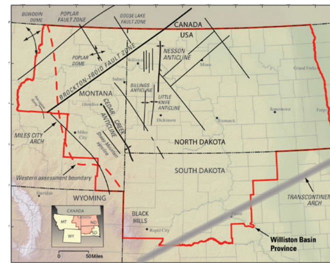


Click here to return to
Volume Title Page

Chapter 5
Geologic Assessment of Technically Recoverable Oil in the Devonian and Mississippian Bakken Formation

By Richard M. Pollastro, Laura N.R. Roberts, and Troy A. Cook

Chapter 5 of 7
Assessment of Undiscovered Oil and Gas Resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010

By U.S. Geological Survey Williston Basin Province Assessment Team

U.S. Geological Survey Digital Data Series DDS–69–W

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Pollastro, R.M., Roberts, L.N.R., and Cook, T.A., 2013, Geologic assessment of technically recoverable oil in the Devonian and Mississippian Bakken Formation, chap. 5 *of* U.S. Geological Survey Williston Basin Province Assessment Team, Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010 (ver. 1.1, November 2013): U.S. Geological Survey Digital Data Series DDS–69–W, 34 p.

Contents

Figures

Tables

Geologic Assessment of Technically Recoverable Oil in the Devonian and Mississippian Bakken Formation

By Richard M. Pollastro, Laura N.R. Roberts, and Troy A. Cook

Abstract

The Upper Devonian and Lower Mississippian Bakken Formation in the U.S. portion of the Williston Basin is a giant continuous (unconventional) oil resource. A recent U.S. Geological Survey assessment estimated a mean volume of undiscovered technically recoverable oil for the Bakken Formation at about 3.65 billion barrels of oil. The estimate is based on a geologic model and a methodology that defines different assessment units by accumulation type (conventional or continuous), structural control, fracture occurrence and prediction, lithology and petrophysical properties, formation thickness, underlying salt movement or dissolution, and level of thermal maturity and oil-generation capacity of Bakken source rocks.

The Bakken Formation consists of three informal members: (1) lower shale member, (2) middle sandstone member, and (3) upper shale member. The lower and upper shale members are rich in marine organic matter (as much as 35 percent by weight) and are the petroleum source rocks, whereas the middle sandstone member varies in depositional facies and lithology and locally exhibits good matrix porosity (as much as 14 percent) but with low permeability characteristic of tight reservoirs. Additional commingled production occurs locally from matrix porosity in the immediately underlying Sanish sand unit (informal name) of the Upper Devonian Three Forks Formation. Combined, the Bakken Formation and Sanish sand define the "Bakken composite continuous reservoir." On a larger scale, thermally mature, organic-rich Bakken shale members also source oils produced from locally occurring Waulsortian mounds or porous strata immediately above the upper shale member in the overlying Lower Mississippian Lodgepole Limestone. As a whole, elements of petroleum source, reservoir, seal, migration, and trap define the stratigraphic and geographic character of a Bakken-Lodgepole Total Petroleum System.

The geographic extent of the continuous oil accumulation within the U.S. portion of the Bakken Formation is defined as the area in which the organic-rich shale members are thermally mature with respect to oil generation. The area of the oil-generation window for the Bakken continuous reservoir was determined using a combination of the following: (1) contour mapping of both the hydrogen index (HI) and log-resistivity well data of the upper shale member, (2) calibration of HI to the transformation ratio from one-dimensional burial history models, and (3) calibration of HI to total organic content.

The area of the oil-generation window was divided into five continuous assessment units: (1) Elm Coulee-Billings Nose, (2) Central Basin-Poplar Dome, (3) Nesson-Little Knife Structural, (4) Eastern Expulsion Threshold, and (5) Northwest Expulsion Threshold. One hypothetical conventional assessment unit, the Middle Sandstone Member, was defined external to the area of oil generation.

Introduction

The Upper Devonian and Lower Mississippian Bakken Formation is a thin (as much as 160 ft; 49 m) but widespread unit within the central and deeper portions of the Williston Basin in Montana, North Dakota, and the Canadian Provinces of Saskatchewan and Manitoba (fig. 1). The first oil discoveries in the Bakken were in the early 1950s at Antelope field in McKenzie County, North Dakota (LeFever, 1991) on the Nesson anticline, one of the Williston Basin's largest and most petroleum-productive structures (fig. 2). At Antelope field, vertical well penetrations produced oil from fractured Bakken strata on a secondary and oblique structure along the east flank of the Nesson anticline where there is thick, tight, porous sandstone within the middle sandstone member. Locally, production is commingled at Antelope with an underlying sandstone reservoir unit, the Sanish sand (informal name), of the Upper Devonian Three Forks Formation (fig. 3).

In 1995, as part of the U.S. Geological Survey (USGS) National Oil and Gas Assessment (NOGA) Project, the USGS assessed both conventional and continuous oil and gas resources of the entire United States (Gautier and others, 1995). In the 1995 NOGA assessment, the Bakken Formation continuous accumulation was assessed for the first time by the USGS, resulting in an estimated mean for undiscovered technically recoverable resource volume of 151 million barrels of oil (MMBO). More recently, two significant discoveries—the Elm Coulee field, Richland County, Mont., in 2000, and the Parshall field, Montrail County, N. Dak., in 2006—have greatly

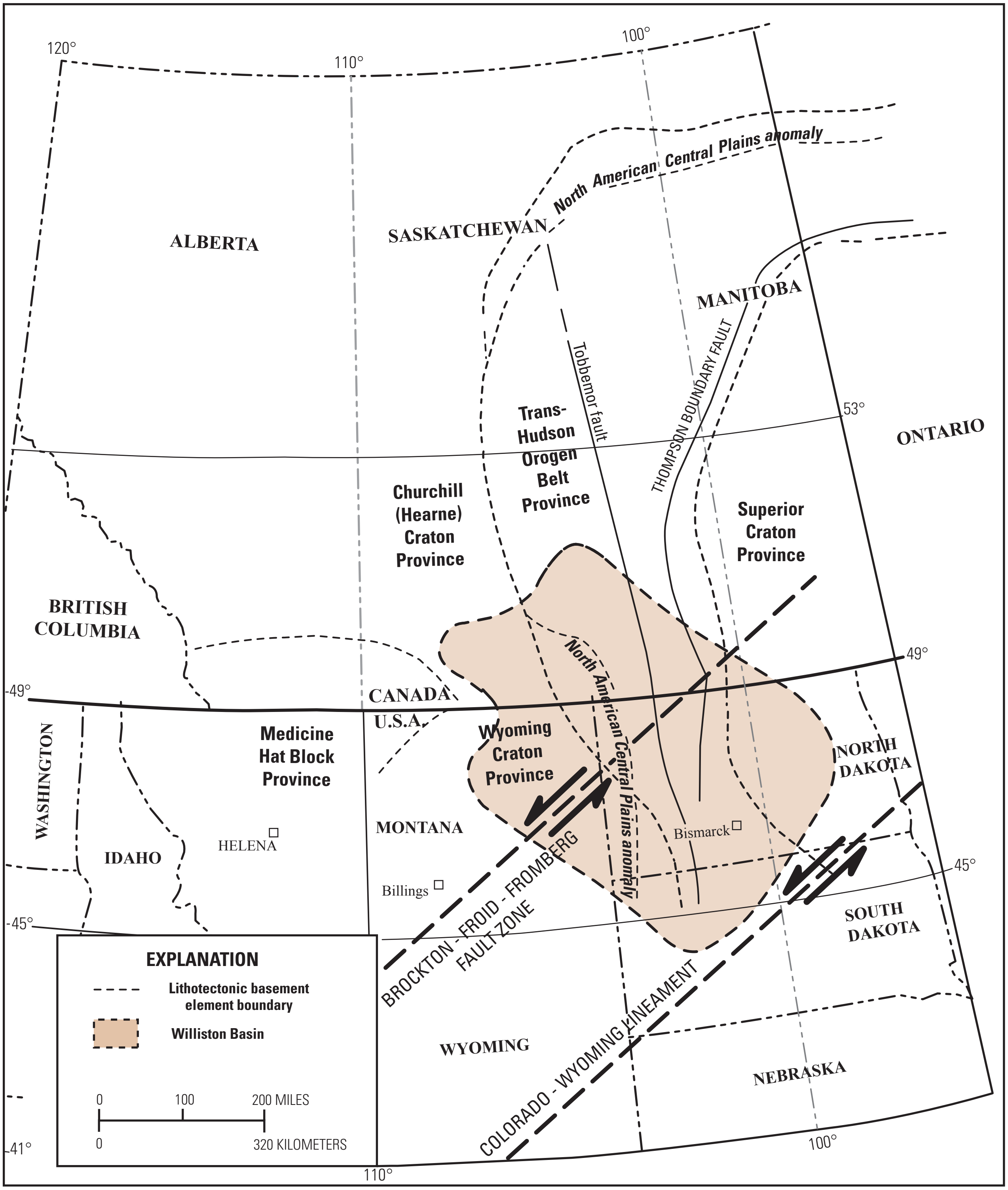


Figure 1. General extent of Williston Basin, two major fault systems responsible for the formation of the basin, and Precambrian basement structural provinces. Location of the North American Central Plains conductivity anomaly is also shown. Modified from Kent and Christopher (2007).

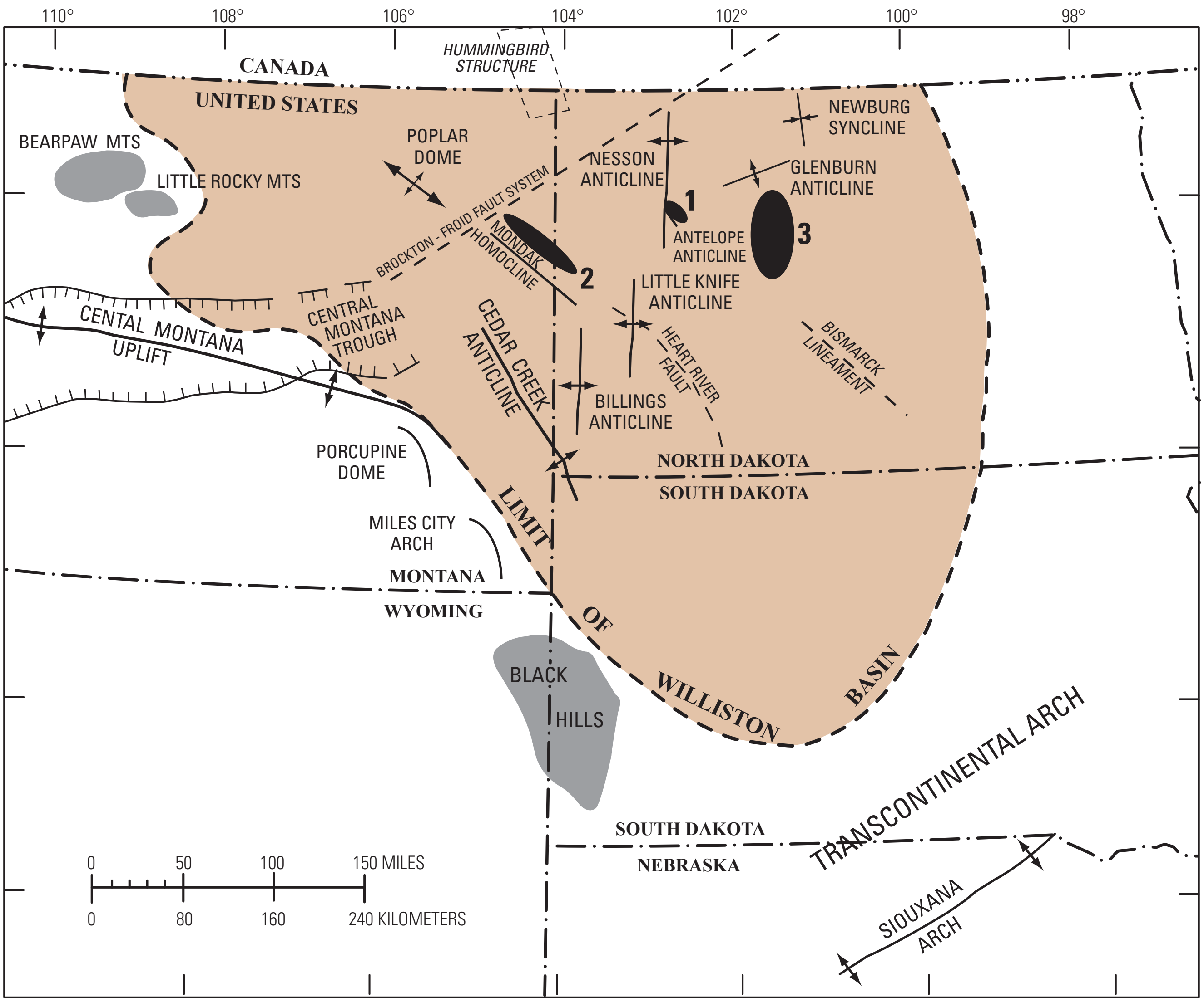


Figure 2. Present-day major structural elements of the U.S. portion of the Williston Basin. Solid black ovals show general location of three major areas of oil production from the Bakken Formation: Antelope field (1), Elm Coulee field (2), and Parshall and Sanish fields (3). Modified from Gerhard and others (1991).

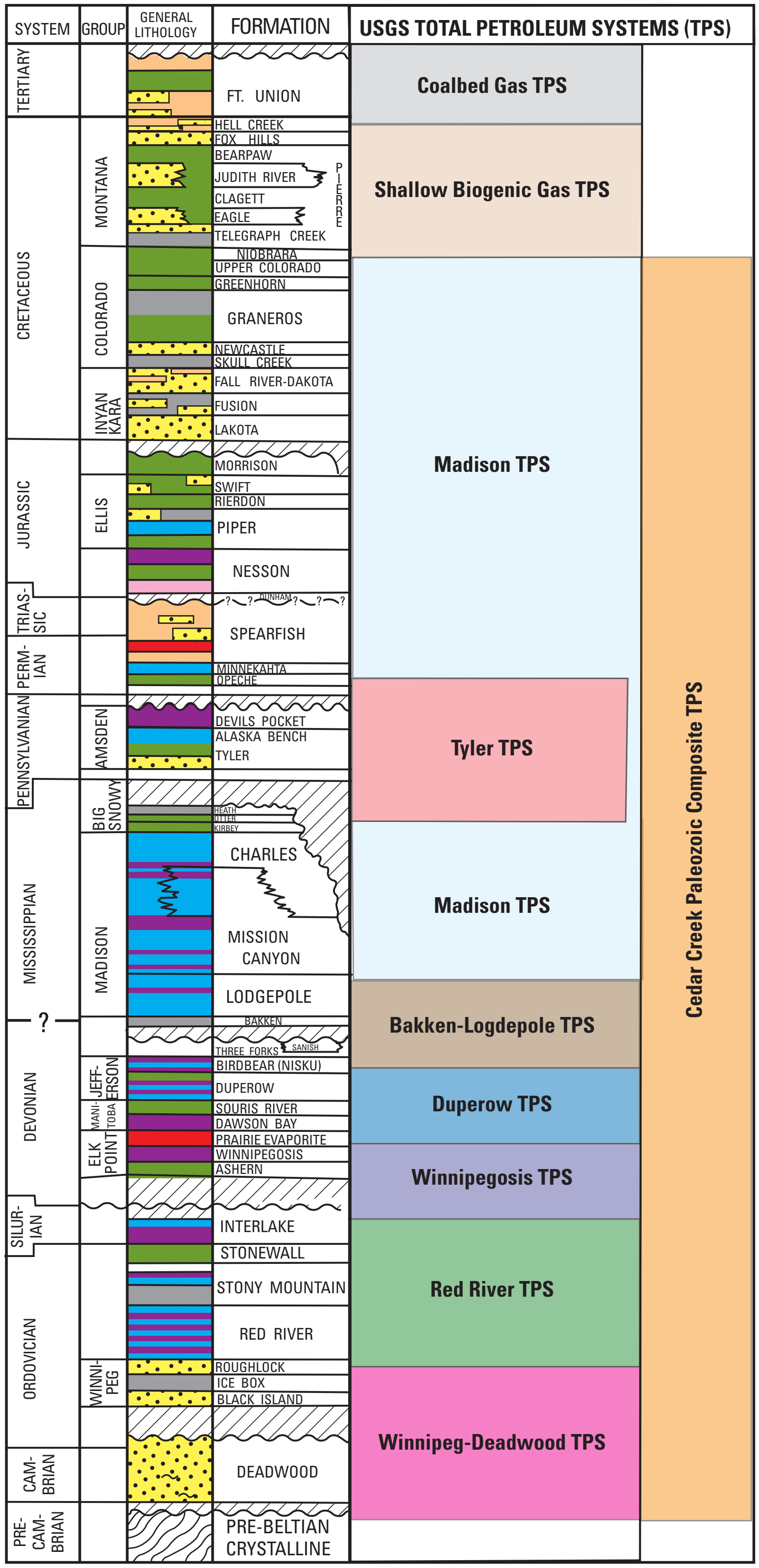


Figure 3. Generalized stratigraphic chart of the Williston Basin, Montana and North Dakota. U.S. Geological Survey (USGS) total petroleum systems (TPS) shown at right. Diagonal-line pattern indicates major periods of erosion or nondeposition. Stratigraphic chart from North Dakota Geological Survey (1995).

heightened the level of Bakken exploration, production, and resource potential. In these areas, the formation exhibits moderate- to high-matrix-porosity reservoir zones within the middle sandstone member. The presence of these reservoirs, as well as both vertical and horizontal natural fractures throughout the formation, combined with the development of new horizontal technology and completion practice, have resulted in wells with estimated ultimate recoveries (EURs) up to about 2 MMBO (Pollastro and others, 2008a).

In April 2008, the USGS completed a new assessment of the undiscovered, technically recoverable oil and gas resources in the Bakken Formation (Pollastro and others, 2008b); an assessment of the entire Williston Basin Province followed shortly thereafter in September 2008 (Anna and others, 2008). The general approach to the assessment was as follows: (1) define the total petroleum system (TPS) and each of its elements (source, reservoirs, traps, seals, pod(s) of active source rock, migration, and areas of undiscovered resource); (2) determine whether accumulations are conventional or continuous (unconventional); (3) define geologic assessment units (AU), which are the resource plays; (4) for continuous accumulations, define the geologic factors that might control differences in drainage area (cell size) and well performance expressed as estimated ultimate recovery (EUR); and (5) provide the input data required for the assessment in the form of a statistical distribution that reflects the geology (or geologic factors) and production characteristics for the AU.

The application of long-lateral, multi-stage fracture technology in horizontal well completions, combined with increased oil prices, have allowed the rapid development of the Bakken and adjacent units such as the underlying Three Forks Formation, particularly throughout North Dakota. Consequently, contemporary knowledge and data on the Bakken and Three Forks Formations have increased significantly over time, even since the 2008 USGS assessment (LeFever and Nordeng, 2008; Pollastro and others, 2008a).

Williston Basin Tectonic Evolution and Petroleum Occurrence

The Williston Basin is a large, roughly circular intracratonic depression that developed on the North American craton and along the southwestern edge of the Canadian Shield. Sediment deposition began during the Cambrian, but major basin subsidence and basin filling began during the Ordovician. The basin occupies a geographic area of about 300,000 mi^2 (770,000 km^2) over portions of North Dakota, South Dakota, Montana, and adjacent Canadian Provinces of Manitoba and Saskatchewan (fig. 1). It is commonly viewed as a structurally simple basin because of its nearly complete stratigraphic section, with most units thinning from basin center to basin edge, and the faults and other structural features commonly having only a small net displacement or movement. Detailed studies reveal, however, a more complex tectonic history due mostly to deformed underlying basement rocks and two major bounding structural fault systems responsible for much of the basin's interior faults and lineaments, block-fault movements, sedimentation patterns, salt dissolution, fluid movement, and thermal history (Green and others, 1985; Brown and Brown, 1987; Gerhard and Anderson, 1988). Consequently, each of these tectonic elements plays an important role in the generation, migration, and distribution of hydrocarbons, as discussed below.

The distribution of oil and gas production in the Williston Basin relative to the locations of major structures, such as the Nesson, Cedar Creek, Little Knife, Billings, and Antelope anticlines, and Poplar dome, is shown in figure 4. Most of these structures have Bakken production; one exception is the Cedar Creek anticline, where the Bakken is absent. Dynamic modifications of these structures at all scales, and associated salt movement, have played a major role in both the depositional and petrophysical character (especially related to fractures) of the Bakken Formation.

