Carbonate reservoir characterization – tightly integrating petrophysics, rock physics, and seismic inversion analysis

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Abstract

Reservoir characterization is an often difficult process in carbonates due to its complex pore system (Giao and Chung, 2017). This study presents an integrated approach of using well logs, rock physics modelling, and seismic inversion studies to characterize complex carbonate reservoirs of the Eocene age in our study area of the Western offshore basin. Based on recorded well logs and shear log data rock physics model developed and these models are further in combination with high tech log data like resistivity image logs, core SEM images, and XRD analysis are finely tuned to help in reducing uncertainties in pore typing and mineralogical problems. It is worth mentioning that results of this integrated analysis approach of petrophysics, rock physics modelling, core, and hi-tech log data inferences, with seismic inversion analysis employed in this study, will improve characterization of these complex carbonate reservoirs and paves a way for further exploration activities in the study area with reduced risk.

Introduction

Rock physics modelling is the bridge between rock elastic properties to reservoir properties. Reservoir properties used in reservoir studies include porosity, lithology, pore fluid, pressure, temperature, etc. and elastic properties include bulk modulus, shear modulus, seismic velocities, density, impedance, etc. With recent advances in rock physics modelling and seismic inversion analysis the efficacy of finding hydrocarbon reservoirs has increased. Hence, the development of an accurate and practical rock physics model is one of the crucial steps for inversing seismic data for rock and fluid properties of the reservoirs (Payne, 2008). The more complex depositional environment and related diagenesis processes involved make the carbonate pore systems more heterogeneous compared to clastics (Lubis and Harith, 2013). This complex pore system makes the building of rock physics model in carbonates a difficult task.

There are many different ways of rock physics modelling. Starting from empirical to analytical. If well log data or measurements on core samples are available then local area specific relation can be generated to estimate required properties. As mentioned, these relations are area specific and may or may not apply outside the calibration area and also may not address non-linearity in the data (Payne, 2008).

The aim of this study is developing an analytical rock physics model of complex carbonate systems and their integration with seismic data for reservoir characterization. In the present study a rock physics model was developed using basic well logs and the recorded shear log data is used for calibration of the model. The workflow adopted in this study helped us to reduce uncertainty in porosity portioning and mineralogy of the carbonates. The results of this tight integration of porosity type information from resistivity images data further their calibration with core SEM images improves prediction of elastic properties through a robust rock physics model. This further improves seismic reservoir characterization through inversion analysis.

The study area belongs to the Western Offshore Basin, which consists of four wells namely Well#A, Well#B, Well#C, and Well#D. Figure 1 shows the base map of the study area. Eocene carbonates of the study area are considered for Rock physics analysis. Out of these four wells Well#A, C, and D are having recorded shear log data and resistivity image data whereas in Well#B shear data was not recorded.

Carbonate Rock physics Modelling

The more complex depositional environment and related diagenesis processes involved make the carbonate pore systems more heterogeneous compared to clastics (Lubis and Harith, 2013). Clastic rocks are mainly contain intergranular pores, whereas carbonate rocks can have a variety of pore types, such as moldic, vuggy, interparticle, and intraparticle (Xu and Payne, 2009). This complex pore system makes the building of rock physics modelling in carbonates makes a challenging task.

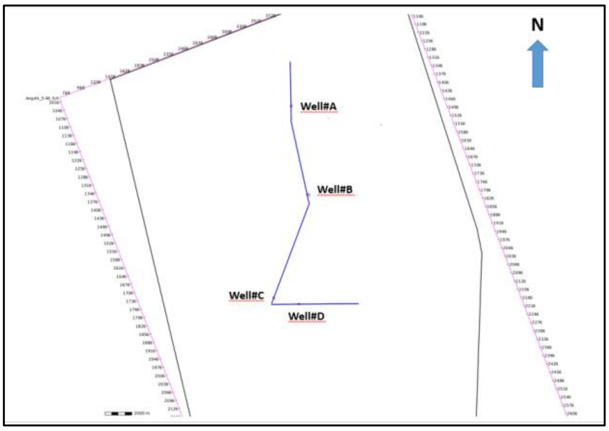

Figure 1: Base map with wells in area of study.

