin-centered deposits (B-zone ?). Proximal areas also include interpreted mud flat deposits consisting of calcrete and/or caliche **(FA-1B)** for the entire Birdbear interval but were only observed in one core from well #207 (Fig. 3B).

Restricted Marine/Lagoonal (FA-2A, FA- 2B, FA-2C)

The restricted marine/lagoonal facies **(FA-2A)** consist of mudstone to wackestone, corresponding to the C facies of Martiniuk et al. (1995) (Table 1). They are commonly dark gray, wavy to ripple cross-laminated, and occasionally burrow mottled. They are locally fossiliferous, dolomitic **(FA-2B)**, and anhydritic **(FA-2C)**. Thin, interbedded dolostone (Fig. 3C), mudstone/shale (Fig. 3D), and bedded anhydrite are also common in these facies within the A-zone.

Bank (FA-3A, FA-3B)

The bank facies **(FA-3A)** represent the main biohermal carbonate across the study area and corresponds to the E1 facies of Martiniuk et al. (1995) (Table 1). It generally consists of wackestone to grainstone, but locally mudstone, bafflestone, and boundstone have been noted (Martiniuk et al., 1995). Stromatoporoids (laminar and bulbous) are the dominant fossil along with significant amphipora with some coral and occasional brachiopods (Fig. 3E). These rocks are commonly dolomitized (FA-3B) and may be oil stained (dark yellowish brown). They have good intergranular, intracrystalline, and vuggy porosity and are locally anhydritic as nodules, within healed fractures, and filled cavities. The bank facies range in thickness from 6 to 26 feet, averaging 10 feet.

Forebank (FA-3C) and Backbank (FA-3D)

The forebank **(FA-3C)** and backbank **(FA-3D)** facies are very similar as they are formed lateral to, and on either side, of the bioherm. They correspond to the E2 and D facies of Martiniuk et al. (1995) (Table 1) and consist of mudstone to packstone, locally dolomitized. They are fossiliferous, but not as robust as the bank facies containing stromatoporoids and amphipora with some brachiopods and coral. Amphipora dominates the backbank facies (Fig. 3F) while coral and brachiopods are more significant in the forebank (Fig. 3G). These facies exhibit fine interparticle and vuggy porosity, interstitial nodules and stringers of anhydrite, and are locally stylolytic and oil stained. The forebank facies attain thicknesses of up to 7 feet while the backbank facies may be significantly thicker at up to 21 feet.

Open Marine (4A, 4B, 4C, and 4D)

The open marine facies **(FA-4A)** consists generally of mudstone and minor wackestone, like the restricted marine facies and corresponding to the A facies of Martiniuk et al. (1995) (Table 1). These facies are commonly burrow mottled with no trace of bedding or sedimentary structures. Fossils include brachiopods, gastropods, and coral (Fig. 3H). These rocks are peloidal and stylolitic with trace vuggy porosity, some filled with anhydrite. These facies range in thickness from 21 to 46 feet.

FA-4B (basin-centered evaporites), deposited during sea-level fall, are somewhat hypothetical as discussed in the next section. They may occur in the basin center but have not been positively identified in this study. This is likely due to lack of core that penetrates the entire Birdbear in the basin center and because these facies would lie directly on top of similar shallow facies of the previous sequence (i.e., nearshore bedded anhydrites **(FA-2C)** that cap those sequences). Identification of a subaerial unconformity between each sequence would allow for a more definitive interpretation as more basin-centered wells are drilled and cored. **FA-4C** represents shallow sub-tidal open marine facies deposited during early progradational sea-level rise and are also discussed below. These facies consist of interbedded, light and dark mudstones and were only observed in well #24456 from 11,455.0 to 11,458.3 ft.

FA-4D was observed in only one core #13698 and represents toe of slope deposits probably from storms (tempestites). The facies consist of bioclastic debris (stromatoporoids, coral, amphipora, and shell hash).

Table 1. Facies Associations

Number	MYL	Facies Association	Rock Type	Dunham	Description	Tidal Zone	SS
1A	<>	Sabkha	Anhydrite	<>	Nodular (chicken wire)	Upper supratidal	FSST/LST
1B	<>	Mud Flats	Limestone	<>	Red to white, vuggy, birdseye structure	Lower supratidal/upper intertidal	FSST/LST
2A	C	Restricted Marine (Lagoonal)	Limestone	Mudstone to Wackestone	Dark gray, laminated to massive, ripple cross-laminated, carbonaceous, anhyditic, hairline fractures	Upper subtidal	TST/HST
2B	F	Restricted Marine	Dolostone	<>	Interbedded, wavy laminated, anhydritic, ripple cross laminated, locally fossiliferous	Lower supratidal-upper intertidal	<>
2C	<>	Restricted Marine	Anhydrite	<>	Bedded/Interbedded, wavy laminated to ripple cross laminated	Lower supratidal	HST
3A	E1	Bank	Limestone	Wackstone to Grainstone	Fossiliferous (stromatoporoids, amphipora)	Lower intertidal–Upper subtidal	TST/HST
3B	F	Bank	Dolostone	<>	Fossiliferous (stromatoporoid, amphipora, relict), vuggy, anhydritic, ripple cross-laminated, wavy bedding	Upper intertidal	<>
3C, 3D	E2, D	Backbank/Forebank	Limestone	Mudstone to Packstone	Fossiliferous-amphipora (backbank; abundant/forebank; some), brachiopods, coral, minor stromotoporoids (forebank); bioclastic (forebank)	Upper subtidal	TST/HST
4A	A	Open Marine	Limestone	Mudstone to Wackestone	Burrow mottled, pelloidal, fossiliferous (coral, gastropods, brachiopods)	Upper–lower subtidal(?)/platform (MYL)	TST/HST
4B	<>	Basin Center	Anhydrite	<>	Bedded	Evaportive basin	FSST/LST
4C	<>	Open Marine	Limestone	Mudstone	Thin interbedded light and dark layers	Upper subtidal–lower intertidal	LST
4D	SD	Open Marine (slope; no bank)	Limestone	Wackestone to Packstone	Bioclastic (fragmental), fossiliferous (stromatoporoids, coral, amphipora)	Slope w/ no developed bank (tempestites)	<>

Table 1. Lithofacies associations for the Birdbear Formation. MYL–Martiniuk et al. (1995), <> – not applicable, SS–sequence stratigraphy, FSST–falling stage systems tract, HST–highstand systems tract, LST–lowstand systems tract, TST–transgressive systems tract.

DISSCUSSION

Stratigraphy

Based on review of core, logs, and identification of facies associations, a stratigraphic framework may be established including confirmation of lithostratigraphy identified by others (A-zone and B-zone) and development of preliminary sequence stratigraphic models.

A-Zone

The A-zone is generally composed of three, thin, shallowing upwards, carbonate and evaporite packages (Burke and Sperr, 2006; Bader, 2019). Each includes interbedded thin shale and massive dolostones, overlain by bedded to nodular anhydrite

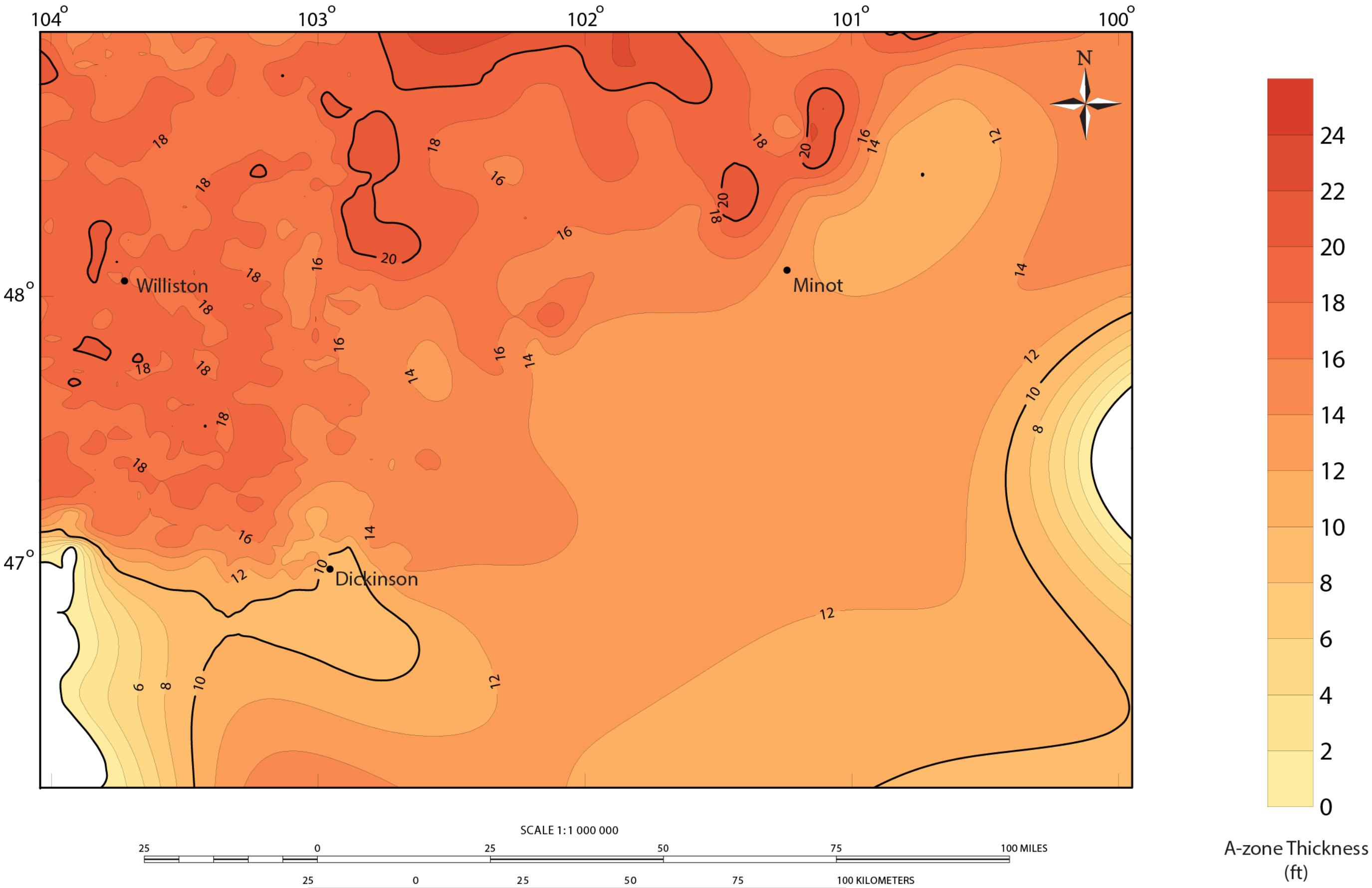

Figure 4. A-zone isopach.

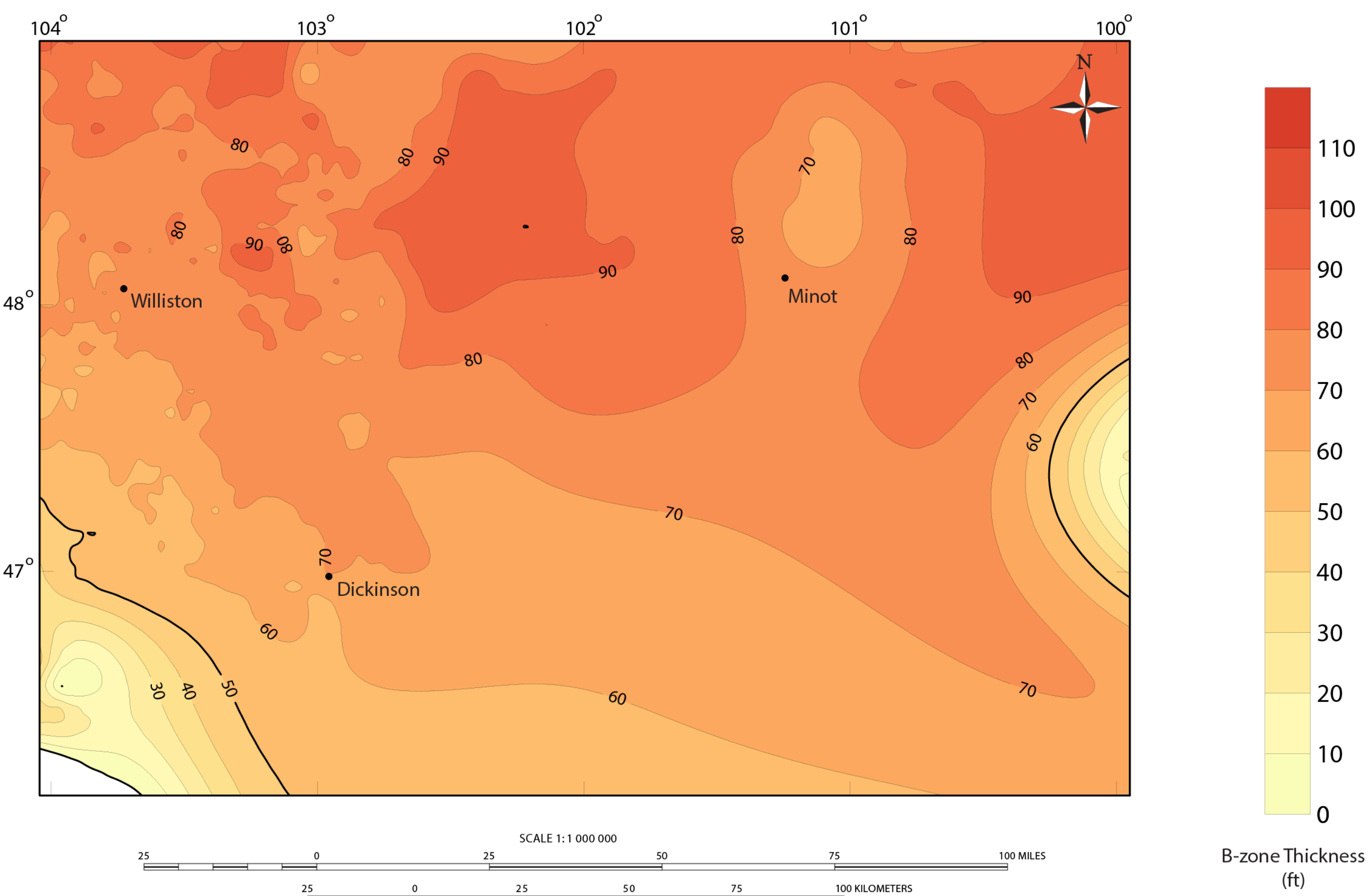

Figure 5. B-zone isopach.

deposited in restricted intertidal and supratidal settings (Martiniuk et al., 1995). The A-zone attains a thickness of up to 23 feet in northwestern North Dakota and thins to the southwest where it eventually pinches out (Fig. 4).

