

Diagenesis and Porosity Development within the Lower “B-Zone” Birdbear Formation, McKenzie County, Williston Basin, North America*

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Search and Discovery Article #11281 (2020)**

Posted January 13, 2020

*Adapted from oral presentation given at 2019 AAPG Rocky Mountain Section Meeting, Cheyenne, Wyoming, September 15-18, 2019

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Abstract

The Birdbear Formation in the Williston Basin is a carbonate-evaporite sequence that extends across western North Dakota, eastern Montana, southern Manitoba and southwestern Saskatchewan. Approximately 180 vertical and horizontal Birdbear wells have cumulatively produced over 25 million barrels of oil equivalent in North Dakota, and Birdbear production also extends into eastern Montana and southern Saskatchewan. This study evaluates the degree of diagenesis and its effects on porosity and permeability, as compared to the depositional patterns/facies that enhanced the reservoir characteristics of the Birdbear Formation in McKenzie County North Dakota, in relation to its hydrocarbon potential in the Williston Basin of North America. This study examined: (1) Core and thin section (thirteen cores and over 50 thin sections), (2) geochemical analysis of prospective petroleum source beds (TOC Rock-Eval program pyrolysis), (3) wireline log correlations and porosity distribution mapping, (4) compiled standard core-plug porosity-permeability measurements, and (5) nuclear magnetic resonance (NMR) spectroscopy measurements.

The aim of this study was to determine the role of deposition and diagenesis on porosity types, lateral and vertical distribution of reservoir porosity, lateral and vertical distribution of prospective source beds and anhydrite seals.

The Birdbear has two distinct units: (1) A lower carbonate dolomite-limestone (boundstone to wackestone) unit, with discontinuous dolomitized reservoir and abundant organic material that is being evaluated as potential source material for hydrocarbon production using TOC Rock Eval Pyrolysis, and (2) an upper anhydrite-carbonate (packstone) unit that has the ability to entrap migrating fluids within the study area. Rocks in the upper section of the lower carbonate unit were exposed to high diagenetic alteration that enhanced permeability and porosity types that includes, intra-crystalline, inter-granular, with the most dominant being solution-enhanced moldic vuggy porosities. These were confirmed by thin section analysis that revealed varying degree, types of porosity and NMR spectroscopy analysis from marked producible fluids indications and porosity maps across McKenzie County (center of the Williston Basin).

The rocks in the formation showed marked selective or partial dolomitization, micritization and dissolution of calcite cement from inclusion of brines, creating excellent reservoir rock qualities of porosity and permeability (average limestone porosity at 1.74%, from a range of 0.48% to 2.26% and average dolomite porosity of 8.69%, from a range of 0.86% to 29.85%, with permeability range of 20-85 md). Hydrocarbon production in the Birdbear Formation has been documented to be from restricted intervals of varying lithological thicknesses of 1-2 foot thick reservoirs in the Upper Birdbear, with 10+ foot thick reservoirs within the lower “B” porous zone, which are more prominent reservoirs for production. TOC Rock-Eval program pyrolysis data indicate fair to good distribution of prospective source beds (TOC range from 1.06% to 11.5%, with a maximum HI value of 182.8 and OI value of 11.9) that are thermally mature and within oil generating window with Tmax value of 452. This indicates the Birdbear Formation may be a self-sourced hydrocarbon system within the Williston Basin.

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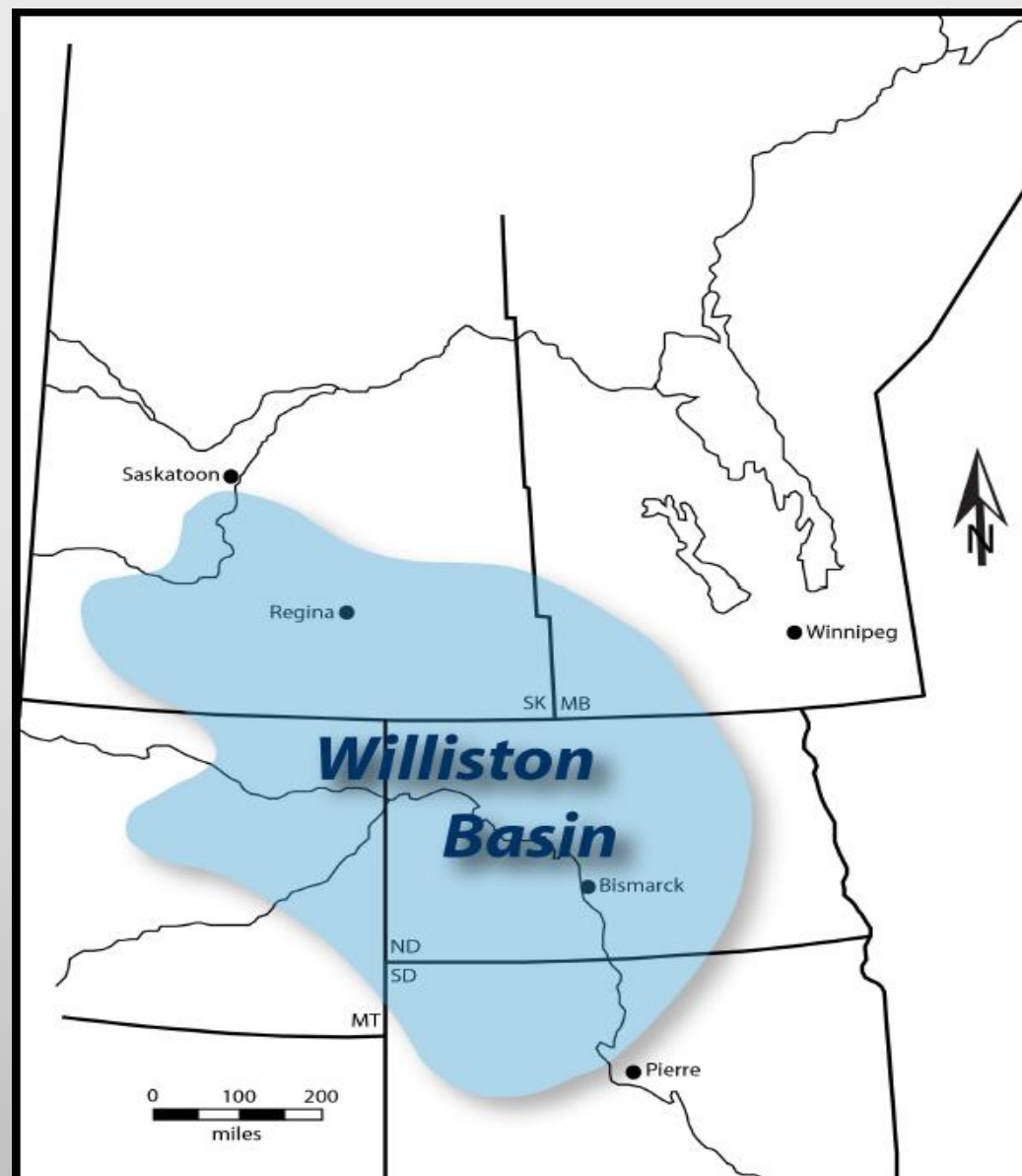
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North Dakota Geological Survey

