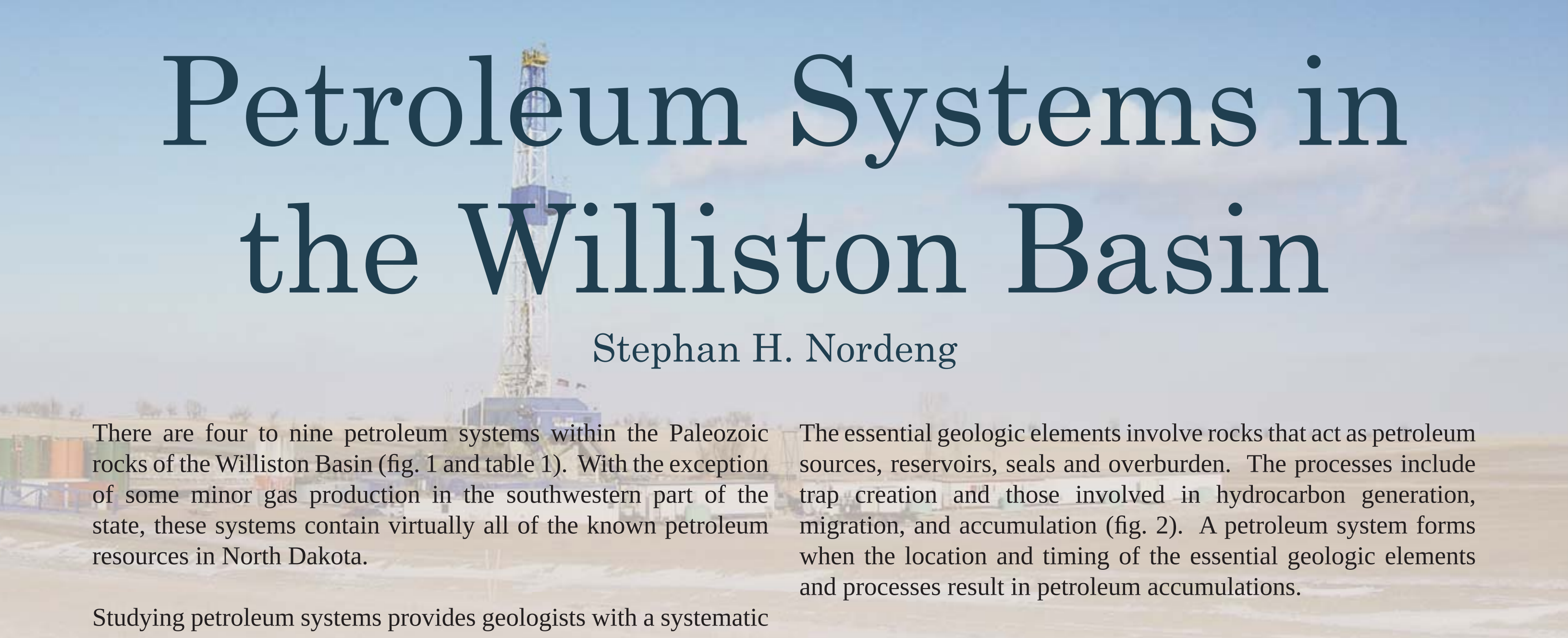

Petroleum Systems in the Williston Basin

Stephan H. Nordeng

There are four to nine petroleum systems within the Paleozoic rocks of the Williston Basin (fig. 1 and table 1). With the exception of some minor gas production in the southwestern part of the state, these systems contain virtually all of the known petroleum resources in North Dakota.

Studying petroleum systems provides geologists with a systematic way of evaluating the subsurface in their search for, and exploitation of, oil and gas resources. Magoon and Beaumont (1999) define a "petroleum system" as:

> "A pod of active source rock and all genetically related oil and gas accumulations. It includes all of the geologic elements and processes that are essential if an oil and gas accumulation is to exist."

The essential geologic elements involve rocks that act as petroleum sources, reservoirs, seals and overburden. The processes include trap creation and those involved in hydrocarbon generation, migration, and accumulation (fig. 2). A petroleum system forms when the location and timing of the essential geologic elements and processes result in petroleum accumulations.

Elements of a Petroleum System

Most of the elements of a petroleum system are inherited from near-surface, sedimentary depositional environments. These include influences imposed by the geography, tectonics and the biotic communities present during deposition as well as modifications to the original sediments that occur during burial and diagenesis.

