Abstract

A great variety of factors can influence production, and it is often difficult to discriminate how significant the impact of a single factor is. The unconventional nature of the Bakken tight oil play requires considering both geological and technological aspects, as completion designs evolved at a rapid pace over recent years. Based on an integrated and correlative approach this study aims to understand why certain areas in the Bakken play are considerably more productive than others, and to identify the responsible factors.

The Late Devonian to Early Mississippian Bakken Formation in the Williston Basin is a world-class petroleum system and represents the most prolific tight oil play known to date. The source rocks in this unconventional system are the highly organic-rich Lower and Upper Bakken shale members. The silty, dolomitic Middle Bakken member, sandwiched in-between the shales, and upper Three Forks member, underlying the Bakken Formation are the main target horizons for production.

The Bakken is a technology-driven play and a clear trend of increasing production rates over time is evident as drilling techniques and the completion design of wells are progressively becoming more sophisticated. Latest since 2010 the majority of operators employ massive hydraulic fracturing treatments with up to 40 stages and millions of pounds of proppant. However, numerous older wells outperform younger wells despite technological advancements, suggesting that geological factors have a larger impact on production than the completion design.

Geological factors influencing productivity can reach from reservoir quality and thickness, over structural and stratigraphic framework, rock-mechanical properties, natural fractures, to pore-overpressure distribution and organic geochemical parameters. The interplay of hydrocarbon generation potential and maturity results in tremendous overpressuring, and creation of fracture permeability and secondary porosity. A combination of overpressure- and buoyancy-driven migration of hydrocarbons into up-dip located traps can result in large-scale accumulations, as for example Sanish-Parshall and Elm Coulee.

The comprehensive and integrated analysis of technological and geological data allowed identification of different Bakken play types, which are productive for different reasons. The knowledge and understanding of where and why sweetspot and low productivity areas occur is invaluable for both current development and future exploration.

Introduction

Disclaimer: The contents of this paper are entirely based on research performed for the dissertation by Theloy (in preparation).

The Bakken is among the most significant oil discoveries in the U.S. in the past 40 years and lifted North Dakota
into second place in terms of top oil-producing states in the United States (DuBose, 2012). Daily production rates amount to more than 684,000 bbls/day in North Dakota alone (NDIC, 2012). Recently released numbers for technically recoverable reserves range between 4.42 to 11.43 billion barrels based on the USGS assessment (Gaswirth et al., 2013). The mean estimates for the Bakken are 3.65 billion barrels and 3.73 billion barrels for the Three Forks. Therefore, it is of great interest to gain a better understanding and insights into which factors are influencing production the most. A comprehensive, integrated study investigating this problem from both geological and technological perspectives should help elucidating contexts and aid in decision making processes for current development strategies and future exploration targets.

The Late Devonian to Early Mississippian Bakken Formation is located in the Williston Basin and extends over parts of North Dakota, Montana, and the Canadian provinces of Saskatchewan and Manitoba. The main focus area of research is outlined in Figure 1, which essentially represents the current boundaries of the active Bakken play in the United States. The Williston Basin is a large, oval-shaped, intracratonic sag basin and accommodates a sediment thickness of over 16,000 ft (4,878 m), reflecting an almost complete stratigraphic record from Cambrian to Tertiary time (Carlson and Anderson, 1965; LeFever et al., 1991). The strata in the Williston Basin are characterized by a draping, layer-cake geometry, interrupted only by few structural features such as the Nesson and Cedar Creek anticlines.

