Brittleness investigation of producing units in Three Forks and Bakken formations, Williston basin

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Abstract

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.

Keywords: brittleness; mineralogy; correlation; Bakken formation; Three Forks formation

37 1. Introduction

38 The boom of tight gas and oil production has led to a significant change in global energy generation.
39 Tight reservoirs are characterized by very low matrix permeability (Wang *et al.*, 2015). Production with
40 economic success from these reservoirs usually depends on the presence of natural or artificial fractures
41 (Nordeng, 2009; Pilcher, 2009); more effective hydraulic fracturing results in improved completion and
42 higher production rates (Saldungaray and Palish, 2012). During hydraulic fracturing, hydraulic fractures
43 interact with natural fractures, forming complex networks (Sun *et al.*, 2015). Geomechanical properties of
44 the formation rock are critical in drilling and hydraulic fracturing operations (Slatt and Abousleiman,
45 2011). Formation intervals with brittle characteristics are easier to fracture; ductile rock is not good for
46 development because the formation will tend to heal any natural or artificial fractures (Guo *et al.*, 2013).
47 Hydraulic fracturing evaluation uses rock brittleness to achieve economic development of tight
48 reservoirs; consequently, evaluation of brittleness is the focus of research (Lai *et al.*, 2015). Brittleness
49 characterization based on elastic properties, petrophysical properties and strength properties has been
50 studied by previous researchers (Grieser and Bray, 2007; Jarvie *et al.*, 2007; Rickman *et al.*, 2008; Wang
51 and Gale, 2009; Jorg *et al.*, 2015)

52 The Bakken formation in the Williston basin is one of the largest oil-producing formations in the world
53 (Fig. 1). Successful development of the Bakken reservoir largely depends on the wide application of
54 hydraulic fracturing. The upper and lower black shale members are the source rock, and the middle
55 dolomite member is the primary oil-producing member (Pei *et al.*, 2014). The black shale members are
56 also the source rock for other formations in the basin. For example, the upper part of the Three Forks
57 formation underlying the Bakken formation receives oil generated from Bakken shales. Production from
58 the upper Three Forks was first established in Antelope Field in 1953 (Sonnenberg *et al.*, 2011a), and
59 recently interest has been rejuvenated due to the successful development of the Bakken reservoir
60 (Berwick and Hendricks, 2011). The upper Three Forks formation is considered a prime target for future
61 exploration and production in the Williston basin. This unit is mainly composed of dolomite, with poor
62 reservoir quality indicated by low porosities ($< 8\%$) and low permeabilities (< 0.1 md) (Sonnenberg *et al.*,
63 2011a). Therefore, similar to the producing zone in the middle Bakken member, large-scale reservoir
64 stimulation is required to establish economic production in the upper Three Forks formation. However,
65 compared with the intensively-studied middle Bakken member, details of the dolomite formation have
66 been investigated less. Some key information, including the geomechanical properties, in identifying
67 sweet spots is still missing.

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

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, 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 9,500 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.

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

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.* (1996), 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.*, 1996).

2.2 The Three Forks formation

The Devonian Three Forks formation lies below the Bakken in many of the same areas in Montana and North Dakota, at depths between 9,000 and 12,000 ft, with a total thickness up to 125 ft (Fig. 2). It is a thicker and more extensive horizon than the Bakken, extending into North Dakota to the east, Montana to the west, and South Dakota to the south (Chang, 2013). The North Dakota Department of Mineral Resources (DMR) generally considers the upper 50 ft of the Three Forks as part of the Bakken pool (Nordeng and Lynn, 2010). Based on over 200 wire line log analyses distributed across the Williston basin of North Dakota, it was estimated that almost 20 billion bbls of oil appear to be in place within the upper Three Forks formation, of which close to 2 billion bbls are expected to be produced. The upper Three Forks is the prime target for oil production, but it has a poor reservoir quality defined by porosities < 8% and permeabilities < 0.1 md (Sonnenberg *et al.*, 2011a).

