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NEW MODEL OF BRITTLENESS INDEX TO LOCATE THE SWEET SPOTS FOR HYDRAULIC FRACTURING IN UNCONVENTIONAL RESERVOIRS

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ABSTRACT

Rock characterization in term of brittleness is necessary for successful stimulation of shale gas reservoirs. High brittleness is required to prevent healing of natural and induced hydraulic fractures and also to decrease the breakdown pressure for fracture initiation and propagation. Several definitions of brittleness and methods for its estimation has been reviewed in this study in order to come up with most applicable and promising conclusion. The brittleness in term of brittleness index (BI) can be quantified from laboratory on core samples, geophysical methods and from well logs. There are many limitations in lab-based estimation of BI on core samples but still consider benchmark for calibration with other methods. The estimation of brittleness from mineralogy and dynamic elastic parameters like Young's modulus, Poison's ratio is common in field application. The new model of brittleness index is proposed based on mineral contents and geomechanical properties, which could be used to classify rock into brittle and ductile layers. The importance of mechanical behavior in term of brittle and ductile in shale gas fracturing were also reviewed because shale with high brittleness index (BI) or brittle shale exist natural fractures that are closed before stimulation and can provide fracture network or avenues through stimulation. The brittle shale also has low breakdown pressure and no fracture healing as compared to ductile shale. The integration of laboratory and geophysical methods (determination of P and S waves from well logs) are recommended for accurate estimation of brittleness index (BI) for shale gas reservoirs.

Keywords: new model of brittleness index, hydraulic fracturing, shale gas reservoirs.

1. INTRODUCTION

The increasing demand of energy urged the exploitation of unconventional hydrocarbon reservoirs especially in shale gas. The shale gas has ultra-low permeability that need enhancement of production rate through hydraulic fracturing stimulation. The successful stimulation is needed with low proppant embedment and high stimulated reservoir volume (Wang and Gale, 2009). The rock mechanical properties and mineralogy are playing crucial role for efficient stimulation.

The mechanical behavior of rock is divided into brittle and ductile [1] [2] [3]. Brittle shale contains more natural fractures and easily fractured by hydraulic stimulation. While ductile rock cause fracture healing [4], [3]; [5]. The mechanical response of source rock is described by term brittleness or fracability [3], [6] [7] [8]. Unfortunate, there is no uniform definition exist for brittleness. According to current studies [9] [10] [1] [11] [4] [12] [8] brittle rock has following characteristics i.e. low value of elongation upon loading, fracture failure, formation of fine particles, higher ratio of compressive to tensile strength, higher internal friction angle, greater percentage of brittle minerals, higher value of Young's modulus, lower value of Poison's ratio, strength reduction occur with failure, and brittle rock fail in an intensive way.

The estimation of brittleness is important in many fields including shale gas recovery through stimulation. During hydraulic fracturing stimulation, a pressure fluid is injected to create fractures or avenues through which gas can flow to wellbore easily. However, the ability of shale to make fractures is described by brittleness because brittle shale can be fractured easily as compared to ductile shale where proppants healing usually happen. Therefore, there is need to have correct estimation of brittleness in order to maximize the production.

1.1 Concept of Brittleness

It is mechanical property of rock and due to non-uniform definition different researchers define and use brittleness for their respective practical use i.e. Brittleness is lack of ductility [47], in brittle behavior there is no plastic deformation [48], a rock will show brittle behavior when its internal cohesion will exceed [47] brittle rock make fracture with little or no plastic flow [49], [50]. The brittleness can be measured from stress strain curve obtained by triaxial compressive tests i.e. ratio of elastic strain to total strain at failure. The most acceptable definition proposed by [9] that fractures in brittle rock initiated at or slightly beyond yield stress and they further observed following characteristics in brittle rock i.e. fracture failure, higher ratio of compressive to tensile strength, low values of elongation of grains higher toughness; higher angle of internal friction, formation of cracks in indentation. Brittleness can be measured from mineralogy, static and dynamic mechanical properties and expressed in index [13], [14] [15], [50], [11]. [16][7]

2. ESTIMATION OF BRITTLENESS INDEX

2.1 Brittleness based on Mineralogy

Brittle minerals in shale reservoir are responsible for fracture initiation or network [11]. Brittleness is now

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calculated by term known as brittleness index ([14], [15]). Brittle minerals play the key role in stimulations, increasing interface between reservoir and the well bore ([11]). However, there is no standard criteria exist for brittle minerals. The quartz, feldspar, and carbonates are considered brittle while clay minerals are ductile that decrease brittleness index [50] [17] [18]. The most brittle mineral is quartz that contribute to high brittleness as shown in Figure-1. The productive well in Barnett shale were located in pay zone with quartz (45%) and clays (27%) and the brittleness can be quantified on bases of mineralogy using equation 1 given below [11]: Some researchers pointed out that quartz is more brittle than carbonates, so carbonate minerals should be treated only partially brittle [55]. However, previous studies have documented that both quartz and carbonate minerals are favorable for hydraulic fracturing [56], [57]. The higher magnitude of brittleness index makes the rock brittle and suitable for fracturing [13]. The mineralogy can be finding from laboratory analysis such as X-ray diffraction testing (XRD).

