Effect of geometries of clay-related pores on elastic properties of shales

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SUMMARY

Clays and clay-related pores play significant roles in controlling the elastic behaviour of shales. After revisiting the workflow of the traditional dual porosity model, we develop a new rock physics model to describe dual porosity in rocks with a more explicit description of the distribution of pores associated with clays and mineral grains in shales. Our explicit dual porosity rock physics model is applied to data from the Barnett Shale, and the results show that it gives similar estimates of aspect ratio of pores associated with non-clay minerals to those of a traditional model. However, the aspect ratios of clay-related pores derived by the new model have more clear correlations with the elastic properties of the shales than those by traditional model. The correlation between Poisson's ratio, Young's modulus and aspect ratio and corresponding crack density of clay-related pores indicates that both the clay-related porosity and geometry of clay-related pores have important effects on the elastic properties and brittleness index of shales.

Introduction

The effect of clays and clay-related pores on elastic properties of the Barnett Shale needs to be considered because they play significant roles in controlling the elastic behaviour of shales. Xu-White model (Xu and White, 1995) is often used to model the dual porosity of clay-sand mixtures, by considering clay-related porosity and sand-related porosity separately. In this study, we revisit the workflow of the popular dual porosity model and propose a new rock physics model to describe dual porosity in rocks with a more explicit description of the distribution of clays and non-clay mineral grains in shales. We work on the data from the Barnett Shale and compare the results from single aspect ratio model, traditional dual porosity model, and our explicit dual porosity model. The accuracy of fitting model velocities to measured velocities from sonic logs is evaluated, and the advantage of our explicit dual porosity model for the estimate of geometries of clay-related pores is shown. Based on our model, the correlations between the aspect ratio of clay-related pores and elastic properties for the Barnett Shale are analyzed for a better understanding of the effect of microstructure on elastic properties and brittleness in shales.

Method

Figure 1 illustrates some common ways to model a porous medium. Figure 1 (a) shows a way to simulate pore space using a single aspect ratio, which consists of estimating elastic properties of the rock matrix using a bounding-average method, and then assigning pores with a single aspect ratio to mixtures of minerals using effective medium theory. Another way shown in Figure 1 (b) is known as the dual porosity model, proposed by Xu and White (1995) to model clay-sand mixtures. The total pore space is divided into clay-related and sand grain-related pores. According to the workflow of this model, however, we find that two sets of pores with different aspect ratios are assigned to the mixtures of sand and clays, which means the workflow does not explicitly describe which set of aspect ratio is assigned to clays or which to sand grains. Therefore, the model does not discriminate between the two different scenarios shown in Figures 1 (b) and (c), in which pores with two aspect ratios have distinct patterns of distribution in the mixtures of mineral grains and clays. In order to explicitly model the specific distributions of pores in clays and pores in non-clay minerals, we propose the new rock physics model shown in Figure 1 (d). This explicit dual porosity model employs effective medium theory to model clays with pores and all other non-clay minerals with pores separately at the first step, and then uses bounding average theory to obtain the final rock model. In this study of the Barnett Shale, we use the self-consistent approximation (SCA) method and Hashin-Shtrikman upper and lower bounds theory for all rock physics models discussed above, and treat pore fluids as inclusions because the pore-pressure equilibrium in Gassmann theory is likely to be violated due to low porosity and extremely low permeability of the Barnett Shale. We also model the distribution of aspect ratio using a statistical distribution to get close to the real rock model (Spikes, 2011), in which pore aspect ratios are likely concentrated around certain particular aspect ratios rather

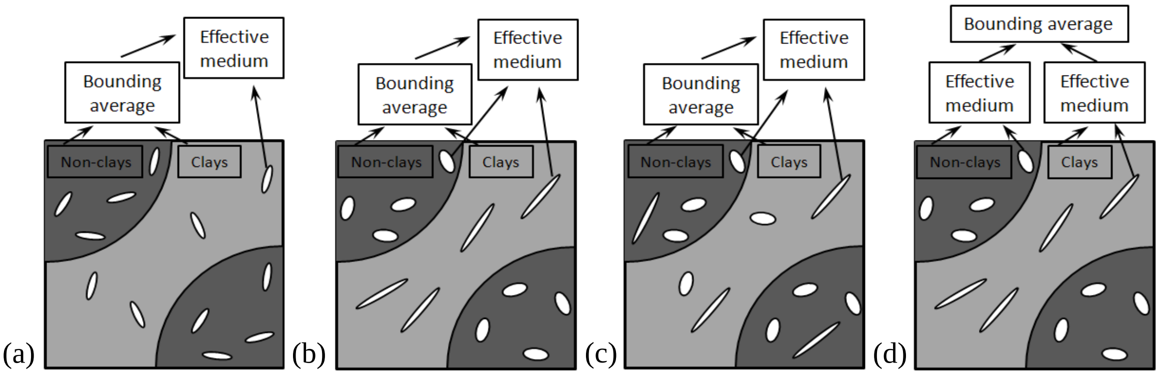

Figure 1 *Schematic representation of different rock physics models for effective medium with (a) single porosity, (b) dual porosity with cracks in clays and stiff pores in minerals of non-clays, (c) dual porosity with complex distributions of cracks and stiff pores in the mixture of clays and non-clays. Figure 1-(d) is our new rock physics model for rock of dual porosity.*

