Correlation of brittleness index with fractures and microstructure in the Barnett Shale

Z. Guo (British Geological Survey), M. Chapman (University of Edinburgh), X.Y. Li (British Geological Survey)

SUMMARY

The effectiveness of fracture stimulation techniques depends on the microstructural features which control the rock strength. We analyze brittleness index, fractures, and microstructure of the Barnett Shale for a better understanding of the correlation between them. The complexity of multiple minerals, pore geometries, and pore inclusions are modeled using the self-consistent approximation (SCA) model, with consideration of statistical distributions of pores and cracks in shales. The method is applied to the data from core samples and well logs to evaluate the aspect ratio of pores, and the proportion of stiff pores and cracks. Results show that the aspect ratio for the Barnett Shale varies between 0.01 and 1 and has a dominant value of 0.1. Comparison indicates that a definition of brittleness index including both quartz and total carbonates gives a more accurate evaluation of rock brittleness in terms of mineralogy. A good correlation between inverted aspect ratio with the brittleness index defined by λ-μ and Poisson's ratio confirms that higher value of brittleness index corresponds to the presence of more natural cracks in the Barnett Shale.

Introduction

Hydraulic fracturing needs to be conducted to produce hydrocarbons in shale rocks due to low porosity and extremely low permeability, and the effectiveness of fracture stimulation techniques depends on microstructural features of rocks which control the rock strength. Rock strength is a function of material brittleness, which is related to lithology and mineralogy, and can also be inferred from mechanical properties. The objective of this work is to analyze the link between mechanical properties, fractures and microstructure in the Barnett Shale. A self-consistent approximation (SCA) method is used to model complex constituents and pore geometries in shales, and the statistical distributions of pores and cracks are considered to be close to the real rock (Jiang and Spikes, 2011). The method is applied to the data from core samples and well logs to estimate the mean value of aspect ratio, and the proportion of stiff pores and cracks. The aspect ratio is then compared with brittleness index defined in terms of mineralogy and mechanical properties, and with fracture density measured in borehole for better understanding of the correlation between them.

Methods

The SCA approach is one of the effective-medium models which is flexible for the modeling of multi-phase compositions and pores. In this study, we use this method to link complex constituents and pore geometries with elastic properties of shales. In order to get close to a model of actual rocks, aspect ratio of pores is regarded as a random variable with 100 samples and normal distribution, specified by mean value and standard deviation. We calculate velocity-porosity relationship in terms of P- and S-wave velocities (Vp and Vs) as a function of porosity for various aspect ratios. The estimate of aspect ratio for pores in shale rocks is based on the constructed velocity-porosity templates for various aspect ratios. The idea is to find the best matched velocities for sonic well logs on the templates, and use the corresponding aspect ratio as the best evaluation of pore geometry. Another way to analyze microstructure in shales is based on the multiple porosity model. As to the estimate of aspect ratio, a reference aspect ratio is determined as a measure of the background pore-space, and then the whole pore-space is divided into two cases: one consists of pores with reference aspect ratio and stiff pores which have near round shapes, and the other includes reference pores and cracks which have a smaller aspect ratio. The aspect ratios for stiff pores and cracks are set to 1 and 0.01 respectively. Significantly, aspect ratio is characterized using the statistical distribution rather than a single value of aspect ratio. The velocity-porosity relationship is calculated with this multiple porosity model and the proportion of stiff pores and cracks is estimated.

Example Data

Figure 1 shows the well logs for the formations of Marble Falls, Barnett Shale, and Ellenburger. The Barnett Shale is recognized by higher values of gamma radiation and lower Vp and Vs velocities compared to surrounding rocks.

