An Innovative Approach to Vclay Analysis and Rock Property Characterization: An Example from the Erha Field, Offshore Niger Delta

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Accurate prediction of rock properties using modern technology is key to improving reservoir characterization which is foundational to estimation of Hydrocarbon Initially in-Place (HCIP). Volume of Clay (Vclay), being a key rock property, has been a constant source of errors in petrophysical and geophysical studies. A misunderstanding of the difference between Vclay and Vshale, as well as, simplistic approaches for estimating Vshale, can lead to net-to-gross (NTG) and porosity errors. Vclay also serves as a key input for accurate rock physics models critical to seismic inversion. Observed scatters in porosity-velocity relationships are attributed to lithology and more specifically to clay content. Not utilizing Vclay therefore, has led to a generalized Vshale adopted by most geoscientists, resulting in rock property errors and an under/over estimation of in place hydrocarbons. This work applied the 'multi-min' software to integrate x-ray diffraction (XRD), scanning electron micrography (SEM) and core analysis data along with acquired and predicted logs to create a model for better predicting individual mineral volumes (quartz, calcite, clay) in areas with inadequate data. Using the Xu-Pane rock physics model, the predicted Vclay were then utilized to effectively determine appropriate clay and quartz aspect ratios that predict sonic velocities from porosity and fluid saturations. This has given rise to a greater understanding of the subtle variations in properties of reservoirs from top to bottom of each well. The results have helped to accurately define reservoir rock properties within the Erha Field for about 30 wells with data paucity, creating an avenue for better reservoir characterization and modeling, well history-match which are basis for evaluating remaining resource potential and identifying drill-well opportunities.

Keywords: VClay, Field, history-match, Reservoir, Characterization, modeling, lithology

INTRODUCTION

The Erha Field is a Miocene deep-water system made of slope -confined channel complexes located offshore western Nigeria in water depths around 1200m. It is a mature asset containing over 20 production wells and several injector wells. The field is set-up by low relief regional detachment fold located in the transition between a linked extensional – contractional system. There are stress-relief faults in the eastern area with less faulting to the west (Seismic section on Figure 1). The field is comprised of 17 (multidarcy) confined to weakly-confined slope channel complexes reservoirs draped on a plunging anticline (Figure 1). The reservoirs have very good permeability in the order of multi-darcy units. It is divided into a shallower Erha North and a deeper Erha Main

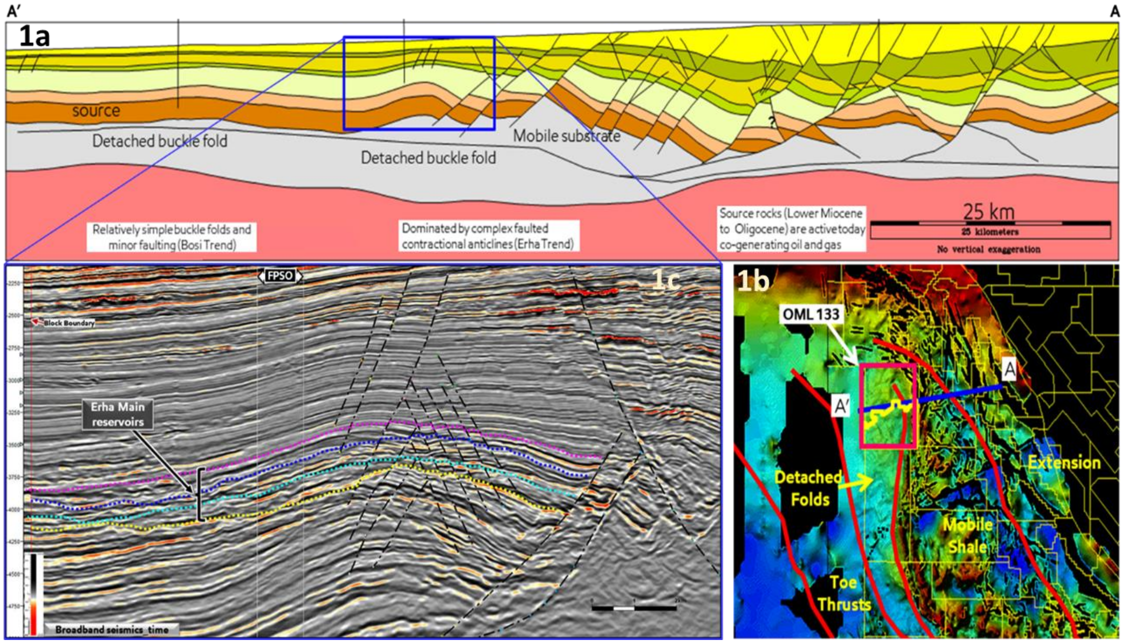

Figure 1: Erha Field location and structural cross-sections. 1a. Regional schematic cross section showing coupled extention and compression in the Western Niger Delta 1b. Tortonian_2 depth structure map showing Erha Field in the Western Niger Delta; 1c. Seismic cross section across the Erha Fied showing low relief detached fold that sets up the Erha Field

