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TECHNOLOGY STATUS ASSESSMENT

Geomechanical Study of Bakken Formation for Improved Oil Recovery

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Current State of technology

Summary of Existing Industry/Sector

Since the first Bakken discovery well was drilled in the 1950s (Anderson, 1953), thousands of wells have been drilled to produce oil from this formation (NDIC, 2008a). The Bakken Formation in the North Dakota Williston Basin is a thin layer (maximum thickness is 145 ft) of interbedded, naturally fractured low permeability black shale, siltstone, silty sandstone and silty carbonate rocks at about 10,000 ft depth (LeFever, 2005). Due to the high total organic carbon (TOC) content in the upper and lower shales, it is estimated to have 200 - 400 billion barrels of original oil in place (OOIP) (Price, 2000). However, an April 2008 assessment by the US Geological Survey indicated that technical recoverable reserve is about 3.6 billion barrels of crude oil (Pollastro et al., 2008). A more recent research report released by North Dakota Geological Survey assessed the current recoverable reserve is 2.1 billion barrels (Brimberry, 2008a). Although there is a big gap between these two assessments, both indicate a recovery factor of about 1%, which is much lower than the US domestic average recovery factor of 30% (Lake, 1989; Green and Willhite, 2003).

Technologies/Tools Being Used

Currently horizontal drilling followed by hydraulic fracturing stimulations are being applied to produce the Bakken crude oil in the North Dakota Williston Basin.

In building the horizontal wells, multilateral (single, dual and tri lateral) technologies were used. Similarly, different completion techniques (perforated liner or open hole, cased and cemented) were tried (Brimberry, 2008b). Corresponding to the above well schemes, different types of well spacing have been used, including: (1) long single lateral 1280 acres, (2) single 640 acres, (3) coplanar dual and tri lateral 1280 acres, and (4) coplanar 640 acres (Helms, 2007).

In the hydraulic fracturing stimulation, both longitudinal and transverse fractures were tried. Different combinations of wellbore azimuth, length, and placement were tested (Cox, et al., 2008).

Benefits and Inadequacies of Current Technology

Maximum thickness of Bakken Formation is about 145 ft, including about 20 ft in Upper Bakken, 85 ft in Middle Bakken, and 40 ft in Lower Bakken. The Middle Bakken is further divided into 5 Lithofacies L1~5. Bakken oil is produced mainly from two central Lithofacies, L2, interbedded shale and silty sandstone, and L3, sandstone. These two Lithofacies are about 10 to 20 ft thick (LeFever, 2005).

It is believed, and confirmed by recovered cores, that the Bakken Formation is naturally fractured due to the action of in-situ stress fields and internal pressure when hydrocarbon was generated in the low permeability shales.

Combination of horizontal wells and hydraulic fracturing in the Bakken Formation has the following benefits:

(1) Horizontal wells increase the exposure to reservoir rock in thin formations. Vertical wells have only limited exposure to the reservoir rock, which is the formation thickness. Instead, exposure of horizontal wells equals the length of the horizontal sections.

(2) Horizontal wells increase the connection between wellbore and the natural fractures, and those laterally isolated fractures. Because horizontal wells have larger exposure to reservoir rock, it is more likely that they hit and connect more natural fractures in comparison with vertical wells.
(3) Hydraulic fracturing stimulation increases the reservoir drainage volume and speeds up the recovery, because the Bakken Formation has very low permeability.

However, due to the complex geological conditions in the Bakken Formation, the above technology has some serious limitations:
(1) Improper well orientation will cause wellbore instability (Roegiers, 2008a). In order to have the most stable wellbore, the optimized orientation is the one that has the most homogeneous stress distribution, or minimum stress difference, around the wellbore. Finding this optimized orientation needs the information of in-situ stresses: both orientation and magnitude.
(2) Improperly selected wellbore orientation may greatly reduce the well performance. Because one of the purposes of using horizontal wells is to connect laterally isolated natural fractures, which usually follow a patterned distribution controlled by in-situ stresses.
(3) Improperly designed hydraulic fracturing treatment may not only ruin the well, but also affect the nearby wells, and lose the reserves in the targeted drainage volume (Roegiers, 2008b). The orientation of the hydraulically induced fractures is controlled by local in-situ stresses. The geometry is partly controlled by the geomechanical properties of both the target formation (Bakken Formation) and the boundary formations.

