Paper ID: 2003191

Depth variable pore aspect ratio for rockphysics modeling using Xu-White method

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Abstract

The Xu-White method is very popular and effective for modeling of elastic properties of clay-sand mixture. Common applications of this method are to i) fill gap in measurements, ii) remove borehole washout effect and invasion correction in reservoir, and iii) predict shear sonic, if not measured or measured shear sonic data is of poor quality.

This model assumes that the geometry of pores associated with sand grains is significantly different from that associated with clay grains but the aspect ratios of these pores remain constant over a large depth interval. In general, this predicts elastic properties in clean sand and pure clay intervals satisfactorily but performs poorly in shaly-sand interval. The cause of relatively poor performance in shaly-sand interval can be ascribed to cementation, over burden pressure, presence of clay etc. An improved prediction of elastic properties in shaly-sand interval is possible by allowing the pore aspect ratio to vary with depth thereby accounting for the effects of cementation, clays and over burden pressure indirectly. In this study we approach the problem directly through estimation of the effective pore aspect ratio for interval of clay-sand mixture from measured velocity through an iterative method. A correlation is established between effective pore aspect ratio and a petrophysical property of the interval, viz. the difference of neutron porosity and density porosity for further use in predicting seismic velocities.

Introduction

Xu and White (1995) proposed a workflow for predicting sonic log of clay-sand mixture from other petrophysical logs such as gamma ray, neutron, density and resistivity. If predicted sonic log matches with sonic data either measured in laboratory or in a borehole, then it can be used for filling up any gap in sonic log, correction in washout zone or complete S-sonic prediction. The essential steps in this workflow are:

- Total porosity of the mixture is considered as the sum of pores associated with weighted volume sand and pores associated with weighted volume of clay.
- Transit time of shear and compressional waves of clay-sand mixture is calculated from the time average equation.
- Bulk and shear moduli of each component of the mixture are calculated from corresponding P- and S-wave transit time and density.
- Elastic property of dry frame is calculated by Kuster and Toksöz theory and empty pore are included using Differential Effective Medium theory (Avseth et al., 2005).
- In order to calculate elastic properties of the dry rock frame, effective mean pore aspect ratio are assigned to clay and quartz. Finally fluids are introduced using Gassmann method to consider fluid relaxation.

One major problem with the model is that it does not consider change in pore aspect ratio due to effects of overburden pressure, clay content or cementation over a long depth interval.

Sams et al. (2012) considered a depth variable pore aspect ratio to incorporate these effects over a long interval. In this workflow, the effective pore aspect ratio is predicted from total porosity. Consider the fact that total porosity and pore aspect ratio are two major parameters in modeling elastic properties of clay-sand mixture using Xu-White method; determination of pore aspect ratio from total porosity alone reduces the degree of freedom of the problem. Since in several situations, the uncertainty associated with estimating total porosity due to lack of knowledge of grain density, adds to the uncertainty in deriving pore aspect ratio from total porosity, we search for an alternative method to estimate pore aspect ratio which is less affected by the uncertainty in total porosity estimation.

In this paper we use the difference between neutron porosity and density porosity (ND_DIFF) for estimating pore aspect ratio. ND_DIFF assumes maximum value over clean shale, minimum value over clean sand and distributes linearly with volume of clay. Further, ND_DIFF includes the effects of clay volume, porosity, grain size, and cementation as well as over burden pressure. Thus, it is expected that use of ND_DIFF to estimate effective pore aspect ratio will provide better estimation of elastic properties in clay-sand mixture compared to that estimated using total porosity alone, provided the clay type does not change in the interval. Once the optimal variation in effective pore aspect ratio over a defined geological zone with similar clay type or clay mixture is determined, one can predict P-Sonic and S-Sonic logs from measured and petrophysical properties, viz. total porosity, volume of clay and water saturation, keeping constant the elastic property of clay and sand grains.

