Reservoirs of the Bakken Petroleum System: A Core-based Perspective

Julie A. LeFever[1], Richard D. LeFever[2], and Stephan H. Nordeng[1]
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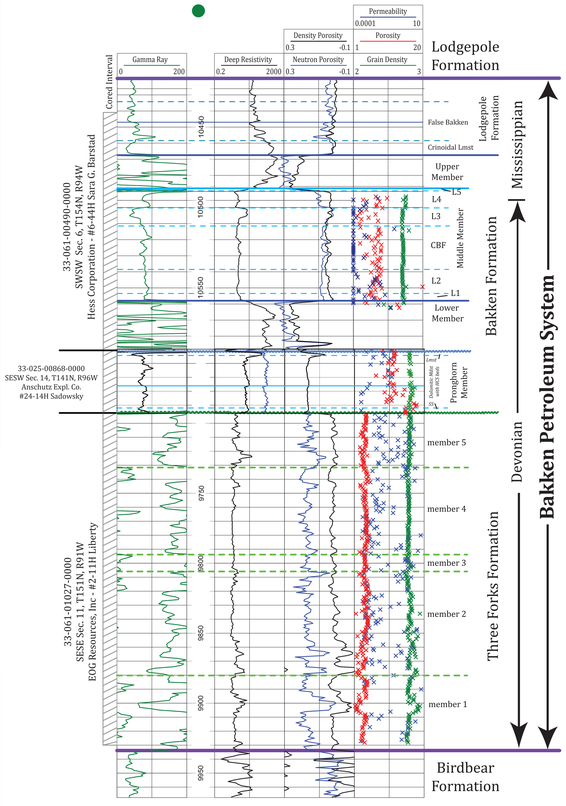
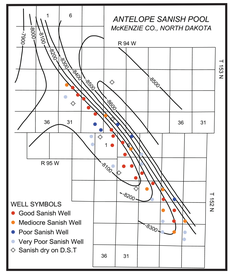
Sheet 1

Composite Log



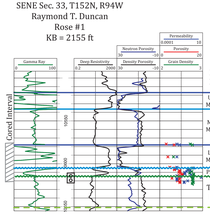
Composite Log – The Bakken Petroleum System was originally described as the lowermost Lodgepole (50 ft), the Bakken, and the top of the Three Forks formations (50 ft). Recent activity has added a new member (Pronghorn) to the Bakken as well as including the entire Three Forks Formation into the source system. In addition to excellent source potential each formation has its own set of unique reservoir rocks.

Antelope Structure - Bakken-Three Forks Formation



Structure map of Antelope Field with wells and their relative production (modified from Murray, 1968). The good wells are associated with the natural fracture network developed along the fault on the northeast flank.

33-053-02163-0000
SENE Sec. 33, T152N, R94W
Raymond T. Duncan
Rose #1
KB = 2155 ft

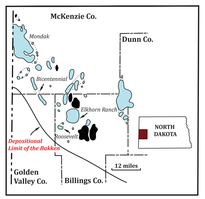


12019-10601.3

Reservoir rocks in Antelope Field are fracture controlled. These fractures opened due to tensile failure along the tightly flexed portion of the steeply-dipping northeastern limb of the anticline and supply an otherwise tight formation with enough oil to be economic. Original formation pressures were significantly above hydrostatic suggesting sourcing from the Bakken. Later attempts in the field to enhance production by additional perforations were generally unsuccessful.

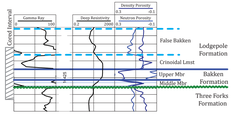
The field produces from the Pronghorn Member of the Bakken and the upper Three Forks section. The Pronghorn in this field reaches a maximum thickness of 24 ft. and consists of a highly burrowed (*Skolithus*), fine-grained sandstone (see photo). It is a transgressive lag deposit and unconformably overlies the apple-green claystones, and tan dolostones of the Three Forks Formation. It is not uncommon for the Pronghorn to be absent; then the uppermost Three Forks becomes the reservoir.

Upper Member - Bakken Shale



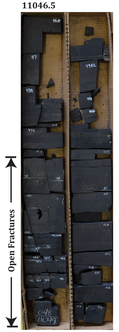
Index Map

33-007-01109-0000
NWSE Sec. 1, T143N, R102W
Meridian Oil, Inc.
MOI Elkhorn #33-11
KB = 2311 ft.



33-007-01185-0000
SWSW Sec. 5, T143N, R99W
Texaco, Inc.
#5-1 Texaco Thompson Unit

Upper Member
11046.5



11052.0

Core with natural vertical fractures stopped above and below by a slight lithologic change.

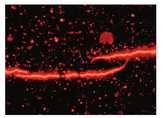
The Bakken Formation exhibits an onlapping relationship. The Three Forks Formation is overlain by stratigraphically higher members of the Bakken. This in turn is overlain by the carbonates of the Lodgepole Formation. The thin shale of the Upper Member overlying regional structures of the area makes it more susceptible to fracturing.

Where it is considered a reservoir, the Upper Member consists of finely laminated shales from a restricted marine setting that are organic-rich. Production is located along the depositional edge from the mature portion of the basin.

The upper shale is divided into 3 parts that have a corresponding gamma-ray log signature. The upper portion of the shale has the highest organic content, the middle portion has the lowest organic content (highest silt content), and the lower portion of the shale is between the upper two. Fracturing is more intense where the organic content is higher. Therefore, the reservoir resides in the upper portion of the shale that has a higher percentage of clay and organic material (Carlisle et al, 1992).

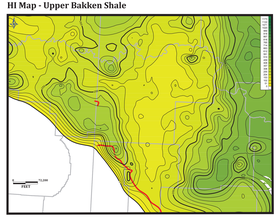
The reservoir is primarily fracture-based. Maturation of the organic-rich shale has resulted in over-pressuring and a system of micro-fractures that are related to generation and expulsion. This network of micro-fractures provides the reservoir with storage and, in conjunction with regional fractures, delivers oil to the wellbore .

Horizontal drilling of the Upper Member (shale) of the Bakken has been actively pursued since 1987 when Meridian Oil drilled and completed the MOI Elkhorn #33-11H well in Billings County, ND. In this area, the members of the Bakken Formation onlap the underlying Three Forks Formation and ultimately pinch-out along a trend commonly referred to as the Bakken fairway. Horizontal drilling targeted areas where the Upper Member was approximately 10 ft thickness which enhanced its ability to fracture over structures.



"Cracked_tip" morphology of horizontal microfractures with widths of 10 to 20 microns. (Carlisle et. al., 1992).

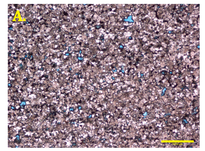
HI Map - Upper Bakken Shale

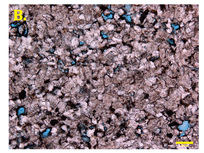


Maturation map of the Upper Member along the "Bakken Fairway". Lighter colors indicate an increase in maturation leading to an increase in fracturing. Red line indicates the depositional edge of the Upper Member.

Elm Coulee - Bakken Formation

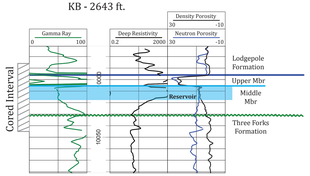
Balcron Oil - 44-24 Vaira (SESE Sec 24, T24N, R54E) – Depths 10,005.5 to 10019.5 ft. - Base of the Upper Member through the reservoir section (Log below; USGS Photograph).



