The Bakken Petroleum System: An Example Of A Continuous Petroleum Accumulation

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Introduction

Recent assessments of the technically recoverable oil in the Bakken Formation point to a significant undeveloped resource within the Williston Basin. Even though the presence of oil in the Bakken has been known since the earliest days of oil production in the Williston Basin it has not been an economically viable play until fairly recently. The reason for this lies primarily with advances in horizontal drilling and well stimulation technologies coupled with rising prices for oil. Unlike conventional oil and gas reservoirs, petroleum accumulations such as the Bakken cover large areas, with poorly defined margins. These accumulations consist of relatively impermeable rock so that economically productive areas or "sweetspots" are often restricted to localized geologic settings. The combination of very large regions containing this type of accumulation coupled with spotty areas of marginally higher permeabilities and fractures makes the determination of the size of the economic resource difficult. Nevertheless, virtually every study that has focused on the Bakken petroleum system has concluded that the resource is enormous with total in-place volumes of oil that are in the range of 10s to 100s of billions of barrels. By conventional standards this resource is not only enormous but the reason for its existence is also profoundly different than the mechanisms that govern conventional oil and gas accumulations.

Both conventional and continuous-type reservoirs need organic-rich source rocks that have matured to the point that they generate oil and gas. Generating oil from organic matter in rock requires elevated temperatures and, depending on temperature, extended periods of time. Because temperatures increase with depth, organic-rich rocks in the deepest parts of a basin are more mature and thus have a greater potential to generate petroleum than source rocks that are less deeply buried.

Conventional Petroleum Accumulations

Conventional oil and gas reservoirs are localized accumulations of petroleum that consist of porous and permeable reservoir rocks overlain by impermeable cap rocks or seals that are folded, faulted or stratigraphically positioned so as to be capable of collecting (trapping) oil and gas (fig. 1). Oil and gas in conventional reservoirs originates in organic-rich source beds. The petroleum generated by

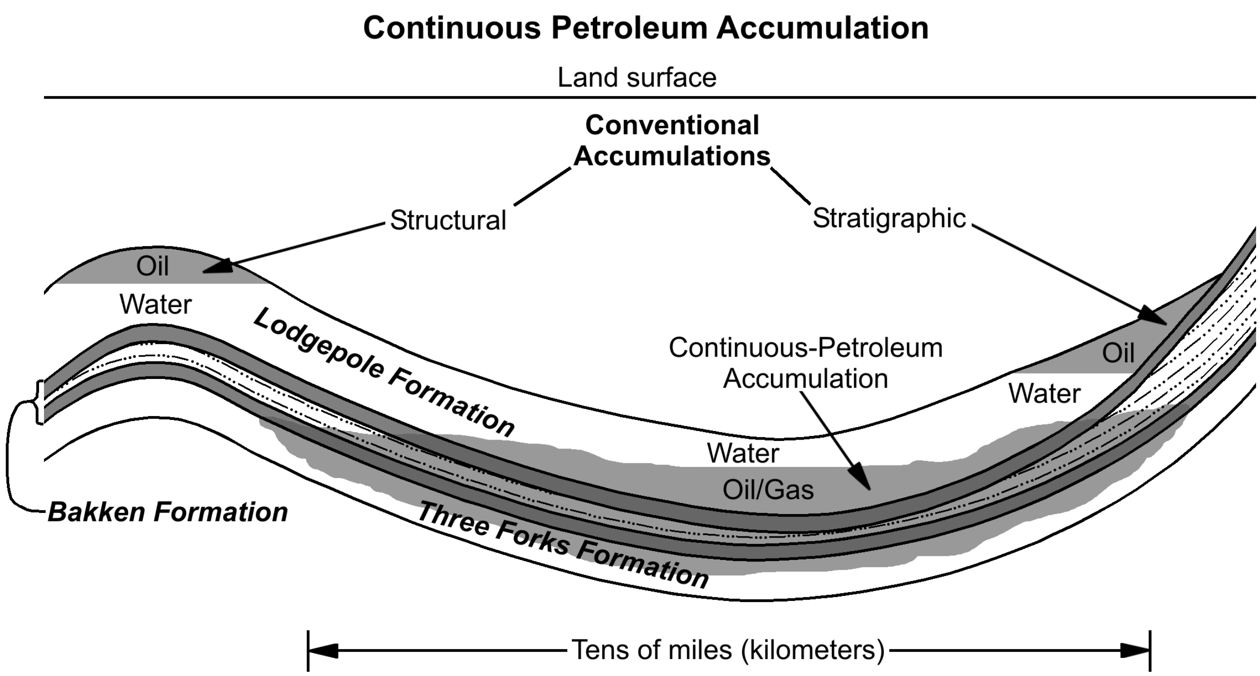
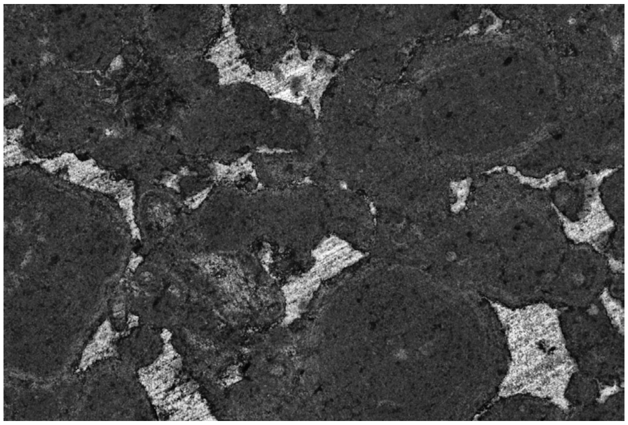