Experimental Details

We describe here the method of estimating effective pore aspect ratio from measured P- and S-velocities through an iterative procedure (Figure 1). A data set from eastern part of Kutch offshore basin has been used in this study. The basin is an east-west oriented basin and is the northwestern part of the western continental margin of India. This basin is bounded by the Nagar-Parkar fault in the north, Radhanpur-Barmer Arch in the east and the North Kathiawar fault in the south. This basin was formed due to rifting and counter-clockwise rotation of the Indian plate after it got detached from Gondwanaland during Late Triassic or Early Jurassic. Thick shallow marine to deltaic sediments were deposited here during the Mid Jurassic-Early Cretaceous period. In the Early Cretaceous, rifting failed and clastics of prograding delta were deposited. The Mesozoic sediments were covered by Deccan Basalt in the Late Cretaceous-Early Paleocene period. Tertiary sediments are relatively thin in the east and thicken towards the west. Tectonic activity during Tertiary was mild and cyclic. A number of sea level changes have influenced sedimentation patterns till Early Mid Miocene. After the Early Mid Miocene, heavy influx of terrigenous sediments was seen, resulting in deposition of monotonous shale/clay.

The study area gained importance after discovery of commercial quantity of gas from Tertiary sequence. So far 13 wells have been drilled out of which 6 wells have produced gas from Tertiary clastics. Electro-logs have been extensively acquired in all the wells including shear-sonic and FMI logs.

Effective pore aspect ratio

We start with a trial estimate of the aspect ratios for sand and clay grains. Elastic parameters for constituent minerals and fluid in the pore serve as other input parameters along with petrophysical interpretations in the reservoir interval. Xu-White mixing algorithm is used to calculate bulk elastic properties and density of the rock. The computed P- and S- wave velocities are compared with the measured ones and the process is repeated until a satisfactory match is obtained. The values of pore aspect ratios giving rise to best match of measured and modelled P- and S-velocities are considered as the effective pore aspect ratio.

In this paper we analyzed the data over a 200m section to first estimate the effective pore aspect ratios from P-velocity and S-velocity separately. A cross-plot of these aspect ratios colored by volume fraction of clay shows different clusters for sand and clay (Figure 2). Pores associated with clay have smaller aspect ratios compared to the corresponding pores in sands. Further, the aspect ratios are variable with the sand values exhibiting greater variations compared to those associated with clay.

Aspect ratio prediction

The major differences between the approaches adopted by Sams et al. (2012) with our method lies in the use of the differences between neutron and density porosity in place of total porosity for establishing a correlations with depth variable effective pore aspect ratios.

Before calculating the difference between neutron and density porosity, ND_DIFF, we first filter the neutron and density logs and calculate density porosity. Since in gas bearing zones, these curves cross-over making ND_DIFF negative, we first apply hydrocarbon correction on neutron density curves in gas affected before computing their differences.
A cross plot of effective pore aspect ratios predicted from ND_DIFF and from modeling of S-velocity (Figure 3) shows a very good correlation.

Fluids

Modelling of elastic property of reservoir with single fluid is well known (Xu and White, 1995). When hydrocarbon is present in the reservoir, it gives rise to number of problems. Due to invasion, hydrocarbon is replaced by drilling fluid and distribution of multi-phase fluids are not homogeneous. Various attempts have been made to calculate effective bulk modulus of the pore fluid mixture. In case of partial saturation there is no effect of pore geometry and gas distribution at low frequency in the seismic range so modeling by Gassmann equation in association with parallel law (Wood’s law) gives reliable results. Gassmann equation also gives reliable result in fully saturated rock at sonic frequency. Therefore, for more accurate rock physics modeling, we require a way to predict the relaxation frequency. At this point, it is difficult to do it. Brie et al. (1995) proposed power law for mixing of fluid which works well in most of the cases. So instead of parallel law we use Brie’s power law for calculation of mixed pore fluid bulk modulus to overcome problem created by high frequency sonic log, invasion and heterogeneity.