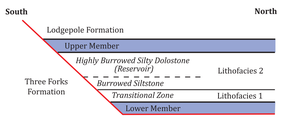


Balcron Oil – 44-24 Vaira (SESE Sec. 24, T24N, R54E) – Depth 10,011.0 ft. – Plane light photomicrographs of the reservoir consisting of a quartz dolostone with minor amounts of feldspars and clay. Intergranular porosity ranges from 10 – 13%. A. 4X; B. 10X.

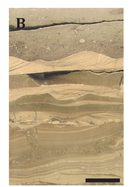
25-083-21775-0000
SESE Sec. 24, T24N, R54E
Balcron Oil Company
#44-24 Vaira
KB - 2643 ft.



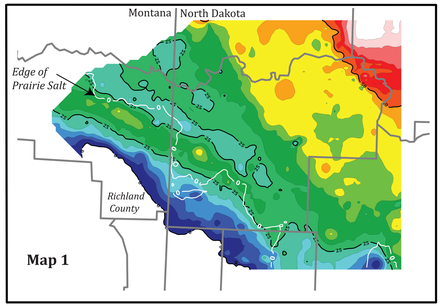
Wireline logs for the overlying core and thin-section photographs. Reservoir section for Elm Coulee is shown in blue.



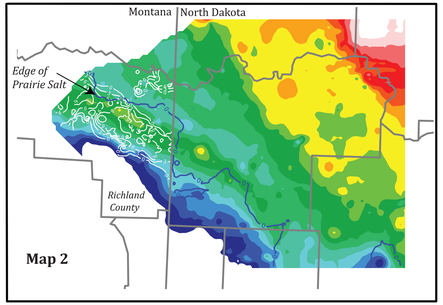
The onlap relationship of the Middle and Upper Bakken Formation in the Elm Coulee area is shown in this schematic diagram. The red line represents an unconformity.



Representative core samples of the highly burrowed silty dolostone that comprises the reservoir (A) and unconformity between the Middle Member and Three Forks Formation (B). American Hunter Exploration Ltd. - #1 H8 Nevins (SESW Sec. 13, T23N, R56W). Scale Bar = 1 inch.



Map 1 - The isopach of the Middle Member of the Bakken Formation shows a noticeable northwest-southeast trend in the Elm Coulee area of Richland County, Montana. This trend is approximately 2 to 3 townships wide and is by 72 miles long. It reaches a maximum thickness of 35 ft before decreasing in thickness towards the depositional limit. It gradually thickens towards the center of the basin. The white zero edge line represents the present edge of the Devonian Prairie salt. The section responsible for the increase in thickness is shown in blue on the log of the Balcron Oil Co. – #44-24H Vaira well.



Map 2 - The porosity along this trend is mapped in white and overlain on the isopach. Notice how the porosity lies immediately southwest of the zero edge of the salt.

Elm Coulee Field was discovered in 2000 with the drilling and completion of the Kelly/Prospector - #2-33 Albin FLB well in the Middle Member of the Bakken Formation. The Bakken Formation in this area consists of the Upper and Middle Members (facies L1 and L2), onlapping the underlying Three Forks Formation. In turn, they are overlain by the dense carbonates of the Lodgepole Formation forming a stratigraphic trap. Only the lowermost facies, L1 and L2 are present in the field. The maximum thickness of the Bakken Formation is 50 ft.

The field is developed along the northwest-southeast trending isopach thick. The reservoir consists of a dolomitized carbonate shoal complex. It has low matrix porosity, typically 3 to 9 %, and low permeabilities averaging .04 md. The field is slightly overpressured at .53 psi/ft.

Elm Coulee also depends on fracturing. Besides providing accommodation space, dissolution of the underlying Prairie salt probably provided a fracture network that allowed dolomitizing fluids to move through the carbonate shoal.

North Dakota Geological Survey
Geologic Investigations No. 171

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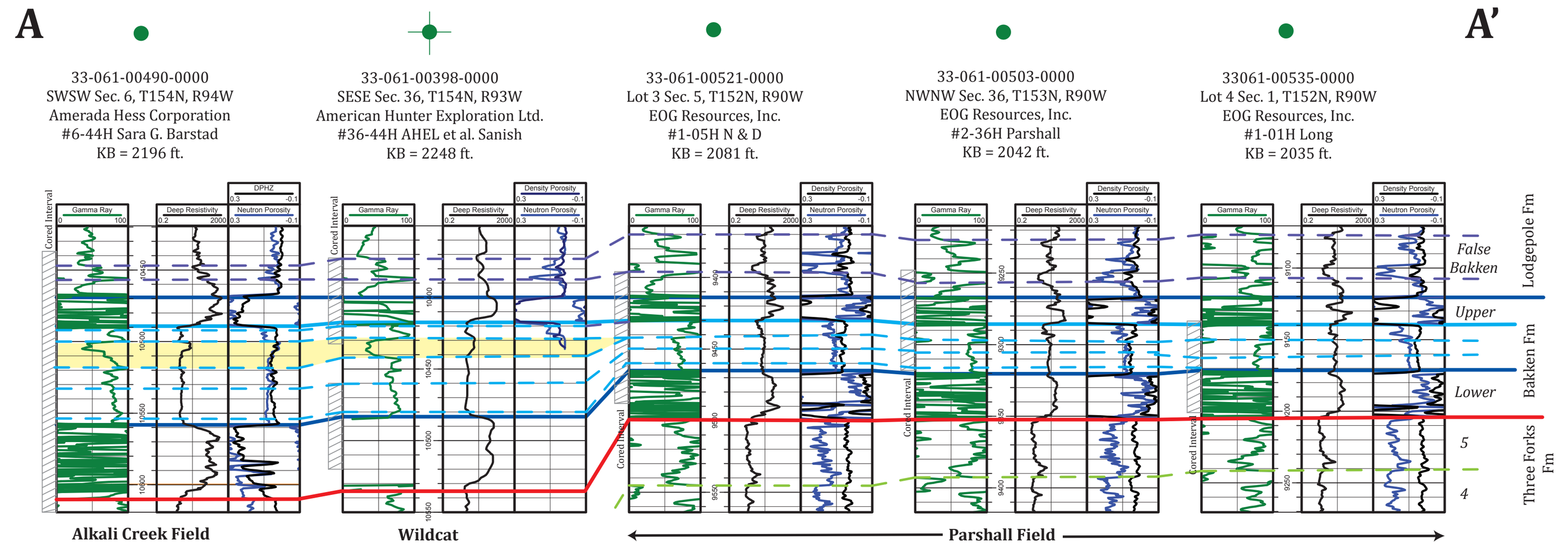
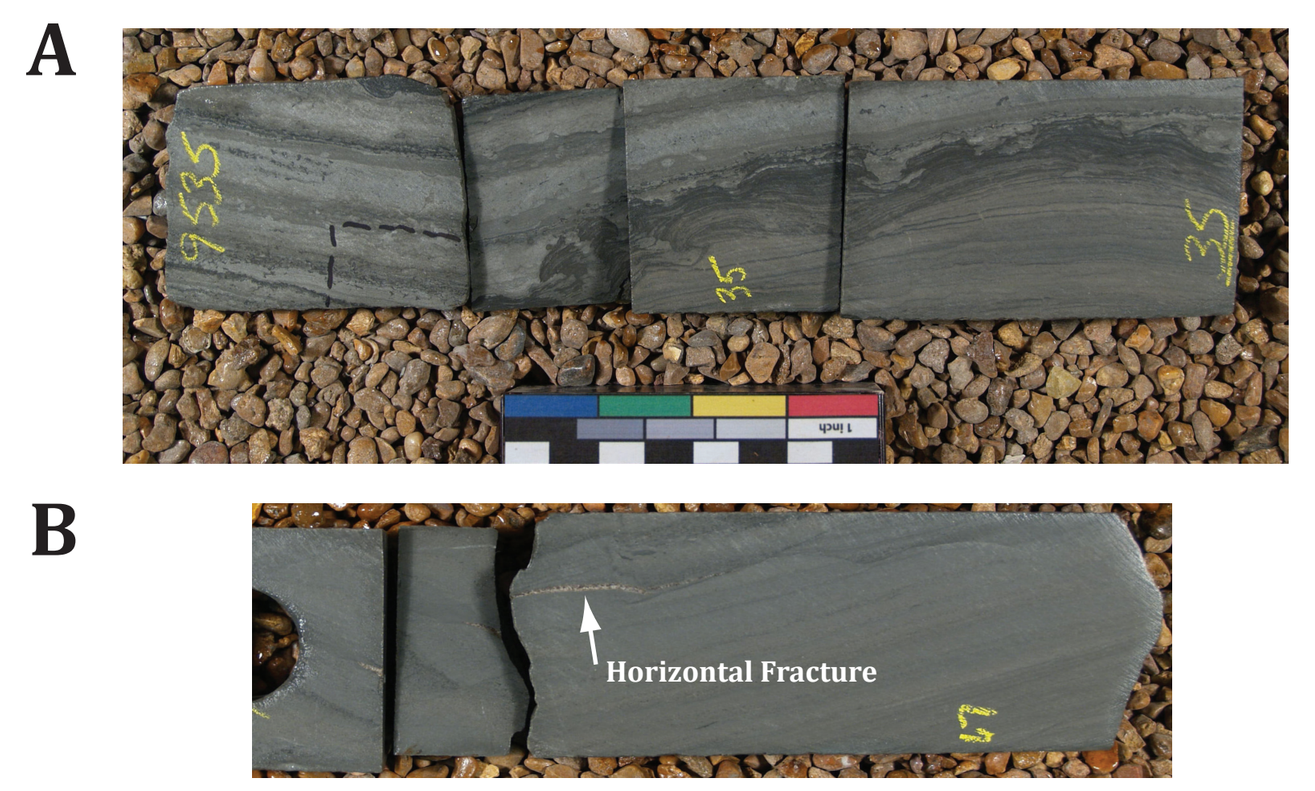
Sheet 2

