Anisotropic elastic modelling for organic shales

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This paper presents an anisotropic rock physics modelling for estimating elastic stiffness of organic shales. The model combines the Reuss-Voigt-Hill average, the anisotropic Differential Effective Medium model and the Brown-Korringa model in order to take mineralogy, kerogen, pores and fluid into consideration. A comparison of the predicted results with experimental measurements indicates that this model has the potential to estimate the elastic stiffness of organic shales. Laboratory measurements of shale samples including both XRD analysis and velocities are needed to further calibrate our model.

Introduction

Shale gas reservoirs are different from the traditional structural and lithologic trapping reservoirs. Organic shales as the source and reservoir rock are characterized by their strong velocity anisotropy, which is current research focus into the seismic responses of shale gas formations. There are multiple causes of anisotropy in shales, such as the shape and preferred orientation of clay platelets as well as kerogen due to mechanical compaction (Lonardelli et al. 2007). The presence of pores and microcracks formed during petroleum generation from organic matter is another reason for shale anisotropy. Microcracks parallel to the bedding plane can enhance the strong intrinsic anisotropy (Vernic and Nur, 1992). Stress-induced natural fractures can also produce anisotropy and affect the stimulation of hydraulic fractures. Natural fractures (Curtis, 2002; Gale, et al. 2007) can provide permeability enhancement if they are open, but can affect the efficiency of hydraulic fracture treatment if sealed.

Rock physics modelling of shales provides links between rock properties and seismic responses. Vernic and Nur (1992) found the traditional Backus average was not able to fit the measured velocity in bedding-parallel directions of core samples from Bakken shale. SEM observation of these core samples (Vernik and Landis, 1996) indicated that Kerogen forms a continuous network in organic-rich shales (Total Organic Carbon, TOC >5%), and discontinued the inorganic minerals into lenticular laminae. A modified Backus average with an empirical constant to control the textural discontinuity was used to model the anisotropy of Bakken shales (Vernik and Landis, 1996; Vernik and Liu, 1997). Bandyopadhyay (2009) showed that the same data can be predicted using the anisotropic Differential Effective Medium (DEM) model with kerogen as the background matrix.

This paper presents a comprehensive rock physics model for estimating the elastic stiffness of organic shales with certain porosity. It takes different mineralogy, kerogen, pores and fluids into account. First we use the Reuss-Voigt-Hill average to calculate the elastic tensor of the inorganic composite (or pure 'shale'). Then, we consider the continuous kerogen as background, and add 'shale', pores and cracks into the background. The anisotropic DEM model is used to analyze the change of stiffness. Finally, fluid is added into pores with the Brown-Korringa model to calculate the elastic stiffness of fluid saturated rock.

Rock physics modelling for organic shales

Since the Bakken shales are typical of their high organic content and very low porosities, the Backus average method and anisotropic DEM model can be used independently to estimate their elastic stiffness. However, for shales with certain porosities (e.g. Bazhenov, Monterey, Niobrara, etc.), the pores and their saturated fluids must be taken into consideration. Figure 1 shows how to construct our rock physics model for organic shales. The workflow consists of four steps:
(1) The elastic constants of minerals (clay, quartz, calcite et al.) present in the rock are calculated using the Reuss-Voigt-Hill average. The minerals make up the 'shale' free of kerogen. It can be considered to be isotropic or anisotropic. Minerals and their respective volume percentages can normally be obtained from X-Ray Diffraction (XRD) analysis.
(2) Consider Kerogen as background material, using the anisotropic DEM model to add 'shale' inclusions into the background, forming a kerogen-'shale' composite. In this step, the shapes of 'shale' and its preferred orientation are the main causes of anisotropy. Shapes can be characterized by aspect ratio. The preferred orientation can be quantified by a statistical Orientation Distribution Function (ODF) derived from SEM observation (Hornby, et al. 1994). The calculated elastic tensor of kerogen-'shale' composite will exhibit vertical transverse isotropy (VTI).
(3) Add pores and cracks into the kerogen-'shale' composite with the anisotropic DEM model again to estimate the stiffness of the dry rock. The pore or crack aspect ratio is used to control the shape.
(4) Add fluid into the pore and crack system and use the Brown-Korrigan model to obtain the stiffness of the fluid saturated rock.

