The effect of low aspect ratio pores on the seismic anisotropy of shales

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Summary

As a result of the increasing stress that develops during burial, plate-shaped clay minerals in shales tend to align with planes oriented approximately perpendicular to the maximum stress direction. This partial alignment results in shale anisotropy, and this needs to be quantified to reliably extract reservoir fluid, lithology and pore pressure from seismic data and to understand time-to-depth conversion errors and non-hyperbolic moveout. The low aspect ratio pores between clay particles play an important role in determining the character of the anisotropy of shales and can be represented by a normal compliance $B_N$ and shear compliance $B_T$ that describe the deformation of the interparticle regions under an applied stress. The relations among the various anisotropy parameters for shales depend on the ratio $B_N/B_T$ of these low aspect ratio pores. For perfectly aligned clay particles, Thomsen’s anisotropy parameter $\gamma$ is a function of the shear compliance $B_T$, but $\varepsilon$ and $\delta$ increase with increasing $B_N/B_T$. The presence of a fluid with non-zero bulk modulus in the regions between clay particles acts to decrease $B_N$ and may lead to significant reductions in $\varepsilon$ and $\delta$ for sufficiently high fluid bulk modulus.

Introduction

Shales are a major component of sedimentary basins, and play an important role in fluid flow and seismic imaging because of their low permeability and anisotropic properties. The seismic anisotropy of shales results from the partial alignment of anisotropic plate-like clay minerals (Kaarsberg, 1959; Tosaya, 1982; Sayers, 1994, 1999, 2005). Figure 1, for example, shows a scanning electron micrograph of a shale sample from the Kimmeridge Clay Formation. This shows a matrix of clay sheets, containing more-or-less isolated silt particles. The clay particles are seen to vary in orientation, but are aligned locally.

Because the low aspect ratio pores between the clay particles are expected to be more compliant than the clay particles themselves, it is important to account for the additional compliance of interparticle regions in any model of elastic wave propagation through shales. In this paper, the effect of the interparticle regions between clay particles on the anisotropy of shales is investigated. An understanding of shale anisotropy is important to obtain reliable information on reservoir fluid, lithology and pore pressure from seismic data, and to understand time-to-depth conversion errors and non-hyperbolic moveout.

Figure 1: Scanning electron micrograph of a shale from the Kimmeridge Clay Formation in Dorset, UK. Photograph by John Cook, Schlumberger Cambridge Research.

Many shales encountered in the subsurface can be described, to a good approximation, as being transversely isotropic with a vertical axis of rotational symmetry. A transversely isotropic medium has five independent elastic stiffnesses. Taking the $x_3$ axis to lie along the axis of rotational symmetry, the non-vanishing elastic stiffness coefficients are $c_{11}=c_{33}$, $c_{12}=c_{23}$, $c_{13}=c_{31}=c_{32}=c_{21}$, $c_{44}=c_{55}$ and $c_{66}=(c_{11}-c_{12})/2$ in the conventional two-index notation (Nye, 1985). Because an isotropic medium can be described by two elastic constants, a transversely isotropic medium has three anisotropy parameters. In the following, the three anisotropy parameters $\varepsilon$, $\gamma$, and $\delta$ of Thomsen (1986) are used. These are defined by the following equations:

$$\varepsilon = \frac{c_{11} - c_{33}}{2c_{33}},$$

$$\gamma = \frac{c_{66} - c_{55}}{2c_{55}},$$

$$\delta = \frac{(c_{13} + c_{55})^2 - (c_{33} - c_{55})^2}{2c_{33}(c_{33} - c_{55})}.$$  

The effect of interparticle regions on seismic anisotropy

An elastic wave induces a jump discontinuity $[\mathbf{u}] = \mathbf{u}^+ - \mathbf{u}^-$ in the $i$th component of the displacement vector $\mathbf{u}$ from its value $\mathbf{u}^-$ in the clay particle on the negative side of the interparticle region to its value $\mathbf{u}^+$ in the clay particle on the positive side of the region, the choice of normal $\mathbf{n}$ to the

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particles defining the positive side of the interparticle region (see Figure 2).

Figure 2: Schematic representation of the region between two clay particles.

The displacement discontinuity may be related to the applied traction vector \( t \) with components \( t_i \) by

\[
S_{ijkl} = \epsilon_{ijkl}^0 + \Delta S_{ijkl}
\]

(Sayers and Kachanov, 1995; Sayers, 1999) where \( \epsilon_{ijkl}^0 \) is the elastic compliance tensor of the shale if the normal and shear compliance \( B_N \) and \( B_T \) were zero, i.e. if the clay particles were welded together.