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2013

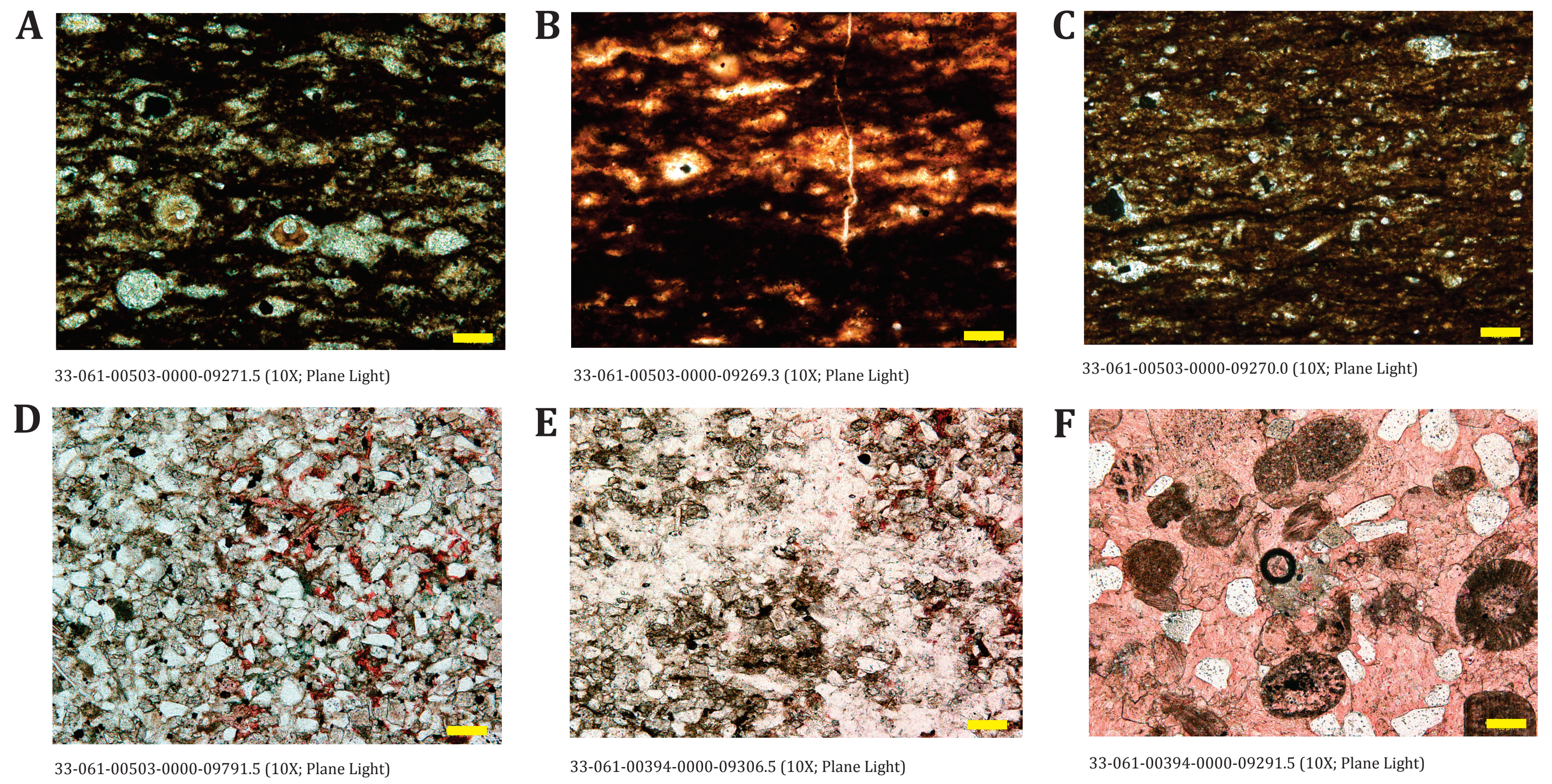
Parshall & Sanish Fields - Bakken Formation



Cross-section A - A' across Parshall and Sanish fields (see Map for Line of Section). Parshall field has limited occurrence of lithofacies 3 (shaded yellow) that compartmentalizes the reservoir elsewhere in the basin. Minor structures, access to the entire productive section, overpressuring and related micro-fractures that end on the east side of the field create the stratigraphic trap that makes Parshall a sweet spot.