The north- to south-trending Nesson anticline and northwest-trending Cedar Creek anticline are the most prominent structural features in the Williston Basin (figs. 2 and 4). These structures are expressed at the surface and have produced large volumes of oil and natural gas from numerous stratigraphic units. Little Knife anticline, Billings anticline, and Poplar dome are less prominent and less productive (fig. 4). Most structural features, including Nesson, Cedar Creek, and Antelope anticlines and Mondak homocline (fig. 2), are bounded by major faults that appear to be basement controlled (Gerhard and others, 1987; Gibson, 1995). Faults and fault blocks have undergone reactivation throughout the basin's history (Thomas, 1974), particularly during the Mississippian and the Cretaceous (Brown and Brown, 1987). In a detailed stratigraphic study of the Williston Basin using isopach maps, Flannery and Kraus (2006) showed clear evidence of periodic basement-block movement throughout the basin's history.

Salt deposits ranging in age from Silurian to Jurassic are widespread throughout the Williston Basin of Montana and North Dakota, and several studies have linked dissolution of thick salt deposits and associated structural movements to petroleum reservoir development. For example, LeFever (2005a) and Sonnenberg and Pramudito (2009) suggested that favorable oil production from the Bakken Formation at Elm Coulee field, Montana, is partly due to salt dissolution and consequent collapse of overlying strata along the present-day limit of the Prairie Evaporite salt (fig. 5). They suggested further that fractures and reservoir properties of the Bakken were enhanced by dissolution, collapse, and the consequent basinward salt-edge movement, followed by the migration of fluids, thus aiding in forming the Elm Coulee production "sweet spot."

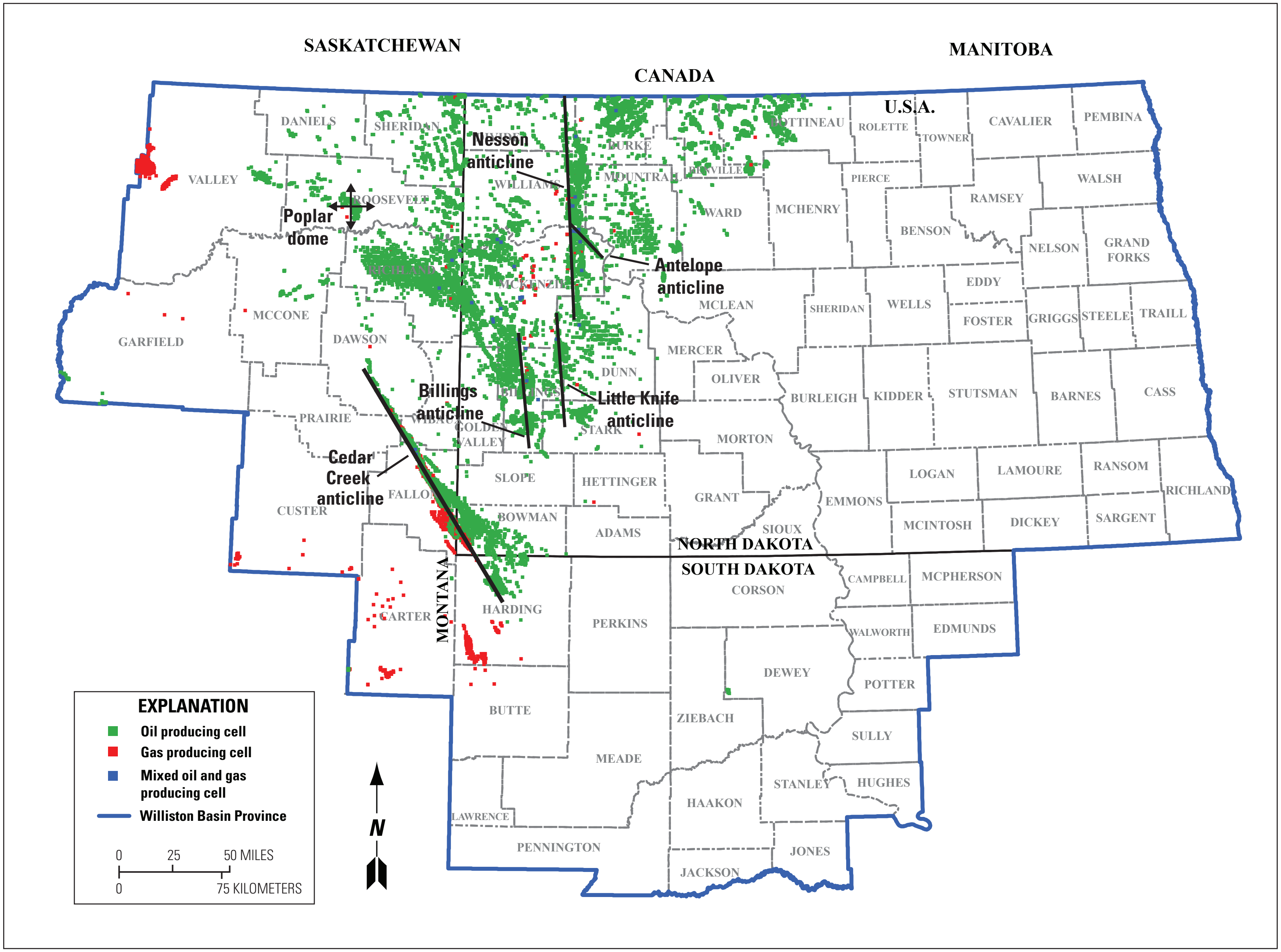


Figure 4. Exploration cells indicating oil production (green), gas production (red), and mixed oil and gas production (blue) in the greater Williston Basin Province, United States. Bold black lines indicate major structural elements. Blue line is the boundary of the Williston Basin Province, as defined by the U.S. Geological Survey. Data derived from IHS Energy Group (2009).

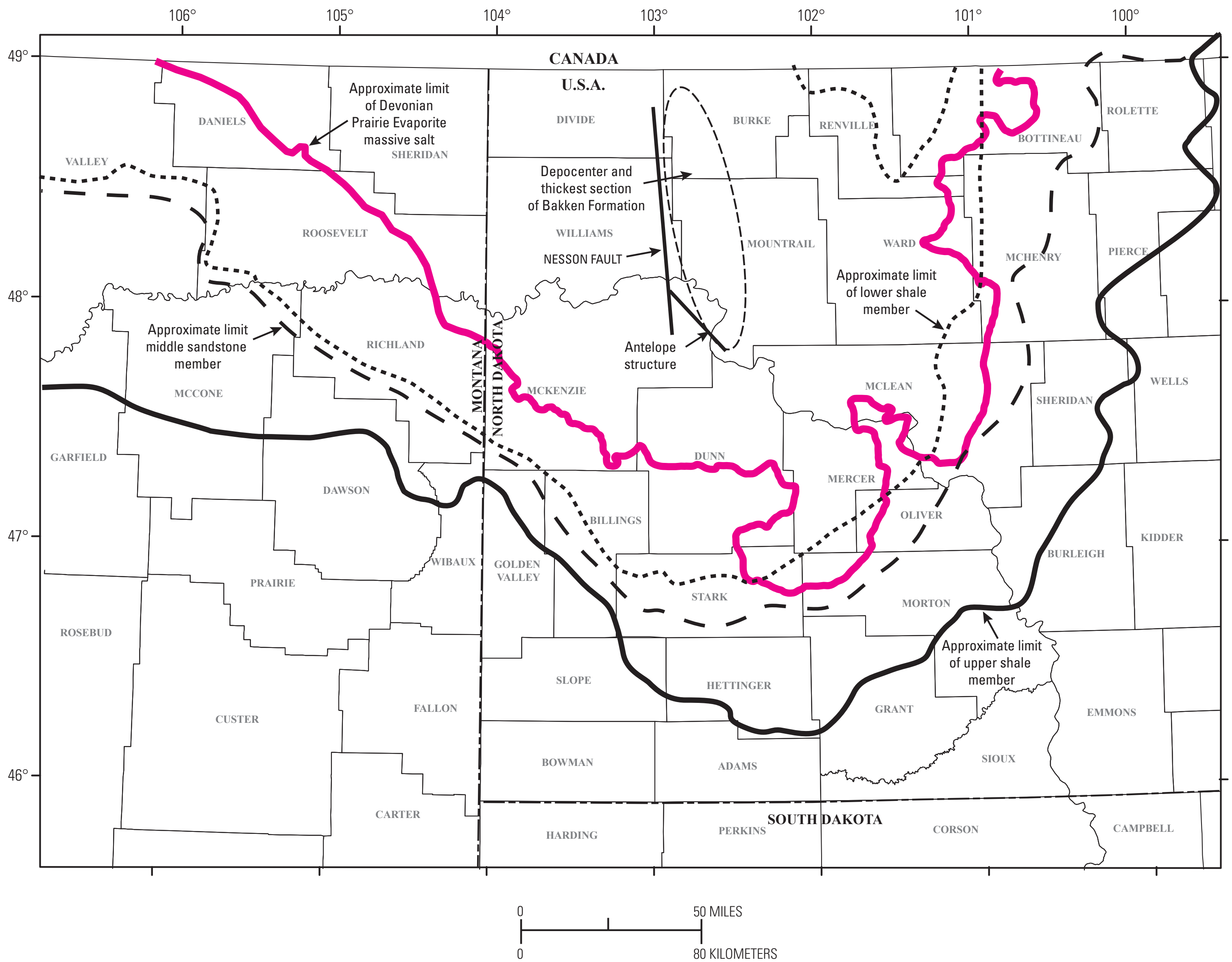


Figure 5. Approximate depositional limits of lower shale, middle sandstone, and upper shale members of the Bakken Formation and location of depocenter and thickest (up to 160 ft; 49 m) section of Bakken Formation immediately east of the Nesson and Antelope anticlines and fault structures. Also shown is present-day limit of massive salt of the Middle Devonian Prairie Evaporite approximated from LeFever and LeFever (2005) and Oglesby (1988). Approximate limits of Bakken members were determined from data compilation for this study and from studies of Webster (1984), Hester and Schmoker (1985), Smith and Bustin (2000), and LeFever (2008).

Stratigraphy of the Bakken Formation

The Upper Devonian and Lower Mississippian Bakken Formation of the U.S. portion of the Williston Basin, Montana and North Dakota, is a highly organic-rich, siliciclastic rock sequence that is present only in the subsurface within the central and deeper portions of the basin. It overlies the Devonian Three Forks Formation and is overlain by the Mississippian Lodgepole Limestone (fig. 3). The Bakken extends throughout the subsurface of the Canada portion of the Williston Basin in Manitoba and Saskatchewan and is continuous with the black shale and gray siltstone members of the Exshaw Formation in Alberta. Maximum thickness is about 160 ft (49 m) within the U.S. portion of the basin (LeFever, 2008). Although this thickness appears to be a minimal part of the total stratigraphic section of 16,000 ft (4,900 m) within the basin (fig. 3), it is a world-class petroleum source and reservoir rock with potential to produce exceedingly large volumes of undiscovered hydrocarbons (Pollastro and others, 2008a, b, c; Anna and others, 2008).

According to USGS geologic nomenclature, the Bakken Formation consists of three informal members: (1) lower shale member; (2) middle sandstone member, and (3) upper shale member. Upper and lower shale members are organic-rich, black marine mudstones of fairly consistent lithology and are the petroleum source rocks for oil produced from the formation. The middle sandstone member throughout the basin varies in thickness, lithology, and petrophysical properties; lithologies include sandstone, siltstone, dolomite, and mudstone (Smith and Bustin, 1996, 2000; LeFever and others, 1991; LeFever, 2007a, b). All three members are generally continuous throughout the Williston Basin, attaining total maximum thicknesses near the basin center in North Dakota and along the east flank of the Nesson anticline (Meissner, 1978; Webster, 1984, 1987; Hester and Schmoker, 1985; LeFever and others, 1991; Smith and Bustin, 1996, 2000; LeFever, 2008). There is a progressive thinning toward and along the northern, southern, and eastern basin margins due to depositional onlap and (or) erosion. Each member is easily distinguished on geophysical well logs, particularly gamma-ray and resistivity logs (fig. 6).

The geographic limits of the three members display an onlapping relation (fig. 5), in that an overlying younger member is of greater geographic extent than the immediately underlying member (Carlson and Anderson, 1965; Meissner, 1978, 1982; Webster, 1984, 1987; Hester and Schmoker, 1985; Smith and Bustin, 1996, 2000; LeFever, 2008). Thus, the limit of the upper shale member is interpreted as the maximum depositional limit for the Bakken Formation because the contact with the overlying Lodgepole Limestone is conformable (Heck, 1978). The maximum thickness of about 160 ft (49 m) is within a well-defined depocenter immediately east, and adjacent to, the Nesson and Antelope structures in western Montrail County, N. Dak. (fig. 5). LeFever (2008) reported anomalous thicknesses mostly in areas south and east of the depocenter, as is evident on detailed isopach interval maps of each member, but particularly that of the upper shale member (LeFever, 2008).

The lower shale member has the smallest geographic extent (fig. 5), with a well-defined depocenter along the east flank of the Nesson anticline. A thick section centered in McKenzie County is coincident with the Heart River fault (fig. 2), and anomalous thicknesses in circular areas along the depositional edge indicate both fault and salt tectonic control during lower shale deposition (LeFever, 2008). The member is a dark-brown to black, quartz-rich, fissile, organic-rich shale, reaches a maximum thickness of 56 ft (17 m) (LeFever, 2008), and has average total organic carbon (TOC) content of about 10 weight percent (Price and others, 1984; Schmoker and Hester, 1983; Smith and Bustin, 1998). Thin laminae of siltstone, limestone, and sandstone are locally present at the base of the member, and lag deposits occur locally as well (Smith and Bustin, 1995).

The middle sandstone member is the thickest (as much as 90 ft; 27 m) member of the Bakken Formation with a much more diverse and complex lithology than either the upper or lower shale members (LeFever, 2008). This member, also referred to as the middle Bakken member (LeFever, 2005a; Smith and Bustin, 1995, 1996, 2000), has recently seen particular focus in exploration of the Bakken Formation. Since 2001, oil discoveries with high production rates within the Bakken have identified local high matrix porosities within the middle sandstone member. In particular, good sandstone and dolomite porosity have been identified at Elm Coulee, Parshall, and Sanish fields (Walker and others, 2006; Canter and others, 2008; Sonnenberg and Pramudito, 2009).

Several studies have identified and mapped various lithofacies within the middle sandstone member: (1) Smith and Bustin (1998, 2000) recognized six lithofacies and three sub-units; (2) LeFever (2007a) identified and mapped seven lithofacies based on log-core correlations; and (3) Canter and others (2008) identified five facies, some having additional subfacies, to predict matrix and fracture porosities.

The upper shale member is organic-rich (as much as 35 weight percent TOC) and exhibits laminated to massive bedding of silt-sized material (Meissner, 1978; Schmoker and Hester, 1983; Price and others, 1986; Smith and Bustin, 2000). A lag unit containing conodonts, fish bones and teeth, and phosphatic grains is commonly at the base (Smith and Bustin, 1995, 1996, 2000). Isopach maps by LeFever (2008) show that the member has a broad, poorly defined depocenter, is generally less than about 30 ft (9 m) thick, and contains isolated pods of thicker (as much as 60 ft; 18 m) shale along the depositional margin, particularly along the boundary between Williams and McKenzie Counties, N. Dak. (fig. 5). These anomalously thick, roughly circular isolated pods of the

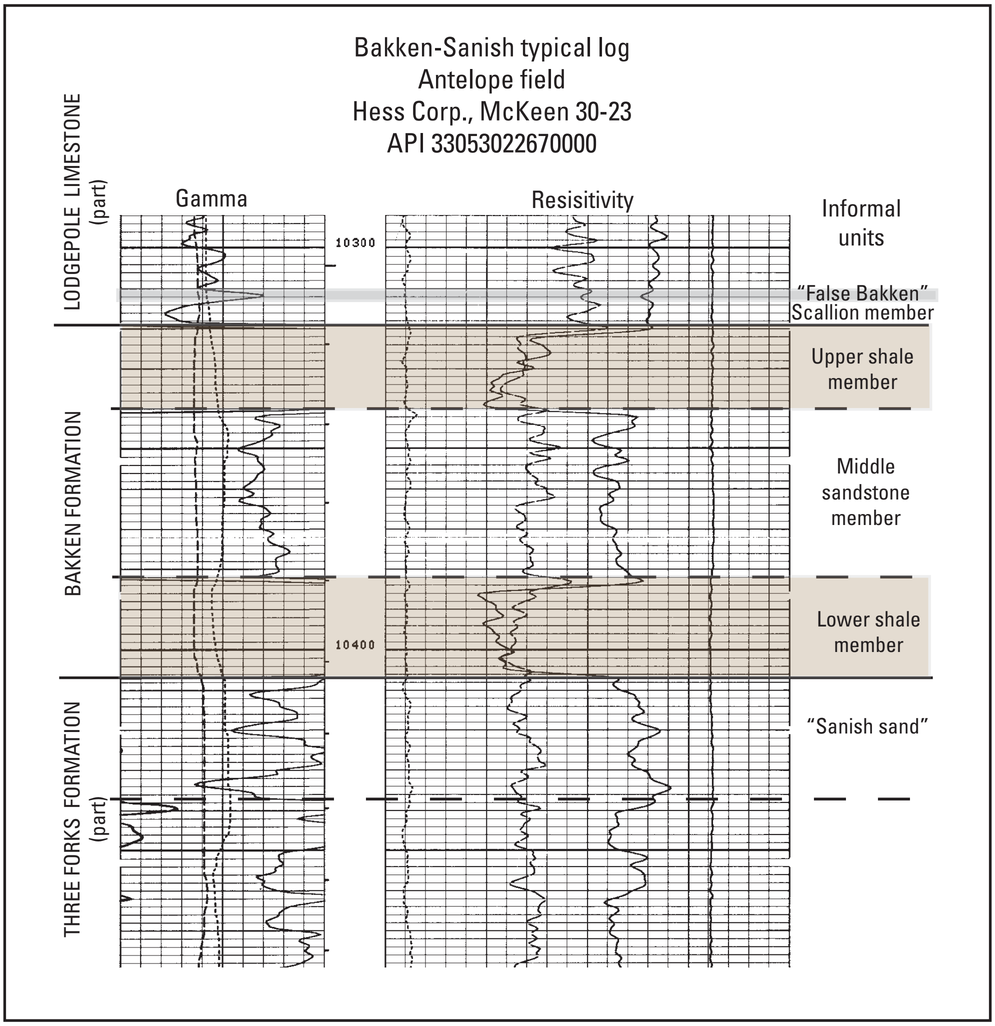


Figure 6. Typical gamma-ray (left) and resistivity (right) curves of the three informal members of the Devonian-Mississippian Bakken Formation, Sanish sand of the Devonian Three Forks Formation, and overlying Mississippian Lodgepole Limestone; location of well log is Antelope field, McKenzie County, N. Dak.

upper shale member in this area are probably related to salt tectonics and multistage dissolution of salt of the underlying Devonian Prairie Evaporite (Oglesby, 1988; LeFever and LeFever, 2005). For example, in the vicinity of the Dickinson Lodgepole Limestone mounds in Stark County, N. Dak., the member locally reaches its maximum thickness of about 60 ft (18 m) (LeFever, 2008).

Immediately underlying the Bakken Formation, local accumulations of a coarse-grained siltstone to fine-grained quartz sandstone and dolomite, informally referred to as the Sanish sand (figs. 3 and 7), are at the top of Upper Devonian Three Forks Formation in the central portion of the Williston Basin (Dumonceaux, 1984; Webster, 1984; LeFever, 1991). The Sanish sand is of particular importance because the discovery well for the Bakken Formation at Antelope field, and subsequent wells at Antelope, include commingled Bakken and Sanish production. The unit was described as a discontinuous unit with variable texture and composition and originally interpreted to represent a beach or nearshore marine deposit by Dumonceaux (1984). In 2006 and 2008, additional discoveries in the upper part of the Three Forks Formation were announced in the U.S. portion of the Williston Basin, which fostered extensive exploration and development of the Sanish unit in conjunction with Bakken exploration, resulting in about 110 new wells producing from the Three Forks Formation (North Dakota Industrial Commission, 2009).

