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Upper and Lower Bakken Shale Production Contribution to the Middle Bakken Reservoir

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Abstract

There is an uncertainty over the production contribution from the Upper and Lower (U&L) Bakken Shale to the Middle Bakken reservoir. For the Bakken system, reservoir studies involving the fluid flow and recovery mechanism cannot be fully understood without resolving this uncertainty. Performance-anomalies in the GOR trends of the production-history of the Middle Bakken wells in the Reunion Bay, Sanish, Parshall and the Elkhorn-Ranch fields indicate the possibility of the anticipated contribution.

Quantifying the U&L Shale contribution requires knowledge of the mechanism of fluid storage and flow in the liquid rich shale systems. For the U&L Shale, adsorption is considered as the significant mode of fluid storage, and the process of diffusion is considered crucial for the matrix-to-fracture fluid transfer. The governing mathematical equations for desorption and diffusion was adopted from the shale gas systems. These equations are utilized in CMG™'s compositional simulator GEM™ to propose a reservoir simulation-based quantification scheme for the U&L Shale contribution.

Through the sensitivity analyses, the effect of variation in the parameters of the U&L Shale, the Middle Bakken layer and the hydraulic fracture is investigated. Utilizing the ranges of these parameters, the U&L Shale layers are found to contribute from 12% to 52% of the cumulative production from a Middle Bakken well, whereas, the mean contribution is 40%. Relative sensitivity study suggested that the U&L Shale production contribution is the most sensitive to the U&L Shale matrix parameters, such as total organic carbon (TOC, wt.%) and molecular diffusion coefficients. The TOC controls the desorption-parameters; therefore, the findings suggest that the phenomena of desorption and diffusion are expected to play a crucial role in the anticipated production-contribution.

Introduction

The Bakken Formation lies within the oil-window of the vast Williston Basin, which extends over the regions of North Dakota, Montana and the Canadian province of Saskatchewan (Figure 1). The production history of the Bakken wells in Figure 2 suggests that before year 2000, most Bakken wells provided marginal economic success, partially because of extremely low matrix permeability (0.0001-.01 mD) and meager chances of exploiting the many localized natural fractures with a vertical well. Commercial production and development activities have become increasingly economically viable in recent years with the advances in horizontal drilling and the use of multi-stage fracture stimulation. In the month of March, in 2013, the Bakken play in North Dakota alone produced with an average daily rate of 0.71 Million BOPD and 681 MMSCF of gas per day.

Bakken play is commonly referred to as shale, but originally it has a dolomitic siltstone lithology. It is generally divided into three main members: 1) Upper organic-rich black shale, 2) Middle silty dolostone to fine-grained sandstone, and 3) Lower organic-rich black shale. The U&L organic-rich shale members are believed to be the source rock, which have expelled oil into the low-porosity and low-permeability Middle Bakken layer. The tight Middle Bakken reservoir with extensive horizontal drilling operations is the focus of the current production and development activities. The horizontal laterals are drilled to multi-mile length and stimulated using the multistage hydraulic fracturing, thus ensuring a better reservoir connection and interlinking of the naturally existing localized fractures. However, in the production from the Middle Bakken reservoir, the contributed from the U&L Shale is largely unclear. This paper is aimed at addressing this critical issue.

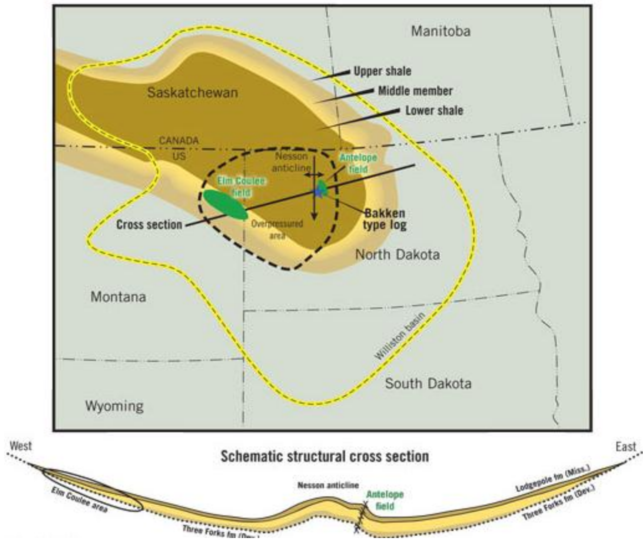

Figure 1: The geographical extent and location of the Williston Basin and the Bakken formation. (USGS 2008)

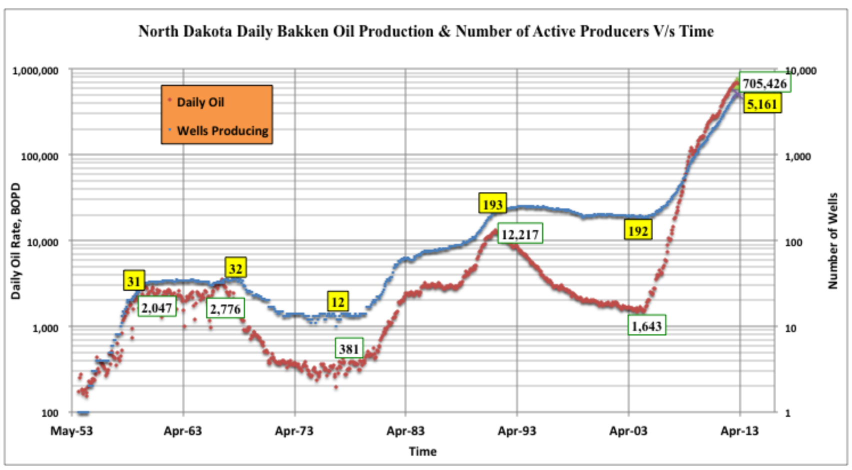

Figure 2: Chart showing historical daily oil production rate and number of active producing wells (Includes Bakken, Sanish, Three Forks, and Bakken/Three Forks Pools). (Data Surce: NDIC Oil and Gas Division 2013)

