PSDistribution of Depositional Environment, Diagenetic Features, and Reservoir Quality of the Middle Bakken Member in the Williston Basin, North Dakota*

Oguzhan Ayhan[1], Ursula Hammes[2], and William L. Fisher[1]

Search and Discovery Article #20368 (2016)**
Posted October 17, 2016

*Adapted from poster presentation given at AAPG Annual Convention & Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

[1]Department of Geosciences, University of Texas at Austin, Austin, Texas (oguzhanayhan@utexas.edu)
[2]Bureau of Economic Geology, University of Texas at Austin, Austin, Texas

Abstract

The Upper Devonian-Lower Mississippian Bakken Formation in the Williston Basin is an important source rock for oil production in North America. The Bakken Formation comprises three units: upper and lower black shales, and a middle member. Upper and Lower Bakken shales are high quality source rocks for reservoirs in the Middle Bakken, Upper Three Forks, and Lower Lodgepole formations. The Middle Bakken Member - which consists of gray, interbedded siltstone and sandstone with shale, dolostone, and limestone - is under investigation in this study. The goals here are to determine the regional distribution of lithofacies and the depositional environment of the Middle Bakken Member and to explain diagenetic sequence and reservoir-quality parameters in the Williston Basin.

The reservoir quality of the Middle Bakken Member is primarily influenced by mineralogy and cementation, which caused low porosity and permeability and are intrinsically linked to facies distribution in the basin. Pore types include primary intergranular, intragranular, and fracture. Secondary moldic and vugular porosity resulted from dissolution of biogenic fragments. Dolomitization is pervasive throughout the Middle Bakken, although we also see facies-exclusive concentrations of dolomite cement that were mapped regionally. Secondary cementation includes quartz overgrowths, K-feldspar, clay cement, and pyrite as both cement and nodules. This study will present the vertical and lateral distribution of dolomite and pyrite cementation zones correlated to lithofacies and depositional environment of the Middle Bakken Member via core and petrographic thin-section analysis in the Williston Basin.

TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

Bureau of Economic Geology

ABSTRACT

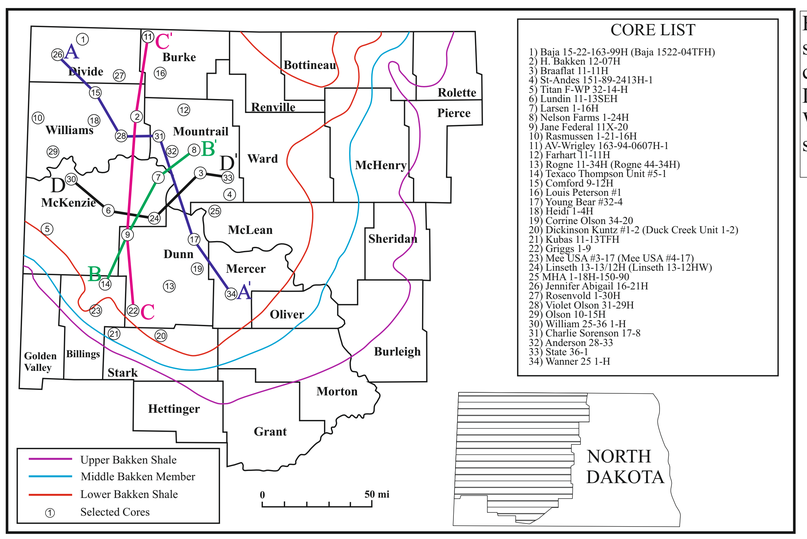
The Upper Devonian-Lower Mississippian Bakken Formation in the Williston Basin is an important source rock for oil production in North America. The Bakken Formation is comprised of three units: Upper and Lower Bakken shales and Middle Member. Upper and Lower Bakken shales are high quality source rocks which source reservoirs in the middle Bakken, Upper Three Forks and Lower Lodgepole Formations. The Middle member of Bakken Formation, which consists of gray, interbedded siltstone and sandstone with shale, dolostone and limestone, is under investigation. The goals of this study are to determine the regional distribution of lithofacies and depositional environment of the Middle Bakken Member and explain diagenetic sequence and reservoir quality parameters in the Middle Bakken reservoir.