Prediction of Velocities

Prediction of P- and S-velocities using variable effective pore aspect ratio is shown in Figure 4. The results show good prediction of velocity using effective pore aspect ratio curve rather than two fix value of pore aspect ratio for clay and sand. For better prediction of pore aspect ratio we need to apply correction on neutron and density log affected due to borehole washout, and filter neutron log due to response of neutron tool.

Comparison of results

For comparison of results, data from the same well is used for prediction of velocity using three different workflows viz. i) fixed mean effective pore aspect ratio for clay and quartz (Xu and White, 1995), ii) Effective pore aspect ratio curve predicted from total porosity (Sams et al. 2012) and using effective pore aspect ratio curve predicted from ND_DIFF curve (Present method). Results obtained from all three techniques are shown in Figure 5 through Figure 7 respectively.

Results from effective pore aspect ratio curve generated from relation with total porosity and ND_DIFF curve are showing improved prediction of elastic property over result obtain from fixed value of effective pore aspect ratio for clay and quartz.

Results are comparable using effective pore aspect ratio curve predicted from total porosity and from ND_DIFF.

Example

Two wells, one with good condition of hole (well X) and the Well A in which the condition of hole was not good when measurement was carried out, have been used in this study. The well X has been used as reference for modeling of shear sonic in the other well.

Well A

In well A calliper log shows bad hole condition in some intervals. The quality of shear sonic is affected because of bad hole condition. It read slow velocity compared to other well with good hole condition. Multiwell crossplot (Figure 8) also shows that the measured shear log in this well is not consistent with reference well X. In this well shear log is generated using rockphysics model established in well X. Effective pore aspect ratio curve is calculated from ND_DIFF curve using relation generated between effective pore aspect ratio and ND_DIFF in well X. Pore fluid mixed elastic property is calculated using Brie power law.

Crossplot of P-Sonic and S-Sonic for well X and well A is shown in Figure 8. Shear from rockphysics modeling is showing consistency with shear log available in well X.

Conclusions

To calculate elastic property of clay-sand mixtures, Xu and White method considers two major inputs, viz. porosity and pore aspect ratio which take care the effect of porosity, pore geometry, cementation, fluid relaxation, clays, over burden pressure and frequency which influence the wave propagation in porous rock. So instead of taking two fixed value of effective mean pore aspect ratio for clay and quartz effective pore aspect ratio curve with optimal variation in clay and quartz gives better prediction of elastic property of clay-sand mixture over a large interval. We can predict effective pore aspect ratio curve from a petrophysical property which represent variation of clay, sand, grain size and porosity. Effective pore aspect ratio calculated from total porosity also yields good result. Since in Xu and White approach porosity and pore aspect ratio are the main inputs, relating effective pore aspect ratio with total porosity means that one is only porosity for elastic property calculation. So in this paper we have related effective pore aspect ratio with ND_DIFF curve which is very good differentiator of clay, sand and degree of clay mixture in sand. After calibrating predicted velocity using effective aspect ratio in one well we can predict sonic log from other petrophysical logs where no sonic data available. In addition we can use the methodology for correction of sonic data in bad hole zone, fill the missing intervals in sonic data. Once we have established rock physics model in a field using this approach then we can get consistent and better prediction of elastic property. Result can be used for seismic inversion and reservoir characterization in shaly sand geological environments.

References

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Acknowledgements

The authors thank the managements of ONGC for permission to present these data.

The authors thank to Dr. Ranjit Shaw (CGG India Services Pvt. Ltd.) for his valuable input and guidance in writing this paper.

