Evaluation of Rock Properties from Logs Affected by Deep Invasion – A Case Study

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Summary

Seismic reservoir characterization is a well-known technique to obtain a better understanding of hydrocarbon-bearing reservoirs by careful analysis and integration of petrophysical and seismic data. The petrophysical properties are normally obtained through the evaluation of well logs and core data. A rock physics model provides the link between these reservoir properties and the surface seismic data. Well log measurements are often subjected to various sources of errors, like borehole rugosity due to washouts and mud filtrate invasion. This invasion effect can be significant for permeable rocks and is the focus of this study.

In this paper, we discuss how we corrected the logs for invasion effects through an iterative workflow between petrophysics and rock physics modeling. This resulted in a set of high quality reservoir and elastic logs used for seismic reservoir characterization. The logs are from six wells in the Scarborough field, located in the Exmouth Sub-Basin, offshore North West Australia. The reservoir consists of Early Cretaceous deep-water turbidite sandstones deposited in a distributary channel to basin floor setting. The dominant reservoir facies are quartzose medium and fine-grained sandstones with average porosities greater than 30% and permeabilities of 100's to 1000's of millidarcies. The resistivity profiles of all the wells show that the drilling mud filtrate invaded the formation during the drilling process and significantly flushed the hydrocarbons near the borehole. The density and sonic logs having shallow depths of investigation were badly affected.

The workflow starts with petrophysics where the volumes of minerals, porosity and fluids are computed. These preliminary volumetrics form the basis of the subsequent rock physics modeling. An inclusion based model was used to predict the measured elastic logs and correct for the invasion effects. In order to account for different invasion profiles and different mud filtrate salinities, we had to iterate several times between petrophysics and rock physics to arrive at a final set of logs for each well. In this way we achieved results that are based on a consistent model for petrophysics and rock physics. We used these logs to compute synthetic seismograms and calibrate the pre-stack seismic data, which is not affected by drilling. The high correlations obtained gave us confidence in our results. This is very important for accurate extraction of reservoir information from the seismic data and further reservoir modeling.

Introduction

The well logs fill a critical gap between core and seismic data and are routinely used for seismic reservoir characterization. The logs provide information to understand the relationship between the elastic and reservoir properties. However, the measured logs are susceptible to errors from numerous sources such as borehole rugosity due to washouts, different generations of tools, missing or bad data and mud filtrate invasion. Therefore, logs need to be corrected for the aforementioned issues. The relationship between seismic and reservoir properties can be better understood if we have a high quality, consistent and complete suite of log data available over the zone of interest.

Rock physics modeling is an essential part of any seismic reservoir characterization workflow. The modeling may be as simple as establishing empirical relationships between rock properties or as complex as poroelastic numerical modeling. The sophistication of the modeling will depend on the objectives and the quality and availability of data. However, challenges often come from inconsistencies in the petrophysical interpretations. The difficulties in generating a predictive and consistent rock physics model for a field may highlight inconsistencies within the petrophysical interpretation. The integrated seismic petrophysics and rock physics modeling provides consistent petrophysical results and also helps in the quality control of the petrophysical interpretation. The rock physics modeling can assist in the quality control of the measured elastic logs (density, P-sonic and S-sonic). This means that a consistent and meaningful rock physics model can often indicate anomalous and poor quality measurements in the elastic logs that need correction or mitigation. Consequently rock physics modeling is the focus of the integration of data and disciplines and is therefore extremely important.

In this paper, we discuss a case study involving six wells from the Scarborough field to perform seismic petrophysics and rock physics modeling. This work was part of a larger seismic reservoir characterization study. The Scarborough gas field is located in the Exmouth Sub-Basin, offshore North West Australia (Sutton and Fittall, 2013). The QC of the input log data (Figure 1) shows clear inconsistencies between reservoir and elastic properties.

