Bakken Source System

Three Forks Formation Assessment

April, 2010

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Executive Summary

This assessment by the North Dakota Geological Survey and Department of Mineral Resources reports the results and methods used to estimate the original oil in place (OOIP) and expected ultimate recovery (EUR) of oil reserves in the Three Forks portion of the Bakken pool. The upper fifty feet of the Three Forks Formation is generally defined as the lowest part of the Bakken pool by the Oil and Gas Division of the Department of Mineral Resources.

Almost 20 billion barrels of oil appear to be in place within the Three Forks portion of the Bakken pool of which close to 2 billion bbls are expected to be produced. This estimate is based on over 200 wire line log analyses distributed across the Williston Basin of North Dakota. This report contains tables of OOIP and EUR estimates on a county-by-county basis as well as statewide totals. Maps detailing the distribution of wells used to make the reserve estimates together with a map of the median OOIP are included. The Three Forks assessment presented here is a companion study to the 2008 DMR assessment of the Bakken Formation (Bohrer and others, 2008). Together the assessments indicate that the Bakken pool contains 169 billion barrels of oil in place of which about 4 billion barrels will likely be produced. The results of these two studies are consistent with the results of several earlier studies focused on the petroleum potential of the Bakken source system (Price and others, 1984; Meissner and Banks , 2000; Price, 2000; Flannery and Kraus, 2006 and Flannery , 2006).

As of the end of 2009, 181 horizontal wells were drilled and completed in the Three Forks Formation with an additional 9 wells in which laterals were drilled into both the Three Forks and middle Bakken. The NDIC maintains an up to date web page (https://www.dmr.nd.gov/oilgas/bakkenwells.asp) dedicated to providing the public with information concerning activity in the Three Forks and Bakken Formations.

Introduction

The upper and lower Bakken shales lie at the heart of the Bakken source system. These shales are rich in organic matter and serve as the source of the oil found within the system. Heating of the Bakken shales for millions of years has thermally matured the organic matter so that hundreds of billions of barrels of oil have been generated and identified within North Dakota of which over 4 billion is producible.

The North Dakota Geological Survey and Department of Mineral Resources recently completed an assessment of the oil reserves contained in the Devonian aged Three Forks Formation. The North Dakota Department of Mineral Resources (DMR) generally considers the upper 50 feet of the Three Forks as being part of the Bakken pool. This study is the second installment of the continuing effort by the DMR to estimate the reserve potential of the reservoirs within the Bakken Source System. The purpose of this study is to determine the total volume of oil that may ultimately be produced from the Three Forks portion of the Bakken Pool in North Dakota.

Geology

The Three Forks Formation is overlain by the Bakken Formation throughout the central portion of the Williston Basin. Along the margins of the basin, where the Bakken is absent, the Three Forks is overlain by the Lodgepole Formation (Fig. 1).

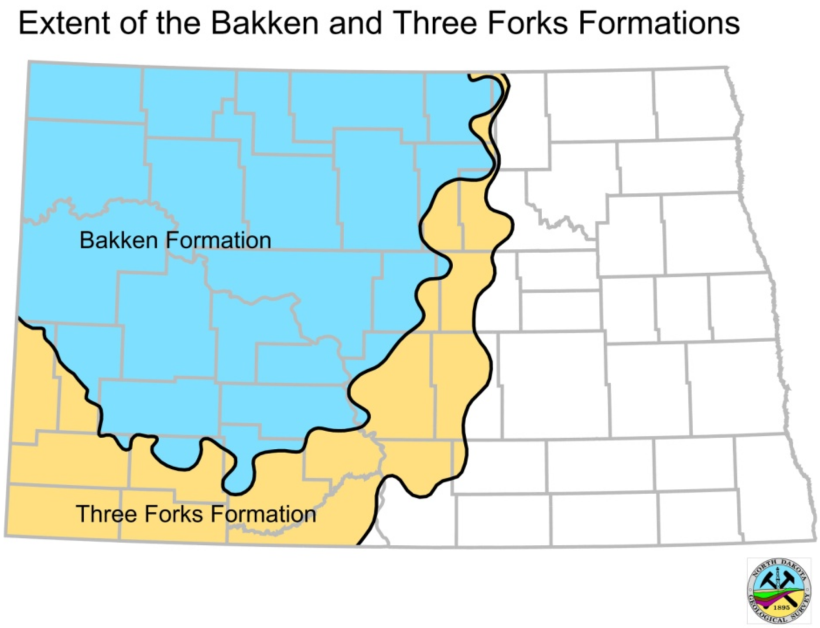

Figure 1. Distribution of the Three Forks and overlying Bakken Formations. This study assumes that the Bakken Formation locally sources the oil in the Three Forks. Therefore, the parts of the Three Forks that lie beyond the Bakken are not included in this assessment.

The Three Forks Formation is informally subdivided into six units labeled Unit 1 through Unit 6 in ascending order (see Figure 2). The upper 50 feet of the Three Forks Formation contains part or all of Unit 6 and, where Unit 6 is thin, parts of Unit 5. Units 5 and 6 typically consist of tight, thinly interbedded dolostones and shaley dolostones that lie unconformably beneath transgressive facies that make up the basal portion of the lower member of the Bakken Formation. Figure 3 is a photograph of a representative piece of core taken from Unit 6.

