Chapter 1
Geology

Abstract The Bakken Formation in the Williston Basin, North Dakota, USA, is an unconventional reservoir that has been one of the major producers of oil for almost 50 years. Recently with new advancements in horizontal drilling, hydraulic fracturing and Enhanced Oil Recovery (EOR) techniques, this formation is considered one of the most prolific oil shale plays in the U.S. and around the globe. The combination of all these technologies have highly increased oil production from the Bakken, resulting the state of North Dakota becoming one of the largest oil producers in America. Innovative production technologies in the Bakken has introduced new challenges to the oil industry which can jeopardize successful stimulation, horizontal drilling operations, EOR and hydraulic fracturing. Considering the fact that unconventional shale plays are becoming a major source of energy recently along with shales being the main constituent of all sedimentary basins around the world, we need to address the problems that would encounter in tight shale oil formations for better field operations. Geomechanical modeling, which plays a significant role for a successful field operation, is one of the major concerns which is notably based on a good understanding of various components within any formation. We need to characterize different shale components and their elastic parameters to input them in different rock physics models to improve mechanical earth modeling (MEM). These formations have a large total organic carbon (TOC) content which is not common in conventional reservoirs. Organic matter which is the reason for high TOC has totally a different physio-chemical properties than other rock forming components. Neglecting to include these properties in our modeling will lead to failure and costly operation. Although the importance of such information organic matter characteristics still requires major investigations. Additionally, the pore spaces where hydrocarbons are stored are very small scale compared to conventional reservoirs which makes the permeability or the flow pathways abnormal. Therefore, we have to expand more in-depth studies in various scales of measurements from nano to macro and mega, to examine how production from this reservoirs can be enhanced from 3% to recovery factor levels of conventional reservoirs. In order to focus our studies in a very small scale, more advanced analytical techniques should be developed and employed.

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1.1 Organization of This Book

This book presents various subjects that will help us to better characterize the Bakken Formation both as a source rock and a reservoir rock. The authors have tried to address problems that scientists would face while, modeling of the Bakken Formation to improve existing rock physics models. The main objective of this manuscript is to include various physical and chemical properties of different components of the Bakken Formation that are mostly unknown to us in geomechanical, geophysical and geological modeling. Such properties in the Bakken Formation is believed to originate from a combination of factors such as a large presence of clay minerals, high concentration of organic matter with various origins, a wide range of small pore sizes and heterogeneous distribution of them. However, recent improvements in materials science and medical field have facilitated characterization of these properties with high accuracy in the lab. The organization of this book follows the following chapters:

Chapter 1 discusses different shale plays and how they are distributed geographically throughout the U.S. as well as their importance. A brief geological setting of the basin and the Bakken Formation, with the operational history in the Williston Basin is provided as well. We have also presented various organic petrography images of different macerals that are found in the samples to form the Bakken Formation organic matter. A detail of organic geochemistry analysis along with kerogen type is presented in this chapter. Readers will find more organic geochemistry analysis in later chapters since the authors' goal was to tie thermal maturity variations to physical and chemical characteristics of the Bakke samples.

Due to the importance of pore structures in controlling the capacity of the oil and gas stored in the reservoir, Chap. 2 is dedicated to a detailed study of pore network. Different properties such as pore size and shape which can impact the physical, mechanical and chemical properties of the rocks including strength, elastic modulus, permeability, and conductivity have been analyzed. Pore structures are characterized and quantified in several scales of measurements with different techniques including gas adsorption, imaging methods combined with advanced data analysis to better understand pore heterogeneity.

Shale reservoirs with organic-rich intervals are often characterized by high quantities of kerogen, bitumen and also moveable hydrocarbons. Despite lots of conducted studies to improve understanding of kerogen characteristics, as one the main constituents of mudrocks, this component is not thoroughly understood. Hence Chap. 3 of this book presents our understanding from organic matter properties in terms of maturity, content type which is crucial for the development of unconventional reservoirs. In this chapter, conventional geochemical methods along with a new analytical techniques, Raman spectroscopy in particular, are discussed for organic matter characterization.

Finally mechanical properties of shale samples in micro- and nano-scale are being investigated in Chap. 4. Nanoindentation and Atomic Force microscopy were used examine elastic modulus and hardness from the force-displacement curves.

AFM PeakForce quantitative nanomechanical mode is a relatively new method of measurement in AFM probing to produce maps of surface height and modulus at the same time. In this chapter, we report the application of these two techniques on shale samples taken from the Bakken and also the advantages and shortages of each techniques were also discussed. This chapter addresses one of the main under-studied properties of organic matter. The reason for lack of information in this area is availability of advanced equipment that can isolate the organic matter and measures is mechanical properties in situ. Nanomechanical properties of organic matter was tested by a new mode in AFM and then was correlated with its thermal maturity.

1.2 U.S. Shale Plays

Significant activities have been carried out in the U.S. to explore and develop America's shale oil plays. The term shale oil plays contain "fine grained, organic rich, sedimentary rocks" where they are both the source and the reservoir for hydrocarbons. They are also defined by the extremely small pore sizes which make them relatively impermeable to fluid flow, unless natural or artificial fractures occur.