In this study, we modeled elastic properties using Xu and Payne rock physics model. Xu and Payne (2009) extended Xu and White (1995) rock physics model of shaly sandstones to carbonates. In which the total pore volumes are classified into four different types clay-related pores, interparticle pores, micro-cracks, and stiff pores.

The following methodology of Xu-Payne rock physics modeling was followed and Density, Compressional velocity (Vp), and Shear velocity (Vs) were modeled and calibrated in the Well-A and C in which recorded shear log data is available. Figure 2 shows a schematic of the Xu-Payne model for carbonates. This method consists of four steps (Xu and Payne, 2009).

1) The minerals present in the rock are mixed using a mixing law (e.g., the Reuss-Voigt-Hill average). We begin with a solid rock matrix having the properties of this mixture.

2a) Micropores with bound water (e.g., clay pores) are added to the matrix using the differential effective medium or DEM (Xu and White, 1996) process and the Kuster- Toksöz theory (1974) to account for the mechanical interaction between the pores. The calculated effective elastic properties (e.g., bulk modulus) will be used later as the “solid” properties for fluid substitution.

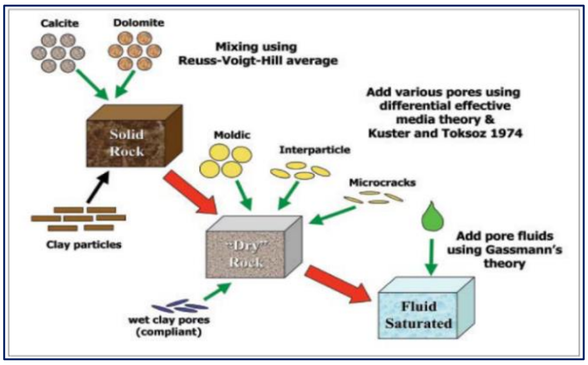

Figure 2: Carbonate rock physics model workflow schematic diagram, Xu, and Payne (2009).

2b) All pores including water-wet micropores and empty (or dry) nonbound-water pores are added into the system using the effective medium theory to provide the effective elastic properties (e.g., bulk modulus) of the “dry” rock frame.

3) The remaining water (which is not bound to micropores) is mixed with the hydrocarbons (oil or/and gas) using a fluid mixing law such as the Wood suspension model.

4) Gassmann’s equations are used to add the fluid mixture into the pore system to obtain the final effective elastic properties for the saturated rock.

In the current study, the aspect ratio (short to long axis ratio) of reference interparticle type pores range from 0.12 to 0.15. The stiff pore aspect ratio ranges from 0.7 to 0.8, and micro crack aspect ratio range from 0.01 to 0.02.

Tight integration to reduce Uncertainty in modelling

Integration of petrophysics, rock physics models with available data sets like core data and other hi-tech log data ensures control on modeling and also on the quality of the results. When modelled results are in agreement with the core data this improves the confidence in interpretation (Jeff, B). When these petrophysics and rock physics are in agreement, its further integration with seismic inversion offers greater accuracy with reduced uncertainty in final results.

In the present study, the uncertainty associated with the formation mineralogy is addressed by the integration of the X-Ray diffraction analysis results into petrophysical and rock physics analysis. From core studies, it is evident that the dominant minerals are Calcite and Dolomite and the associated clay type is Kaolinite as shown in figure 3. As discussed above porosity typing in carbonates is a difficult task and to address this, vuggy porosity is estimated from the resistivity image log used as input for rock physics modeling. Core SEM images and core photographs also validates the porosity estimated from image logs (Figure 4).