Development Strategies

Why New Technology and Research Is Required?

In fact, field cases have shown that the above mentioned problems have occurred repeatedly, due to the lack of in-situ stresses and geomechanical properties, or the inadequate understanding and application of the geomechanical principles.

Some field engineers observed that: (1) successful drilling and fracturing techniques in one section often doesn’t work in another, and (2) in some dual lateral wells, the hydraulic fractures in the east lateral could be different from the west lateral. These facts indicate that there are severe heterogeneities in geological conditions in the Bakken Formation. New technology and research is required to quantify the in-situ stress fields, the geomechanical properties of the Bakken and its neighboring formations, and their distribution in the North Dakota Williston Basin.

This project is aimed at increasing the success rate and performance of horizontal drilling and hydraulic fracturing in the Bakken Formation in North Dakota portion of the Williston Basin, and ultimately improving the crude oil recovery.

Problems to be Addressed in this Research Project

In order to reach this goal, we propose to investigate the following parameters in each represented area in the North Dakota Williston Basin, as defined by USGS (Pollastro et al, 2008): (1) In-situ stresses (orientation and magnitude) and (2) Geomechanical properties (uniaxial tensile strength, uniaxial compressive strength, Young’s modulus and Poisson’s ratio, cohesion and angle of internal friction, Biot’s coefficient, fracture gradient, and fracture toughness.

In-situ Stress Determination

Knowing the in-situ stress field is vitally important to any underground excavation, including petroleum drilling, mining, and tunneling (Jaeger et al, 2007). Many efforts have been made to determine the direction and magnitude of in-situ stresses (Hudson, 1993). Consequently many different methods were developed. After carefully reviewing the existing techniques and our conditions, we propose the following methods for determine the orientation and magnitude of the in-situ stresses.

Stress orientation from analyzing discontinuities: When the rock is subjected to load, it deforms. When the load exceeds a certain limit, it fractures or fails. The failure surface is called discontinuity of the rock. The failure plane and the stress orientation have a certain relationship Narr et al, 2006). Following the geological guidelines, the feature of the discontinuity, i.e., tensile failure (joint) or shear failure (fault) or bedding plane, can be identified from core sample observation (Davis and Reynolds, 1996). Using the relationship between the in-situ stresses and the discontinuities, part of the direction(s) of the principal stresses can be derived. Similar method can be also applied to characterizing naturally fractured reservoirs by using surface lineaments and fractures (Guo et al, 1999). Recent development in this area is a new type of acoustic log for principal stress direction using the split waves (Nihei et al, 2002).

Because the Bakken Formation in Williston Basin is at about 10,000 ft depth, no surface access is available. The North Dakota Geological Survey Core Library, which is located on the University of North Dakota campus, has a large collection of Bakken Formation core samples from the petroleum drilling activities, including some oriented core samples. With the recent booming drilling in the Bakken Formation, more samples are being delivered. The PI has brought students to visit the facilities to conduct sample observation and analysis in several courses. Furthermore, the PI has developed a portable core drilling device for coring specimens from available slabs in another research project, because the Core Library’s drilling machine can not generate core plugs that meet the geometry standards for core flooding and geomechanical research purposes. There is no limitation on this part of research.

Stress orientation and magnitude from Kaiser effect: Any material has more or less memory on its deformation history, thus the stress history. When new load is applied, no apparent failure would occur if the current load is lower than the historical load, similar like pre-stressed concrete. Kaiser (1953) noted this phenomenon in metals at first. When rock is subjected to external force just exceeding its most recent historical load, new micro-cracks will be created, generating acoustic emissions (Lockner and Byerlee, 1992; Scott et al, 2000). This is the Kaiser effect in rocks. Using this phenomenon, it is possible to estimate in-situ stresses. Many researchers have tried to develop and improve this technology since 1970s (e.g. Kurita and Fujii, 1979; Houghton and Crawford, 1987; Holocomb, 1993; Seto et al, 1999). With the advancement of electronic technology and many years of R&D, this technology is now matured for practical applications (WGEPSS, 2002; Villaescusa et al, 2002; Mori et al, 2006). This method has been used in the mining industry for a while. Limited efforts have also been made to apply this method in estimating in-situ stresses for the petroleum industry (Pestman et al, 1998 & 2002).