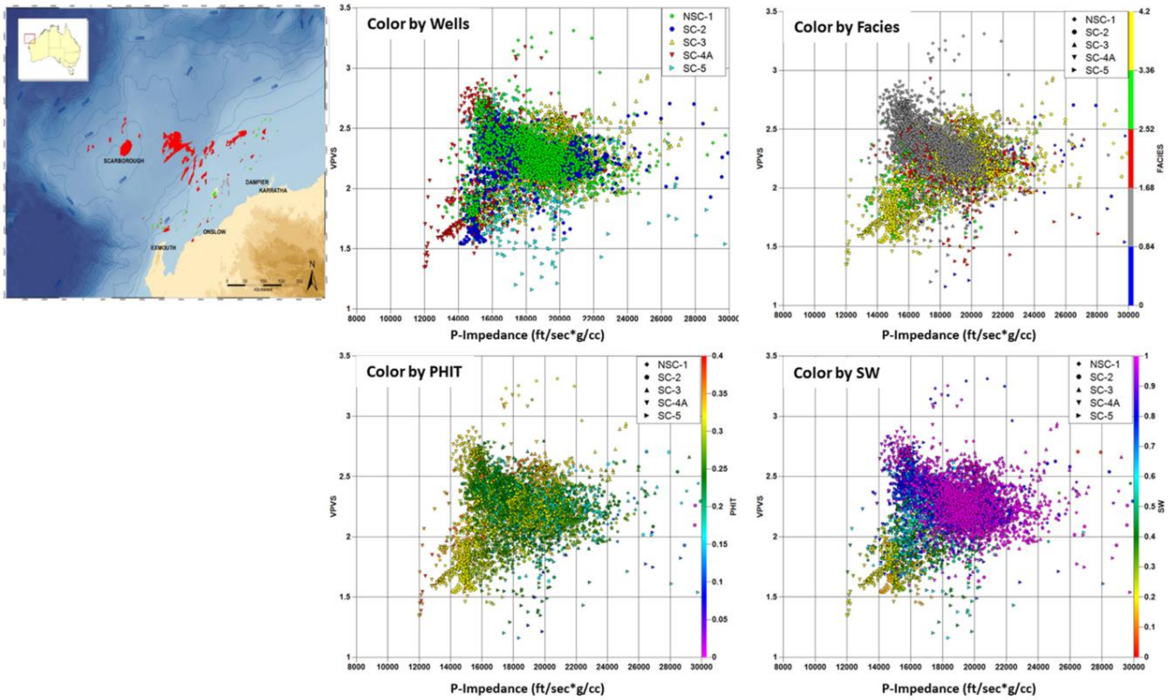

Fig. 1. Map with location of the Scarborough gas field. The crossplot of measured elastic properties (Raw Data) for the interval from Top Reservoir – TD (colour coded by well, facies, porosity and SW), showing inconsistencies and generally poor relationships. There are five litho-facies defined based on core rock typing where S1: Medium grain Sst (Yellow), S2: Fine grain Sst (Green), S3: Very fine grain Sst (Red), Siltstone (Grey), and Cement (Blue).

It was determined that the main source of error and inconsistency between the wells was the invasion of borehole fluids into the highly porous and permeable reservoir rock (Sidi et al., 2006). The invasion of mud fluids is very common in porous and permeable rocks and this process is generally unavoidable during the drilling process. The elapsed time between drilling and logging and differential pressures between the borehole column and the formation cause the invasion of borehole fluids into the formations. This results in the alteration of the formation properties near the borehole. The invasion may range from a few centimeters in high-porosity zones to a few meters in low porosity zones. The main factors effecting the depth of invasion are porosity, permeability, mud type and the pressure difference between the well-bore and the formation. The depth of invasion for a given mud type in contact with a formation of certain permeability and wettability is larger for smaller porosity under given differential pressure.

An integrated seismic petrophysics and rock physics workflow was applied to all six wells in the study. The final logs generated using this workflow show clear relations between elastic and reservoir properties which will be very useful for the subsequent seismic reservoir characterization.

Methodology

Well Data QC and Conditioning

Log data QC and conditioning was performed for all wells. The purpose of this QC was to detect and remove non-geologic differences between well log types across the field, where these differences are caused by tool calibration errors, borehole rugosity or tool variability (these wells were logged between 1979-2012 using different generations of tools). Ideally, wells at similar stratigraphic intervals across the field should have similar data distribution. The main issue observed with the log quality is the invasion over the sand intervals. Figure 2 shows the conditioned data for two wells, where the shallow and deep resistivity logs show that there is significant mud filtrate invasion into the sands. The sands below the GWC also show invasion. The logs having shallow depths of investigation mainly respond to the invaded zone, where an estimated 70-80% of the formation fluids were flushed away.

