Stratigraphic and Structural Relations of the Birdbear Formation (Devonian), Western North Dakota

By

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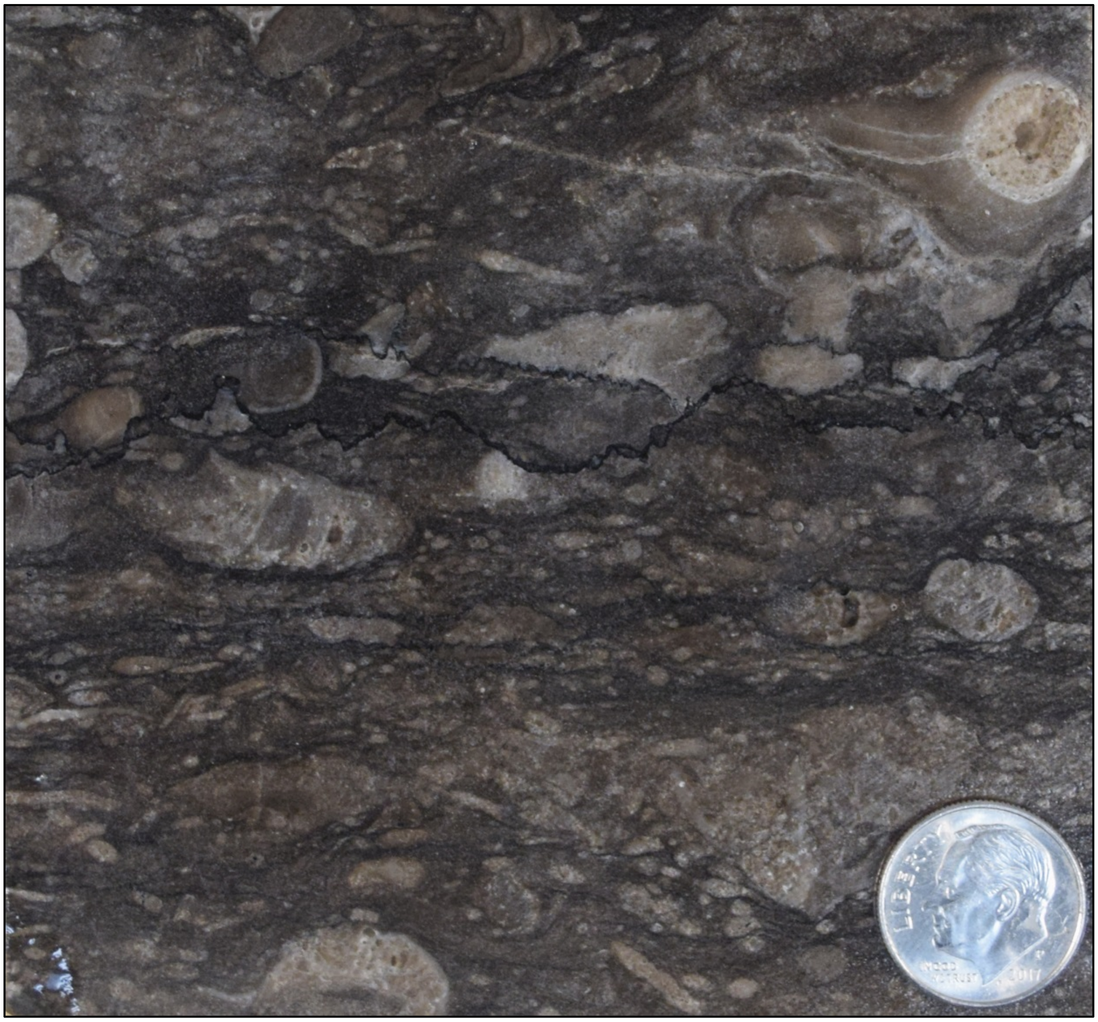

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Introduction

The Late Devonian Birdbear Formation (Birdbear) is one of the many geologic units that produce oil in the Williston Basin of North Dakota, of which the Bakken Formation is most notable (Sonnenberg et al., 2017). Because of the Bakken boom over the last decade, and the recent downturn in oil exploration from 2014-2017, these other geologic units, including the Birdbear, have been overshadowed in terms of the significant oil resources that the rocks likely contain. Burke and Sperr (2006), LeFever (2009), and Bader (2018) indicated that the Birdbear Formation may have significant in-place and untapped petroleum potential across North Dakota. Like many of the carbonate units in the Williston Basin, the Birdbear is potentially a self-sourcing unit containing organic-rich source rocks, porous dolomitic reservoirs, and excellent anhydrite seals (Burke and Sperr, 2006; LeFever, 2009). Therefore, three of the four requirements (source, reservoir, and seal) for a petroleum accumulation in the Birdbear have been documented in western North Dakota, and to some degree in north-central North Dakota (Martiniuk et al., 1995 and LeFever, 2009). However, the fourth requirement, a trapping mechanism, remains poorly understood for the Birdbear, as well as the other non-Bakken units in North Dakota. Bader (2018) has shown that the Williston Basin in North Dakota may be much more complex structurally than previously thought and more importantly, these complexities are apparently very subtle. He also indicated that future exploration in the basin must account for these structural relations in order to best identify new plays or re-evaluate existing plays as petroleum exploration increases in the future. Therefore, this long-term study was undertaken to: 1) develop a better understanding of the stratigraphic relations of the Birdbear, including a sequence stratigraphic assessment utilizing areas with available cores where the Birdbear Formation is presently producing petroleum; 2) identify and map geologic structures in the producing area; 3) evaluate porosity trends across the study area in relation to facies distribution and structural trends; 4) identify depositional and diagenetic systems and assess structural control on each; and 5) extrapolate and apply the findings to other areas of North Dakota that may be similar geologically.