To gain a better understanding of the potential U.S. domestic shale oil resources, Energy Information Administration (EIA) commissioned INTEK, Inc. to develop an assessment of onshore Lower 48 States technically recoverable shale oil resources (U.S. Energy Information Administration 2015). This report estimates shale oil resources for the undeveloped portions of 20 shale plays that have been discovered. Eight of those shale plays are subdivided into 2 or 3 areas, resulting in a total of 29 separate resource assessments. The map in Fig. 1.1 shows the location of the shale plays in the Lower 48 States.

According to the shale report's assessment there are 23.9 billion barrels of recoverable of shale oil in the onshore Lower 48 States. The largest shale oil formation is the Monterey/Santos play in southern California, which is estimated to hold 15.4 billion barrels or 64 percent of the total shale oil resources. The Monterey shale play is the primary source rock for the conventional oil reservoirs found in the Santa Maria and San Joaquin Basins in southern California. The next largest shale oil plays are the Bakken and the Eagle Ford, which are assessed to hold approximately 3.6 billion barrels and 3.4 billion barrels of oil, respectively.

Table 1.1 summarizes the amount of recoverable resources in Billion Barrels of Oil (BBO) of major U.S. shale oil plays with the area of extension in square miles. The Estimated Ultimate Recovery (EUR) in thousands barrels (MBO) per well is denoted in the last column (U.S. Energy Information Administration 2017).

In the lower 48 states, unconventional (tight) oil development dominates as the main driver of total U.S. oil production. According to EIA's latest projections, tight shale will account for 60% of the total cumulative domestic production between 2016 and 2040 (U.S. Energy Information Administration 2017) (Fig. 1.2). The following image shows the production of crude oil in the U.S. compared with other

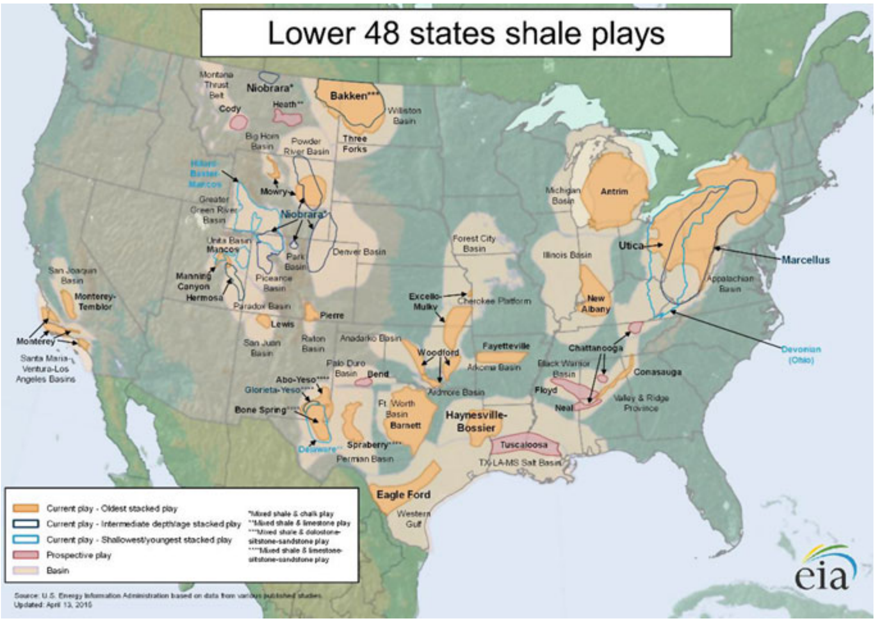


Fig. 1.1 Map of major U.S. shale plays including the Bakken in Williston Basin, ND. *Source* U. S. Energy Information Administration 2015

Table 1.1 Technically recoverable resources in some of the U.S. major shale plays

Region/basin	Play	Area with potential	Average EUR Crude oil	Technically recoverable resources
		(Sq. Miles)	(MMb/well)	(BBO)
Gulf coast				
Western Gulf	Eagle Ford	14,780	0.491	15.5
Western Gulf	Austin Chalk	11,447	0.122	4.7
Western Gulf	Tuscaloosa	7388	0.124	3.7
Southwest				
Permian	Spraberry	15,684	0.098	10.6
Permian	Wolfcamp	18,491	0.151	11.1
Rocky mountain/Dakotas				
Powder River	Tight Oil Plays	19,684	0.035	2.1
Williston	Bakken	14,966	0.953	8.6
Williston	Bakken Three Forks	21,439	0.197	14.9

top producers around the globe. A very interesting aspect of this graph, is the jump in U.S. production in 2010 which is well correlated with the dramatic increase in production in the state of North Dakota. The comparison of these two curves