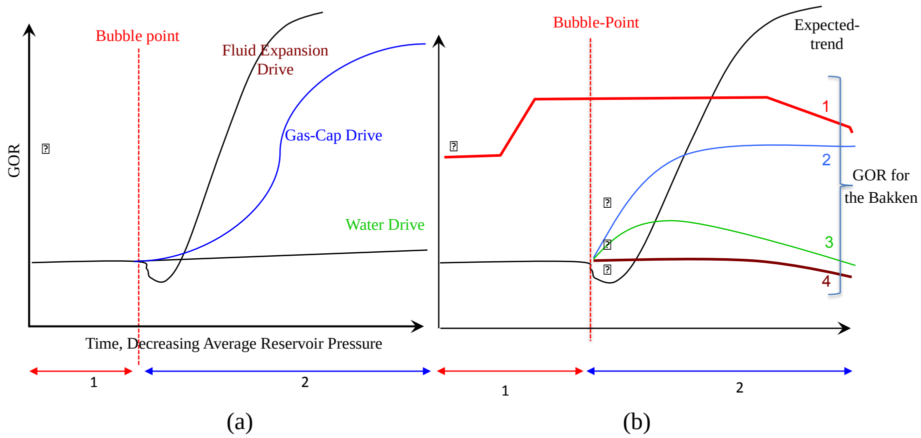

Figure 3: Region 1 and region 2 depict the two production-phases in which average reservoir pressure in above and below the bubble point respectively. (a) Well GOR trends of different primary recovery mechanisms. (b) Expected and Actual GOR trends for the Bakken Wells.

Motivation

The recovery mechanism of a reservoir can be identified with its production performance plots. Figure 3a shows the commonly utilized: GOR versus time plots for the three fundamental primary recovery mechanisms. Fluid expansion drive (FED) is the expected in the Middle Bakken reservoir (O'Brien, et al., 2012). Figure 3b shows the expected trend of the Bakken well GOR, which should ideally remain constant until the reservoir depletes to the bubble-point pressure. After that, the GOR is expected to rise monotonously until the point of well abandonment. However, if there were a production-contribution from the U&L Shales the GOR performance plots for the Bakken wells might deviate from the expected normal trends. To confirm the argument, production history of more than five hundred Bakken wells were analyzed, which supports the idea of the shale production contribution. The GOR response for the wells of Reunion Bay, Sanish, and Parshall fields were plotted and collectively analyzed. The material-balance time (MBT) approach was used for time-scale normalization, and the cumulative GOR (CGOR) helped in minimizing the effect of short-lived rate fluctuations. Contrasts between the expected and the actual GOR trends were readily evident, which can be depicted through the illustration in Figure 3b. Deviation from the expected trend can be observed when the reservoirs seem to be operating below the bubble-point pressure. In this production-phase, after a period of a steep rise, the GOR uncharacteristically became constant or in instances even dropped. The following is a field-wise analysis of the different GOR anomalies reported in selected representative example wells:

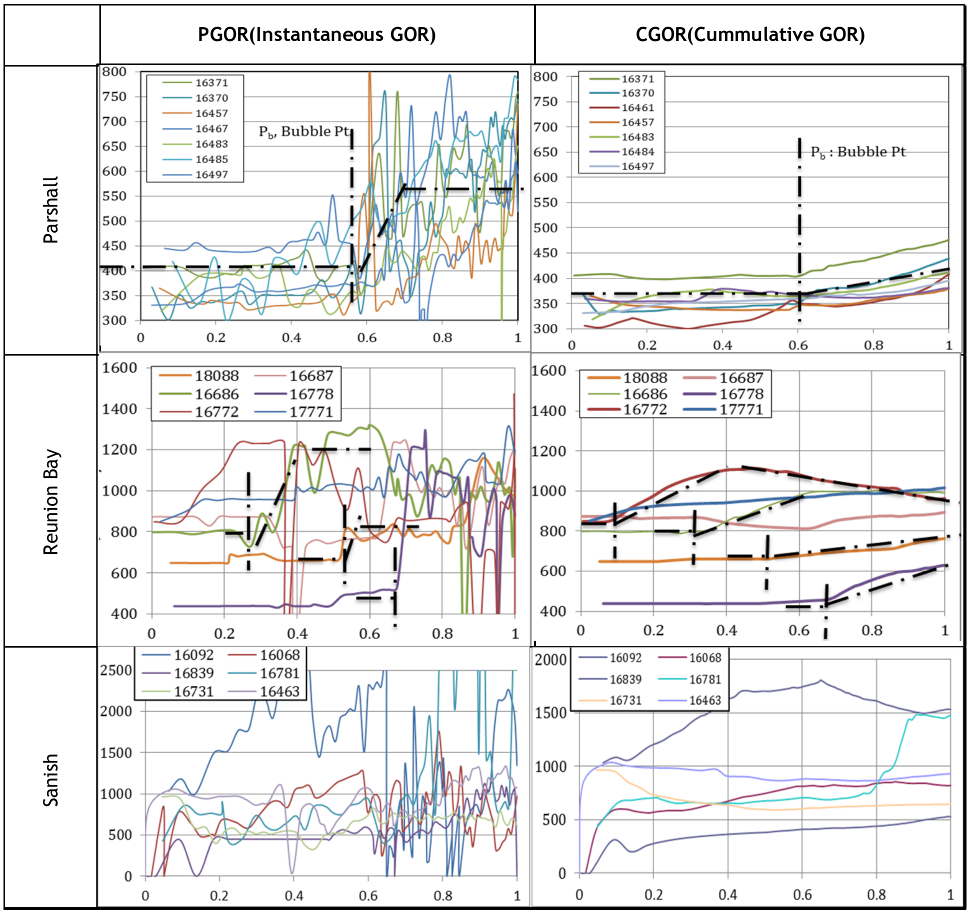

Figure.4: GOR-MBT and CGOR-MBT plots for selected wells in Parshall, Reunion Bay and, Sanish Field. Data Source: (NDIC, Oil & Gas Division 2013)