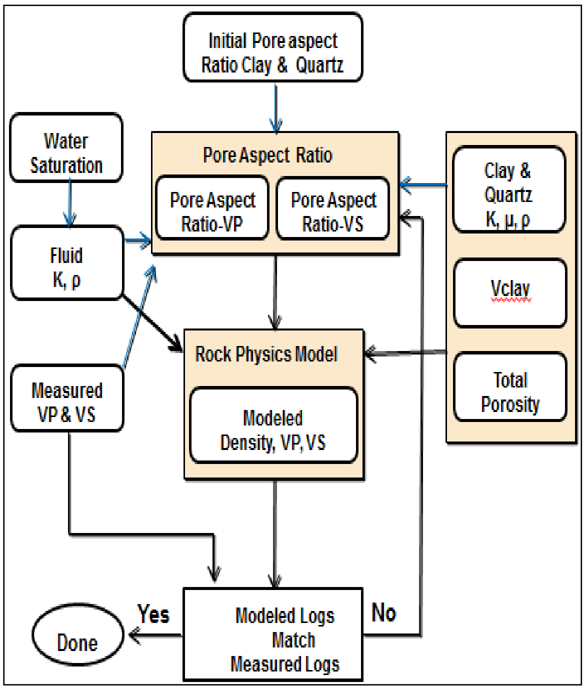

Figure 1: Workflow for calculation of effective pore aspect ratio.

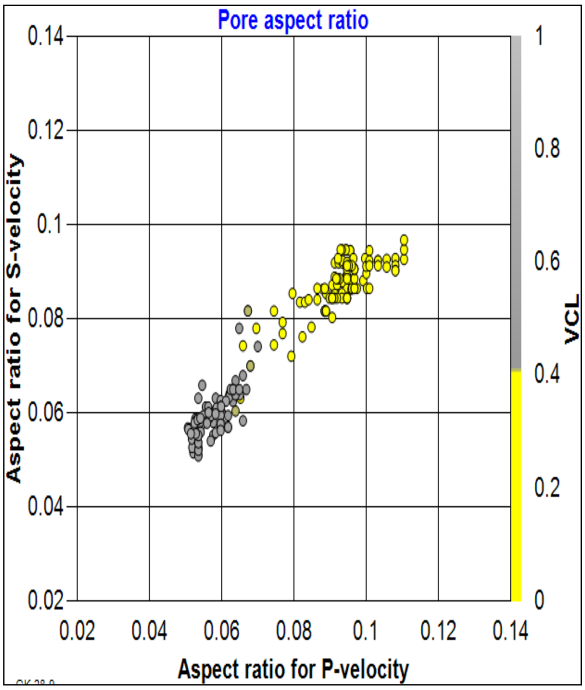

Figure 2: Crossplot of pore aspect ratio required to model P-velocity versus that required to model S-velocity colored by Vclay.

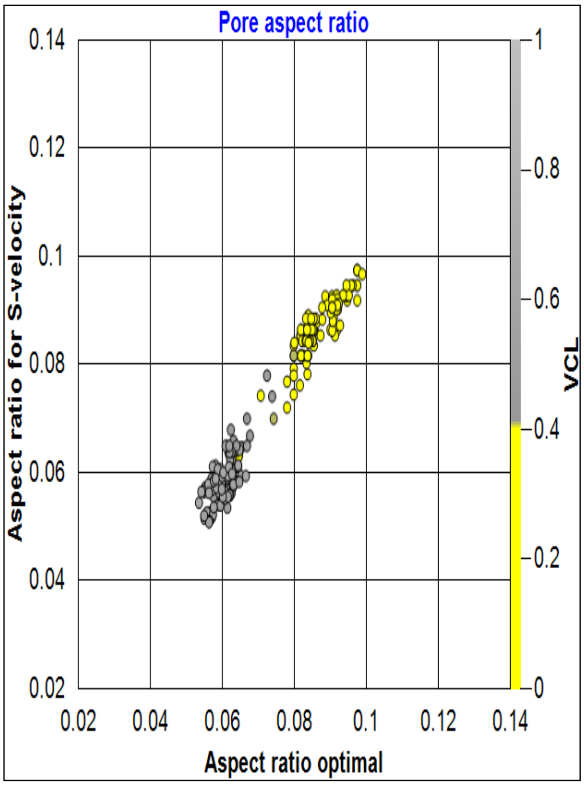

Figure 3: Crossplot of pore aspect ratio predicted from ND_DIFF versus that required to model S-velocity.

