# SOURCE BEDS

### Julie LeFever

**Introduction**

Numerous articles have referred to the Bakken Formation as a "World Class Source Rock," discussed the evaluation of source rocks, and reviewed the basic concepts of petroleum systems (Nordeng, 2012; 2013; 2014). At this point, it is worthwhile to take a step back and discuss the origin of "source rocks," their composition, creation, preservation, and distribution. Understanding the origin is the key to developing the concept of the "Petroleum System."

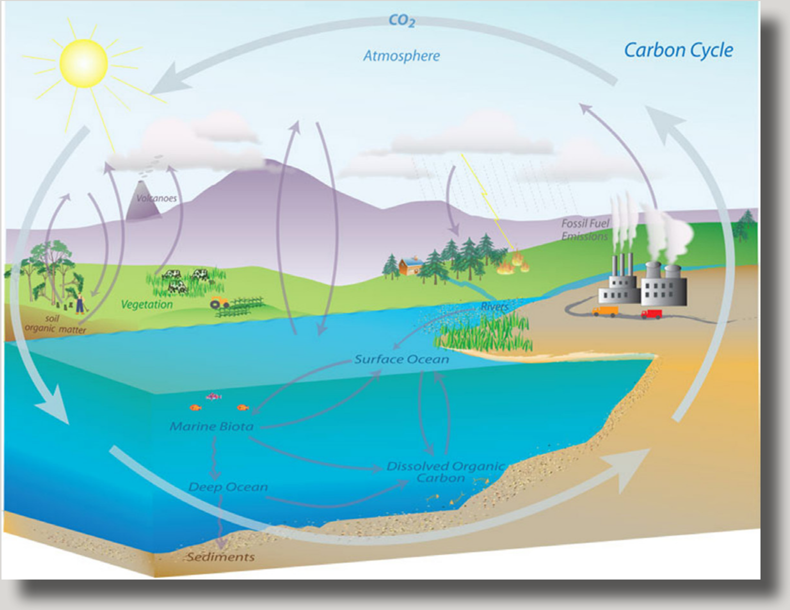
In order to be labeled a source bed, the sediment has to be rich in extra-fine organics, material consisting of compounds made primarily of carbon and hydrogen. These organic compounds react over time and temperature to form kerogen, "a naturally occurring solid, insoluble organic matter that occurs in source rocks and yields oil upon heating" (Schlumberger Oilfield Glossary, 2012). The determination of the kerogen type is done using laboratory methods such as whole rock pyrolysis and microscopic organic analysis (Demaison and Moore, 1980). The bed is considered a source if the organics are oil or gas prone and its overall composition greater than one percent organics by weight (generally the range is from one to greater than 20 percent).

Preservation of organic material in the sediments is a rare event because most of the organic material returns to the atmosphere as part of the carbon cycle (fig. 1). Less than one percent escapes the carbon cycle to accumulate in the sediment. These carbon particles are allowed to accumulate due to specific properties that include the mode of transit to the site, the sediment particle size, and the rate of sedimentation (Demaison and Moore, 1980).

**Origin of Organic Material**

Organic matter comes from both terrestrial and aquatic environments. Plant material on landmasses is dependent on rainfall. However, accumulations of this material are prone to degradation through oxygenation in soil horizons and during transport in rivers and streams. Furthermore, it is usually hydrogen-depleted prior to transport making the organic matter a poor source.

Phytoplankton (microscopic algae) is the principal source of organic matter in an aquatic environment. The distribution of phytoplankton is limited by the available sunlight and nutrients (nitrogen and phosphates). In unrestricted marine environments, water circulation controls productivity. Areas of upwelling supply nutrients from below the photic zone to phytoplankton near the surface. Phytoplankton are consumed by zooplankton which, in turn, is eaten by large invertebrates and fish (Demaison and Moore, 1980).