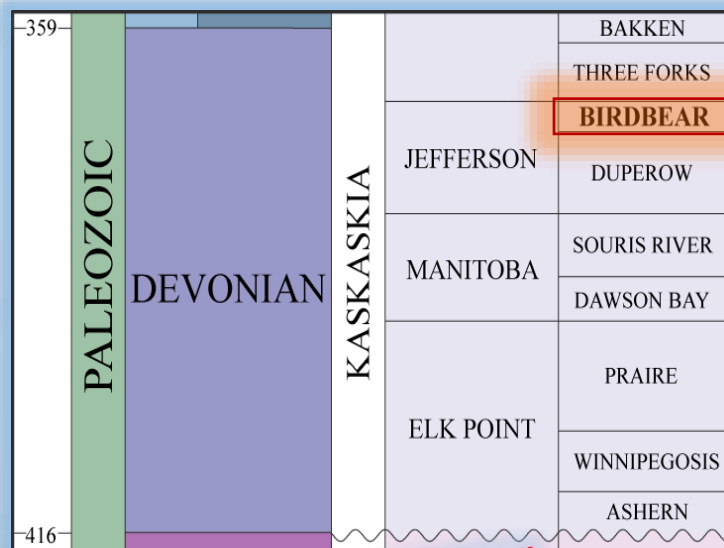
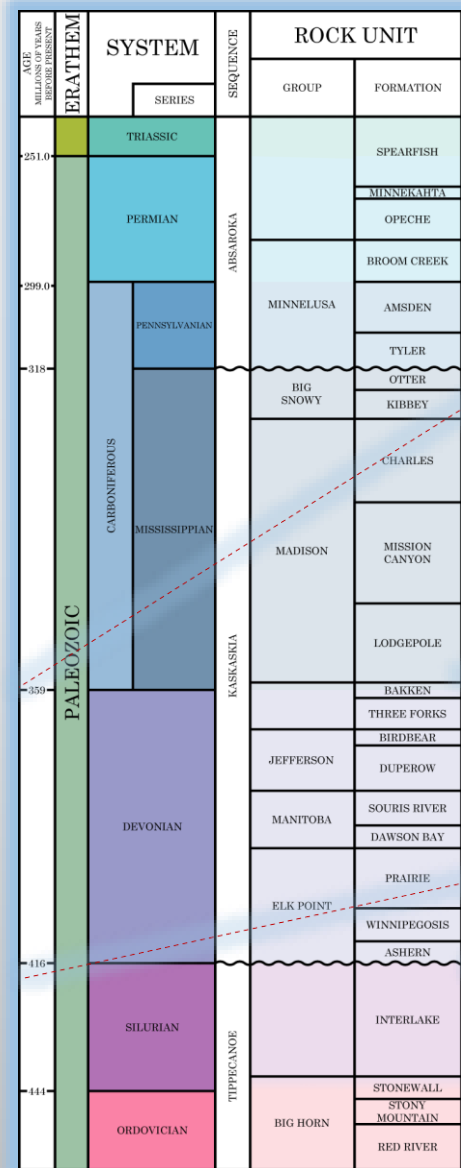
Timothy O. Nesheim



- Intra-cratonic basin
- Present across South Dakota, North Dakota, Montana, Saskatchewan, and Manitoba,
- Sediments from Cambrian to Quaternary (but peaked in Ordovician to Devonian)
- Rock units range from marine, marginal-marine, marine carbonates to fluvial. (Lerud, 1982)
- 20 different formations have commercially produced oil and gas in North Dakota (Murphy et al., 2009)

Birdbear Formation

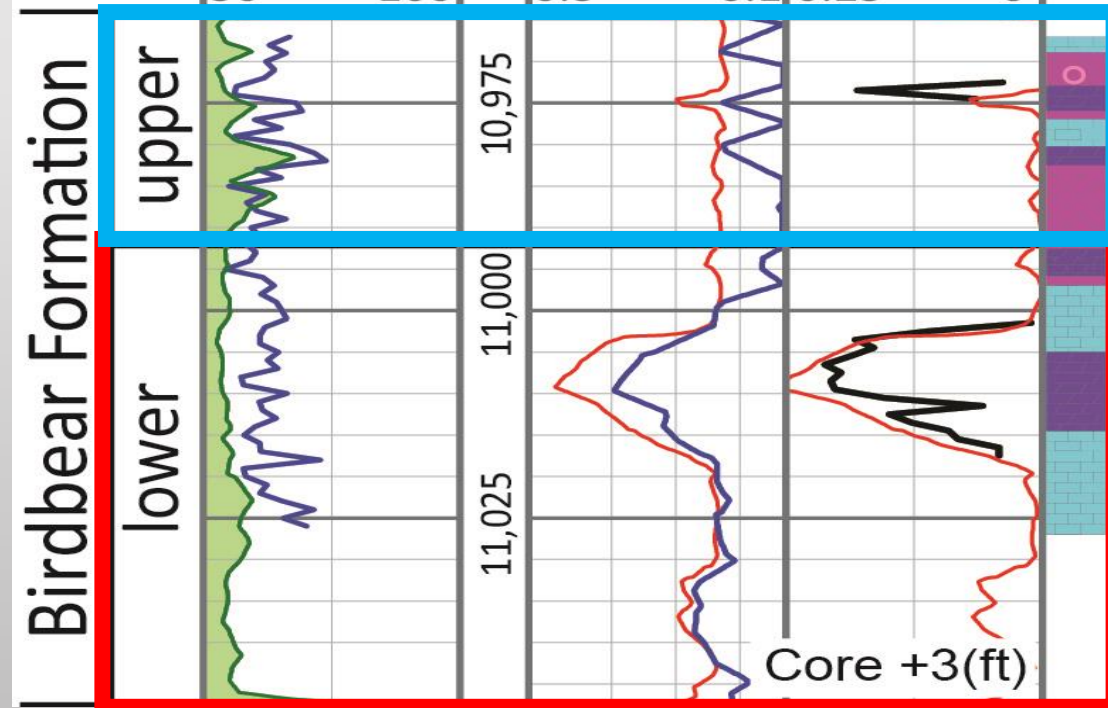
- Overlain by Three Forks Formation (regional unconformity)
- Underlain by Duperow Formation
- A unique formation because it is easily identifiable on logs and traced over a regional scale in the Williston Basin of North America,
- Carbonate-evaporite sequence (Burke & Sperr, 2006)



Birdbear Formation

○
#12249
33053022080000
MOI #21-17

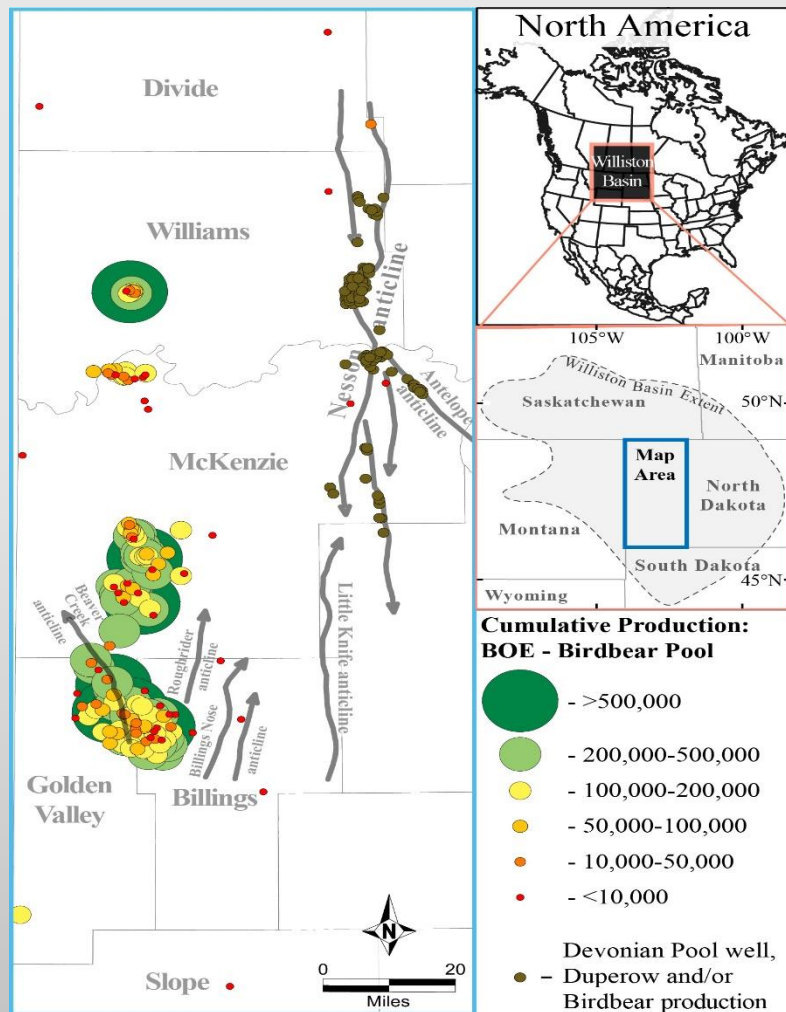
GR		NPHI (L)		CP	
0	125	0.3	-0.1	25	0
CGR		DPHI (L)		NPHI (L)	
50	160	0.3	-0.1	0.25	0



- Two units are recognized from lithofacies descriptions
- Lower carbonate dolomite-limestone unit (variable fossiliferous limestone and dolomite)
- An upper anhydrite-carbonate unit
- Shallow Marine – Sabkha Environment

Birdbear Formation

Cumulative production map of Birdbear across Mckenzie and Williams Counties



- Cumulative production >25 MMBOE (million barrels of oil equivalent) in North Dakota
- Over 180 vertical and horizontal Birdbear wells (2015, NDGS Oil and Gas Review)
- B-zone is primary reservoir for vertical wells (A-zone is secondary). A-zone has been targeted by dozens of horizontal wells towards the south.