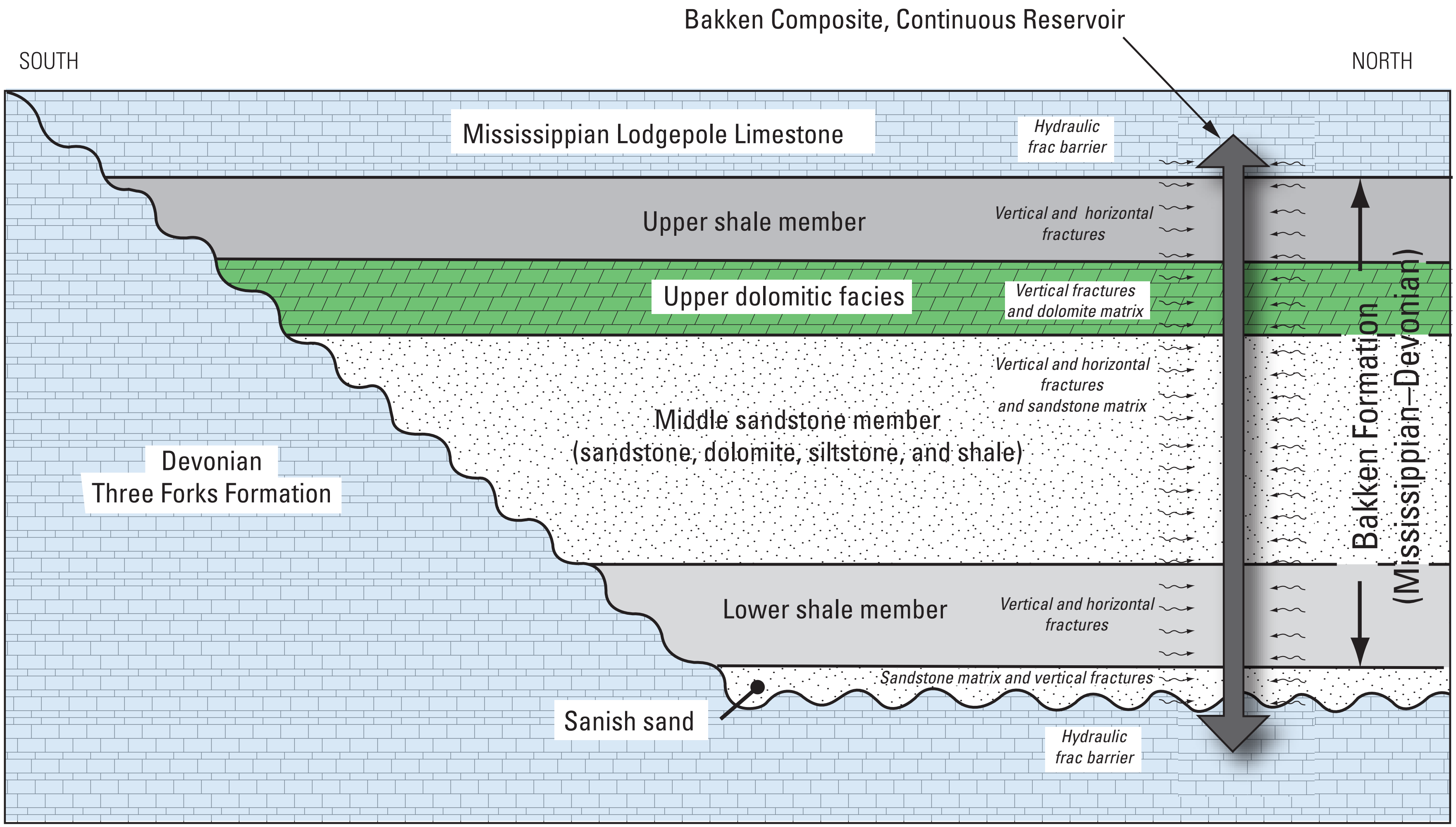


Figure 7. Schematic stratigraphic cross section from north to south across the depositional margin of the Devonian-Mississippian Bakken Formation, showing onlapping relation of members of the Bakken Formation, overlying and underlying units, and the Bakken composite continuous reservoir (large arrow). Physical properties related to oil production are also noted for each of the units. Sanish sand is informal member of Three Forks Formation. Modified from Pollastro and others (2008a).

Bakken-Lodgepole Total Petroleum System and Bakken Composite Continuous Reservoir

Current USGS assessments to estimate undiscovered oil and gas resources are based on the total petroleum system (TPS) assessment unit methodology (Klett and others, 2000; Magoon and Schmoker, 2000; Pollastro, 2007). The USGS defined ten TPSs in the U.S. portion of the Williston Basin (Anna and others, 2008) (fig. 3). The Bakken-Lodgepole TPS was defined on the basis of geographic and stratigraphic distribution of both known and undiscovered hydrocarbon accumulations sourced primarily by organic-rich marine shales of the upper and lower shale members of the Bakken Formation. Minor contributions of petroleum may be sourced from thinner organic-rich units of adjacent formations in close proximity to these shale members; for example, organic-rich "false Bakken" strata of the Lodgepole Limestone (Montgomery, 1996; LeFever, 2005b) almost immediately above the upper shale member of the Bakken Formation (fig. 6), can be identified on logs of some wells. Of the ten TPSs defined for the Williston Basin, the Bakken-Lodgepole TPS is the most prolific producer of hydrocarbons (Pollastro and others, 2008a, b, c; Anna and others, 2008).

Reservoirs of the Bakken Formation included in the Bakken-Lodgepole TPS are both continuous and conventional. The continuous reservoir is a composite of stratigraphic members and units, whereas the conventional reservoir lies only within the middle sandstone member. Additional conventional reservoirs in the TPS are Waulsortian mounds (mud-rich carbonate buildups that lack an identifiable frame-building organism) of the Mississippian Lodgepole Limestone (Montgomery, 1996; Sprain, 1997; Gaswirth and others, 2009).

Although no proven conventional Bakken reservoirs have been identified in the U.S. portion of the Williston Basin, porous, structurally trapped, and stratigraphic pinch-out reservoirs are present in the middle sandstone member of the Bakken Formation in Saskatchewan and Manitoba, Canada. These Canadian Bakken reservoirs produce oil that has migrated north and northeast from thermally mature upper and lower Bakken shale member source beds into conventional traps (LeFever and others, 1991; Osadetz and others, 1992; Burrus and others, 1996; and Kreis and others, 2005, 2006).

The continuous reservoir of the Bakken Formation, referred to in this study as the "Bakken composite continuous reservoir," is defined stratigraphically as the entire Bakken Formation and also includes, where present, the underlying Sanish sand unit (fig. 7) (Pollastro and others, 2008a, b). The composite reservoir is sealed between two thick impermeable limestones of the overlying Lodgepole Limestone and underlying (pre-Sanish) Three Forks Formation.

Waulsortian mounds of the Lodgepole Limestone directly overlie anomalously thick sections of the Bakken Formation. The thick sections of the upper shale member (LeFever, 2008) are along the depositional edge of the formation (fig. 5) and probably resulted from dissolution of salt in the underlying Devonian Prairie Evaporite (Sprain, 1997; LeFever and LeFever, 2005). Therefore, the geographic boundary of the TPS is defined by the combination of all these petroleum system elements. The areal distribution of petroleum source rocks for the Bakken-Lodgepole TPS is best defined by the geographic extent of the upper shale member (fig. 5), the unit that represents the maximum depositional limit of the Bakken Formation. The area of thermally mature upper and lower shale member source rocks (defined in a later section of this report) is critical to the Bakken-Lodgepole TPS model. The boundaries of the Bakken-Lodgepole TPS are defined using the following geologic and (or) geographic criteria: (1) to the east and southeast by the areal extent of the upper shale member as defined by LeFever (2008), (2) to the south and southwest by the extension of the "12-mile mound buffer zone" as defined by Burke and Diehl (1993), (3) to the west by the structural boundary of the Williston Basin, and (4) to the north by the U.S.-Canada border (fig. 8) (Pollastro and others, 2008a, b).

Fractures, Petrophysical Properties, and Bakken Oil Production

A composite fracture-matrix-porosity reservoir model is used in this study for the assessment of undiscovered, technically recoverable oil from the Bakken Formation. Micro-fractures, both vertical and horizontal, interpreted as the result of petroleum generation, were considered in the geologic model for defining the assessment units for the Bakken-Lodgepole TPS. Fractures are of particular importance to continuous (unconventional) reservoirs and constitute a major percentage of the effective porosity and permeability in shale reservoirs. Also, the greater the quantity, quality, length, and resulting interconnectivity of fractures in the Bakken, the greater the flow capacity of the reservoir. The Bakken Formation in the U.S. portion of the Williston Basin produces oil from an area where it is thermally mature with respect to oil generation. The middle sandstone member and the Sanish sand unit locally have measurable matrix reservoir properties (Meissner, 1978, 1991a; LeFever and others, 1991; Walker and others, 2006; Canter and others, 2008). Although matrix porosity from both units is a major contributing factor in establishing storage volume for high-volume Bakken wells, fracturing is also of major importance in establishing a viable Bakken reservoir (Meissner, 1978, 1991b; Sperr, 1991; Nordeng, 2009). For example, Murray (1968) made a strong argument for long tensional (extensional) fractures as the major component in the development of good reservoirs in the Bakken/Sanish zone at Antelope field.

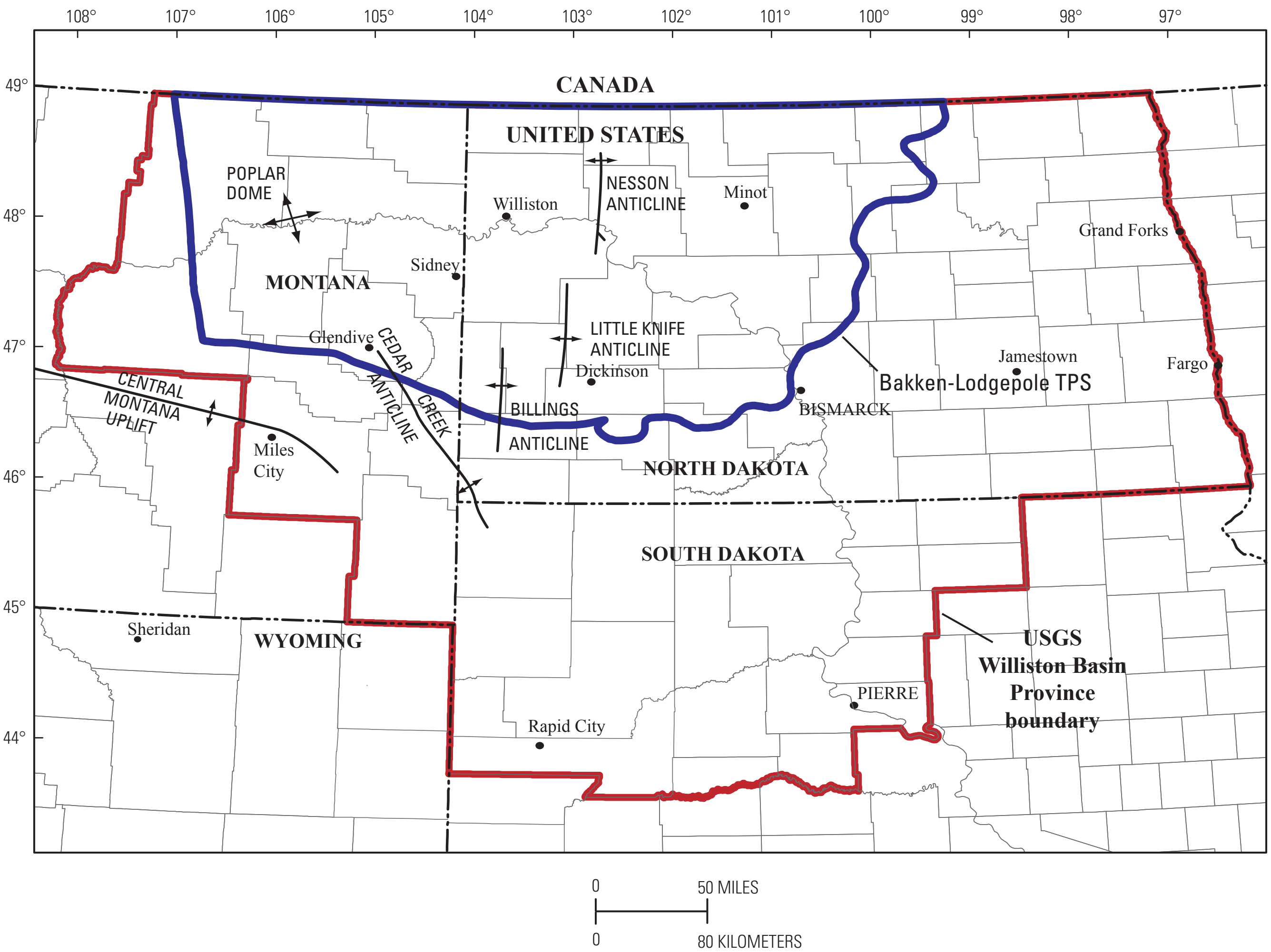


Figure 8. Boundaries of the U.S. Geological Survey (USGS)-defined Williston Basin Province and Bakken-Lodgepole Total Petroleum System (TPS) and major structural elements within the province.

High-volume commercial oil wells in the Bakken Formation require a combination of geologic factors. Most importantly, overpressuring conditions, high (>6 percent) matrix porosity in the middle sandstone member, and natural fractures maximize production from the formation. There are three dominant types of natural fractures in the formation: regional, tectonic, and expulsion (Meissner, 1978, 1984; Carlisle and others, 1992; LeFever, 1992, 2007a; Pollastro and others, 2008a). Such fractures, which are essential to having an economic well, can be lithology dependent and differ in length, orientation, interconnectiveness, and abundance (Carlisle and others, 1992). In the "Bakken composite continuous reservoir," there are both vertical and horizontal fractures in all three of the members.

Several studies have stated that hydrocarbon generation related to the thermal maturation of organic matter in the Bakken played an important role in the development of the reservoir by creating overpressuring and microfractures (Meissner, 1978, 1991a, b; LeFever, 1992; Carlisle and others, 1992; Pitman and others, 2001; Leonard and others, 2008; Pollastro and others, 2008a; Coskey and Leonard, 2009). Both vertical and horizontal microfractures are evident in cores of the lower and upper shale members of the formation (fig. 9). Meissner (1978, 1984, 1991a, b) (1) recognized a close association of fractures in the reservoirs with mature oil-generating source rocks and abnormally high reservoir fluid pressures, and (2) suggested a cause-and-effect relation where hydrocarbon generation caused abnormally high fluid pressures that resulted in the creation of vertical fractures within the reservoirs and some adjacent confining beds.

Lash and Engelder (2005) studied horizontal microfractures in the Devonian Dunkirk Shale of western New York State and concluded that (1) they were the result of kerogen-to-bitumen and bitumen-to-oil generation, and (2) kerogen particle shape and shale or siltstone planar fabric are important to the formation of horizontal microfractures. In their model, elevated pore pressures are formed in organic-rich, low-permeability laminated shale by a combination of

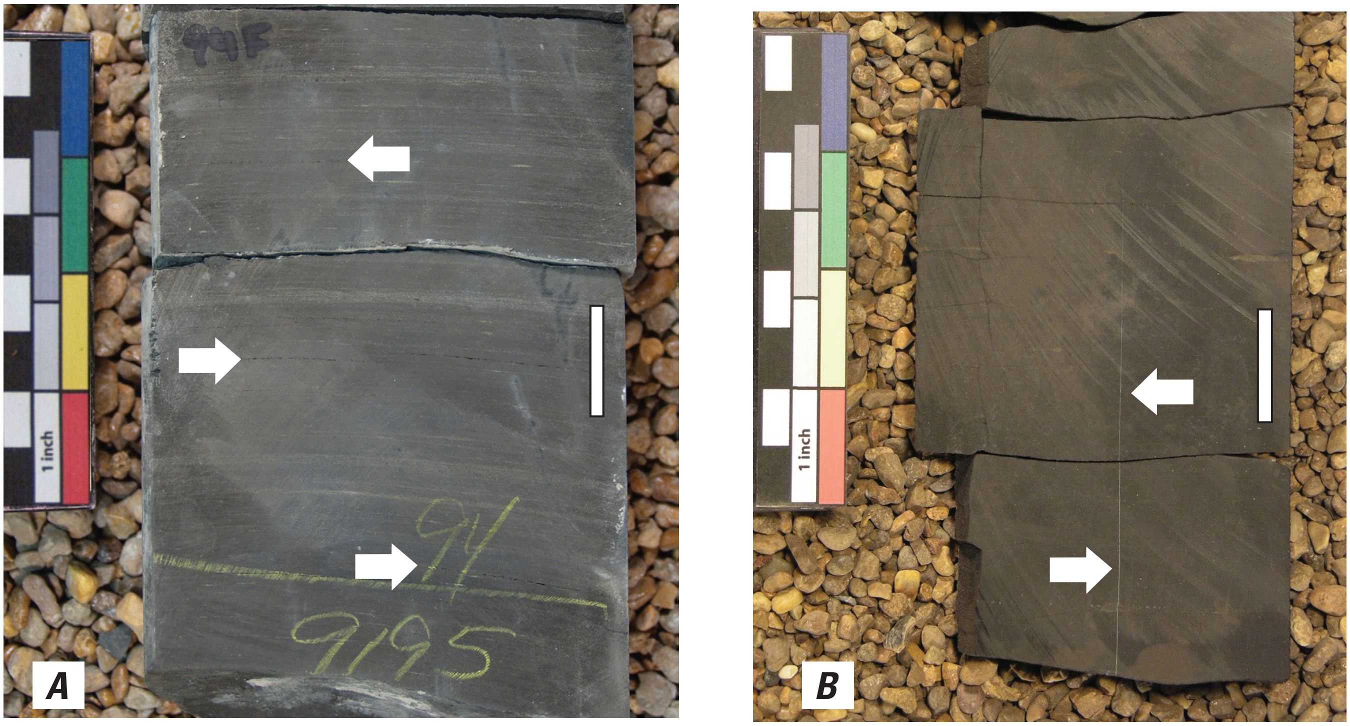


Figure 9. Photographs of microfractures in cores of the Bakken Formation, Parshall field, Montrail County, N. Dak. *A*, Horizontal microfractures (solid arrows) in lower shale member in the EOG Resources, Long 1-01H well. *B*, Vertical microfractures(?) in upper shale member in the EOG Resources, Inc., Fertile 1-12H well. Scale bars on right of photograph equal 1 in. Photographs courtesy of North Dakota Industrial Commission (2009).

processes. These processes, including catagenesis, compaction disequilibrium, and hydrocarbon generation, elevated in-place horizontal stress in excess of vertical stress that favored the propagation of horizontal microcracks. Microfractures formed by hydrocarbon generation are much different than the larger vertical fractures formed by local or regional tectonic stress, including wrench faulting, compression and extension events, recurrent fault-block movement, and salt dissolution and collapse.

Coskey and Leonard (2009) suggested that the high original organic carbon content of immature Bakken is, in part, kerogen supported. As kerogen matures to levels of oil generation, it becomes pliable, loses strength, and develops locally elevated pressure cells with the volumetric increase associated with the conversion to liquid hydrocarbons. The increased pressure induces the formation of microfractures. Oil is then expelled from the kerogen through microfractures, causing the shale to collapse and the shale bulk density to increase with increased thermal maturity through the oil maturity window. Areas that recently entered the oil window are microfractured and retain overpressuring conditions, whereas areas where the Bakken is immature with respect to oil, the system is normally pressured and Bakken rocks are not microfractured and impermeable, and thus act as updip barriers to oil migration.

Thermal Maturity, Oil Generation, and the Bakken Continuous Oil Accumulation

The Bakken Formation is an excellent example of a self-sourced, continuous shale-oil accumulation. A primary requirement for a continuous shale-oil accumulation is that the self-sourced shale reservoir is presently, or was at sometime in its burial history, within the thermal oil-generation “window” (Pollastro and others, 2003). Thus, the oil-generation window for the Bakken shale member source rocks, and the Bakken continuous oil accumulation, must be defined and then mapped as to their areal extent before continuous resource plays can be identified or assessed.