Parshall Field: Figure 4 shows the GOR plot for few selected producing wells of the Parshall Field. Onset GOR for the wells was consistently within a 300-450 SCF/bbl range, suggesting that they have behaved normally. The reservoirs around all the wells seemed to have depleted to the bubble point pressure at approximately 0.6 MBT, and after that a steep rise in the producing GOR was observed. In contrary to the expected monotonous ever-rising trend, the GOR uncharacteristically became constant after a while.

Reunion Bay Field: Relatively higher rate fluctuation during the initial monthly data was observed, which could be attributed to the water after-flow that follows the hydraulic fracture job in the wells. The Initial CGOR for most of the wells occurred within a 800-1000 SCF/bbl range. However, wells 16778 and 18088 have shown considerably lower initial CGOR of 450 and 650 SCF/bbl respectively. Low initial GOR is certainly an anomaly as adjacent wells from the same undersaturated reservoir are producing with almost a double initial CGOR values. Alternatively, it can also be proposed that the wells with low GOR might be producing exclusively from the middle layer. While, the wells with high initial CGOR (or high gas rate) might be getting the extra gas-volume from desorption taking place in U&L Shale.

For well 16778, which had lower initial GOR, it took considerably longer (0.7 MBT) time to reach the bubble-point pressure. As discussed earlier, this well was expected not to be getting desorped-gas from the U&L Shale; it might bear the actual PVT signatures of the reservoir fluid. For well 18088, 16686 and 16772, it took almost 0.5, 0.3 and 0.1 MBTs respectively to witness the characteristic steep-rise in CGOR. This CGOR rise might or might not be an indication of the bubble-point pressure attainment. The reason for this uncertainty is that the steep rise in CGOR could be happening because of the breakthrough of the desorped-gas from the U&L Shale. After this point, an unusually diversified GOR trends were observed:

- For wells 16778, 18088 and 16686, the GOR later became constant after a while
- For well 16772, CGOR first rose, stabilized, and later declined. The well 17771 seemed to have produced below the bubble point pressure since its inception
- For the well 16687, it had higher CGOR during initial above the bubble-point production phase than those during below the bubble point production-phase

Sanish Field: The GOR values seemed inconsistent throughout the production history of the wells (Figure 4). A contrast was expected between the production-phases separated by the time when bubble-point pressure is attained, which appeared not to have happened for the Sanish Field. For this reason, the bubble-points could not be identified from the GOR performance curve, and it seems as if the GOR has the similar trends throughout their production-life.

TOC and GOR: It is known that the total organic carbon (TOC) controls the adsorption capacity of the organic rich shales. Hence, the desorped-hydrocarbon volume from the U&L Bakken Shale layers is expected to vary in accordance with the respective areal TOC distribution map . With that, the diverse GOR response can be explained by considering the intermingling of the Middle Bakken oil with varying amount of desorped hydrocarbon contributed from the U&L Shale. This is expected to prompt alteration in reservoir fluid composition altogether and the effect is expected to vary with varying TOC in the U&L Shale layers. The following performance analysis of the Elkhorn Ranch Field further elaborates this idea.

Located in the well-known Fairway area, the Elkhorn Ranch field is one of the oldest producing-field of the North Dakota Bakken play. In Year 1961, oil was accidentally discovered in the Upper Bakken Shale when Shell (operator of the field) tried this prospect as their secondary objective in a well. The well eventually produced consistently for many years. The field has been a marginal producer from the tight Upper Shale and to enhance the production hydraulic fracturing and horizontal drilling options were first tried in the year 1976 and 1987 respectively. This long history is marked by diversified results, which has limited commercial viability of the Upper Shale prospect in the region. After the year 2000, it was further pushed to the brim with the overwhelming evolution of the middle-Bakken prospect as the major producer.

The field was chosen for this study as it had offered analyzable production data from both: the Upper Shale and the Middle Bakken reservoirs. Cumulative-GOR (CGOR) versus cumulative produced oil performance curve were plotted to investigate the production performance for all the wells from the field. Figure 5 shows the variety of the CGOR response for the wells. However, based on the nature of the performance curves, the wells can be categorized in the following three groups:

1. **Group-1** wells seemed to have achieved distinctly high CGOR in the early stages, and the enormous gas production might be the reason behind their early abandonments. Two wells: 13219 and 13256, in particular, produced with unusually high CGOR of 17,000 and 40,000 SCF/Bbl, which was up to 30-40 times higher than normal.
2. 2.**Group-2** wells initially produced with subdued CGOR of around 1000 SCF/Bbl, but in later stages it has increased abruptly. The CGOR values might seem to have risen to moderate levels of 4000 SCF/Bbl, but these wells produced with high instantaneous producing GOR values ranging up to 30000 SCF/Bbl.
3. 3.**Group-3** wells produced with much-subdued CGOR and instantaneous producing GOR values of around 1000 SCF/Bbl throughout their life.