B-Zone

The B-zone consists of a lower, relatively thin package of regressive, outer platform deposits (Martiniuk et al., 1995). Above this basal unit, transgressive burrow mottled to nodular, fossiliferous mudstone (open marine facies) grade upwards into more fossiliferous limestone bank facies that can be subdivided into forebank (outer), bank, and backbank (inner) facies. The upper B-zone is capped with anhydrite interbedded with thin dolostones of the shallow lagoon/sabkha facies. The B-zone ranges in thickness from 0 to 100 feet (Fig. 5).

Facies Architecture

Cross-sections A-A' and B-B' were constructed utilizing well logs from the cores evaluated during this study (Plate I). The aforementioned facies were correlated across northwestern North Dakota, providing a representative stratigraphic framework for the Birdbear of North Dakota. Section A-A' was constructed to include the bank facies in order to better understand lateral variations in lithology and thickness of this easily identifiable reservoir horizon. The bank facies, including inner and outer bank, attain greatest thickness in the western portion of North Dakota (# 15412) at 31 feet, but maintain a thickness of greater than 15 feet across depositional strike from western to north-central North Dakota. Continuity of the bank facies between wells #25688 and #9045 is unknown due to lack of well control, but the lack of core bank facies in well #25688 and Birdbear isopach maps (Figs. 4 and 5) suggest that banks did not form in this area, possibly due to greater water depth across the basin axis and/or lack of structural highs that may have enhanced bank development (Fig. 6; Bader, 2019). From the base of the section, platform deposits of the lowstand normal regression are present characterized by a shallowing upward response on the gamma-ray log. These deposits are overlain by the transgressive/regressive open marine units which are dominantly regressive in north-central North Dakota (well #9045 and #11434). These are in turn overlain by the regressive bank, lagoonal, and sabkha facies of the upper B-zone. Three, fourth-order progradational sequences of the A-zone are present at the top of the Birdbear, except in well #26582, where the A-zone begins to pinch out over the Cedar Creek anticline.

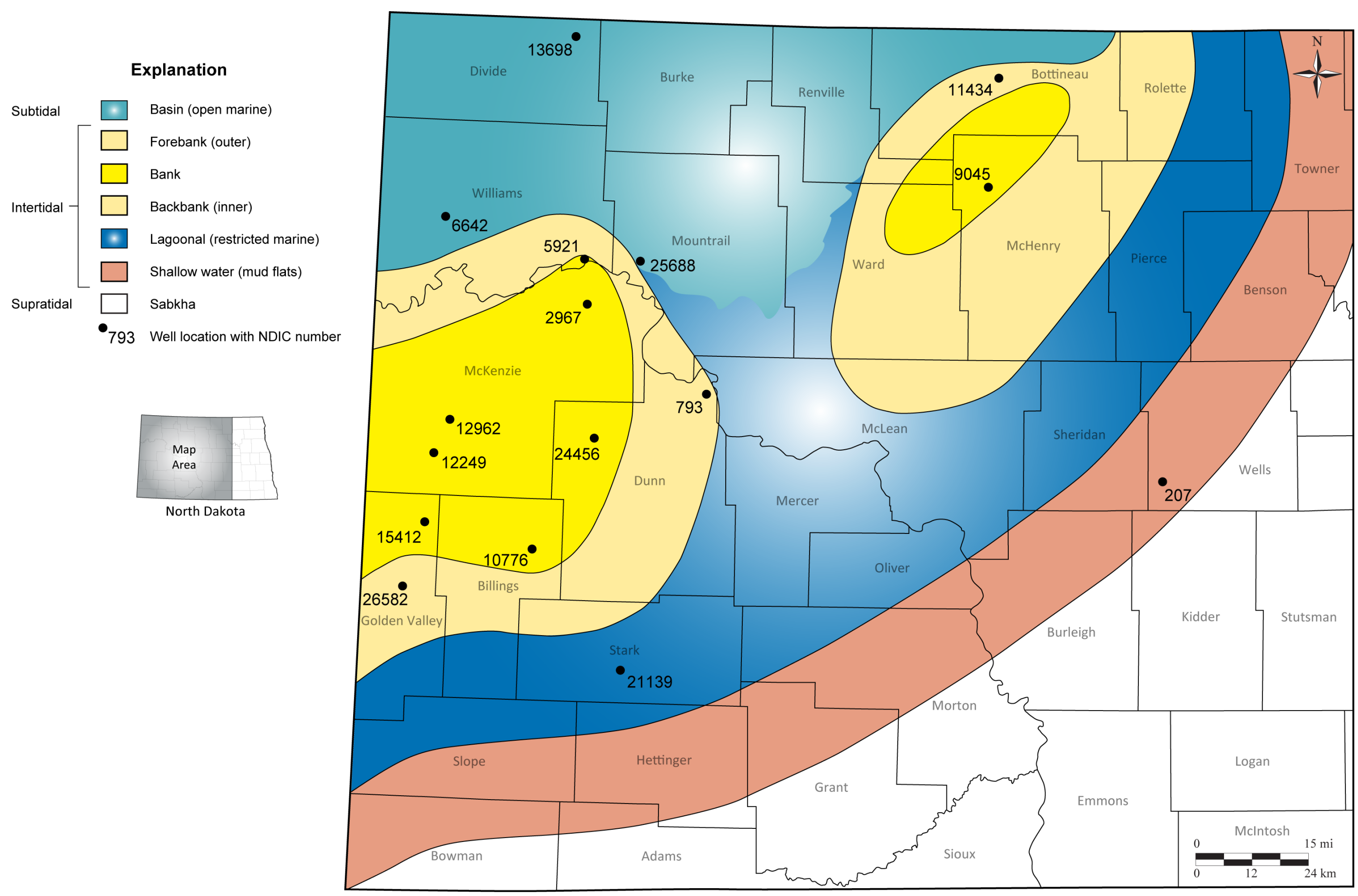

Figure 6. B-zone paleogeographic map.

Section B-B’ was constructed from proximal to distal along depositional dip. Platform and open marine deposits are thickest to the north and thin southwards until interfingering with lagoonal facies. Bank facies are not present to the north in the B-zone, indicating that water depths were likely too great for bank development (Fig. 6). Bank facies are also thickest to the north and thin to the south where they also grade into lagoonal facies. Lagoonal and sabkha facies complete the shallowing upward cycle in the B-zone. These facies grade into caliche/calcrete to the southeast.

Preliminary Sequence Stratigraphic Models

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) which control 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.

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. 7; Catuneanu, 2006). Because of this, sediment supply (as related to base-level change) is key to understanding carbonate sequence stratigraphy. Changes in 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. 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.

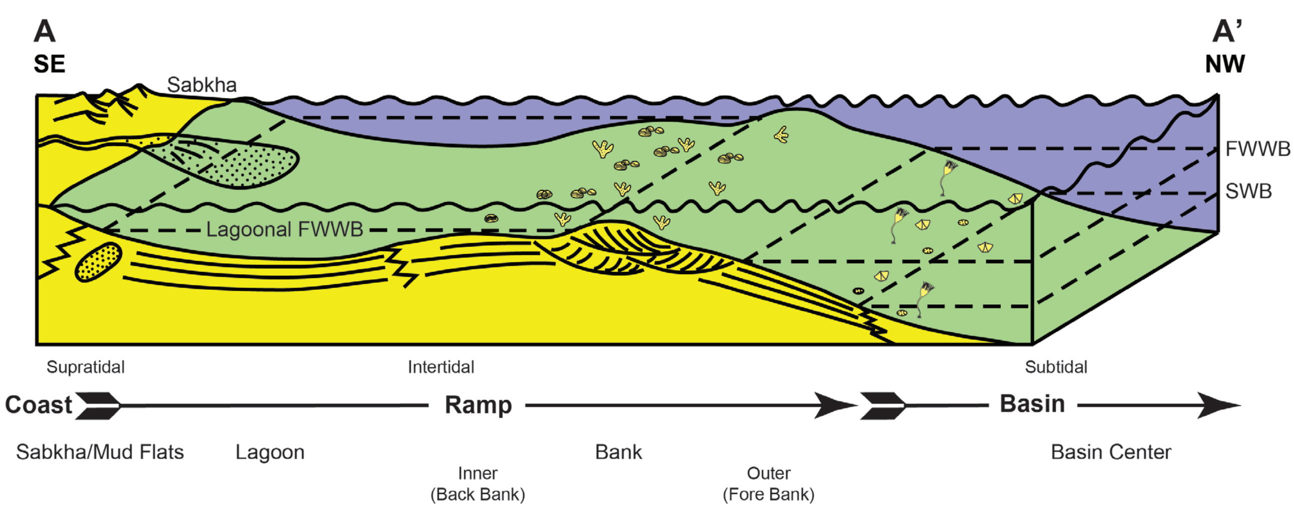

Figure 7. Epeiric platform schematic. Modified from Wilmsen et al. (2018).

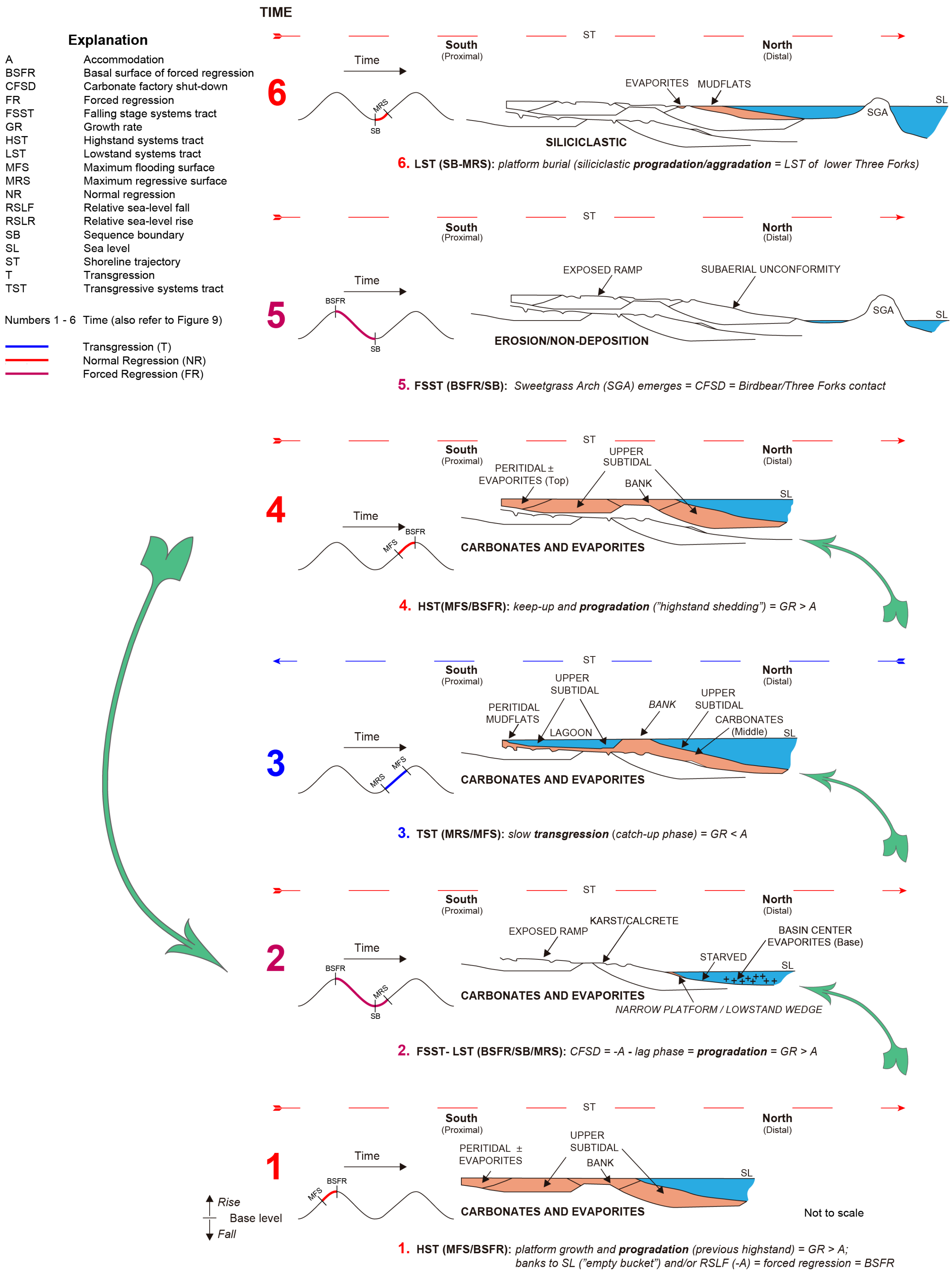

Figure 8. Preliminary sequence stratigraphic model for an epeiric platform. Modified from Catuneanu (2006).

Sequence Stratigraphy and Facies Associations

Figure 8 is a preliminary 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 (Figure 9). 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. 8 and 9). 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 (FA-4C) 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 (FA-4B). Landward, the forced regression also leads to shut down of the carbonate factory thus subjecting the exposed platform to karstification, or calcrete deposits (FA-1B) in more arid settings, as seen in core #207. The basal, deepening upwards platform package (FA-4C) is inferred in core from north-central North Dakota (Martiniuk, et al., 1995) and is present in core from this study (#24456).

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. 9). The regressive open-marine deposits are subsequently overlain by bank deposits of the HST, where water depth and environment allow for bank development.

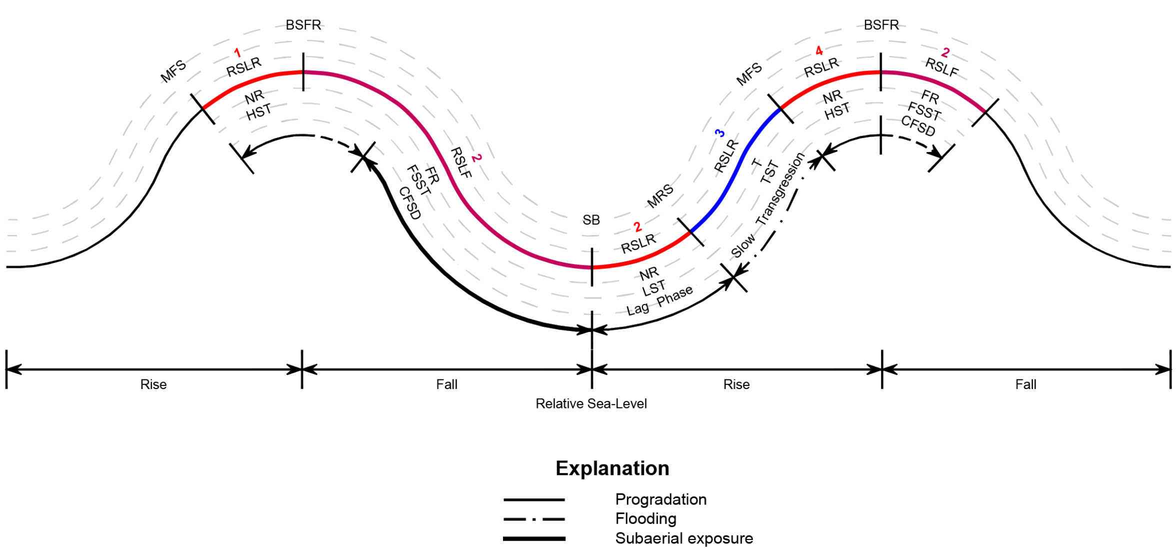

Figure 9. Sea-level curve. See Figure 8 for abbreviations.

