Estimation of anisotropy parameters for a clay-rich shale formation based on a rock physics model

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SUMMARY

Shale represents strongly intrinsic vertical transverse isotropy (VTI) due to its unique microstructure. Effectively modelling the seismic anisotropy is important in seismic processing and inversion, as well as hydraulic fracture monitoring. In order to construct a realistic rock physics model for clay-rich shales, it is important to simulate the intrinsic VTI anisotropy caused by the presence of various clay minerals.

In this paper, we propose a practical framework for estimation of the effective elastic stiffness of clay-rich shales. The intrinsic VTI anisotropy is simulated by the construction of background basic units using variously aligned clay minerals as well as kerogen, which allows a more general model than previous models. Other minerals, and pores, are included in the anisotropic background by means of the anisotropic differential effective medium (DEM) method. We apply this rock physics model to predict the elastic properties of a shale formation in Western Sichuan basin, and the results are demonstrated with the corresponding logs. The predicted vertical P- and S-wave velocities show good agreement with the real logs; the estimated anisotropy parameters are used to calibrate the AVA (amplitude versus angle) response and to correct the P-wave velocity log in the horizontal well.
Introduction

Shale shows strongly intrinsic vertical transverse isotropy (VTI) due to its unique microstructure. Effectively modelling the seismic anisotropy is important in seismic processing and inversion, as well as hydraulic fracture monitoring. One of the major reasons for the seismic anisotropy of shale is the platy shape and preferred orientation of clay particles and kerogen (Vernik and Nur, 1992; Hornby et al., 1994; Vernik and Landis, 1996; Sondergeld et al., 2000; Lonardelli et al., 2007). Many efforts have been made to study the relation between the properties of shale and its anisotropic seismic responses. Vernik and Nur (1992) and Vernik and Landis (1996) applied the modified Backus average to calculate the effective elastic stiffness of the organic-rich shale. Hornby et al. (1994) proposed a theoretical framework to model the fluid saturated shale and analyse the influence of porosity on the anisotropy. In order to construct a realistic rock physics model for clay-rich shales, it is important to simulate the intrinsic VTI anisotropy caused by the presence of various clay minerals.

In this paper, we propose a practical framework for estimation of the effective elastic stiffness of clay-rich shales. The intrinsic VTI anisotropy is simulated by the construction of background basic units using variously aligned clay minerals as well as kerogen, which allows a more general model than previous models. Other minerals, and pores, are included in the anisotropic background by means of the anisotropic differential effective medium (DEM) method. We apply this rock physics model to predict the elastic properties of a shale formation in Western Sichuan basin, and the results are demonstrated with the corresponding logs. The predicted vertical P- and S-wave velocities show good agreement with the well logs; the estimated anisotropy parameters are used to calibrate the AVA (amplitude versus angle) response and to correct the P-wave velocity log in the horizontal well.

Rock physics modelling of clay-rich shales

The clay minerals in shale include illite, smectite, chlorite and kaolin, which usually have a platy shape and are well laminated. They show various elastic properties which can be referenced in published literatures (Mavko et al., 1998; Wang et al., 2001; Mondol et al., 2008). The intrinsic VTI anisotropy is considered as the result of the present of these various clay minerals. Therefore, the anisotropic background of the rock physics model can be constructed using the Backus average. Backus (1962) provided long wave-length effective constants $C_{\text{eff}}$ of a medium composed of transversely isotropic materials as follows:

$$C_{\text{eff}}^{11} = C_{22}^{\text{eff}} = \left\{ C_{11} \cdot C_{33}^{2} \right\}, \quad C_{13}^{\text{eff}} = \left\{ C_{13} \cdot C_{33}^{2} \right\}, \quad C_{23}^{\text{eff}} = \left\{ C_{23} \cdot C_{33}^{2} \right\}, \quad C_{33}^{\text{eff}} = \left\{ C_{33} \cdot C_{33}^{2} \right\},$$

$$C_{44}^{\text{eff}} = C_{55}^{\text{eff}} = C_{66}^{\text{eff}} = \left\{ C_{44} \cdot C_{55} \right\},$$

where $\{ \cdot \}$ represents weighted average of the enclosed parameters.