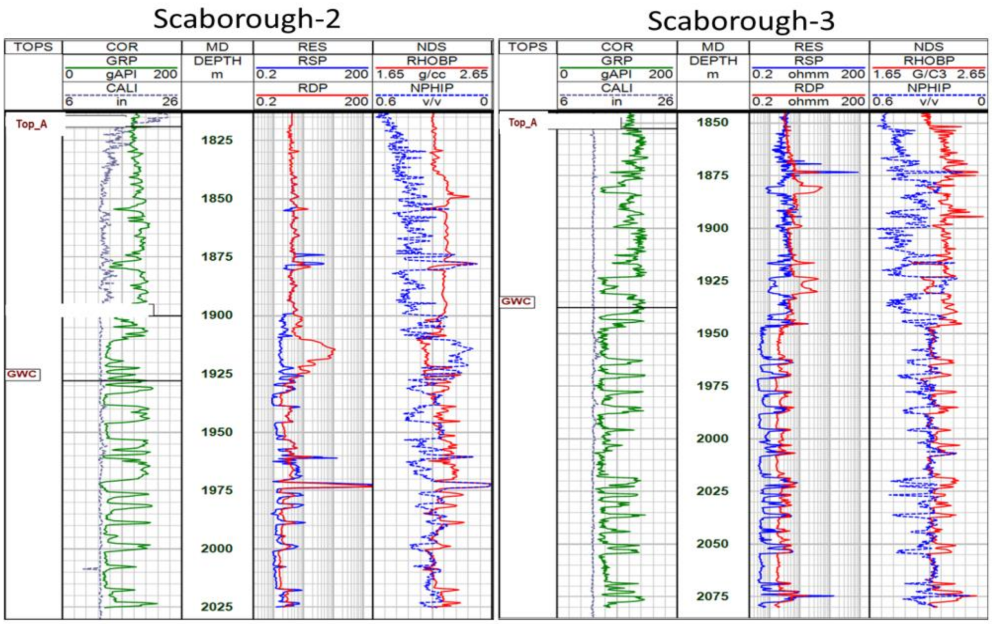

Fig. 2. Log plot for two wells after initial data conditioning. The resistivity profiles show the different amounts of invasion in the sands above and below GWC.

Seismic Petrophysics

Seismic petrophysics is a critical part of establishing a predictive and consistent rock physics model that focuses on the reservoir and non-reservoir rocks in the zone of interest. An accurate and consistent petrophysical model is required for computation of minerals, porosity and fluids. Conventional petrophysical results are often only available over the reservoir section and can be inconsistent between wells due to different approaches or petrophysical models that have been used.

The integrated seismic petrophysics and rock physics modeling workflow eliminates potential inconsistencies between petrophysics and rock physics modeling. An important aspect of this approach is the use of consistent and accurate fluid and mineral properties. The fluid acoustic properties used in the petrophysical and rock physics work are determined using empirical relationships from the 2009 Fluids Consortium using sampled reservoir fluid properties. In this case study the resistivity data indicated that invasion had taken place and the petrophysical interpretations were made under the assumption that the density (and neutron) logs were measuring the invaded zone. A water based mud was used for drilling in all six wells. Salinities for the invaded zone were determined using shallow resistivity as the actual brine properties near the borehole represent the mixture of mud filtrate and in-situ pore water. The mud filtrate salinities derived from shallow resistivity are significantly different from the formation water salinities due to the variability of drilling mud properties (Table 1). These salinity variations have profound effect on the fluid acoustic properties and subsequent elastic properties of the rocks.

Water	SC-1	SC-2	SC-3	SC-4A	SC-5	N. SC-1
Drilling Mud Type	NACL WBM	NACL WBM	KCL WBM	KCL WBM	KCL WBM	KCL WBM
Formation water salinity in ppm at 120 DegF.	27,000	35,000	30,000	20,000	35,000	30,000
Salinity in ppm estimated from Shallow Resistivity at 120 DegF. and used for invasion correction	30,000	77,000	163,000	145,000	115,000	119,000

Table-1. The table shows large variation between the formation water salinities and salinities estimated from shallow resistivity for different wells. These salinity variations have profound effect on the fluid acoustic properties and subsequent elastic properties of the rocks. (WBM=water based mud)

In this study, the petrophysical evaluation was carried out using a multi-mineral model based on the known lithology from well completion reports and conventional petrophysical analysis. The petrophysical evaluation consists of estimation of the volumes of minerals and fluids present in the invaded and virgin zones. The volume of clay was estimated using a combination of Gamma Ray and Neutron-Density cross-plot. The porosities (effective and total) were determined by an iterative procedure of mud invasion correction and/or light hydrocarbon correction based on the Density and Neutron log. Figure 3 shows the final clay volume and total porosity for all wells before and after the seismic petrophysics workflow. The seismic petrophysical outputs are observed to be consistent across all the wells.