Objectives/Questions



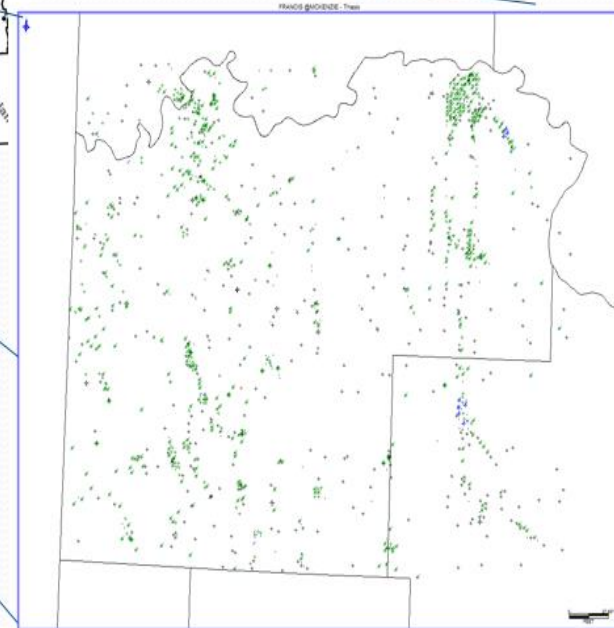
- **What are the reservoir characteristics? (In relation to level of diagenesis, porosity and permeability)**
- **What is the reservoir (porosity) distribution look like in the study area?**
- **Is the Birdbear self-sourcing?**
- **What is the TOC content of the source beds?**
- **Are these source beds extensive in the basin?**

Methodology

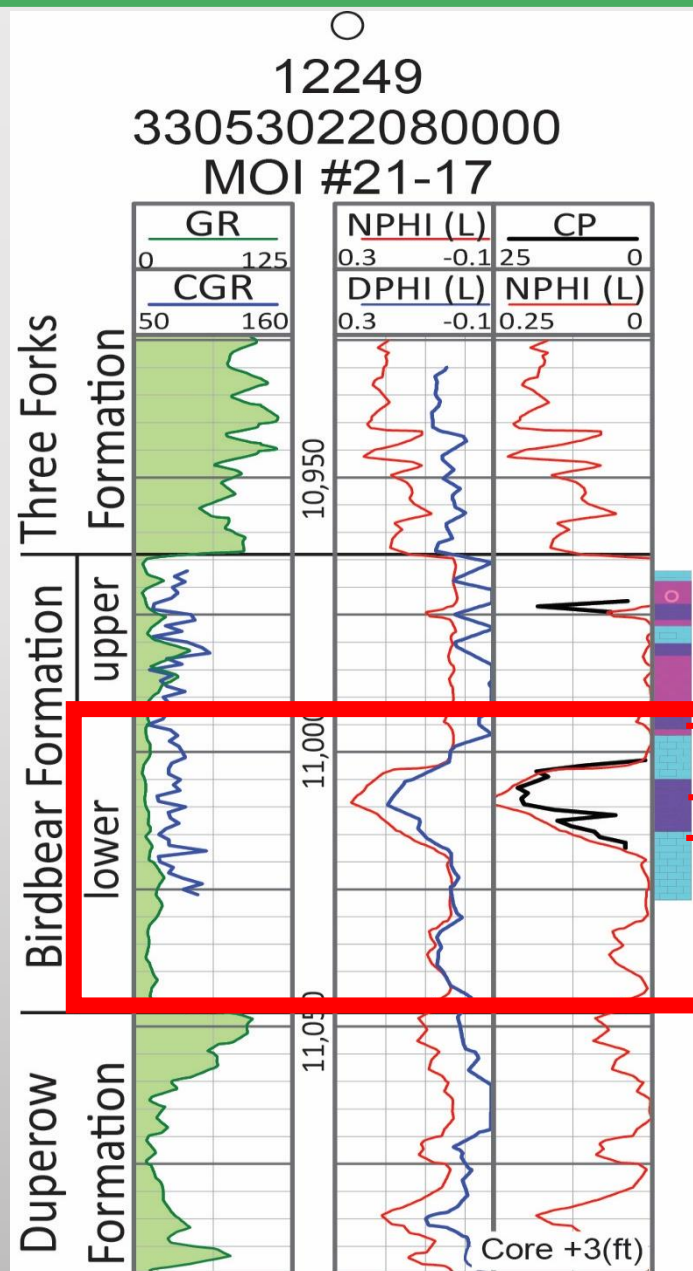
- **Core description and lithofacies identification**
 - Identify types of lithofacies present
- **Correlation and lithofacies mapping**
 - Evaluate extent and scale of Birdbear lithofacies (units)
- **Thin section analysis (over 110 slides)**
 - Evaluate level of diagenesis, rock grain fabric (porosities) and general rock characteristics (reservoir qualities)
- **Nuclear Magnetic Resonance (reservoir quality characteristics) and T2 distribution**
 - Correlate porosity and permeability
- **SRA- programmed pyrolysis**
 - Determine source beds and type of kerogen present

- **Study location (McKenzie County)**
- **Data (number of wells that penetrate the Birdbear, 1143)**
- **Number of wells that have available core (13)**
- **Wells with available thin sections (7 with over 110 slides)**

