REDUCING PRODUCED WATER DISPOSAL VIA EFFECTIVE TREATMENTS METHODS AND RE-USE: PROPOSED SUSTAINABLE APPLICATION FOR BAKKEN, NORTH DAKOTA

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Dedication

To the loving memories of my parents, Olamigoke Felix and Risikat Tomomewo

Abstract

It is true that the advancements in both the hydraulic frack and directional drilling technologies led to less time and a bit easier ways to develop unconventional oil and gas assets worldwide. In the Bakken North Dakota, the result of these breakthroughs and advancements in technologies are that they drastically reduce the time it takes to drill and complete a well leading to more wells **(347 in 2004 to 16,300 in 2020).** In 2019, the United States became the largest global crude oil producer, and the unconventional Bakken Play in North Dakota is one of the major contributors to this feat. As more wells are being drilled, more waste water are being produced. Analysis also showed early increases in water cuts even in younger (less than 3 years) wells drilled around McKenzie and Williams Counties. The concern here is that the wastewater produced by these increased oilfield activities is highly saline **(~170,000 to 350,000 ppm TDS),** and the most commonly used water disposal method in the Bakken Formation is deep injection into disposal wells. Notwithstanding, there are growing environmental and operational concerns about the sustainability and impacts of this approach. However, if the wastewater is efficiently treated, it could be reused in hydraulic fracturing operations or to support coal mining and irrigation activities. This research uses various method to investigate the root cause of the high volume of wastewater production in the Bakken, North Dakota and how these flow back and produced water could be treated using various novel technologies like, the advanced and improved desalination, advanced electro-oxidation and dilution methods. Lastly, the research was able to provide robust and detailed results on how the Bakken treated produced water could be transformed to good use especially as base fluids for hydraulic frack fluid formulation.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

1 Global Water Issues

1.1 Introduction

It is a very true saying that there is nothing more indispensable and essential to life on this Planet than water. However, it is also still very obvious that there are a lot of unfavorable factors militating against water sustainability (Parashar et al.,2003). Looking around the world, from Cape Town in Africa to Beijing in Canada and other teaming Asian and American megacities, it is glaring there exists a global water crisis (WWAP,2009). It is becoming increasingly difficult for the citizens to access the volume and the quality of water they need for basic life needs like cooking, drinking, bathing, washing, for irrigation, and at some point for oil well drilling activities. The crisis issue is getting worse by the year with no sign that it’s going to recede. It is also important to say that some improvements have been made in making clean drinking water accessible to some 2.6 billion people in less developed Nations from 1990 to 2015. In terms of population, the number is equivalent to an increase from 76% of the world population to 91% during within the time horizon (Miller, 2003). The United Nation has been trying to address this global water crisis many times, during the World Water Day event that usually is held every March 22. Still, water shortages is ravaging more than 785 million people living in most of the emerging and developing nations worldwide. It has been predicted by WHO in 2019 that by 2025, about half of the World Population will be living in a water shortage crisis situation. It is also believed that between 80-90% of all the health issues leading to about 30% of all deaths emanate from the use of water with very poor quality (WHO report, 2019).

Some main activities that are posing great risks and threats to clean water availability and use are both the conventional and unconventional energy extraction like oil exploration, refining and distribution, including coal mining. Fossil fuels still provide over 85% of Global energy needs (Zabbey and Olsson,2017). Ninety percent of the world transportation energy sector depends on fossil fuels. Any interruption in the supply of fossil energy will have serious consequences, not only will this hamper movements, but will also affect food production, distribution, space heating and cooling, health care, global national securities, manufacturing sectors, and so many other very essential sectors globally (EIA Report, 2019). Energy exploration companies undergoing mining activities will only aggravate the water crises, in particular for those locations that have the tendency to have water scarcity by overstressing the available water resources (Tomomewo et al, 2020: Zabbey and Olsson,2017).

The amount of water needed to frack an unconventional well differs widely by region. Globally about 140 billion gallons of water are used for fracking operations annually (API Report, 2020; Ellafi et al, 2020 and Tomomewo et al, 2020). Up to about 4.5 million gallons are needed to frack a single well, 600,000 gallons of water are needed to drill each new well (Tomomewo et al, 2020). On a drilling site up to 50 million gallons of fresh water are needed to complete the entire operation of drilling a well (EERC,2019). On the effect of the waste water generated from this exploration activity on the environment, off-shore fossil fuel exploration activities have the greatest effect as it threatens the sustainability of the marine life. The storing and transportation of fossil fuel products usually increases risk to the environment in the event there are spill or accidents (Johnsson et al, 2019). There has been apprehension that the deposition of the separated produced water through deep well injection has been linked to seismic activities (Sbell et al, 2014 and

Tomomewo et al,2020). Accidents, leakages and spills are hardly preventable in fossil energy resources mining, transportation through pipelines and haulage through oil tankers. Whenever this accident occurs, the effects of these activities on the available water resources and water quality are the same everywhere (Odu et al, 2015).

During fossil fuel exploration activities, water is needed for so many activities including the actual extraction of the hydrocarbon from reservoirs and for the refining of the crude oil after extraction. To drill these wells, water is required for preparing drilling fluid that is needed for cleaning and cooling of the drill bit, suspending and transporting the of crushed rocks and sediments to surface while providing pressure to avoid collapse of the well (Leusbrock, 2003). Water is also used as base liquid to maintain the reservoir pressure. Other fluids like gas or steam could also be used for this purpose. Depending on the situation, water may be more available and inexpensive. Steam is used at some instances where the oil is too heavy to flow. To do this, an injection well drilled either close or into the same reservoir and steam is injected under pressure (Gao et al., 2020; Faruk and Karanikas,2020 and Zheng et al.,2012). The heat from the incoming steam thins out the heavy oil in the reservoir, and the pressure build up enhances the oil to flow up the well. Today, most oil producers re-inject produced water or reuse it for onshore wells (98%).This is not the case in the Bakken because the produced water is hyper-saline (between 170,000 – 350,000 Mg/L) and need to be treated to a level before it can be re-injected (Tomomewo et al., 2020).

For offshore wells, 91% of produced water from is usually discharged into the ocean. A typical drilling accident that can cause produced water to be spilled is caused by blowouts of hydrocarbons (Semiat, 2008). This usually occurs when the well has encountered a zone or zones with abnormally high reservoir pressure. A “blowout” occurs when a mixture of pressurized natural gas, oil, mud, and water escapes from a well, shoots up the drill pipe to the surface, expands and ignites. Blow outs can be catastrophic if the scenario result in a strong and continued hydrocarbon flowing out on surface. Here, the cause most times is as a result of high pore pressure above the hydrostatic pressure that the drilling can provide in the drilling zone (Zein et al., 2017; Awe et al.,2015 and Blotto et al.,2001). The drilling fluids are usually the primary means to check blowout during any drilling operation while blowout preventers (a gigantic stack of valves and auxiliary equipment that are placed on the well head) are most times used as the secondary means of preventing flow back from the wells. It is a fact that when an accident like this occurs, it usually generates a substantial environmental risk to the both the plant and marine bodies. Risk of water aquifer deep pollution and natural habitat destruction that could eventually lead to the extinction of some important species of both plant and animals. All these of course depend on the frequency and extent of occurrence (Hodes et al.,2004).

Over the years, technologies advancement have mostly favored hydrocarbon extraction from conventional reservoirs. However, investors have the understanding that shale is “source rock”—rock from which hydrocarbon can formed. Shale is also a good “trap” suitable for storing the formed hydrocarbon and preventing it from flowing or migrating. Example of shale include: siltstone, sandstone, limestone, dolomite and also volcanic rocks. Shale oil means hydrocarbon (liquid) locked in impermeable mudstone and shale that are effective source rocks (Verba et al.,2017). These fluids are usually trapped in the traditional reservoirs for many millions of years. Just like the shale oil, shale gas is natural gas trapped in layers of impervious hard mudstone and shale that are also effective source rocks, shale formations (Onwumelu et al.,2019). The advent of two technologies can be decisively linked to the commercial breakthrough of shale oil and gas exploration globally - Directional Drilling and Hydraulic Fracturing technologies (Tomomewo et al., 2019; Charles and Breant,1999). One revolutionary technology in directional drilling was in the early 1990s, great progress was made in combining vertical and horizontal drilling. This was the first time a well was first drilled with long vertical interval (typically ≈3000 m) and then turned 90° and keep constant for another long lateral section drilling in other to access horizontal shale layers where huge volume of hydrocarbon is usually trapped (Whitfield, 2017). This long section provides a means to access and produce the trapped hydrocarbon in the reservoir. Another important technology that is making shale gas economically viable is the breakthrough in the development of hydraulic fracturing tools (Richmanto et al., 2020). The hard mudstone, siltstone, dolomite or the prevailing rock of that reservoir must be fracked to create access to the trapped oil in the pores of the rock (Onwumelu et al., 2020). The first documented experiments with hydraulic fracturing occurred in 1947. Fracking helps in further expanding the existing natural cracks by pumping at a predetermined pressure, hydraulic frack fluid(polymers) mixed with proppants (usually sand with various grain sizes). As mentioned earlier, the duo of hydraulic fracturing and horizontal drilling technologies have made the U.S. Unconventional resources extraction, a once perceived impossible endeavors possible (Tomomewo et al, 2020).

The two principal issues with these technological booms are; 1) the fact that large amount of freshwater that later gets polluted and will never useful again to humans, animals or plants for any purpose except another specialized technology (very expensive and at some point, not yet feasible) are again deployed for its treatment, and 2) the need to protect the aquifers and fresh water resources from pollution emanating from frack fluids and/or traveling gas deposits

(Tomomewo et al., 2020 and Chen et al.,2019). Most frack fluids formulations are made up of a blend of chemicals, say around 0.5-2% (by volume) often patented, that improve and maintain the fluid's properties. Some frack fluids contain biocides and other additives that are highly hazardous chemicals that are dangerous and could cause health risks that varied from rashes to even cancer and the variation in the chemical composition also has a consequential effect on the toxicity of the produced water. (Chen et al.,2019). In the Bakken, there is a lot of attention and concern directed towards the possibility of subsurface leaks of fracturing fluids or produced water into groundwater aquifers (Maaz and Hascakir, 2015). In in some hydrocarbon bearing formations, ow-permeability hydrocarbon resources may be locked in shallow reservoir rocks located at depths of 1500–3000m below the surface (Hui and Sonnenberg,2013). At these depths, the formations may have drinking water aquifers directly above it, albeit that the aquifers are mostly between 30–100m below the surface at some places in the Bakken, with a considerable distance separating the aquafers from the reservoir rock. However, considering the risks involved in the handling of produced water and/or fracking fluid as regards leakages from the drilling (Thyne, 2016), handling of returned water–spills and accidents (Glenda et al., 2014 and Tomomewo et al.,2020), one can conveniently say that the potential to pollute the available fresh water sources during or after these activities mentioned does exist.

Bakken Produced water is known to contain very high total dissolve solids with NaCl as a major component of the dissolved solids. This highly saline water needs special handling. The water needs to be treated for organics and salinity reduction to about 65,000mg/l before it can safely be reused for frack fluids. However, this is not really feasible yet as there is no technology that is capable of reducing the salinity of Bakken produced water down to that level. The Institute for Energy Studies (IES) in the University of North Dakota (UND) has a proof of concept water desalination technology (Whitfield, 2017). This technology leverages the solvation principle to separate the water from the solute(impurities). The concept proved that if Bakken produced water is heated above the supercritical conditions (pressure and temperature) of water, the salinity content can be reduced by 80% and even more (Tomomewo et al., 2020). However, there are limitations to this technology requiring additional development. This research will be discussed in more detail in subsequent chapters.

1.2 Water Management Issues Associated with Fossil Fuel Extraction.

Generally, the development of unconventional, onshore natural gas resources in deep shales is rapidly expanding to meet global energy needs. However, the environmental risks that come with the extraction of these unconventional resources development, especially those connected to water handling and induced seismicity are the main concern of this research. These were also the center of discussions in the 2016 U.S. National Academy of Sciences workshop, and innovation. There, possible approaches that can help in managing these risks were discussed. The boom and ease of recovery of oil and natural gas from unconventional low-permeability shales and tight rocks like the Bakken recently increased greatly. This is mainly attributed to the advancement in the horizontal drilling and high-water volume hydraulic fracturing technologies (Tomomewo et al., 2019 and Jabbari et al., 2013). Also, because of this advancement and ease at which the unconventional resources are being mined, the United States became the largest oil (18% of global total) and dry natural gas (20% of global total) producer globally in 2019 (Al-Alwani et al., 2019). More than 60% of her domestic oil and 70% of her domestic natural gas supplies are met from productions coming from the unconventional hydrocarbon production *(Show figure)*. This sudden development in energy productions was immediately noticed as there is great decrease in the U.S. reliance on energy imports. This is also helping in improving the internal energy security(EIA,2020). However, those benefits come with environmental issues have the potential to hamper the steady and future growth in hydrocarbon supply and the perceived role of the United States in global energy stage.

It is projected that the United States and global fossil fuel demand and usage will remain steady or progressively increase until 2040 if there is no major policy change or environmental conditions (EIA,2020). Also, the U.S is expected to continue to take the lead in the supply of hydrocarbon in the world market up till 2050. It is expected that most of the demand will basically come from the developing economies like China and India. Since Bakken, North Dakota is projected as key and an important player in ensuring the steady delivery of the high volume hydrocarbon products, there two main issues that will always be there to contend with; (a) the high volume of water required due to the amount of water need for hydraulic fracturing, and (b) developing the best methods to manage the high-water volumes of wastewater that are co-produced with hydrocarbon and separated on surface. These mixtures include the produced water, flowback water from hydraulic fracking operation, and connate water from the reservoir rocks. The need to reuse water for hydraulic fracking is more concerning in the Permian Basin oil play, as fresh water sources are not readily available (Ramesh et al.,2015 and Aaditya et al., 2019). The Bakken, North Dakota has a lot of fresh water and lakes where water can be drawn for hydraulic frack exercise; however, there are still concerns that water scarcity is eminent at some point. In unconventional drilling, high water need and usage means high volume of wastewater will also be produced in large amount with the hydrocarbon during testing before commissioning and also during the actual production from the reservoirs (Platt et al., 2013 and Chuang et al., 2019). The highest volumes of produced water recycled for use is still coming from the Permian Basin because the Basin is currently drilling more unconventional wells than the Bakken, North Dakota and therefore has more water need than the Bakken (Tang et al.,2017; Tomomewo et al., 2019 and Sharma and Thomasset, 2019).

Due to the large volume and the high salinity nature of these water and how difficult it is to treat, the prevailing approach to waste or produced water management has been subsurface injection or disposal through disposal wells (Moati et al., 2013). Wastewater separated from unconventional production activities can be directly injected into the shale or tight rock reservoirs similar to where they were produced because of low permeability. Because of that, the wastewater or produced water are mostly being injected into nonreservoir geologic units. In the Bakken North Dakota, the wastewater is injected into the Dakota group (Mohamed et al.,2016). This is causing a lot of apprehension that water disposal into this formation through this means could alter the subsurface fluid stability and related pressures and may result in induced seismicity (Tomomewo et al.,2020 and Abhash et al., 2019). Most documented seismicity is connected to the fact that when wastewater disposal is conducted around the basement it can sometimes results in seriously stressed faults, such as the case of the State of Oklahoma (Trent and Rassenfoss, 2017; Hemami and Ghassemi,2018 and Julie et al., 2019).

Currently in the Bakken, deep-well injection is the primary means of managing wastewater. There are over 3000 injection wells that have been drilled over the years to take care of wastewater disposals (Trent and Rassenfoss, 2017 and Tomomewo et al., 2020). With global concerns over the quality and quantity of fresh water, the environmental impact, and how costly is the water management issues is to the different unconventional resource investors within the Bakken, there is a need for efficient water management strategies and treatment technologies that will enable environmentally sustainable and economically viable unconventional resource extraction for the continued development of this vast energy source (Tang et al.,2017)

1.3 An overview of Drilling and Hydraulic Fracturing methods

Before the breakthrough in the advancement of both the directional drilling and hydraulic fracturing technologies, oil production from unconventional resources was, for the most cases, not economically feasible (Tomomewo et al., 2019 and Tomomewo et al., 2021). Horizontal drilling is done in other to help increase access to the locked hydrocarbon in the thin but flat and widespread unconventional reservoirs in terms of length of contact between the trapped hydrocarbon and the wellbore. In comparison, a single horizontal well may take an equivalent to drilling 3-4 conventional wells (Tomomewo et al,.2019). Horizontal wells help in cost optimization by reducing the number of wells that would have been required to fully harness the unconventional resources to a few horizontal wells. Here, in addition to the cost that will be saved, the environmental risks that usually accompanies oil well projects are also minimized if not completely eradicated (Ogwumike et al,2015). Hydraulic fracking involves the application of frack fluid (usually aqueous) at a designed rate (based on the reservoir conditions) sufficient enough to increase the well downhole pressure above the fracture pressure of the reservoir/formation rock pressure (Zillur, 2020). The induced strain coming from the pump pressure breaks and create fissures and connect the already available natural fracks thereby creating more interconnected flow of the fluids trapped within the reservoir and towards the Wellbore (Tomomewo et al., 2020). A good frack job will increase the permeability of the formation and enable greater flow rates of hydrocarbon into the wellbore (Zillur, 2020). At the end of the hydraulic frack job, the pump pressure is removed and the remaining frack fluid returns to the surface with the hydrocarbon through the production tubing.

1.4 North Dakota Water Use and Handling Policies

In order to study the pressure that shale oil and gas extraction activities have placed on the available water resources in the Bakken, North Dakota side of the Williston Basin, it is important to first study and understand how the water resources are being managed in the State. It is stated, in the Constitution of the State of North Dakota that “All flowing streams and natural watercourses shall forever remain the property of the state for mining, irrigation and manufacturing purposes.” The rights to use water for any purpose in the State are managed through the Office of the State Engineer under the policy of prior adoption as governed under North Dakota Century Code (NDCC) §61-04 and North Dakota Administrative Code Article 89-03. Water permit priorities are based on first come first serve. Any entity applying for water permits must meet a list of the North Dakota water use requirements. This includes but is not limited to the conditions that the use must positively impact the people and the State at large, will not negatively affect other previous water rights, and the water use is in to enhance the standard of living of North Dakotans. All requirements and a list of items that could affect the people are codified under the NDCC §61-04-06. All water use permit submissions are checked and scrutinized by the State Hydrologic Engineer. In addition, the hydraulic engineer is also assigned the task of recommendations and decisions proposition to the State Engineer about each submission.

As the shale oil and gas developmental activity in the Bakken increases the stress on the available resources, water supplies will become of a major concern. To alleviate this anxiety, a more rigorous analytical method, such as groundwater models, are adopted, and it becomes more important to have a good monitoring systems. At some point in the water allocation process, philosophies of incremental development are adopted, whereby requests for water use are granted incompletely by holding the remaining requests in a state of temporary suspension while the hydrologic impacts are observed. At times, it takes many years before approving an additional request for water use. For efficient monitoring of the hydrologic impacts, instead of applying for new permits for water use on new wells to be drilled, additional wells may be added to an ongoing drilling and exploratory campaign of North Dakota State Water Commission. At this point, more data acquisition will be conducted, managed, and the hydrologic effect will be evaluated to enable good understanding in a way to efficiently advise the State Engineer to help him make efficient decisions.

All well documentation and offset data like well logs, water tables, water chemistry, permit status, and all additional data are managed in a central database created by the State. Almost all of the data are available for public use on the website of North Dakota State Water Commission(NDIC). As soon as the water allocations from aquifers in the State become fully taken, the State Engineer has the permission of the legislature to place the aquifers or sections of aquifers on abeyance, with no more allocations. Under the previous adoption system, if there is a threat of an adverse condition, water uses are put on hold in the opposite order of priority date, within the area that is affected. The water-permit application process may take several months or years in some cases to complete. This is because almost all of the oil and gas operators in the

Bakken, North Dakota side of the Williston Basin need large volumes of water for their hydraulic fracturing operations. These activities need the water to be trucked from various water depots in the Williston Basin to their oil pads. These water depots are either privately or institutionally owned organization that have already been granted water permits (permanent and/or temporary) by the North Dakota Office of the State Engineer to withdraw freshwater from North Dakota streams/lakes and aquifers and sell it to oil companies for hydraulic fracturing and other related activities. It is the duty of the State Engineer at the North Dakota Industrial Commission (NDIC) using real-time telemetry including monthly written reports. The water depots are also intermittently inspected by the supervisors and technicians from the state water use Authority. At times, the state may partner with local cooperating agencies, such as emergency managers and local law enforcement to monitor water use in the State.

On the water use, North Dakota State University(NDSU) scientists led a research on the impact water use by the oil and gas operators working in the Bakken oilfield in North Dakota. Their finding revealed how regional water use for hydrocarbon extraction could impact the available fresh water resources in the Bakken (NDSU Bakken Water Research, 2017) This same result could be applied to similar situations in other unconventional plays in the U.S. and around the world. The research also analyzed the water management strategies and policies in use at the Bakken North Dakota. This report can be used as a guide that policymakers can leverage to effectively come up with adaptive management approaches and policies to take care of the steadily increasing needs for water by the by the oil and gas operators for unconventional resource extraction activities. The research analyzed the completion reports of all horizontal wells drilled and completed between 2008 and 2014, the date from the approval granted by the state for water use between 2000 and 2014, and the level of the groundwater and streamflow in the arear between 2000 to 2014. The research revealed that the massive increase of the oil industry in the Bakken has tremendous increase the demand for water use. This was seen on the record of water usage for Bakken shale oil development from 2008 to 2014, as water usage increased by almost 20 times form 550 million to 10,200 million gallons per year. The total annual industrial (hydrocarbon extraction and other industrial use) water use between 2008 and 2014 varied between 0.5 and 10 percent of the total water consumption in the State of North Dakota. There was also a sharp increase in industrial water use in the Bakken oil production counties, like McKenzie, Mountrail, Williams and Dunn. Here, around 3 to 40 percent water use increase was noticed. It was also shown that the freshwater sources for Bakken oil field development were shared equally between groundwater and surface water and out of the nine rivers and 15 shallow aquifers that were studied, only Charbonneau, Tobacco Garden Creek and Killdeer, all in McKenzie and Dunn counties are most affected by Bakken shale oil extraction activities because the average groundwater levels fell. The remaining 12 shallow aquifers and all the nine average sized rivers were recorded to have increased groundwater levels or elevated average annual seven-day reduced streams. This was attributed to the fact that the counties had more a little above 20 percent more rainfall than usual between 2008-2014. Within that period, water use in the Bakken was managed adaptively through strictly enforcing the water management policies, where water use for irrigation (mainly groundwater) only allows permits holders to only transfer water for a short period of time from irrigation to industrial water uses like hydraulic frack for the oil extraction purposes. Because of these restrictive guidelines, limited amount of water was taken for hydraulic frack jobs in the Bakken from the deep regional aquifers like the Fox Hills that holds the Hell Creek aquifer. The policies of temporary permits are helping prevent the deep regional aquifers from being affected by the Bakken shale oil extraction activities.

On the Federal Scene, the United States Geological Services' (USGS) National Water-Use Information Program assembles data about the amount of water taken from all sources in the US any use like irrigation, mining, public supply, domestic use, industrial, power generation, livestock, and aquaculture. The future health and welfare of the State and Nation's population is heavily reliant on a sustainable supply of clean fresh water. Increasing withdrawals for oil extraction activities, including the pollution through spills and deep well injection will not only threaten to the available water resources but will also limit efforts to meet the ever increasing demands for fresh water now and in the future. There is need for a constant and detailed water-use data collection and analysis to enable better quantification of the stress on current supplies. This is important because it will be a better modelling exercise and evaluation of possible water-distribution management options to replace outdated water-supply methods. In 2010, water use in the US alone was estimated to be about 355 billion gallons per day (Bgal/d) (USGS Report, 2011). Freshwater withdrawals were 306 Bgal/d, or 86 % of total withdrawals, and saline-water (sea water) withdrawals were 48.3 Bgal/d, or 14 % of total withdrawals. Fresh surface-water withdrawals (230 Bgal/d) were almost 15 % less than all surface water withdrawers in 2005. Fresh groundwater withdrawals were 76.0 Bgal/d and about 4 % less than in 2005. Saline surface-water withdrawals were 45.0 Bgal/d, or 24 % less than in 2005. Updates to the 2005 saline groundwater withdrawals, mostly for thermoelectric power, reduced total saline groundwater withdrawals to 1.51 Bgal/d, down from the originally reported 3.02 Bgal/d. Total saline groundwater withdrawals in 2010 were 3.29 Bgal/d, mostly for mining use (USGS Report, 2011).

1.5 Brie History of oil exploration in the Bakken, North Dakota

The Bakken Formation was first discovered in 1951. It was named after Henry Bakken, a farmer and landowner in Tioga, North Dakota, where the play was initially discovered. Extracting oil from the Bakken has been very difficult, especially during the early 1950s. The current efficiency in the drilling and production of the Bakken has been achieved with long, lateral wells drilled through the middle of the Bakken – Three Forks, which are the main reservoirs – at depths ranging from 8,000 ft.–10,500 ft. (2,438 m to 3,200 m) true vertical depth (TVD) (Sbell et al., 2014). The desired reservoir depths and the extended horizontal wellbore lengths demand more powerful land rigs to withstand the operational loads of the well designs in the Bakken Play. The increased cost and tight economics associated with this formation present a strong need to constantly improve drilling performance by looking for every avenue to reduce the overall well development time, cost, and operations. In 2000, the Middle Bakken was discovered in the Elm Coulee Field in Eastern Montana. Previous drilling activities had shown that oil could accumulate inside the middle member, but this was not truly explored at that time because of the unavailability of the necessary technologies. Since the field discovery, more than 15,000 horizontal wells have been drilled, and between 2008 and 2013, 450 million barrels of oil were produced (NDIC, 2019; USGS, 2019). The Nesson anticline remains a very active developmental area of the Bakken Play today. Recently, the Bakken Play became one of the main contributors to U.S. oil production growth and, in 2019, pushed the U.S. up the scale as the highest hydrocarbon producer in the world. Active well development in the Bakken began around the second half of the 2000s. The progressive, high oil prices between 2008 and 2014 and the advancement of both directional drilling and hydraulic fracturing technologies are the main pointers to the success of unconventional drilling in the Bakken. The introduction of horizontal drilling and hydraulic fracturing technologies allowed operators to increase production in the Bakken, where limited conventional development had been pursued for a long time. The temporary drop in oil prices in 2009 did not have much impact on drilling activity, but the collapse of the oil price after 2014, along with sustained low prices, stopped well development decisions and production growth by mid-2015.

Figure 1 1 WTI Price Fluctuation 2012 to 2020

Records show that in 2018 alone a total of 2,666 horizontal wells with an average total depth (TD) of 10,000 ft. and total measured depth (MD) of 19,500 ft. were drilled in the North Dakota side of Bakken (EIA, 2016; North American Shale Magazine, 2020). The average daily production for 2019 was 103.5 bbl per well, while monthly production per well hovered around 3,142 bbl. At the time of writing this thesis, a total of 14,000 wells are producing an average of 1,357,186 bbl per day. It is projected that to maximize production from the Bakken between 60,000 and 80,000 producing wells must be drilled across all the producing counties (North American Shale Magazine, 2020). As of 2019, approximately 15,650 wells have been drilled. This means the Bakken still has room for more wells to be developed (EERC, 2012; EIA, 2016; Oasis Annual Report, 2019). However, every technological advancement comes with issues. For the Bakken, the breakthroughs in the directional drilling and hydraulic fracturing technologies made it easier to develop wells, thereby creating an environment that enables maximum recovery, but also creating room for lots of water production. Oil is a sought-after commodity, but the water poses a high threat, as it is highly saline and potentially contains naturally occurring radioactive material (NORM) elements that need special handling before disposal. The only available disposal medium for produced water in the Bakken is by injection into the Dakota group, which costs an average of about $9/bbl (EERC, 2012; EIA, 2016; Oasis Annual Report, 2019). This does not include the cost of hauling water from the production location to the injection site. The problem here is that the water is produced with the hydrocarbon. In the Bakken, this water is highly saline, very corrosive, high in bacteria, could contain trace elements of naturally occurring radioactive material (NORM), and, most importantly, is very harmful to the environment. The cost of handling this water (operating cost) is huge and has been shown to have a large negative impact on revenue streams and profitability. This thesis is a continuation of the work done on how factors like oil price fluctuations impair good well-development decisions that can eventually lead to poor well quality and high water production.

1.6 Legislation concerning produced water disposal in North Dakota

Most of the oil and gas-producing states have stringent laws that prohibit improper disposal of wastewater, including the produced water. In the U.S., the EPA regulates all household and industrial manufacturing of solid and hazardous wastes through the Resource Conservation and Recovery Act (RCRA). The RCRA's goals are to protect citizens from the hazards of harmful waste disposal, reduce or totally eliminate activities that could lead to the production of hazardous waste, and help in the clean-up operation of waste that may have been spilled, leaked, or improperly and unlawfully disposed of. In North Dakota, produced water disposal is strictly controlled by the Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA 1974 [EPA, 2015]). The responsibility of UIC is the regulation of all operations related to the injection wells that are used to inject fluids into the Dakota Group formation or other wastewater disposal wells. An injection well is used to push fluids deep underground into rock units with significant pore space, such as sandstone or limestone, and also has the trap and seal properties similar to an oil and gas reservoir. Injection wells are grouped into six classes by the EPA in North Dakota, saltwater disposal (SWD) wells, considered Class II UIC wells, were most common and used for all produced water disposal. The use of the injection well began in the U.S. in the 1930s and used to dispose of wastewater accumulated during oil and gas operations.

1.7 Produced Water Handling and Management

As mentioned in the above sections, water production involves understanding the best available options for managing all water needs in addition to the production of crude oil or gas, which is the goal of any production operation. This is one of the main concerns for both the operators and the oil and gas sector regulators because of the almost irreversible harmful effects these heavily contaminated waters could pose on the environment if not properly neutralized before any form of disposal. For effective water management, an understanding of the production status of the well in terms of water cut and all impurities that the produced water may contain is needed. Impurities in produced water may include dissolved minerals, dissolved gasses, and suspended solids. Suspended solids usually found in a mixture of produced water may be naturally occurring, generated as a result of precipitation of dissolved solids in the water mix, corrosion of production pipes, or the bacterial activities. Moreover, the water supply available in the Missouri River system and Lake Sakakawea is believed to be in excess, and the general public seems to think that the impact of drawings from these sources is negligible in terms of the total accessible water capacity, which is untrue. Currently, in the Bakken Formation, there are more than 3,000 disposal wells already drilled and in operation and within miles of the Bakken operators. It is very true that the treatment cost of the Bakken produced water will be cumbersome and energy consuming, considering the high salinity and heavy metals present (Stepan et al., 2010). Recently, research has shown that some technological developments related to salt-tolerant fracturing fluid, such as HVFRs systems, could allow for the use of lightly treated produced water. *This technology is opening up new opportunities for the treatment and recycling of Bakken produced water and thereby reducing wastewater injection. This is the basis of this research.*

Table 1. 1 Approximate water handling cost in the Bakken Formation (EERC Bakken Water Report, 2019).

Cost Items	Cost, $/bbl.
Freshwater	0.25–.05
Transportation (Freshwater)	0.63–5.00
Transportation (Wastewater)	0.63–9.00
Deep Injection Cost	0.50–1.77

1.8 Research Questions and Objectives

1.8.1 Research Question 1

To what extent can WTI price fluctuations and government policies influence stakeholders' decision?

Objectives

i. To investigate the role that WTI price fluctuation plays in influencing Stakeholders choices in directional drilling technology utilized.

ii. To evaluate how the current regulations is helping or preventing excess water disposal in the Bakken North Dakota.

1.8.2 Research Question 2

What are the connections among the technology choice, skill set, well quality and production (oil and produced water)?

Objectives

I. To identify how the choice of technology and the level of skill set deployed contributes to well quality and waste water production.
II. To explore the combination of scenarios (technologies + skillsets) in a bit to identify the best combination that can give the best optimization.

1.8.3 Research Question 3

Can effective water treatment and recycling reduce water disposal and operating cost in the Bakken North Dakota?

Objectives

i. To investigate the extent of salinity and impurities in the Bakken produced water
ii. To explore and develop new technologies that can help treat the highly saline Bakken produced water
iii. To explore methods to make the treated water recyclable and acceptable to the operators in the Bakken North Dakota.

Two justifications are offered to authenticate the proposed research questions and objectives itemized above. Firstly, Bakken well development models need to be evaluated in the context of energy systems structure with the aim to understand the system interconnectivities from conceptualization all the way to development. To achieve this, the function of innovation system FIS framework is used to investigate and map the system responses to understand the events that may have led to the current high wastewater production we are currently experiencing in the Bakken North Dakota as well as identifying factors acting as drivers or barriers to the much needed result from all stakeholders. In addition, the need to assess these expected ‘outcomes’ based on the specific context of the causes of high water production in a way to reproduce and reveal the interactive and complex procedures that initially influence the rational choices made by the stakeholders is considered.

Lastly, it is important to look at the institutional development of both the structure and the behavior that influenced the outcomes linked with existing drilling policies and technologies in the Bakken. In lieu of this, the FIS sufficiently complements the system thinking and system dynamics structure because the former explains the structure while systems thinking help understand the interrelationships of the systems. Based upon the background provided in this chapter, *the hypothesis of this thesis is that a mixture of the two frameworks can disclose the degree to which various exogenous and endogenous factors can contribute to the menace of high waste water production in the Bakken oil and gas energy asset development system which is governed' both by government regulations, WTI prices (exogenous influences), the operators and the other endogenous factors and how these factors have produced certain results that can then be altered to arrive at the anticipated outcomes.*

1.9 Research Design and Methodology

In order to reveal the complicated and context specific development of the topic of this research, system analysis and investigative case study is adopted as the desired methodology of this thesis. The research philosophy is that of constructivism and there is a mixed approach to generate both quantitative and qualitative primary data for the study. The study areas used as case studies are wells from McKenzie, Williams and Montreal Counties and all are from Bakken North Dakota. The data collection procedure relied mainly on archival and documentary analysis, questionnaire surveys and semi structured interviews. As represented in the research flowchart in figure 1.2 below, the thesis starts literature reviews of global water issues, the evolution of oil and gas asset development in the Bakken. Comparative events related to the production pattern between 2004 - 2019 are described in the chart below. Using these multiple events sourced from documentary and archival records an in-depth picture of how the Bakken oil and gas energy assets development infrastructure have evolved under various influence is presented.

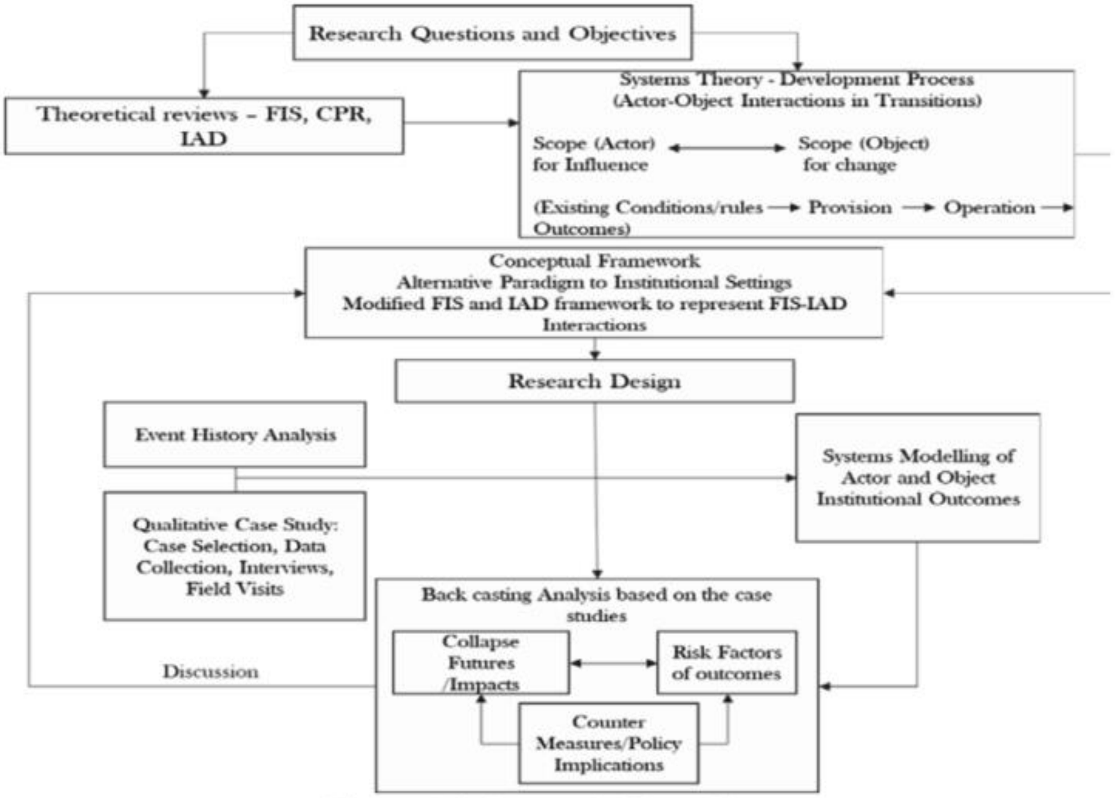

Figure 1.2: Research Flow Chart. Source: (Bello, 2017)

The research was carried out various phases; The first was to understand the production patterns (rate, volumes, amount of oil and water) over a period between 2004-2019 for all the wells that were drilled and in service up till August 2019. We then streamlined to the 3- wells used as the case study. The research then studied the drivers that may influence stakeholders (operators) decisions in the choice of technology and the level of skills they used in developing the wells. This was done by scrutinizing the production records provided by the North Dakota Industrial Commission (NDIC). The research then took a big dive explaining ways to educate engineers, the important technologies that are critical to efficient well placement and hydraulic frack designs as it affects unconventional resource like the Bakken. In an attempt to make Bakken produced water recyclable, the research introduces technologies(new) and suggested methods that could be used to treat Bakken produced water before going further to test the extent that the treated water can be stable if used as base fluids for hydraulic fracturing fluids iterations using high viscosity friction reducers (HVFRs) as the polymers of choice. This is a concern because of the need to understand how the polymers will perform with some level of salinity still remaining in the system (some new technologies believe that the water will be stable and reusable if organics and heavy metals can be removed and the salt elements in the water are made inactive even if the total dissolved solids content (TDS) are reduced to about 20%. This research tested this hypothesis and the result was promising. Results are explained further in subsequent chapters.

1.10 Research Aim and Structure.

The high wastewater production in the Bakken and the continuous disposal of these waters in the Dakota and other formation cannot be sustained and needs to be reduced and eventually stopped. The reality is that there will be consequences, including water scarcity, continuous environmental pollution, and possible future seismic activity if water disposal continues at this rate. This will be accompanied by an increase in operating cost for the operators. Conventional methods like reverse osmosis(RO), multi-stage flash(MSF) and electro- dialysis (ED) of waste water treatments have major setbacks and would not be efficient for the Bakken produced water because of the high salinity. The treatment of this kind of hyper-saline waste water stream has always proved not to be technically, economically and environmentally feasible with these technologies. This research and well as others are currently looking at technologies that support zero liquid discharge, considering the fact that environmental regulations regarding hyper-saline disposal into the formation would at one time be stricter than it is now or might propose a stop to hyper-saline waste water disposal into the formation. This research is aimed at investigating and assimilating information in way that some unanswered questions in the areas of how stakeholders' activities, like the choice of well development technology and response to high or low WTI prices affect well quality. The impact, positive or negative, of the kind of well quality on production (oil and water) were also studied to effectively understand the relationships among oil and water production. Lastly, the effects on operating cost was also checked.

This research is presented in seven chapters and two appendices Chapter **1** contain a detailed literature overview of problems affecting global water supply. The North Dakota water handling and management policies as it affects hydrocarbon extraction and the history of hydrocarbon extraction in the Bakken were explained. Lastly, chapter one briefly presented the available technologies for unconventional asset development. The aim of this research is to seek how to reduce waste water disposal by first investigating the factors supporting its production and then proposing recycling methods that will be acceptable to the operators in Bakken Formation.

To achieve this, real understanding of the technologies and how best to deploy them for unconventional formation like the Bakken is very mandatory to achieve this. **Appendix A** talks about the directional drilling technologies and how they can be effectively used for unconventional energy assets like the Bakken. **Appendix B** focuses on how to better understand the diagenesis, formation and storing mechanism of hydrocarbon bearing rocks. To achieve this understanding, a general review of reservoir Geology was conducted. Geology was looked at as the science of the solid earth including how its internal processes could be influenced by factors like the atmosphere, oceans, rivers and some biological activities. Technically, to effectively position a well for maximum recovery, effective well placement must be carefully done. This does not exclude wells drilled in unconventional shale plays. In this Appendix, special attention was also paid to all major points that are pertinent to application of effective well placement and how they could be used to improve hydrocarbon production and limit water production in unconventional hydrocarbon reservoir like the Bakken.

It is also important to understand the source and reservoir rocks characteristics of the Bakken Formation. **Chapter 2** explained the characterization of different lithofacies of the Middle Bakken, presenting additional data on the petrophysical properties of the Bakken Formation by conducting a real laboratory research using core samples from McKenzie, Mountrail, and Williams. All are hydrocarbon producing counties of North Dakota. To achieve the objective of characterizing the lithofacies of these formations, nuclear magnetic resonance (NMR) and scanning electron microscope (SEM) were employed as tools to analyze the core samples from these counties. This gave more accurate measurements of porosity and permeability and natural fracture connectivity of the Bakken rock.

Chapter 3 and 4 present the theoretical and conceptual framework upon which this thesis is founded. Using the Actor-Object theory as an approach to explain ‘what can change’, ‘who can make the change happen’, and the consequences (positive or negative) of these changes. This thesis explores the role of actors (operators, service companies, technologies, and workers) and the domain of governance which is the important context with an identification of the stimuluses that inform deviation in the natural balance of an energy system and the need to see and treat hydrocarbon extraction platforms as energy infrastructure and as a common pool resource (Goldthau, 2014; Gollwitzer, 2014). This chapter also outlines the methodology section that describes the approach the thesis takes in defining the problems, understanding the research questions and setting of policies that were used to calibrate and validate the hypothesis. This chapter emphasize the description of the two case studies (oil wells), the stakeholder interview and focus group processes, and application and the use of VENSIM DSS system dynamics software to draw causal loop diagrams (CLDs) that explain the multiple order of relationships and the processes within the energy systems. These interrelationships were then model still using the VENSIM DSS system dynamics software and the outcome were analyzed and discussed.

Most oil & gas energy resources mining policies and regulation have loop holes that enable the targeted entities to avoid directly following the regulations, or in some cases, prefer to default and face the consequences. Most times these consequences involve paying penalties with only few that will lead to mining license withdrawal. It is more sustainable to provide pathways to operate in a way that is less harmful to the environment rather than enforcing rules without giving operators alternatives. It is on this basis that **Chapter 5-7** were developed. Here, we looked at technologies and methods that could help treat the hyper-saline Bakken produced water in a way that it presentable and acceptable to the Bakken oil field operators. An understanding of the problems (why the Bakken Produced water is not being reused by the operators) is developed from the results of the system dynamics plot in **chapter 4.** Supercritical water desalination is introduced, as well as a concept that we called dilution methods to treat Bakken hyper-saline produced water. These treated waters were tested in the lab at various iteration of hydraulic frack fluid formulations. These fluids where then tested for stability under reservoir conditions (shear rate, viscosity and temperatures) to see how the viscoelasticity will be affected. Each chapter has the outcome of the research discussed extensive before making possible recommendations. the research also presented the limitations encountered in carrying out the study as well as in the general applicability of the proposed theoretical framework.

1.11 Contributions to research field

Based on the findings and discussions presented herein, this research will contribute more to the theoretical and empirical literature around the development of energy systems.

The first contribution of this thesis is in studying the stakeholder's behaviors at various levels of participation with respect to understanding how their decisions and governance mechanisms affect the quality of well development in the Bakken. This study critically points out the effect of technology choices and governance methods adopted by the operators of the oilfield in the Bakken in response to disturbances (fluctuation in the WTI Prices, Government Policy and Regulations) within the energy sectors on the quality of the well and the impacts on the production. The thesis looked at the effects with respect to hydrocarbon and water production and believed that the quality and impact of the decision is clearly reflected in the volume of water and hydrocarbon produced.

This thesis’s second contribution is in the analysis of how high water production can increase the operating cost in the area of water handling and management. These cost are huge as they can erode the operators profit margins and can result in negative profitability. The thesis took a critical look into all the costs of producing a well and did some sensitivity analysis with various production scenarios using water cut (oil to water production) for a period with the average WTI price to determine the level of profitability. It was noted that wells with more than 50% water cut are actually not making profit, rather, they are taking from the profits coming from the other wells from the same pad. This finding will be very useful to the Bakken oil field operators and reveal to them what they need to check and look out for in a situation where various wells are comingled to produce through the same platform

The third contribution will be in proposing technologies and methods for the treatment and recycling of the hyper-saline Bakken produced water in way that it is acceptable for the regulators and the operators of Bakken oil field. This will help the water use regulators and policy makers in the Bakken in the kind of policy they make that will help reduce water disposal through deep well injection that has been seen as a great threat to the environment and the ground water aquifers. The sensitivity analysis shows various scenarios and benefits in the area safety to the environment and humans living around the Williston basin. The thesis revealed that that although a lot has been achieved in the area of technology advancement in both directional drilling and hydraulic fracturing technologies, a lot is the needed in understanding how to design and place production fracks for optimum production, where production here refers to hydrocarbon. We know that there is no way hydrocarbon can be produced without water, but the thesis revealed how to limit water production to the connate water within the targeted reservoir not water intrusions from neighboring non hydrocarbon producing reservoirs or even aquifers.

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CHAPTER TWO

2 The Bakken Formation Characterization using NMR and SEM Techniques

This chapter is taken from the paper entitled ***"Characterization of the Bakken Formation using NMR and SEM Techniques"*** *published in the* ***"53rd US Rock Mechanics/Geomechanics Symposium"****. Co-authors on this work include:* ***H Jabbari, N Badrouchi, C Onwumelu, M Mann"*** *They contributed to this work by providing help in performing some of the experiments and reviews. I have contributed more than 85% of the effort to this work. My efforts include developing the original idea, preparing and analyzing samples, identified major issues, developed interpretations, fully drafted papers, discussions and conclusions,*

Abstract

As fewer new oilfields are being discovered, with most of the conventional reservoirs having reached their peak production, maximizing the recovery from existing unconventional reservoirs has become crucial. With the development of horizontal drilling and hydraulic fracturing in recent years, unconventional formations, such as the Bakken Formation, have come into the foreground of the oil and gas industry at state, national, and global levels. However, due to its heterogeneity and very low permeability and porosity, the Bakken recovery factors remain minimal (5–10 %). One of the potential methods for solving this specific problem and improving oil recovery lies within the injection of solvent fluids to interact with the reservoir rock and fluids to enhance fluid flow toward the wellbore. Previous studies have generated a great deal of information regarding the characterization of different lithofacies of the Middle Bakken, and in this study, we present additional data on the petrophysical properties of the Bakken Formation in the McKenzie, Mountrail, and Williams counties, North Dakota. The main objective is to

characterize the lithofacies of the Bakken Formation using nuclear magnetic resonance (NMR), and scanning electron microscope (SEM), for more accurate measurements of porosity and permeability.

2.1 Introduction

Oil production from unconventional reservoirs, such as the Bakken, has become very important and their optimal development has been studied in detail worldwide, especially in North America. This is because, over the past few years, unconventional reservoirs have substantially added to the national reserves of the US hydrocarbon resources (Jabbari and Zeng, 2012). With the development of horizontal drilling and hydraulic fracturing in recent years, unconventional formations, such as the Bakken Formation, have come into the foreground of the oil and gas industry at state, national, and global level. However, due to its heterogeneity and very low permeability and porosity, the Bakken recovery factors remain small (5–10 %). One of the potential methods for solving this specific problem and improving oil recovery in North Dakota lies within injection of a solvent fluid (CO_2, methane, ethane, reservoir gas, low-salinity water, or a mixture) to interact with the reservoir rock and fluids and enhance fluid flow toward wells (Jabbari and Zeng, 2012; Energy and Environmental Research Center, ND). For optimal enhanced oil recovery (EOR) development, accurate characterization of the reservoir rock and fluids is essential. The Bakken Formation is in the Williston Basin, which is an organic-rich shale, mainly composed of mudstone and sandstone deposited during the Late Devonian and Early Mississippian periods. It stretches about 200,000 square miles across parts of North Dakota, Montana, South Dakota, and the provinces of Manitoba and Saskatchewan in Canada (Jabbari and Zeng, 2012).

The Bakken petroleum accumulations are known to have poorly defined margins with wide, relatively thin and tightly packed lithofacies. Successful completion of Middle Bakken wells for sustainable economic gain greatly depends on the pores' connectivity and the quality of the matrix with respect to permeability and brittleness (i.e., frackability). Permeability estimation in such a tight oil reservoir as the Bakken is an important element of the geological models that can help us to predict the long-term production profile of the reservoir and determine the optimal methods for stimulation and enhanced oil recovery.

There are several challenges to economic production from Bakken wells, such as a tight matrix with thin reservoir pay zone and an ineffective network of natural fractures with limited connectivity. A combination of horizontal drilling and hydraulic fracturing is a promising technique for drilling and completion of Bakken wells (Jabbari and Zeng, 2012; Pei et al., 2014; Griffin et al., 2018). In this work, a few characterization techniques (NMR T_2 relaxation and SEM with a thorough facies analysis) were employed to yield the pore-size distribution and permeability in Bakken core samples from three wells with file numbers (#16,433, #18,413, and #17,351).

2.2 Geological Setting of Bakken Formation

Bakken is in the central region of North America and an unconventional, liquid-rich shale oil with an estimated 30 billion to 40 billion barrels of recoverable oil (Grand Forks Herald Newsthesis, ND; United States Geological Survey-USGS) deposited during the Late Devonian to Early Mississippian periods in the Williston Basin (Jabbari and Zeng, 2012; LeFever and Helms, 2008). From a stratigraphy point of view, the Bakken Formation underlies the Lodgepole Formation and overlies the Three Forks (see Fig. 3.1) and is defined as two laterally persistent, thin, organic-rich, black shales (upper and lower member), separated by a thin gray sequence of siliciclastics and carbonates (middle member), and a basal member, the Pronghorn. The reservoirs are in the middle member lower Lodgepole and the upper Three Forks (Energy and Environmental Research Center, ND). The thickness of the Middle Bakken ranges from 30 to 70 feet and can be characterized by a few distinctive lithofacies (between five to seven). The facies present unique properties that affect the porosity, permeability, fluid flow and ultimate recovery (LeFever and Helms, 2008; Sorensen et al., 2018). The fine-grained carbonates and clastic nature of the Middle Bakken are major indications of a tight fractured reservoir rock that can allow economical fluid flow and production only if the duo of horizontal drilling and hydraulic fracturing are implemented.

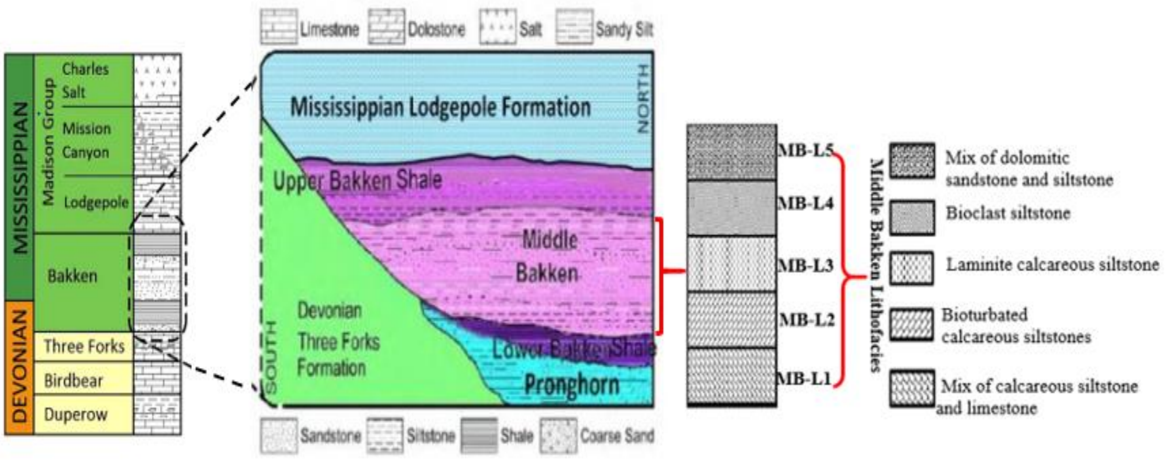


Figure 2.1 Stratigraphic column and schematic profile of the Middle Bakken lithofacies (modified from Sorensen et al. 2018).

The middle member of the Bakken Formation is the primary oil producing layer but has low porosity (typically < 10%), very low permeability (typically < 1 mD), very fine-grained minerals (4–60 µm), which vary in thickness, lithology, and petrophysical properties. The variation of lithology includes heterogeneous layers of sandstone, siltstone, dolomite, and mudstone and clay-sized particles less than 5 μm (LeFever and Helms, 2008). The Middle Bakken exhibits highly heterogeneous layers of lithofacies that are challenging to produce economically due to the complexities related to chemical reactions (i.e., scaling) and low production rates. In practice, an unconventional reservoir, such as the Bakken, stores an abundant amount of hydrocarbon. However, the fluid transmissibility and diffusion (e.g., in CO_2-EOR) are limited due to ultra-low porosity and permeability.

2.3 Characterization of the Middle Bakken

2.3.1 The Study Area and Reservoir Properties

Core plugs were collected from three wells located in the oil fields of Blue Buttes, East Forks, and Alger, and at depths of 10,639 ft, 10,675 ft, and 10,104 ft, respectively. These oil wells are within McKenzie, Williams, and Mountrail counties in the Williston Basin (see Fig. 2.2). Fig. 2.1 illustrates the lithology and their corresponding deposition pattern and highlights the major lithofacies present in the Middle Bakken while Fig. 2.2 shows the study area where the three cores used for this study were collected. The Bakken is known to have very complex lithofacies with heterogeneous properties as depicted in Fig. 2.1 (Sorensen et al. 2018).

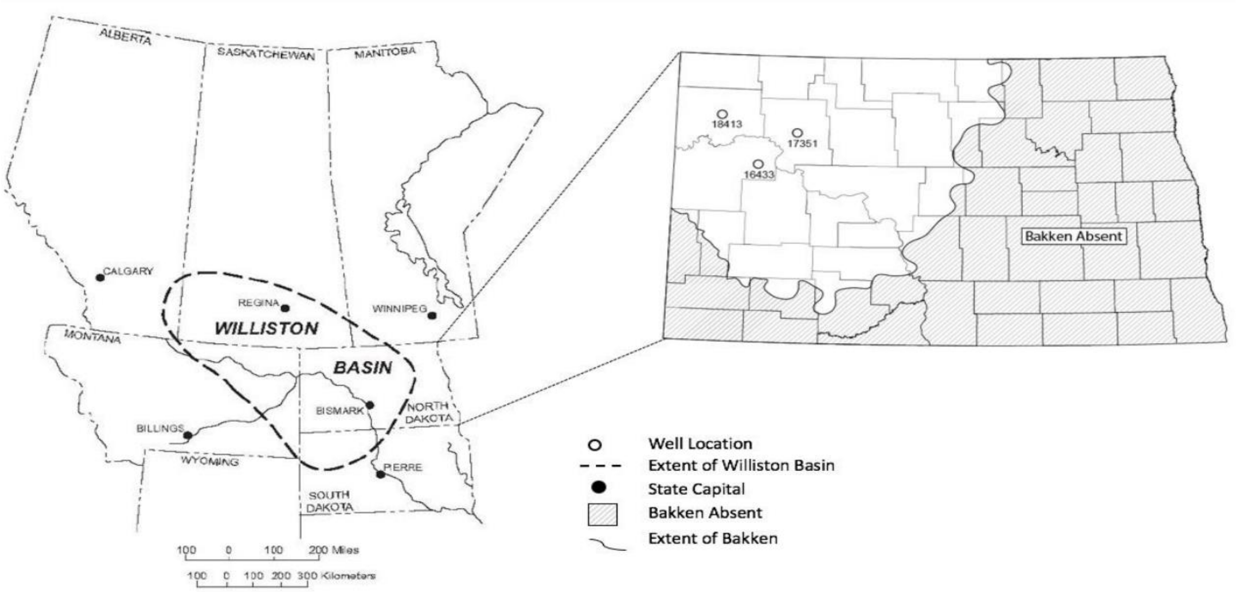


Figure 2.2: The map of the study area

Similar to previous studies on the lithofacies of the Middle Bakken, in this work, the major lithofacies are categorized into five major groups, from bottom to top: MB-lithofacies 1 (crinoid-brachiopod, calcareous siltstone), MB-lithofacies 2 (bioturbated calcareous siltstones), MB-lithofacies 3 (laminite calcareous siltstone), MB-lithofacies 4 (bioclast siltstone), and MB-lithofacies 5 (dolomitic sandstone). Fig. 2.1 illustrates a degree of variation in lithofacies in the Middle Bakken with respect to matrix features, particularly the depositional features and the mineralogy distribution (LeFever and Helms, 2008; Sorensen et al. 2018). Detailed evaluation of rock characterization was conducted using the SEM digital image analysis of the core samples. Although porosity is very low (< 10 %) in the Middle Bakken, it is somewhat uniform across the member, while permeability is not only very low (ranging between 0.0001 to 0.57 mD) but also varies across the different lithofacies of the Middle Bakken (Pei et al., 2014; LeFever and Helms, 2008). The porosity of rocks can be influenced by cementation, burial depth, and oil emplacement.