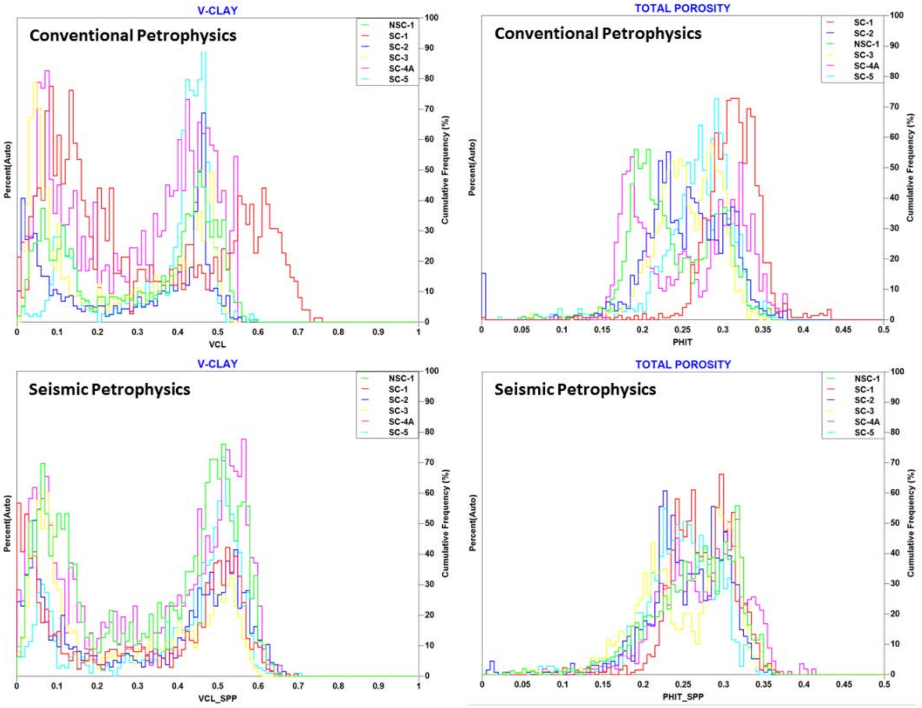

Fig. 3. The multi-well histograms show V-Clay and total porosity from conventional petrophysics (above) and integrated petrophysics-rock physics (below).

Rock Physics Modeling

The self-consistent scheme of Berryman (1980) was used to build a rock physics model with variable pore aspect ratio or Alpha (the ratio of the short axis to the long axis in an ellipsoid). The minerals and pore space were combined to calculate the effective properties of the rock frame. The fluids were then included using Gassmann's equations (Gassmann, 1951). The input parameters required for this model were density, Vp, Vs, Alpha for quartz and clay and also density and Vp for brine and gas. The S-wave velocity was modelled concurrently with the P-wave velocity. In the intervals where no hydrocarbons was present both the S-wave and P-wave velocity was used to fix the unknown clay parameters. In the case where hydrocarbons are present the unknown parameters can be fixed based on the match to the S-wave velocity, which is relatively independent of the fluids present and therefore relatively independent of assumptions concerning invasion. To determine the optimum pore aspect ratio value for sand and clay, constant values for Alpha-quartz and Alpha-clay were first applied and the error in modeling the S-wave velocity was then used to adjust Alpha values for quartz and clay. The following workflow was used for rock physics modeling:

- Assign elastic properties to minerals and fluids from the petrophysical results.
- Mix the mineral and fluid properties to predict elastic properties of the rock using the self-consistent model using constant values for Alpha-quartz and Alpha-clay.
- Optimize the parameters to match good quality measured data at the invaded zone (Sxo) saturation (Fig. 4).
- Generate an Alpha curve for each well by finding the best match between the model and the conditioned data using P- and S-wave velocity.
- Drive a regional relationship between Alpha and clay volume, total porosity and depth is derived using all of the wells and applied to generate Alpha curve at each well.
- Apply rock physics model to predict missing P- and S-sonic data.

- Apply invasion correction using rock physics model to mitigate the effect of invasion on elastic logs (Sxo to Sw saturation condition) (Fig. 5).