From Figures 4a and 4b, it is seen that the average vuggy porosity estimated from resistivity images in Well A and D are 0.04 and 0.1 respectively. The reason for decreasing vuggy porosity from Well A to D is because of the total porosity variations from Well to Well. This variation can also be confirmed from NMR log data that the average porosity in Well #A is about 0.12 and in Well #D is 0.18 (Figure 4a & 4b). SEM images and core photographs show the development of vuggy porosity in the reservoir which is in agreement with the vuggy porosity from image log data (Figure 4c, d & e).

By tightly integrating data from the petrophysical analysis, core data, and hi-tech log data rock physics modelling was carried out in four wells of the study area to model compressional and shear velocities. The predicted compressional and shear logs are in very good agreement with the recorded log data.

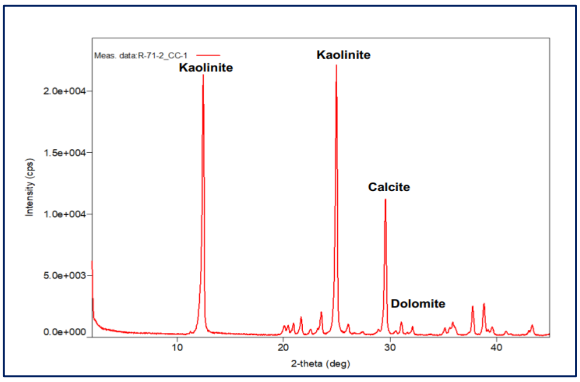

Figure 3: XRD analysis of a core sample from Well#C showing the presence of Calcite, Dolomite, and Kaolinite.

Rock physics to Seismic

The cross plot of P-Impedance (PIMP) versus Vp/Vs ratio from rock physics modelled data labelled with facies, shows that data is separated into four distinct clusters interpreted to be hydrocarbon bearing, brine saturated, shaly/tight limestones, and shale (Figure 5b). All these four facies are merging in cross plot of recorded data as shown in Figure 5a. The cross-plot analysis clearly shows that hydrocarbon bearing zones have low Vp/Vs, brine sands have moderate Vp/Vs ratio, while shale has high Vp/Vs ratios (figure 5b).

The main purpose of the seismic inversion is to characterize the reservoir by predicting rock and fluid properties from seismic data (Munyithya, et.al., 2019). In seismic inversion studies, the seismic data is converted into layer properties such as P- impedance, S-impedances etc., and all the other related seismic attributes. Well to seismic tie of four wells was carried out by using angle stacks for Pre-stack seismic inversion studies and extracted multi-well wavelet. A constrained sparse spike inversion algorithm has been applied for inverting the available angle stacks using multi-well wavelet and initial model as inputs. It is possible to discriminate hydrocarbon-bearing zone from the cross-plot of P-impedance vs Vp/Vs ratio colored with facies. Figure 6a & 6b shows a section display of inverted P-impedance and Vp/Vs passing through all wells and at well locations both the data are in agreement with each other. Neutron porosity section as shown in Figure 7 will help in identifying porous pods in the zone of interest. By tight integration of petrophysics, rock physics modelling analysis, and seismic inversion studies will further helps in bringing out reservoir facies.