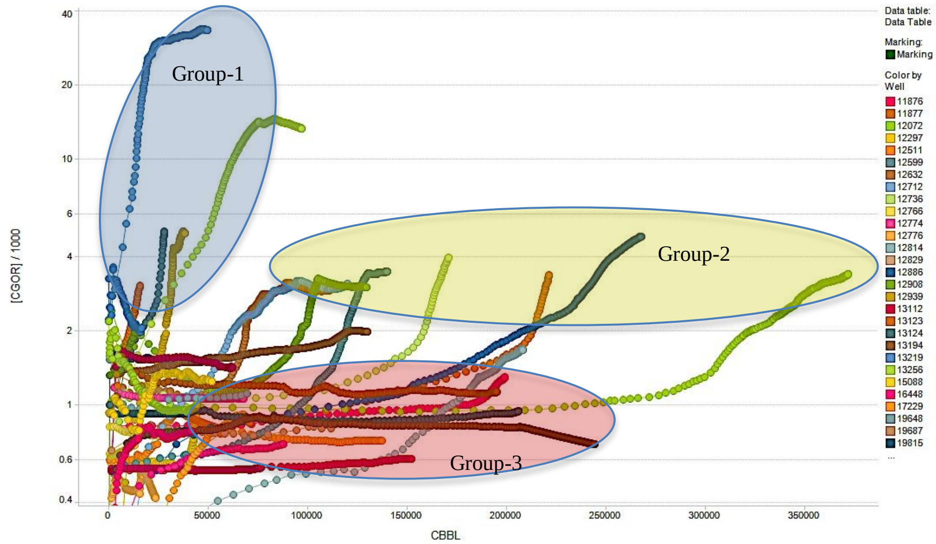

Figure.5: Chart showing the cumulative GOR response of the wells plotted with the respective cumulative oil production in Bbl. (Data Source: NDIC, Oil & Gas Division 2013)

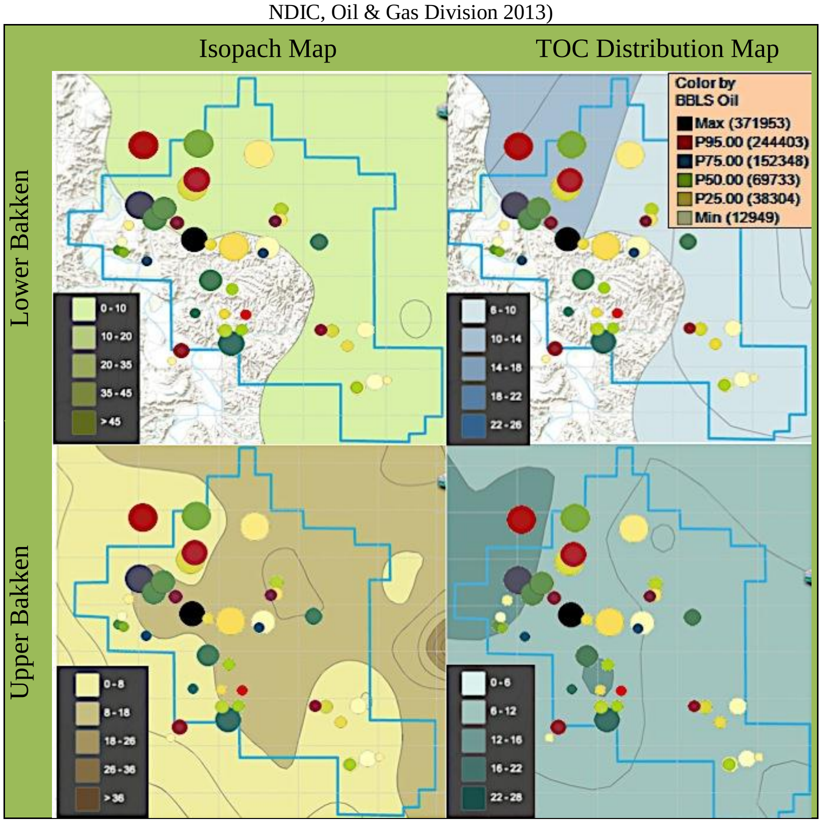

Figure.6: CGOR and Ultimate oil bubble plotted (Data Source: (NDIC, Oil & Gas Division 2013) over the TOC distribution and Isopach Maps (EERC 2013) for the Upper and Lower Shale Members

Such a diversified GOR response for wells, producing from the same field can be dubbed as unusual. Varying degree of production support from the U&L Shale layers could be the reason behind this abnormality. To pursue this idea, production data of the wells and the available geological information on the U&L Shale were collectively analyzed. Abandonment-CGOR and ultimate cumulative oil data for all wells were traced on the areal TOC content distribution and isopach maps of the U&L Shale (Figure 6). The size of the bubble represents the CGOR, and the color scheme indicates the ultimate cumulative oil for the wells. It was assumed that all the three Bakken-layers are interconnected as all of them are marginally developed within a cumulative thickness of 50-60ft in this area of the

Bakken. Figure 6 suggests that the Lower Shale layer terminates within the field-boundaries, and several wells are located in the regions where this layer is absent. Such regions have smaller CGOR bubbles, suggesting that the extra gas in the larger bubbles across the layer-termination boundary may be attributed to the gas desorption taking place in the Lower Shale. The argument was further substantiated by the fact that the wells located in the high TOC content (higher desorption) regions of the Lower Shale (Figure 6, dark blue shade) have a concentration of larger bubbles. Similarly, the thickness of the Upper Shale also seemed to have an effect the CGOR variation. The effect of Upper Shale's TOC content distribution was not very prominent, although an increase in TOC content resulted in bubble-size increase in more than four instances.