The Kaiser effect method will become one of the best technical choices for determining in-situ stresses for several reasons. It can determine both the direction and the magnitude of the in-situ stresses if oriented core is available. If there are no oriented core samples, the directions can still be determined by combining the information of the well axis direction (available to the public from NDIC) and the analysis of the discontinuities mentioned above. It uses small samples (1-in diameter by 2-in length), which is especially valuable to the petroleum industry. This measurement can be combined with uniaxial compression geomechanics tests. In addition to the above advantages, we chose this method because the PI started using acoustic emission techniques since the early 1990s (Zeng et al, 1994; Zeng, 2002; Zeng et al, 2008), and knows the state-of-the-art of both the acoustic system and the transducers.

Geomechanical properties of Bakken Formation

Geomechanical properties of rocks are important parameters for well design to avoid instability and for a hydraulic fracturing treatment plan (Fjaer et al, 1992, Zeng, 2002). However, the Bakken Formation hasn’t been investigated very much in this aspect; only one reference was found with limited data (Kuhlman et al, 1992; Zhou et al, 2008); this is far behind the research on the petroleum geology of the Bakken Formation (e.g. LeFever, 1991; Webster, 1992; Gosnold, 1999).

While there could be many reasons for this lack of geomechanical research on the Bakken Formation, a good combination of expertise, facilities and demand is essential. Now the demand is obviously there. The PI has been trained and practiced since 1984 for geomechanics experimental research and application, and is well prepared to the proposed investigation. As for the facilities, North Dakota Geological Survey Core Library on UND campus provides the best access to the valuable Bakken Formation core samples, both for observing and for cutting core specimens. The PI has built a simple but well functioning Petroleum Engineering Lab in the Department of Geology and Geological Engineering at UND using the new faculty start-up funds, which set up a solid foundation for the proposed work. With the addition of one geomechanics loading frame and one acoustic emission system, this petroleum engineering lab will be very well equipped for petroleum-related geomechanics research. It can serve not only the exploration and production of crude oil in the Bakken Formation, but also the rest formations of the Williston Basin. In addition, this will also enable us to better serve the needs for assessment of cap-rock capacity and seal integrity for the ongoing Phase-II and Phase-III CO2 sequestration in the Williston Basin and the rest of the PCOR partnership, managed by UNDEERC.

We propose to conduct geomechanical experimental investigation on Bakken Formation rocks, especially we plan to test the rock specimens for the following properties: (1) Uniaxial compressive and tensile strengths, (2) Cohesion and angle of internal friction, (3) Young's modulus and Poisson's ratio, (4) Triaxial strength at three different confining pressures, (5) Biot's coefficient, and (6) Fracture toughness.

International Society for Rock Mechanics' (ISRM) suggested methods and other related guidelines will be followed in specimen preparation and experiment (Zeng et al, 2004). Most of the testing methods for all these rock properties have been well developed.

Uniaxial compressive strengths, Young's modulus, Poisson's ratio and in-situ stresses: Uniaxial compressive strength will be measured together with Young's modulus, Poisson's ratio, and acoustic emission. Axial load, axial and lateral deformations will be measured during the compression until failure of the specimen. Acoustic emission activities will be monitored and recorded during the same time. Load-deformations curves will be converted to stress-strain curves using the specimen's geometry, from which the Young's modulus and Poisson's ratio will be obtained using the linear portion. Accompanying the stress-strain curve, a cumulative acoustic emission activity curve will be developed, on which the stress level corresponding to the deflection point is the most recent historic stress in that specific direction (WGEPSS, 2002). Because the Williston Basin is very flat-lying, we can assume that one of the three principal stresses will be parallel to the vertical direction. With this assumption, using the measured historic stresses in three different directions in the bedding plane would allow the determination of the two principal stresses in the bedding plane.

Tensile strength: Point load test will be used to measure the tensile strength.

Triaxial strength, cohesion and angle of internal friction: Triaxial strength under three different confining pressures will be measured. Using these results and the uniaxial compressive and tensile strengths, a Mohr envelope of this rock will be developed, from which the cohesion and angle of internal friction will be determined.