However, low values of porosity and permeability in the MB could be attributed to the presence of poor pore-size distribution and unconnected pores within the matrix of the reservoir rock.

2.3.2 Measurement Techniques and Analyses

In this section, a detailed analysis of the reservoir rock properties is presented by using the nuclear magnetic resonance (NMR-T_2) measurements to determine porosity and pore-size distribution. We also used the concept of T_2-relaxation time and the Coates model for permeability measurement in Eq. (1) to estimate the permeability, κ (Coates et al., 1998).

$$k = \left(\phi / C \right)^{a} \left(\frac{FFI}{BVI} \right)^{b} \qquad (1)$$

SEM was utilized to observe the rock composition, pore-size distribution, throat sizes, and the connectivity of natural fractures.

2.3.3 Nuclear Magnetic Response Measurement (NMR T2 Relaxation)

Reservoir rocks normally have variable ranges of pore size, which can be characterized through NMR measurements on core samples. Using a relaxation experiment to monitor a single-phase fluid gives us the pore-size distribution and thus the degree of sorting on the rock sample. The relationship between T_2 transverse relaxation time, the bulk relaxation time (T_{2bulk}), T_2 surface, and T_2 diffusion is given in Eq. (2) (Coates et al., 1999).

$$\frac{1}{T_2} = \frac{1}{T_{2bulk}} + \frac{1}{T_{2surface}} + \frac{1}{T_{2diffusion}} \qquad (2)$$

Surface relaxation occurs at the fluid-solid interface (at the grain surface of rocks). It has been shown through theoretical analysis by several researchers that in a fast diffusion limit, the dominant term in T_2 surface relaxation is given by Eq.3 Coates et al. (1999)

$$\frac{1}{T_{2surface}} = \rho_2 \left(\frac{S}{V} \right)_{pore} \qquad (3)$$

Molecular diffusion in wetting fluids is often restricted at the boundary between rock grains and fluids and/or by the interfacial tension between fluids. Because of this restriction, the diffusion coefficient for a fluid in a rock differs from the diffusion coefficient of the bulk fluid at the same pressure and temperature. Diffusion effects become unimportant at short inter-echo spacings for most fluids, which is applicable in our experiment. Combining Eq. (2) and Eq. (3) while neglecting diffusion gives equation Eq. (4), which is a fundamental NMR equation governing T_2 transverse relaxation measurement and the connection between transverse relaxation and the pore size (Coates et al., 1999 and Kenyon, 2000).

$$\frac{1}{T_2} = \frac{1}{T_{2bulk}} + \rho_2 \left(\frac{S}{V} \right)_{pore} \qquad (4)$$

For equations Eq. (2), Eq. (3), and Eq. (4), T_2 = transverse relaxation time of the pore fluid, T_{2bulk} = T_2 transverse bulk relaxation time of the pore fluid as it would be measured in the entire core sample, T_2surface = T_2 surface relaxation time as it will be measured at the surface, T_2 diffusion= T_2 transverse relaxation of the pore fluid as induced by diffusion in the magnetic field gradient, ρ2 = T_2 surface relaxivity (T_2 relaxing strength of the grain surfaces), and $\left(\frac{S}{V} \right)_{pore}$ = ratio of pore surface to fluid volume.

NMR T_2 relaxation measurement quantifies transverse magnetization decay signal, $M_i(t)$, at discrete time slots and for constant time spacing. Next, the sum of the decaying signals, $M_i(t)$, is computed and analyzed as given by the exponential decay formulation (Marc et al. (2007):

$$M_{i(t)} = \sum_{i=1}^{N} A_i e^{\left(-\frac{t}{T_i}\right)} \qquad (5)$$

Where, N is the number of T_2 relaxation values, $A_{(i)}$ is the amplitude of each relaxation (depending on the number of protons in the pores of the sampled size), and T_i is the decay time constant given in Eq. (2).The relation between T_2 relaxation and pore-size distribution can be examined through a plot of A_i versus T_2, which must be rescaled to fit into Eq. (5) (Coates et al., 1999 and Kenyon, 2000).

If we assume that the fluid is probing the pore sizes in the sample, then there is a simple relation between T_2 relaxation and the pore size through (Sørland et al., 2019). This shows that the surface-to-volume ratio is coupled to the surface relaxivity, ρ. In this experiment, we considered a short echo spacing and conducted measurements at room temperatures (20–25 ^oC). The surface, S, to volume, V, ratio is a representation of pore size and can be directly related to T_2 through the relaxivity parameter. In characterizing the pore-size distribution of a rock sample using NMR, we are seeking the surface-to-volume ratio calculated from the T_2 distribution. This relation is obtained by estimating the distribution using the corrected magnetization, given by Eq. (6) (Marc et al. (2007):

$$\frac{M_{(t)}}{e^{\left(\frac{t}{T_{2i}}\right)}} = \sum_{i=1}^{N} A_i e^{\left(-\frac{t}{T_{2i}}\right)} \qquad (6)$$

All the distributions examined in this work are corrected for the bulk relaxation time and are plotted up to 10,000 ms.

2.4 SEM for Rock Sample Characterization

The porosity of a rock sample can be measured through the SEM and digital image processing (Marc et al., 2007). The analysis of SEM images was primarily introduced through different mathematical morphology in order to provide a digital image of pore geometry and distribution of clay and other authigenic minerals associated with the pore system of a rock. SEM characterization includes a -step procedure: a) sample preparation, b) specimen scanning process, c) image enhancement, d) pixel classification, e) pixel clustering, and f) image capturing (Mike and Yunhong, 2017; Dougal et al., 2007).

Figure 2.3: Scanning electron microscope at UND material characterization laboratory

The key to performing an accurate SEM porosity measurement and matrix-pores characterization is defining effective threshold images to accurately distinguish between voids and grains. In addition, a focused ion beam (FIB) setup can be used for site-specific analysis, deposition, and ablation of materials (Orloff, 1996). FIB is a scientific instrument that resembles a SEM and provides complementary information on the rock composition of the sample surface and detects the void-solid contrasts according to Eq. 7 (Mike and Yunhong, 2017).

$$C = \frac{\eta_1 - \eta_2}{\eta_1} \tag{7}$$

where, C is the relative contrast between signals while η_1 and η_2 are the backscattering coefficients for high and low signal density materials.

2.5 Core Samples Preparation

As mentioned above, core samples were collected from three wells (Blue Buttes, East Forks, and Alger) at the Middle Bakken depth equivalent for within the different counties in western North Dakota. Regarding the NMR measurements, these steps were followed: a) the samples were placed in a vacuum of negative 30 psi to evacuate the air inside the samples, b) the bulk volumes of the core plugs were measured using a 3D laser scanner, c) the samples were polished using a LaboPol–21 polisher with different abrasive thesis (from 240 µm-grit CarbiMet through 1 µm grit CarbiMet, see Fig. 4.4), d) the samples were saturated with brine solutions under 100 psi pressure for 30 days, and e) T_2 relaxation times were measured using the NMR instrument at the UND-PE lab to determine the pore-size distributions, porosity, and permeability of the rock samples.

Figure 2.4: Core samples used for NMR and SEM experiment

2.6 Results and Discussions

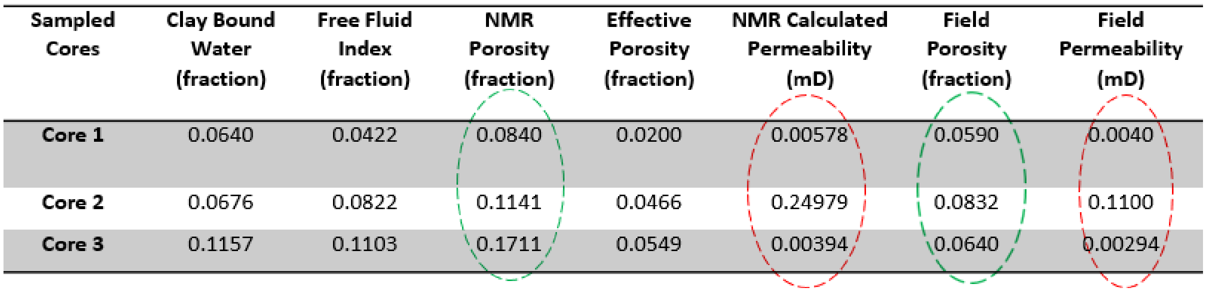
Knowledge of total porosity, oil in place, producible oil, and permeability of a reservoir is crucial for the overall investment and developmental planning of an unconventional field like the Bakken Formation. The methods used in this work provides the tools to estimate these parameters for the core samples from the formation. We applied the T_2 cutoffs to divide pore-size distribution into microporosity ($T_2 \leq 1$ ms, which represents clay bound water), mesoporosity (T_2 between 1 ms and 10 ms, which describes the capillary bound water), and macroporosity ($T_2 > 10$ ms, which indicates the producible fluids) as proposed by Green and Veselinovic, (2010).The average pore-size distribution in the three Middle Bakken cores examined showed 19% microporosity (clay bound fluids), 46% mesoporosity (capillary bound fluids) and 35% macroporosity (producible fluids). The NMR data shows a relatively average producible fluid porosity < 8% and calculated permeability < 1 mD as (see table I).

The microporosity (clay bound water) explains that 19% of the fluids (water and/or hydrocarbons) may never be producible, no matter the recovery method applied, due to the extra tight pore sizes and zero pores connectivity within the matrix of the rocks (Coates et al., 1999).The mesoporosity (capillary bound fluids) distribution suggests that 46% of the fluids in the reservoir rock matrix will be producible if tertiary methods of recovery are efficiently applied. The mesoporosity is higher than that of the clay bound fluid pores, which means that the trapped oil within that certain pore-size range can be produced if proper EOR techniques, such as CO_2-EOR, are applied.

Finally, the 35% macropores (producible fluids) can be produced with efficient completion designs, that is, with the optimal design of primary and secondary recovery techniques. However, 35% producible fluids does not mean 35% producible hydrocarbon, this includes the connate water, gas and may in most cases be more than 50% of the total producible fluids depending on the efficiency of the well placement done during completions and at what point in the well or the reservoir lifecycle that it starts experiencing a high water cut.

The SEM images complement the NMR results by showing the distribution of averagely large pores and grain sizes which are unconnected (see Fig. 2.7, 2.9, and 2.11) This is evidence of the tightly packed unconventional reservoir rock. In this experiment, we noted no direct relationship between the NMR calculated porosities and permeabilities of the core samples. We compared NMR and SEM data to verify the connection between porosity and permeability across the Middle Bakken samples studied, (see Table 2.1).

Table 2.1: NMR porosity and permeability results



Sampled Cores	Clay Bound Water (fraction)	Free Fluid Index (fraction)	NMR Porosity (fraction)	Effective Porosity (fraction)	NMR Calculated Permeability (mD)	Field Porosity (fraction)	Field Permeability (mD)
Core 1	0.0640	0.0422	0.0840	0.0200	0.00578	0.0590	0.0040
Core 2	0.0676	0.0822	0.1141	0.0466	0.24979	0.0832	0.1100
Core 3	0.1157	0.1103	0.1711	0.0549	0.00394	0.0640	0.00294

We discovered that the core with the highest NMR porosity is not the one with the best permeability, perhaps because the pores network structure within the Middle Bakken are poorly connected, even though they seem to have big pore sizes but, the grains are too tightly packed to allow the stored fluids to permeate through the rock matrix. This proves to us that high porosity does not always translate high permeability. The results from these characterization studies also showed that a relatively large portion of Bakken porosity lies within a very tight range, which means that Bakken's ultimate recovery may be increased through EOR techniques.

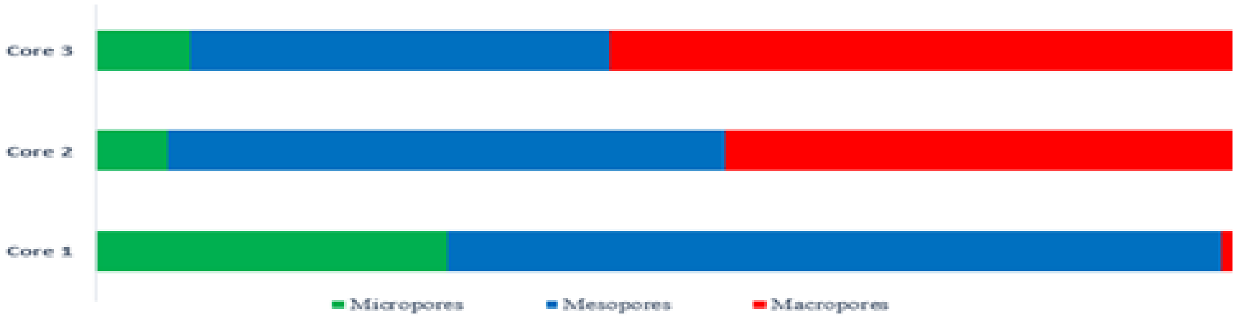


Figure 2.5: Pore-size distribution of each of the sampled cores. Evidence of more mesopores and macropores than Micropores

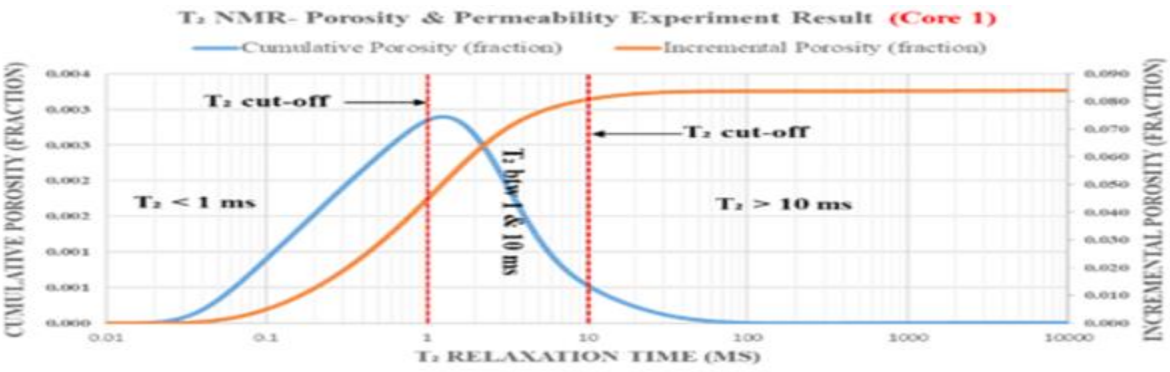
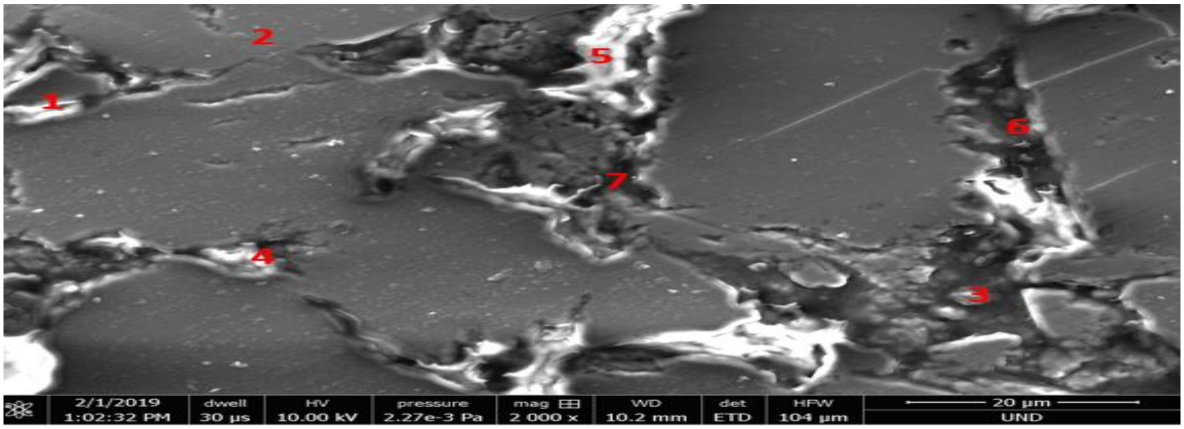


Figure 2.6: T_2 NMR-porosity experiment result (core 1)



Legend: 1- Quartz, 2-Dolomite, 3-Feldspar, 4-Calcite, 5-Pyrite, 6-Micro fracture, 7-pore size

Figure 2.7: SEM image showing pores and grain sizes. Evidence of larger grains and unconnected pores (core 1).

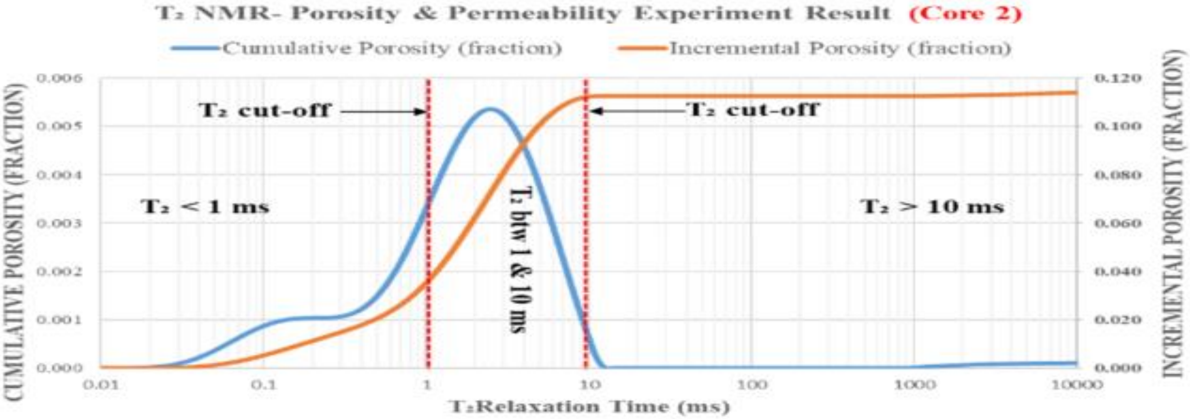
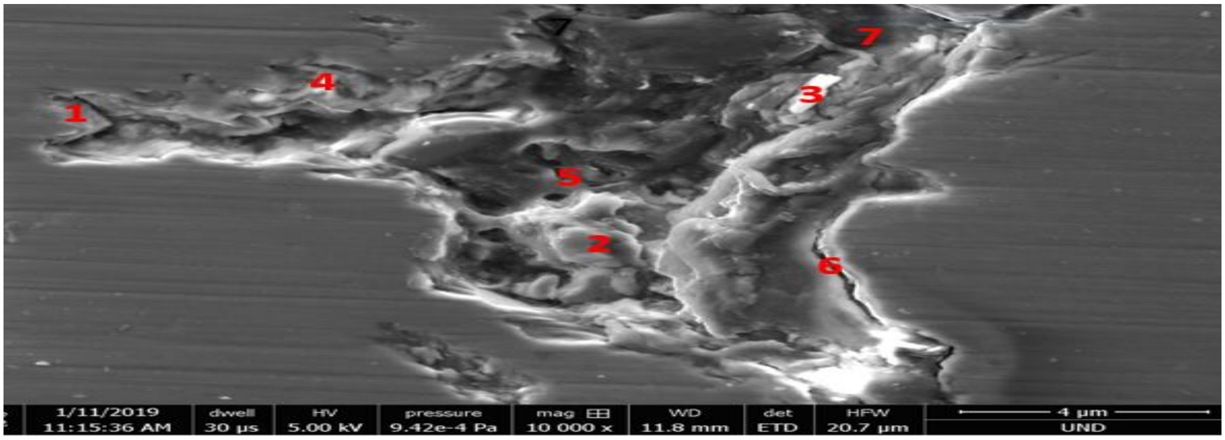


Figure. 2.8. T_2 NMR- porosity and permeability experiment result (core 2)



Legend: 1- Quartz, 2-Dolomite, 3-Feldspar, 4-Calcite, 5-Pyrite, 6-Micro fracture, 7-pore size.

Figure 2.9: SEM image showing average, large, and connected pore sizes and some mineral composition (core 2).

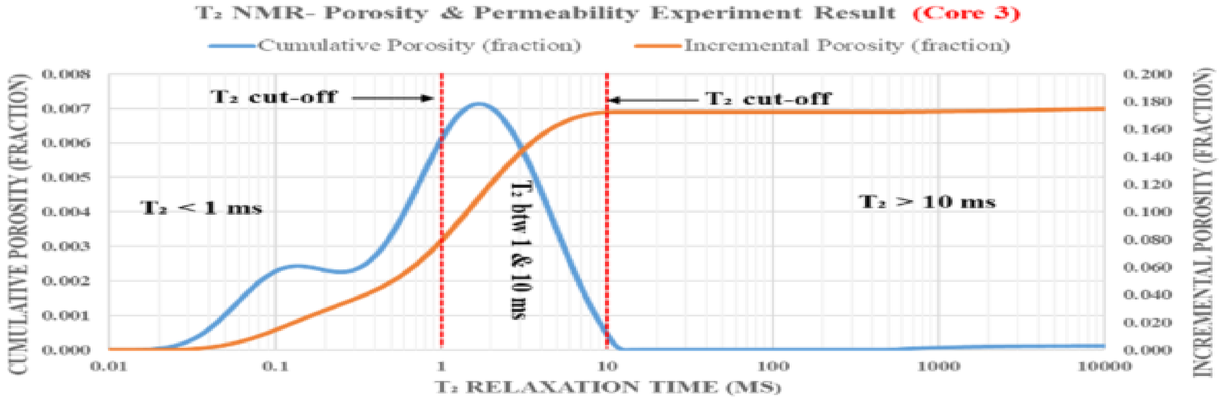
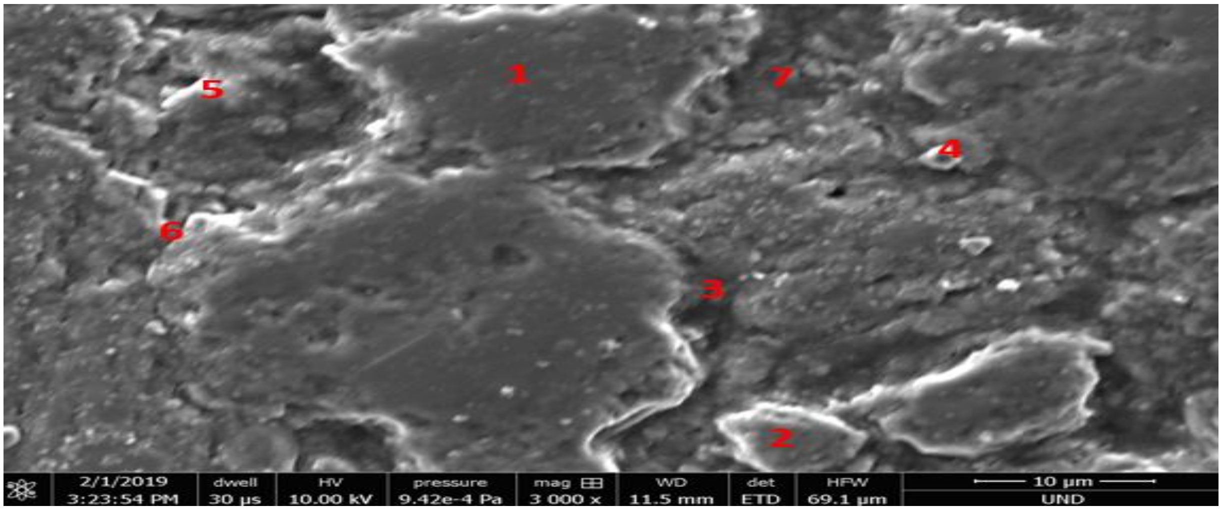


Figure 2.10: T_2 NMR-porosity experiment result (core 3).



Legend: 1- Quartz, 2-Dolomite, 3-Feldspar, 4-Calcite, 5-Pyrite, 6-Micro fracture, 7-Pore size.

Figure 2.11: SEM image showing pore void, grains, and mineral composition (core 3).

2.7 Conclusion

Irrespective of how tightly packed the grains of the Middle Bakken rocks are, we were able to use both NMR data and SEM digital imaging to capture pore-size, distributions. We then categorized these into micro, meso, and macroporosity before estimating permeability from the pore's distribution using the Coates model in Eq.(1). We observed there are significant variations in porosity and permeability within the Middle Bakken members studied due to variation in the lithofacies and the depositional patterns across the members. Finally, knowledge of a reservoir's petrophysical properties is needed for effective well life cycle planning and effective recovery. Our study was able to show that effective application of T_2 relaxation measurement and pore-size distribution portioning can help determine producible fluids, which is key to estimating oil in place and making important investment decisions.

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CHAPTER THREE

3 Methodology- Applying System Dynamics Approach

3.1 Case Study Strategy

The case study approach was used in this research to help understand the important dynamics of Bakken oil and gas industry in the area of factors influencing certain decisions that stakeholders take during the entire life cycle (drilling, completions, commissioning and abandonment) of a well or and an entire pad. We want to know how the emergence and operations of markets, attitudes, policies, and behaviors of stakeholders co-evolve with regards to contributing to the high water production we are currently noticing in the Bakken North Dakota oil field today. The use of the case study approach lies in the believe that, the use of systems dynamics can answer the question of ‘how to change’ which is keen at solving the problem of the confusion that could come as a result of oil price fluctuations and its destabilization of the system, understanding how this affects the thinking of the important stakeholders in their choices of technology and skills that are usually deployed to do the work. The effect of those the choices are then investigated in the area of how they affect the quality of the wells developed. The case study approach is suitable in this scenario because it provides a more detailed study of the most important factors contributing to the current behavior of the oil wells in term of oil and water productions and how stakeholder’s behaviors, the North Dakota oil industry policies, regulations and the global oil industry are contributing to the real problems (Denscombe, 2010). The main exposure to disapproval that the case study approach usually has is mostly its reliability in assuming the results from the case studied are applicable to the specific area of study. Even though these doubts are true, this has been taken care of in this thesis because of the following reasons. Firstly, the fact that this study is not intended to make a generalizable theory, instead it connects itself with the few available theories and data obtained after studying the Bakken oil and gas energy systems and before disclosing the study specific findings (KoUn, 2012). This should enrich the understanding of the systems and the behavior of the important stakeholders and well development decisions that are required for a successful implementation of policies that will lead to good quality wells with less water production. It also introduces a better package of produced water recycling ideas that could lead to sustainability and better safety (people and environment) and that will meet projected economic and long term goals of the individual oil and gas investors in Bakken North Dakota. Secondly, exploring and scrutinizing multiple sources of data and conducting multiple stakeholder interviews strengthens the study's worth for other settings (Marshall & Rossman, 2016: 253). It's also generalizable in explaining the dynamics in the Bakken oil and gas sector in the area of water production issues over time and the possible causes.

This thesis adopts multiple methods on two case studies within Bakken North Dakota. As a methodological approach, this thesis adopts systems dynamics modelling, based on its ability to build on theoretical foundations in improving the understanding of a problem (Gallati, 2011). The reasons for adopting the systems thinking and dynamics approach and its explanations on how it fits with the methodologies within the case studies are further described in subsequent sections.

3.2 System Dynamics

System dynamics is a modelling method used to study any intricate system by studying the interaction of the various parts and elements of such system (Sokolowski & Banks, 2010). System thinking and system dynamics have been used and are still very relevant methodology applied in the field of policy mostly because of its practicality in defining and breaking a complex problem to units that can now be understood. Saeed (1994), acknowledged and added to the knowledge base that the systems thinking and system dynamics approaches are sciences that brings to fore, the cognizance of the variety of knowledge driven by the framework within which it is formed. Therefore, explanatory case studies on the causes of an abnormal trends, procedures or interactions within any system will gain from systems dynamics. This is even more useful in setting strategy to best respond to ‘how and ‘why’ questions whenever they are raised. It can also be used in a scenario where the investigation has little control over events (Yin, 2014). Case studies can also be said to have good effect in theory testing, and also provides a clear advantage in understanding or apprehending the complex situation under study, which in the reality (Denscombe, 2010 and Jackson & Sorensen, 2007). This perfectly agrees with the strength of the systems dynamics methodology, as one of the best tools for investigation and understanding the interactions within a complex system that are co-existing and causing the problem. System thinking promotes the understanding that the world is a complex setting, in which ‘everything is connected with everything else’ in such a way that ‘you cannot just do one thing’ (Bello, 2016). Sterman, (1994), is of the opinion that if people can have a holistic view of the world, they might act to conform with the long lasting behavior that best positively the stability and sustainability of the system as a whole.

In the real sense, our choices and decisions usually alter the real world (the natural balance of a system); we then receive response in form of feedbacks due to our disturbances or activities on the system (the real world), and using the new information from the feedback, we would revise our understanding of the system and the decisions we make to bring back the system closer to our goal or the original state before our disturbances as shown in Figure 3.1 (Sherman 2000). System dynamics modelling approach offers a tool that can capture and address the short-term and long-term impacts of decision makers on a system (Bello,2016). In general, the advantage of using system dynamics models is their ability to integrate mathematically and systematically, the knowledge gotten from some variables and processes during the analysis stage, and then allow their interactions produce something of interest. With clear assumptions and clarity of fundamental factors of a system, one of the main usefulness of system dynamic models is to play with new ideas and analyze their implications of their outputs. Often times, research that would literarily be considered impossible, unreasonable or unethical with a real system can be tried with system thinking and system dynamics.

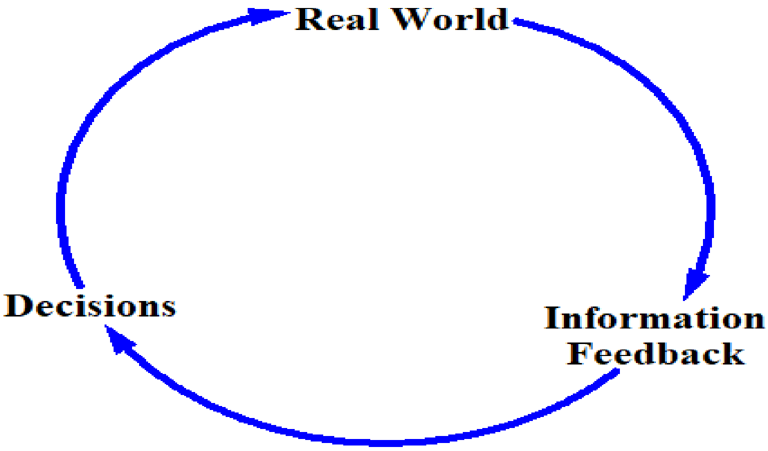

Figure 3.1: Feedback process in decision-making

Source: (Sterman, 2002).

The important component of systems dynamics modelling includes diagrams to collate and communicate the feedback structure of a problem. These causal loop diagrams (CLDs) are important when conducting the qualitative investigation to understand the causal structure of the issue under study, and to create an understanding of the operating of the current system. Systems dynamics modeling also provides a means of quantitative analysis, through the simulation of the identified important variables to study its dynamic pattern and consequences using feedback loop analysis that are developed from the causal loop diagrams

From the explanation from the above, it is clear that the systems dynamics modeling method uses various tools and mixed methods approach in conducting any study. It is very useful when the investigation is wide and there is a need to answer the questions of the ‘how’, ‘why’, ‘who’ and ‘what’. This tool increases the possibilities for triangulation as one of the only ways to validate research outcomes. This study employed a qualitative using system thinking to first understand the interrelationship of the Bakken oil and gas sector with the global, national and local energy systems using systems dynamics focusing and relying on the generation of feedback loops as the main system analysis methodology. Causal loop diagrams were generated using participatory methods through interviewing important stakeholders, well programs, the North Dakota Industrial Commission(NDIC) website, literatures and one-on-one interviews with ‘problem owners’. These interviews were used to evaluate the sustainability and better ways to reduce water handling issue we are currently experiencing in most oil and gas producing counties in the Bakken North Dakota.

This richness in data gives system dynamics its relevance in the way it documents the needs of stakeholder engagement and their participation. This is even more important when dealing with groups of stakeholders that do not have much technical know-how in finding solution or in a situation the research has limited time and resources (Inam, et al., 2015). The causal loop diagram is based on the feedbacks, which is a circle of relationships, a closed loop of events and interactions. We use the causal loop methodology to study the patterns of behavior of any two variables in a closed loop and how they are related. Here, focus is on how each is influencing, and also responding to the behavior of the other variables (Richardson, 2011). The concept of feedback loops involves the gathering of data about the condition of the system, followed by some influencing action.

The procedure followed for this research is characterized by an iterative process. The problem definition was the first step, followed by system conceptualization based on the defined problem, formulation of the applicable model, model evaluation/testing, policy analysis, and implementation (Hovmand, 2012). As depicted below, the study began with the review of related literature in the study area, carried out in accordance with the objectives of this project. Data were collected from various journals, reports, and theses and carefully analyzed. This data was used to conceptualize the model, after which it was built in Vensim DSS, analyzed, and tested. Lastly, for efficient model performance, all system components and their mutual relationships were determined from the very beginning. Theory- based modeling was integrated by allowing oilfield operators, regulators and some energy and petroleum engineers within Williston Basin to participation through interviews. This helped to genuinely assess institutional outcomes within a case study. Table 4.2 provides an overview of this procedure. Building on the contextual information about Nigeria provided in Chapter 2, the details of the research strategies as employed is provided in Section 5.4 below.

The data collection process for this thesis was in six parts. Most was through the North Dakota Industrial Commission Website (NDIC), and North Dakota Geological Survey Wilson M. Laird Core and Sample Library. This was augmented with data from literatures, textbooks, field experience, interviews and various focus group (among the Bakken oilfields executives and engineers) meetings that have be going on since late 2018 and about 15 years' oilfield experience. When the problem/research involves investigating system malfunctioning that is causing a domino effect on other sub systems, and as a result affect the system as a whole, there are four main options for data collection and these are: questionnaires, interviews, observations and documents Denscombe, (2010). For this research, no questionnaire was used, so only three of the four methods were used mainly. This is due to the novelty of the research approach and the lack of significant literature that is focused on the main research questions of this study with any detail.

In this chapter a hypothetical model will be created that will provide the background to understand the source or sources of the system malfunctioning which will lead to a holistic analysis of potential solutions. This is accomplished by being able to identify all the important and key variables needed to develop a sustainable systems dynamics model. Model development was followed by more stakeholder analysis and interviews within the case studies (McKenzie, Williams and Montreal Counties), to provide empirical evidence about the problems and the action area outcomes as related to high water production in the Bakken North Dakota oil production systems. The objectives of the literature reviews, textbooks, field experience, interviews and various focus group meetings are to help on deciding what an acceptable future normative scenario will be and create links between the envisioned future and the present, with the hope of defining short term actions that will make the normative future vision a reality.

3.3 Structure Definition

The step is defining the structure that will explain interdependencies and that can dictate the drivers and blockades that are also known as "motors" of changes, in the system. This research believes that if we can identify all or most of the motors of innovation and we are able to also represent the historical analysis through systems dynamics, the interaction between system functions will be revealed and understood. This research accomplished this by carefully documenting most of the sequences of events that we were able to get to give vicious or virtuous cycles as defined by the intended outcomes; interpreted as variables that are influencing effort along design, investment, finance, development and operation of oil and gas fields in the Bakken North Dakota.

In this research, starting from the system thinking all the way to the system dynamics, instead of a simple, clear and progressive pathway, we notice several paths and some offshoots, and more. This provides more than a single after-the-fact assessment of feedback, we see a lot of in-process assessments (Van de Ven, 1990). This has to do with the identified important variables either as part of the fundamental causes of cumulative change (drivers and barriers), or as probable targets for change (impact). In guaranteeing validation, the author ensured that the development of the arrangements was carried out considering the most possible impartial state. However, it is invariable that the author’s prior knowledge of the success or failure of the processes can lead to a bias in the findings. To minimized this, the narrative was checked with the feedback from the what is actually going on in the field concerning what the industry believes to be causing high water production on surface and how the policies support or prevent wastewater disposal and also noting any deviation from reality. Where there is any discrepancy, reconstruction was made to adjust in a way to reflect the actual stakeholder feedback as it affects the principle of qualitative research (Marshall & Rossman, 2016).

In other to determine a reasonable outcome when applying the technology innovation system (TIS), it is important to set identifiable and boundaries of analysis. According to Suurs et al., (2010), the TIS will focus on structures and/or processes guided by the research question and delineated on factors that contributes to high water production as it regards stakeholders' behavior or response to high or low WTI prices or suitable or unfavorable government policies. The structural factors are the standing aspects of the Technological Innovation System(TIS), they are elements which although are in the formative stages, are relatively stable, and dictate the pace of change if any. The structures are distinguished into three basic elements which are; actors (stakeholders), operators and technologies, the operators and technologies usually represent the object with regards to the conceptual framework generated (Wangel, 2011; Yücel, 2010).

This thesis sees this study in terms of actors of two groups of technology analyzers, users and selectors (Suurs et al., 2010) based on those whose success rely on the developed technology and those who have the option to choose which technology to use and the what determine or influence their choices. Also, keeping in mind the goal of this research which is to look at the causes and how the menace of high water production that is causing high wastewater disposal into the formation, this thesis is looking first to get the combination of the optimized technologies and skillsets that provide professional inputs that will lead to good well quality at moderate cost during the entire well development period. Secondly, how to transform the wastewater into reusable input instead of disposing by injection into the formation.

The only means of wastewater disposal in the Bakken North Dakota is through injection into the Dakota Formation (Tomomewo et al., 2020). In addition to any negative effects of the produced water on the environment, it also very costly for the operators to manage the whole process the wastewater has to go through before the final disposal. So the understanding how technology works and the behavior of stakeholders and what determines their choices is very important. This thesis focuses within Bakken North Dakota, analyzing the causes of high water production and looking at the all possible technologies, behaviors and skills that could help reduce this problem. It also includes identifying technologies that could help treat the unavoidable water that will still be produced. This is important to understand how to effectively reuse rather than disposing. Special focus will also be directed to the activities evolving from operators, regulators, service companies and the oilfield personnel(employees) using the FIS. The FIS analysisis will help identify and simplify the connections created by the interaction of the various group mentioned above. These interactions and connection will be modeled using systems dynamics.

The drivers and barriers to selecting the right technologies and skill sets that could help prevent or reduce the inherent contextual problems and deliver the intended targets are explored. The focus on the system thinking in answering this question is based on the flow and creation of knowledge instead of just processes. This is to allow for a dynamic view of the aspects and sectors involved in this problem. This is because, the barriers and drivers identified will not only be dependent on the WTI prices fluctuation but also seek to find rationales driving policies, the actions as a result of the policies (Ahlborg & Hammar, 2011; Leandro, 2011).

3.4 System Documentary Analysis

The event history method is applied as a way of checking production history and pattern of the Bakken producing wells in a bit to measure system operations from historical and current references. This is to effectively give both a contextual and practical edge to methodically analyze the qualitative Bakken production historical data gotten from the NDIC Website (Jacobsson &

Bergek, 2011; Suurs et al., 2010). The review of qualitative historical data does not include only production data from the Bakken, it also involves activities such as studies conducted form conferences organized, policy measures analysis, expert interviews, field visits, field experience amongst others are extensively used to communicate the relationship between the process and the structure of the system. The dependence relationship between the process and the structure are also emphasized in the empirical analysis carried within the time horizons and this will help understand the conditions that shape motors of innovation. The methodological steps followed are as enumerated below but more explained in each of the chapters. Constructing the data base for the event history analysis from the well file and other data was a very strenuous exercise where the functions of the innovation systems framework were leverage upon as mental escort. All oil and water productions from the Bakken between 2004-2019. This was done by reading thorough each well file, the production excel file, the few available literature and the field expert interview transcripts and, then separating the timeline for the event reported. For the systems mapping as required for the generation of the causal loop diagrams, the description provided by the system functions are then used to fit with the content and type of events from the generated database of responses.

3.5 Problem Definition

The problem definition process involves all the activities carried out in sequence in other to identifying of a problem, while bearing in mind the potentially diverse perspectives of different problem owners on a problematic situation. As adopted in this thesis, it involves conceptualizing the problem bearing in mind factors contributing to high water production considering the contributions from various stakeholders. This is important in other to first understand the root cause and what is influencing the behavior that is leading to the output we are observing (Bureš, 2017).

3.6 System Conceptualizations

In this context, system conceptualization means the process of developing a causal representation of the issue under study. Its aim is to capture its feedback structure of the problem, causal loop diagrams are explained based on the knowledge and/or theoretical evidence (Riva et al., 2018). For causal loop diagrams, link and loop polarity are determined. The developed diagrams show a visual picture of the ‘dynamic hypothesis’ fundamental to understanding of the problem under study (Gallati, 2011). The feedback structure of the CLD can then be analyzed qualitatively, and problematic and unclear pattern can be discovered and debated (Friel et al., 2017). For this thesis, this is conducted these out in two steps using Vensim DSS Software.

3.7 Model Formulation/Simplification

Combining the causal loop diagrams for several aspects of the system being modeled most times is very daunting and confusing. It can be too large to present and hard to read. Sometimes because of how large and complex causal loop diagrams can be, it makes it hard to see the loops, understand which are important, or determine how they generate certain behaviors (Sterman,2002). Therefore, it is important that causal relationships based on the merged model is further simplified to avoid the over-complication, and the limited clarity that a full representation of all the variables identified in merged model will bring. Simplifications of models is widely used in the field of systems dynamics for better understanding and in communicating the results, and ensuring that the final model is actually a simplified version of real world scenario (Bureš, 2017). In this thesis, loop relationships generated automatically by the Vensim Software based on the assigned defined causal relationship variables serves to encapsulate exogenous variables as a practice of CLD simplification (Inam et al., 2015). The method use was heavily dependent on encapsulation, to make sure that the stakeholder's analysis and feedback is represented as necessary. Encapsulation is also more a more suitable to a normative method in the examination of cause and effect related problem when it comes to energy models (Neshat, et al., 2014), which is the case in this thesis. Encapsulation is preferred to help in sequence of simplification other to minimize the suppression of the influence factors and in-between variables, which might be important in terms of the total problem definition in this thesis (Bureš, 2017; Neshat, et al., 2014).

3.8 Analysis of Model behavior

The reinforcing and balancing loops within the merged CLD is vital to describing the qualitative behavior of the system in terms of determining the critical issues, increasing the understanding of the perception of stakeholders and, finding the conflicts and alignments within the sub systems amongst others (Inam et al., 2015; Sarriot et al., 2015). The resulting final merged CLD model includes the diverging perspectives of stakeholders therefore, model details will be improved by identifying all the sub models that are linked to form the overall CLD. This thesis will be identifying the sub models through the loop nomenclature. This is a usual practice in CLD modeling. Gallati, (2011) employed the theories of collective action to elect the thematic sub models in the modeling for collective irrigation, Inam et al., (2015) split the merged group CLD model into different thematic models on the basis of environmental, social and physical aspects through a case study completed by the authors in Pakistan's Rechna Doab region.

Analyzing the behavior of the model in this thesis will be based on the principles of a feedback loop analysis and this will give insight into describing the qualitative behavior of the

Bakken oil and gas system through its different reinforcing and balancing loops. Feedback loop analysis of causality according to Dinno, (2015) generates meaningful inquiry, based on the characterization of the causal feedback among interrelated variables. It is best applied when trying to answer questions about ‘what can we see about the behavior of objects in a system as defined by the causal feedback?’. This characteristic of the loop analysis is also an area that this research is much interested in because it can be used to answer questions on ‘what’ and ‘who’, that are important in defining how specific causal linkages can dictate the behavior of the overall system. The loop analysis is also important for demonstrating the implications of a change in the causal relationships or ‘even the insertion of new objects into the causal system’.

3.9 Model Validation

Model validation involves the direct comparison with available empirical and/or theoretical knowledge, the latter assess the validity of the structure indirectly, by applying certain behavior policies on the model generated behavior patterns. The loop analysis carried out in the analysis of the model behavior has been derived mainly from empirical evidence from the application some scenario base policies framework on the case studies, using theoretical propositions from the function of the currently available technological innovation systems and the type and level of skill set available to apply these technologies. As a result, model validation can be done more efficiently by ensuring that there is a testable hypothesis and that can really be validated by direct empirical observation (Dinno, 2010). In this research, the approach taken for the validation of the model in this case comes mainly from the testable policy implications. Policy analysis is focused on changes of decision points in the model and their effects on certain outcome variables. Based on the analysis of model behavior results and the interpretations for system unsustainability, this thesis will be conducting some sensitivity by applying the policies based on the 4- scenarios to validate the model.

In summary, the system dynamics modelling as employed in this thesis is an analytical exercise to develop the causal loop diagrams (CLDs), that determine the alignments the various CLD.

3.10 Conclusion – Conducting the Studies

The approach in this thesis is it evaluate the possible factors and variables contributing or supporting the issues that contribute to high saline water production from some oil and gas producing counties in the Bakken North Dakota. The thesis approached the understanding of processes within the use of sustainable energy sources for oil and gas development and production systems. This thesis did that by considering various entry points and then used the different data collection methods that mixes theory-based models with local contribution. The development of a conceptual framework based on theoretical grounds, created a lens through which the study and the data collection techniques have been designed and analyzed. Actual well data was collected and compared with the data generated from the model as a validation of the structuration within the developed conceptual model that was supported by the theoretical analysis and the collection of actual field data. From the theoretical considerations, the model boundaries were created in a way that make it consistence for a system dynamics causal loop model, while the case studies at McKenzie and Williams Counties, provided empirical evidence and local knowledge, about the problems and factors that relate to causes of high water production from the McKenzie and Williams Counties oil fields in Bakken, North Dakota.

As Sokolowsski and Banks (2010), explained, the causal relationships demonstrated by applying the system dynamics approach, is firstly trying to depict a holistic macro-level illustration of events as and also opening up opportunity to explore the micro-level perspectives. This method is very relevant for modeling complex system interaction by identifying action/activities common point and their impact on the system. This is the major focus of this and what its hoping to investigate the system.

3.11 Summary and Limitations of Approach

The methodology used in this research has combined various experimental and qualitative means to represent the institutional dynamics within decentralized oil and gas energy processes over a period of 25 years (An average lifespan of a well in the Bakken, North Dakota). Field visits to the Williston Basin that lasted a week were made to the drilling and production platforms of the top ten operators in the Bakken. This visit afforded the opportunity to interview various key stakeholders including some regulators in an effort to understand how their activities and decisions could influence and impact well development and maintenance efforts. This visits and interviews were important because it helped understand the actual dynamics of the system. The major limitation was getting more key holders together for further discussions that may have helped understand more of the problems. This was not possible due to the COVID-19 Pandemic that affected the World in 2020. It would have also have been useful to gather all the actors at the different scales from the energy ministry, the academia as well as the disposal wells operators**,** in the same room for some further analysis, however this was not possible, because of this thesis depended on data gathered from the North Dakota Industry Commission (NDIC) and the author’s understandings, to form a consensus of the opinion in defining the problems.

The other limitation has to do with the deciding on the best way to conceptualize the qualitative outcomes into systems and representing the results of these activities in a dynamic way. By mapping the actions within the two conceived systems of technological innovation and stakeholders' behaviors, this thesis was able to draw from the two perspectives and deduced the best way it can positively impact sustainability of the energy system. The conclusion this thesis drew, is to serve as a means of understanding the mechanism of change that the Bakken oil and gas energy system is transitioning towards and how the menace of high water production and disposal can be prevented or reduced. These limitations could benefit from further quantitative studies, for a clear linkage between institutional change and the success of hyper saline water recycling technology.

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CHAPTER FOUR

4 The Effects of Well Quality on Desired Production Rates, Oil Production, and Desired Profitability

Abstract

It is true that the recent increase in the development of unconventional oil and gas assets worldwide is a result of the breakthroughs and advancements in both horizontal drilling and hydraulic fracturing technologies. In 2019, the United States became the largest global crude oil producer, and the unconventional Bakken Play in North Dakota is one of the major contributors to this feat. However, analysis shows a trend of early increases in water cut in younger wells, with water cut as high as 75%. The problem is that the wastewater produced from these increased oilfield activities is highly saline (~175,000 – 350,000 ppm Total Dissolve Solid (TDS). 90% of all wastewater is lightly treated to remove organics and then disposed of by injection through disposal wells in the Dakota Group Formation. This directly impacts operating costs and is always expensive. There is a strong belief that these instances of high-water production are directly linked to poor well quality. Using Vensim DSS, this thesis modeled and simulated the effects of well quality on desired production rates, oil production, and desired profitability. We also modeled the effects of well quality on water cut rate; water production; wastewater hauling, treatment and disposal cost; and their effects on the overall profitability of the well. We used McKenzie County, on the Bakken side of North Dakota, as a case study, and our results show that well quality plays a major role in both oil and water production. The conclusion was that operating costs are reduced

in wells with less than 50% water cut, while wells with higher water cuts have higher operating costs.

4.1 Introduction

In this section of this thesis, we first give the background of the Bakken oil drilling and production activity from the time when current technologies were unavailable. We then assess the impact of these technological advancements on the production pattern of oil and water within the Bakken (Kolawole et al., 2020). The Hypothesis here is **"Straightness (well quality) has influence (negative or positive) on production and overall profitability"**. Using a System Dynamics Model (SDM), we study the effects of important variables, like oil price, on the pressure to innovate (decisions on the quality of the technology applied for well development) and how it impacts well quality, and how well quality affects productions (oil and water). Lastly, the contribution of production to profit or loss is also analyzed. The results of the simulation are reported and discussed.

The Bakken Formation extends from western North Dakota and northeastern Montana into two Canadian provinces, Saskatchewan and Manitoba. At about 14,700 square miles, the Bakken seems to be the largest continuous crude oil accumulation in the United States (USGS, 2020). In the same study by the USGS, it was reported that the Bakken and Three Forks formations jointly hold nearly 24 billion barrels of potentially recoverable crude oil (20 billion barrels of oil and 4 billion barrels of natural gas equivalent). The Bakken is still seen as a young play, as real, active well development began in 2010.

4.2 Brief History of the Bakken Formation

The Bakken Formation was first discovered in 1951. It was named after Henry Bakken, who was a farmer and landowner in Tioga, North Dakota, where the play was initially discovered. Extracting oil from the Bakken has been very difficult, especially during the early 1950s. The current efficiency in the drilling and production of the Bakken has been achieved with long, lateral wells drilled through the middle of the Bakken – Three Forks, which are the main reservoirs – at depths ranging from 8,000 ft.–10,500 ft. (2,438 m to 3,200 m) true vertical depth (TVD) (Sbell et al., 2014). The desired reservoir depths and the extended horizontal wellbore lengths demand more powerful land rigs to withstand the operational loads of the well designs in the Bakken Play. The increased cost and tight economics associated with this formation present a strong need to constantly improve drilling performance by looking for every avenue to reduce the overall well development time, cost, and operations.

In 2000, the Middle Bakken was discovered in the Elm Coulee Field in eastern Montana. Previous drilling activities had shown that oil could accumulate inside the middle member, but this was not truly explored at that time because of the unavailability of the necessary technologies. Since the field discovery, more than 15,000 horizontal wells have been drilled, and between 2008 and 2013, 450 million barrels of oil were produced (NDIC, 2019; USGS, 2019). The Nesson anticline remains a very active developmental area of the Bakken Play today.

Recently, the Bakken Play became one of the main contributors to U.S. oil production growth and, in 2019, pushed the U.S. up the scale as the highest hydrocarbon producer in the world. Active well development in the Bakken began around the second half of the 2000s. The progressive, high oil prices between 2008 and 2014 and the advancement of both directional drilling and hydraulic fracturing technologies are the main pointers to the success of unconventional drilling in the Bakken. The introduction of horizontal drilling and hydraulic fracturing technologies allowed operators to increase production in the Bakken, where limited conventional development had been pursued for a long time. The temporary drop in oil prices in 2009 did not have much impact on drilling activity, but the collapse of the oil price after 2014, along with sustained low prices, stopped well development decisions and production growth by mid-2015.

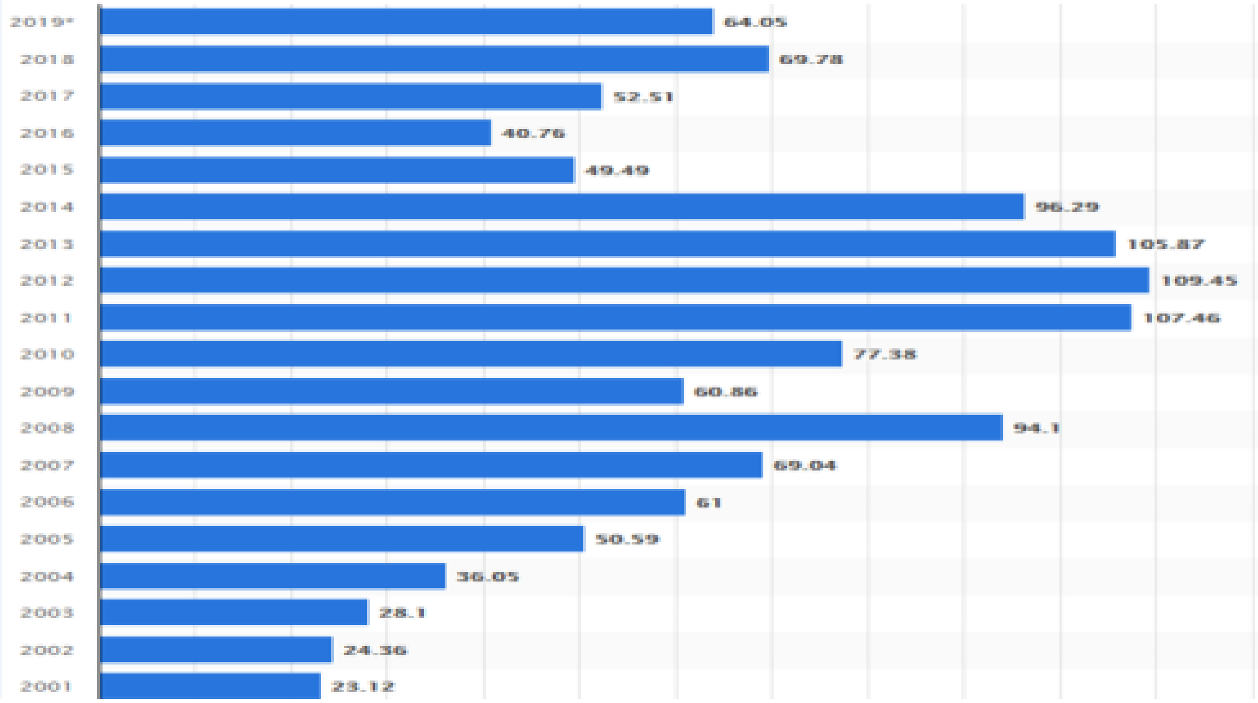

Figure 4.1: Average oil price in USD, 2000–2019 (Source: EIA, 2019)

Records show that, in 2018 alone, a total of 2,666 horizontal wells with an average total depth (TD) of 10,000 ft. and total measured depth (MD) of 19,500 ft. were drilled in the North Dakota side of Bakken (EIA, 2016; North American Shale Magazine, 2020). The average daily production for 2019 was 103.5 bbl per well, while monthly production per well hovered around 3,142 bbl. At the time of writing this thesis, a total of 14,000 wells are producing an average of 1,357,186 bbl per day. It is projected that, to maximize production from the Bakken, between 60,000 and 80,000 producing wells must be drilled across all the producing counties (North American Shale Magazine, 2020). As of 2019, approximately 15,650 wells have been drilled. This means the Bakken still has room for more wells to be developed (EERC, 2012; EIA, 2016; Oasis Annual Report, 2019). However, every technological advancement comes with issues. For the Bakken, the breakthroughs in the directional drilling and hydraulic fracturing technologies made it easier to develop wells, thereby creating an environment that enables maximum recovery, but also creating room for lots of water production. Oil is a sought-after commodity, but the water poses a high threat, as it is highly saline and may sometimes contain naturally occurring radioactive material (NORM) elements that need special handling before disposal. The only available disposal medium for produced water in the Bakken is by injection into the Dakota group, which costs an average of about $9/bbl (EERC, 2012; EIA, 2016; Oasis Annual Report, 2019). This does not include the cost of hauling water from the production location to the injection site. The problem here is that the water is produced with hydrocarbon. In the Bakken, this water is highly saline, very corrosive, high in bacteria, could contain trace elements of naturally occurring radioactive material (NORM), and, most importantly, is very harmful to the environment. The cost of handling this water (operating cost) is huge and has been shown to have a large negative impact on revenue streams and profitability. This thesis is a continuation of the work done on how factors like oil price fluctuations impair good well-development decisions that eventually lead to poor well quality. But here, we are analyzing the effect of this well quality on fluid production from the well, the percentages of oil and water, and how each contributes to operating costs.