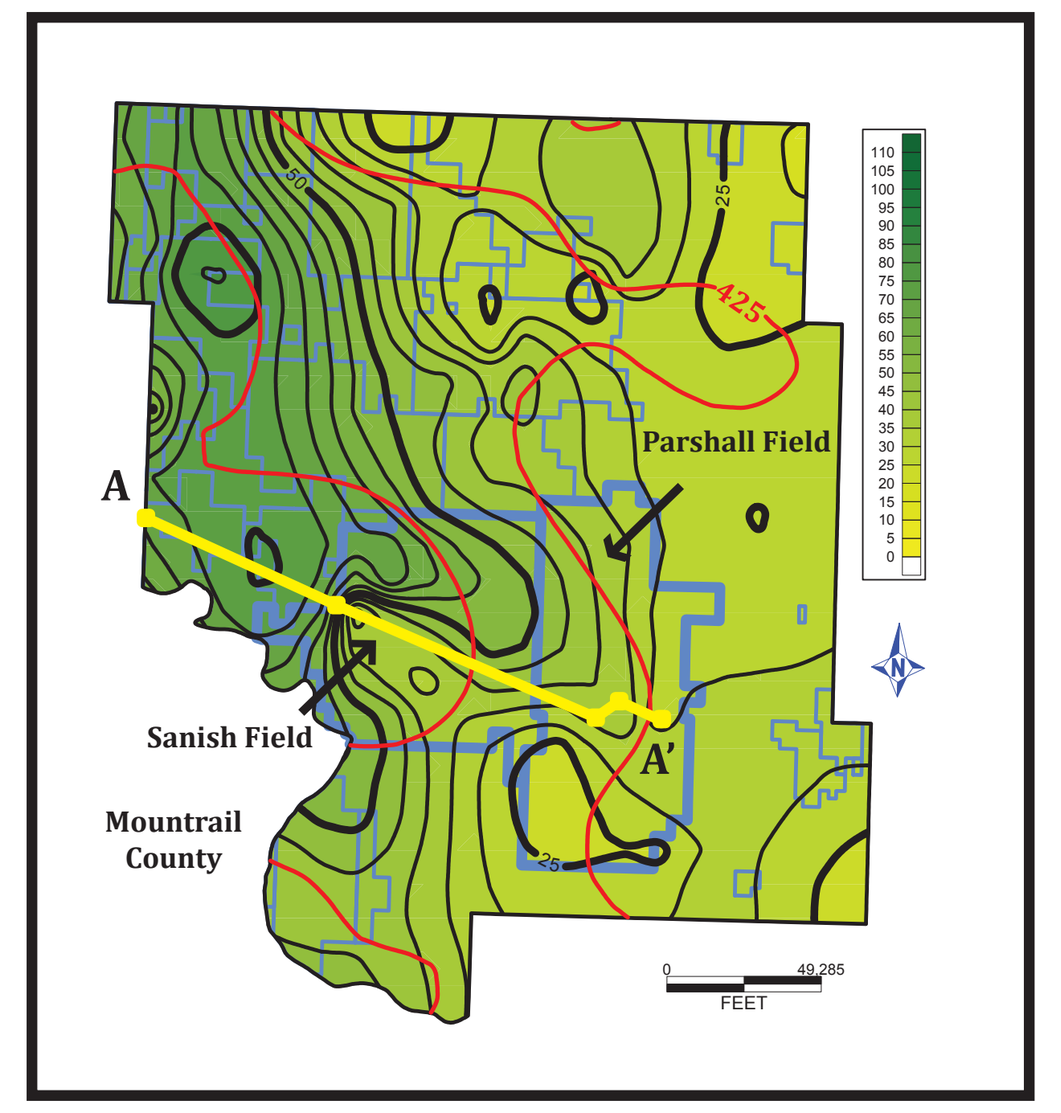


Core pieces are from the EOG Resources, Inc. - #1-10H Hoff well (NWNW Sec. 10, T152N, R90W). Well was cored through the build section cutting Lithofacies 3 through 5. A – Core displays the stromatolites that are common in lithofacies 4 and is representative of the pay section. The stromatolites develop in the sandier sections allowing for fluid movement and the dolomitization of any cement. This increases the porosity and permeability of the interval. B – Core is representative of lithofacies 3. A sandstone to grainstone interval that is generally well cemented and may compartmentalize the reservoir rocks above and below. Note the cemented horizontal fracture.



A: 33-061-00503-0000-09271.5 (10X; Plane Light)
B: 33-061-00503-0000-09269.3 (10X; Plane Light)
C: 33-061-00503-0000-09270.0 (10X; Plane Light)
D: 33-061-00503-0000-09791.5 (10X; Plane Light)
E: 33-061-00394-0000-09306.5 (10X; Plane Light)
F: 33-061-00394-0000-09291.5 (10X; Plane Light)

Thin-section photomicrographs from two wells in Mountrail County, North Dakota (A-C - 33-061-00503-0000 – EOG Resources, Inc. - #2-36H Parshall; D-E – 33-061-00394-0000 – Marathon Oil Company - #26-1 Laredo). A and B are photographs from the Upper Member. Considered to be immature to marginally mature, the shale consists predominantly of clay, silt, organic matter, small carbonate grains that are probably calcispheres, and *Tasmanites.* Intervals appear to alternate between mudrock and shale. Thin-sections also reflect those changes. *Tasmanites*, organic matter, and other grains are unchanged in photographs A and C (mudrock), whereas compression and the organic matter is starting to coalesce in B. D shows the reservoir facies consisting predominantly of quartz sand, dolomite, pyrite, and calcite cement (stained with Alizarin Red). Multiple microfractures can be identified throughout the sample. Photomicrograph E shows the same lithofacies with cross-cutting filled fractures. F shows the dominant marine cement present in the sandstone-grainstone common to lithofacies 3 (shaded yellow on Cross-Section A-A').



Isopach of the Middle Member of the Bakken Formation in Mountrail County, North Dakota. The boundaries of Parshall and Sanish fields are indicated by the heavy blue lines. The Line of Section (A – A') is shown in yellow. Superimposed on the map is the Tmax of the Upper Member based on available data, shown in red (Contour interval of 10° C). The isopach thins to the east moving from Sanish to Parshall field. Also note the swing in the Tmax gradient towards the east over the two fields.