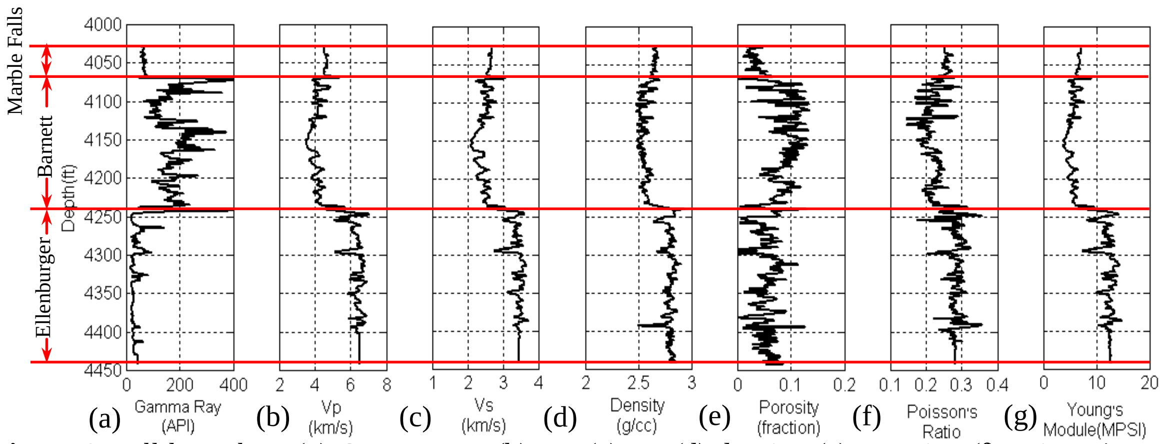

***Figure 1** Well logs show (a) Gamma ray, (b) Vp, (c) Vs, (d) density, (e) porosity, (f) Poisson's ratio, and (g) Young's modulus.*

Figures 2 (a) and (b) illustrate Vp and Vs as a function of porosity in the Barnett Shale. Data points are from sonic well logs and colour-coded by shale volume. The solid lines indicate constant values of aspect ratio. Nearly all data points are within the range of modeling lines which indicate that the SCA model fits the data. As shown in Figure 2, the scattering of velocities can be explained by the variation of aspect ratio, though shale volume can be regarded as a factor affecting the velocity-porosity relationship. We use the averaged volumetric fraction of minerals in the calculation but detailed information on composition will surely reduce uncertainty in velocity-porosity analysis.

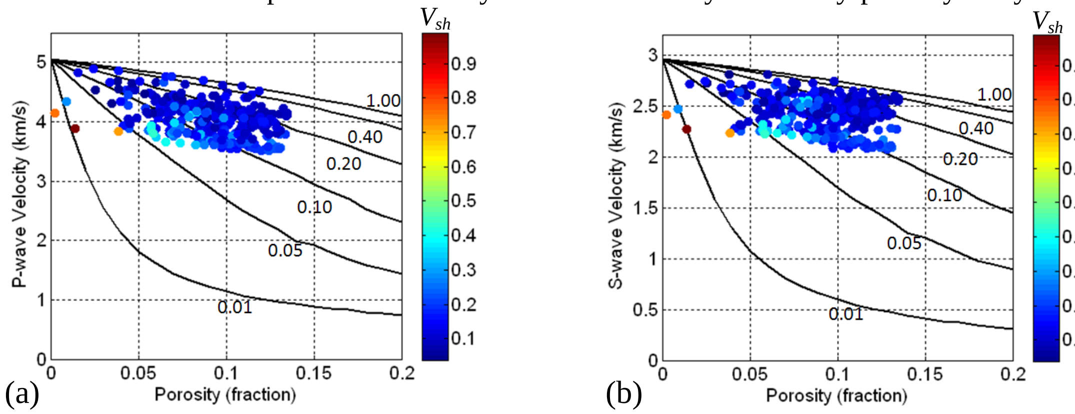

Figure 2 *(a) P- and (b) S-wave velocities as a function of porosity color-coded by shale volume derived from gamma ray log. Solid lines are constant aspect ratio lines calculated by the SCA method.*