*Source: NOAA*

**Figure 1.** The diagram shows some of the land and ocean processes. The carbon cycle consists of inorganic and organic carbon. The inorganic carbon exists as atmospheric dissolved carbon dioxide and carbonate minerals. The organic portion (hydrogen-carbon compounds) is found in living and dead organisms, fossil fuels, small deposits in rocks, and dissolved in water or dispersed in the atmosphere. There is a continuous two-way flow in the use of organic and inorganic carbon. Most of the carbon resides in the crust and has a long residence time and is unavailable for cycling (British Geological Survey Natural Environment Research Council, 2014).

Dead organic material is chemically unstable in the presence of oxygen and is an energy source for other microorganisms. Aerobic bacteria consume the organic material until the oxygen level is depleted. Anaerobic bacteria continue degrading the matter using nitrates and then sulfur. Methane-generating bacteria complete the process. The bacterial phase is rich in lipid and hydrogen (Demaison and Moore, 1980).

Organic matter present in sediments on the sea floor continues to be consumed by benthic fauna (e.g. worms, bivalves) in an anoxic environment. This suggests that organic richness is a function of sedimentation rates. In the anoxic environment, benthic activity decreases as oxygen content decreases. Ultimately the only consumption of organic matter is by anaerobic bacteria. The resulting sediment is finely laminated and organic-rich (fig. 2).

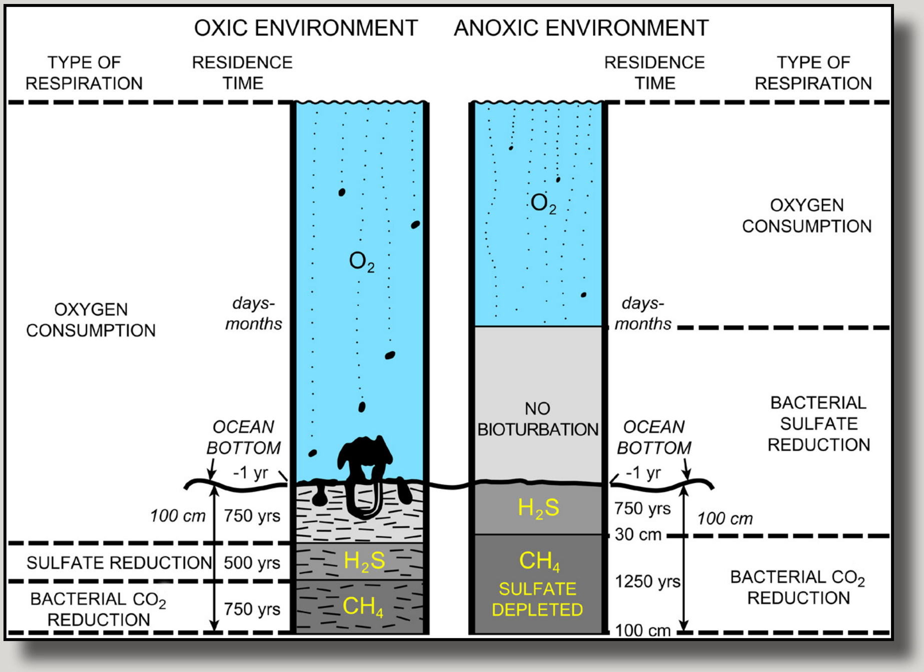


**Figure 2.** Diagram compares the degradation of organic matter in an oxic versus anoxic environment. A well oxygenated (oxic) environment results in poorer preservation due to animal scavengers at the sediment interface, bioturbation, and a lesser amount of reaction with heavy metals. Richness preservation can be attributed directly to sedimentation rate. The oxygen depleted (anoxic) environment results in a greater amount of organic matter due to less biological reworking. Bioturbation of the sediments becomes minimal below oxygen concentrations of .5 ml/l. (modified from Demaison and Moore, 1980.)

**Preservation**

As previously discussed, the majority of organic matter is returned to the atmosphere. The remaining matter consists of dead zooplankton, algal cells, fecal pellets, and fish carcasses that fall to the ocean floor at rates varying from 0.1 to 5 m/day (Demaison and Moore, 1980). Exposure to an oxygenated water column enables the material to be further consumed by animals. Grain size and shape determine the speed of the fall. Size is also a concern in preservation; coarser sediment is able to be degraded faster and therefore has lower organic content than fine-grained sediments. The “organic rain” that reaches the bottom of the sea floor is predominantly fecal material.

