Estimation of shale reservoir properties based on anisotropic rock physics modelling

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Summary

In our study, an improved anisotropic rock physics model has been built. The kerogen in shale is simulated using anisotropic SCA+DEM theory. The pore space of shale is divided into ductile pores and brittle pores in terms of clay volume. A new parameter, the standard deviation of the distribution function, is introduced to model the lamination of shale. For data analysis, a new 3D template method is introduced to take the mineralogy effect into consideration, which makes the model more realistic than the usual methods.

A real shale data set from Southwest China has been analysed using our model. Reservoir properties like pore aspect ratio which indicates the microstructure of reservoir, Thomsen anisotropic parameters and S wave velocity, have been predicted using the 3D template. The predicted results coincide well with the measured data.
Introduction

Rock physics modelling has been fully proved in many conventional reservoirs as an efficient method to bridge the elastic properties of geophysical data with the physical properties of a reservoir. However, construction of an appropriate rock physics model for shale is not easy. Many existing models are not valid for a shale reservoir due to its strong anisotropic properties. How to model anisotropy in shale is the key to shale model construction. We use SCA+DEM to model the kerogen effect in shale and introduce the standard deviation of the distribution function to model the lamination of shale. The feasibility of our model is tested by applying our model to a real shale dataset from southwest China. A new 3D template method is introduced to take the mineralogy effect into consideration during data analysis, which makes the template more suitable for real data. The reservoir quality, as well as the S wave, is predicted and it coincides well with measured data.

Anisotropic shale rock physics model

The key to build a reasonable shale rock physics model is to find an appropriate way to model the anisotropy of shale. Many studies state the anisotropy of shale can be summarized into three main aspects: 1) Existence of organic matter; 2) Lamination of clay and kerogen particles; 3) Complicated pore system (Sayers, 1994, Vernik and Liu, 1996, Sondergeld and Rai, 2011).

In previous work (Qian, 2014), we used the combination of an anisotropic Self-Consistent Approximation model and anisotropic Differential Effective Medium model to model the clay-kerogen mixture which is the first origin of shale anisotropy. The advantage of using SCA+DEM to model the kerogen in shale is that it can preserve the connectivity between clay and kerogen even when the concentration of one phase is varied. Meanwhile, SCA+DEM theory has the benefit of treating different phases equally, which solves the order problem of DEM, since DEM presents various results due to the different orders of inclusions used.

Here, we improve our model by introducing the standard deviation of the orientation distribution function to model the lamination of clay and kerogen. Many identical bi-connected kerogen-clay blocks, which are modelled by SCA+DEM, are rotated and combined to model the lamination. The angle of rotation for each block is satisfied by a normal distribution with mean value equal to zero according to the VTI property of shale. The portions of flat blocks will change based on the value of the standard deviation, which lastly affects the anisotropy of shale.

In addition, aspect ratio is introduced to model the pore shape and microstructure of shale. Since the pores of existing shale models are rarely discussed, following the idea of the dual porosity Xu-White model, the total pore volume is considered to be clay-related pores and brittle mineral-related pores based on the clay volume. The workflow of our organic shale model is shown in Figure 1.

![Figure 1 Workflow of the rock physics model for shale.](image-url)
The lamination of clay and kerogen

In a real shale reservoir, the major portion of clay is laminated, while a little portion of the clay is distributed randomly (Hornby, 1994). The key factor, standard deviation, can control how much portion of the clay or kerogen is laminated. As the standard deviation is equal to zero, all the clay-kerogen blocks stay flat, which gives the strong VTI properties of the block. As the standard deviation increases, the VTI properties decrease, which means that more and more blocks are rotated.

Figure 2 shows how the standard deviation can control the lamination and influence the anisotropy of clay. The elastic properties of clay are quoted from Sayers (2013): $C_{11}=85.6\text{Gpa}$, $C_{33}=65.5\text{Gpa}$, $C_{44}=24.6\text{Gpa}$, $C_{66}=29.7\text{Gpa}$ and $C_{13}=21.1\text{Gpa}$.

**Figure 2** Variation of stiffness tensors with standard deviation of orientation distribution function.

3D Templates for microstructure inversion

In our model, both anisotropic SCA and DEM theories are used. The SCA and DEM are all inclusion theories (Hornby, 1994). As the name implies, inclusion theories treat all the compositions in shale as inclusions, and they introduce an important parameter, aspect ratio, to control the shape of individual inclusions, which can help us to model the anisotropy caused by un-spherical pores in the shale.