Table 1. Petroleum Systems of the Williston Basin. The systems are defined on the basis of the source rock (**first name**) and reservoir (**second name**) where the punctuation following the source-reservoir name reflects the confidence of the assignment. Exclamation points are assigned to well-defined and widely accepted petroleum systems, whereas question marks denote systems that are debated or speculative. Modified from Jarvie, 2001.

Source Rock - Reservoir	**Oil Production (total barrels) as of Oct. 2011**	**References**
Tyler – Tyler (!)	**84,817,137**	Dow, 1974; Williams, 1974
Madison	**931,284,884**	Dow, 1974
Ratcliffe – Ratcliffe (?)		Jarvie, 2001
Mission Canyon – Mission Canyon (!)		Jarvie, 2001; Jarvie and Walker, 1997
Mission Canyon – Spearfish (!)		Jarvie, 2001
Bakken	**555,680,976**	
Bakken – Spearfish (?)		Dow, 1974; Osadetz and Snowdon, 1995
Bakken – Lodgepole (!)	58,428,724	Jarvie, 2001; Jarvie and Walker, 1997
Bakken – Bakken (!)	460,244,884	Dow, 1974; Williams, 1974
Bakken – Three Forks (!)	17,601,004	
Bakken – Birdbear (!)	19,486,927	Williams, 1974; Jarvie, 2001
Duperow	**55,113,913**	
Duperow – Duperow (?)	51,033,720	Zumberge, 1983
Duperow – Dawson Bay (?)	4,080,193	Jarvie, 2001
Winnipegosis	**9,707,260**	
Winnipegosis – Winnipegosis (?)	9,707,260	Osadetz and Snowdon, 1995
Winnipegosis – Interlake (?)		Jarvie, 2001
Red River	**106,107,322**	
Red River – Interlake (!)	8,568	Jarvie, 2001
Red River – Red River (!)	105,960,226	All post-1974 studies
Red River – Winnipeg (!)	138,528	Jarvie, 2001
Winnipeg – Winnipeg (?)		Dow,1974; Jarvie, 2001
Cambro – Ordovician – Deadwood (?)	36,075*	Zumberge, 1983; Peterson, 1988

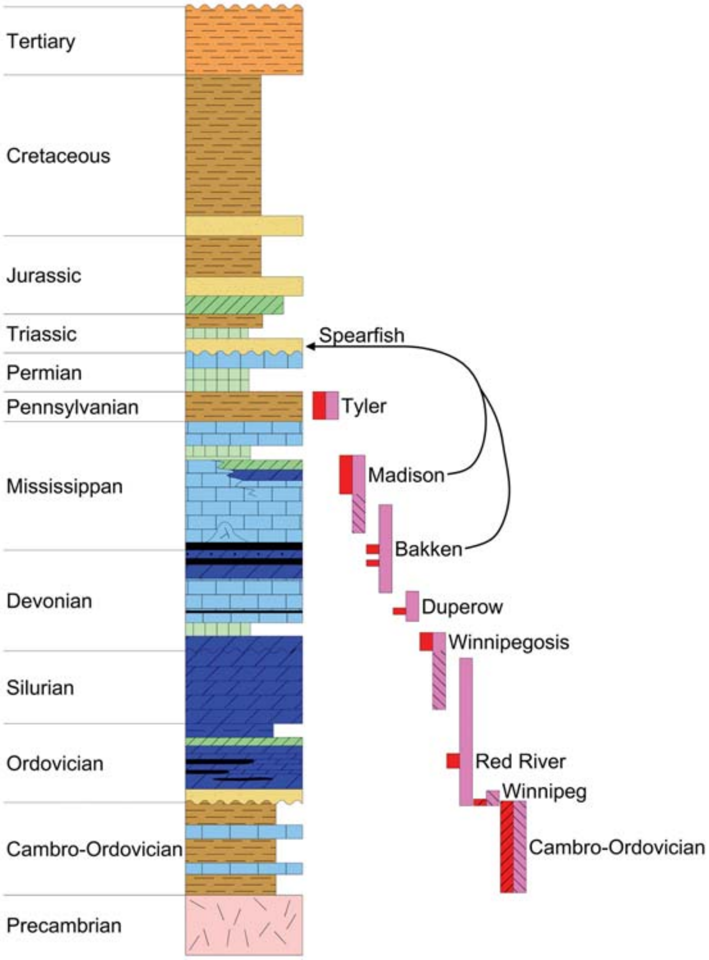

Figure 1. Simplified stratigraphic column showing the approximate range of the petroleum systems in table 1. The stratigraphic range of source beds is shown in red and the range of reservoirs in pink. Ranges and source beds that are questionable or speculative are hashed.