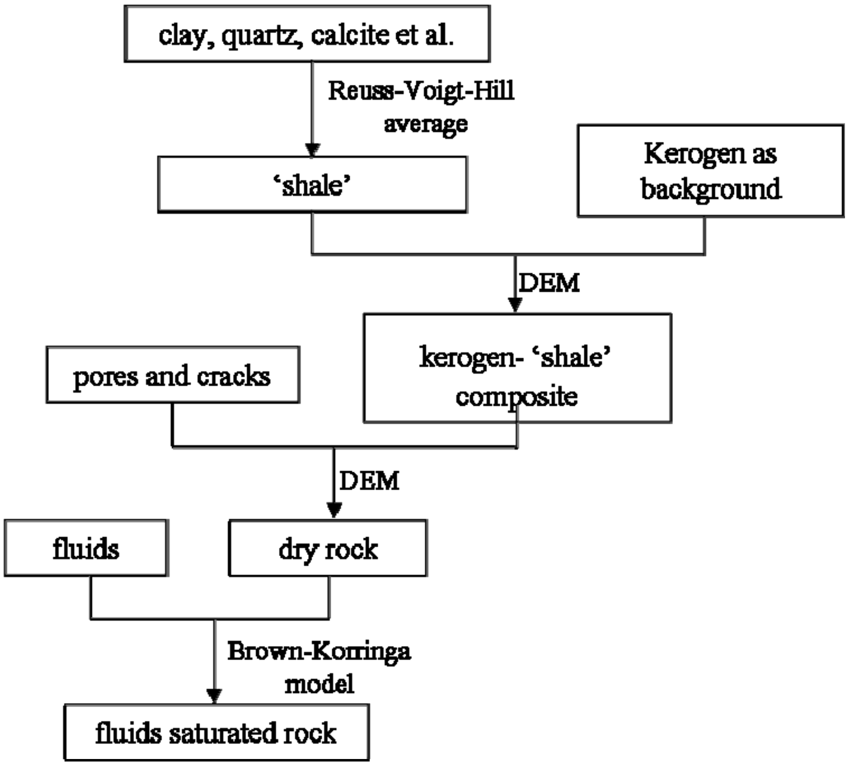


Figure 1 *Workflow of the rock physics model to estimate elastic stiffness of organic shales.*

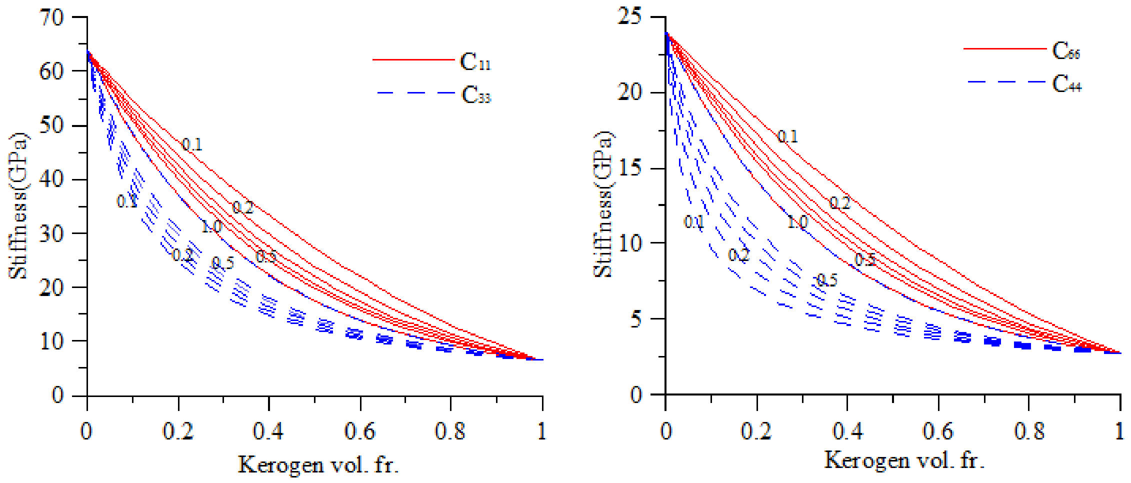
Example

Vernic and Landis (1996) gave the average mineralogy (% vol.) of 8 shale core samples from Bazhenov formation through Whole-Rock XRD Analysis. These core samples came from a single well located in the northeastern part of the West Siberian basin at depths from 3784m to 3842m. Vernik and Liu (1997) further provided the ultrasonic velocities of the 8 samples under dry condition and 5 samples under brine-saturated condition. Table 1 shows four mineral groups that dominate the mineralogy. The volume percentage of each mineral was given on a kerogen-free basis. We take the average mineralogy as an example, and assume that the volume percentage of kerogen is 16.8%, the porosity is 4.12% (referring to No.3 sample of Bazhenov in appendix A, Vernik and Liu, 1997). The elastic moduli of clay are cited from Hornby et al. (1994). The others are from Mavko et al. (1998). The elastic stiffness of dry rock and brine-saturated rock are calculated with our shales model.

Table 1 *The average volume percentage and elastic moduli for each ingredient of the Bazhenov shale.*

	quartz/ feldspar	carbonate	clay	Pyrite	kerogen	porosity	Fluid(brine)
% Vol.	46	3	48	3	16.8	4.12	
K(GPa)	37	76.8	22.9	147.4	2.9		2.2
μ(GPa)	44	32	10.6	132.5	2.7		0

We assume isotropic elastic properties for both 'shale' and kerogen. Using the Reuss-Voigt-Hill average, we obtain that the elastic moduli for 'shale' are K=32.08 GPa; μ=23.92 GPa, corresponding to C_{33}=63.97 GPa; C_{44}=23.92 GPa; C_{12}=16.13 GPa. The stiffnesses of kerogen are C_{33}=6.50 GPa; C_{44}=2.70 GPa C_{12}=1.10 GPa. Figure 2 displays a series of stiffness curves changing with kerogen volume fraction by varying the aspect ratio of the 'shale' inclusions, using anisotropic DEM model. We can see that thinner inclusions exhibit higher anisotropy. When the aspect ratio is 1.0, C_{11} and C_{44} coincide with C_{33} and C_{66} respectively, exhibiting the characteristics of isotropy. Since the 'shale' is lenticular, we give a small aspect ratio of 0.1 to calculate the stiffness of the kerogen-'shale' composite.