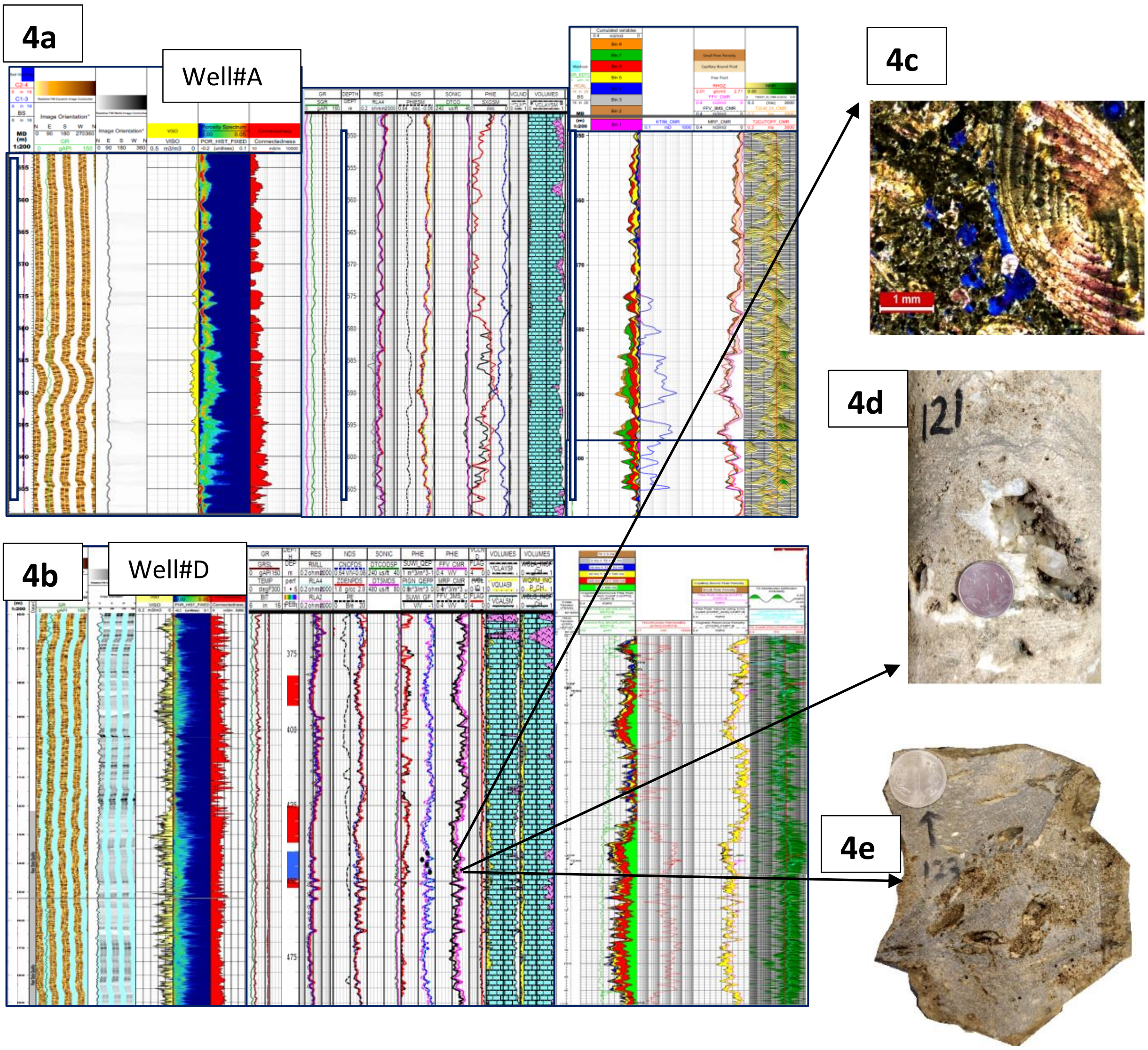

Figure 4: **4a &4b**: Composite plot of vuggy porosity from resistivity images, petrophysical volumes, and NMR log of Well#A and Well#D respectively. Vuggy porosity estimated is shown in track 4 and its connectedness in track 6. NMR porosities are shown in the second last track. **4c**: SEM image showing fossils grains consist of bioclasts, foraminifers, and pelloids in partially sparitized matrix with moderate porosity in the form of vugs and molds.**4d**: Core photograph of limestone: Light grey, hard, compact, crystalline, moderately fossiliferous showing major vugs partially filled with blocky calcite and good porosity. **4e**: core photograph of limestone Light grey to buff, hard, compact, poor to moderately fossiliferous with good porosity in the form of major vugs, solution channels, and molds.