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 west (Time T6; Figs. 8 and 10).

Devonian Sequence Stratigraphy

Late Devonian (Duperow, Birdbear, and Three Forks Formations) sequence stratigraphic relations are preliminarily shown on Figure 10 utilizing logs from the Pierre Creek 21-17 well. The entire section likely 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 (Wilson and Pilatzke, 1987). 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. 10). Systems tracts and sequence boundaries can be identified within each of these cycles, just like in the siliciclastic environment, as was discussed above for the B-zone (Fig. 10). 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. 8). Sea level then dropped again, and the shallowing cycle repeated itself three more times during deposition of the A-zone shallow-water lagoonal and sabkha deposits. This repetitive pattern is represented by the "Systems Tracts/Times 1, 2, 3, 4, 2-pattern" shown on the inset blow-up in Figure 10 and depicted on Figure 8. A representative fourth-order sequence boundary is shown from 10,996 feet on Figure 10.

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. 8 and 10) leading to a more restricted basin with hypersaline conditions in an arid environment during deposition of the Three Forks.

SUMMARY

The stratigraphic framework presented herein provides a foundation from which additional studies may be conducted, particularly as related to carbonate sequence stratigraphy for the Birdbear, which, until now, has not been addressed. Sequence stratigraphy is an important, novel, and modern concept utilized to evaluate sedimentary rocks in terms of base-level changes and depositional trends that arise from the interplay between accommodation space and sedimentation. It is a powerful tool that may be used to analyze local to global sea-level fluctuations in sedimentary settings such as the Williston Basin. Specifically, sequence stratigraphy may be utilized in data- and model-driven hydrocarbon exploration to better formulate and predict: 1) lateral and vertical facies changes including cyclicity; 2) diagenetic trends; 3) reservoir compartmentalization; and 4) source rock distribution, among others.

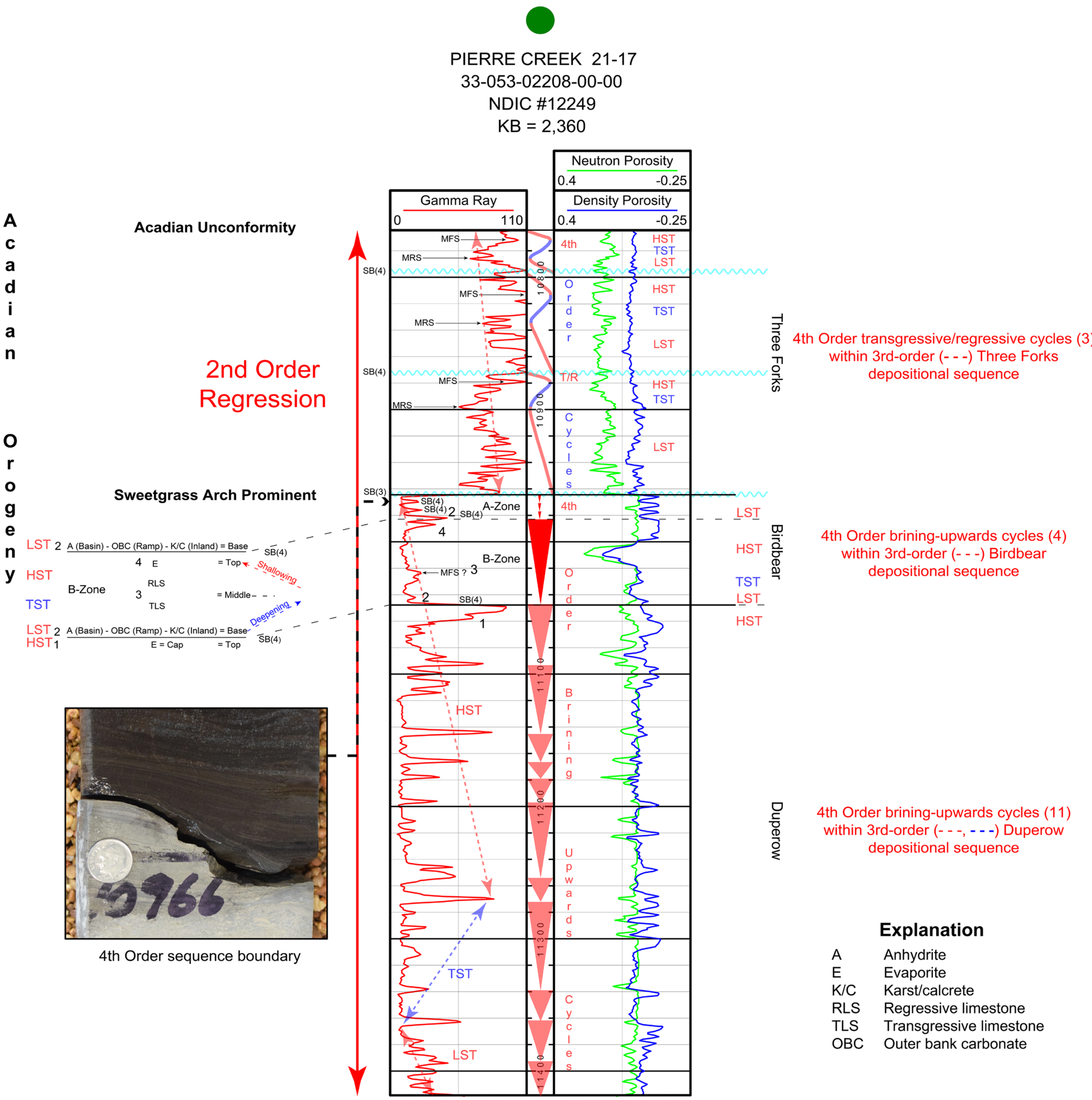

Figure 10. Type log Devonian sequence stratigraphy. See Figure 8 for other abbreviations.

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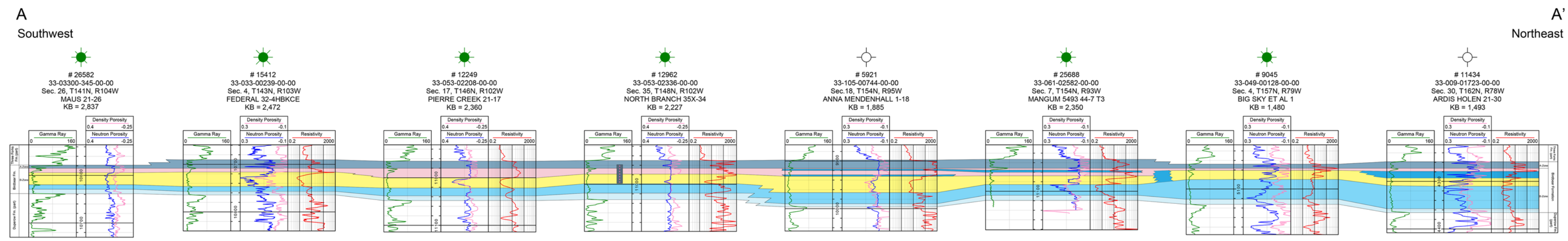
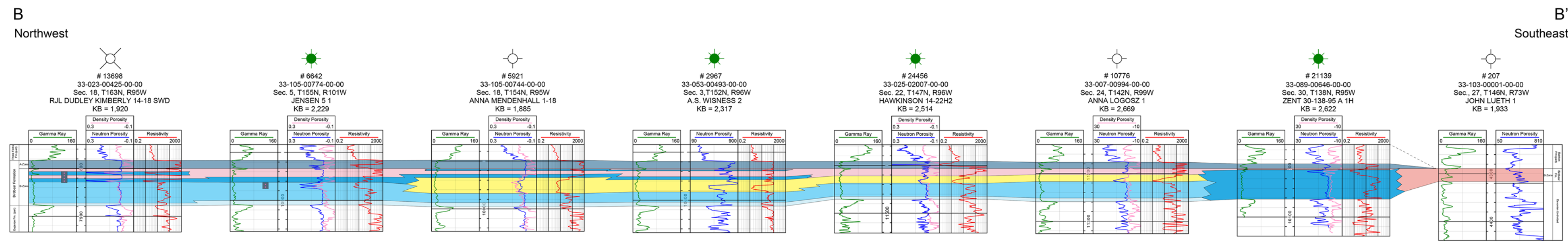
North Dakota Geological Survey
Report of Investigation No. 125
Plate I

Core/Log Cross-Sections A-A’ and B-B’

Edward C. Murphy, State Geologist
Lynn Helms, Director Dept. of Mineral Resources
2020





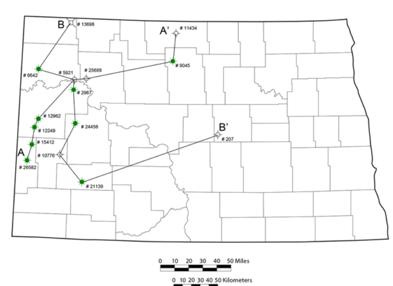
Explanation

B-Zone:

- A-Zone
- Sabkha (HST)
- Mud Flats (HST)
- Restricted Marine (HST)
- Bank (HST)
- Open Marine (TST and HST)
- Open Marine (LST)

Symbols:

- Oil and Gas Well
- Dry Hole
- Water Injection Well
- Perforated Interval
- KB Kelly Bushing Elevation (ft)



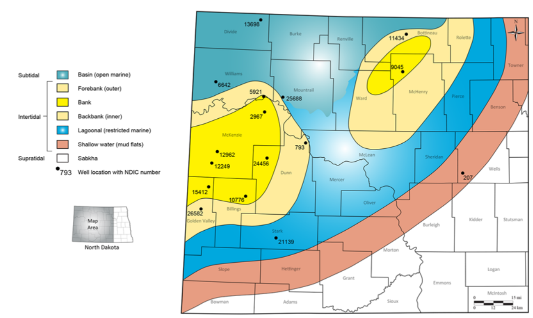


Figure 6

Plate 1. Core/Log cross-sections A-A’ and B-B’ with B-zone paleogeographic map (Fig. 6) for reference.