The main source rock for the upper Three Forks formation is the lower Bakken shale. Where the lower and middle Bakken members thin in the southern part of the Williston basin, the primary source rock becomes the upper Bakken shale. The Three Forks is overpressured, which is related to hydrocarbon generation (Sonnenberg *et al.*, 2011a). The upper Three Forks formation is mainly composed of dolomite with imbedded mudstone and sandstone, yet the details of dolomite formation and its relative timing are unknown (Kolte and Egenhoff, 2014). The lithoface is similar to that of the middle Bakken member. The Three Forks formation was most likely deposited on a mixed carbonate-siliciclastic ramp as a limestone unit with varying amounts of detrital input. Initial replacement of limestone into dolomite probably occurred early, entirely changing the texture of this unit (Kolte and Egenhoff, 2014). The formation can be subdivided into three main facies: a) massive to chaotic bedded dolostone, b) interbedded dolostone with green mudstones, and c) bioturbated dolostone to sandstone. These facies represent an overall transgressive sequence ranging from upper intertidal/supratidal to subtidal. Within the sequence, up to six parasequences can be recognized (Sonnenberg *et al.*, 2011a). Although the upper Three Forks formation is a potential reservoir, its characteristics have been studied less than the well-known Bakken formation (Chang, 2013).

3. Correlation Methodology

The question of how easily the rock can be fractured and whether an ideal fracture network can be formed is important to the developers. As an increasing stress is applied, the rock passes through three successive stages of deformation: elastic, ductile, and fracture. Based on these behaviors, it is possible to classify the

rocks into two types: ductile and brittle. If the rock has a smaller region of elastic behavior and a larger region of ductile behavior, absorbing much energy before failure, it is considered ductile. In contrast, if the rock under stress has a larger region of elastic behavior but only a smaller region of ductile behavior, it is considered brittle (Altamar and Marfurt, 2014). Differentiating brittle from ductile rock has been key to stimulation success in tight reservoir development. Identifying intervals and areas in the formation where the rock is brittle leads to the development of a fracture fairway long enough to connect the maximum rock volume to the well. Brittleness is a function of mineral composition and diagenesis and can be quantified based on mineralogy or elastic properties. Based on the mineralogy content, ductility is controlled by clay, calcite, and total organic contents; the presence of quartz and dolomite tends to increase the brittleness of reservoir rocks. The mineralogy-based brittleness index, BI_{mnl} , can be expressed as (Jarvie *et al.*, 2007; Wang and Gale, 2009):

$$BI_{mnl} = \frac{Qz + Dl}{Qz + Dl + Ca + Cl + TOC} \quad (1)$$

where Qz is the fractional quartz content, Dl is the dolomite content, Ca is the calcite content, Cl is the clay content, and TOC is the total organic carbon content in the rock.

In the elastic property-based method, Young's modulus and Poisson's ratio are used to reflect the rock's ability to fail under stress and maintain a fracture. In general, the higher the Young's modulus and the lower the Poisson's ratio, the more brittle the rock is. The elastic property-based brittleness index, BI_{ep} , can be calculated as shown in Equations (2) to (4) (Grieser and Bray, 2007; Guo *et al.*, 2013):

$$BI_{ym} = \frac{ym - ym_{min}}{ym_{max} - ym_{min}} \times 100 \quad (2)$$

$$BI_{pr} = \frac{pr - pr_{max}}{pr_{min} - pr_{max}} \times 100 \quad (3)$$

$$BI_{ep} = \frac{1}{2} (BI_{ym} + BI_{pr}) \quad (4)$$

where BI_{ym} is the brittleness index based on Young's modulus; ym is measured Young's modulus in gigapascal (GPa); ym_{min} is the minimum value of measured Young's modulus range in GPa; ym_{max} is the maximum value of measured Young's modulus range in GPa; BI_{pr} is the brittleness index based on Poisson's ratio; pr is the measured Poisson's ratio; pr_{max} is the maximum value of measured Poisson's ratio range; and pr_{min} is the minimum value of measured Poisson's ratio range.

ym_{min} and pr_{max} represent the most ductile rock in the formation. ym_{max} and pr_{min} represent the most brittle rock. These values usually are determined from the distribution of the measured results of samples taken

from the same formation. If the calculated value of BI_{ep} is higher than 40, the rock is considered brittle. If the value is above 60, the rock is very brittle (Griesser and Bray, 2007).

Assuming that the rock is a composite material with different minerals, if the mineral composition of the rock is known, then its Young's modulus and Poisson's ratio can be predicted by rule of mixtures (ROM). The Voigt model and Reuss model which predict properties of a composite material by a weighted mean, are usually employed (Clyen and Withers, 1993; Barrett *et al.*, 1973). This provides a theoretical upper- and lower-bound on properties. The Voigt model, as shown in Equation (5), is used for axial loadings:

$$E_{comp} = \sum f_i E_i \quad (5)$$

where E_{comp} is the elastic property of the composite material; f_i is the volume fraction of the individual material; and E_i is the elastic property of the individual material.

