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Identification of brittle and ductile zones in sandstone reservoir using well log analysis; a case study, Southern Indus Basin, Pakistan

I Khan[1], A Ismail[2], and I Ali[1]

[1] Department of Geological Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta Pakistan
[2] Department of Petroleum and Gas Engineering, University of Engineering and Technology, Lahore Pakistan

Email: ibraheemgeo12@gmail.com

Abstract. Brittleness and ductility play a very important role in the stimulation design of unconventional reservoirs as it controls the fracture length and shape of hydraulic fractures. The estimation of mechanical properties of the reservoir rock is very important for the successful execution of reservoir drilling, production, and development operations. In this study, the mechanical properties are calculated using well log responses for selected reservoir section after a quality check of the data. Brittleness is estimated from empirical correlations based on mechanical properties estimated from well logs response, uniaxial compression strength and tensile strength. High values of young modulus and corresponding low values of Poison's ratio were indicating the brittle zones in the reservoir. Brittle-ductile zone identification based on mechanical properties were giving consistent results. Brittle-ductile categorization is done for identification of brittle, less brittle, less ductile and ductile reservoir lithology in each studied well. It was found from the computer-assisted approach and graphical presentation that, there was a high brittleness in the lower part of the reservoir which is due to highly compressed shale formation. This part of the reservoir could be a good candidate for hydraulic fracturing if it satisfies all other constraints for a prospective reservoir.
Keywords: Brittleness, ductility, petrophysical properties, Southern Indus Basin, Pakistan

1. Introduction
The failure of the material depends upon the nature of the brittleness which is very effective in terms of the definition of sweet spots for hydraulic fracturing and assessment of the wellbore stability, [1, 2]. If a material breaks without any substantial deformation then it is called as of brittle [3]. This shows that if a material is brittle then there will be high options of fracture potential. Brittle rocks have no characteristics of ductility and plasticity and break straight after the loss of a stress-strain relationship. The transition of ductility to brittleness depends upon the magnitude of the stress applied to the material,[4]. The initiation of the fractures in the rock depends upon the applied stress and strength parameters, [5].

Depending upon stresses, strength attributes and mineralogical properties of the reservoir, numerous researchers have expressed brittleness into different definitions. The calculations of brittleness depend upon the selection of compatible approach according to reservoir conditions [6]. The lack of ductility of the material also shows the brittle nature of it [7, 8]. Brittleness is a very important factor in the identification of sweet spots which require precise indices to quantify [9]. The definition of brittleness on the basis of elastic waves is commonly used [10]. The brittleness of the unconventional reservoirs can be estimated using sonic and density logs. The brittleness index based on wireline log data needs to be correlated with other available indices [11].

The Sawan field lies in the Southern Indus basin extending beside eastern boundary of Pakistan [12]. The present study is confined to the discussion on Cretaceous rocks with special reference to the

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Goru Formation which has the main lithology of sandstone with low to high permeability along the depth section. Cretaceous rocks are widely distributed in different parts of middle Indus Basin. The reservoir is highly heterogeneous in terms of supply of sediment and conditions of the environment. The upper part of the reservoir has very good potential as a candidate of the reservoir in different parts of the Sawan field. In general, the depositional environment of the Goru formation is deep marine while the Lower Goru section is a combination of the barrier to deltaic environments [13, 14].

Figure 1. Base map of the studied area [15]

2. Material and Methods

For the study, three wells; Sawan-7 (Well-A), Sawan-8 (Well-B) and Sawan-9 (Well-C) of a gas producing field from middle Indus basin Pakistan was selected (Figure 1). All well logs suite and routine core analysis data were available for all studied wells (Table 1). The well trajectory of the wells is vertical with completion in sands of the lower Goru formation. All the wells have wireline suite containing gamma ray log, sonic log, density log, resistivity log. Petrophysical information measured from routine core analysis were porosity and permeability. Sonic logs, density log, the gamma-ray log was prominent in the estimation of mechanical properties from wireline log study. The estimated petrophysical properties from wireline log data of the wells were matched against the values of core data for the same reservoir interval.

Table 1. Available Data for Analysis.

Data	GR	DT4P	DT4S	RHOB	DRHO	LLD	Core Data
Well-A	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Well-B	Yes	Yes	Yes	Yes	No	Yes	No
Well-C	Yes	Yes	Yes	Yes	Yes	Yes	Yes

2.1 Quantification of Brittleness
Brittleness of the rock can be used to quantify the reservoir rock. Depending upon the different characteristics and availability of the data, many approaches have been proposed by the researchers [2, 13, 16].