Legend

Anhydrite

Dolostone

Limestone

Shale

Claystone

Mudstone

Siltstone

Amphipora

Anhydritic

Anhydrite-Bladed

Anhydrite-Nodular

Brachiopod

Brecciated/Disrupted Bedding

Burrow

Carbonaceous

Cemented Fracture

Coral

Cross Laminated

Dolomitic

Fossil

Gastropod

Intraclast

Ostracod

Pelloid

Ripple Lamination

Rugose Coral

Skeletal Material

Stromatoporoid

Stylolite

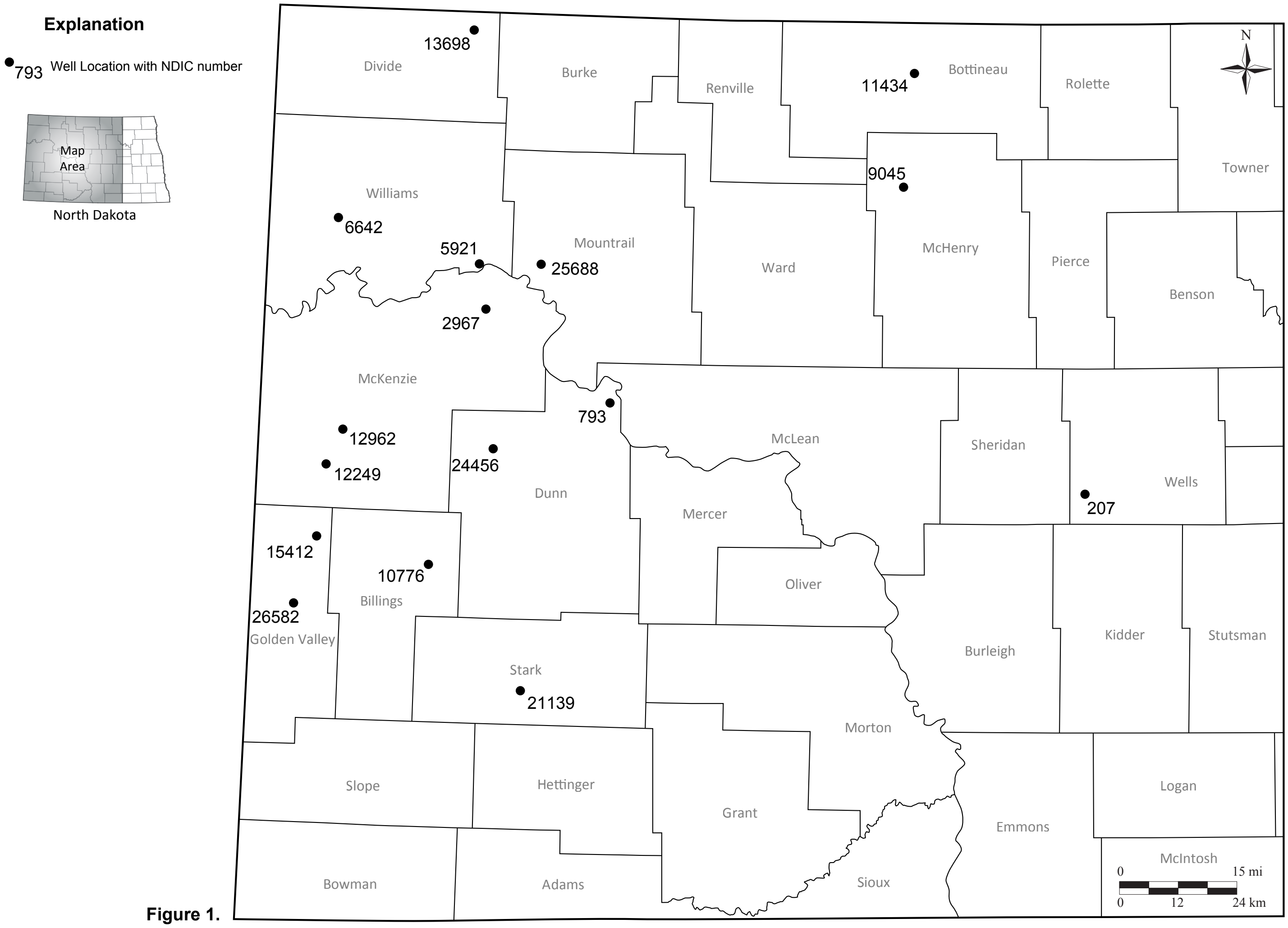
Burrow Mottled

Undulatory Bedding

Vuggy Porosity

Wavy Bedding

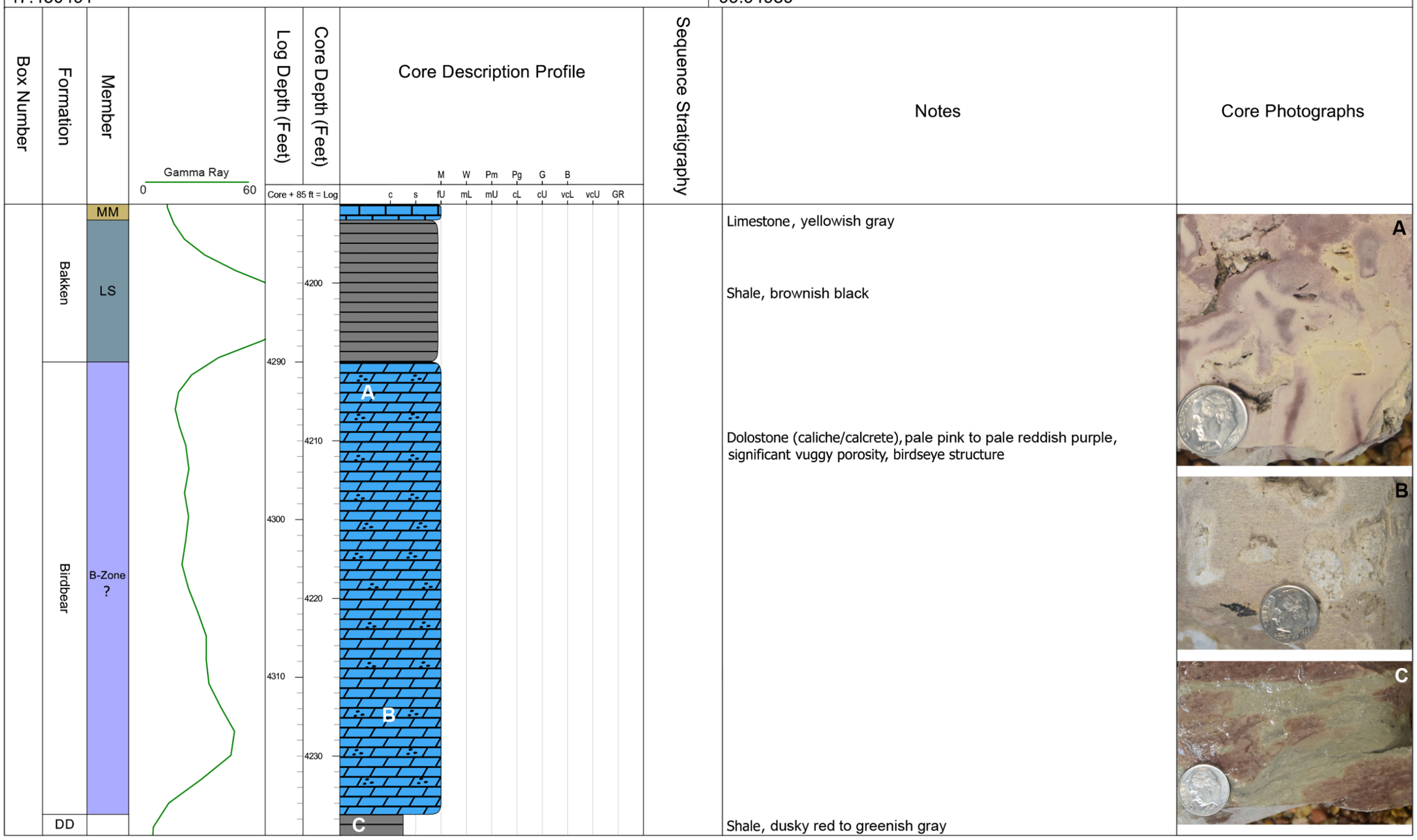
DD	Duperow Formation
DTF	Three Forks Formation
LS	Lower Shale (Bakken)
LTF	Lower Three Forks
MM	Middle Member (Bakken)
UD	Upper Devonian



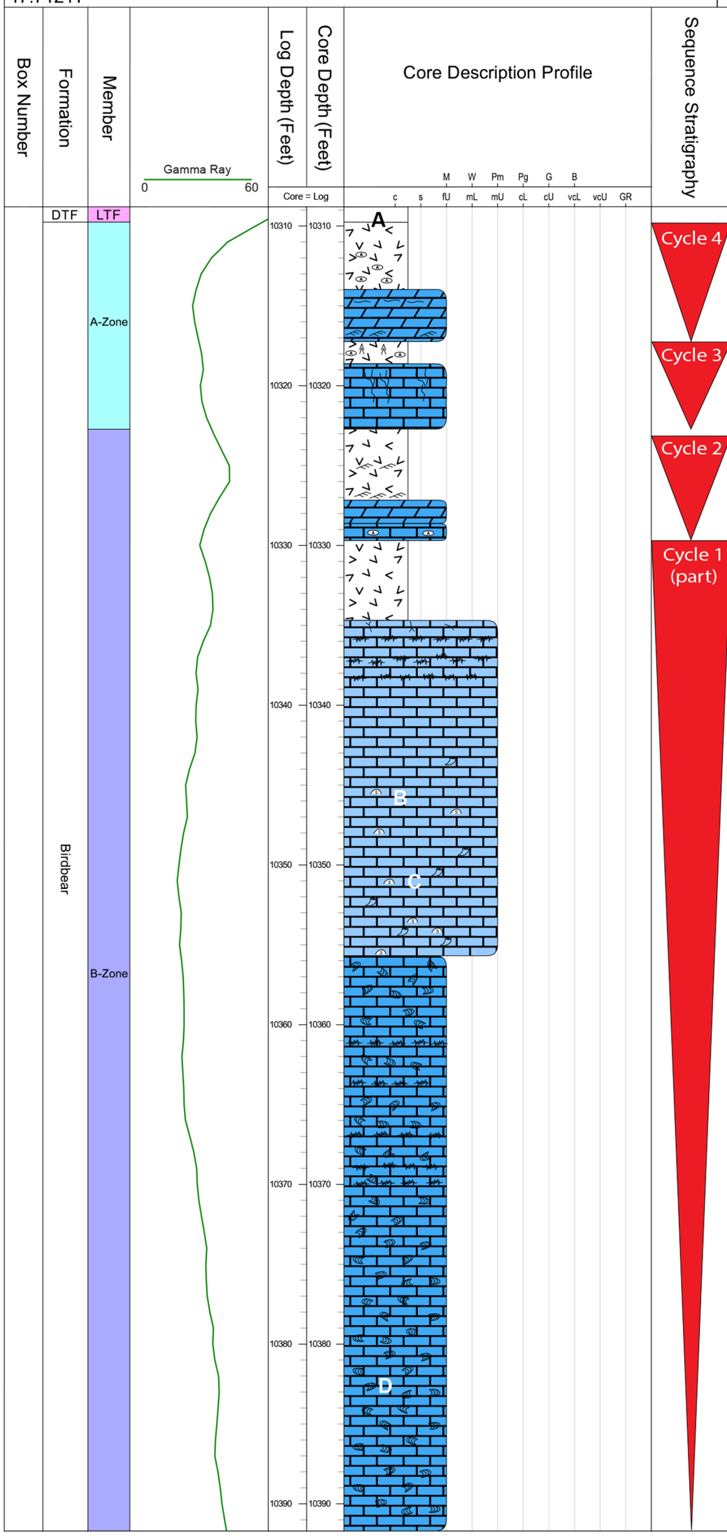
Explanation
793 Well Location with NDIC number
Map Area
North Dakota
N
Divide
13698
Burke
Renville
Bottineau
11434
Rolette
Towner
Williams
6642
5921
25688
Mountrail
Ward
9045
McHenry
Pierce
Benson
2967
McKenzie
793
12962
12249
24456
Dunn
McLean
Sheridan
Wells
207
Mercer
15412
10776
Billings
26582
Golden Valley
Oliver
Burleigh
Kidder
Stutsman
Stark
21139
Morton
Slope
Hettinger
Grant
Emmons
Logan
Bowman
Adams
Sioux
McIntosh
0
15 mi
0
12
24 km

Figure 1.

Original Operator: Continental Oil Co.	
Top: 4195 ft	Bottom: 4235 ft
Original Well Name & No.: John Lueth 1	Location: SESE Sec. 27, T146N, R73W
Logged by: Jeffrey W. Bader	Date: Fri Aug 2 2019
Basin: Williston	UWI No.: 33-103-00001-00-00
NDIC No.: 207	Field: Wildcat
KB: 1933 ft	TD: 6031 ft
Latitude: 47.430491	Longitude: -99.94989



Original Operator	
Mobil Producing Company	
Top: 10308.8 ft	Bottom: 10391.7 ft
Original Well Name & No.: Pegasus Div Soloman Birdbear #F 22-22-1	Location: SENW Sec. 22, T149N, R91W
Logged by: Jeffrey W. Bader	Date: Thu Mar 14 2019
Basin: Williston	UWI No.: 33-033-025-00005-00-00
NDIC No.: 793	Field: Wildcat
KB: 2102 ft	TD: 13481 ft
Latitude: 47.71211	Longitude: -102.313085



Notes

Anhydrite, medium bluish gray, bedded to nodular

Dolostone, pale yellowish brown to pinkish gray, laminated to ripple cross laminated

Anhydrite, pinkish gray to medium dark gray, nodular to bladed

Limestone (mudstone), olive gray, laminated to thin-bedded, hairline anhydrite-filled fractures, becomes dolostone from 10,318.6 to 10,318.9 ft. and from 10,321.0 to 10,32.7 ft., dolostone is thin-bedded to massive.

Anhydrite, medium bluish gray, bedded, thin dolostone interbeds

Dolostone, very pale orange, massive

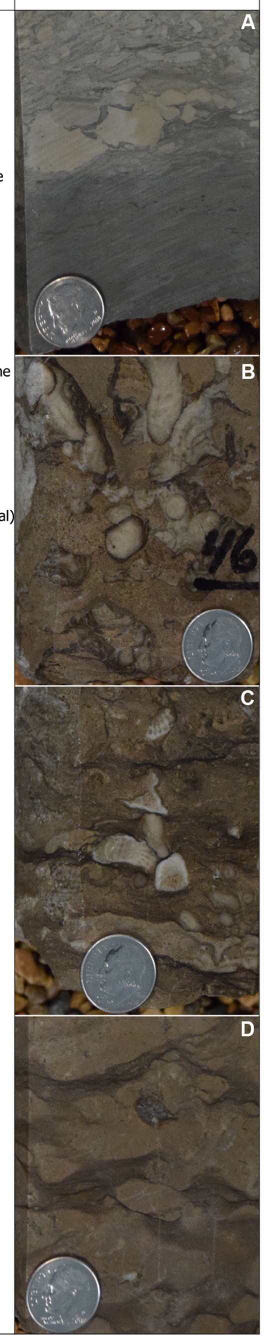
Limestone, brownish black, dolomitic

Anhydrite, light bluish gray to light olive gray, bedded, thin dolostone interbeds from 10,331.6 ft.

Limestone (mudstone to packstone), dusky yellowish brown, laminated to massive, fossiliferous (amphipora, stromatoporoids, coral)

Limestone (mudstone), olive gray, wispy laminated to massive (burrowed/bioturbated), stylolitic

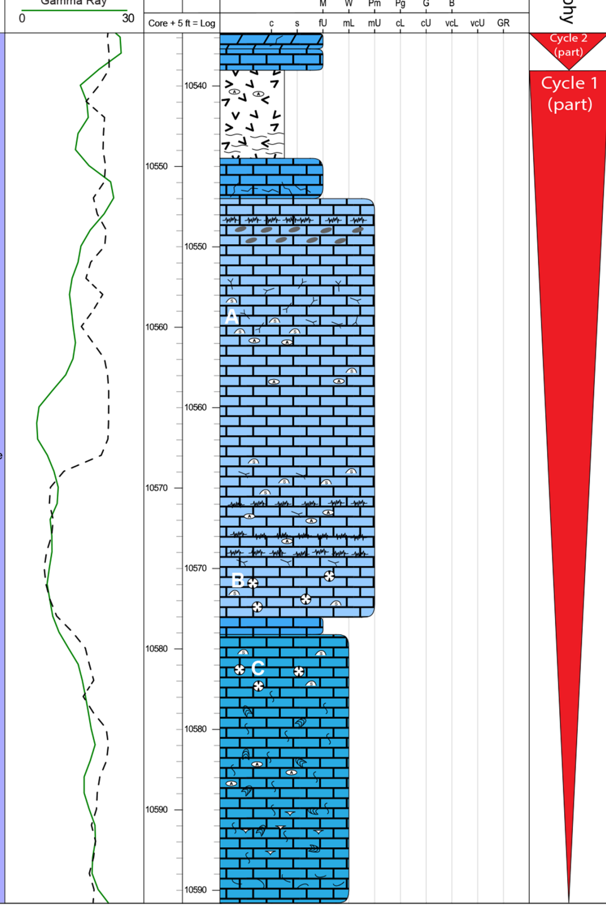
Core Photographs



Original Operator
Texaco Inc.

Top 10536.7 ft	Bottom 10590.8 ft
Original Well Name & No. A.S. Wisness #2	Location NWSE Sec. 3, T152N, R96W
Logged by Jeffrey W. Bader	Date Thu Apr 18 2019
Basin Williston	UWI No. 33-053-00493-00-00
NDIC No. 2967	Field Keene
KB 2317 ft	TD 11092 ft
Latitude 48.012382	Longitude -102.948411

Box Number	Formation	Member	Resistivity / Gamma Ray	Log Depth (Feet)	Core Depth (Feet)	Core Description Profile	Sequence Stratigraphy	Notes	Core Photographs
	Birdbear	B-Zone							



Dolostone, pale yellowish brown

Limestone (mudstone), brownish black

Anhydrite, medium dark gray, bedded, thin dolostone interbeds

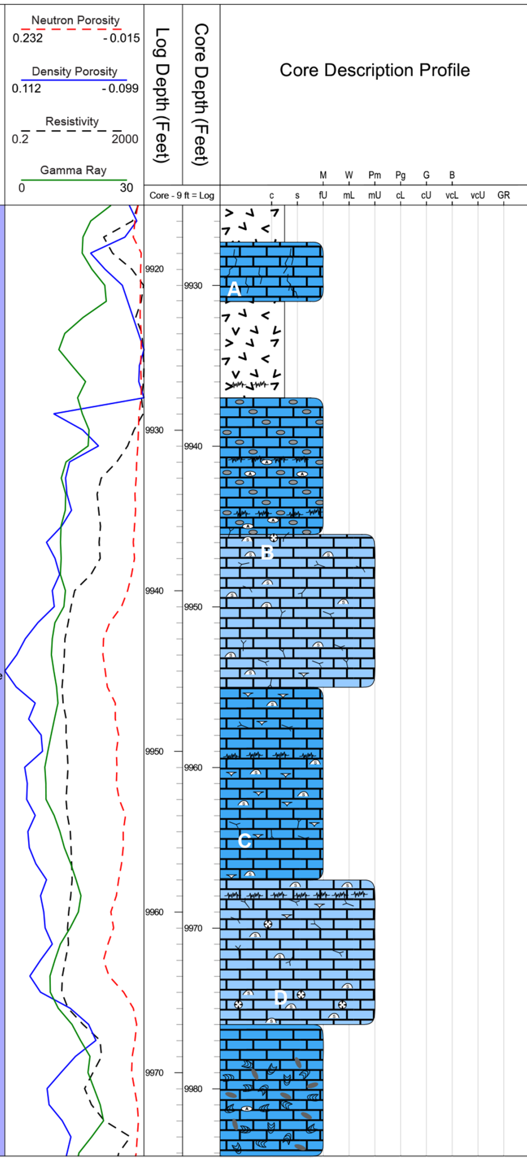
Limestone (mudstone), brownish gray to greenish gray, calcite-filled fractures

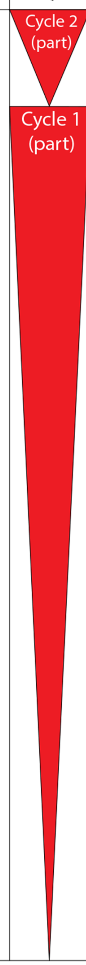
Limestone (wackestone to packstone), pelloidal, stylolitic, fossiliferous (amphipora, laminar and bolbous stromatoporoids, coral, brachiopods), burrow mottled at 10,578 ft.

