Improving Petrophysics & Rock Physics modelling through Data Analysis in Carbonate Reservoirs for effective Seismic Reservoir Characterization - A Case Study of Western Offshore Basin, India

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Summary
Petrophysics and rock physics both play a critical role in the evaluation of well and field potential. The analysis of the data in detail will lead to build conceptual model for defining the reservoir properties through petrophysical modeling. Petrophysics combines well log, core, mudlog, and other data to evaluate, predict, and establish formation lithology and porosity, hydrocarbon saturation, permeability, producibility, and estimate the economic viability of a well. Rock-physics establishes relationship between petrophysical properties and elastic properties of the rock necessary for the complete understanding and utilization of seismic data for future production activities. The accuracy and consistency of petrophysical and rock physics models determines the quality and reliability of all subsequent evaluation. Well log data and its analysis from various angles plays a crucial role in the process of integration. During drilling process log data are affected by borehole rugosity, invasion, mud cake formation, salinity, temperature & pressure etc. and even some times logs could be entirely missing or not usable due to bad hole conditions. Thus log data needs to be conditioned before starting its evaluation. Petrophysics outputs in addition with pore information are the building blocks of carbonate rock physics model. Pore systems are more complex in carbonate rocks than they are in clastics. Carbonates can have a variety of pore types, such as moldic, vuggy, interparticle, and intraparticle. Pore type analysis is the important parameter to reduce uncertainty in rock physics model. In general, most of the times, petrophysical evaluation, petro-elastic modeling and synthetic to seismic tie are done separately. This introduces uncertainty and inconsistency across the geoscientific data. Hence the input parameters in petrophysics and rock physics must be accurate enough to provide reliable results for effective seismic reservoir characterization. This paper highlights detail data analysis by various technique to firm up petrophysical evaluation and rock physics modeling of X field of Western Offshore Basin, India.

Geology of the Study Area
X is a wedge out prospect of Bassein Upper and Lower (Layer-I &II) in the southern and SE flank of B-121/119 high. The area under study is located 160 km West of Mumbai city in the Bombay High-Deep Continental Shelf (BH-DCS) tectonic block between adjoining shelf margin. The sedimentation in Mumbai Offshore Basin was initiated during the Late Paleocene period after the eruption of Deccan Basalt. First marine transgression was witnessed during early part of Late Paleocene. Subsequently, extensive transgression during late Paleocene and Early Eocene has deposited clastics in the proximal areas where as carbonates were deposited in the distal areas further south of the study area within basin. The area had experienced the first tectonic pulse probably by the close of Paleocene/Early Eocene which resulted in the uplift of a large part of the southern DCS

Fig: 1 Area of Study
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area and recorded a minor hiatus. It is envisaged that this tectonic pulse has manifested into a number of discrete highs. The onlapping sequence grades from silt, coal, shale to sand followed by carbonates. The subsequent rise in sea level has flooded the rift shoulders and a thick carbonate unit has been deposited through the Early and Middle Eocene with intervening shales at places. Middle Eocene marine transgression has resulted in extensive carbonate deposition. The sedimentation in the area has taken up on basaltic or granitic / metamorphic basement. The deposition of Paleocene to Early Eocene clastics and equivalent carbonates (Panna) took place unconformably over the Basement. The Middle to Late Eocene Bassein Formation, deposited unconformably over the Panna Formation. The Bassein Formation is overlain by Early Oligocene Mukta Formation & late Oligocene Panvel formation.

Methodology
Out of the 12 wells studied, 7 wells were selected for Petrophysics & rock physics modelling. 3 of these 7 wells had been logged with DSI and have core data available. After data gathering, all the data were loaded in the software for analysis. The common problems faced by interpreter are the data set of different service companies with different tool vintage. Sometimes the wells are drilled with different drilling fluids and also it is possible that data could not be recorded in the zone of interest due to bad hole condition. To overcome these situations the data from the different source needs to be rescaled, normalised, synthesised and edited for erroneous values. This process is known as log conditioning. The data is then depth matched and corrected for the environmental effects.

Quality Control of the log Data
After conditioning, the conditioned data should be confirmed by using the multi-well histogram as Quality control method in order to guarantee the correct and reasonability for the logging data conditions. The multi-well histograms are used to show the consistency of the log data among the 7 wells in this study. The following figure 2 shows the multi-well histograms of the conditioned log data at the Bassein, Mukta and Panvel formations. In the figure 2, left is the density histogram, middle is the compressional sonic histogram and right is the shear sonic histogram of Bassein, Mukta & Panvel formations. The histograms in the figure 2 indicate that there are very good consistency of the conditioning log data in these 7 wells. In Panvel formation, there are two types of litho units having two different porosity systems as indicated by density and sonic histograms. The QCs of log data indicate high quality log data conditioned has been achieved in this study. This will reduce the part of uncertainties in petrophysical evaluation and improve the petrophysical analysis.