Each mineral has its own brittleness factor as shown in Figure-4 [21] BI > 40% considered brittle and BI > 60% considered highly brittle [22]. Brittleness based on mineralogy may have some limitations because to get mineralogy of deep shale is complex and expensive [23] but mineralogy from well logs is quite economical as compared to laboratory. [23] reviewed the literature and found that weight percentage of minerals may not give precise description of brittleness because two rock mass with same mineralogy can have different porosity and density due to different compaction history and based on this explanation the strength and failure process may be different. According to [24] rock grain and cementation also affect the brittle behavior of rock and also compressive stresses effect the brittleness [3] [7] [25]. Therefore, all the brittle minerals i.e. Silicates (quartz, feldspar and mica) and carbonates (limestone, dolomite, and siderite) and ductile (clays) should be consider in order to accurately determine brittleness Index based on mineralogy. However, there may be different value of BI on same rock using different approaches because the lithology and mineralogy is changing from rock to rock. Therefore, along with mineralogy the other properties like grain size, cementing material, acoustic properties and mechanical properties of rock should be considered.

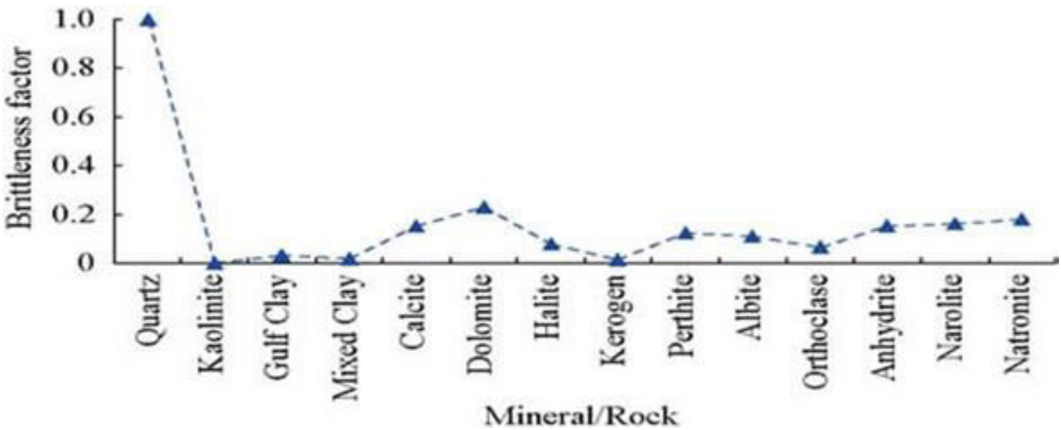

Figure-1. Brittleness factor of several minerals [21].

2.2 Brittleness based on dynamic mechanical properties

Brittleness can be quantified from Young's modulus and Poison's ratio because they represent the mutual effect of stress and strain and more accurate than individual use of stresses and strains [23]. For brittle rock the Young's modulus should be high while Poison's ratio should be low and in such condition the shear modulus will be high under brittle failure [26]. The high young's modulus and low poison's ratio under brittle failure has been confirmed by many researchers [20], [22] [27]. The relationship between young's modulus and poison's ratio for brittleness as shown in Figure-2. The elastic parameters can be estimated both in laboratory and through wireline logs. The calibration is required between log-based and core-based parameters, and calibrated elastic parameters should use to estimate brittleness index (Equation 1-3) [57].

$$YM.log = \rho V^2 \frac{3V_p^2-4V_s^2}{V_p^2-V_s^2} \quad \text{…..………….. Equation (1)}$$

$$PR.log = \frac{V_p^2-2V_s^2}{2V_p^2-2V_s^2} \quad \text{…………….Equation (2)}$$

$$BI\_1 = \frac{\dfrac{100(YM.Cali.-YM\_Cali_{\min})}{(YM\_Cali_{\max}-YM\_Cali_{\min})}+\dfrac{100(PR\_Cali-PR\_Cali_{\max})}{(PR\_Cali_{\min}-PR\_Cali_{\max})}}{2} \quad \text{…………….Equation (3)}$$

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Where YM.log and PR.log are dynamic Youngs modulus and poison's ratio based on well logs. V_s and V_p are secondary and primary waves from sonic logs in ms/ft, ρisthebulkdensity.YM. Cali and PR- Cali are calibrated Youngs modulus and poison's ratio respectively, and $YM.Cali_{min}$, and $YM.\ Cali_{max}$ area minimum and maximum Youngs modulus respectively, where $PR\text{-}Cali_{min}$ and $PR\text{-}\ Cali_{max}$ are minimum and maximum poison's ratio It can be in average of brittleness based on Young's modulus (E) and brittleness based on Poison's ratio as given below [28]; [18]. The static elastic parameters can be found from dynamic values by using equations4 and 5below:

$E_s = E_d \times (0.8 - \varphi_{total})$ …………….……. Equation (4)

Or

$E_s = (\frac{E_d}{3.3674})^{2.042}$ ………………..………. Equation (5)

Where, E_s and E_d and φ_{total} are static young's modulus, dynamic young's modulus and total porosity respectively. The brittleness based on equation 3 for Chang 7 tight shaly sandstone in Ordos's basin showed positive correlation with Young's modulus while negative correlation with Poison's ratio [20]. the optimal hydraulic fracturing layers identified in XC32 well was on layer with high value of Young's modulus and lower value of Poison's ratio [28]. The brittleness index were also calculated by taking average of young's modulus (E) and poison's ratio (v) as shown in equation 6 [24], whereas, Sun replace the young's modulus (E) with new parameter Erho (Eρ: multiplication of young's modulus and bulk density) to evaluate brittleness index as shown in equation 7 [62].