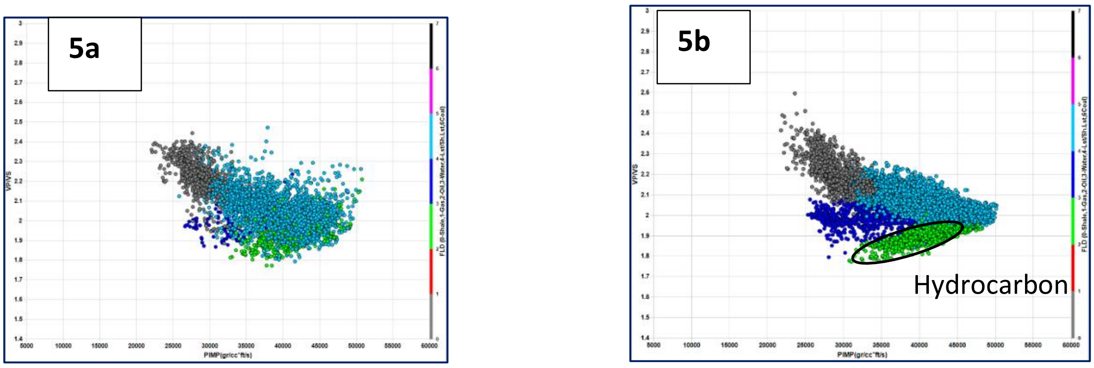

Figure 5: 5a & 5b shows P-Impedance (gr/cc*ft/s) versus Vp/Vs ratio cross plot of raw data and modeled data respectively. Facies codes: **0**-shale, **1**-Gas, **2**-Oil, **3**-Water, **4**-Shaly/tight Limestone.

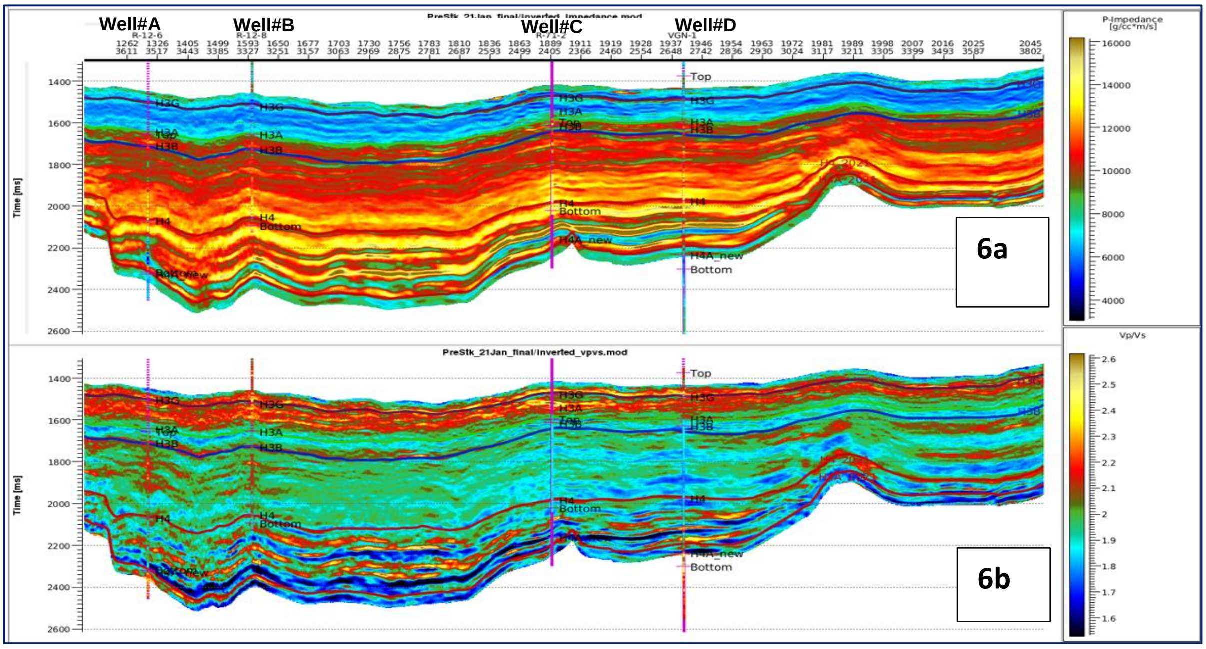

Figure 6: Figure 6a and 6b show P-Impedance and Vp/Vs ratio sections of pre-stack seismic inversion analysis respectively.