The measured mineralogy volumetric fraction of the core samples is displayed in Figure 3 (a). Quartz and clays are dominant in the Barnett Shale. Given the measured total porosity, and Vp and Vs from well logs at corresponding depths, we calculate the aspect ratio of pores for each core sample. Results are shown in Figure 3 (b) with the aspect ratios inverted from Vp (blue) and Vs (red). The inverted aspect ratios from Vp and Vs are consistent and show a range between 0.01 and 1, with a dominant value of 0.1. So we treat pores with an aspect ratio of 0.1 as background pore space, and values which deviate from it as corresponding to the presence of stiff pores or cracks. In another important concept, rock brittleness index plays a significant role in hydraulic fracturing during the production of shale gas. Quartz in the rocks is generally believed to be responsible for rock brittleness, and increasing quartz content makes shale rocks easier to be fractured. Interestingly, our study suggests that calcite and dolomite may also contribute to rock brittleness. If we assume rocks with high value of brittleness index may have more potential for the presence of natural cracks which corresponds to smaller aspect ratio, comparisons show that the inverted aspect ratio in Figure 3 (b) correlates to the brittleness index defined by quartz and total carbonates in Figure 3 (c), better than that defined by quartz only in Figure 3 (d). This may illustrate that a definition including both quartz and total carbonates gives a more accurate evaluation of rock brittleness index in terms of mineralogy.

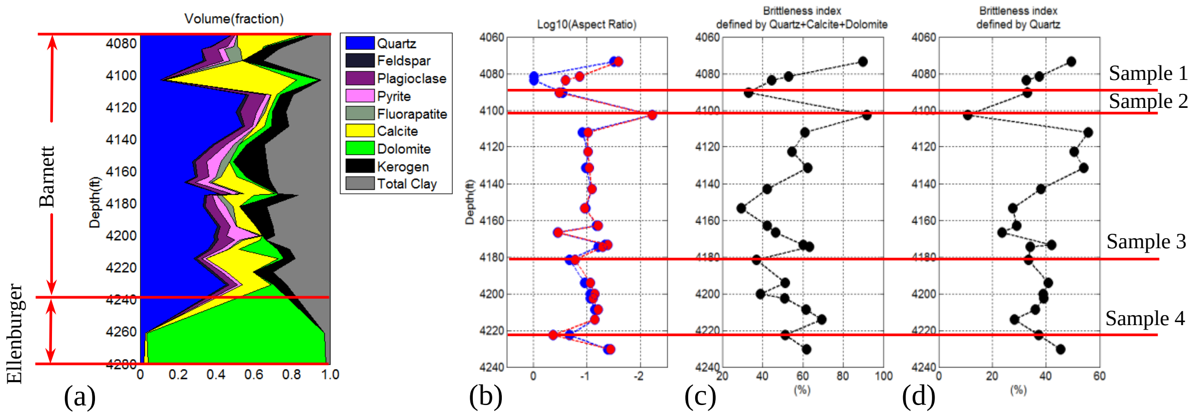

Figure 3 *(a) Mineralogical volumetric fraction from core samples, (b) Inverted aspect ratio, (c) Rock brittleness index defined by mineral content of both quartz and total carbonates, and (d) Rock brittleness index defined by content of quartz only.*

We then apply the method to the well log data, and analyze the correlation between the inverted aspect ratio with brittleness index defined by mechanical properties of shales. Goodway et al. (2010) propose that the most fracable zones occupy low $\lambda\rho$ *and* midrange $\mu\rho$. In this study, we use the modified version of their result as the definition of rock brittleness index in Equation (1):

$$Brittleness = \frac{\lambda + 2\mu}{\lambda} \quad (1)$$

Rickman et al. (2008) give the concept of rock brittleness index by Poisson's ratio and Young's modulus shown in Equation (2) and (3). Low Poisson's ratio and high Young's modulus indicate more brittle rocks. Poisson's ratio is believed to reflect rock's ability to fail under stress, and Young's modulus the ability to maintain a fracture once the rock fractures.