The geomechanical properties of the reservoir; Young's modulus and Poisson's ratio are the properties, which consider both the effects of stress-strain and considered as a better approach to defining the brittleness of the reservoir. If the rock has low Poisson's ratio and high Young's modulus then the rock is considered as a highly brittle rock [17]. Low Poisson's ratio and high Young modulus are considered favorable factors for effective hydraulic fracturing of the brittle rocks [10].

2.2 Unconfined compressive strength (UCS) and Brazilian tensile strength (BTS) approaches
Uniaxial compression strength (UCS) and Brazilian tensile strength (BTS) are geomechanical properties, which can be measured by laboratory experimentation. UCS and BTS can be estimated using empirical equations as well [18, 19]. The ability of the rock to compress is shown by UCS while the force of cohesion between the grains of the rock is expressed by the magnitude of the BTS. The relative difference between UCS and BTS is the brittleness of the rock mass [20].

2.3 Geomechanical Cross plots
The brittleness of the rock can be analyzed using the cross plot of geomechanical properties whose results can be extended to ductile and brittle zones of the reservoir depth. Poisson ratio's and Young's modulus to create a cross plot for the brittleness assessment of the reservoir [21].

3. Research methodology
The research methodology is comprised of six steps. The first step is the identification of horizons and the next two are the estimation of petrophysical and mechanical properties. The last step is the identification of the ductile-brittle zone. The main steps to perform the study are explained in figure 2.

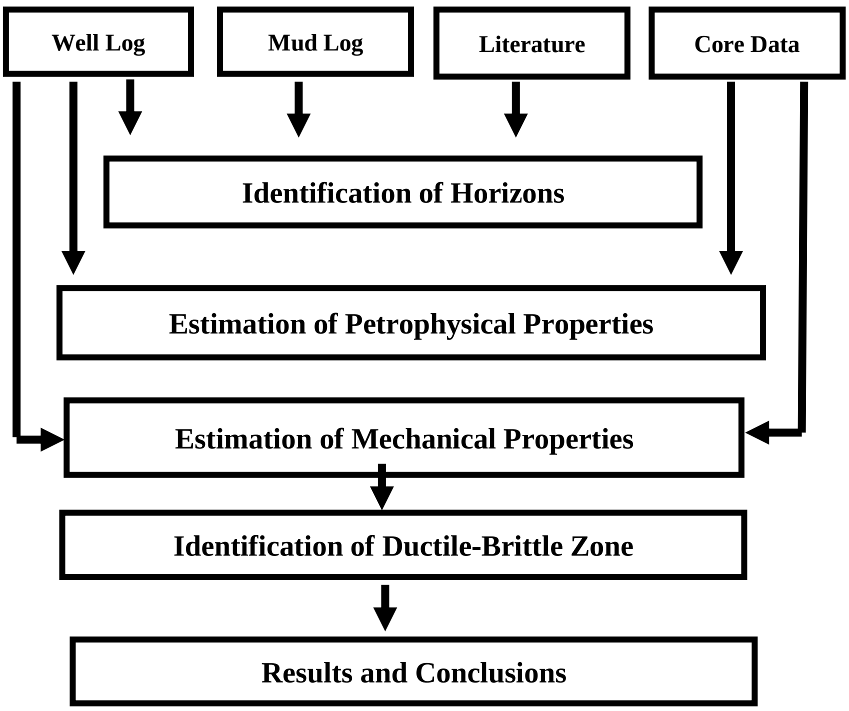

Figure 2. The methodology of workflow.

3.1 Identification of Horizon
The horizon is identified by curve matching technique in which the well log response of particular reservoir is matched with identified well log signature of the same reservoir. The particular signature for the studied reservoir was taken from literature was used for identification for the horizon.