Methods

Three Birdbear cores from western North Dakota (NDIC #12962, NDIC #12249, and NDIC #15412) were examined and described at the Wilson M. Laird Core Library in Grand Forks, North Dakota (Plate 1-Figs. 1 and 2). Cores were logged using EasyCore digital core description software (Version 1.2.9). The geophysical logs (gamma ray, resistivity, density porosity, and neutron porosity) of 801 wells were also examined to identify mappable zones in the Birdbear Formation. Select wells were also used for structural mapping on top of the Birdbear, and for stratigraphic correlation from proximal to distal across western North Dakota and through the Birdbear producing area (Plate 2-Figs. 3 and 4). Isopach maps for the A- and B-zones including 3D perspectives were also constructed and interpreted from the wells in the study area (Plate 2-Figs. 5 and 6).

Stratigraphy

The Birdbear Formation can be divided into two distinct packages, defined as upper and lower units by Martiniuk et al. (1995) for north-central North Dakota (Plate 1-Fig. 1). These upper and lower zones were further informally defined as the A- and B-zones in western and north-central North Dakota (Burke and Sperr, 2006; LeFever, 2009). In the study area, the Birdbear consists of a transgressive-regressive cycle of limestone and dolostone capped by thick anhydrites interbedded with dolomitic units (Plate 1-Figs. 1 and 2). The limestones of the B-zone are burrow mottled to nodular, fossiliferous mudstone (basinal facies) containing brachiopods and crinoids (?) that grade upwards into more fossiliferous limestone (packstone to grainstone) bank facies. Bank facies consist of anhydritic mudstone to grainstone. This facies is extremely fossiliferous with a bioclastic lower zone containing stromatoporoids, brachiopods, and amphipora. A middle zone makes up the main bioherm and consists of packstone to grainstone composed predominantly of stromatoporoids with lesser amounts of amphipora. The upper portion of the bioherm bank facies is a packstone to grainstone containing thamanopora and amphipora (Plate 1-Figs. 1 and 2). The upper B-zone is capped with anhydrite interbedded with thin dolostones of the carbonate platform/sabhka and ranges from 9 to 16 feet thick.

The lower portion of the Birdbear Formation, up into the lower part of the B-zone, defines the transgressive systems tract and consists of basinal facies (Plate 1-Figs. 1 and 2). A possible maximum flooding surface capping the transgressive systems tract was identified on gamma-ray logs and in the three cores in the lower portion of the B-zone; however, these facies are heavily burrowed making it difficult to clearly define the maximum flooding surface in core. Basinal facies of the transgressive systems tract are overlain by bank facies and dolomitic shallow water anhydrites of the platform/sabhka facies, all defining the regressive, highstand systems tract above the maximum flooding surface.

The upper Birdbear is composed of three, thin (<10 ft), carbonate and evaporite packages that represent 4^{th}-order progradational cycles (Plate 1-Figs. 1 and 2; Burke and Sperr, 2006; LeFever, 2009). Each cycle includes an interbedded sequence of thin shale and massive dolostones, overlain by bedded to nodular (chickenwire) anhydrite. These cyclic sedimentary packages are excellent for hydrocarbon entrapment as source rock, reservoir, and seal are juxtaposed properly in the stratigraphic sequence, with shale underlying carbonate reservoir rock that are in-turn overlain by impermeable anhydrite seals. However, reservoir thickness is limited to 2–3 ft. The three regressive packages in the A-zone are parasequences of the highstand systems tract. A subaerial unconformity marks the contact between the overlying Three Forks lowstand systems tract rocks and the upper Birdbear (Bader et al., 2018).

Plate 2-Figure 3 is a generalized regional N–S cross-section from northwestern North Dakota (distal) to southwestern North Dakota (proximal). The three cores examined in this study are included in the cross-section. Transgression was from north to south; whereas, progradation was from south to north, into the basin.

Production

Birdbear production has generally occurred along a north-south trend extending from Williams County southwards into southern McKenzie and northern Billings/Golden Valley counties, with lesser production along major structural features to the east (Bader, 2018). In general, structural/stratigraphic traps (combination traps) exist where dolostones pinch out, or are present with closure, over structural highs in both the A-zone and B-zone (Sperr and Burke, 2005; LeFever, 2009).