$$Brittleness = 100 \times (Young'sModulus - 1)/(8-1) \quad (2)$$

$$Brittleness = 100 \times (Poisson'sRatio - 0.4)/(0.15 - 0.4) \quad (3)$$

Rock brittleness indexes defined by Equations (1), (2), and (3) are illustrated in Figures 4 (a), (b), and (c). By comparing Figures 4 (a), (b), and (c) with (d), we find that the inverted aspect ratio has a good correlation with the brittleness index defined by λ-μ and Poisson's ratio in the Barnett Shale, which confirms that higher value of brittleness index corresponds to the presence of more natural cracks. Brittleness index defined by Young's modulus is not consistent with the others, which indicates the relationship of mechanical properties to rock brittleness index deserves further study. Also, the inverted aspect ratio for the Barnett Shale varies between 0.01 and 1 and has a dominant value of 0.1, which is consistent with the results from the core analysis.

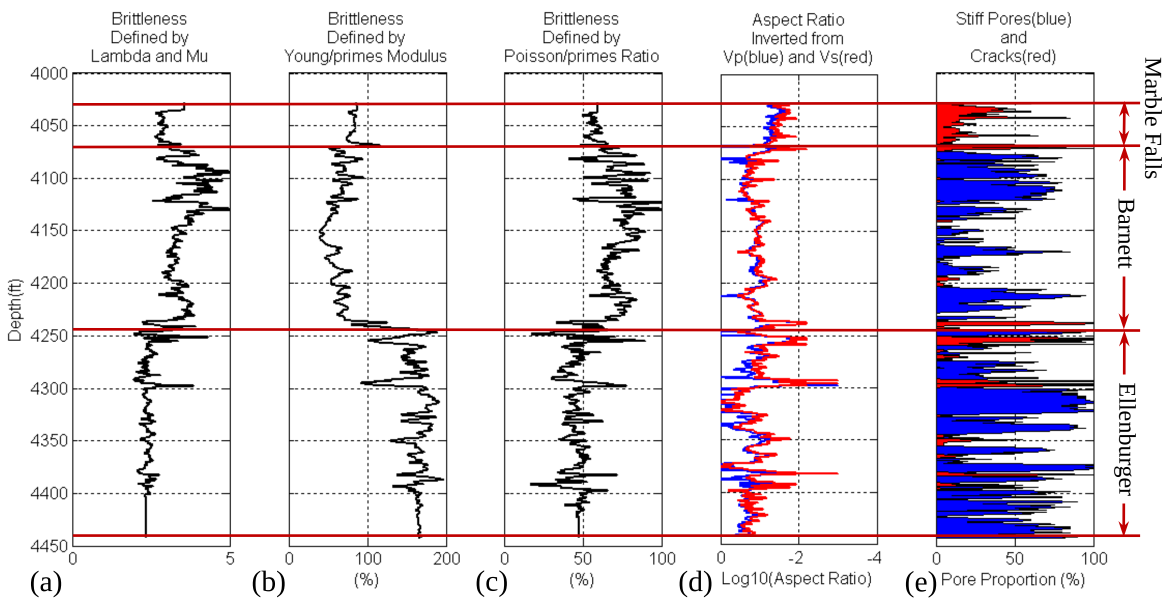

Figure 4 *Brittleness index defined by (a) Lambda and Mu, (b) Young's modulus, and (c) Poisson's ratio. (d) Aspect ratio inverted from Vp and Vs. (e) Proportion of stiff pore and cracks from Vp and Vs joint estimates.*

Figure 5 (a) shows the formation image and fracture densities for the Barnett Shale and surrounding formations, in comparison with the inverted average aspect ratio for the Barnett Shale in Figure 5 (b). Correlation can be found between the measured fracture densities and the inverted average aspect ratio. We should note that fracture density is a measure of visible cracks, while aspect ratio gives a full estimate of the pore space geometry.