![Figure 1: The main focus area (shaded in red) is defined by data availability and encompasses basically the U.S. portion of the active Bakken play in the Williston Basin. The structure contour lines indicate the dish-shaped geometry of the basin, only interrupted by few major structural elements such as the Nesson anticline and Billings anticline. Note, that the area to the east of Parshall is thermally immature and is not part of the active Bakken play (modified from Sonnenberg and Pramudito, 2009).](image-url)
The Bakken petroleum system encompasses from stratigraphic bottom to top the Three Forks, Bakken, and lower Lodgepole formations (Figure 2). The Bakken Formation is a very thin, widespread unit and reaches a maximum thickness of 150 ft (46 m) (Pitman et al., 2001). The Bakken Formation is composed of four members: the basal Pronghorn, the Lower Bakken shale, the Middle Bakken, and the Upper Bakken shale. LeFever et al. (2011) elevated the upper, middle and lower members of the Bakken Formation to formal status and added as fourth member the Pronghorn, which was formerly known as ‘Sanish sand’ or ‘Lower Bakken silt’. The two black shales are the source rocks of the petroleum system and reveal average total organic carbon contents of 11 to 12 weight percent (Schmoker and Hester, 1983). The Middle Bakken and the Pronghorn are very heterolithic units and contain varying amounts of silt, sand, dolomite, limestone, and clays, and can be further subdivided into distinct facies. The main reservoir units are the Middle Bakken and the upper Three Forks Formation, and exhibit permeability and porosity ranges typical for tight reservoirs. The dolomitic Three Forks Formation unconformably underlies the Bakken Formation, and has gained rapidly in interest as target horizon since 2010. The Pronghorn attains its greatest thickness in the south and represents a rather ancillary target in the remainder of the basin. The overlying tight limestones of the Lodgepole Formation form the regional seal of the Bakken petroleum system, and only minor amounts of production were derived from Waulsortian-type mounds.

The approach of this study is based on integrating parameters and observations from both geological and technological sides and determining their impact on production. The multidisciplinary analysis covers aspects of drilling techniques, completion design strategies, production data analysis, stratigraphic and structural framework implications, organic geochemistry of source rocks and oils, pore-overpressure analysis, reservoir and rock-mechanical properties of the Middle Bakken and Three Forks, as well as the regional stress regime and occurrence of natural fractures.

The primary objectives of this research are:

- Understand which factors in both technological and geological terms exert the largest control on production and whether those control parameters vary across the basin.
- Identify sweetspot and low productivity areas and analyze their causes.
- Evaluate the effect of improving technology and procedural differences by operators on production.
- Develop a method to distinguish between completion-related enhancement of production versus geological-induced variations in productivity.
- Investigate the relationship between hydrocarbon generation, observed pore-overpressure in the Middle Bakken and Three Forks, and productivity based on a much larger dataset than Fred Meissner had available for his landmark paper in 1978.
- Create a pressure map for the Middle Bakken based on high quality bottom hole pressure (BHP) and diagnostic fracture injection test (DFIT) data without using older, unreliable drillstem test (DST) data.
- Determine the role of natural fractures in the Bakken play.
- Describe the impact of facies variations on rock mechanical properties and fracturing behavior.
- Elicit whether secondary migration of hydrocarbons is a significant process in the Bakken petroleum system, in particular for the U.S. portion of the basin.
- Examine the importance of traps within the Bakken play and what impact their presence or absence has on hydrocarbon accumulations.

Data

For the research, presented in this study, no samples have been taken or analyzed. The database of this study is exclusively based on the collection of existing datasets and the integration of their information. While the majority of data derives from publicly accessible sources other datasets come from company-internal sources and remain confidential. Sources used for data compilation include the Energy and Environmental Research Center (EERC) in North Dakota, a number of Colorado School of Mines Bakken Consortium companies, previous Bakken Consortium studies, Geomark Research, Ltd., the United States Geological Survey (USGS) and the North Dakota Industrial Commission (NDIC).

The resulting dataset comprises general production data (initial and cumulative production) for almost all Bakken and Three Forks wells, detailed production and completion information for a subset of 1095 wells, estimated
Figure 2: Stratigraphic chart of the Bakken petroleum system with facies descriptions, depositional environments and interpreted sea level trends. Reservoir units are indicated with yellow stars, the most significant targets being Middle Bakken facies C and E, and the upper Three Forks laminated facies (UTF-H) and clean dolomite bench (UTF-I). FB = false Bakken, S = Scallion, UBS = Upper Bakken shale, MB-A through MB-F = Middle Bakken facies, LBS = Lower Bakken shale, PH = Pronghorn, UTF = upper Three Forks, MTF = middle Three Forks (modified from Sonnenberg et al., 2011; Three Forks facies adapted from Gantyno, 2010).
ultimate recoveries for 2246 Bakken wells, source rock analysis data from the Upper and Lower Bakken shales (> 500 wells), biomarker distributions for 214 oil samples and 95 source rock extract samples, quality controlled pressure data points from bottomhole pressure tests (BHP) and diagnostic fracture injection tests (DFIT) for 92 Bakken wells and 70 Three Forks wells, static rock properties from 28 Middle Bakken and 20 Three Forks samples, as well as core analysis data, XRD and QEMSCAN reports, and other information.