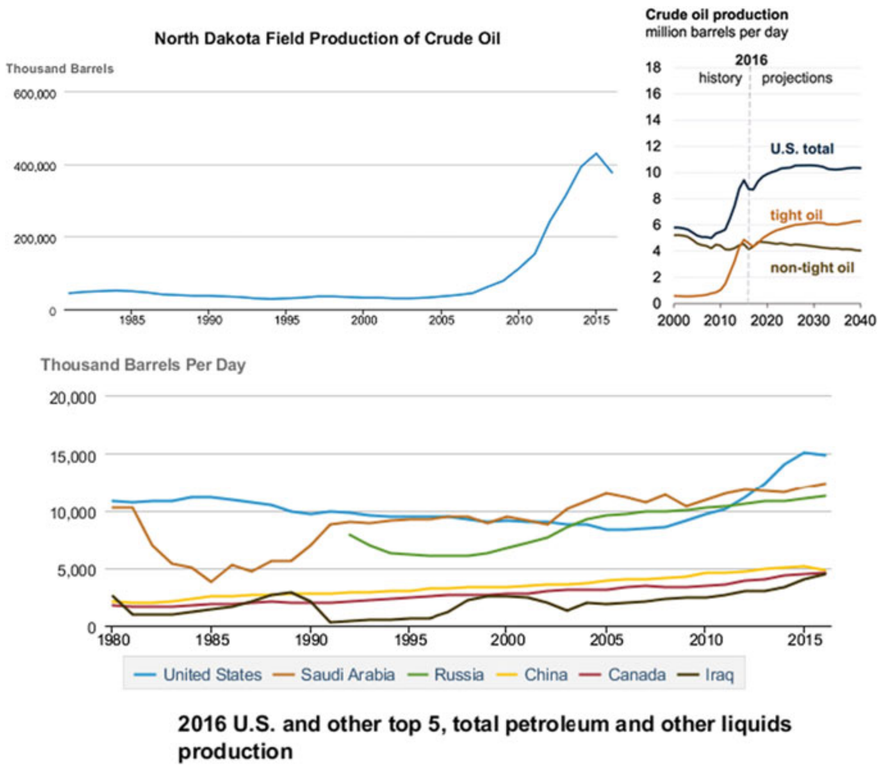


Fig. 1.2 U.S. versus North Dakota crude oil production and projection. *Source* U.S. Energy Information Administration 2017

reveals the importance of the Bakken Formation which accounts for majority of production in Williston Basin, ND. Due to the importance, this book and analysis that is provided is dedicated and focused on the samples from the Bakken Formation, one of the main shale oil plays in the U.S. and in the world.

1.2.1 History of the Bakken

Oil production from the Bakken goes back to 1950 when Antelope field discovery took place. The Bakken production and development history then continued by more vertical drilling when the first horizontal well was drilled in the beginning of 1990s. The Parshall Field discovery in 2006 was a breakthrough in the Bakken production history and caused a skyrocket in the number of horizontal wells drilled in the region. Production from the low permeability Bakken has been significantly enhanced by technologies like horizontal drilling and new stimulation techniques, such as multi-stage hydraulic fracturing. The Bakken is characterized as a "resource play" or "self-sourced" where all the wells are productive, and the petroleum system, source, reservoir and seal are intermixed.

The Bakken shale oil play is located within the Williston Basin in Montana and North Dakota and extends into the Canadian provinces of Manitoba and Saskatchewan. In 2008, USGS conducted an assessment of the Bakken shale (Pollastro et al. 2008) showing that the total undiscovered resource was estimated between 3063 and 4319 MMOE (Million Barrels of Oil Equivalent), with a mean at 3645 MMBO (Million Barrels of Oil Equivalent) of total continuous resources (U.S. Energy Information Administration 2011). According to EIA's more recent estimates, the Bakken oil play contains an estimated 8.6 billion barrels in technically recoverable reserves which would be the largest finding in U.S. history (U.S. Energy Information Administration 2017). A net acreage area for Bakken is