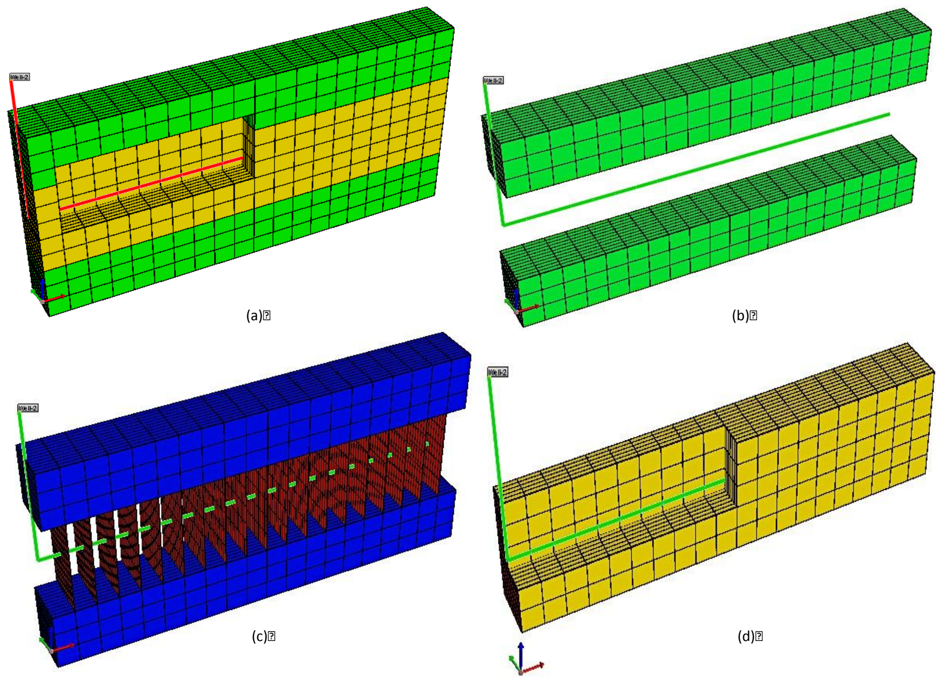

Figure 7: (a) Gridding-scheme's 3-D graphical representation. Three Bakken layers: U&L Shale shown in green and the Middle-layer shown in yellow. The horizontal well (red-line) centrally penetrates through middle-layer. (b) The U&L Shale matrix (c) The natural and the hydraulic (parallel, red vertical planes) fractures in the three layers. (d) The Middle Bakken Matrix

Simulation Scheme

For the quantification of the proposed contribution, the reservoir simulation was utilized to provide the robustness and the flexibility to incorporate the mathematical formulations for the crucial desorption and diffusion processes in the U&L Shale. GEM™, the compositional simulator of CMG™ was used in this study. The simulation scheme consisted of a Dual-porosity media for all the three layers. Two distinct dual-porosity media were incorporated: one in the shale layers and another in the Middle Siltstone layer (Figure 7). The U&L Shale is considered to have the diffusive matrix-to-fracture and adsorption dominated fluid-storage in Organic Matter (OM) pores, whereas the middle layer is thought to have Darcy matrix-to-fracture fluid transfer and conventional fluid storage in the pores. The heterogeneities in the reservoir properties were ignored in this study for the limited scope of this research and non-availability of information. O'Brien, et al. (2012) reported that the hydraulic fracture (HF) height in a Montana Bakken well may extend from 190 to 450ft. Therefore, the HFs in the wells were considered to extend throughout the three members of the Bakken. It was assumed that there was no interference effect from the nearby producing wells and the well confined its influence inside the stimulated reservoir volume (SRV). Geomechanical effects on porosity and permeability were neglected and water was considered to remain as immobile at all times.

For this research, the three-layered Bakken system was emulated in a simplified prototype to study the implications of gas desorption on Middle Bakken production. The prototype consisted of three horizontal layers stacked together, in which the top and the bottom layers represented the U&L Shale and the central layer represented the middle-siltstone reservoir. A 0.25ft radius horizontal well symmetrically penetrates the middle layer. The utilized hydrocarbon fluid consisted of 40% methane, 40% normal hexane and 20% normal dodecane. The relative-permeability table was generated using the correlations available in CMG. Figure 8 shows one of the utilized

Langmuir isotherms to model the multicomponent desorption in the U&L Shale. The separate Langmuir isotherm for three components (methane, hexane and dodecane) represent the varying degree of desorption in the U&L Shale matrix over the different ambient pressures.

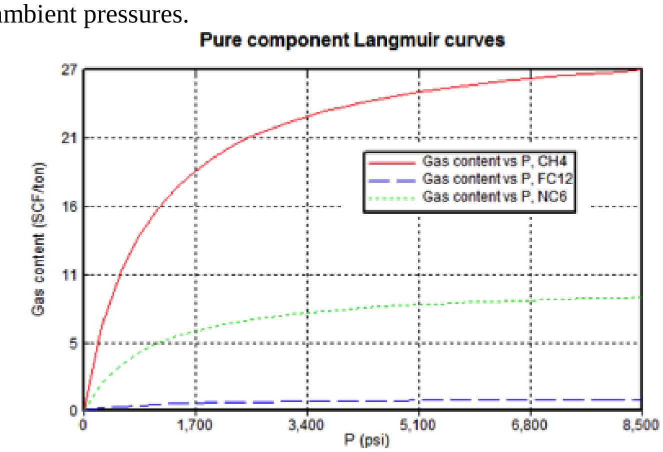

Figure 8: Langmuir isotherm used in the simulation scheme

Results

The results of quantification are presented along with the sensitivity of the parameters, which control the process of the anticipated contribution. The simulation scheme was utilized to derive quantitative results for the shale production-contribution at different values of these parameters. However, deriving meaningful quantitative results from the simulation scheme were contingent on the validity of the chosen range and values for these input parameters. These parameters could be categorized in three main groups: U&L shale properties, Middle Layer properties and HF properties. The Table 1 outlines the various sources for the numerical values of these parameters.