Stratigraphic traps have been proposed for the extensively dolomitized stromatoporoid bank facies where these porous units pinch out laterally against impermeable mudstone and packstone facies in both north-central (Martiniuk et al., 1995) and western North Dakota (Sperr and Burke, 2005). In addition, up-dip porosity/permeability pinch-outs due to anhydritization and/or secondary dolomitization may occur along unconconformities at basin margins (Martiniuk et al., 1995). This study helps to clarify these proposed relations.

The Birdbear is estimated to contain approximately 2,313 million barrels of oil (MMBO) of which 644 MMBO is considered recoverable (LeFever, 2009). The Birdbear has produced approximately 21 MMBO to date in North Dakota (NDIC, 2018).

Subsurface Mapping

Structure contour mapping on top of the Birdbear Formation along with isopach mapping of the A-and B-zones in the study area are shown on Plate 2-Figures 4, 5, and 6, respectively. At first glance, the structure contour map seems relatively straightforward with a gentle homoclinal dip to the north-northeast into the basin. However, this surface also has several anticlinal structures trending northwest (Sperr and Burke, 2005), oblique to the north-northeast regional dip, including the Beaver Creek anticline. The anticlinal structures are distinctly en échelon, appear to terminate along a north-northeast linear trend, and are the locus of Birdbear producing wells in the study area. The Birdbear A-zone also appears to be thickest across this zone of deformation, with maximums trending northwest to southeast (Plate 2-Fig. 5).

The linear trend that defines the southeast-terminus of anticlines in the study area is likely a fault that cuts the top of the Birdbear Formation (Plate 2-Fig. 4). This is substantiated not only by anticlinal trends (drag folds), but also by the significant depression at the northern end of the interpreted fault, as well as porosity trends described below. The fault is interpreted to be a right-reverse oblique-slip fault based on the orientation of the folds and location of the depression. Change in sense of displacement along the fault is also suggestive of dextral-slip on a basement-rooted wrench fault. The fault is further defined by the linear surface expression of the Little Missouri River.

Trends

A-zone and B-zone porosity trends for the northern half of the study area, including wells #12962 and #12249, were mapped by Nwachukwu et al. (2018). A distinct porosity low in the A-zone is observed along the dextral fault trend, indicating that the fault may have provided a conduit for cementing fluids along the fault zone during or shortly after A-zone deposition (Plate

2-Figure 4). However, this trend is not as significant in the thicker B-zone, indicating that the porosity variations in the thin (< 2 ft) A-zone reservoirs may be due to low resolution. Even so, these porosity maps indicate that structurally elevated areas on the up-thrown side of the dextral fault may have significantly better porosity than areas on the down-thrown side. Areas where anticlines are present on the west also have better developed porosity, again increasing to the south along the up-thrown block. This south-southwest trend of increasing porosity also is consistent with increasing dolimitization of the upper B-zone from north to south (Plate 1-Figs. 1 and 2). The greater thickness of the A-zone and the porosity trends across anticlines suggest that development of the bank facies and/or subsequent diagenesis may be, at least in part, structurally controlled (Plate 2-Fig. 5). In addition, the fourth element (trapping mechanism) of a petroleum accumulation is present only along anticlinal trends, even though good porosity zones are present to the east of the dextral fault zone. This suggests that porosity in the A-zone, both laterally and off-structure, may be more inconsistent and unpredictable and thus not as attractive for horizontal drilling as substantiated by field observations of Birdbear laterals (Murphy, 2018, personnel communication), and discussed by Sperr and Burke, 2005. Thickness trends in the B-zone indicate bank facies were thicker to the northeast during B-zone deposition and that the Nesson anticline area was likely more structurally active at that time (Plate 2-Fig. 6).

Of the four main elements of a petroleum accumulation, the presence and extent of source rocks for the Birdbear Formation remain most uncertain (Lillis, 2012). Nwachukwu et al. (2018) indicated that thermally mature, potential source rocks with up to 2% total organic carbon are present within the Birdbear in core from well #12962 (Plate 1-Fig. 1). This suggests that the Birdbear may be a self-sourced petroleum system and hydrocarbons generated down-dip may be migrating up-dip along more porous zones, fractures, and/or dolomitized stylolites (Burke and Sperr, 2006) where they are structurally trapped. Vertical migration of hydrocarbons is also likely, especially in the A-zone where source, reservoir, and seals are in proximity. Potential migration routes for hydrocarbon migration are shown on Plate 1, Figure 1.

Conclusions

Bader (2018) suggested that distribution of oil accumulations across North Dakota may indicate that oil reservoirs for many producing intervals are localized along geologic structures formed from Phanerozoic movement on basement-rooted Precambrian faults. He also suggested that the nature of the geologic structures and the resulting strain effects from repeated movement on them is not well understood, or easily discerned. This study is one of the first to demonstrate that geologic structures in sedimentary cover rocks in western North Dakota are very subtle, but are significant in controlling sedimentation, diagenesis, and oil accumulation in the Birdbear A-zone and probably the B-zone as well. This possibility was first suggested by Burke and Sperr (2006).

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