Organic matter deposited in anoxic conditions is richer than in oxygenated environments regardless of the rate of sedimentation. In oxygenated environments, there is a direct correlation between sedimentation rate and richness (0.3 to 4%). A high rate of sedimentation with large amounts of inorganic detritus spreads the organic material through a greater area and effectively dilutes the source rock (Waples, 1985). This is especially noticeable in shales with high accumulation rates. Anoxic conditions generally form when biochemical demand depletes the oxygen supply due to a lack of mixing (circulation) between the vertical levels in the water column.

**Models for Source Deposition**

According to Demaison and Moore (1980), anoxic conditions can be generated in three main types of environments: 1) large anoxic lakes; 2) anoxic silled basins; and 3) anoxic layers caused by upwellings.

**Large Anoxic Lakes**

Oxygen supply in inland seas and lakes depends upon the amount of planktonic activity which requires nutrients, phosphates and nitrogen supplied to the lake by rivers and streams. Colder water entering the lake, and seasonal variations in temperature, result in a turnover in the water column bringing oxygen to the bottom sediments.

In a temperate climate, if the turnover of waters does not occur, lakes can become oxygen-starved, to the point of anoxia. This is particularly likely to happen if the lake is greater than 100 m in depth. Sediments in these lakes are often rich in organic material and carbonate minerals. Lake Tanganyika is the type example for a “large anoxic lake.” The lake is 650 km by 70 km and reaches a depth of 1500 m. At 150 m conditions are lethal to metazoan (animal) life owing to anoxic conditions. Shallow portions of the lake contain 1 to 2 percent organic carbon whereas in the deeper, anoxic portions of the lake the organic content ranges from 7 to 11 percent (fig. 3). In the rock record, the Green River Formation of Colorado and Utah, fits the model of a large anoxic lake system. It has all of the required characteristics including rare bioturbation, thin seasonal laminations (varves), and geochemical parameters that suggest a permanent oxygen stratification in the lake.

**Anoxic Silled Basins**

A silled basin forms when physical barriers restrict mixing within the water column. This, combined with climate, can result in anoxic conditions. Anoxic silled basins are classified as either having a positive or a negative water balance.

A positive water balance refers to a silled basin that has strong salinity contrasts. This occurs when there is an excess outflow of fresher water resulting in a low salinity of the surface waters. This forms a permanent halocline with the saline and nutrient-rich deeper waters present in the basin. This enhances production and preservation of organic matter. A modern day example of this type of basin is the Black Sea (fig. 3).