4.3 Produced water

Produced water, also known as formation water, is naturally occurring water that is pushed to the surface with the stream of oil and gas during production (Ellafi et al., 2020). The salinity of produced water from a well or a pad of wells depends on the nature of the geology of the depositional environment (Enercom, 2017). Basins that produce water with lower salt levels are believed to be deposited in a freshwater environment, while basins like the Bakken are formed in a brackish, marine environment (Nordeng, 2012). This explains the reason for the high total dissolved solids (TDS) being experienced around the Williston Basin (Enercom, 2017). Water production from a well also depends on the quality of the drilling, completion, and the hydraulic frack jobs delivered during the well developmental stages of the well (Goodman & Troake, 1983; Bloomindale, 1988; Wryness & Romer, 2016; Rassenfoss, 2017). The physical and chemical properties of produced water vary depending on geology, hydrocarbon composition, and geographical location. Produced water is made up of impurities that must be removed before it can be reused for various purposes or disposed of without negative effects on the environment. The contaminants in produced water include oil, dissolved oil, dispersed oil, suspended solids, scales, NORMs, waxes, grease, sand, dissolved salts, carbon dioxide (CO_2), hydrogen sulfide (H_2S), gases, hydrocarbons, production chemicals, and various heavy metals (Ellafi et al., 2020). The treatment and disposal costs depend on the water cut a reservoir has.

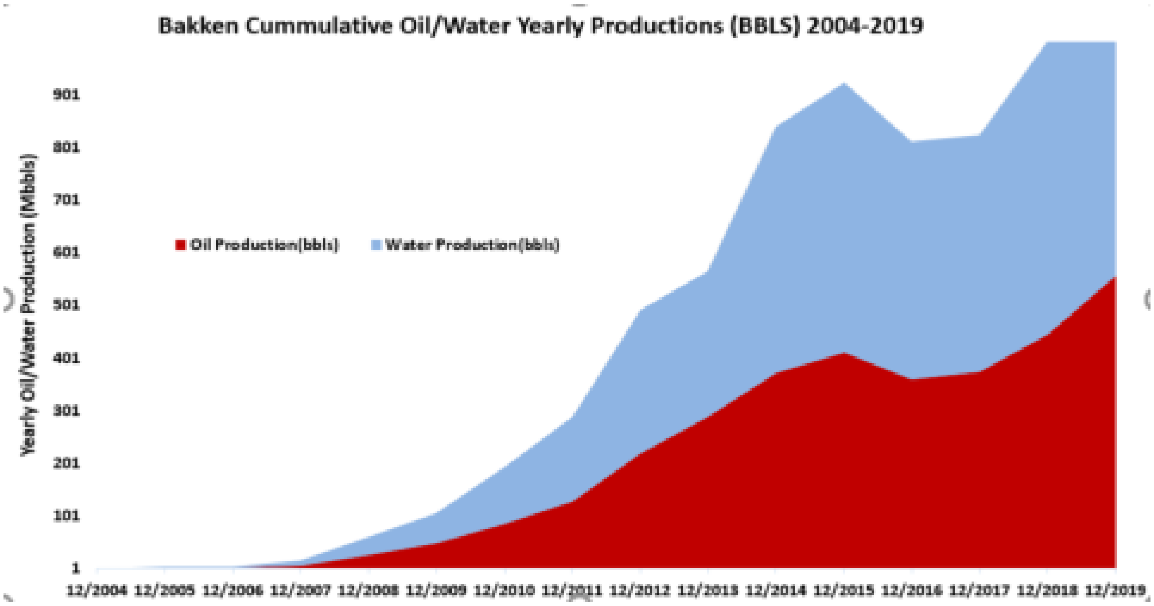

Figure 4.2: Bakken oil/water production history 2004–2019 (Source: NDIC Website)

The simple relationship here is that as water cut increases, so do scaling and corrosion tendencies. If not properly checked, this will lead to constant breaks in production activities resulting from equipment breakdowns that will eventually lead to well shut-in. In addition to the loss of revenue due to well shut-in, the operator will also incur costs from workovers or remediation to put the well back in production.

Data from the EIA's drilling productivity report shows that the major U.S. shale basins combined are producing 15–21 million barrels (2.4 billion gallons) of water per day (Clark & Veil, 2009; USGS, 2020).

4.4 The Bakken Petroleum System

The Mississippian–Devonian Bakken petroleum system of the Williston Basin is known to consist of low-porosity, low-permeability, organic, rich-source rocks (upper and lower Bakken), and regional hydrocarbon charge rocks (Onwumelu et al., 2019). The Bakken Formation is split into a middle dolomitic siltstone to silty dolomite member, which is the reservoir and the focus of any horizontal drilling. It lies between the upper and lower Bakken, which have very similar features of firm, siliceous, pyritic, fissile, organic, rich black shales and are classified as source rocks with total organic content (TOCs) as high as 40% wt., high HC indicating anoxic environments (amorphous-sapropelic OM), and HC Generation of 11–400 bbl of oil (Cobb et al., 2013). Three Forks is also a member of the Bakken petroleum system and a prolific producing formation in the basin. It is mainly composed of dolostone that is covered by the lower shale, which serves as the top seal, and it is also the focus of horizontal drilling in the Bakken (Nordeng, 2012).

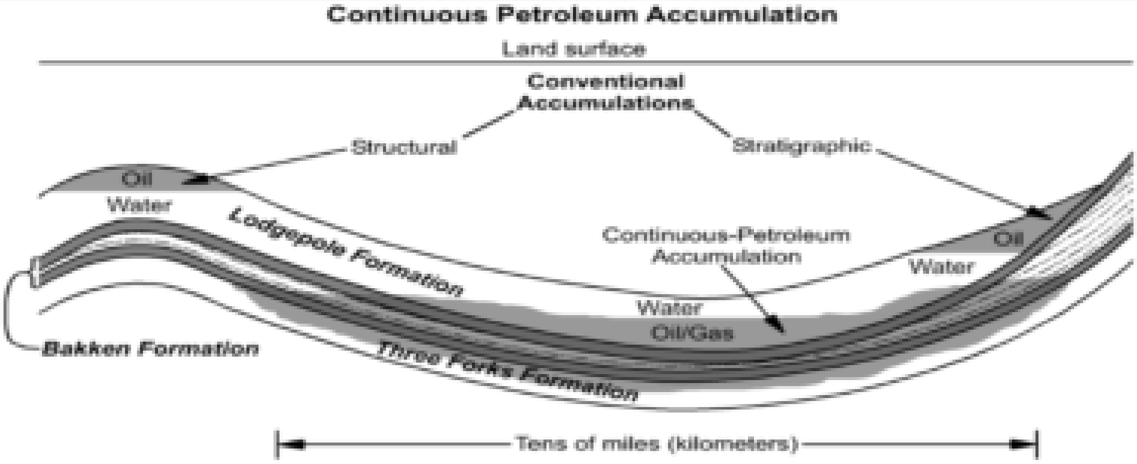

Figure 4.3: Continuous Petroleum Accumulation (Nordeng, 2012)

4.5 Study Area

McKenzie County lies on the western line of North Dakota. Its western boundary line abuts the eastern boundary line of Montana. The Missouri River flows easterly along the western portion of the county's north boundary line, and the enlargement of the Missouri River as it discharges into Lake Sakakawea forms the eastern portion of the county's north and northeastern boundary lines. The Yellowstone River flows into the northwest corner of the county from Montana and discharges into the Missouri at the county's northern boundary line. It is known as the county with the deepest part of the Williston Basin, with more than 4,500 wells currently producing makes McKenzie County the most sought-after county when it comes to hydrocarbon drilling.

4.6 Methodology

4.6.1 The System Dynamics Model

The goal of every Bakken operator is to ensure well development and production are executed in such a way that the wealth of shareholders is maximized to yield reasonable returns on investment. Another objective is to enhance the investment of shareholders in the company through a continuous flow of revenue with consistent growth and performance stability. For this to happen, there must be a deliberate effort to block or reduce any additional costs that can increase the already known operating expenses and create every avenue to drive down production operating costs. The first path to accomplish this is to ensure effective integration of all the various stakeholders' agreements, experience, and buy-ins that can accommodate oil prices along with social, environmental and technological conditions that promote cost reductions in all well development projects. A SDM approach has the distinctive ability to model a system in a way that shows how different parameters relevant to the system can contribute (positively or negatively) and their individual influences on different stages of the system (Albin et al., 2001). Few technical publications have discussed the application of a system dynamics approach to analyzing drilling issues, and no one has looked at how parameters like well quality can impact production and profitability. This study intends to do so by building a model from scratch that can analyze and simulate how well quality impacts production, operating cost, revenue streams, and profitability. Modeling drilling and completion activities and linking them to well quality and productivity while also looking at the influence on the economics variables would constitute a robust and cohesive modeling approach for this study. System dynamics software is not a reservoir modeling software. This project does not intend to model the reservoir in terms of the volume of oil or water produced. However, it does intend to analyze the system to see how activities and interdependencies could affect the production from a well, which will invariably have an impact (positive or negative) on production and profitability.

4.6.2 A brief description of a System Dynamic Model

A SDM project first involves defining a problem, followed by system conceptualization based on the defined problem, formulation of the applicable model, model evaluation/testing, policy analysis, and implementation (Hovmand, 2012). Lastly, for efficient model performance, it is important to determine all system components and their mutual relationships from the very beginning. The SDM in this study was developed using VENSIM DSS software. Two stocks were defined for this model. The two stocks – actual production and desired production – have many variables that flow in to show the connections between well quality on oil production and profitability. By considering the relevant activities and the stages involved in total well development, the effect of inefficiencies in each activity was carefully modeled and simulated, and the contributions to the overall productions of oil and water were critically analyzed. Lastly, the economic consequences related to these as a result of oil and water productions were also checked.

The methodology adopted for this project is explained in Section 4.6. We begin with the review of related literature in the study area, carried out in accordance with the objectives of this project. Data were collected from various journals, reports, and papers and carefully analyzed. We moved to conceptualize the model, after which it was built in Vensim DSS, analyzed, and tested. After the identification of key variables, the model for the actual and desired oil production was developed based on the causal loop diagram. In this model, Vensim DSS was used, considering the "Actual Production" and "Desired Production" as the stocks and the "Actual Production Rate" and "Desired Production Rate" as the flows for the time horizon of 25 years (300 months). The datasets used in this model are actual data from wells still in active production. The oil and water production history of well No. 22096 between 2004 and 2019 was collected and plotted with Petra. Cumulative monthly oil production averaged 9,685 bbl, while cumulative water production averaged 32,160 bbl. The datasets related to different costs are summarized in Table 4.1. The cost values are accordingly used in the model to calculate the final cost.

Table 4.1 Cost Items Input for the Model

Well Development Cost Items	Explanation	Cost ($)
Lease Acquisition Cost	This is a one-time payment. It is paid per well and is a flat cost. In a pad of many wells, cost is charged per well.	2.4 million/well (Oasis Petroleum Report, 2017)
Drilling Cost	Includes all costs of drilling the well (vertical and horizontal sections).	4.8 million/well (Oasis Petroleum Report, 2017)
Completion Cost	Cost of running production tubing, cost of perforation and all hydraulic frack costs, including cleanout costs, during coil tubing operation.	4.75 million/well with 50 stages of completion (Oasis Petroleum Report, 2017)
Operating Cost	This is defined in this thesis as the cost of produced water handling (treatment, transportation and injection cost). It also includes the cost of hauling oil produced.	Ranges between 3–6/bbl, dependent on water cut. This involves the cost of chemicals and well remediation costs as a result of excess water production (Oasis Petroleum Report, 2017)
Lease Operating Cost	Lease operating costs include labor costs, site preparation cost, permitting fees – including bond and registration (initial application) – cost and costs of power and maintenance	4.76/bbl of oil produced (Oasis Petroleum Report, 2017)

Water Hauling Cost	Cost of transporting the produced water out of the production location to the disposal location	9/bbl (EERC, 2019)
Water Injection Cost	Cost per barrel for wastewater injection	1.77/bbl (EERC, 2019)
Oil Hauling Cost	Cost of transporting the oil to sales or refining location	9/bbl (EERC,2019)

4.6.3 Process

To effectively conduct this research in a way that will critically help analyze the system and achieve results, we adopted the following processes as depicted in figure 6.5:

1) **Reviewing Literature:** We scrutinized the work of previous researchers for important information related to this subject.
2) **Defining the problem:** We defined the problem around how oil price fluctuation can affect well development decisions from the investor's (stakeholder's) side.
3) **Collecting Data:** We studied all offset data in an attempt to collect the most updated and relevant data to our research. We obtained most of the datasets from the North Dakota Geological Survey, various journals, reports, and papers.

4) **Analyzing the datasets:** All acquired data were analyzed. We looked at well path deviations and drilling methods, and we studied the production history of over 200 selected wells (between 2012 and 2019) from the study area (McKenzie County). We did this to understand the pattern of water cut increases between the time the well was commissioned and 2019.
5) **Conceptualizing the model:** Here, we brought together the entire concept in readiness to build the model.

6) **Building the model:** We then created the model and put all the necessary data into Vensim DSS, analyzed the system based on our defined constraints, and tested and made adjustments as needed. Lastly, we simulated the model several times to ensure it created real scenarios. Then results were plotted and discussed.

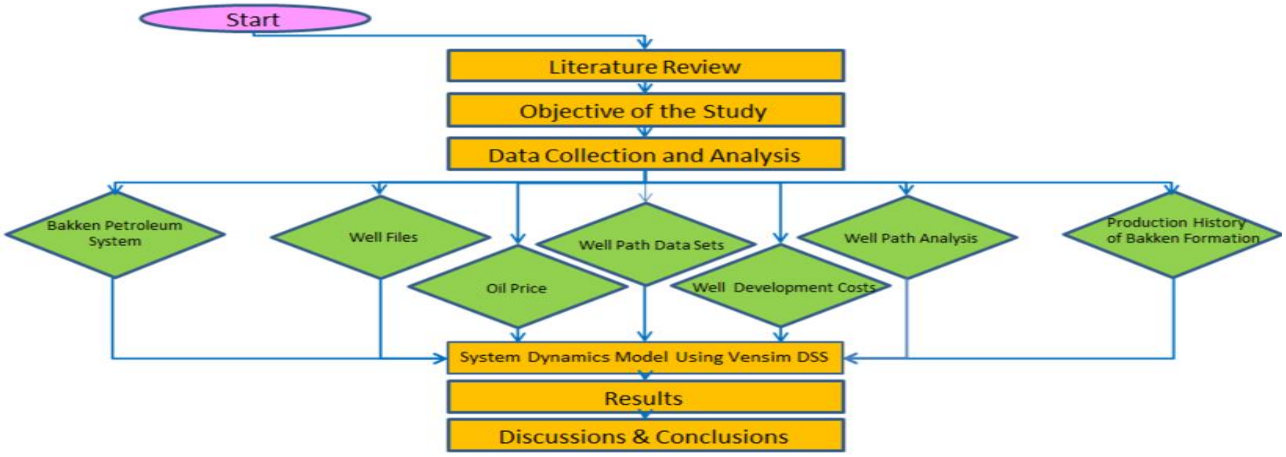

Figure 4.4: The methodology Flow Chart

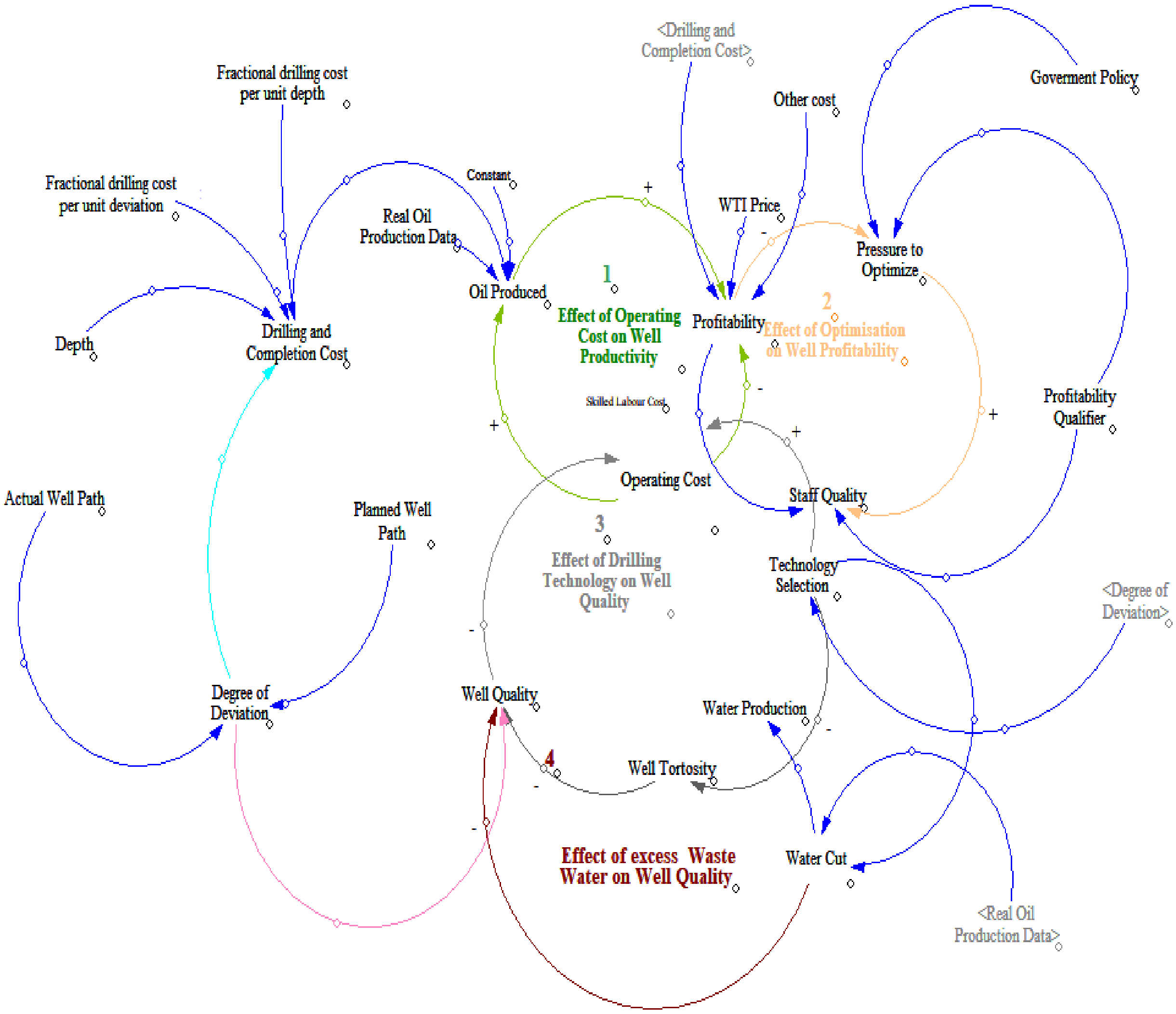

Figure 4.5: The Causal Loop Diagram

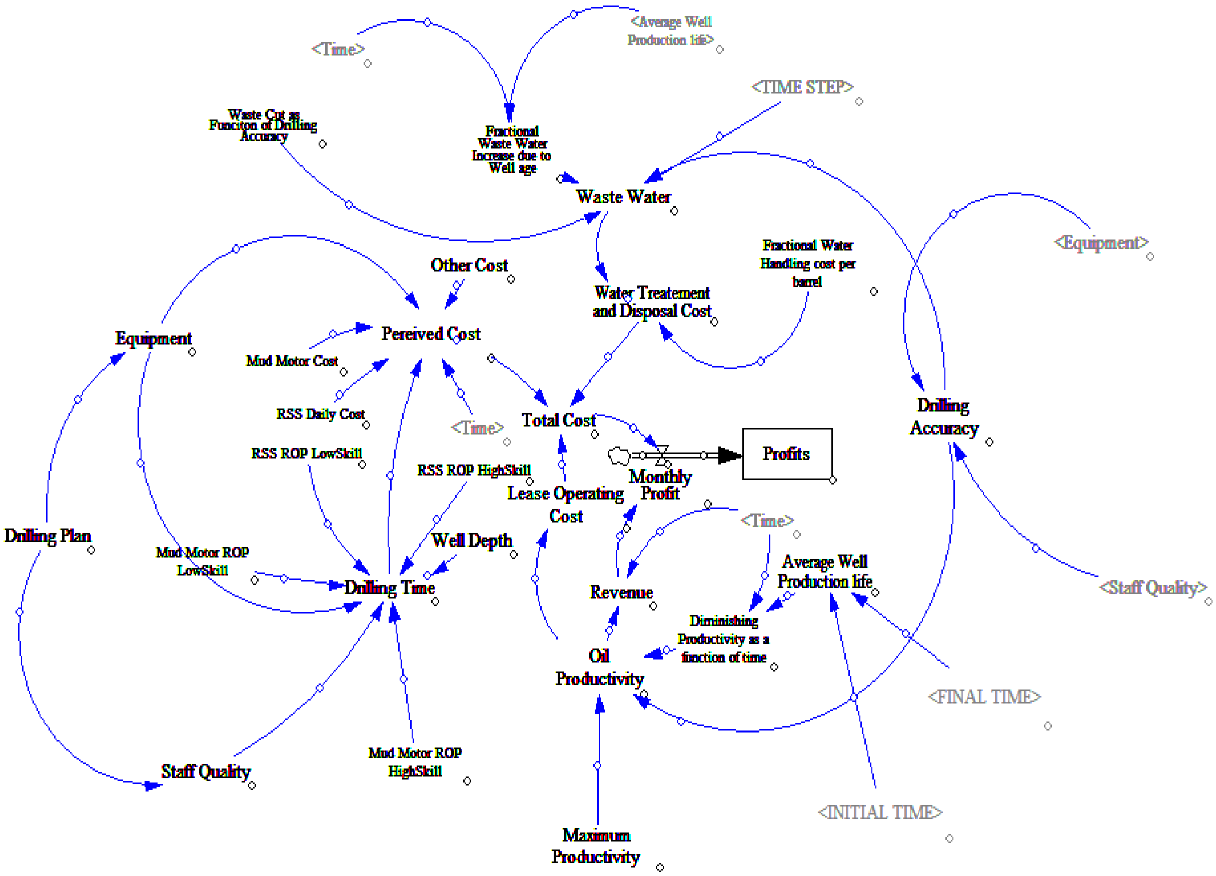

Figure 4.6 The Stock and Flow Diagram

4.7 Results

The model focuses on the effect of well path deviations and straightness on well quality and their ultimate contributions to fluids production and profitability. This research made use of actual datasets obtained from the well files of well No. 22096 from McKenzie County**.** The actual, desired, and deviations of the well path are shown in figure 4.7. We defined the desired well path as 0" and any transverse fluctuations from the desired well path as values higher or lower than "0". The deviation from the desired well path is defined as **the Desired Well Path–Actual Well Path**

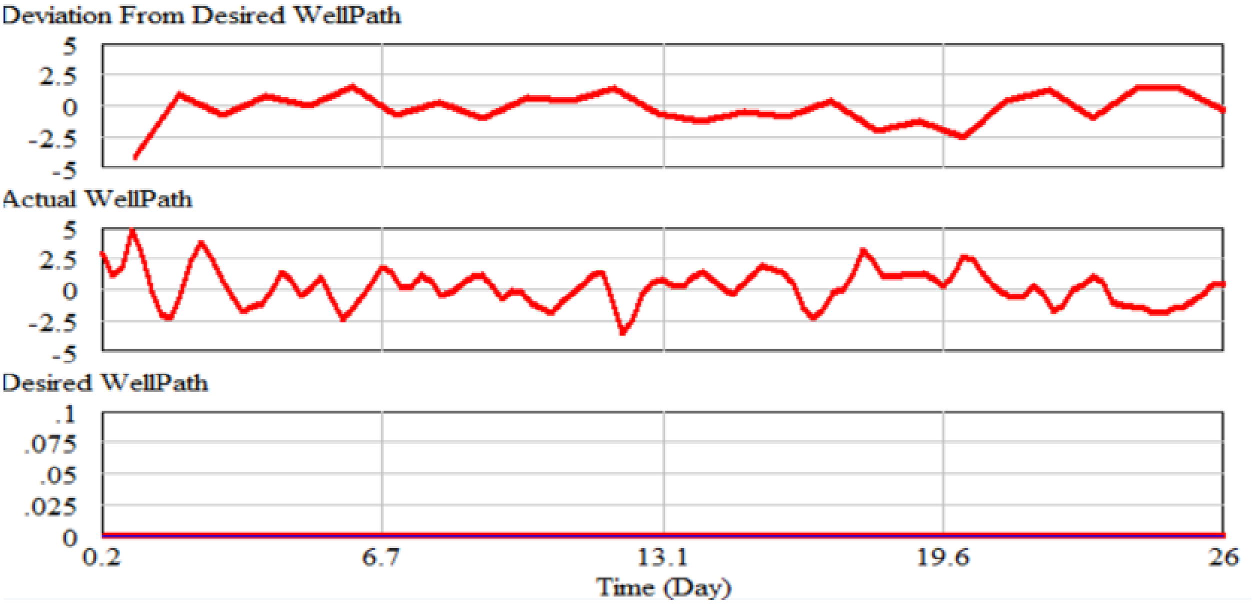

Figure 4.7: Well Path Deviation Result [The Y-axis represents Horizontal Deviations and is measured in feet]

The following graphs presents results from the modeling. Each figure is presented along with the primary equation that defines the function presented in that graph.

Figure 4.8 shows the effect of what on oil price fluctuations within the chosen time horizon.

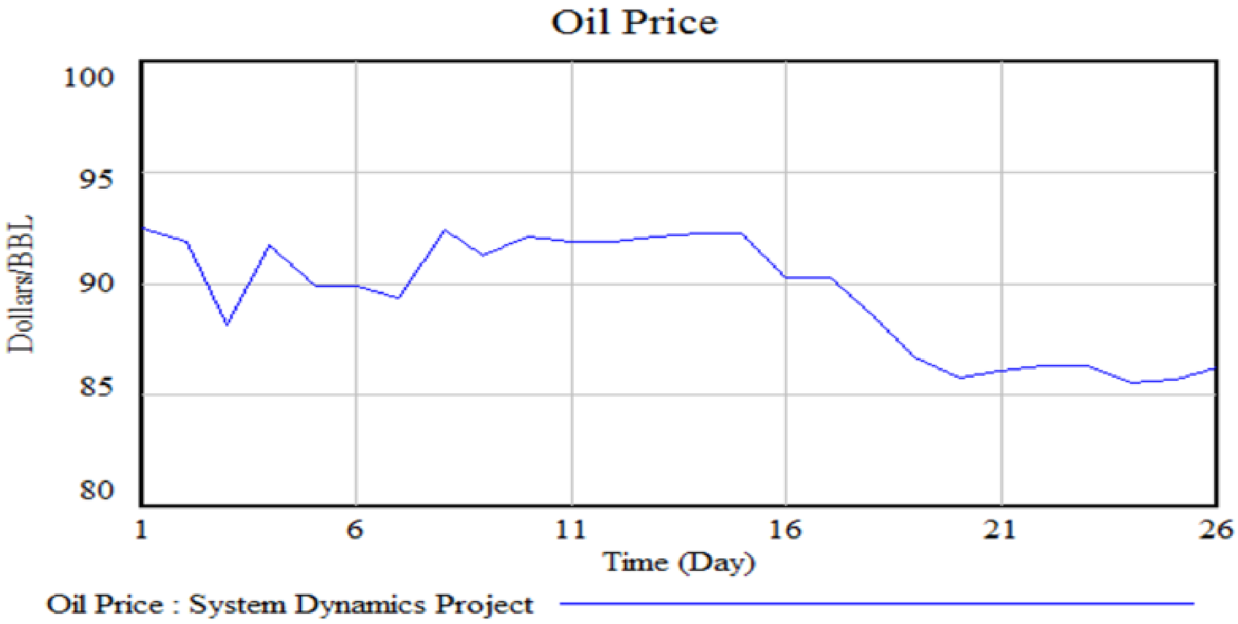

Figure 4.8: Oil Price Fluctuation Plot

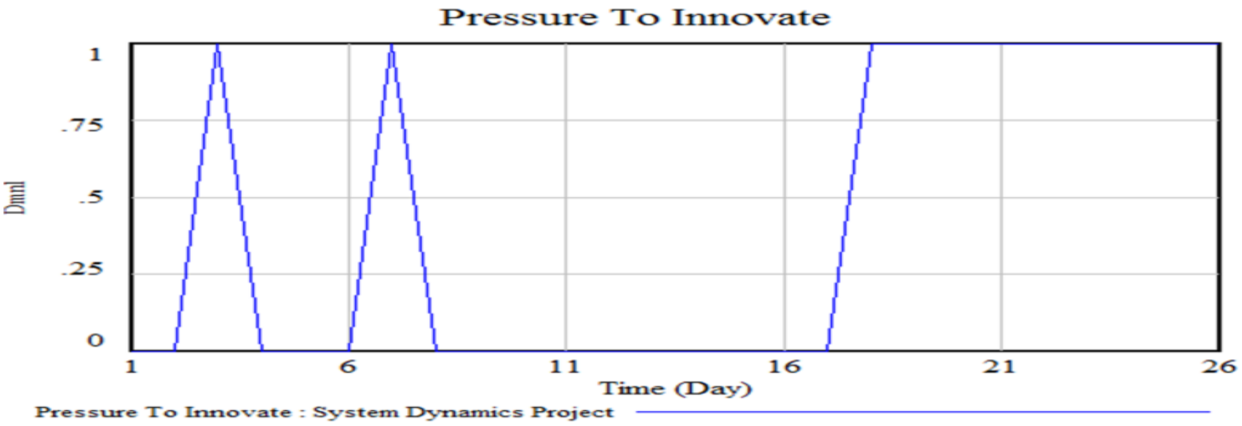

Figure 4.9: Effect of oil price on pressure to innovate (output)

Pressure to innovate is based on an oil price of $89.5/bbl. The research set the system to trigger the need for pressure to innovate when oil prices fall below $89.5/bbl.

Pressure to Innovate = IF THEN ELSE (Oil Price>=89.5, 0, 1)

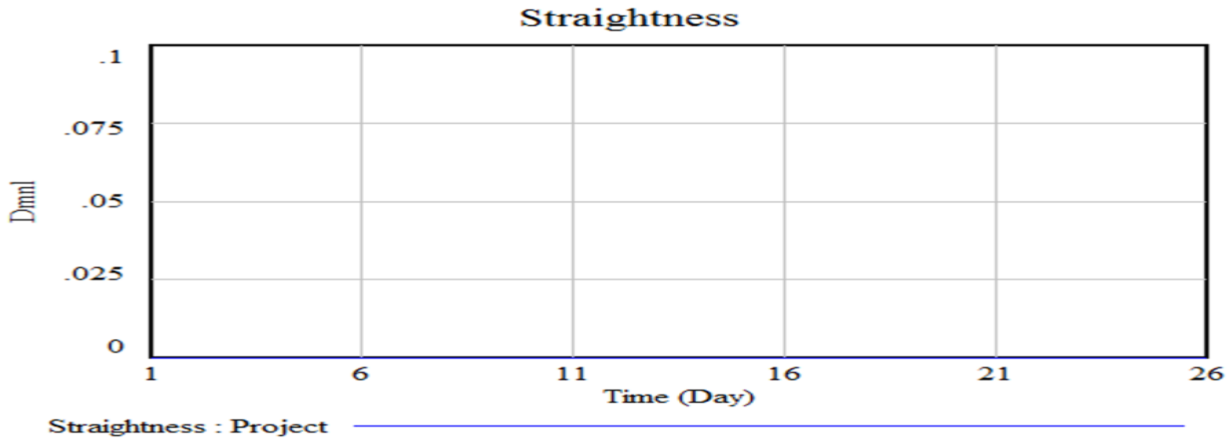

Figure 4.10: Desired straightness (Well Quality)

Straightness was defined based on the variables that influence well quality, as seen below.

Straightness = IF THEN ELSE (Deviation From Desired WellPath>0: OR: Deviation From Desired WellPath<0: AND: Pressure To Innovate=1, 0, 1)

The actual production rate and cumulative fluid production are directly influenced by the straightness that defined well quality. In this model, the research compared the results from the actual production and desired production based on the equations defined below; the results are shown in Figures 4.12 and 4.13.

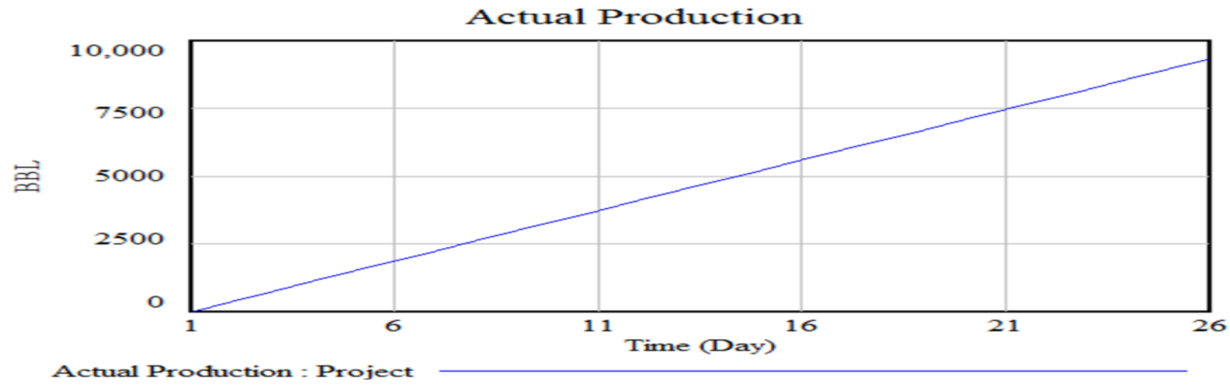

Figure 4.11: Effect of well quality on actual production

Actual Production Rate = IF THEN ELSE (Straightness=0, (Oil Production/ (Constant Time*26)), 1)

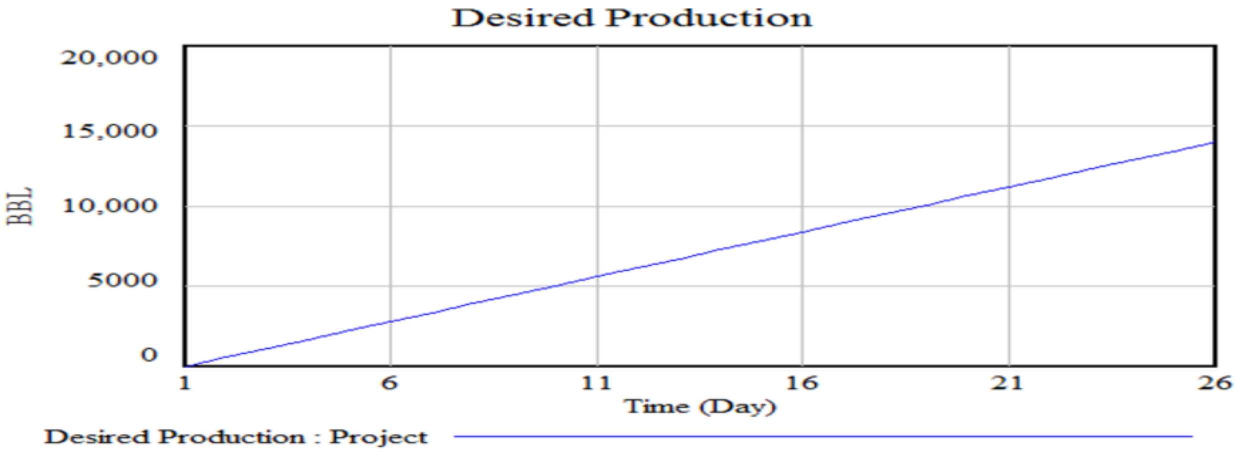

Figure 4.12: Effect of well quality on desired production

Desired Production Rate=IF THEN ELSE (Straightness=0, Actual Production Rate, ((1.5*Oil Production)/ (Constant Time*26))

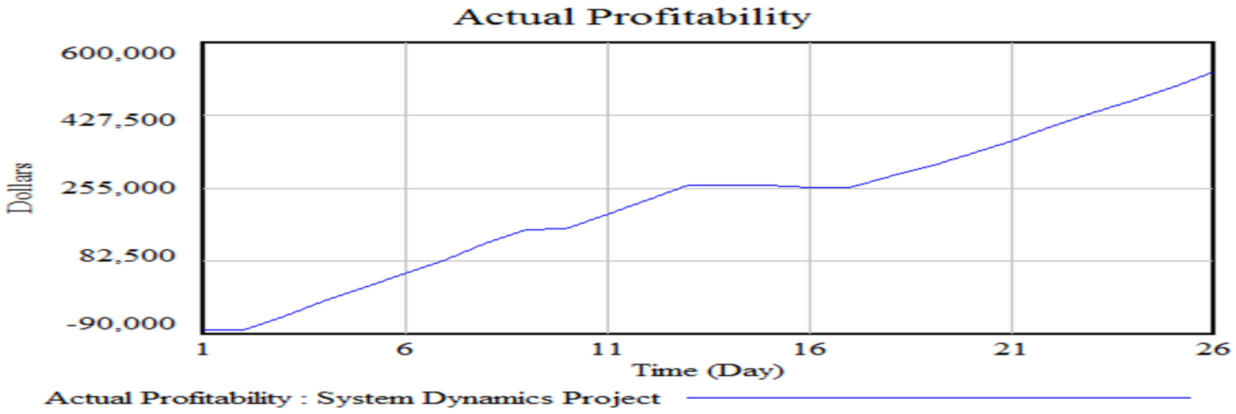

Figure 4. 13: Effect of straightness (Well Quality) on desired production

Actual profitability= (Actual Production*Oil Price)-Cost

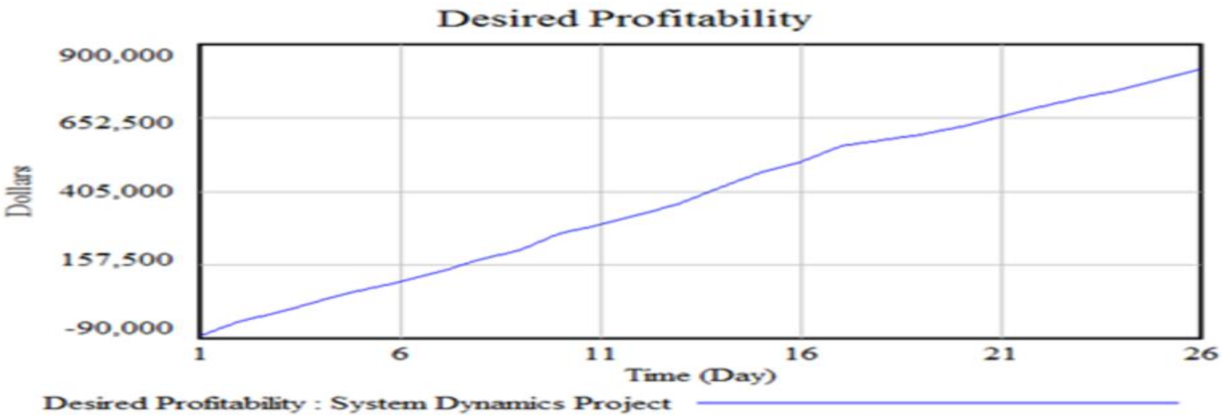

Figure 4.14: Effect of well quality on desired production

Desired Profitability= (Oil Price*Desired Production)-Cost

4.8 Discussion

Directionally drilled wells show an efficient way to reach specific targets that are challenging to reach using vertically drilled wells. In the Bakken, the only way to maximize contact with the reservoir is to drill long (about two miles) lateral sections. The pattern and rate of movement in the transverse (up and down below the total TVD) section, after the well makes its maximum horizontal deviation and is expected to hold its angle throughout the lateral section, is known as the well deviation. From our results, we observed visible well path deviations. The model also showed that the higher the deviation from the planned horizontal trajectory, the more fluids that were produced.

Higher fluid production does not mean high hydrocarbon production, contrary to the belief of most operators in the Bakken. The more wells deviate from their plan, the further they move away from the middle of the Middle Bakken. The completions will have nothing to do other than to frack based on the trajectory already handed to them by the drilling team. What this means is that most of the hydraulic frack propagation may be further away, into other rocks, even breaking through aquifers. That means high water production and high operating costs that impact overall profitability. The reason is, as water production increases, scaling, corrosion, and H_2S tendencies increase, and this will significantly increase the spending of chemical additives to prevent or treat these production issues. Also, in the Bakken, 90% of all produced water is disposed of through disposal wells. This is strictly regulated and enforced. All produced water must be treated for organics before disposal. Table 4.1 above shows that it costs an average of $9/bbl to handle water disposal. That is a lot of expense in a situation where more water is produced than hydrocarbons. Any time there is pressure to innovate, the effect goes directly to well quality. As the pressure to innovate increases, the straightness decreases, which reduces well quality.

The quality of the well is directly impacted by the difference between the actual and desired well path (Figure 4.8). Actual and desired productions are directly influenced by straightness (well quality) that directly impacts hydrocarbon production and profitability. Looking at the results from actual production and desired production, we can see that correcting the well path deviations can improve well quality. Production increased from 7,084 bbl to 10,430 bbl, and profitability increased from $529,300 to $817,900, as shown by Figures 4.11, 4.12, 4.13, and 4.14. Furthermore, the slopes of the actual and desired production graphs show that improving the well quality helps support oil production growth within the time horizon and keeps it steady.

4.9 Conclusion

With this research, we have been able to analyze and see how well straightness (well quality) from the drilling and completions team can affect production, increase operating costs, and hamper profitability. With the SDM, there is no problem without a cause and solutions. We analyze the system and see where the problem is coming from, then apply the best solution. Stakeholders must ensure every aspect of the drilling is critically planned, executed, monitored, and closed. Closing involves ensuring the quality required by the different teams is achieved before acceptance by the next team. We encourage oil operators globally to employ SDMs to examine all factors that could impact operating costs before embarking on full-scale development of the field, as this may uncover areas of system dysfunction that could affect the overall efficiency of the system.

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CHAPTER FIVE

5 Proposed Potential Mitigation of Wastewater Disposal Through Treated Produced Water in Bakken Formation

This chapter is taken from the paper entitled ***"Proposed Potential Mitigation of Wastewater Disposal through Treated Produced Water in Bakken Formation"*** *published in the* ***"54th US Rock Mechanics/Geomechanics Symposium".*** *Co-authors on this work include N Dyrstad-Cincotta, D Mann, A Ellafi, M Alamooti, S Srinivasachar, T Nelson. They contributed to this work by providing help in performing some of the experiments and reviews.* **Dr. Srinivasachar came up with the idea of the supercritical treatment method**. *I have contributed more than 65% of the effort to this work. My efforts include preparing and analyzing samples, identified major issues, fully drafted papers, discussions and conclusions,*

Abstract

The recent global expansion in the development of unconventional oil and gas assets has also resulted in a tremendous increase in the number of extended horizontal drilling and hydraulic fracturing projects in the Bakken. The United States is presently the largest global crude oil producer, and the Bakken Formation in North Dakota is one of the major contributors to this achievement. However, the wastewater produced from these increased oilfield activities are highly saline (~170,000 to 350,000 ppm TDS) and no technology currently available can satisfactorily treat it. As a result, more than 90% of wastewater in the Bakken is disposed of by deep injection into disposal wells. However, there are growing environmental and operational concerns about the sustainability and impacts of this approach. Research has shown that cumulative wastewater

injection in some areas could increase the chances of earthquakes in those areas. However, if this produced water is efficiently treated, it could be reused in hydraulic fracturing operations or to support coal mining and irrigation activities. All these applications would reduce the need for wastewater injection and reduce the demand for fresh water used in hydraulic fracturing operations across North Dakota. For this purpose, we propose an enhanced supercritical technology we call Supercritical Water Extraction – Enhance Targeted Recovery to handle the issue of high TDS of flowback and produced water in the Bakken.

5.1 Introduction

Oil production from unconventional reservoirs, such as the Bakken, has become very important and their optimal development has been studied in detail worldwide, especially in North America. This is because, over the past few years, unconventional reservoirs have substantially added to the national reserves of the US hydrocarbon resources. Recently the United States has become self-sufficient in hydrocarbon needs, a feat it has been trying to achieve for many decades. The United States did not only stop the importation of crude oil but was also willing to export and add crude oil export as part of the source of revenue generating streams. The Bakken Formation is contributing immensely to this feat. In 2019, oil production from the top 10 Bakken producers rose to 176,603,000bbl from 13,500 producing wells at an average of 3142 bbl/month from each well (North American Shale Magazine, 2020). For maximum primary oil recovery, between 60,000 to 80,000 wells must be drilled in all the oil producing counties in the Bakken; it is projected that this cannot be achieved until 2025 (North American Shale Magazine, 2020). However, with the current trend in drilling and completions technologies, the projected time may be shortened because the advancement in both the horizontal drilling and hydraulic fracturing technologies (Kolawole et. al., 2019a; Wigw aszxze et. al., 2019a) in recent years has made it easy and has also reduced the time it usually takes to drill wells in the Bakken. The good thing is that there is a great reduction in both the drilling and completions cost (Wigwe et al., 2019b). However, as with every technological advancement, there are some problems. For the case of the Bakken, as more wells are drilled, completed and commissioned for production and as hydrocarbon production continues to increase, so also does water production. This water (formation water) is produced to surface with the hydrocarbon. Generally, the norm in production is that, as the well life cycle increases, water cuts increase and so does water production. But we have noticed that some wells in the Bakken reach as high as above 75% water cuts in less than 2 years after commissioning. That raises a big concern because the impact (negative) of the produced water on both the desired production and revenue has been seen to be very high. High water cuts increase operating costs.

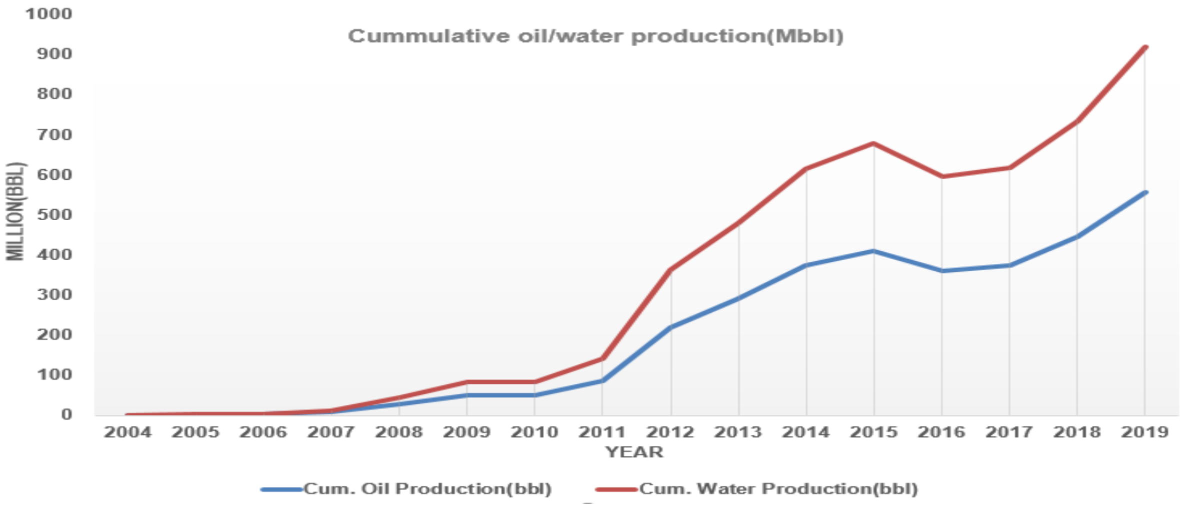

Figure 5.1: Bakken cumulative oil and water production 2004 –2019 (NDIC, 2020).

Our study into the production history of the Bakken between 2004 and 2019 reveals (Fig. 5.1) that only one-third of fluid of all fluids produced from the Bakken is actually the hydrocarbon that we desire while two-thirds is water (saline water). The question here is: are the operators really making a profit? We know that high water production means high spending on production chemicals such as scale and corrosion inhibitors and that there are many other chemicals that prevent or reduce the effect caused by the increased water production. It also means that the well will be frequently shut in for remediation works and even full workovers that may involve pooling production pipes and running a new production accessory. On the other hand, the water produced needs to be handled specially, as stipulated by regulations. Hauling, treatment and disposal all represent additional costs. How do we break even with all these costs? It is really difficult. This research intends to help reduce our operating costs in the area of water handling.

This thesis will present insight into the recent developments of a Department of Energy funded project called Supercritical Treatment Technology for Water Purification, which investigates the application of supercritical water properties for the desalination of produced waters. Our approach represents a unique opportunity to treat high total dissolved solids (TDS) produced waters, thus creating a benefit in the form of reducing the acquisition and disposal costs of water, as well as a credit from the sale of solids separated from the produced water stream. The Bakken Formation is in the Williston Basin, which is an organic-rich shale, mainly made up of mudstone and sandstone deposited during the Late Devonian and Early Mississippian periods. It extends about 200,000 square miles across parts of North Dakota, Montana, South Dakota, and the provinces of Manitoba and Saskatchewan in Canada (Fig. 5.2) (Jabbari and Zeng, 2012).

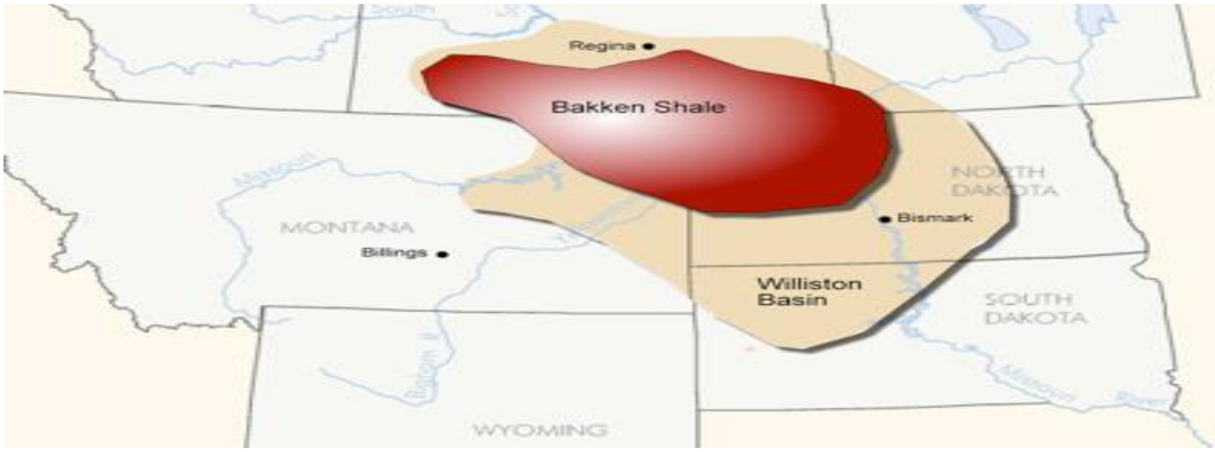

Figure 5. 2: The Bakken Formation in Williston (Energy and Environmental Research Center, ND).

The Bakken petroleum accumulations are known to have irregularly defined margins with wide, relatively thin and closely packed lithofacies. Successful production of Middle Bakken wells for sustainable economic gain greatly depends on the pores' connectivity and the quality of the matrix with respect to permeability and brittleness, also called frackability (Tomomewo et al.,2019 and Onwumelu et al.,2019) Permeability estimation in such a tight oil reservoir as the Bakken is an important element of the geological models that can help us to predict the long-term production profile of the reservoir and determine the optimal methods for stimulation to reduce water production effectively as we also focus on improved oil recovery. There are several challenges to economic production (Kolawole et al., 2019b, 2020; Wigwe and Watson, 2020) from Bakken wells, for example, the tight matrix with a thin reservoir pay zone and an ineffective network of natural fractures (Kolawole and Ispas, 2019a, b) with little or no connectivity. However, the combination of horizontal drilling and hydraulic fracturing are still the only promising techniques for drilling, completion and producing Bakken wells (Jabbari and Zeng, 2012; Pei et al., 2014; Ellafi et al., 2020). The Bakken is in the central region of North America and an unconventional, liquid-rich shale oil with an estimated 30 billion to 40 billion barrels of recoverable oil (Grand Forks Herald Newsthesis; USGS). Looking from a stratigraphy point, the Bakken Formation lies beneath the Lodgepole Formation and lies on top of the Three Forks (Fig. 5.3) and is well-defined as two laterally persistent, tinny, organic-rich, black upper and lower shales separated by a thin gray structure of siliciclastic and carbonates (middle member), and a basal member, called the Pronghorn. The reservoir is in the middle member lower Lodgepole and the upper Three Forks (Nordeng, 2009; LeFever and Helms, 2008: Energy and Environmental Research Center, ND).

The thickness of the Middle Bakken ranges from 30 to 70 feet according to the depth and location with the Basin. It is also characterized by several distinctive lithofacies. The facies show unique features that affect the porosity and permeability affecting fluid flow and ultimate recovery (LeFever and Helms, 2008; Tomomewo et al., 2019). The fine-grained carbonates and clastic nature of the Middle Bakken are the main sign that it is a tightly fractured reservoir rock that can permit a cost-effective fluid flow.

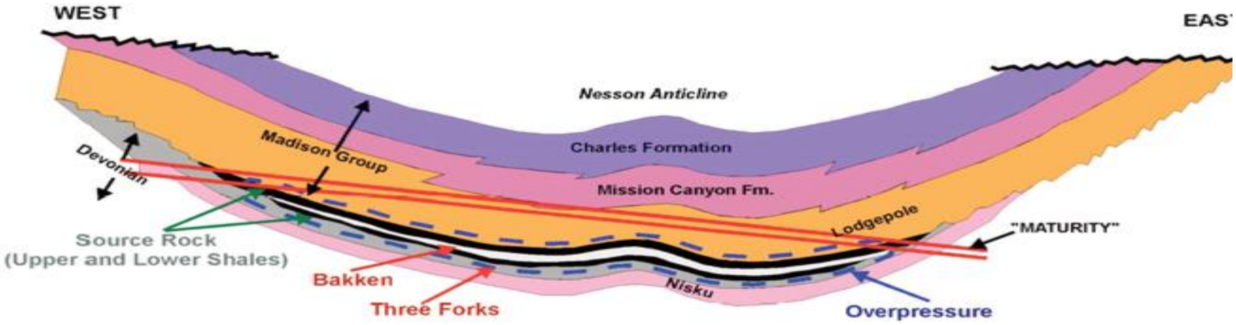

Figure 5.3: The Bakken Petroleum System (modified from Sorensen et al. 2018).