Table 1: The eight finalized sensitivity analysis parameters and their range for sensitivity analysis

Category	Parameters	Unit	Min	Max	Mean	Source
U&L Shale Properties	TOC	%	3	20	11	(Schmoker and Hester 1983)
	D	cm^2/sec	0.005	0.5	0.05	(Chen and Chen 2008)
	Fracture Perm	md	0.1	10	1	Appropriately Chosen
	Fracture Spacing	feet	5	10	15	Appropriately Chosen
Middle Layer Properties	Matrix Porosity	fraction	0.02	0.04	0.05	(Dechongkit and Prasad 2011)
	Matrix Permeability	md	0.001	0.1	0.01	(Sonnenberg and Pramudito 2009)
HF Properties	HF Spacing	feet	350	550	400	(O'Brien, et al. 2012)
	Fracture Half Length	feet	250	750	750	(O'Brien, et al. 2012)

Multiple iterations were performed on the simulation scheme. The output of the simulation-run was oil rate, cumulative oil production and gas-oil-ratio (GOR) performance plots. To conduct a descriptive sensitivity analysis, there could be numerous schemes to shortlist the most effective cases among the possible iterations with the different combination of the three values of eight parameters in Table 1. For this paper, the following scheme was utilized to shortlist those critical iterations.

U&L Shale contribution-case iterations: Sensitivity analysis for a particular parameter was performed by running models with the minimum, mean and maximum values. All parameters, other than that particular parameter, were set at their mean values. The sensitivities of the anticipated U&L Shale production contribution to the eight parameters listed of Table 1 are evaluated, and their corresponding combinations of the parameter-values are listed in Table 2. The first case is when each parameter is set to its mean values (Iteration #1). Since, there are two iterations each for the minimum and maximum values of the eight sensitivity analysis parameters, which makes a total of another sixteen iterations (#2 to #17).

Non-contribution case iterations: Additionally, for the quantification of the U&L Shale production contribution for the seventeen iterations (#1 to #17), equal numbers of non-contribution case iterations (# 1NC to # 17NC) are also performed by setting the fracture permeability (kf) of the Upper and Lower Shale to zero and keeping other parameters unchanged. For iterations #1NC to #9NC, kf is set to zero, ensuring that there is no fluid flow in the U&L Shale. Therefore, the values of U&L Shale parameters (TOC, D, kf and Lx) will not affect the results for such non-contribution iterations. These iterations resulted in the same output for all their simulation-runs. For other non-contribution case iterations (#10NC to #17NC), results for simulation-runs are different from each other.

Table 2: The first seventeen combinations for variation in parameter values, rest is for no-contribution cases. Note that iteration #1NC to #9NC, circled with the red dashed line caused the same results.

Iteration type	Parameters	Iteration #	(TOC, D, Kf, Lx, Φm, Km, FHL, HFS)	TOC	D	Kf	Lx	Φm	Km	FHL	HFS
	Mean	1	(MD, MD, MD, MD, MD, MD, MD, MD)	11	0.050	1.0	10	4%	0.010	450	450
	U&L Shale	2	(MN, MD, MD, MD, MD, MD, MD, MD)	3	0.050	1.0	10	4%	0.010	450	450
		3	(MX, MD, MD, MD, MD, MD, MD, MD)	20	0.050	1.0	10	4%	0.010	450	450
		4	(MD, MN, MD, MD, MD, MD, MD, MD)	11	0.005	1.0	10	4%	0.010	450	450
		5	(MD, MX, MD, MD, MD, MD, MD, MD)	11	0.500	1.0	10	4%	0.010	450	450
		6	(MD, MD, MN, MD, MD, MD, MD, MD)	11	0.050	0.1	10	4%	0.010	450	450
		7	(MD, MD, MX, MD, MD, MD, MD, MD)	11	0.050	10.0	10	4%	0.010	450	450
		8	(MD, MD, MD, MN, MD, MD, MD, MD)	11	0.050	1.0	5	4%	0.010	450	450
		9	(MD, MD, MD, MX, MD, MD, MD, MD)	11	0.050	1.0	15	4%	0.010	450	450
	Middle Layer	10	(MD, MD, MD, MD, MN, MD, MD, MD)	11	0.050	1.0	10	2%	0.010	450	450
		11	(MD, MD, MD, MD, MX, MD, MD, MD)	11	0.050	1.0	10	6%	0.010	450	450
		12	(MD, MD, MD, MD, MD, MN, MD, MD)	11	0.050	1.0	10	4%	0.001	450	450
		13	(MD, MD, MD, MD, MD, MX, MD, MD)	11	0.050	1.0	10	4%	0.100	450	450
	Hydraulic Frac	14	(MD, MD, MD, MD, MD, MD, MN, MD)	11	0.050	1.0	10	4%	0.010	250	450
		15	(MD, MD, MD, MD, MD, MD, MX, MD)	11	0.050	1.0	10	4%	0.010	750	450
		16	(MD, MD, MD, MD, MD, MD, MD, MN)	11	0.050	1.0	10	4%	0.010	450	350
		17	(MD, MD, MD, MD, MD, MD, MD, MX)	11	0.050	1.0	10	4%	0.010	450	550
	Mean	1NC	(MD, MD, ZERO, MD, MD, MD, MD, MD)	11	0.050	0	10	4%	0.010	450	450
	U&L Shale	2NC	(MN, MD, ZERO, MD, MD, MD, MD, MD)	3	0.050	0	10	4%	0.010	450	450
		3NC	(MX, MD, ZERO, MD, MD, MD, MD, MD)	20	0.050	0	10	4%	0.010	450	450
		4NC	(MD, MN, ZERO, MD, MD, MD, MD, MD)	11	0.005	0	10	4%	0.010	450	450
		5NC	(MD, MX, ZERO, MD, MD, MD, MD, MD)	11	0.500	0	10	4%	0.010	450	450
		6NC	(MD, MD, ZERO, MD, MD, MD, MD, MD)	11	0.050	0	10	4%	0.010	450	450
		7NC	(MD, MD, ZERO, MD, MD, MD, MD, MD)	11	0.050	0	10	4%	0.010	450	450
		8NC	(MD, MD, ZERO, MN, MD, MD, MD, MD)	11	0.050	0	5	4%	0.010	450	450
		9NC	(MD, MD, ZERO, MX, MD, MD, MD, MD)	11	0.050	0	15	4%	0.010	450	450
	Middle Layer	10NC	(MD, MD, ZERO, MD, MN, MD, MD, MD)	11	0.050	0	10	2%	0.010	450	450
		11NC	(MD, MD, ZERO, MD, MX, MD, MD, MD)	11	0.050	0	10	6%	0.010	450	450
		12NC	(MD, MD, ZERO, MD, MD, MN, MD, MD)	11	0.050	0	10	4%	0.001	450	450
		13NC	(MD, MD, ZERO, MD, MD, MX, MD, MD)	11	0.050	0	10	4%	0.100	450	450
	Hydraulic Frac	14NC	(MD, MD, ZERO, MD, MD, MD, MN, MD)	11	0.050	0	10	4%	0.010	250	450
		15NC	(MD, MD, ZERO, MD, MD, MD, MX, MD)	11	0.050	0	10	4%	0.010	750	450
		16NC	(MD, MD, ZERO, MD, MD, MD, MD, MN)	11	0.050	0	10	4%	0.010	450	350
		17NC	(MD, MD, ZERO, MD, MD, MD, MD, MX)	11	0.050	0	10	4%	0.010	450	550