Results

The Bakken petroleum system is categorized as continuous unconventional hydrocarbon resource play (Pollastro et al. 2008). However, despite the ‘continuous’ nature, production is not uniform across the basin and a number of sweetspots as well as low productivity areas have been identified based on production and estimated ultimate recovery data. In order to understand the causes for observed variations in productivity (Figure 3) both technological and geological factors have been investigated.

One of the most prevalent technological factors is the number of hydraulic fracturing stages applied during stimulation, as it directly correlates to the size of the stimulated rock volume. Intuitively, one would assume that production increases with higher number of fracturing stages, however when plotted versus production no correlative pattern becomes evident. Figure 4 shows a subset of the data for three specific areas: Elm Coulee, North Nesson, and South Nesson. Elm Coulee field in Montana was discovered in 2000 and most wells were short single and dual laterals and completed with one fracturing stage either per lateral or per well, the so-called ‘pump and pray jobs’ or ‘Hail Mary fracs’. In contrast, wells in the North and South Nesson areas were stimulated with up to 38 fracturing stages, yet those wells do not yield higher production rates than the much older wells in Elm Coulee. This observation suggests that geological factors have a greater impact on production than technological advancements.

The effects of proppant choice on production were investigated in three areas (Bear Den, North Nesson and South Nesson), where sufficient data variability was available. Wells in the Bakken are traditionally stimulated with sand proppants, but recently a shift towards higher quality ceramic proppants is noticeable. For comparison purposes, the utilized proppant types were subdivided into three categories. The first category is ‘Sand’ and refers to wells, which have been stimulated with only sand proppants. The second category is ‘Sand and Ceramic’ and refers to a mixture of roughly two thirds sand proppants and one third ceramic proppants. The third category ‘Ceramic’ applies to wells, which have been stimulated with ceramic proppants making up at least two thirds, if not the total amount, of proppants used. In all three areas similar results were observed, and a mixture of two thirds sand and one third ceramic proppants yielded the best production performance.

The Bakken play is characterized by widespread pore-overpressure and pressure gradients exceed 0.7 psi/ft for large parts of the basin (Figure 5). The Middle Bakken pressure map is based on 92 quality controlled bottom hole pressure (BHP) and diagnostic fracture injection test (DFIT) data. Six hydrostatic data points were added in the eastern immature part of the basin, and six more data points were included in the Sanish-Parshall area. The pressure data of the Middle Bakken and Three Forks are indicative for an inverted continuous system, leaking pressure at the top. An exception to this is the Parshall area, where a distinct high-pressure compartment could be identified. Meissner (1978) attributed elevated pore-pressures to have been caused by the volume expansion taking place during kerogen maturation, when solid organic matter transforms into liquid and gaseous hydrocarbons. The organic matter in the Bakken shales is dominantly kerogen type II, and therefore an average maturation path for kerogen type II was created using the source rock analysis parameters Tmax and hydrogen index (HI). The beginning of intense oil generation (Tmax = 430°C, HI = 500 mgHC/gTOC) was mapped for both the Upper and Lower Bakken shales. The resulting maturity boundary zone encompasses the area of the Bakken play, which is currently in or past the stage of intense oil generation, and thus currently is or was capable of generating high overpressures.

When high pore fluid pressures locally and temporary exceed the fracture gradient of the rock, natural fractures are created. The existence of a dual permeability system is the key to achieve such extraordinary production rates, the Bakken is known for, from tight reservoir rocks. Natural fractures can be broadly subdivided into larger-scale tectonically-induced fractures, reservoir-scale fractures (tens of centimeters to meters), and hydrocarbon generation-induced microfractures (millimeters to centimeters). Furthermore two generations of fractures are present, older tightly cemented fractures and younger, often open fractures. By far the most common type of fractures observed in cores and thin sections are microfractures, which are likely also the main contributors to production as they greatly
Figure 3: Average estimated ultimate recovery values (Mbbl) from wells drilled between 2010 and 2011, with exception of Elm Coulee, for ten subareas of the Bakken play indicate significant differences in productivity.