The hydrogen index (HI), from Rock-Eval pyrolysis, in conjunction with resistivity measured from geophysical well logs for both the upper and lower shale members of the Bakken Formation, were used as indicators of oil generation to aid in determining the extent and geographic area of the Bakken continuous oil accumulation in the U.S. portion of the Williston Basin, that is, the Bakken oil-generation window. The hydrogen index is determined in the routine analysis of organic-rich rocks from a combination of measurements and is the amount of hydrocarbon (HC) generated (mg HC from Rock-Eval pyrolysis) relative to TOC (g) in the rock: that is, HI = (mg HC/g TOC) × 100. Thus, HI commonly decreases with increased thermal maturation of the hydrocarbon source rock; however, this may not always be the case over the entire range of HI for all kerogen types (Lewan and Ruble, 2002).

Shales are commonly characterized by low electrical conductivity because major constituents are nonconductive clay and pore water. Meissner (1978) determined that log resistivities through upper and lower shale members of the Bakken at depths generally less than 6,500 ft (1980 m) were low (<30 ohm-m), which is common to most shale. Logs from wells where the upper and lower shale members were deeper, however, commonly had anomalously high (>30 ohm-m to immeasurably high) resistivities. Meissner (1978) concluded that anomalously high resistivities in the shale members of the Bakken Formation represented the onset of hydrocarbon generation and consequent replacement of high-conductive (saline) formation water with nonconductive oil generated from organic matter. He further suggested that the "resistivity effect" may be interpreted as a measure of hydrocarbon generation and expulsion.

Schmoker and Hester (1983) and Hester and Schmoker (1985) later produced a series of contour maps, based on interpretations from well logs, that included the geographic limit, thickness, depth below surface, present-day temperature, and average density, resistivity, and neutron porosities of each of the Bakken members. In particular, average resistivity of the lower and upper shale members tended to be either high (>100 ohm-m) or low (<25 ohm-m). High resistivity is in a large, nearly continuous area of the central Williston Basin and is separated by a narrow transition area of low resistivity in both the eastern and northwestern parts (fig. 10). Schmoker and Hester (1983) and Hester and Schmoker (1985) (1) concluded that in these impermeable shale members, the transition between the two resistivity domains corresponds to a transition from thermally mature shale to immature shale that has not generated oil and is indicative of a thermal maturity boundary; and (2) suggested that in the central basin, (a) oil expulsion from the shale members should be greatest, and (b) the water saturation of the middle sandstone member should be at a minimum, which is supported by no water being recovered during drill-stem tests in that area (Meissner, 1978).

Hydrogen index data from the USGS Organic Geochemical Database (2007) for the Bakken shale members, most of which was generated from the studies by Leigh C. Price (USGS), were plotted and contoured for this study using both EarthVision and ArcGIS software. Similarly, well-log resistivity data measured in this study was combined with the data of Hester and Schmoker (1985) from the upper and lower shale members and then plotted and contoured using the same software. The resulting contour map of HI for the upper shale member is shown in figure 11*A*. Intervals where HI is highest (HI >600) indicate least mature or immature areas of the upper shale member source rock. Similarly, intervals where HI is lowest (HI <200), indicate where the upper shale member is highly mature to overmature. The pattern of darker green shaded intervals on the HI map of figure 11*A*, showing where the upper shale member is most thermally mature, indicates two well-defined oil-generation "kitchens": (1) a north- to south-trending area through McKenzie and Billings Counties in western North Dakota, approximately along the axis of the Williston Basin, and (2) an east- to west-trending zone in the Poplar dome area of Montana. In addition, a similar contour map of HI generated for the lower shale member shows a similar maturity pattern (fig. 11*B*). Maps showing similar patterns of HI for the upper and lower shale members were also published by Pollastro and others (2008a), LeFever (2008), and Coskey and Leonard (2009). The north–south trending pattern of mature Bakken shale members in western North Dakota coincides with the North American Central Plains (NACP) conductivity anomaly (Jones and Craven, 1990; LeFever and others, 1991; Nelson and others, 1993; Osadetz and others, 1992, 2002), a feature (fig. 11*B*) postulated to have once been an area of anomalously high heat flow resulting in high thermal maturity of Bakken source rocks (Coskey and Leonard, 2009).

The onset of oil generation, oil-expulsion windows, and calibration of HI to the transformation ratio (TR, the percent of hydrocarbons expelled) for the Bakken Formation were further determined from one-dimensional (1-D) modeling at five wells in the Williston Basin (fig. 11*A*; table 1). The modeling of burial history and thermal maturity was performed using PetroMod1D (version 9.0) software of Integrated Exploration Systems (2005) GmbH (IES), Germany, and following the methods of Roberts and others (2008).

Burial history and timing of petroleum-generation profiles for the five modeled wells are shown in figure 12. The timing and extent of petroleum generation from the Bakken shale member source rocks at the five locations are summarized in figure 13; time of maximum burial in all wells was estimated at about 50 Ma (Eocene) and is shown by the vertical dashed line in figures 12 and 13. Heat-flow values range from 54 mW/m^2 near Parshall field, to 95 mW/m^2 in the Robbins no. 1 well at Poplar field. Timing of the start, peak, and end of oil generation (transformation ratios of 0.01, 0.50, and 0.99, respectively) for Type II source rocks was calculated at a horizon in the middle of the source-rock intervals and summarized in figure 13.

The modeling indicates that the easternmost wells, wells 4 and 5, are in early stages of oil generation and have not reached peak generation. In contrast, oil generation has gone to completion in wells 1 and 2, and near completion (96 percent) in well 3. Calibration of the HI to the TR indicates that an HI of about 650 approximates the start or onset of oil generation, that is, the beginning of the oil-generation window for Bakken shale member source rocks (Pollastro and others, 2008a). Thus, the HI = 650 contour line in figure 11*A* was used to map the outermost geographic limit of the Bakken continuous oil accumulation.

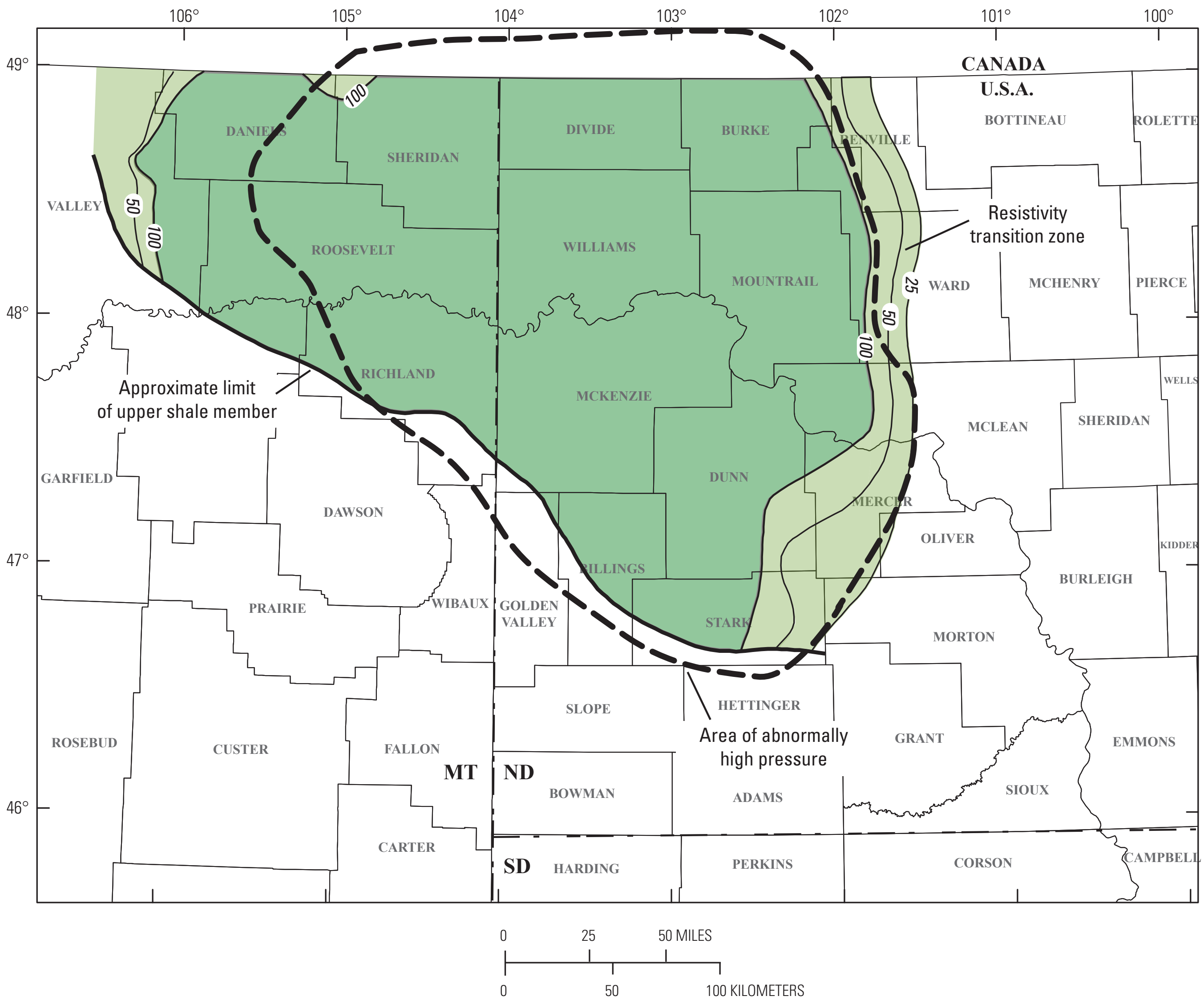


Figure 10. Log resistivity (in ohm-m) of upper shale member, Bakken Formation. Modified from Hester and Schmoker (1985). Area of abnormally high formation pressure (bold dashed line) approximated from Meissner (1984). Resistivity >100 ohm-m indicated by dark-shaded area; resistivity transition zone in lighter shaded areas between 25- and 100-ohm-m contours.

Oil Expulsion Model and the "Expulsion Threshold"

Several studies discussed earlier in this paper suggest a relation between horizontal and vertical microfractures in the Bakken Formation and hydrocarbon generation (Meissner, 1978, 1991a; LeFever, 1992, 2007a, b; Carlisle and others, 1992; Pitman and others, 2001; Pollastro and others, 2008a; Coskey and Leonard, 2009). A hydrocarbon expulsion model was constructed from the relation between HI and TOC, in which a mean TOC of about 17 percent at an HI = 800 is decreased to about 12 percent at an HI = 300. The results show that the most distinctive change in TOC is within the interval range of HI = 650 to 400 (fig. 14). Because the onset of oil generation for the Bakken was approximated at an HI = 650, the range of HI from 650 to 400, where loss of TOC appears greatest, is interpreted as the range for primary oil expulsion. Thus, the range in HI from 400 to 650 and corresponding contoured intervals of HI will be referred to in this study as the "expulsion threshold."

The area of the oil-generation window for the Bakken continuous oil accumulation, and corresponding Bakken composite continuous reservoir, was approximated using a combination of the resulting contour maps of both the HI and log-resistivity well data of the upper shale member. Because HI data were limited both in number and in the geographic distribution in the western and northwestern parts of the area underlain by the member, log resistivity data were used as a secondary maturity parameter to supplement and complete the geographic outline for the area of the Bakken oil-generation window.

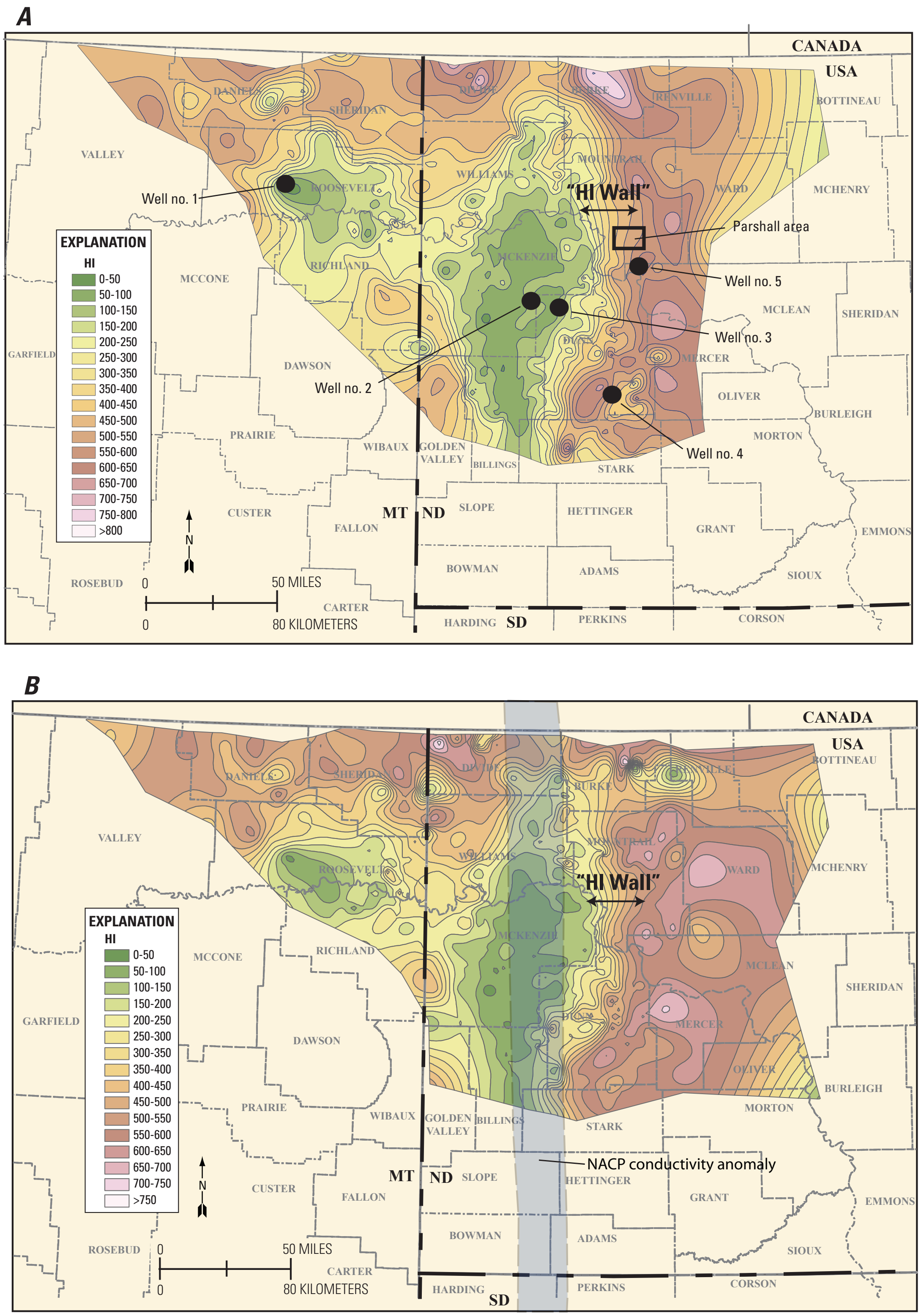


Figure 11. Hydrogen index (HI) values for (*A*) upper shale member, and (*B*) lower shale member of the Bakken Formation, Williston Basin. Also shown in (*A*) are locations of five modeled wells listed in table 1. Approximate position of the North American Central Plains (NACP) conductivity anomaly (Jones and Craven, 1990) is shown in (*B*). Contour interval = 50 HI units. "HI Wall" is the area of close north–south trending HI contours mostly through Mountrail and Dunn Counties, N. Dak., indicating a large change in thermal maturity over a short distance. Data is from U.S. Geological Survey (2007).

Table 1. Identification and locations of wells used for one-dimensional models, Williston Basin, Montana and North Dakota.

[Locations shown on hydrogen index contour map of figure 11A. TD, total depth]

Well no.	Operator	Lease name	API no.	County, State	TD (feet)	Field
1	Colorado Oil Co., Inc.	Robbins #1	25085053790000	Roosevelt County, Mont.	7,969	Poplar
2	Chevron USA, Inc.	Rough Creek Unit #1	33053000260000	Mckenzie County, N. Dak.	12,050	Wildcat
3	Gas Producing Enterprises, Inc.	BN #1	33025001120000	Dunn County, N. Dak.	14,460	Corral Creek
4	Conoco, Inc.	Conoco-Fridley 15 #1	33025003870000	Dunn County, N. Dak.	13,080	Wildcat
5	Home Petroleum Corp.	Tribal #1-1	33055000240000	Montrail, N. Dak.	14,275	Wildcat

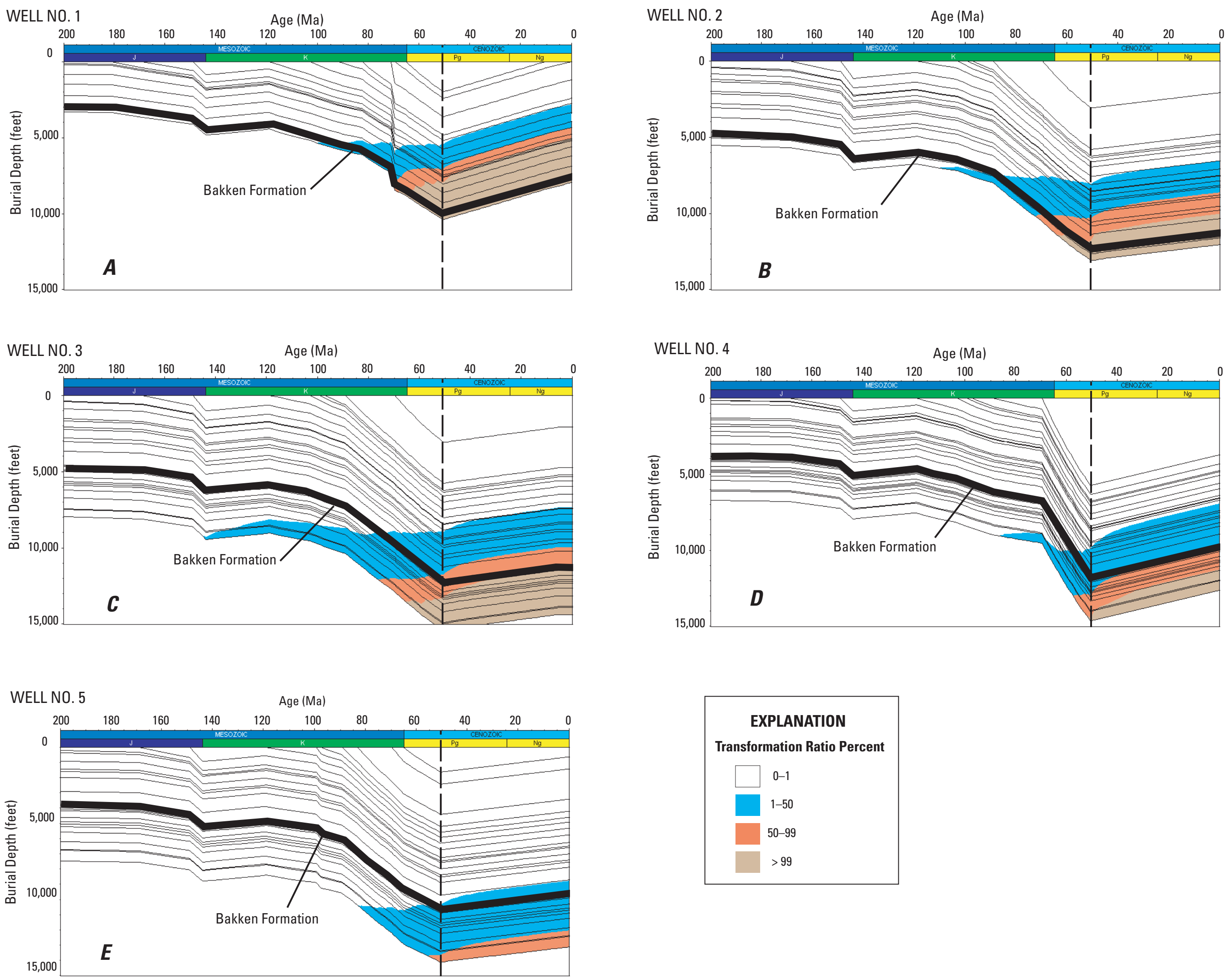


Figure 12. Generalized burial history curves at five well locations in the Williston Basin, Montana and North Dakota. Burial history model locations are shown on hydrogen index (HI) map of figure 11*A*. Well names, designations, and locations given in table 1. Colors on burial history curves represent calculated transformation ratios with respect to burial depth, time, and temperature (see color key). Bold line represents burial history of Devonian-Mississippian Bakken Formation. Dashed lines indicate maximum burial at about 50 Ma. *A*, Well no. 1 in high-maturity area of Poplar dome. *B*, Well no. 2 in high-maturity area of basin depocenter. *C*, Well no. 3 at eastern edge of depocenter along Nesson anticline. *D*, Well no. 4 along southeastern edge of "HI wall." *E*, Well no. 5 along "HI wall" in Parshall field area. J, Jurassic; K, Cretaceous; Pg, Paleogene; Ng, Neogene; Ma, Mega-annum.