Map of Study Area

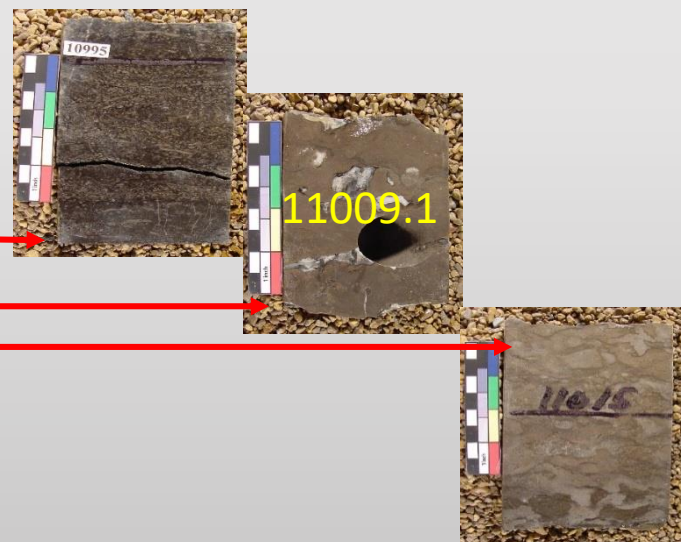


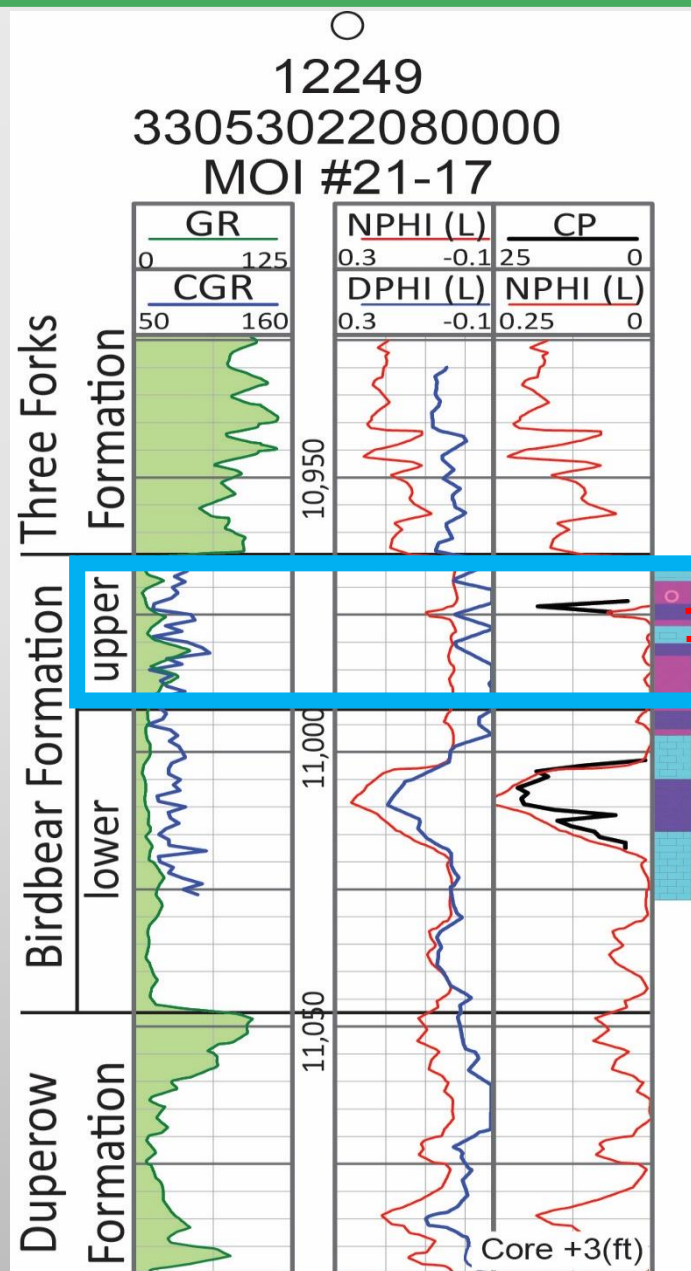
Results and Interpretations



- Lower carbonate unit

- B-zone, with porous dolomitized facies
- Stromatoporoid and amphiporia bank facies





- An upper anhydrite-carbonate unit
 - A-zone, consists of two or three thin dolostone beds
 - Anhydrite couplets
 - Dolomitized porous beds

Thin Section Analysis



#2602 (10084.5) inter-granular/Crystalline porosity, Mag x10



#2602 (10057.9) Vuggy porosity, Mag x10



#2820 (10916.8) Solution enhanced porosity, Mag x10



#2820 (10913.2) Intra-granular porosity, Mag x10



Results and Interpretations



- **High diagenetic alterations with vadose zone characteristics prominent.**
 - **Mineral dissolution**
 - **Re-precipitation and re-crystallization**
 - **Dolomitization**
 - **Inter-crystalline and intra-crystalline porosities**
 - **Vuggy porosity**
 - **Solution enhanced porosity**
- **Hydrocarbon production from extensively dolomitized stromatoporoid banks**
 - **From stratigraphic, structural or combination traps**

Results and Interpretations

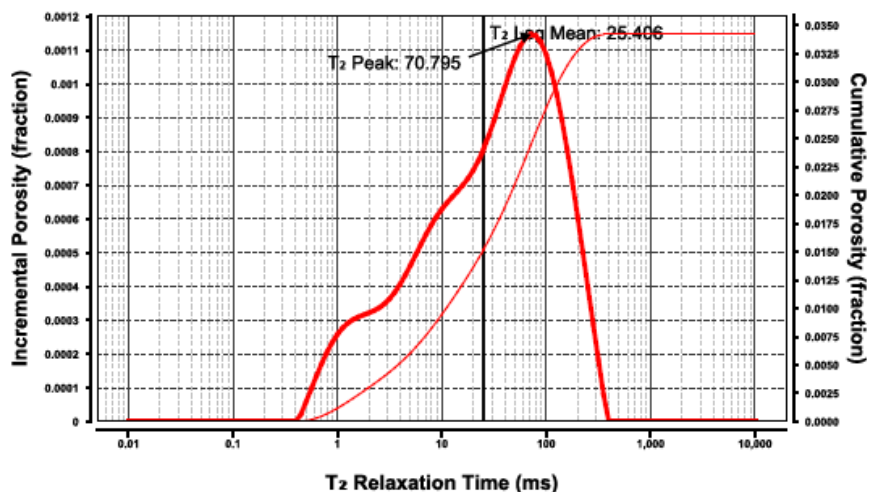
NMR T2 response for porosity evaluation on a dolostone and limestone facie showing high producible fluids in the dolomite facie as against more clay bound fluids in limestone facie

T₂ NMR

Project	francis	Helium Porosity	0.0000 fraction
Sample	DOL (Confining Stress	0.00 psi
Well	2820	Gas Permeability	0.000000 mD
Sample Depth	10,897.0ft	Brine Permeability	0.000000 mD
Legal Location / Block		Bulk Volume	5.400 ml

Total NMR Porosity	0.0342 fraction	T ₂ Log Mean	25.406 ms
Sample State	Undefined	SNR	21.90
Date Performed	2016/01/26 12:06 PM	NSA	1,008
Calibration	5.9087E-5 ml/m.u.		

Porosity 3.4%

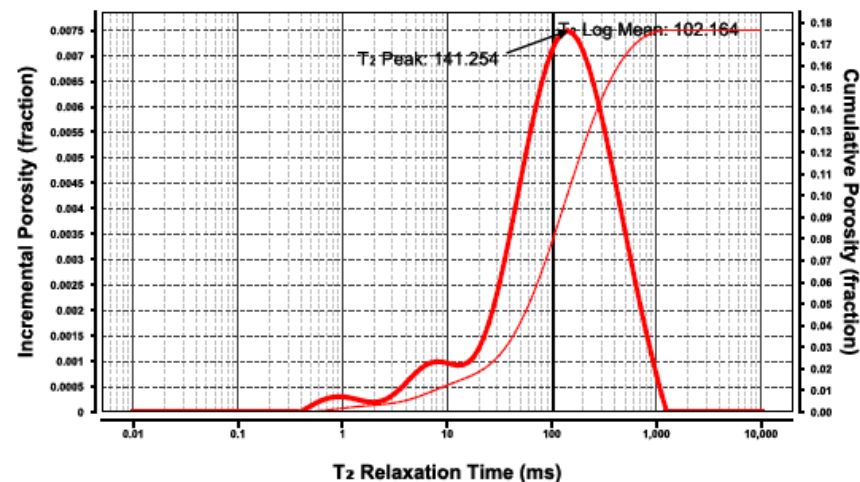


T₂ NMR

Project	francis	Helium Porosity	0.0000 fraction
Sample	DOL	Confining Stress	0.00 psi
Well	12249	Gas Permeability	0.000000 mD
Sample Depth	11,004.0ft	Brine Permeability	0.000000 mD
Legal Location / Block		Bulk Volume	5.400 ml