The depth varying pore Alpha was used in rock physics modeling. The following steps were used to derive the final aspect ratio curve at each well:

- Different constant Alphas were used for pore space associated with quartz and clay initially.
- Optimize rock physics parameters i.e. clay bulk and shear modulus, quartz and clay aspect ratios.
- Generate Alpha curves by finding the best match between modelled and conditioned P-sonic and S-sonic at each well location.
- Establish a regional relationship between Alpha and clay volume, total porosity and depth using all of the wells was derived
- Use the regional relationship to generate the Alpha curve for each well

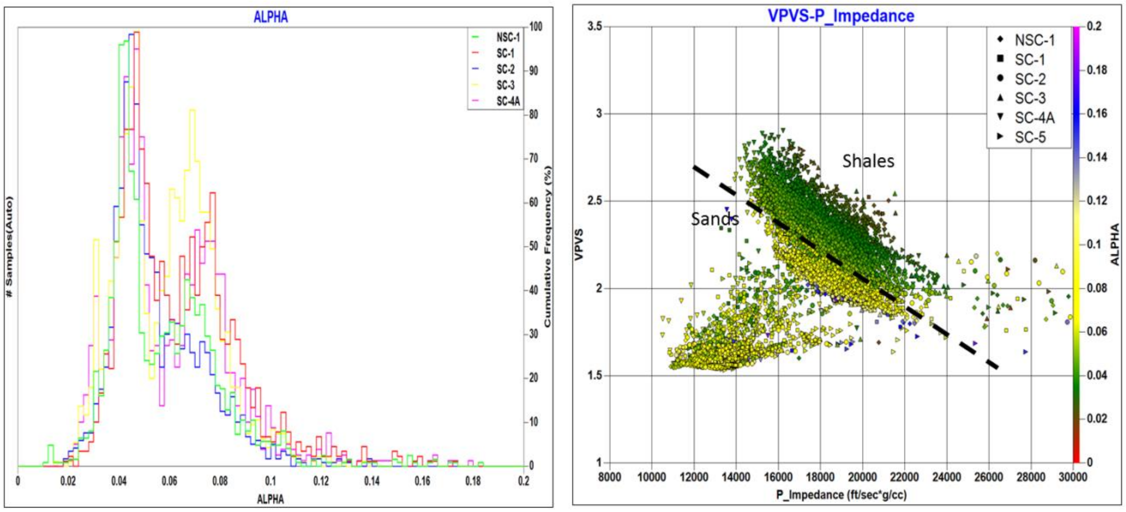

Fig. 4. Multi-well histogram for estimated Alpha (pore aspect ratio), and P-Impedance vs. Vp/Vs cross-plot color-coded by Alpha.

With the rock physics parameters fixed (i.e. minerals bulk and shear moduli and aspect ratios), the P-wave velocity will vary dependent on the type of fluids and how they are mixed (i.e. patchy or homogenous). The effective acoustic properties of the fluid mix are estimated that give a good fit to the conditioned data. The Brie formula (equation 1) is used for fluid mixing, where K is the bulk modulus and "e" is an exponent to vary the fluid mixing. When e = 1 the mixing is a Voigt average, and when e = 40 the mixing approximately follows Wood's law (Brie et al. ,1995).

$$K_{Brie} = \left(K_{liquid} - K_g\right)\left(1 - S_g\right)^e + K_g \qquad (1)$$

Figure 5 shows the rock physics modelled logs for invaded zone saturation (Sxo) conditions for the Sc-4A well. The log plot shows the conditioned logs (black) and the modelled logs (red) in density, P-sonic, S-sonic, Vp/Vs and P-Impedance tracks. The modelled logs are reasonably consistent with conditioned data. The same rock physics model was applied to all the wells using well-specific Alpha curves determined using the workflow described above. The filtrate properties determined at each well for the invaded zone and Sxo saturation curve were used when predicting the measured log response. For the in-situ formation response the saturation curve was changed to Sw and brine salinity for formation water was used in the modeling. Figure 6 shows the final invasion corrected logs, where the difference between the conditioned logs (black) and the modelled logs (red) is due to correction for the invasion. The invasion corrected logs also show a difference with conditioned data below the GWC as the effect of changing salinities in the mud filtrate and formation water has been compensated.