$BI = \frac{E}{V}$ …………….……………… Equation (6)

$BI = \frac{E\rho}{V}$ …….………………..…. Equation (7)

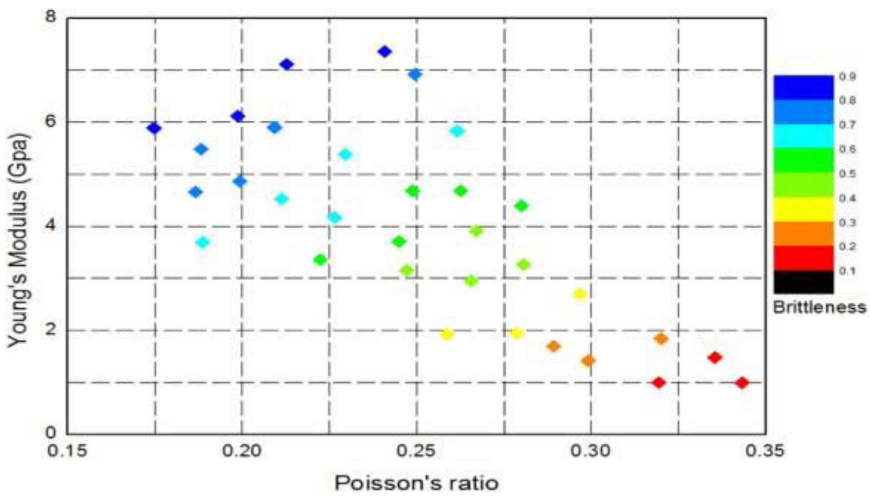

Figure-2. Showing variation of BI with Young's modulus and Poison's ratio [14].

2.3 Brittleness based on static mechanical properties

2.3.1 Unconfined compressive strength (UCS) and Brazilian tensile strength (BTS)

These two experiments measure rock mechanical properties in laboratory by using core samples. The UCS give compressibility of rock while BTS measure cohesion between rock grains [9] The brittle rock must have low BTS and high UCS because brittle rock has low BTS that easily make tensile fracture propagation and initiation and rock with high UCS resist the closure of natural and induced fractures ([29]). The following equation use for brittleness evaluation 8 and 9 given below:

$BI = \frac{\sigma_c}{\sigma_t}$ …………………………………..… Equation (8)

$BI = \frac{\sigma_c - \sigma_t}{\sigma_c - \sigma_t}$ …..……………. Equation (9)

Where, σ_c is the unconfined compressive strength, and σ_t is the Brazilian tensile strength [13] Goktan established correlation shown below in equation (10) to find brittleness and they used equation 8 and 9 and found very meaningful correlation of brittleness based ontheir proposed correlation with specific energy of rock cutting efficiency as shown in Figure-3.

$BI = 2.065 + K(log\sigma_c)^2$ ……..………… Equation (10)

Where k is constant and depend upon rock type as grouped by Hoek and valued from 0.170-0.659.

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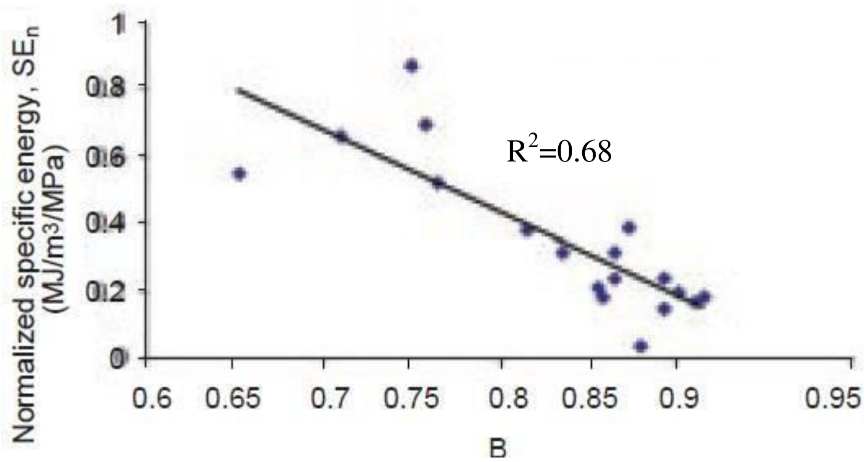

Figure-3. Showing positive correlation of brittleness based on equation 18 with SE (specific energy) [13].

The rock cutting efficiency depend upon compressive and tensile strength of rock that can be quantified using equation 11. The unreliability of equation 9 and 10 were also observed because there was no meaningful correlation found between brittleness based on these two equations (9 and 10) with specific energy for rock cutting while very positive correlation found between brittleness based on equation 19 with specific energy (SE) and density as shown in Figure-4 [30] below:

$$BI = \frac{\sigma_c \sigma_t}{2} \quad \text{………………..… Equation (11)}$$

Where brittleness determined from area under line of σ_c (compressive strength) and σ_T (tensile strength).

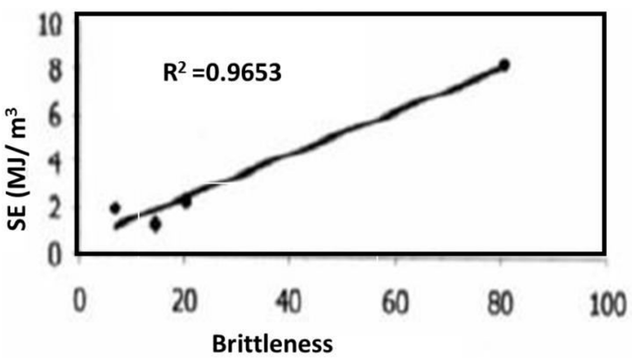

Figure-4. Showing positive correlation of BI based on equation 19 with specific energy values [60].