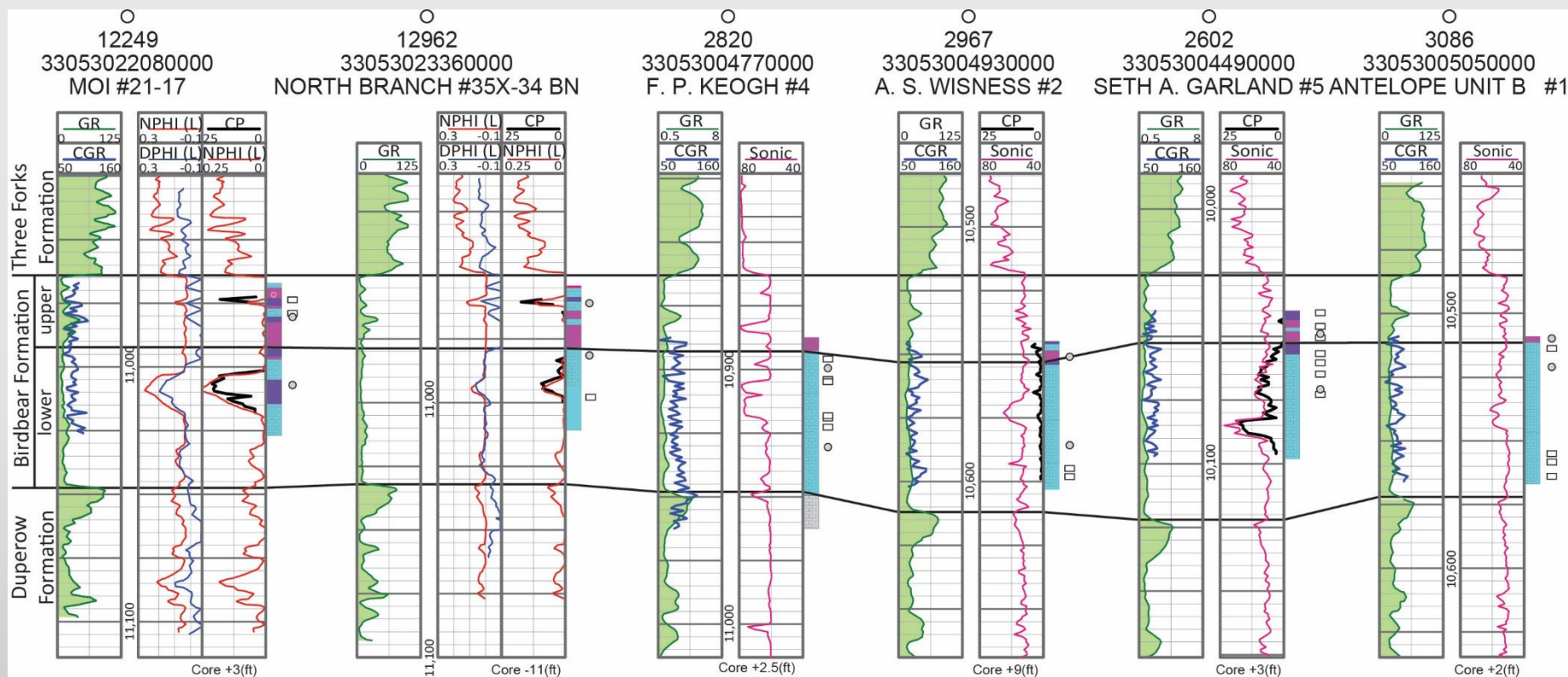
Total NMR Porosity	0.1761 fraction	T ₂ Log Mean	102.164 ms
Sample State	Undefined	SNR	82.33
Date Performed	2016/01/27 03:21 PM	NSA	608
Calibration	5.9087E-5 ml/m.u.		

Porosity 17.6%



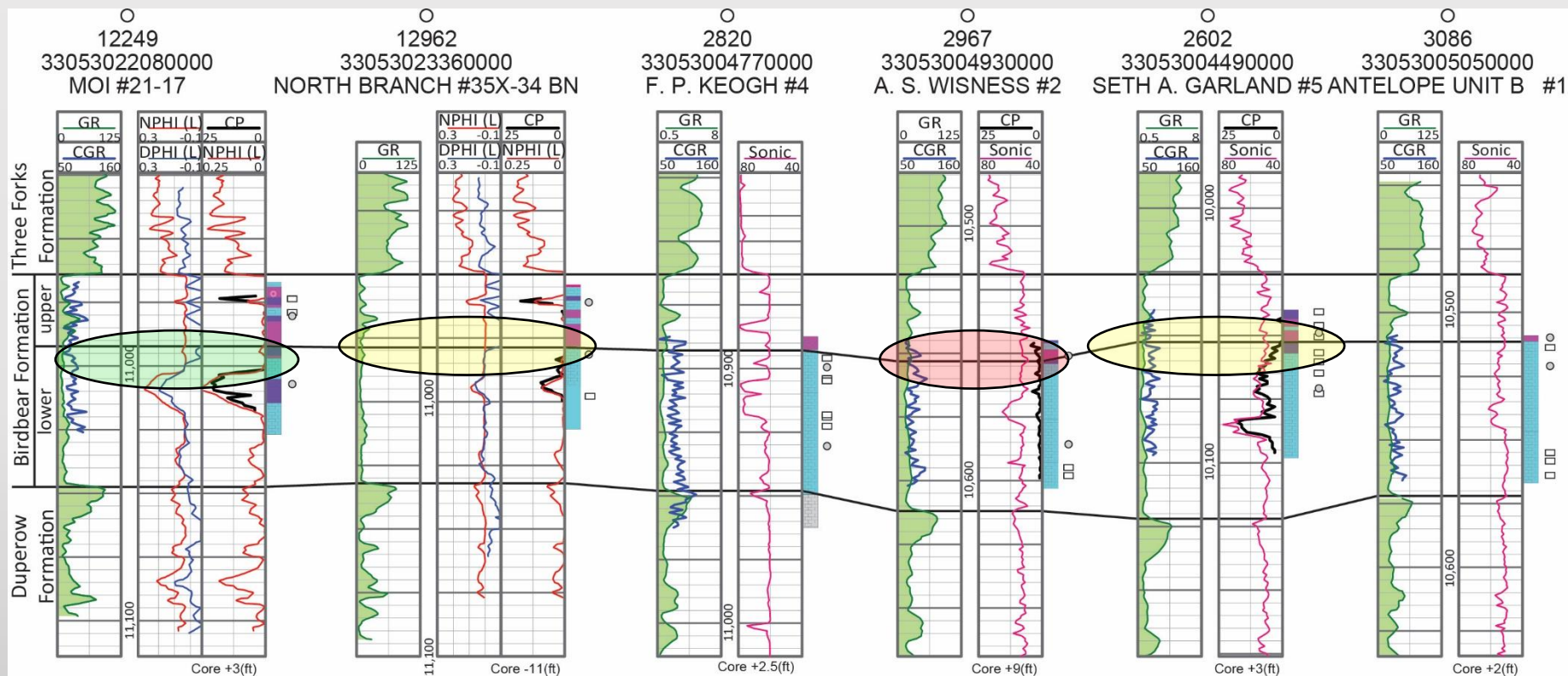
- Average porosity value is about 12.5%,
- Average permeability value is about 4.8 md