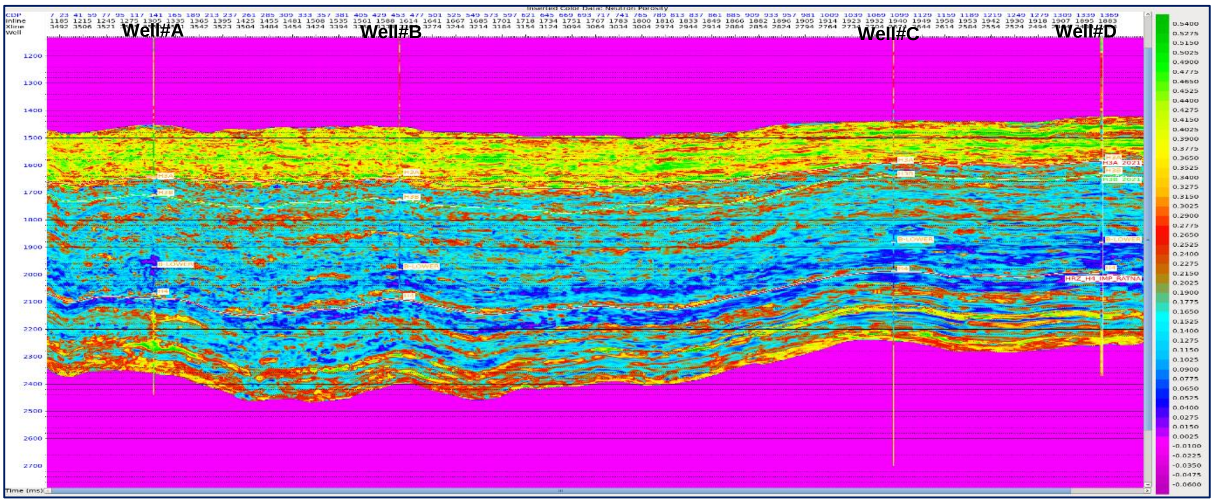

Figure 7: Neutron porosity section passing through wells in study area. Neutron porosity logs are overlaid on section.

Conclusions

In this study, the Xu-Payne carbonate rock physics model which is based on the Xu-White model is applied to derive compressional and shear wave velocities. The main challenge of carbonate porosity partitioning is achieved by the integration of resistivity image logs, SEM images of cores, core photographs, and NMR logs. This tight integration of core data, hi-tech log data has certainly reduced the uncertainty of porosity portioning in carbonates. When modelled results are in agreement with the core data this improves the confidence in interpretation. Cross plot of P-impedance vs. Vp/Vs colored with facies from recorded logs shows the mixing of different facies. Using the modelled logs from rock physics modelling probable hydrocarbon-bearing sections are identified. Geo-bodies can be extracted using the most probable hydrocarbon polygon, which may be indicative of reservoirs. This analysis needs to be combined with other G&G studies to firm up the identified prospects. It is worth mentioning that results of this tightly integrated analysis approach of petrophysics, rock physics modelling, core, and hi-tech log data inferences, with seismic inversion analysis, will improve characterization of these complex carbonate reservoirs and paves a way for further exploration activities in the study area with reduced risk.

Acknowledgement

The authors are indebted to ED-HOI-GEOPIC, ONGC, Dehradun, India for providing the technical input and guidance for writing this paper. Thanks are due to Head-INTEG, GEOPIC, ONGC, Dehradun, India for providing all kinds of support for this work. Thanks to Mr. Madhukar Singh, Superintending Geophysicist, GEOPIC, ONGC for his valuable technical input for this work. We thank ONGC management for allowing us to submit this paper in GEOINDIA - 2022.
The views expressed in this paper are solely of the authors and do not necessarily reflect the view of ONGC.

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