Three phases of deposition have been established within the field. The first was an early phase of deposition and associated mini-basin development at ~35 ma. This was followed by contraction expressed as buckle folding linked to up-dip extension at ~20 ma. Finally as the depositional system prograded, the location of extension migrated basin-wards

The complex stratigraphy within the field has resulted in challenges in building a rock physics model that fully integrates the stratigraphic and structural complexity in the depositional cycles. The prediction of sonic logs as a tool for facies characterization and its use with density logs to predict facies distribution/character is challenging because of the spatial distribution of clay minerals within the Erha system. Consequently, there is a need to integrate several data sets in building a robust inversion model for Erha.

This work aims to integrate X-ray diffraction information from cores to build a Vclay model that serves as an input for seismic inversion.

The impact of Clay on Petro-Elastic Properties

The most commonly utilized log for estimating the reservoir net sand is the Vshale log. This is done using acquired gamma-ray, resistivity or neutron-density logs but are limited in their function with regards to the description of rock properties. At a larger scale, and in combination with other logs, they can be a useful tool for facies classification but when considering the effects of clay minerals on pore throat and wave velocity, the limitations of Vshale arise.

Clay plays an important role in the seismic and petrophysical properties of rocks. Loose clay particles in rock pores have an effect on wave velocity and attenuation. Han *et al*., (1986) found that the P-wave velocity was a linear function of both porosity and clay content, decreasing as the porosity/clay content increases. Marion *et al.,* (1992) however, noticed an initial increase as a result of porosity reduction from clay particles filling spaces between sand grains. After a critical value, the P-wave velocity then decreased with clay content.

Xu White (1995) reported that well log data alone was not satisfactory in interpreting the porosity-velocity relationship between rocks and proposed a sand clay model which relates elastic wave velocities (P & S-waves), log porosity and shale volume. This model is utilized in creating consistent rock physics model employed in the facies based inversion. The model is useful to account for the effect of clay minerals on prediction of transit-time by incorporating the effect of aspect ratios.

Pore Size Aspect Ratio

Two parameters generally control pore and pore throat size:

1. Absolute size
2. Aspect ratio

1. Absolute size of a pore throat refers to the radius of a circle existing perpendicular to fluid flow and fitting within the narrowest point of the throat. On the other hand, the absolute size of a pore is the radius of the largest sphere that will fit inside it (Dan *et al.,* 1999).

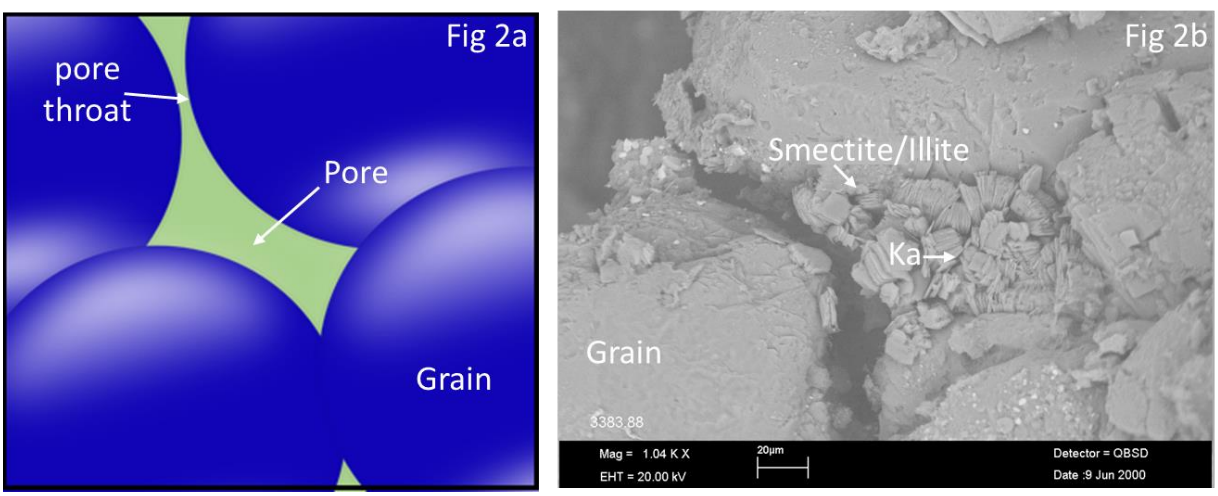

Figure 2: Illustrating pore structure. Figure 2a. Zoomed in rock matrix showing difference between Absolute size of a pore throat and a pore. Aspect ratio is a ratio of both. Pore size can be

estimated visually by using a Scanning Electron Micrograph (SEM) Figure 2b. Example from Erha-X SEM showing pore filled with clay mineral