Correlation and Lithofacies Identification



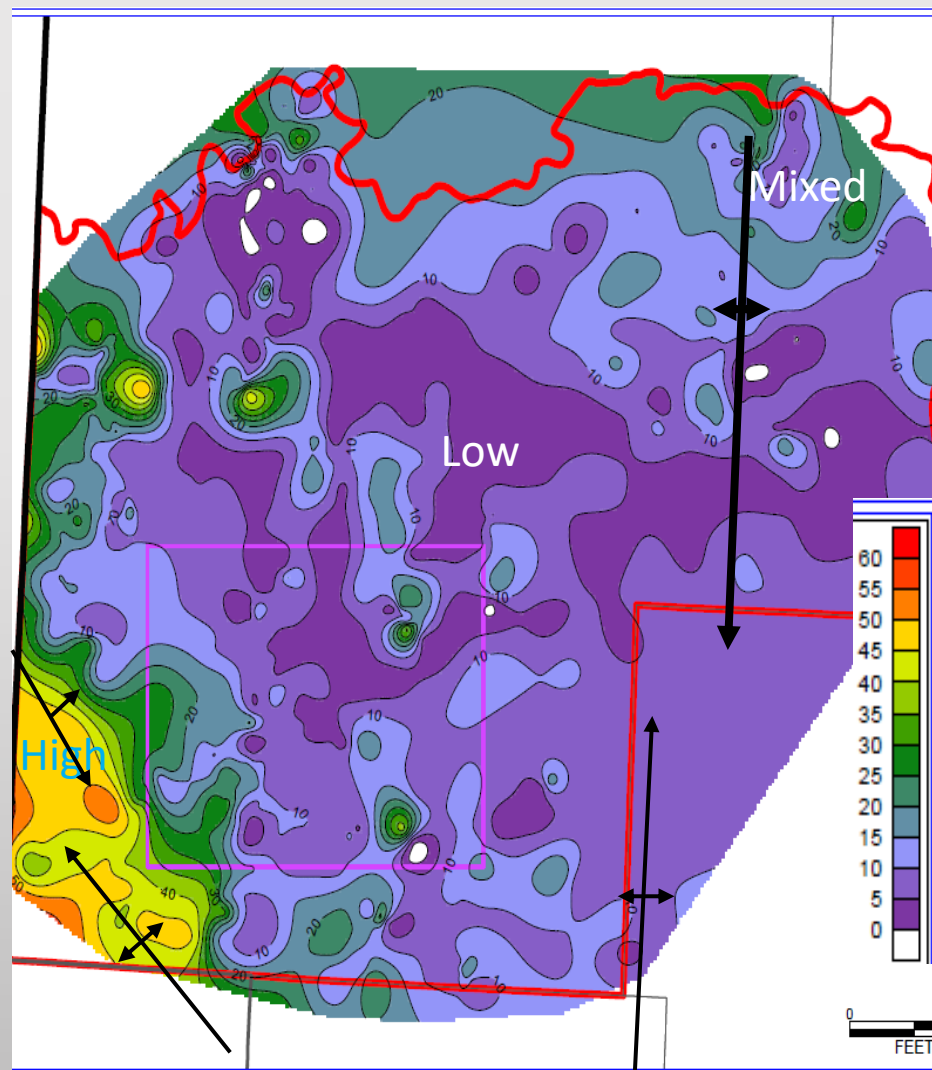
Results and Interpretations

Correlation and Lithofacies Identification

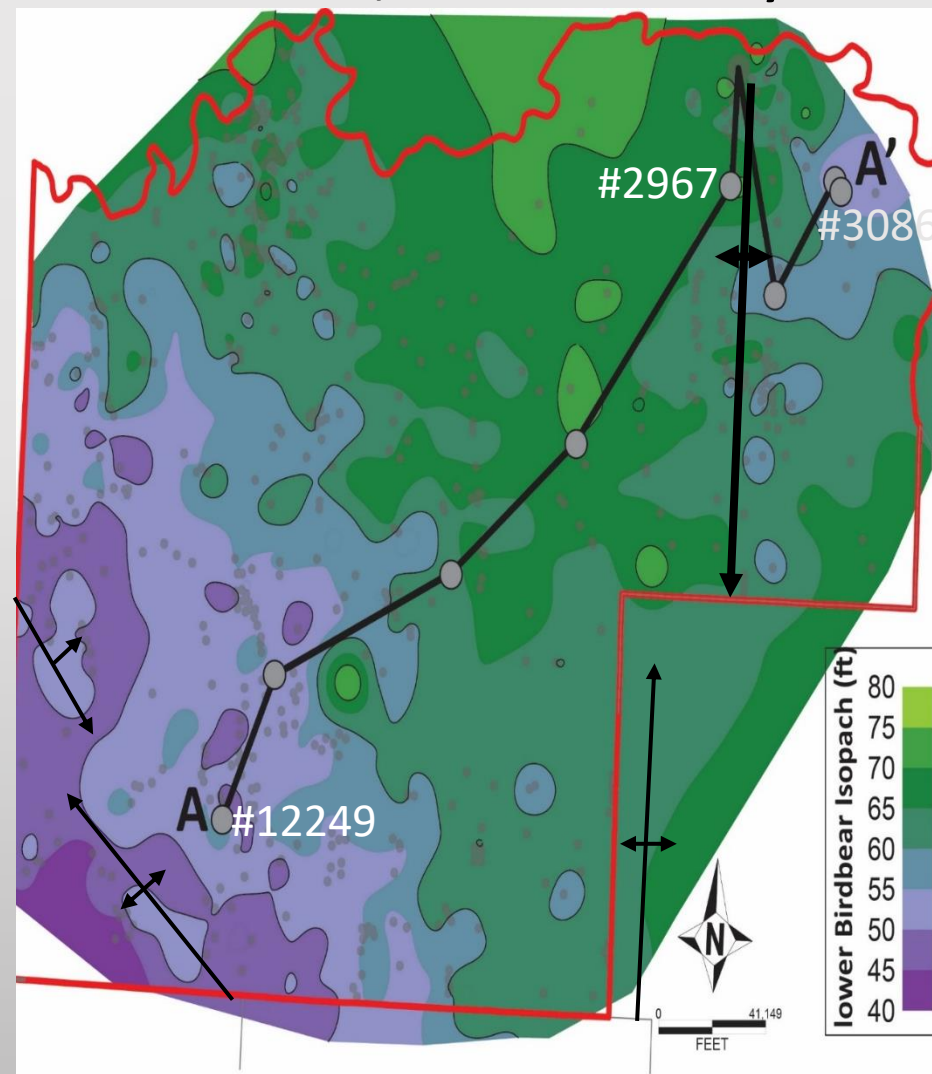


Results and Interpretations

Total porosity map of Birdbear Formation, McKenzie County



Isopach map of lower Birdbear Formation, McKenzie County



Discussions and Implications

Summary of combined Total Organic Carbon programmed pyrolysis results from this study and other Birdbear studies

API No.	NDIC Well No.	Depths (ft.)	TOC	Pyrolysis		HI	OI	T _{max}	
				S ₁	S ₂				
33053002030000	1343	10550.6	11.55	2.45	21.11	182.8	11.9	442	Sigler, 2015
33053004770000	2820	10895	5.94	1.62	12.68	213.5	9.9	450	
33105005990000	2887	9203	5.62	0.8	14.8	263.3	9.4	438	
33053004930000	2967	10537.2	2.965	1.33	3.6	121.4	13.8	452	
33013007040000	4599	7471	2.6	1.55	14.36	552.3	18.5	429	
33013007040000	4599	7481.2	1.45	5.86	7.31	504.1	14.5	423	
33013007040000	4599	7488	1.595	0.97	5.57	349.2	18.2	428	
33105007740000	6642	10819	11.3	4.59	46.22	409	4	444	
33105011150000	10837	10794.1	2.94	0.7	14.24	484.4	10.2	440	
33023004250000	13698	7030.9	3.725	0.77	15.59	418.5	12.9	434	
33053038430000	21786	11424.5	6.8	3.97	8.25	121.3	4.7	462	
33007000160000	859	11199	1.52	0.47	0.82	54.02	25.69	445	Engelman, 2015
33053023360000	12962	10987	1.58	0.97	2.5	158.73	20.32	453	
33053023360000	12962	10965.1	3.49	1.21	7.58	217.19	8.31	450	
33053023360000	12962	10991.2	2.45	0.85	4.3	175.51	13.06	450	
33053023360000	12962	11000.1	2.27	1.27	4.32	190.31	11.45	449	
33033002510000	15679	10716	1.57	0.97	6.26	397.97	18.44	438	
33033002510000	15679	10726	1.67	3.85	5.19	310.04	17.92	443	
33053022080000	12249	10992	6.87	1.93	14.29	208.01	4.51	452	
33089006460000	21139	10004.5	2.88	2.43	9.65	334.84	7.63	439	
33089006460000	21139	10006.8	5.37	2.12	20.9	389.34	5.77	440	
33033003080000	21734	10511.5	2.71	1.51	7.03	259.03	13.26	439	
33053023360000	12962	10972	2.05	0.28	1.52	74	23	447	This study
33053023360000	12962	10991	2.1	0.41	2.39	114	14	454	
33053023360000	12962	10992	1.21	0.3	1.08	89	26	449	
33053023360000	12962	10993	2.1	0.32	3.29	157	15	449	

