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Brittleness investigation of producing units in Three Forks and bakken formations, williston basin

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A B S T R A C T

Brittleness is a key factor in identifying intervals and areas for fracking in tight oil and gas reservoirs. The brittleness index of reservoir rocks can be calculated by elastic properties, but laboratory measurement of elastic properties is usually expensive and time consuming. In this paper, a method is proposed to predict the brittleness from known mineralogy and applied to assess the upper Three Forks formation in the Williston basin. In this method, a correlation between the elastic properties of the formation rock and mineralogy was first established based on rule of mixture. This correlation was verified by the measured elastic properties of the middle Bakken member. Then the correlating approach was used to predict the elastic property-based brittleness index of the upper Three Forks formation. The results indicate that the upper Three Forks formation should be conducive to reservoir stimulation as its predicted brittleness index ranges from 53 to 67 in the direction parallel to the bedding plane and 58 to 70 in the direction perpendicular to the bedding plane. Its brittleness is comparable to that of the middle Bakken member, which has been already successfully stimulated. The correlating method presented in this paper is also applicable to other major tight reservoirs.

1. Introduction

The boom of tight gas and oil production has led to a significant change in global energy generation. Tight reservoirs are characterized by very low matrix permeability (Wang et al., 2015). Production with economic success from these reservoirs usually depends on the presence of natural or artificial fractures (Nordeng, 2009; Pilcher et al., 2009); more effective hydraulic fracturing results in improved completion and higher production rates (Saldungaray and Palish, 2012). During hydraulic fracturing, hydraulic fractures interact with natural fractures, forming complex networks (Sun et al., 2015). Geomechanical properties of the formation rock are critical in drilling and hydraulic fracturing operations (Slatt and Abousleiman, 2011). Formation intervals with brittle characteristics are easier to fracture; ductile rock is not good for development because the formation will tend to heal any natural or artificial fractures (Guo et al., 2013). Hydraulic fracturing evaluation uses rock brittleness to achieve economic development of tight reservoirs; consequently, evaluation of brittleness is the focus of research (Lai et al., 2015). Brittleness characterization based on elastic properties, petrophysical properties and strength properties has been studied by previous researchers (Grieser and Bray, 2007; Jarvie et al., 2007; Rickman et al., 2008; Wang and Gale, 2009; Herwanger et al., 2015).

The Bakken formation in the Williston basin is one of the largest oil-producing formations in the world (Fig. 1). Successful development of the Bakken reservoir largely depends on the wide application of hydraulic fracturing. The upper and lower black shale members are the source rock, and the middle dolomite member is the primary oil-producing member (Pei et al., 2014). The black shale members are also the source rock for other formations in the basin. For example, the upper part of the Three Forks formation underlying the Bakken formation receives oil generated from Bakken shales. Production from the upper Three Forks was first established in Antelope Field in 1953 (Sonnenberg et al., 2011a), and recently interest has been rejuvenated due to the successful development of the Bakken reservoir (Berwick and Hendricks, 2011). The upper

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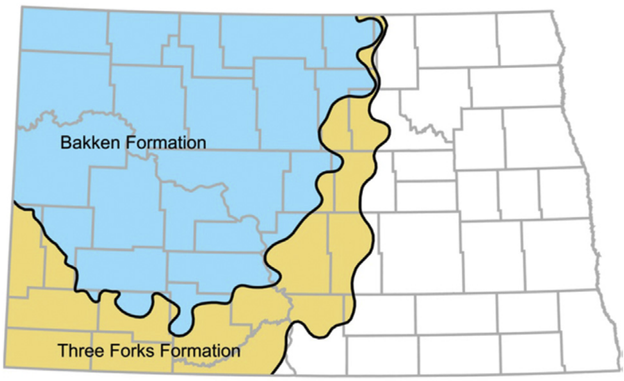

Fig. 1. The Bakken and Three Forks formations (after Nordeng and Lynn, 2010).

Three Forks formation is considered a prime target for future exploration and production in the Williston basin. This unit is mainly composed of dolomite, with poor reservoir quality indicated by low porosities (<8%) and low permeabililties (<0.1 md) (Sonnenberg et al., 2011a). Therefore, similar to the producing zone in the middle Bakken member, large-scale reservoir stimulation is required to establish economic production in the upper Three Forks formation. However, compared with the intensively-studied middle Bakken member, details of the dolomite formation have been investigated less. Some key information, including the geomechanical properties, in identifying sweet spots is still missing.

