Xu and White Revisited
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Introduction

Xu and White (1995) proposed a workflow for estimating the elastic properties of sand and clay mixtures based on the petrophysical analysis of well log data. The workflow was aimed at generating synthetic shear data in wells, where none was measured, for the purposes of seismic reservoir characterisation. Despite some criticism, primarily aimed at the idealised representation of the pore space as ellipsoids, the method has proved effective and thus popular. The workflow mixes the elastic properties of quartz and clay using the time average equation. The total pore space is assigned to either quartz or clay on a volume weighted basis and assigned a different aspect ratio dependent on whether it is a quartz or clay pore. The empty pores are then included into the quartz-clay mix using the Differential Effective Medium method and finally the fluids are introduced through Gassmann. The effective elastic properties of the clay component and the aspect ratios assigned to the quartz and clay pores are adjusted until a match with measured data is achieved.

The recognition that the effective aspect ratio of the pore space associated with each mineral differs was a significant contribution to the ability to effectively model real rocks using pore shapes as the control for the rock micro-structure. However, it does seem rather a gross assumption and intuitively one might expect that there is more variation in the aspect ratios than can be modelled through the choice of two fixed values. On the other hand, if a higher degree of variability in the aspect ratio produces an improved fit to the data, the problem becomes one of being able to predict those variations so that the modelling method can be applied to other wells with poorer quality data or where elastic logs were not measured.

In this paper we show that a single aspect ratio applied to the total porosity of a sand-clay mixture can accurately model both P- and S-sonic data. We also show that the variation of this optimal aspect ratio can be predicted from the petrophysical properties of the rocks, whilst keeping the effective elastic properties of the minerals constant over large geological intervals. The use of one variable aspect ratio applied to the total porosity provides a much better fit to the data than using a single aspect ratio for each mineral.

Dataset

The dataset shown here comes from a field in the Malay Basin. The rocks penetrated are a sequence of Mid-Miocene claystones, siltstones, sandstones and coals. A sand-filled incised valley forms a 30 meter thick, channel-reservoir with both oil and gas. Five vertical wells penetrate this sandstone channel, four in the hydrocarbon interval and one entirely in the aquifer. These wells were logged with a comprehensive suite of logs that allow for formation evaluation. All the wells have measured P- and S-sonic except for one well that has only p-sonic measurements. Core samples have been taken within the reservoir sand that indicate the clay content is substantial ranging from 15 to 25%. Total porosity within the reservoir generally varies by only a few porosity units (pu), approximately 26 pu.

A petrophysical analysis has been applied that keeps the link to the input data straight forward. Clay content has been derived from the gamma ray log calibrated to the volume of clay measurements from core. The total porosity has been estimated from the density and neutron logs and the saturation using the Dual-Water equation. The coals are not included in the rock physics modelling and have been identified where possible and removed from the analysis. The analysis described will be carried out between two regional coal markers. This interval represents over 450 metres of rock.
Effective aspect ratio

The first step is to assess whether an effective aspect ratio applied to the total porosity can model both P- and S-sonic measurements. This assessment is made using a slight modification to the Xu and White approach, whereby the time average equation is replaced by the Hill average of the component minerals. The aspect ratio at each depth is adjusted until the modelled velocity matches the measured velocity. This was carried out for both the compressional and shear velocities independently. The values found will not necessarily be the same, but the elastic properties of the clay can be adjusted to fit the data. Although this is an arbitrary adjustment there are some valid reasons and limitations. Unlike quartz, the elastic properties of clay are not well established and are also typically anisotropic. The effective elastic properties of the clay observed in the vertical direction (parallel to the borehole) are therefore probably a function of the clay type and the orientation of the clay particles (inter alia), neither of which are readily determined from standard petrophysical analysis. The effective properties are therefore unknown, but here are assumed to be constant over the interval of interest.

There is sufficient room for a range of aspect ratio and elastic property combinations that are reasonably effective. For example, if the shear velocity of clay is set high then the effective aspect ratio required to match the s-sonic is reduced. This increases the Vp/Vs of the model results that can in turn be compensated by a decrease in the Vp/Vs ratio of the clay. By applying this approach to the wet well in the dataset, this well is chosen to initially avoid the complications of hydrocarbons, it is possible to find a combination of elastic properties for clay that minimises the difference between the optimal aspect ratios for P- and S-sonic data. Figure la shows the correlation of the optimal aspect ratios to match the P-sonic versus those required to match the s-sonic. Note that some of the scatter is due to the effect of washouts on the calculation of porosity as will be discussed later.

Figure 1 (a) Crossplot of the aspect ratio required to model the P-velocity versus that required to model the S-velocity coloured by volume of clay. The line of perfect match is shown. (b) Crossplot of optimal aspect ratio for modelling S-velocity versus aspect ratio predicted from porosity and clay content. Shales are shown in grey and wet sands in blue.