![Figure 1](image1.png)

**Figure 1** (a) Shale consisting of anisotropic background and ellipsoidal inclusions. (b) Templates of effective moduli of various clay volumes. The porosity is 10%, with the aspect ratio 0.1.

Once the effective elastic moduli of the background are derived, silt minerals such as quartz and feldspar, cements such as calcite and dolomite, as well as pores, can be included in the anisotropic background by means of the anisotropic differential effective medium (DEM) theory. The DEM theory presents a solution of the effective elastic constants $C_{\text{eff}}^{i}$ of adding inclusion materials with certain volume fractions $v$ to a host material matrix. The stiffness update due to the change of volume fractions of included material $C_{i}$ is given as (Hornby et al., 1994, Wu et al., 2012):
\[ dC^{\text{eff}} (v) = \frac{dv_i}{1 - v_i} (C_i - C_i^{\text{eff}} (v)) [I + \overline{G} (C_i - C_i^{\text{eff}})]^{-1}, \]

where \( i \) refers to the \( i \)-th inclusion material, \( I \) is the fourth-rank identity matrix and \( \overline{G} \) is the fourth-rank tensor calculated from the response of an unbounded matrix of the effective medium.

Figure 1(a) shows the framework for estimating the effective elastic properties of shales. We use the data based on the petrophysical analysis of the shale-gas well (Figure 2(a)) to generate a rock physics template. The volumetric fraction of the clay mixture is formed by 57% illite, 20% interstratified illite/smectite (I/S) with 20% smectite, 14% chlorite and 19% kaolin; while the mineral inclusions consist of 61% quartz, 5% feldspar, 16% calcite and 18% dolomite. We assume that the inclusions contribute most of the pore spaces and the total porosity is set at 10%. Ellipsoidal inclusions are considered with the aspect ratio 0.1. Figure 1(b) compares the estimated elastic constants with the clay volume varying from 0 to 100%. The differences between \( C_{11} \) and \( C_{33} \), and \( C_{44} \) and \( C_{66} \) steadily increase with the clay volume. Although this template does not reveal the effect of organic matters, kerogen could be considered as one of the background units and mixed with the clay minerals by means of equation (1).

**Prediction of velocities and anisotropy parameters using log data**

The study area is in Western Sichuan basin, southwest China. Figure 2(a) shows the vertical logs of a shale-gas well. The shale formation (2750m-3200m) contains a great quantity of clay and has very low porosity and permeability. Tight sands of varied thickness are characterized in the shale formation, thus three reservoir patterns could be identified as shown in Figure 2(b).

The logs of volumetric fraction of clay (\( V_{\text{clay}} \)) and other brittle minerals (\( V_b \)) are available (grey and yellow curves in Figure 2(a)). As we know, the shale formation has very complex mineral composition: clay consists of illite, I/S (20% S), chlorite and kaolin; brittle minerals consist of quartz, feldspar, calcite and dolomite. The content of each mineral, which could be obtained from the results of core samples analysis, is crucial for estimating both of the vertical velocities and the anisotropy parameters. However, there is a limited number of core samples. A practical approach is proposed to solve this problem: (1) the shale formation is divided into three subsequences based on the geological interpretation; (2) within each subsequence, the volumetric fraction of clay mineral composition derived from core sample is adjusted based on the P-wave velocity, S-wave velocity and density when \( V_{\text{clay}} \) reaches the maximum value (100% at 2758.9m, 2824.0m, 2844.2m, et al.); (3) similarly, the volumetric fraction of each brittle mineral composition can be derived from those logs when \( V_{\text{clay}} \) reaches the minimum values (0 at 2849.9m, 2915.0m, 2941.2m, et al.).

![Figure 2](image)

**Figure 2** (a)Well logs in the vertical section of a shale gas reservoir: P-wave velocity, S-wave velocity, density, Poisson’s ratio, porosity, water saturation, clay volume, brittle mineral volume and seismic waveforms from left to right. (b) Reservoir patterns of the shale formation. The grey sections represent the clay-rich shales, while the yellow sections represent the thin-layer sands.