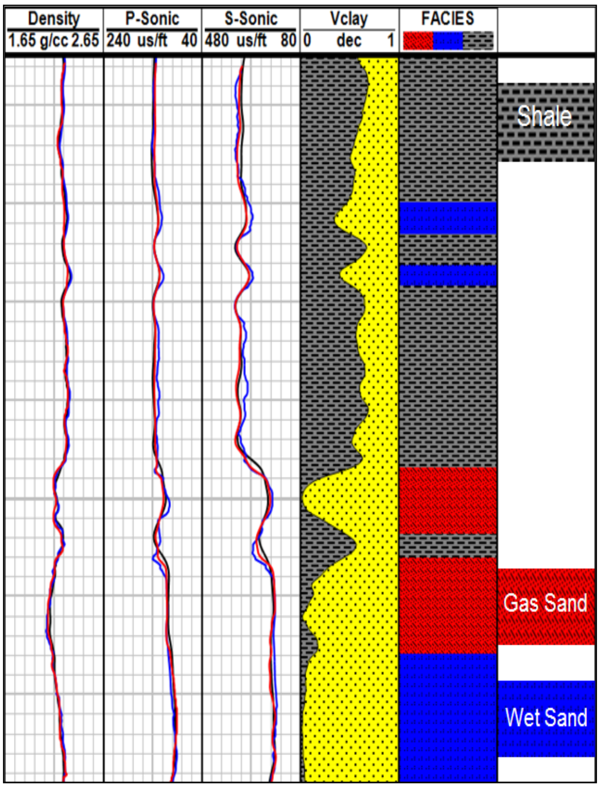

Figure 4: Tracks 1-3 show density, P-Sonic and S-Sonic respectively with measured (black), modeled (blue) using fix aspect ratio and modeled (red) using depth variable pore aspect ratio. Track 4 shows Vclay and Track 5 Facies.

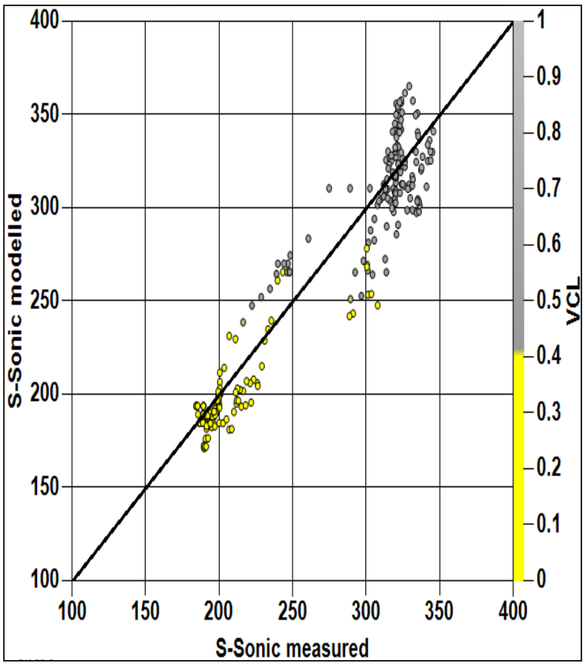

Figure 5: Crossplot of measured S-Sonic and Modelled S-Sonic from fixed pore aspect ratio For clay and quartz using Xu-White (1995)

