THREE-DIMENSIONAL RESERVOIR CHARACTERIZATION OF THE BAKKEN GEOLOGIC SYSTEM

Project DE-NT0005672

TECHNOLOGY STATUS ASSESSMENT

1) CURRENT STATE OF TECHNOLOGY

A) Initial Assessment of Bakken Petroleum System

The Mississippian-Devonian Bakken Petroleum System of the Williston Basin is characterized by low porosity and permeability reservoirs, organic rich source rocks, and regional hydrocarbon charge. This unconventional play is the current focus of exploration and development activity by many operators. Estimates of oil generated from the petroleum system range from 10 to 400 billion barrels (1.6 to 63.9 billion m^3) (Dow, 1974; Meissner and Banks, 2000; Flannery and Kraus, 2006; LeFever and Helms, 2006; Webster, 1984; Schmoker and Hester, 1983). The USGS mean technologically recoverable resource estimates for the Bakken are 3.65 billion barrels (0.58 billion m^3) of oil and 1.85 trillion cubic ft (52.3 billion m^3) of associated/dissolved natural gas, and 148 million barrels (23.5 million m^3) of natural gas liquids (USGS, 2008). Previous workers in the Bakken have suggested the significant source rock potential of the Bakken (Meissner, 1978; Dow, 1974; Williams, 1974; Pitman et al., 2001; Price et al., 1984).

The Williston Basin is a large, intracratonic sedimentary basin that occupies parts of North Dakota, South Dakota, Saskatchewan, and Manitoba (Fig. 1). The basin is semi-circular in shape and prominent structural features are the Nesson, Billings and Cedar Creek anticlines (Fig 1). The Nesson Anticline is the location of the first oil discoveries in the 1950s. Many of the structural features have a documented ancestral origin and influenced Paleozoic sedimentary patterns (Gerhard et al., 1990). The Elm Coulee Field is located in the western part of the Williston Basin in Montana (Fig. 1). The field is a recent giant discovery in the middle Bakken. Horizontal drilling began in the field in 2000, and to date over 500 wells have been drilled. The estimated ultimate recovery for the field is over 200 million barrels (31.8 million m^3) of oil. Horizontal drilling and fracture stimulation of the horizontal leg are key technologies that enable a low permeability reservoir to produce. A detailed understanding of trapping mechanisms and reservoir properties will aid in the exploration and discovery of other areas in the Bakken petroleum system.

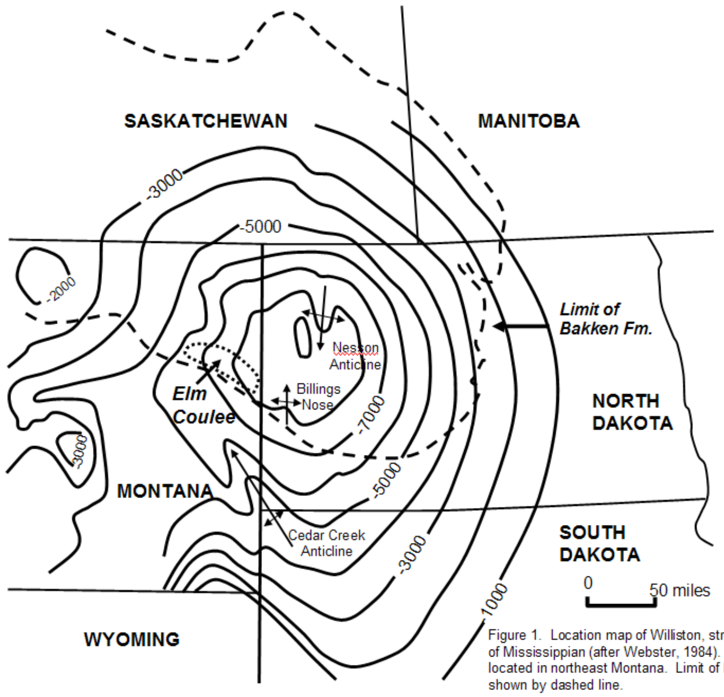

Figure 1. Location map of Williston, structure contours base of Mississippian (after Webster, 1984). Elm Coulee Field is located in northeast Montana. Limit of Bakken Formation shown by dashed line.