The brittleness can be quantified from UCS, tensile strength and density by using equation 12 below [31]:

$$BI = 0.198\sigma_c - 2.174\sigma_t + 0.913\rho - 3.807 \quad \text{… Equation (12)}$$

These above BIs derived from mechanical properties measured in laboratory and show positive relationship with confining stress [12] but rock behave ductile at high confinement which create doubts [23]. Secondly, every rock has its own geological and other properties that may give different results by using nay empirical relations that were proposed on specific rock type.

2.3.2 Brittleness from Punch penetration test

This test used for quantification of hardness, brittleness, toughness and drillability [23]. Brittleness can be quantified from force penetration graph (Figure-5) by using equation 13 ([31], [32]

$$BI = \frac{F_{max}}{P} \quad \text{…………..… Equation (13)}$$

Where F_{max} is maximum applied force and P is the penetration in mm [32]. In Figure-8 the curve with more fluctuation of force and penetration gave high line gradient that is indictor of high brittleness and this brittleness is more useful in investigation of drillability and rock tunneling assessment and [31] also gave limits for brittleness and ductility.

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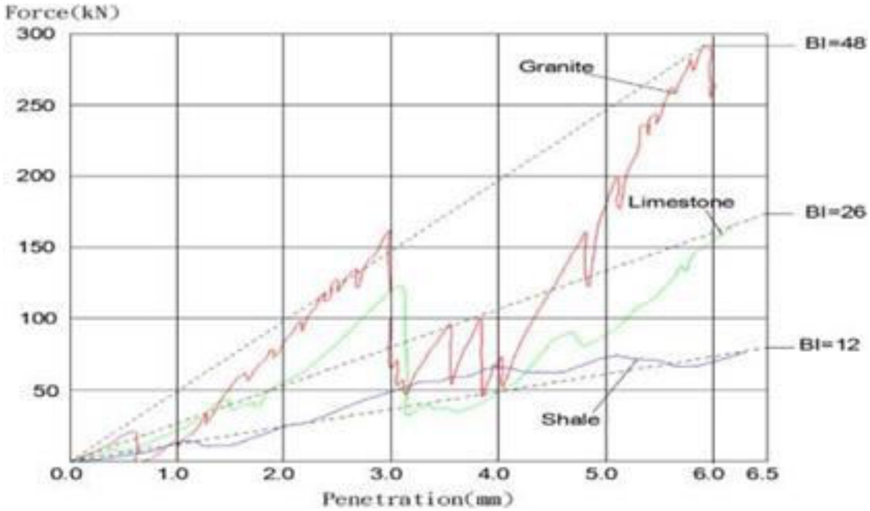

Figure-5. Showing force penetration chart of different rock [31].

2.3.3 Impact test and hardness test

The Protodyakonov (1962) [51] gave the expression for brittleness quantification based on Protodyakonov impact test and UCS by using equation below. The quantification of brittleness was based on concept that brittle rock breaks in to higher ratio of fine to coarse fragments under impact because the formation of fines depends upon degree of impact and UCS where it forms with loss of cohesion and usually brittle failure occur due to loss of cohesion.

$BI = q\sigma_c$ ………………………………… Equation (14)

where q represents percentage of fines (-28 mesh) and $\sigma_c$is UCS. This approach is usually used to investigate performance of percussive drilling.Honda and Sanada quantified rock brittleness based on concept that brittle rock has more ability to make cracks during indentation tests by using equation 15 below. They checked macro and micro indentation hardness by using large and small sized in-debtors respectively [52]. [58].

$BI = \frac{H_\mu - H}{K}$ …………..……….…………… Equation (15)

Where Hμ is micro indentation hardness, H is macro indentation hardness and K is constant. These geotechnical approaches proved effective in drilling purposes. However, these approaches may not be reliable in estimation of rock brittleness for shale fracking or any other application.

2.4 Brittleness based on porosity and grain size

Porosity has direct effect on flow ability, strength and deformational behavior of rock. The rock in depth has less porosity and more density and strength as compared to outcrop rock due to its more compaction or digenesis. The deformational behavior, density and strength of rock decrease with increase in porosity. The UCS of sandstone, shales, limestone and dolomite decrease with increase in porosity [33]. The enhancement in deformational ability or strain rate with shrinkage of micro cracks and pores during triaxial compression testing proved the negative impact of porosity on deformation ability. These facts clearly showing that brittleness decrease with increase in porosity. The negative correlation of brittleness based on mineralogy with neutron porosity were also observed on Barnett, Woodford and Eagle Ford shales shown in Figure 6 and the empirical relation for brittleness quantification can serve as a benchmark. A global correlation proposed as shown
[20] below:

$BI = -1.8748 \times \phi + 0.9679$ ……………..Equation (16)

where φ is neutron porosity.