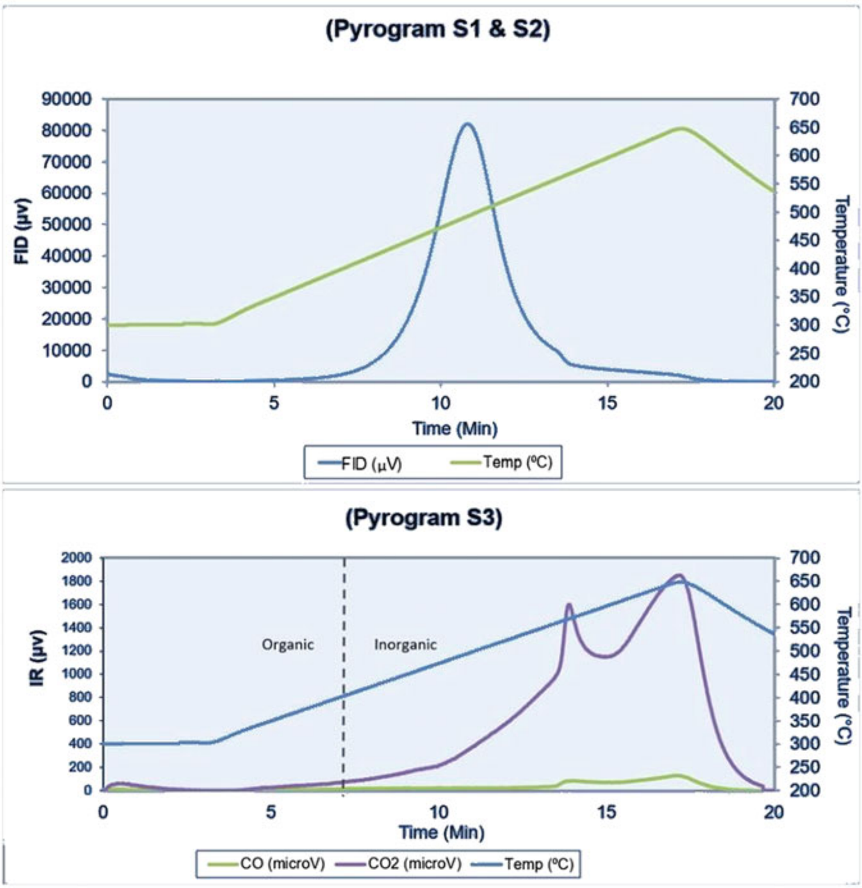


Fig. 1.3 Rock-Eval pyrolysis pyrogram for a sample of the Bakken shales

approximately 14,966 square miles in the U.S. The shale oil play has an average EUR of 953 MBO per well. Figure 1.3 provides a representative type curve for the Middle Bakken and the Three Forks as the main reservoirs in the Bakken play for the state daily production.

1.2.2 Geological Setting of the Bakken

The Bakken petroleum system in Williston Basin is one of the most important unconventional shale plays in North America. The Late Devonian to Early Mississippian Bakken Formation is a widespread clastic formation and occupies portions of North Dakota, Montana, and the Canadian provinces of Saskatchewan and Manitoba. The Bakken Formation consists of three members; the upper and lower members which are black organic-rich shales and the middle member, which is comprised of carbonaceous sandstone and siltstone (LeFever et al. 1991; LeFever 2008). In North Dakota, all three members of the Bakken Formation have an onlap truncation pattern with surrounding sediments and each member has more extensive spread than the older one. The onlapping geometry of the members could have occurred due to a transgression of the Late Devonian-Early Mississippian Sea (Webster 1984; Meissner 1991). The Bakken Formation is underlain by the Three Forks Formation and is overlain by the Lodgepole Formation. This succession creates the Bakken Petroleum System. This system is characterized by low porosity and permeability reservoirs, organic-rich source rocks, and a regional hydrocarbon charge (Sonnenberg and Pramudito 2009).

Conodonts, Tasmanites algae, amber-colored spores, small cephalopods, ostracodes, small brachiopods, and also fish remains are the most abundant fossil assemblages of the Bakken (Wall 1962; Hayes 1985). Presence of the mentioned fauna and flora assemblages, as well as the planar and thin laminations in the Bakken Shale, indicate that deposition has taken place in very low energy water conditions. The very high concentrations of organic matter and pyrite in the Lower and Upper Bakken represent a reducing, deep stratified, and anoxic depositional environment while the middle Bakken was deposited in well oxygenated water (LeFever 1991). The concept of the Devonian-Mississippian "Black Shale Sea" of North America (Ettensohn and Barron 1981) and also a stratified water column in the Williston Basin during Bakken deposition (Lineback and Davidson 1982) is confirmed by the presence of nectonic (fish, cephalopods, and ostracodes), planktonic (algal spores), and epiplanktonic (inarticulate brachiopods) fossil fauna abundance (Webster 1984).

The Bakken Formation has a maximum thickness of 150 ft. ($\sim$50 m) in the central part of the basin without any surface outcrop (LeFever et al. 1991). The formation is a unique case study for geochemical analysis since all stages of thermal maturity (from immature to relatively post-mature stages) can be recognized within a single stratigraphic unit (Webster 1984). The upper and lower shales of the Bakken consist mostly of hard, brittle, waxy-looking black shale, having a very dark brown color. The upper shale mostly consists of organic matter with lesser amounts of clay, silt, and dolomite grains whereas the lower shale member appears to become less organic-rich and more-clayey, silty, and dolomitic (Meissner 1991).

Different methods have been suggested to determine the source rock potential and quality (Jackson et al. 1980; Epistalié et al. 1985; Tissot and Welte 1978; Peters 1986; Langford and Blanc-Valleron 1990; Bordenave 1993; Peters and Cassa 1994; Burwood et al. 1995; Hunt 1996; Dyman et al. 1996; Lafargue et al. 1998; Petersen and Nytoft 2006; Dembicki 2016). Rock-Eval analyses is the most common analyses initiated on rock samples to assess various bulk geochemical characteristics. This technique were first used to assess the source potential and thermal maturity of cuttings, core, or outcrop samples as an initial screening step.

1.2.3 Organic Geochemistry and Rock Eval Pyrolysis

TOC (wt%), representing organic richness, S_1 (mg HC/g Rock), as free, thermally extractable hydrocarbons present in the whole rock sample, S_2 (mg HC/g Rock), as the hydrocarbons resulting from the cracking of the remaining kerogen and high molecular weight free hydrocarbons that do not vaporize in the S_1 peak, and Tmax (°C) as the temperature of maximum rate of evolution of S_2 hydrocarbons, S_3 (mg CO_2/g Rock) as the organic carbon dioxide evolved during low temperature pyrolysis (<390°C), S_4 (mg/g Rock) as the residual carbon (RC), are the main outcomes of the geochemical analysis by Rock Eval pyrolysis. Using these parameters, other indices can be calculated such as: Hydrogen Index (S2 × 100/TOC), Oxygen Index (S3 × 100/TOC), Production Index (S1/S1 + S2) and S1 + S2.