Source Rock

There is, at the core of every petroleum system, a source rock containing hydrogen and carbon compounds that when heated form petroleum (gas or oil). The only significant source of these compounds is the preserved organic molecules assembled by living organisms at or near Earth's surface. The vast majority of these organic compounds first form when inorganic carbon (i.e. CO_2) is converted into an organic (carbon bonded with hydrogen) compound by photosynthesis. Even though the specific organic compounds are modified as they are transferred through a food chain the original hydrocarbon bonds remain. Following death, degradation-resistant organic molecular fragments collect in sediments and over the course of time and burial react to form kerogen. The term kerogen refers to "naturally occurring, solid, insoluble organic matter that occurs in source rocks and yields oil upon heating" (Schlumberger Oilfield Glossary, 2012). The quality of a potential source rock depends upon the amount and types of organic compounds present in the kerogen mixture. Obviously, an organic-rich source rock is capable of generating more oil than one that has little organic carbon.

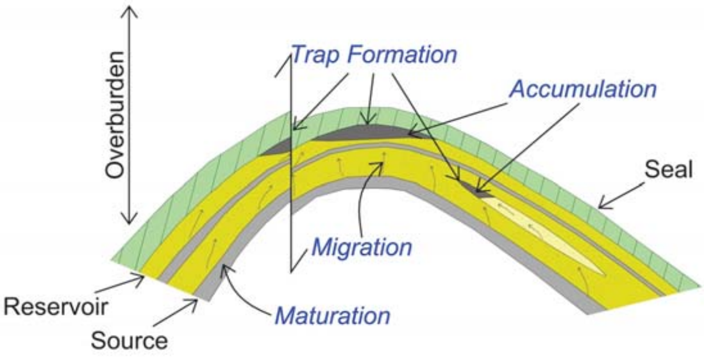

Figure 2. Schematic diagram illustrating the elements (bold text items) and processes (blue italics) involved in the formation of a petroleum system.

The organic compounds in kerogen determine what sort of petroleum product might be generated. These organic compounds may be used to develop a classification scheme that predicts what sorts of petroleum products might be generated during maturation (Tissot et al., 1987). One of the simplest compositional classification systems uses the amount of hydrogen relative to the amount of oxygen that is bonded to carbon. This relationship is inherited from the original organic material that went into the source bed and in many cases the organic compounds act as "fossils" that reveal details of the kerogen-forming organisms and environment.

Type I kerogen is sapropelic (meaning "putrid mud") and is rich in proteins, waxes and fatty acids. These compounds have molecular structures dominated by long hydrocarbon chains (fig. 3). This kerogen contains much more hydrogen than it does oxygen so that when it thermally decomposes the resulting product is almost exclusively oil. Type III kerogen, on the other hand, contains compounds such as cellulose derived from land plants (fig. 4). These compounds contain chains of carbon ring structures bonded to oxygen as well as to hydrogen. The relatively high concentration of oxygen is a distinguishing feature of this kerogen. Natural gas is the only significant hydrocarbon produced by the thermal maturation of Type III kerogen. Type II kerogen contains "planktonic" material consisting of various mixtures of hydrocarbon chains and rings. Type II kerogen is deposited in low-oxygen marine settings and can produce oil, gas or some combination of the two. Not all organic matter preserved in kerogen is capable of generating petroleum. The bonding in Type

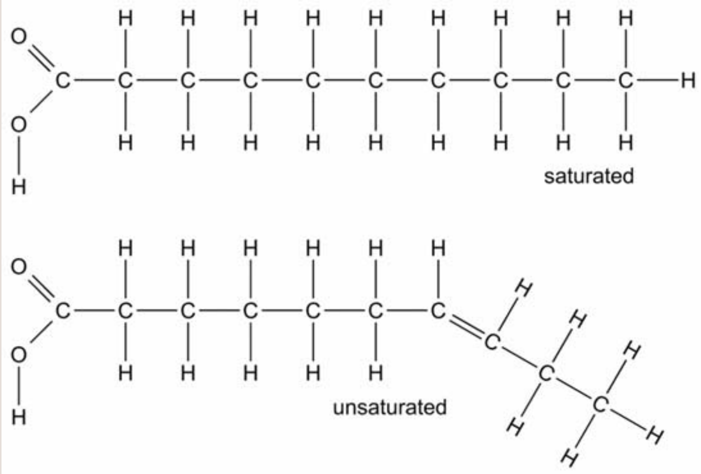

Figure 3. Schematic representations of a couple of fatty acids made up of chains of carbon (C) atoms bonded to hydrogen (H). Kerogen containing these long hydrocarbon chains are prone to generating oil and are heavily represented in Type I kerogen and, to a lesser extent, Type II.