The excess compliance, \( \Delta S_{ijkl} \), resulting from the normal and shear compliance of the low aspect ratio pores, can be expressed as

\[
\Delta S_{ijkl} = \frac{1}{4} \left( \delta_{ik} \alpha_{jl} + \delta_{il} \alpha_{jk} + \delta_{jl} \alpha_{ik} + \delta_{jk} \alpha_{il} \right) + \beta_{ijkl}.
\]

Here \( \alpha_{ij} \) is a second-rank tensor and \( \beta_{ijkl} \) is a fourth-rank tensor, defined by Sayers and Kachanov (1995) as

\[
\alpha_{ij} = \frac{1}{V} \sum_r \left( B_T^{(r)} n_i^{(r)} n_j^{(r)} \right) A^{(r)},
\]

\[
\beta_{ijkl} = \frac{1}{V} \sum_r \left( B_N^{(r)} - B_T^{(r)} \right) n_i^{(r)} n_j^{(r)} n_k^{(r)} n_l^{(r)} A^{(r)}.
\]

In these equations, \( B_N^{(r)} \) and \( B_T^{(r)} \) are the normal and shear compliances of the \( r \)th interparticle region in volume \( V \), \( n_i^{(r)} \) is the \( i \)th component of the normal to the pore, and \( A^{(r)} \) is the area of the pore. The elastic stiffness tensor is obtained by inverting the compliance tensor given by equations 4-7.

Figures 3-5 plot the anisotropy parameters \( \epsilon \) and \( \delta \) as a function of \( \gamma \), and \( \delta \) as a function of \( \epsilon \) for the values predicted by this theory assuming that the clay sheets are perfectly aligned, with normals parallel to the \( x_3 \) axis.

Figure 3: Plot of \( \epsilon \) versus \( \gamma \) predicted by the theory assuming that the clay sheets are perfectly aligned for various values of \( B_N \) and \( B_T \) indicated on the curves, compared with the values obtained from the measurements of Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995) and Wang (2002) for shales.

Figure 4: Plot of \( \delta \) versus \( \gamma \) predicted by the theory assuming that the clay sheets are perfectly aligned for various values of \( B_N \) and \( B_T \) indicated on the curves, compared with the values obtained from the measurements of Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995) and Wang (2002) for shales.
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Figure 5: Plot of $\delta$ versus $\epsilon$ predicted by the theory assuming that the clay sheets are perfectly aligned for various values of $B_N/B_T$ indicated on the curves, compared with the values obtained from the measurements of Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995) and Wang (2002) for shales.

The assumption that the clay sheets are perfectly aligned, with normals parallel to the $x_3$ axis, implies that $n_z=n_x=0$, $n_y=1$ for all interparticle regions, and the only non-zero components of $\alpha_{ij}$ and $\beta_{ijkl}$ are $\alpha_{33}$ and $\beta_{3333}$, given by

$$\alpha_{33} = \frac{1}{V} \sum_r B_T^{(r)} A^{(r)},$$

$$\beta_{3333} = \frac{1}{V} \sum_r \left( B_N^{(r)} - B_T^{(r)} \right) A^{(r)},$$

as follows from equations 6 and 7. The non-zero $\Delta S_{ij}$ are then, from equation 5,

$$\Delta S_{44} = \Delta S_{55} = \alpha_{33}$$

$$\Delta S_{33} = \alpha_{33} + \beta_{3333}$$

For the computations shown in figures 3-5, the clay sheets are assumed to be isotropic, with Poisson’s ratio $\nu=0.3154$ given by Wang et al. (2001) for illite. Also shown are the values calculated from the measurements of Jones and Wang (1981), Vernik and Nur (1992), Hornby (1994), Johnston and Christensen (1995), and Wang (2002) for shales.

It follows, from the assumption of perfectly aligned clay particles, that $\gamma$ depends on the properties of the interparticle regions only through the shear compliance $B_T$. By contrast, $\epsilon$ and $\delta$ are seen in Figures 3 and 4 to increase with increasing values of $B_N/B_T$. It should be noted that the anisotropy parameter $\gamma$ can be determined from sonic logs using the dipole shear and Stoneley wave velocities.

As shown in Figures 4 and 5, negative values of $\delta$ may occur if $B_N/B_T$ is sufficiently small. As a result of a fluid, with non-zero bulk modulus, in the interparticle space, the normal compliance $B_N$ is expected to be less than the shear compliance $B_T$. Drying of a shale sample in the laboratory would be expected to lead to an increase in $B_N/B_T$ and may result in an overestimation of $\epsilon$ and $\delta$ relative to $\gamma$. It is important, therefore, to perform measurements on fully saturated shale samples to correctly characterize the in-situ anisotropy of the shale.

Clay mineral anisotropy

In the analysis presented above, the clay particles are assumed to be isotropic. However, because clays are layered minerals, it is expected that the theoretical model of equations 4-7 may give a reasonable representation of the elastic anisotropy for clay minerals, with $B_N$ and $B_T$ representing the normal and shear compliance acting between clay layers. To test this hypothesis requires measurements of single crystal elastic constants for clay minerals which are currently unavailable.