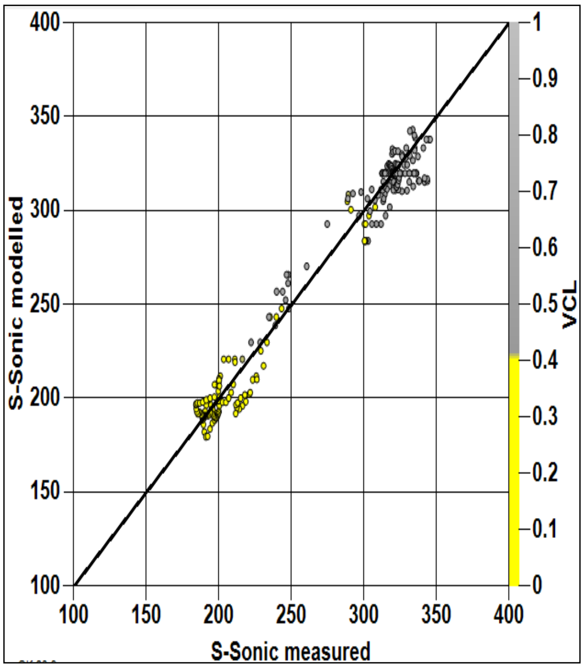

Figure 6: Crossplot of measured S-Sonic and modelled S-Sonic using depth variable pore aspect ratio generated from total porosity using Method proposed by Sams et al. (2012)

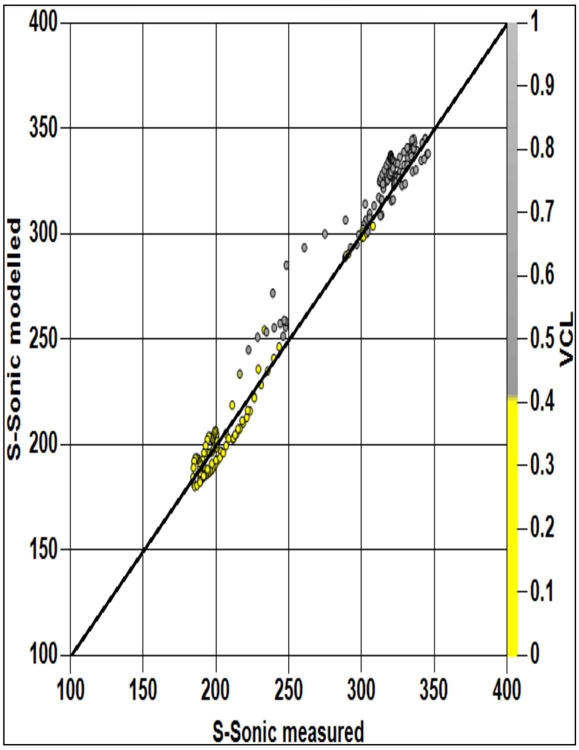

Figure 7: Crossplot of measured S-Sonic and Modelled S-Sonic using pore aspect ratio Curve generated from the difference of Neutron and density porosity.

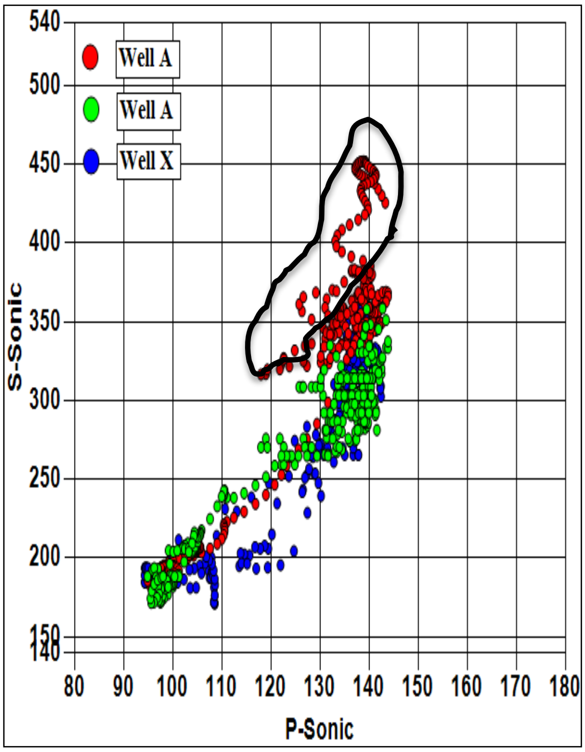

Figure 8: Cross plot of P-Sonic and S-Sonic, Blue data points are from reference well X, Red data points are measured log of well A and Green Data points are modelled shear log of well A