than having a single value. Each aspect ratio is regarded as a random variable with a sampling number of 100 which has a normal distribution represented by a mean value and standard deviation.

Examples

We then take the Barnett Shale as an example to compare the results from three different rock physics models discussed above. Table 1 lists the bulk and shear moduli, density, and average volumetric fractions of the mineralogy of the Barnett Shale. Figures 2 (a) and (b) illustrate shale volume and porosity of the Barnett Shale, respectively. Shale volume is derived from a gamma ray log based on the non-linear relationship of Rider (1991) and is used to evaluate the clay-related porosity. Figures 2 (c), (d), and (e) shows the comparisons between P-wave velocity (Vp) and S-wave velocity (Vs) measured from sonic logs, and those estimated by rock physics models: a single aspect ratio model, traditional dual porosity rock physics model, and our new explicit dual porosity model. Detailed examinations are given by cross-plots of the measured and the estimated velocities in Figure 3. All the three models give a good fit between the measured and the estimated data, while the single aspect ratio model gives the best match. The traditional dual porosity model and our explicit dual porosity model give similar results.

Mineral	Quartz	Feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Flourapatite	Kerogen	Clay
K(GP)	37.9	37.5	75.6	76.8	94.9	147.4	86.5	2.9	25.0
μ(GP)	44.3	15.0	25.6	32.0	45.0	132.5	46.6	2.7	9.0
$\rho(g/cm^3)$	2.65	2.62	2.63	2.71	2.87	4.93	3.21	1.30	2.55
Volume fraction	0.372	0.012	0.054	0.145	0.036	0.039	0.018	0.074	0.25

Table 1 *Bulk (K), shear (μ) moduli, and density of minerals used in the modeling (Mavko et al. 2009).*

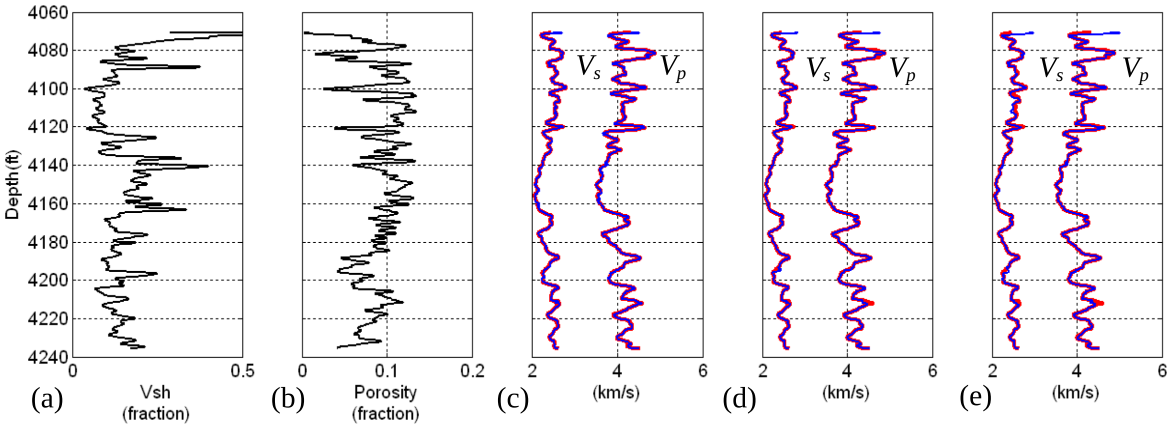

Figure 2 *(a) Shale volume, (b) Total porosity, and Measured (red) and predicted (blue) Vp and Vs by fitting modeling data to sonic logs using (c) single porosity model, (d) traditional dual porosity model, and (e) explicit dual porosity mode.*