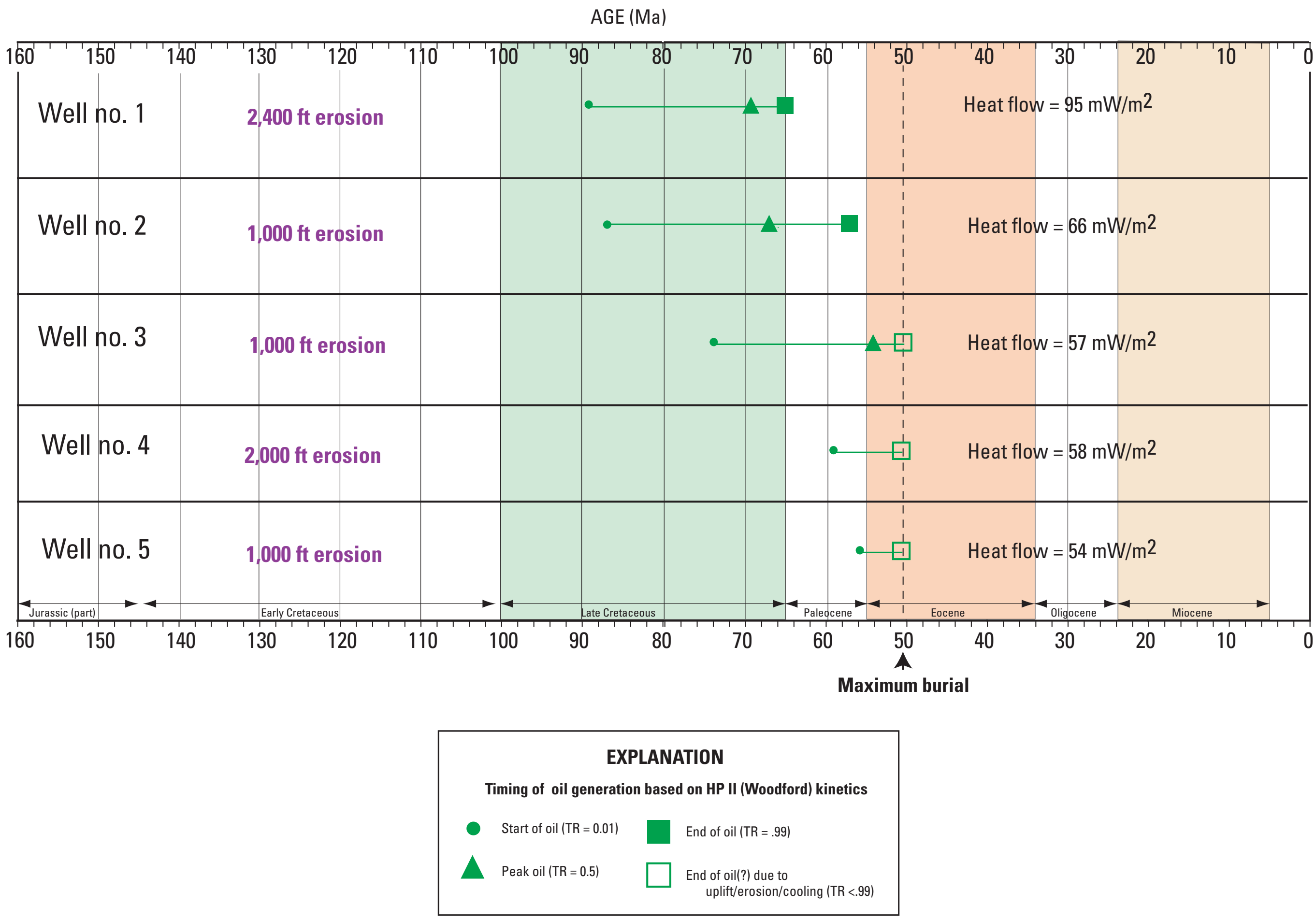


Figure 13. Summary chart showing timing and extent of oil generation modeled from hydrous pyrolysis Type II kinetics (HP II) of Bakken Formation source rocks for five wells in the Williston Basin, Montana and North Dakota. Locations of wells are shown in figure 11*A* and burial history models are shown in figure 12. Well names, designations, and locations given in table 1. No oil was cracked to gas in any of the modeled locations. Estimates of heat flow and erosion also indicated. TR, transformation ratio (percent of hydrocarbons expelled); Ma, Mega-annum.

The area where log resistivity of the upper shale member is >100 ohm-m was assumed to be the area of mature oil generation for the member. The lighter green shaded areas labeled as "resistivity transition zone" in figure 10, corresponding to resistivity values between 25 and 100 ohm-m, are interpreted to represent the conversion of kerogen to bitumen in the upper shale member and not oil generation (saturation) from bitumen. Thus, the outermost geographic extent of the oil window, which represents the onset of oil generation for the Bakken continuous oil accumulation, was defined primarily by the HI = 650 contour in figure 11*A* and (or) where log resistivity equals 100 ohm-m for the upper shale member in figure 10. Thus, the area where HI for this member is >650 and resistivity is >100 ohm-m defines the oil-generation window for the Bakken Formation. The resulting oil-generation window for the upper shale member, which also represents the approximate geographic extent of the Bakken continuous oil accumulation, is shown in figure 15. This implies that oil is present within the Bakken composite reservoir everywhere within the boundary of the Bakken continuous oil accumulation.

Geologic Model and Continuous Assessment Units

The geologic model used to define continuous assessment units (AUs) for resource assessment of the Bakken Formation is based on the following: (1) levels of thermal maturity and generation capacity of the Bakken shale members from the HI and TR, (2) structural complexity of the basin, (3) lithofacies and petrophysical character of the middle sandstone member, and (4) presence of the Sanish sand of the upper part of the Three Forks Formation. Five continuous AUs were defined for the Bakken continuous oil accumulation (fig. 16). Two

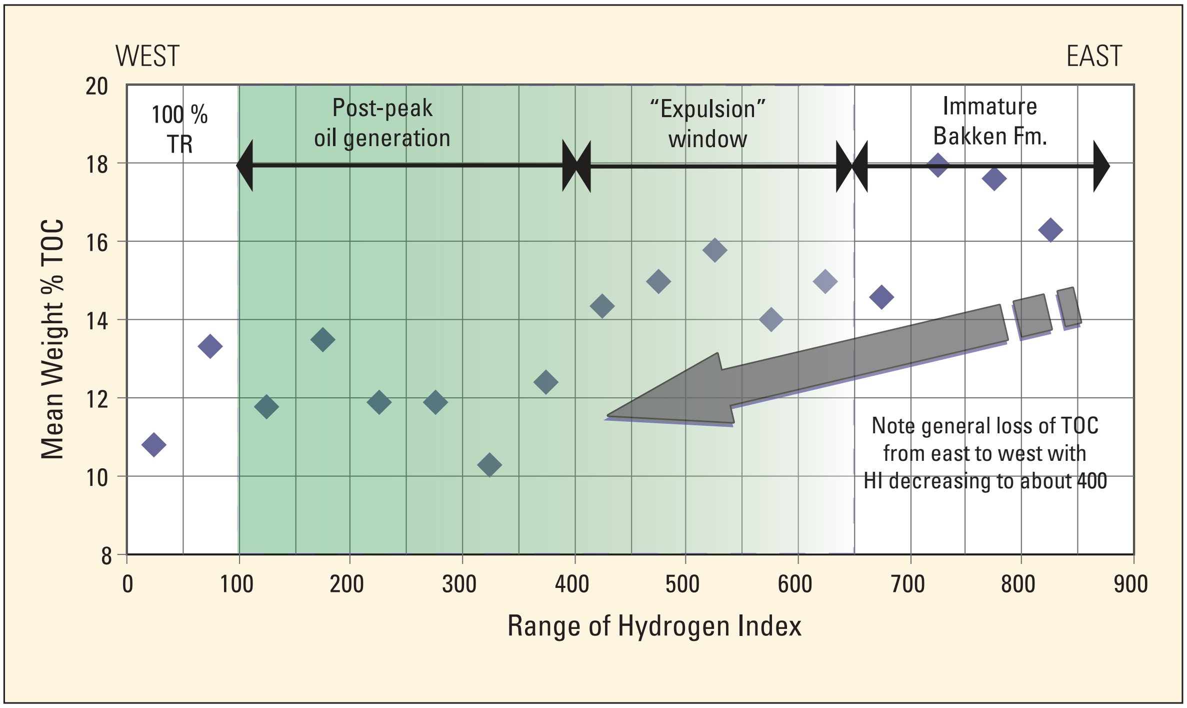


Figure 14. Plot of mean total organic content (TOC) versus range of hydrogen index (HI) in upper shale member of Bakken Formation, showing general decrease in TOC from east to west with decreasing HI and stages of oil generation with respect to HI. TR, transformation ratio (percent of hydrocarbons expelled).

AUs—the Eastern Expulsion Threshold AU and the Northwest Expulsion Threshold AU—were defined within the "expulsion threshold" parameters, where HI contours of the upper shale member are between 400 and 650 (fig. 11*A*). In these AUs, upper and lower shale member source rocks have greatest generation and expulsion capacity, expulsion microfractures may be present, and dolomite and sandstone porosity within the middle sandstone member is well developed. The Eastern Expulsion Threshold AU is best represented by the Parshall field area, where several high-volume oil wells have been drilled. In contrast, the Northwest Expulsion Threshold AU (fig. 16) is mostly a hypothetical area for exploration. Although it is defined as being within the "expulsion threshold window," indicating greatest generation and expulsion capacity, few proven oil wells have produced from the Bakken Formation. In addition, the area of the AU is of high exploration risk compared to its eastern counterpart because of (1) the presence of the Brockton-Froid fault zone (figs. 1 and 2), which is the primary conduit for the migration of Bakken oils generated in this area to Canadian conventional Bakken oil fields to the northeast; (2) the scarcity of geochemical data and poor and variable patterns of HI contouring over much of the AU; and (3) minimal knowledge of the depositional facies and petrophysical properties of the middle sandstone member.

The Nesson-Little Knife Structural AU (fig. 16) defines an area of primary hydrocarbon exploration and production due to major structural enhancement, thick sections of the Bakken Formation (depocenter of the formation), and the presence of the Sanish sand of the Devonian Three Forks Formation—all of which favor economic oil production. The western and northern boundaries of the AU were determined from a structure contour map generated on the top of the Bakken Formation that outlines the Nesson and Little Knife structures (Pollastro and others, 2008a). The eastern boundary was defined by the HI = 400 contour (fig. 11*A*) that also defines the western boundary of the adjacent Eastern Expulsion Threshold AU (fig. 16).

The Elm Coulee-Billings Nose AU (fig. 16) also was defined and incorporates the area of extensive exploration and production from Elm Coulee field, Montana, and the area along the northern part of the Billings anticline commonly referred to as the Billings nose upper shale member play of North Dakota. In this area, thickness and porosity of the middle sandstone member at Elm Coulee is anomalously high (Walker and others, 2006). The northern boundary of the Elm Coulee-Billings Nose AU is marked by the present-day dissolution edge of salt of the Devonian Prairie Evaporite (fig. 5) as outlined by LeFever and LeFever (2005) and Oglesby (1988), and the southern boundary is defined by the 5-ft-isopach contour of the Bakken Formation (fig. 16) (LeFever, 2008). A Central Basin-Poplar Dome AU (fig. 16) also was defined in the central portion of the Bakken continuous accumulation, where 1-D models of this study (fig. 13) indicate that there is little or no remaining oil-generation capacity of Bakken shale

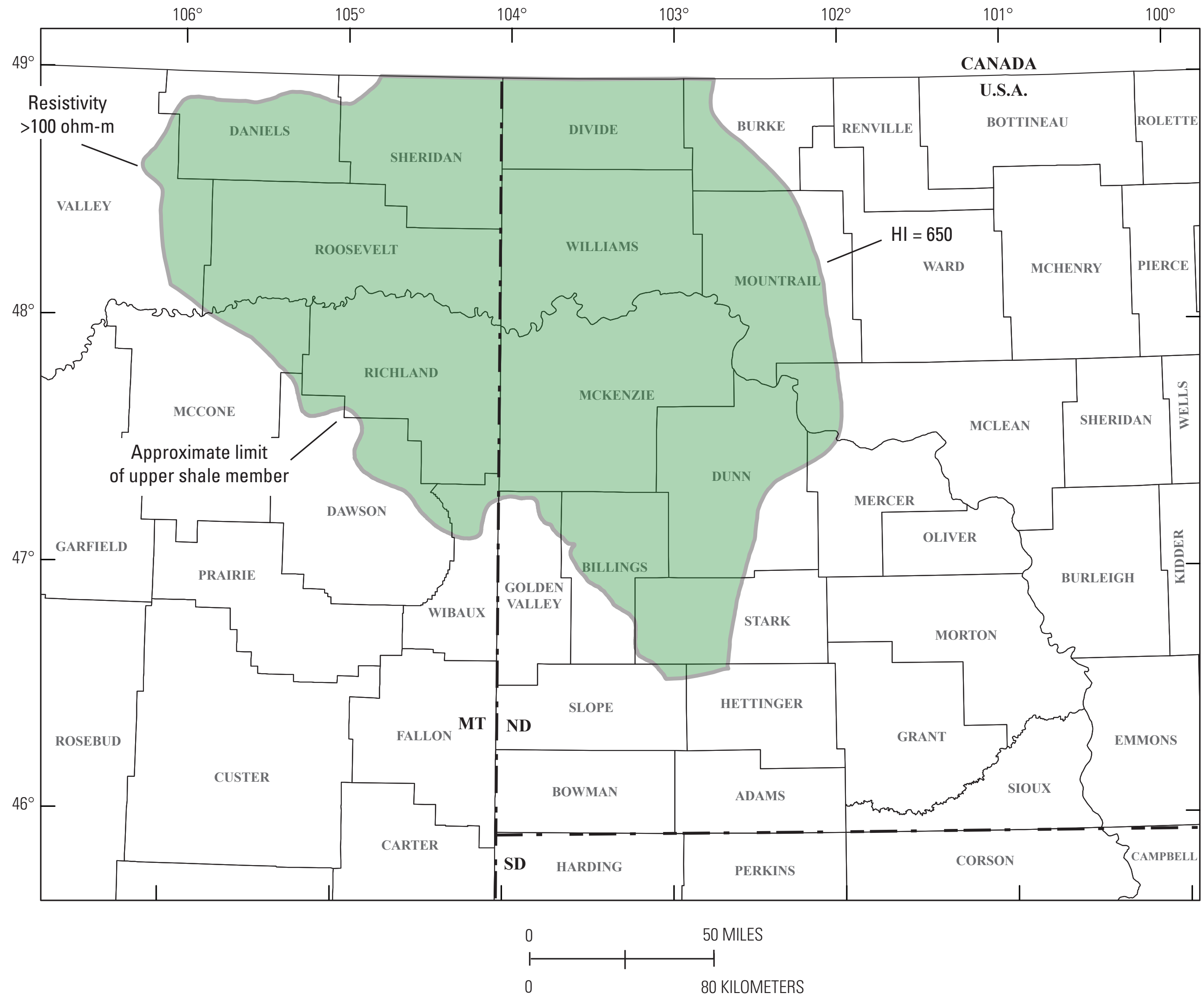


Figure 15. Area (shaded green) of thermally mature shale member source rocks for oil generation (that is, area of the oil-generation window) and continuous oil accumulation for the Bakken Formation in the U.S. portion of the Williston Basin. Area of continuous oil accumulation was determined from the hydrogen index (HI) and from well-log resistivity. Southwest boundary of the Bakken maturity window is represented by depositional limit of upper shale member.

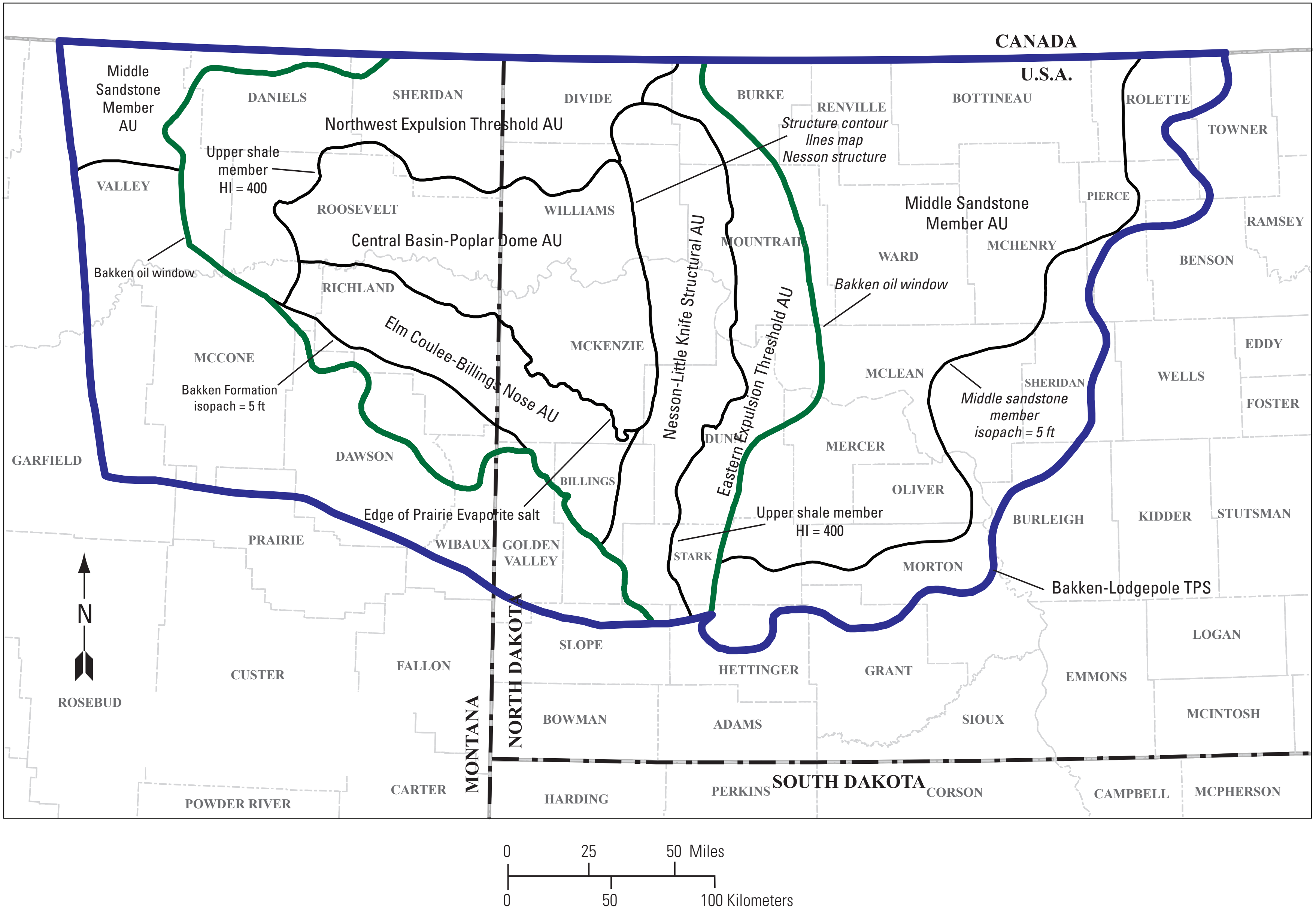


Figure 16. Five continuous assessment units (AU) within Bakken Formation oil window and conventional Middle Sandstone Member AU outside of the oil window and Bakken-Lodgepole Total Petroleum System (TPS), Williston Basin, Montana and North Dakota. Geologic boundary conditions for each assessment unit are noted in italics. HI, hydrogen index.

source rocks. Thus, the conditions within the Central Basin-Poplar Dome AU are where the HI >400 and the TR >0.8. In addition, the Central Basin-Poplar Dome AU describes an area of the basinal facies of the middle sandstone member of the Bakken Formation, which is mostly of poor reservoir quality. At this location, the middle sandstone member is mostly fine siltstone and shale (LeFever, 2007b).