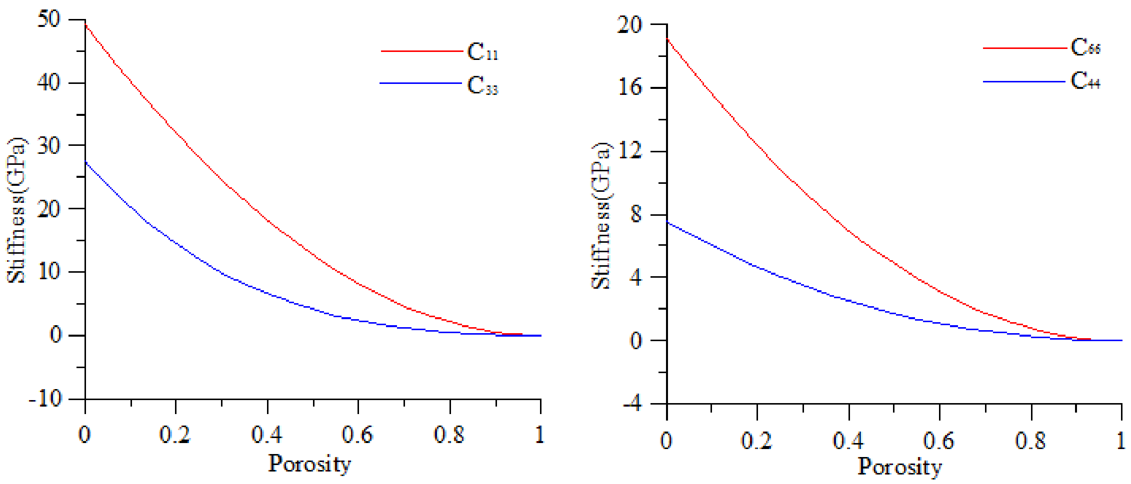


(a) C_{11} and C_{33} (b) C_{44} and C_{66}

***Figure 2** Stiffness changes with kerogen volume for the Kerogen-'shale' composite using anisotropic DEM model. Kerogen background and 'shale' inclusions are both considered to be isotropic. 'Shale' aspect ratio=0.1, 0.2, 0.3, 0.4, 0.5, 1.0.*

Likewise, pores are added to the composite using the anisotropic DEM model again to form the dry rock. For simplicity, we give an aspect ratio of 0.6 for the pores and assume the distribution of 'shale' to be perfectly aligned. However, for the same porosity, pore types can cause different P-wave velocity. Xu and Payne (2009) considered different types of pores in their carbonate model. The bulk density of dry rock is 2.34g/cm^3. The density of brine-saturated rock would be 2.38 g/cm^3. Figure 3 displays the stiffness of dry rock changing with porosity. Evidently, stiffness decreases with increasing porosity.

Finally, the Brown-Korringa model is used to calculate the elastic stiffness for brine-saturated rock. Table 2 is a comparison of predicted stiffness using our model and stiffness transformed from the measured velocities of No.3 sample of Bazhenov formation by Vernic and Liu (1997). We can see that the predicted C_{33} changes significantly, but the predicted C_{44} and C_{66} remain the same when saturated with fluid. The error of C_{44} for the dry case is slightly larger than those of C_{11}, C_{33} and C_{66}. Since we use the average mineralogy rather than the accurate XRD result for this sample, the errors for the four elastic stiffnesses are acceptable.



(a) C_{11} and C_{33} (b) C_{44} and C_{66}

***Figure 3** Stiffness changes with porosity for the dry rock using anisotropic DEM model. Pore aspect ratio=0.6.*

Table 2 *Comparison of predicted stiffness using our model and stiffness transformed from the measured velocities of No.3 shale sample from Bazhenov formation by Vernic and Liu (1997).*

	Rock	C_{11} (GPa)	C_{33} (GPa)	C_{44} (GPa)	C_{66} (GPa)	C_{13} (GPa)
predicted stiffness	Kerogen-'shale'	49.25	27.60	7.53	19.11	7.01
	Dry	45.44	24.43	6.87	17.62	6.35
	Brine-Saturated	45.45	31.33	6.87	17.62	6.05
transformed stiffness of No.3 sample	Dry	45.50	25.17	10.32	17.82	
	Brine-Saturated	42.38	26.23	8.68	15.23	

Conclusions

In this paper, we have combined the existing rock physics models to construct an organic shales model which takes pores and fluid effect into account. The model is able to estimate elastic stiffness of organic shales if the mineralogy and kerogen content are known to us. Further calibration with laboratory measurements including both XRD analysis and velocities of shale samples is needed for our model.

Acknowledgements

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