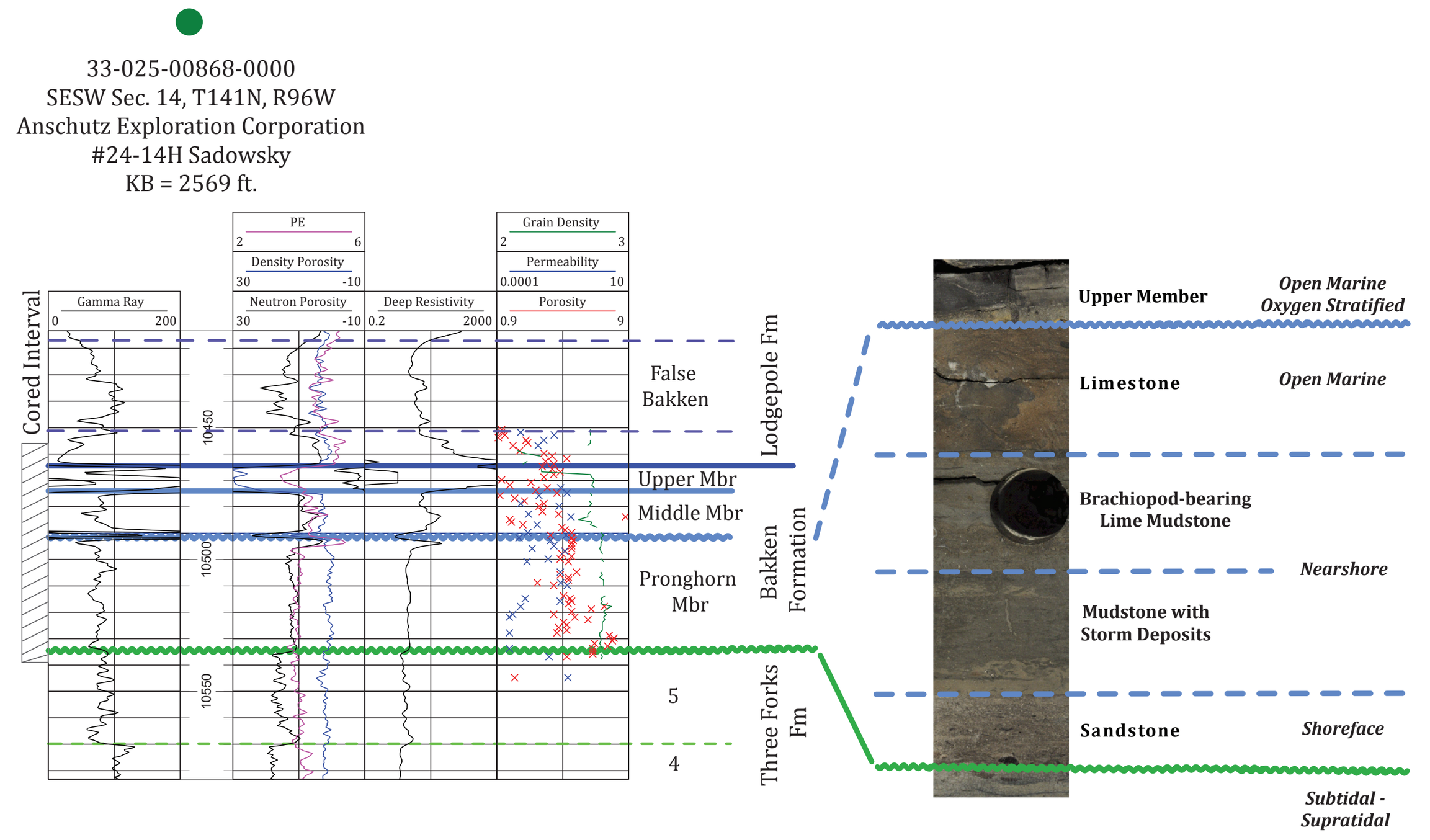
Reservoir

The reservoir at Parshall Field is located within lithofacies 4 of the Middle Member and consists of an algal-rich dolomitic siltstone to very fine-grained sandstone probably lagoonal in origin. Porosity ranges from 5 to 9% with an average permeability of .02 mD. The reservoir section is overpressured which is probably responsible for creating a well-developed network of microfractures enhancing the transmissibility.

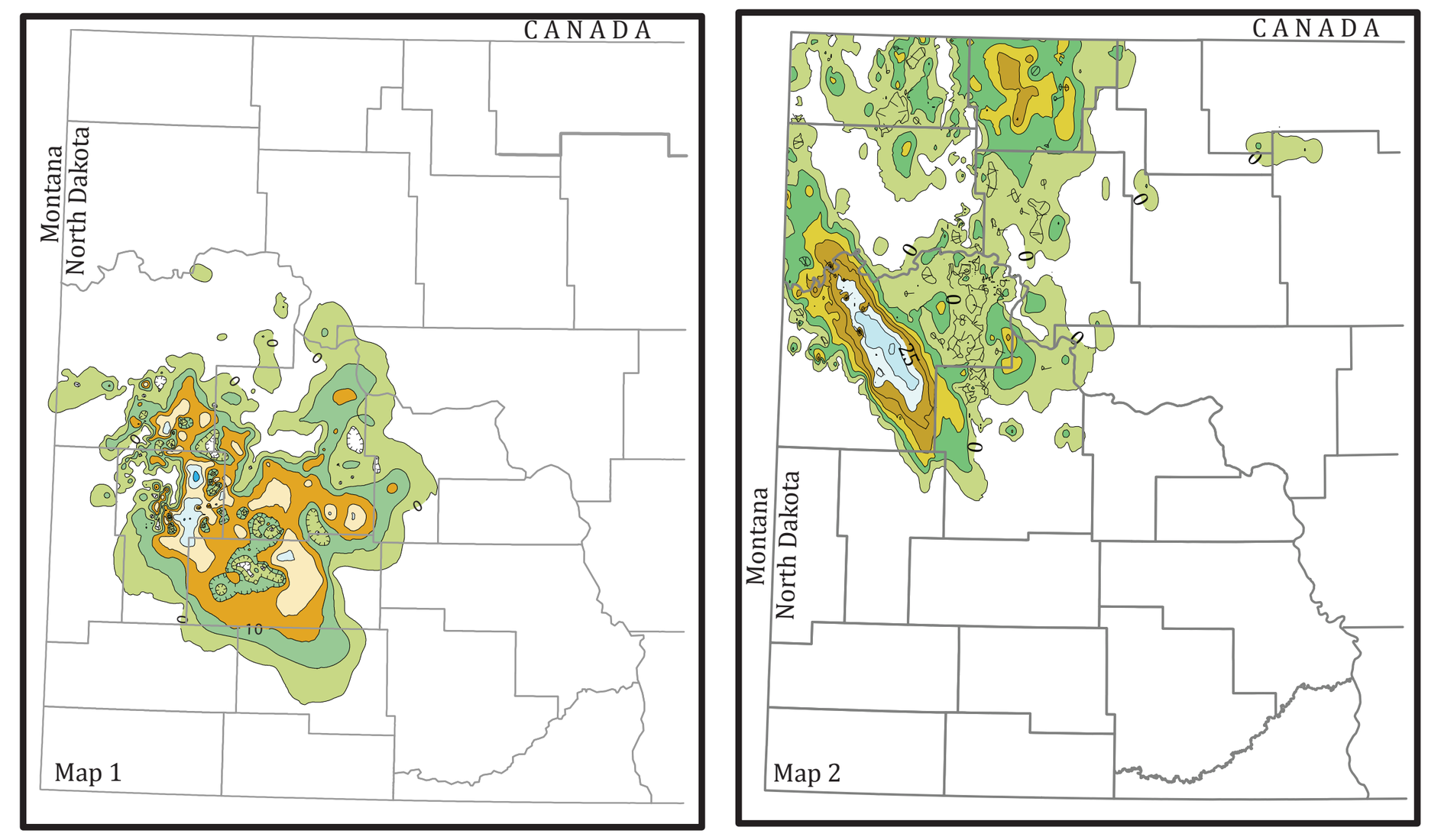
In addition to the microfractures, a network of macrofractures and larger regional scale fractures exist. Macrofractures present in lithofacies 3 tend to be calcite-filled and v-shaped. The existence of natural horizontal fracturing is confirmed visually in the EOG Resource Inc. - #1-10H Hoff. Regional fractures in the area are probably related to combination of basement tectonics, basin tectonics, and dissolution of the Devonian Prairie salt and subsequent collapse.