Discussions and Implications



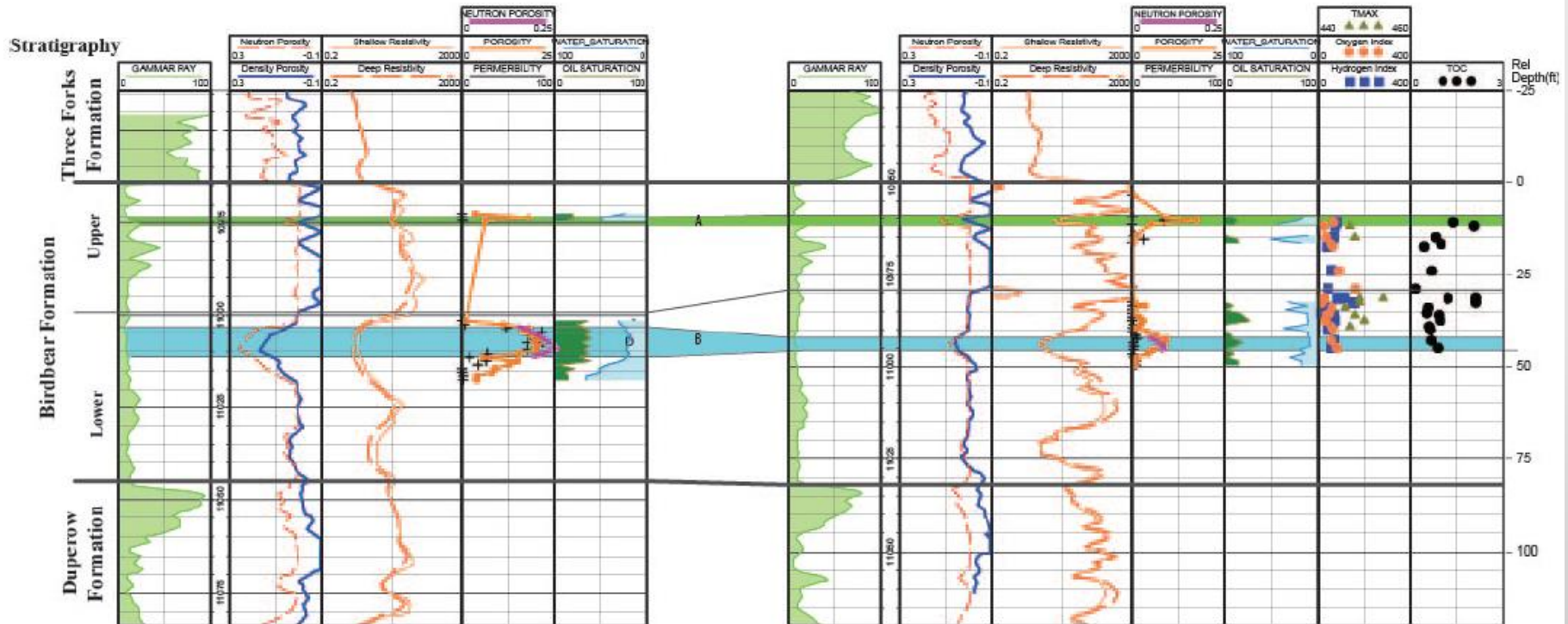
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MOI #21-17



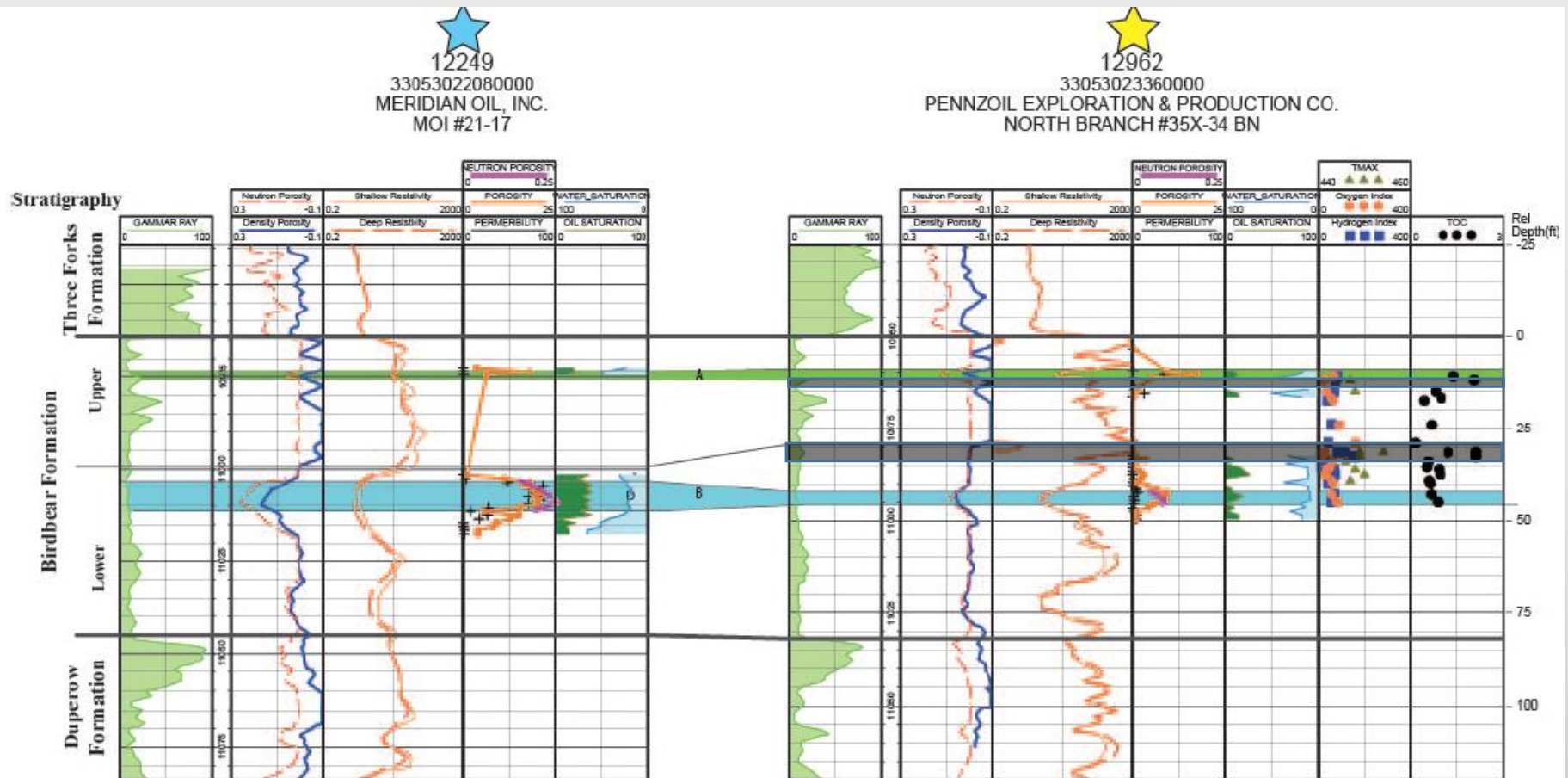
12962

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PENNZOIL EXPLORATION & PRODUCTION CO.
NORTH BRANCH #35X-34 BN



Cross-section showing stratigraphy of the Birdbear Formation with units of the A and B-zones correlated, depths and thickness with associated water and oil saturation, TOC, HI index and OI index