Original Operator
Ashland Oil, Inc.

Top 9925 ft	Bottom 9984.2 ft
Original Well Name & No. Anna Mendenhall 1-18	Location SESE Sec. 18, T154N, R95W
Logged by Jeffrey W. Bader	Date Sat Mar 2 2019
Basin Williston	UWI No. 33-105-00744-00-00
NDIC No. 5921	Field Grinnell
KB 1885 ft	TD 10600 ft
Latitude 48.155641	Longitude -102.938406

Box Number	Formation	Member	Logs	Log Depth (Feet)	Core Depth (Feet)	Core Description Profile	Sequence Stratigraphy	Notes	Core Photographs
	Birdbear	B-Zone							



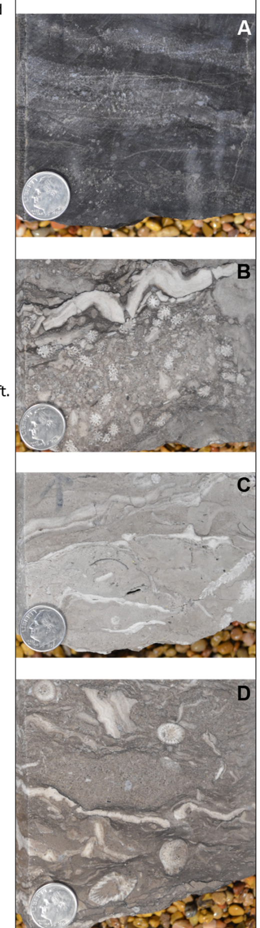


Anhydrite, medium dark gray, interbedded with ripple cross-laminated dolostone

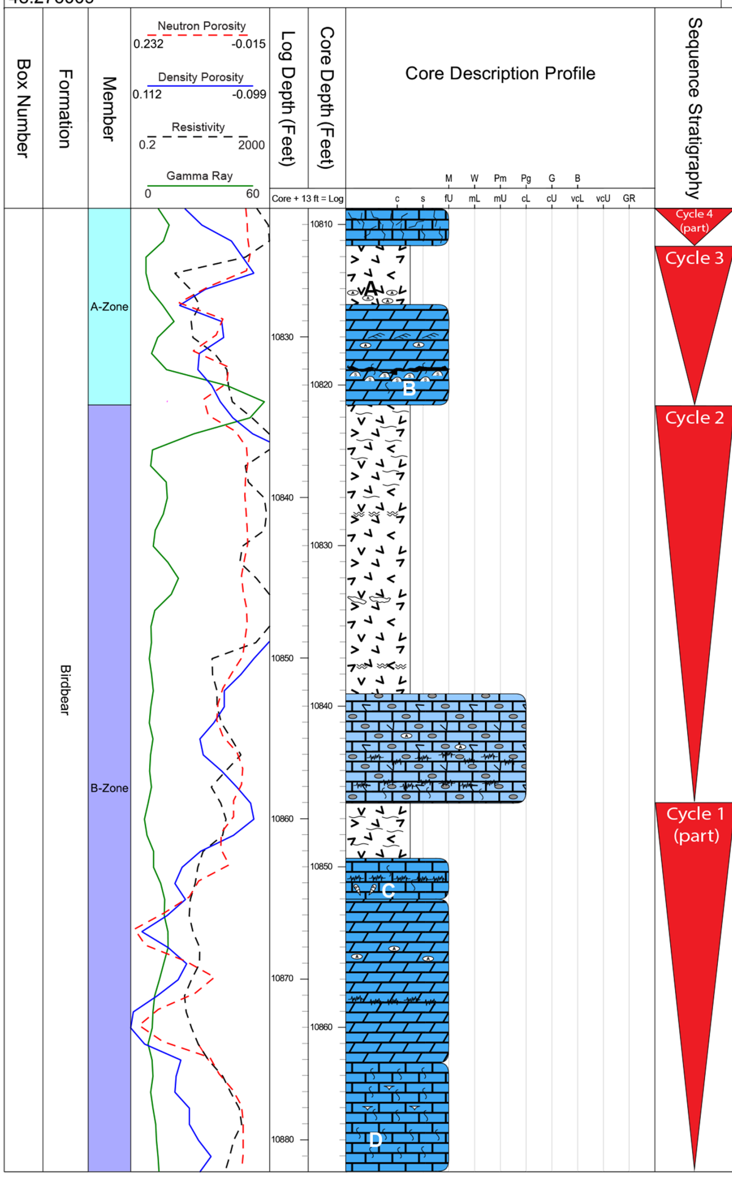
Limestone (mudstone), dark gray, laminated to massive

Anhydrite, dark greenish gray, interbedded with dolostone and carbonaceous laminations

Limestone (mudstone to packstone), yellowish gray, laminated to massive, fossiliferous (amphipora, thamnopora, laminar and bolbous stromatoporoids, brachiopods), pelloidal, burrow mottled from 9978.2 ft.



Original Operator	Tenneco Oil Company		
Top	10809 ft	Bottom	10869 ft
Original Well Name & No.	W.C. Jensen et al #1-5	Location	NESE Sec. 5, T55N, R101W
Logged by	Jeffrey W. Bader	Date	Wed Feb 27 2019
Basin	Williston	UWI No.	33-105-00774-00-00
NDIC No.	6642	Field	Missouri Ridge
KB	2229 ft	TD	13536 ft
Latitude	48.276009	Longitude	-103.693631



Notes

Limestone (mudstone), dark greenish gray, becomes dolostone at 10,811.1 ft.

Anhydrite, medium gray to very light gray, bedded to nodular

Dolostone, pale yellowish brown, oil stained, laminated to ripple cross-laminated, interbedded with thin limestone beds, fossiliferous (stromatoporoids), carbonaceous

Anhydrite, light bluish gray to medium dark gray, bedded, algal stromatolites ?

Limestone (sucrosic to packstone), grayish black to greenish gray, peloidal, fossiliferous (gastropods ?), thin dolostone interbeds

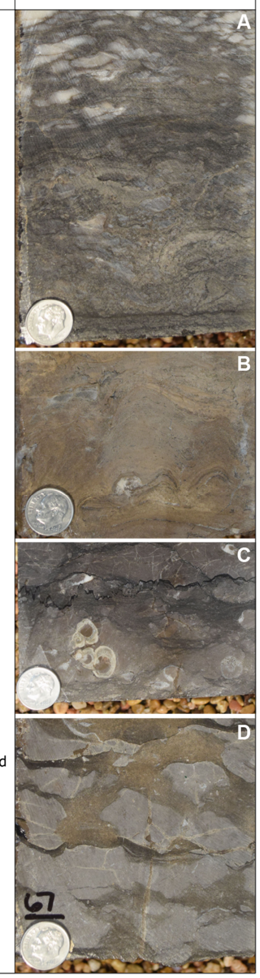
Anhydrite, bedded

Limestone (mudstone), fossiliferous (gastropods), burrowed

Dolostone, light olive gray, porous, relict burrows, minor anhydrite-filled vugs, carbonaceous stringers throughout, oil stained, limestone from 12,858-12,859 ft.

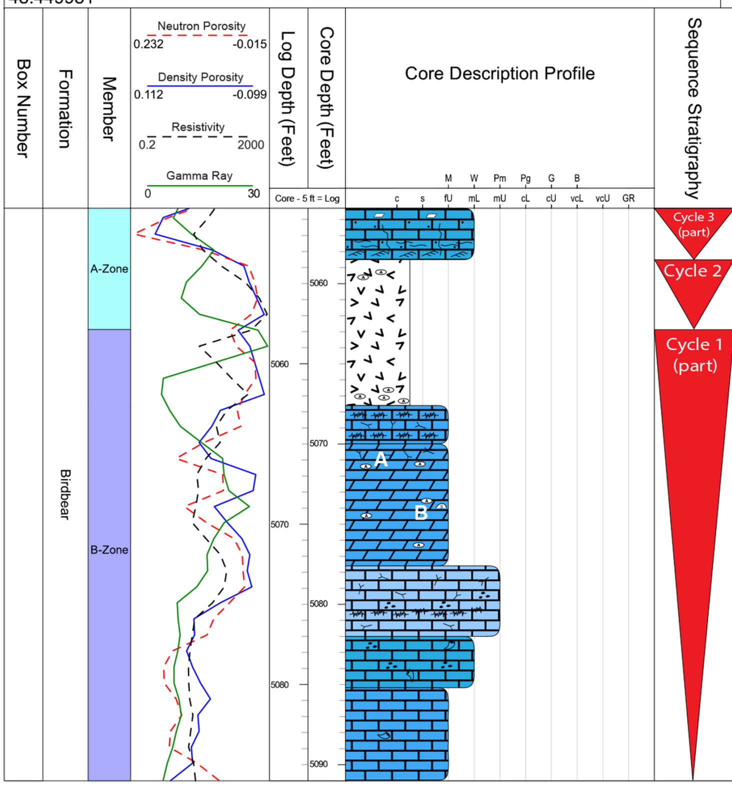
Limestone (mudstone), burrow mottled ?, fossiliferous (brachiopods)

Core Photographs



Original Operator
Energy Reserves Group Inc.

Top 5055.3 ft	Bottom 5091 ft
Original Well Name & No. Big Sky et al #1	Location NWSE Sec. 4, T157N, R79W
Logged by Jeffrey W. Bader	Date Mon Mar 11 2019
Basin Williston	UWI No. 33-049-00128-00-00
NDIC No. 9045	Field Wildcat
KB 1480 ft	TD 5550 ft
Latitude 48.449981	Longitude -100.872124



Notes

Limestone (mudstone to wackestone), very pale orange to pale yellowish brown, ripple-laminated to cross bedded, anhydrite-filled fractures, dolomitic mudstone from 5055.3 to 5055.8 ft.

Anhydrite, greenish gray to medium bluish gray, thin dolostone interbeds

Limestone (mudstone), very pale orange, dolomitic, fossiliferous (amphipora), stylolitic

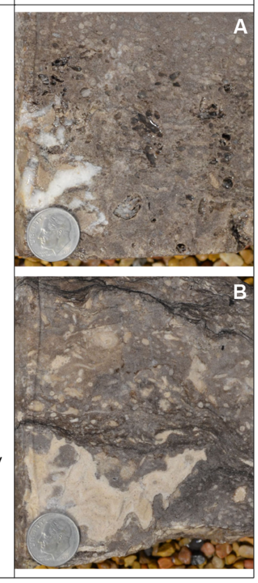
Dolostone, dark yellowish brown, fossiliferous (amphipora, tabular stromatoporoids, coral), vuggy porosity, some anhydrite-filled cavities

Limestone (packstone), dusky yellow, fossiliferous (amphipora), finer intraparticle and vuggy porosity, stylolitic

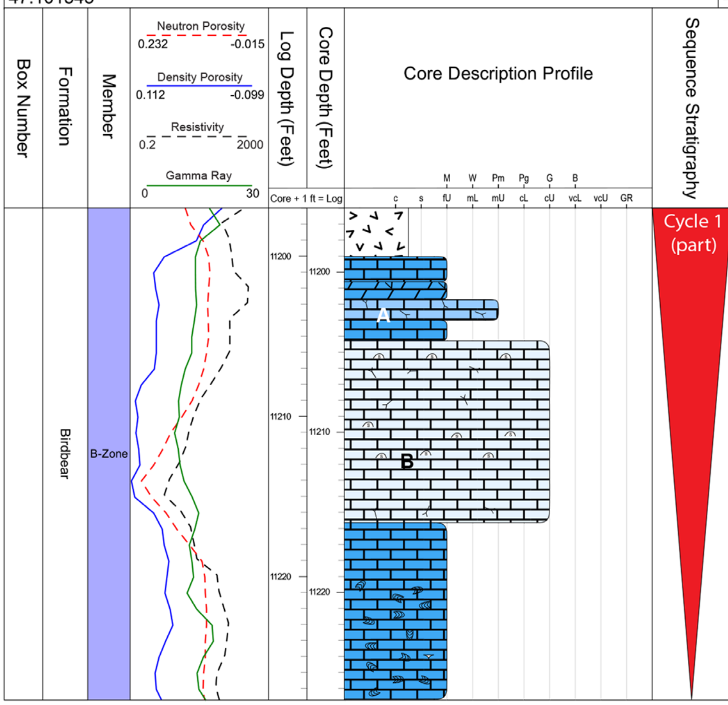
Limestone (wackestone to packstone), grayish yellow, fossiliferous (amphipora, solitary rugose coral), interparticle and vuggy porosity with some anhydrite filled, stylolytic

Limestone (mudstone), pinkish gray, dolomitic, sucrosic, trace vuggy porosity and coral

Core Photographs



Original Operator Propel Energy Co.	
Top 11196 ft	Bottom 11226.7 ft
Original Well Name & No. Anna Logosz 1	Location NESW Sec. 24, T142N, R99W
Logged by Jeffrey W. Bader	Date Mon Jul 29 2019
Basin Williston	UWI No. 33-007-00994-00-00
NDIC No. 10776	Field Wildcat
KB 2669 ft	TD 11636 ft
Latitude 47.101543	Longitude -103.172644



Notes

Anhydrite, dark greenish gray, bedded, interbedded with grayish claystone

Limestone (mudstone), dark gray, massive

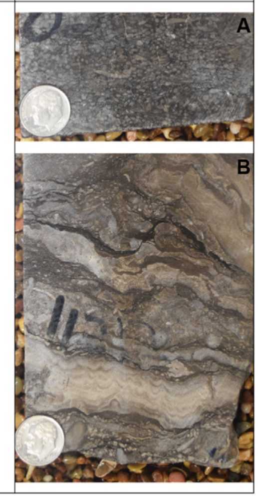
Dolostone

Limestone (packstone)