The Bakken Formation shales have a very high concentration of the total organic carbon (TOC) range from 5 to 20%, with an average of 11.3% across the basin (Webster 1984). TOC measures the quantity of the dispersed organic matter in the rock. The average TOC for the Bakken Shales makes it to be considered as a "very good" source rock from the richness point of view (TOC > 2%; Peters 1986). The TOC (wt%) amount decreases in source rocks as hydrocarbons are generated and expelled (Daly and Edman 1987; Dembicki 2016). The TOC amount has not a uniform distribution across the Williston Basin. The intermediate parts of the basin have the highest concentration of TOC (~17 wt%) and upper and lower Bakken shales are richer in organic matter whereas, the lowest concentration of TOC could be found along the eastern margin of the basin in the North Dakota and the Bakken shale is relatively organic-lean (>10 wt% of TOC) which probably caused by terrigenous sediments entrance from land and lead to organic matters dilution. Bakken shales contains moderate levels of organic richness (TOC amounts between 13 and 17 wt%) in the central part and eastern Montana area of the basin. The most immature organic matters are located in the Canadian part of the basin with average TOC 20 wt% (Jin and Sonnenberg 2013). Recent evaluation methods consider the

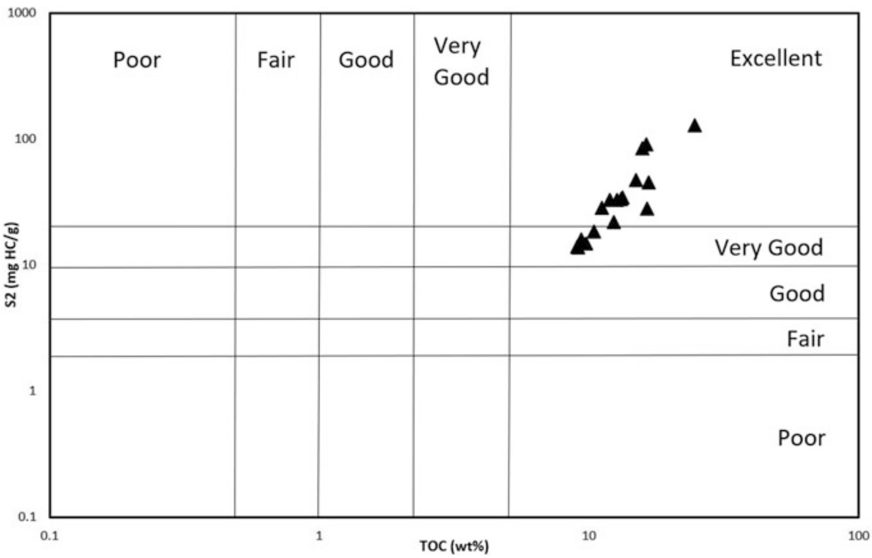


Fig. 1.4 S_2 versus TOC for source rock quality identification for some of the samples from the Bakken shales, from Peters (1986), Abarghani et al. (2018)

S_2 parameter as the principal source richness indicator. Additionally, the S_2 parameter, when in combination with TOC in a cross-plot, provides valuable data for-source rock quality interpretation (Dembicki 2016) (Fig. 1.4).

It should be mentioned that rating the source rock by using cross-plots provides only a general overview of the quality of source rocks and their potential to generate hydrocarbons. Therefore, these results should be confirmed by thermal maturity data and other analytical methods including organic petrography using reflected and transmitted light microscopy (Jackson et al. 1980; Saberi et al. 2016; Dembicki 2016) (Fig. 1.5).

Various methods have been suggested to determine the source rock maturity. Bakken shales maturity has been investigated using different techniques such as Rock-Eval pyrolysis derived thermal maturity data and also by using organic petrology and vitrinite reflectance measurement. Webster (1984) suggests the average threshold of oil generation to occur at 9000 ft and the average threshold of intense oil generation at 10,000 ft and deeper for Bakken Formation. There is no uniform relationship between maturity and depth across the Williston basin. This nonuniformity probably could be explained by different rates of heat flow in various parts of the basin in the geologic history of the basin (Webster 1984).

Jin and Sonnenberg (2013) have shown a meaningful threshold between Tmax and Production Index (PI) in the Bakken shales based on Rock-Eval derived data. Below 425 °C, PI values of Bakken shales are well below 0.08 but with increasing Tmax up to 430 °C and above it, the averaged PI values reach 0.08 and continue to increase up to ~0.4, until Tmax reaches above ~445 °C.

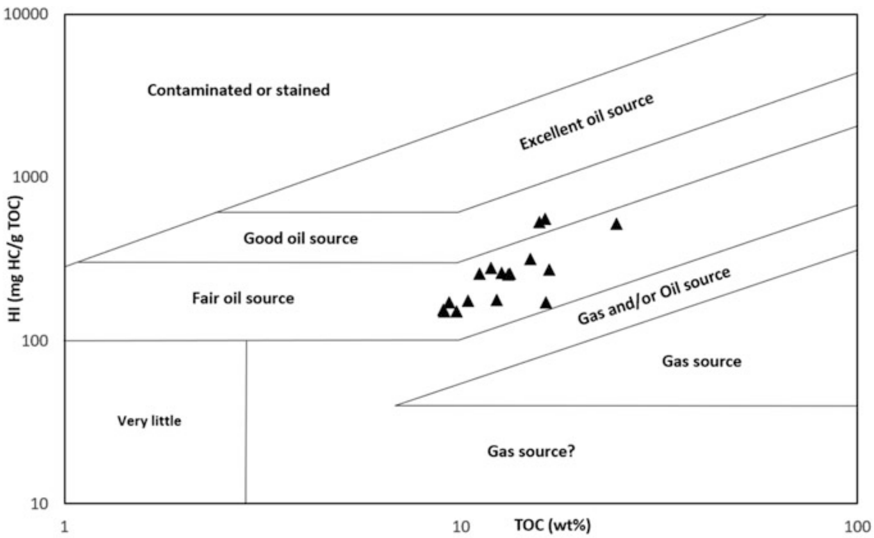


Fig. 1.5 HI versus TOC for source rock quality identification for some of the samples from the Bakken shales Abarghani et al. (2018)