The reservoir quality of the Middle Bakken Member is mainly influenced by mineralogy and cementation resulting in low porosity (average ~2.5%) and permeability (average ~0.04 mD) and linked to facies distribution in the basin. Dolomitization is pervasive throughout the unit; however, we see local concentration of dolomite cement. Moreover, secondary cementation occurred including quartz overgrowths, K-feldspar, clay cement and pyrite as both cement and nodules. Not only dolomitization but also pyrite cementation plays an important role in reducing pore spaces in the reservoir. The pore types are intergranular, intragranular, fracture and vugular. Secondary intragranular porosity generally resulted from dissolution of biogenic fragments.

The distribution of dolomitization and pyrite cementation zones are shown correlating with the lithofacies and depositional environment of the Middle Bakken Member via core and petrographic thin section analysis in the Williston Basin.

1. INTRODUCTION

- The Williston Basin is an approximately 285.000 km^2 large intracratonic basin that extends across the United States and Canada. The thickness of the basin is up to 16.000 ft.
- The Upper Devonian-Lower Mississippian Bakken Formation in the Williston Basin is an important source rock for oil production in North America.
- The Bakken Formation is comprised of three units: upper and lower organic-rich black shales and middle member, which is gray, interbedded siltstone and sandstone with shale, dolostone and limestone (Pitman et al., 2001).
- Five facies have been described and each of them represents different depositional environments in a shallow-water environment (Smith and Bustin, 1996).



CORE LIST

1) Baja 15-22-163-99H (Baja 1522-04TFH)
2) H. Bakken 12-07H
3) Braaflat 11-11H
4) St-Andes 151-89-2413H-1
5) Titan F-WP 32-14-H
6) Lundin 11-13SEH
7) Larsen 1-16H
8) Nelson Farms 1-24H
9) Jane Federal 11X-20
10) Rasmussen 1-21-16H
11) AV-Wrigley 163-94-0607H-1
12) Farhart 11-11H
13) Rogne 11-34H (Rogne 44-34H)
14) Texaco Thompson Unit #5-1
15) Comford 9-12H
16) Louis Peterson #1
17) Young Bear #32-4
18) Heidt 1-4H
19) Corrine Olson 34-20
20) Dickinson Kuntz #1-2 (Duck Creek Unit 1-2)
21) Kubas 11-13TFH
22) Griggs 1-9
23) Mee USA #3-17 (Mee USA #4-17)
24) Linseth 13-13/12H (Linseth 13-12HW)
25 MHA 1-18H-150-90
26) Jennifer Abigail 16-21H
27) Rosenvold 1-30H
28) Violet Olson 31-29H
29) Olson 10-15H
30) William 25-36 1-H
31) Charlie Sorenson 17-8
32) Anderson 28-33
33) State 36-1
34) Wanner 25 1-H

Figure 1.1: The map shows selected core locations and cross section lines in North Dakota portion of the Williston Basin used for this study.

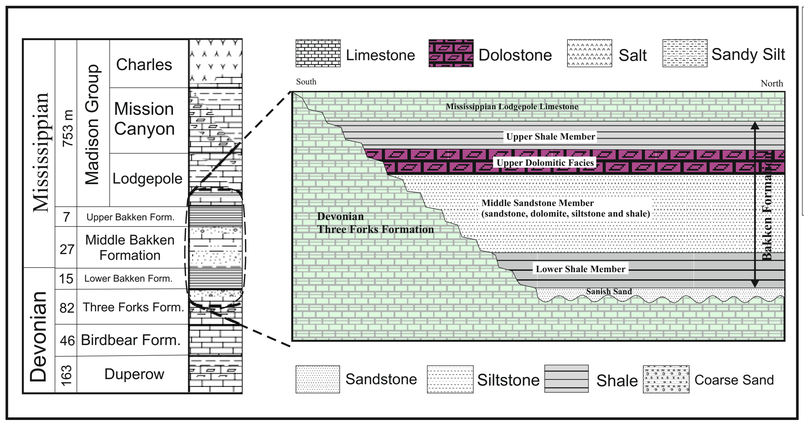


Figure 1.2: Stratigraphic column of Bakken-Lodgepole Petroleum System and north-south cross section in the Williston Basin (modified from Webster, 1984)