2. Aspect ratio is the ratio of the pore size to the pore throat size. Archie rock types such as quartz-cemented sandstones have aspect ratios that can range from 5:1 and 10:1. Non-Archie rock types have even larger variations (Coalson *et al*., 1994).

Eastwood and Castagna (1983) postulated that aspect ratios play a significant role in rock property evaluation, especially when considering aspect ratios less than 0.05. This is illustrated when considering rocks with poorly compacted shales. These rocks tend to have large aspect ratios and play a role in the porosity-velocity relationship (Xu White *et al.*, 1995).

Xu White (1995) suggests the effects of the pore aspect ratios as three fold:

1. Clay particles create pores with very small aspect ratios

2. Cementation reduces the number of gaps with small aspect ratios. Rocks with less cementation have more gaps.

3. Effective pressure controls the closure of those cracks.

Vclay Prediction as a Tool for Log Prediction

From the discussions so far, it is clear that getting an accurate description of the volume of clay is important in rock property description/prediction and serves as a useful tool in facies discrimination. In this work, the predicted Vclay logs were used to define aspect ratios for quartz and clay facies and this served as a basis for sonic velocity prediction from porosity and fluid saturations using the Xu-pane model.

A limitation that creeps up in doing this, however, is the paucity of Vclay data. Vclay is not a log acquired during drilling and must be calculated from X-ray diffraction analysis done on cores. Unfortunately, cores are not always readily available and even when acquired, might be limited to a small section of a well. It is therefore important to utilize a method that accurately predicts the Vclay in areas with no cores. This becomes even more complicated when comparing areas of the field with different petrophysical properties.

METHODOLOGY

Analysis of Clay Minerals from X-ray Diffraction Data

X-ray diffraction is a powerful non-destructive technique used for characterizing crystalline materials. It depends on the principles of X-ray interactions with solid minerals and is considered the best tool for the categorization of different clay minerals that are optically similar (openei.org).

In carrying out the X-ray diffraction analysis, the rock samples are ground to a fine powder and the results reported in weight percent. In this study, the only available well with XRD data was Erha-X and the Vclay model had to be built from that. Below is table of result of the the X-ray diffraction analysis of samples from Erha-X (Table 1).

Table 1: X-Ray Diffraction (XRD) of Erha-X (the only well with XRD data in Erha Field). Mineral composition is in the first column and percentages for the various depths in the other columns. TR represents trace amounts of mineral

Depth (m)	3357.23	3359	3359.58	3382.41	3383.83	3384.53	3385.48	3386.51	3386.67
QUARTZ	91	90	89	94	95	95	92	91	85
K-FELDSPAR	3	3	4	2	2	2	3	3	5
ALBITE	2	2	2	1	1	1	1	2	3
ANATASE	TR	TR	TR	TR	TR	TR	TR	TR	TR
APATITE	0	0	0	0	0	0	0	0	0
CALCITE	TR	TR	TR	TR	TR	TR	TR	TR	TR
SIDERITE	0	0	0	0	0	0	1	0	1
PYRITE	TR	TR	TR	TR	TR	TR	TR	TR	TR
AMPHIBOLE	TR	TR	TR	TR	TR	TR	TR	TR	TR
HEMATITE	0	0	TR	TR	TR	TR	0	0	0
KAOLINITE	TR	TR	2	TR	TR	TR	1	TR	1
CHLORITE	1	2	TR	TR	TR	TR	TR	TR	TR
ILLITE	1	1	1	TR	TR	TR	TR	1	1
SMECTITE	1	1	1	1	1	TR	TR	1	1

The first process was to understand the data and how the different mineral types were categorized within it. In the table above, Quartz grains formed the bulk of the mineral weight percentage of the samples analyzed. A combination of other mineral types, including Calcite and trace amounts of hematite were also present.

Kaolinite, Chlorite, Illite and Smectite were grouped together as clay minerals and Quartz, K-feldspar and Albite grouped together since they formed part of the same mineral class (Quartz minerals).This grouping was done for all the mineral classes identified from X-ray diffraction analysis of Erha-X and the result is displayed below (Table 2).