The Bakken petroleum system consists of the Bakken, lower Lodgepole and upper Three Forks (Fig. 2). The Bakken regionally in the Williston Basin consists of three members: upper and lower organic-rich black shale (TOC's average 11%); a middle member (silty dolostone or limestone to sandstone lithology) (LeFever et al., 1991; LeFever, 2006) (Fig. 2). The source beds for the petroleum system are the upper and lower organic-rich Bakken shales. The reservoir rocks for the petroleum system are all the members of the Bakken, lower Lodgepole, and upper Three Forks. The Bakken ranges in thickness from a wedge edge to over 140 ft (42.7 m, Fig. 3). The thickest area in the Bakken is located in northwest North Dakota. The three members of the Bakken thin and converge towards the margins of the Williston Basin and have an onlapping relationship with the underlying Three Forks (Fig. 4). The deposition limits of the members of the Bakken are shown in Figure 3. The contact between the Bakken and Three Forks is probably conformable in the deep parts of the basin and unconformable along the basin flanks. The Bakken is conformably overlain by the Lodgepole.

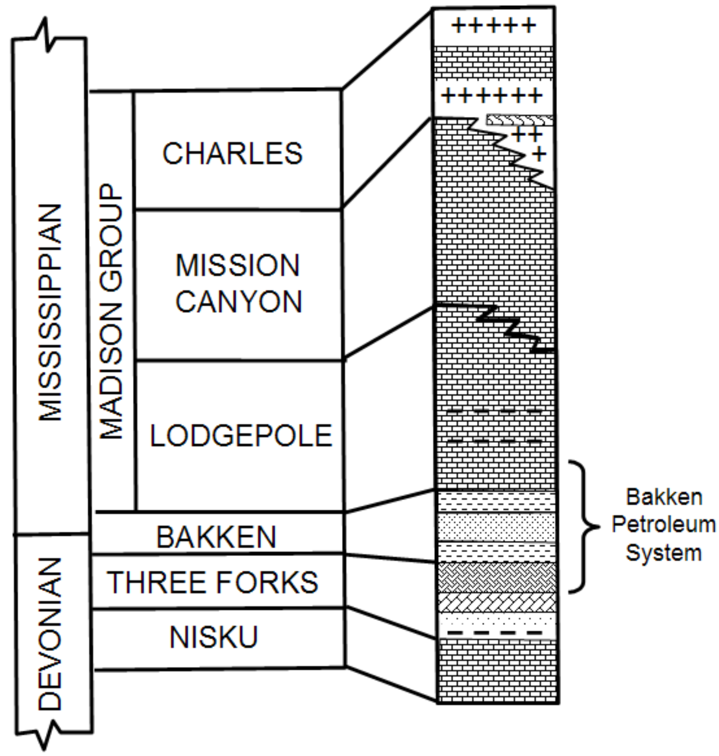

Figure 2. Stratigraphic column for the Bakken Formation and adjacent intervals. Bakken petroleum system consists of source rocks in the Bakken Formation and reservoir units in the Bakken, lower Lodgepole, and upper Three Forks (modified from Webster, 1984)