3.2 Young's modulus
Dynamic Young's modulus (D_{ynamic}) and Static Young's modulus (E_{static}) can be estimated using shear wave velocity (Vp) and sonic wave velocity information (Vs) [22, 23].

$$E_{dynamic} = \rho_b V_s^2 \left(\frac{3V_p^2 - 4V_s^2}{V_p^2 - V_s^2} \right) \times 10^{-6}\, Gpa \quad (1)$$

$$E_{static} = 0.96 E_{dynamic} - 2.64\, Gpa \quad (2)$$

3.3 Dynamic Poisson's Ratio
Dynami Poisson's ratio ($\upsilon_{dynamic}$) can be estimated by equation while approach can be used for static Poisson's ratio (υ_{static}) calculation [23, 24].

$$\nu_{dynamic} = \left(\frac{V_p^2 - 2V_s^2}{2V_p^2 - 2V_s^2} \right) \quad (3)$$

$$\nu_{static} = 1.2437\, \nu_{dynamic} \quad (4)$$

3.4 Dynamic Shear Modulus
The dynamic shear modulus ($G_{Dynamic}$) and static shear modulus (G_{Static}) can be estimated as [22]

$$G_{dynamic} = \rho_b V_s^2 \quad (5)$$

$$G_{static} = \frac{E_{static}}{2\,(1 + 2\nu_{static})} \quad (6)$$

3.5 Dynamic Bulk Modulus
Dynamic ($K_{dynamic}$) and static (K_{static}) bulk modulus can be determined by empirical equations as [25].

$$K_{dynamic} = \frac{E_{dynamic}}{3\,(1 - 2\nu_{dynamic})} \quad (7)$$

$$K_{static} = \frac{E_{static}}{3\,(1 - 2\nu_{static})} \quad (8)$$

3.6 Unconfined Compressive Strength
The unconfined compressive strength (UCS) can be determined by using equation [18].

$$UCS = 254\ (1 - 2.7\phi)^2 \quad (9)$$

3.7 Brazilian Tensile Strength
The Brazilian Tensile strength can be obtained by using equation [10].

$$BTS = \left(\frac{UCS}{12.38}\right)^{1.0725} \tag{10}$$

3.8 Brittleness index

The brittleness index can be estimated by using equation [10].

$$E_{Brittleness} = \frac{E - E_{\max}}{E_{\max} - E_{\min}} \tag{11}$$

$$\nu_{Brittleness} = \frac{\nu - \nu_{\max}}{\nu_{\min} - \nu_{\max}} \tag{12}$$

$$BA = \frac{E_{Brittleness} + \nu_{Brittleness}}{2} \tag{13}$$

3.9 Identification of Brittle and Ductile Zone

By utilizing a computational approach, the analysis of the estimated mechanical properties is done. Using discriminant approach brittle and ductile zones are identified in two-dimensional space in each well. The brittle and ductile zones are identified and compared with offset wells.

4. Results and Discussions

In all the three wells brittle and ductile zones are identified by using computer analysis and graphical representation of data. Figure 4, shows high values of brittleness in the lower part of the formation as compared to upper section which is due to the presence of highly compressed shale rock whose strength increases than sandstone due to excessive overburden pressure in Well-A. In case, this part of the Zone satisfies the requirements of shale gas prospective, it is suitable depth for execution of hydraulic fracturing [15].

The identified brittle and ductile zones of the Zone were matching with the results concluded from Young's modulus and Poisson's ratio colour coding; the magnitude of higher values of Young's modulus and lower values of Poisson's ratio defines the range of brittleness. The newly drilled wells will have high stability in the lower part of the reservoir as compared to upper section due to the behavior of mechanical properties

From the cross-plot analysis of static Young's modulus and static Poisson's ratio, it is concluded that studied formation has both brittle and ductile zones. In Well-A, most of the data points were falling in the brittle area of the cross plot showing the high capacity of the formation for activities whose success depends upon the brittle behavior of the rock as shown in figure 3.

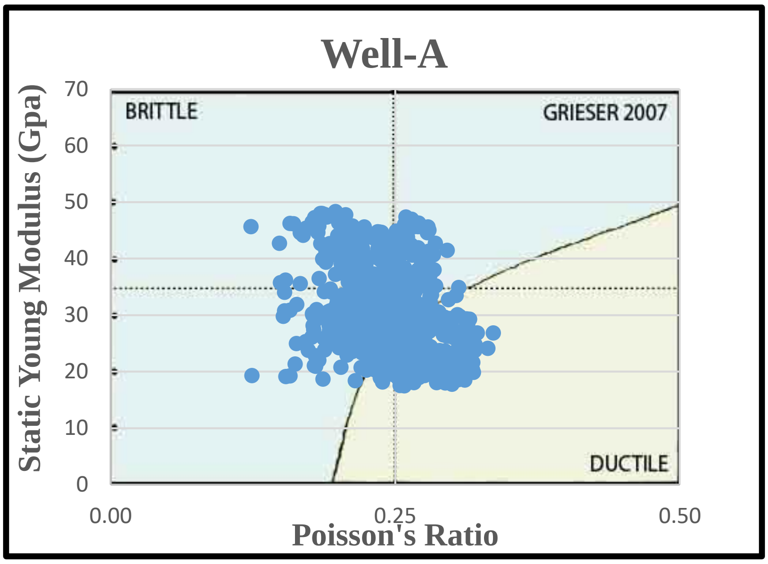

Figure 3. Cross plot of poison's ratio v.s Young's Modulus Well-A; most of the data points were falling in the brittle area of the cross plot in this well.