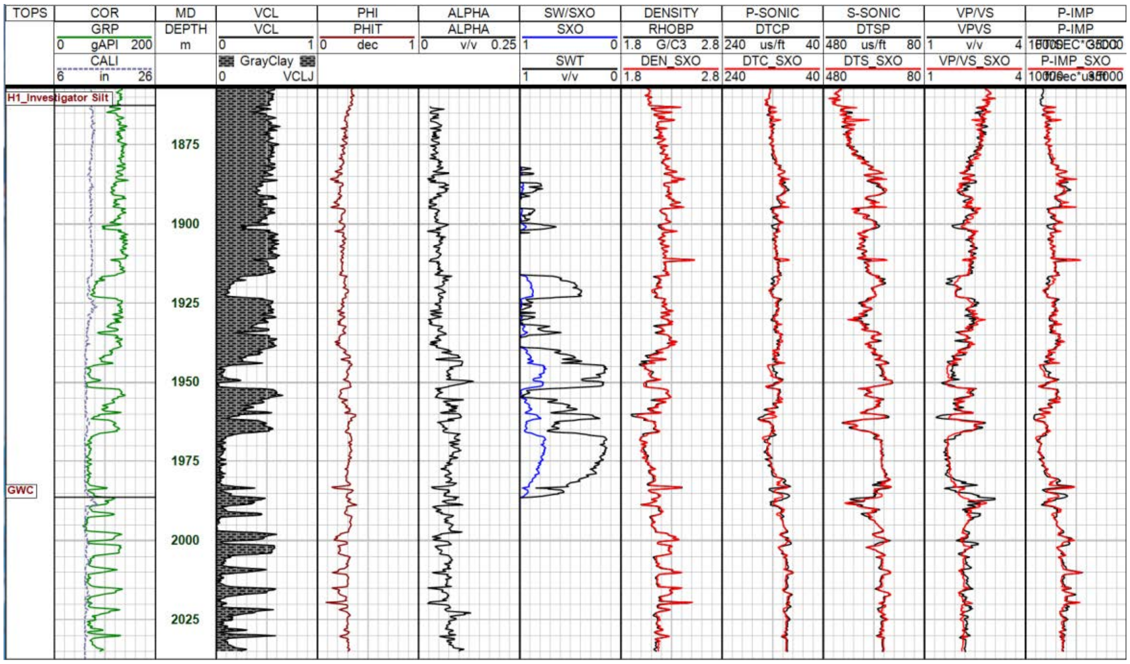

Fig. 5. Rock Physics modeling results for Sc-4A well at invaded zone saturation (Sxo). Track "ALPHA" shows the final Alpha curve; track "SW/SXO" shows the in-situ and invaded zone saturation, tracks "Density", "P-Sonic", "S-Sonic" , "Vp/Vs" and "PIMP" tracks show the conditioned and modelled elastic logs, Black – Measured logs, Red – Modelled logs.