2. GEOLOGIC HISTORY

Basin Formation

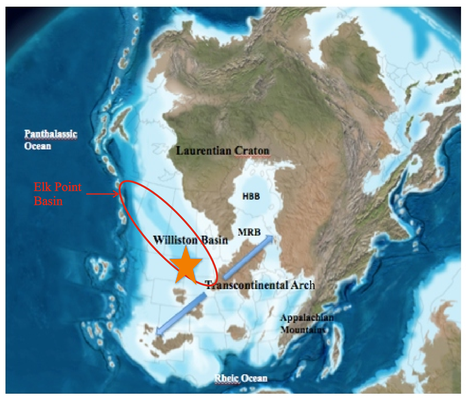


Figure 2.1: Paleogeographic map of North America during Late Devonian (360 Ma) showing the Williston Basin (modified from Blakey, 2005). HBB= Hudson Bay Basin, MRB= Moose River Basin.

- As a result of uplift of the Transcontinental Arch in Devonian, the basin configuration changed from a circular basin to an elongated shelf basin (Figure 2.4).
- A major second order T-R cycle resulted in deposition of the Bakken Formation (Anna, 2011).
- 3rd and 4th order cycles were determined in the Middle Bakken Member (Figure 2.3).

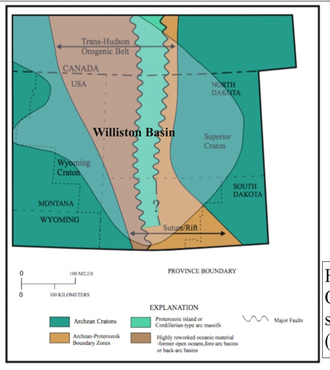


Figure 2.2: Trans-Hudson Orogenic belt and north-south structures in the Williston Basin (modified Nelson et at., 1993).

Depositional Environment

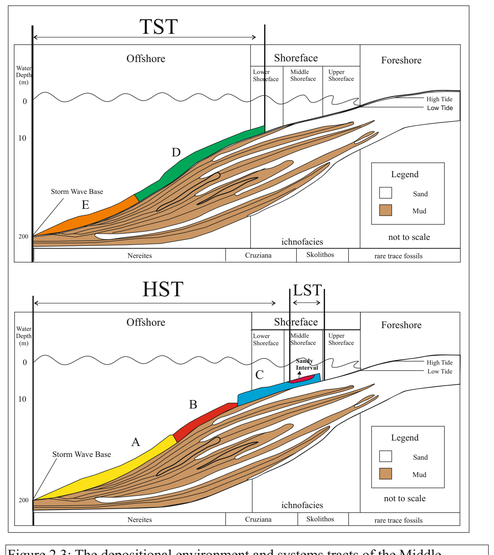


Figure 2.3: The depositional environment and systems tracts of the Middle Bakken Member facies (modified from Smith & Bustin, 1996). A, B, C, D and E represent facies and their positions in shallow marine environment. Sandy interval was deposited as a part of Facies C.

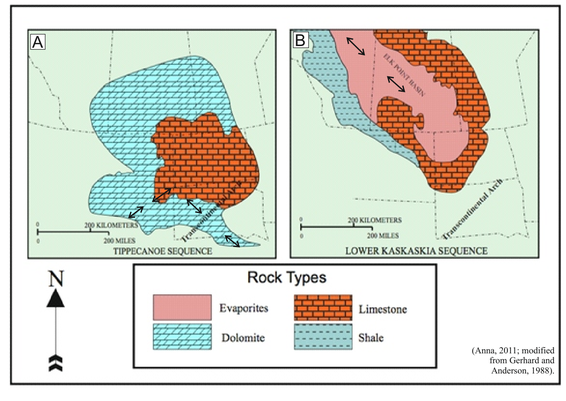


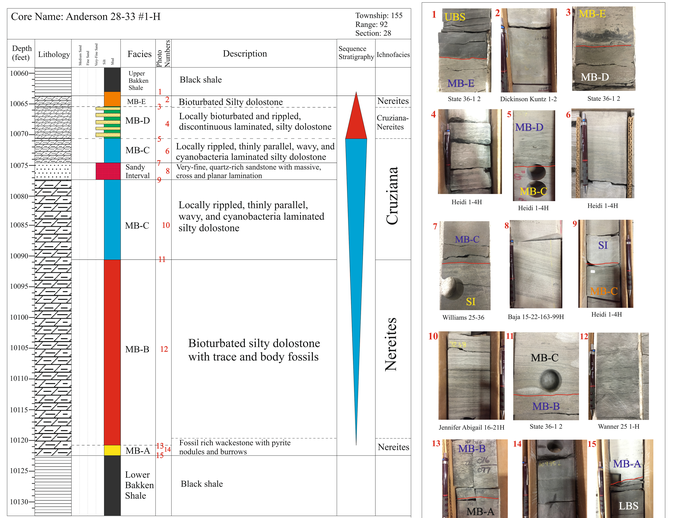
Figure 2.4: Maps show depositional pattern of Tippecanoe and Kaskaskia sequences in the Williston Basin. (A) Ordovician to Late Devonian with southwest and southeast seaway connections; (B), Late Devonian to Early Mississippian with a northwest seaway connection through the Elk Point Basin in Canada. Arrows indicate seaway connections.