Figure 4: Despite employment of sophisticated completion designs wells in North and South Nesson areas do not outperform early, mainly single stage-completed wells in Elm Coulee.
enhance the reservoir contact area and flow path connectivity to artificially induced hydraulic fractures. Logically, microfractures related to hydrocarbon generation and inherent build-up of high pore fluid pressures would occur throughout the mature source pod, and therefore not define sweetspot areas.

To investigate how much the varying facies lithologies of the Middle Bakken and Three Forks impact the brittleness and fracturing behavior, a rock-mechanical dataset including 28 Middle Bakken samples and 20 Three Forks samples was analyzed. The data was generated by triaxial testing according to the ISRM type 2 procedure by the Energy and Environmental Research Center (EERC) in North Dakota. Young’s moduli and Poisson’s ratios were cross-plotted and evaluated whether any clustering of data points occurs according to formation adherence of the samples, facies, texture, presence or absence of natural fractures within proximity of the sampling depth, and mineralogical composition. No distinct clustering effects have been observed and the rock properties of both the Middle Bakken and Three Forks appear to be relatively similar.

Redistribution of hydrocarbons by secondary migration, as pore fluids tend to move from higher to lower pressure gradients, has likely influenced the location of sweetspots. Large-scale secondary migration is evidenced by movement of significant volumes of hydrocarbons from the mature U.S. part of the basin into the Canadian immature part, where the Middle Bakken attains conventional reservoir characteristics (Jarvie, 2001). Much more debated is whether secondary migration is a process of importance within the U.S. part of the basin. The analysis of biomarker maturity data of oils and source rock extracts revealed that in shallow, basin marginal areas, the oils are often higher mature than adjacent source rocks, suggesting that secondary migration of hydrocarbons has occurred. In the Parshall area, specifically, several biomarker maturity indicators allude to mixing of low maturity in-situ generated oils with higher maturity migrated oils.

The geologically favorable core area, characterized by the stage of maturity and high pore-pressure gradients, was further refined by integrating high oil / (oil + water) ratios, derived from cumulative production values. The smallest common area of those parameters, the core area, was then compared to the high productivity area based on initial production rates and estimated ultimate recoveries (Figure 6). The geologically favorable core area is fully enclosed.
Figure 6: The overlay of eight different maps and integration of their information shows a geologically favorable core area (shaded in black) within the high productivity outline (purple dashed line). Prolific production areas outside of the core area are likely influenced by other factors than the ones, which were integrated for this overlay. LBS = Lower Bakken shale, UBS = Upper Bakken shale, Tmax (°C), HI = hydrogen index (mgHC/gTOC), IP = initial production, EUR = estimated ultimate recovery, OOW = oil / (oil + water) ratio of cumulative production.

Figure 7: The effect of a technological parameter on production can be illustrated for any given geological area. For example, an acreage area produces the same amounts of oil and water, and has therefore an oil / (oil + water) ratio of 0.5, the improvement in production due to increasing the number of fracturing stages is shown by the arrow.
within the high productivity zone, however known high productivity locations such as Parshall, Rough Rider, and Elm Coulee lie beyond the boundary of the core area. These sweetspots are influenced by factors, other than those integrated in this illustration. Possible factors may include, for example, enhanced reservoir properties, secondary migration, presence of trapping mechanisms, and distinct differences in completion technology.

The integration of technological, geological, and production information led to a method to discriminate the effect of technological parameters, such as number of hydraulic fracturing stages and proppant loading, on production. When the oil / (oil + water) ratio is plotted against normalized production (to lateral length), the technological parameter can be overlaid in series ranges (Figure 7). In this way the increasing trend in production due to a specific technological parameter can be illustrated for a given geological area.