Kerogens of the Bakken Formation source rock is mostly consisting of the amorphous organic matter which is assumed to have algal origin (Powell et al. 1982; Webster 1984). Numerous studies on kerogen typing (e.g. Jin and Sonnenberg 2013; Liu et al. 2017; Khatibi et al. 2018) show that the kerogen type II is the most abundant constituents of the Bakken shales organic matters, however, there is a minor contribution of Kerogens type I and III. Petrographic studies also revealed that most of the organic matter in the Bakken Formation consists of amorphous kerogen under transmitted white light. Additionally, whole-rock microscopic analysis under reflected white and UV light has shown the occurrence of the oil-prone marine kerogen type II of planktonic algal origin (Barker and Price 1985; LeFever 1991; Stasiuk et al. 1991). One way to determine kerogen types is using Rock-Eval derived data and geochemical cross-plots such as HI versus Tmax or S_2 versus TOC (Figs. 1.6, 1.7).

1.2.4 Organic Petrography

Recent organic petrography study in incident light microscopy, polished epoxy-mounted samples shows that the Bakken Upper and Lower shales are mainly consist of primary bitumen, lower-reflecting hydrogen rich bitumen, granular bitumen, amber colored liquid bitumen accumulation, amber-colored bitumen accumulations which are probably generated from algal matter, matrix bituminite, Alginite, Liptodetrinite, Inertinte and minor Zooclast-like abundant large and loose

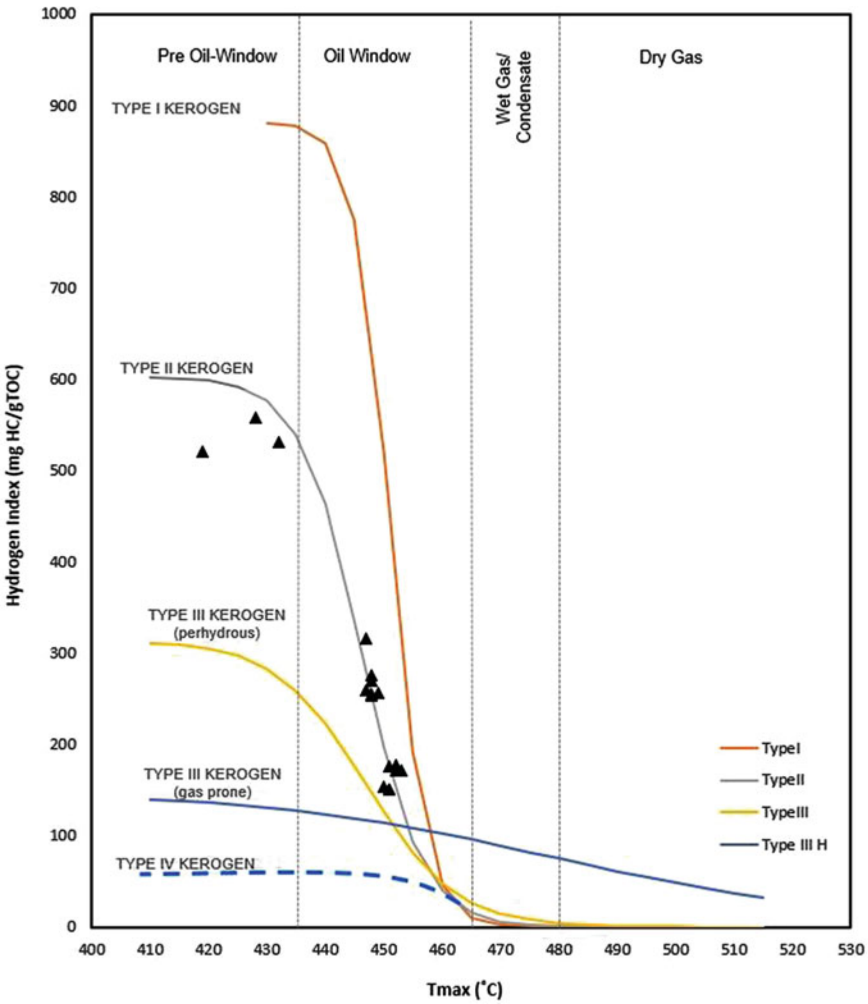


Fig. 1.6 HI versus Tmax for kerogen type identification for some of the samples from the Bakken shales Abarghani et al. (2018)

organic grains Alginite were observed to have dull-yellow fluorescence color under UV light. These findings show that the organic matter is thermally mature and in the middle stage of the oil window. In mature samples, a mean VR_o, ran of 0.88–1.01% measured on some samples from the Bakken Formation. This VR_o values, together with a dull-yellow to light-orange fluorescence color observed for Alginite under UV light, shows that the organic matter is thermally mature and in the middle and early upper stage of the oil window. In the other hand, immature samples mostly

