Shale anisotropy estimation from well logs based on Hudson-Cheng's model and deep neural network

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Introduction

Shales are transverse isotropic media due to textural alignment of clay minerals, non-spherical pores, and cracks at sub-seismic scale. Anisotropic rock physics models are necessary for shale anisotropy estimation from well logs due to the single directional nature of log data. The Hudson-Cheng's model, which decomposes an intact rock into an isotropic background with inclusion of spherical pores and a set of aligned thin-cracks, was employed by Li et al. (2017) to predict Thomsen's anisotropy parameters (ε, γ and δ). In this paper, we prove this method to be effective and practical through (1) the validation of the Hudson-Cheng's model against published lab measurements of shale anisotropy and (2) a successful application on log data from Sichuan, China. Furthermore, we construct a deep neural network (DNN) for shale anisotropy estimation based on inverted results of Hudson-Cheng's model on Sichuan well logs. The predictions of the DNN model on the training set, validation set, and test set all fit well with the labels, proving it to be a well-trained model.

Hudson-Cheng's model

In Hudson-Cheng's model, an intact rock is decomposed into three sections: a homogenous isotropic rock matrix, a set of randomly-distributed brine-saturated spherical pores, and a group of aligned thin-cracks that contribute to anisotropy. The elastic moduli of the isotropic background comprised of rock matrix and pores can be approximated with the Hashin-Shtrikman upper bound (Hashin and Shtrikman, 1962). Based on the difference between effective and background bulk moduli or shear moduli, we can derive two indirect measurements of crack densities. Then the anisotropy parameters can be inverted through minimizing the difference between crack densities generated from P- and S-wave velocity logs.

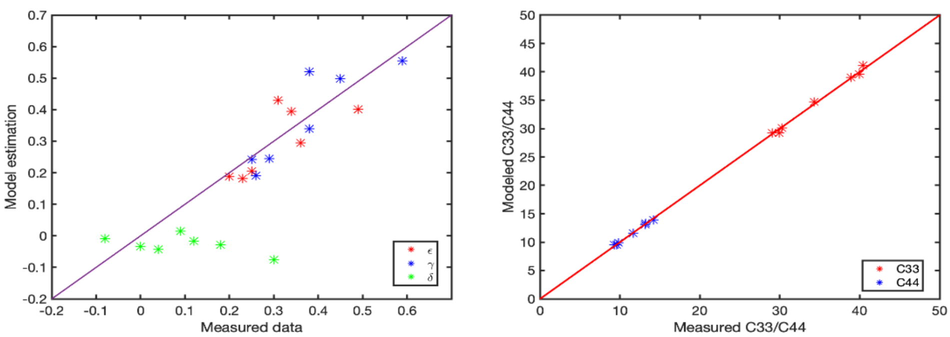

Figure 1 *Comparison between estimations of Hudson-Cheng's model and lab measurements of* ε, γ, δ, C_{33} *and* C_{44} *when* K_0=32GPa, μ_0=21GPa, α=0.03

We validate Hudson-Cheng's model with lab measurements of anisotropy parameters of shale samples from the Williston Basin by Vernik and Nur (1992). By adjusting the values of rock matrix moduli (K_0, μ_0) and aspect ratio of cracks (α) in Hudson-Cheng's model, we achieved a reasonably good fit between model predictions and lab measurements of ε, γ, C_{33} and C_{44}, as shown in Figure 1. We cannot obtain a good fit for δ because lab measurements of velocity at 45° may have large errors, leading to inaccurate δ.

DNN model

The DNN model is constructed in three steps. The first step is data acquisition and preparation. We obtained log data of a well in Sichuan, China. Anisotropy parameter inversion is implemented for different shale layers based on the Hudson-Cheng's model. A number of 5247 sets of input features (density, porosity, P- and S-wave velocities, bulk and shear moduli) labelled with inverted anisotropy parameters are extracted from well logs along depth. We further separate these data into training set (60%), validation set (20%) and test set (20%) randomly. The second step is model configuration. We construct a fully connected neural network with five hidden layers. The last step is to tune super-parameters, including leaning rate, learning decay rate, etc. As shown in Figure 2, the inverted anisotropy parameters based on Hudson-Cheng's model are consistent with the mineralogy log of YS108 well. Anisotropy parameters tend to be larger at clay-rich depth as expected. Moreover, the DNN predictions fit well with the inversion results except for some extreme points.

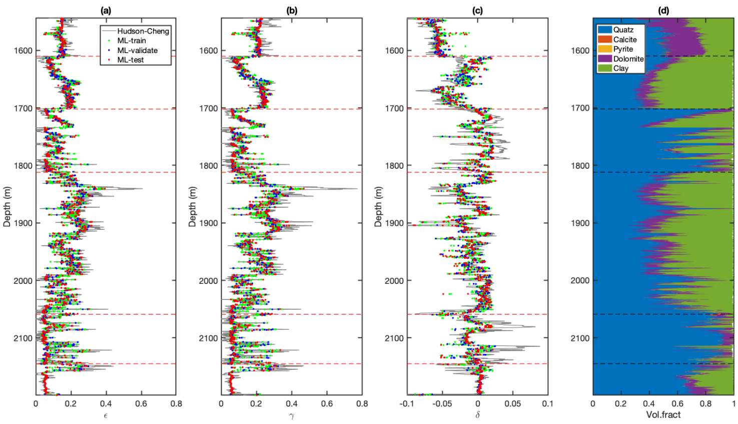

Figure 2 Inverted and DNN predicted anisotropy parameters of YS108 well

Conclusions

In our work, we construct a well-trained DNN model to predict anisotropy parameters from well logs. We label well logs from a well in Sichuan with inverted anisotropy parameters based on Hudson-Cheng's model after we proved Hudson-Cheng's model to be accurate enough for shales by fitting it to published lab data. The inversion results and DNN predictions fit with each other quite well. They all display good consistency with the mineralogy log of the same well. This demonstrates that the DNN model and the inversion method based on Hudson-Cheng' model are both accurate and practical for shale anisotropy estimation from well logs.

References

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