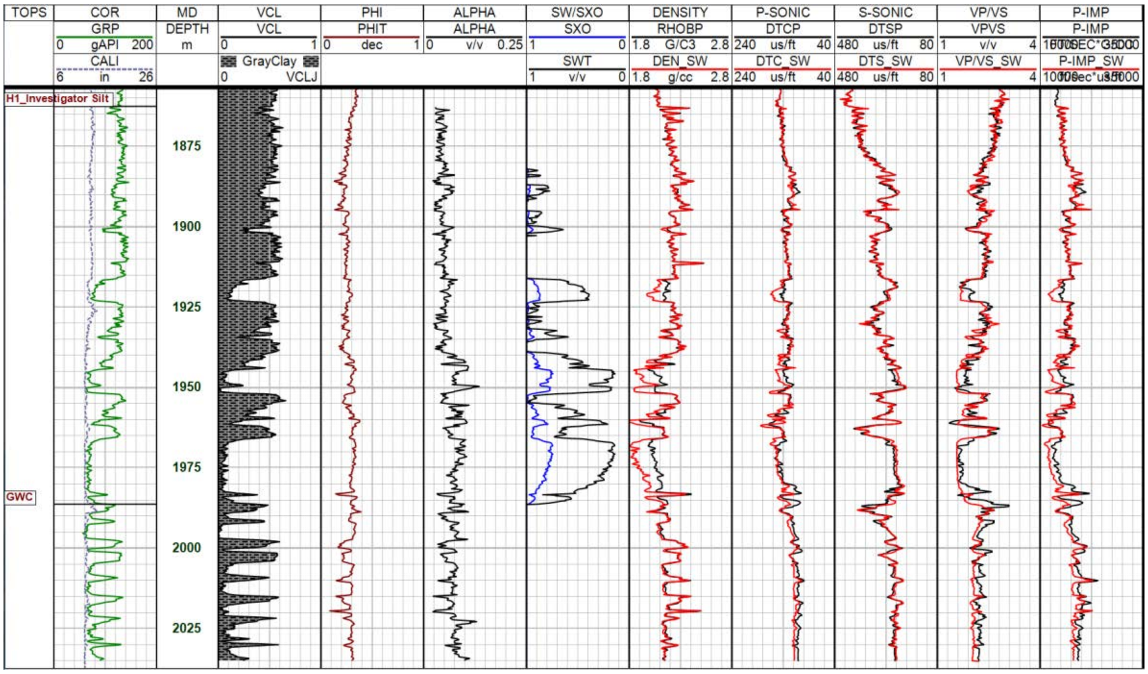

Fig. 6. Rock Physics modeling results for Sc-4A well at in-situ saturation (Sw). Track "ALPHA" shows the final Alpha curve; track "SW/SXO" shows the in-situ and invaded zone saturation, tracks "Density", "P-Sonic", "S-Sonic" , "Vp/Vs" and "PIMP" tracks show the conditioned and modelled elastic logs, Black – Measured logs, Red – Modelled logs.

Figure 7 shows crossplots of the modelled logs after invasion correction. The crossplots show much better associations for lithofacies and reservoir properties compared to the measured logs (Figure 1). Cemented facies in the logs of some wells can be clearly identified by their high impedance response (e.g. P-Impedance values greater than 23,000 (ft/sec*g/cc). These cemented sections have been assessed as being localized and are not observed on surface seismic data. The cemented sand was not included in the rock physics modeling and the modelled logs were replaced with measured data over these cemented sections.

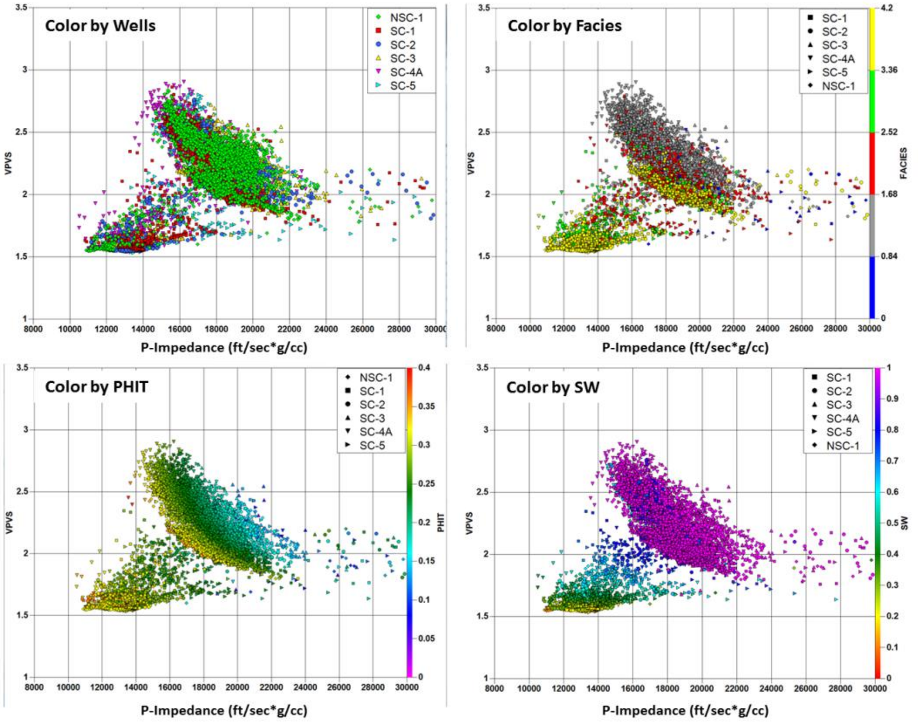

Fig. 7. Crossplot of modelled elastic properties for the interval from Top reservoir – TD (colour coded by well, facies, porosity and SW) showing consistent relationships. There are a total of five litho-facies defined based on core rock typing where S1: Medium grain sst (Yellow), S2: Fine grain sst (Green), S3: Very fine grain sst (Red), M1: Siltstone (Grey), and Cement (Blue).