Data Analysis for fixing Petrophysical parameters
The data after conditioning is now ready for the analysis. Crossplots are a convenient way to demonstrate how various combinations of logs respond to lithology and porosity. They also provide visual insight into the type of mixtures. Neutron porosity and density Crossplot is one of the strongest combination for identification of different lithology with fluid on linear scales with water-saturated pure lithologies graduated in porosity units. When the matrix lithology is a binary mixture (e.g., sandstone-lime or lime-dolomite or sandstone-dolomite) the point plotted from the log readings will fall between the corresponding lithology lines. In Fig.3, the Neutron-Density $Z_c$- plot with GR on Z axis of Bassein formation indicates dominant lithology as Limestone along with Dolomite and minor Clay. Pyrite and Dolomite have also been reported in core data (Ref.1). Therefore, based on these $Z_c$-plots along with the reported core, side wall core and cutting data analysis, Calcite, Dolomite, Pyrite and clay has been incorporated into petrophysical model and used for the processing of log data. In addition to these, the basic parameters which are applied throughout the interval covering different formations under study are the Temperature at the depth of computation (obtained from the surface and bottom hole temperatures), Mud density, Resistivity of mud, mud filtrate and mud cake (recorded in laboratory during drilling), Formation water salinity/ resistivity from Rt VS Phi Crossplot (Picket plot), Hydrocarbon type and its density from testing. The Petrophysical parameters $a$, $m$, $n$ which are responsible for saturation estimation are generally obtained from laboratory. The selection of water saturation equation depends upon the various situations of hydrocarbon accumulation and type of rock & its properties.
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Results of Petrophysical Analysis
The petrophysical parameters for Bassein processing were taken as $a = 1.08$, $m = 1.94$ and $n = 1.93$ from core study.
Using multi mineral model and other parameters interpreted from log data analysis, processing has been done. Good match has been observed between processed and core data for matrix density and porosity (Fig.4).
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Rock Physics Analysis for fixing Rockphysics parameters
The objective of the rock physics modelling is to provide a link between the petrophysical properties and the elastic properties of the rocks (Vp, Vs, ρb).

The methodology applied was to construct a rock physics model that was consistent with the petrophysical analysis and the elastic properties of the rocks. In this study, the Xu & Payne model 2009, extension of the Xu-White model (1995) was used to model the elastic logs based on the petrophysical results. The elastic parameters of the rock matrixes consisting of the minerals were estimated by using the following algorithms.

In this method, the mineral components are mixed together using Voigt-Reuss-Hill mixing, the pore space is included using the Differential Effective Medium (DEM) process (Xu and White, 1996) and Kuster-Toksoz (1974) theory to account for the mechanical interaction between the pores; the micro-pores with bound water (e.g., clay pores) are added first and will be included in the solid material for fluid substitution, followed by all other pores including water-wet micro-pores and empty (or dry) non-bound-water pores, which will used to calculate the dry frame elastic properties and the fluids are introduced using Gassmann’s equations. The key to the method is that, the total pore volume is divided into four pore types: (1) clay-related pores, (2) interparticle pores, (3) microcracks, and (4) stiff pores:

\[ \phi = \phi_c + \phi_{ip} + \phi_{crack} + \phi_{stiff} \]

In this area, analysis has been done on core data to quantify the pore types.

In 11m core, it is found that Open & Partially filled vugs are 12, healed fractures are 6, filled vugs are 4 and Open Fractures are 2. As per core data, vugs are partially filled with spar. Presence of drusy calcite and kaolinite and smectite clay in pore spaces has reduced the porosity of these reservoirs (fig.5).

Hence using Sensitivity Analysis, the final volume fraction of pore types that give the best fit between modelled and measured curves are:

<table>
<thead>
<tr>
<th>( \phi_c, \alpha_{clay} )</th>
<th>( \phi_{ip}, \alpha_{ip} )</th>
<th>( \phi_{crack}, \alpha_{crack} )</th>
<th>( \phi_{stiff}, \alpha_{stiff} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01, 0.06</td>
<td>0.92, 0.2</td>
<td>0.02, 0.03</td>
<td>0.05, 0.8</td>
</tr>
</tbody>
</table>

\( \phi \) is the porosity and \( \alpha \) is aspect ratio of respective pores.

The modelling result and the comparison with the measured data are presented for Well#A as in Fig.6. Red are the modelled logs and black are the conditioned logs.

There is good match observed between the conditioned & measured density, compressional sonic and shear sonic logs.
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Fig. 5: Reservoir Attributes of Bassein Formation: WELL#A, CC-1 Depth- 2342.15

Quality Check of Rock Physics Modelling
Quality check of the rock physics modeling is to ensure a high level of consistency to enable a single rock physics model to match all the data. The regression analysis of the elastic logs measured and modeled is used to carry out the quality check for the rock physics modelling in this study. The correlation coefficient is more than 70% in general for shear velocity whereas it is very high for density (more than 90%) and for compressional velocity (more than 75%) (Fig7). Result Analyses of Rock Physics Model
After integrating petrophysics and rock physics modelling, the effect of lithology, porosity and fluids are improved (Fig8). Figure 9 shows the Vp/Vs VS AI crossplot where fluids & lithology are clearly discriminating. Moreover it shows the two different shale trends corresponding to different clay types of Panvel formation. Based on this calibrated model, prediction have been done for shear velocity, compressional velocity and density for the remaining wells where shear wave data is not recorded.

Conclusion
The analysis of data in detail will lead to build robust Petrophysical & Rock Physics model that gives more realistic and consistent elastic logs. The lithology and fluid are identifiable in VpVs and p-impedance plots. However demarcation of type of fluid is not that distinct may be due to presence of stiff carbonates rock and low order of reservoir porosity. The various type of lithology like shale, porous limestone, tight limestone, argillaceous limestone are identifiable in VpVs and p-impedance cross plots. These modelled elastic logs will be used for Pre-stack seismic inversion study and finally to identify hydrocarbon bearing sand bodies in 3D volume.

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Fig. 7: Correlation between measured vs model data, Well# A (right), Well# D (left)

Fig. 8: VPVS VS AI Crossplot of measured logs (left) and modelled logs (right) of Well#A

Fig. 9: VpVs VS AI crossplot of modelled logs of Well#B (left) and Elan and 1D match with litho log in the right