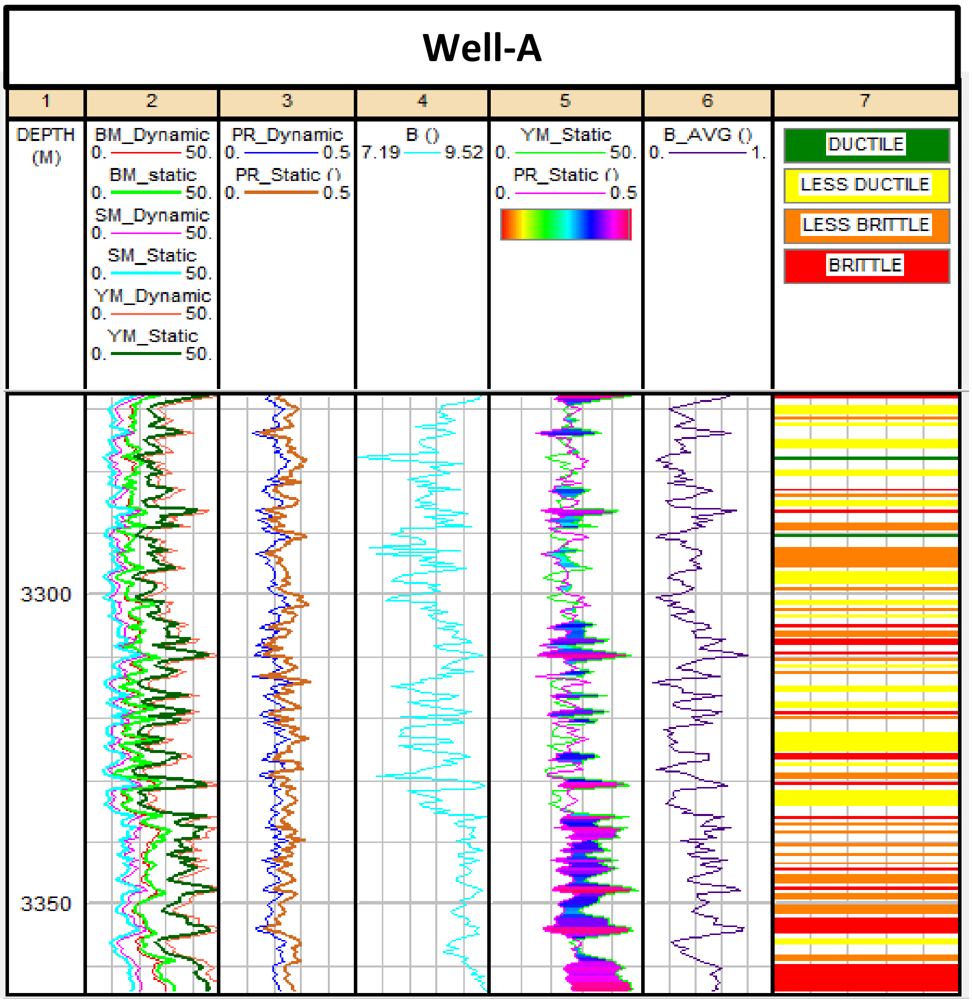

Figure 4. Discriminant analysis of Well-A; shows that studied formation has both brittle and ductile zones.

The erroneous values in Well-B were removed near 3300m, which caused a break in the trend of mechanical properties in all tracks of figure 6. High values of brittleness were seen in the lower part of the reservoir in Well-B, as was in Well-A. There was no indication of ductile or less ductile rock features in Well-B, which was clear from brittle-ductile color-coding and discriminant analysis. High brittleness layers were present in interbedded form from middle to lower part of the reservoir. The results of Young's modulus and Poisson's ratio color coding had a discrepancy with the discriminant analysis in the upper part of the reservoir as shown in figure 5. In figure 6, the cross plot of Young's modulus and Poisson's ratio shows that reservoir Zone has more of the data points falls in the brittle zone near to the brittle-ductile boundary. The results of this approach should also be checked against the mineralogical approaches for the studied Formation.