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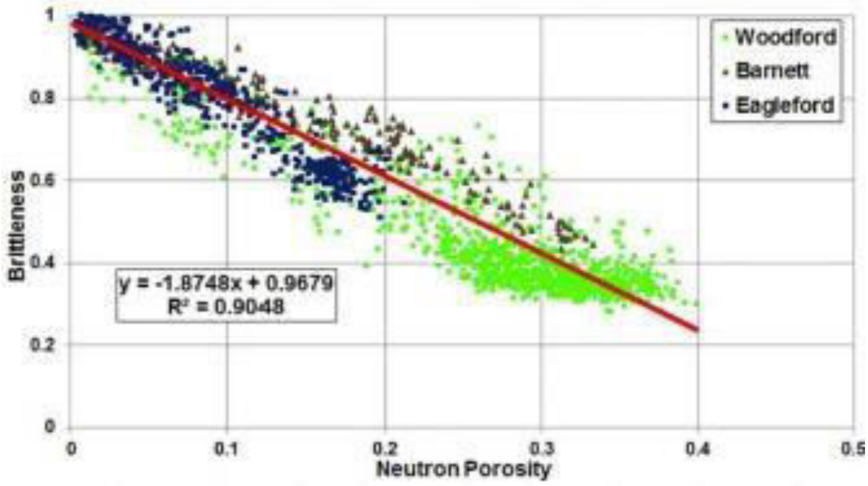

Figure-6. Showing negative correlation of neutron porosity with brittleness [19].

However, some researcher opposed this negative relationship of porosity with brittleness and they claimed that highly porous rocks has more ability to fail and make fracture during hydraulic fracturing [34] which is opposite to above correlation. Heidari also showed that there is no direct relationship of tensile strength and UCS with porosity [35]. However, each rock has its own characteristics and empirical relation of one rock may not work on other rock.

2.4.1 Grain size-based analysis

The grain size also effects on rock's brittle behavior, the rock with homogeneous fine grained is less brittle as compared to heterogeneous coarse - grained rocks [10]. Eberhardt found more breaking in coarse grained pegmatite and the rack initiation and propagation is more as compared to fine grained granidioirite and grey granite which are similar to pegmatite in composition and even in same in-situ stresses and environmental condition. According to Eberhardt, larger grain due to its larger and longer inter-granular cracks in them require less stress for crack initiation and propagation because according to Griffith theorem, stress need in fracturing decrease with increase in length of crack [51] that can be equal to grain size of rock mass [36] [23].

$$\sigma_f = \sqrt{\frac{2E_\gamma}{\pi\alpha}} \qquad \text{…………… Equation (17)}$$

Where σ_f is stress required during fracturing, E is Young's modulus, γ is surface energy, α is length of fracture. The effect of grain size also observed in AE performance where fine grainedgranidiorite showed 60% and 90% less AE event as compared to coarse grained grey granite and pegmatite [36]. The relationship between relative brittleness measured from point load test and grain size was observed and results indicated that relative brittleness with larger grain size is greater than other two granite samples with similar composition [37] [38]. Furthermore [37] there is weak intergranular planes and feldspar cleavage in coarse grained minerals that make fracture initiation and propagation easier than fine grained rock [37].Based on the facts it has been clear that larger grain size is more prone to fracture initiation and propagation during fracturing.

2.5 Internal friction angle and over consolidation ratio approach

2.5.1 Brittleness based on internal friction angle

The internal friction angle has significant impact on rock brittleness which implies that brittle rockhas high internal friction angle. The internal friction angle can be found from Mohr circle as where the normal stresses increase that reduce the internal friction angle and consequently, reduce brittleness. The brittleness can be quantified from internal friction angle [9] as shown below:

$$BI = Sin \qquad \text{……….…… Equation (18)}$$

The internal friction angle can also be found from oblique shear plane angle from Mohr envelope by following equation

$$BI = \frac{\pi}{2} - 2\alpha \qquad \text{…………… Equation (19)}$$

Where 2α is the oblique shear plane angle.

Internal friction angle can also be found from well log data. Internal friction angle decreases with increase in porosity. The internal friction angle can be quantified using sonic log [39] as shown below:

$$Sin\theta = \frac{V_p - 100}{V_p + 100} \qquad \text{…………………… Equation (20)}$$

However, to obtain accurate Mohr envelop many samples should be tested in laboratory which may limit the use of this laboratory approach because to get core samples of shale from greater depth is challenging and mostly the core samples not available in public domain.

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2.5.2 Brittleness based on Over-consolidation ratio (OCR)

The sedimentary rocks undergo many changings during digenesis, compaction and uplifting during burial process especially stresses because stresses has a significant effect on brittle and ductile behavior of rock and stresses during burial process is different than after burial process. Therefore, stress history should be observed because these changing in stresses alter mechanical properties like strength and brittleness of rock [40]. This stress history can be calculated in term of Over-consolidation ratio (OCR) as shown below:

$$OCR = \frac{\sigma'_v max}{\sigma'_v} \quad \text{Equation (21)}$$

Where σ'$_v$ max is maximum applied effective vertical stress in history (Pre-consolidation stress) and σ'$_v$ is current effective vertical stress. Where σ'$_v$ max can be obtained from UCS tests or well log data [59]. The σ,v max can be related with UCS (σ_c) because both are related to compaction and cementation of materials.

$$\sigma'_v\text{max} = 8.6(\sigma_v)^{0.55} \text{ or } \sigma'_v\text{max} = 1 \times 10^{-7}(V_p)^{205} \quad \text{Equation (22)}$$

The σ'$_v$max and σ'$_v$can be found from well log which is more easy and reliable way for reservoir evaluation.