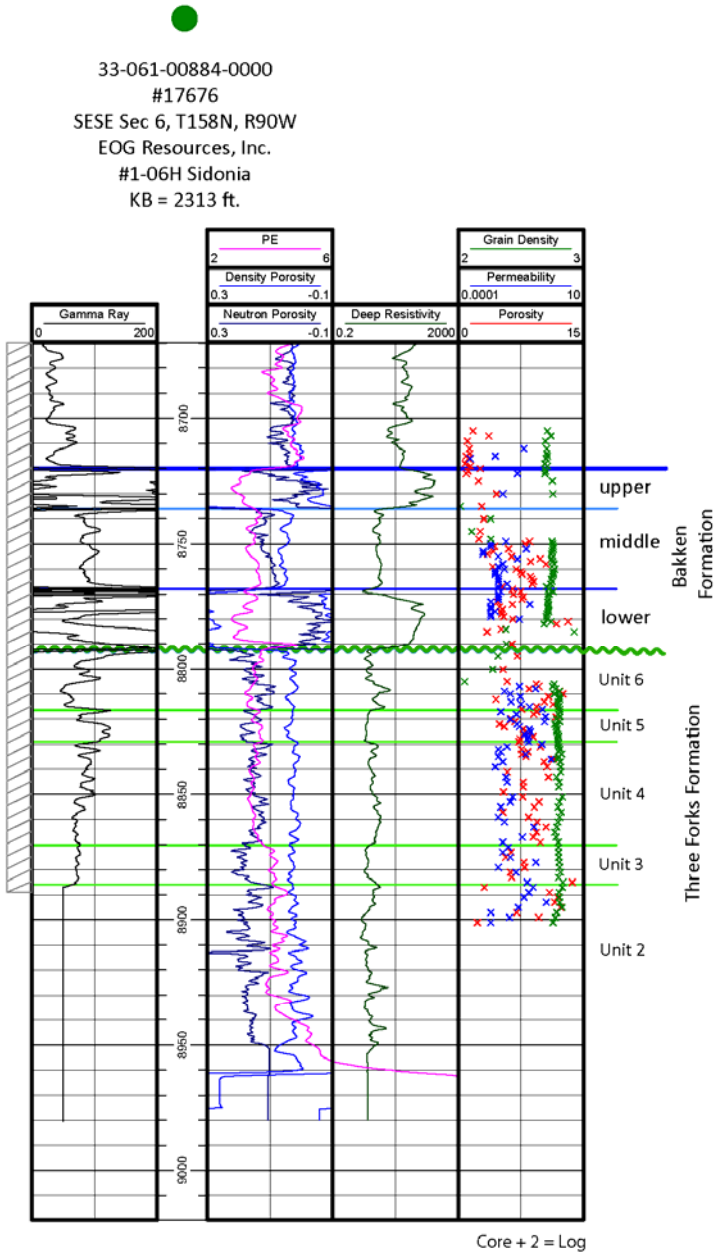

Figure 2. Example wireline log illustrating the stratigraphic relationships of the Bakken Source System. Unit 1 lies below the logged interval shown above.

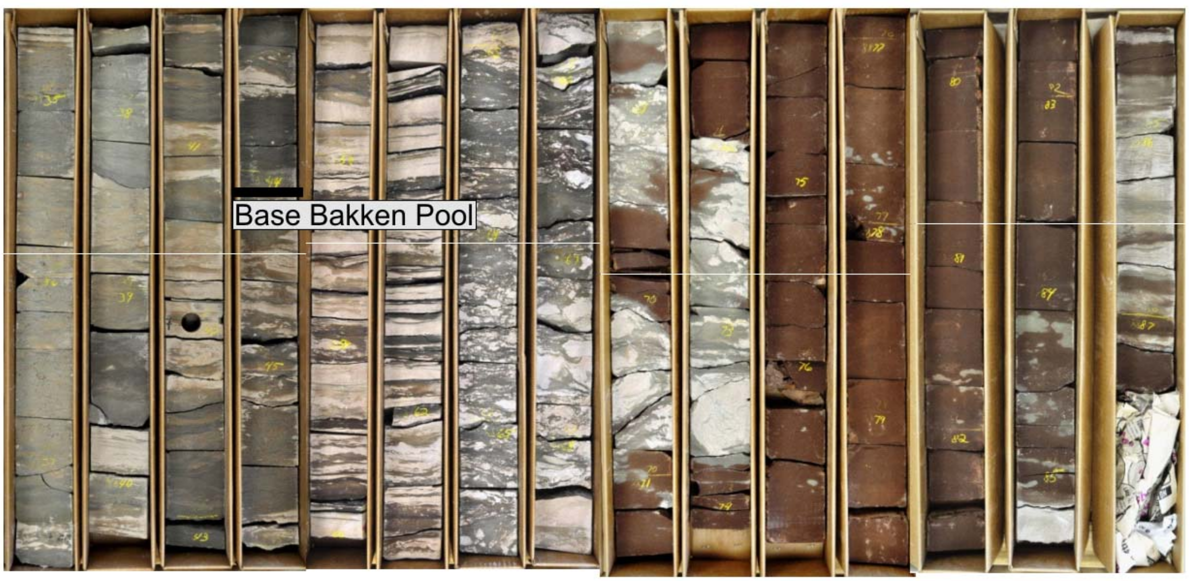

Figure 3) A representative core from the Sidonia 1-06H showing the lower five feet of the Bakken Formation and the upper 50 feet of the Three Forks Formation that are generally included in the Bakken pool by the NDIC. The top of the core is in the upper left corner and the bottom of the core is in the lower right corner. The core segments proceed down hole from top to bottom and from left to right.

Methods

Estimates of the original oil in place (OOIP) are based on digital wireline logs (LAS) and digitized log traces on file with the North Dakota Industrial Commission (NDIC). The logs used in this study include density porosity logs together with deep induction logs both of which are needed in order to estimate the amount of petroleum that is present in the subsurface. The porosity logs provide estimates of the pore space and the induction logs measure the resistivity of the rocks in the Three Forks. The combination of porosity and formation resistivity are related to the fraction of the pore space that is filled with formation water by the Archie equation. The simplest form, often used in evaluating carbonate reservoirs, is as follows (Asquith and Krygowski, 2004):

Eq. 1 $$S_w = [R_w/(R_t\phi^2)]^{1/2}$$

Where:

- S_w – Fraction of the pore space occupied by water with a resistivity of R_w
- R_w - Resistivity of the formation water (ohm-m)
- R_t – Resistivity of the formation (ohm-m)
- ϕ – Porosity – Fraction of the total rock volume that is pore space.