IV kerogen (fig. 5) prevents this component from decomposing into petroleum during normal burial and maturation. Because of this, Type IV kerogen is usually considered, from the petroleum generating standpoint, to be inert or “dead.”

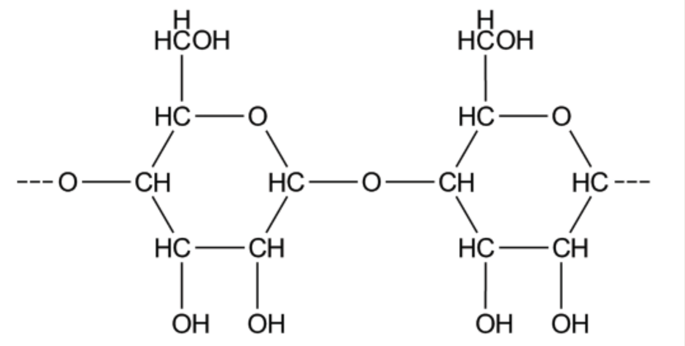

Figure 4. Schematic structure of cellulose showing the inclusion of oxygen (O) in the chain of ring structures formed by hydrogen (H) and carbon (C) atoms. Elevated organic oxygen levels are characteristic of Type III kerogen.

Reservoir Rock

The most important properties of a reservoir rock involve the ability to accept, store and release sufficient (economic) amounts of oil to a well bore. The measured rock properties of porosity and permeability summarize these characteristics. The porosity of a rock is the fraction, usually in terms of percent, of the total rock volume that contains void space capable of containing oil, gas or water. Permeability is the capacity of a rock to transmit fluids through its pore space. Much of the porosity found in sedimentary rocks such as sandstone and dolostone occurs in the spaces between mineral grains or between crystals. Additional porosity may form by fracturing and/or dissolution of sedimentary minerals during deposition and burial. However, porosity may diminish because changes in the chemical environment during deposition and burial cause new minerals to grow into the original void space. Obviously, rocks with greater porosities are potentially capable of containing more petroleum per unit volume than are rocks with little porosity.

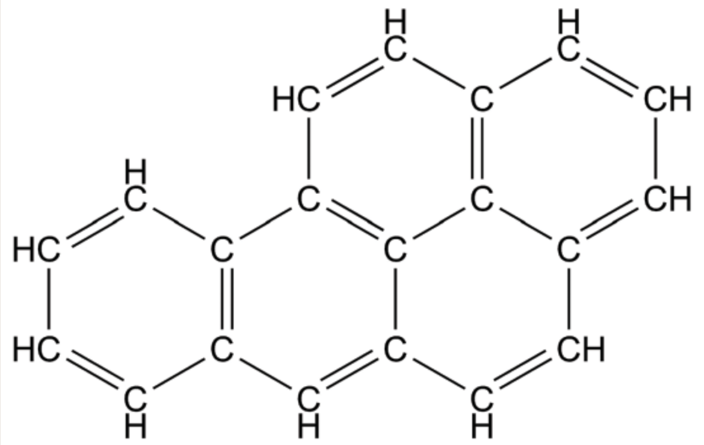

Figure 5. Schematic structure of a polyaromatic hydrocarbon (PAH). This component of kerogen contains little hydrogen and the tightly bonded carbon ring structure renders this kerogen (Type IV) almost inert and therefore not capable of generating petroleum.

One of the challenges in reservoir characterization lies in unraveling the complex relationship between the size, shape, orientation and connections between pores (voids) that dictate the force needed to transmit fluid through reservoirs. A poorly permeable rock consisting of microscopic or poorly connected pore spaces requires more force (pressure) to drive fluid through it than does a more permeable rock containing well-connected, large pores. In the absence of stimulation, highly porous and permeable rocks are more likely associated with economically successful wells.