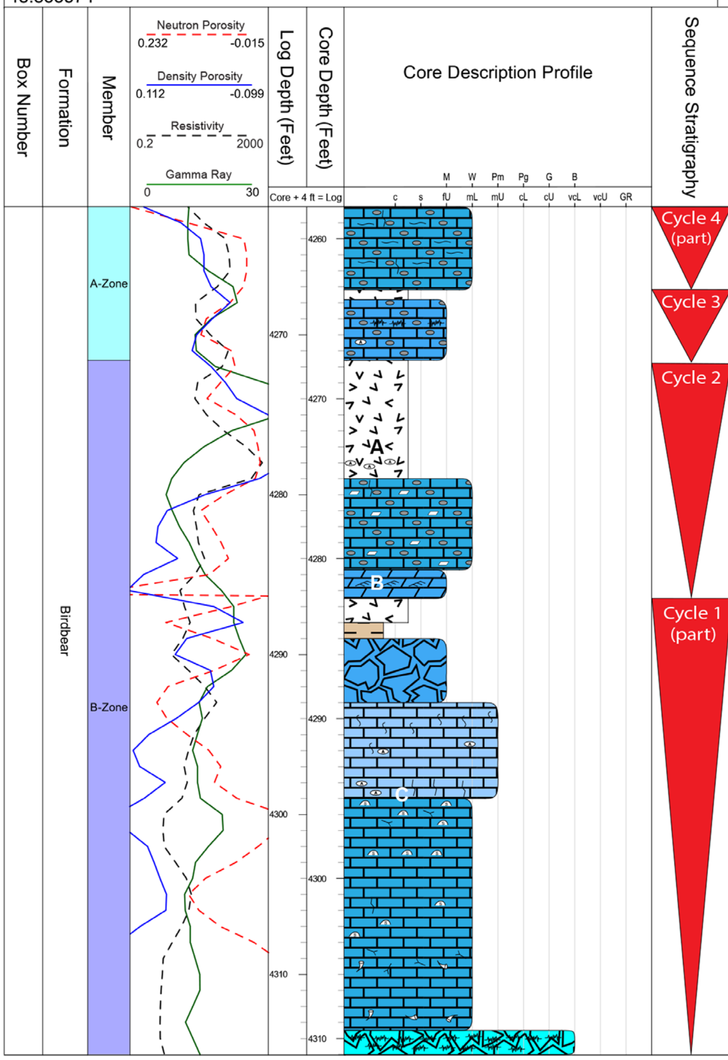
Limestone (packstone to bindstone), fossiliferous (laminar and bolbous stromatoporoids, amphipora, coral)

Limestone (mudstone), burrow mottled, fossiliferous (brachiopods)

Core Photographs



Original Operator Citation Oil and Gas Corporation	
Top 4258 ft	Bottom 4311 ft
Original Well Name & No. Ardis Holen #21-30	Location NENW Sec. 30, T162N, R78W
Logged by Jeffrey W. Bader	Date Mon Mar 4 2019
Basin Williston	UWI No. 33-009-01723-00-00
NDIC No. 11434	Field Wildcat
KB 1493 ft	TD 4500 ft
Latitude 48.833574	Longitude -100.831976



Notes

Limestone (mudstone to wackestone), dark yellowish brown, laminated to thin-bedded to disrupted bedding, anhydrite-filled fractures, pelloids, becomes silty mudstone from 4262.6 to 4263.2 ft.

Limestone (mudstone to wackestone),very pale orange to dusky yellowish brown, dolomitic, calcispheres, pelloids, hairline anhydrite-filled fractures

Anhydrite, medium bluish gray to medium light gray, bedded to nodular, thin claystone interbeds, becomes more silty at 4274.2 ft.

Limestone (mudstone to wackestone),very pale orange to dark yellowish brown, dolomitic, hairline anhydrite-filled fractures, pelloids

Dolostone, dusky yellow, ripple cross-laminated, silty

Anhydrite

Claystone, grayish green, silty

Limestone (mudstone), pinkish gray, brecciated, anhydrite clasts/nodules at 4288.4 to 4288.8 ft.

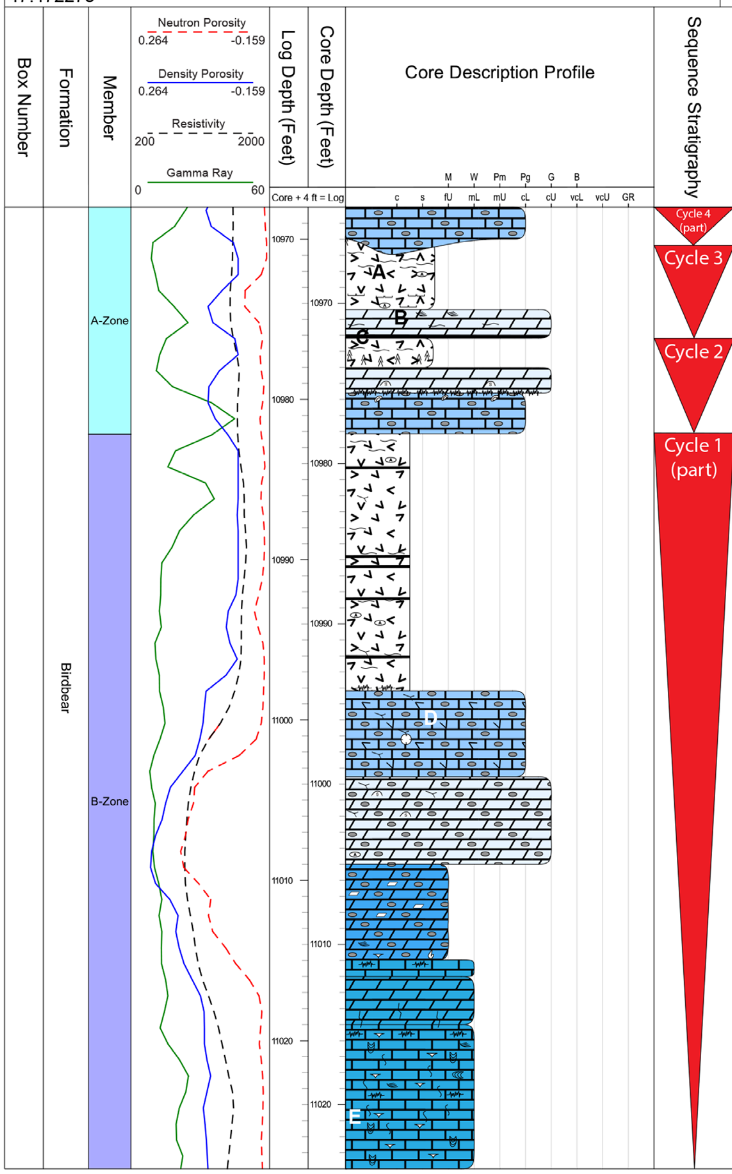
Limestone (packstone), pale yellowish brown, heavily burrowed, calcispheres, anhydrite-filled voids and fractures, stylolites, carbonaceos (coaly) laminations, fossiliferous ? (brachiopods)

Limestone (mudstone), pale yellowish brown, very fossiliferous (stromatoporoids, amphipora, coral), calcispheres, becomes more wackestone to packstone at 4299.1 ft.; floatstone ? in places

Limestone (boundstone ?), pink to black, highly stylolitic and brecciated

Core Photographs

Original Operator: Meridian Oil, Inc.	
Top: 10964 ft	Bottom: 11024 ft
Original Well Name & No.: MOI # 21-17	Location: NENW Sec. 17, T146N, R102W
Logged by: Jeffrey W. Bader	Date: Tue Aug 14 2018
Basin: Williston	UWI No.: 33-053-02208-00-00
NDIC No.: 12249	Field: Pierre Creek
KB: 2360 ft	TD: 13323 ft
Latitude: 47.472273	Longitude: -103.707705



Notes

Limestone, brownish black, massive to planar laminated

Anhydrite, very light gray to olive gray, thin-bedded to laminated, wavy and more nodular at base, disrupted/brecciated bedding

Dolostone, light olive brown, crystalline, oil stained, carbonaceous at base

Anhydrite, light bluish gray, bladed

Dolostone, fossiliferous (stromatoporoids)

Limestone, brownish black, fossiliferous (ostracods), peloidal

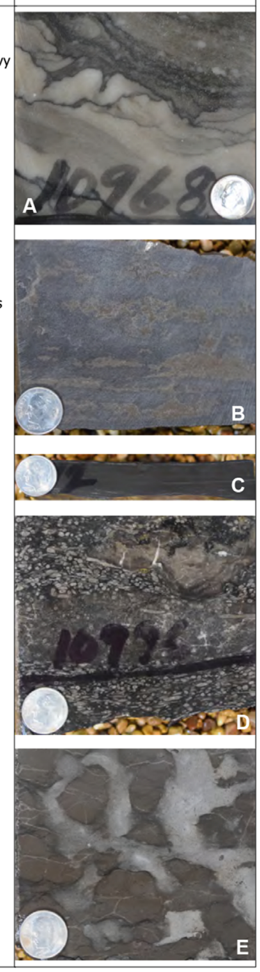
Anhydrite, thin-bedded to laminated, greenish gray to light gray, interbedded with dolostone and carbonaceous shale, nodular in places

Limestone, olive black, fossiliferous (amphipora, thamnopora), trace anhydrite

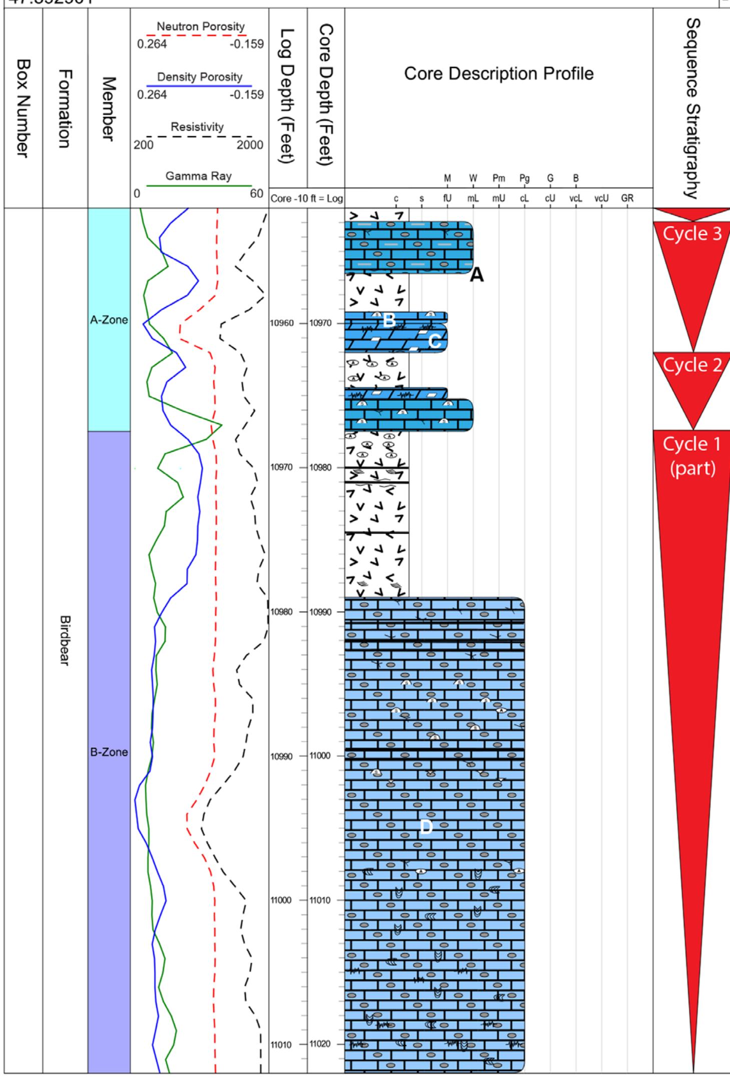
Dolostone, dark yellowish brown, crystalline, fossiliferous (stromatoporoids, amphipora), oil stained, wavy bedded to cross laminated, minor anhydrite filling in fractures and voids, peloidal

Limestone, brownish gray, fossiliferous (brachiopods, crinoids ?), massive (wavy- to cross-laminated locally), dolomitic from 11,012.0 to 11,015.0, burrow-mottled from 11,012.5 to 11,024.0 ft.

Core Photographs



Original Operator	
Penzoil Exploration and Production Company	
Top: 10962 ft	Bottom: 11022 ft
Original Well Name & No.: North Branch 35X-34 BN	Location: SWSE Sec. 35, T148N, R102W
Logged by: Jeffrey W. Bader	Date: Fri Aug 31 2018
Basin: Williston	UWI No.: 33-053-02336-00-00
NDIC No.: 12962	Field: North Branch
KB: 2227 ft	TD: 13465 ft
Latitude: 47.592901	Longitude: -103.635141



Notes

Limestone, greenish black, fossiliferous (amphipora), massive, carbonaceos material throughout, peloidal

Anhydrite, dolomitic interbeds

Limestone, fossiliferous (stromatoporoids), laminated

Dolostone, dark yellowish brown, fossiliferous (amphipora), laminated- to thin-bedded, anhydritic, oil stained

Anhydrite, bluish white, nodular, bedded

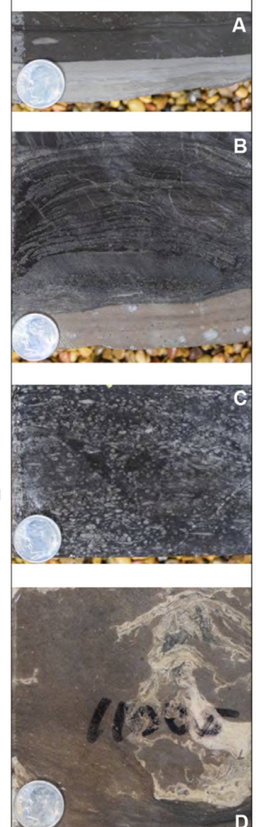
Dolostone, pale yellowish brown, wavy laminated to massive

Limestone, greenish black, massive, fossiliferous (stromatoporoids, amphipora), anhydritic