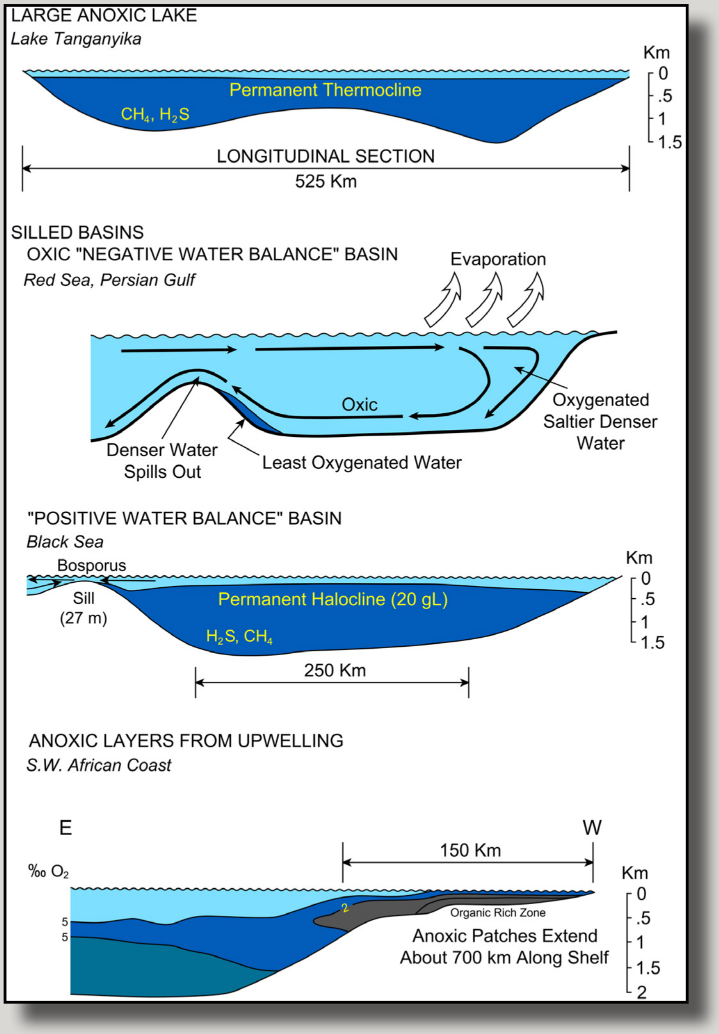


**Figure 3.** A large anoxic lake (e.g. Lake Tanganyika) is illustrated by the first diagram. Organic deposits in the oxic zone range from 1 to 2%, and in the anoxic portion of the basin are from 7-11%. Sedimentation rate ranges from 5 to 50 cm/1000 years. The types of silled basins are indicated in the lower two diagrams. In the oxic "negative water balance" basin, circulation is good so that the water column is well oxygenated so there is no deposition of organic matter. In contrast, the "positive water balance" basin has fresher surface water overlying saline bottom waters. The lack of circulation results in anoxia and allows for the deposition of organic matter that ranges from 1 to 15% in the anoxic portion in contrast to about 2.5% in the oxic portion. An example from the Southwestern African Coast illustrates the anoxic layers caused by upwelling. Anoxic sediments in this setting range from 3 to 26% organic carbon whereas, oxic sediments have less than 3% (modified from Demaison and Moore, 1980).

A negative water balanced basin occurs in a hot, arid climate when the inflow of fresh water is sufficient to compensate for the evaporation rate. The input of fresher water allows hypersaline water formed by intense evaporation to sink and flow out of the basin as an undercurrent (Demaison and Moore, 1980). The result is a silled basin with a well oxygenated and nutrient depleted water column without organic enrichment. Modern day examples of this type of basin are the Red Sea and Persian Gulf (fig.3).

Silled basins also occur in the oceans of the world. Most of these are well oxygenated; however there are rare depressions that have become anoxic. The Cariaco Trench is a modern day example of this. The Mowry Formation (Cretaceous) is one of the best examples of an anoxic silled basin in North America. The formations containing sequences of laminated mudstones, bioturbated mudstones, and bioturbated sandstones represent a progression from anoxic low-energy to high-energy oxygen-rich environments.

### Anoxic Layers Caused By Upwelling

Upwelling is the process of moving waters from depth towards the surface in the sea. This creates a system of complex currents and counter-currents that are due to offshore winds. These areas are rich in nutrients, nitrogen and phosphates that promote biological activity. The abundant material creates a high demand for oxygen easily causing anoxic conditions (fig. 3). However, not all of the areas with high productivity due to upwelling are anoxic. In these situations the oxygen supply is renewed by the deeper currents. A modern day example of this type of deposit is along the southwestern African shelf (Demaison and Moore, 1980). In the rock record, many examples of upwelling are seen in the Miocene strata of California.

The quality of a potential source bed is not just determined by the amount of organic carbon present. Well oxygenated environments often contain between 0.5 and 4% organic carbon depending on sedimentation rate. The organic matter in the oxygenated environment is consumed by a variety of life forms present in the water column and on the seafloor, resulting in preservation of the organic material that is hydrogen-depleted.