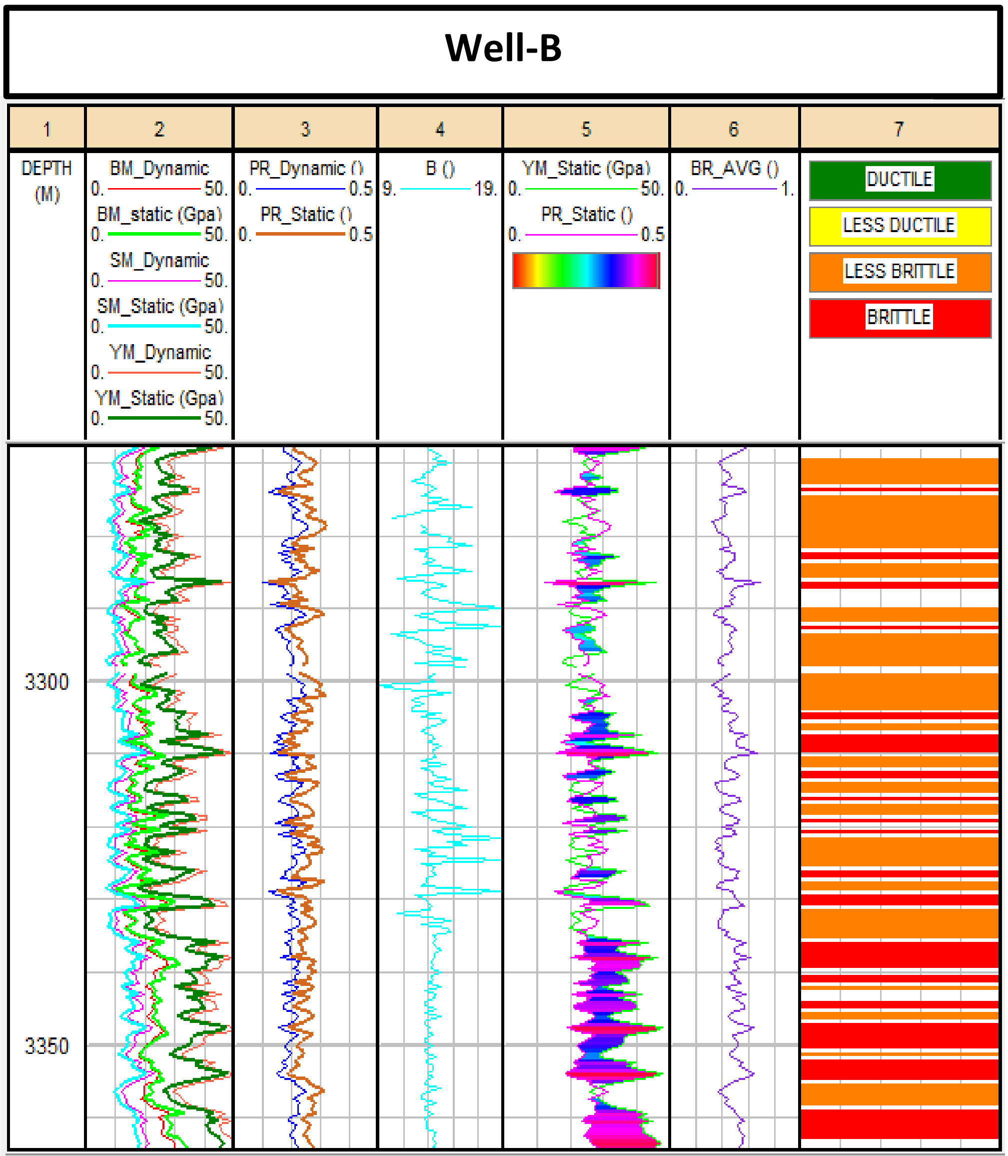

Figure 5. Discriminant analysis of Well-B; there is no indication of ductile or less ductile rock features in this well which is clear from brittle-ductile colour coding and discriminant analysis.