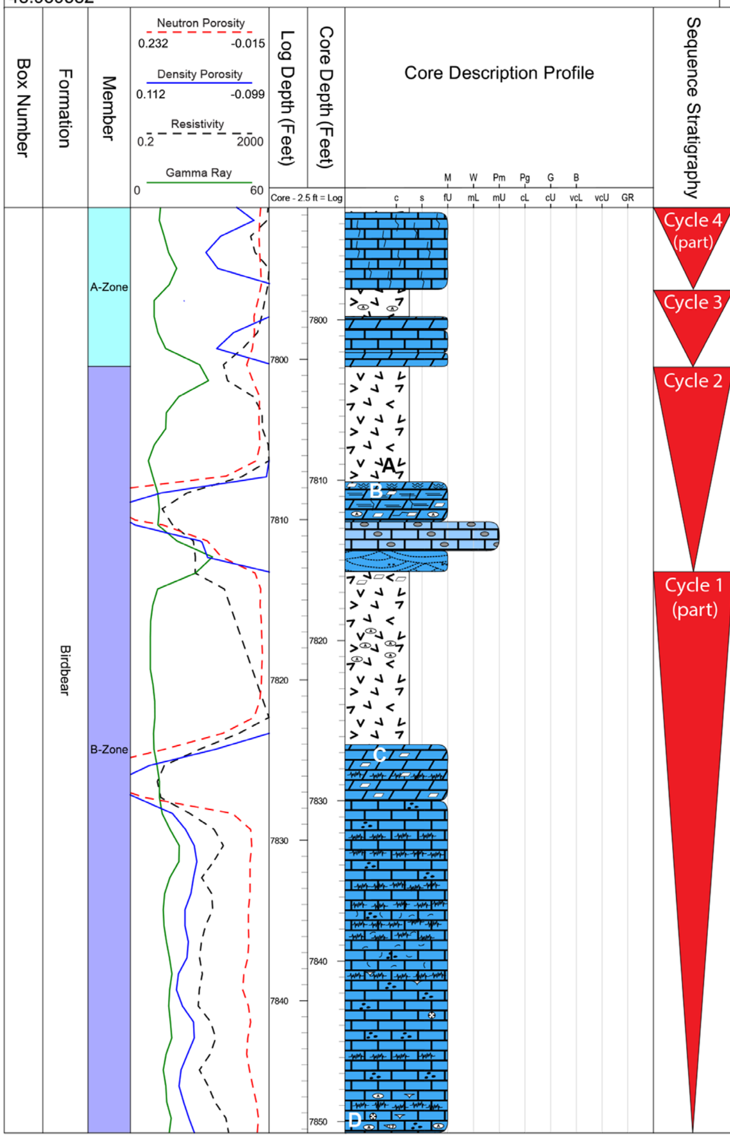
Anhydrite, bluish white, nodular- to thin-bedded, interlaminated with dolostone and black carbonaceous shale

Limestone, olive black, fossiliferous (stromatoporoids, amphipora, brachiopods), laminated to thin-bedded and more massive towards base, dolomitic locally, becomes burrow-mottled at 11,008 ft., peloidal

Core Photographs



Original Operator	
RJL Oil and Gas, Inc.	
Top: 7793 ft	Bottom: 7850.7 ft
Original Well Name & No.: RJL Dudley Kimberly #14-18	Location: SESW Sec. 18, T163N, R95W
Logged by: Jeffrey W. Bader	Date: Mon Feb 11 2019
Basin: Williston	UWI No.: 33-023-00425-00-00
NDIC No.: 13698	Field: Kimberly
KB: 1920 ft	TD: 7950 ft
Latitude: 48.939582	Longitude: -103.061891



Notes

Anhydrite, very light gray to light gray, bladed

Limestone (mudstone), dusky brown, sucrosic, calcite-filled fractures, trace anhydrite

Anhydrite, medium gray to medium light gray, bedded, becomes nodular at 7799.3-7799.5 ft.
Dolostone
Limestone
Dolostone

Anhydrite, greenish gray, bedded, nodular at 7809.5 to 7810 ft.

Dolostone, grayish orange

Limestone, dusky yellow to brownish black

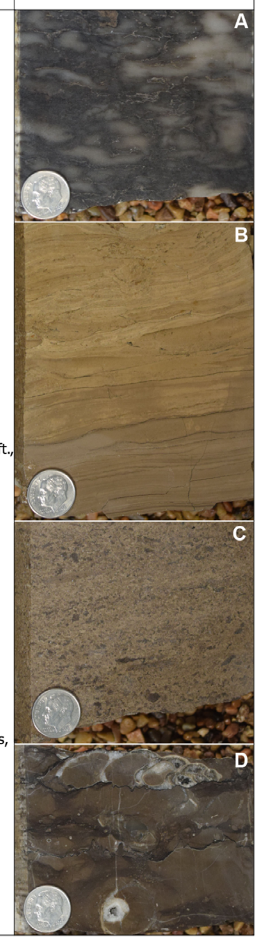
Dolostone, light olive gray

Anhydrite, medium dark gray, bedded, nodular from 7819.8 to 7821.5 ft., dolomitic, carbonaceous stringers throughout

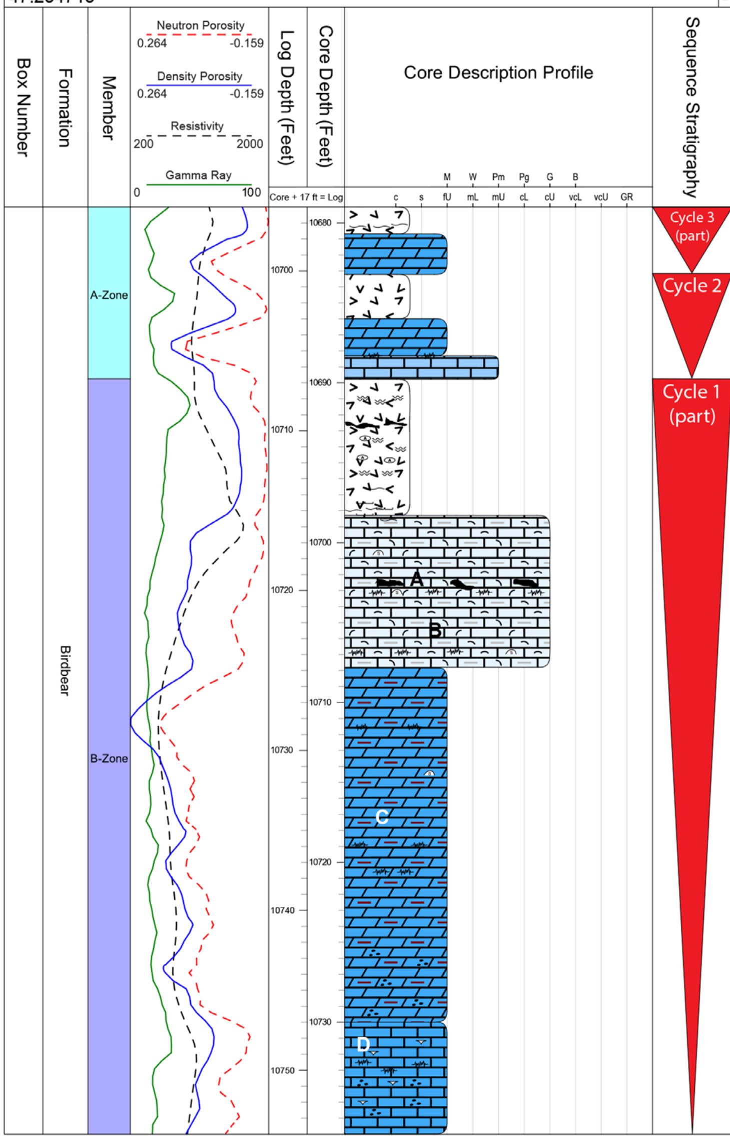
Dolostone, yellowish gray, very porous, kerogenous/oil stained, some stylolites

Limestone (mudstone to wackestone), brownish gray to olive gray, burrow-mottled at 7837 ft., vuggy porosity throughout; some filled with anhydrite, fossiliferous (brachiopods, gastrpods, coral), kerogenous, many lenticular carbonate clasts, shell debris at 7841.3 ft., oolitic ?

Core Photographs



Original Operator	
Equity Oil Company	
Top: 10679 ft	Bottom: 10737 ft
Original Well Name & No.: Federal 32-4	Location: SWNE Sec. 4, T143N, R103W
Logged by: Jeffrey W. Bader	Date: Fri Aug 24 2018
Basin: Williston	UWI No.: 33-033-00239-00-00
NDIC No.: 15412	Field: Beaver Creek
KB: 2472 ft	TD: 18368 ft
Latitude: 47.234713	Longitude: -103.739459



Notes

Anhydrite, nodular

Dolostone, laminated to thin-bedded to massive

Anhydrite

Dolostone

Limestone

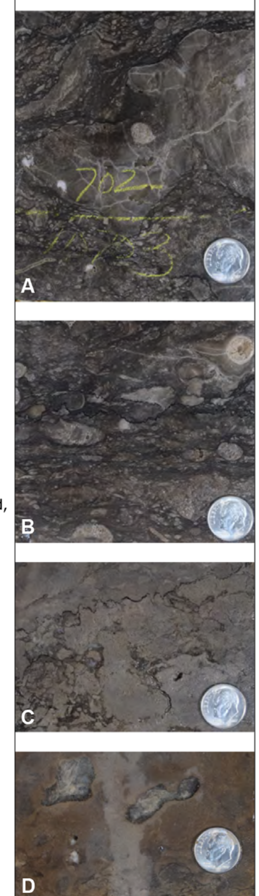
Anhydrite, bluish white to light bluish gray, interbedded with wavy laminated dolostone and carbonaceous shale

Limestone, bluish white to light bluish gray, fossiliferous (stromatoporoids, amphipora, thamnopora), carbonaceous from 10,702.4-10,702.8 ft.

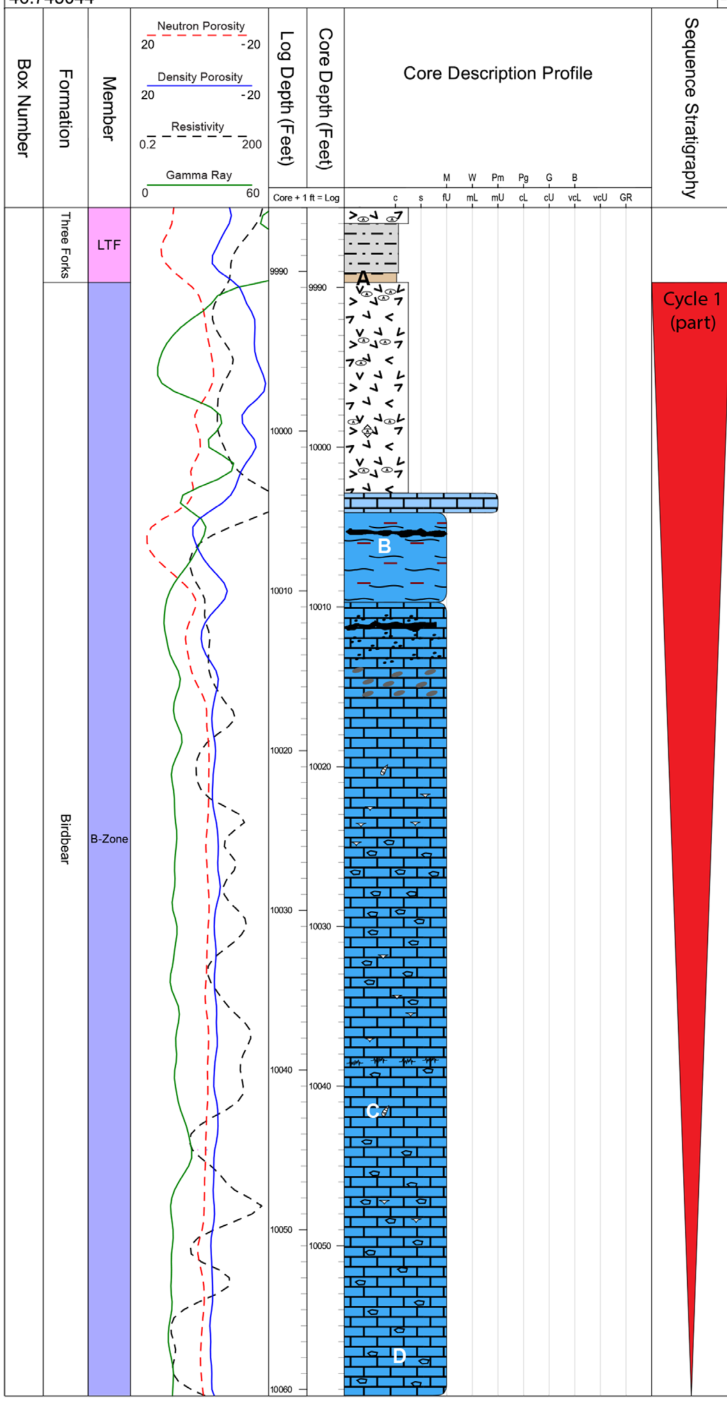
Dolostone, dark yellowish brown, massive with vuggy porosity and minor infilling with anhydrite that increases with depth, oil stained, relict fossils

Limestone, light olive gray, fossiliferous (amphipora, brachiopods), anhydite-filled vugs

Core Photographs



Original Operator Chesapeake Operating, Inc.	
Top 9985 ft	Bottom 10059.4 ft
Original Well Name & No. Zent 30-138-95 A 1H	Location NENE Sec. 30, T138N, R95W
Logged by Jeffrey W. Bader	Date Mon Jul 22 2019
Basin Williston	UWI No. 33-089-00646-00-00
NDIC No. 21139	Field Wildcat
KB 2622 ft	TD 19630 ft
Latitude 46.745044	Longitude -102.711538



Notes

Anhydrite

Mudstone, dark reddish brown

Claystone, dark yellowish green

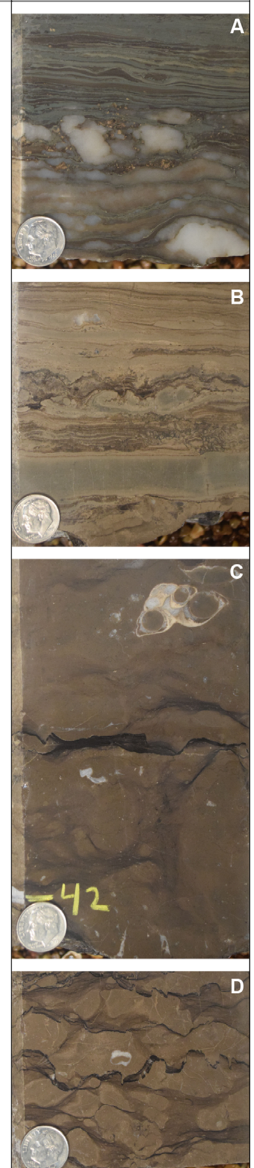
Anhydrite

Limestone (packstone to grainstone), olive gray, thin bedded

Dolostone, yellowish gray to grayish olive, interbedded with thin-bedded to laminated claystone and carbonaceous material, brecciated near base