| ANOXIC BASIN TYPE | PALEOGEOGRAPHIC SETTING | STRATIGRAPHIC DISTRIBUTION OF ANOXIC SEDIMENTS |
|---|---|---|
| ANOXIC LAKES | EQUABLE, WARM, RAINY.<br>EARLY RIFTS.<br>INTERMOUNTAIN BASINS | CONTINUOUS WITHIN SAME ANOXIC LAKE SYSTEM. |
| ANOXIC SILLED BASINS | TEMPERATE TO WARM, RAINY.<br>INTRACRATONIC SEAS. ALSO ANOXIC POCKETS ON SHELVES. | VARIABLE. TENDS TO BE RICHEST AT BOTTOM OF BASIN OR POCKET. |
| ANOXIC LAYERS WITH UPWELLINGS | OCEANIC SHELVES AT LOW LATTITUDES. WEST SIDE OF CONTINENTS. | OFTEN NARROW TRENDS.<br>CAN BE WIDESPREAD.<br>PHOSPHORITES, DIATOMITES. |

**Table 1.** Summary of the depositional models for anoxic basins. Individual items may be combined in certain marine settings (modified from Demaison and Moore, 1980).

Anoxic environments are conducive to deposition of kerogen that is hydrocarbon-rich, lipid-rich, and oil-prone. Source beds formed in these environments contain 1 to 20% organic carbon because there are few predators. The activity of anaerobic bacteria enhances the kerogen. Due to the lack of oxygen, sediments deposited in an anoxic environment are varved or laminated with no burrowing or deposit-feeding infauna. Source rocks commonly contain abnormally high concentrations of uranium, copper, molybdenum, nickel, phosphorus, and sulfur. Although, anoxic environments occur in large lakes the condition is rarely permanent. The depositional models for anoxic sedimentation are summarized in table 1.

Understanding the environment that results in the deposition of source beds is important when working with the rock record. Sequence stratigraphy places rocks in a genetic framework. This information is then placed into a sequence stratigraphic framework. It is common for potential source rocks to be associated with a thin distal section that represents a considerable span of time in a thin layer, a condensed section, and slow sea level rise with lesser detrital input (Jacobsen, 1991; Schlumberger Oilfield Glossary, 2012). Use of this technique allows for the prediction of source beds and their associated reservoir beds.

## Source Beds within the Williston Basin

Nineteen separate formations produce oil in the Williston Basin (fig. 4). These formations are grouped in four to nine petroleum systems as described by Nordeng (2013). This expands the ability to model and predict the presence of an oil-producing horizon. The concept is not new and will continue to change in the future as more data becomes available. Dow (1974) wrote a landmark paper discussing the oil systems within the Williston Basin. In that paper, Dow placed a geologic perspective on the geochemistry presented by Williams (1974) in a companion paper.

Dow (1974) designated three formations as the major source rocks for Williston Basin oil: the Winnipeg shale (Icebox Formation), the Bakken, and Tyler Formations. These major source beds have a distinctive geochemical signature that enables the correlation of oils produced from other formations to the original source. Dow stated that there were additional source beds in other formations that were not considered significant (open petroleum system vs. closed).