The reuse of produced water for various industrial applications is not a new concept, but it is really challenging when the salt content is high. Removing or reducing the salt content to an industry-acceptable level could be a daunting and capital-intensive exercise. Recently, the trend of reusing produced water as a fracturing fluid is gradually increasing in the field since it offers substantial gains, both environmentally and economically.

5.2 Challenges Related to high Water Production in Bakken North Dakota

Water cuts differ across the producing counties in the North Dakota side of the Bakken Formation, with McKenzie County representing the highest trend (Thyne, 2016). The main factor driving the high saline nature of Bakken-produced water is the halite (NaCl) concentration in the water. The composition of sodium (Na+) and Chloride (Cl-) elements show a huge dominance over all other elements that make up the produced water as seen in Table 5.1. This is common in every field or geological area where the main salt make-up of the reservoir water is halite (NaCl). This is becoming a global issue since most formations in the world have NaCl base in their produced water make-up (Wang et al., 2016). The high saline water contains a very high proportion of total dissolved solids (TDS) that usually precipitates when there is a change in well bore temperature, pressures and incompatibility of the fresh water injected into the reservoir either through hydraulic fracturing fluids or water flooding. Under these conditions, the tendencies of scaling, corrosion, H_2S and the formation of Naturally Occurring Radioactive Material (NORM) increases. This also directly relates to frequent well shutdowns for intervention and remediation. In order to reduce or prevent some of these difficulties peculiar to high water production, a more accurate understanding of the water chemistry of the reservoir and the geographical location will help in the planning of all chemical applications that may be needed (Thyne & Brady, 2016).

Table 5.1. Chemical Composition of the Produced Water Analysis from the Bakken, Williston Basin (LeBas et al. (2013)

	Produced Water
Specific gravity	1.20
pH	4.83
Conductivity (µS/cm)	257
Turbidity (NTU)	182
Dissolved Oxygen	8.24
Chloride (mg/L)	163,637
Sulfate (mg/L)	40
Aluminum (mg/L)	1.42
Boron (mg/L)	20.30
Barium (mg/L)	5.69
Calcium (mg/L)	29,222
Iron (mg/L)	34.60
Potassium (mg/L)	1,660
Magnesium (mg/L)	4,347
Sodium (mg/L)	70,342
Strontium (mg/L)	2,204
Total TDS (mg/L)	267,588

TSS (mg/L)	10,623
TPH (ppm)	>20

In the Bakken, like most unconventional places, various halite scale management methods include first identifying wells that need freshwater injections and corrosion inhibition, freshwater volume optimization, and treatment before injection in order to prevent the formation of other scales that could precipitate as a result of the applied treatment. Most of the problems with the Bakken concerning high water production are also associated with a spike in operating costs. This cost is usually reflected in production chemical usage, water treatment, and water haulage and disposal costs.

5.3 Water Management Options for Bakken North Dakota

Bakken wastewater handling is under the control of the Oil and Gas Division of the North Dakota Department of Mineral Resources. This body is charged with the regulation of all facets of wastewater management as defined and stipulated by the Oil and Gas Division (NDIC, 2019). These aspects encompass water storage in tanks, production and fresh hauling and deep well injection. In the Bakken, approximately three million gallons of water is needed per well during drilling and completions (Hydraulic fracturing) operations (EIA, 2019) and the main source of such water is the available freshwater bodies. As this water is used, they mix with the formation water and some of the additives used for the drilling or hydraulic fracture jobs and are produced back on the surface as flowback water. At this point, they are polluted and need to be treated for reusability. Since Bakken-produced water is highly saline, the only viable option for operators regarding disposal has traditionally been hauling it to a disposal well and injecting it into the Dakota group formation. In the Bakken, the Oil and Gas Division of the North Dakota Department of Mineral Resources always ensures that water management encompasses the entire water cycle associated with the well or pad development, and processes and policies that are strictly enforced are in place.

Water management consideration should be more proactive than reactive. Strategy should come first, to offer effective completion designs that will limit the infiltration of other water from rocks or reservoirs that the well is not producing from (Whitfield, 2017). Second, since we cannot produce hydrocarbon without water, water produced can be transformed and turned into a great value proposition through technologies that could treat and reduce both the impurities and the salinity. This water can then be used as a base fluid for hydraulic frack job, re-injected for pressure maintenance, and also as influent water for power generation and/or irrigation (Du et al., 2005). However, treating water to an acceptable level where it can be reused needs very effective technologies: it needs a lot of energy as well as a great deal of effort but in the end, it can represent great cost savings on operations, water hauling (fresh and waste) cost reduction and water disposal (treatment and injecting) expenses for the operators as well as having less impact on the environment as the volume of disposed water will be reduced.

Usually, the preferred hierarchy for water management for unconventional places like the Bakken should be a detailed reservoir analysis to understand the water saturation extent and the geomechanical properties of the rock (Kolawole et al., 2018) including the direction of the principal stresses of the desired reservoir. The behaviors and the nature of all the aquifers and surrounding water tables that could easily transmit fluids like water should be seriously studied (Du et al., 2005). Hydraulic fracture designs that could limit propagation within the desired production zone should also be studied. We know this is not easy, but with sufficient planning, it is achievable. Most operators believe that the length of hydraulic fracture propagation is directly linked with high hydrocarbon production. This is not always correct. In fact, it is the other way around in the Bakken Formation. A high fracture propagation is highly desired only in the direction of the horizontal stress and within the horizontal plane (Jabbari & Benson, 2013). However, because of how the Bakken petroleum system is structured, hydraulic fracture propagation transmits more than desired in the transverse (upwards direction into the Upper Bakken and Lodgepole and downwards into the Lower Bakken and Three Forks) directions.

After considering all options to reduce water production, the next option will be to consider reuse options. Reuse options depend on the level of salinity and the ease of applicable treatments. Some counties in the Bakken do not produce water at hyper saline levels (NDIC, 2019). Produced water from these counties could easily be filtered and treated for organics and perhaps used as completion fluids, frack fluid-based water, or for pressure maintenance (Ellafi et al., 2020). The next option would be the available treatment alternatives for the very high salinity waters. In the treatment of saline fluids like produced water, reverse osmosis (RO), Multistage Flash distillation (MSF) and electrodialysis (ED) technologies are recognized. However, it has been observed that these technologies cannot efficiently cope with the high salinity level of Bakken-produced water. For example, reverse osmosis (RO), even though promising and reliable as one of the world's leading saltwater desalination processes, will still need a technology that can treat in such a way as to reduce the salinity of Bakken produced water to a level suitable for its functionality. Reverse osmosis (RO) operates a semi-permeable process in which a preferential material like water in transferred through the membrane counter to osmotic pressure of the saline water feed. Most times the plants are run at an averagely low energy consumption (30 MJ_{el}/m^3 and a pressure between 53–

79 atm (Odu et al., 2017). Multistage Flash (MSF) is mostly used in the Middle East and currently accounts for more than 40% of the world's desalination capacity. MSF is made up of various flash compartments and different compartment pressures that allow for the vaporization or evaporation of saline water by sequentially lowering the pressure in each compartment (Odu et al., 2017). However, all these technologies still cannot cater to the full treatment of wastewater in a way that can lead to a zero-level discharge (ZLD). This thesis presents one of the technologies that can handle Bakken production in such a way that it will lead to ZLD. See more of this discussion in the next sections.

5.4 Water Disposal Methods

In 2019, there were an average of 62 rigs that actively drilled every month and that resulted in more than 2500 new wells drilled and commissioned for production. Also, in 2019, a cumulative average of 1,357,186 bbl of hydrocarbon production was recorded between January–September 2019 (NDIC, 2019; North America Shale Magazine, 2020) and there were more than 13,500 wells in active production. Based on the statistics above, it is reasonable to also expect a huge volume of wastewater production and a plan should be in place to effectively cater for this. Unfortunately, because of how saline Bakken produced water is, most operators seem not to even try recycling but rather prefer to treat it slightly to remove organics and then dispose of it by deep injection into the Dakota group. The following are available methods of water disposal currently used in the Bakken:

1. Injection into a disposal well (Mainly Dakota group in the Bakken). For shallow injection wells, this method may allow injection water to make its way through the cracks and faults in the sealing rock. This can contaminate the freshwater bodies.

2. Reinjection for pressure maintenance and reuse for frack job, drilling and completions. This method seems to be favorable but not often used in the Bakken and is one of the main reasons for this thesis.
3. Reuse for irrigation or industrial processes like power generation.

In the Bakken, the type of disposal wells includes private Class II saltwater disposals mostly owned by operator companies and commercial class II saltwater disposals operated by third party companies for commercial purposes.

5.5 Methodology

The energy industry uses tremendous volumes of water for various applications, including oil & gas operations, power plants and coal mining. The oil and gas industry, in particular, is a big consumer, where water is primarily used as a frack fluid. The oil and gas industry is also a tremendous producer of hypersaline brines (produced water). It is estimated that the total flowback and produced water from six of the major unconventional oil and gas formations in the U.S. yields up to 5.6 million gallons of produced water per well and that 90+% of the produced water is derived from naturally occurring formation brines that are extracted together with oil and gas (kondash et al., 2017).

The produced water from these wells contains a high percentage of TDS, of (50,000 to 350,000 mg/L) and organics concentrations of up to ~2,000 milligrams/liter (U.S. EPA, 2016). For example, the Marcellus and Bakken formations yields TDS values towards the upper end of the range (Kondash et al., 2017). The salinity and chemical composition of these formation brines are the main limiting factors for the beneficial reuse of oil and gas wastewater.

As mentioned earlier, the most common method for handling produced water in the Bakken is deep injection into disposal wells. However, with this conventional method, there is an increasing concern of groundwater contamination and seismic activity. Recycling of produced water for frack job is limited. Frack fluids typically require a TDS of less than 70,000 mg/L, and oil/organics of less than 25 milligrams per liter to maintain fluid stability according to the EPA. It would also be desirable to reduce the TDS sufficiently to access high value water markets, such as irrigation, well maintenance, and potable supplies.

While reverse osmosis (RO) is an economical and widely used method available for saline water treatment, it cannot be used to treat very high TDS brine (above 45,000 mg/L) due to membrane fouling or being used to destroy organics. Supercritical water treatment can handle the very high TDS brine. In this study, we introduce a novel and enhanced supercritical technology named “Supercritical Water Extraction – Enhanced Targeted Recovery” (SWEETR™). The SWEETR™ supercritical water desalination (SCWD) treatment can handle the very high TDS of flowback and produced waters. The separation principle is based on the changed solvation behavior of water under supercritical conditions. While water represents an excellent solvent for salts at ambient conditions, it becomes an extremely poor solvent at supercritical conditions (T > 370°C and P> 230 bar) (Hodes, et al. 2004). For example, the corresponding salt solubility for NaCl is 10^6 ppm (360°C) versus 10^3 ppm (400°C). The resulting ultra-low salt solubility results in the precipitation of a separate solid phase, which is separable from the clean water stream. This separation method can be operated without the production of an aqueous waste stream, an advantage in comparison with hyper-saline brine wastes of reverse osmosis. The SCW medium also exhibits high solubility for oxygen, oxidizing organics more effectively than at non-supercritical conditions (Gloyna and Li, 1998). Although SCW treatment is a promising approach, there are significant challenges that need to be addressed to make the technology commercially viable. These include high energy requirements, the scaling and corrosion of process equipment, and difficulty in the removal of separated solids under supercritical conditions.

5.6 Supercritical Water Background & Prior Work

Studies report that the thermal energy consumption for SCWD is 450 MJth/m^3 of product water (Odu, 2015; Lopez et. al, 2017). This is higher compared to 300 MJth/m^3 for multi-stage flash plants. An investigation into the enthalpy and solubility levels of NaCl as a function of temperature at 230 bars was conducted by Luesbrock (2011). Through this study, it was determined that the salt concentration is not a limiting factor of SCWD and that a wide range of feed streams is possible. More importantly, it was found that the energy demand for the process depends on the outlet quality. An additional benefit of SCWD is the separation of the solids of the feed stream by precipitation.

Figure 5.4 represents tailoring of the operating conditions to achieve a lower end quality (~30,000ppm), which results in smaller energy input than attempting to achieve a higher end quality (>1000ppm).

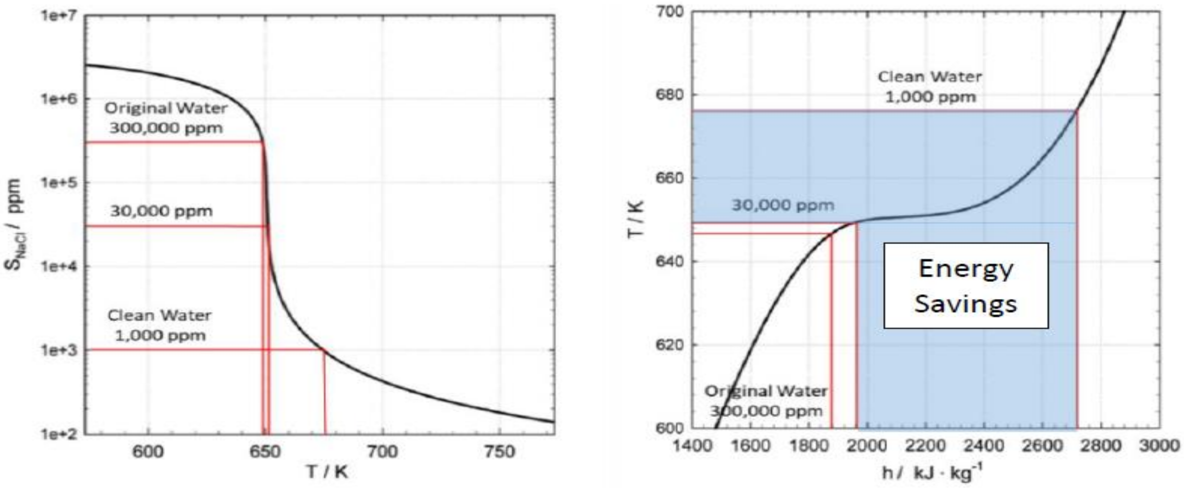

Figure. 5.4. Left: Solubility of NaCl in water as a function of temperature at 230 bar; Right: enthalpy of water as a function of temperature (Leusbrock, 2011).

5.7 The Supercritical Water Desalination Preliminary Results

SCWD technologoy was investigated to develop the novel SWEETER™ technology with the goal of separating saltwater into a pure water stream and recovering valuable solids while also destroying organics and producing zero liquid discharge. The method for heat addition can be dependent on the treatment site. This in-situ heat addition can be accomplished by utilizing energy sources that are abundant to each particular site, such as the excess flared/fired natural gas on a wellsite, electricity, or solar thermal energy that would help to reduce the cost of treatment. This would reduce the overall energy penalty for supercritical water desalination technology. Additional goals were to develop a proprietary technique for targeted precipitation to reduce scaling and corrosion on equipment and to make the technology modular in order to combine with reverse osmosis to improve economics. Figure 5.5represents a process schematic for a supercritical water treatment system that utilizes solar energy as the method of adding heat.

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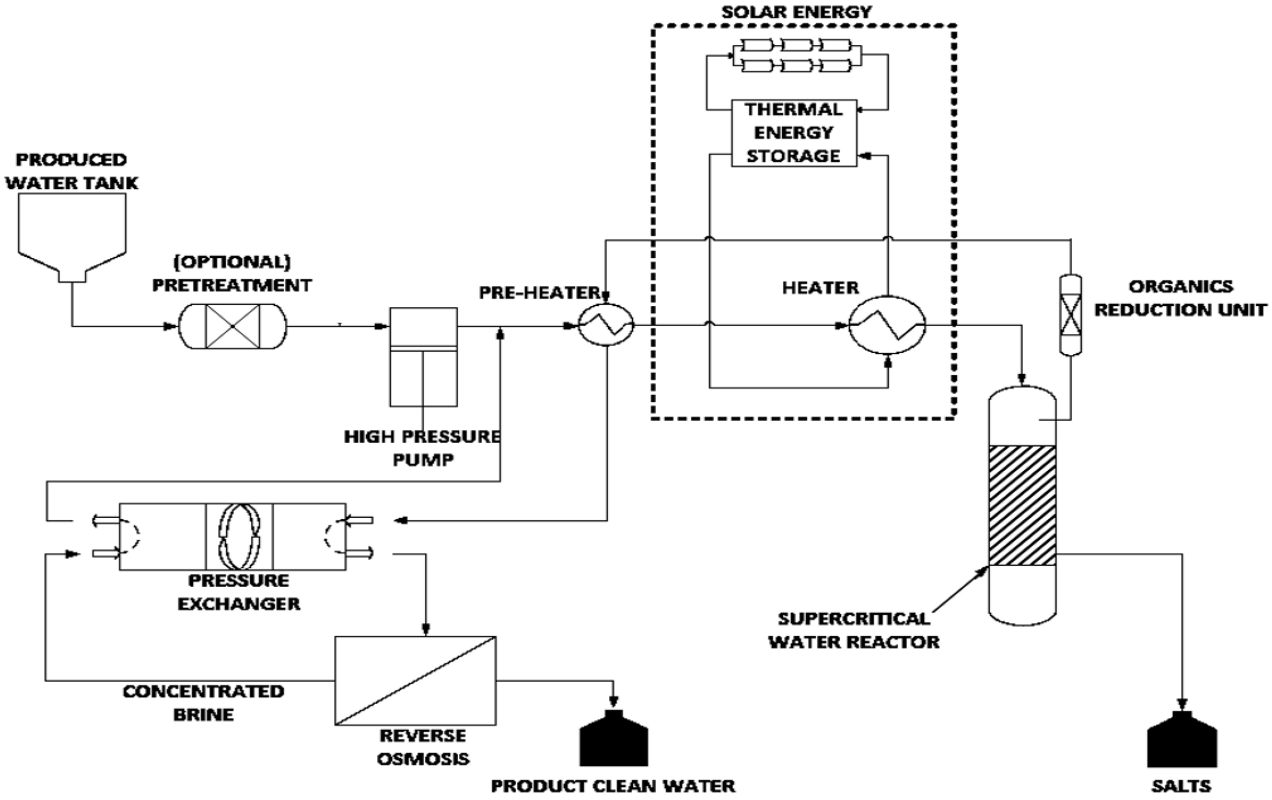

Figure. 5.5: Process Schematic for Solar Desalination Supercritical Treatment System

Initial research focused on developing energy requirements of treatment using in-situ heat to create the supercritical zone and precipitate out salts. The supercritical reactor was heated to subcritical conditions (360°C and P> 230 bar) and energy was supplied to bring a targeted area of the reactor to supercritical conditions. Operation would continue until the salt loading capacity of the reactor was reached requiring shut down, meaning this experiment was batch style in nature. Through this research, it was found that the location where the salt precipitates could be controlled, avoiding precipitation on the reactor walls or piping. This work validates and matches closely with previous experiments conducted by Odu & Hodes.

As mentioned previously, the removal of salts from a supercritical is complex and technically challenging unit operation. Current state-of-the-art work in supercritical solids separation makes use of a two stage process, where a vapor phase (750 ppm NaCL) and concentrated liquid phase (50 wt.% brine) are separated from one another. The 50 wt.% brine is flashed to atmospheric pressure with the final result being ZLD (Odu 2015).

The primary purpose of our research was to verify that targeted salt precipitation could be achieved by utilizing in-situ localized heat delivery. Achieving targeted precipitation allows for additional opportunities for separation and collection of the raw salts to be pursued. Targeted precipitation is also suspected to improve the control of scaling and corrosion, reducing the CAPEX by allowing for lower grade materials of construction in the heated zones. However, this is not a variable we have fully investigated as part of this lab-scale experiment. Preliminary results have show that the outlet TDS is tunable and based on the energy input into the system. This means that the process can be tailored to the end user process.

Table *5.1* represents a series of tests, their total desalination removal efficiency, and their resulting energy requirements for a 10 wt.% NaCl starting solution. The resulting experimental energy requirements were positive, with a requirement of 310–339 MJ/m^3 to remove 73% and 82% of TDS respectively for a 100,000 TDS starting brine solution. For a flowrate of ~30ml/min, we have also successfully been able to desalinate 200,000 TDS brine feed to 70,000 TDS for fracking, and 30–40,000 TDS for reverse osmosis, even down to roughly 500 ppm. Energy requirements for this set of experiments was not monitored.

The project is currently at the lab-scale, operating with flowrates of under 1 liter per minute. The technology is still being developed and we are confident that the operating parameters and energy requirements can be fine-tuned, and that the overall energy consumption will decrease as we scale up and improve the technology.

Table 5.1. Preliminary supercritical desalination results

Test ID	Mass Flow Rate (g/min)	Vol. Flow (m^3/s)	Energy Requirements (MJ/m^3)	Percent Reduction in TDS	Total TDS Removed
I	44	7.48E-07	214	35%	37000
C	20.9	3.55E-07	310	73%	77000
A	27.8	4.73E-07	339	82%	86500
J	41	6.97E-07	373	66%	69000
G	25.3	4.30E-07	395	33%	35000
B	21.1	3.58E-07	428	79%	82900
K	40	6.80E-07	441	84%	88000
F	15	2.55E-07	451	67%	70000
J	45	7.65E-07	484	100%	105000
E	19.5	3.32E-07	513	71%	74100
H	22.5	3.83E-07	706	100%	105000

The impact of our desalination technology could be huge in the oil and gas industry as it has many cost and environmental impacts, such as mitigating the cost of transporting water to disposal sites, disposal via deep well injection and the costs of clean water acquisition. There is also the added opportunity to recover valuable minerals from the targeted salt recovery, giving an additional cost benefit credit.

Produced water has been sourced from several wells located in the Bakken and characterized by Standard Labs, Inc. TDS has ranged from 110,000 to 330,000, where Type I and Type II salts make up 95% of the components. NORM was found to be non-detect in these samples, however, a contingency plan would be developed to ensure that NORM would not accumulate over time. This water was tested in the supercritical reactor. In addition, an initial techno-economic assessment was conducted by UND and Doosan Heavy Industy (DHI) for commercialization of our approach. While the specifics are proprietary, utilizing a hastelloy reactor with a monel/monel heat exchanger was found to have a CAPEX of \$4.91/m^3 of treated produced water. When taking into consideration OPEX, credit for the sale of recovered salts, disposal cost mitigation, and freshwater mitigation, the net treatment cost (value proposition) is -\$1.68/m^3 for a 50,000 m^3/yr well and -\$8.67/m^3 for a 1,000,000 m^3/yr central site. This makes the technology a good first entry point in this field due to higher margins. Another application for the technology could be applied to reverse osmosis, treating the high TDS reject stream, resulting in zero liquid discharge.

The proof of concept of using other methods for heat delivery and desalination has been established, where we were able to desalinate 188,000 TDS produce water to sub <0.6wt% with energy requirements in the range of 185 to 230 MJ$_{th}$/m^3. The complete scope and details is considered proprietary and will be released in subsequent publications.

5.8 Discussions

Results from the current work have verified that supercritical treatment can be used to produce clean water (<1000 ppm TDS) water from a high saline brine. Waters with TDS as high as 200,000 mg/L have been tested in UND’s desalination reactor. It has been demonstrated that the level of removal can be adjusted through control of the amount of heat provided in selected areas of the desalination reactor. Further, and of importance to the development our supercritical water desalination technology, the energy costs for treating the water for high levels of TDS removal can be controlled to a reasonable level by judicious selection of operating conditions and reactor design (as it pertains to the distribution and transfer of heat).

5.9 Conclusions

Supercritical water desalination technology is an innovative, efficient, and economical approach for the separation of contaminated saltwater into usable water and valuable recovered solids, and for the destruction of organics in the wastewater, resulting in zero waste liquid discharge (ZLD). The market for our novel supercritical water desalination technology is the treatment of high salinity brines. Highly concentrated salt brine effluents are generated from a variety of sources, including seawater and brackish water desalination processes, produced water from fossil fuels (oil and gas) production, power plant scrubbers and cooling tower blowdowns, and coal and metal ore mine tailing leachates.

We focus on two of these markets: treatment of produced water (PW) from oil and gas operations, as the initial focus, and desalination of brines from existing desalination processes over the longer-term. Using IEA estimates, the annual production of produced water is approximately 5 million m^3 per day, representing a large growth market for water treatment technologies. The International Desalination Association reports that there are more than 19,000 desalination plants worldwide, also providing a huge potential market for the proposed technology.

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CHAPTER SIX

6 Increasing Reusability of Bakken Produced Water using Electro-Oxidation Process

Abstract

Recently, there has been an expansion of unconventional oil and gas development worldwide, leading to an increase in extended horizontal drilling and hydraulic fracturing operations. The United States is presently the largest global crude oil producer, and the Bakken formation in North Dakota is one of the major contributors to this status. However, the wastewater produced by these increased oilfield activities is highly saline (~170,000 to 350,000 ppm TDS), and the most commonly used water disposal method in the Bakken Formation is deep injection into disposal wells. Notwithstanding, there are growing environmental and operational concerns about the sustainability and impacts of this approach. However, if the wastewater is efficiently treated, it could be reused in hydraulic fracturing operations or to support coal mining and irrigation activities. We experimentally investigated how flow-back and produced water could be treated using advanced electro-oxidation treatment technology. We provided a robust and detailed report on how the oxidants directly created in this non-chemical treatment process are extremely effective in acting as biocide for bacterial disinfection, water softening to reduce scaling tendencies, the chemical precipitation of heavy metals (in an inert state), and rendering all in very fine particles without the need for conventional (chemical) biocide treatment, scale inhibitors or filtration

6.1 Introduction

Oil production from unconventional reservoirs, such as the Bakken, has become very important, and optimal development has been studied in detail worldwide, especially in North America. This is because, over the past few years, unconventional reservoirs have substantially added to the national reserves of U.S. hydrocarbon resources. In 2019, United States became self-sufficient in hydrocarbon production and even ready to start exporting to other countries (EIA, 2020). With the continuous advancement in both horizontal drilling and hydraulic fracturing technologies, unconventional formations, such as the Bakken Play (Onwumelu et al., 2019a, b), will continue to be relevant and at the forefront of oil and gas development at all levels (state, national, and global). However, as these technologies continue to advance and improve, more wells are being drilled in less time, leading to increased production of fluids (hydrocarbon and produced water) (Kolawole et al., 2018). Despite the increase in hydrocarbon production, the wastewater produced from these increased oilfield activities far outweighs the hydrocarbon and is highly saline wastewater (~170,000 to 350,000 ppm TDS). This makes it extremely difficult to treat for reuse purposes. The common produced water disposal method in the Bakken Formation is deep injection into disposal wells. However, there are growing environmental and operational concerns about the sustainability and impact of this approach. The wastewater could be reused in hydraulic fracturing operations or to support coal mining and irrigation activities, if efficiently treated. Realistically, wastewater injection will continue to be the norm and, in fact, will increase as more wells are being drilled. As a result, all the injection wells will soon reach their capacity, and this could lead to chaos viz Oklahoma seismic activities associated to produced water injection (McNamara et al., 2017; Machado et al., 2018 and Julie et al., 2019). The only way to reduce water injection and avoid problems in the future is to create reliable and cost-effective treatment technologies that can adequately handle the harshness of the Bakken produce water. Such technologies would benefit the environment by reducing the need for wastewater injection in the Bakken formation, and they would reduce the demand for fresh water used in hydraulic fracturing operations across North Dakota. Moreover, the operators would benefit from reduction in water acquisition and handling costs that usually negatively impact their cash flow and profitability.

Previous studies have proposed various methods of treating produced water for recycling and re-use, but these methods have failed to adequately address the problem of treating very high TDS wastewater (with organics and heavy metals) to industry-acceptable standards for reuse. In this study, we assessed the current saltwater treatment options available for unconventional plays across North Dakota, and we proposed a novel, efficient, and more economical treatment method for the Bakken-produced saltwater. We experimentally investigated ways in which Bakken flow-back and produced water could be treated using advanced electro-oxidation technology, and we undertook a robust and detailed analysis of how the oxidants directly created in this non-chemical treatment process are extremely effective in acting as a biocide for bacterial disinfection, water softening to reduce scaling tendencies, the chemical precipitation of heavy metals (in an inert state), and rendering all in very fine particles without the need for conventional (chemical) biocide treatment, scale inhibitors, or filtration. This process provided an efficient treatment of highly saline produced wastewater from the Bakken Formation to a standard that meant the treated produced water could replace freshwater, which is in high demand for hydraulic fracturing operations, or brine for completion. The investigations also show that wastewater injection in the

Bakken formation can now be significantly reduced, as we can recycle more wastewater and brackish water, thereby reducing the use of fresh water required for fracking jobs.

6.2 The Bakken Geological and Petroleum System

The Bakken Formation is an organic-rich shale play. It is primarily composed of mudstone and sandstone formed during the late Devonian and early Mississippian eras. It stretches approximately 200,000 square miles through portions of North Dakota, Montana, South Dakota, and the provinces of Manitoba and Saskatchewan in Canada as shown figure 6.1 (Tomomewo et al, 2019).

It is a well-known, unconventional, liquid-rich shale oil, with an estimated 30 to 40 billion barrels of recoverable oil (Grand Forks Herald Newsthesis, ND; United States Geological Survey [USGS]) formed during the late Devonian to early Mississippian periods (Jabbari and Zeng, 2012; Nordeng, 2012; LeFever and Helms, 2008).

From a stratigraphy point of view, the Bakken Formation lies beneath the Lodgepole Formation and overlies the Three Forks; it is characterized as two laterally constant, thin, organic-rich, black shales (upper and lower members), divided by a thin, gray sequence of siliciclastic and carbonates (middle member), and a basal member, the Pronghorn. The reservoirs are in the middle member lower Lodgepole and the upper Three Forks (Nordeng, 2012; LeFever and Helms, 2008, Tomomewo et al., 2019). The thickness of the Middle Bakken ranges from 30 to 70 feet and can be characterized by several distinctive lithofacies (between five and seven). The facies depict unique characteristics of the rocks that affect the porosity and permeability and thus fluid flow and ultimate recovery (LeFever and Helms, 2008; Nordeng, 2012). The fine-grained carbonates and clastic nature of the Middle Bakken rocks are major indicators of a tight fractured reservoir that will only allow economical fluid flow and production if horizontal drilling and hydraulic fracturing are employed.

Core 1
Depth: 10,639ft
Formation: Middle Bakken
County: McKenzie

Core 2
Depth: 10,675ft
Formation: Middle Bakken
County: Montreal

Core 3
Depth: 10,104ft
Formation: Middle Bakken
County: Williams

Figure 6.1: Lithofacies pattern of the sampled cores.

6.3 Water Disposal Methods in the Bakken

Drilling activities in the Bakken produced an average of 41.1 million and 51.4 million bbl of oil and water, respectively, in 2019 (NDIC, 2019). This represents a significant quantity of highly saline water, of which 90% is usually injected into the Dakota Group. The following are available methods of water disposal currently used in the Bakken and around the globe:

1. Injection into a disposal well (mainly Dakota Group in the Bakken.) For shallow injection wells, this method may allow injection water to make its way through the cracks and faults in the sealing rock and find its way to fault or contaminate fresh water below it.
2. Reinjection for pressure maintenance and reuse for fracking, drilling and completions. This method seems to be favorable and is one of the main reasons for this technical thesis. If this method is used properly, produced water could reduce or even replace the use of fresh water.

3. Reuse for irrigation or industrial processes such as power generation.

In the Bakken, the types of disposal wells include private Class II saltwater disposals, which are primarily owned by the operator companies, and commercial Class II saltwater disposals, which are operated by third party companies for commercial purposes.

Reuse of produced water for various industrial applications is not a new concept, but it becomes more challenging when the salt content is high. Reducing the salt content to an industry-acceptable level could be a daunting and capital-intensive exercise. Recently, the practice of re-using produced water as fracturing fluids has gradually increased, since it offers substantial gains, both environmental and economic.

6.4 The Advanced Electro-Oxidation Wastewater Treatment Technology

Great improvement and advancement in electronics and materials technology have also triggered basic, but important, shifts in the electro-oxidation reactor designs, substantially enhancing their functionality, and safety, and allowing efficient and cost-effective treatment of oil field wastewater around the world. This review shows how multiple oxidants can be formed within the wastewater volume, by simply using electricity without the addition of harmful reagents or oilfield chemicals. These oxidants have been proven to be exceptionally effective biocides for bacteria sterilization. Electrochemical precipitation formed in the process has also been shown to decrease the scaling tendencies of the treated produced water. This treated water can be used as a base for hydraulic fracturing fluids, water recycle, or water injection for pressure maintenance.

6.5 Equipment Description

The primary equipment is a reactor consisting of several anode/cathode plate packs with a minimum of two independent direct current (DC) power supplies. The DC power supplies will always need direct short current trips. For improved wastewater treatment and savings in energy consumption, the plates are usually spaced approximately a quarter of an inch from each other, as scaling issues become a problem if the spacing is condensed to an eighth of an inch. Energy demand also increases significantly for spacing above three eighths of an inch. For high salinity wastewater like that in the Bakken, the plate spacing should range between three eighths to half an inch, which gives room for more mineral scale build up before back wash. However, the cost of power rises as a result of increased operational voltage.

To treat produced water with this technology, there is a requirement to first oxidize the stream in order to remove total dissolved organic carbon and then reducing hardness before recycling. Wastewater is pushed through the process reactor where it undergoes the electro-oxidation process. Electrodes with a distinct configuration are positioned inside the reactor to treat pollutants in the wastewater. The electrode set-up consists of anode and cathode plates at some distance from each other and are connected to DC power supply that can hold a direct short. As mentioned earlier, at least two different coatings are needed to create the multiple-oxidant mix required for treating different organic and inorganic pollutants in the saline produced water.

Field application has shown that a higher DC power level does not translate to a faster treatment frequency and increasing the injection of oxygen gas does not remove the organics more quickly. This is linked to the limit of hydrogen peroxide production on the cathode. The operator must ensure that the DC power and oxygen gas concentration levels match the influent being oxidized. As the total dissolved solids increases in the effluent, the operating DC voltage reduces correspondingly. The power requirements also reduce. However, it will be necessary to constantly swap the DC current if there is a high hardness loading in the brine. Impurities such as frack fluids additives, dissolved hydrocarbon, drilling fluids, and plant fibers present in Bakken produced water will necessitate frequent mechanical cleaning. However, these impurities can be eliminated use with the use of pre filtration to reduce these unwanted solids.

The plate electrode reactor is designed as a flow-through system that will not exert any noticeable backpressure on the fluid flow during treatment. The equipment is fitted with sensors installed around the inlet/outlet pipe feeds, and it transmits real-time data which enables the operator to monitor and control the process. This equipment is shown in the picture presented in figure 6.2.

Figure 6.2: 48kW electro-chemical reactor with dual power supplies

6.6 Electro-Chemical Process

Consider a perfectly flowing electro-chemical reactor: the DC is employed between the anode and the cathode surfaces, which are held at a specific distance apart in the raw fluid contained in the reactor. On the anode surface, the pH will approach 2; oxidants are created from anions, and with the excess current, oxygen gas is generated. On the cathode surface, the pH will approach 12; residues are created from cations, and with the excess current, hydrogen gas is generated. For treatment of real petroleum brines, iron and other heavy metals will oxidize and precipitate on the anode surface, while calcium, barium and magnesium hardness ions will precipitate on the cathode surface, therefore compelling a DC swapping operation to precipitate dissolved ions on the electrode surfaces. Some applications may generate more contaminates, for example, clay pellets and hydrocarbon will create a mixture of sticky gels and sludge that may not be easily removed with pH reversal, so periodic use of shear force, such as ultrasonic cleaning, may be required to sweep this sludge off the electrode.

The oxidation reaction takes place on the surface of the anode plate to create oxygen gas, hydrogen peroxide, hypochlorous acid, heavy metal oxides, and carbon dioxide from oxidized organic molecules. Iridium oxide alloy electrode coatings are one choice for anode materials. With iridium oxide coatings, the current productivity for organic compounds in the field for chlorine-facilitated oxidation hovers around 40%, mainly as a result of oxidation of metals and formation of oxygen gas. Energy utilization is approximately 300 kWh/kg of mixed petroleum depending on the saturation level of the organic material. If the raw water is more saturated with oxygen gas, then the cathode surface will produce a hydroperoxyl radical or hydrogen peroxide instead of hydrogen gas. The hydrogen peroxide produced will then react with the iron (II) ion in the influent to make the hydroxyl radical that is required for the organic material oxidation process. There are more oxidation reactions in the bulk saline produced water downstream from the reactor due to excess oxidants such as hydrogen peroxide and bleach produced by the electrode surfaces. Hydrogen peroxide breakdown in the fluid stream provides the necessary gas to create gas bubble suspension to the surface for biomaterial and oil sludge decomposition.

If significant bicarbonate ion concentration exists in the untreated produced water with pH above neutral, the oxidation capability of organic compounds by the hydroxyl ion will be reduced in the main streams of the produced water and on the anode surface. This is due to transformation of the bicarbonate ion to carbonate ion with the hydroxyl radical. Treated produced water should be stored in tanks for effective preservation. If it must be stored in an open pit for an extended period, it is best to oxidize all organic material present to carbon dioxide; all heavy metals should be converted to their maximum oxidation state, and ammonia or any amine compounds present should be converted to nitrogen gas through breakpoint chlorination. Breakpoint chlorination will eliminate most of the nutrients in the water, leaving phosphates in the residue and carbon dioxide from air exposure. The reason for converting all organics to carbon dioxide is to remove all chloro-methane waste in the treated water and to prevent the formation of algae and the production of hydrogen sulfide odor that could result from the activities of sulfate-reducing bacteria in the pit residue.

Excess boron of up to 40 ppm in the treated water can be reduced by the electro-chemical cell, forming iron (II) or iron (III) borate that is co-precipitated with iron oxide on the anode surface or calcium borate that is co-precipitated with calcium carbonate or calcium sulfate on the cathode surface. If the treated brine is used in real time, the brine’s oxidation-reduction potential can be treated below breakpoint chlorination to kill all the bacteria. Actual application in the field has shown that hydraulic or ultrasonic cavitation can treat the total produced water stream.

It is necessary to reduce the hardness ion concentration in the produced water, i.e. to lower the ion level to an acceptable target Langelier Saturation Index (LSI) of -2, in order to prevent any precipitation hardness after fracture treatment (Kolawole et al., 2019; Kolawole and Ispas, 2019) has been applied and the fluids have mixed with reservoir formation fluids. The precipitated particles can be used in the frack fluid and pushed into the formation with proppant with no significant loss of fracture conductivity. The power requirements for hardness precipitation are approximately 19 kWh/kg of CaCO3 equivalent scale for 8 volts across electrodes. Most produced water has sufficient iron ion concentration to promote the Fenton reaction with hydrogen peroxide in the bulk brine to oxidize most oil field polymers from the fracturing fluids. But the Fenton reaction can be curbed if the produced water contains high bicarbonate ion. Bakken produced water is plagued by cations or anions imbalance with pH as low as 2.4 in some cases. To treat this kind of water, it is best practice to first raise the pH to near neutral before treating with quick lime or muriatic acid respectively.

6.7 Results from Bakken Produced Water Treatment Bacteria Treatment

In this field application, the process was used to treat Bakken produced water. The bacterial level of the water was checked before the experiment and after (figure 6.3). The influent bacteria count of over 110,000 MPN/ml for each bacterium (GHB, APB and SRB) before treatment, was removed completely after the treatment. This result was attributed to approximately 1.2 ppm of free chlorine present in the treated effluent water, and to the fact that most of the TOC was oxidized to carbon dioxide scale inhibition compound.

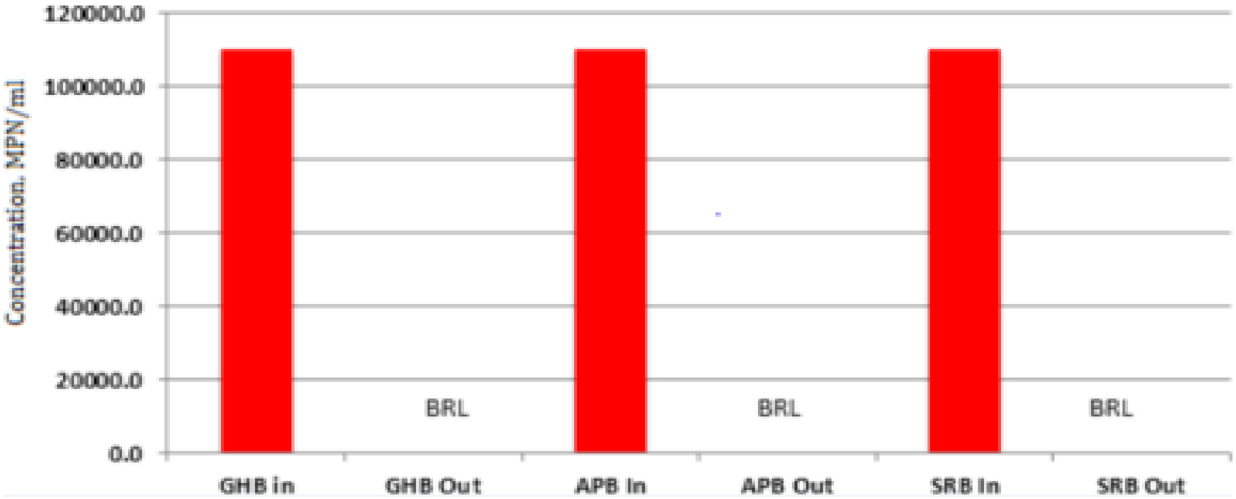


Figure 6.3: Bacteria count analysis before and after treatment in electro-chemical

6.8 Scale Inhibition Treatment

Produced water from the Bakken predominantly contains divalent ions such as Calcium (Ca^{2+}), Barium (Ba^{2+}), and Strontium (Sr^{2+}). When there is any imbalance in the composition of the water, used either for hydraulic fracturing or water flooding, there will be dissociation of the ions make-up and as result ions movement. As the fluids try to mix, ions will move from water with a higher concentration to the one with lower concentration in other to create equilibrium in the system. In addition, unsteady flow rate, and changing temperature and pressure of the across the wellbore or system are also factors that usually promotes scaling. Scaling usually from small particles nucleation that eventually leads to a bigger precipitation. To starve the water of the necessary conditions for scaling to occur, the electro-oxidation process is fitted with special geometry electrodes that can make the scale-sensitive divalent cations (e.g. Ca^{2+}, Ba^{2+} and Sr^{2+}) precipitate on the cathode surface.

In a case study presented, the electro-chemical oxidation process was used to treat Bakken produced water. Figure 6.4 shows how the divalent cations were precipitated on the cathode surface as hydroxides, carbonates and sulfates.

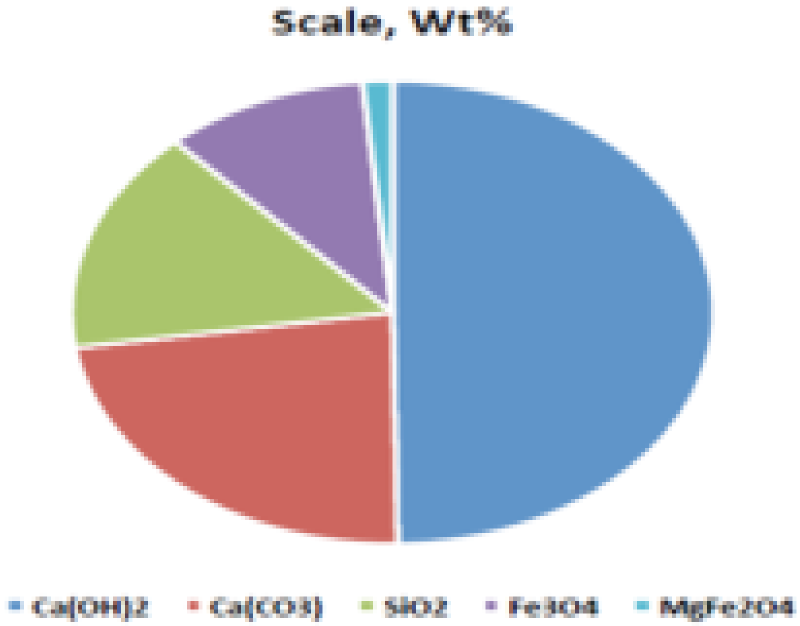


Figure 6.4: Analysis of scale buildup on cathode surface, Fayetteville Shale Pit

The precipitation shown above happens during the electro-oxidation process and, at an extremely small level, are enough to prevent scaling. It is therefore referred to as a micro-precipitation process and occurs because the scale-causing minerals are in steady form and have become ellipsoid in shape. This process also helps reduce solid particle size to less than 0.4 microns as shown by the scanning electron microscope (SEM) image in figure 6.5.

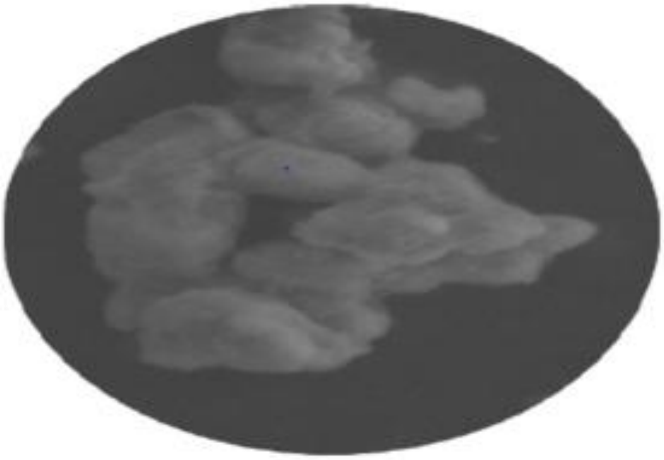


Figure 6.5: Scanning Electron Microscope image of precipitated calcium-rich

Since we have demonstrated that in the electro-chemical oxidation process, divalent cations are precipitated on the cathode surface as hydroxides, carbonates and sulfates, the next step was to check the effect of scale buildup in the capillary tube test. This test procedure is an accelerated scaling test, meant to provide an indication of the scaling propensity of saline waters. The research used two water samples: untreated and treated Bakken produced water. The charting of delta pressure shown in figure 6.6 reveals that influent feeds, i.e. untreated produced water, begin scaling inside the capillary tube after about 4 hours, while figure 6.7 shows that delta pressure remains unaffected throughout the standard nine-hour test for the treated Bakken produced water.

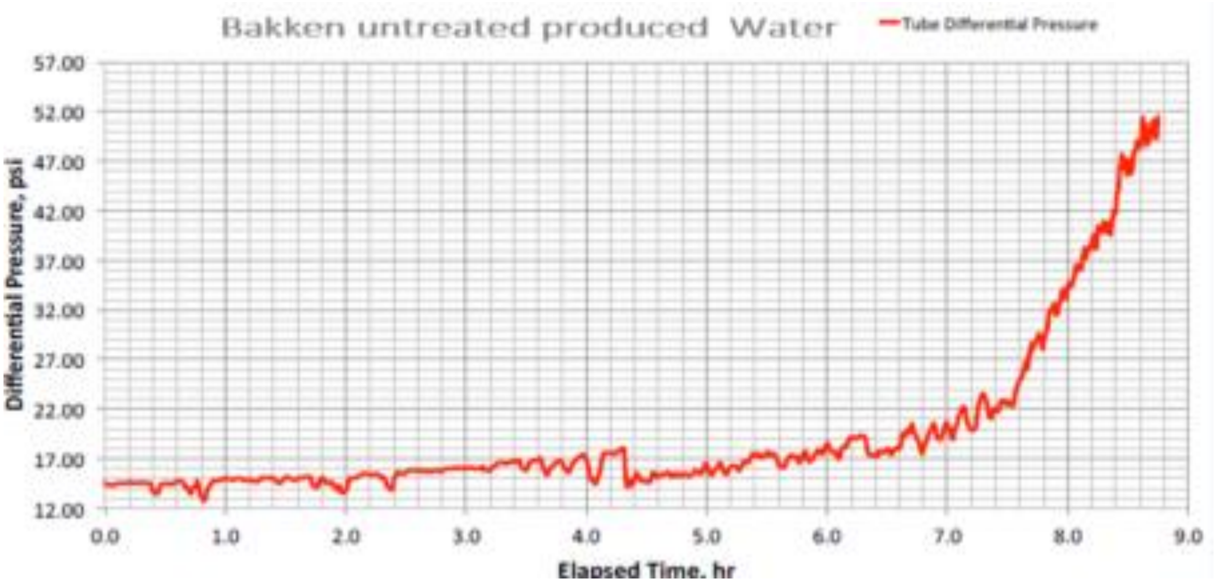


Figure 6.6: Untreated fluid dynamic capillary tube blocking test

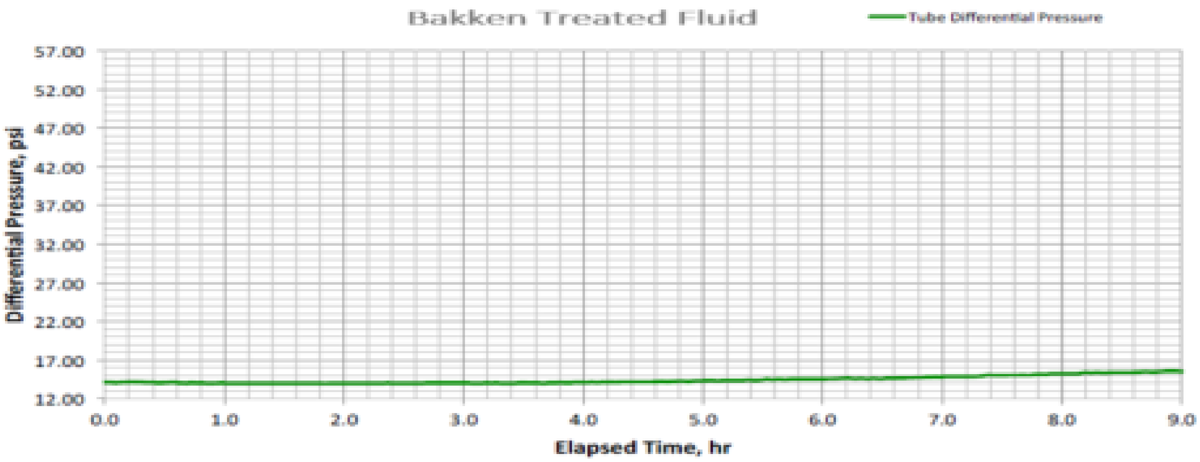
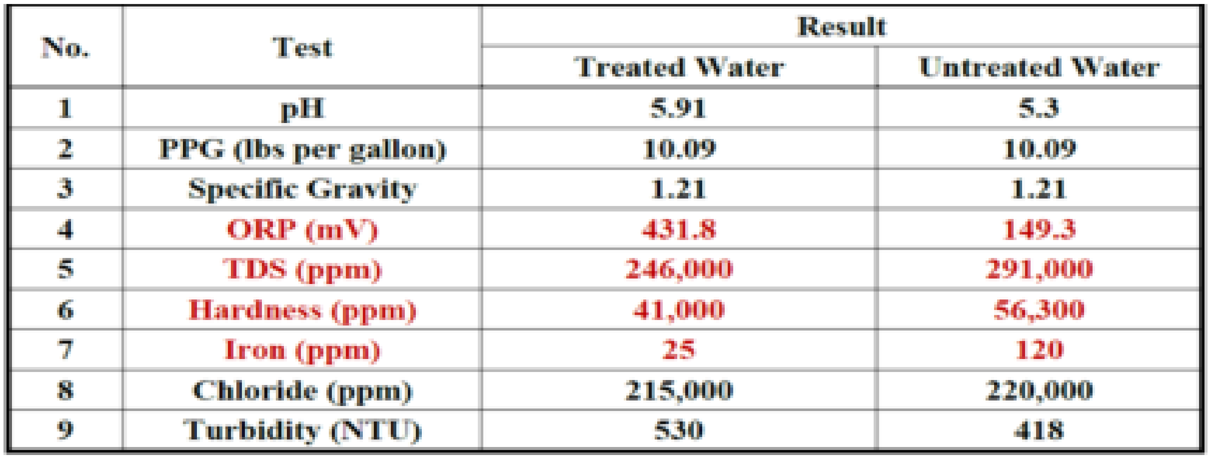


Figure 6.7: Treated fluid dynamic capillary tube blocking test

This experiment further shows that after the produced water is treated with this technology, scaling tendency of the treated water is almost zero. We also presented lab results of the various hydraulic frack fluid formulations made with the electro-chemical oxidation process-treated produced water.

We checked their stability with an advanced Rheometer from Grace Instrument. Results revealed that the hydraulic frack fluid made with the produced water treated with the electro-chemical oxidation process was completely stable under the various shear rates, reservoir temperatures, and different salinity level of the water. Table 6.1 and figures 6.8 and 6.9 show the results before and after treatment.

Table 6.1. Sample comparison between Bakken produced water treated with the electro-oxidation process and untreated produced water



No.	Test	Result	
		Treated Water	Untreated Water
1	pH	5.91	5.3
2	PPG (lbs per gallon)	10.09	10.09
3	Specific Gravity	1.21	1.21
4	ORP (mV)	431.8	149.3
5	TDS (ppm)	246,000	291,000
6	Hardness (ppm)	41,000	56,300
7	Iron (ppm)	25	120
8	Chloride (ppm)	215,000	220,000
9	Turbidity (NTU)	530	418

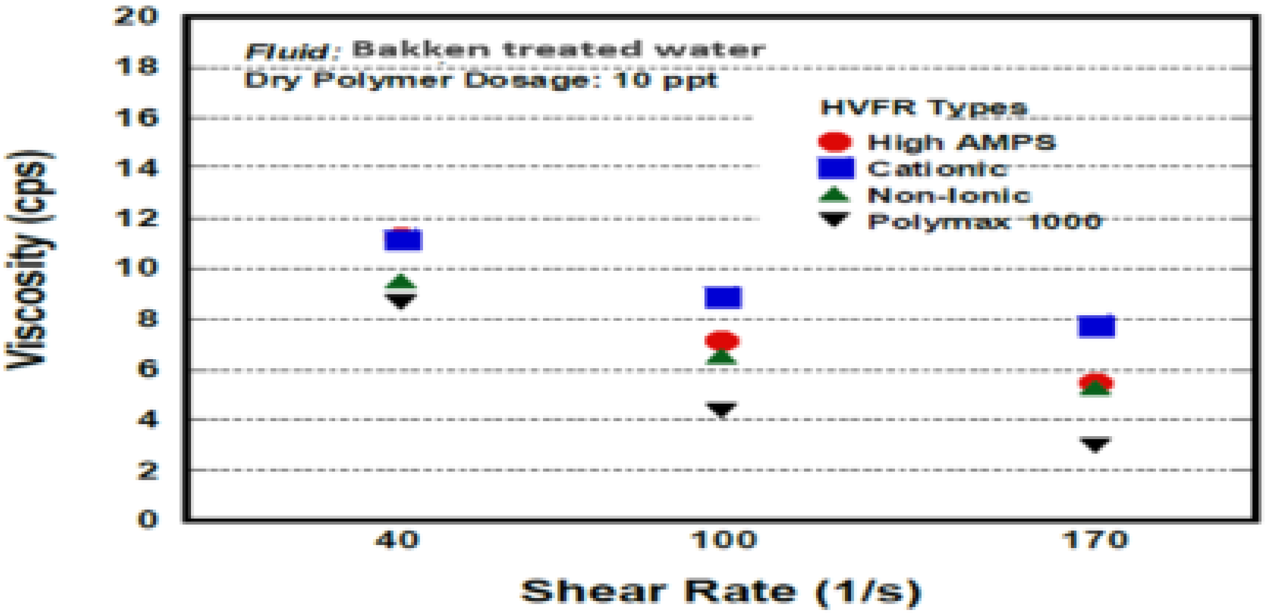


Figure 6.8: *Result showing viscosity versus shear rate profile of different types of HVFRs formulated with Bakken produced water treated with the electro-oxidation reactor.*

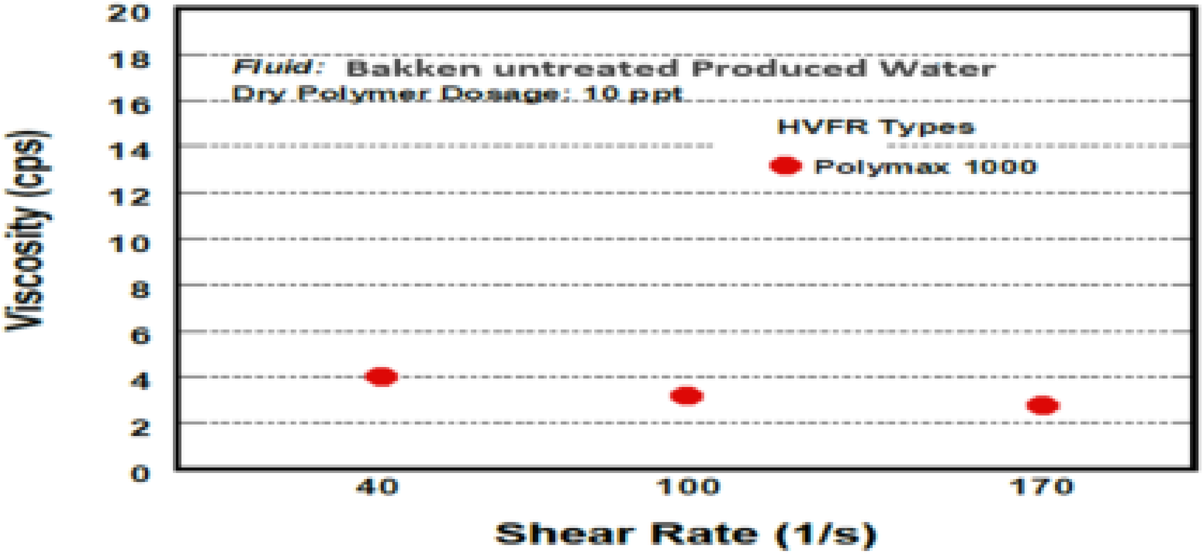


Figure 6.9: Result showing viscosity versus shear rate profile of different types of HVFRs formulated with untreated Bakken produced water

6.9 Discussion

In the Bakken, produced water production is increasing, and the handling cost is heavily impacting both the operator and the environment. This situation calls for intervention and a real shift in the way we legislate and regulate produced water management. High water production increases the occurrence of well-production issues like scaling, production string and surface equipment corrosion, bacteria, and possibly the formation of Naturally Occurring Radioactive Material (NORM). Transportation and disposal of the produced water is an additional burden on the logistic and operational cost. It is true that the mixing of two incompatible waters during hydraulic frack or water flooding jobs can be the main contributory factor in scaling tendency. The immediate problem is that developing a technology capable of treating the hypersaline produced water from the Bakken Formation to a level that is acceptable to the operators is almost infeasible.