Table 2: Grouping the various mineral types together. The quartz minerals are in yellow and the clay minerals in gray. Trace amounts of calcite are present and indicated in light blue. Calcite and other trace minerals (apatite, anatase and siderite) are ignored for the model.

Depth (m)	QUARTZ	K-FELDSPAR	ALBITE	ANATASE	APATITE	CALCITE	SIDERITE	PYRITE	AMPHIBOLE	HEMATITE	KAOLINITE	CHLORITE	ILLITE	SMECTITE
3357.23	91	3	2		0		0			0		1	1	1
3359	90	3	2		0		0			0		2	1	1
3359.58	89	4	2		0		0				2		1	1
3382.41	94	2	1		0		0							1
3383.83	95	2	1		0		0							1
3384.53	95	2	1		0		0							
3385.48	92	3	1		0		1			0	1			
3386.51	91	3	2		0		0			0			1	1
3386.67	85	5	3		0		1			0	1		1	1
3387.08	89	4	2		0					0	1			1
3387.48	92	4	2		0					0	1		1	
3387.76	92	3	2		0		1			0	1		1	
3388.66	94	3	1		0		0							
3389.09	89	5	3		0					0	2			1
3389.31	85	6	4		0					0	2		1	1
3391.18	92	3	1		0		0						1	1
3391.93	68	11	8	1	0	1	1			0	6	1	3	1
3392.24	78	5	2			1	6		1	0	1	2	2	2
3392.7	82	6	5		0		1		0	0	1		3	2
3392.75	74	9	7		0	1	2		0	0		2	3	2
3393.03	66	10	8		0	1	2		0	0	3	1	4	3
3393.1	66	10	9		0	1	2		0	0	4	1	5	3
3539.05	94	2	1		0		0		0					
3540.03	93	2	1		0		0		0				1	
3540.37	93	2	1		0		0		0			1		1
3540.85	38	9	6	1		1	5		0	0	19	3	9	8

The weight fraction was then converted to volume fraction to get the percentages of the different mineral groups that occupy each sample measured. This was done using the simple equation:

$$volume = \frac{Weight\ fraction}{Density}$$

Calculating the volume as a fraction of the total gave the percentage of each mineral type in each sample tested (Table 3). This served as the input in Geolog for the multi-min model.

Table 3: Grouping the various minerals as volume percentage. The volumes are calculated first on the left and then computed as percentages of the total on the right

Depth (m)	QFM	CLAY	CALCITE	TOTAL
3357.23	0.362	0.012	0.000	0.374
3359	0.358	0.016	0.000	0.374
3359.58	0.358	0.016	0.000	0.374
3382.41	0.366	0.004	0.000	0.370
3383.83	0.370	0.004	0.000	0.374
3384.53	0.370	0	0.000	0.370
3385.48	0.362	0.004	0.000	0.366
3386.51	0.362	0.008	0.000	0.370
3386.67	0.351	0.012	0.000	0.363
3387.08	0.358	0.008	0.000	0.366
3387.48	0.370	0.008	0.000	0.378
3387.76	0.366	0.008	0.000	0.374
3388.66	0.370	0	0.000	0.370
3389.09	0.366	0.012	0.000	0.378
3389.31	0.358	0.016	0.000	0.374
3391.18	0.362	0.008	0.000	0.370
3391.93	0.328	0.044	0.004	0.376
3392.24	0.325	0.028	0.004	0.356
3392.7	0.351	0.024	0.000	0.375
3392.75	0.340	0.028	0.004	0.371
3393.03	0.317	0.044	0.004	0.365
3393.1	0.321	0.052	0.004	0.376
3539.05	0.366	0	0.000	0.366
3540.03	0.362	0.004	0.000	0.366
3540.37	0.362	0.008	0.000	0.370
3540.85	0.200	0.156	0.004	0.360

Depth (m)	QFM	CLAY	CALCITE	TOTAL
3357.23	0.968	0.032	0.000	1
3359	0.957	0.043	0.000	1
3359.58	0.957	0.043	0.000	1
3382.41	0.989	0.011	0.000	1
3383.83	0.989	0.011	0.000	1
3384.53	1.000	0.000	0.000	1
3385.48	0.989	0.011	0.000	1
3386.51	0.978	0.022	0.000	1
3386.67	0.967	0.033	0.000	1
3387.08	0.978	0.022	0.000	1
3387.48	0.979	0.021	0.000	1
3387.76	0.979	0.021	0.000	1
3388.66	1.000	0.000	0.000	1
3389.09	0.968	0.032	0.000	1
3389.31	0.957	0.043	0.000	1
3391.18	0.978	0.022	0.000	1
3391.93	0.873	0.117	0.010	1
3392.24	0.911	0.079	0.010	1
3392.7	0.936	0.064	0.000	1
3392.75	0.915	0.075	0.010	1
3393.03	0.869	0.121	0.010	1
3393.1	0.852	0.138	0.010	1
3539.05	1.000	0.000	0.000	1
3540.03	0.989	0.011	0.000	1
3540.37	0.978	0.022	0.000	1
3540.85	0.556	0.434	0.010	1