Depositional Environment, Diagenesis and Reservoir Quality of the Middle Bakken Member in the Williston Basin, North Dakota

Oguzhan Ayhan[1], Ursula Hammes[2], William L. Fisher[1]

1) University of Texas at Austin, Department of Geological Sciences
2) University of Texas at Austin, Bureau of Economic Geology

3. STRATIGRAPHIC SECTION



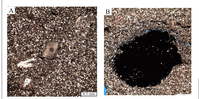
ANDERSON 28-33 #1-H

Figure 3.1: The Facies of Middle Bakken Member from Anderson 28-33 #1-H core. MB-A: Facies A; MB-B: Facies B; MB-C: Facies C; MB-D: Facies D; MB-E: Facies E; SI: Sandy interval; UBS: Upper Bakken Shale; LBS: Lower Bakken Shale.

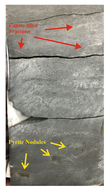
4. FACIES ANALYSIS

A

-Silt and clay grains reflect low energy conditions.
-High bioturbation demonstrate favorable benthic life destroyed primary sedimentary structures.
-Storm-event sedimentation indicates it was deposited close to storm wave base.



Charlie Sorenson 3TH, 10514.2 ft., XPL; Olson 10-15 1H, 10650.55 ft., PPL.

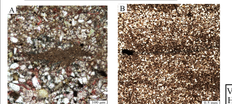


Wanner 25 No.1, 8852.8 ft.
Pyrite Nodules and calcite-filled fractures.

Braaflat 11-11H, 9931 ft.
Transition from the Lower Bakken Shale to Facies A.

B

- The fine grain size reflects relatively lower energy conditions.
- Nereites trace fossils suggest deposition below fair-weather wave base. Teichichnus trace fossils indicate shallow marine storm-event sedimentation.



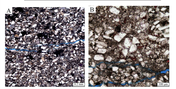
Olson 10-15 1H, 10640.3 ft., PPL; Williams 25-36, 10686.1 ft., PPL.

Violet Olson 31-29H, 10013.6 ft.
Helminthopsis trace fossils and marine storm-event sediment.

Wanner 25 No.1, 8844.5 ft.
Nereites Trace Fossils (Helminthopsis).

C

-Laminated siltstone deposited in a relatively higher energy environment showing upper flow regime conditions.
-Above normal wave base since no low-energy sediment is present.
-Lenticular and wavy bedding and wave ripples reflect unidirectional and bidirectional currents.
-This facies is interpreted to have been deposited in an intertidal environment.



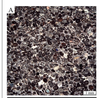
Charlie Sorenson 3TH, 10656.2 ft., XPL; State 36-1 2H, 10777.1 ft., PPL.

St. Andes 2413H-1, 9089.3 ft.
Reverse faults.

Heidi 1-4H, 10682.6 ft.
Planar lamination to cyanobacteria lamination.

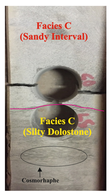
F

-Constant high energy conditions because of absence of bioturbation and low energy sediments.
-Cross and planar laminations are interpreted as channel fills and bars.
-The massive appearance was produced by liquefaction resulting from either storm waves (Madsen, 1978) or earthquake (Obermeier, 1996).
-Deposited in a Middle Shoreface environment.



Charlie Sorenson 3TH, 10459.4 ft., XPL; Williams 25-36, 10675.7 ft., PPL.

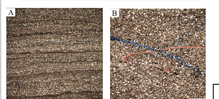
Rosenvold 1-3017, 9293.2 ft.
Cross lamination in sandy interval.