The combination of porosity logs with measurements of formation resistivity provide two of the three basic pieces of data needed to estimate the fraction of the pore space that is saturated with water (S_w) as well as the amount of pore space that is filled with oil and gas ($1-S_w$). The resistivity of the formation water is the third piece of information that is needed to estimate S_w.

Determination of formation water resistivity (R_w)

Most of the water in the Bakken Formation is close to, if not at, the saturation point of sodium chloride. Consequently, the resistivity of the formation waters (R_w) may be confidently assumed to be close to the resistivity of a salt saturated brine (0.04 ohm-m at 75^o F). Because resistivity decreases with increasing temperature a correction is needed to convert the formation water resistivity measured at the surface to a resistivity that corresponds to the temperature of the formation at depth (see Appendix A for details).

Determination of formation porosity (ϕ)

Several logs provide estimates of formation porosity. Of these, the compensated density log is probably the most robust. As the name suggests, the compensated density log measures the bulk density of the formation adjacent to the tool. The bulk density can be used to estimate how much pore space is present in a rock when the densities (g/cm^3) of the rock matrix (grain density) and formation fluid are known (see Appendix B for details). A review of grain densities obtained during routine core analyses indicate that the density of the mineral matrix in the Three Forks is greater than the density of limestone (see Table 1; Appendix B). This is significant because most of the compensated density logs on file with the NDIC are presented in terms of porosity and that these porosities are based on the assumption that the mineral matrix is that of calcite, the dominant mineral in limestone (2.71 g/cm^3). Therefore, in order to compensate for the difference in density between limestone and the mix of minerals in the Three Forks Formation, the correction given by Equation 2 was applied to the density porosity logs used in this assessment (see Appendix B for details).

Eq. 2 $$\phi_{tf} = 0.05 + 0.95\ \phi_{ls}$$

Where:

ϕ_{ls} = Compensated density porosity based on a limestone matrix.
ϕ_{tf} = Compensated density porosity based on "Three Forks" matrix density.

The Archie Equation (Eq. 1) was used with temperature corrected formation water resisitivities (R_w) and density corrected porosity logs (ϕ_{tf}) together with measurements of formation resistivity (R_t) provided by deep induction logs to estimate the water (S_w) and oil (S_o) saturations present in the Three Forks Formation. These estimates used the 211 wells presented in Figure 4. Water saturations for each well were calculated through the upper 50 feet of the Three Forks Formation in 0.5 foot increments.

Most of the technical exhibits containing reserves estimates presented to the NDIC at legal hearings use water saturation as a critical threshold that defines the thickness of pay zone in the Three Forks. This assessment made use of three thresholds that correspond to the highest, lowest and most likely water saturations that could be expected to "pay" in the development of the Three Forks Formation. These thresholds correspond to water saturations of 60%, 50% and 40% respectively. In practice, the threshold "flagged" potential pay zones so that only those intervals that were less saturated with water than the threshold would contribute to the net pay of the well. Summing the product of incremental thickness (0.5 ft), porosity (ϕ_{tf}) and oil saturation (S_o) for each "flagged" interval provides an equivalent thickness of oil present in a given well.

Eq. 3 $$\text{Feet Oil} = \Sigma\ (1-S_w) \times \phi_{tf} \times \text{incremental thickness (ft)}$$

The total amount of producible oil present in the Three Forks Formation was estimated by calculating the volume of original oil in place (OOIP) from oil thickness maps contoured using the results of Eq. 3. Figure 4 is an example of this type of map. This assessment used three maps that correspond to the oil thicknesses that resulted from the three water saturation thresholds discussed earlier. The volumetric analysis of the OOIP, on a county-by-county basis, are presented in Tables 2, 3, 4. Tables 2, 3 and 4 also include the assessment of the Bakken Formation conducted by the NDIC in 2008. The porosities and oil saturations that correspond with the most likely scenario (S_w<50%) agree well with the average values used by industry in their submissions to the NDIC (see Table 1). However, the average pay thickness arrived at in the assessment is much less than the current net pay that is being currently exploited. The average pay thickness listed for the assessment contains large areas in which economic oil production from the Three Forks is not likely because the pay interval is thin. Including the sub-economic parts of the Three Forks in The average pay thickness for the entire Three Forks is therefore reduced when areas containing sub-economic are included in the average.

Eq. 4 $$EUR = RF \times OOIP / FVF$$

Where:

EUR = Expected Ultimate Recovery (bbls).
RF = Recovery Factor.
OOIP = Original Oil In Place (bbls in the formation).
FVF = Formation Volume Factor.

The expected ultimate recovery (EUR) for the Three Forks Formation was determined using Eq. 4 for the low ($S_w<0.4$), high ($S_w<0.6$) and most likely ($S_w<0.5$) water saturation thresholds. This assessment used a 9% recovery factor (RF) which is assumed to represent the fraction of the OOIP that could be expected to be produced. This recovery factor is based on the average value submitted during expert testimony to the NDIC.

The volume of in place oil is also adjusted to account for the decrease in fluid volume that occurs during production. This adjustment involves dividing the volume of producible oil in place at depth by the formation volume factor (FVF) of 1.5. This value is close to the average FVF used by industry in their submissions to the NDIC. The EUR's found in this assessment are presented in Tables 2, 3, 4 and Figure 8. Additional maps illustrating the OOIP, on a county-by-county basis, for the Bakken and total Bakken-Three Forks assessments are presented as Fig. 6 and 7 with the corresponding EUR maps presented as Fig. 9 and 10.

Table 1) Summary statistics obtained from DMR exhibits.