MD=Mean, MN=Minimum, MX=Maximum, B=Base

Sensitivity Analysis: The aim of this analysis was to identify those parameters for which a change in their numerical values affect the cumulative production the most and the least. This study was also intended to understand the degree of proportionality or disproportionality between the cumulative production and the values of the different parameters. The iteration listed in Table 2 was utilized to derive simulation results for this relative sensitivity study.

Data Preparation: Table 3 outlines the steps and calculations involved in the sensitivity analysis. Columns 2, 3 and 4 list the minimum, mean and the maximum values for each of the eight sensitivity-analysis parameters listed in column 1. The different values for the sensitivity analysis parameters were adopted from the Table 1.

Simulation results for the cumulative oil in the first eight years production were derived for the contribution-case iterations (# 1 to 17). Column 5 lists the eight cumulative production results for the eight iterations in which one of the sensitivity-analysis parameters is set to its minimum value. Similarly, column 7 lists the cumulative production for those cases in which one of the eight parameters is set to the maximum value. Column 6 lists the cumulative production for the case when all the parameters are set to their respective mean values. The same convention is followed in column 8, 9 and 10 to list the simulation results for the cumulative production in non-contribution cases, which were derived utilizing Iteration# 1NC up to #17NC.

Table 3: Calculation Table and the Tornado-chart

	Sensitivity Analysis Parameters			Cummulative Oil For eight Years of Production			Base Case (Without Contribution)			Contribution From the U&L Shale			Tornado-Chart %	
1	2	3	4	5	6	7	8	9	10	11 (=(5-8/5)	12 (=(6-9)/6)	13 (=(7-10)/9)	14 (=11-12)	15 (=13-12)
Parameter	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max	Min	Mid	Max	Min	Max
TOC	3	11	20	460016.5	586381.3	608809	350331	350331	350331	23.8%	40.3%	42.5%	-16.4%	2.2%
D	0.005	0.05	0.5	456090.2	586381.3	654114.5	350331	350331	350331	23.2%	40.3%	46.4%	-17.1%	6.2%
Kf	0.1	1	10	582721.8	586381.3	609372.8	350331	350331	350331	39.9%	40.3%	42.5%	-0.4%	2.3%
Lx	5	10	15	626236.8	586381.3	572881.1	350331	350331	350331	44.1%	40.3%	38.8%	3.8%	-1.4%
Φm	0.02	0.04	0.06	465672	586381.3	669713.9	259456	350331	413217	44.3%	40.3%	38.3%	4.0%	-2.0%
Km	0.001	0.01	0.1	369191	586381.3	679238.6	214012	350331	429438	42.0%	40.3%	36.8%	1.8%	-3.5%
FHL	250	450	750	630192	586381.3	722816	391304	350331	429760	37.9%	40.3%	40.5%	-2.3%	0.3%
HFS	350	450	550	793487.4	586381.3	224343.2	451304	350331	143760	43.1%	40.3%	35.9%	2.9%	-4.3%

Contribution from U&L Shale: The row-wise differences of the values in the contribution-case columns (5, 6 and 7) and non-contribution case columns (8, 9 and10) are basically the U&L Shale production contribution. Column 11, 12 and 13 lists these U&L Shale contributions as the percentage of contribution case cumulative production. Note that while deriving the U&L Shale contribution results at the minimum, mean and the maximum values of a particular parameter, other parameters are maintained as constants at their respective mean values.

Column 14 and 15 lists the difference between the columns 11 and 12, and columns 13 and 12 respectively. The values in column 14 could be interpreted as the rise or fall in the U&L Shale production contributions as the value of one of the eight parameters is changed from its minimum to its mean. Similarly, column 15 lists the same rise or fall, but this time the value of the parameters is changed from its maximum to its mean.