Oil Migration Model

Although all U.S. Bakken oil production is within the Bakken oil window as defined in this study, most historic Canadian Bakken production resulted from the northerly migration of Bakken-generated oils from thermally mature Bakken shale source rock mainly in the U.S. portion of the Williston Basin (LeFever and others, 1991) (fig. 17). Petroleum geochemistry studies by Osadetz and others (1992), Burrus and others (1996), and Kreis and others (2005, 2006) showed that oils generated from mature Bakken source rocks migrated into structurally trapped, porous conventional reservoirs of the middle sandstone member and into carbonate reservoirs of the Mississippian Madison Group in Canada. The migration model for Bakken oils from the pod of mature source rock (fig. 17) is consistent with the migration model of LeFever and others (1991) and the hydrologic flow model of Bachu and Hitchon (1996). A hypothetical conventional assessment unit, the Middle Sandstone Member AU (fig. 16), was defined and assessed outside the area of the oil window and included in the USGS assessment. In the geologic model for this AU, oil generated from mature Bakken shale source rocks is proposed to have migrated into conventional traps of the middle sandstone member of the Bakken Formation.

Assessment of Technically Recoverable Oil in the Bakken Formation

Continuous Assessment Units

USGS assessments of continuous-type accumulations are performed using the FORSPAN methodology (Klett and Charpentier, 2003) and require the following input parameters for each AU:

- Number of cells (interpreted from well history) that have tested the AU
- Number of cells that were "successful" (EUR >2 thousand barrels of oil (MBO)
- Mean acreage of AU based on geologic uncertainty (estimated from GIS analysis with minimum and maximum)
- Estimated cell size (that is, effective drainage area)—A distribution reflecting inherent geologic uncertainty
- Percent of the area that is untested—An uncertainty distribution
- Percent of the area untested that has potential to add reserves—An uncertainty distribution
- Estimated future success ratio—An uncertainty distribution
- EUR for untested area—A distribution reflecting inherent geologic variability

Critical to the USGS continuous assessment methodology is estimating a distribution of the cell size, which corresponds to the effective drainage area for an individual well, for the area of each AU that has potential for undiscovered resources. Both horizontal and vertical well performance is considered here because current initial and infill development of Bakken continuous resource plays incorporates both types of wells. In this study, Elm Coulee field was used as a model (fig. 18), in conjunction with the results of Cox and others (2008), to aid in developing an effective drainage-size-distribution scenario for unexplored areas of the Bakken continuous AUs. The resulting cell-size distribution was used as input data for assessment of the Bakken continuous AUs, except for the Central Basin-Poplar Dome AU: minimum = 80 acres; mode = 320 acres; maximum = 800 acres; and calculated mean = 400 acres. These cell sizes are in close agreement for effective drainage areas with both vertical and horizontal Bakken wells calculated by Cox and others (2008).

Assessment data input for EUR in each continuous AU was determined after constructing and evaluating a series of EUR distribution graphs from historical well production. Wells were grouped in corresponding continuous AUs using GIS; a EUR was generated for each well recorded in the IHS Energy production file (IHS Energy Group, 2007) through April 2007 with a producing formation listed as Bakken or Sanish/Bakken. An initial series of EUR distributions was generated for each of the AUs using the method of Cook (2003) for the following: (1) all wells, (2) verticals wells, (3) horizontals wells, and (4) Sanish/Bakken vertical wells for the Nesson-Little Knife Structural AU. Where sufficient well data were available, a series of EUR distribution graphs was also generated as discovery thirds—that is, graphs of equal thirds relative to sequential date of completion—to aid in evaluating resource development relative to time and the state of technology (Cook, 2003). Such graphs are particularly useful for evaluating continuous-type resource plays with long exploration and production histories and where there have been changes in well performance in response to changes in both conventional drilling and completion methods, increased knowledge of the geology and reservoir characteristics, and major advances in well-site technology.

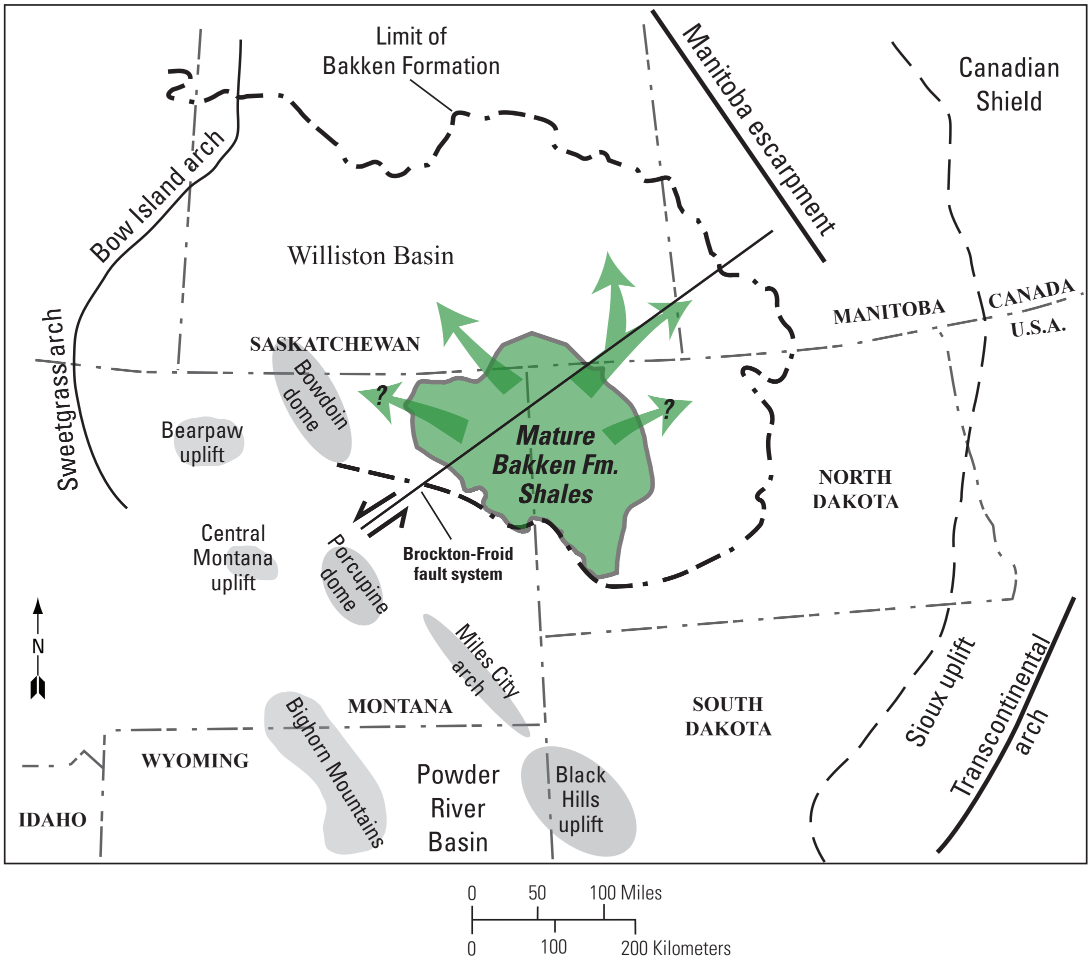


Figure 17. Area of thermally mature, oil-generating source rocks of the Bakken Formation and probable oil migration pathways in the Williston Basin.

For this report, an example from the Elm Coulee-Billings Nose AU, the most explored AU at the time of the USGS assessment, will be used to demonstrate the approach to the assessment of the Bakken Formation. EUR distribution graphs for the Elm Coulee-Billings Nose AU are shown in figures 19 and 20. Wells with EURs <2 MBO (below defined minimum and considered unsuccessful tests) were removed from the distribution, but are counted as tested cells. The total number of tested cells for the Elm Coulee-Billings Nose AU was 894, with 835 cells each having a total recovery of >2 MBO (table 2), thus resulting in a historical success ratio of 0.93. The distribution of all producing wells in the AU having EURs greater than the minimum (>2 MBO) is shown in figure 19*A*; median EUR is about 145 MBO and maximum EUR is about 1,975 MBO. When the data are plotted in exploration-discovery thirds, median EUR increases from about 100 MBO in wells of the early third, to 270 MBO in wells of the middle third, and then decreases to 120 MBO in wells of the late third (fig. 19*B*). This trend of highest median EURs in the middle third wells probably reflects the historical exploration trend within the AU and initial improvement in well performance due to the earliest wells representing vertical wells and early, short-lateral, and nonstimulated horizontal wells of the older upper shale play in the area along the northern part of the Billings anticline referred to as the Billings nose. The middle third wells likely represent those in the higher productive Elm Coulee field “sweet spot,” where the middle sandstone member is thick and porous and where more recent state-of-the-art horizontal wells were completed using longer lateral and multilateral wells that also included multistage-induced fracture methods. Finally, the late third likely represents wells outside the Elm Coulee high-porosity “sweet spot” and along the outer edges of the field, where the middle sandstone is thinner with lower porosity, thus less productive.

The difference in well performance, expressed in terms of EUR, between vertical and horizontal well completions is clearly shown in the EURs distribution graphs of figure 19*C* for the Elm Coulee-Billings Nose AU. Median and maximum EUR for vertical completions are about 91 MBO and 474 MBO, respectively, and for horizontal completions are

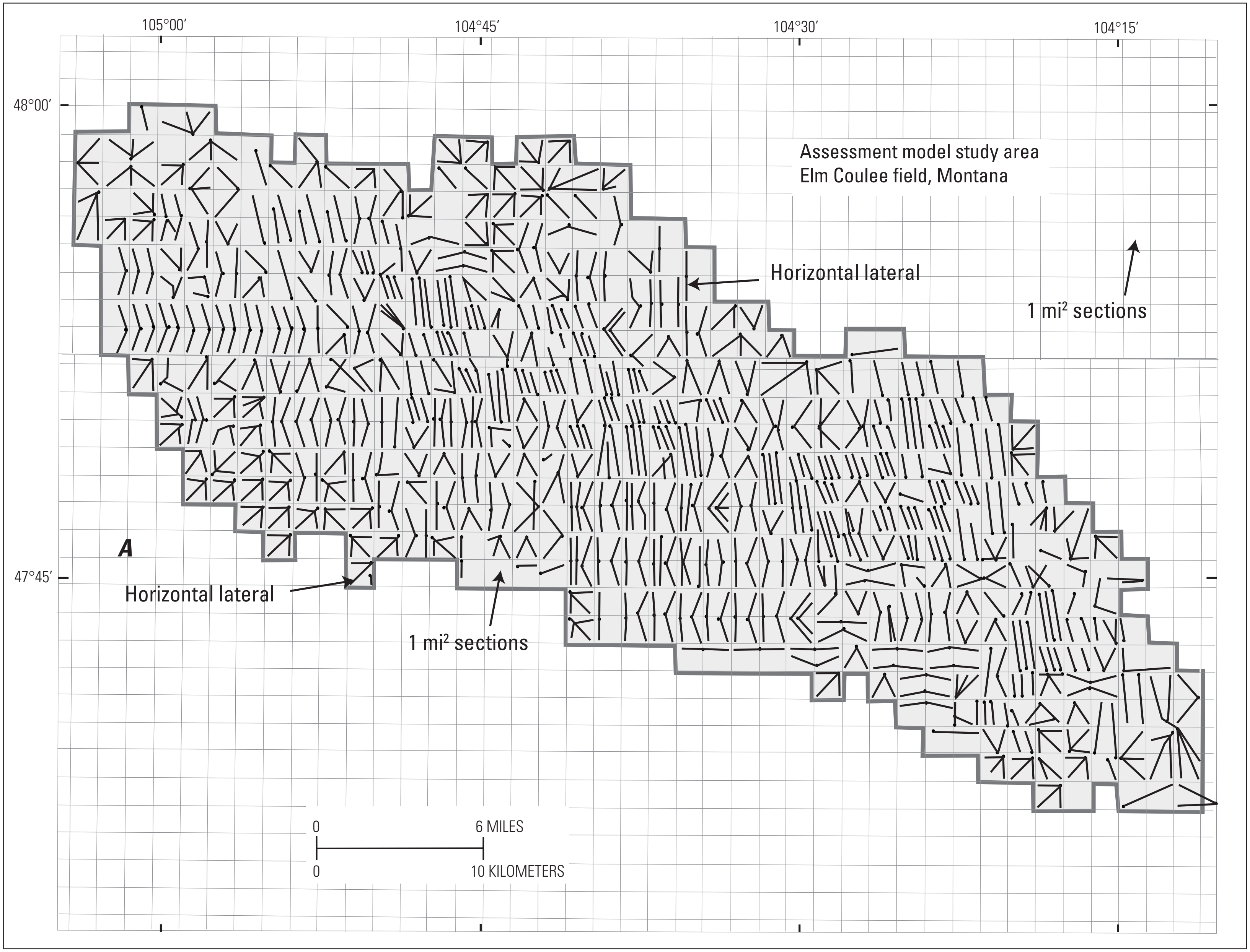


Figure 18. Well-bore configurations of horizontal laterals (bold lines) within 1-mi² (640-acre) sections used in effective drainage study area (shaded) at Elm Coulee field, Montana. Note direction and number of bold lines. Data and well-lateral configuration map from Montana Department of Natural Resources and Conservation (2008).

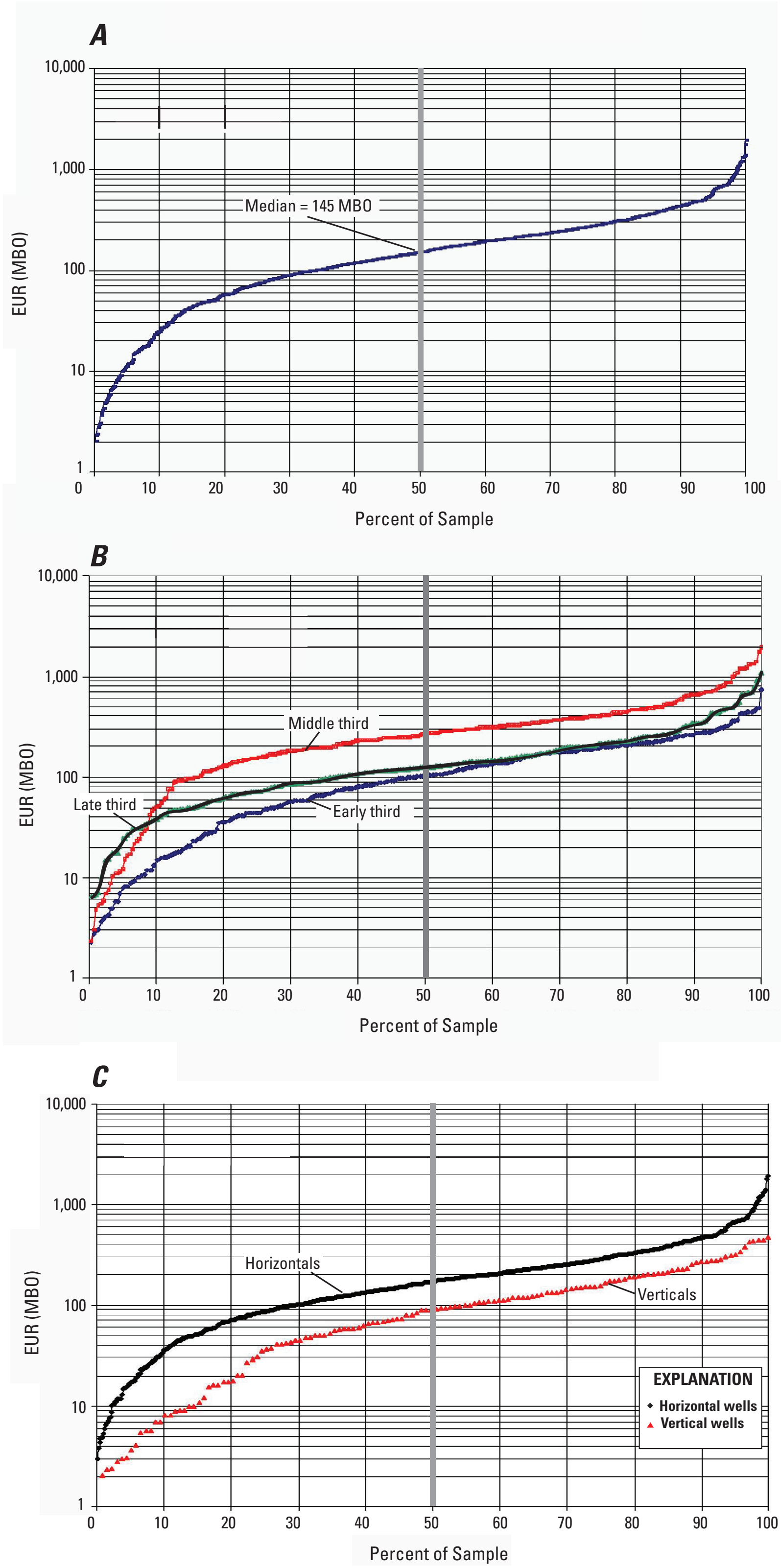


Figure 19. Distribution of estimated ultimate recovery (EUR) greater than minimum recovery of 2,000 barrels of oil as calculated for the Elm Coulee-Billings Nose Assessment Unit. *A*, All wells; *B*, All wells in historical thirds (early, middle, and late); *C*, Comparison of horizontal and vertical wells. MBO, thousand barrels of oil.

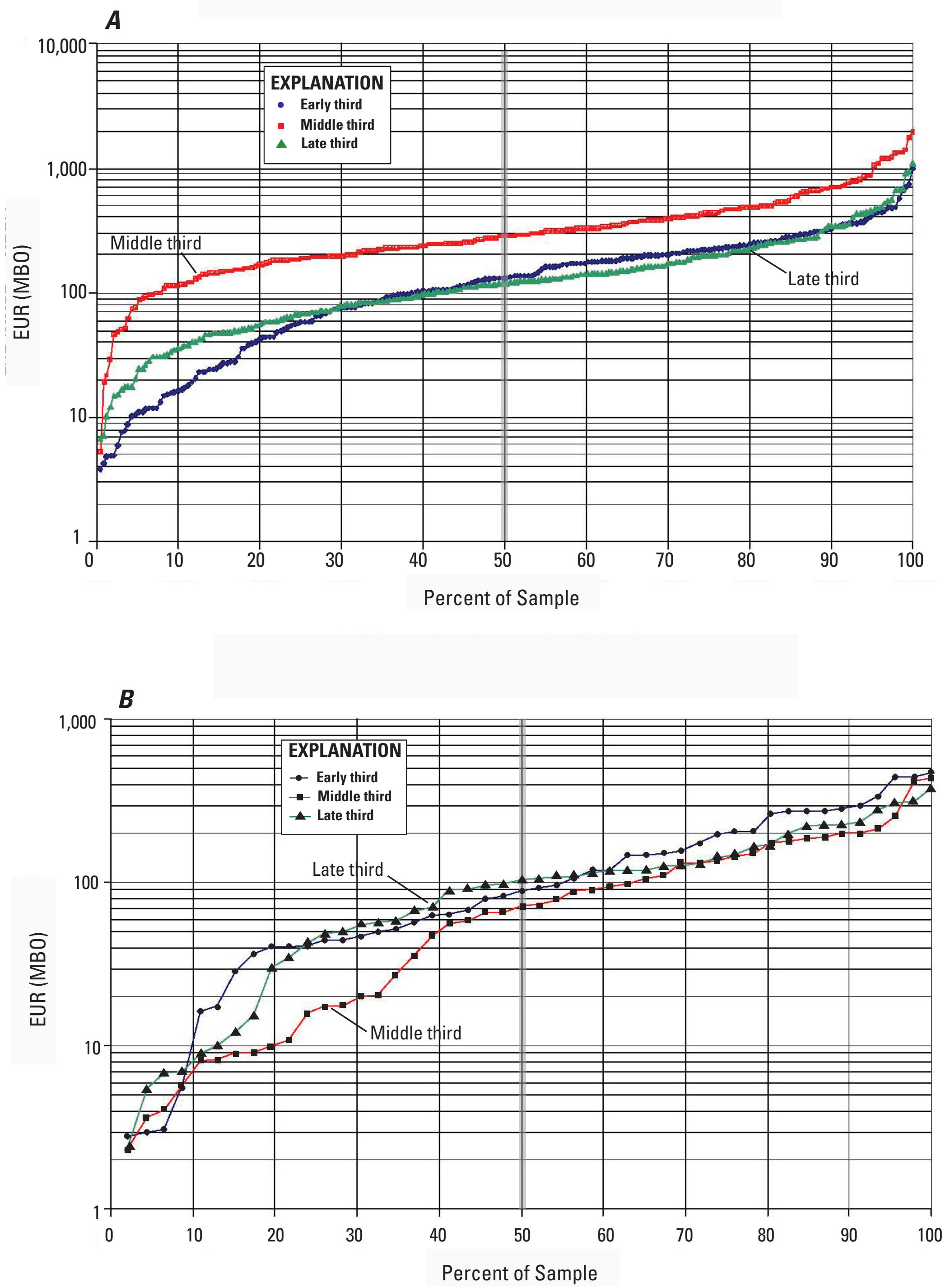


Figure 20. Distribution of estimated ultimate recovery (EUR) greater than minimum recovery of 2,000 barrels of oil as calculated for the Elm Coulee-Billings Nose Assessment Unit: *A*, Horizontal wells in historical thirds (early, middle, and late); *B*, Vertical wells in historical thirds. Note differences in log scale between *A* and *B*. MBO, thousand barrels of oil.