The technology to transform Bakken produced water to fresh water could be very costly prohibitive. Therefore, the question to ask is “Do we really need to extract all the salt in Bakken water before it can be recycled and reused?” The answer is no. The technology presented here will not remove the salinity of the produced water. Rather, it will deal with organics, heavy metals, and bacteria, after which the water can be recycled or reused. As this technology is able to treat 100% of flow-back and produced water for bacteria and other organic material, scale-causing minerals, and oxidation and precipitation of heavy metals, it is now possible to process and treat all flow-back and production water and reuse it for hydraulic fracturing, water flooding or disposal into the right target without fear of reservoir contamination. This technology will help the operators in the Bakken to reduce the costs on freshwater acquisition, biocide treatment and disposal. It will help the state conserve its water resources. Also, the electro-oxidation water treatment process can achieve great cost savings as a result of its low use of additives during hydraulic fracturing jobs, because of the reduction in, or elimination of from oxidized metals that interfere with the fracking additives. In addition, the process can be tuned for high or low flow in order to match the flow treatment rates required for hydraulic fracturing jobs. Finally, the electro-chemical process leaves no footprint of harmful chemicals, which are thought to cause damage to production accessories on surfaces and wellbore. Because the process is relatively simple with regards to equipment deign, required minimal labor to operate the system, and uses electricity rather than chemical addition, the costs involved are low in comparison to other available treatment options.

6.9 Conclusions

Enormous advances have taken place in the development of the electro-chemical oxidation process, which can be applied to treat challenging water streams like super-saline Bakken flow-back and produced water efficiently and economically for reuse and recycle. This review has shown that electro-chemical treatment technology is efficient and versatile, able to handle a wide variety of production water conditions with challenging chemistry without any change in setup. As the electro-oxidation process encourages precipitation, these precipitated minerals are in the form of inert suspended solids rather than in a dissolved state. Thus, they are more stable; their state does not change, irrespective of changes in temperature and pressure. This unique property of the treated fluid enables the operators to recycle the hard, high-TDS produced water and use it in hydraulic fracturing operations as a fracking fluid by using salt-tolerant polymers.

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CHAPTER SEVEN

7 Treating and recycling Bakken Produced Water.

This chapter is taken from the paper entitled ***"Creating Value for The High-Saline Bakken Produced Water by Optimizing its Viscoelastic Properties and Proppant Carrying Tendency with High-Viscosity Friction Reducers"*** *published in the* ***"SPE Western Regional Meeting, April 20–22, 2021". Co-authors on this work include O. S. Tomomewo, M.D. Mann, A. Ellafi, H. Jabbari, C. Tang, M. Ba Geri, O. Kolawole, A. Adebisi, O. Ibikunle, M. Alamooti, A. Iroko.*** *They contributed to this work by providing help in performing some of the experiments and reviews. I have contributed more than 75% of the effort to this work. My efforts include preparing and analyzing samples, identified major issues, developed interpretations, fully drafted papers, discussions and conclusions,*

Abstract

Since the arrival and advancement of horizontal drilling and hydraulic fracturing technologies, developing and producing unconventional formations like the Bakken Formation have become a mystery solved for operators in North America. This has made unconventional reservoir assets the central focus of the oil and gas/energy industry at the state, national, and global levels. However, the water produced from these activities has high salt contents (~170,000 to 350,000 ppm) total dissolve solids (TDS) in the Bakken Formation) and hazardous if untreated and in contact with the environment. The most common disposal method in the Bakken Formation is deep injections into disposal wells. However, there have been some fears that continuous *injections, in addition to contaminating the ground water, could potentially lead to seismic activities either at the time of injection or in the near future. If treated and made fit for its respective applications, this water could be reused in the hydraulic fracking process, thereby reducing operator costs of water acquisition and disposal. In addition, it could be used for power generation or to support coal mining and irrigation. Previous studies have discussed various means of improving the quality of the water produced. However, none have been able to cope with the issue of wastewater and residual oil high in TDS. This thesis aims to study all relevant means that allow the Bakken Formation to produce water that can be used as an alternative based fluid for use with polymers like high viscosity friction reducers (HVFRs) to make hydraulic frack fluids that will be stable with reservoir conditions and able to reduce environmental footprints and operating costs. This research presents an experimental investigation using the Bakken Formation's hypersaline water with HVFRs. This work includes experimental research divided into base case scenarios that serve as a standard for comparison of the effectiveness of the other cases. The results show that the Bakken water high in TDS treated with higher dosages (4–8 GPT) of HVFRs withstand the effect of hardness, salinity, and heavy metals and remain stable at various shear rates (66–330* s^{-1}*). No treatment was done on the Bakken produced water except filtration and dilution.*

7.1 Introduction

Globally, hydraulic fracturing is one of the only means of extracting the locked hydrocarbon in an unconventional resource. To generate fractures, large volumes of fracturing fluid must be pushed at high rates into the reservoir. Fracturing fluids primarily consist of a water and sand mix with a small proportion of chemical additives. Among the additives, polymers are key and mandatory for properties such as friction reduction, increased viscosity, clean breaks, and high and sustainable conductivity from the well after commissioning. Recently, an urge to improve cost savings, environmental concerns, and operational efficiencies has necessitated a drive towards the use of fewer chemicals and less fracturing equipment on location. Therefore, the use of polyacrylamides as friction reducers has also increased since it fits into all of the above requirements. Among the many polyacrylamides used in unconventional well development, viscosity-building friction reducers (VFR), also known as high-viscosity friction reducers (HVFRs), are being increasingly used today (Motile et al., 2016; Sanders et al., 2016; Van Domelen et al., 2017; Dahlgren et al., 2018; Geri et al., 2019). The HVFR fluid systems have proven successful, and since they can reduce pipe friction during hydraulic fracturing operations, they develop higher viscosities than traditional hydraulic frack additives. High-viscosity friction reducer fracture fluids have also shown to be one of the best fracture fluids in terms of stability with reservoir temperature requirements, the salinity level of the water produced, high fracture length (Ellafi et al., 2020), and most importantly, for their low cost.

Government regulations regarding freshwater use and wastewater disposal have expanded due to an increase in well development activities. This increase has also led to an increase in hydraulic frack water requirements of unconventional assets like the Bakken Formation. According to the record of the U.S. Environmental Protection Agency (EPA), the hydraulic fracturing operations of wells that consists of 42 stages of hydraulic frack completion designs would require between 3 and 5 million gallons of water (API, 2017). The use of that amount of water could threaten access to freshwater for other communities. In addition, the cost of acquiring the water and transporting it to the well location could be high. Therefore, operators should explore all means of recycling the water produced by reusing it as base fluids for compatible hydraulic fracking fluid polymers. The use of water produced instead of freshwater as base fluids in the formulation of hydraulic fracking fluids is uncommon in the Bakken Formation.

The only way to minimize freshwater usage, reduce wastewater disposal, reduce operating costs, and increase hydrocarbon recovery from unconventional formations like the Bakken is to develop a means of efficiently recycling the water produced. Typically, polymer friction reducers perform inefficiently in highly saline water. Several researchers have conducted research to understand the behavior of different polymers with different salinity levels. Yamak et al. (2018) presented rheology studies of cross-linked fracturing fluids applied to seawater. Results established that a dual-cross-linked seawater-based fracturing fluid stability was practical, as viscosity was stable above 500 cP for two hours. In addition, Johnson et al. (2018) described successful case studies realized in Marcellus and Bakken Formations using high-brine viscosity-building friction reducers (HBVB) in produced water with high salinity. The TDS in the Marcellus Formation was in the range of 30,000 to 50,000 ppm. The Marcellus shale HBVB was favored over guar-based systems as it proved to have better performance, optimal lab measurements, and various field applications. However, in the Bakken Formation, none of the seven different types of friction reducers chosen and applied were compatible with the water produced except one, which contained loadings from 1.5–3.6 GPT HBVB. Due to this, slick water fracturing fluid became undesirable, and HVFRs in fracturing fluids were seen more favorably as they appeared to be more compatible with shale plays. In addition, HVFRs are inexpensive and can support effective proppant transport mechanisms (Goma et al., 2015; Ellafi et al., 2019).

Ba Geri et al. (2019) investigated identical shear-viscosity profiles of fracturing fluids, such as HVFRs and linear gel in both freshwater and produced water. Even though the tested fluids had similar viscosity measurements in freshwater, the rheological characterization differed in the produced water. The elasticity properties (normal forces of HVFRs) showed a significant reduction with saline water, which could mean that there could be poor proppant transport if not enhanced. This thesis focuses on the application of produced water with fracturing fluids (HVFRs) in unconventional shale plays through a case study of the Bakken Formation, Williston Basin, ND. This work is extended from our previous publications (Ba Geri et al., 2019; Ellafi et al., 2019; Tomomewo et al., 2020) to study the capability of high viscosity friction reducers (HVFRs) in harsh conditions using lab investigations and simulation works. The fracturing fluid characterizations (rheology) of HVFRs were performed to address the evaluation of the HVFRs viscosity profile at 70 under a wide range of shear rates (66–330 s^{-1}), different dosages, and various dilution percentages of produced water (e.g., 10% produced water and 90% freshwater). Moreover, various temperature effects were investigated to evaluate the HVFRs heat resistance. To conclude, utilizing produced water for hydraulic fracturing in the oil and gas industry is gaining popularity as using produced water had led to operational cost savings and environmental benefits. However, the compatibility of the friction reducers with the various types of produced water requires different test protocols.

7.2 Legislations concerning produced water disposal in North Dakota

Most of the oil and gas-producing states have stringent laws that prohibit improper disposal of wastewater, including the produced water. In the U.S., the EPA regulates all household and industrial manufacturing of solid and hazardous wastes through the Resource Conservation and Recovery Act (RCRA). The RCRA’s goals are to protect citizens from the hazards of harmful waste disposal, reduce or totally eliminate activities that could lead to the production of hazardous waste, and help in the clean-up operation of waste that may have been spilled, leaked, or improperly and unlawfully disposed of. In North Dakota, produced water disposal is strictly controlled by the Underground Injection Control (UIC) program under the Safe Drinking Water Act (SDWA 1974 [EPA, 2015]). The responsibility of UIC is the regulation of all operations related to the injection wells that are used to inject fluids into the Dakota Group formation or other wastewater disposal wells. An injection well is used to push fluids deep underground into rock units with significant pore space, such as sandstone or limestone, and also has the trap and seal properties similar to an oil and gas reservoir. Injection wells are grouped into six classes by the EPA in North Dakota, saltwater disposal (SWD) wells, considered Class II UIC wells, were most common and used for all produced water disposal. The use of the injection well began in the U.S. in the 1930s and used to dispose of wastewater accumulated during oil and gas operations.

7.3 Bakken Petroleum System (BPS), Williston Basin

The Williston Basin is a shared area between the U.S. and Canada, as shown in Figure 1. The basin occupies about 225,000 square miles of the subsurface and covers parts of Eastern Montana, Southern Saskatchewan, Manitoba, and Western North Dakota (Meissner, 1991). According to the North Dakota Industrial Commission (NDIC), the Williston Basin consists of sedimentary rock layers 16,000 ft below ground that were formed millions of years ago and accumulated near the center of the basin. As a result, the basin is a major source of fossil energy, such as oil, natural gas, and coal. Furthermore, the most productive formation in the Williston Basin is the Bakken Formation, known as the Bakken Petroleum System (BPS). The initial oil in place was estimated to be between 100 to 900 billion barrels of oil and produced from several reservoirs, such as Parshall, Sanish, Reunion Bay, Bailey, Murphy Creek, Antelope, and Elm Coulee Fields.

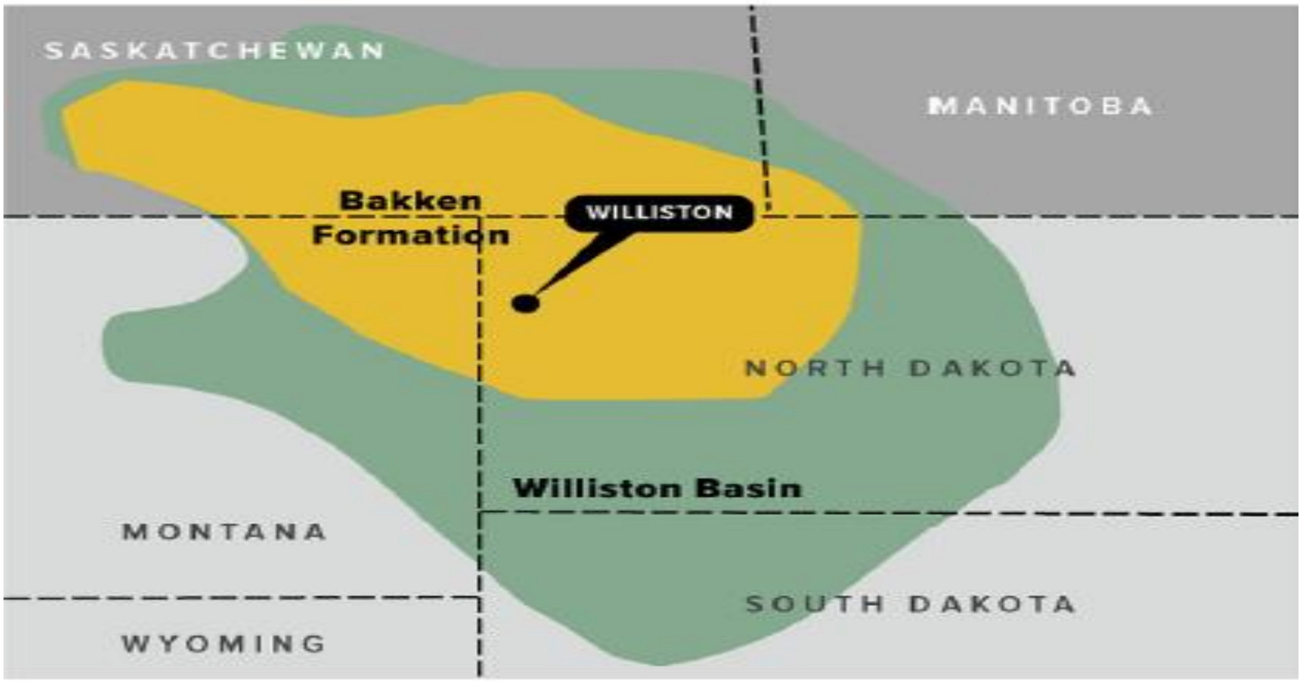

Figure 7.1: Location of the Bakken formation and extent of the Bakken Formation (U.S. Bureau of Land Management).

LeFever (1991) described the sequence of the Bakken Formation as "two, black fissile shales separated by light grey to grey brown fine grained sandstone". The Bakken Shale Play is subdivided into three distinct stratigraphic members: Upper Bakken (UB), Middle Bakken (MB), and Lower Bakken (LB), listed from top to bottom, as illustrated in Figure 7.2.

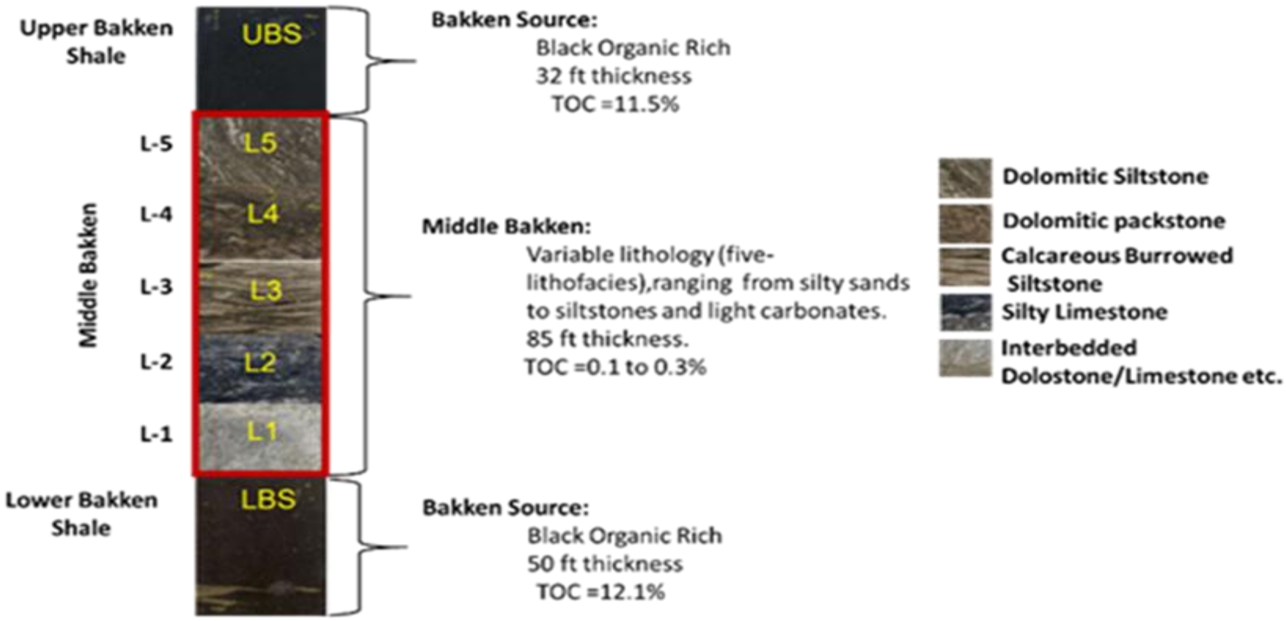

Figure 7.2: The Schematic of Bakken Petroleum System Stratigraphy (Jin et al., 2016).

As illustrated in Figure 8.2, the lithofacies in the middle member represent mixed lithology of limestone, sandstone, and dolomite throughout the basin, where five primary facies were found in the Middle Bakken Formation. This member acts as a reservoir rock and the target pay-zone for horizontal wells with a thickness of 85 ft. In addition, the total organic carbon (TOC) content in the middle member has a low range from 0.1 to 0.3 wt%. On the other hand, the upper and lower members are mainly organic-rich black shale and considered a seal and source rock due to a high amount of TOC ranging from 12 to 36 wt%, and with a high concentration of Type II kerogen. The formation thickness in both upper and lower members are 32 ft and 50 ft, respectively (Meissner, 1991; Kurtoglu, 2013; Klenner et al., 2014; Assady et al., 2019). The pore structure of the Bakken Formation is very complex, where the Middle Bakken member is characterized by low porosity (<10%) and ultra-low permeability (<0.01 md). Therefore, based on these reservoir properties, the Bakken Shale Play is classified as an unconventional reservoir. Furthermore, geostatistics modeling has indicated that the Middle Bakken Member is highly heterogeneous throughout the Williston Basin. In addition, the fluid transport is governed through the fracture networks (natural and artificial fracture) at both the micro and macro scale (Klenner et al., 2014). Therefore, a stimulation process is required to use modern horizontal drilling and a multi-stage hydraulic fracture application to develop and produce economically from this vast reserve.

7.4 Characteristics of produced water from unconventional wells: The Bakken Case Study

Unconventional fields may be defined as fields that harbor crude oil and natural gas that can only be produced with both directional drilling and hydraulic fracturing technologies (EIA, 2019). Unconventional reservoirs include tight oil, tight gas, coalbed methane (CBM), and shale gas and have a very high saline composition of produced water. For CBM, the produced water compositions are unfit for immediate reuse of any form. Coalbed methane produced water contains heavy metals, high salt contents, and some traces of iron, boron, and magnesium (ALL, 2003). As mentioned above, produced water may differ in physical and chemical properties, and these differences may be a result of different geographic locations in the field, the geologic formation source reservoirs, and the type of production. For example, the production of methane from coalbed methane will have produced water different from produced water from the production of oil or gas.

In 2008, Benko and Drews conducted a study on produced water in the western U.S. and concluded that oil and grease in produced water exist at a range of 70–2,000 mg/L. Salt is the largest constituent of produced water globally, and the main concern for both onshore and offshore operators. The study done by Benko and Drewes (2008) found that the TDS of produced water from wells around the Western and Northern parts of North America vary between 1,000 mg/L and 400,000 mg/L. However, the median TDS concentration from most unconventional wells in our study was not less than 141,000 mg/L. Saltwater in the Bakken also varies in characteristics such as the pH, TDS, concentrations, and several other individual chemical properties (figure 7.3). For produced water from oil drilling, completion, and production activities, there are usually other components present in addition to those that naturally formed with the produced water within the reservoir rock.

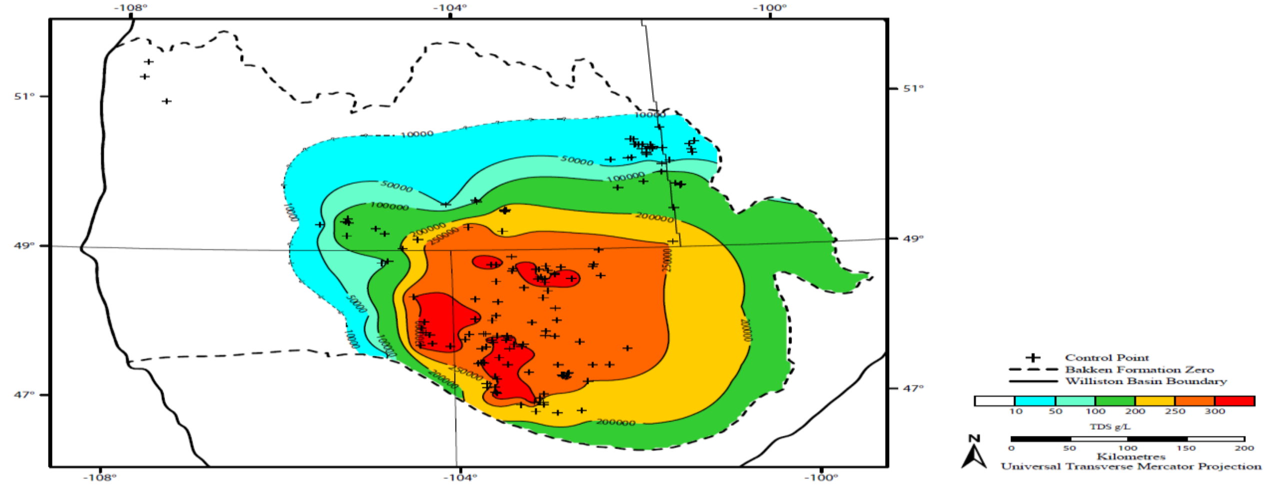

Figure 7.3: Total dissolved solids (TDS) distribution in the Bakken Formation water (Montreal et al., 2014).

7.5 Fundamentals of Na-Cl-Br Systematics

Sodium-Chloride-Bromide (Na-Cl-Br) systematics is the most extensively used system to investigate the source and drifting history of saline formation waters in sedimentary basins like the Bakken (Carpenter, 1978; Engle and Rowan, 2012; Sminchak et al., 2014). Researchers have shown that Br- does not participate in diagenetic reactions, making it the best tracer for the evolution of brines originating as seawater (Carpenter, 1978; Kuznetsov, 1996; Galeev et al., 2014). At the time of the progressive evaporation of seawater, Na^+, Cl^-, and Br^- concentrations would always increase by the same factor prior to halite saturation (Danjo et al., 2014; McCaffrey et al., 1987). At the point where brine attained halite saturation, Na^+ and Cl^- were naturally removed from the solution while Br^- was virtually excluded from the halite lattice. Continued evaporation past halite saturation led to a rapid increase in the Br^- concentration relative to the TDS of the remaining solution (Rittenhouse, 1967). Thus, the behavior of Br^- relative to Cl^-, Na^+, and TDS provided useful information in determining the origin of salinity in produced water. In addition, brines resulting from the evaporation of seawater usually have lower Na^+/Br^- and Cl^-/Br^- ratios than seawater, while brines resulting from halite dissolution were depleted in Br^- and have Na^+/Br^- and Cl^-/Br^- ratios greater than those of seawater, according to Walter et al. (1990). In addition, in most water, the only appreciable source of Na^+, Cl^-, or Br- is from halite dissociation or the evaporation of seawater, and as a result, water is believed to evolve along a single linear trend known as the seawater evaporation trajectory (SET) (McCaffery et al., 1987; Engle and Rowan, 2012).

7.6 Ion chemistry of the Bakken connate water (major ions)

Bakken connate water primarily consists of Na-Cl type waters. Nevertheless, there are also Na-SO_4-produced water types that are spatially linked with Na-SO_4 formation waters around the northwest corner of the Bakken Formation. However, the Na-Cl waters are the most common type everywhere in the Bakken Formation. Understanding the variability of the Bakken Formation in terms of TDS water is key to understanding the type and level of treatment that will be suitable. For sodium (Na^+), it is a linear relationship with TDS of up to 350,000 mg/L in some counties. As soon as the TDS rises above 200,000 mg/L, the direct relationship begins to drop with more variable Na^+ content. The spread of the chlorine/sulfate distributions within the Bakken is shown in Figure 7.4.

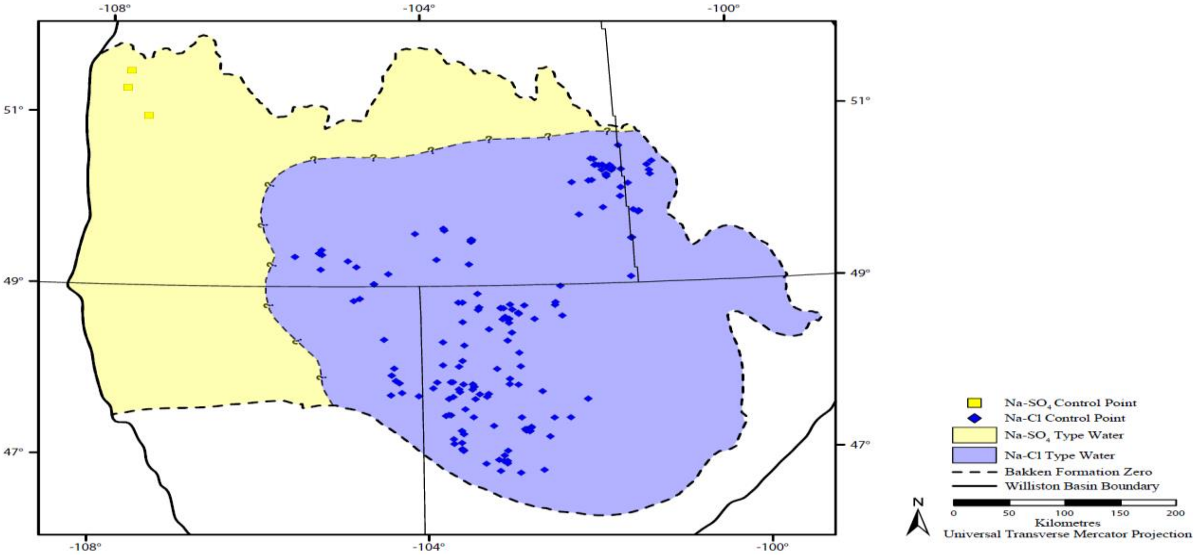

Figure 7.4: The spread of Na-SO4 and Na-Cl type waters in the Bakken Formation water (Montreal et al., 2014).

Chloride is the leading anion in the Bakken Formation water, with most samples being above 75%, while Sulphate (SO_4^{2-}) was among the anions with the lowest concentration in the Bakken Formation water. However, for waters with TDS greater than 50,000 mg/L, SO_4^{2-} accounts for about 85% of the total anions in the Bakken Formation waters. From a literature study of various concentrations of Bakken produced water, we confirmed that water at approximately 100,000 mg/L TDS usually contained approximately 10% SO_4^{2-}, and at double the TDS concentration (waters with TDS >200,000 mg/L), SO_4^{2-} was noticed to decrease to 2.5%. As the TDS increased further, SO_4^{2-} presence in the even reduce further (Montreal et al., 2014).

The relationship of other major ions are shown in the Piper diagram in figure 9.5. Calcium (Ca^{2+}) concentrations in the Bakken rocks are extremely unbalanced. About 30% of the total cations in the Bakken Connate water are calcium with almost 50,000 mg/L TDS. Produced water compositions with a TDS between 50,000 mg/L and 200,000 mg/L would have a low Ca^{2+} percentage (between 1% and 8%), while brines with salinities over 200,000 mg/L consist of up to

25% Ca^{2+}. Potassium (K^+) concentrations were also found to be highly dynamic as they showed an exponential increase as TDS increased. The Bakken Formation waters with TDS values of less 200,000 mg/L contained roughly the same K^+ concentration regardless of salinity as K^+ concentrations over this range were approximately 115 mg/L to 600 mg/L. At salinities greater than 200,000 mg/L, K^+ concentrations may also become highly unstable. Formation waters with TDS greater than 50,000 mg/L would usually have Mg^{2+} consisting of up to 5.7% of the total cations (Montreal et al., 2014).

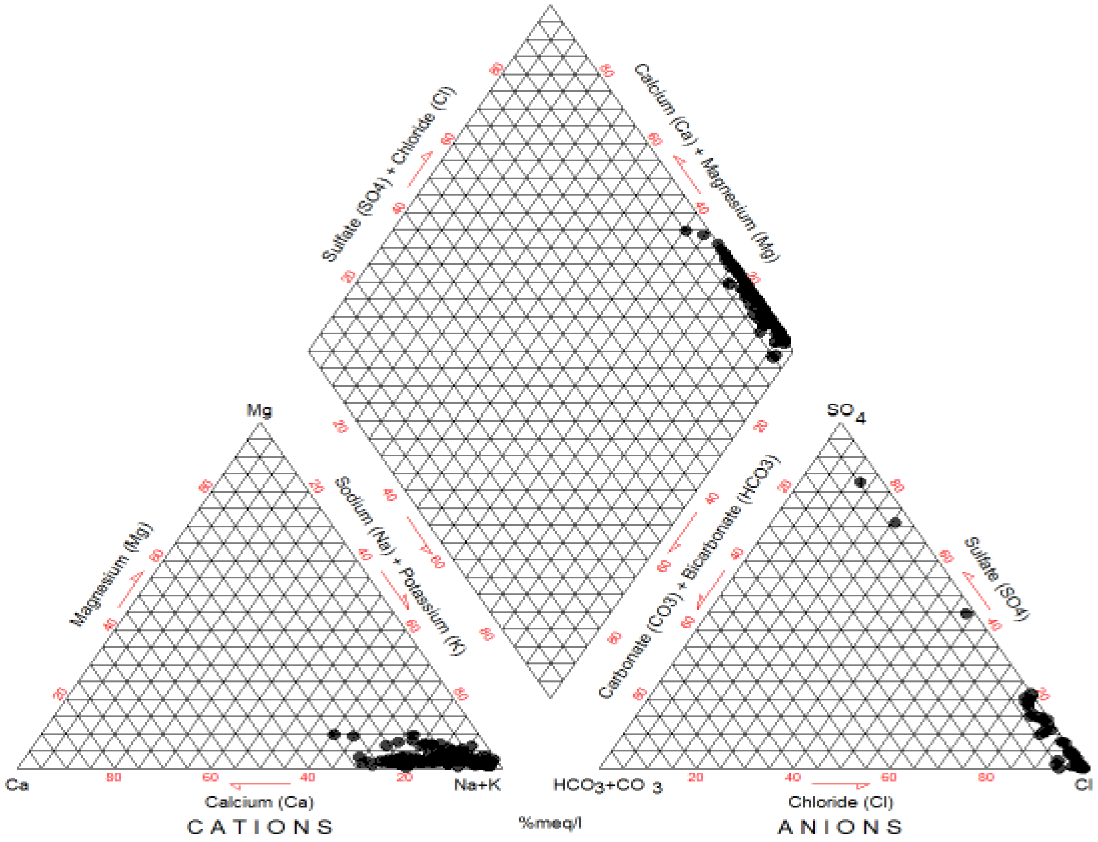

Figure 7.5: Piper diagram for Bakken produced waters (Meredith and Kuzara, 2018).

7.7 Produced water handling and management

As mentioned in the previous sections, water is produced in conjunction with the production of crude oil or gas. This causes both the operators and the oil and gas sector regulators concerns; per the almost irreversible harmful effects this heavily contaminated water could pose on the environment if not properly neutralized before any form of disposal. For effective water management, an understanding of the production status of the well in terms of water cut and all impurities that the produced water may contain is needed. Impurities in produced water may include dissolved minerals, dissolved gasses, and suspended solids. Suspended solids usually found in a mixture of produced water may be naturally occurring, generated as a result of precipitation of dissolved solids in the water mix, corrosion of production pipes, or the bacterial activities.

Moreover, the water supply available in the Missouri River system and Lake Sakakawea is believed to be in excess, and the general public seems to think that the impact of drawings from these sources is negligible in terms of the total accessible water capacity, which is untrue. Currently, in the Bakken Formation, there are more than 3,000 disposal wells already drilled and in operation and within miles of the Bakken operators. It is true that the treatment cost of the Bakken produced water will be cumbersome and energy consuming, considering the high salinity and heavy metals present (Stepan et al., 2010), however, the cost of the current disposal options are equally expensive (see Table 8.1). Recently, research has shown that some technological developments related to salt-tolerant fracturing fluid, such as HVFRs systems, could allow for the use of lightly treated produced water. This technology is opening up new opportunities for the treatment and recycling of Bakken produced water and thereby reducing wastewater injection. This is the basis of our research.

Table 7.1. Approximate water handling cost in the Bakken Formation (EERC Bakken Water Report, 2019).

Cost Items	**Cost, $/bbl.**
Freshwater	0.25–.05
Transportation (Freshwater)	0.63–5.00
Transportation (Wastewater)	0.63–9.00
Deep Injection Cost	0.50–1.77

7.8 History of hydraulic fracture treatment fluids

The earlier hydraulic fracturing treatments were conducted in the early 1940s with oil-based fluids having gelled hydrocarbons. Water-based fracturing fluids became popular in the 1950s (Smith, 1965) and have since become the preferred hydraulic fracturing fluids. One of the reasons for this is due to water-based fracturing fluid systems being less expensive and safer options compared with the oil-based fluids. Common types of water-based hydraulic fracking fluids are slick water, linear gel fluids, and cross-linked fluids. Moreover, HVFRs, the focus of this thesis, are also a type of water-based hydraulic fracking fluids. Other types of water-based fracturing fluids include viscoelastic surfactant (VES) fluids (Ozden et al., 2017; Afra et al., 2019; Fontana et al., 2007). An efficient hydraulic fluid should have some basic characteristics to be acceptable and able to initiate a frack and transport proppant. Other acceptable features of hydraulic frack fluid that can make it acceptable by the operators includes the ease of formulation, low fluid loss to the formation, stable viscoelastic properties under reservoir conditions that support efficient proppant transport, moderate friction pressure, enough shear resistance, minimal formation, proppant pack damage, reservoir compatibility, and low cost.

Slick water hydraulic fracking fluids predominantly consist of water with some components of a friction reducer like acrylamide-based polymers and copolymers to reduce resistance to fluid flow in surface lines and well casing during pumping. Slick water viscosity resembles that of freshwater and is usually pushed at high rates (>62 bpm) to create slim cracks with low doses of proppant, typically on the range of 0.25–1 pound per gallon added (Murphy et al., 2019). The linear fluids analogy is based on uncross-linked solutions of polymers such as guar, guar cellulose, cellulose derivatives, other polysaccharides such as xanthan gum or synthetic polymers. From the literature review, we found that most of the water-based fluids were formulated with guar or guar derivatives (Sanders et al., 2016). Guar is a high molecular weight polymer with a mannose backbone and galactose side chains.

The viscosity of a linear fluid can be several orders of magnitude higher than that of slick water; therefore, possessing much better proppant suspension and transport capability. However, this is dependent on the polymer dosage in the designed formulation for the required application. Compared with linear fluids, cross-linked fluids show improved performance without increasing the polymer concentration. For example, cross-linked fluids have a larger capacity to suspend and transport proppant particles than the corresponding uncross-linked fluids with the same polymer dosage.

Guar fluids are still the most widely used fluids in fracturing operations due to their low cost, performance flexibility, and shear stability (Lei et al., 2004; Alharbi et al., 2017; Pandey et al., 2001). In the early 1970s, metal-cross-linked water-based fracturing fluids were implemented for jobs at higher bottom hole temperatures. The most common metal cross-linkers were based on the zirconium and titanium compounds. The metal cross-linkers were usually complexes of zirconium or titanium with certain organic ligands or chelators, such as zirconium ammonium lactate, zirconium acetate, or titanium triethanolamine (Fontana et al., 2007).

Slick water or hybrid fluid systems are typically used to create more complex fracture networks than conventionally used cross-linked fluids (Sanders et al., 2016; Ozden et al., 2017). However, as mentioned above, due to their intrinsic low viscosity, slick water fluids have low capabilities for proppant transportation and must be pushed at higher rates. The high pumping rate in slick water jobs can significantly affect the pump and other running tools. It can also cause erosion that can quickly erode production tubing and increase the corrosion tendency. To reduce the equipment breakdown and to enhance the proppant transport and placement, hybrid treatments were implemented to maximize the benefits of both slickwater treatments and linear/cross-linked fluid treatments for unconventional reservoirs. During a hybrid treatment, slick water injections were carried out to generate complex fracture networks, followed by linear, cross-linked, and HVFRs fluids with a better capability of transporting and placing the proppant. Recently, such hybrid jobs have grown rapidly for horizontal wells in unconventional formations like the Bakken Formation (Lei et al., 2004).

The use of HVFRs for hydraulic fracking fluids in unconventional plays is a result of its successful record and many advantages over other fracture fluids. Some of these advantages include better proppant carrying capabilities, the ability to create more complex fracture system networks with a higher half-length, and, more importantly, cost-effectiveness due to fewer additives, less surface, and running tool damage. However, there remain some notable concerns such as the stability of the visco-elastic propertied under different water salinity and reservoir conditions (temperature, pressure, and shear rate). This raiases the following research question: How will the fluid react under 10%, 30%, and 50% base fluid salinity?

Considering that the cost of fresh and produced water disposal continues to increase, the oilfield services companies and operators should see the need to minimally treat and recycle as much produced water as possible, without the expensive purchase and trucking of freshwater. More specifically, for hydraulic fracturing operations, the target is to have fracturing fluid systems that can be formulated directly with produced water and ensure compatibility with the native water of the reservoir to reduce issues that result from water incompatibilities. More fracturing fluids are being formulated with high-TDS produced water and have been successfully implemented in hydraulic fracturing jobs (Ellafi et al., 2020).

7.9 General experiment description

This study aims to investigate how to create value and reusability for the Bakken produced water. In order to do this, we conducted an experiment to blend the raw Bakken produced water with freshwater. The research used a base case, created three treatment scenarios, and compared the base case with the best scenario(s) selected. After dilution, treatments were admitted on the fluid with different dosages of HVFRs (non-ionic). This type of HVFRs was used for its compatibility with the Bakken oil-bearing shales. Cationic types of HVRs, if used in the fracturing fluids mixture, will react with the Bakken shale and cause serious damage and instability issues to the well.

7.10 Experiment design

7.10.1 Water analysis

Even though freshwater availability continues to grow scarce, the total volume of water needed for hydraulic frack jobs continue to increase in response to increasing population and energy needs. Generally, the level of ions in produced water samples depends on its salinity levels, and this affects the HVFR performance. This is a result of the fact that HVFR has a clear hydrophilic property, and anionic features that allow monovalent and divalent cations to interfere with the polymer by extending the polymer chains of anionic HVFR. The type of HVFR used in this thesis is ionic. It is important to ensure proper handling of divalent cations, such as Fe $^{2+}$, Ca^{2+}, and Mg^{2+}, due to their strong ability to interact with the anionic charge of HVFR and divalent cationic charges. In this study, we created four scenarios: Base Case, Case 1, and Case 2. The dilution factor and the HVFR loading used for each case follows:

Base Case: 100% freshwater was used as the base case. About 1,000 mg of raw Bakken produced water from McKenzie County was filtered and sent to the lab for a full analysis. To measure the friction reduction and viscosity profile in the Bakken freshwater, different dosages (0.25, 0.5, 2.0, 4.0, 6.0, and 8.0, GPT) of HVFRs were applied. These formulations were then tested for stability (viscosity, cp and shear rate, and 1/s) with the Brookfield Coaxial Cylinder Rheometer at a 70°F to 150°F temperature range. The equipment and procedure is described in Section 8.10. Figure 9.6 depicts the experimental procedures used.

Figure 7.6: The frack fluids formulation process.

Case #1: 90% Bakken freshwater and 10% filtered Bakken produced water as base fluid was used for Case#1. To measure the friction reduction and viscosity profile in the blend of BFW and BPW, different dosages (0.25, 0.5, 2.0, 4.0, 6.0, and 8.0 GPT) of HVFRs were applied. This was then tested for stability (viscosity, cp and shear rate, and 1/s) with the Brookfield Coaxial Cylinder Rheometer at a 70°F to 150°F temperature range.

Case #2: 70% BFW and 30% filtered BPW as base fluids was used for Case # 2. **To measure the friction reduction and viscosity profile in the blend of BFW and BPW, we reduced the dosages of higher loading as the effect of salinity on the elastic chains of the HVFRs increased with higher salinity composition of the base fluids. Thus, we applied (4.0, 6.0, and 8.0 GPT) of HVFRs. This was then tested for stability (viscosity, cp and shear rate, and 1/s) with the Brookfield Coaxial Cylinder Rheometer at a 70°F to 150°F temperature rang**e.**Case #3:** 50% BFW and 50% filtered BPW as base fluids was used for Case #3. To measure the friction reduction and viscosity profile in the blend of BFW and BPW, we reduced the dosages of higher loading, and the effect of salinity on the elastic chains of the HVFRs increased with higher salinity compositions of the base fluids. Thus, we applied (6.0 and 8.0 GPT) of HVFRs. This was then tested for stability (viscosity, cp and shear rate, and 1/s) with the Brookfield Coaxial Cylinder Rheometer at 70°F and 150°F temperature range.

Figure 7.7 shows the different formulations used for the testing.

Figure 7.7: Different case formulations of the hydraulic frack fluids.

7.11 Rheology Experiment Setup

The rheological measurements for the HVFR fluids were conducted using a Brookfield coaxial cylinder rheometer with a ± 1% of measured range accuracy. The coaxial cylinder rheometer is a rotational rheometer that measures the torque required to spin a spindle immersed in an HVFR fluid sample at a specified rotational speed. The spindle attached to the rheometer was connected to a calibrated spring and driven by a precision motor. The shear stress and viscosity for an HVFR fluid sample were measured from the angular deflection of the spring in proportion to the spindle’s rotational speed. The relative angular deflection experienced by the spring, in response to the viscous resistance of an HVFR fluid sample, was detected by a rotary variable differential transformer (RVDT) in the rheometer. The shear rate was adjusted by varying the spindle's rotational speed. In this experimental study, the viscosities of the HVFR fluids were measured at five different shear rates, between 66 and 330 s^{-1}.

Temperature is a factor that affects the rheological behavior of an HVFR fluid. In this experimental study, the viscosities for the HVFR fluids were measured at 70°F and 150°F. To maintain a constant temperature for the HVFR fluid sample during the measurement, the sample chamber was inserted into a water jacket. The water jacket was then connected to a constant temperature controller/bath, and precise temperature control was achieved with circulating water from the temperature bath to the water jacket. A resistance temperature detector (RTD) was embedded in the sample chamber to provide direct temperature measurement of the HVFR fluid sample with an accuracy of ± 0.2°F. A schematic for this rheological experiment is illustrated in Figure 7.8. The rheometer and the constant temperature controller/bath were connected to a computer. A data acquisition software in the computer served as an interface to communicate between the computer, the rheometer, and the constant temperature controller/bath. The data acquisition software was programmed to record viscosity measurements from the rheometer at the prescribed shear rates and temperatures.

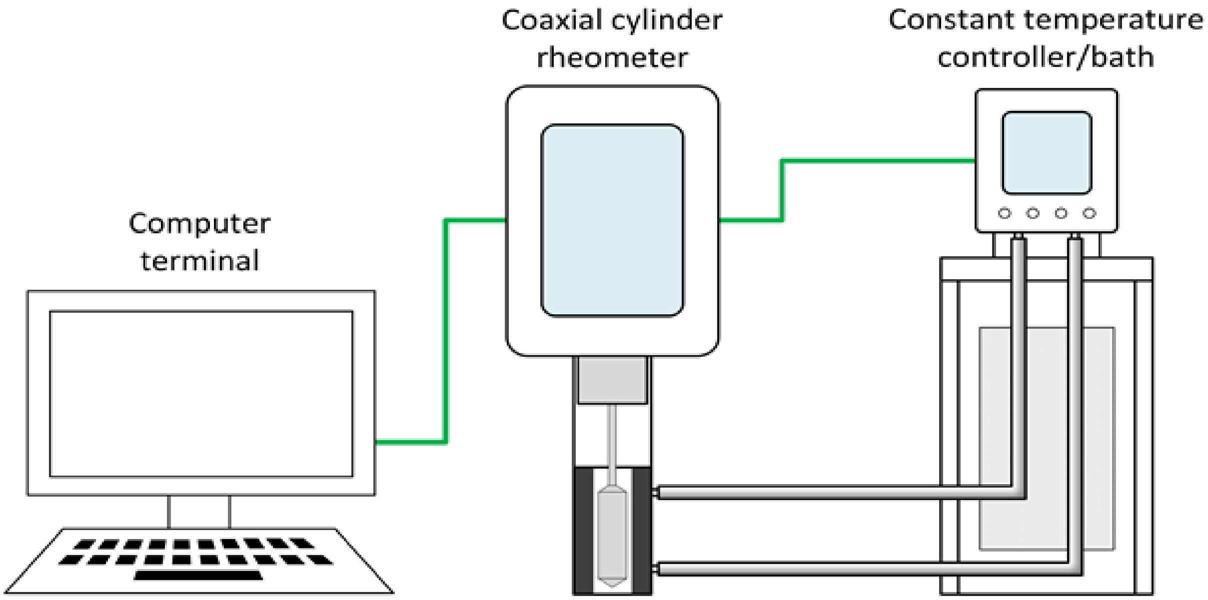

Figure 7.8: Experimental setup schematic for the rheological measurements of HVFR fluids.

7.12 Results and Discussion

7.12.1 HVFR viscosity profiles of the Bakken produced water

For this experiment, we first analyzed untreated Bakken produced water to understand the chemical composition and concentration of elements present in the water. Table 9.2 presents the composition of the Bakken fresh water and the Bakken produced water used for these experiments. An undiluted sample was used to establish a baseline, with subsequent cases performed on diluted samples in accordance to the cases discussed above and presented in Table 9.3.

Table 7.2. Summary of rheology case scenarios.

	Base Case	**Case 1**	**Case 2**	**Case 3**
Rheometer Type	Coaxial Cylinder Rheometer	Coaxial Cylinder Rheometer	Coaxial Cylinder Rheometer	Coaxial Cylinder Rheometer
Base Fluids Blending Ratios	100% FW	90% FW / 10 PW	70% FW / 30 PW & 50%FW / 50% PW	70% FW / 30 PW & 50% FW / 50% PW
Dosage	0.2, 0.5, 2.0, 4.0, 6.0, and 8.0 GPT	0.25, 0.5, 2.0, 4.0, 6.0, and 8.0 GPT	6 GPT and 8 GPT	8 GPT
Shear rate	66–330 s^{-1}.	66–330 s^{-1}.	66–330 s^{-1}.	66–330 s^{-1}.
Experiment Temperature	70°F and 150°F	70°F and 150°F	70°F and 150°F	70°F and 150°F

Data from the rheology experiments for the base case are presented in figures 9.9 and 9.10. In addition to the typical shear versus viscosity curves, the data in the plots for the base case show that as temperature increases the viscosity profiles decreases.

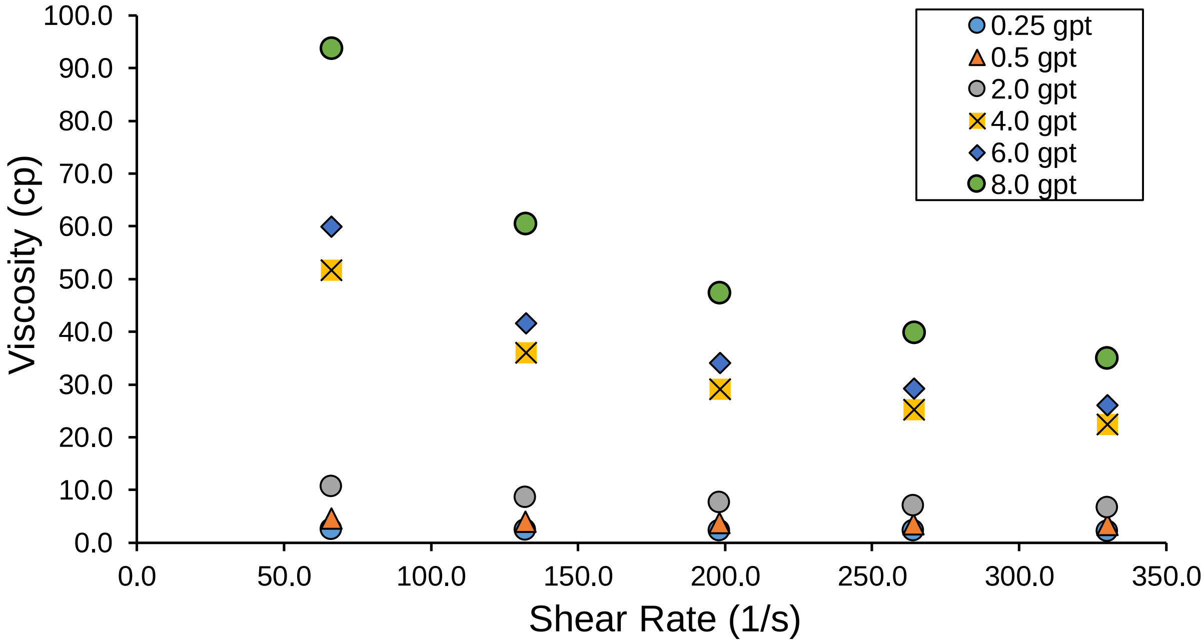

Figure 7.9: Viscosity profile of the HVFR fracturing fluid with 100% Bakken freshwater as the base fluid. The temperature was kept constant at 70°F.

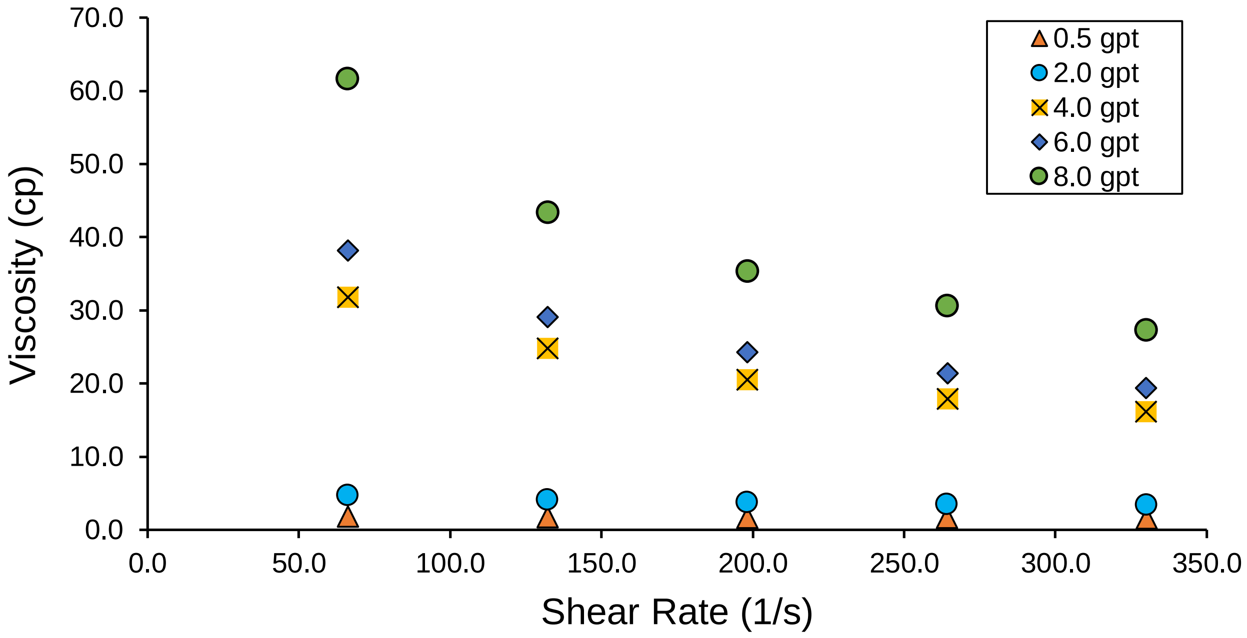

Figure 7.10: Viscosity profile of the HVFR fracturing fluid with 100% Bakken freshwater as the base fluid. The temperature was kept constant at 150°F.

Case #1

Case #1 used a 10% base fluid solution of Bakken produced water diluted with 90% freshwater. As can be seen from figures 7.11 and 7.12, the dilution has a significant effect on the viscosity profile. Considering an 8 GPT dosage, the viscosity dropped to 25 cp at a 66 s^{-1} shear rate and a constant temperature of 70°F when compared with the base case that had almost 100 cp at 66 s^{-1}. At a constant temperature of 150°F, the viscosity went as low as 6.8 cp and remained relatively stable as the shear rate increased.