It is noticeable that the optimal aspect ratios tend to cluster based on the clay content. The cleaner sands require higher aspect ratios than the shales. This is consistent with the findings of Xu and White (1995). However, the distribution suggests that a fixed aspect ratio for quartz and clay pores might not provide an accurate prediction of all the velocities. A direct comparison with the standard Xu and White approach is made later in this abstract after dealing with a number of issues.

Aspect ratio prediction

The methodology of using a variable aspect ratio is most useful if the values can be predicted from other data. Visual observation indicates that the aspect ratio varies with both clay content and porosity. In this case a simple, linear combination of porosity and clay content was rapidly found through trial and error that gave a reasonable prediction of the estimated optimal aspect ratio for all of the wells for shales and wet sands (Figure 1b). Some of the shale points drift away from the line of
parity and observation of the log data indicates that many of these points are associated with poor borehole conditions where the density and neutron logs are affected by the borehole rugosity. The prediction for the wet sands is reasonable but not highly accurate. By taking a different relationship within the channel sand an improved prediction can be found. Interestingly this improved fit in the channel sand requires the aspect ratio to increase with increasing clay content, whereas the opposite is true in the rest of the interval.

Further improvements

There are a couple of areas in which the results obtained so far can be improved. The borehole conditions in a number of wells in the section above the channel are such that the density and neutron logs are affected. This can easily be seen by observing unusual scatter in the relationship between P-velocity and density. A correction was applied to the density log to improve the consistency with the P-velocity log. This correction changed the porosity and thus the predicted aspect ratios. The changes in porosity resulted in much greater consistency between all predictions of elastic properties and the measured data. Although this is self-fulfilling for the P-velocity, the improvements to the S-velocity prediction, as well as the improved match between optimal P- and S-velocity aspect ratios, justifies the changes.

In the section below the channel there are a number of areas where the predictions are also poor. However, it was observed that the clay content derived from the gamma ray log and the neutron-density combinations is very different at these points. If the neutron-density combination is used for clay content in this lower section, all the modelling improves considerably.

Fluids

The presence of hydrocarbons causes a number of problems. Hydrocarbons are often displaced by drilling fluids away from the borehole wall and thus many logging tools with a shallow depth of investigation do not measure the properties of the in-situ hydrocarbon saturated rocks. There is uncertainty about what effective saturation many tools measure, but density, neutron and sonic tools are usually affected. In addition, the fluids in the rocks are potentially not evenly distributed across the pore space. There can be heterogeneities that mean the standard Wood’s mixing law for fluids is not applicable. Brie et al. (1995) provided an equation to mimic the heterogeneity of the fluid distribution in rocks using a power law for the saturation. The effect of invasion is also often
mimicked through a power law for the saturation. Therefore the combination of invasion and heterogeneity are here modelled through a power law, where the power term is empirically found based on the assumption that the model of a single aspect ratio for P- and S-velocities is valid. It is found that the power law required for gas and oil are different, but there is no direct evidence from the data how much of the effect is due to invasion and how much is due to fluid distribution heterogeneity.

Comparison with Xu and White

The final model based for one of the wells is shown in Figure 2. The match to the measured data is very-high as a result of the accurate prediction of the optimal effective aspect ratios. Using the same approach to fluid modelling and correction for washouts it was found that this methodology gives a significant improvement over the use of fixed aspect ratios for quartz and clay pores as per the original Xu and White methodology. A comparison with the fixed aspect ratio method is shown in Figure 3. For the fixed aspect ratios the optimisation has caused systematic over- and under-estimation for shales with different degrees of shaliness and porosity. Clearly a constant aspect ratio for all clay and quartz pores is not appropriate. Although the use of fixed aspect ratios predicts the mean properties of the channel sands, the variable aspect ratio methodology shows a much better prediction.

Figure 3 Cross-plots of measured S-velocity versus modelled S-velocity using (a) fixed aspect ratio for quartz and clay and (b) variable aspect ratio for total porosity

Conclusions

The standard Xu and White approach to modelling clay-sand mixtures can be improved by assuming a variable aspect ratio that is applied to the total porosity. These aspect ratios can be predicted from measurements other than the velocity logs after calibration in one well. This means that elastic properties can be predicted in wells with no measured sonic data provided the other log data are of a reasonable quality. In addition, this approach allows for the identification and correction of errors in the log data and petrophysical analysis, providing a means to understand the influence of hydrocarbons on the rock elastic properties. The methodology results in a complete, consistent and corrected dataset suitable for use in seismic reservoir characterisation. Once the rock physics model has been established, there is the possibility to constrain the petrophysical analysis with the elastic logs in a joint inversion where the aspect ratio becomes the link between the rock physics and the petrophysics.

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References