Brittleness is usually estimated from laboratory stress-strain measurements, rock properties, and mineral contents analysis using well logs. However, geomechanical measurements of rock samples can be expensive and time consuming, and well log-based brittleness only shows the properties near the borehole (Zhang et al., 2015). Brittleness can also be estimated by mineral composition which is controlled by deposition and diagenesis process (Jarvie et al., 2007; Wang and Gale, 2009). In this paper, a study of the brittleness of the upper Three Forks formation and middle Bakken member is presented. The objective is to predict the elastic properties and brittleness of the upper Three Forks formation from known mineralogy. A correlation is first established and validated between the measured elastic properties and mineralogy of the middle Bakken member. Then the correlating method is used to predict the elastic properties and brittleness of the upper Three Forks formation based on its mineralogy. The main objective of this paper is to develop a methodology which can estimate or predict formation mechanical properties without the expensive time consuming in geomechanical testing. This approach becomes more important when experimental investigation is limited by the cost cuts as a result of low oil price, which often occurs in oil industry. The methodology developed in this paper is also applicable to other tight reservoirs.

2. The Bakken and Three Forks formations

2.1. The Bakken formation

The late Devonian to early Mississippian Bakken formation holds a significant amount of recoverable oil and is one of the most promising tight oil plays in the world. The formation, which covers over 200,000 square miles in parts of Montana, North Dakota, Saskatchewan, and Manitoba, is one of many hydrocarbon-producing formations in the Williston basin (Fig. 1) (Vincent, 2011). Bakken has geology that is very conducive to horizontal drilling and hydraulic fracturing. The formation consists of three members: the upper member, middle member, and lower member (Fig. 2). The upper and lower members are uniform, black, organic-rich shales. Estimated original oil in place ranges from 10 to 400 billion barrels (bbl) (Sonnenberg et al., 2011a). The middle member, which is the focus of most current production activities, is highly variable and consists of an interbedded sequence of dolomitic siltstone and sandstone. In North Dakota, the middle member typically consists of gray interbedded siltstones and sandstones. At depths of 9500 to 11,000 feet (ft), the thickness of the middle member can reach about 80 ft (Vincent, 2001). Pitman et al. (2001) interpreted that the middle Bakken contains seven lithofacies, which are mainly siltstones and sandstones, with less amounts of shale, dolostones, and limestones.

During the transition from the Devonian to the Mississippian periods, the sea withdrew to the area covered by the lower Bakken shale. The lower Bakken shale created deposits in an offshore marine environment during sea-level rise (Pitman et al., 2001) at the rate of 3–10 ft per million years (Smith and Bustin, 2000). Deposition of shales took place in a stratified hydrological regime (Pitman et al., 2001; LeFever, 1991). Shales in the lower member indicate a change from oxidizing conditions during the underlying Three Forks time to anoxic conditions in the lower Bakken time (LeFever, 1991; Rickman et al., 2008). The middle Bakken time followed a rapid sea-level drop, and the member was deposited in shallow, well-oxygenated water in a proximal costal marine environment. The upper Bakken member was again deposited in an offshore marine environment very similar to the lower member, therefore displaying the same lithological features.

According to Egenhoff et al. (2011), the middle Bakken shows a distinct order of sequence and parasequence. The sequence encompasses the entire middle and parts of the lower and upper members and is reflected in the overall grain-size trend. The basal two-thirds to three-quarters of the middle Bakken member represents a prograding, shallowing-upward package, reflecting a regressive phase. The uppermost one-third to one-quarter of the middle Bakken represents a retrograding, deepening-upward package, reflecting a transgressive phase. Three or four parasequences exist at the margin of the basin, and up to six parasequences exist in the central basin. The variation in the number of parasequences was attributed to the depth-dependent facies belts; when one or two additional parasequences were deposited in the basin center, the margins were subaerially exposed (Egenhoff et al., 2011).

2.2. The Three Forks formation

The Devonian Three Forks formation lies below the Bakken in

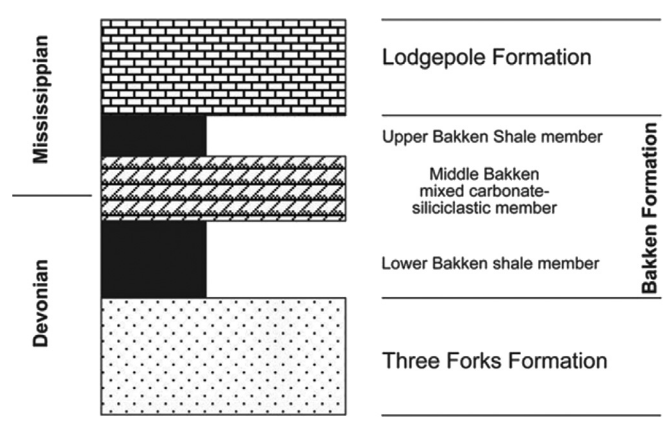

Fig. 2. General Stratigraphy of the Bakken and Three Forks formations (Egenhoff et al., 2011).