Utilizing the Multi-Min Tool for Vclay Modelling

The multi-min tool is an optimization tool for statistically determining mineral and fluid characteristics and volumes from petrophysical data such as logs, cores, XRD and petrographic data (pdgm.com)

The software uses a complex algorithm to predict logs based on a set of input parameters. Embedded Monte Carlo uncertainty analysis enables the petrophysicist to assess overall uncertainty on an analysis and identify variables with the greatest impact. These predicted logs are matched to already acquired/derived logs and used as a guide for building a model that will predict the Vclay in other non-cored areas. The process is very iterative with continuous variations in the uncertainty analysis until predicted logs have a near one-to-one match with the acquired logs. The greater the quantity of logs available for prediction, the better the output of the resultant model. In Erha Field, given the paucity of data, the main logs predicted were the porosity, density and sonic logs.

These predictions were carried out using wireline equations for modeling in the multi-min tool based on existing logs (Figure 3).

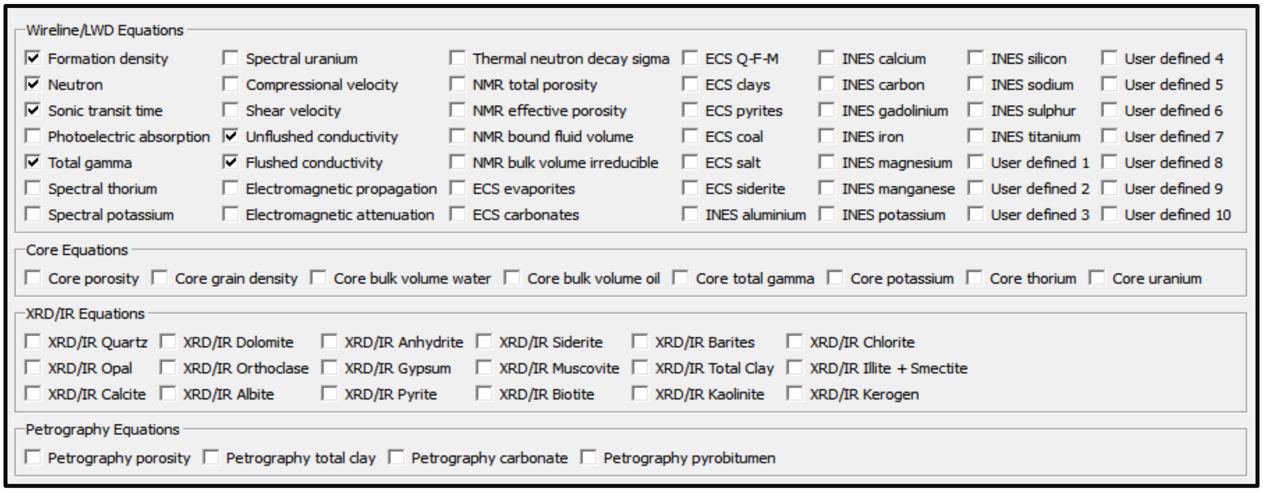

Figure 3: The equations for modeling in the multi-min tool are selected based on the available logs

The equations provided uncertainty values in modeling which were modified iteratively untill a match for the predicted logs were achieved. In tandem with the predicted logs, mineral logs were also generated by the model (Figure 4). The selection of minerals for the multi-min analysis was based on the available core data.

Figure 4: Mineral predictions based on XRD minerals

Rock Physics Application

The Vclay, porosity, saturation logs and aspect ratios were used in Xu-Pane rock physics model to predict Vs, Vp and density logs. A key part of this process is incorporating the right aspect ratio in the model. In Erha Field, very good match with measured logs were obtained. This match enabled the creation of a consistent rock physics model. The rock physics model formed an input to the ExxonMobil facies- based petrophysical inversion, which inverts for Vclay and porosity volumes as well as elastic volumes (Vp, Vs, and Rho).