However, the advantage of our explicit dual porosity model is that it gives an estimate of the geometry of clay-related pores with a more explicit distribution. Aspect ratios derived by the three rock physics models for matching the measured and the estimated Vp and Vs are shown in Figure 4. Figure 4 (a) corresponds to the single aspect ratio model, and the corresponding histogram in Figure 5 (a) shows that the aspect ratios concentrate around 0.16 with most values below 0.2. It can be seen in Figures 4 (b) and (d) that the traditional dual porosity model and our explicit dual porosity model give similar estimates for the aspect ratio of pores associated with non-clay minerals, and the histograms in Figures 5 (b) and (d) show that the corresponding aspect ratios associated have similar statistical distributions with mean values of 0.43 and 0.49, respectively. However, Figures 4 (c) and (e) show that the aspect ratios of clay-related pores derived using traditional dual porosity model and our explicit porosity model are different, and the histograms in Figures 5 (c) and (e) show that they have distinct statistical distributions with mean values of 0.49 and 0.11, respectively.

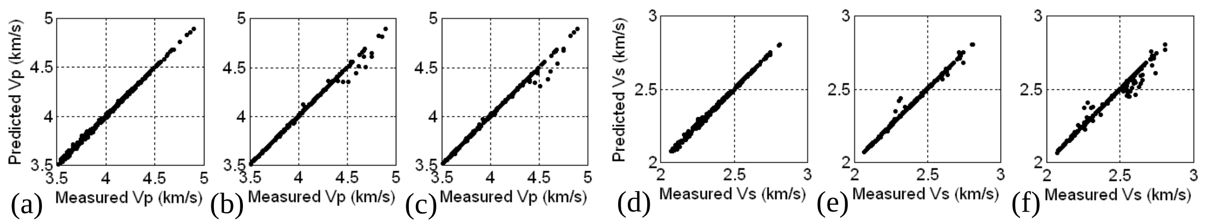

Figure 3 *Cross-plot of the measured Vp versus the predicted Vp using (a) single porosity model, (b) traditional dual porosity model, and (c) explicit dual porosity model. (d), (e), and (f) are the corresponding cross-plots of the measured Vs versus the predicted Vs.*

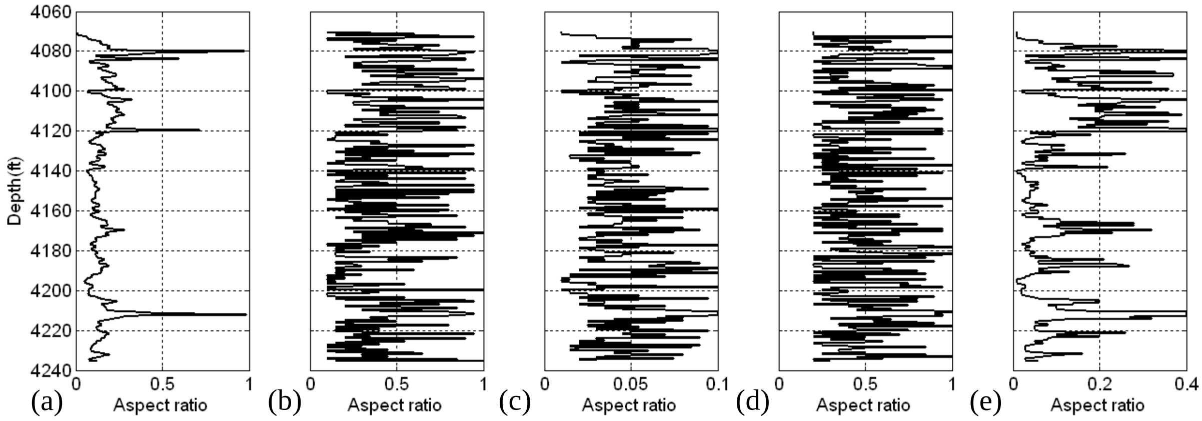

Figure 4 *(a) Aspect ratio derived using the single porosity model. (b) and (c) are aspect ratios of pores associated with non-clay mineral grains and clays derived using the traditional dual porosity. (d) and (e) are those derived using the explicit dual porosity model.*