Questions remain concerning the sourcing of the reservoir. Core and thin-section work suggest that the shales are marginally mature and probably are responsible for at least some oil being generated in place. Additional oil may result from the algal material that is available in the Middle Member. Measured TOCs of up to 10% have been reported in the Parshall area (Dan Jarvie, pers. comm.). Oil has also migrated updip into the field from the deeper portions of the basin immediately west of Parshall Field. The shale becomes immature immediately east of the field.

Pronghorn Member



Wireline log of the Anschutz Exploration Corp. - #24-14H Sadowsky well showing the proximal portion of the Pronghorn Member of the Bakken Formation with core analyses, representative core section, and environments of deposition.

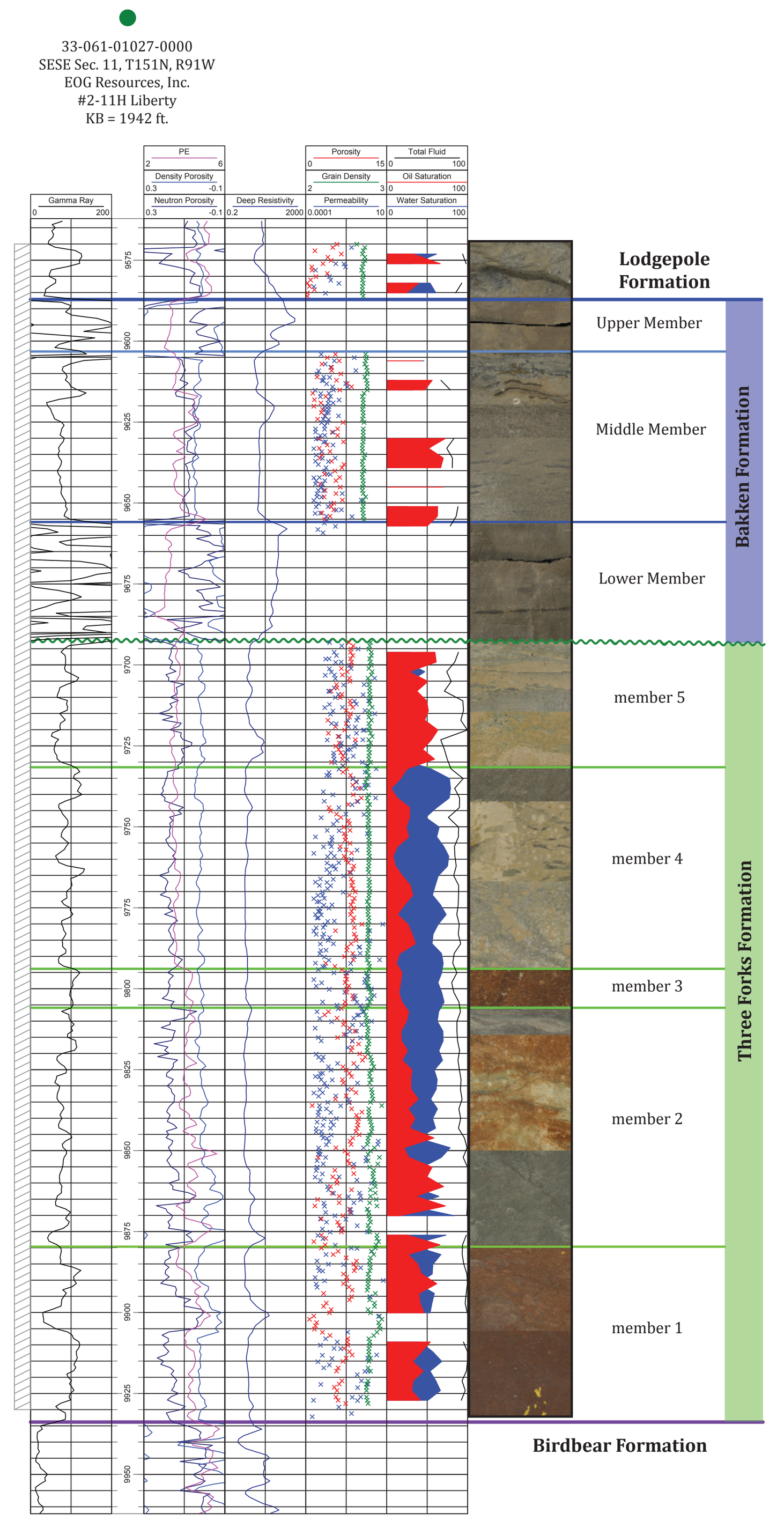


The Pronghorn Member was named in 2011 as a result of new core data. Map 1 shows the distribution of the proximal beds and is represented in the log and core section shown above. Consisting of a sequence of mixed siliciclastics and carbonates it is restricted to the southwest. It is unconformably overlain by the Lower Member and unconformably overlies the Three Forks Formation. It reaches a maximum thickness of 52 ft.

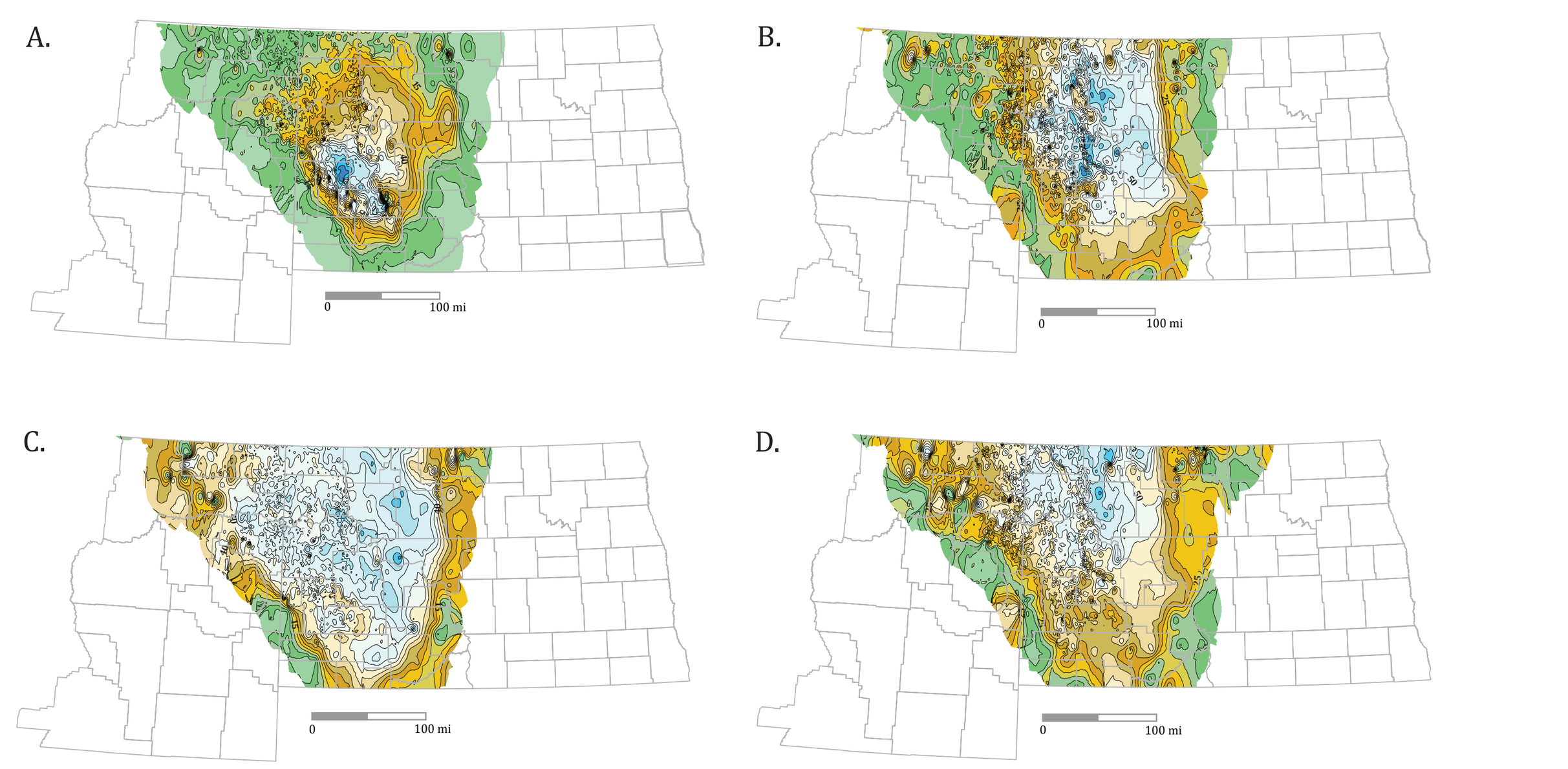
Map 2 shows the distribution of the distal beds to the Pronghorn Member. Beds resemble the Lower Member but have less organic matter and a higher carbonate and silt component. It reaches a maximum thickness of 58 ft in the linear trough-like feature.