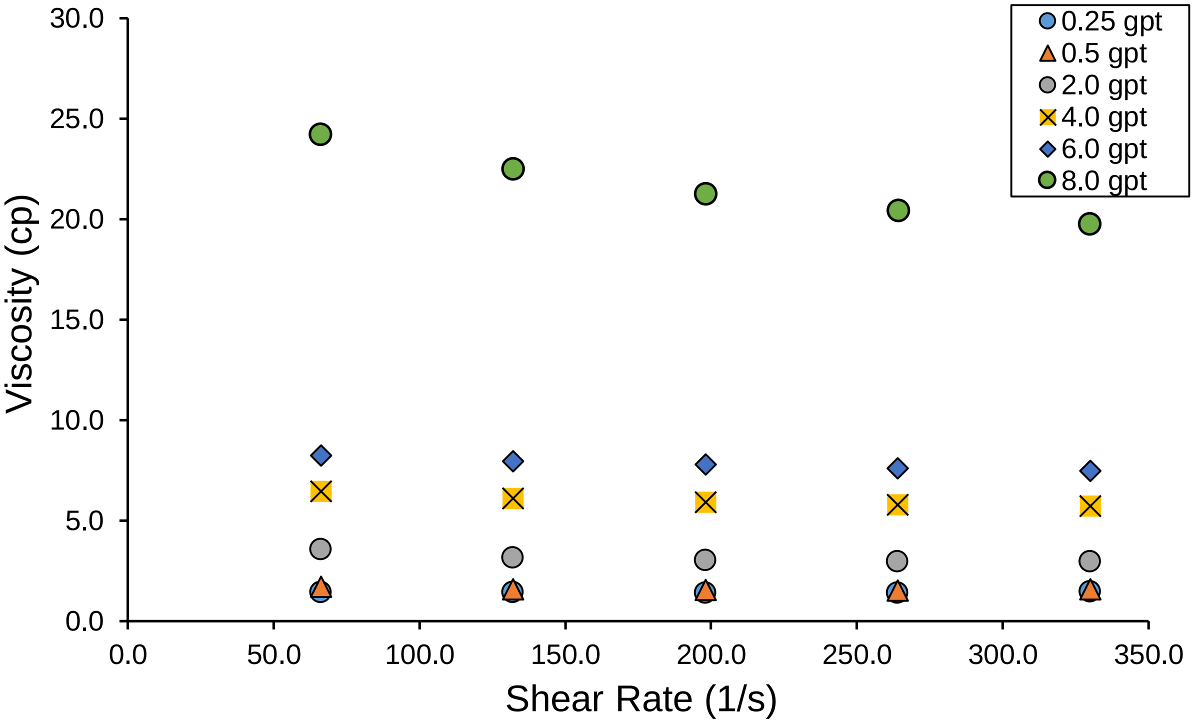

Figure 7.11: Viscosity profile of the HVFR fracturing fluid blend at 90% Bakken freshwater and 10% Bakken produced water as the base fluid. The temperature was kept constant at 70°F.

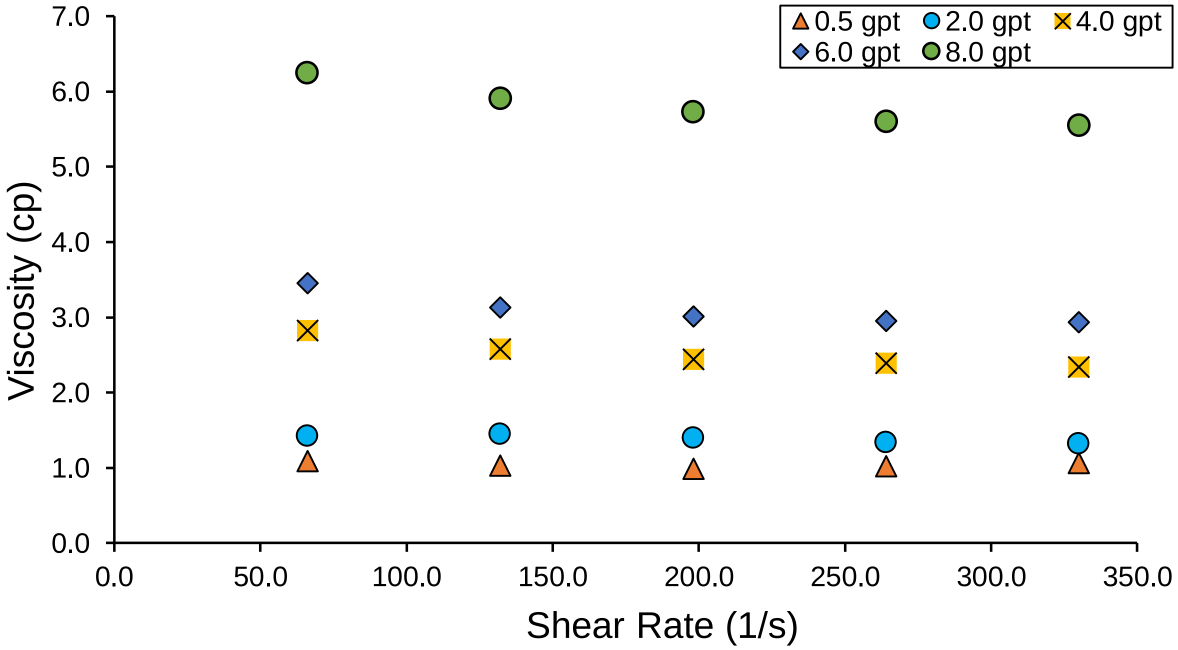

Figure 7.12: Viscosity profile of the HVFR fracturing fluid blend at 90% Bakken freshwater and 10% Bakken produced water as the base fluid. The temperature was kept constant at 150°F.

Case #2

For Case #2, there was a 30% base fluid solution of Bakken produced water with 70% freshwater. The effect of high-water salinity was immediately seen on the viscosity profile. Lower dosages of polymers could not withstand the effect of the produced water. Only 4, 6, and 8 GPT could tolerate the effect. Again, looking at the 8 GPT dosage, viscosity dropped to 18 cp at a 66 s^{-1} shear rate and remained relatively stable and at a constant temperature of 70°F when compared with the base case that had almost 100 cp at 66 s^{-1}. In addition, at a constant temperature of 150°F, viscosity went as low as 5.8 cp and remained relatively stable as the shear rate increased, as shown in figures 7.13 and 7.14.

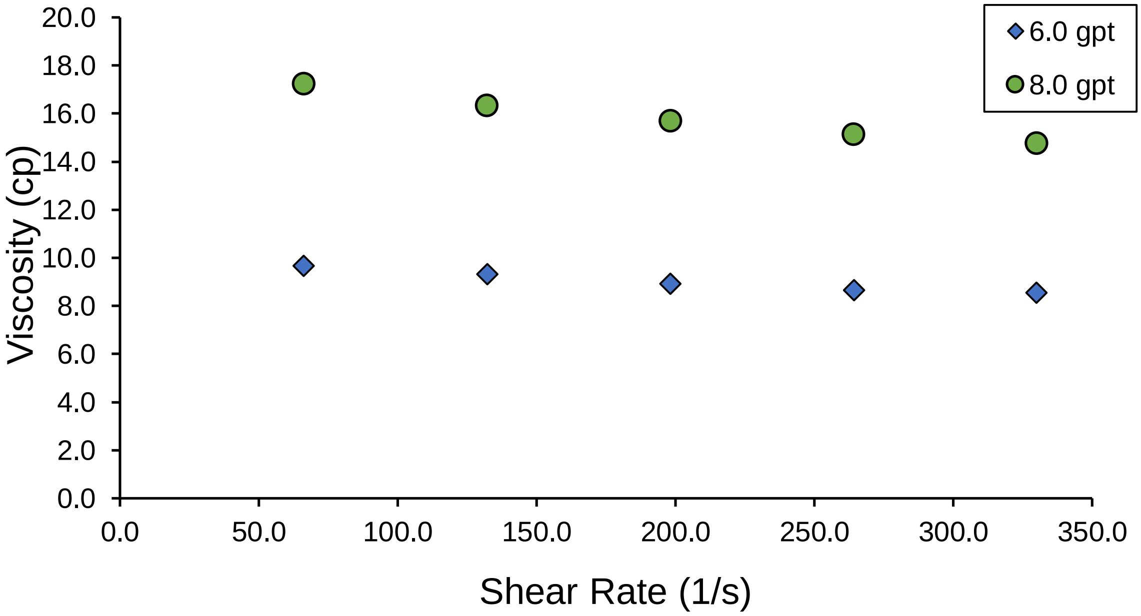

Figure 7.13. Viscosity profile of HVFR fracturing fluid blend at 70% Bakken freshwater and 30% Bakken produced water as the base fluid. The temperature was kept constant at 70°F.

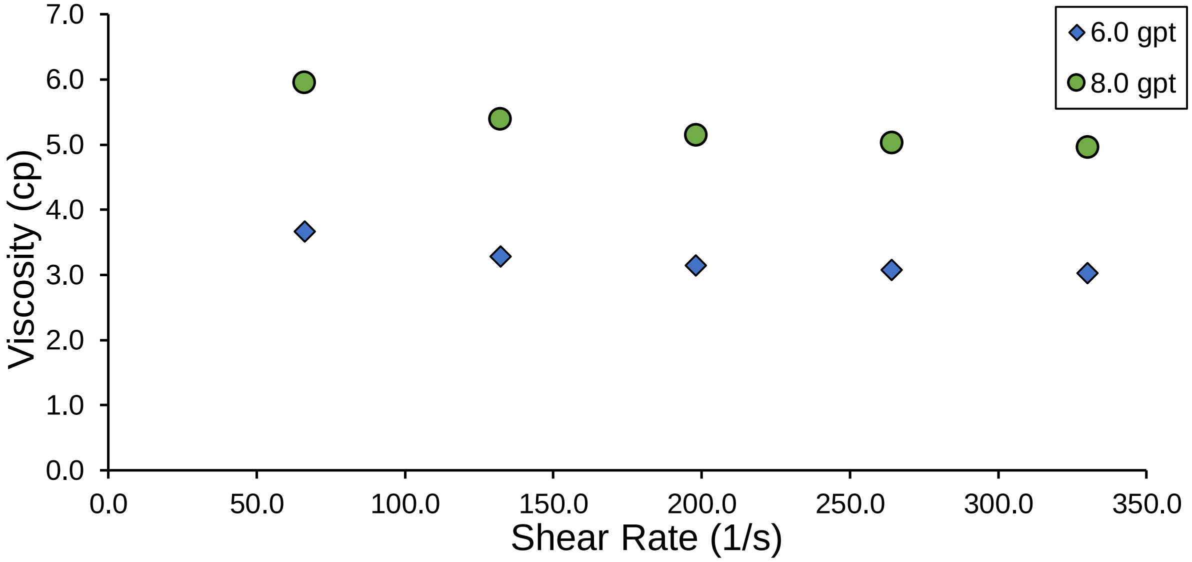

Figure 7.14. Viscosity profile of HVFR fracturing fluid blend at 70% Bakken freshwater and 30% Bakken produced water as the base fluid. The temperature was kept constant at 150°F.

Case #3

The effect of high-water salinity was immediately seen on the viscosity profile. Only 8 GPT could withstand the effect. Looking at the 8 GPT dosage at the 50/50% base fluid blend, we can see that viscosity dropped to 14 cp at a 66 s^{-1} shear rate and remained relatively stable at a constant temperature of 70°F when compared with the base case that was almost 100 cp at 66 s^{-1}. In addition, at a constant temperature of 150°F, viscosity went as low as 4.8 cp and remained relatively stable as the shear rate increased, as shown in figures 7.15 and 7.16.

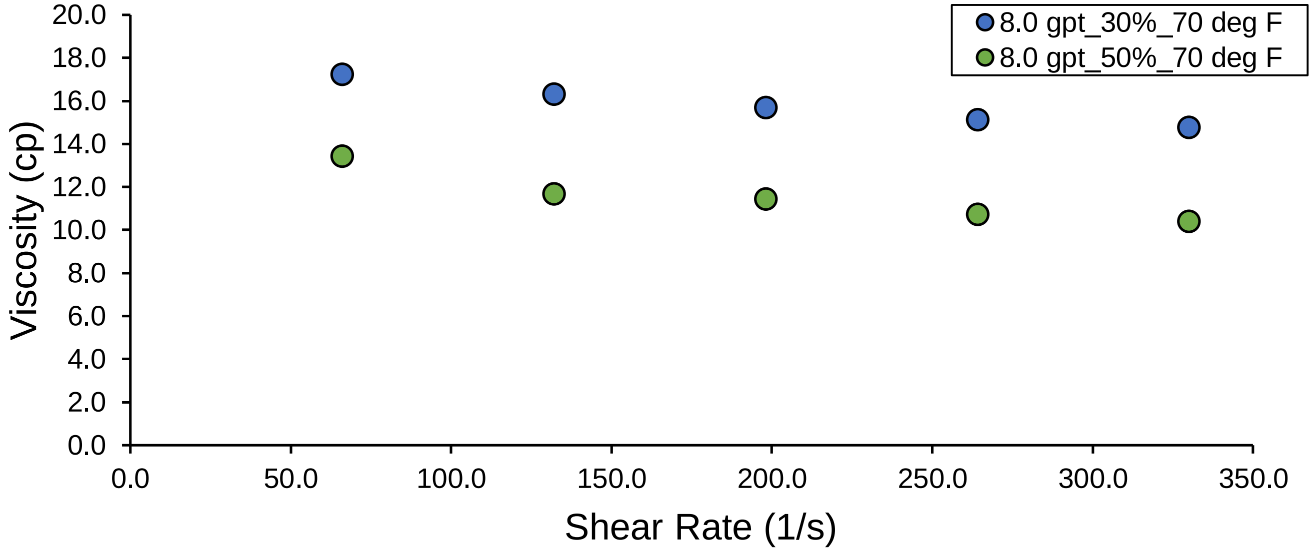

Figure 7.15. Viscosity profile of the HVFR fracturing fluid blend at 70/30% and 50/50% Bakken freshwater and Bakken produced water, respectively. The temperature was kept constant at 70°F.

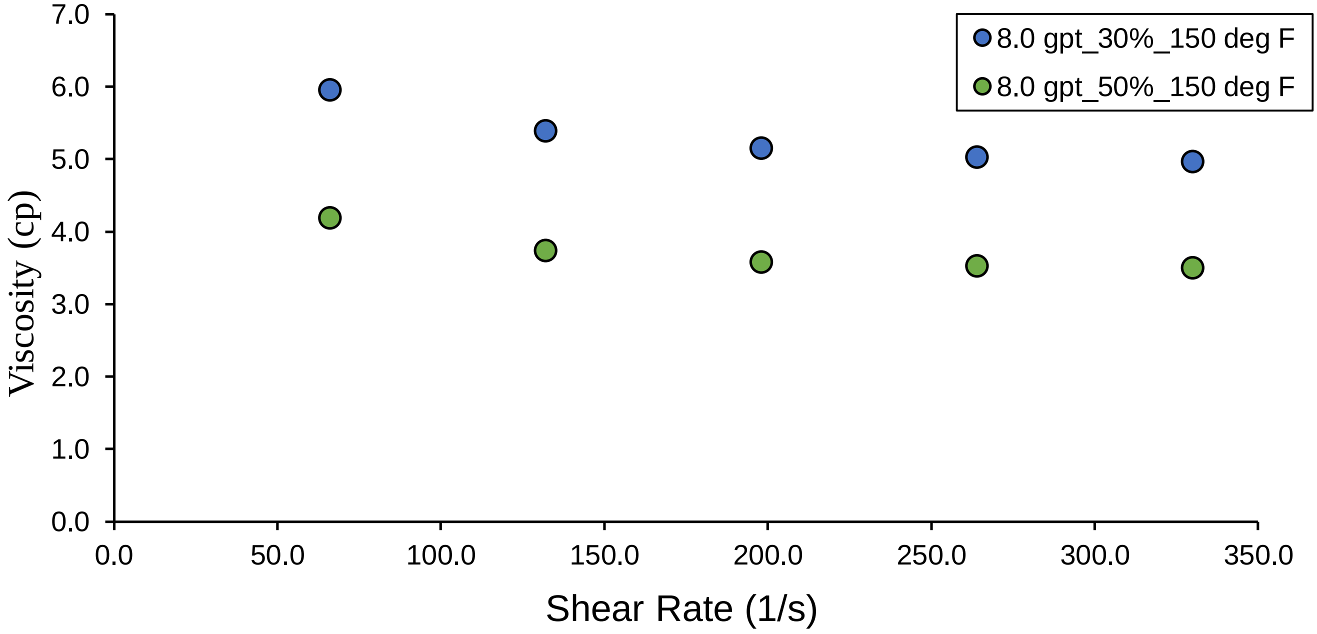

Figure 7.16. Viscosity profile of the HVFR fracturing fluid blend at 70/30% and 50/50% Bakken freshwater and Bakken produced water, respectively. The temperature was kept constant at 150°F.

To allow for a more direct comparison, the viscosity profiles of all the cases at higher loading (8 gpt HVFR) are presented in figures 7.17 and 7.18 for the two temperatures tested. Increasing the salinity significantly reduces the viscosity at both of the temperatures tested. A comparison of the data at 6 gpt and 4 gpt HVFR are presented in figures 7.19 and 7.20, respectively. The same impact of saline concentration (dilution ratio) is seen for these add rates. It decreases in viscosity with the decrease in HVFR loading is also apparent when comparing these figures.

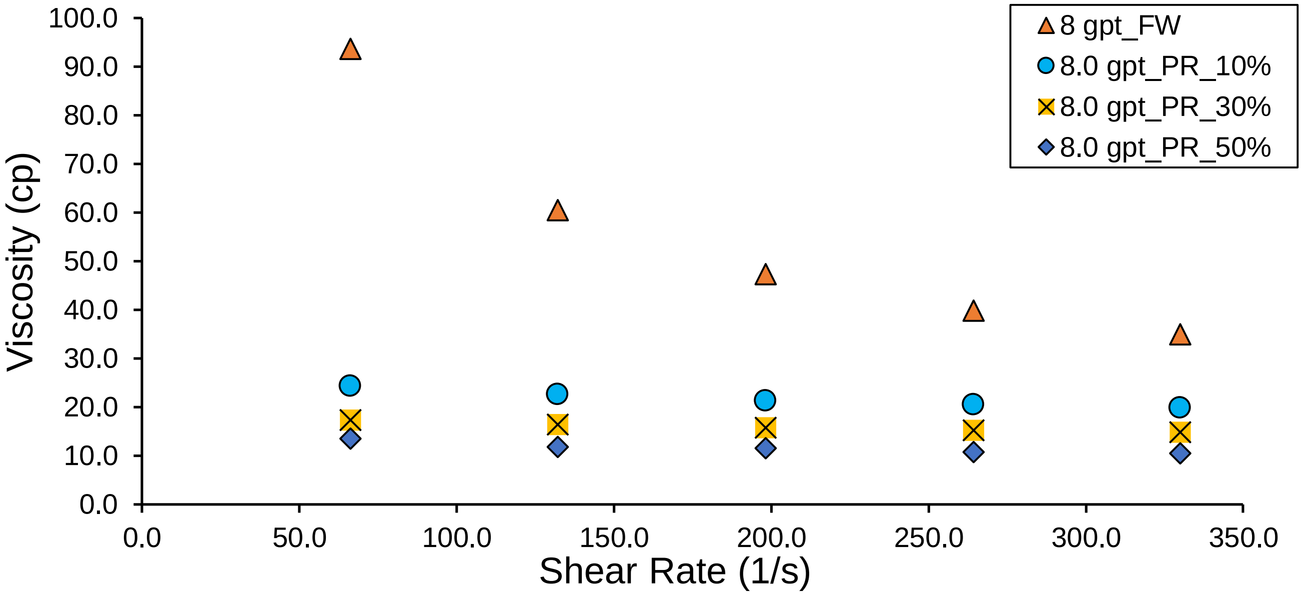

Figure 7.17. Viscosity profiles of the HVFR 8 GPT dosage of the fracturing fluid at different blends, including the base case at 70°F.

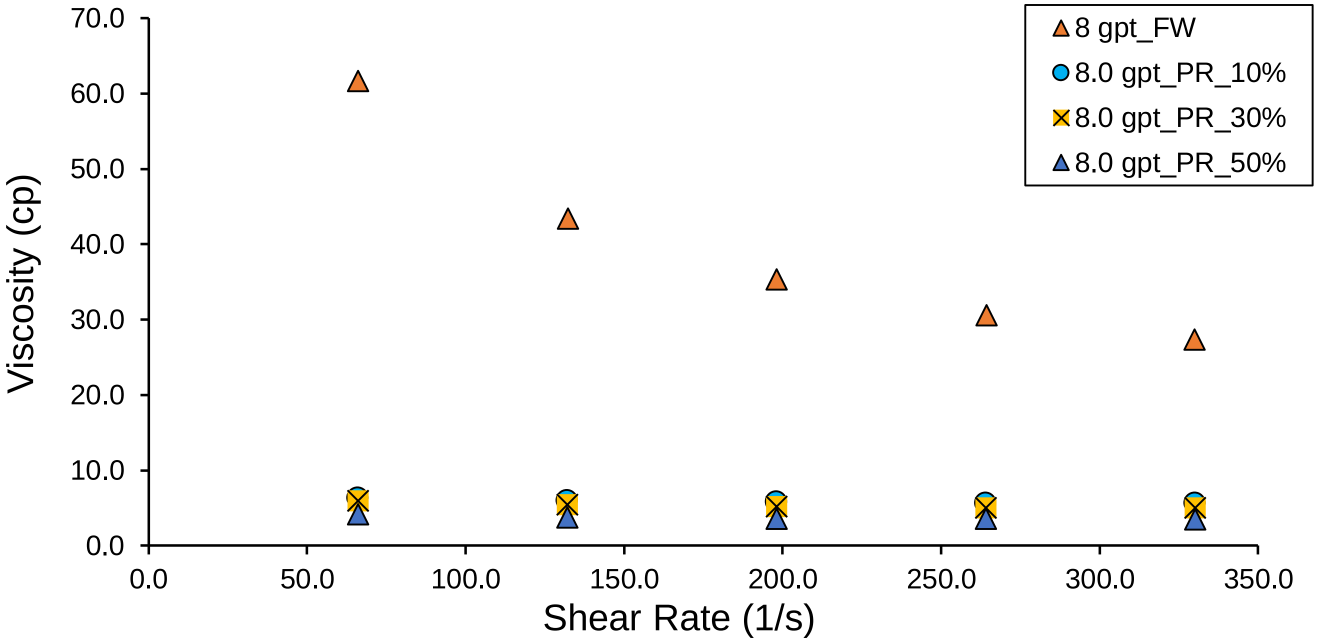

Figure 7.18. Viscosity profiles of the HVFR 8 GPT dosage of fracturing fluid at different blends, including the base case at 150°F.

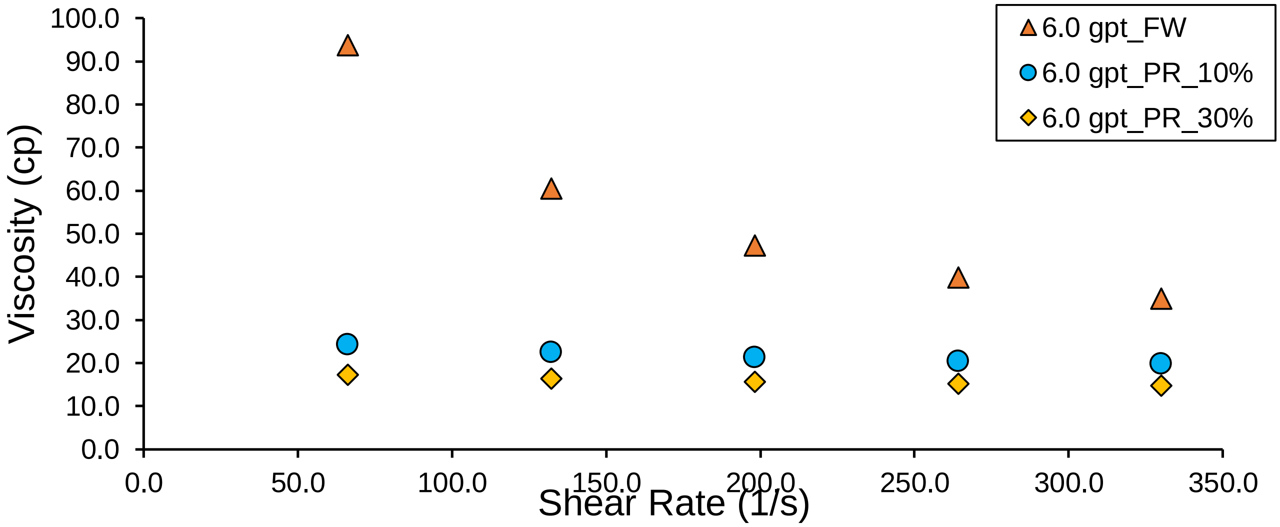

Figure 7.19. Viscosity profiles of the HVFR 6 GPT dosage of fracturing fluid at different blends, including the base case at 150°F.

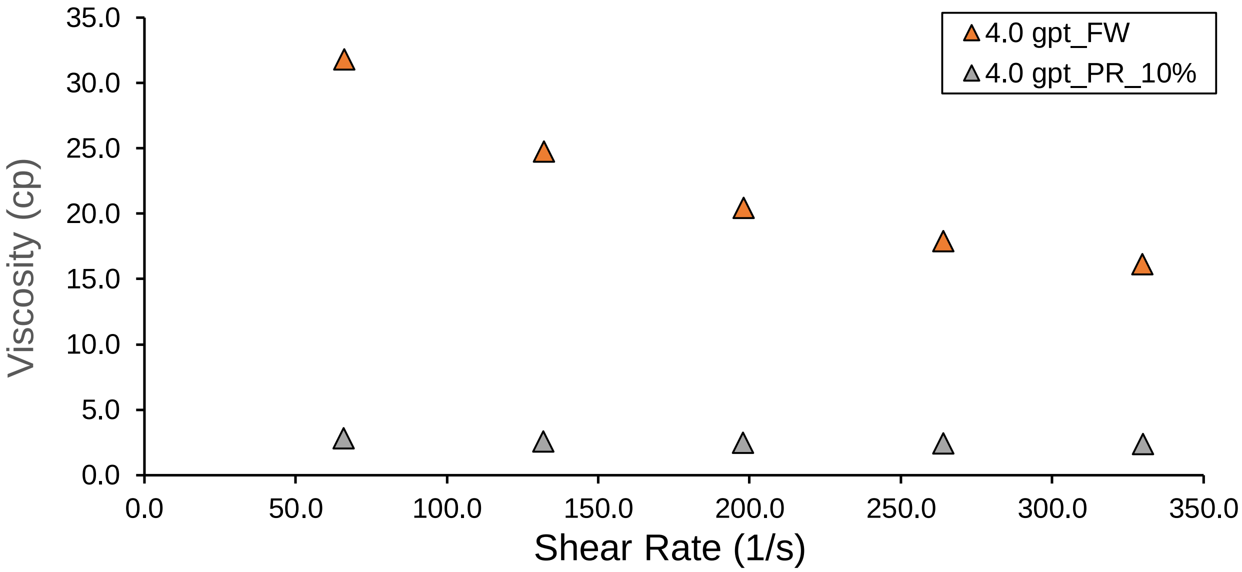

Figure 7.20. Viscosity profiles of the HVFR 8 GPT dosage of fracturing fluid at different blends, including the base case at 150°F.

7.13 Discussions.

The results above show there are options to save cost with regards to freshwater usage by considering recycling and using a portion of the produced water for fracking operations. The temperature and concentration of untreated water affects the viscosity profile of HVFRs used in the formulation of the hydraulic fracking fluid in this research. We know that salinity affects the viscoelastic of the polymer chains in all hydraulic fracking fluids, though not as much as the organics, dissolved hydrocarbons, iron, sulfide, and most importantly, the water hardness. We acknowledge that it is cumbersome to completely treat Bakken produced water to remove all salt.

The salinity of the Bakken produced water is not the principle problem preventing the reuse of Bakken produced water. Rather, bacterial presence, heavy metals, and organics proved to be the problem. Fortunately, this could be easily treated. In a recent study (see Chapter 6), Tomomewo et al. (2020) presented a technology that could treat super saline produced water like the Bakken through the electro-oxidation process. This method works by accounting for the organics, heavy metals, and bacteria in the produced water. The salinity remained the same and may have actually been made inert. With this, the water can be used as a base fluid for hydraulic fracking fluids. This technology is currently being used in Midland and has been saving on operator costs and preserving the environment by reducing saltwater disposals.

7.14 Conclusion

In this thesis, experimentation was employed for optimizing fracture treatment fluids utilizing Bakken produced water. The research findings point out the following:

- The common type of HVFRs is anionic fluid due to its lower cost and better drag reduction.
- Although anionic HVFRs tend to have minimum formation damage they cannot tolerate a high TDS level of saltwater and are more sensitive to iron constituents.
- Cationic HVFRs have been successfully used in up to 100% produced water with the lower-cost operation, but cationic HVFRs may not be compatible with formations that contain a high amount of quartz and/or clay.
- This research enhanced the ability of anionic HVFRs in Bakken produced water condition by using dilute water (for example 10% to 50% instead of using the water treatment and freshwater). The research outcomes concluded that increasing HVFRs dosage can extend the performance of frac-fluids when 50% of produced water is used.
- Surfactant might be a good candidate to enhance the unfolding time anionic HVFRs in high TDS conditions and cold water as well as improving oil recovery from unconventional shale plays

- Reusing produced water, including formation and flow back water has many benefits, such as saves high-quality water for domestic and agricultural needs, minimize environmental footprint, and reduce operating costs.

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APPENDIX A

Advanced Well Placement Technology for the Bakken.

Introduction

Well placement is the organized interactive placement of a wellbore using geological criteria and real-time measurements. The activities are associated with drilling and steering a well to get to one or more pre-determined locations (Yang et al., 2018; Alonzo et al.,2020 and Xiaodong et al., 2021). The well placement process is a collaborating method to well development that utilizes technology and skills to deliver efficiently placed wellbores in a given geological setting to maximize production or injection performance. Accurate well placement helps improve the return on the money invested in drilling the well (Xiaodong et al., 2021). The success of a well can be measured both in the short and long term. Short term the success of the well is determined by whether it is drilled safely, efficiently, on time and on budget, and is producing hydrocarbons at the expected rate or better (Mohammed et al., 2020). The long term the considerations such as access to reserves, delayed onset of water production, extended production and reduced intervention costs determine the total revenue generated from the well and hence the return on investment from drilling the well. Well placement improves both the long-term and short-term performance of a well. Drilling rate of penetration (ROP) is generally improved because the well remains in the more porous reservoir, which drills faster than the surrounding formation. By staying in the reservoir rather than the nonproductive surrounding formation production is also improved (Yang et al., 2018 and Xiaodong et al., 2021) The key to maximizing reserves recovery is placement of the well in the reservoir such that it produces hydrocarbons for the longest possible time and drains the formation as completely as possible. By accessing pockets of untapped formation and avoiding unwanted fluids a well will ultimately deliver the maximum return on investment by delivering the maximum possible hydrocarbon volume with the minimum associated water or unwanted gas production (Mohammed et al., 2020). It is very important to have well placement designs that will support maximum hydrocarbon recovery and less associated or infiltrated water production.

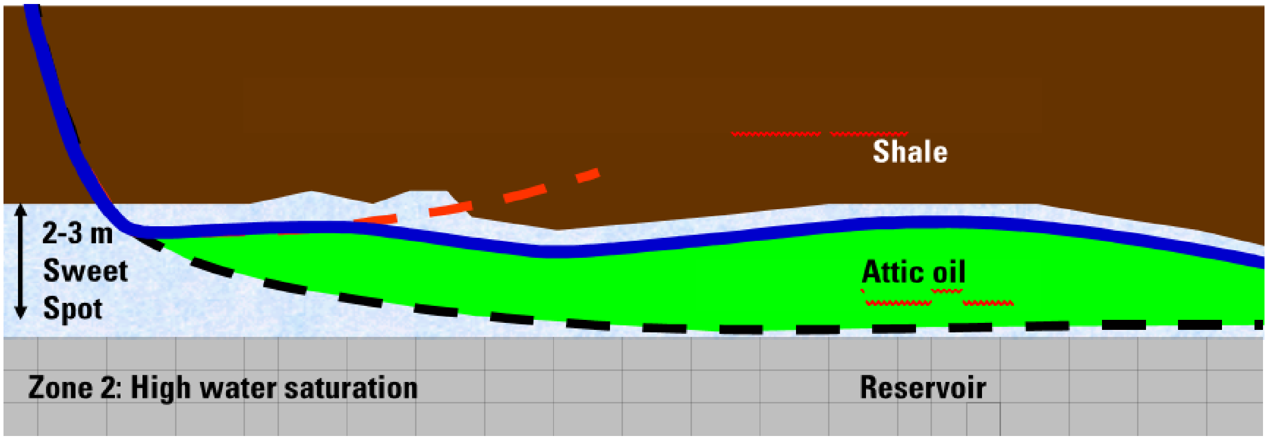


Figure A.1: Placing a well for long term production and delayed high water cut (Mohammed et al., 2020).

Methods of Well Placements

There are basically 3- matching methods (Shahid et al., 2016 and Seyed Mahdi et al., 2020) of well placement namely: model, compare and update. These are the original methods, which entails modeling log responses based on a formation model and well path and then comparing the modeled responses to real-time measured logs and matching the formation model in a way that it corresponds to the real-time measured logs. This method is applicable to any real-time collected log data (Shahid et al., 2016). Real-time dip determination involves formation data from opposite sides of the wellbore, most importantly, images scanned from the inner part of the wellbore that were transmitted while drilling. This allows formation dip to be calculated by correlation of features from opposite sides of the borehole. The dip is then extrapolated away from the borehole and the well steered on the assumption that the formation dip does not change dramatically (Zaid and Stephen 2020). Remote detection of boundaries for real-time well placement currently requires the deep azimuthal electromagnetic measurements of the PeriScope distance to boundary service. Through an inversion process, the distance and direction to changes in formation resistivity can be determined. Well placement using this technique requires knowledge of what resistivity boundaries exist within a reservoir sequence of layers and which of those boundaries the measurements and inversion will detect (Leo et al., 2018). Traditional well placement involves specification of a geological target or targets which drilling engineers then design a well trajectory to hit. In engineering a planned trajectory drilling engineers must consider factors such as avoidance of nearby wells a term called “anti-collision”; hole cleaning, removal of cuttings and formation pressure control (hydraulics); the ability to manipulate the drill string without exceeding drillpipe torque and tensile limits (torque and drag); and the ability to steer the well (Bottom Hole Assembly tendencies). Flexibility of the BHA needs to be considered when designing a well to Carter for any changes that may come up in the course of drilling (Rashid et al.,2017: Zhao et al., and Willerth et al., 2019). Target locations are generally selected based on a reservoir structural model derived from seismic data and well-to-well log correlation. Due to the limited vertical resolution of surface seismic data and the assumptions made during the well to well log correlations, the actual subsurface structure is often different to that indicated by the model. In fact, the formation was not as smooth and continuous as expected but had sub-seismic faulting which, if drilled according to the original geometric plan, would have resulted in the well having very little exposure to the reservoir. Through monitoring of real-time data and the application of well placement principles, the actual well (red line in the lower panel) achieved far greater reservoir exposure and hence production. At the point the question remains what volume of the production is water and oil (hydraulic). The case of the real drilling (the red line) we can see that the drilling went out at some point, this may be underlying source rocks (Lower Bakken) or even another producing reservoir or an aquifer. Whichever one it may be means more water infiltration into the wellbore that will be produced on surface. Even though it seems like more access to the formation or reservoir, it also means high water productions. As we all know that high water production also come with high cost of operating cost in the area of production chemicals and other remediation that may come with it (Tomomewo et al, 2020).

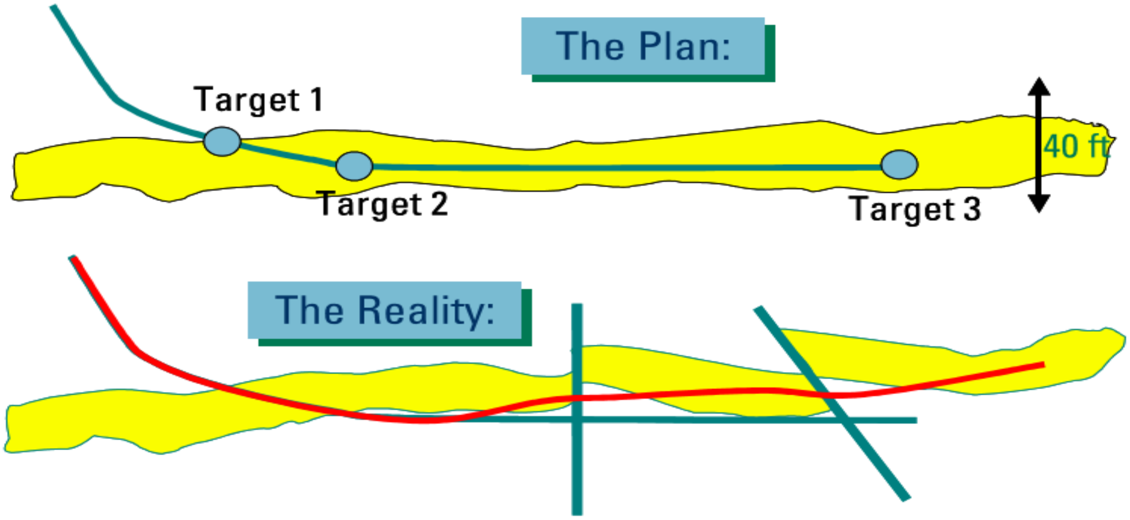


Figure A.2: Traditional well placement options.

It is important to remember that all data has associated uncertainty. The limited vertical resolution of surface seismic data and the assumptions made during well-to-well log correlations result information models with uncertainty in the TVD of formation tops and lateral changes in both formation dip and thicknesses (Ashik et al., 2018 and Bangtang et al.,2015). Even subsurface measurements such as the position of the wellbore computed from surveys have associated uncertainty. Each survey station has an ellipsoid of uncertainty associated with the uncertainty in the measured depth of the survey and the accuracy of the magnetometers and inclinometers used in the survey measurements themselves (Mohammed et al., 2020). As the position of a well is computed from these surveys, the accumulation of uncertainties from each of the survey stations results in an expanding cone of uncertainty along the well within which the well is expected to lie with a given probability as shown schematically in Figure A.3

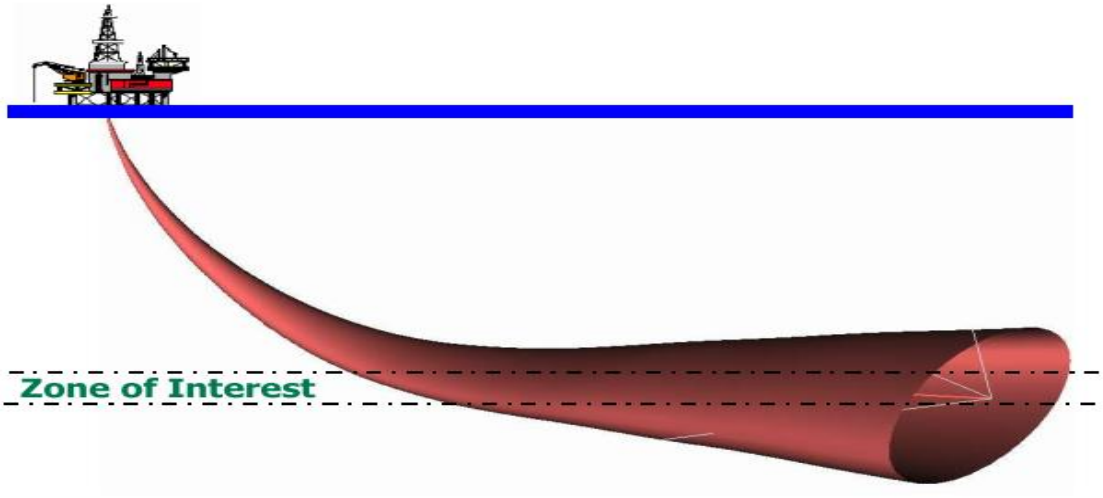


Figure A.3: The cone of Uncertainty (Mohammed et al., 2020).

Model, Compare and Update.

The model, compare and update technique requires that a structural model of the formation of interest is built and populated with the formation parameters that will be measured in real-time (Valdisturlo et al., 2013). These formation parameters are typically gamma ray, resistivity, density and neutron response. The real-time measurements are made with LWD tools and the data transmitted to surface in real-time using an MWD system. The MWD surveys are used to define the position of the well trajectory in 3-dimensional space and the corresponding point on the formation model (Azike, 2011). With the LWD tool position and the properties of the surrounding layers known, the theoretical response of the LWD measurement can be computed and compared to the measured response from the downhole tool (Gonzalez et al., 2014). If they match, then the model gives a reasonable representation of the borehole position relative to the surrounding layers. If they differ then the formation model must be adjusted to give a match between the theoretical LWD response computed from the model and the measured response from the downhole LWD tools (Hedge et al., 2018). The scope of the study will not talk about how to build the model.

Real-Time Dip Determination from Azimuthal Measurements

The limitations of non-azimuthal measurements

The model, compare, update well placement technique can be applied to any LWD data. If only average data (i.e. data without azimuthal sensitivity) is used, the technique is limited by its inability to distinguish between a boundary that is approaching the well from above versus one approaching the well from below, or a lateral change in the layer being drilled. Figure 2.4 below shows an example where three different scenarios could explain the decrease in average density porosity, each of which requires a different well placement response (Butt et al., 2007and Kamgang et al.,2017).

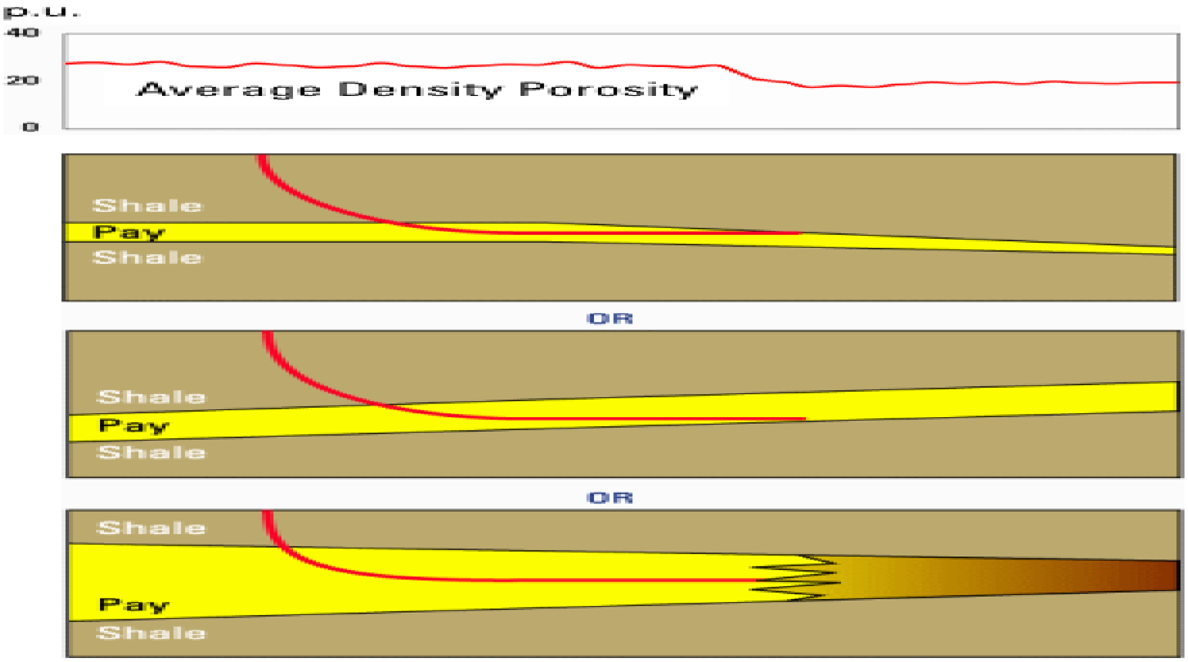


Figure A.4: Scenarios showing results from average density porosity (Valdisturlo et al., 2013).

Azimuthal measurements

Azimuthal measurements (measurements focused to a sector of the borehole rather than the average around the borehole) provide the information required to distinguish the direction from which features approach the borehole (Jin et al.,2019). In contrast to wireline imaging tools that have an array of sensors, LWD imaging is achieved by using BHA rotation to scan a single set of sensors around the inner surface of the borehole. The information is binned into azimuthal sectors. The azimuthal aperture or width of the sectors depends on the degree to which the measurement can be focused (Khurram et al., 2016). Neutron measurements are difficult to focus and hence are generally presented as an azimuthal average. Formation gamma-ray measurements can be focused into four quadrants around the borehole, which are generally defined as the bottom, left, up and right (B-L-U-R) quadrants. For the density measurement, each of these quadrants can be further subdivided into four sectors, giving a total of 16 sectors around the borehole in a density image (Gonzalez et al.,2014). The currents of the laterolog resistivity measurement can be even more tightly focused into 56 sectors around the borehole. Examples of quadrants and sector measurements are given in figure A.5. Note that the density and photoelectric images are subdivided into 16 sectors, while the density and photoelectric measurements are delivered as quadrants. This is because these statistical measurements require counts from four sectors to have the statistical precision required for use as quantitative measurements. Similarly, the laterolog image is delivered with 56 sectors while the resistivity measurements are in quadrants due to signal to noise considerations.

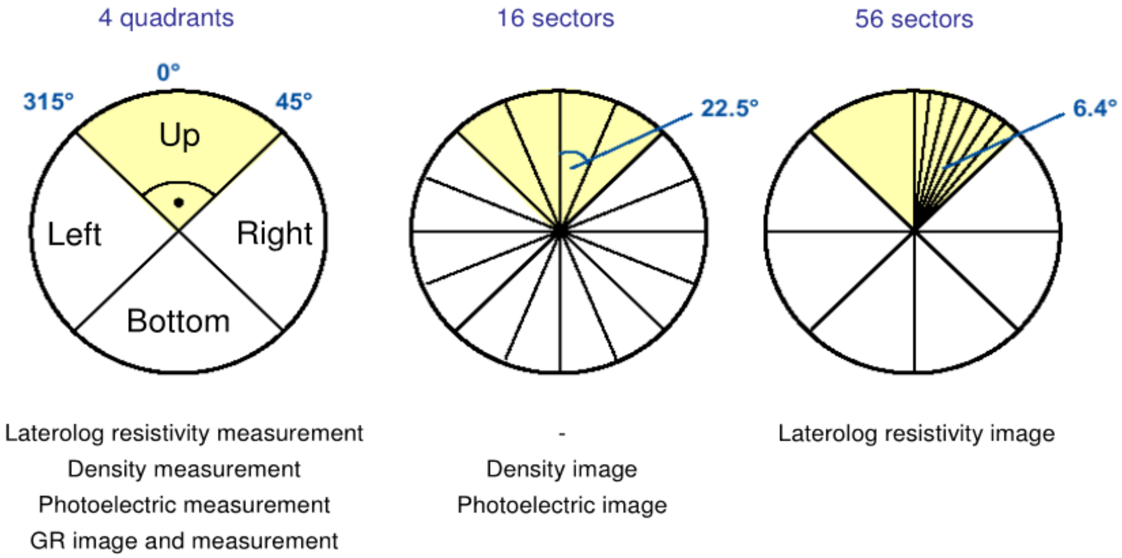


Figure A.5: The Azimuthal Resolution of each measurement (Jin et al.,2019).

The azimuthal resolution of each measurement depends on how tightly the measurement can be focused. Quantitative measurements generally require averaging across several sectors to improve measurement signal-to-noise, so while the image is delivered in sectors, the measurement may be in quadrants.

The vertical resolution of images is related to how tightly the measurement can be focused. Figure A.7 compares the pixel sizes of various LWD and wireline imaging technologies. The vertical resolution of the LWD images is influenced by the drilling rate of penetration (ROP) compared to the sampling rate of the imaging measurement. For example, when drilling at 36 feet per hour the LWD tool moves 1 foot in 100 seconds (Zhao et al., 2019). If the measurement cycle takes 10 seconds, then 10 samples per foot, or 1 sample each 1.2", are acquired, giving the lower limit to the vertical resolution.

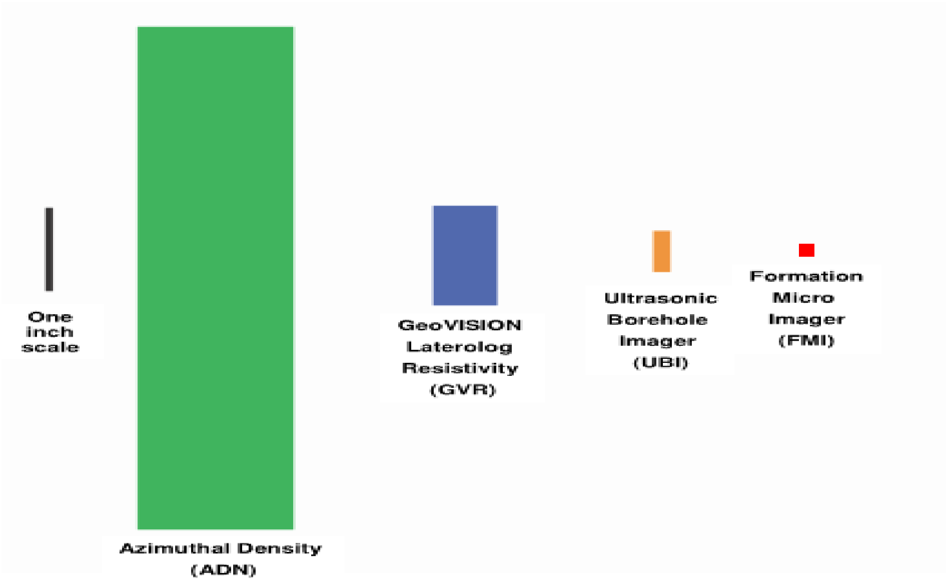


Figure A.6: Relative Imaging of common LWD and Wireline Imagine (Zhao et al., 2019).

Comparing the relative pixel size of common LWD and wireline imaging technologies in a 6-in. borehole, each pixel represents the area of the borehole wall resolved. From left to right; LWD density image pixel, 16 sectors; LWD laterolog image pixel, 56 sectors; wireline ultrasonic borehole image pixel, and wireline Formation Micro-Imager pixel.

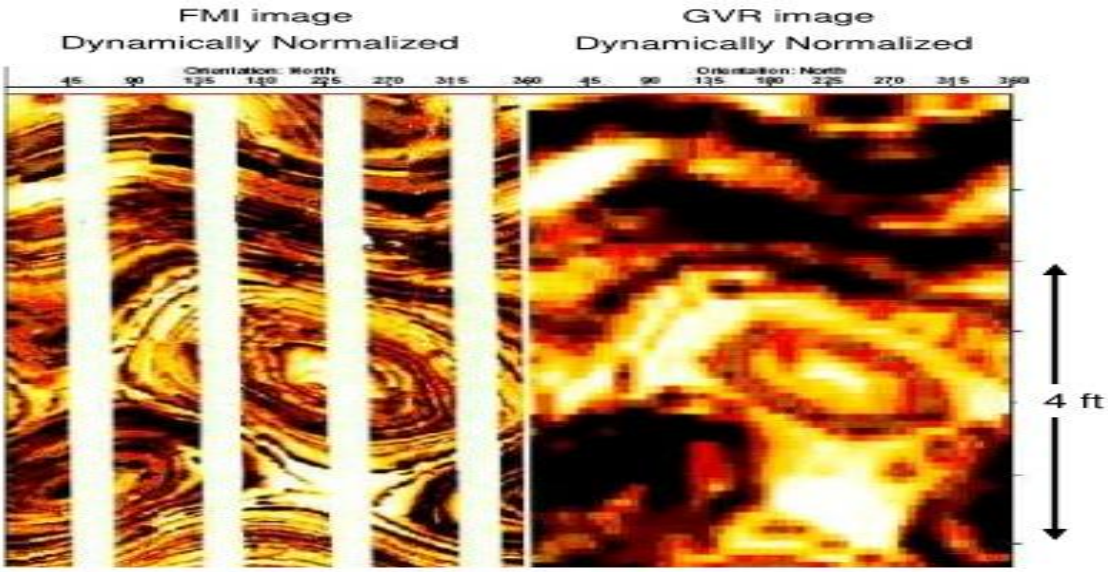


Figure A.7: Relative Imaging of common LWD and Wireline Imagine (Zhao et al., 2019).

Comparison of an FMI image (left) to a GVR image (right) in figure A.6 shows that the major features seen on the higher resolution FMI image are also visible on the GVR image. Azimuthal measurements detect changes in formation properties around the borehole. Images made with different measurement physics from the same borehole may show different features, as the formation properties they measure do not all change in the same way. Figure A.7 shows an example of five LWD images acquired at the same time in the same borehole. The acoustic image responds to tool standoff and borehole breakouts; and photoelectric image responds to changes in formation lithology; the density image responds to changes in formation lithology, porosity and fluid content; the gamma ray image responds to the total formation gamma ray count (from Thorium, Uranium and Potassium); and the resistivity image responds to the porosity and water content of the pore space (Leo et al., 2018). While the images show common events that can be correlated, the differences between them yield additional information about the formation.

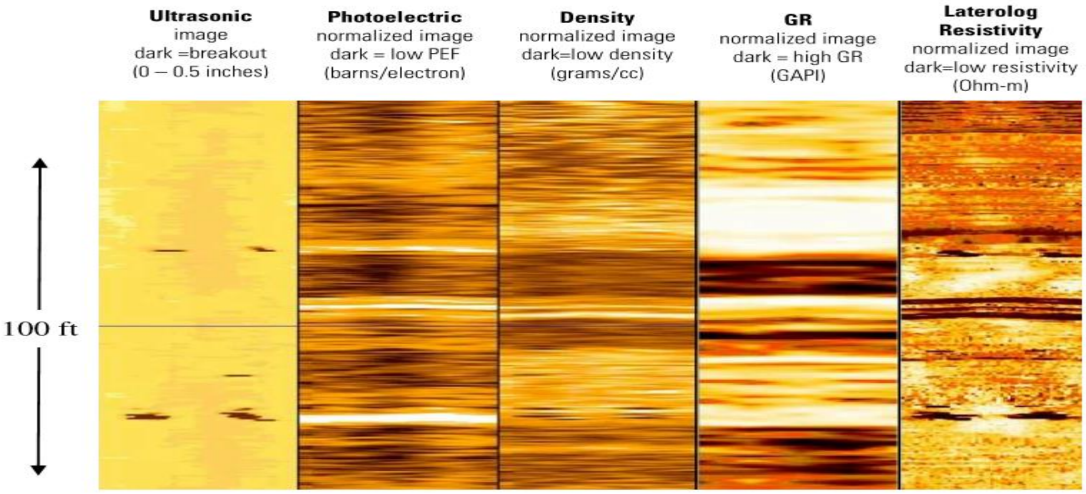


Figure A.8: Various LWD Images (Leo et. Al. 2018).

Various LWD images respond to different formation properties and hence display different formation features. It is the formation structural information contained in azimuthal data and images that is of interest for well placement (Dutta et al., 2018 and Alrashid et al, 2020). When the borehole crosses a layer with some contrast in formation property relative to the zone being drilled, the azimuthal measurements will detect the layer as it traverses from one side of the borehole to the other. As shown in Figure A 9 2-D LWD images are generally displayed as if the borehole has been split along the top and unfolded so that the center of the image corresponds to the bottom of the borehole (Dutta et al.,2018). If a borehole drills down into a layer the bottom of the borehole will see the layer first, then the sides and finally the top. On the image the layer will appear first in the middle and then create a sinusoidal shape that ends at the edges of the image corresponding to where the last of the layer is seen at the top of the borehole. The amplitude of this sinusoid is related to the relative angle between the wellbore and the layer (Khural et al.,2016). Even without calculating this relative angle, the “happy face” and “sad face”, (Schlumberger Oilfield Review, 2014) features on an image due to drilling up through layers and down through layers respectively can assist in well placement decision making, as they indicate where the wellbore is positioned relative to the layering (Schlumberger Oilfield Review, 2014). For example, if “happy face” features are seen on the image while drilling in a reservoir, this indicates drilling up through the sequence, requiring a drop in well inclination to come parallel to the layering so as to remain in the reservoir (Kamgang et al., 2017).