Figure 1. Schematic cross-section illustrating conventional reservoirs consisting of buoyancy-maintained oil/water contacts in which traps have been formed by a dome structure and a stratigraphic pinchout. In contrast, the continuous petroleum accumulations are not maintained by buoyancy and therefore do not have well-defined oil/water contacts. Modified from the U.S.G.S. National Oil and Gas Resource Assessment Team, 1995.



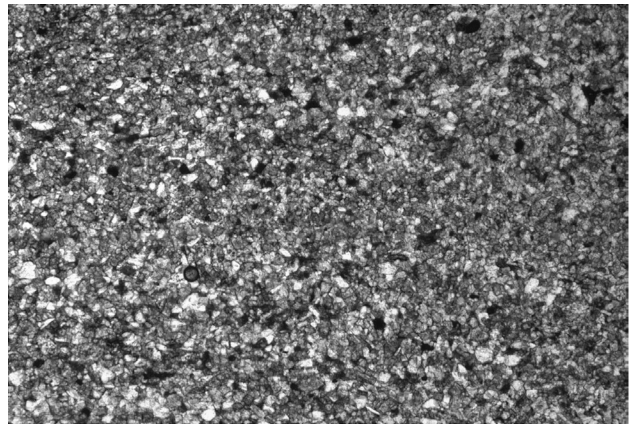


Figure 2. The thin section on the left is a good example of the porosity found in conventional reservoirs. The large pore space (areas in gray) allows oil and gas to bubble through the water-filled pores and to collect in traps. The thin section on the right consists of silt-sized grains in which the pore space is too small to easily see. Unlike the conventional reservoir, oil can only move into this rock under pressure. The rock on the right is typical of the reservoir that is producing significant amounts of oil from the Bakken Formation.

these beds migrates, sometimes many miles, laterally and upwardly through water-filled pores before entering porous and permeable reservoir rocks within a trap.

The accumulation of oil and gas into conventional reservoirs is due, in large part, to differences in density that exist between oil, gas and water. Because petroleum is less dense than water, buoyancy drives petroleum upward through water-filled fractures and pores in the overlying rock until it encounters an impermeable seal or cap rock that forms a trap in which oil and gas accumulates.

A cap rock or seal can be formed in many settings including unfractured rocks that contain no pore space or where the pore space is unconnected. However, in most cases seals form when the size of the pore space within the rock decreases. Small pores are usually associated with very fine-grained rocks such as shale or siltstone or finely crystalline limestone or dolostone.

In conventional reservoirs, trapped oil and gas "floats" on underlying water-saturated rocks across fairly sharp oil or gas/water contacts. Mapping out these oil/water contacts is the traditional method by which oil field boundaries are established. Together with the geometry and total pore volume that is present in the reservoir, reasonably good estimates of the total volume of oil in a conventional field can be made from these field boundaries.