The pore aspect ratio is the key parameter for inclusion theories, but it is hard to measure it directly. Geophysicists usually use a rock physics model to construct a 2D template which illustrates the relationship between pore aspect ratio and other elastic parameters (velocity and impedance), and then using template and measured elastic parameters to invert for pore aspect ratio (Jiang 2013). However, this procedure has an assumption that the volume fractions of each mineral stay unchanged during template construction. For example, if we are dealing with well-logging data, the common way to invert for pore aspect ratio is to calculate an average volume fraction of each mineral for the target depths, and then use this unchanged fraction to build the template, and finally invert the pore aspect ratio by using the template. However, the volume fractions for each depth do change. So here we add the third dimension, the volume fraction of clay and kerogen, to build a 3D template which can take mineralogy into consideration during inversion. The mineral constitution of shale is complicated; it is unrealistic to analyse every volume fraction of minerals. Here we introduce a volume fraction of ductile minerals ($V_{\text{sh}}$) to represent the mineralogy of the rock. We roughly divide all the minerals into brittle minerals and ductile minerals, and the ductile mineral contains the clay and kerogen.

The Figure below is the 3D template. The x-axis, y-axis and z-axis represent the volume fraction of ductile minerals ($V_{\text{sh}}$), porosity and elastic wave velocity, respectively. The top coloured curve represents the modelling P wave velocity for pore aspect ratio equal to 1 and the bottom one is the modelling velocity for pore aspect ratio equal to 0.01. The blue points are from a real shale reservoir in south China.

By using the 3D aspect ratio template, we can invert for pore aspect ratio. The P wave velocity is set as the object parameter, and then many modelling P wave velocities are modelled by varying the pore aspect ratio. The value of aspect ratio which can minimise the difference between the modelling result and real velocity is the inverted result.
Figure 3 3D templets for pore aspect ratio inversion (a)Vp  (b) Vs.

All the data points are covered by the top and bottom curve which means all the data points can be modelled by our model with pore aspect ratio changing from 0.01 to 1. A similar procedure is performed on both P and S wave data. The pore aspect ratio seems more sensitive to the S wave. Besides, these two curves only coincide with each other when porosity equals zero, which means the pore aspect ratio cannot influence the modelling results when porosity equals zero. In addition, since both brittle pores and ductile pores are considered in our model, the pore aspect ratio does influence the modelling results even if the rock contains no brittle minerals (Vsh=1) or ductile minerals (Vsh=0).

A case study from Sichuan basin, southwest China

Figure 4 below illustrates real well-logging data from Well A. The target formations are the lower part of the Longmaxi shale formation and Wufeng shale formation in the depth between 2045m and 2065m. Gamma ray, porosity, P and S wave velocity, total organic carbon, density, Vp/Vs ratio and Poisson’s ratio are plotted from left to right. Two gamma ray curves are shown in the left-most column. The red curve indicates total gamma value and the blue one shows the gamma value without uranium. The majority radioactive element of kerogen comes from uranium. The gap between these two curves can help us to locate our target zone, and the larger gap presents the higher TOC fraction existing in the corresponding formation. The other logging curves also show typical features of a shale reservoir: relatively high porosity compared with the surrounding formations, low P and S wave velocities and low density caused by the presence of clay and kerogen minerals, and a high TOC value. The ternary shows the mineralogy of the target depths. The background colour indicates the TOC value, from which we can find that lower TOC corresponds to lower clay content.

(a)
Figure 4 (a) Well logging data from south China. Panels from left to right indicate GR,Porosity,Vp,Vs,TOC,Density,Vp/Vs and Poisson’s Ratio. (b) Mineralogy of target depths. (c) Panels from left to right show the result of predicted Vp,Vs and pore aspect ratio. Red and blue lines represent modelling velocity and measured velocity respectively. (d) Predicted anisotropic parameters

The pore aspect ratio, S wave velocity and Thomsen anisotropic parameters has been predicted; the predicted results coincide with the measured data well which prove the feasibility of our model. Some difference can be found between the measured velocity and predicted velocity, which may be caused by the fixed standard deviation of ODF. For this data set, we set the standard deviation equal to 20 while inverting for the pore aspect ratio, since it can help to construct a good 3D template which can match the data points well. In future work, we may try to eliminate this difference by taking lamination into consideration during inversion.

Conclusions

An improved anisotropic rock physics model has been built for a shale reservoir in our study. The kerogen in shale is simulated using anisotropic SCA+DEM theory. The pore space of shale is divided into ductile pores and brittle pores in terms of clay volume. A new parameter, the standard deviation of the distribution function, is introduced to model the lamination of shale. For data analysis, a 3D template is constructed. The mineralogy effect is taken into consideration, which makes the model more realistic than the usual methods. A real shale data set from Southwest China has been analysed using our model. Reservoir properties like pore aspect ratio which indicates the microstructure of reservoir, Thomsen anisotropic parameters and S wave velocity, have been predicted using the 3D template. The predicted results coincide well with the measured data.

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