Sealing Rock

The primary function of a sealing rock (or simply “seal”) is to provide a barrier to the migration of petroleum resulting in a localized accumulation. In most cases, changes in permeability along migration pathways are responsible. Because oil and gas are less dense than water, differences in density cause oil and gas to migrate upward through water. Upward migration through porous and permeable rock, when barred by overlying poorly permeable rocks forces oil and gas to “pool’ in the pore space previously occupied by water next to the barrier. Buoyancy-driven accumulations usually exhibit a clearly defined contact between overlying petroleum accumulations and underlying water-saturated portions of the reservoir. Buoyancy-driven accumulations usually maintain formation fluid pressures that are “hydrostatic.” That is, fluid pressures that are equal to what would be exerted by a column of water that extends from the surface to the reservoir.

In some rarer cases, most notably the Bakken, the reservoir and seal rocks are one and the same (Meissner, 1978). The reason is that the rocks that lie above and below the source beds in the Bakken Formation contain a small amount of porosity and are almost impermeable. Consequently, oil generated in the upper and lower Bakken source beds cannot escape though simple buoyancy. Furthermore, when solid kerogen is converted into liquid petroleum part of the weight of the overburden previously supported by the kerogen is imposed on the fluids present in the source bed. This increases the fluid pressure within the source beds and with enough pressure injects source-bed fluids, including oil and gas, into the neighboring rocks. Expelled petroleum accumulates in the pore space of the “reservoir” next to the source beds and because of low permeability the bounding rocks also act as a “seal” that prevents the accumulation from dissipating. In this way, oil accumulations form in poorly permeable rocks that act as both reservoir and seal.

Overburden

The chemical processes that convert kerogen into oil or gas require temperatures substantially above those found at or near Earth’s surface. In order to achieve the necessary temperature (~ 100°C) source rocks must be buried several thousand feet. The overburden thickness needed to achieve critical reaction temperatures depends upon the insulating properties of rocks between the source rock and surface as well as the amount of heat that is flowing upward from deep-seated sources in the underlying sedimentary pile, crystalline crust and mantle. Silica-rich sedimentary rocks such as sandstone, siltstone and shale are poorer conductors of heat than are rocks such as limestone, dolostone or salt. Overburden made up of poor thermal conductors (good insulators) cause temperatures to increase with depth more rapidly than does thermally conductive (poor insulators) overburden. What this means is that it takes less insulating overburden (sandstone and shale) to reach critical reaction temperatures than it does non-insulating overburden (limestone and salt). Temperatures within a source rock not only depend upon the thermal characteristics of the overburden but also depend heavily upon how much heat flows through the section. With all else equal, regions of high heat flow generate higher temperatures at shallower depths than regions with lower heat flow. The combination of overburden thickness, thermal characteristics of the rock present and the flow of heat all contribute to the depth that corresponds with critical oil-forming temperatures within the oil window.

Petroleum System Processes

Petroleum system processes that result in significant resources typically occur well after the system's elements formed. These processes include the creation of a physical trap before or during the time that the source rock generates oil. A "trap" consists of a reservoir rock positioned against a seal in such a way that migrating oil stops, or is sufficiently slowed so that the reservoir fills and accumulates hydrocarbons.

Trap Creation

Trap creation may be the result of tectonic processes that fold or fault reservoir and seal rocks into configurations that allow hydrocarbons to accumulate. Examples of this include the axes of anticlinal folds or domes that contain seals that behave as inverted bowls that collect hydrocarbons in reservoirs situated below the seals (fig. 2). The geometry of these structures tends to collect migrating hydrocarbons along the highest points of these features. Similar geometries form when ancient bioherms or reefs form porous and permeable mounds of fossil debris. These "reef" deposits form excellent traps when surrounded by impermeable rock. In other situations hydrocarbons may migrate upward and laterally through dipping permeable layers that are overlain by seals. When these permeable layers encounter an up-dip permeability barrier migration slows or stops, forming a trap in which hydrocarbons accumulate. Permeability barriers may include faults that place impermeable rocks across the permeable beds or when permeable zones thin and pinch out in an up-dip direction. Such "pinch outs" are frequently inherited from the original depositional environment responsible for the stratigraphic architecture involved.