Continuous Petroleum Accumulations

Unlike conventional reservoirs, "continuous" or "basin centered" petroleum accumulations do not form through buoyancy. Instead, oil and gas is injected into a reservoir that usually includes the source rock and the rocks close to the source (fig. 1). This frequently results in abnormally high formation pressures in the reservoir and the formation of a petroleum accumulation surrounded by water-saturated rock. In many respects the rocks surrounding continuous-type accumulations are much like the cap rocks or seals that overly conventional reservoirs. In both cases, the migration of petroleum by buoyancy must be stopped before petroleum can accumulate. In order to do this some force must be present that counteracts buoyancy. The surface tension that exists between droplets of oil and the water that is present in the subsurface is one such force. Surface tensions exist whenever immiscible fluids, such as oil and water, are in contact.

The ability of surface tension to counteract buoyancy can be easily demonstrated by recalling the grade school science experiment in which a steel needle can be made to float on the surface of water as long as the surface tension of the water is unbroken. A gentle push provides enough force to overcome this surface tension and the needle sinks.

The force associated with the surface tension between water and either oil or gas increases as the size of the pore throat that the oil or gas is moving through decreases. In other words, small pore throats tend to prevent buoyancy in the same way that surface tension prevents a needle from sinking in a glass of water. In general, small pore throats are associated with rocks containing small crystals and/or mineral grains such as shale, siltstone and finely crystalline or chalky limestone and dolostone (fig. 2).

Even though the sealing rock may be porous, surface tension between migrating oil or gas and water originally present in the seal prevents oil in the reservoir from moving through the small pore throats that make up the seal (fig. 3). Consequently, finer grained rocks block the migration of oil or gas until there is enough pressure on the petroleum to overcome the restraining surface tension and force the oil and gas into the pore space of the rock next to the source. In this way over-pressured oil "charges" a reservoir that acts both as reservoir and seal. The accumulation acts a bit like a balloon in that the original water in the pore space surrounding the source rock is pushed outward by the petroleum generated in the source rocks, with the surface

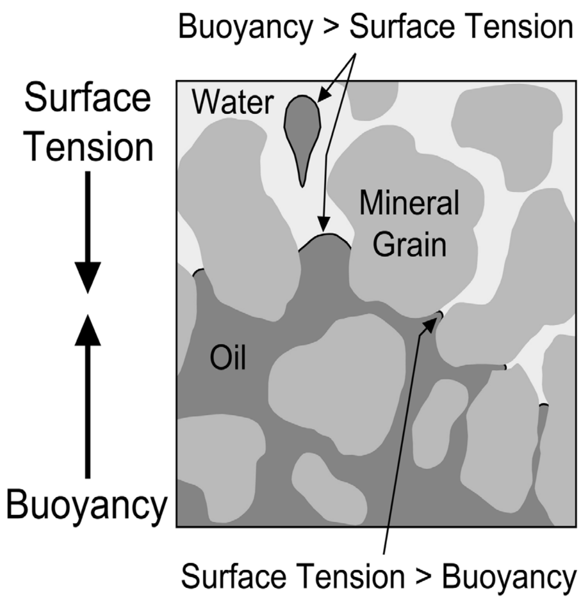


Figure 3. This diagram illustrates the interaction of buoyancy and surface tension. The relative magnitudes of these opposing forces can either move oil and gas through large pores, when buoyancy is greater than surface tension, or oil and gas can be stopped when the force of buoyancy through small pores is less than the restraining force caused by surface tension.

tension between the petroleum and water acting as the skin of the balloon.

After oil generation begins, available pore space in the source and surrounding rock fills with oil or gas as petroleum is forced into the space previously occupied by water. If the rock that the oil is being forced into is permeable or heavily fractured the oil may migrate through buoyancy and end up in a conventional reservoir. If however, there is no buoyant route for oil to escape from the source beds then this oil must displace water originally present in the rocks above, below or within the source.

The absence of a true petroleum/water interface in continuous petroleum accumulations makes it difficult to define field boundaries or estimate the total volume of oil or gas that may be present. Continuous petroleum accumulations typically cover very large areas so that wells drilled into them are almost never truly "dry". However, because the petroleum-bearing rocks have little permeability, economic success frequently depends on the presence of naturally occurring fractures or the creation of new fractures formed by injecting highly pressurized water (hydrofracing) into the reservoir after drilling. In either case, fractures substantially enhance oil flow from these rocks.