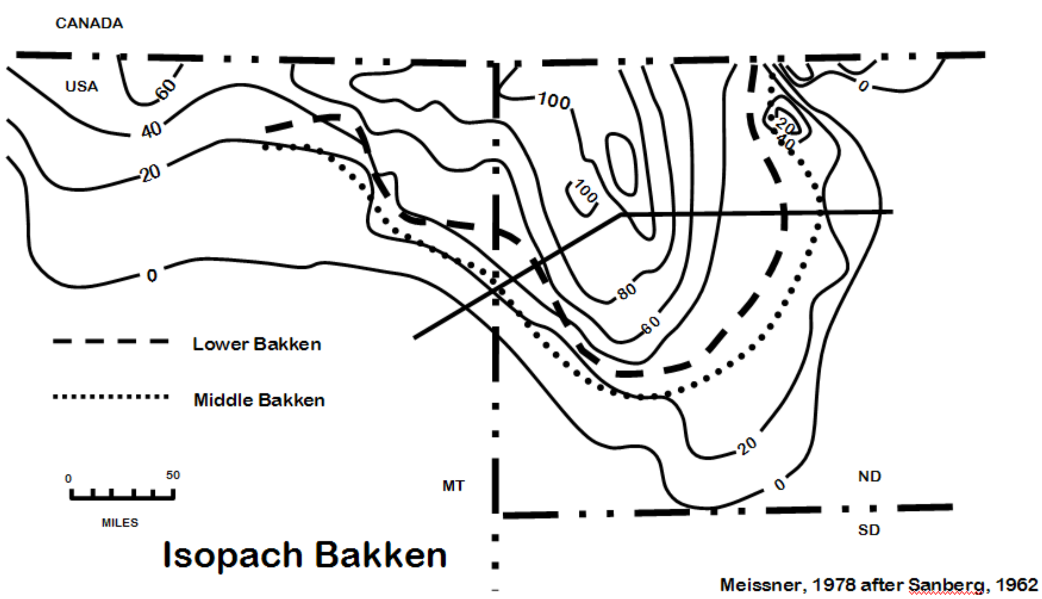

Figure 3. Isopach map of Bakken Formation for the U.S. part of Williston Basin. Limits of the lower Bakken and middle Bakken shown on map. Cross section shown in Figure 4. Modified from Meissner, 1978.

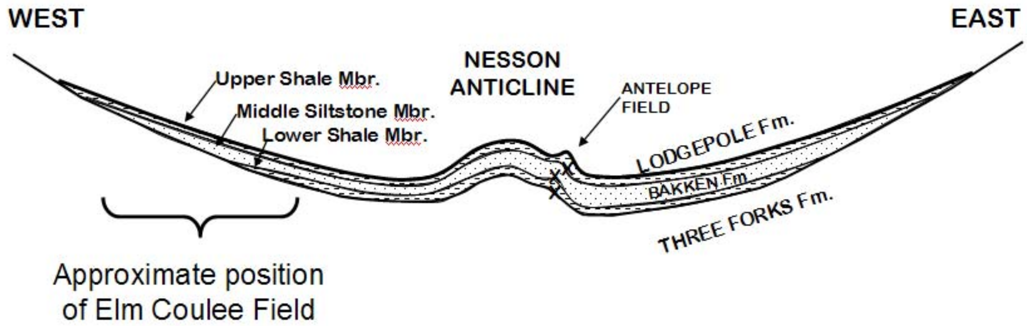

Figure 4. Diagrammatic structural cross section across Williston Basin showing three members of the Bakken and the onlapping relationship with the Three Forks. Antelope Field was the first Bakken production associated with a sharp anticlinal fold (modified from Meissner, 1978).

The Bakken shales are considered important source rocks in the Williston Basin (Meissner, 1978; Dow, 1974; Williams, 1974; Webster, 1984; Schmoker and Hester, 1983; Hester and Schmoker, 1985). The upper and lower shale members are lithologically similar throughout much of the basin. The shales are dark-gray to black, hard, siliceous, slightly calcareous, pyritic, massive to fissile, and generally either break along horizontal fractures or with conchoidal fractures. The shales are dissimilar in that the upper shale lacks limestone and greenish-gray shale beds (Pitman et al., 2001). Pyrite occurs disseminated throughout the shale interval and as individual laminations. The shales consist of dark organic material, clay, silt-sized quartz, and some calcite and dolomite. The shale is kerogen rich in the deeper parts of the basin and the organic material is distributed throughout. The Bakken kerogen is regarded as a Type II kerogen and the composition consists of 70 to 90% amorphous material, 0 to 20% herbaceous material, up to 30% coaly material, and 5% woody material (LeFever, 2007).

Fractures enhance the reservoir quality of the tight Bakken reservoir (Murray, 1968; Meissner, 1978; Pitman et al., 2001). Three types of fractures are reported to occur in the Bakken: (1) structural related tectonic fractures; (2) stress-related regional fractures; and (3) expulsion fractures associated with overpressuring due to hydrocarbon generation (Druyff, 1991). Murray described the fractured reservoir in the Antelope Field (Fig. 4) being the result of sharp folding of the Antelope structure.