The σ'$_v$max is greater than σ'$_v$, the OCR will be greater than Unity and it means rock has already over consolidated (OC). If σ'$_v$is greater than σ'$_v$, the OCR will be unity one and is called normally consolidated(NC). The greater the OCR the greater will brittle behavior and rock show stiffer shear stress-strain curves and distinct failure surfaces [55]. Nygard observed very close relationship between OCR and rock brittleness as shown below in such a way that brittleness will be enhance if OCR increase with increase in σ'$_v$max and decrease with σ'$_v$[52].

$$BI = OCR^b \quad \text{Equation (23)}$$

Where b is empirical constant. This method has been verified using field data of mud rock and shales obtained from North Sea [52]. According to wang and Gale, 2009 the uplifting of Barnet shale reservoir made exploration successful because deep burial makes the rock mature, brittle and later uplifting lower effective stress that increase OCR value [54].

2.5.3 Brittleness based on Stress – strain curve

The brittleness can be estimated from stress-strain curves based on strength and deformational performance of rock in such a way that brittle rock fail at low strain in elastic region while ductile rock fail at high strain under plastic region (inelastic).The ratio of elastic strain to total strain can quantify brittleness where high ratio corresponds to high brittleness.

$$BI = \frac{\epsilon_{el}}{\epsilon_{tot}} \quad \text{Equation (24)}$$

This BI ratio can be show on graph in such a way that draw line CE parallel to linear part of stress strain curve (AB), the BI will be ratio of horizontal projection EF of line CE that represent elastic strain and total strain that is OF in Figure-7.

The brittle part and ductile part can be distinguished based on energy aspects of elastic and inelastic deformation. Brittle rock deformed under elastic at low energy while ductile deform under plastic region with inelastic deformation at high energy because ductile rock continuously absorb energy and deform at great strain. The brittleness can be estimated based on energy aspects at failure by ratio of energy at elastic strain (W_{el}) area between CEF and energy at total strain (W_{tot}) area between OABCF [9].

$$BI = \frac{W_{el}}{W_{tot}} \quad \text{Equation (25)}$$

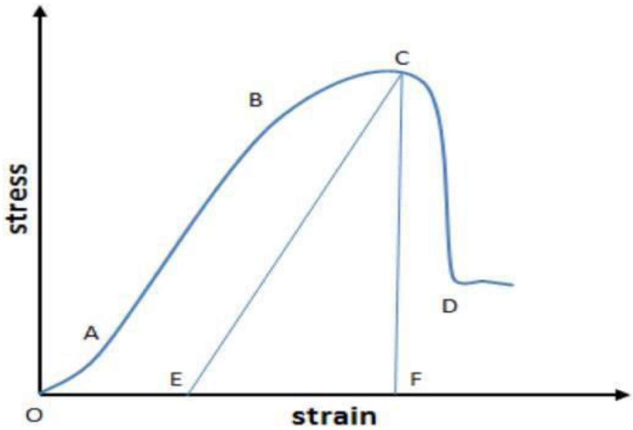

Figure-7. Showing stress- strain curve for brittle rock [61].

Brittleness can be estimated from irreversible longitudinal strain under axial load Andreev 1995 measured brittleness from irreversible longitudinal strain based on concept that brittle rock hasεli<3%, ductile rock hasεli>5% and transition range have εli equal to 3%-5% [53]

$$BI = \varepsilon_{li} \times 100 \quad \text{Equation (25)}$$

Brittleness can be estimated based on shear failure because rock under triaxial usually show shear failure. Brittle rock show sudden and great reduction in shear strength as shown in Figure-6 by large gap between point C and D while ductile rock show gentle reduction in strength. Bishop 1967 first estimated brittleness based on shear failure.

$$BI = \frac{\tau_p - \tau_r}{\tau_p} \quad \text{Equation (26)}$$

Where τ_p peak is shear strength and τ_r is residual shear strength.

The above equation reflect post failure behavior by considering only strength and ignored the confining stress because brittle rock show sudden and significant reduction in strength beyond peak strength and this behavior of brittle rock depend upon confining stresses and this behavior can be reduced by increasing applied confining stress that can transformed brittle to ductile behavior ([6] [7]. Such relationship cannot show stress or strain path difference. Therefore, confining stress must be considered that can be explained by strain performance [10]. For instance, in Figure-7 the BI value is same but stress paths are different due to post and pre stress- strain performance. Hajiproposed equation based on strain performance [10].

$$BI = \frac{\varepsilon^{p}{}_{f} - \varepsilon^{p}{}_{c}}{\varepsilon^{p}{}_{c}} \quad \text{.................. Equation (27)}$$

Where $\varepsilon^{p}f$ is plastic strain in which friction strength is mobilized and $\varepsilon^{p}c$is plastic strain at which cohesive strength reduce to residual value as shown in Figure-8.