Depositional History

The North Dakota Industrial Commission defines the "Bakken petroleum system" as the interval that contains the "Devonian-Mississippian Bakken Formation, the upper 50 feet of the Devonian Three Forks Formation, and the lower 50 feet of the overlying Mississippian Lodgepole Formation". Deposition of these rocks occurred during the Late Devonian and Early Mississippian when North Dakota was situated in the tropics, very near the equator along the western margin of what would become North America. The Williston Basin was part of an embayment along this ancient seacoast. The Three Forks Formation was deposited along this seacoast during the Late Devonian in a shallow, nearshore marine environment that produced thinly bedded, tan to apple-green, muddy to very finely crystalline dolostone, siltstone and the occasional fine-grained sandstone. Near the end of Three Forks time, sea level dropped enough for widespread erosion of the Three Forks to occur. This resulted in an unconformity between the Three Forks and the overlying Bakken Formation along the margins of the basin. Closer to the center of the basin, however, the contact appears to be conformable.

Rising sea levels and/or restricted circulation formed an oxygen-stratified water column, allowing for the growth, deposition and preservation of a massive amount of organic carbon that makes the shales in the Bakken Formation world-class source beds. This organic carbon is the product of intense biological activity that bloomed in the seas that covered much of North Dakota during Late Devonian through Early Mississippian time. Throughout this period, organic matter settled onto an oxygen-free bottom where it accumulated before being buried. Fluctuating sea levels and slow subsidence of the basin deposited at least two organic-rich shales, probably in deeper water, offshore settings. These shales include the upper and lower members of the Bakken Formation - carbonaceous shales sometimes found near the bottom of the Lodgepole Formation known as the "False Bakken", and local occurrences of organic-rich shale in the Three Forks. The middle member of the Bakken contains a variety of rock types including heavily cemented limestone, and mixtures of siltstone, silt and mud-sized dolostone, and fine-grained sandstones. Dense limestone and microcrystalline dolostone found near the bottom of the Lodgepole Formation reflect the final phase of deposition that is included in Bakken petroleum system. This final stage occurred as carbonate platforms built out into open seas and covered the Bakken Formation.

Thermal Maturation

Following deposition of the Bakken petroleum system, subsidence and infilling of the basin continued and subjected the preserved organic material in the Bakken source beds to ever increasing temperatures. Reconstruction of the burial history indicates that the Bakken Formation was rapidly buried throughout the Mississippian. However, this initial phase of subsidence did not bury the Bakken deep enough to encounter temperatures capable of generating oil. It appears that subsidence of the Williston Basin was insufficient to bury the Bakken deep enough for oil generation until the most recent phase of subsidence that began approximately 100 million years ago. During this last phase of subsidence a large portion of the Bakken has been buried to depths and temperatures at which intense oil generation is possible.