The Bakken well log signatures have been studied across the Williston basin, and core samples from the three Bakken units have been measured and correlated to reservoir quality and hydrocarbon maturation. These measurements have been used to calibrate logs to matrix properties such as porosity and permeability, and many of the background trends in properties are already established. Schmoker and Hester (1983) derived an equation to calculate total organic carbon content using bulk density logs. The upper and lower shale are interpreted to have been deposited in an offshore marine anoxic or oxygen restricted environment during periods of sea-level rise (Pitman et al., 2001; Webster, 1984; LeFever et al., 1991). The anoxic conditions resulted from a stratified hydrologic regime (Smith and Bustin, 1996; 2000). Anoxic conditions are indicated by the lack of benthic fauna and burrowing, high TOC content, and presence of pyrite.

The Bakken is regionally overpressured because of hydrocarbon generation and the overpressures cause hydraulic fractures in the Bakken by the generated liquids (Meissner, 1978; Pitman et al., 2001; Nordeng and LeFever, 2008). Horizontal expulsion fractures have been reported in the Bakken shales in clay and organic rich intervals (Carlisle et al., 1992; Pitman et al., 2001). The maturation process and oil generation causes a lowering in velocity in the Bakken shales that can be recognized utilizing sonic logs (Carlisle, 1991; Meissner, 1978).

The Bakken is not thermally mature throughout the Williston Basin. The shales are thermally immature in the eastern part of the basin and characterized on well logs by low resistivity (water-wet). In the western Williston, the shales are characterized by high resistivity and are thought to be oil-wet (Meissner, 1978).

Organic maturity has recently been modeled using the Time-Temperature Index (TTI) method by Nordeng (2008) and Nordeng and LeFever (2008). Their models suggest that organic maturity started in the Mesozoic. Carlisle (1991) suggests that hydrocarbon generation started in the early Cretaceous. Webster (1984) utilized TTI plots to conclude that oil generation initiated approximately 75 million years ago (late Cretaceous). Most of the oil generated in the Bakken black shales may have been expelled into the middle member of the Bakken (Pitman et al., 2001). Price and LeFever (1994) also presented evidence that most of the oil generated in the Bakken stayed in the Bakken and did not migrate into the overlying Madison group.

The middle member of the Bakken was deposited in a shallow water regime following a rapid sea level drop (Smith and Bustin, 1996). In the central part of the basin, the middle member consists of argillaceous, greenish-gray, highly fossiliferous, pyritic siltstones which indicate an environment that was moderately well oxygenated but occasionally dysaerobic. The upper parts of the middle member have cross stratified sandy intervals which suggests strong current action (LeFever et al., 1991). The mineralogy of the middle Bakken is variable across the basin and consists of 30 to 60% clastic material (quartz and feldspar), 30 to 80% carbonate (calcite and dolomite), minor matrix material (illite, smectite, chlorite, and kaolinite) (LeFever, 2007).

Thickness variations in the Bakken result from a variety of factors including varying depositional rates, paleostructures created by either basement fault movement or Prairie evaporite dissolution, and onlap of units towards the basin edges. Older structural features such as the Nesson anticline, have dramatically influenced Bakken depositional patterns and also influenced hydrocarbon migration (Fig. 3).

B) Summary of Existing Industry/Sector

The Bakken Formation of the Williston Basin has seen several cycles of exploration and development since the 1950s. The earliest discovery occurred in the Antelope Field of North Dakota in 1953 and development continued into the 1960s. Fifty-six wells targeted Bakken and the Sanish member of the Three Forks on a tightly folded structure. The wells were drilled vertically and after a sand-oil fracture stimulation treatment were capable of producing an average of 209 BOPD (33.2 m^3 per day). Following the Antelope discovery, exploration proceeded slowly. The significance of Antelope is that it established the Bakken and upper Three Forks as petroleum reservoirs in the basin.