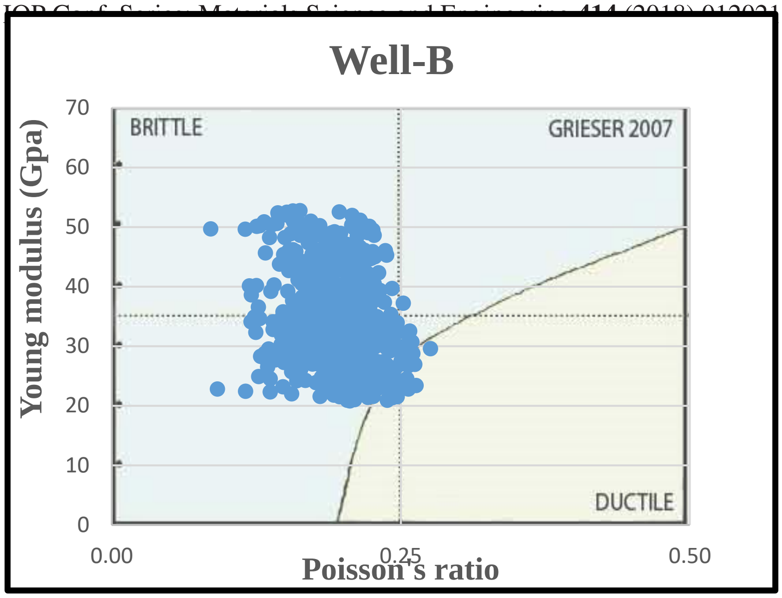

Figure 6. Cross plot of poison's ratio v.s Young's Modulus Well-B; shows that reservoir has more of the data points falls in brittle zone near to brittle-ductile boundary.

In Well-C, the brittleness estimated from the empirical equation of laboratory testing had very anomalous behavior along the reservoir depth as shown in figure 8. The same trend in the calculated mechanical properties were evident from other plots in the tracks as well. A ductile portion was identified in the Zone, which should be correlated to nearby offset wells to understand its lateral behavior. It was found that in all studied wells, there was high brittleness in the lower part of the reservoir, which is due to highly compressed shale formation. That part of the reservoir could be a good candidate for hydraulic fracturing if it satisfies all constraints of the prospective reservoir. Most of the data was falling in the low brittle zone to brittle zone ranging from 0.31 to 0.44 brittleness. Very small number of data points were present in the high brittleness zone. Ductile behavior was high in the studied formation as compared to brittle zone as shown in figure 7. Cross plot of Poisson's ratio and Young Modulus show that the higher the value of young Modulus and lower the value of Poisson's ratio it will be brittle and vice versa [10].

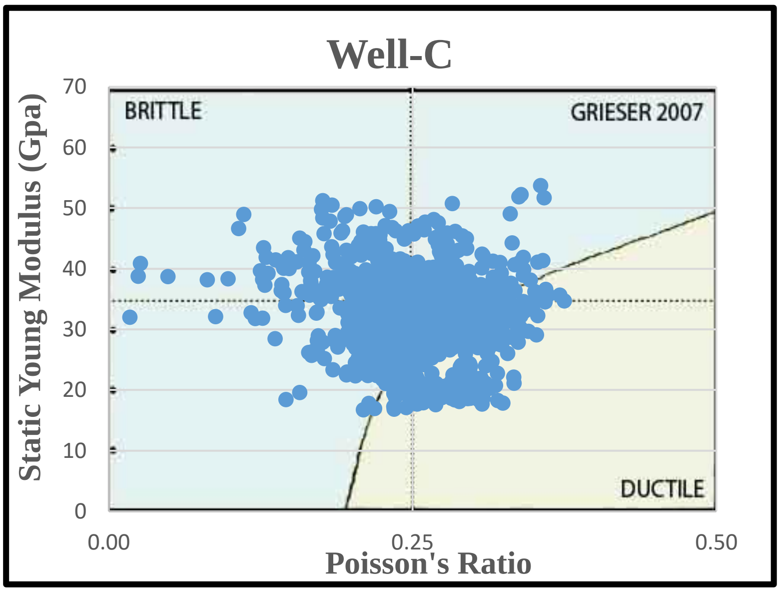

Figure 7. Cross plot of poison's ratio v.s Young's Modulus Well-C; Most of the data was falling in the low brittle zone to brittle zone ranging from 0.31 to 0.44 brittleness. Very small number of data points were present in the high brittleness zone.