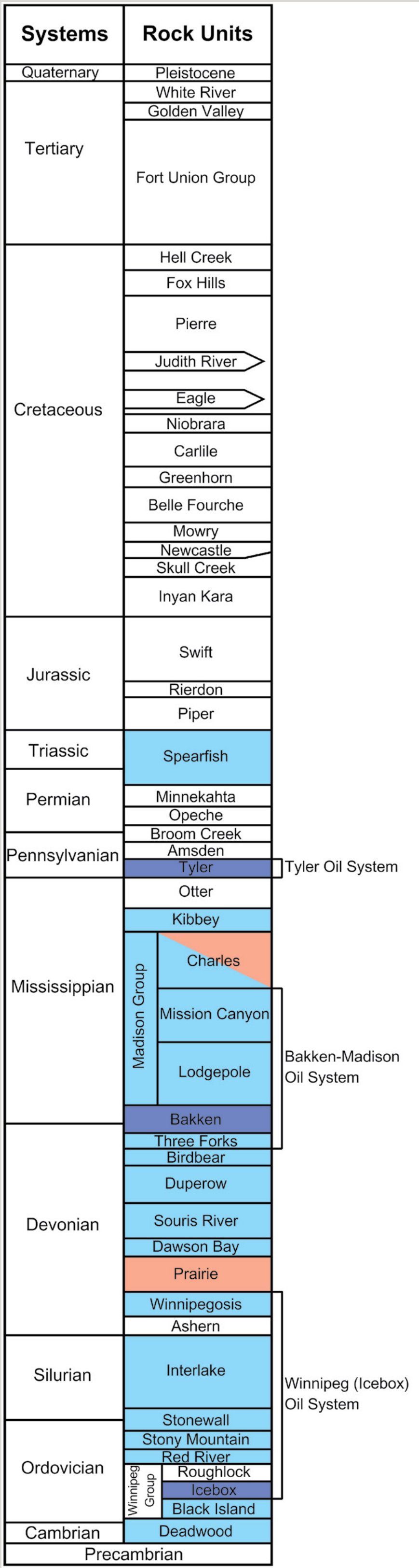


**Figure 4.** Stratigraphic column of the North Dakota portion of the Williston Basin with blue shaded areas representing oil producing formations.

### Winnipeg Group – Icebox Formation

The shales of the Icebox Formation (Ordovician) are organically lean, ranging from 0.5 to a maximum of 4%, and generate Type I oil (figs. 4, 5). The Icebox reaches a maximum thickness of 49 m (160 ft.) and consists predominantly of gray-green shale with some siltstone and sandstone lenses. It is locally bioturbated and contains brachiopods, trilobites, and various fossil fragments. The presence of bioturbation and fossils is suggestive of a mildly oxidizing environment, at least in the upper part of the formation. This is supported by the presence of localized sandstone bodies

**Figure 5.** Photograph of a representative core sample showing the source beds in the Icebox Formation (SESW Sec. 1, T152N, R90W, EOG Resources, Inc. – Shell Creek #1-01; Depth 13,143.5 – ft.). The Icebox consists of a gray-green massive to finely laminated, fissile, organically-lean shale that reaches a maximum thickness of 49 m (160 ft.). Scale bar shown in white is 1 inch.

which suggests that water depths were not great. The Icebox is thought to have been deposited seaward of a nearshore marine environment (LeFever, 1996).

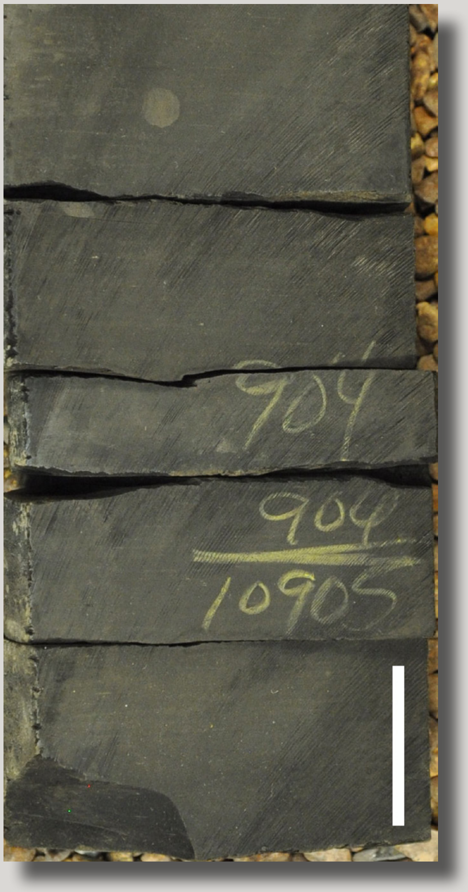


**Figure 6.** Photograph of a representative core sample of shale from the Upper Member, Bakken Formation (NESE Sec. 27, T150N, R97W, Astral Oil Company, LLC. – Astral Stenehjem #43-27; Depth – 10,905 ft.). The two shales of the Bakken are dark brown to black, organic-rich and have a combined thickness of 23 m (75 ft.). The core is photographed dry. Scale bar shown in white is 1 inch.

The Icebox begins to generate oil at 2,134 m (7,000 ft.). The mature portion of the Icebox is centered in eastern Montana and western North Dakota. Outside of the mature area the source rocks contain limited organic matter that is incapable of generating large quantities of oil. Even if the Icebox was generating oil, there is no reservoir in which to expel it (Dow, 1974). This probably explains why there are more oil shows than production.