The next significant discovery was by Shell in the Elkhorn Ranch Field in 1961. The Bakken was completed in the well as a bail-out zone after the deeper primary Red River objective was not successful. The Elkhorn Ranch well was very significant in that it showed that significant reserves could be found in the upper Bakken shale. Because of product prices and remoteness of the area, the next Bakken well was not drilled until 1976. This area then became known as the “Bakken Fairway” area. Wells drilled in the “Fairway” targeted the upper Bakken shale and other horizons (both shallower and deeper). The area occurs along the southwest margin of the Bakken depositional basin in the general Billings Nose area (Fig. 1). Where the Bakken thins, it becomes more susceptible to fracturing. Sand-oil fracture stimulation treatment was also used on these wells.

Horizontal drilling in the upper Bakken shale commenced in 1987. The first well drilled by Meridian was the #33-11 MOI well which had a horizontal displacement of 2,603 ft (794 m) in the Bakken. The well was completed for 258 BOPD (41 m^3) and 299 MCFD (8461 m^3) and was remarkably stable in production for the first two years. The success of this well set off the horizontal drilling phase of the upper Bakken shale. The play continued into the 1990s with over twenty operators. Product prices declined significantly in the 1990s and along with the somewhat unpredictable production in the upper Bakken shale brought this phase to a close. The “fairway” play met with mixed results. Good producing wells were often offset with poor producing wells. In addition, some pressure depletion and cross well communication was reported (LeFever, 2006).

Because of mixed results in the “fairway” trend and low product prices, the Bakken again returned to the status of being a bail-out zone type of a reservoir rather than a primary objective of exploration. This status changed with the discovery of significant reserves in the middle Bakken, in the Elm Coulee Field. The discovery and development of the middle Bakken has resulted in the most significant of the cycles to date. The Elm Coulee discovery and development prompted operators to also target the middle Bakken in North Dakota. Prior to Elm Coulee most operators targeted only the upper shale in the Bakken.

The Elm Coulee field of Richland County Montana was discovered in the late 1990s and horizontal drilling in the field commenced in 2000. The key well for identifying the potential in the Bakken was the Kelly/Prospector Albin FLB 2-33 well (Sec. 33-T24N-R57E; Richland County). This well was drilled to test the Nisku. This deeper horizon was not productive, so the Bakken "bail-out" zone was pursued, and the 2-33 well was perforated in only the middle Bakken because of the shows seen on the mud log. The well was treated with a water-sand fracture stimulation (instead of the more normal oil-frac) consisting of 80,260 gallons (303,382 L) of water and 151,800 pounds 68,917 kg) of sand. The middle Bakken flowed 157 barrels (24.9 m^3) of oil for the first 20 days beginning in March of 1996 and was still making 80 BOPD (12.7 m^3) after three months. The results of this well were very encouraging and it was recognized that a large field existed in the area that had previously been drilled through with over 100 wells. An area 4 to 5 miles (6.4 to 8 km) wide and 30 miles (48 km) long was mapped out where the porosity development is accompanied by high resistivity. Several re-entries/recompletions were done in the late 1990s to pursue the play. The play evolved to horizontal drilling in the middle member, in 2000, which lead to the development of the Elm Coulee Field since that time. Individual horizontal wells are sand-water fracture stimulated and have initial production of 200 to 1200 BOPD (31.8 to 191 m^3/d) and estimated recoveries of 300,000 to 750,000 BO (47700 to 119,250 m^3) per well. The field is estimated to have an ultimate recovery of greater than 200 million (31.8 million m^3) BO (Walker et al., 2006). Technology plays a very important role in this development with the horizontal wells and fracture stimulation.

The expansion of the play into North Dakota is currently underway and has resulted in new discoveries, including the Parshall Field. The new discoveries in North Dakota suggest the existence of an extremely large unconventional resource play. Product prices will probably influence this cycle too. Although regarded as a maturely drilled basin, the Williston continues to yield giant oil discoveries.