Table 2. Assessment input data and mean recovery per cell for U.S. Geological Survey assessment of continuous assessment units of the Bakken Formation, Williston Basin, Montana and North Dakota.

[MMBO, million barrels of oil]

Assessment unit (AU) name	Assessment unit area (mean acres)	Cell size in acres (minimum; mode; maximum; mean)	Historical success ratio	Future success ratio (minimum; mode; maximum; mean)	Total no. cells tested	Recovery per cell (MMBO) (median; maximum; mean)	Percent of untested area as potential reserves (minimum; mode; maximum; mean)
Elm Coulee-Billings Nose AU	1,735,000	80; 320; 800; 400	0.93	0.80; 0.92; 0.95; 0.89	894	0.08; 2.0; 0.14	80; 92; 95; 89
Central Basin-Poplar Dome AU	3,146,000	80; 200; 640; 307	0.42	0.50; 0.80; 0.92; 0.74	33	0.025; 2.0; 0.07	50; 80; 92; 74
Nesson-Little Knife Structural AU	2,321,000	80; 320; 800; 400	0.85	0.75; 0.92; 0.98; 0.88	237	0.09; 4.0; 0.20	75; 92; 98; 88
Eastern Expulsion Threshold AU	1,940,000	80; 320; 800; 400	0.67	0.70; 0.85; 0.96; 0.84	21	0.12; 5.0; 0.25	70; 85; 96; 83.7
Northwest Expulsion Threshold AU	3,512,000	80; 320; 800; 400	0.28	0.30; 0.75; 0.92; 0.66	32	0.65; 4.0; 0.16	30; 75; 92; 65.7

about 170 MBO and 1,975 MBO, respectively. The EUR distribution graphs for exploration discovery thirds of horizontal and vertical wells in the Elm Coulee-Billings Nose AU are shown in figures 20*A* and *B*, respectively. Median EUR for early, middle and late discovery thirds for horizontal wells is about 130 MBO, 280 MBO, and 120 MBO, respectively (fig. 20*A*). Similar to the explanation for the trend in all wells within the AU (fig. 19), the trend for horizontal wells represents the differences in exploration areas and stages of horizontal drilling practices within the AU. The early third distribution mostly represents the early horizontal wells of the Billings nose upper shale member play initiated in the late 1980s. The middle third includes mostly horizontal wells within the central Elm Coulee field "sweet spot" where the middle sandstone member is thickest and has high (as much as 15 percent) dolomite porosity. The latest third likely represents horizontal wells drilled in the less favorable thinner and lower (<6 percent) porosity rim area of Elm Coulee field and might also represent some infill wells.

The trend established for vertical wells (fig. 20*B*) is much different than that of the horizontal wells (fig. 20*A*) within the Elm Coulee-Billings Nose AU. The median EURs for early, middle, and late discovery thirds are 88 MBO, 72 MBO, and 105 MBO, respectively. For vertical wells, the EUR distribution is lowest for wells of the middle third and highest for the last historical third (fig. 20*B*). This trend is probably indicative of an initial decline in EURs for earlier (first and second third) vertical wells of the Billings nose area, North Dakota; higher EURs for late third vertical wells probably represent more advanced completions and wells drilled at Elm Coulee field, Montana, where production was typically higher.

Conventional Middle Sandstone Member Assessment Unit

A hypothetical conventional AU, the Middle Sandstone Member AU, was defined outside the mapped area of the Bakken oil-generation window and Bakken continuous oil accumulation (fig. 16) and assumes some potential for migration of oil from the Bakken source kitchen along structures into structural traps of the middle sandstone member. Assessment of this AU was performed based on sizes and numbers of grown discovered fields used by Henry (2000) in an assessment of the Bakken Sandstone AU in the Canadian portion of the Williston Basin, which is considered to be the geologic analog. A plot of the pool discovery year versus known oil-pool size through 1996 for this Canadian analog is shown in figure 21. Known pool size of the Canadian middle sandstone member analog ranges from >0.5 to <4 MMBO. A greater geologic risk was assigned to the Middle Sandstone Member AU relative to the Canadian discoveries because of the lack of major structural pathways (that is, fault systems), possible updip seals, and its position relative to hydrologic flow and oil migration models (fig. 17) as compared to those in Canada.

Assessment Results

The USGS assessed undiscovered oil and associated gas resources in the five continuous (unconventional) AUs and one conventional AU for the Bakken Formation. A summary of the assessment input data for each of the five continuous AUs given in table 2. Recovery per cell (median, maximum, and mean), or EUR, for each of the continuous AUs is also listed in table 2. There is no geologic risk assigned to any of the continuous AUs. Results of the 2008 USGS assessment of undiscovered, technically recoverable resources in the U.S. portion of the Bakken Formation (Pollastro and others, 2008b) are shown in table 3.

For continuous oil resources, the USGS estimated a total mean resource at 3.65 billion barrels of oil (BB0), which combines means of 410 MMBO in the Elm Coulee-Billings Nose AU, 485 MMBO in the Central Basin-Poplar Dome AU, 909 MMBO in the Nesson-Little Knife Structural AU, 973 MMBO in the Eastern Expulsion Threshold AU, and 868 MMBO in the Northwest Expulsion Threshold AU. A mean resource of 4 MMBO was estimated for the conventional Middle Sandstone Member AU.

The study predicts that the largest undiscovered oil volume in the Bakken Formation and highest mean EUR per cell for future discoveries are in the Eastern Expulsion Threshold AU and Nesson-Little Knife Structural AU (tables 2 and 3). Subsequent to the 2008 USGS assessment, these AUs have been the most successful areas for exploration and oil production from the Bakken Formation in the U.S. portion of the Williston Basin (Pollastro and others, 2008a; Nordeng, 2010).

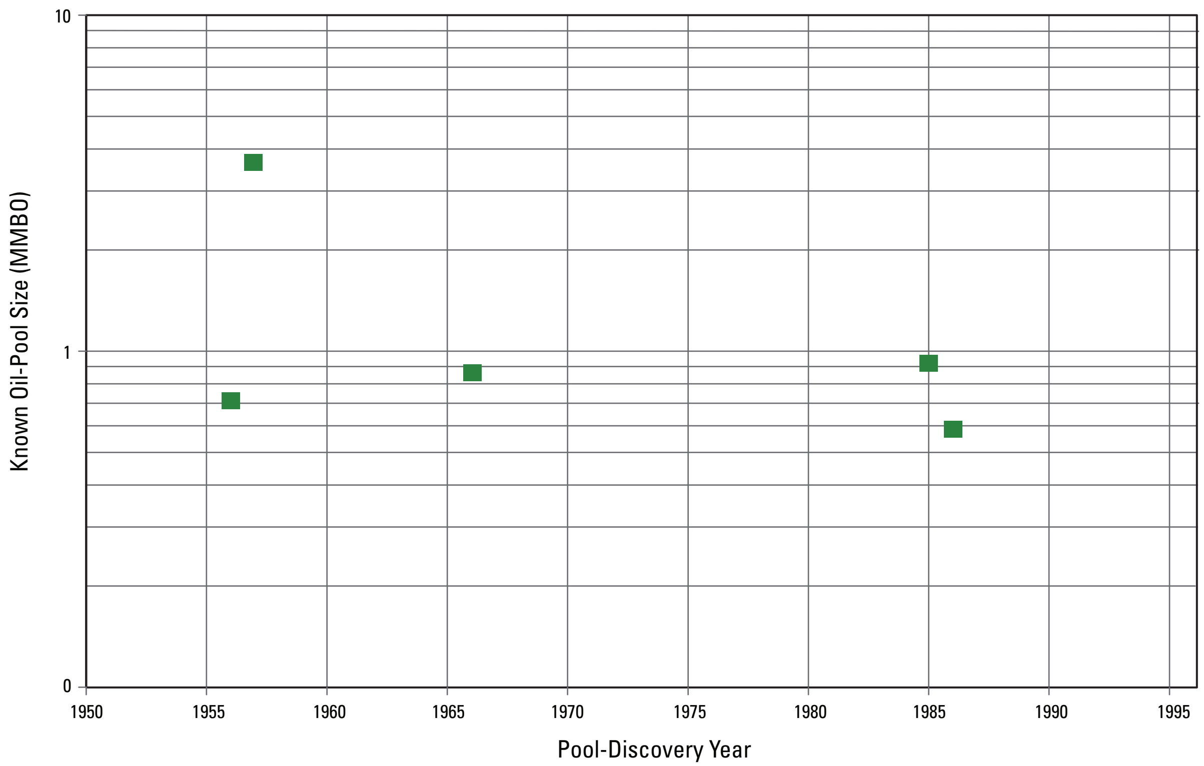


Figure 21. Known pool size in millions of barrels of oil (MMBO) versus pool discovery year for conventional reservoirs in the middle sandstone member of the Bakken Formation, Canada, as of 1996.

Table 3. Summary of mean volumes of oil, gas, and natural gas liquids from the 2008 U.S. Geological Survey assessment of undiscovered, technically recoverable resources in the Bakken Formation, Montana and North Dakota.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates]

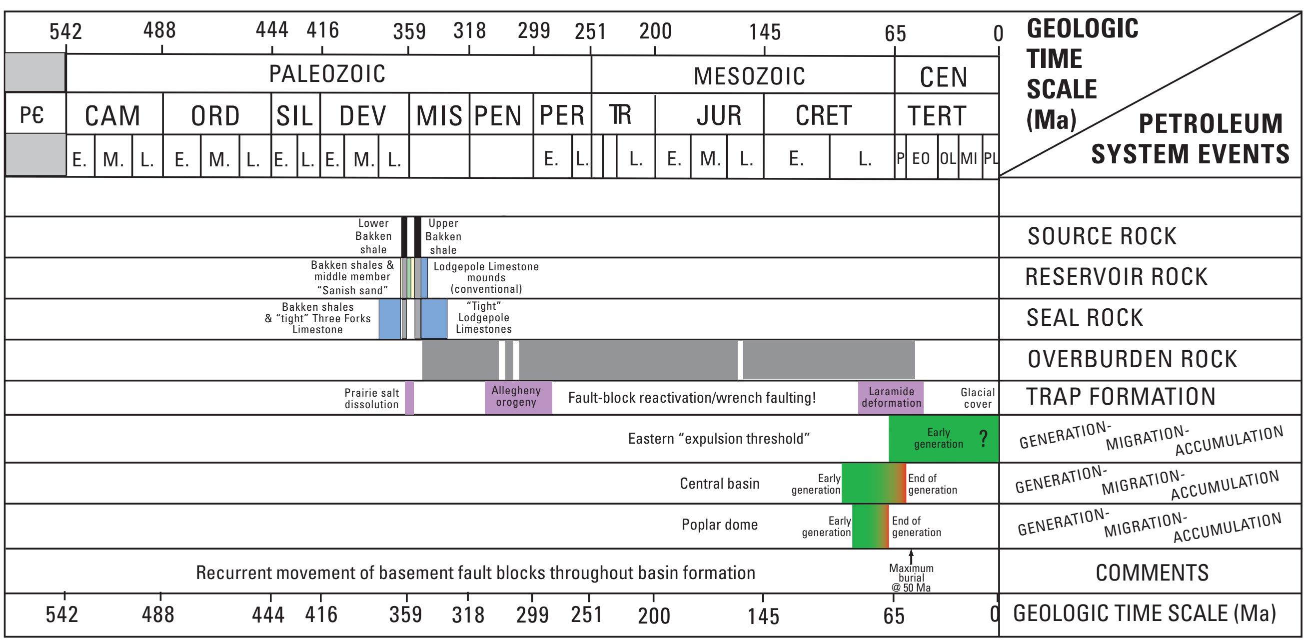
Total petroleum systems (TPS) and assessment units (AU)	Field type	Undiscovered, technically recoverable resource		
		Oil (MMBO)	Gas (BCFG)	NGL (MMBNGL)
		Mean	Mean	Mean
Bakken-Lodgepole TPS				
Continuous oil resources				
Elm Coulee-Billings Nose AU	Oil	410	208	17
Central Basin-Poplar Dome AU	Oil	485	246	20
Nesson-Little Knife Structural AU	Oil	909	461	37
Eastern Expulsion Threshold AU	Oil	973	493	39
Northwest Expulsion Threshold AU	Oil	868	440	35
Total Continuous Bakken Formation resources		**3,645**	**1,848**	**148**
Conventional oil resources				
Middle Sandstone Member AU	Oil	4	2	0
Total Conventional Bakken Formation resources		**4**	**2**	**0**

Summary

The Bakken Formation is mainly a continuous-type oil accumulation of giant proportions in the U.S. portion of the Williston Basin, where thermally mature, organic-rich shale members of the Bakken generate, expel, and produce mostly oil from a fractured and porous composite reservoir consisting of shale, sandstone, siltstone, and dolomite. Production is greatest where (1) major structures and lineaments are abundant; (2) middle sandstone member is thick and matrix porosity is high; (3) additional reservoir storage is available in adjacent, porous Sanish sand of the Devonian Three Forks Formation; and (4) thermally mature shale member source rocks are between early and peak oil generation. This composite, continuous reservoir within the Bakken continuous oil accumulation, combined with conventional reservoirs in the middle sandstone member and Waulsortian mounds in the overlying Mississippian Lodgepole Limestone, define the Bakken-Lodgepole TPS. A summary of the Bakken-Lodgepole TPS is shown in the petroleum system events chart (fig. 22).

The area of the oil generation window for the Bakken Formation, which defines the area of the Bakken continuous oil accumulation and reservoir, was determined using a combination of contour mapping of both the hydrogen index (HI) and log-resistivity well data of the upper shale member, calibration of HI to the transformation ratio (TR) from 1-D burial models, and calibration of HI to total organic content. The Bakken continuous oil accumulation was further subdivided into five continuous assessment units using a geologic model that generally assumed levels of thermal maturity and generation capacity of the Bakken shale members from HI and TR, relation of HI and TR to potential fracturing and structural complexity of the Williston Basin, salt movement and dissolution, and lithofacies distribution and petrophysical character of the middle sandstone member. A sixth hypothetical conventional AU, a Middle Sandstone Member AU, was defined external to the area of oil generation.

For continuous oil resources, the USGS estimated a total mean resource at 3.65 BBO, which combines means of 410 MMBO in the Elm Coulee-Billings Nose AU, 485 MMBO in the Central Basin-Poplar Dome AU, 909 MMBO in the Nesson-Little Knife Structural AU, 973 MMBO in the Eastern Expulsion Threshold AU, and 868 MMBO in the Northwest Expulsion Threshold AU. A mean resource of 4 MMBO was estimated for the conventional Middle Sandstone Member AU.



P€, Precambrian; CAM, Cambrian, ORD, Ordovician; SIL, Silurian; DEV, Devonian; MIS, Mississippian; PEN, Pennsylvanian; PER, Permian; TR, Triassic; JUR, Jurassic; CRET, Cretaceous; TERT, Tertiary; CEN, Cenozoic; E., Early; M., Middle; L., Late; P, Paleocene; EO, Eocene; Ol, Oligocene; MI, Miocene; PL, Paleocene; Ma, million years.

Figure 22. Petroleum system events chart summarizing the geologic elements of the Bakken-Lodgepole Total Petroleum System.

Acknowledgments

The authors are grateful to several individuals and exploration companies and USGS colleagues for valuable discussions of the Bakken Formation and for providing data and information that aided in the assessment of technically recoverable oil in the Bakken. We are particularly thankful to Robert Coskey, Dan Jarvie, Michael Lewan, Julie LeFever, Mark Smith, and Steve Sonnenberg. We would also like to thank Jeff Kraus, Jeff May, Mark Williams, Stephanie Gaswirth, Larry Anna, Michael Johnson, Monte Bessler, Bill Walker, and Al Powell for sharing their knowledge and thoughts on the Williston Basin and Bakken petroleum system.

Special thanks are due to members of the U.S. Geological Survey National Oil and Gas Assessment Review Committee, Chris Schenk, Ron Charpentier, and Tim Klett.

We are grateful for the constructive technical reviews of the manuscript by USGS colleagues Mark Kirschbaum and Russel Dubiel. The manuscript has especially benefited from the editorial review by USGS Central Energy Resources Science Center editor, William Keefer.

References Cited

Anna, L.O., Pollastro, R.M., Gaswirth, S.B., Lewan, M.D., Lillis, P.G., Roberts, L.N.R., Schenk, C.J., Charpentier, R.R., Cook, T.A., and Klett, T.R., 2008, Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2008: U.S. Geological Survey Fact Sheet 2008–3092, 2 p.

Bachu, S., and Hitchon, B., 1996, Regional-scale flow of formation waters in the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 80, p. 248–264.

Brown, D.L., and Brown, D.L., 1987, Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin, *in* Longman, M.W., ed., Williston Basin: Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, p. 57–70.

Burke, R.B., and Diehl, P.E., 1993, Waulsortian mounds and Conoco's new Lodgepole well: North Dakota Geological Survey Newsletter, v. 20, no. 2, p. 6–17.

Burrus, J., Wolf, S., Osadetz J., and Visser, K., 1996, Physical and numerical modeling contraints on oil expulsion and accumulation in the Bakken and Lodgepole petroleum systems of the Williston Basin (Canada-USA): Bulletin of Canadian Petroleum Geology, v. 44, p. 429–445.

Canter, L., Skinner, O., and Sonnenfeld, M.D., 2008, Facies and mechanical stratigraphy of the middle Bakken, Mountrail County, North Dakota [abs.]: Program and Abstracts, Rocky Mountain Energy Epicenter 2008, Annual Meeting, Rocky Mountain Section, American Association of Petroleum Geologists, Denver, Colo., p. 80–81.

Carlisle, W.J., Druyff, L., Fryt, M.S., Artindale, J.S., and Has Von Der, D., 1992, The Bakken Formation—An integrated geologic approach to horizontal drilling, *in* Schmoker, J.W., Coalson, E.B., and Brown, C.A., eds., Geologic studies relevant to horizontal drilling: Examples from Western North America: Rocky Mountain Association of Geologists, p. 215–226.

Carlson, C.G., and Anderson, S.B., 1965, Sedimentary and tectonic history of North Dakota part of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 49, p. 1833–1846.

Cook, T.R., 2003, Calculation of estimated ultimate recovery (EUR) for wells in continuous-type oil and gas accumulations of the Uinta-Piceance Province, chap. 23 *of* USGS Uinta-Piceance Assessment Team, Petroleum systems and geologic assessment of oil and gas in the Uinta-Piceance Province, Utah and Colorado: U.S. Geological Survey Digital Data Series DDS–69-B, 8 p., CD-ROM.