The modelled logs after the invasion correction were used to compute synthetic seismograms and calibrate the pre-stack seismic data, which is not affected by drilling. Figure 8 shows the synthetic-to-seismic tie for Scarborough-2 using conditioned and rock physics modelled logs. The correlation of the seismic to well tie within the zone of interest has improved significantly using the final rock physics modelled logs. It is very important to extract accurate reservoir information from the seismic data as this is then used for reservoir modeling.

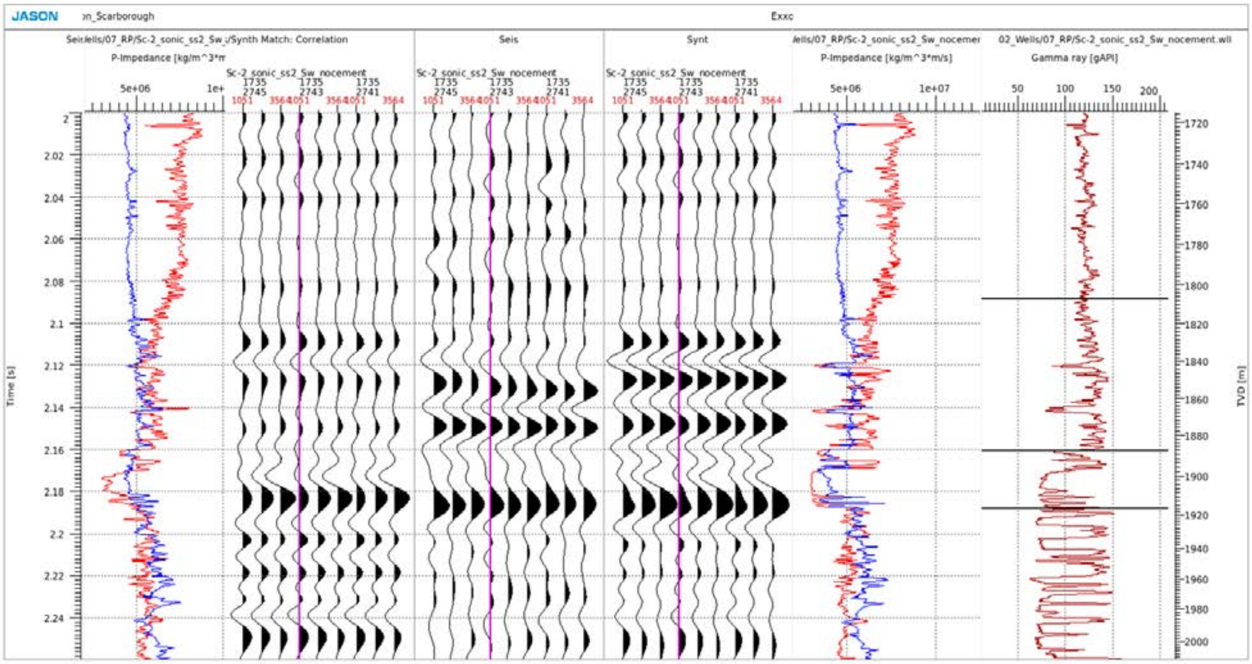

Fig. 8. Scarborough-2 well tie using conditioned logs and modelled logs. Track-1: conditioned p-impedance (blue) and Vp/Vs (red), track-2: AVA synthetics for the conditioned logs, track-3: seismic gathers, track-4: AVA synthetics for the modelled logs, track-5: modelled conditioned p-impedance (blue) and Vp/Vs (red) and track-6: GR log. In the synthetics and seismic tracks 3 traces (near, mid and far) are shown at 3 CDP's.

Conclusions

In this paper we discussed how an iterative workflow between petrophysics and rock physics modeling results in a set of high quality reservoir and elastic logs. The following are the key conclusions to be drawn from this study.

- An integrated and iterative workflow to build a robust inclusion based rock physics model has been demonstrated.
- The rock physics model is sufficiently detailed to generate elastic logs that adequately match the measured data.
- Modelled elastic logs for all the wells are based on a consistent rock physics model, and have been corrected for invasion effects.
- The final rock physics modelled logs show an elastic log response that better matches expectations, for example the separation of fluids and lithology in the elastic domain.
- The workflow enforces consistency between petrophysical, reservoir and elastic properties that provides optimal inputs for subsequent seismic inversion and reservoir characterization work.

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