C) Technologies/Tools Used

Exploration and development of the Bakken has, to date, used traditional methods of mapping structure from seismic, and using well logs to identify source intervals and maturity, and reservoir zones. We propose to do a quantitative analysis of the Bakken hydrocarbon and reservoir systems. The study will address the issue of the importance of the matrix versus fracture permeability as they exist. In addition, the study will examine the importance of horizontal fractures that are present in the middle Bakken. The Elm Coulee study will focus on core, and thin section description, image log interpretation, and QEMSCAN® SEM analysis to characterize the reservoir, quantify the pore systems, and to build a reservoir model. Importantly, attribute analysis of the seismic reflection data in the Elm Coulee area (3-D and/or fracture mapping data) will be interpreted and integrated into the reservoir model. Pressure information (DST and other data) and geochemical information (source rock data) will also be analyzed and integrated into the reservoir model. If successful at Elm Coulee, this approach and work will extend to the new Parshall Field area of North Dakota with similar objectives in mind.

Concurrently and integrated with this structural/stratigraphic effort will be an examination of the controls on multi-scale impedance in the Bakken organic-rich shale. The seismic properties of kerogen remain poorly understood and so, predictions of the seismic response of a rock-kerogen system and the kerogen maturity remains a big challenge. Kerogen maturity changes shale texture, for example, it generates microcracks and fractures in the matrix. Assessment of maturity from indirect measurements can be greatly enhanced by exploiting any existing correlations between physical properties, microstructure, and kerogen content. In this part of the research, we will study how impedance microstructure of organic rich shale's can be related to their maturity and elastic wave velocity. A systematic study will be done of the textural variations of the Bakken organic-rich shale with varying maturity, and its correlation with elastic and inelastic properties under pressure. This part of the work will be done in partnership with the Idaho National Lab. We will study this organic-rich shale at different maturities (rock-eval, microstructure, seismic, and transport properties) and relate these to microstructural impedance variations, to calibrate the seismic response to shale maturity and richness. To date, most core handling processes have not been concerned with preserving any hydrocarbon content. The effort above will, in all likelihood, require new core handling processes that seal the core upon reaching the surface.

D) Benefits/Inadequacies of Current Technology

Various traditional methods have been used to explore for the Bakken (Sperr, 1991; Rogers and Mattox, 1985). These include: exploring along the depositional edge (more susceptible to fracturing); exploring structural flexures and lineaments; looking for Prairie dissolution areas as they may be areas of more intense fracturing; looking for geothermal anomalies (intense hydrocarbon generation may cause more intense fracturing); looking for primary reservoirs (i.e., middle Bakken); and looking for fractured areas identified by well logs. The fracture signature on well logs has been described by Hansen and Long, 1991. Wireline logs can exhibit wide separation between the micro-spherically focused log (MSFL) and dual laterologs (DLL) within the Bakken interval. This is an indication of evasion effects, and either matrix or fracture permeability. The effect can occur when heavy salt-based mud is used in a hole to control the abnormal pressures in the Bakken, and for minimizing salt solution in several of the shallow salt horizons in the Williston Basin (e.g., Charles salts). There is a need to improve well log criteria to identify mature source rocks and assess reservoir quality.

Seismic data has been used primarily for structural and gross stratigraphic interpretation. In the past, 2-D data has been used to define potential fractured Bakken reservoir areas, defined by Prairie evaporite solution and/or structural anomalies. This limited use of the seismic can be attributed largely to the often poor quality of older seismic data, plus inadequacies of previous integrated inversion procedures to extract attributes related to important properties such as fracturing and porosity. New 3-D data has been acquired in several of the emerging resource play area, and this new data should be interpreted to help understand the geomechanical and reservoir properties of the Bakken. Fracture mapping of Bakken reservoir stimulation will aid in completion technologies and help in orientating horizontal drill wells.

2) DEVELOPMENT STRATEGIES

A) Consortium Roles/Responsibilities

We are presently forming an industry consortium to partner with us during this study. Seven companies have currently committed to the consortium, and an additional ten companies are considering joining. Objectives of the consortium are to expand in-kind contributions of seismic, well logs, core, and fracture mapping data; to conduct additional field studies; to obtain additional facies and fracture analyses; and to add source typing, maturity analysis, and burial history to our project work. This will hopefully include taking core with an effort to preserve open fractures and hydrocarbon content. Consortium funding will also support additional students to those funded by this NETL project.