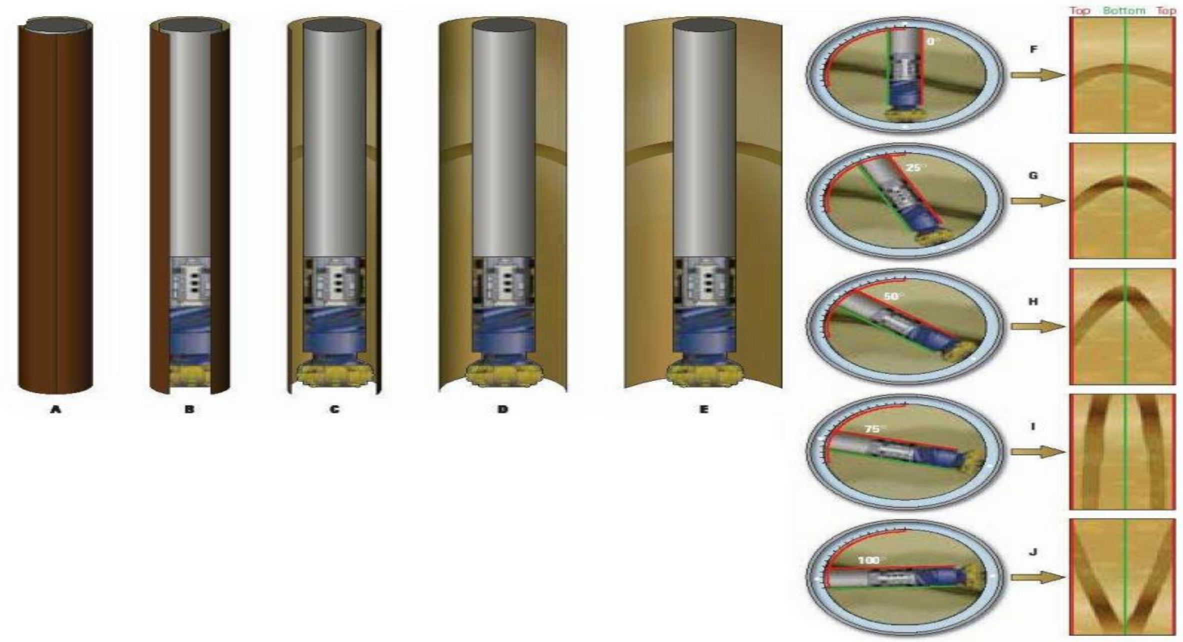


Figure A.9: Tool Image while drilling (Schlumberger Oilfield Review, 2014).

Images A through E in figure A.9 depict how azimuthal LWD data is presented in 2-D. Conceptually, the borehole is split along the top and unfolded such that the middle of the image corresponds to the bottom of the borehole. In the images F through J, inclination is adjusted from vertical, through horizontal, to drilling up at 100°. The bedding plane is parallel to the wellbore at an inclination angle of about 75°. Images F, G and H reflect drilling down section (the layer crossing the borehole creates a “sad face” on the image). Image I shows the parallel “railroad tracks” characteristic of drilling along at the same angle as the bedding plane. Image J shows the “happy face” that occurs when the borehole drills up through a layer. In each case the amplitude of the sinusoid is characteristic of the relative angle between the borehole and the layer.

Image Color Scaling

Color is used to encode information about the magnitude of the formation parameter used in the creation of the image. For example, a density image is acquired by a single set of density detectors (gamma ray source, long and short spacing scintillating detectors) as they scan the internal surface of the borehole during rotation of the drill string. The density of the formation is independently measured in each of 16 sectors (360 degrees/16 sectors = 22.5 degrees of borehole azimuth coverage per sector). To convert this density information into an image the density value is mapped to a color, where darker colors generally indicate lower density while lighter colors indicate higher density. Image normalization is a method by which features can be visually enhanced. A static image has a fixed, user-defined scale over which the color spectrum is applied. For example, the colors of a density image may be scaled over 16 colors with dark colors starting at 2.2 g/cc to light colors at 2.7 g/cc. A dynamic image uses a depth window within which the minimum and maximum values are used as the end points for the color scaling. This allows subtle contrasts between features to be enhanced.

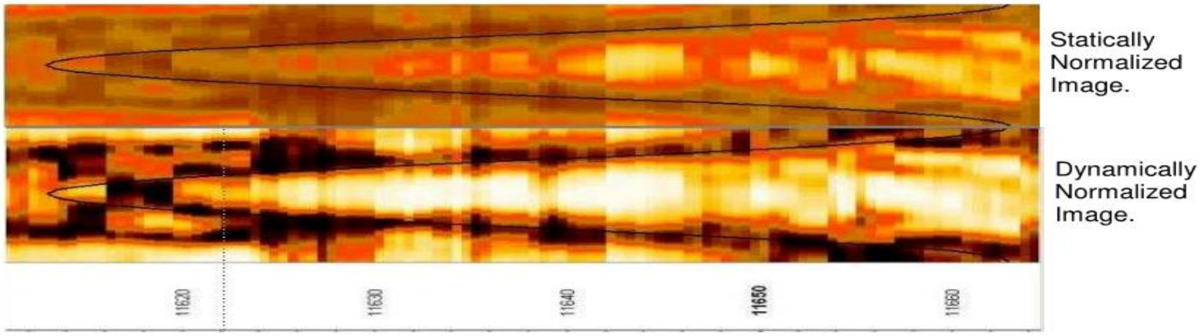


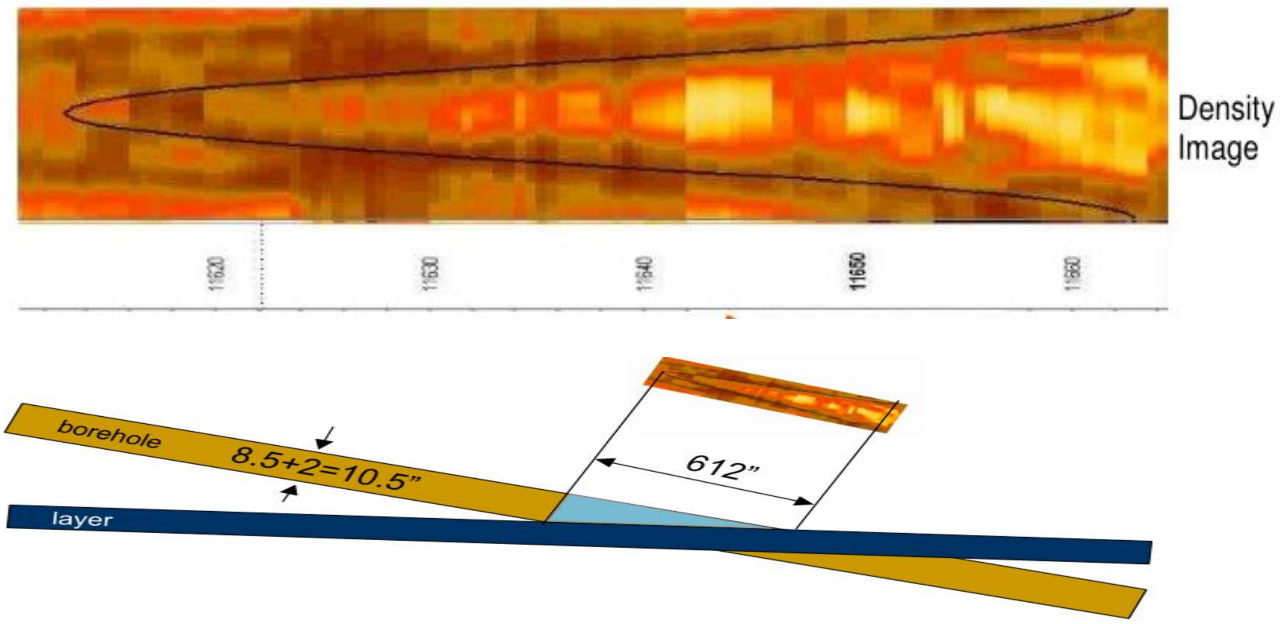
Figure A.10: Static (upper) and dynamically (lower) normalized images (Aibusairi and Carlos 2019).

Static (upper) and dynamically (lower) normalized images are shown over the same interval in figure A.10. The static image has a fixed density range for each color. The dynamic image uses the full range of available colors over a user-specified depth window. It is generally good practice to use both static and dynamic images as the static image tends to highlight large scale features while the dynamic image enhances features within the normalization depth window, but tends to reduce the visibility of the large scale features (Aibusairi and Carlos 2019).

Image orientation

Many static surveys are referenced to grid north instead of true north, specifically so the directional driller can determine from the plan view of the survey whether he is drilling "on plan" and within the lease boundaries. However, since geology is referenced to true north, the grid correction needs to be removed before using the MWD survey to interpret LWD images (Pettit and Tom, 2020). The accuracy of MWD surveys is typically +-1 deg in azimuth, so the grid correction should be removed in most cases since it can be in the order of a few degrees. Errors in azimuth can translate into significant errors when transforming apparent dip to true dip in horizontal wells (Aibusairi and Carlos, 2020). Images are used to calculate the relative angle between a layer and borehole. The relative angle between the borehole and formation layering defines a triangle. **Adjacent side -** The amplitude of the sinusoid on the image is measured along the borehole. The measured depth amplitude of the sinusoid must be converted to the same units as the borehole diameter. **Opposite side -** Images do not scan the surface of the borehole. They represent the formation property at the depth of investigation of the measurement from which they are derived. Hence we must add the depth of investigation of the imaging measurement on each side of the borehole diameter. In the case of the density measurement this is approximately 1 inch, so for an 8.5-inch borehole the diameter at which the image is acquired is 10.5 inches. For a laterolog resistivity image the electrical penetration depth is approximately 1.5 inches, so 3 inches should be added to the diameter of the borehole when calculating a formation dip from an LWD resistivity image.

Figure A.11 shows a schematic of a wellbore crossing a layer with the corresponding image and relative dip calculation



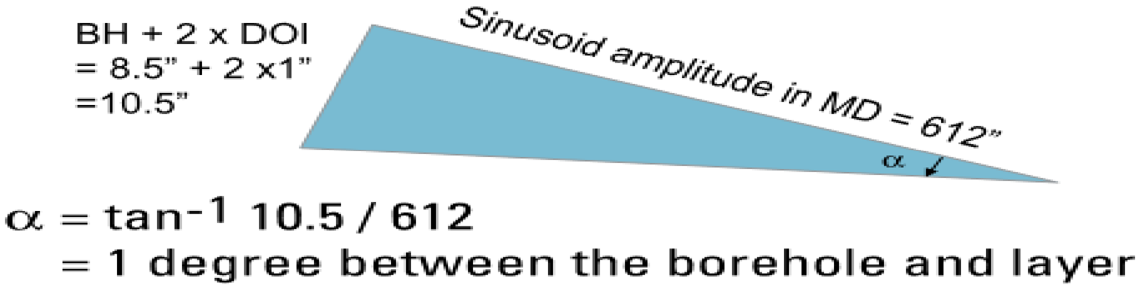


Figure A.11: Relative Angles between borehole and Formation Layering

The relative angle between the borehole and formation layering can be deduced by solving the trigonometry of a triangle. Note that this is the projection of the relative angle between the borehole and formation in a vertical plane along the length of the borehole.

Apparent and true dip

As can be seen in figure A.12, if the azimuth of the formation dip and the azimuth of the borehole inclination are different then the true relative angle will be greater than that indicated by this calculation. A horizontal well drilling along the strike line (A) will see the relative dip of the layer along the length of the borehole as zero. If a horizontal well is drilled along line A-B the relative dip of the layer seen along the borehole length will increase until it is a maximum when the well is drilled perpendicular to the line of strike. Remember that when drilling through a layer the relative dip along the length of the borehole is all that is required to make TVD change decisions if the well continues to be drilled in the same azimuth. If the well changes azimuth (i.e. turns left or right) then the projected relative angle will change and this must be taken into account to be able to stay in the required layer.

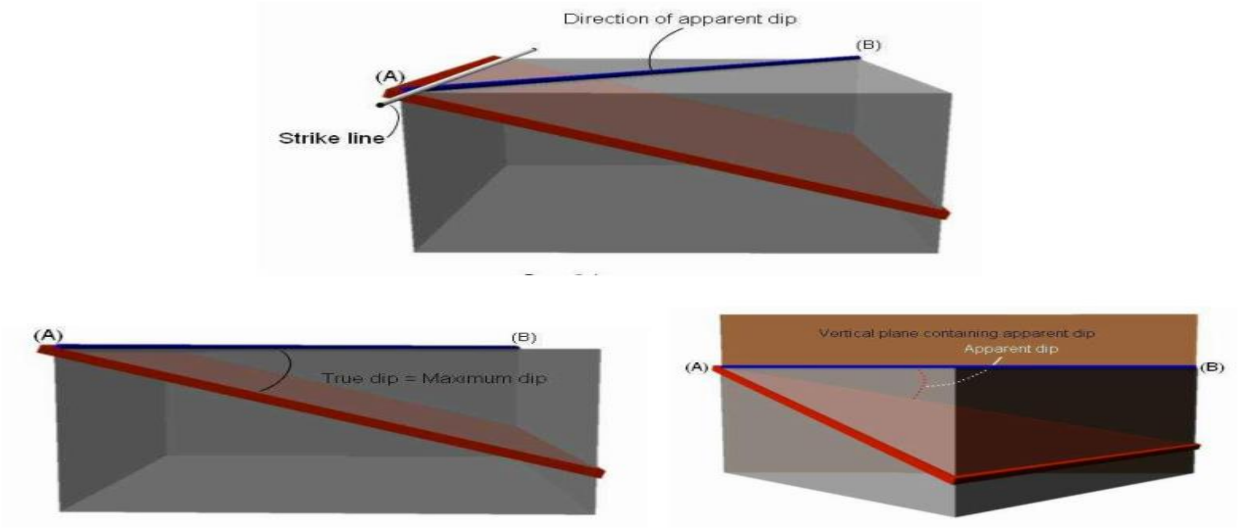


Figure A.12: Formation Deep Projection Figure A.14: A Sample LWD and Gamma Ray Logs (Schlumberger Oilfield Review, 2014).

The projection of the formation dip is a maximum when perpendicular to the strike, the projection in any other vertical plane will give a lower projection of the dip.

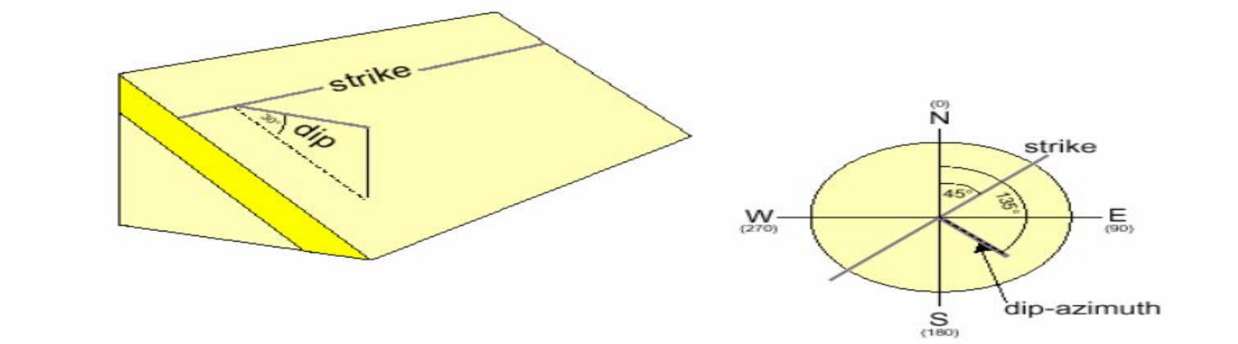


Figure A.13: The Dip and Strike Angle Figure A.14: A Sample LWD and Gamma Ray Logs (Schlumberger Oilfield Review, 2014).

Strike is the azimuth of the intersection of a plane, such as a dipping bed, with a horizontal surface. Dip is the magnitude of the inclination of a plane from horizontal. True, or maximum, dip is measured perpendicular to strike. These features are shown in figure A.13.

Using quadrant data to calculate relative angles

While images make the recognition and correlation of an event across the borehole easier, a similar relative dip calculation can be performed based on quadrant data alone if correlation of the features in the up and bottom quadrants is clear. The same logic for calculation of the relative dip applies, though rather than using the amplitude of the sinusoid the measured depth difference between correlated events as seen in the up and bottom quadrants is used. Figure A.14 shows a typical LWD log from a horizontal borehole The top track shows quadrant density responses and an azimuthal average thermal neutron response. The middle track shows three phase resistivity of differing depths of investigation. The depth track includes a pink line labeled ARPM (ADN Revolutions per Minute) that indicates where the density tool is rotating. Where this curve drops to zero it indicates that the density tool is not rotating and hence the azimuthal data (which requires rotation to scan around the borehole) is not available. Note that across this interval the two quadrant density curves collapse to a single value. Care must be taken to quality-control azimuthal data by checking that the tool that acquired it was rotating over the interval of interest.

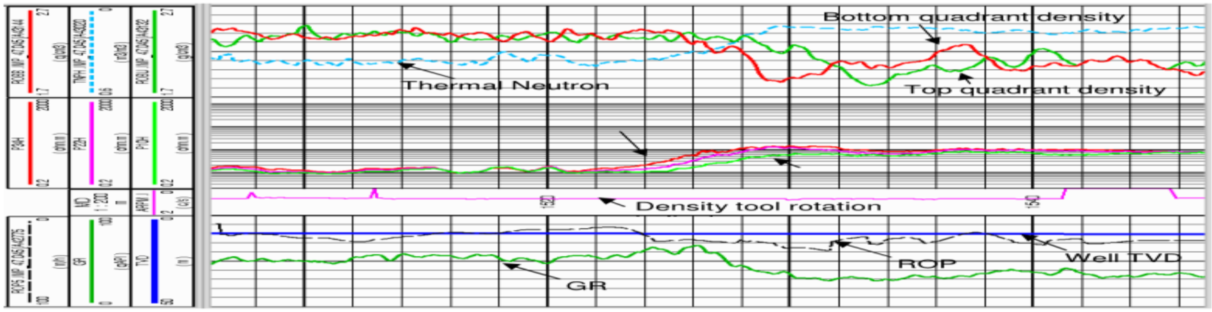


Figure A.14: A Sample LWD and Gamma Ray Logs (Schlumberger Oilfield Review, 2014).

Figure A.14 shows a typical LWD log from a horizontal borehole with quadrant density information displayed in the top track. Bottom density (red line) and up density (green line) show a clearly correlated drop in density. The lower image in Figure A.14 shows the gamma ray (green line), drilling rate of penetration, ROP (black dashed line) and the true vertical depth, TVD (blue line) of the borehole. There is a 4 meter measured depth difference between the density drop seen by the bottom and up density measurements. The bottom density measurement decreases first indicating that the well is drilling down into a layer of lower density. From the TVD curve, we can see that the well is horizontal, so the layer must be dipping up.

As an example, for a density measurement depth of investigation = 1-inch

Tan α = (Borehole diameter + 2 x Measurement depth of investigation) / MD difference

(Schlumberger Oilfield Review, 2014)

$= (6 + 2 \times 1)/157.5$

$= 0.0508$

$\Rightarrow \alpha = \tan$

-1

0.0508

= 2.9 degrees' relative dip between the borehole and layer.

This relative dip information, derived either from images or quadrant curves, allows positioning of the wellbore relative to the layering. For the example shown above, if the intention was to maintain the wellbore parallel to the layering, the well inclination must be increased by 2.9° to achieve the well placement objective.

Using dip to calculate layer thickness

To fully define a formation layer, we need its true thickness and dip. When directionally drilling through a layer of unknown dip, non-azimuthal logs can only provide the measured depth thickness of the layer, which can be converted to the true vertical thickness (TVT) based on the well deviation. To define the True Bed Thickness (TBT) the formation dip must be known (Schlumberger Oilfield Review, 2014).

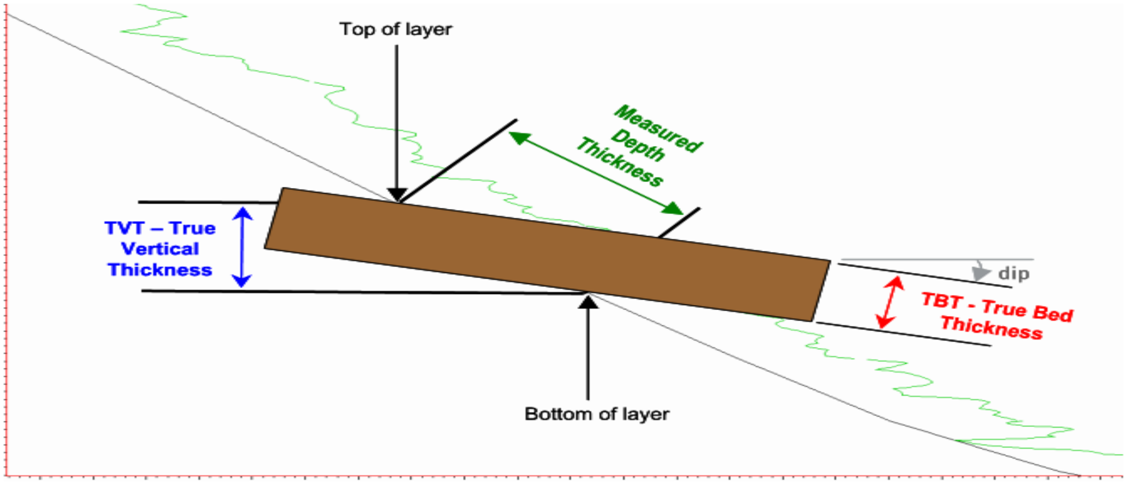


Figure A.15: The Bed Thickness (Wielemaker et al., 2020).

The True Bed Thickness (TBT) cannot be determined from conventional logs unless the formation dip is known. In the absence of any formation dip information, the conventional model, compare and update well placement method generally assumes that a formation layer thickness is the same as was observed in the offset well (Schlumberger Oilfield Review, 2014 and Wielemaker et al., 2020).

Remote Detection of Boundaries

While azimuthal data greatly enhances well placement by permitting determination of the direction from which features contact the borehole, most azimuthal measurements have limited depth of investigation (Abbas et al.,2020 and Ahmet et al.,2020). Effectively this means that with these measurements a boundary can only be detected once the borehole has come into contact with it. Directional measurements of electromagnetic phase shift and attenuation are analyzed downhole to determine the direction to the nearest conductivity contrast and then transmitted from the downhole tool to surface where inversion processing extracts the distance to boundary information (Abbas et al., 2020). Inversion processing converts raw directional phase and attenuation measurements, acquired at multiple frequencies and transmitter-receiver spacing's, into a three-layer formation model. The inversion solves for the resistivity and distance to the layer above, the resistivity and distance to the layer below, and the resistivity of a layer in which the well is being drilled. This information is then displayed in real time as a color-coded resistivity cross-section of the formation along the wellbore, as displayed in Figure A.16

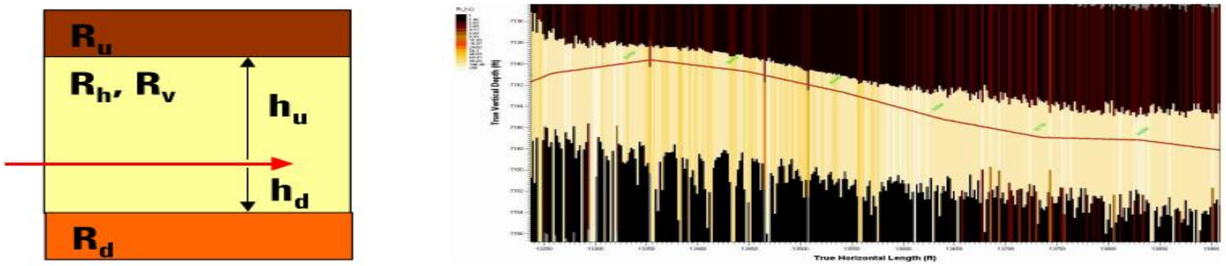


Figure A.16: Periscope Inversion (Abbas et al., 2020).

The PeriScope Inversion solves for the resistivity and distance to layers above and below the wellbore based on a three-layer model (left) and the resulting information is displayed in real time as a color-coded resistivity cross-section of the formation (right). In addition to the distance to boundary (DTB) information, the PeriScope service provides an azimuth to the boundaries, based on the assumption that the layers above and below are parallel (Schlumberger Oilfield Review,2014). This information is presented in an azimuthal view as shown in Figure A.17

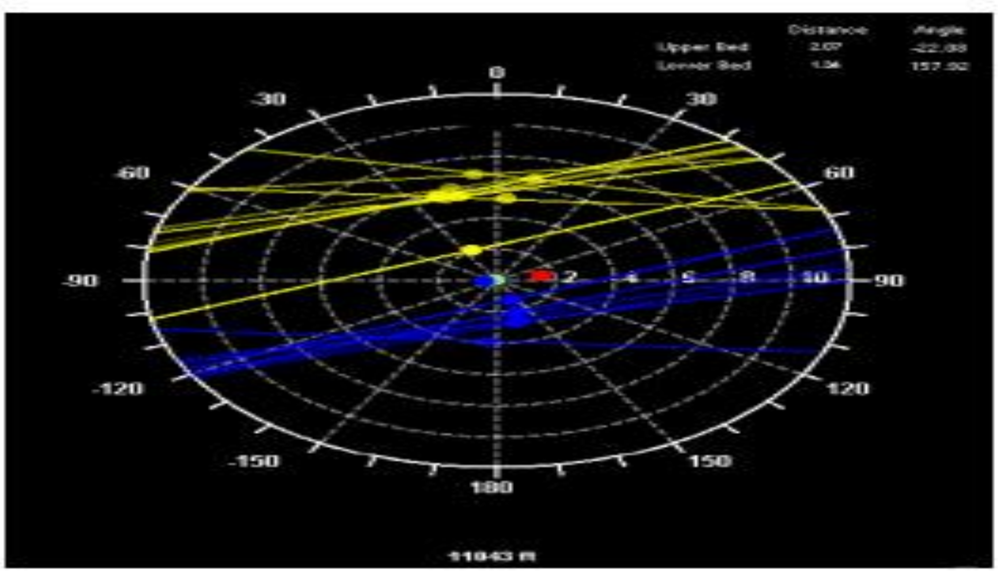


Figure A.17: The Azimuthal Viewer (Abbas et al., 2020).

The azimuthal viewer provides a representation of the subsurface as if looking down the borehole (center) with the upper (yellow) and lower (blue) boundaries shown at the distance and azimuth around the borehole determined from the PeriScope measurements. The distance and azimuth information enables steering of a well in both TVD and azimuth relative to a resistivity boundary without having to come into contact with it. For example, in the situation shown in figure 2.17 the well could either be turned up to avoid the lower boundary or turned to the left, or a combination of the two depending on the most appropriate position for the wellbore in the target layer.

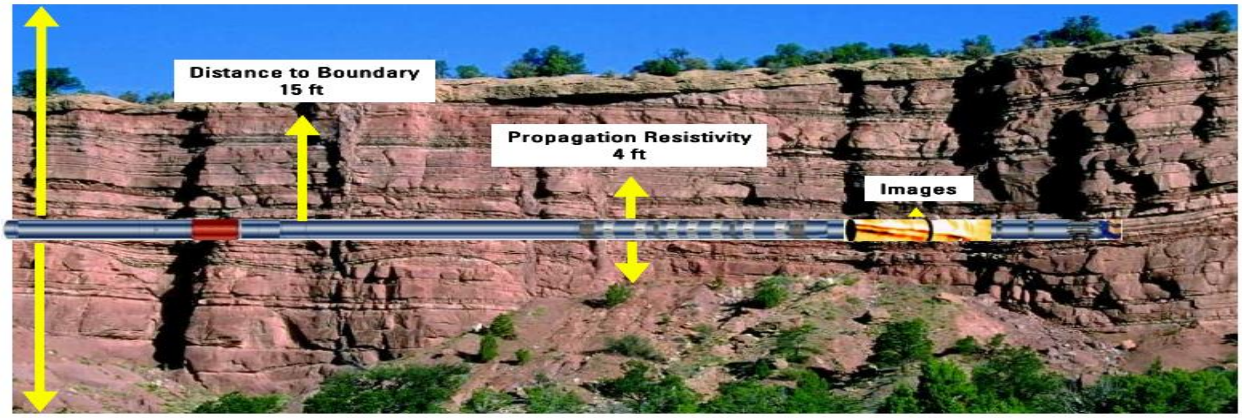


Figure A.18: PeriScope Distance to Boundary (Denney, 2011).

The PeriScope distance to boundary service delivers both directionality and depth of investigation. Seismic data is able to visualize large structural features, but due to the limited frequency content of surface seismic data, some features are below seismic resolution. The PeriScope 15 service, with its 30 ft diameter of investigation (15 ft up, 15 ft down) is often able to evaluate events such as sub-seismic faults. As thinner reservoirs are being drilled, evaluation of sub-seismic faulting becomes increasingly important as the borehole may exit the reservoir on encountering such a fault. In addition, the evaluation of reservoir compartments is improved through being able to track the top and bottom of the layer, thereby improving estimation of the volume of hydrocarbons in place.

The Three Components of Well Placement

Downhole Tools

Directional-Drilling Technology

Directional drilling is the technique of deviating a wellbore along a planned course to a subsurface target whose location is a given lateral distance and direction from the vertical. The drilled well must be drilled safely, placed in the required target, facilitate the planned logging program, allow smooth running of casing and completion hardware, should not result in excessive casing wear from subsequent operations, be accessible for future well intervention, and most importantly must be drilled at the lowest possible cost (Wylie et al.,2018; Eltayeb et al.,2011 and Denney, 2011). While there are a number of directional drilling technologies such as jetting, whipstocks, and rotary steerable assemblies, the two most commonly used for well placement are steerable motors (SM) and rotary steerable systems (RSS). Steerable motors consist of a positive displacement motor (PDM) with a surface adjustable bent housing which allows the bit to be oriented in the desired drilling direction. Positive displacement motors convert hydraulic power from the mud circulation into mechanical power in the form of bit rotation. This is achieved through a progressing cavity design in which the movement of the mud pushes on a rotor with one less lobe than the stator in which it is housed. This turns the rotor and thus the bit that is coupled to the rotor (Schlumberger Oilfield Glossary). Note that with a positive displacement motor the bit rotates (when there is mud circulation) even if the drill string is stationary (Sugiura and Jones,2020).

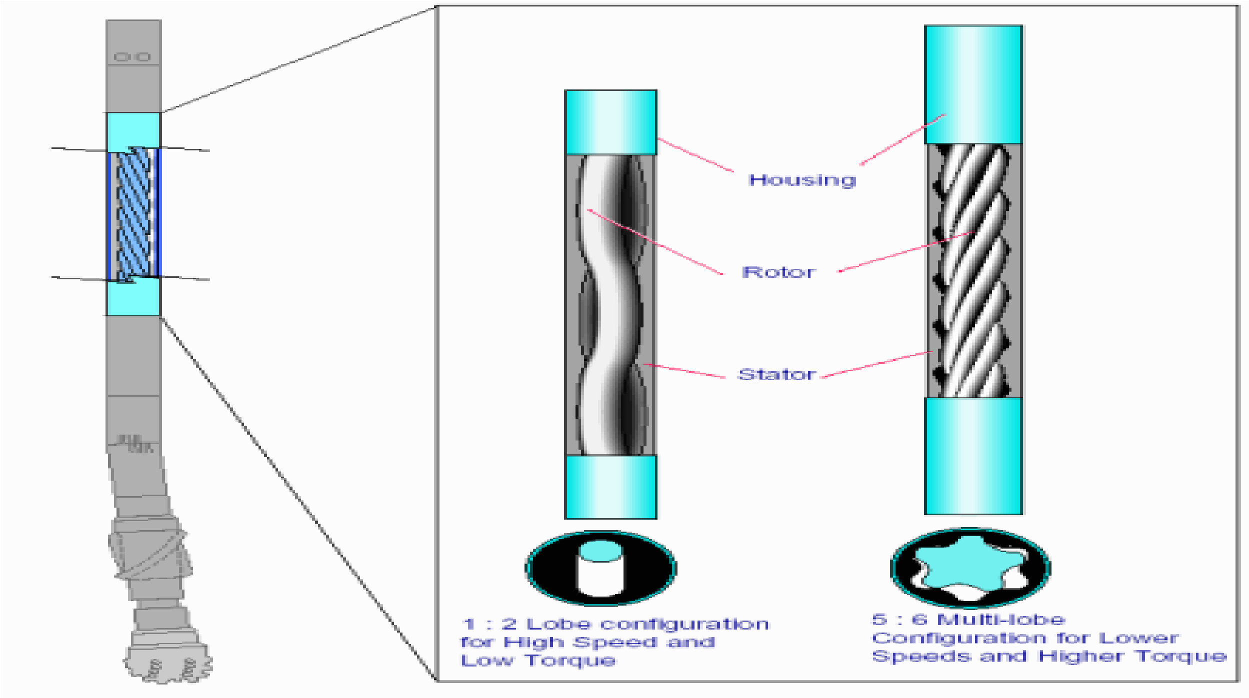


Figure A.19: A Positive Displacement Rotary Steerable Motor (Schlumberger Glossary, 2020).

Positive Displacement Motors (PDM) convert hydraulic power from the mud flow into mechanical power in the form of bit rotation. Increasing the number of lobes increases the torque available but decreases the speed of bit rotation.

As shown in figure A.19, various lobe configurations are available. An increasing number of lobes gives increasing torque to turn the bit but at lower revolutions per minute (RPM). In addition to changing the number of lobes, the number of spirals or stages can be varied. Increasing the number of stages increases the mud pressure drop across the motor and hence the power available from the motor (Schlumberger Oilfield Glossary and Sugiura and Steve, 2020).

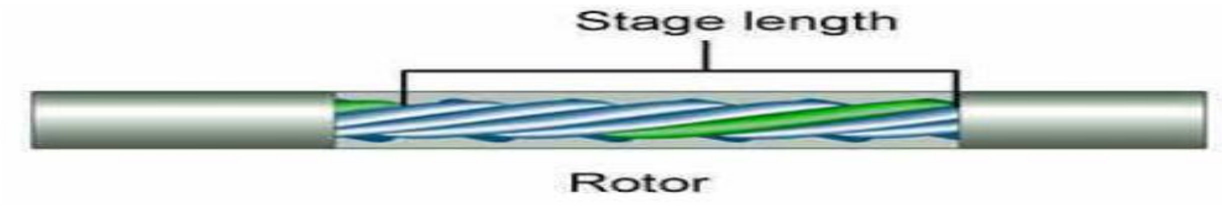


Figure A.20: A Stage Length (Schlumberger Glossary, 2020).

A stage corresponds to one 360°spiral on the rotor as shown in figure A.20. By orienting the surface adjustable bent housing in the desired drilling direction and rotating the bit by pumping mud through the positive displacement motor it is possible to drill in a desired direction. The process of keeping the drill-string oriented in a desired direction while drilling is called “sliding”. The orientation, or tool face, is referenced to the high side of the hole in deviated and horizontal wells. A tool face of 0° indicates building angle, while a tool face of 90° indicates drilling right. A tool face all of 180° indicates dropping well angle and a tool face of 270° indicates drilling left. In near vertical holes the tool face is oriented relative to North. In this case it is called a Magnetic Tool Face (MTF) to distinguish it from the Gravity Tool Face (GTF) used in high angle wells. Because the angle on the bent housing is small (typically less than 3°) the steerable motor can also be rotated. This negates the effect of the bend and gives a relatively straight borehole, which is slightly over-gauge (slightly larger than bit size). By alternating sliding and rotating intervals the directional driller can control the rate at which the borehole angle is changed. The rate of change in borehole angle is normally given in degrees per 100ft (or 30 m.), the so-called dog leg severity (DLS). The difficulty with slide-rotate sequences is that orienting prior to each slide section is time consuming, and hence reduces the overall rate of penetration achieved for the well. In addition, because the mud is not agitated during sliding hole cleaning efficiency is reduced. Finally, the overall length of the well may be limited because static friction during sliding, which is greater than dynamic friction while rotating, may prevent effective weight transfer to the bit. To overcome these limitations, the rotary steerable systems were developed.

Rotary Steerable Systems (RSS)

RSS delivers continuous steering while rotating (Cao et al.,2020). This gives the benefits of steadier deviation control, a smoother hole, better hole cleaning, extended hole reach and overall improvement in the rate of penetration compared to a steerable motor. It is also advantageous for well placement as the continuous rotation of the BHA ensures that when formation images are acquired, they are available over the entire length of the well (Ruszka et.,1999). There are two main types of RSS; **Push-the-bit:** applies side force to increase the side-cutting action of the bit. And **Point-the-bit:** introduces an offset to the drilling trajectory similar to a bent housing but allowing continuous rotation (Eltayeb et al., 2011 and Denney et al., 2012).

A push-the-bit system (figure A.21) uses three pads to push against the borehole wall and so deflects the drill bit in the opposite direction. As the system is rotating the pads must be activated in sequence to ensure consistent steering in the desired direction (Schlumberger Glossary,2020 and Kenneth and Russell, 2016). The control unit contains the electronics for control of the tool face and the percentage of time spent steering. The system operates by diverting a small percentage of the mudflow to activate the pads. By sensing the rotation of the BHA relative to the earth’s magnetic field and controlling a motor to rotate in the opposite direction, the control unit holds a control valve (blue element in Figure A.22) geostationary. A small proportion of the mudflow is thus diverted behind each of the pads in sequence as the entry port to the piston behind each pad rotates in front of the geostationary port in the control valve.

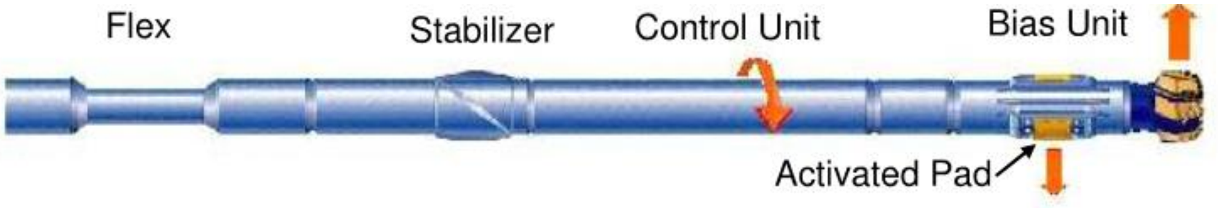


Figure A.21: A Push the Bit Rotary Steerable System (Schlumberger Glossary, 2020).

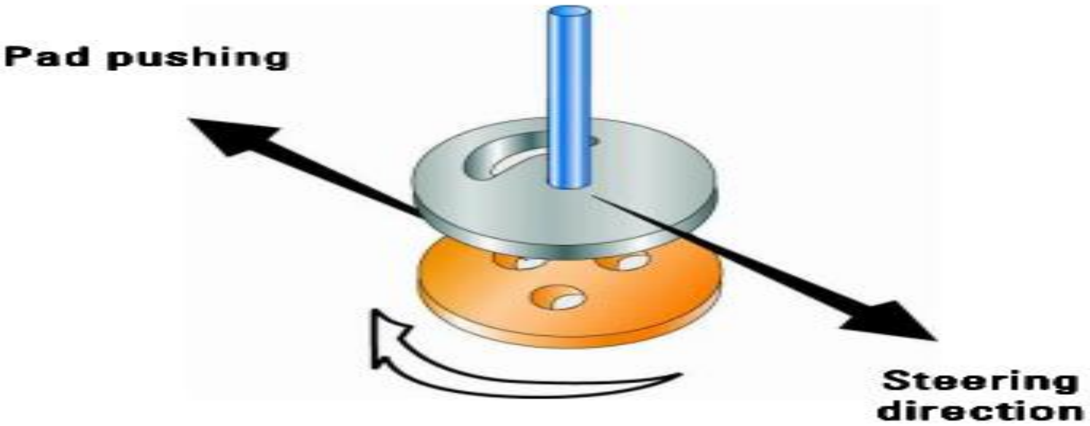


Figure A.22: A Push the Bit Rotary Steerable System Spindle System (Schlumberger Glossary, 2020).

The spindle (blue) is held geostationary by the control unit, thereby diverting a small proportion of the mudflow behind each of the pads in sequence as their respective entry ports rotate in front of the hole in the control valve. Due to the high power requirements of the control motor the system has its own power generation capabilities through a high power turbine and alternator assembly above the control unit. The diameter of the bias unit at the pads is only slightly smaller than bit size so the pads do not have to travel far before contacting and applying force to the borehole wall (figure A.23). Pad travel is limited to approximately ¾” (Schlumberger Glossary, 2020 and Cao et al., 2020).

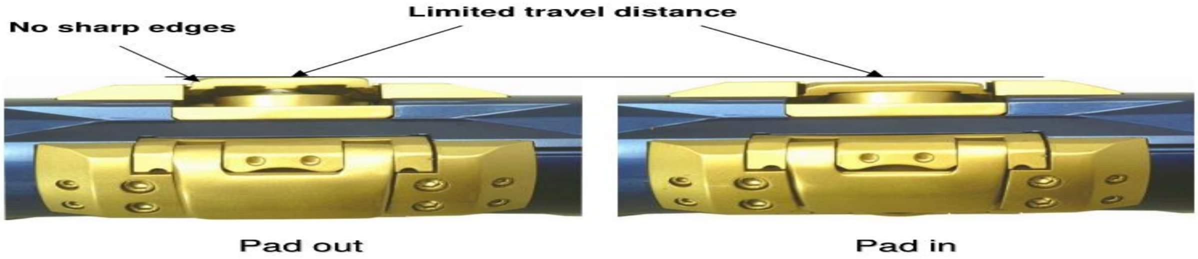


Figure A.23: The Diameter of Bias and the Pads (Schlumberger Glossary, 2020).

The dogleg delivered by the push-the-bit system depends both on the interaction of the pads with the formation (e.g. DLS will be lower in unconsolidated formations) and the proportion of time spent steering (Schlumberger Glossary, 2020). The directional driller communicates with tool through a sequence of mud flow rate changes called downlinking. This enables the driller to command the tool what proportion of time the control valve should be held oriented (i.e. steering) versus time in neutral mode where the control valve is rotated so there is no active steering (Denney, 2012). Compared to the slide-rotate sequences of a motor with a bent housing, the continuous steering of a RSS delivers smoother trajectories, which improves the drilling operation itself, as well as subsequent casing and completion runs, and later well intervention operations (Ruszka et al., 2012).

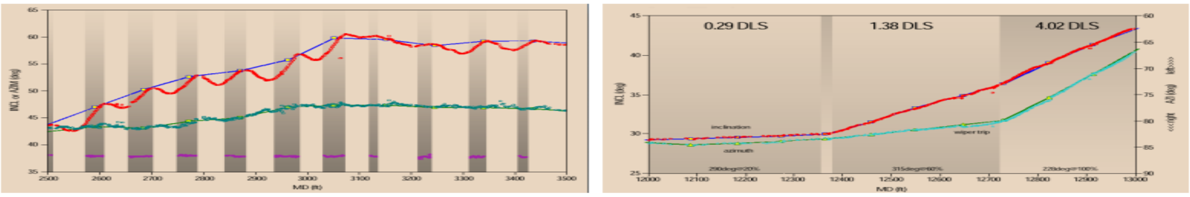


Figure A.24: Trajectory Oscillations (Ruszka et al., 2012).

The trajectory oscillations (figure A.24) resulting from steerable motor slide-rotate sequences (left) are eliminated by the continuous steering of rotary steerable systems (right). A point-the-bit system delivers all the benefits of a push-the-bit system with reduced sensitivity to the formation, resulting in more consistent steering, and generally higher dogleg capability (Schlumberger Oilfield Glossary; Hung et al., 2009 and Peach et al., 2006). The system is centered on a universal joint that transmits torque and weight on bit, but allows the axis of the bit to be offset with the axis of the tool. The axis of the bit is kept offset by a mandrel that is maintained in a geostationary orientation through the use of a counter rotating electrical motor. Due to the high power requirements the system has its own power generation capabilities through a high power turbine and alternator assembly (Peach et al.,2006) The system also contains high power electronics to control the motor, and sensors that monitor the rotation of the collar and motor. These sensors provide input and feedback for the control of the system.

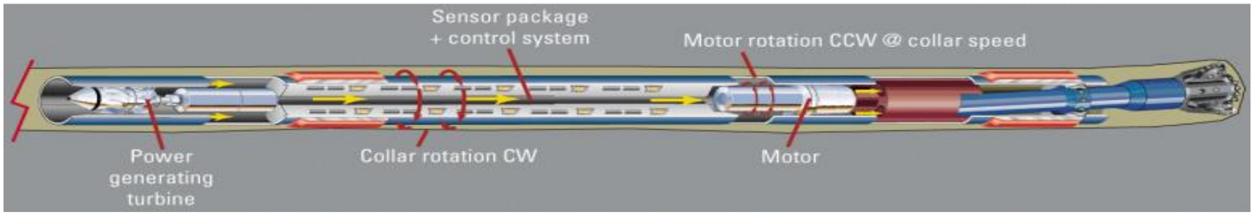


Figure A.25: The Point–the-Bit System

The point-the-bit system uses an electric motor to counter rotate a mandrel against the rotation of the collar. This keeps the mandrel, and thus the bit oriented in the same direction while still rotating with the collar. A geostationary offset angle between the bit and collar is used to create a steering tendency. As with the push the bit system, the directional driller controls the dogleg by downlinking to the tool to change the proportion of steering versus neutral time (Cao et al.,2020). Because there is no rotation provided downhole by either of the rotary steerable systems, the entire drill string must be continuously rotated from surface. If additional downhole RPM is desired, or surface rotation must be kept to a minimum (such as when casing wear is a concern), a mud motor (without the bent housing) can be used above the RSS to provide downhole rotation of the RSS assembly (Schlumberger Oilfield Glossary and Peach et al., 2006).

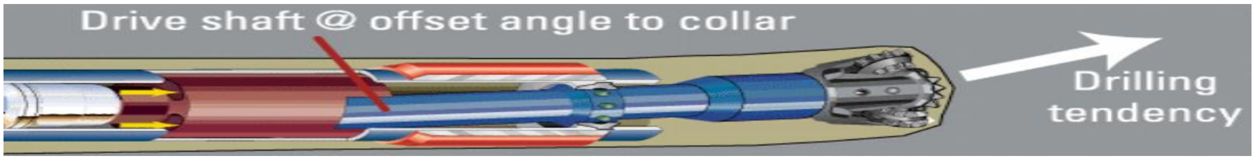


Figure A.26: The Point–the-Bit System off set Angle (Schlumberger Oilfield Glossary, 2006)

Measurement-While-Drilling (MWD) Technology

In general, MWD tools have four major capabilities that include but not limited to real-time surveys for directional control (Inclination, Azimuth, Toolface), real-time power generation, real time mud pulse data transmission telemetry system and real-time drilling related measurements (Weight-on-Bit, Torque-at-Bit, Mud Pressure) (Eduardo and Goodwin,2015). Real-time wellbore position surveys and BHA orientation measurements knowledge of the well location in a formation and in 3-D space is critical for all facets of well construction and formation evaluation. The inclination of a wellbore from vertical is determined using a set of triaxial accelerometers to measure the components of the earth’s gravitation. In conjunction with the inclination data, a set of triaxial magnetometers are used to measure the components of the earth’s magnetic field and hence the azimuth of the borehole with respect to North (Gao et al.,2018 and Hussain et al.,2014). When drilling directionally, the orientation of the drilling system defines the direction in which the well will deviate. Toolface is the angle between a reference, either gravity in a deviated well or North in a vertical well, and the direction in which the BHA will tend to deviate the hole. Toolface is used by the directional driller to ensure that the drilling assembly is oriented to give the desired direction to the well (Kok et al., 2009 and Cao et al., 2020).

Real-Time Power Generation

While batteries could be used to deliver power to the measurement electronics and telemetry system, the duration of drilling runs would be limited to the life of the batteries. For this reason, many MWD systems incorporate a downhole mud turbine and alternator electrical power generation system. Whenever mud is being pumped through the drilling system, hydraulic power from the mud flow is converted into electrical power as the turbine rotated and drives the attached alternator. This electrical power is then available to the MWD subsystems and, where an inter-tool electrical connection is available that provides power and data connectivity along the BHA, power from the MWD turbo-alternator system can also be used by other tools in the BHA (Hussain et al., 2014). Hydraulic power from the mudflow is converted into electrical power through use of a turbine and alternator system depicted in figure A.26. The stator (blue) deflects the mud flow (from left to right) on to the rotor (red) causing it to turn. The alternator (inside the yellow housing to the right) converts the rotation to electrical power.

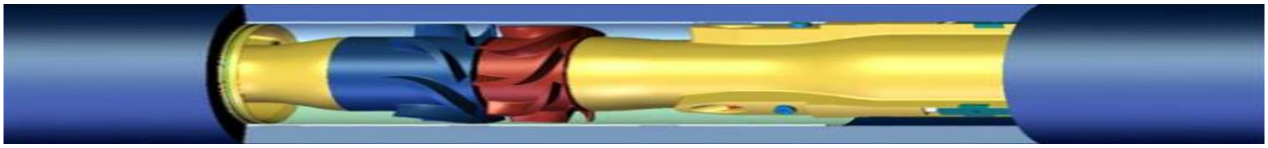


Figure A.27: The Hydraulic Power (Hussain et al., 2014).

Real-time mud pulse telemetry

Real-time mud-pulse data telemetry techniques were originally developed to improve the efficiency of wellbore surveying while drilling, which had previously been acquired by the time-consuming process of running and retrieving single- or multi-shot mechanical surveying devices (Sugiura and Jones, 2020). The introduction of electronics and sensors capable of surviving the drilling environment, combined with the means to transmit the data to surface, significantly reduced the time required to survey a well (Cao et al. 2020). There are now several methods for transmitting data from the downhole tools to surface including electromagnetic propagation and wired-drillpipe; however, the vast majority of real-time data transmission from downhole to surface is still performed by mud-pulse telemetry. Mud pulse telemetry involves encoding data in pressure pulses that propagate up through the mud inside the drillpipe. These pressure pulse sequences are detected at surface and decoded to recreate the numerical value of the data from the downhole tools (Valverde and Goodwin, 2018). There are three main ways of creating a mud pressure pulse as shown in Figure A.27. Positive pulse systems impede mud flow with a poppet valve resulting in a temporary increase in pressure. Negative pulse systems use a bypass valve to bleed pressure off to the annulus resulting in a temporary drop in pressure (Schlumberger Oilfield Glossary, 2020 and Peach et al.,2006). A continuous wave carrier or siren system uses a rotating valve system that alternates between opened and closed positions resulting in an oscillating pressure wave. Data can be encoded on the siren system by frequency, phase or amplitude modulation.

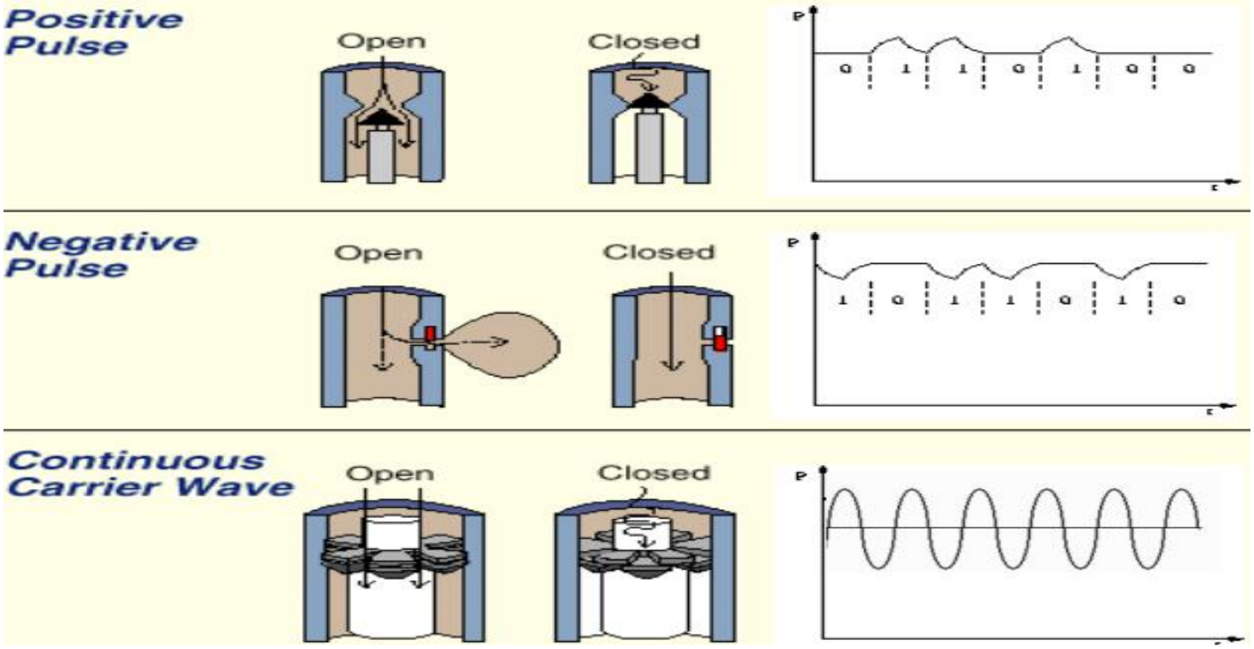


Figure A.28: The Major Pulse Telemetry (Goodwin, 2018).

Real-time drilling-related measurements

Downhole measurements of weight on bit and torque at bit allow the driller to determine whether weight and torque are being smoothly transferred to the bit or whether friction between the drill string and borehole wall is impeding the smooth transfer of mechanical power to the drilling interface (Elasby et al.,2010). The tools to acquire formation evaluation measurements while drilling are generally referred to as Logging-While-Drilling (LWD) tools to distinguish them from the drilling-oriented MWD tools. In general, LWD tools send selected formation evaluation data via an internal tool bus to the MWD tool for transmission to surface (Ronald et al.,2018). All data transmitted in this way along with the corresponding surface data acquired during drilling is referred to as Real-Time (RT) data. Downhole tools also have memory in which all the measured data (as distinct from the limited selection of data sent in real time) is stored for retrieval when the tool returns to surface. Data extracted from the tool memory is referred to as Recorded Mode (RM) data (Mohamed and Abba,2018).

Logging-While-Drilling (LWD) Technology

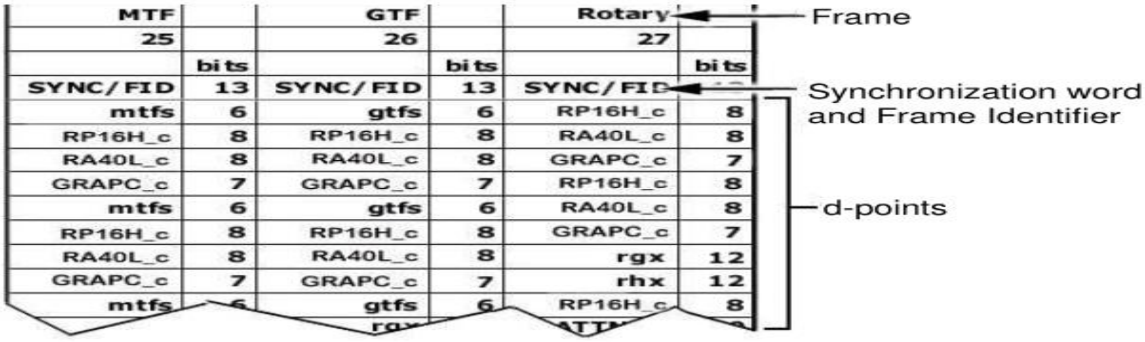
When formation evaluation measurements were first migrated from wireline tools to drill collars, naturally the key triple combo measurements of resistivity, density and neutron response were the first to be made available in addition to the GR measurement which was also available from the MWD tools (Valverde and Goodwin, 2015). Due to the nature of the drilling environment, in addition to the limitations imposed by having to fit detectors and electronics is a drill collar, some changes were made to the configuration of sensors. Because of these necessary changes LWD tools and wireline tools measuring the same formation parameter generally have slightly differing raw responses (Goraya et al., 2020). After appropriate environmental corrections are applied any remaining discrepancies are generally due to differences in the invasion profile and borehole condition between the early LWD log and the subsequent wireline log. The evolution of LWD technology has seen significant improvements in the triple-combo services and the addition of numerous additional measurements including imaging of multiple formation properties, magnetic resonance, sonic and seismic acquisition, capture spectroscopy and sigma measurements (Gao et al., 2018). In addition to increasing measurement sophistication, the use of LWD data has broadened from petrophysical evaluation of the formation, to use of the real-time measurements for evaluation of the wellbore location within the layering (well placement) and wellbore stability (geomechanics).