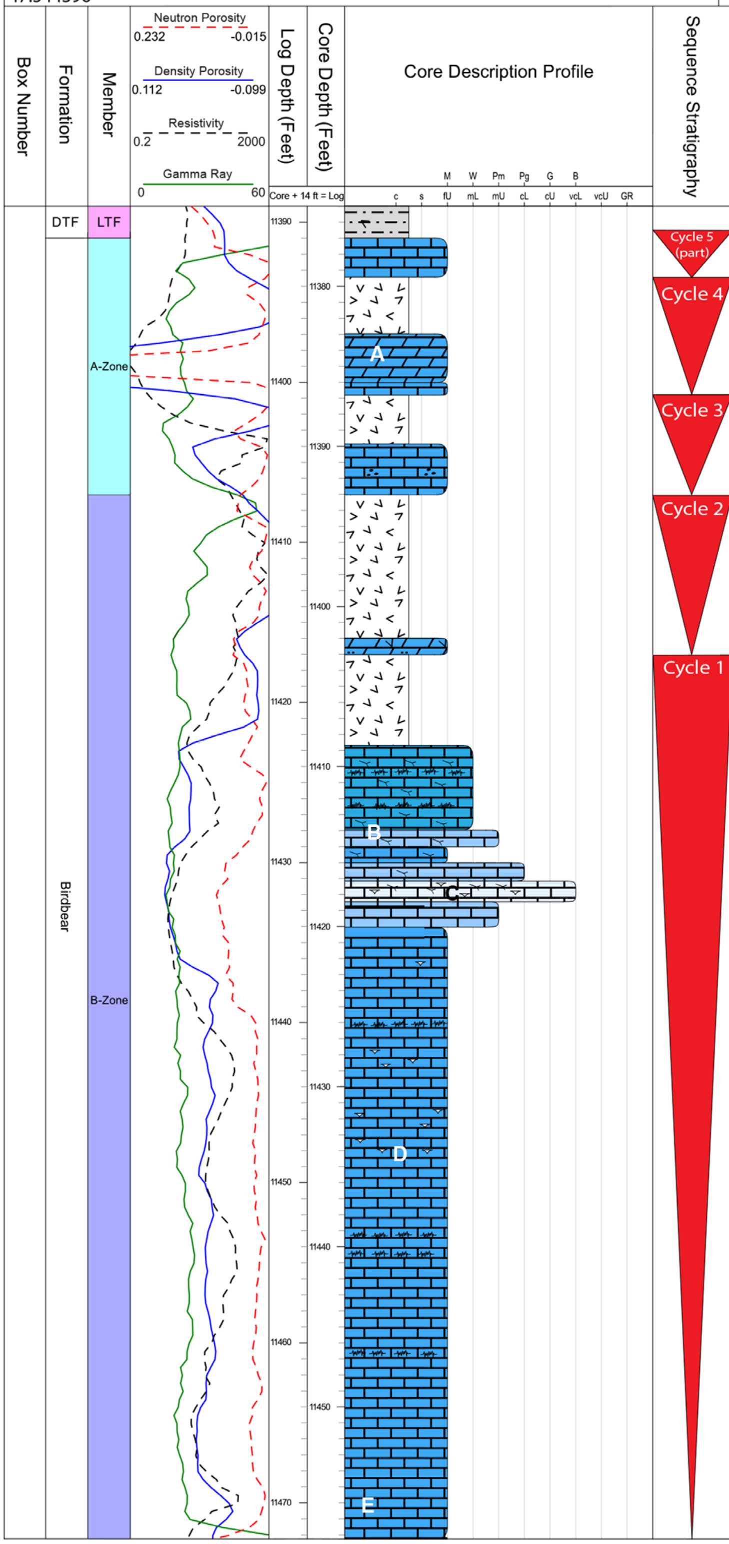
Limestone (mudstone), brownish black, laminated to thin-bedded, intraclasts? in muddy matrix, fossiliferous (gastropods, brachiopods)

Core Photographs



Original Operator
Continental Resources, Inc.

Top 11375 ft	Bottom 11460.5 ft
Original Well Name & No. Hawkinson 14-22H2	Location NENE Sec. 22, T147N, R96W
Logged by Jeffrey W. Bader	Date Thu Apr 4 2019
Basin Williston	UWI No. 33-025-02007-00-00
NDIC No. 24456	Field Oakdale
KB 2514 ft	TD 20838 ft
Latitude 47.544396	Longitude -102.889294



Notes

Mudstone

Limestone (mudstone), greenish black, massive

Anhydrite, white to medium bluish gray, bedded

Dolostone, yellowish brown, laminated to cross-laminated, sucrosic

Limestone

Anhydrite, medium bluish gray

Limestone, greenish black, massive to thin-bedded, vuggy porosity

Anhydrite, greenish gray to light bluish gray, bedded

Dolostone, light olive gray, silty, anhydritic, porous

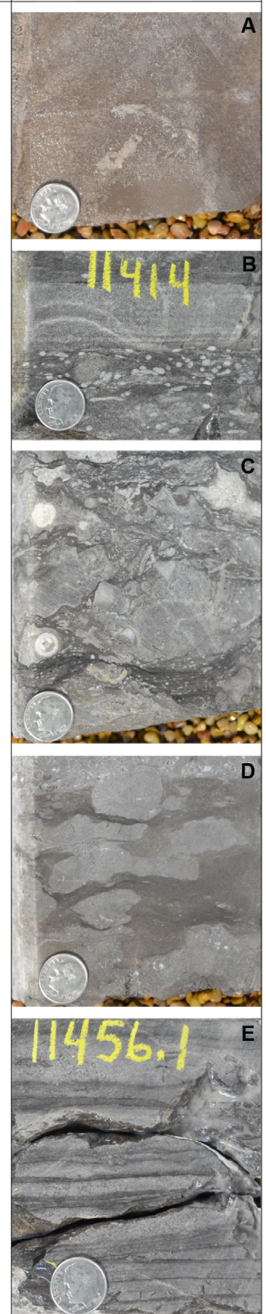
Anhydrite interbedded with dolostone ?, carbonaceous, porous

Limestone (wackestone), medium dark gray, fossiliferous (amphipora, brachiopods, stromatoporoids, corals), stylolitic

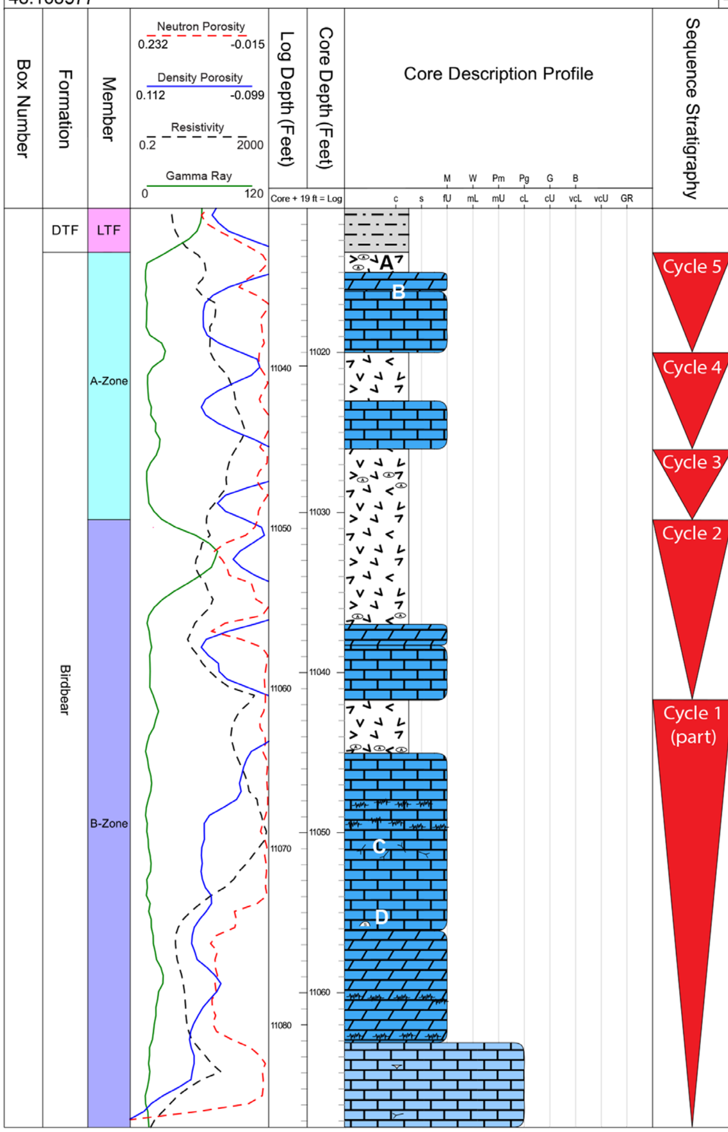
Packstone
Mudstone
Grainstone
Grainstone to boundstone
Packstone

Mudstone

Core Photographs



Original Operator Oasis Petroleum North America LLC	
Top 11011 ft	Bottom 11068.4 ft
Original Well Name & No. Mangum 5493 44-7B	Location SESE Sec. 7, T154N, R93W
Logged by Jeffrey W. Bader	Date Tue Apr 2 2019
Basin Williston	UWI No. 33-061-02582-00-00
NDIC No. 25688	Field Robinson Lake
KB 2350 ft	TD 20800 ft
Latitude 48.168577	Longitude -102.681297



Notes

Mudstone

Anhydrite, medium dark gray to very light gray

Dolostone, pale yellowish brown, wavy laminated, anhydritic

Limestone (mudstone), olive gray, carbonaceous laminations, fractured

Anhydrite, olive gray, wavy laminated to ripple cross laminated, thin dolostone interbeds

Limestone (mudstone), olive gray, carbonaceous laminations, fractured

Anhydrite, olive black, nodular to bedded, wavy bedded to carbonaceous/dolostone interbeds, becomes limestone (mudstone) from 11,028.7 to 11,030.5 ft.

Dolostone, grayish orange pink

Limestone (mudstone)

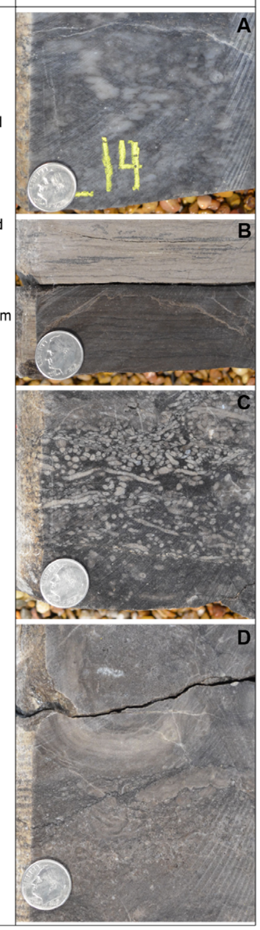
Anhydrite, grayish olive, bedded

Limestone (mudstone), dark gray, fossiliferous (amphipora, stromatoporoids), anhydrite-filled cavities, packstone at 10,050.2 to 10,051.6 ft.

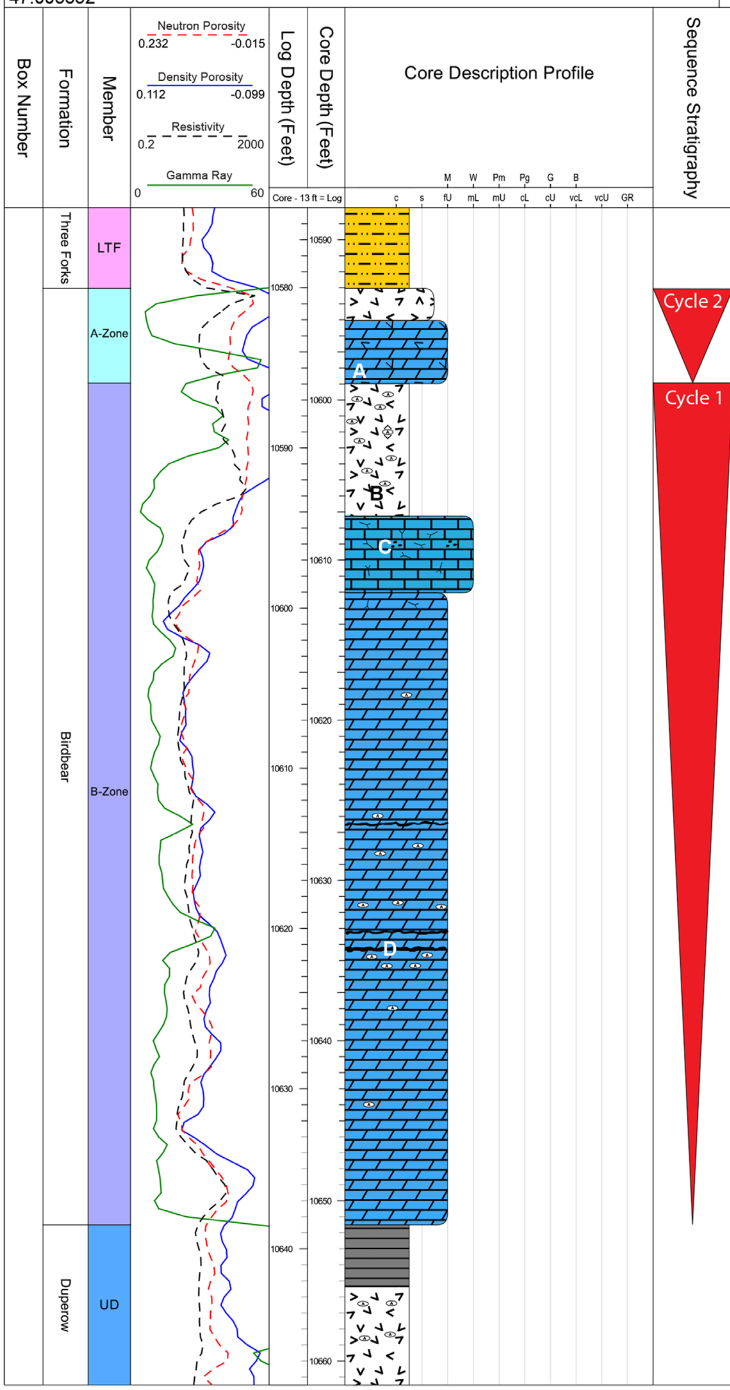
Dolostone, dusky yellowish brown, anhydrite-filled cavities, carbonaceous stringers

Limestone (packstone), olive gray, fossiliferous (stromatoporoids, brachiopods, amphipora, calcispheres)

Core Photographs



Original Operator: Whiting Oil and Gas Corporation	
Top: 10588 ft	Bottom: 10661.5 ft
Original Well Name & No.: Maus 21-26	Location: NENW Sec. 26, T141N, R104W
Logged by: Jeffrey W. Bader	Date: Thu Jun 27 2019
Basin: Williston	UWI No.: 33-033-00345-00-00
NDIC No.: 26582	Field: Camel Hump
KB: 2837 ft	TD: 12375 ft
Latitude: 47.005852	Longitude: -103.827503



Notes

Siltstone, mottled greenish red

Anhydrite, grayish pink to very light gray

Dolostone, pinkish gray, massive, becomes anhydritic and bedded at 10,597.4 ft

Anhydrite, pinkish gray to medium gray, bedded to nodular, carbonaceos, dolomitic and claystone (?) interbeds

Limestone (mudstone to wackestone), pinkish gray to medium gray, fossiliferous (amphipora), some moldic porosity

Dolostone, light olive gray, massive, moldic/vuggy porosity, some anhydrite-filled cavities

Good porosity to 10,651.5 ft

Shale, medium bluish gray, very hard, massive

Anhydrite, medium bluish gray, dolostone interbeds

Core Photographs