B) Why New Technology Needed

The Bakken resource play is a significant emerging play in the Rocky Mountain region. The Upper Devonian-Lower Mississippian Bakken Formation in North Dakota and Montana has produced 105 million bbl of oil through 2007 (Figure 1). The USGS has recently estimated the Bakken to contain 3-4.3 billion bbl of undiscovered and recoverable oil. The Bakken Petroleum System contains all the aspects of a large resource play (e.g., widespread source and reservoir rocks). It contains reservoir rocks, organic rich source beds and abundant seals. The various productive lithologies are all low porosity and permeability. No predictive hydrocarbon system or reservoir geo-model exists for this play. This study proposes to conduct an initial assessment of the hydrocarbon potential of this shale and tight sandstone, siltstone, and carbonate resource; and to develop an integrated reservoir geo-model for this important stratigraphic interval in the Williston basin. A systematic study of the textural variations of the Bakken organic-rich shale with varying maturity, and its correlation with elastic and inelastic properties under pressure is lacking. We will study this organic-rich shale (rock-eval, microstructure, seismic, and transport properties) at different maturities, and relate these to micro-structural impedance variations, to calibrate the seismic response to shale maturity and richness.

A better, integrated scheme is needed to identify ‘sweet spots’ and optimize well placement and completions. Log data is abundant, but this data has not been adequately tied to reservoir parameters that control production. Logs are often evaluated outside of the geologic and diagenetic context. In addition, a vast variety of log types and vintages are available. Old logs have valuable information but usually are limited in the type and quality data collected. Complete, modern log suites are rare. Hence, transforms between old and new log sets will be developed. Predictive analysis will include the capability to add, for example, fracture content and calculate the fracture signature on both logs and surface seismic data. By combining this with in situ stress indications (break outs, regional stress patterns), dominant fracture locations and directions can be estimated.

Successful exploration and production programs for organic-rich shale must rely on reliable identification of the kerogen content and its maturity through indirect seismic methods. The seismic properties of kerogen remain poorly understood and so, predictions of the seismic response of a rock-kerogen system and the kerogen maturity remains a big challenge. Kerogen maturity changes shale texture, for example, it generates microcracks and fractures in the matrix. Assessment of maturity from indirect measurements can be greatly enhanced by exploiting any existing correlations between physical properties, microstructure, and kerogen content. In this part of the research, we will relate the impedance microstructure of organic rich shale's to their maturity and elastic wave velocity. If microstructural variations can be related to bulk property measurements, indirect methods for detection of kerogen-rich shale sequences will be greatly enhanced. Due to the opaque nature of the kerogen, and the associated pyrite, it is rather difficult to characterize them with optical methods. Elastic properties of clay minerals, on the other hand, are almost entirely unknown due to their small grain sizes.

We propose to use two new analytical methods to help assess bulk properties and the seismic response to different maturity levels (1) SAM (scanning acoustic microscopy) analyses at different frequencies to map impedance changes at a micron-scale; (2) QEMSCAN analyses to correlate the impedance changes to mineralogy. These analyses may give images that are comparable to optical and SEM images but give impedance information and information about surface and sub-surface impedance changes not obtainable in optical and SEM images. In a preliminary paper (Prasad et al., 2003), we have shown that we can map textural changes with shale maturity with the SAM. We imaged micro-scale impedance of different constituent grains, grain clusters, and matrix areas in organic shale samples with varying amounts of kerogen and at different maturity grades. The acoustic images were calibrated to quantify the impedance. These studies showed a correlation between the impedance of shale matrix, the total organic content and the hydrogen index of the shale.

To relate maturity levels as expected to be seen in nature to the acoustical and high frequency measurements, we will partner with the Idaho National Laboratory to conduct three thermal treatment experiments. They will assemble an initial laboratory data set to evaluate the effect of Bakken shale maturity on the acoustic and high frequency geophysical measurements on confined shale samples. After the initial geophysical and petrophysical characterization of the shale core samples, we will thermally treat these samples using three retorting methods to alter the shale thermal maturity. We will be conducting three types of retorting experiments (fully saturated, anhydrous, and partial hydrous) on confined shale samples in an effort to simulate expected maturity levels in the Bakken shale.