Software and Information Technology

Real-time transmission from downhole to the surface system

Data acquired by the downhole LWD tools is compressed, encoded and transmitted to surface, most commonly through a mud-pulse telemetry system (Cao et al.,2020). Due to the limited bandwidth of the current mud-pulse systems (typically 0.5 to 12 bits per second) the amount of data that can be transmitted to surface in real-time is limited (Peach et al.,2006) Improvements continue to be made in telemetry rate (the number of bits that can be transmitted per second) and data compression (the amount of data transmitted per bit). Selection of what data is to be sent is still required as bandwidth capable of transmitting all the data all the time, as is the case with wireline tools, is unlikely to be widely available in the near future (Kok et al.,2006). Real-time data is grouped into data points (d-points) each of which represents a particular measurement (e.g. formation bulk density) or part of a larger collection of data such as part of an image which is spread across several d-points (Eltayeb et al.,2011 and Denney, 2012). These d-points are grouped into frames which define the data to be transmitted when the BHA is in a particular mode of operation. For example, a frame designed for use when the BHA is sliding in a deviated well would contain the gravity tool face (GTF) and non-azimuthal formation measurements, as there is no point wasting bandwidth sending azimuthal data which cannot be acquired when the BHA is not rotating. A frame designed for use when the BHA is rotating would, in contrast, likely contain d-points for azimuthal and perhaps image data, but would not contain a tool face d-point as the tool face is not of interest when the BHA is rotating (Russia et al., 1999 and Wylie et al.,2018). Generally real-time data is transmitted in 4 designated frames namely; magnetic tool face (MTF) frame that is used in near vertical wells when sliding; gravity tool face (GTF) frame that is used in deviated and horizontal wells when sliding; rotary frame used when the BHA is rotating; and utility frame used to transmit data acquired while the mud pumps were off and hence the mud-pulse telemetry was not operational (Zhou et al., 2020). This frame will generally contain the static surveys (acquired when the BHA is quiet) and hydrostatic mud pressure. It is increasingly used for applications such as acoustic (sonic and seismic) transit times and waveforms as well as formation pressure data acquired with the pumps turned off to minimize measurement interference (Gutierrez and Hanak,2021)

d-points containing the measurement data are grouped into frames as shown in figure 2.27. The selection of which frame to transmit is made by the downhole tool based on the well inclination (MTF or GTF frame), whether the tool is rotating (rotary frame) and whether the mud flow has just started again after a period of no-flow (utility frame). After a few training bits to allow the surface system to synchronize, the frame identifier is sent (Wielemaker et al., 2020). As both the surface and downhole systems have been programmed with the same frames, the subsequent stream of bits will be divided into the corresponding d-points and decoded by the surface system. Decoding involves the conversion of the binary bit stream to decimal followed by application of the reverse transform that was applied to the data downhole. For example, a downhole density measurement of RHOB = 2.4 g/cc may have 0.9 g/cc subtracted and the remainder divided by 0.01 giving a decimal number of 150. The eight-bit binary equivalent, 10010110, is transmitted via the mud-pulse system so the binary number 10010110, is now available at surface where it is converted back to the decimal number 150 and the reverse transform, RHOB_RT = 0.01*X + 0.9g/cc is applied (Abbas et al.,2020). The real-time RHOB_RT = 2.4 g/cc measurement (the _RT designating it as real- time data so that it can be distinguished from the recorded mode RHOB) is then available for visualization and interpretation (Gupta et al., 2019).



MTF		GTF		Rotary	
25		26		27	
	bits		bits		bits
SYNC/FID	13	SYNC/FID	13	SYNC/FID	
mtfs	6	gtfs	6	RP16H_c	8
RP16H_c	8	RP16H_c	8	RA40L_c	8
RA40L_c	8	RA40L_c	8	GRAPC_c	7
GRAPC_c	7	GRAPC_c	7	RP16H_c	8
mtfs	6	gtfs	6	RA40L_c	8
RP16H_c	8	RP16H_c	8	GRAPC_c	7
RA40L_c	8	RA40L_c	8	rgx	12
GRAPC_c	7	GRAPC_c	7	rhx	12
mtfs	6	gtfs	6	RP16H_c	8

Figure A.29: The d- Points (Denney, 2012).

Real-time Information Extraction

Having transmitted the data from the downhole tools to surface and from the surface acquisition computer to the decision maker, the data must then be presented in a manner that helps the decision maker extract the relevant information encoded in the data stream. In the case of image data this is generally best achieved by 2-D and 3-D visualization of the data, it is color coded to represent the formation parameter being measured (Abusairi and Carlos, 2019). The addition of interactivity and dip-picking to the visualization environment allows the decision-maker to extract quantitative information about the formation dip from the data stream. This facilitates well placement using the real-time dip determination technique. The model-compare-update well placement method requires more sophisticated software support as the incoming real-time data must be displayed in comparison to modeled tool responses. The software must be able to create and modify a formation structural model populated with multiple formation properties, and a planned well trajectory. In addition, the software must be able to simulate (forward model) the response of the LWD tools and stream in the real-time trajectory and logging data so that they can be compared to the simulated log response (Pettitt-Schieber and Graham, 2020). As discussed earlier, discrepancies between the simulated and real data are an indication that the formation model does not accurately represent the subsurface formation and hence the model needs to be updated so that the simulated and actual data match. Once they match the position of the wellbore in the formation can be assessed and appropriate well placement decisions taken and communicated to the directional driller (Jin et al.,2019). Presentation of this data is generally of the form shown in figure A.28. A curtain section of the formation along the planned well trajectory, color coded to show one of the formation properties of interested is plotted in the lower panel with true vertical depth as the vertical axis and true horizontal length as the horizontal axis. Formation structural information is captured in the scaled geometry of the curtain section layers and faults. The formation model can be color-coded for any of the formation properties entered during the pre-drilling model construction (Azike, 2011 and Abbas et al.,2020). Horizontal log tracks in the upper panel display both the real-time data and forward modeled log responses so that any discrepancies between them can be identified. Image data may also be displayed in the horizontal log tracks. If a discrepancy between the forward modeled and real- time logs is identified, then interactive adjustments are made to the formation model. The simulated log responses are then recomputed for the edited formation model and compared again to the real-time data. This model-compare-update cycle is repeated until a match is achieved (Nakayama and Glenn, 2016).

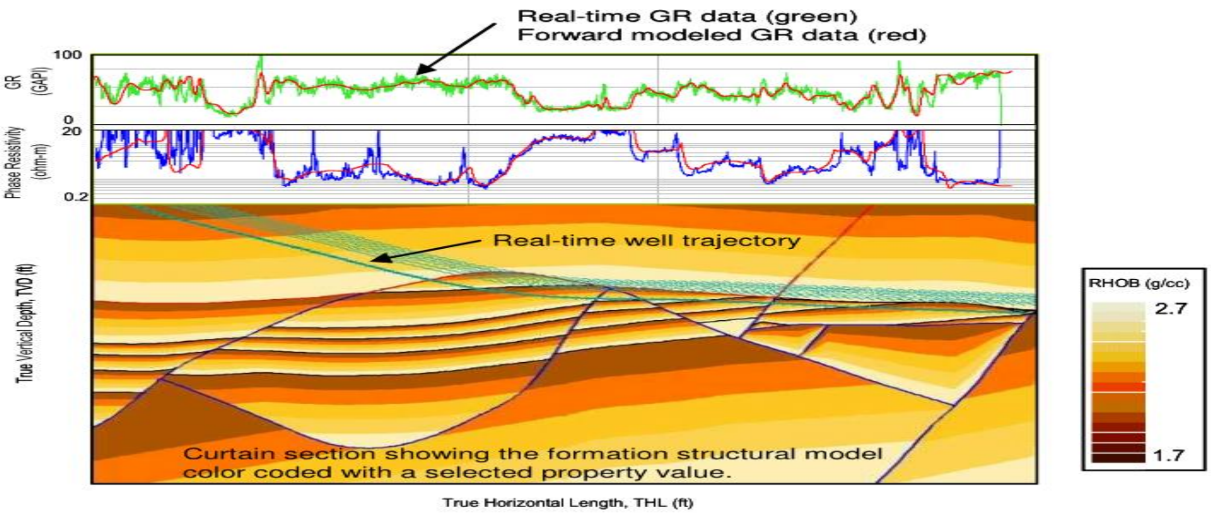


Figure A.30: The Forward Model (Azike, 2011 and Abbas et al.,2020).

A 3-D representation of the formation and wellbore trajectory (figure A.29) removes the 2-D constraint that the curtain section is only valid if the planned and drilled wells are in the same vertical plane.

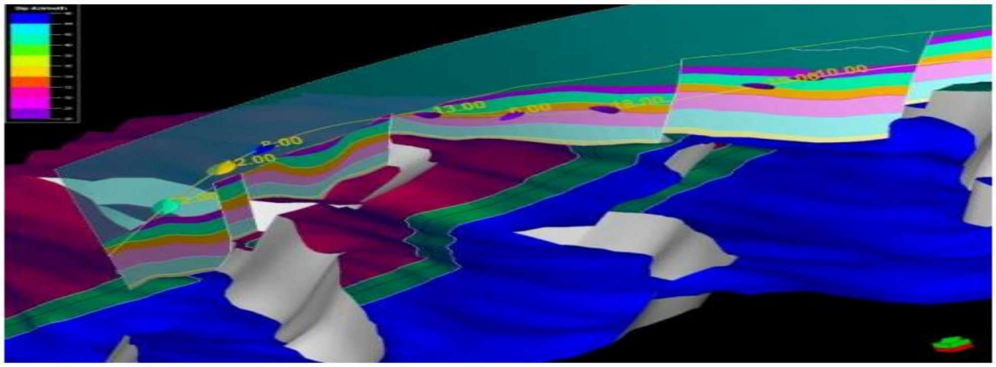


Figure A.31: 3-D Image: Formation and Wellbore Trajectory (Nakayama and Glenn, 2016).

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APPENDIX B

Understanding Geology for Efficient Well Placement

Reservoir Geology Fundamentals

Geology (derived from the Greek word Geo[earth] and Logos[study]) is the science of the solid earth and its internal processes, influenced by the atmosphere, oceans, rivers and biological activity. Geology is a large and complex subject (Barbosa et al., 2011 and Green et al., 2018). The following is a very brief summary of the major points relevant to well placement. In placing wells within a geological target it is important that the well placement engineer have a basic understanding of the geological processes that create reservoirs. This not only allows the well placement engineer to anticipate the likely shape of the reservoir (for example, whether layers are likely to be straight or undulating) but also be able to discuss possible geological scenarios with the operating company geologist (Temizel et al., 2018).

Rock Classifications

There are three main classes of rock: igneous, metamorphic and sedimentary. **Igneous rocks** crystallize from molten rock, or magma, with interlocking mineral crystals. Igneous rocks that crystallize slowly, typically below the surface of the Earth, are plutonic igneous rocks and have large crystals (large enough to see with the naked eye). Volcanic igneous rocks crystallize quickly at the Earth's surface and have small crystals (usually too small to see without magnification). Common examples include granite (plutonic) and rhyolite (volcanic), diorite (plutonic) and andesite (volcanic), and gabbro (plutonic) and basalt (volcanic). Igneous rocks typically comprise the minerals quartz, mica, feldspar, amphibole, pyroxene and olivine (Temizel et al., 2018). **Metamorphic rocks** form from the alteration of preexisting rocks by changes in ambient temperature, pressure, volatile content, or all of these. Such changes can occur through the activity of fluids in the Earth and movement of igneous bodies or regional tectonic activity. The texture of metamorphic rocks can vary from almost homogeneous, or nonfoliated, to foliated rocks with a strong planar fabric or foliation produced by alignment of minerals during recrystallization or by reorientation. Common foliated metamorphic rocks include gneiss, schist and slate. Marble, or metamorphosed limestone, can be foliated or non-foliated. Hornfels is a nonfoliated metamorphic rock. Graphite, chlorite, talc, mica, garnet and staurolite are distinctive metamorphic minerals (Gonzalez et al.,2020). **Sedimentary rocks** are formed at the Earth's surface through deposition of sediments derived from weathered rocks, biogenic activity or precipitation from solution. Clastic sedimentary rocks such as conglomerates, sandstones, siltstones and shales form as older rocks weather and erode, and their particles accumulate and lithify, or harden, as they are compacted and cemented. Biogenic sedimentary rocks form as a result of activity by organisms, including coral reefs that become limestone. Precipitates, such as the evaporite minerals halite (salt) and gypsum can form vast thicknesses of rock as seawater evaporates(Carpenter,2020). Sedimentary rocks can include a wide variety of minerals, but quartz, feldspar, calcite, dolomite and evaporite group and clay group minerals are most common because of their greater stability at the Earth's surface than many minerals that comprise igneous and metamorphic rocks. Sedimentary rocks, unlike most igneous and metamorphic rocks, can contain fossils because they form at temperatures and pressures that do not obliterate fossil remnants. The vast majority of the world’s hydrocarbon reservoirs are of sedimentary origin (Gonzalez et al.,2020).

Depositional Environments

Sediments are deposited under various conditions. Depositional environments describe the area in which and physical conditions under which sediments are deposited, including sediment source; depositional processes such as deposition by wind, water or ice; and location and climate, such as desert, swamp or river (Tomomewo et al., 2020). Alluvial deposition pertains to the subaerial (as opposed to submarine) environment, action and products of a stream or river on its floodplain, usually consisting of detrital clastic sediments, and distinct from subaqueous deposition such as in lakes or oceans and lower energy fluvial deposition (Bondabou et al., 2015). Sediments deposited in an alluvial environment can be subject to high depositional energy, such as fast-moving flood waters, and may be poorly sorted or chaotic. Lacustrine deposition pertains to deposition in lakes, or an area having lakes (Shao et al., 1994). Because deposition of sediment in lakes can occur slowly and in relatively calm conditions, organic-rich source rocks can form in lacustrine environments. Fluvial deposition pertains to deposition by a river or running water. Fluvial deposits tend to be well sorted, especially in comparison with alluvial deposits, because of the relatively steady transport provided by rivers. Deltaic deposition pertains to an area of deposition or the deposit formed by a flowing sediment- laden current as it enters an open or standing body of water, such as a river spilling into a gulf (Shao et al.,1994). As a river enters a body of water, its velocity drops and its ability to carry sediment diminishes, leading to deposition. The term has origins in Greek because the shape of deltas in map view can be similar to the Greek letter delta. The shapes of deltas are subsequently modified by rivers, tides and waves (Bueno, 2014). There is a characteristic coarsening upward of sediments in a delta. The three main classes of deltas are river-dominated (Mississippi River), wave-dominated (Nile River), and tidedominated (Ganges River). Ancient deltas contain some of the largest and most productive petroleum systems. Marine deposition pertains to deposition in seas or ocean waters, between the depth of low tide and the ocean bottom (Bondabou et al., 2015).

Plate Tectonics is the unifying geologic theory that was developed to explain observations that interactions of the brittle plates of the lithosphere with each other and with the softer underlying asthenosphere result in large-scale changes in the Earth. The major composition layers of the earth are shown in Figure 3.1 (Kozlowski et al.,2020). The theory of plate tectonics initially stemmed from observations of the shapes of the continents, particularly South America and Africa, which fit together like pieces in a jigsaw puzzle and have similar rocks and fossils despite being separated by a modern ocean (Ridha et al.,2019). As lithospheric plates heat up or cool down depending on their position, or their tectonic environment, relative to each other and to warmer areas deeper within the Earth, they become relatively more or less dense than the asthenosphere and thus tend to rise as molten magma or sink in cold, brittle slabs or slide past each other. Mountain belts can form during plate collisions or an orogeny; diverging plates or rifts can create new midoceanic ridges; plates that slide past one another create transform fault zones (such as the San Andreas fault); and zones of subduction occur where one lithospheric plate moves beneath another (Bueno, 2014).

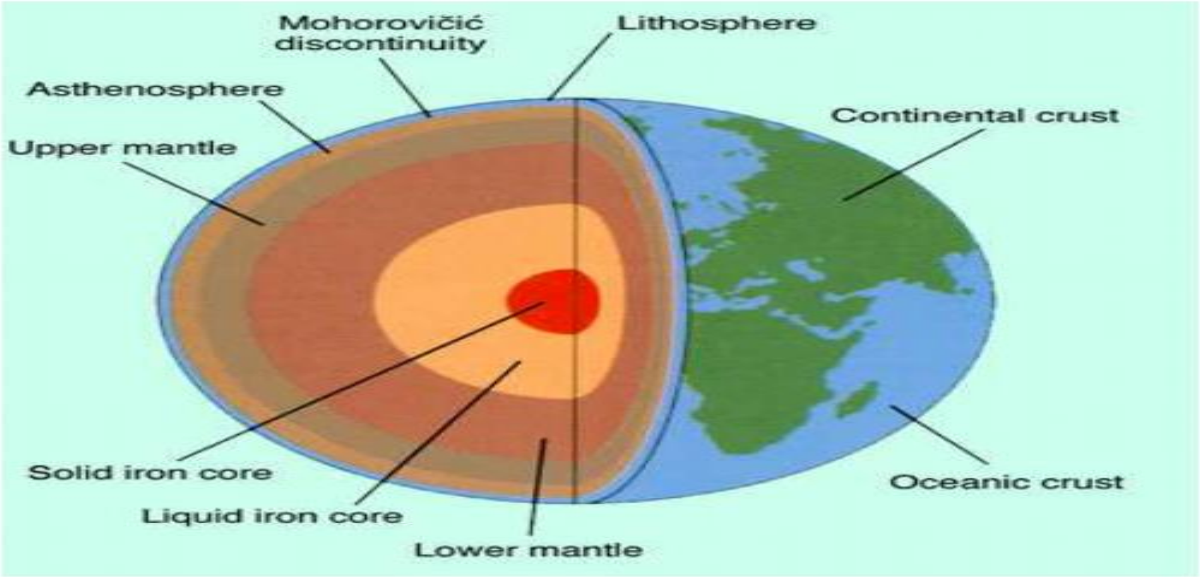

Figure B.1: The compositional layers of the Earth (Bueno, 2014).

The major compositional layers of the Earth are the core, the mantle and the crust. The lithosphere includes all of the crust and the uppermost part of the mantle. The asthenosphere comprises much of the upper mantle. The Moho, or Mohorovicic discontinuity, is the boundary between the crust and the mantle. These compositional and mechanical layers play a significant role in the movement of the Earth's tectonic plates.

Plate tectonic theory can explain such phenomena as earthquakes, volcanic or other igneous activity, midoceanic ridges and the relative youth of the oceanic crust, and the formation of sedimentary basins on the basis of their relationships to lithospheric plate boundaries. Convection of the mantle is postulated to be the driving mechanism for the movement of lithospheric plates (Figure B.2). Measurements of the continents using the Global Positioning System confirm the relative motions of plates. Age determinations of the oceanic crust confirm that such crust is much younger than that of the continents and has been recycled by the process of subduction and regenerated at midoceanic ridges (Pilisi et al., 2019). Convection within the Earth has been proposed as a cause of development of midoceanic ridges and subduction zones according to plate tectonic theory.

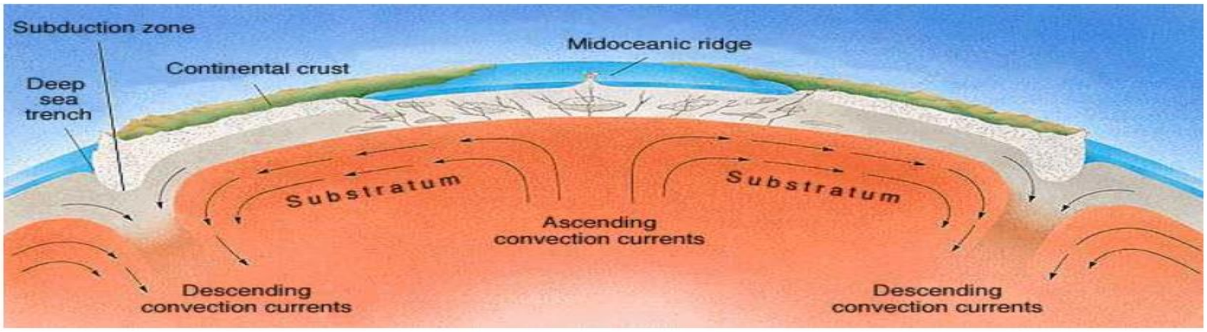

Figure B.2: Convection within the Earth (Bueno, 2014).

Divergent Margins

Divergent margins occur where tectonic plates move apart. Such splitting of the crust is known as rifting. Rifting is initiated when warm mantle material rises to beneath the crust. It stretches and thins the crust, causing it to fracture and separate. The material from the mantle undergoes partial melting due to the decrease in pressure and rises to fill the gap between the separating plates (Thompson, 1978) as shown in Figure B.3.

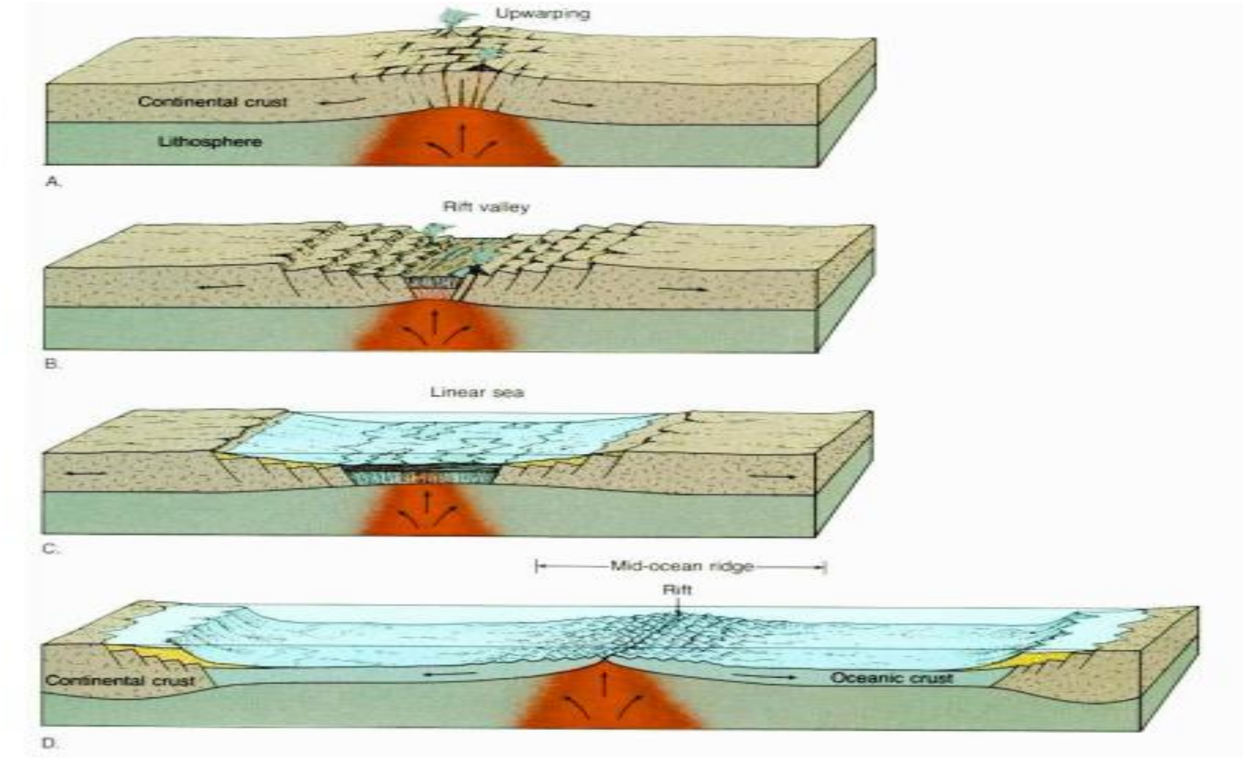

Figure B.3: Divergent margins occur where tectonic plates move apart (Fouquet, 2009).

At divergent margins, the region is initially uplifted due to thermal expansion (e.g. Colorado Plateau), normal faults and a rift valley develops as the plates begin to separate (Gadde and Peng, 2009). Volcanism and earthquakes are frequent. (e.g. the African Rift Valley), new oceans form as oceanic crust is produced (e.g. Red Sea), eventually a large ocean is created (e.g. the Atlantic Ocean). Extensive sedimentary deposits often form in the newly opened basin, due to the difference in relief between the uplifted horst blocks on either side and the graben, or valley floor. As the rift expands, it may be periodically flooded by the sea forming shallow water clastic marine sediments interspersed with evaporites in hot, dry climates. Continued rifting sees the opening of a new ocean (Thompson, 1978). The two edges of the new continents are no longer tectonically or volcanically active and become passive continental margins. When two plates move toward one another, they form either a subduction zone or a continental collision (Gadde and Peng, 2005). This depends on the nature of the plates involved, as shown in Figure 3.6**.** In a subduction zone, the subducting plate, this is normally a plate with oceanic crust, moves beneath the other plate, which can be made of either oceanic or continental crust (Fouquet, 2009). During collisions between two continental plates, large mountain ranges, such as the Himalayas, may be formed.

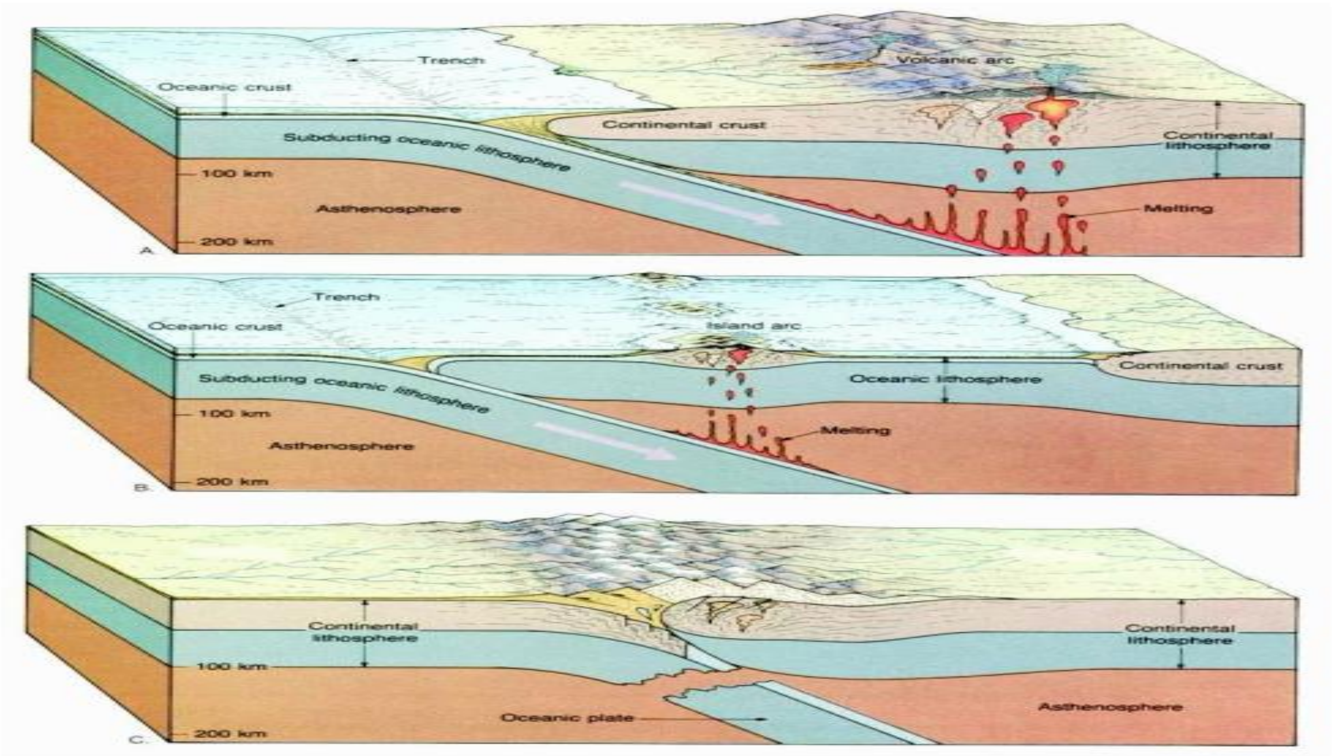

Figure B.4: Convergent margins. This happens occur where tectonic plates move toward one another (Fouquet, 2009).

Strike-slip Margins

Strike slip margins (also known as transform fault boundary, transform plate boundary, transform plate margin, sliding boundary, or conservative plate boundary) is said to occur when tectonic plates slide and grind against each other along a transform fault. The relative motion of such plates is predominantly horizontal.

Faults

The dynamic nature of the earth's crust results in faults and folds. A fault is a break or planar surface in brittle rock across which there is observable displacement. Depending on the relative direction of displacement between the rocks, or fault blocks, on either side of the fault, its movement is described as normal, reverse or strike-slip (Figure B.5). Fault movement depends on the stresses on the rock. The fault block above the fault surface is called the hanging wall, while the block below the fault is the footwall. Fault throw is the vertical displacement of the layers due to faulting.

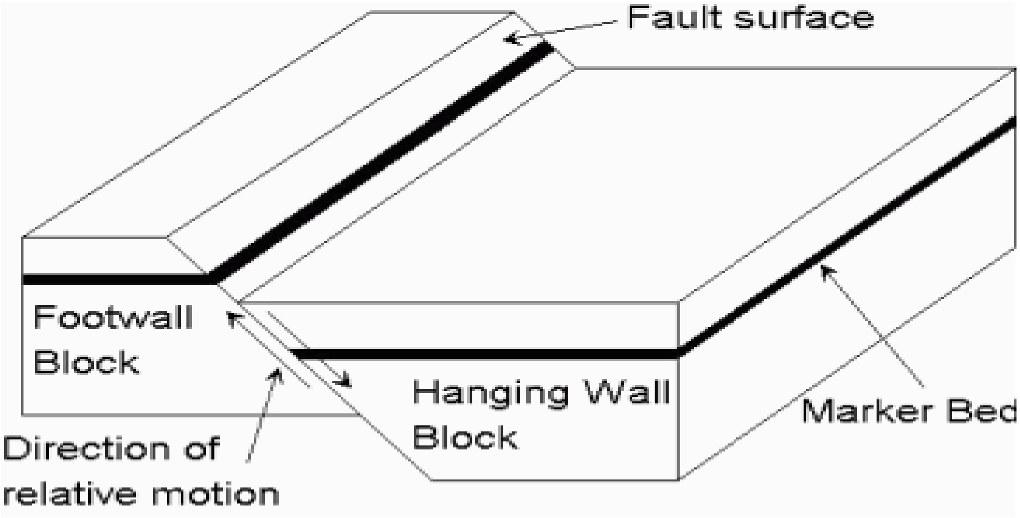

Figure B.5: Fault block terminology.

In a normal fault, the hanging wall moves down relative to the footwall along the dip of the fault surface, which is steep, from 45° to 90°. Groups of normal faults can produce horst and graben topography, or a series of relatively high- and low-standing fault blocks, as seen in areas where the crust is rifting or being pulled apart by plate tectonic activity (Figure 3.6). A growth fault is a type of normal fault that forms during sedimentation and typically has thicker strata on the downthrown hanging wall than the footwall.

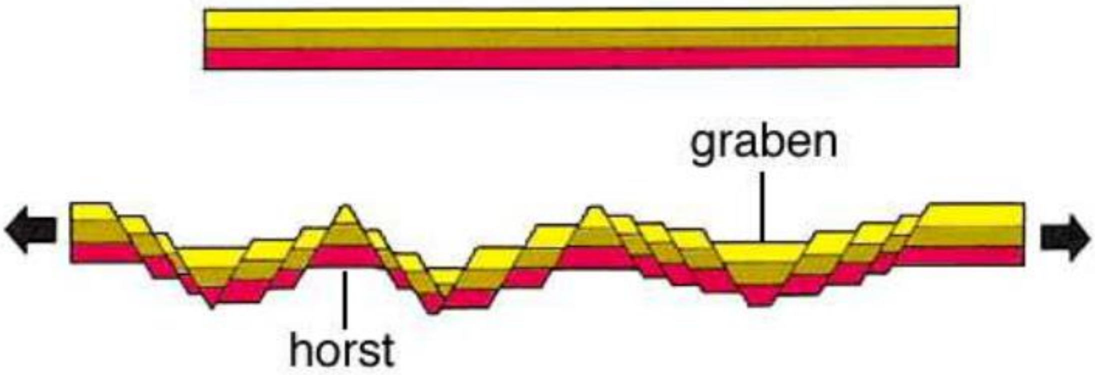

Figure B.6: Horst and graben topography (Schlumberger Technical Report, 1982)

Horst and graben topography can occur where the crust is being pulled apart.

A reverse fault forms when the hanging wall moves up relative to the footwall parallel to the dip of the fault surface. A thrust fault is a reverse fault in which the fault plane has a shallow dip, typically much less than 45°. In cases of considerable lateral movement, the fault is described as an over thrust fault. Thrust faults can occur in areas of compression of the Earth's crust (Stockton et al.,1984). Movement of normal and reverse faults can also be oblique as opposed to purely parallel to the dip direction of the fault plane. The motion along a strike-slip fault, also known as a transcurrent or wrench fault, is parallel to the strike of the fault surface, and the fault blocks move sideways past each other. The fault surfaces of strike-slip faults are usually dextral strike-slip fault. If it moves left, the relative motion is described as sinistral (**Figure 3.7).** A transform fault is a particular type of strike-slip fault that is a boundary of an oceanic tectonic plate.

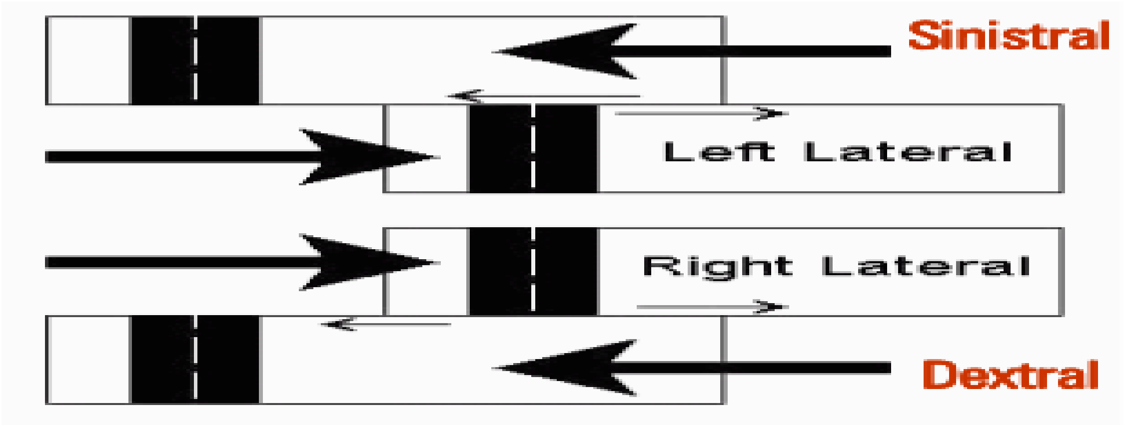

Figure B.7: The fault surfaces of strike-slip faults (Schlumberger Technical Report, 1982)

The presence of a fault can be detected by observing characteristics of rocks such as changes in lithology from one fault block to the next, breaks and offsets between strata or seismic events, and changes in formation pressure in wells that penetrate both sides of a fault. Some fault surfaces contain relatively coarse rubble that can act as a conduit for migrating oil or gas, whereas the surfaces of other faults are smeared with impermeable clays, broken grains or have had impermeable minerals deposit in the fault plane resulting in a sealing fault that can act as a fault seal (Desheng et al., 1987 and Tyurin and Benefield,2008). Given the geological complexity of some faulted rocks and rocks that have undergone more than one episode of deformation, it can be difficult to distinguish between the various types of faults. Also, areas deformed more than once or that have undergone continual deformation might have fault surfaces that are rotated from their original orientations, so interpretation is not straightforward.

Folds

A fold is a wave-like geologic structure that forms when rocks deform by bending instead of breaking under compressional stress. Anticlines are arch-shaped folds in which rock layers are upwardly convex. The oldest rock layers form the core of the fold, and outward from the core progressively younger rocks occur. A syncline is the opposite type of fold, having downwardly convex layers with young rocks in the core. Folds typically occur in anticline-syncline pairs. The hinge is the point of maximum curvature in a fold. The limbs occur on either side of the fold hinge. The imaginary surface bisecting the limbs of the fold is called the axial surface (Figure 3.8). The axial surface is called the axial plane in cases where the fold is symmetrical and the lines containing the points of maximum curvature of the folded layers, or hinge lines, are coplanar. Concentric folding preserves the thickness of each bed as measured perpendicular to original bedding. Similar folds have the same wave shape, but bed thickness changes throughout each layer, with thicker hinges and thinner limbs (Chilingar, 1978).

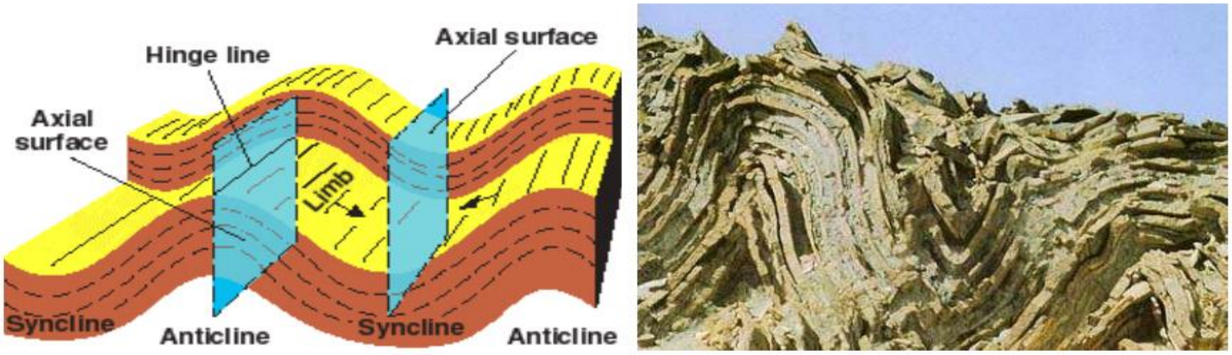

Figure B.8: Folds wave-like structures (Onwumelu et al., 2019)

Folds are wave-like structures that often include pairs of anticlines and synclines. Axial surfaces are imaginary surfaces that bisect the limbs of folds. A dome is a type of anticline that is circular or elliptical rather than elongate. The upward migration of salt diapirs can form domes, called salt domes. A basin is a depression, or syncline that is circular or elliptical rather than elongate (Figure 3.9).

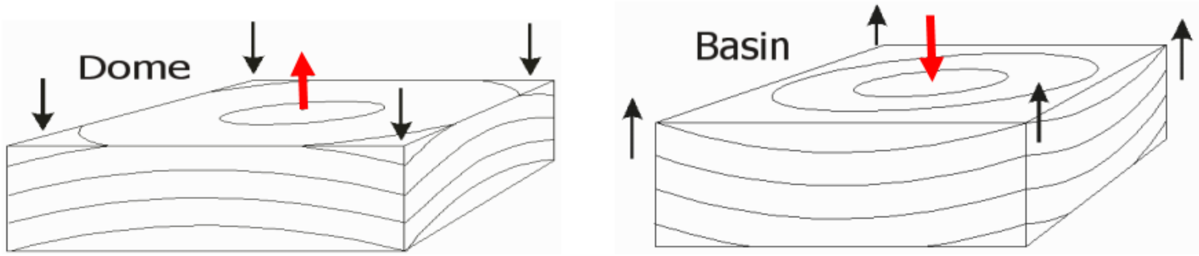

Figure B.9: Domes and basins (circular or elliptical forms of anticlines and synclines respectively).

Petroleum Systems

A petroleum system comprises the geologic components and processes necessary to generate and store hydrocarbons, including a mature source rock, migration pathway, reservoir rock, trap and seal (Ismagulova et al.,2008) (Figure 3.10). Appropriate relative timing of formation of these elements and the processes of generation, migration and accumulation are necessary for hydrocarbons to accumulate and be preserved. Exploration plays and prospects are typically developed in basins or regions in which a complete petroleum system has some likelihood of existing.

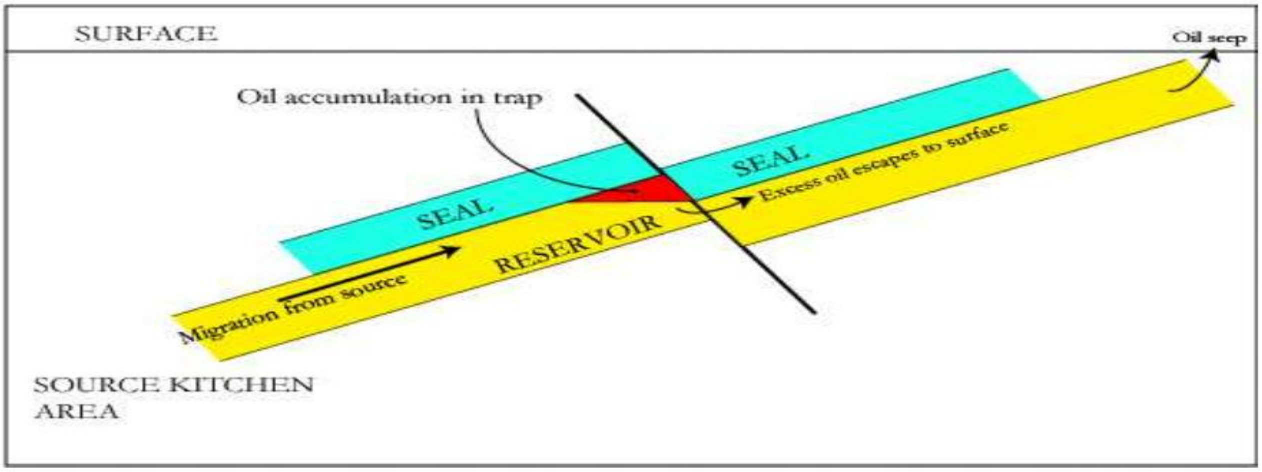

Figure B.10: A Petroleum System (Tomomewo et al., 2019)

A petroleum system must have a mature source rock from which hydrocarbons are generated and migrate to a suitable reservoir rock which has a seal, thereby creating a trap where the hydrocarbons accumulate rather than migrating all the way to surface. The timing of all these components is critical, as is the preservation of the reservoir seal and properties over time to ensure the hydrocarbons are not lost (Zumberge et al., 2016).

Source rock is rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone (Mullins et al., 2016). Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Maturity refers to the state of a source rock with respect to its ability to generate oil or gas. As a source rock begins to mature, it generates gas. As an oil-prone source rock matures, the generation of heavy oils is succeeded by medium and light oils. Above a temperature of approximately 100^{o}C [212^{o}F], only dry gas is generated. The maturity of a source rock reflects the ambient pressure and temperature as well as the duration of conditions favorable for hydrocarbon generation (Mohamad et al.,2015).

Migration is the movement of hydrocarbons from their source into reservoir rocks. The movement of newly generated hydrocarbons out of their source rock is primary migration, also called expulsion. The further movement of the hydrocarbons into reservoir rock in a hydrocarbon trap or other area of accumulation is secondary migration (Amer,2015). Migration typically occurs from a structurally low area to a higher area because of the relative buoyancy of hydrocarbons in comparison to the fluids in the surrounding rock (Ismagulova et al.,2016). Migration can be local or can occur along distances of hundreds of kilometers in large sedimentary basins, and is critical to the formation of a viable petroleum system (Onwumelu et al., 2019).

A reservoir is a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system (Tomomewo et al, 2019). A trap is a configuration of rocks suitable for containing hydrocarbons and sealed by a relatively impermeable formation through which hydrocarbons will not migrate. Traps are described as structural traps (in deformed strata such as folds and faults) or stratigraphic traps (in areas where rock types change, such as unconformities, pinch-outs and reefs). A trap is an essential component of a petroleum system (Pilisi et al., 2012. Structural traps (fibure B.11) are formed by the deformation of strata such as faulting or folding. Stratigraphic traps (figure 3.12) are formed by erosional and sedimentary processes.

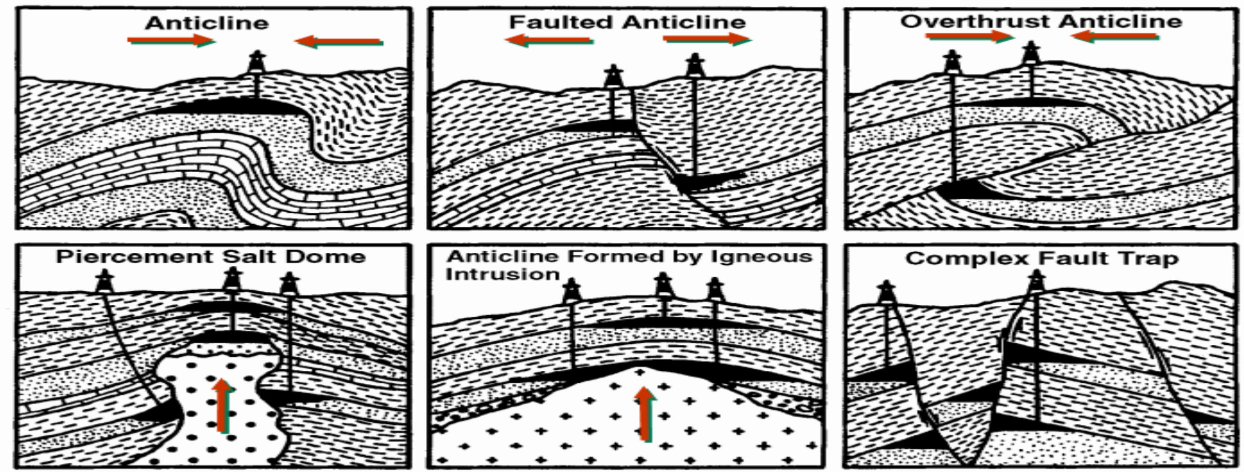

Figure B.11: Structural traps

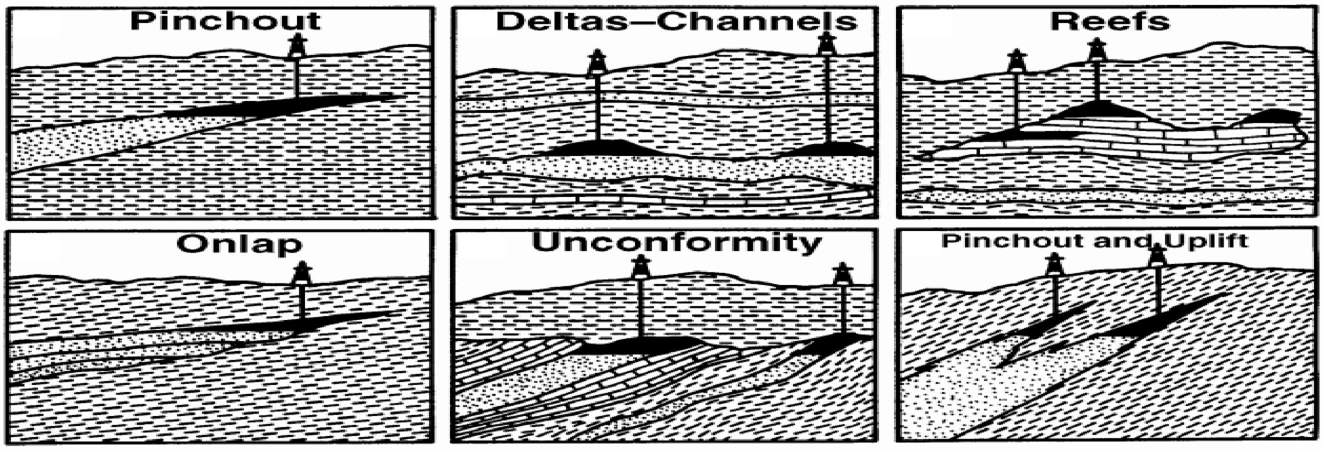

Figure B.12: Stratigraphic Traps (Kazakove et al., 2019)

A seal is a relatively impermeable rock, commonly shale, anhydrite or salt, which forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system. The permeability of a seal capable of retaining fluids through geologic time is ~ 10-6 to 10-8 Darcies. Timing refers to the sequence in which the components form and processes occur. For example, if the source rock reaches maturity and generates oil but there is no trap formed over the reservoir rock then the oil will eventually seep to surface and be lost to the atmosphere, so no hydrocarbon will accumulate.

Preservation refers to the stage of a petroleum system after hydrocarbons accumulate in a trap and are subject to degradation, remigration, tectonism or other unfavorable or destructive processes (Zhang et al., 2020. As shown in Figure B.12, if the hydrocarbon volume that migrates into the reservoir exceeds the volume that can be held, then the excess hydrocarbons will spill from the trap. The spill point is the structurally lowest point in a hydrocarbon trap that can retain hydrocarbons. Once a trap has been filled to its spill point, further storage or retention of hydrocarbons will not occur for lack of reservoir space within that trap. The hydrocarbons spill or leak out, and continue to migrate until they are trapped elsewhere or seep to the surface (Roberts, 1963).

Hydraulic Fracturing Technology

Hydraulic fracturing is the breaking or cracking of reservoir rocks by a pressurized liquid. In the rock, some fractures occur naturally as shown in some veins or dikes seen from rock samples taken from some oil and gas reservoirs. Hydraulic fracturing is a method in which water, sand and chemicals (vicosifying agent or some polymers) are mixed, and the mixture is then pushed at high pressure into a wellbore to initiate micro fractures (in most cases, less than 1mm), along which fluids such as gas, petroleum, uranium-bearing solution, and brine water may migrate to the well (Alekseev, 2018). Once introduced, pressure created by the fluid is then removed, and some small grains sizes of proppant, usually sand, aluminum oxide or grounded ceramics are then pushed in at high pressure to hold earlier created fractures open to allow for continuous flow of fluids from the well. This method is mostly applied to unconventional hydrocarbon exploration like the shale gas, tight gas, tight oil, and coal seam gas (Gupta et al., 2015) including hard rock wells. This hydraulic frack method of well stimulation is usually conducted rarely, like once in the life of the well and greatly enhances hydrocarbon production and general well productivity.

The first time hydraulic fracturing was used was in 1947, and that was in the experimental research trying to understand how to deploy the technology. It was not until 1949 before the first commercial applications was tested. As of 2014, the US has over 1.7 million wells drilled and 3.5 million hydraulic fracturing jobs performed on oil and gas wells worldwide. More than two million of the hydraulic frack jobs were performed in the United States (Al-Fatlawi et al.,2019; Voevodkin et al., 2019 and Alekseev, 2018). The benefit of the hydraulic fracturing is mainly the economic benefits in the area of increases revenue from high production resulting from high well accessibility which positively impacts the extraction of the hydrocarbons**.** The main issues against hydraulic fracturing are the environmental risks, including ground water pollution, fresh water depletion, air pollution, noise pollution, possible escaping gas migration and hydraulic fracturing chemicals to the surface (Voevodkin et al., 2019). The bigger problem is the environment pollution and the increasing possibility of seismic activity that is has been linked with deep well injection disposal both the produced and flowback from hydraulically fractured wells activities (Kang and Feng, 2015). Because of these negative effects, hydraulic fracturing has come under international investigation and condemnations. Some countries including US are still utilizing hydraulic fracturing, while other countries are suspending or completely eradicating its use (Gupta et al,2015 and Anthony et al., 2015). Some of those countries, including most the U.K, have recently lifted their bans, choosing to focus on regulation instead of outright prohibition.

The connection between well performance and reservoir response pressures was first researched by Floyd Farris, a former staff of the Oil and Gas Corporation. This study which was carried out in 1947 at the Hugoton gas field in Grant County Kansas later became the standard for conducting hydraulic fracturing experiment (Schorn, 2011). For the well treatment 1,000 US gallons of gelled gasoline(napalm) and sand from the Arkansas River was pumped into a gas-producing limestone formation that was 2,400 feet deep. After the experiment, the well pressure did not improve that much, a sign that the experiment was not very successful. Later the experimental procedure was modified and improved by J.B. Clark of Stanolind in a thesis he published in 1948. A patent on this modified process was finally issued in 1949. Halliburton did the first two known commercial hydraulic fracturing jobs, one in Stephens County, Oklahoma, and the other one in Archer County, Texas (Anthony, 2015). Since the two jobs done by Halliburton, hydraulic fracturing technology has been used to stimulate close to two million oil and gas reservoirs across the globe including the Bakken, North Dakota (Abdul-Rahman et al.,2006) with good success.

The first massive hydraulic frack job (also known as high-volume hydraulic fracturing) was carried out by the American Petroleum. This job was done at Stephens County, Oklahoma, USA in 1968. After this job, American geologists started becoming more increasingly aware that the hydraulic technology can help recover huge hydrocarbon from any gas-saturated sandstones with permeability with too low (generally less than 0.1 millidarcy). This technology started spreading as awareness grew and in 1973, massive hydraulic fracturing was applied in many (thousands) of gas wells in the San Juan Basin, Denver Basin, (Jiang et al., 2006) the Piceance Basin, (Scorn, 2015) and the Green River Basin, and in other hard rock formations of the western US. It was not until 1987 that the technology was first used in the Bakken North Dakota to stimulated the first horizontal well drilled. There was no very great success as the technology was still new to the environment at that point. The technology started becoming more prevalent in 2002 and by 2006, it has helped the in the Bakken increase hydrocarbon production from the Bakken to the point that the North oil boom was known all over the Globe.

In 2019, the United States not only became self-sufficient in their oil need, they became the largest oil producer in the world as a result of the hydraulic frack technology. Hydraulic fracturing is important in shales due to rocks tightness that has led to very low porosity and permeability. To get this done, scientific research, development and demonstration become very paramount before hydraulic fracturing could be widely used to extract hydrocarbon from any to shale hydrocarbon deposits. George P. Mitchell is called the "father of fracking". He bagged the prestigious name in a way to recognize his role in deploying this technology(successfully) in shales (Manrique, 1996). In 2013, hydraulic fracturing has been the widely used technology to produce the shale oil and gas field in the United States, Canada, and China. Right now, some countries are still planning on adopting and deploying hydraulic fracturing technology to develop their untapped unconventional oil and gas assets when they are ready (Zhao, 2005; Veatch and Moschovidis, 1986). Even countries that have previously placed ban on cracking like the United Kingdom, are lifting their bans to allow for hydraulic fracturing**.**

Hydraulic fracturing is carried out by pumping the fracturing fluid into the wellbore at a rate high enough to increase the downhole pressure above the frack strength (pressure gradient) of the shale at the target zone (Kazakov et al., 2019). The fracture gradient is defined as the pressure gradient at which point the rock starts to break. This frack gradient is important to understand how to calculate the expected bottom hole treatment pressure (BHTP) that is crucial before a frack job can be started. It is measured in pounds per square inch per foot or bars per meter. Operators most times try to maintain "fracture width", or reduce its decline, following treatment by introducing into the injected fluid a proppant. Understanding proppant strengths and preventing failure becomes more important at deeper depths where pressure and stresses on fractures are much. The important factor here is to ensure that the cracked fracture is leaky enough to allow the flow of fluids to the wellbore. Formation fluid is made up of hydrocarbon (oil, natural gas), salt water and other associated compounds. It may also include some of the chemicals introduced into the wellbore during the hydraulic frack operation (Manrique, 1996). Frack operation needs to be conducted carefully and with a workable procedure to avoid frack fluid leak off (loss of frack into the reservoir). If this is allowed to happen and the leaks exceed 70% of the injected frack fluid volume, may result in reservoir formation matrix damage. This is an unwanted formation fluid communication that can altered fracture geometry and eventually lead to negative production as a result of decreased production efficiency (Kazakov et al.,2019). The location of one or more fractures in the borehole is stringently measured by various methods that create or seal off holes in the side of the wellbore.

Most hydraulic frack jobs are performed in cased wellbores and the zones to be fracked are accessed by first perforating the casing at those sections. Hydraulic-frack tools used for oil and gas well development comprise a slurry blender, one or more high-pressure, high-volume frack pumps, and a checking unit. Other equipment includes frack tanks, some tanks to store fluids and proppant, treating iron (that can withstand high pressure), a chemical mixing and monitoring unit, flexible hoses (low pressure), and many gauges and meters to measure flow rates, fluid density, and treating pressure (Tomomewo et al., 2020). Chemical additives are most times 0.5% percent of the total fluid volume. Frack equipment operates over a range of pressures. Rates of injection can go as high as 100 megapascals (15,000 psi) and 265 litres per second (9.4 cu ft/s) (100 barrels per minute). (Onwumelu et al., 2019)

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