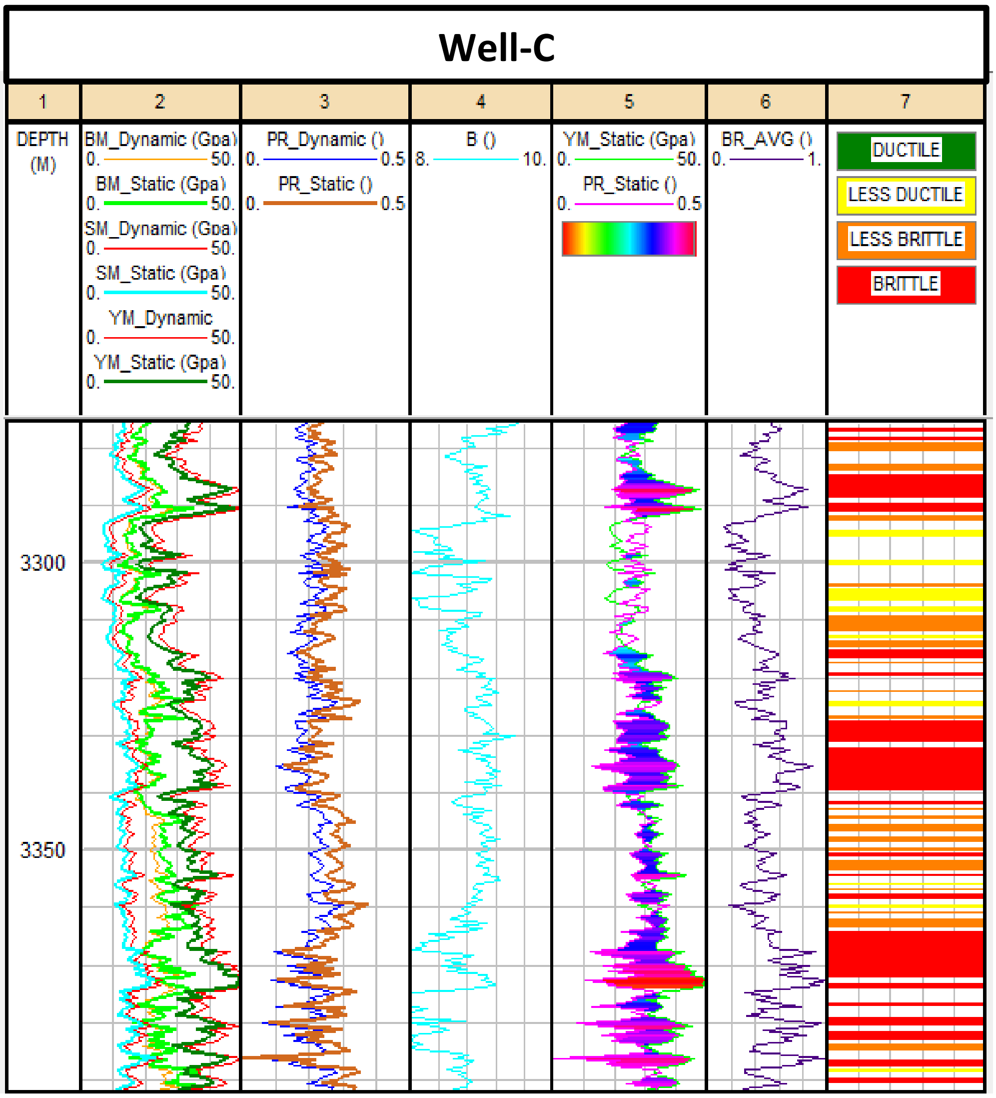

Figure 8. Discriminant analysis of Well-C;The brittleness estimated from empirical equation of laboratory testing has very anomalous behaviour along the reservoir depth. Ductile behaviour was high in the studied formation as compared to brittle zone.

5. Conclusions

- The understanding of brittle and ductile nature of the reservoir is the keystone for the successful execution of petroleum activities ranging from exploration to production.
- Brittleness and ductile behavior can be identified successfully using the empirical approaches and well log data.
- Brittle and ductile behavior depends upon the clay content as a part of the mineralogy of the rock.
- The upper part of the reservoir Zone-X has high sand content while the lower part is primarily based on shale interval in compressed morphology.
- High ranges of Young's modulus and corresponding low values of Poisson’s ratio are an indicator of high brittleness in the formation.
- The behavior of mechanical properties is not consistent in Well-A, Well-B, and Well-C, due to heterogeneity in these wells.