The Reuss model, as shown in Equation (6), is used for transverse loadings:

$$\frac{1}{E_{comp}} = \sum \frac{f_i}{E_i} \quad (6)$$

In geomechanical test, two groups of specimen were sampled: horizontal group and vertical group. The horizontal specimens were sampled with their axis parallel to bedding planes; and the axis of vertical specimen is perpendicular to bedding planes. During the test, stress was applied along the sample axis when measuring Young's modulus and Poisson's ratio. Therefore, in this paper, the Young's modulus and Poisson's ratio in the direction parallel to bedding (*i.e.*, axial) is predicted by the Voigt model, and the Young's modulus and Poisson's ratio in the direction perpendicular to bedding (*i.e.*, transverse) is predicted by the Reuss model.

In this study, both the elastic properties of the middle Bakken formation samples were measured but not the upper Three Forks formation. Based on available mineralogy, the composite elastic properties of the middle Bakken member, including Young's modulus and Poisson's ratio, were calculated by the Voigt and Reuss models and validated by the measured values. Then this method was employed to calculate the composite Young's modulus and Poisson's of the upper Three Forks formation. The calculated composite elastic properties were used to predict the brittleness of the upper Three Forks formation.

4. Mineralogy and mechanical properties of middle Bakken member

4.1 Measured Elastic Properties

In a previous geomechanical study of the Bakken formation performed at the University of North Dakota (Ling *et al.*, 2013), 114 middle Bakken specimens were tested. Among these specimens, 85 were drilled in the direction parallel to beddings and 29 were drilled perpendicularly to beddings. These specimens were taken from cores of eight wells across the basin. Young's modulus and Poisson's ratio were measured under a confining pressure of 30 megapascals (MPa) through a three-cycle procedure. The AutoLab 1500, a multi-purpose, high-temperature/high-pressure testing system, was used to conduct the tests. Fig. 3 displays the measured values of elastic properties from the parallel group, and Fig. 4 displays the measured values of elastic properties from the perpendicular group. The black curves in the figures are used to generally divide the brittle and elastic regions (Grieser and Bray, 2007). From the figures, it is clear that most specimens are located in the brittle region. Also, one should notice that the Young's modulus measured in the direction perpendicular to bedding planes is lower than that measured in a direction parallel to bedding planes. This result is in agreement with Sierra *et al.* (2010).

Fig. 3. Measured elastic properties of middle Bakken member parallel to beddings.

Fig. 4. Measured elastic properties of middle Bakken member perpendicular to beddings.

The brittleness index values were calculated with the measured Young's modulus and Poisson's ratio. Based on the distributions of tested data, the data of ym_{min} , ym_{max} , pr_{min} , and pr_{max} were set as listed in Table 1. It should be noted that the values in Table 1 are the maximal and minimal values in the measured data range of entire Bakken formation (Grieser and Bray 2007), including the upper, middle, and lower members.

Table 1 Parameters used in elastic property-based brittleness index calculation

Group	ym_{min} , GPa	ym_{max} , GPa	pr_{min}	pr_{max}
Parallel	0	120	0.05	0.5
Perpendicular	0	100	0.05	0.5

The distribution of brittleness indexes of parallel plugs is shown in Fig. 5. Frequency (y -axis) indicates the number of BI values per unit interval on the x -axis. Most specimens have a brittleness index between 55 and 80. A large portion of the specimens indicates very brittle characteristics: about 50% of the specimens have an index values higher than 60.

Fig. 5. Histogram and distribution of BI_{ep} at middle Bakken member, parallel to beddings.

Fig. 6 shows the distribution of brittleness index of the perpendicular group. Most of the values are in the range between 60 and 70. Over 80% of the plugs have index values higher than 60. Similar to the parallel group, the formation has very brittle characteristics in the direction perpendicular to beddings. These results are consistent with the fact that hydraulic fracturing has been extensively and successfully applied in the Bakken formation.

Fi. 6. Histogram and distribution of BI_{ep} at middle Bakken member, perpendicular to beddings.