Production in the Pronghorn Member is currently restricted to the proximal beds shown in Map 1. The reservoir consists of a series of dolomitic mudstones with HCS beds with intercrystalline porosities ranging from 6 to 9%. As clay content increases, the distal beds' production decreases. Total fluids also decrease with the presence of lithofacies 3.

Three Forks Formation



The wireline log of the EOG Resources, Inc. - #2-11H Liberty well is displayed with core analyses, fluid saturations, nomenclature, and a representative core section. The Liberty well shows high oil saturations throughout the lower portion of the Three Forks section suggesting potential for oil.

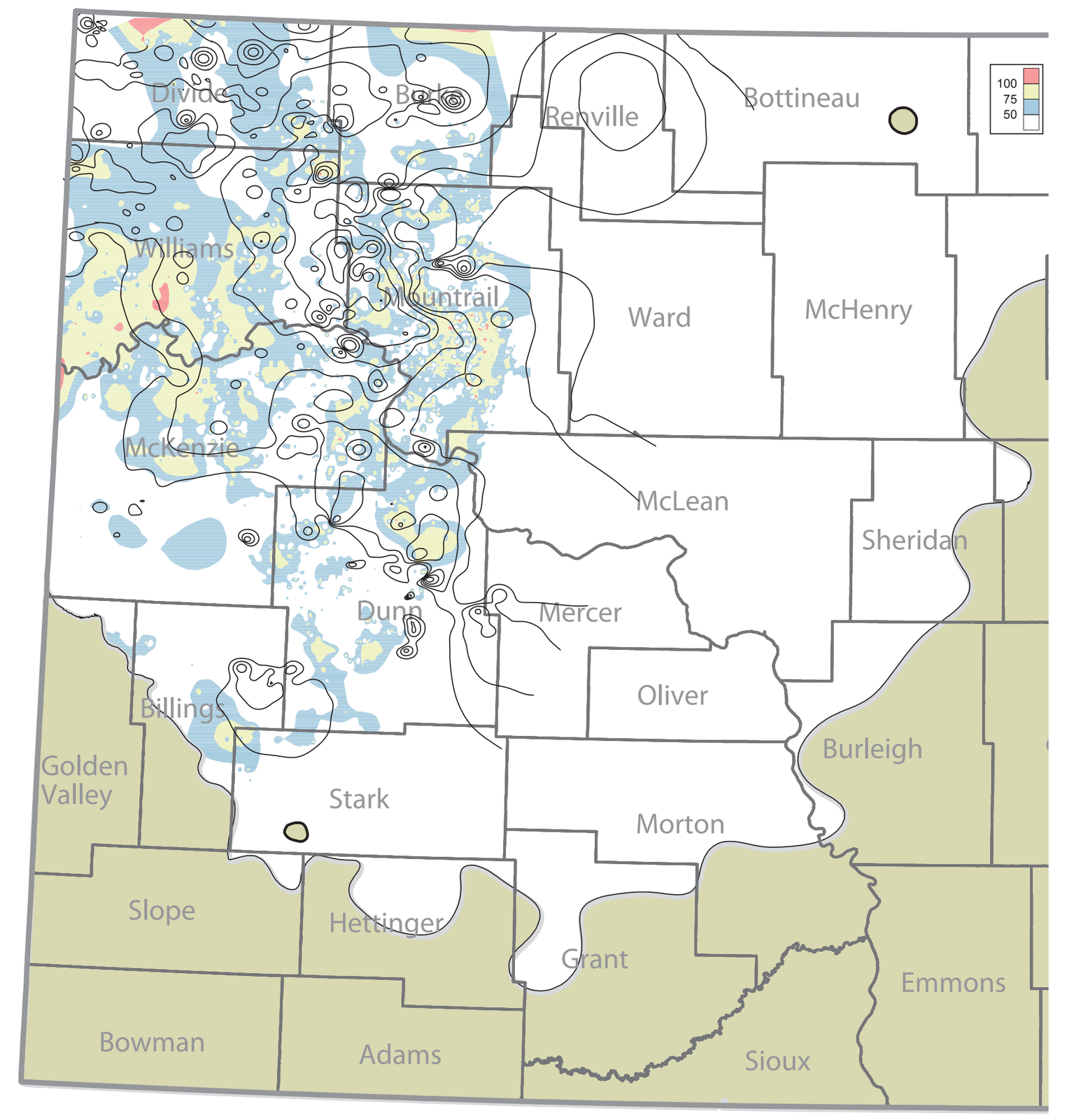


Isopach maps of the individual members, in descending orders, of the Three Forks Formation in North Dakota and Montana. A – Three Forks member 5 ("Bench 1") reaches maximum thickness of 85 ft. B – Three Forks member 4 reaches a maximum thickness of 67 ft ("Bench 2"). C – Three Forks member 2 ("Bench 3"). D – Three Forks member 1 reaches a maximum thickness of 77 ft. All maps have a contour interval 5 ft ("Bench 4").