References

[1] Charlez P, 1997. The impact of constitutive laws on wellbore stability: a general review. *SPE Drilling & Completion, 1997*. **12(02)**: p. 119-128.
[2] Rickman R. 2008. A practical use of shale petrophysics for stimulation design optimization: All shale plays are not clones of the Barnett Shale. in SPE Annual Technical Conference and Exhibition. *Society of Petroleum Engineers*.
[3] Song L, 2015. Prediction of continental shale brittleness based on brittle-ductile transition analysis. in 2015 SEG Annual Meeting. *Society of Exploration Geophysicists*.
[4] Jaeger, J.C., N.G. Cook, and R. Zimmerman, 2009. Fundamentals of rock mechanics. *John Wiley & Sons.*
[5] Valko, P. and M.J, 1995. Economides, *Hydraulic fracture mechanics*. Vol**. 28.** Wiley Chichester.
[6] Zhang, D., P. Ranjith, and M. Perera, 2016. The brittleness indices used in rock mechanics and their application in shale hydraulic fracturing: A review. *Journal of Petroleum Science and Engineering*. **143**: p. 158-170.
[7] Hetenyi, M.I, 1950. *Handbook of Experimental Stress Analysis*.
[8] Morley A, 1944. *Strength of Materials*: with 260 Diagrams and Numerous Examples. New York: Longmans, Green and Company.
[9] Huang, X.-R, 2015. Brittleness index and seismic rock physics model for anisotropic tight-oil sandstone reservoirs. *Applied Geophysics*, **12(1):** p. 11-22.
[10] Grieser, W.V. and J.M. Bray, 2007. Identification of production potential in unconventional reservoirs. in Production and Operations Symposium. *Society of Petroleum Engineers*.
[11] Shi, X, 2016. Brittleness index prediction from conventional well logs in unconventional reservoirs using artificial intelligence. in International Petroleum Technology Conference. *International Petroleum Technology Conference*.
[12] Zaigham, N.A. and K.A. Mallick, 2000. Prospect of hydrocarbon associated with fossil-rift structures of the southern Indus basin, Pakistan. *AAPG bulletin*, **84(11)**: p. 1833-1848.
[13] Kadri, I. B,1995. Petroleum geology of Pakistan: Pakistan Petroleum Limited.
[14] Munir, K., Iqbal, M. A., Farid, A., & Shabih, S. M, 2011. Mapping the productive sands of Lower Goru Formation by using seismic stratigraphy and rock physical studies in Sawan area, southern Pakistan: a case study. *Journal of Petroleum Exploration and Production Technology*, **1(1)**, 33-42. doi: 10.1007/s13202-011-0003-9.
[15] Ismail, A, 2017. A comparative study of empirical, statistical and virtual analysis for the estimation of pore network permeability. *Journal of Natural Gas Science and Engineering*.
[16] Nygård, R, 2006. Brittle–ductile transition, shear failure and leakage in shales and mudrocks. *Marine and Petroleum Geology*, **23(2)**: p. 201-212.
[17] Jahandideh, A. and B. Jafarpour, 2016. Optimization of hydraulic fracturing design under spatially variable shale fracability. *Journal of Petroleum Science and Engineering*. **138**: p. 174-188.
[18] Altindag, R. and A. Guney, 2010. Predicting the relationships between brittleness and mechanical properties (UCS, TS and SH) of rocks. *Scientific research and Essays*. **5(16)**: p. 2107-2118.
[19] Bradford, I., 1998. Benefits of assessing the solids production risk in a North Sea reservoir using elastoplastic modelling. in SPE/ISRM. Rock Mechanics in Petroleum Engineering. *Society of Petroleum Engineers*.
[20] Hucka, V. and B. Das, 1974. Brittleness determination of rocks by different methods. in *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Elsevier.
[21] Perez Altamar, R. and K. Marfurt, 2014. Mineralogy-based brittleness prediction from surface seismic data: Application to the Barnett Shale. *Interpretation*. **2(4):** p. T255-T271.
[22] Mavko, G., T. Mukerji, and J. Dvorkin, 2009. *The rock physics handbook*: Tools for seismic analysis of porous media. Cambridge university press.

[23] McPhee, C. and C. Enzendorfer, 2004. Sand Management Solutions for High-Rate Gas Wells, Sawan Field, Pakistan in SPE International Symposium and Exhibition on Formation Damage Control. 2004. *Society of Petroleum Engineers*.
[24] Lal, M, 1999. Shale stability: drilling fluid interaction and shale strength. in SPE Asia Pacific Oil and Gas Conference and Exhibition. *Society of Petroleum Engineers*.
[25] Archer, S. and V. Rasouli, 2012. A log based analysis to estimate mechanical properties and in-situ stresses in a shale gas well in North Perth Basin. *WIT Transactions on Engineering Sciences*. **81**: p. 163-174.