Generation

Hydrocarbon generation is strongly influenced by the temperature history of the source bed as well as the nature and amount of kerogen it contains. As temperatures increase during burial the rate at which kerogen decomposes into oil or gas also increases, though at a much greater rate. As a rule of thumb, the amount of hydrocarbons generated per unit time doubles with every 10°C increase in temperature (Lopatin, 1971). That is to say, the amount of hydrocarbons generated in a million years at 100°C is roughly half the amount that would be generated at 110°C. Raising the temperature another 10°C would again double the reaction rate so that at 120°C the amount of hydrocarbons generated in a million years would be twice that generated at 110°C and four times greater than what would be generated at 100°C. The generation of hydrocarbons, even at these temperatures, is very slow and requires time on the scale of millions of years to produce significant volumes of hydrocarbons. Obviously, with time, deeper burial and ever-increasing temperature, the kerogen within a source bed increases its rate of hydrocarbon production until all of the reactive kerogen decomposes into hydrocarbons (fig. 6). The time interval in which most hydrocarbons are generated is limited to a range of temperatures and corresponding depths that are controlled by crustal heat flow, basin subsidence rates, overburden thickness and thermal conductivity as well as the nature and quantity of the kerogen present in the source bed. This time interval and corresponding source-rock depths define the conditions in which intense oil generation begins. Shallower depths maintain temperatures too low for intense oil generation whereas depths below the window correspond with regions in which the original reactive kerogen is exhausted. At higher temperatures, usually beginning within the deeper portions of the oil window, temperatures are great enough to cause the decomposition of oil into shorter-chain hydrocarbons called condensate or "wet gas." At greater temperatures, oil and condensate continue to decompose until the final product is methane, or dry gas.

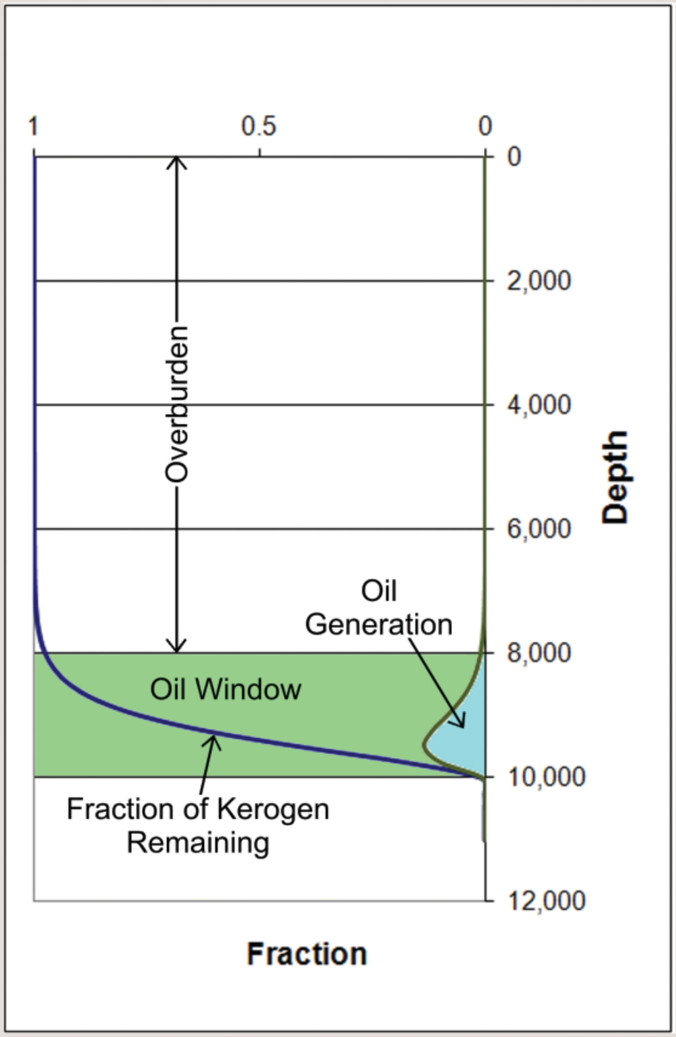

Figure 6. Schematic diagram illustrating the change in kerogen content (blue line) during oil generation (blue filled curve). The light green fill illustrates the "oil window" in which intense oil generation occurs. Temperatures at depths above the window are insufficient to generate oil and those below the window represent depths where the reactive kerogen is exhausted.

Migration

Even though source rocks frequently contain some porosity that is often oil-saturated, the very low permeability of these rocks makes them very poor reservoirs. Much of the oil generated by these rocks escapes from the source beds and travels through permeable rocks or fractures, sometimes over significant distances, before encountering a trap. The process of migration links the original source rock to the productive accumulation.