RESULTS

Vclay results

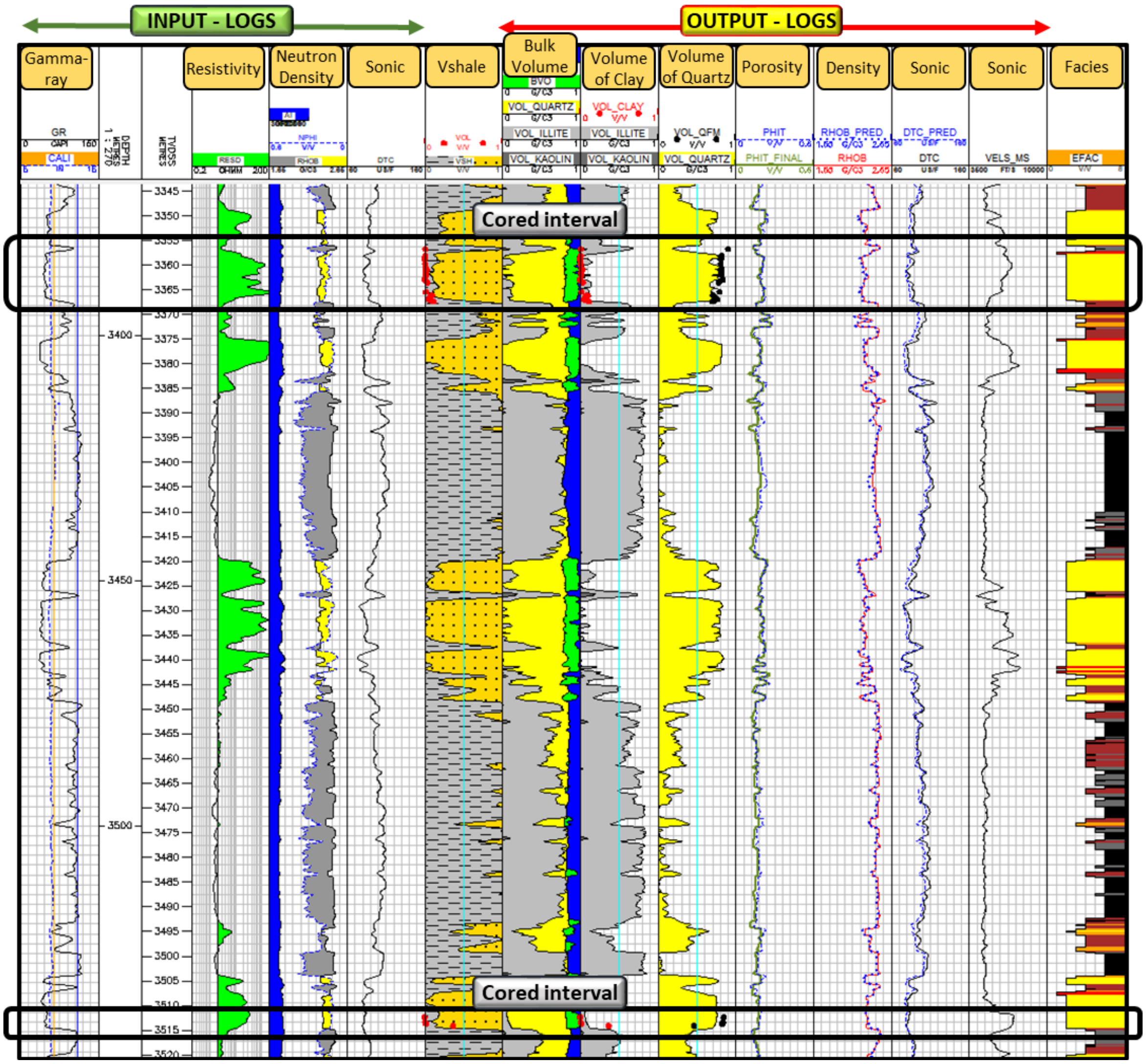

Figure 5: Result of the modelling with multi-min in Erha-X well. The predicted porosity, density and sonic logs are displayed and they form an almost one- to- one match with the input logs. The volume of quartz and Vclay also generated match with XRD information

The above picture (Figure 5) shows the result of the multi-min model when applied to the whole of the Erha-X well. After several iterations on the model parameters, a near one-to-one match was visible in the predicted logs (sonic, density and porosity) when compared with the original logs. Also, the model generates a Vclay and Vquartz log from top to bottom of the well. This also matches the XRD data indicated in black and red points. At this stage, the model was deemed suitable for Vclay prediction in other wells without XRD data points. This was applied across the field with generally good to very good matches and an example shown in well Erha-Y (Figure 6).