Overall, the research led to the conclusion that the Bakken cannot be regarded as a uniform play, but rather consists of several play types or sweetspot types (Figure 8). Elm Coulee is not comparable to Rough Rider, nor is Sanish-Parshall comparable to Bear Den. It appears that the sweetspots are unique in the way what makes them successful for hydrocarbon production. Rough Rider, for example is not a geologically outstanding area, however the dominant operator in this area performs the most sophisticated completion designs. In contrast, Sanish-Parshall is a geological sweetspot, where up-dip migration, the presence of a trap on the eastern margin, in combination with high pressure and favorable reservoir properties makes for prolific wells without the necessity of high-end completion methods. This has two-fold implications: firstly, a barrel of oil comes at higher costs out of Rough Rider than in comparison to a geological sweetspot like Sanish-Parshall; and secondly, with ambitious completion techniques even moderately geologically favorable areas can be turned into prolific sweetspots.

Figure 8: Different Bakken play types are productive for different reasons as the sweetspots are characterized by their own set of ‘ingredients’ to render them successful.
Conclusions

This multidisciplinary, comprehensive work of investigating which factors are influencing the productivity basinwide in the U.S. Bakken play provides a substantially improved evaluation basis for development and exploration strategies.

The main findings of this research are:

- Production increases with more sophisticated drilling and completion technology, but geological factors have a larger impact on production than technological improvements.
- There is a good correlation between hydrocarbon generation, pore-overpressure, oil / (oil + water) ratio, and production. However, hydrocarbon accumulations became partially redistributed due to migration processes.
- The ratio of oil / (oil + water) based on cumulative production values from 3379 wells is a good indicator for the distribution of prospective areas and location of sweetspots within the Bakken play.
- A method to determine the effect of technological parameters (e.g. number of hydraulic fracturing stages) on production is to plot the oil / (oil + water) ratio against production, normalized by the lateral length. The technological parameter can then be displayed in various series ranges.
- Despite ceramic proppants being of superior quality over sand proppants, wells which have been stimulated only with ceramic proppant did not perform as well as wells where a mixture of about 2/3 sand and 1/3 ceramic proppant was used, within the same area.
- As part of the pore-overpressure analysis a new pressure map for the Middle Bakken was created. The Three Forks reservoir is generally higher overpressured than the Middle Bakken. The maximum pore pressure - depth plot characterizes the Bakken as an inverted continuous system, leaking pressure at the top. Only at Parshall field at the up-dip eastern margin was a discrete pressure cell detected.
- Natural fractures play an important role for production. As part of the dual permeability system they are responsible for quick deliverability of hydrocarbons to the wellbore and result in tremendous initial production rates. Natural fractures, however, do not define sweetspot areas. Tectonically-induced, large scale fractures are rare and likely quantitatively insignificant for production. The majority of fractures, as frequently observed in cores, are small-scale fractures related to hydrocarbon generation. This implies that this type of fractures occur throughout the mature source pod and are thus not a discriminative feature of sweetspots.
- The process of secondary migration within the Bakken petroleum system is widely accepted with regard to migration of hydrocarbons from the U.S. part of the basin into the immature Canadian part as reservoir properties improve northwards. Secondary migration of hydrocarbons within the U.S. portion, however, is still a subject of debate, in particular for the Parshall area. Maturity ratios of thermo-sensitive biomarkers from oil and source rock extract samples suggest Parshall hosts a combination of self-sourced low maturity oils as well as higher maturity migrated oils.
- Trapping mechanisms appear to play a crucial role for the formation of large scale hydrocarbon accumulations (e.g. Sanish - Parshall, Elm Coulee) with oil being almost the exclusive reservoir liquid. The oil / (oil + water) ratio map provides a good basis for trap detection, as the contact between highly oil-bearing and highly water-saturated reservoir is of very sharp and abrupt nature. In places where traps are absent this contact is gradational.
- By integrating all the above information it becomes clear that the Bakken consists of multiple play types. Every play type has a different set of `ingredients`, which accounts for the observed variations in productivity across the basin. While, for example, the outstanding production rates in Sanish - Parshall and Elm Coulee areas are dominated by favorable geological conditions, the high production rates in Rough Rider are attributable to aggressive completion methods.
- Other investigated parameters which showed little or no influence on production are variations in rock mechanical properties of the Middle Bakken and Three Forks, the regional stress regime, lineaments, and deep-seated faults below the Prairie salt.
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