**Bakken Formation**

The Upper and Lower Members of the Bakken Formation (Devonian-Mississippian) consist of greenish-gray, brown-black to black, non-calcareous, fissile, organic-rich shales to mudstones (figs. 4, 6). Unlike the Upper Member, the Lower Member has less siltstone, limestone and sandstone. The Upper Member is richer in organic material. Pyrite is present as laminae, lenses, nodules or disseminated throughout the shale. Fossils include conodonts, fish bones and teeth, brachiopods, and Tasmanites. The Upper Member is more fossiliferous than the Lower Member. Also common are thin lag deposits containing fossil fragments, silt, sand, bitumen and pyrite. The Bakken shales reach a combined thickness of 23 m (75 ft.). The presence of fossils suggests a stratified water column, fresher oxygenated waters. The shales were deposited in an offshore environment. Water depths were probably not very deep.

The Bakken source beds are responsible for Type II oils. Dow (1974) proposed that these source beds were responsible for the oil found between the Prairie and the Charles Formations. Other source beds are present but were not considered significant. Rich in organic matter, the Upper Member reaches a maximum 27 weight percent organic carbon, averaging 11.5, and the Lower Member reaches 25 weight percent. A depth of 2,134 m (7,000 ft.) is necessary to start generation with peak expulsion occurring during the Cretaceous Period.

**Tyler Oil System**

The Tyler Formation (Pennsylvanian) is probably the most localized of these oil systems (figs. 4, 7). The Tyler Formation is comprised of two parts: 1) a lower unit consisting of non-calcareous, varicolored red, green-gray, dark gray, and gray-black silty mudstone and shale, and 2) an upper unit made up of dark gray argillaceous limestone alternating with carbonaceous shale with a sandstone bed at its base (Sturm, 1982). Ostracods are present along algal mats within the upper unit. The varicolored portion represents deposition in a well oxygenated environment. These beds are organically lean. The lower unit was deposited in a deltaic environment where sediment transport was through stream channels to the delta front leaving a pattern of sandstones and coals encased in marine and non-marine mudstones and shales. The upper section was deposited as a result of barrier islands (sandstones at the base of the upper section) in a regressive sea. The estuarine and lagoonal environments indicated by the mudstones, plant remains, coal, and shales prograded north after the development of these barrier islands. Multiple lithofacies may allow for the preservation of organic material in near anoxic or anoxic conditions. In the conventional system, the source beds appear to occur adjacent to the reservoirs.

**Figure 7.** Photograph of the source beds from the Tyler Formation (SWSW Sec. 26, T.156N, R.100W, Atlantic Richfield Company – Harmon #1026; Depth – 10,905.0 ft.).

The source and the reservoir are within the Tyler Formation due to the viscous nature of Type III oils (Dow, 1974). Production and oil shows are tightly clustered around the non-oxidized shales. The Tyler averages 0 to 2 weight percent organic carbon, but localized zones contain over 20 percent total organic carbon. Maturity is generally reached when the formation is buried to a depth 2,134 m (7,000 ft.), but may vary locally depending on temperature.

## Summary

Source rocks form as a result of biologic productivity and depositional conditions that allow for the concentration and preservation of organic material. Generally, source beds accumulate in an oxygen-restricted environment, below wave-base. The waters are stagnant due to density contrasts or temperature-stratification resulting in a low replenishment of oxygen. The resulting rock is dark gray, black, to chocolate brown, thinly laminated with no apparent bioturbation, and has a high concentration of organic material to minerals.

Knowing the depositional environment allows the strata to be placed in a genetic framework referred to as sequence stratigraphy and tied to a global sea level curve. When the information is place into this model, it becomes apparent that source rocks are generally deposited in a condensed section offshore during sea level highstands. The condensed section results from the deposition of pelagic or hemipelagic particles in a low energy environment where they can be preserved (Jacobsen, 1991). The model can then be used to predict the distribution of potential source and reservoir beds.

Three examples of source beds have been presented for the Williston Basin: Winnipeg Group (Icebox), the Bakken, and Tyler Formations. All three meet the criteria discussed to be considered source beds developed under anoxic conditions in a restricted offshore marine environment with similar rock characteristics.

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