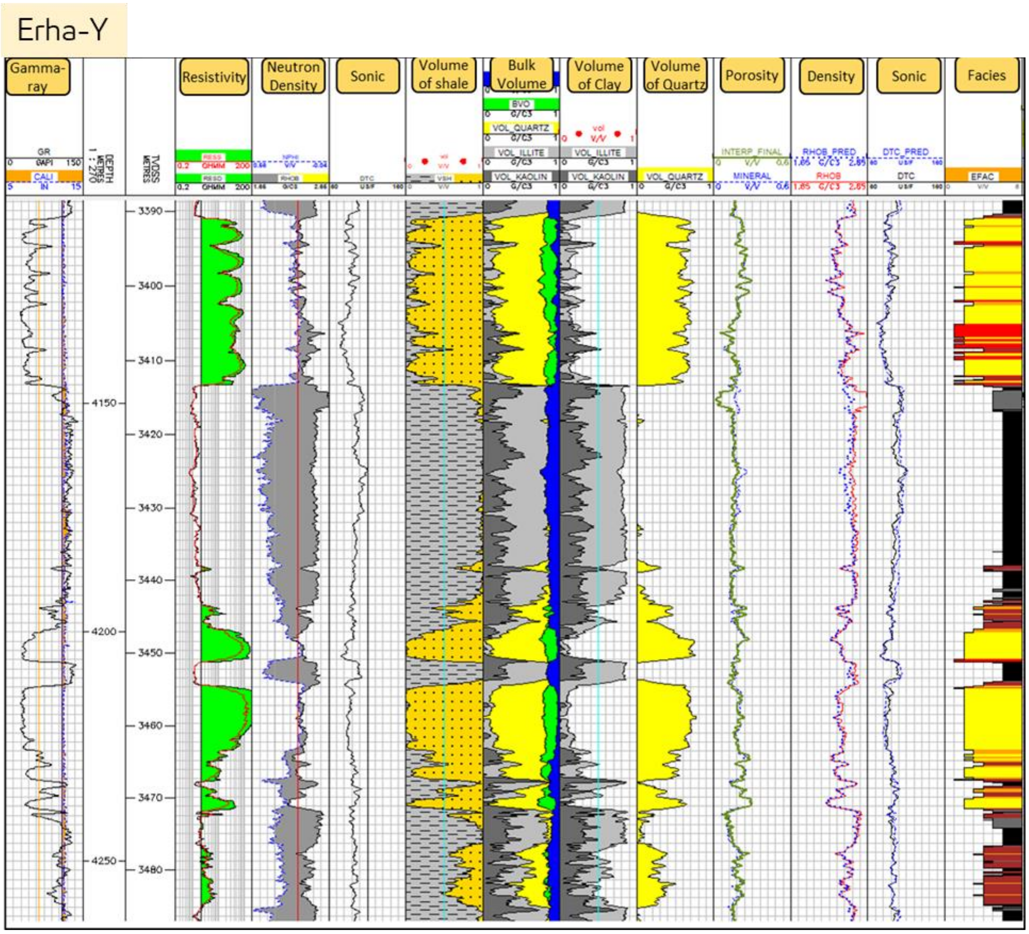

Figure 6: Result of applying the model in Erha-Y which has no XRD data. The predicted porosity, density and sonic logs are displayed and show an almost one to one match with the input logs.

Inversion results

Vp/Vs is a very useful tool to discriminate sand and clay facies. Vclay tends to increase in concurrence with an increase in the Vp/Vs ratio. Building a volume with these results helps to visualize the distribution of sand and shale in a 3D seismic volume which can be very useful in facies description, volume capture and well planning.

The result of the modelling is blind to well which means that the algorithm is not guided by well location or property but by integrating the well log property with seismic to act as a facies discriminant.