	Three Forks Formation	Pay Thickness (ft.)	Oil Saturation (% pore space)	Porosity (%)	Formation Volume Factor	Recovery Factor (%)
NDIC Exhibits	Average	30.5	64.8	6.9	1.45	8.93
	Standard Deviation	19.78	11.40	2.33	0.20	5.32
	Number of Cases	84	85	85	84	76
Assessment	Assessment Statistics For the Most Likely Case	6.1 **Average Assuming 50% S_o Cutoff**	61.8 **Average Assuming 50% S_o Cutoff**	7.60 **Average From Density Porosity Logs**	1.5	9.0

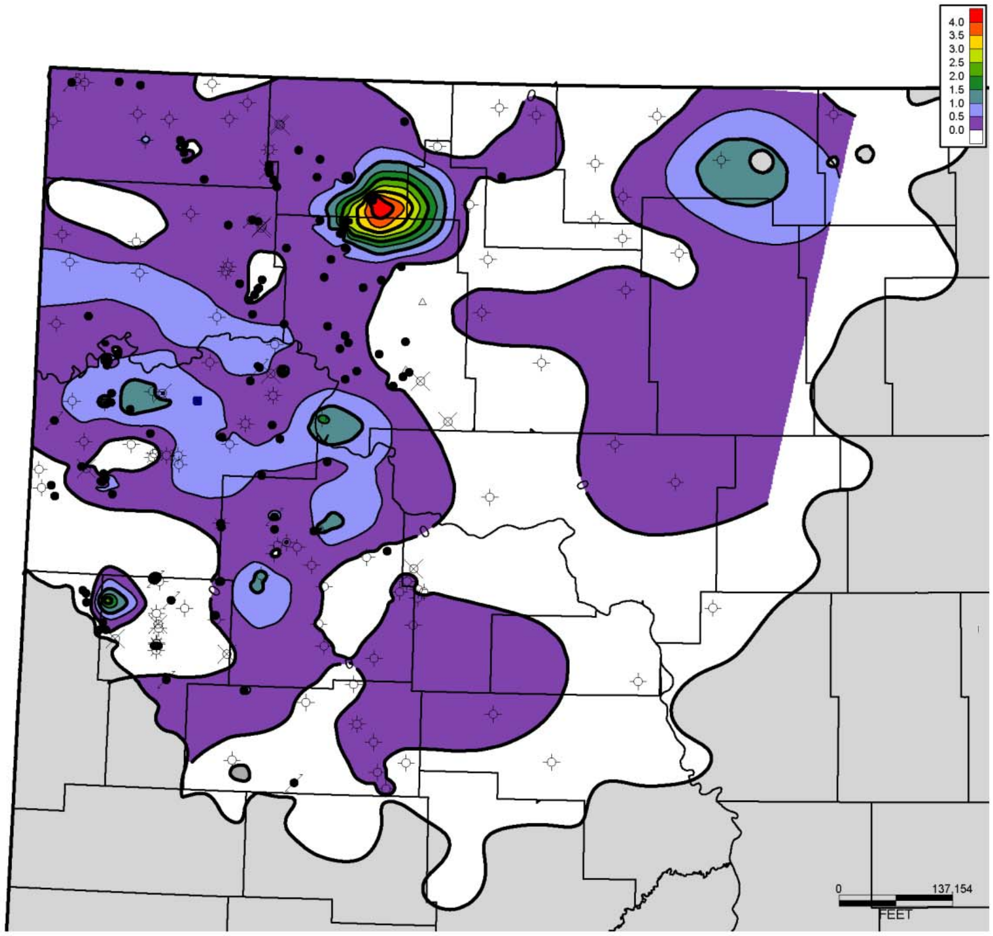

Figure 4) Total original oil in place (OOIP) for the Three Formation contoured as acre-feet oil. Only those intervals containing at least 50% oil-filled porosity contribute to the net pay that is contoured as acre-feet oil. The well locations illustrated correspond to the wells used in this study.

Table 2. County-by county summary of most likely original oil in place (OOIP) and expected ultimate recovery (EUR).

Most Likely						
	Bakken		Three Forks		Total	
County	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**
Billings	3,141,271,156	115,858,434	1,717,909,400	154,611,846	4,859,180,556	270,470,280
Bottineau			1,642,257,140	147,803,143	1,642,257,140	147,803,143
Burke	14,891,719,317	187,975,278	2,084,609,970	187,614,897	16,976,329,287	375,590,175
Divide	16,836,857,774	123,315,660	855,513,980	76,996,258	17,692,371,754	200,311,919
Dunn	18,059,716,691	294,169,921	2,008,459,540	180,761,359	20,068,176,231	474,931,279
Golden Valley	66,147,411		25,519,700	2,296,773	91,667,111	2,296,773
Grant	62,508,094				62,508,094	
McHenry			539,104,280	48,519,385	539,104,280	48,519,385
McKenzie	32,438,937,580	382,654,320	3,941,684,770	354,751,629	36,380,622,350	737,405,950
McLean	3,253,719,118		351,841,190	31,665,707	3,605,560,308	31,665,707
Mercer			118,427,220	10,658,450	118,427,220	10,658,450
Morton			84,144,950	84,144,950	84,144,950	84,144,950
Mountrail	27,242,795,837	424,826,873	1,676,048,980	150,844,408	28,918,844,817	575,671,281
Oliver			9,002,880	810,259	9,002,880	810,259
Renville			183,377,880	16,504,009	183,377,880	16,504,009
Slope	10,586,089				10,586,089	
Stark	2,349,351,546	86,371,150	1,604,239,450	144,381,551	3,953,590,996	230,752,701
Ward	4,540,670,907		446,420,030	40,177,803	4,987,090,937	40,177,803
Williams	26,263,485,095	474,392,108	2,666,823,630	240,014,127	28,930,308,725	714,406,235
Total	**149,157,766,614**	**2,089,563,745**	**19,955,384,990**	**1,872,556,554**	**169,113,151,604**	**3,962,120,299**

Table 3. County-by county summary of minimum expected original oil in place (OOIP) and expected ultimate recovery (EUR).