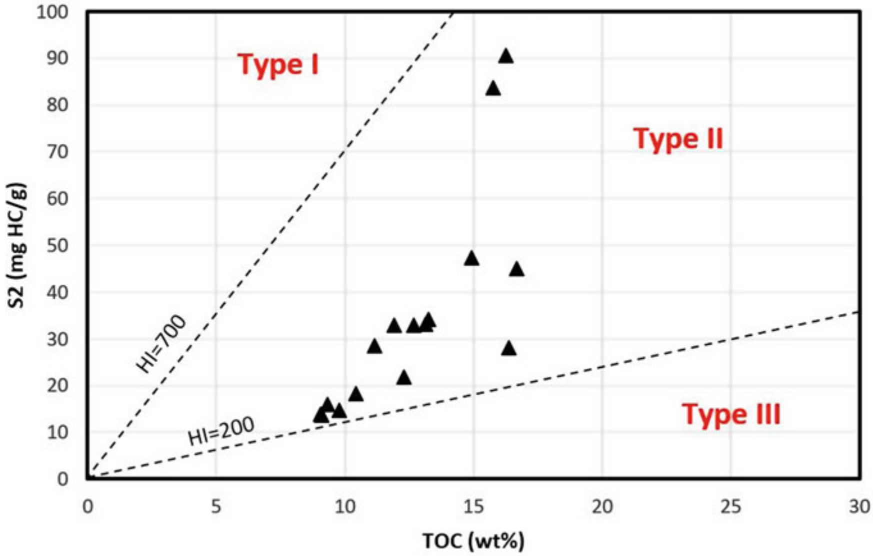
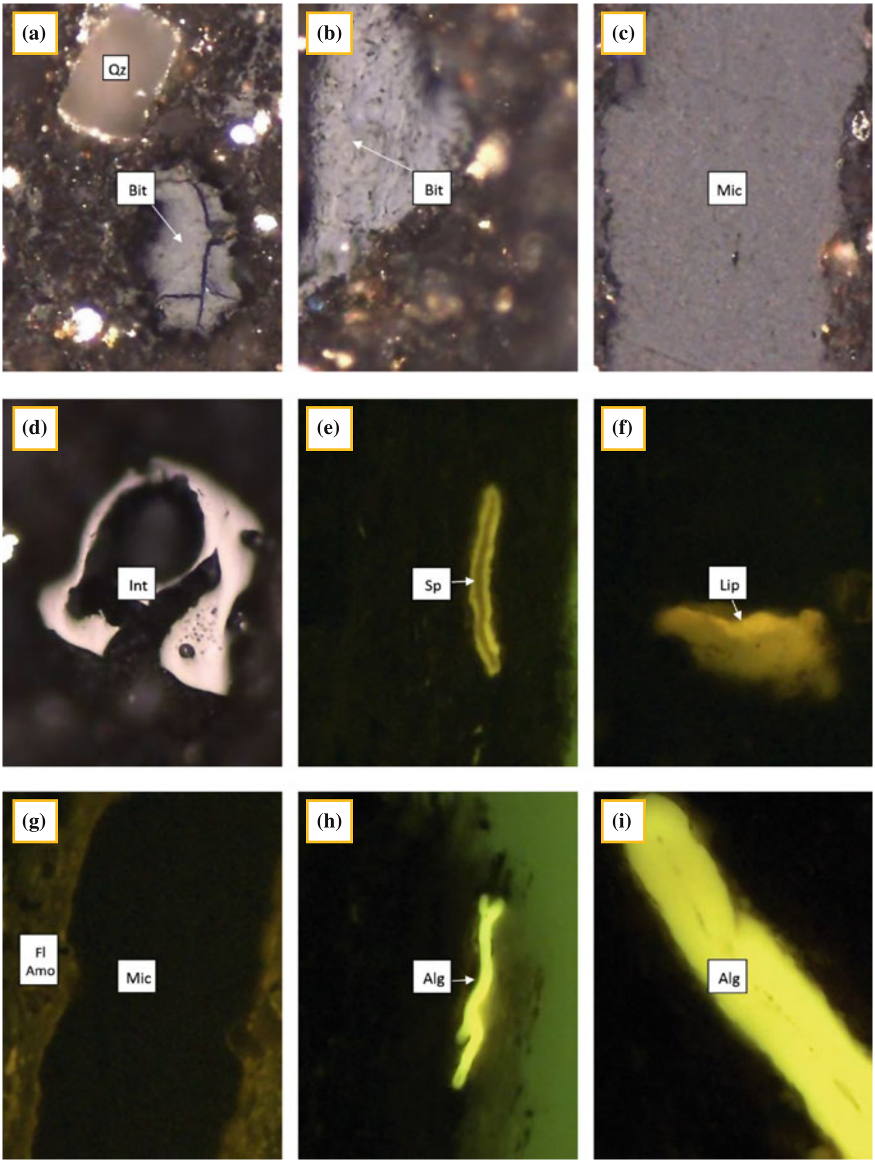


Fig. 1.7 S_2 versus TOC for kerogen type identification for some of the samples from the Bakken shales, from Langford and Blanc-Valleron (1990), Abarghani et al. (2018)

consist of solid bitumen, prasinophyte (blue-green) alginite, unicellular marine alginite (Tasmanites), sporinite, granular macrinite, amorphinte, liptinite, and shell fragments (Figs. 1.8, 1.9).