Finally, we estimate the proportions of different pore types using a multiple porosity model (Xu and Payne, 2009). We divide pore space into two cases: one consists of reference pores and stiff pores, while the other is composed of reference pores and cracks. According to the previous analysis, the aspect ratio of reference pores is set to be 0.1, while those of stiff pores and cracks are 1 and 0.01, respectively. For the consideration of statistical distribution, aspect ratios with mean values of 0.01, 0.1, and 1.0 have standard deviations of 0.001, 0.01, and 1.0, respectively. Figure 6 demonstrates scenarios of pore space with different geometries. The statistical distributions of pores are illustrated by histograms. A rock physics template of Vp as a function of porosity is constructed, with lines showing constant proportions of stiff pores and cracks. Proportions of stiff pores and cracks are calculated by finding the best match of velocities for various pore proportions, with the result shown in Figure 4 (e). It can be seen that depth intervals of lower aspect ratio usually have more cracks.

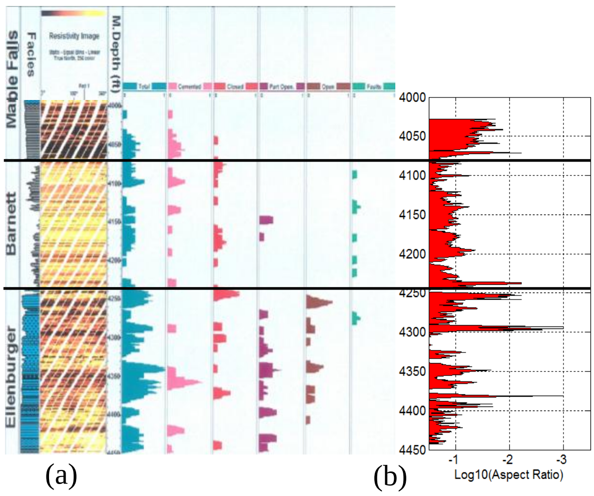

Figure 5 *Formation image and fracture density (a) and inverted aspect ratio of cracks (b).*

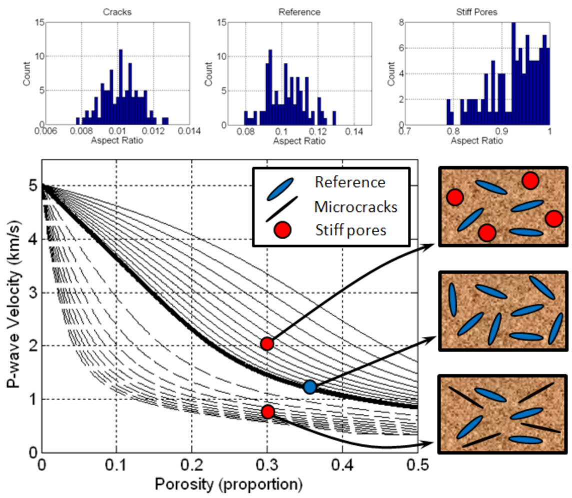

Figure 6 *Rock physics templates showing effect of pore type on Vp of the Barnett Shale.*

Conclusions

We have analyzed the correlation of brittleness index with fractures and microstructure in the Barnett Shale. A rock physics model compiling with the statistical distribution of pore shapes is used to estimate the mean value of aspect ratio. Results show that the aspect ratio for the Barnett Shale varies between 0.01 and 1 and has a dominant value of 0.1. Comparison indicates that a definition including both quartz and total carbonates gives a more accurate evaluation of rock brittleness index. A good correlation between inverted aspect ratio with the brittleness index defined by mechanical properties confirms that higher value of brittleness index corresponds to the presence of more natural cracks.

Acknowledgements

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