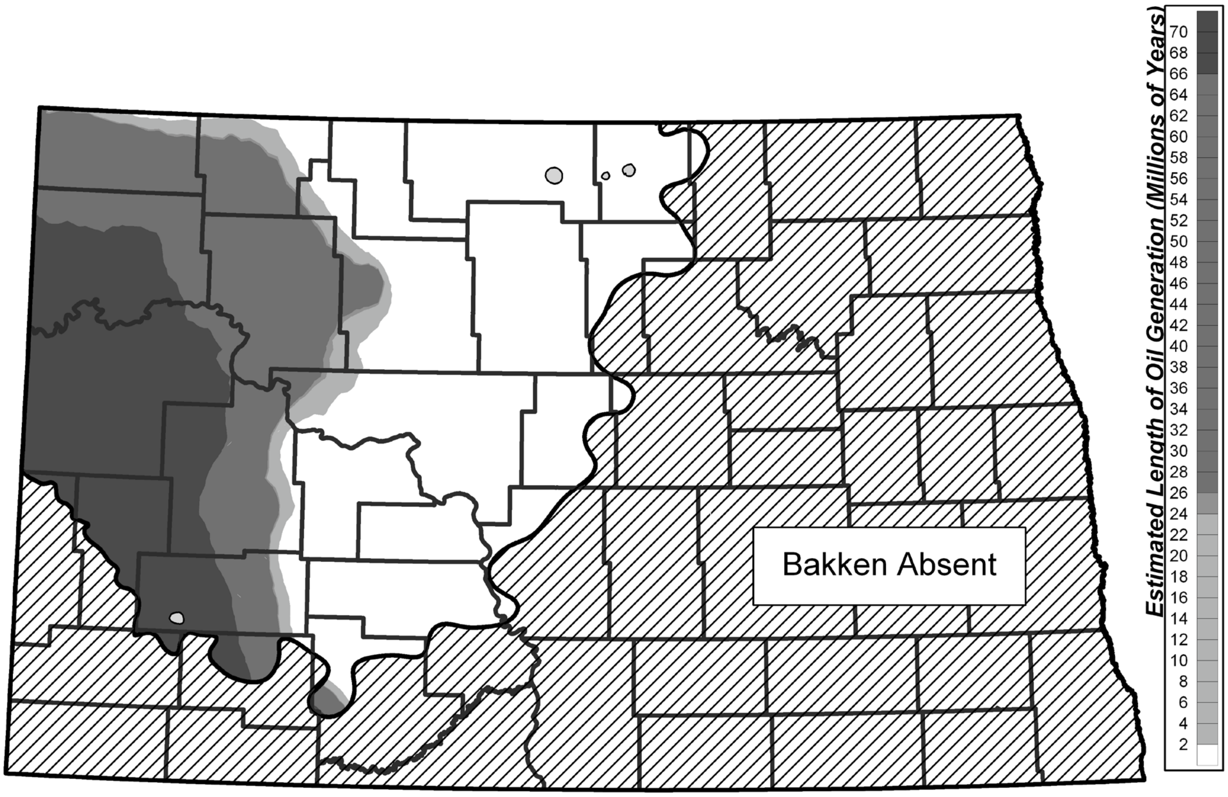


Figure 4. This map illustrates how long the Bakken Formation has been generating oil in millions of years. Oil generation is believed to begin when the time-temperature index (TTI) for the Bakken reaches 15 (see North Dakota Geological Survey Geological Investigation 61 for details). The map is based on calculations of the thermal maturation of the Bakken Formation based on the subsidence history of the Williston Basin and modern measurements of heat flow through the crust. The parts of North Dakota that do not have Bakken in the subsurface are designated by the hatched pattern. Areas in which oil generation within the Bakken has begun are indicated by shades of gray with darker shades indicating longer periods of generation. Areas in which oil generation has not yet begun, but which may still contain "migrated" oil, are shown in white.

Of course the Bakken is not (and has not been) buried to the same depth throughout the basin. Consequently, the length of time the Bakken was generating oil at any given place depends upon the local degree of thermal maturation. Understanding the thermal maturation of the Bakken is therefore critical in defining where oil production from the Bakken is possible (fig. 4).

The Bakken Formation as a Model of a Continuous Petroleum Accumulation

The proliferation of horizontal drilling coupled with increasing sophistication of well stimulation, suggests that a new age in oil and gas exploration in the Williston Basin has begun. Given the current level of excitement surrounding the Bakken production in Mountrail and Dunn counties, it is tempting to speculate on the existence of other, similar, continuous petroleum accumulations that might be present elsewhere in the basin. Using the Bakken Formation as a basic model of a continuous petroleum accumulation, the following characteristics might prove useful in developing an inventory of other possible exploration targets:

1) Regionally extensive, organic-rich source rock. (i.e. upper and lower members of the Bakken).

2) Source rock burial to depths with temperatures sufficient to convert organic matter into oil or gas.

3) Overlying and underlying rocks that are sufficiently thick, widespread and impermeable so as to isolate the accumulation (i.e. Bakken Formation, Three Forks Formation, and the Lodgepole Formation).

4) Overlying and/or underlying rocks that are sufficiently permeable to accept and sufficiently porous to accumulate economic quantities of oil or gas. (i.e. middle member of the Bakken Formation, Three Forks Formation, and possibly the Lodgepole Formation).

5) The absence of permeable zones, fractures or faults that would allow oil and gas to freely migrate away from the accumulation.