Accumulation

Accumulating petroleum involves displacing the original water present within a reservoir by oil and/or gas. Because oil and gas are less dense and largely immiscible in water, petroleum accumulations tend to stratify with respect to density so that gas overlies oil and both overlie water. This situation is commonly present in conventional oil and gas accumulations where oil displaces water and collects along the uppermost portions of a trap because its lower density makes it buoyant.

Of the petroleum systems present in the Williston Basin, those associated with the Bakken and Red River Formations are of interest because both are "self-sourced" and prolific producers. The notion of self-sourcing is noteworthy because productive accumulations within these systems are frequently close, at least stratigraphically, to the source beds. When this is true then identifying source beds that have and/or are generating hydrocarbons could provide a way of exploring for accumulations. Even though both formations are "self-sourced" there are significant differences in the processes and elements responsible for the accumulations derived from the source beds in these two systems. An examination of the similarities and differences might prove useful in understanding the complexities inherent in exploration within the Williston Basin.

A petroleum system is defined on the basis of the elements and processes that are bracketed by the petroleum source and the resulting accumulation. The challenge in defining a petroleum system therefore lies in being able to demonstrate that the petroleum present in a particular accumulation originated in a particular source rock. In cases such as the Bakken continuous petroleum system, the presence of oil within the source beds as well as the neighboring reservoir/seal makes the linkage seem almost trivial. This system provides a wonderful test of methods used to establish the source/accumulation link, because the only physical link between the source beds and the accumulation is the petroleum contained within the accumulation itself. Therefore, comparing the chemistry of oil collected in an accumulation with oil extracted from a source bed may provide evidence linking the two. These methods frequently use chromatographic analyses to separate oil samples into their various organic constituents. The distribution of the different types and amounts of organic compounds present in an oil provide the organic geochemist with a "fingerprint" that, with careful examination, may provide a convincing link between oil accumulations and source beds that may be many miles apart. However, variations in oil composition originating from the same source rock do occur. Compositional variations can be traced back to variations in the composition and reactivity of the original