In certain periods of Earth's history, there were circumstances that deep oceans became oxygen depleted. These particular periods are called "Oceanic anoxic events" or OAE (Meyer and Kump 2008). In the absence of oxygen in an anoxic environment, the level of hydrogen sulfide concentration increased as a result of anaerobic microbial activities. In such conditions, high concentrations of organic matter within the rock matrix occur. In many OAEs the continuation of these conditions led to the creation of an euxinic state, which is characterized by various factors such as high degree of pyritization (Raiswell et al. 1988), pyrite narrower size distribution (Wignall and Newton 2003; Nielsen and Shen 2004), and strong enrichment in Mo, U, V, and Zn (Algeo and Maynard 2004).

Fig. 1.8 Photomicrographs of the Bakken Shale Members: **a** Bitumen (Bit) with Ro of 0.92%. *Qz* Quartz; **b** Bitumen (Bit) whose mean Ro is 1.04%; **c** A thick band of micrinite (Mic) showing slight granularity. Mean *Ro* 0.0.55%; **d** Inertinite (Int), **e** Sporinite (Sp) with yellow fluorescence in the outer part and dull-yellow fluorescence in the center. The spore shows surface punctation; **f** Liptinite (Lip), likely algal, having dull-yellow fluorescence; **g** Granular micrinite (Mic) with Ro of 0.28%, Note the fluorescing amorphinite (Fl Amo) or matrix bituminite; **h** A small oil-prone marine Tasmanites telalginite (Alg) exhibiting golden-yellow fluorescence color; **i** Highly oil-prone thick-walled Tasmanites telalginite (Alg) having golden-yellow fluorescence. All photomicrograohs were taken using a 50X oil immersion objective. UV light parameters were as follows: Excitation filter was at 465 nm; combined dichroic and barrier filters have a cut at 515 nm, Abarghani et al. (2018) ►



The Kellwasser anoxic oceanic event is known as one of the most widespread evidences for OAEs and basinal euxinia and is reported to have taken place from the Late Devonian and Early Mississippian (Meyer and Kump 2008). Devonian-Mississippian New Albany shales (Ingall et al. 1993), Kellwasser

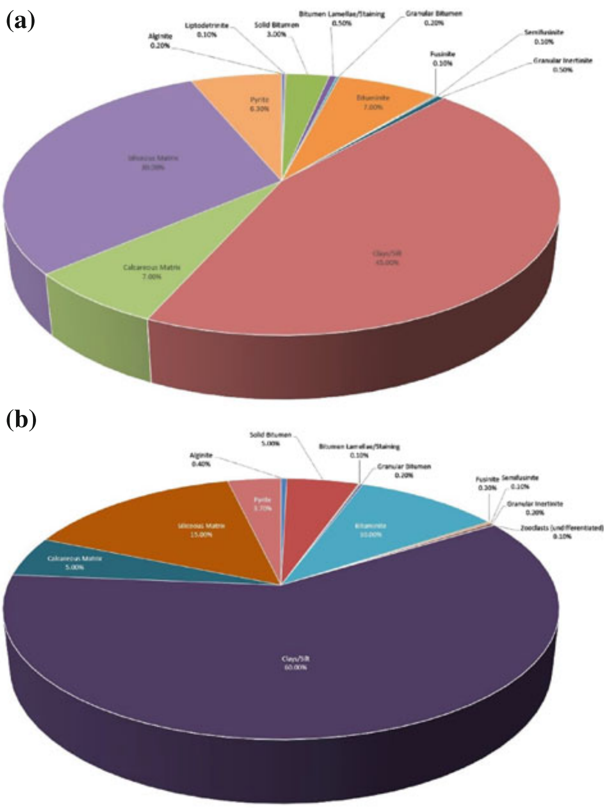


Fig. 1.9 2Pie-diagrams for a Sample from Upper Bakken (**a**) and a Sample from Lower Bakken (**b**) illustrating the composition of each sample , Abarghani et al. (2018).

horizons in the black shales (Frasnian/Famenian) from New York State (Murphy et al. 2000), Black shales from the Illinois and Michigan basins (Brown and Kenig 2004), the classic Frasnian/Famennian Kellwasser events of the Holy Cross Mountains of Poland (Bond et al. 2004) and the lower Mississippian Sunbury Shale of Kentucky (Rimmer 2004) are few examples of this anoxic oceanic event. The reason for this anoxic state is determined to be the thermal stratification which is perpetuated by anoxic productivity feedbacks (Meyer and Kump 2008). The Bakken Formation shales, with very high concentration of organic matter, very high degree of pyritization, the presence of pyrite framboidal shape and narrower size distribution, strong enrichment in Mo, V, and Zn, as well as petrographic evidences could be linked to the remarkable anoxic/euxinic conditions that characterized the Late Devonian (latest Frasnian) and Early Mississippian Kellwasser oceanic anoxic events.

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