4.2 Correlating mineralogy with measured elastic properties

Mineralogy of middle Bakken member has been investigated intensively. Mineral contents detected by X-ray diffraction (XRD) technology were presented by Sorensen *et al.* (2010), Alexandre *et al.* (2011), Sonnenberg *et al.* (2011a), Sonnenberg *et al.* (2011b), etc. Major minerals in the middle Bakken include clay, calcite, quartz, dolomite, and feldspar. In general, contents of calcite and quartz have a greater variation than the others. Based on the variation of mineralogy from these literature, the composite elastic properties were calculated as a function of clay and quartz contents, respectively. In material science, there are two general approaches to predicting properties of a composite material: the Voigt model, used for axial loadings, and the Reuss model, used for transverse loadings (Younes *et al.*, 2012). These two models provide the upper and lower bounds of the predicted material materials. Therefore, in this study, elastic properties of the rocks in the direction parallel to beddings were calculated following the Voigt model, and properties in the direction perpendicular to beddings were calculated following the Reuss model. Parameters use to calculate the composite properties are listed in Table 2. The calculation results are displayed in Fig. 7.

Table 2 Major mineral content of middle Bakken member.

Mineral	Fraction	Young's Modulus, GPa	Poisson's Ratio
clay	15%	22	0.25
calcite	5~50%	45	0.3
quartz	60~15%	87	0.07
dolomite	15%	55	0.26

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Fig. 7. Variation of Young's modulus and Poisson's ratio with calcite and quartz contents, middle Bakken member.

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In the direction parallel to the bedding planes, Young's modulus varies between 51 and 70 GPa and Poisson's ratio varies between 0.15 and 0.25. The calculated composite properties are indicated by the red box in Fig.8, which is located in an area with the densest measured data points. The calculated composite properties fit the experimentally-obtained data. The corresponding brittleness index, calculated in Table 3, is between 49 and 68, which also fits the range of BI_{ep} obtained from test results (Fig. 5).

Fig. 8. Comparison between composite and measured elastic properties, parallel to beddings, middle Bakken member.

Table 3 Composite elastic property based brittleness index parallel to beddings, middle Bakken member.

Young's modulus, GPa	Poisson's ratio	BI_{ym}	BI_{pr}	BI_{ep}
51	0.25	43	56	49
70	0.15	58	78	68

In the direction perpendicular to the beddings, the Young's modulus varies between 45 and 57 GPa and Poisson's ratio varies between 0.10 and 0.19. The calculated composite properties also well fit the experimentally-obtained data, as shown in Fig. 9. The corresponding brittleness index, calculated in Table 4, is between 56 and 72, which is consistent with the BI_{ep} obtained from test results in Fig. 6.

Results displayed in Figs. 8 and 9 validate the correlation between the elastic properties and mineralogy. Assuming the rock is a composite material made of different mineral components, and applying the Voigt and Reuss models, the calculated Young's modulus and Poisson's ratio fall in the range of laboratory-measured data.

Fig. 9. Comparison between composite and measured elastic properties, perpendicular to beddings, middle Bakken member.

Table 4 Composite elastic property based brittleness index perpendicular to beddings, middle Bakken member.

Young's modulus, GPa	Poisson's ratio	BI_{ym}	BI_{pr}	BI_{ep}
43	0.19	43	69	56
55	0.10	55	89	72

5. Estimation of mechanical properties of upper Three Forks formation

Mineralogy of the upper Three Forks formation were studied by Sonnenberg *et al.* (2011a), Sonnenberg *et al.* (2011b), Bottjer *et al.* (2011), LeFever *et al.* (2013), and Ashu (2014). Major elements detected by XRD include quartz, dolomite, clay, and feldspar. The correlation between mineralogy and elastic properties derived in Section 4 was used to estimate the brittleness of the upper Three Forks formation. Based on the variation of mineralogy in the aforementioned literature, the composite Young's modulus and Poisson's ratio were calculated as a function of dolomite content and quartz content, respectively. Properties parallel to beddings were calculated following the Voigt model, and properties parallel to beddings were calculated following the Reuss model. Parameters used to calculate the composite properties are listed in Table 5. As shown in Table 5, the major mineral content of upper Three Forks is close to that of the middle Bakken (Table 2). The calculated elastic properties as a function of quartz and dolomite contents are shown in Fig. 10.

Table 5 Major mineral content of upper Three Forks formation.

Mineral	Fraction	Young's Modulus, GPa	Poisson's Ratio
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clay	13%	22	0.25
calcite	5-47%	45	0.3
quartz	62-20%	87	0.07
dolomite	13%	55	0.26
k-feldspar	7%	70	0.28

Fig. 10. Variation of Young's modulus and Poisson's ratio with calcite and quartz contents, upper Three Forks formation.