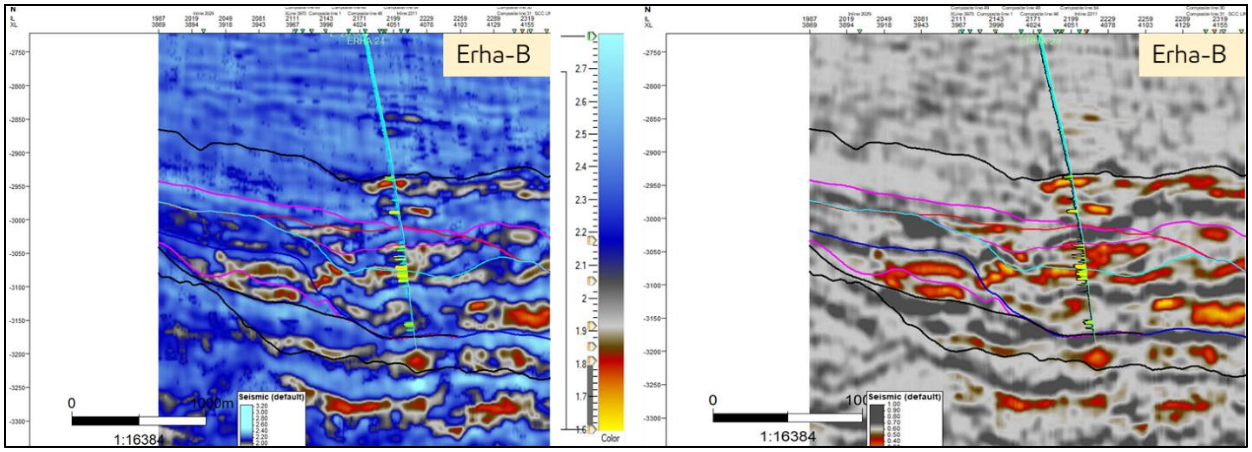

Figure 7: Inversion results showing the Vp/Vs and Vclay volumes in an example well. The well is overlain with Gamma-ray log. The volume quite clearly matches with well result in the distribution of sandy facies (indicated by the warm colours)

The result is even more visible when taking a cross section through various wells in the field and overlaying the well results with the predicted volume (Figure 8)

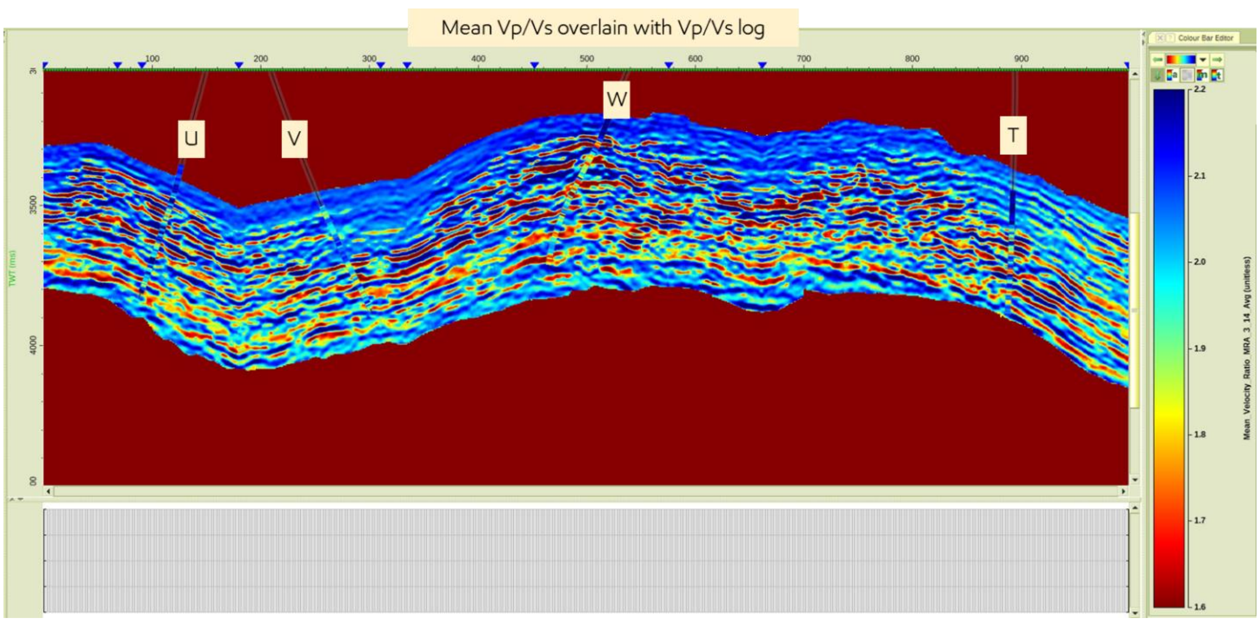

Figure 8: Overlaying the Vp/Vs ratio logs with the Vp/Vs volume. The log results are almost invincible with a very good match at seismic scale

CONCLUSIONS

The method utilized in this work showed great results for Vclay prediction in the Erha field especially given the limited available data. This formed the foundation for predicting volumes across the field which might otherwise have been challenging.

Building a Vclay model for Erha Field was a very iterative process with several modifications to the model parameters. This was especially so given that the shallower Erha North has different properties from the deeper Erha Main. Being shallower, the porosity values are much higher than would be found as you go deeper. These all needed to be accounted for while building the model. The statistical distribution of parameters in the Multi-min tool was varied by testing the model on several wells both in Erha Main and Erha North. This gave rise to a robust tool that could be used for the prediction of Vclay across the field.

Taking the results of the Vclay analysis, and the well logs to the inversion tool resulted in the creation of very detailed volumes for the whole field which enhance opportunity generation within the field, static model building and well planning to capture remaining volumes.

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