Although measurements of single crystal elastic constants for clay minerals are currently unavailable, the crystallographic structure and composition of illite is similar to that of muscovite (Tosaya, 1982), for which Alexandrov and Ryzhova (1961) obtained the values $c_{11}=178$ GPa, $c_{33}=54.9$ GPa, $c_{55}=12.2$ GPa, $c_{66}=67.8$ GPa, $c_{12}=42.4$ GPa, and $c_{13}=14.5$ GPa from their measured compressional and shear wave velocities. The corresponding components of the elastic compliance tensor are found by inversion to be $s_{11}=6.04$ TPa$^{-1}$, $s_{33}=18.9$ TPa$^{-1}$, $s_{55}=82.0$ TPa$^{-1}$, $s_{66}=14.7$ TPa$^{-1}$, $s_{12}=-1.34$ TPa$^{-1}$, and $s_{13}=-1.24$ TPa$^{-1}$.

Assuming that the clay layers in muscovite may be approximated as isotropic layers with elastic compliances $s_{11}^0 = s_{22}^0 = s_{33}^0 = 6.04$ TPa$^{-1}$, $s_{44}^0 = s_{55}^0 = s_{66}^0 = 14.7$ TPa$^{-1}$, and $s_{12}^0 = s_{13}^0 = s_{23}^0 = -1.34$ TPa$^{-1}$ given by the in-plane compliances $s_{11}=6.04$ TPa$^{-1}$, $s_{12}=1.34$ TPa$^{-1}$, $s_{55}=14.7$ TPa$^{-1}$ of muscovite, equations 10 and 11 lead to $B_N/B_T=0.191$ for muscovite.
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Including the effects of the interlayer compliances $B_N$ and $B_T$, the elastic compliances can then be calculated using equations 10 and 11.

The elastic stiffness components can then be obtained from the $S_{ij}$ by matrix inversion and are given by

$$C_{11} + C_{12} = S_{33}/S,$$  \hspace{1cm} (12)

$$C_{11} - C_{12} = 1/(S_{11} - S_{12}),$$  \hspace{1cm} (13)

$$C_{13} = -S_{13}/S,$$  \hspace{1cm} (14)

$$C_{33} = (S_{11} + S_{12})/S,$$  \hspace{1cm} (15)

$$C_{55} = 1/S_{55},$$  \hspace{1cm} (16)

where

$$S = S_{33}(S_{11} + S_{12}) - 2S_{13}^2.$$  \hspace{1cm} (17)

The value $B_N/B_T = 0.191$ predicts the values $c_{11} = 178.6$ GPa, $c_{33} = 55.2$ GPa, $c_{44} = 12.2$ GPa, $c_{66} = 67.8$ GPa, $c_{12} = 43.0$ GPa, and $c_{13} = 15.7$ GPa, which are in excellent agreement with the values obtained by Alexandrov and Ryzhova (1961). This confirms that a model of isotropic elastic layers interacting through normal and shear compliances $B_N$ and $B_T$ is a reasonable model of the elastic anisotropy of muscovite.

The applicability of the theory to the clay particles themselves is further demonstrated by the phase slowness surfaces shown in figure 6, which compares the results obtained using the elastic stiffnesses obtained by Alexandrov and Ryzhova (1961) with those obtained using the current theory. It is seen that the difference between the results is of the order of the width of the lines drawn. Thus the curves in Figures 3-5 can be regarded as representing the combined effect of the interparticle regions and the gaps between layers in the clay minerals making up the shale.

Finally, note that comparing the value $B_N/B_T = 0.191$ obtained for muscovite with Figure 4 suggests that $\delta$ should be negative for muscovite. This is confirmed by the anisotropy parameters calculated for muscovite using the elastic stiffnesses obtained by Alexandrov and Ryzhova (1961) which give $\varepsilon = 1.1211$, $\delta = -0.2368$ and $\gamma = 2.2787$.

Figure 6: Comparison of the phase slowness curves of muscovite (red curves) computed using the elastic stiffnesses obtained by Alexandrov and Ryzhova (1961) with those obtained using the model of isotropic elastic layers interacting through normal and shear compliances $B_N$ and $B_T$ presented in this paper (blue curves). The green curves show the phase slowness curves for an elliptically anisotropic medium having the same axial compressional and shear wave velocities as muscovite.

Conclusion

The low aspect ratio pores between clay particles play an important role in determining the character of the anisotropy of shales, and can be represented by a normal compliance $B_N$ and shear compliance $B_T$ that describe the deformation of the interparticle regions under an applied stress. The relation among the various anisotropy parameters for shales depends on the ratio $B_N/B_T$ of the interparticle regions. For perfectly aligned clay particles, Thomsen’s anisotropy parameter $\gamma$ is a function only of the shear compliance $B_T$, but $\varepsilon$ and $\delta$ increase with increasing $B_N/B_T$. The presence of a fluid with non-zero bulk modulus in the regions between clay particles acts to decrease $B_N$, and can lead to negative values of $\delta$ for sufficiently high fluid bulk modulus. Drying of a shale sample in the laboratory would be expected to lead to an increase in $B_N/B_T$ and may result in an overestimation of $\varepsilon$ and $\delta$ relative to $\gamma$. It is important, therefore, to perform measurements on fully saturated shale samples in order to correctly characterize the in-situ anisotropy of the shale.
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