Once the volumetric fraction of each mineral composition is derived, we estimate the effective elastic constants by means of the two-step method introduced in this paper. The porosity when \( V_{\text{clay}} \) reaches the maximum value is extremely low, while the brittle minerals contribute most of the porosity. Figure 3(a) compares the estimated vertical P- and S-wave velocities with corresponding well logs. Both of the predicted velocities show good agreement with the log over a wide range of the vertical depth. However, the S-wave velocity of those depth intervals with extreme low clay volume is slightly
overestimated. This could be further improved by adjusting the volumetric fractions of brittle minerals. Figure 3(b) shows the estimated of Thomsen’s parameters over the vertical well. Strong anisotropy is found in the clay-rich shales. The estimated result is then demonstrated by its application to the AVA analysis and correction of the horizontal well sonic log.

Figure 3 (a) Comparison of predicted logs (dashed blue curves) with real logs (solid black curves): P-wave velocity, S-wave velocity and the real log of clay volume from top to the bottom. (b) Predicted Thomsen’s parameters: $\varepsilon$, $\gamma$, and $\delta$.

Calibration of AVO and correction of horizontal well sonic log

Anisotropy has a great influence on the seismic amplitude responses. To analyse the amplitude response of the shale formation, we look at the AVA at around 1645ms (2953m) of a PP-wave angle gather near the borehole. The picked amplitude between $0^\circ$ to $35^\circ$ and its interpolated AVA curve are plotted in Figure 4(b). We use the elastic parameters extracted from logs to generate the synthetic isotropic reflection coefficients, represented by the green curve in Figure 4c, which is compared with the anisotropic expression (black curve in Figure 4c) calculated using anisotropy parameters extracted from the estimated logs ($\varepsilon$ =0.3, $\delta$ =0.05). For convenience of comparison, all the AVAs are normalized to the amplitude at normal incidence. A poor match is seen between the interpolated amplitude and the isotropic AVA curve even within this small angle range. This mismatch is corrected by taking the anisotropy into account, and the anisotropic AVA curve shows a good agreement with the amplitude variation in the real data.

Figure 4 (a) An angle gather and logs of Thomsen’s parameters. (b) Normalized picked amplitude values (red dots) at around 1645ms and their interpolated AVA (black curve). (c) Normalized theoretical anisotropic (black) and isotropic (green) AVA curves for comparison.

Another application of the estimated anisotropy parameters is the correction of sonic logs of deviated or horizontal wells, which are common in the development of unconventional reservoirs. The P-wave velocities measured in deviated or horizontal wells penetrating the shale formation are generally faster than those measured in corresponding vertical wells. Using the same framework, we predict the
vertical velocities and anisotropy parameters in the horizontal section of the same well. The predicted vertical P-wave velocity (dashed red curve in Figure 5(a)) generally has a smaller value than the measured P-wave velocity (solid black curve), especially for intervals with a large volume of clay. The horizontal P-wave velocity (dashed blue curve) is calculated using the estimates of vertical P-wave velocity and Thomsen’s parameters, and it agrees well with the measured P-wave velocity over a wide range of the horizontal section. Thus we consider that the predicted vertical P-wave velocity and anisotropy parameters have reasonable accuracy. In fact, compared with the sonic logs, the measured S-wave velocity in the horizontal well is barely affected by anisotropy. The anisotropy has great influence on Poisson’s ratio but little influence on Young’s modulus (Figure 5b). Therefore, the predicted P-wave velocity helps correct the overestimated Poisson’s ratio of clay-rich shale, and thus improves characterization of the brittleness of the shale reservoirs.

Figure 5 (a) Comparison of predicted logs (dashed curves) with real logs in horizontal well (solid black curves): vertical P-wave velocity, horizontal P-wave velocity and estimated $\varepsilon$ from the top to the bottom. (b) Comparison of predicted (dashed red curves) and real logs (solid black curves) of Poisson’s ratio, Young’s modulus and clay volume from the top to the bottom.

Conclusions
A practical framework is proposed and applied to predict the velocities and anisotropy parameters of a shale-gas well in China. The accuracy of predicted vertical P- and S-wave velocities are demonstrated by comparison with the real logs. Estimates of Thomsen’s parameters show the clay-rich shale formation has strong anisotropy, which strongly affects the AVO response and the sonic logs in the horizontal well. The estimated anisotropy parameters are used to generate the theoretical AVA curve which is calibrated with amplitude variation of the real angle gather. The sonic log in the horizontal well is corrected based on the predicted result. This correction also improves characterization of the brittleness of the shale formation.

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References