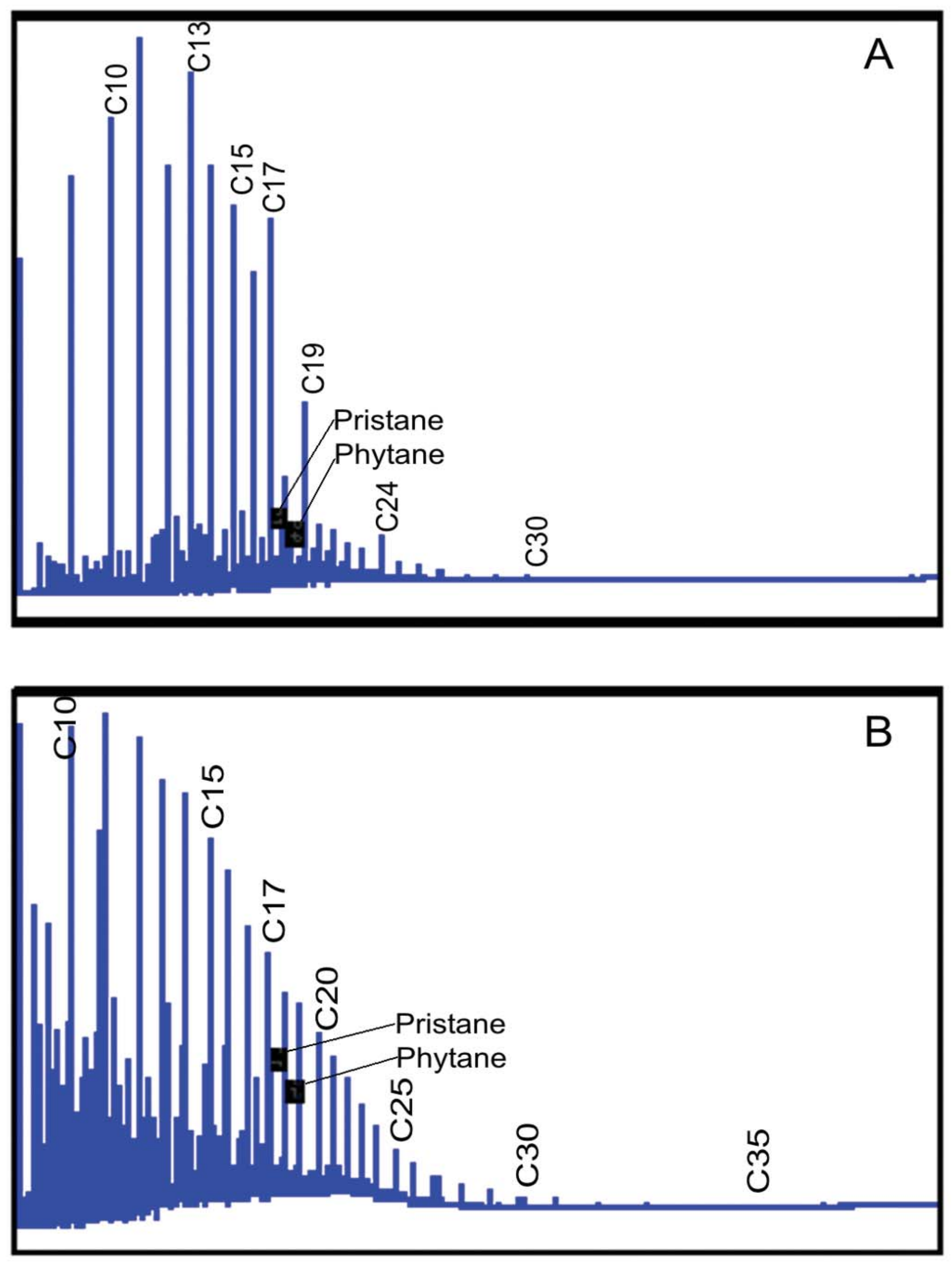

Figure 7. Gas chromatograms of oil extracts from the Red River Formation (A) and Bakken Formation (B). The Red River oil chromatogram shows the characteristic odd carbon preference in C13-C19 range and the diminished amount of chlorophyll-derived pristine and phytane as well as the general absence of hydrocarbons beyond C20. From Jarvie, 2001.

kerogen as well as chemical changes in the petroleum caused by physical or chemical processes that occur during migration and accumulation and changes that occur following accumulation. Additional complexity is added when mixtures of oils from different sources occur within the same reservoir (Jarvie, 2001).

One of the most compelling and interesting examples of tying petroleum accumulations back to specific source beds and kerogen types is found in the Red River petroleum system. Oil in the Red River Formation is derived from source beds called kukersites that frequently contain very organic-rich, oil-prone (Type I) intervals that sometimes have total organic carbon (TOC) contents in excess of 50% (Kohm and Louden, 1978; Jacobson et al., 1988). The term kukersite was originally coined by Zalessky (1917) to describe source beds in Estonia that consisted almost entirely of organic matter derived from a colonial micro-organism he called *Gloeocapsomorpha prisca* (*G. prisca*). This association of *G. prisca* and its distinctive fingerprint is present in many mid-Ordovician oils throughout North America, Northern Europe and Australia. Fossil *G. prisca* not only links source beds to oil accumulations but also provides an interesting insight into mid-Ordovician life. *G. prisca* is readily identified because remains found in kerogen often show a distinctive microstructure that resembles some modern day cyanobacteria. However, the debate about its biological affinity is still ongoing. This debate revolves in part about whether or not *G. prisca* accumulated as non-photosynthetic burrow linings and bacterial mats that episodically blanketed Ordovician seafloors (Longman and Palmer, 1987) or whether it was a photosynthetic, planktonic organism that occasionally "bloomed" (Derenne et al., 1992). One part of the argument in favor of a non-photosynthetic life style of *G. prisca* is inferred from associated oils that typically contain very low concentrations of a couple of distinctive organic fragments (pristine and phytane) found in photosynthetic chlorophyll (Longman et al., 1987). The relatively small abundance of these two organic markers helps distinguish oils generated in mid-Ordovician kukersites from other source beds such as the Bakken Formation that contains significantly greater amounts of these compounds (fig. 7). In addition to the near absence of these organic fragments, oil derived from *G. prisca* has an unusual tendency to contain hydrocarbon chains dominated by odd numbers of carbon. A third distinctive feature is the near absence of hydrocarbons containing more than 20 carbon atoms. The combination of these factors makes the connection between the Red River kukersites and oils in the Red River and elsewhere possible (Jarvie, 2001).

Once the connection between the source rock and accumulation is established, then questions concerning the regional distribution of seals, potential migration pathways, timing and location of trap formation can be worked out. The end result is a more comprehensive view of the total petroleum system and more effective exploration and production strategies.

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