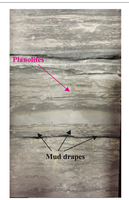
AV-Wrigley 0607H-1, 7270.5 ft.
The bottom of sandy interval and cosmorhaphe.

D

-Low energy conditions due to the fine grain-sized sediments.
-Ripples and laminations show energy fluctuation.
-Intercalated coarser grains from land via storms.
-High bioturbation reflects favorable benthic life.
-Low intertidal environment.



Olson 10-15-1H, 10622.4 ft. PPL; Olson 10-15-1H, 10620.3 ft., PPL.

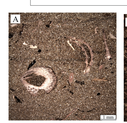


Baja 15-22-163-99H, 7900.6 ft.
Planolites and mud drapes.

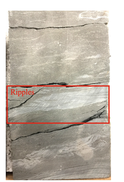
Farhart 11-11H, 7640.8 ft.
Small faults.

E

-Low energy conditions due to the clay-silt size grains.
-Pervasive bioturbation.
-Well-oxygenated environment during deposition in an offshore environment.



Williams 25-36, 10663.5 ft., PPL; Charlie Sorenson 3TH, 10440.2 ft., PPL.



Rogne 44-34H, 10673.5 ft.
Ripples.

Comford 9-12H, 9435.2 ft.
Planar mud lamination and Floatstone in Facies E.

All core width: 3 inches

5. ISOPACH MAPS

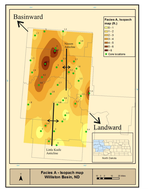


Figure 5.1: Facies A shows its thickest deposition in the northwest of the area due to Nesson Anticline. Numbers represent the thickness in feet.

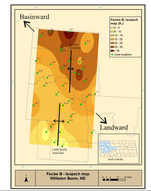


Figure 5.2: Facies B gets thinner towards south. Numbers represent the thickness in feet.

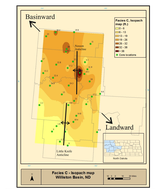


Figure 5.3: Facies C gets thinner towards south. The thickest deposition is in the east of Nesson Anticline. Numbers represent the thickness in feet.

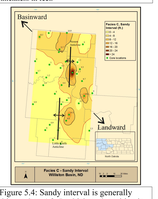


Figure 5.4: Sandy interval is generally thinner then 4 ft. Its thickest deposition in the east of Nesson Anticline. Numbers represent the thickness in feet.

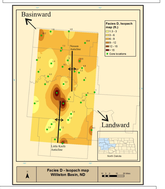


Figure 5.5: Facies D shows its thickest deposition in the limbs of Little Knife Anticline. Numbers represent the thickness in feet.

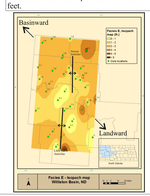


Figure 5.6: Facies E shows its thickest deposition in the north and south of the study area. The anticlines might have not affected the deposition of Facies E so much. Numbers represent the thickness in feet.

6. STRUCTURAL CROSS SECTIONS

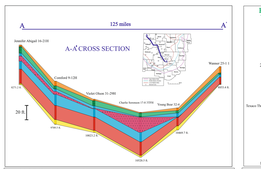


Figure 6.1: NW-SE oriented cross section shows all facies get thinner towards south. Sandy interval is thickest in the center of the basin because of the structures in the basin.

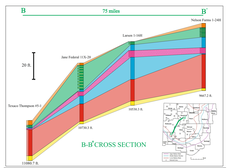


Figure 6.2: NE-SW oriented cross section shows all facies get thinner towards southwest except Facies D whose thickness was effected by Nesson Anticline.

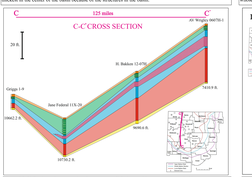


Figure 6.3: N-S oriented cross section demonstrates all facies get thinner towards south. No structures effected the thicknesses along the line in general.

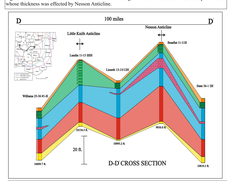


Figure 6.4: W-E oriented cross section. The thicknesses of facies are variable along the line because of Little Knife and Nesson Anticlines.