Coskey, R.J., and Leonard, J.L., 2009, Bakken oil accumulations—What's the trap? [abs.]: Abstracts volume, American Association of Petroleum Geologists Annual Convention and Exhibition, Denver, Colo., p. 48.

Cox, S.A., Cook, D.M., Dunek, K., Daniels, R., Jump, C., and Barree, R., 2008, Unconventional resource play evaluation: A look at the Bakken shale play of North Dakota: Society of Petroleum Engineers, Paper No. 114171, 14 p.

Dumonceaux, G.M., 1984, Stratigraphy and depositional environments of the Three Forks Formation (Upper Devonian), Williston Basin, North Dakota: Grand Forks, University of North Dakota, M.S. thesis, 189 p.

Flannery, J., and Kraus, J., 2006, Integrated analysis of the Bakken Formation: U.S. Williston Basin: American Association of Petroleum Geologists Search and Discovery Article No. 10105, 3 panels, accessed at *http://www.searchanddiscovery.net/documents/2006/06035flannery/index.htm?q=%2Btitle%3Abakken+title%3Apetroleum+title%3Asystem*.

Gaswirth, S.B., Pollastro, R.M., Anna, L., Lillis, P., and Roberts, L.N.R., 2009, Geology and assessment of undiscovered oil and gas resources in the Lodgepole Formation, Williston Basin, North Dakota and Montana [abs.]: Program and Abstracts, American Association of Petroleum Geologists 2009 Annual Convention and Exhibition, Denver, Colo., accessed at *http://www.searchanddiscovery.net/abstracts/html/2009/annual/abstracts/gaswirth.htm?q=%2Btext%3Agaswirth.*

Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995, 1995 National assessment of United States oil and gas resources: Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, CD-ROM.

Gerhard, L.C., Anderson, S.B., and LeFever, J.A., 1987, Structural history of the Nesson anticline, *in* Longman, M.W., ed., Williston Basin: Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, p. 337–353.

Gerhard, L.C., and Anderson, S.B., 1988, Geology of the Williston Basin (United States portion), *in* Sloss, L.L., ed., Sedimentary cover—North American craton; U.S.: Boulder, Colo., Geological Society of America, The Geology of North America, v. D-2, p. 221–241.

Gerhard, L.C., Anderson, S.B., and Fischer, D.W., 1991, Petroleum geology of the Williston Basin, chap. 29 *of* Leighton, M., Kolata, D., Oltz, D., and Eidel, J., eds., Petroleum geology of interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 507–559.

Gibson, R.I., 1995, Basement tectonics and hydrocarbon production in the Williston Basin: An interpretive overview, *in* Hunter, L., and Schalla, R., eds., Seventh international Williston Basin symposium guidebook: Montana Geological Society, North Dakota Geological Society, Saskatchewan Geological Society, and Fort Peck Tribes, p. 3–11.

Green, A.G., Weber, W., and Hajnal, Z., 1985, Evolution of Proterozoic terranes beneath the Williston Basin: Geology, v. 13, p. 624–628.

Heck, T.J., 1978, Depositional environments of the Bottineau interval (Lodgepole) in North Dakota, *in* Estelle D., and Miller, R., eds., The economic geology of the Williston Basin, Montana, North Dakota, South Dakota, Saskatchewan, and Manitoba: Billings, Mont., Montana Geological Society, p. 191–199.

Henry, M.E., 2000, Bakken sandstone assessment unit, *in* U.S. Geological Survey World Energy Assessment Team, 2000, U.S. Geological Survey world petroleum assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS–60, four CD-ROM set, also available at *http://energy.cr.usgs.gov/WEcont/regions/reg5/P5/tps/AU/au524431.pdf.*

Hester, T.C., and Schmoker, J.W., 1985, Selected physical properties of the Bakken Formation, North Dakota and Montana part of the Williston Basin: U.S. Geological Survey Oil and Gas Investigations Chart 126, 1 sheet.

IHS Energy Group, 2007, Petroleum Information/Dwights PetroROM, U.S. well production file on CD-ROM: Houston, Tex., IHS Energy Group.

IHS Energy Group, 2009, Petroleum Information/Dwights PetroROM, U.S. well production file on CD-ROM: Houston, Tex., IHS Energy Group.

Integrated Exploration Systems, 2005, PetroMod® basin and petroleum systems modeling software: IES GmbH, Ritterstrabe 23, D-52072 Aachen, Germany.

Jones, A.G., and Craven, J.A., 1990, The North American central plains conductivity anomaly and its correlation with gravity, magnetic, seismic, and heat flow data in Saskatchewan, Canada: Physics of the Earth and Planetary Interiors, v. 60, p. 163–194.

Kent, D.M., and Christopher, J.E., 2007, Geologic history of the Williston Basin and Sweetgrass arch, chap. 27 *of* Mossop, G., and Shetsen, I., comps., Geologic atlas of the Western Canada sedimentary basin: accessed at *http://www.ags.gov.ab.ca/publications/ATLAS_WWW/A_CH27/CH_27_F.shtml*

Klett, T.R., Schmoker, J.W., and Ahlbrandt, T.S., 2000, Assessment hierarchy and initial province ranking, chap. AR *of* U.S. Geological Survey World Energy Assessment Team, eds., U.S. Geological Survey world petroleum assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS–60, ver. 1.0, CD-ROM, disk 1, 31 p.

Klett, T.R., and Charpentier, R.R., 2003, FORSPAN model user's guide: U.S. Geological Survey Open-File Report 2003–354, 37 p., accessed February 2008 at *http://pubs.usgs.gov/of/2003/ofr-03-354/ofr-03-354.html*.

Kreis, L.K., Costa, A., and Osadetz, K.G., 2005, New perspectives on the hydrocarbon potential of the Bakken and Torquay Formations, southeastern Saskatchewan: Canadian Society of Petroleum Geologist 2005 Core Conference, Exploring Energy Systems, p. 134–177, accessed at *http://www.cspg.org/conventions/abstracts/2005Core/kreis_l_hydrocarbon_potential_bakken_torquay.pdf*.

Kreis, L.K., Costa, A., and Osadetz, K.G., 2006, Hydrocarbon potential of Bakken and Torquay Formations, southeastern Saskatchewan, *in* Gilboy, C.F., and Whitaker, S.G., eds., Saskatchewan and Northern Plains oil and gas symposium 2006: Saskatchewan Geological Survey Special Publication 19, p. 118–137.

Lash, G.G., and Engelder, T., 2005, An analysis of horizontal microcracking during catagenesis: Example from the Catskill delta complex: American Association of Petroleum Geologists Bulletin, v. 89, p. 1433–1449.

LeFever, J.A., 1991, History of oil production from the Bakken Formation, North Dakota, *in* Hanson, W.B., ed., 1991 guidebook to geology and horizontal drilling of the Bakken Formation: Billings, Montana Geological Society, p. 3–17.

LeFever, J.A., 1992, Horizontal drilling in the Williston Basin, United States and Canada, *in* Schmoker, J.W., Coalson, E.B., and Brown, C.A., eds., Geological studies relevant to horizontal drilling: Rocky Mountain Association of Geologists, p. 177–197.

LeFever, J.A., 2005a, Oil production from the Bakken Formation: A short story: DMR Newsletter, Industrial Commission of North Dakota, Department of Mineral Resources, v. 32, no. 1, p. 1–6, accessed at *https://www.dmr.nd.gov/ndgs/newsletter/newsletternew.asp*.

LeFever, J.A., 2005b, Williston Basin correlation cross-section—Bakken Formation: North Dakota Geological Survey Geologic Investigations 14, accessed at *https://www.dmr.nd.gov/ndgs/bakken/Papers/Willistonbasinpostersession.pdf*.

LeFever, J.A., 2007a, Hydrocarbon potential of the Bakken Formation: North Dakota Geological Survey Geologic Investigations 15, PowerPoint slide presentation, 26 p., accessed at *https://www.dmr.nd.gov/ndgs/bakken/bakkenthree.asp*.

LeFever, J.A., 2007b, Lithofacies of the middle Bakken member, North Dakota: North Dakota Geological Survey Geologic Investigations No. 45, CD-ROM.

LeFever, J.A., 2008, Structural contour and isopach maps of the Bakken Formation in North Dakota: North Dakota Geological Survey Geologic Investigations No. 59, CD-ROM.

LeFever, J.A., Martinuik, C.D., Dancsook, D.F.R., and Mahnic, P.A., 1991, Petroleum potential of the middle member, Bakken Formation, Williston Basin, *in* Christopher, J.E. and Haidl, F.M., eds., Sixth international Williston Basin symposium: Regina, Saskatchewan Geological Society Special Publication No. 11, p. 74–94.

LeFever, J.A., and LeFever, R.D., 2005, Salts of the Williston Basin, North Dakota: North Dakota Geological Survey Report of Investigations No. 103, 46 p.

LeFever, J.A., and Nordeng, S.H., 2008, Three Forks Formation: North Dakota Geological Survey Newsletter, v. 35, no. 2, p. 4–5, accessed at h*ttps://www.dmr.nd.gov/ndgs/newsletter/newsletternew.asp.*

Leonard, J.E., Coskey, R.J., and Matt, V.J., 2008, Shale oil in the eastern Williston Basin: "It's a Mystery Wrapped in a Riddle Inside an Enigma!" [abs.]: Program and Abstracts, American Association of Petroleum Geologists Annual Convention, San Antonio, Tex., accessed at *http://www.searchanddiscovery.net/abstracts/html/2008/annual/abstracts/409935.htm.*

Lewan, M.D., and Ruble, T.E., 2002, Comparison of petroleum generation kinetics by isothermal and nonisothermal open-system pyrolysis: Organic Geochemistry, v. 33, p. 303–327.

Magoon, L.B., and Schmoker, J.W., 2000, The total petroleum system—The natural fluid network that constrains the assessment unit, chap. PS *of* U.S. Geological Survey World Energy Assessment Team, eds., U.S. Geological Survey world petroleum assessment 2000—Description and results: U.S. Geological Survey Digital Data Series DDS–60, ver. 1.0, CD-ROM, disk 1, 31 p.

Meissner, F.F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana, *in* Rehrig, D., ed., The economic geology of the Williston Basin, Montana, North Dakota, South Dakota, Saskatchewan, Manitoba: Billings, Montana Geological Society, p. 207–227.

Meissner, F.F., 1982, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana: Corpus Christi Geological Society Bulletin, p. 14–34.

Meissner, F.F., 1984, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana, *in* Demaison, G., and Murris, R.J., eds., Petroleum geochemistry and basin evaluation: American Association of Petroleum Geologists Memoir 35, p. 159–179.

Meissner, F.F., 1991a, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana, *in* Hanson, W.B., ed., 1991 Guidebook to geology and horizontal drilling of the Bakken Formation: Billings, Montana Geological Society, p. 19–42.

Meissner, F.F., 1991b, A geological/mechanical basis for creating fracture reservoirs in the Bakken [abs.], *in* Hanson, W.B., ed., 1991 Guidebook to geology and horizontal drilling of the Bakken Formation: Billings, Montana Geological Society, p. 165.

Montana Department of Natural Resources and Conservation, 2008, Online oil and gas information system: Board of Oil and Gas, accessed at *http://bogc.dnrc.mt.gov/onlinedata.asp*.

Montgomery, S.L., 1996, Mississippian Lodgepole play, Williston Basin: A review: American Association of Petroleum Geologists Bulletin, v. 80, p. 795–810.

Murray, G.H., 1968, Quantitative fracture study—Sanish pool, McKenzie County, North Dakota: American Association of Petroleum Geologists Bulletin, v. 52, p. 57–65.

Nelson, K.D., Baird, D.J., Walters, J.J., Hauck, M., Brown, L.D., Oliver, J.E., Ahern, J.L., Hajinal, Z., Jones, A.G., and Sloss, L.L., 1993, Trans-Hudson orogen and Williston Basin in Montana and North Dakota: New COCORP deep profiling results: Geology, v. 21, p. 447–450.

Nordeng, S.H., 2009, The Bakken petroleum system: An example of a continuous petroleum accumulation: DMR Newsletter, Industrial Commission of North Dakota, Department of Mineral Resources, v. 36, p. 21–24, accessed at *https://www.dmr.nd.gov/ndgs/newsletter/winter09/PDF/Bakken%20Petroleum.pdf*.

Nordeng, S.H., 2010, A brief history of oil production from the Bakken Formation in the Williston Basin: DMR Newsletter, Industrial Commission of North Dakota, Department of Mineral Resources, v. 37, p. 5–9, accessed at *https://www.dmr.nd.gov/ndgs/newsletter/nl2010/A%20Brief%20History%20of%20Oil%20Production.pdf*.

North Dakota Geological Survey, 1995, Correlation chart of Williston Basin, *in* Vern Hunter, L.D., and Schalla, R.A., eds., Seventh International Williston Basin Symposium guidebook: North Dakota Geological Survey, p. ii.

North Dakota Industrial Commission, 2009, Web site: Department of Mineral Resources, Oil and Gas Division, accessed at *https://www.dmr.nd.gov/oilgas/*.

Oglesby, C.A., 1988, Depositional and dissolution of the Middle Devonian Prairie Formation, Williston Basin, North Dakota and Montana: Golden, Colorado School of Mines, M.S. thesis, 79 p.

Osadetz, K.G., Brooks, P.W., and Snowdon, L.R., 1992, Oil families and their sources in Canadian Williston Basin (southeastern Saskatchewan and southwestern Manitoba): Bulletin of Canadian Petroleum Geology, v. 40, p. 254–273.

Osadetz, K.G., Kohn, B.P., Feinstein, S., and O'Sullivan, P.B., 2002, Thermal history of Canadian Williston Basin from apatite fission-track thermochronology—Implications for petroleum systems and geodynamic history: Tectonophysics, v. 349, p. 221–249.

Pitman, J.K., Price, L.C., and LeFever, J.A., 2001, Diagenesis and fracture development in the Bakken Formation, Williston Basin: Implications for reservoir quality in the middle member: U.S. Geological Survey Professional Paper 1653, 19 p.

Pollastro, R.M., 2007, Total petroleum system assessment of undiscovered resources in the giant Barnett Shale continuous (unconventional) gas accumulation, Fort Worth Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 91, p. 551–578.

Pollastro, R.M., Hill, R.J., Jarvie, D.M., and Henry, M.E., 2003, Assessing undiscovered resources of the Barnett-Paleozoic Total Petroleum System, Bend Arch-Fort Worth Basin Province, Texas: Transactions of the American Association of Petroleum Geologists Southwest Section Convention, Fort Worth, Tex., March 2003, American Association of Petroleum Geologists/Datapages, 18 p., CD-ROM, also available at *http://search.datapages.com/data/ftworth/09/09031/09031.htm?q=%2Bauthor%3Apollastro*.

Pollastro, R.M., Roberts, L.N.R., Cook, T.M., and Lewan, M.J., 2008a, Assessment of undiscovered technically recoverable oil resources of the Bakken Formation, Williston Basin, Montana and North Dakota, 2008: U.S. Geological Survey Open-File Report 2008–1353, 3 sheets, accessed at *http://pubs.usgs.gov/of/2008/1353/*.

Pollastro, R.M., Cook, T.M., Roberts, L.N.R., Schenk, C.J., Lewan, M.J., Anna, L.O., Gaswirth, S.B., Lillis, P.G., Klett, T.R., and Charpentier, R.R., 2008b, Assessment of undiscovered oil resources in the Devonian–Mississippian Bakken Formation, Williston Basin Province, Montana and North Dakota, 2008: U.S. Geological Survey Fact Sheet 2008–3021, 2 p., accessed at *http://pubs.usgs.gov/fs/2008/3021/*.

Pollastro, R.M., Roberts, L.N.R., Cook, T.M., and Lewan, M.J., 2008c, Assessment of undiscovered, technically recoverable oil and gas resources of the Bakken Formation, Williston Basin, Montana and North Dakota, 2008 [abs.]: Program and Abstracts, Rocky Mountain Energy Epicenter 2008, Annual Meeting, Rocky Mountain Section, American Association of Petroleum Geologists, Denver, Colo., p. 111.

Price, L.C., Ging, T., Daws, T., Love, A., Pawlewicz, M., and Anders, D., 1984, Organic metamorphism in the Mississippian–Devonian Bakken Shale North Dakota portion of the Williston Basin, *in* Woodward, J., Meissner, F.S., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 83–133.

Price, L.C., Daws, T., and Pawlewicz, M., 1986, Organic metamorphism in the Lower Mississippian–Upper Devonian Bakken shales—Part 1: Rock-Eval pyrolysis and vitrinite reflectance: Journal of Petroleum Geology, v. 9, p. 125–162.

Roberts, L.N.R., Finn, T.M., Lewan, M.D., and Kirschbaum, M.A., 2008, Burial history, thermal maturity, and oil and gas generation of source rocks of the Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Scientific Investigations Report 2008–5037, 27 p.

Schmoker, J.W., and Hester, T.R., 1983, Organic carbon in Bakken Formation, United States portion of the Williston Basin: American Association of Petroleum Geologists Bulletin, v. 67, p. 2165–2174.

Smith, M.G., and Bustin, R.M., 1995, Sedimentology of the Late Devonian and Early Mississippian Bakken Formation, Williston Basin, *in* Seventh International Williston Basin symposium guidebook: Billings, Montana Geological Society, p. 103–114.

Smith, M.G., and Bustin, R.M., 1996, Lithofacies and paleoenvironments of the Upper Devonian and Lower Mississippian Bakken Formation, Williston Basin: Bulletin of Canadian Petroleum Geology, v. 44, p. 495–507.

Smith, M.G., and Bustin, R.M., 1998, Production and preservation of organic matter during deposition of the Bakken Formation (Late Devonian and Early Mississippian), Williston Basin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 142, no. 3-4, p. 185–200.

Smith, M.G., and Bustin, R.M., 2000, Late Devonian and Early Mississippian Bakken and Exshaw black shale source rocks, Western Canada sedimentary basin: A sequence stratigraphy interpretation: American Association of Petroleum Geologists Bulletin, v. 84, p. 940–960.

Sonnenberg, S.A., and Pramudito, A., 2009, Petroleum geology of the giant Elm Coulee field, Williston Basin: American Association of Petroleum Geologists Bulletin, v. 93, p. 1127–1153.

Sperr, J.T., 1991, Exploration models for Bakken reservoirs: Williston Basin, North Dakota and Montana, *in* Hanson, W.B., ed., 1991 Guidebook to geology and horizontal drilling of the Bakken Formation: Billings, Montana Geological Society, p. 143–149.

Sprain, J.C., 1997, Seismic expression of the Versippi Lodgepole field, Stark County, North Dakota, *in* Coulson, E., Osmond, J.C., and Williams, E.T., eds.: Innovative applications of petroleum technology in the Rocky Mountain area: Denver, Colo., Rocky Mountain Association of Geologists, p. 87–92.

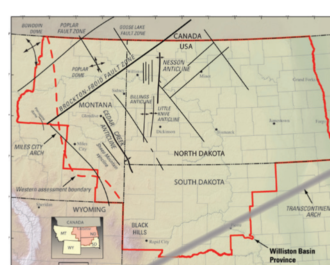
Thomas, G.E., 1974, Lineament-block tectonics; Williston-Blood Creek Basin: American Association of Petroleum Geologists Bulletin, v. 58, p. 1305–1322.

U.S. Geological Survey, 2007, Organic geochemical database: U.S. Geological Survey, accessed at *http://energy.cr.usgs.gov/prov/og/data2.htm*.

Walker, W.B, Powell, A.R., Rollings, R.A., and Shaffer, R.V., 2006, Elm Coulee oil field, middle Bakken member (Lower Mississippian/Upper Devonian), Richland County, Montana: American Association of Petroleum Geologists Search and Discovery Article No. 20041, accessed at *http://www.searchanddiscovery.net/documents/2006/06131walker/index.htm?q=%2Btitle%3Aelm+title%3Acoulee*.

Webster, R.L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, Colo., Rocky Mountain Association of Geologists, p. 57–81.

Webster, R.L., 1987, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota, *in* Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin; anatomy of a cratonic oil province: Denver, Colo., Rocky Mountain Association of Geologists, p. 269–286.



***Click here to return to* Volume Title Page**