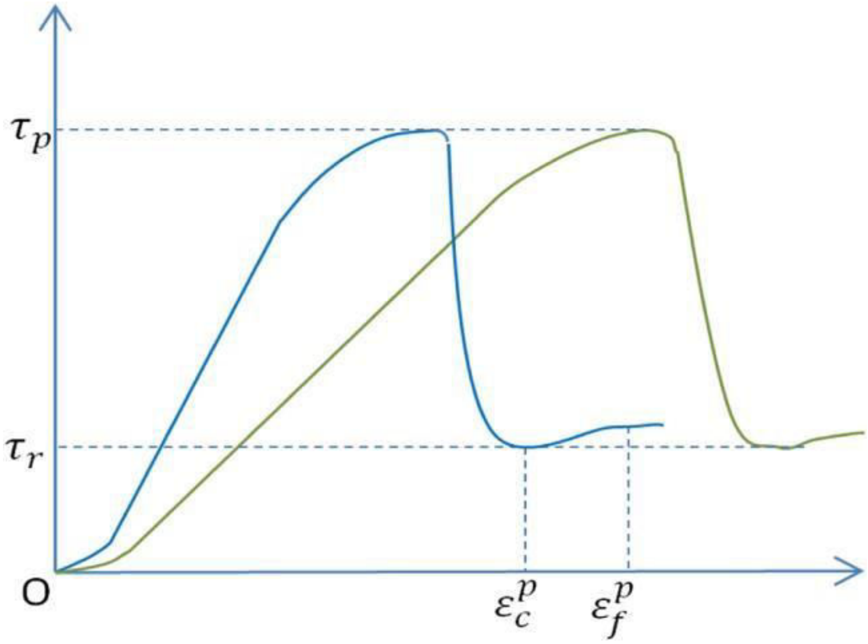

Figure-8. Showing stress-strain curves of rocks with same peak and residual strength but different stress path [10].

The $\varepsilon^{p}f$and$\varepsilon^{p}c$can be estimated from damage-controlled test [62] or stress-strain path back analysis [10]. For brittle rock value should be low (high cohesive strength-loss rates) and high (small friction-strengthening rates. However, this strain dependent BI also has some limitation [23] i.e. it considers only plastic strain and not strength gain and does not consider any strength development with strain development. Therefore, rocks with different stress-strain shapes may have same strain based BI values although they have different strength behavior. The best way to estimate brittleness is based on Young's modulus that combine both strength and strain performance

2.6 Brittleness based on geophysical approaches

The elastic constants like Bulk modulus, shear modulus and Young's modulus which are measure of material resistance to change in volume, measure of rigidity of rock and measure of stiffness of rock respectively used to find the brittleness of rock. These physical properties can be determined from P-impedance (Ip) and S-impedance (Is) and density from prestack inversion of surface seismic data like [41] determined rock physics parameters such as lame constants ((λ and μ)) from Ip and Is. [41] used $\lambda\rho$–$\mu\rho$) cross plot to predict brittleness of various shales and carbonates and showed that use of $\lambda\rho$–$\mu\rho$) withy Poison's ratio can differentiate brittle and ductile shales well as shown in Figure where quartz mineral found in lower $\lambda\rho$)and high $\mu\rho$)and relative increment in ultimate recovery of Barnet shale from 30% to 53% estimated with reduction of $\lambda\rho$) and in this method the effect of mineral and Poison's ratio was also noticed [41]. [42] also confirmed the validity of this cross plot for Barnett shale with microseismic experiments and showed that most of microsesimic event occur in brittle zones, few events in ductile shale and few in limestone fracture barriers. In $\lambda\rho$–$\mu\rho$) cross plot brittle shale has low ($\lambda\rho$) and high ($\mu\rho$) as shown in Figure-9. [43]) proposed new attribute of Eρ which is scaled version of $\mu\rho$) and good brittleness indicator and they showed that clusters in kρ- Eρcross plate discriminate well the lithology and fluid than kρ- $\mu\rho$. Good way *et al*. 2010 used the equation to find minimum horizontal closure pressure in term of λ and μ).

$$\sigma_{xx} = \frac{\lambda}{\lambda+2\mu}\left[\sigma_{zz} - B_v P_p + 2\mu e_{yy}\left(\frac{e_{yy}{}^{2zz} - e_{xx}{}^{2}}{e_{yy}{}^{2}}\right)\right] + B_H P_p \quad \text{Equation (28)}$$

where σ_{xx} is the horizontal closure pressure, σ_{zz} is the overburden stress, $\sigma_{yy}=\mu e_{yy}$ is the maximum horizontal stress, e_{xx} and e_{yy} are the strain on x and y axis, PP is the pore pressure, BV and BH are the vertical and horizontal poro-elastic constants, λ is Lame's first parameter, and μ is the shear modulus.

The effective vertical stress and maximum horizontal stress are transformed to horizontal direction aligned with minimum stress by λ/(λ+2μ) and λ) in numerator can dominate closure stress. Therefore, Guo measured brittleness by taking reciprocal of this term [44] i.e.

$$BI = \frac{\lambda+2\mu}{\lambda} \quad \text{……………………. Equation (29)}$$

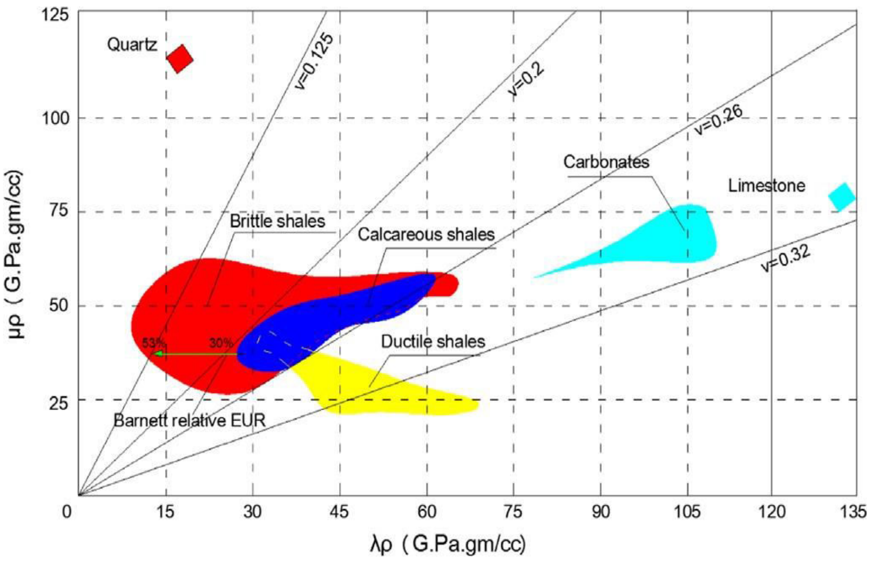

Figure-9. Showing difference of brittle and ductile rock based on λρ–mρ of different rocks [41]).