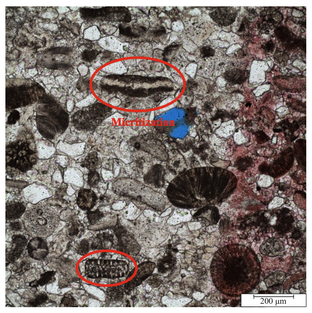
TEXAS Geosciences
The University of Texas at Austin
Jackson School of Geosciences

BUREAU OF ECONOMIC GEOLOGY

7. DIAGENESIS AND RESERVOIR QUALITY

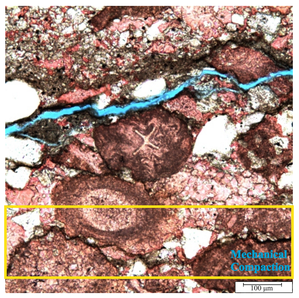
Diagenetic Processes

1. Micritization



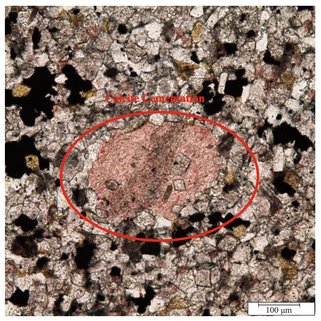
Micritization of grains in Facies B.
(Williams 25-36 1-H, 10695.2 ft.)

2. Mechanical and Chemical Compaction



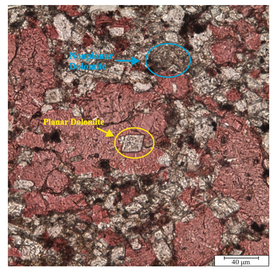
Mechanical Compaction as evidenced by cone-like stylolite structure
(State 36-1 2H, 10777.7 ft.)

3. Calcite Cementation



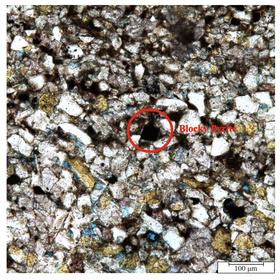
Calcite cementation
(Olson 10-15 1H, 10619.7 ft.)

4. Dolomitization



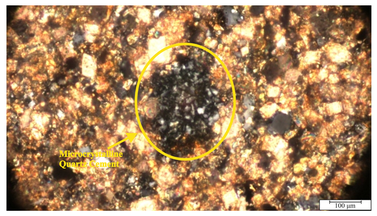
Dolomitization Process. In the photomicrograph, a planar dolomite crystal and nonplanar microcrystalline dolomite are present. The planar dolomite crystal represents early-stage dolomitization, while the nonplanar dolomite micricrystals represent late-stage dolomitization.
(State 36-1 2H, 10768.8 ft., PPL)

5. Pyrite Cementation



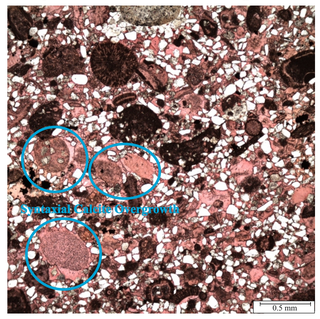
Pyrite cementation. In the photomicrograph, blocky pyrite is present.There are two importances of pyrite: 1) Filling the voids in a rock decreasing porosity; 2) Representing anoxic environment conditions.
(Williams 25-36 1H, 10675.2 ft.)

6. Microcrystalline Quartz Cementation



Microcrystalline Quartz Cementation. The shape of the cement is an evidence of pore-filling type of cement
(William 25-36 1-H, 10696.2 ft., XPL)

7. Syntaxial Calcite Overgrowth

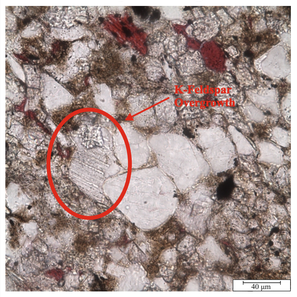


Syntaxial calcite overgrowth of echinoderm fragments in Facies C.
(State 36-1 2H, 10777.7 ft., PPL)

8. Quartz Overgrowth

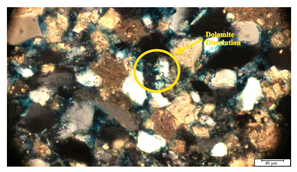
Quartz Overgrowth in Facies C.
(State 36-1 2H, 10777.1 ft., XPL)