Minimum						
	Bakken		Three Forks		Total	
County	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**
Billings	1,242,100,878	10,147,480	1,429,528,190	128,657,537	2,671,629,068	138,805,017
Bottineau			1,406,951,290	126,625,616	1,406,951,290	126,625,616
Burke	10,985,956,451	50,780,051	1,636,905,690	147,321,512	12,622,862,141	198,101,563
Divide	8,202,264,716	18,874,119	499,034,600	44,913,114	8,701,299,316	63,787,233
Dunn	7,486,735,279	38,483,854	1,235,421,870	111,187,968	8,722,157,149	149,671,823
Golden Valley	24,538,677		5,664,900	509,841	30,203,577	509,841
Grant	23,265,040				23,265,040	
McHenry			408,155,300	36,733,977	408,155,300	36,733,977
McKenzie	12,768,723,210	78,006,785	2,884,459,150	259,601,324	15,653,182,360	337,608,108
McLean	1,277,048,034		107,683,390	9,691,505	1,384,731,425	9,691,505
Mercer			65,094,280	5,858,485	65,094,280	5,858,485
Morton			14,995,930	1,349,634	14,995,930	1,349,634
Mountrail	14,054,974,161	100,872,134	1,048,466,640	94,361,998	15,103,440,801	195,234,132
Oliver			427,140	38,443	427,140	38,443
Renville			33,652,670	3,028,740	33,652,670	3,028,740
Slope	3,922,551				3,922,551	
Stark	1,046,331,232	62,020,731	1,307,214,790	117,649,331	2,353,546,022	179,670,062
Ward	2,261,265,978		331,340,380	29,820,634	2,592,606,358	29,820,634
Williams	12,218,256,790	422,874,413	1,924,560,850	173,210,477	14,142,817,640	596,084,890
Total	**71,595,382,997**	**782,059,568**	**14,339,557,060**	**1,290,560,135**	**85,934,940,057**	**2,072,619,703**

Table 4. County-by county summary of maximum expected original oil in place (OOIP) and expected ultimate recovery (EUR).

Maximum						
	Bakken		Three Forks		Total	
County	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**	**OOIP per County**	**EUR per County**
Billings	5,796,035,234	206,400,129	1,823,379,410	164,104,147	7,619,414,644	370,504,276
Bottineau			1,765,706,390	158,913,575	1,765,706,390	158,913,575
Burke	22,189,139,910	199,556,693	2,538,332,760	228,449,948	24,727,472,670	428,006,641
Divide	33,046,783,554	241,602,214	1,259,877,240	113,388,952	34,306,660,794	354,991,166
Dunn	38,148,811,183	569,306,630	2,610,804,300	234,972,387	40,759,615,483	804,279,017
Golden Valley	130,056,732		56,227,800	5,060,502	186,284,532	5,060,502
Grant	126,677,986				126,677,986	
McHenry			594,894,150	53,540,474	594,894,150	53,540,474
McKenzie	61,092,805,333	904,171,770	5,936,775,500	534,309,795	67,029,580,833	1,438,481,565
McLean	6,871,671,997		719,401,490	64,746,134	7,591,073,487	64,746,134
Mercer			300,429,520	27,038,657	300,429,520	27,038,657
Morton			258,154,420	23,233,898	258,154,420	23,233,898
Mountrail	48,066,522,137	739,082,368	2,341,957,450	210,776,171	50,408,479,587	949,858,538
Oliver			297,027,120	26,732,441	297,027,120	26,732,441
Renville			483,920,760	43,552,868	483,920,760	43,552,868
Slope	21,249,293				21,249,293	
Stark	4,479,035,609	108,655,741	1,879,946,640	169,195,198	6,358,982,249	277,850,939
Ward	7,454,033,280		755,925,470	68,033,292	8,209,958,750	68,033,292
Williams	52,407,038,986	804,963,984	4,006,468,020	360,582,122	56,413,507,006	1,165,546,106
Total	**279,829,861,234**	**3,773,739,530**	**27,629,228,440**	**2,486,630,560**	**307,459,089,674**	**6,260,370,089**

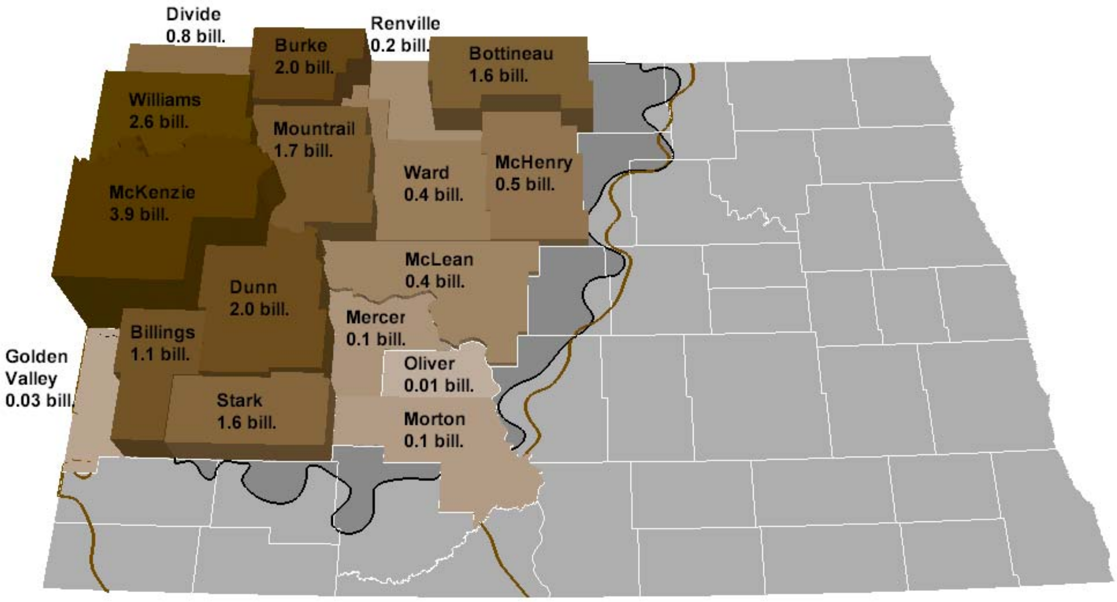

Fig. 5) OOIP for the Three Forks portion of the Bakken pool by county.