Biot's coefficient: Biot's coefficient defines the relationship among total stress, effective stress and pore fluid pressure (Biot and Willis, 1957; Geertsma, 1957). It describes how soon the matrix stress will respond when the pore fluid pressure is changed. It is more important to low permeability rocks, such as the Bakken Formation. This parameter is used in hydraulic fracturing treatment design and wellbore stability. It will be measured using triaxial and hydrostatic compression (Azeemuddin et al, 2002).

Fracture pressure gradient: Fracture pressure gradient is defined as the breakdown pressure divided by the well depth. The breakdown pressure depends on several different factors. Knowing the above measured parameters and the reservoir pressure, the upper and lower breakdown pressures at different combinations (vertical well, horizontal well at different directions; vertical fracture, horizontal fracture) can be calculated (Zeng, 2002). Using the calculated breakdown pressure, the fracture pressure gradient can be obtained.

Fracture toughness: Fracture toughness, K_{IC}, is a material characteristic property that describes the ability of a material containing a crack to resist fracture initiation and propagation. It is closely related to the geometry of the hydraulically induced fractures, such as length and width. This is a fundamental parameter for any hydraulic fracturing treatment design (Valko and Economides, 1995). There are different recommended methods to determine K_{IC} of rocks (e.g., Ouchterlony, 1983; Atkinson and Meredith, 1987; ISRM, 1988), but most of them are hard to apply directly to the petroleum industry due to the fact that cylindrical cores retrieved from oil drilling are often not large enough to meet the geometric requirements of those methods. In order to overcome this difficulty, Zhao and Roegiers (1990) proposed a CDISK method which uses chevron-notched disk specimens to measure K_{IC}. Zeng et al (2004) further improved this method. It has two advantages: first it can use samples as small as about 2.2-inch in diameter; secondly, it provides the possibility of measuring the K_{IC} in any desired direction inside the disk plane (Zeng, 2002). This method will be used in the proposed research.

Future

What Barriers shall the Research Overcome

The research will need to overcome several barriers.
The first barrier is the detection of Kaiser Effect. There might be no detectable acoustic emissions during the rock sample compression for Kaiser Effect in-situ stress measurement. This could happen in some old, completely relaxed rock samples. The first option is to choose the intact core sections for samples. The second remedy is to pre-compress the sample, i.e., to load and unload the sample to close the pre-existing cracks. The third choice is to use the overburden to calculate the vertical stresses, and use a transverse isotropic model to calculate the horizontal stresses. In the most challenging case, an isotropic model will be used to calculate the horizontal stresses.

The second barrier is the capability of preparing water-sensitive Bakken Formation samples. First remedy is to drill with compressed gas (N2, CO2 and He). Second remedy is to drill with mineral oil, which has been a routine method used in the petroleum industry.

The third barrier is the availability of the Bakken Formation rocks. This will be overcome by using similar water sensitive samples for training and tool preparation. Currently two candidate shales are under investigation. Also industrial partners have expressed their support on this.

Impact on the U.S. Domestic Oil and Gas Supply Industry

Results form this research project will directly serve the technical demand on recovering oil and gas from the Bakken Formation in North Dakota Williston Basin. These results can also be used to help oil and gas development in many other naturally shale formations, such as the Antrim shale in the Michigan, the New Albany shale in Illinois, and the Eastern Devonian shale in Appalachian region (Kentucky, West Virginia, Ohio, and Pennsylvania), and Pierre shale in Colorado. In fact, it is the PI's belief that using the technologies developed in this project to improve gas recovery in the above mentioned shale formations will have huge impact on domestic gas supply and reduction of green house gas emission, due to the fact those formations are close to big population centers.

Deliverables (Tools, Methods, Instrumentation, Products, etc.)

(1) Three-dimensional petroleum geological model of Bakken formation and its neighboring zones in North Dakota Williston Basin,
(2) Three-dimensional in-situ stress map of Bakken formation and its neighboring zones,
(3) Shale sample drilling system,

(4) Rock quality designation (RQD) based Bakken formation minor and micro fracture system,
(5) Bakken formation geomechanical property database,
(6) Kaiser Effect method for in-situ stresses,
(7) CDISK method for fracture toughness, and
(8) Application guidelines for horizontal drilling and hydraulic fracturing.

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