C) Problems to Address

This study proposes to conduct an initial assessment of the hydrocarbon potential of this shale and mixed siliciclastic and carbonate resource, and to develop an integrated reservoir geo-model for this important stratigraphic interval in the Williston basin. The resource assessment will include measurements of impedance changes at different Bakken source rock maturity levels, using both samples at different measured maturity levels; and by measuring properties of samples retorted to different maturity levels. The integrated reservoir study of the Bakken will include detailed subsurface mapping of depositional and fracture systems using seismic attributes, core and well logs, and sequence stratigraphic analysis; and reservoir characterization using a new high-resolution SEM tool to quantify pore systems. Such a model that integrates sub-regional stratigraphic and reservoir characterization, rock physics calibrated seismic attribute analyses, acoustic impedance developed for different levels of organic richness and maturity, and a secondary permeability potential derived from a fracture analysis has not been attempted. These results may be applicable to other Bakken areas in the Rocky Mountain region.

Objectives of this project and problems to address include:

- Characterization of geologic, geochemical, geophysical, and operational parameters that characterize the Bakken reservoirs, and that differentiate high performing wells;
- Development of methods to accurately assess the potential of shale and tight reservoirs for oil generation and production from common industry petrophysical measurements;
- Accurate delineation of the natural fracture system for guiding horizontal wells to intersect a large number of open fractures;
- Conduct an initial assessment of the hydrocarbon potential of frontier oil resources. The successful results of this study will develop an initial Alpha version of a predictive exploration model that could be used for future identification of high potential fairways and traps for the Bakken hydrocarbon system.

3) FUTURE

A) Barriers Research will Overcome

Barriers this research will overcome include (1) the current lack of a predictive exploration model to identify Bakken “sweet spots”, where organic maturity and reservoir quality combine to result in high productivity wells and long field life; (2) a predictive model to identify open fracture systems that contribute significantly to reservoir permeability; (3) help to explain the range of completion results and optimize completion strategies for the Bakken

B) Impact on Oil Production Deliverables

The primary goal of this portion of the research is to provide an integrated and calibrated analysis of the distribution of reservoir quality on both regional and local scales. Both log and seismic data will be evaluated in terms of reservoir properties controlling production. Industry will benefit from this project in a number of important ways: (1) this study will establish a new predictive stratigraphic framework and geologic model for the Bakken interval that will improve play and prospect assessment, and allow a more accurate estimate of reserve volumes; (2) a new predictive geo-model will improve understanding of Bakken producibility and reduce drilling risk and provide more accurate resource estimates; (3) companies will significantly improve their cost recovery by optimizing drilling and completion strategies; and (4) reservoir characterization will optimize reservoir development and reduce drilling locations which leads to a smaller environmental footprint.

C) Deliverables

We will provide the following deliverables over the course of this project:

1. Subregional integrated stratigraphic/structural framework.
2. Quantitative reservoir geo-model for Elm Coulee field.
3. Maps of lateral and vertical reservoir and source maturity on a subregional basis that compose an integrated exploration model for the Bakken system.
4. Working with the geomechanics and production groups from the University of North Dakota, we will develop predictive algorithms to estimate rock strength and fracturing from logs.
5. Based on published and our own rock property measurements, we will calibrate logs to estimate important reservoir properties from logs.
6. From the calibrated logs, we will produce synthetic seismic traces that correspond to variations in important reservoir properties such as thickness, porosity, density, and fracture content.
7. Lithology-microstructure-velocity attenuation models from SAM and QEMSCAN analyses of Bakken organic-rich shales.
8. From the surface seismic data, attributes such as curvature, amplitudes, frequency content, and coherence will be calculated and compared to known Bakken maturity and productivity.

Depending on the type and quality of the seismic data supplied by corporate partners, geologically constrained multiple attribute analyses, including inversion will be run to extract reservoir properties from the seismic data.

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