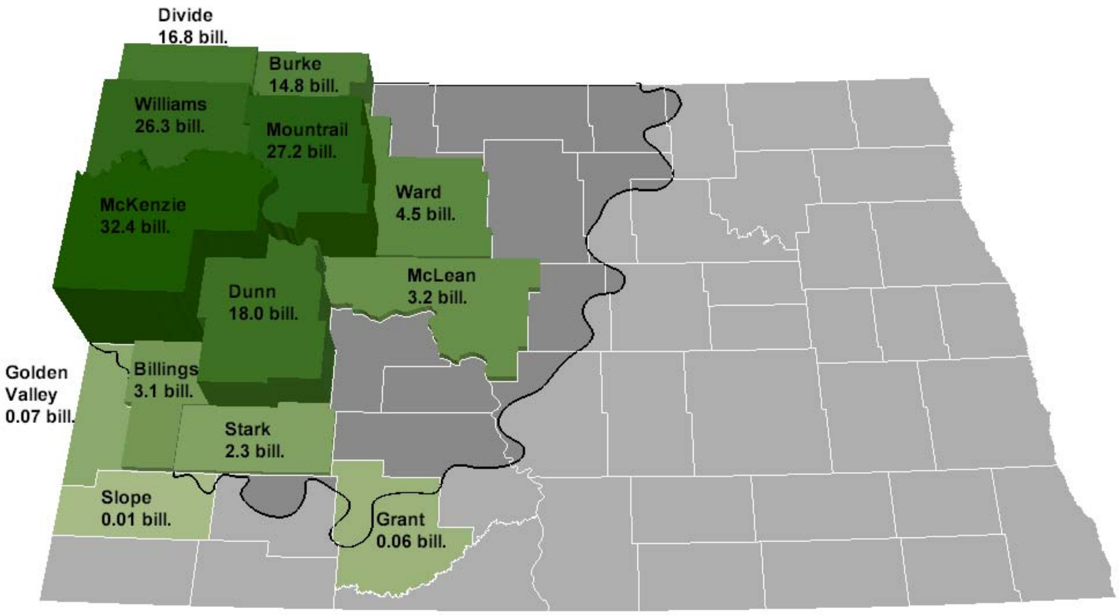

Fig. 6) OOIP for the Bakken portion of the Bakken pool by county.

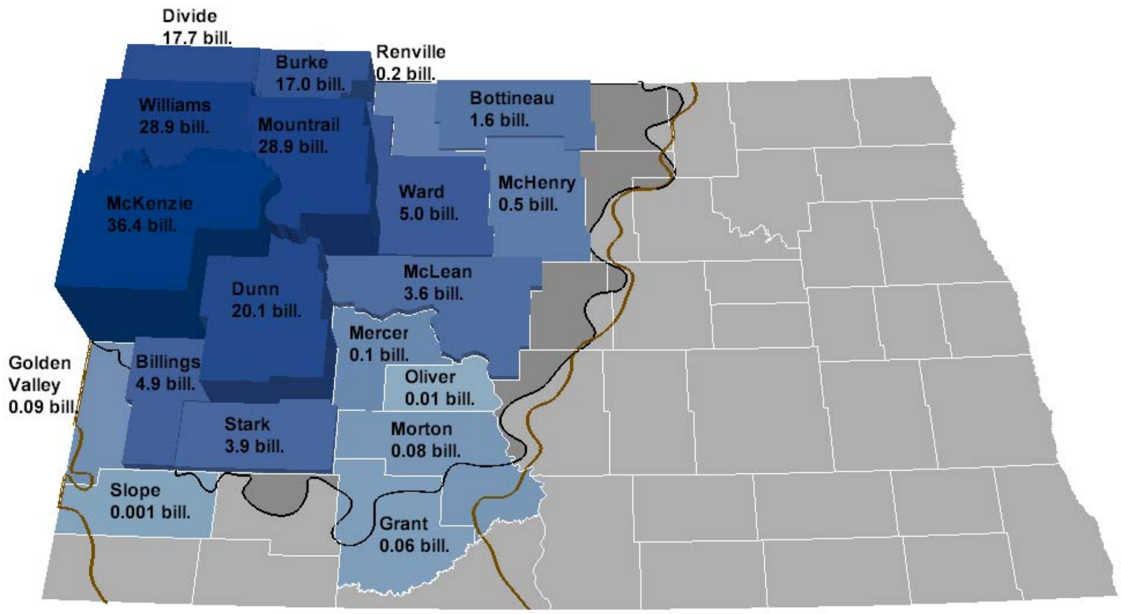

Fig. 7) Combined OOIP for the Three Forks and Bakken by county.