The Three Forks Formation overlies the anhydrites of the Birdbear Formation and underlies the Bakken Formation. Recent cores provide a view of the entire stratigraphic succession (see wireline log). Member 1 is a redbed sequence consisting of a tan to grey-green to red interbedded mudstones mixed with siltstones and sandstones. Anhydrite is present as nodules and layers. The member is representative of a sabkha environment of deposition. Member 2 is an interbedded sequence of grey-green and dark red mudstones with occasional anhydrite nodules and beds. Member 2 represents environments ranging from sabkha to tidal mudflat. Member 3 is a red to grey-green slightly dolomitic mudstone mixed with poorly sorted clasts representing a mudflat. Basal member 4 consists of grey-green, tan and orange-red interbedded mudstone to sandy dolostone that is brecciated probably due to dewatering. This is overlain by an interbedded sequence of apple-green dolomitic mudstone and tan dolostone with desiccation breccia at the base and structures that include ripples, flaser beds, syneresis cracks, and mudcracks. Capping the sequence is a massive dark brown to dark red dolomitic mudstone. Member 4 represents a fining-upward sequence indicative of tidal mudflat to intertidal to shallow offshore environments. Member 5 repeats the sequence with basal tan dolomitic, brecciated dolostone that is overlain by the apple-green claystone and tan dolostone with ripples, flaser beds, syneresis cracks, and mudcracks. This also represents a progression from tidal mudflat to intertidal to supratidal environments. At the top of the Three Forks is a significant unconformity.

Current industry terminology refers to the member 5, 4, 2, and 1 as benches (i.e. member 5 is referred to as the "First Bench"). Careful attention to the stratigraphy is necessary when discussing producing intervals. The wireline log for the Liberty well also plots the fluid saturations. It is interesting to compare the oil saturations (red) against the water saturations (blue). Oil saturations are consistent through the Bakken, but tend to taper off below member 5 of the Three Forks Formation.

Total Produced Fluid vs Lithofacies



The colored filled contours represent regions in which the daily total fluid production for existing wells lies above the 50th percentile. Regions in white represent portions of the basin in which total fluid production is below the 50th percentile. Solid contours are isopach lines of the lithofacies 3. Thickness of the lithofacies appears to affect total fluid production suggesting that the fracture stimulation treatments may not be penetrating the entire section for wells that have a horizontal leg in the upper lithofacies.

References:

Carlisle, W. J., Druyff, L., Fryt, M. S., Artindale, J. S., and H. Von Der Dick, 1992, The Bakken Formation – an integrated geological approach to horizontal drilling, *in*, Schmoker, J. W., Coalson, E. B., and C. A. Brown, eds., Geological Studies Relevant to Horizontal Drilling: Examples from Western North America: RMAG, Denver, p. 215-226.

Gaswirth, S.B., Marra, K.R., Cook, T.A., Charpentier, R.R., Gautier, D.L., Higley, D.K., Klett, T.R., Lewan, M.D., Lillis, P.D., Schenk, C. J., Tennyson, M.E., and K.J. Whidden, 2013, Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota: USGS Fact Sheet 2013-3013.

Murray, G.H., Jr., 1968, Quantitative fracture study – Sanish Pool, McKenzie County, North Dakota: AAPG Bulletin, vol. 52, no. 1, p. 57-65.

Summary

A variety of unconventional reservoirs exist within the Bakken Petroleum System. Each of these reservoirs has been the focus of severeal episodes of drilling throughout the history of the Williston Basin.

Six reservoirs have been discussed. Variations in rock composition have resulted in continued use of available cores and the continued acquisition of additional cores. It becomes readily apparent that each area within the source system requires examination of cores with possible adjustment to drilling and completion methods. Data obtained from cores and samples are strategic in making those adjustments.

The additional data also generate additional questions. Uncertainty exists as to what is actually producing in both Bakken and Three Forks reservoirs. Are the current wellbores draining the Middle Member, the Upper Member or both? What portion of the Three Forks is actually producing or are the fracture stimulations for the lower units? Saturations exist in some wells within the Three Forks and are absent in others. The discontinuous nature of these saturations requires further work.

The ability to extract oil from the Bakken has increase with each technological advance. Reserves estimates of 7.4 billion barrels of technically recoverable oil drive the activity (Gaswirth et al., 2011).

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Sheet 3

Edward C. Murphy, State Geologist
Lynn D. Helms, Director Dept. of Mineral Resources
2013

33-007-01185-0000
SWSW Sec. 5, T143N, R99W
Texaco, Inc.
#5-1 Texaco Thompson Unit

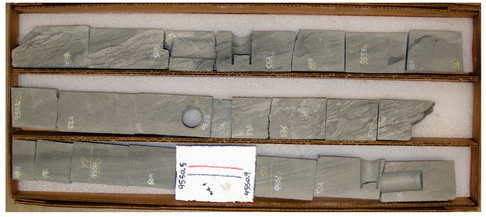
11046.5

11052

Upper Member of the Bakken Formation

33-061-00520-0000
NWNW Sec. 10, T152N, R90W
EOG Resources, Inc.
#1-10H Hoff

9556



9549.5

9549.5

9542.5

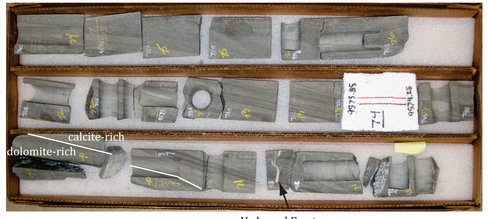
9542.5

9535 Lithofacies 4 - Algal-rich dolomitic siltstone to sandstone.
(TVD - 9245.3)

L3 - Calcite-cemented interbedded siltstone and sandstone. The change from dolomitic sandstone to calcareous sandstone marks the base of the reservoir.

(TVD - 9251.1)

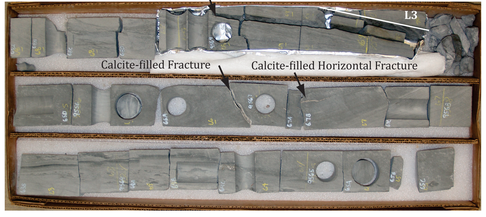
9576



9569

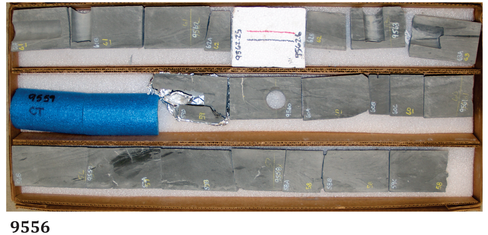
V-shaped Fractures

9569



9563.5

9563.5



9556

Middle Member (lithofacies 4 - 3) - Core is cut on the build-section (87°-88°).

Open Fractures

33-025-00868-0000
SESW Sec. 14, T141N, R96W
Anschutz Exploration Corporation
#24-14H Sadowsky

11047

11072.6

Upper and Pronghorn Member of the Bakken Formation

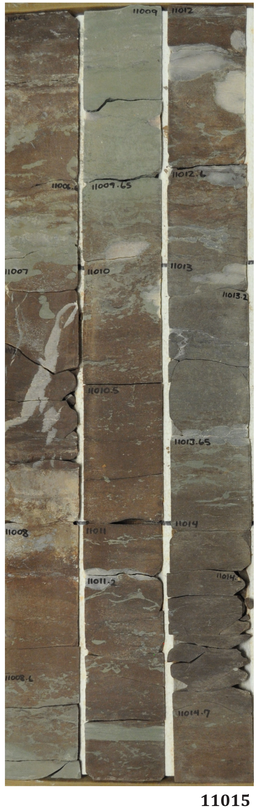
33-025-01453-0000
NESE Sec. 27, T145N, R95W
Denbury Onshore, LLC.
#43-27WNH Johnson

10899.1

10916

Three Forks member 5 ("bench 1")

11006



11015

Three Forks member 2 ("bench 3")