9. K-Feldspar Overgrowth



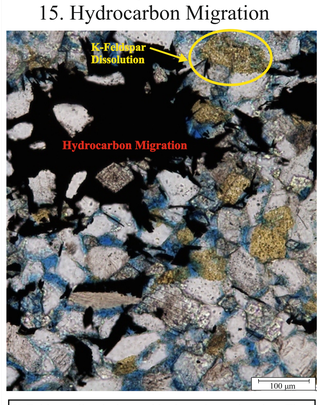
K-Feldspar overgrowth on plagioclase.
(State 36-1 2H, 10786.5 ft., PPL)

10. Dolomite Dissolution



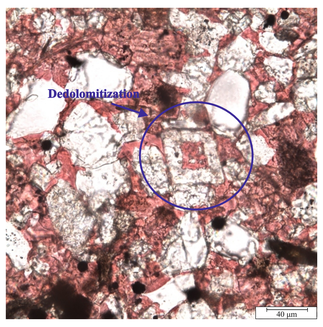
Dolomite dissolution. A 40-µm-planar dolomite crystal was dissolved creating secondary porosity.
(Williams 25-36 1H, 10673.9 ft., XPL)

11. K-Feldspar Dissolution and 15. Hydrocarbon Migration



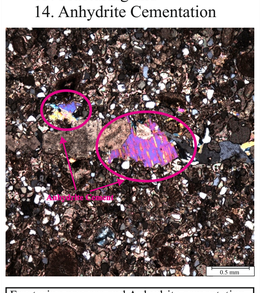
K-Feldspar dissolution and hydrocarbon migration. The spread black-colored structure hydrocarbon migrated from the Lower or Upper Bakken shale into the Middle Bakken member. K-Feldspar dissolution is present at the right-bottom part.
(Charlie Sorenson 17-8, 10475.2 ft.)

12. Dedolomitization



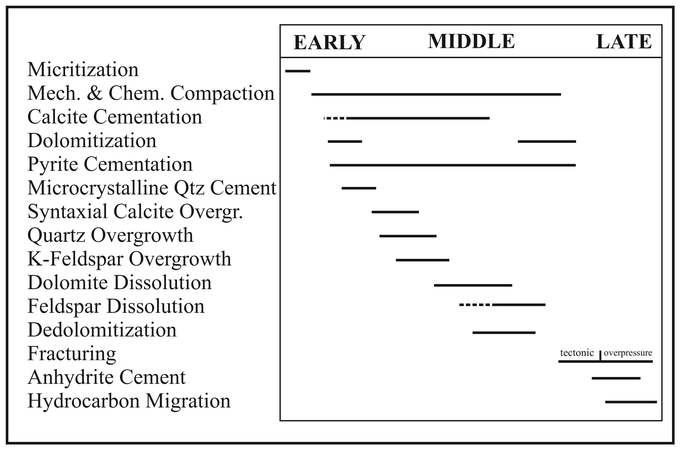
Dedolomitization in Facies D. In the photomicrograph, calcite cement replaces planar dolomite crystal.
(Williams 25-36 1H, 10695.3 ft., PPL)

13. Fracturing and 14. Anhydrite Cementation

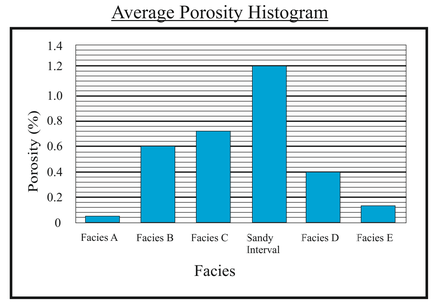


Fracturing process and Anhydrite cementation. The cement fills the fracture decreasing porosity in sandy interval.
(Charlie Sorenson 17-8, 10460.2 ft, XPL)

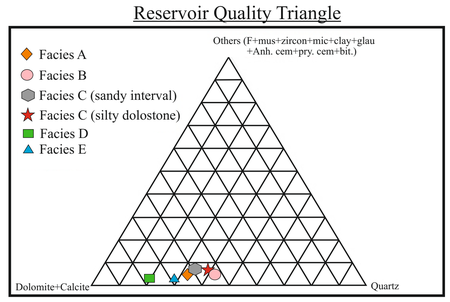
Paragenetic Sequence



Average Porosity Histogram



Reservoir Quality Triangle



RESERVOIR QUALITY

- Point counting of 36 thin sections.
- The upper portion of the Middle Bakken interval generally includes the most dolomite content (up to 80%) and micro-faults increasing porosity and permeability.
- Porosity value ranging from 0.2% to 1.2% in point-counted samples but 4% to 8% in core plugs, sandy interval has the highest, lithofacies A and B have the lowest values.
- Lower portion does not have good reservoir quality because of cementation.
- Fracture, intragranular, intergranular and moldic porosity.