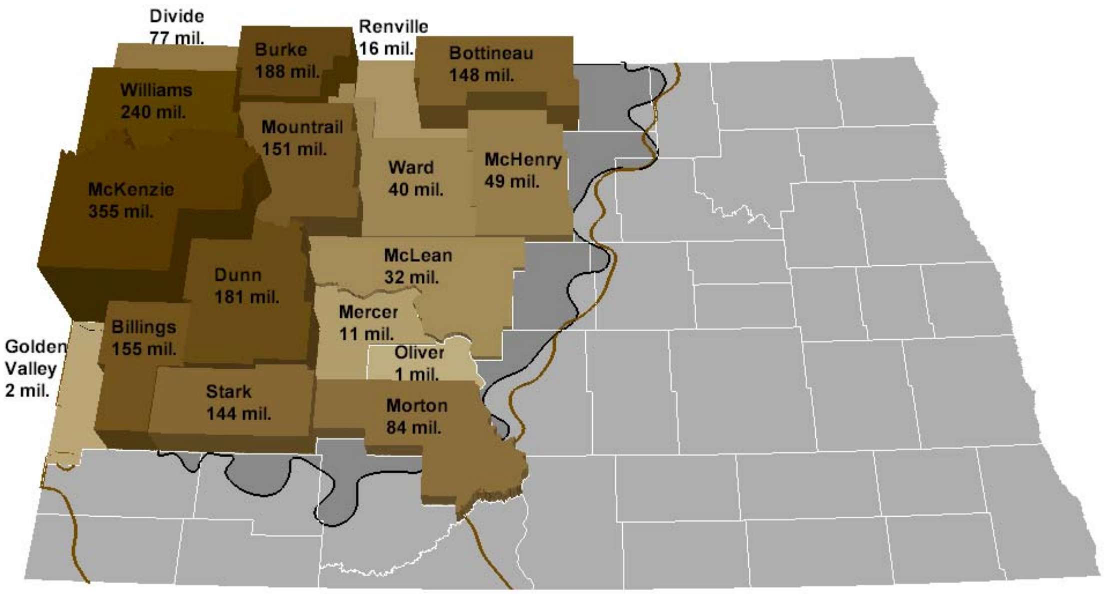

Fig. 8) EUR for the Three Forks portion of the Bakken pool by county.

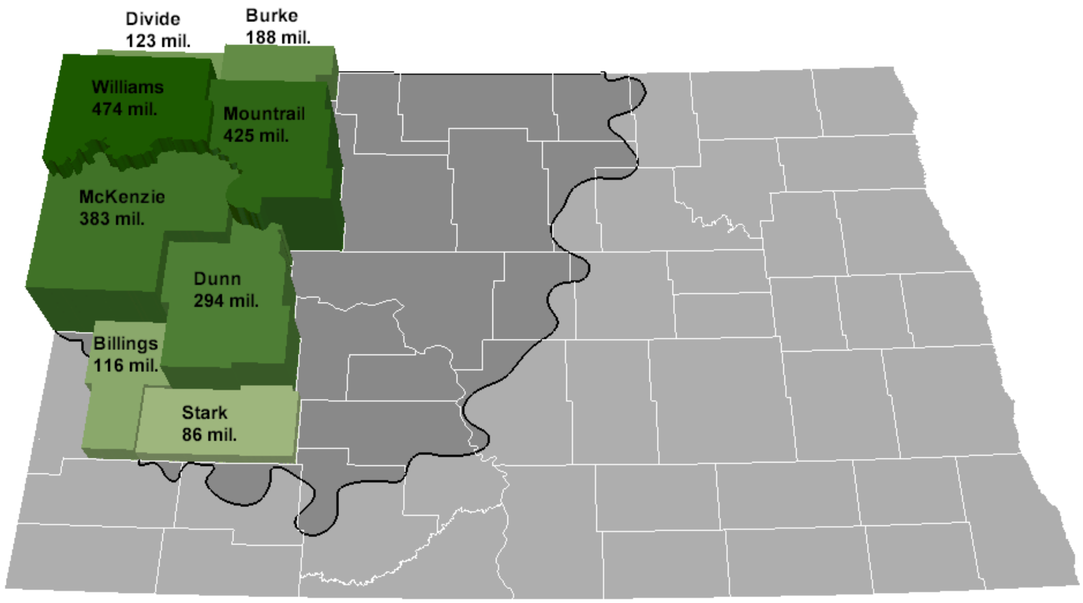

Fig. 9) EUR for the Bakken portion of the Bakken pool by county.

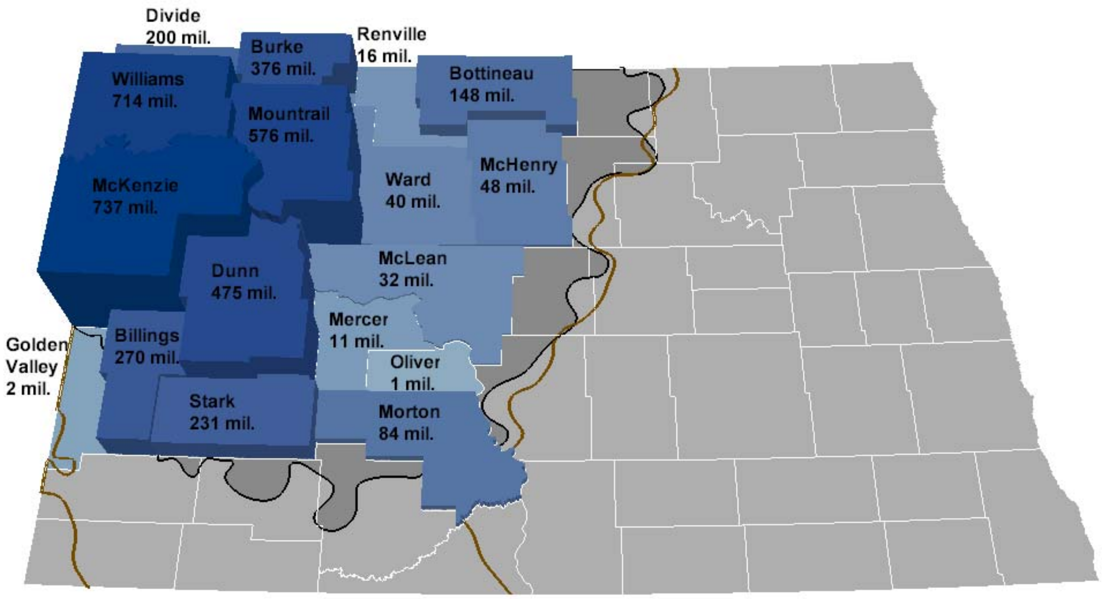

Fig. 10) Combined EUR for the Bakken and Three Forks by county.

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Appendix A

Corrections that translate surface measured resistivities to resistivities at depth.