Discussions and Implications

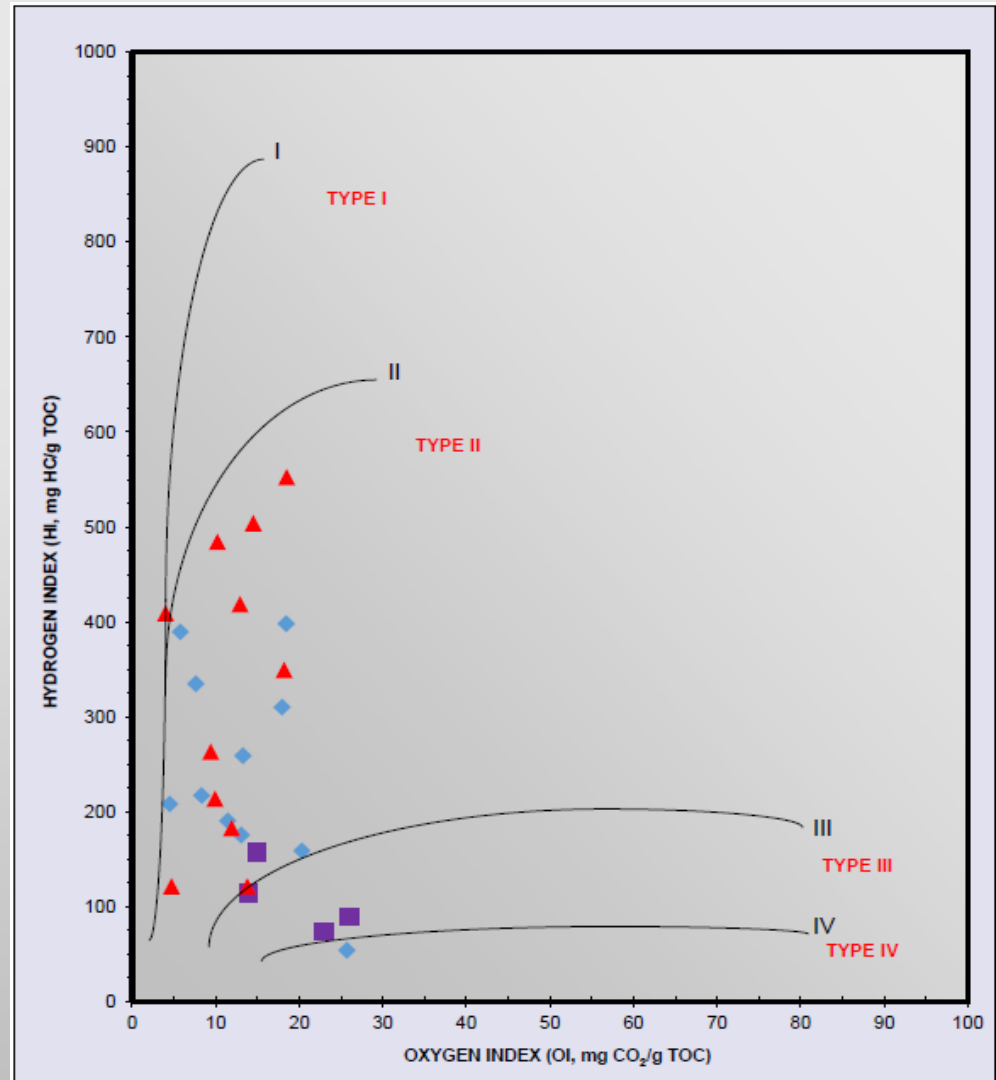


Cross-section showing stratigraphy of the Birdbear Formation with mapped source bed thickness from A and B-zones.

Discussions and Implications

- TOC values range from 1-11%
- Type II kerogen signature in less mature samples

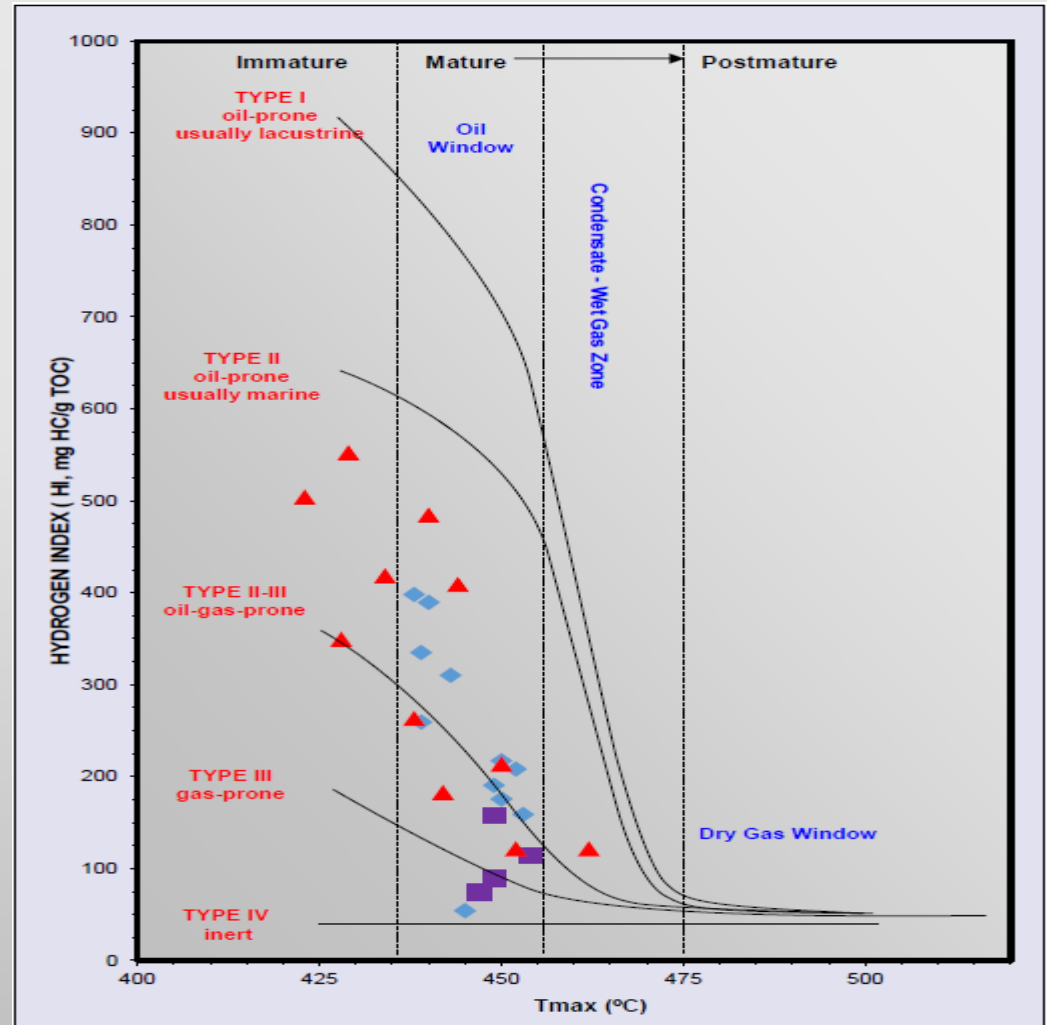
Plot of HI vs OI indices for kerogen maturity



Discussions and Implications

- Birdbear source beds are thermally mature
- Within the oil generating window
- HI decreases with increasing Tmax values
- Tmax values reach 450+ °C

Plot of production vs maturity of source beds





Discussions and Implications

- **Sediments of the Birdbear have undergone significant diagenesis**
- **Vuggy, solution enhanced, intra-crystalline and inter-crystalline porosities are abundant**
- **Source beds are thermally mature and within the oil generating window**
- **Type II kerogen signature (marginally mature samples)**
- **Production is localized in stratigraphic traps at some intervals**
 - **High potential from Well # 12962**
 - **Production depth is at approximately 10,800 ft**



Conclusions

- **The Birdbear Formation has a distinct anhydrite, dolomite and limestone lithology that is easily identifiable and traceable across the Williston Basin**
- **Significant diagenetic alterations in the Birdbear producing excellent reservoir with increased effective porosity and permeability within the mapped area**
- **Production is present in the Birdbear, but is localized in stratigraphic traps at some intervals of depth approximately 10,800 ft within the porous influential zones**
- **Source rock present is self sourced, from two important porous zones, A and B, with enhanced hydrocarbon potential within the Birdbear from sporadic dolomitized reservoir unit of about a few feet that are traceable across the basin**
- **Birdbear appears to be at least a partly self-sourcing hydrocarbon formation. Contains distinct beds that are organic-rich (1-11% TOC), oil prone (400+ HI), and thermally mature (445+ Tmax)**



Acknowledgement



- **God Almighty**
- **HHS GGE University of North Dakota**
- **Late Julie LeFever, (former director NDGS)**
- **Director and staff of Wilson M. Laird Core and Sample Library, Grand Forks**
- **Tim Nesheim NDGS**
- **AAPG Rocky Mountain Section**
- **North Dakota Geological Society**