In the direction parallel to the beddings, Young's modulus varies between 54 and 67 GPa and Poisson's ratio varies between 0.15 and 0.23. The corresponding brittleness index, shown in Table 6, is between 53 and 67, comparable with the BI_{ep} obtained from tested results. As indicated in Fig. 11, the elastic properties of the upper Three Forks formation in the parallel-to-beddings direction is located in the brittle region, similar to the middle Bakken member.

Fig. 11. Comparison between composite elastic properties of upper Three Forks formation and measured elastic properties of middle Bakken member, parallel to beddings.

Table 6 Composite elastic property based brittleness index parallel to beddings, upper Three Forks formation.

Young's modulus, GPa	Poisson's ratio	BI_{ym}	BI_{pr}	BI_{ep}
54	0.23	45	60	53
67	0.15	56	78	67

In the direction perpendicular to the beddings, the Young's modulus varies between 45 and 51 GPa and the Poisson's ratio varies between 0.10 and 0.18. These predicted results are close to the well-logging derived values (Sonnenberg *et al.*, 2011b). The well-logging derived Young's modulus is between 45 and 55 GPa, and the well-logging derived Poisson's ratio is between 0.10 and 0.20 (Sonnenberg *et al.*, 2011b). The corresponding brittleness index, calculated in Table 7, is between 58 and 70. As indicated in Fig. 12, the elastic properties of the upper Three Forks formation in the perpendicular-to-beddings direction is located in the brittle region, similar to the middle Bakken member.

Fig. 12. Comparison between composite elastic properties of upper Three Forks formation and measured elastic properties of middle Bakken member, perpendicular to beddings.

Table 7 Composite elastic property based brittleness index perpendicular to beddings, upper Three Forks formation.

Young's modulus, GPa	Poisson's ratio	BI_{ym}	BI_{pr}	BI_{ep}
45	0.18	45	71	58
51	0.10	51	89	70

From the results in Tables 6 and 7, it is obvious that the upper Three Forks formation rock can be categorized as brittle, with its predicted BI_{ep} higher than 40 both parallel and perpendicular to the bedding planes. Figures 11 and 12 indicate that brittleness of the upper Three Forks formation is comparable to the middle Bakken in directions, although the predicted BI_{ep} of upper Three Forks formation is lower than the medium BI_{ep} value of the middle Bakken member.

6. Conclusions

Successful development of the upper Three Forks reservoir will require large-scale stimulation similar to the producing middle Bakken member, but detailed information on the upper Three Forks formation characteristics remains unknown. As with all unconventional plays, there are clearly delineated areas of highly productive acreage (Chang 2014). Brittleness is key in assessing the tight reservoir potential and selecting fracturing intervals and areas. Based on the theory that elastic properties are controlled by the mineral composition and diagenesis process, this study presents a methodology to predict the brittleness of the formation rock based on its mineralogy. In this methodology, the rock was treated as a composite material and its elastic properties were calculated by the rule of mixtures. Properties parallel to beddings

were calculated by the Voigt model, and properties perpendicular to beddings were calculated by the Reuss model. The calculated composite elastic properties and brittleness were verified by the experimentally-obtained results of the middle Bakken samples as displayed in Figs. 8 and 9. Then this correlating approach was applied to predict the brittleness of the upper Three Forks formation. The predicted brittleness of the upper Three Forks formation is greater than 40 both parallel and perpendicular to bedding planes, comparable with the producing middle Bakken member. Therefore, the upper Three Forks reservoir should be as conducive to fracking as the middle Bakken. Laboratory measurement of rock mechanical properties and well logs are relatively expensive and time consuming, whereas the mineralogy of the formation is easier to obtain than its geomechanical properties. Therefore, this method provides an alternative approach to predict the properties of the reservoir when there is limited access to test data.

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Nomenclature

Symbols

<i>BI</i>	brittleness index
<i>Ca</i>	calcite content
<i>Cl</i>	clay content
<i>Dl</i>	dolomite content
<i>E</i>	elastic property
<i>f</i>	fraction
<i>Pr</i>	Poisson's ratio
<i>Qz</i>	quartz content
<i>TOC</i>	total organic carbon
<i>ym</i>	Young's modulus (GPa)

Subscripts

<i>comp</i>	composite
<i>ep</i>	elastic property-based
<i>i</i>	mineral component <i>i</i>
<i>max</i>	measured maximum value

<i>min</i>	measured minimal value
<i>minl</i>	mineral-based
<i>pr</i>	Poisson's ratio-based
<i>ym</i>	Young's modulus-based

Units

bbl	barrel
ft	feet
GPa	gigapascal
MPa	megapascal

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