Equation 1 is called Arp's equation and is an empirical relationship that corrects the resistivity of a formation water measured at the surface to the temperature of the formation at depth.

Eq. 1 $$R_{w1} = R_{w2} (T_2+7)/ (T_1+7)$$

Where R_{w1} and R_{w2} are the resistivities (ohm-m) of a formation fluid at temperature T_1 and T_2 (^oF) respectively. If the resistivity of the brines in the Bakken Formation are assumed to be 0.04 ohm-m at 75^o F then R_{w2} is 0.04 ohm-m and T_2 is 75^oF. Therefore, the temperature at depth that corresponds with the Bakken Formation (R_{w1}) at depth and temperature (T_1) must also be known. Adequate estimates of formation temperature use basic temperature and depth data that are recorded on wire-line log headers. Most log headers that accompany induction logs contain a maximum recorded temperature that presumably corresponds with the total logged depth. Estimates of formation temperature are often calculated as follows:

Eq. 2 $$T_f = T_s + D_f[(T_{td} – T_s)/D_{td}]$$

Where T_f is the formation temperature at depth D_f. Temperature is assumed to follow a linear gradient between the average surface temperature (T_s) and the maximum temperature (T_{td}) presumably measured at the bottom of the logged well at a depth of D_{td}. Substituting T_f for T_1 in Eq. 2 provides the resistivity of the water in the formation. According to the USGS, the normal average annual temperature in North Dakota ranges from 37° F in the northeast to 43° F along the southern border (http://www.npwrc.usgs.gov/resource/habitat/climate/temp.htm). The mid-point between these values (40^o F) is used here as the average surface temperature (T_s) in Eq. 2.

Appendix B

Available core data indicate that the average grain density in the upper part of the Three Forks is 2.79 g/cm^3. Using the relationship between porosity and density measurements provides a means of converting density porosity measurements based on a limestone matrix to porosity measurements using the observed matrix density.

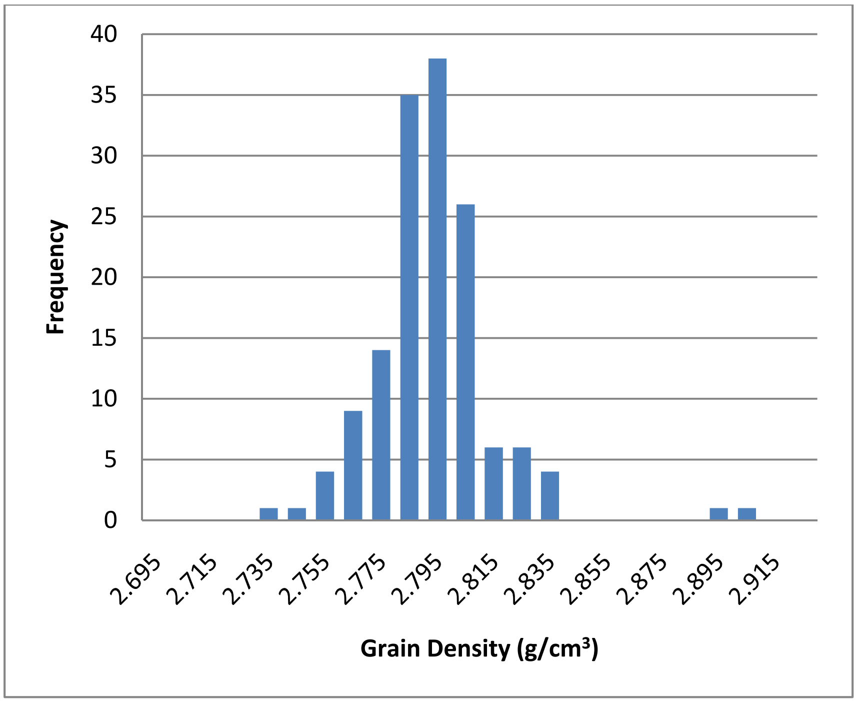

Figure 1 Frequency distribution of grain densities measured from the Three Forks cores listed in Table 1.

Table 1 – Summary statistics for the grain density of Three Forks Formation from core analysis.

Well Name	NDIC #	Average Grain Density	S.D. Grain Density	Number of Samples
VAN HOOK 1-13H	16997	2.785	0.0168	37
ST-ANDES-151-89-2413H-1	17043	2.801	0.0292	14
SUN MARATHON SHOBE 1	12033	2.774	0.0175	16
BRAAFLAT 11-11H	17023	2.794	0.0282	81
Composite		2.791	0.026	147

The equation for porosity (ϕ) from log measures of bulk density ρ_b, and the densities of the rock matrix ρ_{ma} and fluid ρ_{fl} is:

Eq. 1 $$\phi = (\rho_{ma}-\rho_b)/(\rho_{ma}-\rho_{fl})$$

Almost all of the density porosity logs run through the Three Forks formation use a limestone matrix density (ρ_{ls} = 2.71 g/cm^3)to calculate the porosities presented. The core derived matrix densities summarized above indicate that the log porosities are less than what is present in the Three Forks. This can be corrected by calculating the bulk density that corresponds to the recorded limestone density porosity as follows:

Eq. 2 $$\phi_{ls} = (2.71 - \rho_b)/(2.71-1.18)$$

Where:

ρ_{ls} = Limestone density = 2.71 g/cm^3

ρ_{fl} = Salt saturated brine density = 1.18 g/cm^3

ρ_b = bulk density that corresponds to the recorded limestone porosity ϕ_{ls}

Solving for ρ_b and substituting the result into Eq. 2 with the same fluid density and a matrix density (ρ_{ma}) of 2.79 g/cm^3 corrects a limestone porosity (ϕ_{ls}) to one consistent with the density of the Three Forks:

Eq. 3a $$\phi_{tf} =\{ 2.79-[2.71-\phi_{ls}1.53]\}/[2.79-1.18]$$

or

Eq. 3b $$\phi_{tf} = 0.05 + 0.95\ \phi_{ls}$$