The bars in columns 14 and 15 represent a tornado chart of the values. It is evident from the chart that the U&L Shale TOC, which controls matrix storage capacity; and D, which control the matrix-to-fracture fluid transfer, have the maximum impact on the anticipated contribution. The chosen range for other U&L shale parameters seems not to alter the contribution-percentage significantly. As the TOC (Wt. %) in the U&L Shale dropped from the mean values of 11% to the minimum of 3%, the contribution-percentage dropped by 16.4%. However, a rise in TOC from 11% to 20% enhanced the contribution by a meager 2.2%. This result indicates that with the adopted values of the parameters, the effect of rise in TOC beyond 20% should not alter the results for the contribution. The result for component diffusivity is similar in the left wing of the chart as the value dropped from the mean to the minimum value. However, the result of 6.2 % rise in the contribution-percentage in right wing of the chart suggest that there is still a room for an increase in parameter D, which is expected to enhance the U&L Shale contribution-percentage. Enhancements in the Middle Bakken matrix with an increase in parameters Φ_m and k_m had a negative impact on the Shale contribution, as it was reflected from the corresponding bars in the Tornado chart. However, the effects of change in these parameters on the contribution-percentages are not as pronounced as the U&L Shale parameters. Lastly, hydraulic fracture enhancements have a positive impact on the contribution-percentage, which is reflect in the chart for FHL (fracture half lengths) and HFS (hydraulic fracture spacing) bars in the chart. The closely spaced fractures seem to further improve the U&L contribution-percentages.

The best and the worst case: To generate a most contributing and least contributing case, all parameters were set to values that maximized and minimized the U&L shale contribution. Iterations #1 and #3 in Table 4 display the most and least contributing scenarios. In Iteration #2 all the parameters were set to their mean values. The last three iterations in the table are the corresponding non-contribution case iterations. Following the calculation procedure followed in Table 3, the results for the worst (11%), the most expected (40%) and the best (52%) possible values for the U&L Shale production contribution with the surveyed data-ranges in Table 4.

Table 4: The combination of sensitivity analysis parameters used in the most and the least U&L Shale contribution case.

Iteration type	Parameters	Iteration #	(TOC, D, Kf, Lx, Φm, Km, FHL, HFS)	TOC	D	Kf	Lx	Φm	Km	FHL	HFS
Contribution Case	Worst Case	1	*(MN, MN, MN, MX, MX, MX, MN, MX)*	3	0.005	0.1	15	6%	0.100	250	550
	Mean	2	*(MD, MD, MD, MD, MD, MD, MD, MD)*	11	0.050	1.0	10	4%	0.010	450	450
	Best Case	3	*(MX, MX, MX, MN, MN, MN, MX, MN)*	20	0.500	10.0	5	2%	0.001	750	350
Non-Contribution Case	Worst Case	1NC	*(MN, MN, ZERO, MX, MX, MX, MN, MX)*	3	0.005	0	15	6%	0.100	250	550
	Mean	2NC	*(MD, MD, ZERO, MD, MD, MD, MD, MD)*	11	0.05	0	10	4%	0.010	450	450
	Best Case	3NC	*(MX, MX, ZERO, MN, MN, MN, MX, MN)*	3	0.005	0	5	2%	0.001	750	350
MD=Mean, MN=Minimum, MX=Maximum											

Conclusion

1. The production performance anomalies of the Middle Bakken wells could be attributed to the interference from the U&L Shale layers. This interference might act like an active production-support to aid the recovery mechanism of the Middle Bakken reservoir.
2. The phenomena of desorption and diffusion of hydrocarbon molecules in the organic rich U&L Shale matrix are expected to play a significant role in this production-contribution. By including their mathematical formulations in the reservoir simulation, the proposed contribution can be quantified to some extent.
3. Results from the simulation utilizing the surveyed primary input data suggest that the U&L Shale layers might be contributing in a range of 10%-50% of the total cumulative production of the Middle Bakken wells. With the mean values of each of the primary input parameters, the contribution was estimated as 40% of the cumulative production.
4. Parametric sensitivity analysis in suggests that the contribution from the Shale layers is the most sensitive towards the total organic carbon (TOC) and the diffusivity coefficients (D). The enhancements in the Middle layer's reservoir quality have a negative impact on the proposed contribution. However, the improvements in hydraulic fracturing encourage the contribution.

References:

1. Chen, Jiansheng, Chen, Songhua. 2008. A New Mixing Rule of Self Diffusivities in Methane Hydrocarbon Mixtures and the Determination of GOR and Oil Viscosities From NMR Log. SPE 115510 Presented at Annual Technical Conference and Exhibition, Denver, Colorado.
2. Dechongkit, Piya, Prasad, Manika. 2011. Recovery Factor and Reserves Estimation in the Bakken Petroleum System (Analysis of the Antelope, Sanish and Parshall fields). CSUG/SPE 149471 Presented at Presented at Canadian Unconventional Resources Conference, Calgary, Alberta.
3. EERC. GIS for Bakken and Three Forks formation. Website: http://www. undeerc.org/bakken/dss/. Accessed on 30th April 2013.
4. NDIC, Oil & Gas Division. Monthly Well Production. February 2013. https://www.dmr.nd.gov/oilgas/.
5. O'Brien, Darien G., Larson, Robert T. Jr, Parham, Ronald C., Thingelstad, Blane L., Aud, William W., Burns, Richard A., Weijers, Leen. 2012. Using Real-Time Downhole Microseismic To Evaluate Fracture Geometry for Horizontal Packer-Sleeve Completions in the Bakken Formation, Elm Coulee Field, Montana. SPE 139774 Published in Production and Operations Journal. February, Volume 27, No.1, 27-43.
6. Schmoker, J. W., Hester, T. C. 1983. Organic carbon in the Bakken Formation, United States portion of Williston basin. Published in American Association of Petroleum Geologists Bulletin. Volume 67, 2165-2174.
7. Sonnenberg, Stephen A., Pramudito, Avis. 2009. Petroleum Geology of the giant Elm Coulee field, Williston Basin. Published in American Association of Petroleum Geologists Bulletin. September, Volume 93, 1127-1153.
8. USGS. 2008. U.S. Geological Survey petroleum resource assessment of the Bakken Formation, Williston Basin Province, Montana and North Dakota. Slide Presentation for US Department of Interior, Washington, D.C. April.