8. CONCLUSIONS

- Middle Bakken facies were deposited on a low-inclined ramp system between storm-wave base (~200m water depth) and middle shoreface.
- Facies A, B, C and the sandy interval were deposited during regression, while Facies D and E were deposited during transgression. The sandy interval is interpreted as channel fill or bar.
- The upper portion of the Middle Bakken Member includes more dolomite content and micro-faults than the middle and lower portions and is usually favorable reservoir. Facies A and B generally has the lowest porosity and reservoir quality.
- Intragranular, intergranular, fracture and moldic porosity are main pore types in the Middle Bakken Member.
- According to the isopach maps, the thicknesses of Facies A, B, C and sandy interval within Facies C were affected by Nesson Anticline and the thickness of Facies D was affected by Little Knife Anticline, while the structures might have not affected the thickness of Facies E.
- The facies in the Middle Bakken Member have variable aspects and reservoir qualities throughout the North Dakota portion of the Williston Basin as explained above. That is why, the facies should be studied separately instead of studying the whole member simultaneously.

REFERENCES

Anna, L.O., 2011, Geologic assessment of undiscovered oil and gas in the Williston Basin Province, Montana, North Dakota, and South Dakota, chap. 3 of U.S. Geological Survey Williston Basin Province Assessment Team, Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010: USGS Digital Data Series 69-W, 76 p.

Blakey, R., 2005, "North American paleogeographic maps, late Devonian (360Ma)." Paleogeography and geologic evolution of North America. Web. 1 July. 2015. <https://www2.nau.edu/rcb7/namD360.jpg >.

Embry, A.F., 2002, Transgressive-regressive (T-R) sequence stratigraphy. In: J.M. Armentrout and N.C. Rosen (eds.). Sequence Stratigraphic Interpretations for Exploration and Production. Gulf Coast Section SEPM, Conference Proceedings, Houston, Texas, p. 151–172.

Gerhard, L. C., and Anderson, S. B., 1988, The Williston basin—Sedimentary cover—North American Craton— U.S.: Geological Society of America, Chapter 9, Geology of North America, D-2, p. 221-242.

Gerhard, L.C., Anderson, S.B., and Fischer, D.W., 1990, Petroleum geology of the Williston Basin, *in* Leighton et al. Interior cratonic basins: *AAPG Memoir 51*, pp. 507-559

Moore, C.H., 2001, Carbonate reservoirs: Porosity evolution and diagenesis in a sequence-stratigraphic framework: Elsevier, Amsterdam,444 p.

Pitman, J. K., L. C. Price, and J. A. LeFever, 2001, Diagenesis and Fracture Development in the Bakken Formation, Williston Basin: Implications for Reservoir Quality in the Middle Member: U.S. Geological Survey Professional Paper 1653, 19 p.

Smith, M. G., and R. M. Bustin, 1996, Lithofacies and paleoenvironments of the Upper Devonian and Lower Mississippian Bakken Formation, Williston Basin: Bulletin of Canadian Petroleum Geology, v. 44, p. 495-507.

Webster, R. L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota in Woodward J., F. F. Meissner, J. L. Clayton, eds., Hydrocarbon source rocks of the greater Rocky Mountain region, Rocky Mountain Association of Geologists, p. 57 - 82.

Nelson, K.D., Baird, D.J., Walters, J.J., Hauck, M., Brown, L.D., Oliver, J.E., Ahern, J.L., Hajnal, Z., Jones, A.G., and Sloss, L.L., 1993, Trans-Hudson orogen and Williston Basin in Montana and North Dakota—New COCORP deep- profiling results: Geology, v. 21, p. 447–450.

ACKNOWLEDGEMENT

Thank you Statoil for providing the thin sections and cores used for this study, Turkish Petroleum Corporation and Jackson School of Geosciences for their support.

Statoil

Author information: Oguzhan Ayhan; oguzhanayhan@utexas.edu