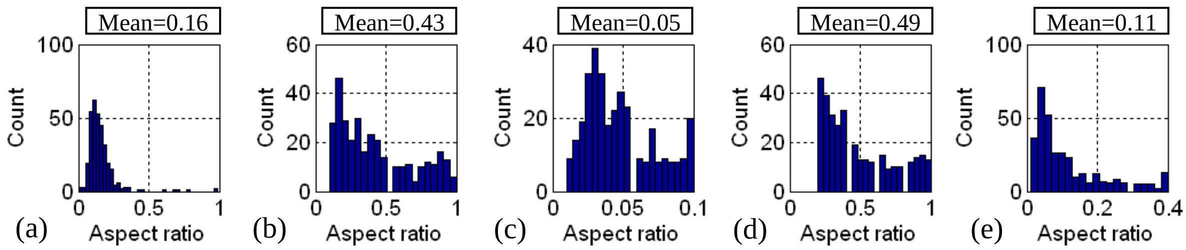

Figure 5 *Histograms of derived aspect ratios corresponding to Figure 4.*

Base on the explicit dual porosity model, we then calculate the aspect ratios of pores, and then analyze the correlations between porosities, aspect ratios, crack densities, and elastic properties such as Poisson's ratio and Young's modulus. Figures 6 (a), (b), and (c) are pore properties associated with non-clay mineral grains, and Figures 6 (d), (e), and (f) are those associated with clays. We can find in Figures 6 (d) and (e) that clay-related porosities are generally lower at the upper depth intervals between 4080 and 4120 feet. Certain depth intervals below that also present local lower clay-related porosities, while aspect ratios of clay-related pores have higher values at these depth intervals. Figures 6 (d) and (e) show lower clay-related porosities generally correspond to a high clay-related aspect ratio, which means stiffer pores. Comparisons also indicate that there is a negative correlation between clay-related porosity in Figure 6 (d) and Poisson's ratio and Young's modulus in Figures 6 (g) and (h). Meanwhile, a positive correlation can be found between the clay-related aspect ratio in Figure 6 (e) and the two elastic properties. This is consistent with our physical instinct that higher porosity will decrease elastic moduli and higher aspect ratio means stiffer pores and hence increases the elastic moduli. Moreover, the most interesting discovery is that these correlations are explicitly related to clays rather than other minerals, as for the Barnett Shale in Figure 6.

Additionally, because Poisson's ratio and Young's modulus are usually related to rock brittleness index (Rickman et al., 2008), the porosity and geometry of clay-related pores may have a significant impact on rock brittleness according to the discovered correlations. The crack density of clay-related pores derived from corresponding porosity and aspect ratio also has a good correlation with the elastic properties of the Barnett Shale.

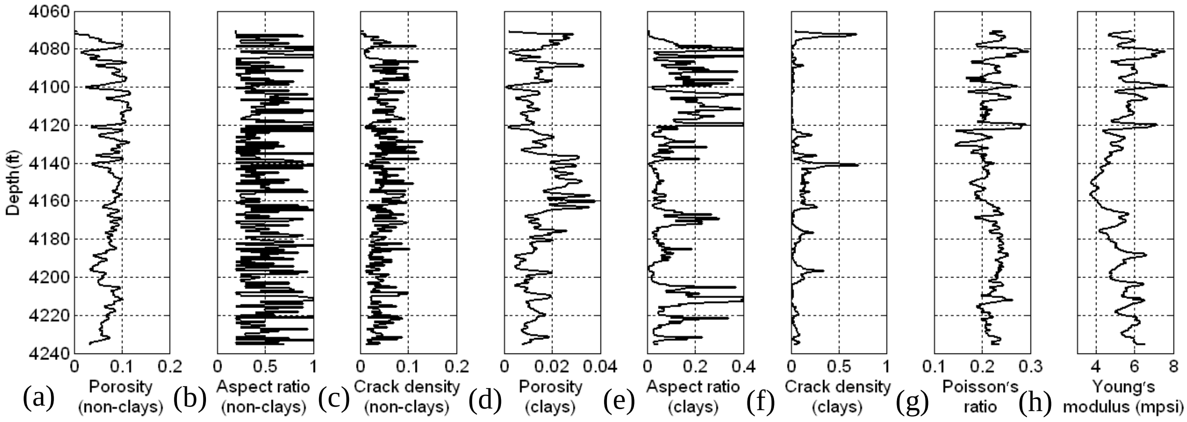

Figure 6 *(a) Porosity, (b) Aspect ratio, and (c) Crack density associated with pores for non-clay minerals. (d), (e), (f) are those for clays. All these aspect ratios are derived using our explicit dual porosity model. (g) and (h) are Poisson's ratio and Young's modulus, respectively.*

Conclusions

We develop a new rock model to explicitly consider the role of clay-related pores in controlling the elastic properties of shales. Our explicit dual porosity model has the same accuracy in fitting model velocities to measured ones from sonic logs, and gives similar estimates for aspect ratio of pores associated with non-clay minerals as a traditional model does, but the aspect ratios of clay-related pores derived by our new model show explicit correlations with the elastic properties of the Barnett Shale, which makes the interpretation of the results more meaningful. Such correlations indicate that the geometries of pores in clays significantly affect elastic properties and hence brittleness in shales. Future work may include the analysis of the correlation between the aspect ratio of clay-related pores and the lamination of clay particles, as well as the effective pressure.

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