The brittleness can be estimated for gas bearing shales based on concepts that increase in porosity, organic content and gas content in pores cause an increase in E/λ value because high porosity, high organic matter and gas mean better production [17]:

$$BI = \frac{E}{\lambda} \quad \text{…………..…. Equation (30)}$$

The cross plotλρ–μρ) can effectively use rock brittleness that can screen out best candidates for fracturing. The brittleness estimation from well log is more reliable and easier than core data because of great thickness of reservoir, large cost, time consuming, fragile nature of shale, and un-availability of shale sample in public domain.

Based on the above literature review, it has been observed that that brittleness index is more related with elastic parameters, mineralogy and petrophysical parameters with respect to petroleum exploration. For instance, the brittleness index increases with an increase in young's modulus, and decrease in poison's ratio. Similarly, quartz and carbonates minerals increase the brittle characteristics of reservoir, meanwhile, porosity, clay mineral and total organic contents reduce the brittle behaviors of reservoir as documented in our previous studies [57]. Based on these concepts, new model of brittleness index is proposed to classify the rock into brittle, less brittle, ductile and ductile layers in equation 30 bellow;

$$BI = \frac{W_{sb}F_{sb}}{W_{sb}F_{sb}+W_{Cb}F_{Cb}+W_{wd}F_{wd}+W_{\varphi}\varphi} \quad \text{……… Equation (31)}$$

Where Q = quartz, Car = carbonates, Dol = dolomite, TOC = Total organic content, Wsb = weighing factor (0-1) for strong brittle minerals, Wwd = weighing factor (0-1) for weak ductile minerals, W_{Cb}= weighing factor (0-1) for carbonate minerals, F_{sb} = fraction of strong minerals like quartz, feldspar and Pyrite, Fwd = fraction of weak/ductile minerals like clays and TOC, F_{Cb} = fraction of carbonates , $W_{sb} = W_{wd} = W_{\phi}$= 1 and W_{Cb}=0.5 in case of BI6 while it is W_{Cb}= 1 in BI.

The total brittleness index can be computed by taking average of brittleness using above model and brittleness index based on elastic parameter. The rock with BI > 0.4 (40%) considered brittle and suitable for fracturing (Guo *et al.*, 2015).

2.7 Application of brittleness index in shale fracturing

Brittleness indexes have been used in rock mechanics as material evaluation in different field [23]. There are different empirical relations for brittleness estimation was proposed and they may give different BI on same rock and therefore institute condition should be considered [9], [6] [7]. The brittleness of reservoir plays important role in hydraulic fracturing stimulation of unconventional reservoir because brittle shale contains many pre-existing fractures that can create well distributed fractures and creation of new fractures in brittle shale is easier than ductile shale because more energy is required to create fractures in ductile rock [45].

There are different ways to estimate brittleness. The laboratory method is easy way to estimate BI on core samples but the brittleness based on laboratory test may be dubious because of change in stress, temperature and moisture content during extraction and preparation of samples damage samples and cause micro-cracking. The samples cannot represent the rocks in field condition [6], [46]. The shale has high level of heterogeneities', anisotropies, large thickness and wide horizontal coverage; the time-consuming samples can only give properties at specific points [19] while geophysical can give us 3-D view of shale properties which is more applicable [6]. Despite of limitations, laboratory method still remains the benchmark for calibration with other methods.

The best way to estimate the brittleness in insitu temperature, pressure, and stresses conditions is using well logs or surface seismic data. The log-based data then calibrate with lab-based results to get more accurate results of BI. The brittleness in this way can be validated by micro-seismic events and production performance [42]. However, the better understanding of concept and application of brittleness can optimize the performance of hydraulic fracturing stimulation treatment.

CONCLUSIONS

Following conclusions has been drawn by reviewing almost maximum approaches to find brittleness index (BI):

a) There is no uniform or standard definition of brittleness exist that can be used as standard. Each definition was proposed based on different purposes.

b) The brittleness is important in hydraulic fracturing stimulation treatment because brittle rocks require less amount of energy to create new fractures and brittle rock has already exist natural fractures that can increase interference between reservoir and well bore.

c) The estimation of brittleness is not easy because brittleness depends upon several rock properties like mineralogy, organic matter, porosity, grain size, failure parameters (Cohesion and internal friction angle), in-situ earth stresses. Therefore, all the properties of reservoir should be considered in determining accurate brittleness index. The new model considers the impact of effective parameters on brittleness index.

d) The brittleness Index from core samples may have many limitations but still consider benchmark for calibration with other methods.

e) The most promising and applicable way to and brittleness is based on well logs and geophysical methods because shale covered wide horizontal area and thickness that can be covered through geophysical methods.

f) The shale gas exploration highly depends upon geomechanical properties like brittleness and the integrating method of well logs and laboratory would be recommended to find BI in shale gas reservoirs.

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